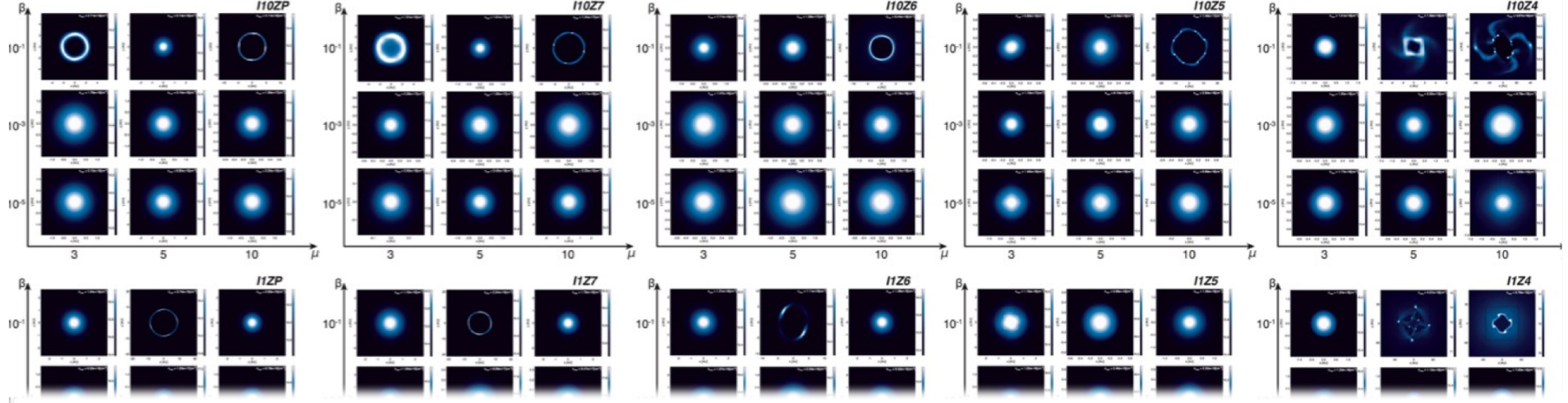
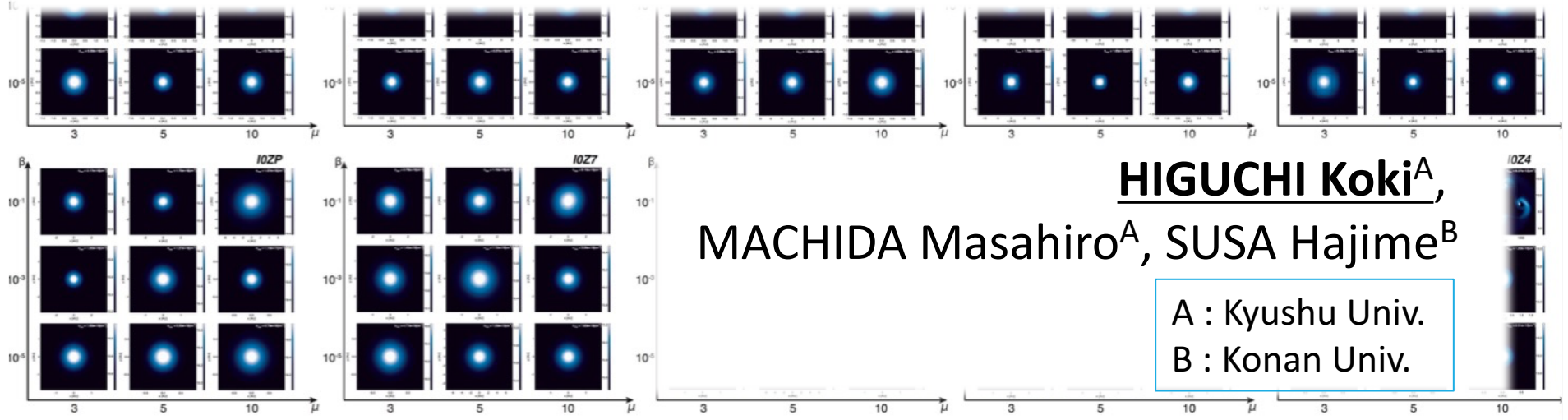


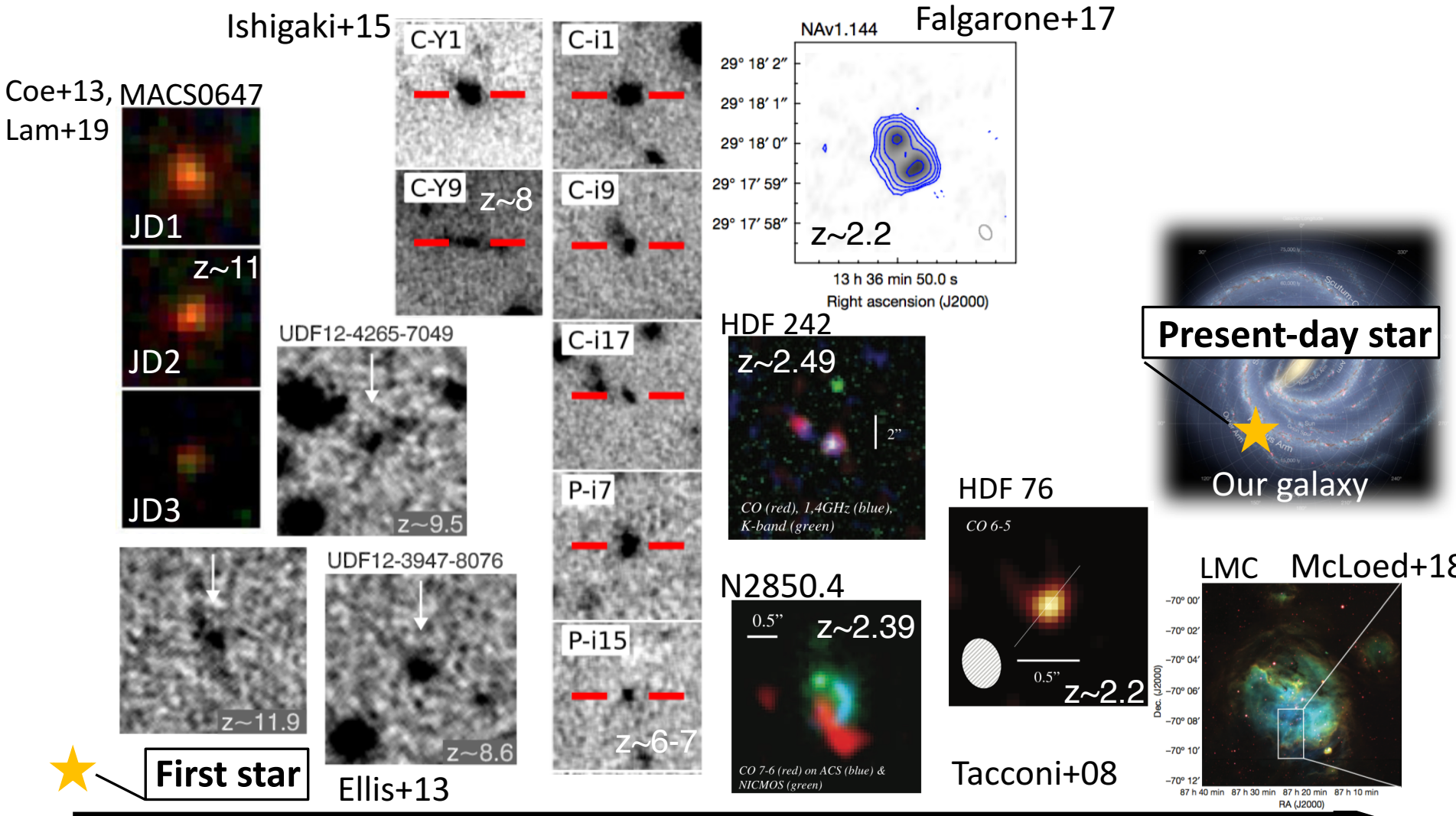

# Fragmentation of collapsing cloud with different environments




**HIGUCHI Koki**[A],
MACHIDA Masahiro[A], SUSA Hajime[B]

A : Kyushu Univ.
B : Konan Univ.

