東北大学

Theoretical Astrophysics
Tohoku University

Evolution of Primordial Protostars under Global Gas Accretion in 3D RHD Simulations

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Collaborators

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The 10th East Asian Numerical Astrophysics Meeting
@ Jeju, South Korea, 15 -19. September. 2025

Outline

1. Introduction
2. Method
3. Results
4. Summary

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