# Various star-forming environments



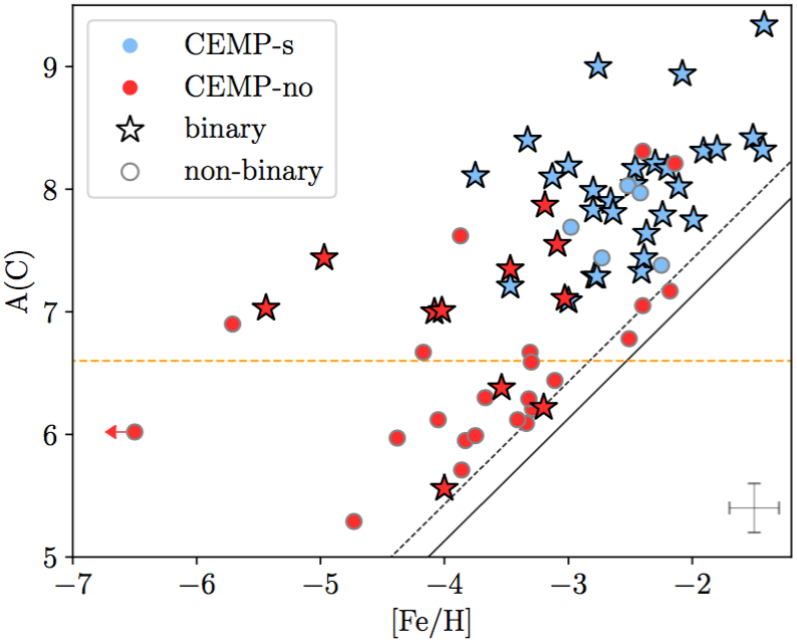
# Binary

- field stars -> 60%–80% (e.g., Duquennoy Mayor 1991)
- metal-poor stars

CEMP-s stars -> almost 100% (e.g., Mc-Clure & Woodsworth 1990 , Lucatello+05)

CEMP-no stars -> 47% with A(C) > 6.6

18% with A(C) < 6.6 (Arentsen +19)



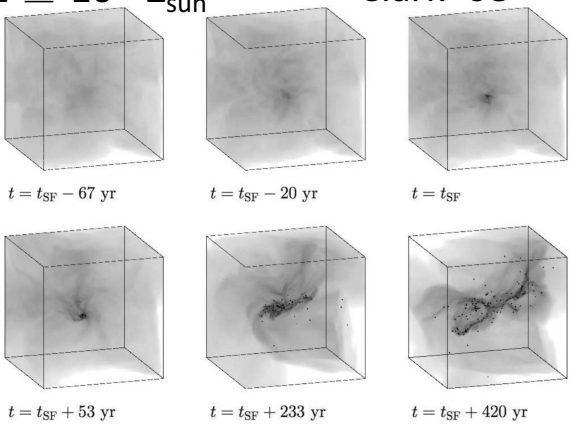

In lower metallicity star formation, the same trend as this figure?

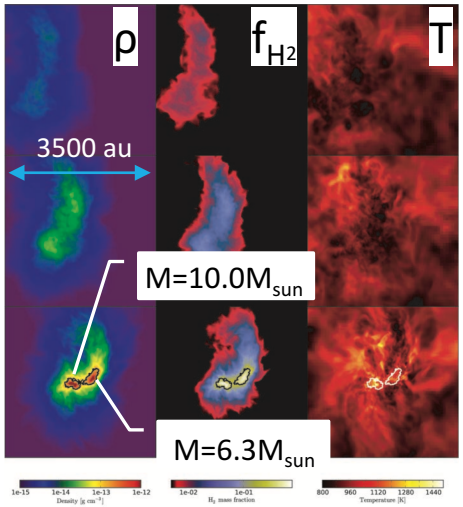
# Binary

Z = 0 (cosmological initial conditions)

binary fraction of ~35 %, with semi-major axes as large as 3000 au

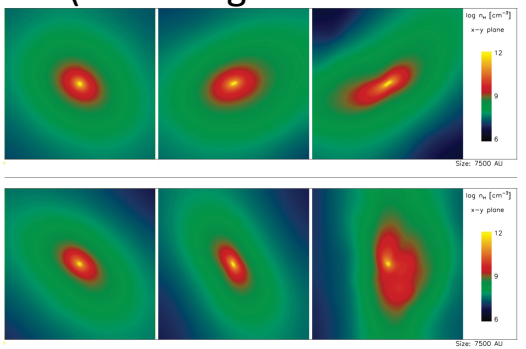
$Z \leqq 10^{-5}\ Z_{sun}$ Clark+08



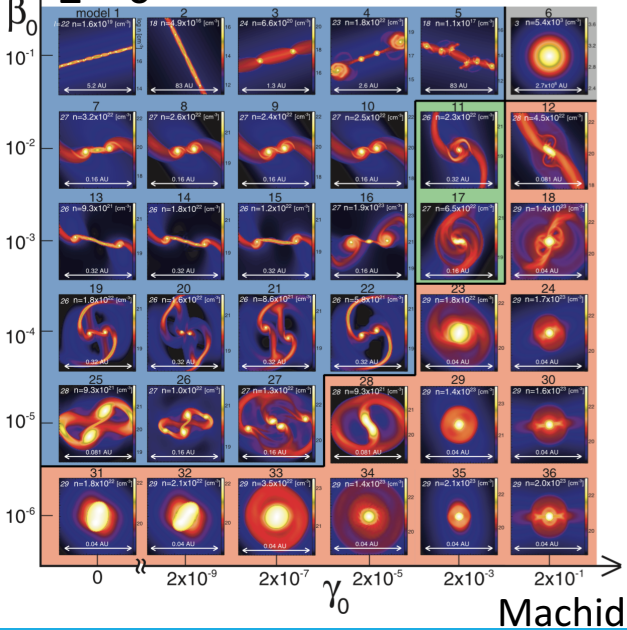

Turk+09

Z = 0 (cosmological initial conditions)



Stacy & Bromm 13

Z = 0 Ideal MHD simulation




Machida+08

magnetic braking, flow launching

Magnetic fields play a critical role in binary formation
(e.g. angular momentum transfer)
-> bainary formation is changed?

# Models:

## three-dimensional non-ideal MHD nested grid simulations

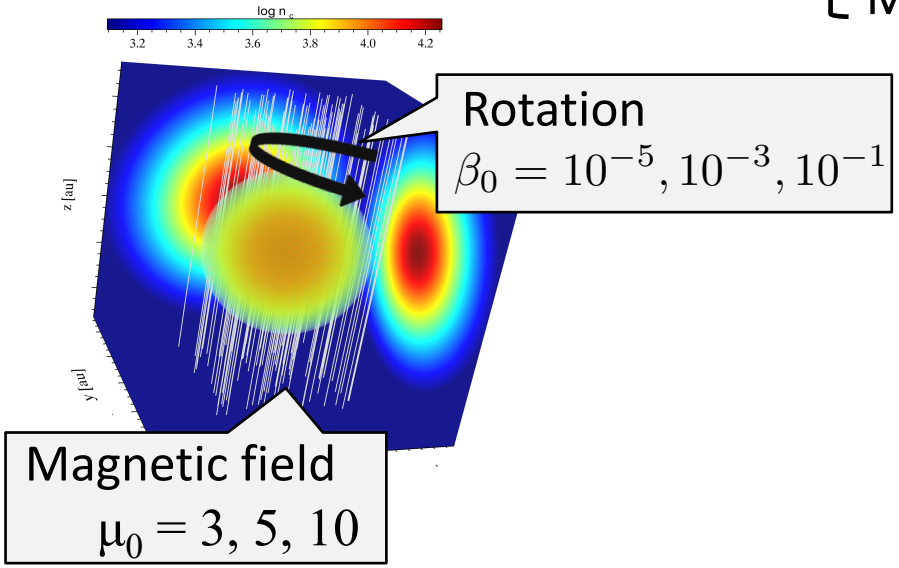
### INITIAL CONDITIONS

- Clouds have each critical Bonner-Ebert density profiles

Ionization parameter $C_\zeta = 0,\ 0.01,\ 1,\ 10$

×

Metallicity $Z/Z_\odot = 0,\ 10^{-7},\ 10^{-6},\ 10^{-5},\ 10^{-4},\ 10^{-3},\ 10^{-2},\ 10^{-1}$




Rotation

$\beta_0 = 10^{-5}, 10^{-3}, 10^{-1}$

Magnetic field

$\mu_0 = 3,\ 5,\ 10$

Definition

$$\mu_0 = \frac{(M/\Phi)}{(M/\Phi)_{\rm cri}},\quad \left(\frac{M}{\Phi}\right)_{\rm cri} = \frac{1}{2\pi G^{1/2}}.$$

### BASIC EQUATIONS

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

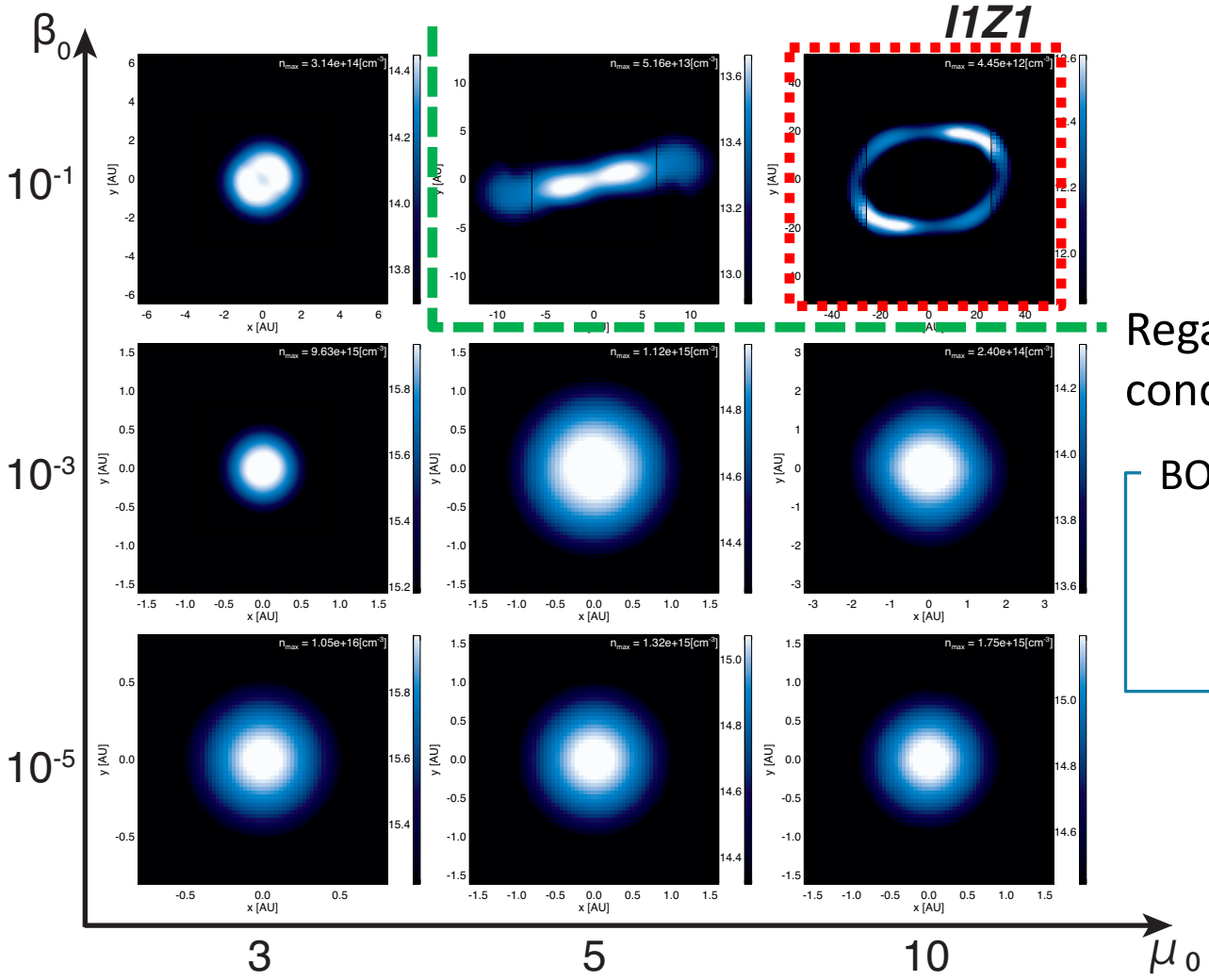
$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + \rho(\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = -\nabla \boldsymbol{P} - \frac{1}{4\pi}\boldsymbol{B} \times (\nabla \times \boldsymbol{B}) - \rho \nabla \phi$$

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

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

$$P = P(\rho)$$

# Fragmentation in model I1Z1 ($C_\zeta = 1$, $Z/Z_{sun} = 10^{-1}$)




Regarding initial condition ($\mu_0$, $\beta_0$),

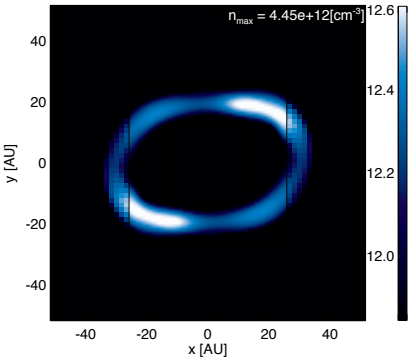
BOUNDARY

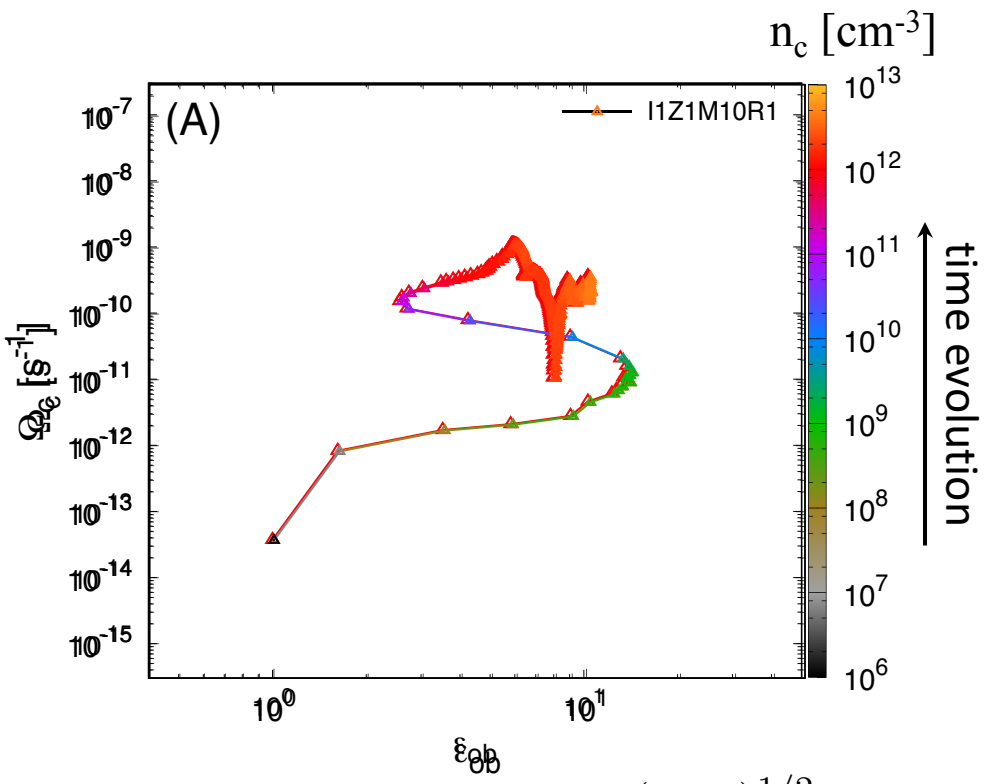
$$\mu_0 > 3$$

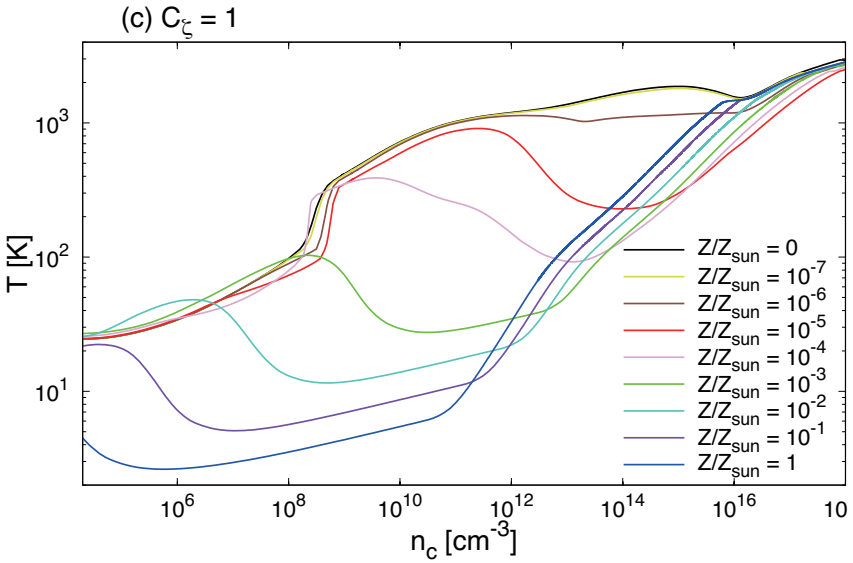
$$\beta_0 > 10^{-3}$$

# Fragmentation in model I1Z1M10R1

## ($C_\zeta = 1$, $Z/Z_{sun} = 10^{-1}$, $\mu_0 = 10$, $\beta_0 = 10^{-1}$)



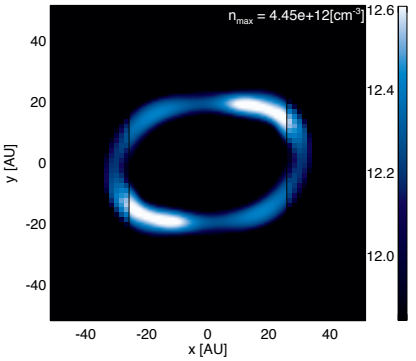



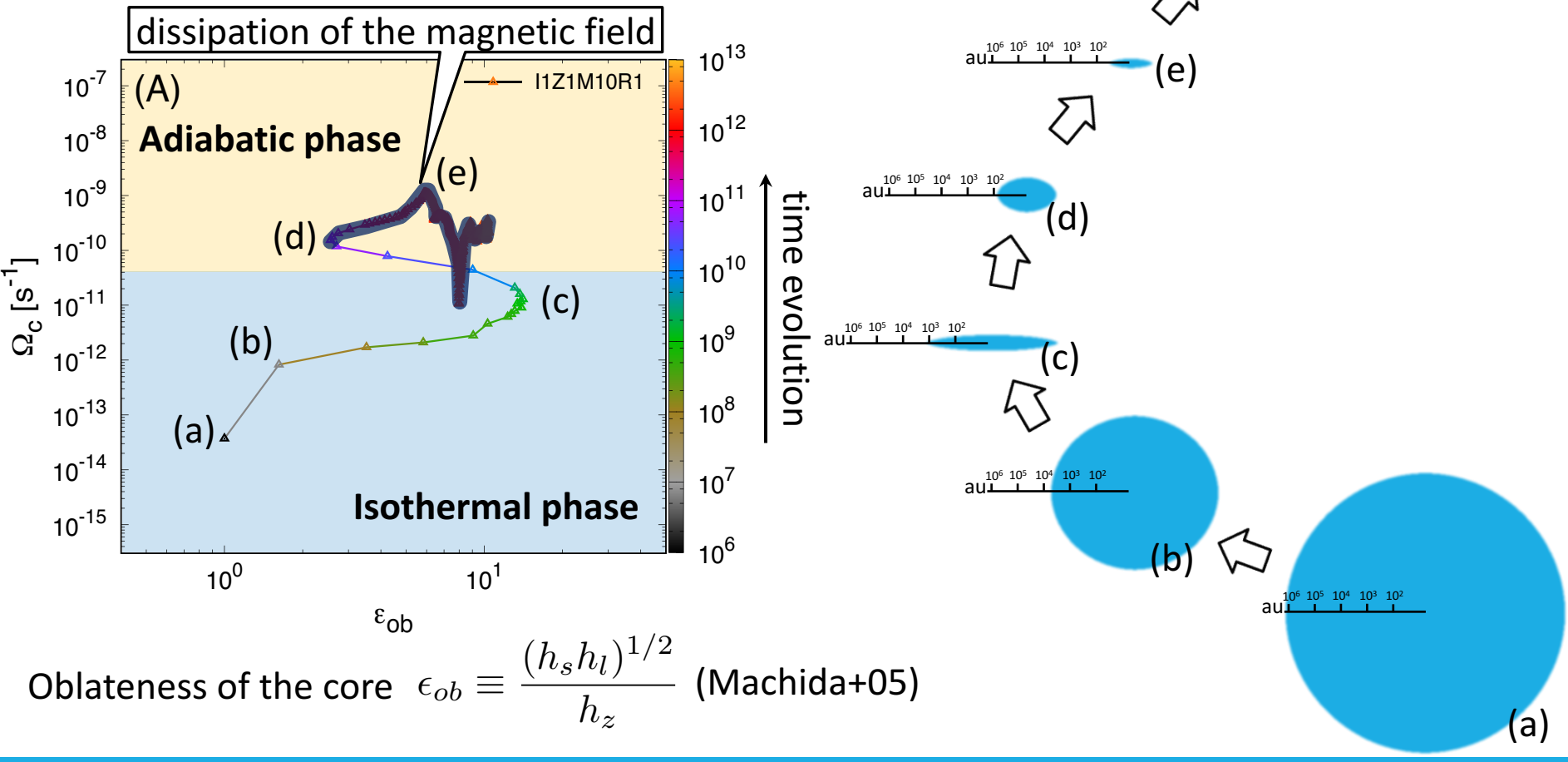




Oblateness of the core $\epsilon_{ob} \equiv \dfrac{(h_s h_l)^{1/2}}{h_z}$ (Machida+05)

# Fragmentation in model I1Z1M10R1

## ($C_\zeta = 1$, $Z/Z_{sun} = 10^{-1}$, $\mu_0 = 10$, $\beta_0 = 10^{-1}$)

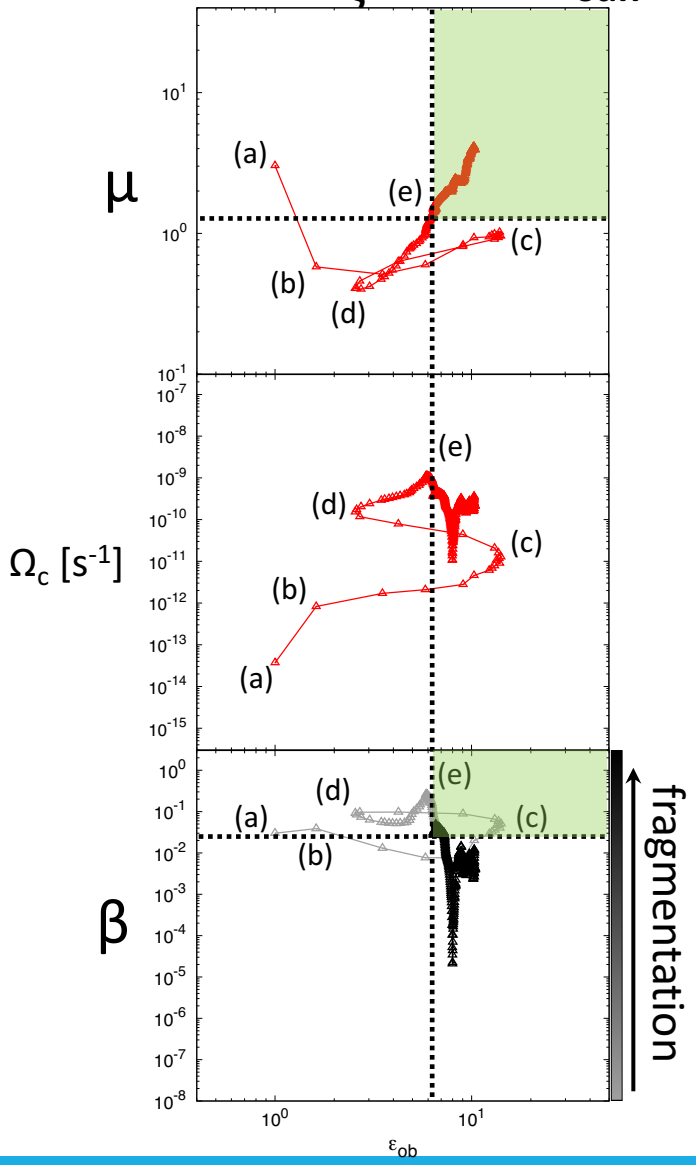


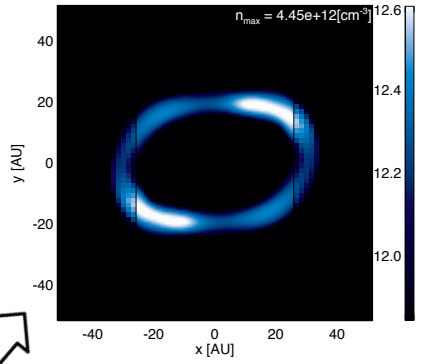



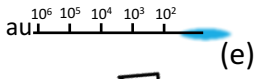

Oblateness of the core $\epsilon_{ob} \equiv \dfrac{(h_s h_l)^{1/2}}{h_z}$ (Machida+05)

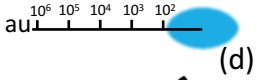
# Fragmentation in model I1Z1M10R1

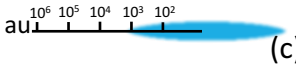
## ($C_\zeta = 1$, $Z/Z_{sun} = 10^{-1}$, $\mu_0 = 10$, $\beta_0 = 10^{-1}$)




Dissipation of magnetic field

↓

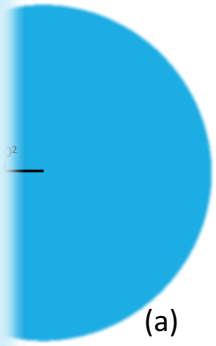
μ high

&

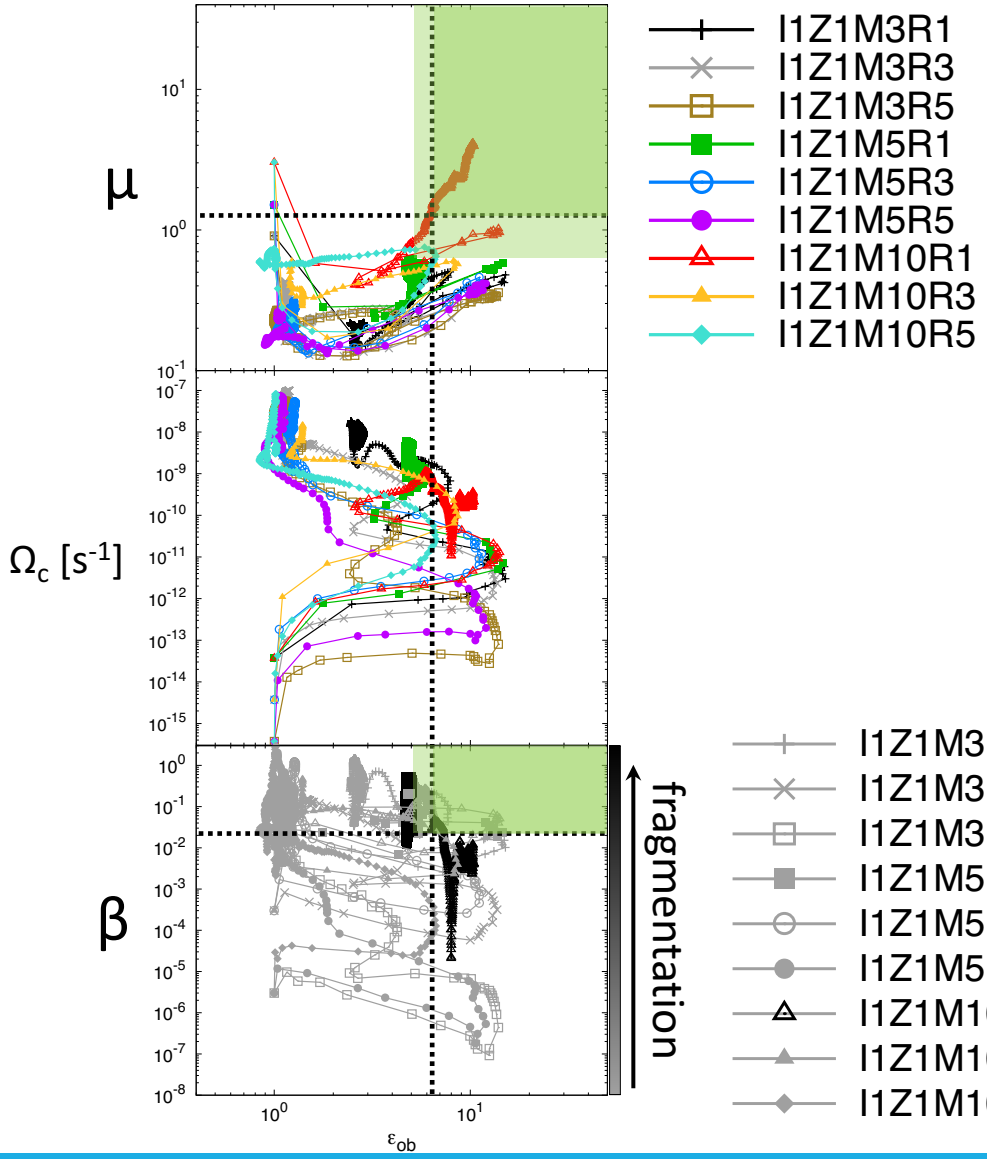
Promotion of fragmentation

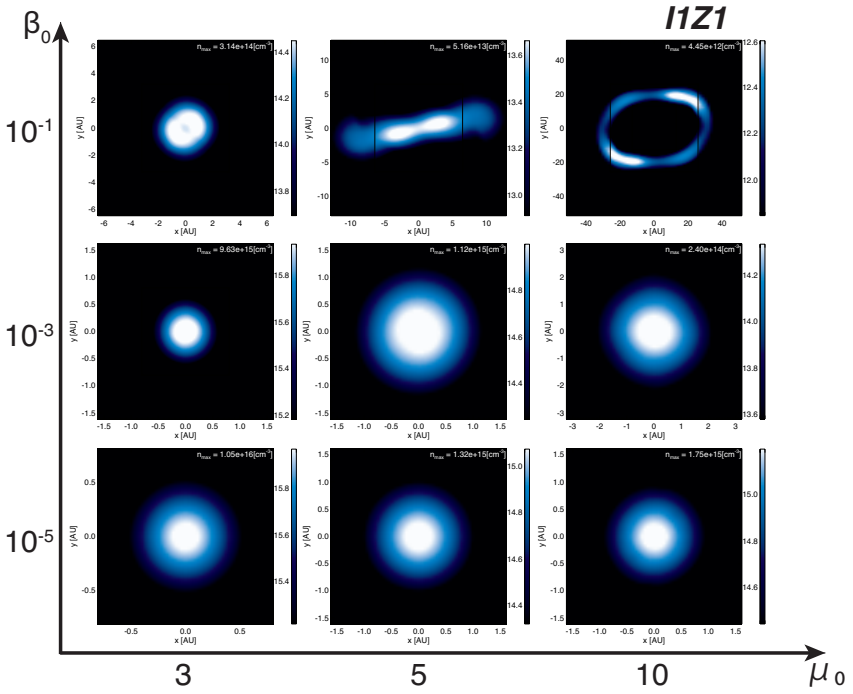
Fragmentation timing:

1. $\epsilon_{ob} \geq 6$
2. $\mu \geq 1$
3. $\beta \geq 10^{-2}$



# Fragmentation in model I1Z1 ($C_\zeta = 1$, $Z/Z_{sun} = 10^{-1}$)

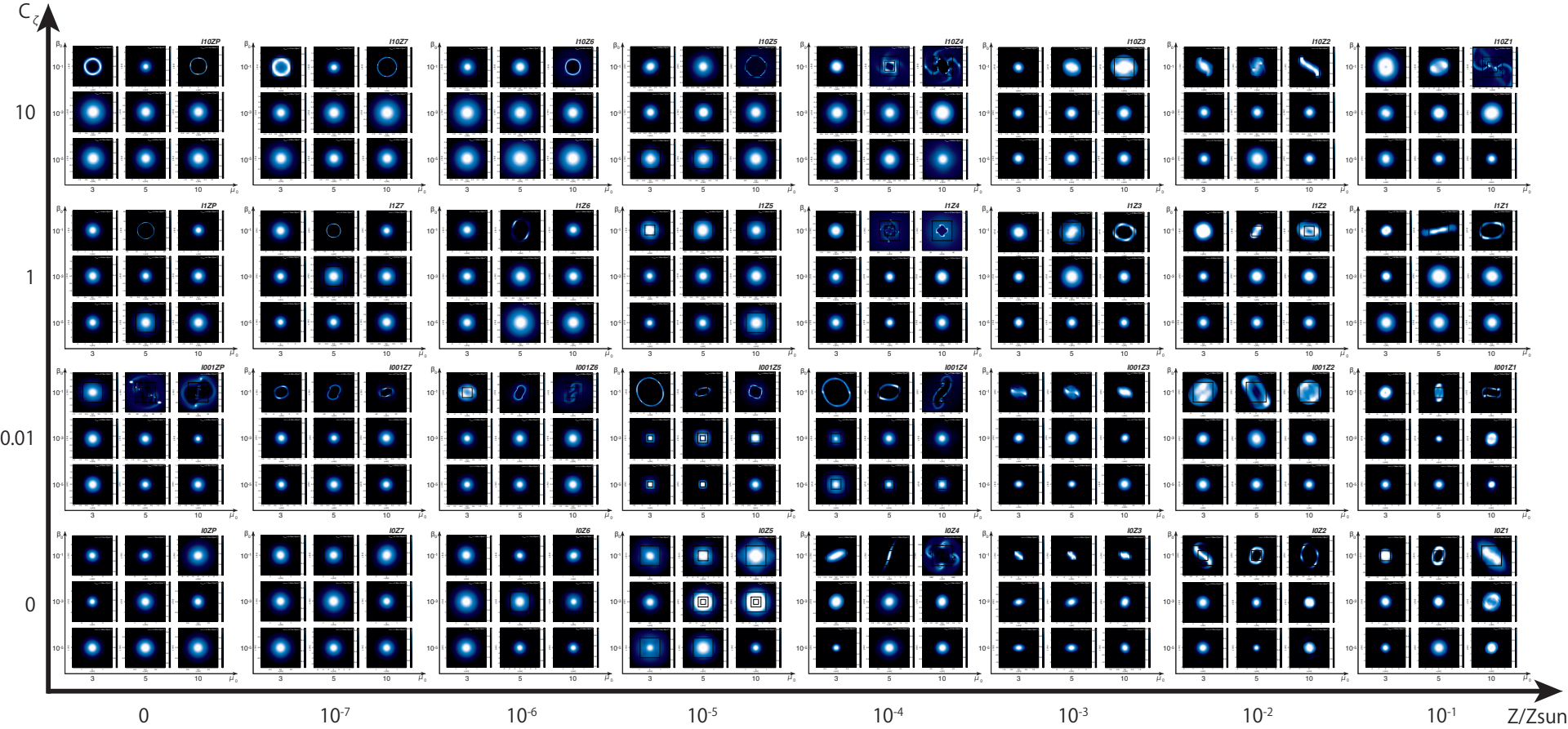



## Fragmentation timing:

1. $\epsilon_{ob} \geq 5$
2. $\mu \geq 0.6 - 1.0$
3. $\beta \geq 10^{-2}$

# ALL RESULTS


C_ζ
10
1
0.01
0
I10ZP
I10Z7
I10Z6
I10Z5
I10Z4
I10Z3
I10Z2
I10Z1
I1ZP
I1Z7
I1Z6
I1Z5
I1Z4
I1Z3
I1Z2
I1Z1
I001ZP
I001Z7
I001Z6
I001Z5
I001Z4
I001Z3
I001Z2
I001Z1
I0ZP
I0Z7
I0Z6
I0Z5
I0Z4
I0Z3
I0Z2
I0Z1
0
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
Z/Zsun

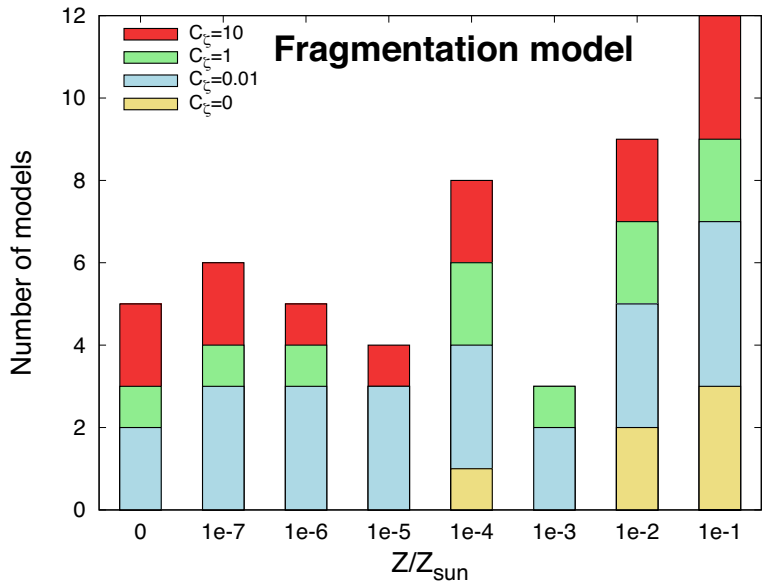
# ALL RESULTS

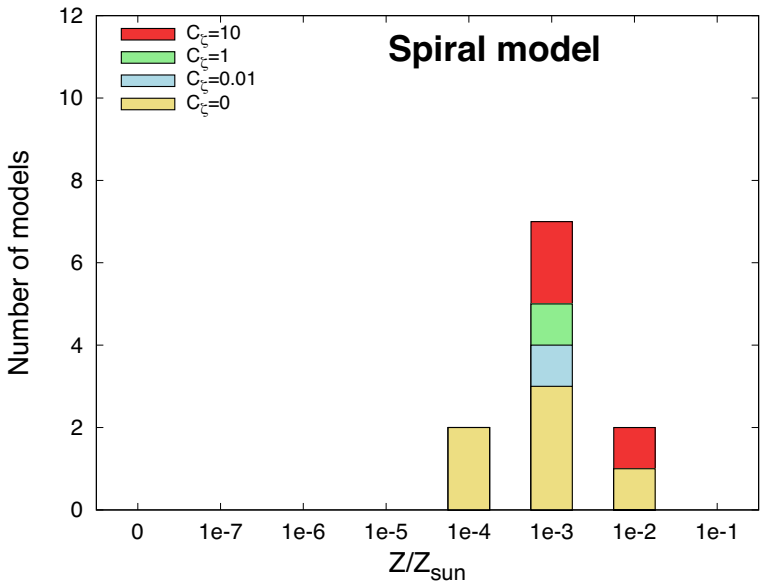
Boundary condition of fragmentation:

1. **high ionization strength**
2. **high metallicity**
3. $\mu_0 > 3$
4. $\beta_0 > 10^{-3}$

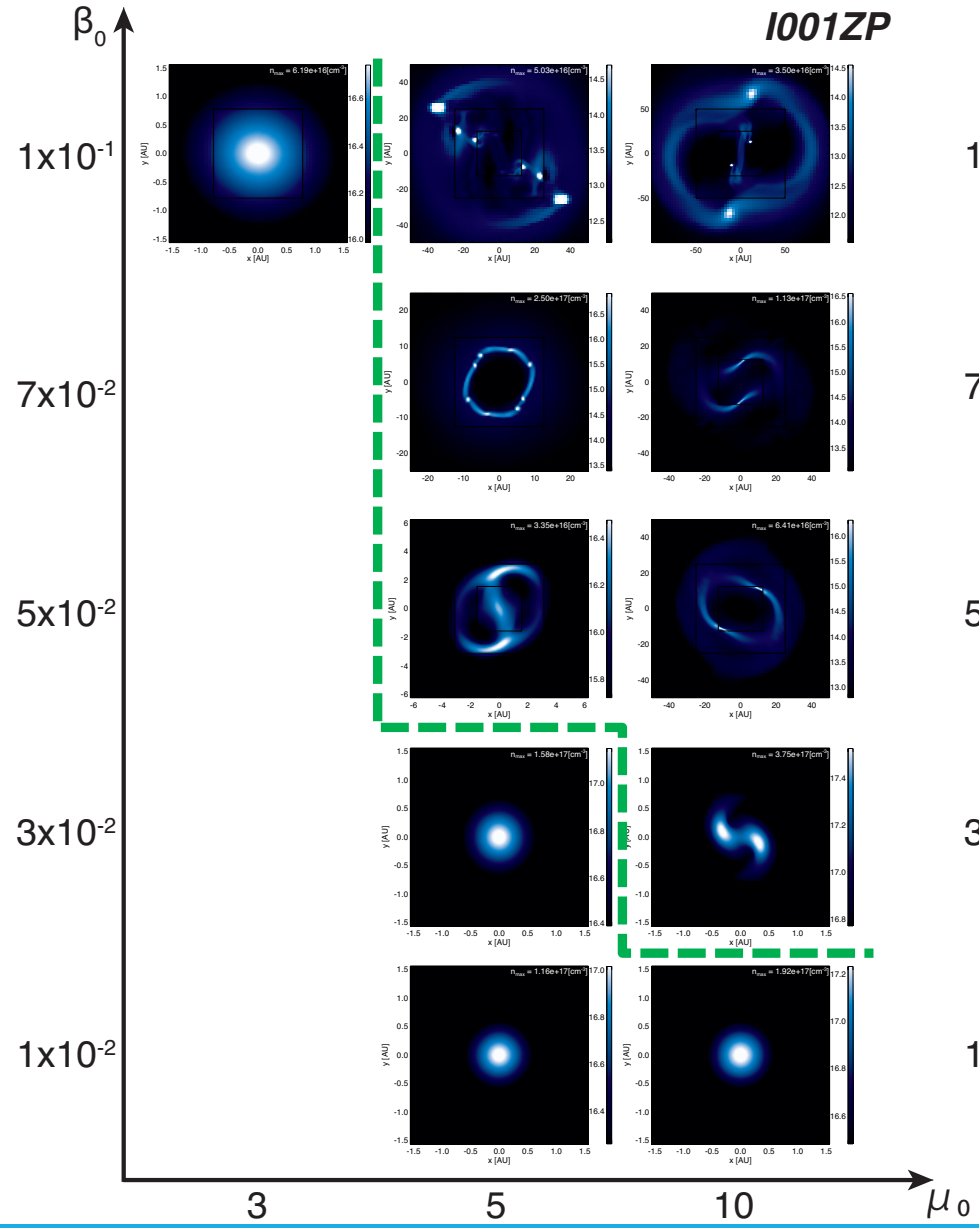
Fragmentation timing:

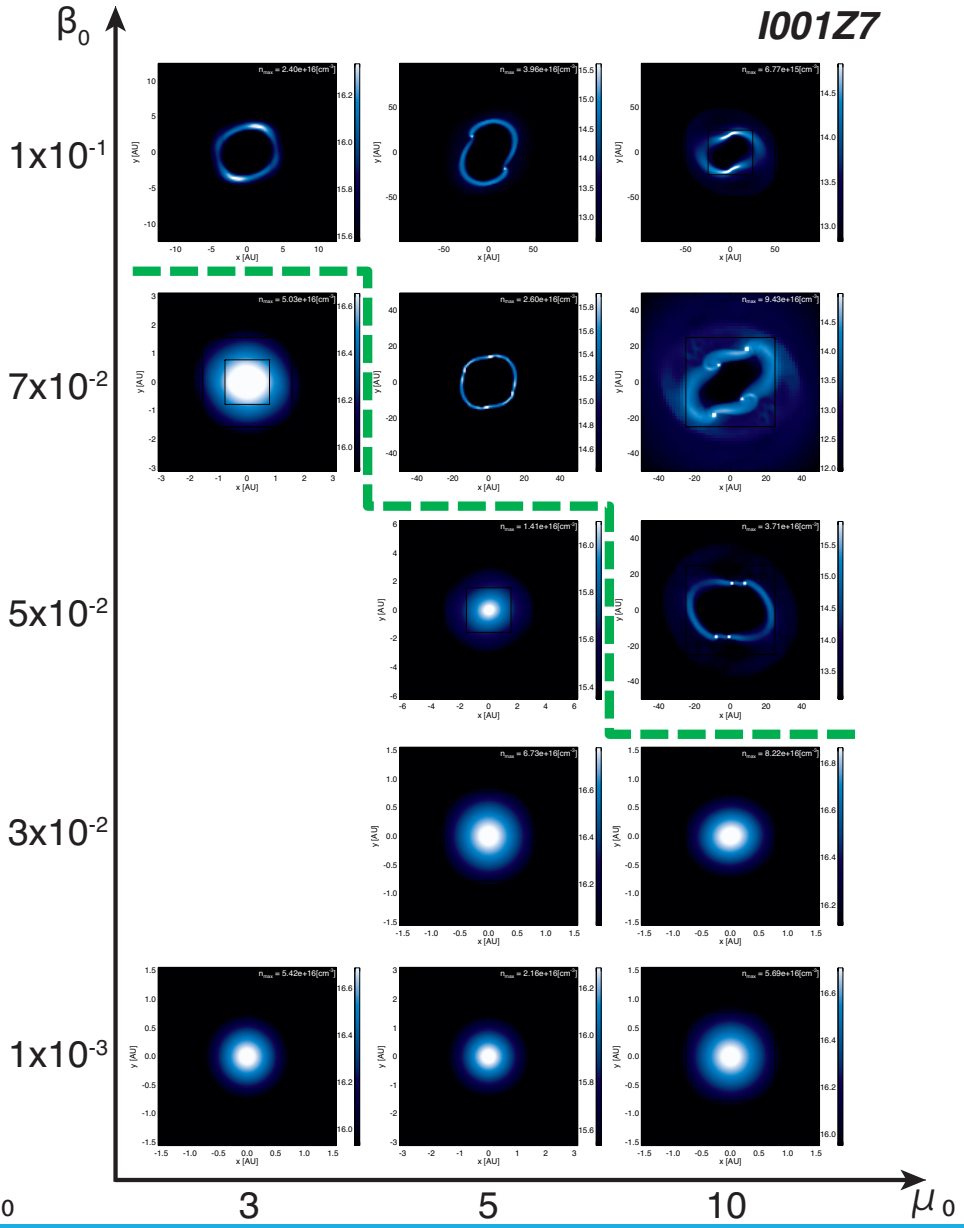
1. $\epsilon_{ob} \geq 5$
2. $\mu \geq 0.6 - 1.0$
3. $\beta \geq 10^{-2}$



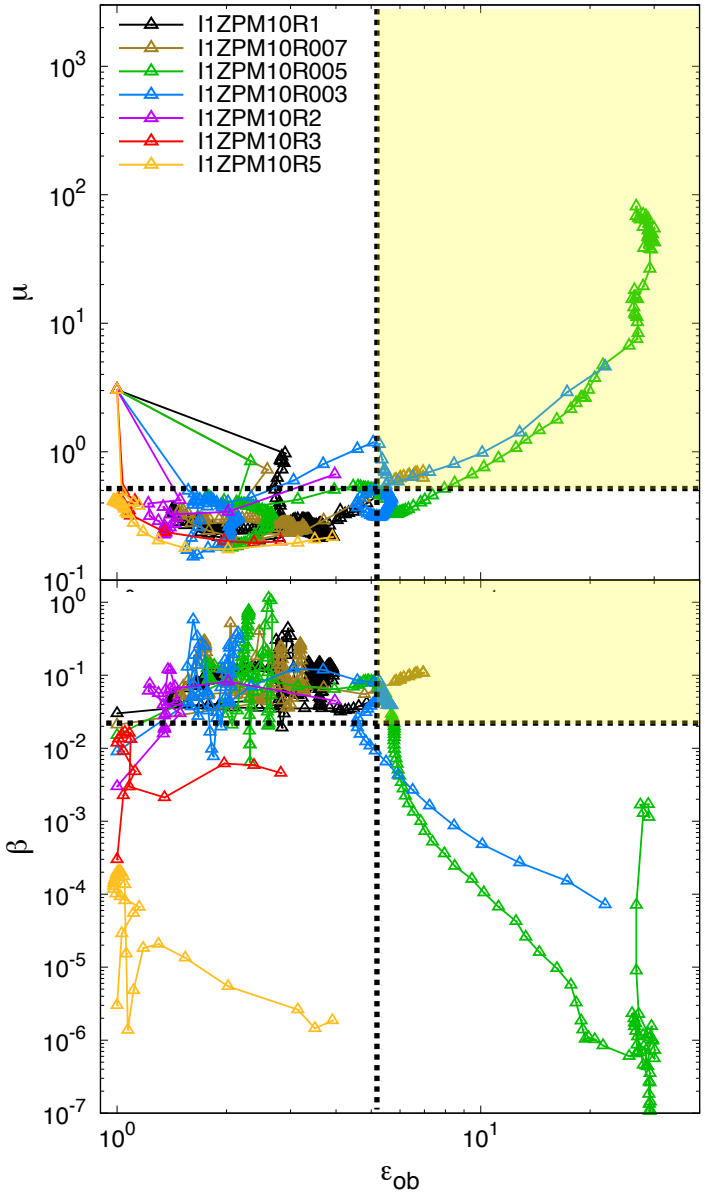



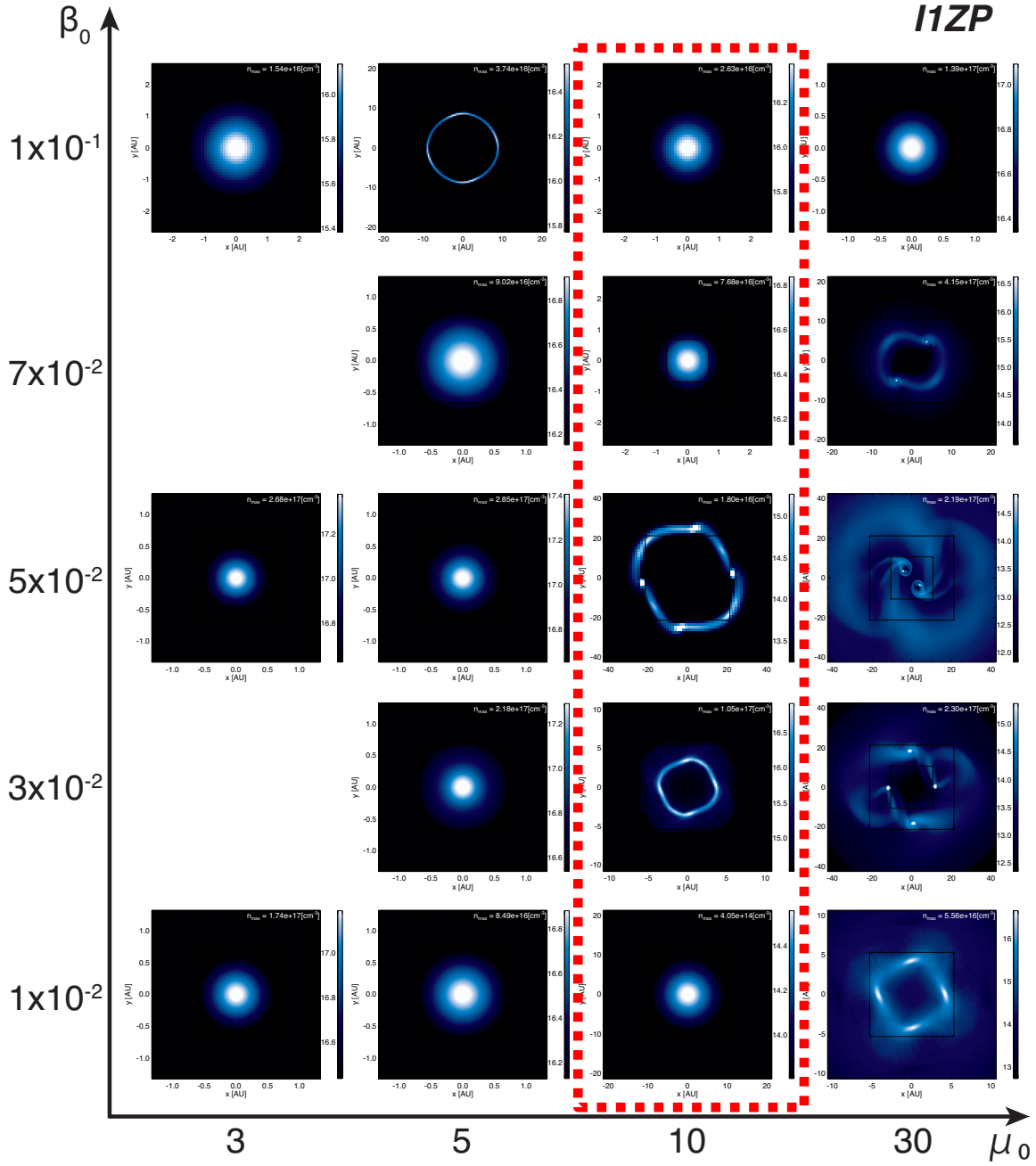
# The case of model I001ZP, I001Z7



# The case of model I1ZP



# SUMMARY

・Of our 334 models,
71 fragment, 15 form a spiral structure but do not fragment

Boundary condition of fragmentation:

1. $\mu_0 \geq 10$
2. $\beta_0 \geq 3 \times 10^{-2}$

→ In almost any environments, the cloud is fragmented.

Fragmentation timing:

1. $\epsilon_{ob} \geq 5$
2. $\mu \geq 0.6 - 1.0$
3. $\beta \geq 10^{-2}$

Non-fragmentation models (with high $\mu_0$ and $\beta_0$) may fragment when further evolution occurs
→ closed binary
(the origin of BH binary ???)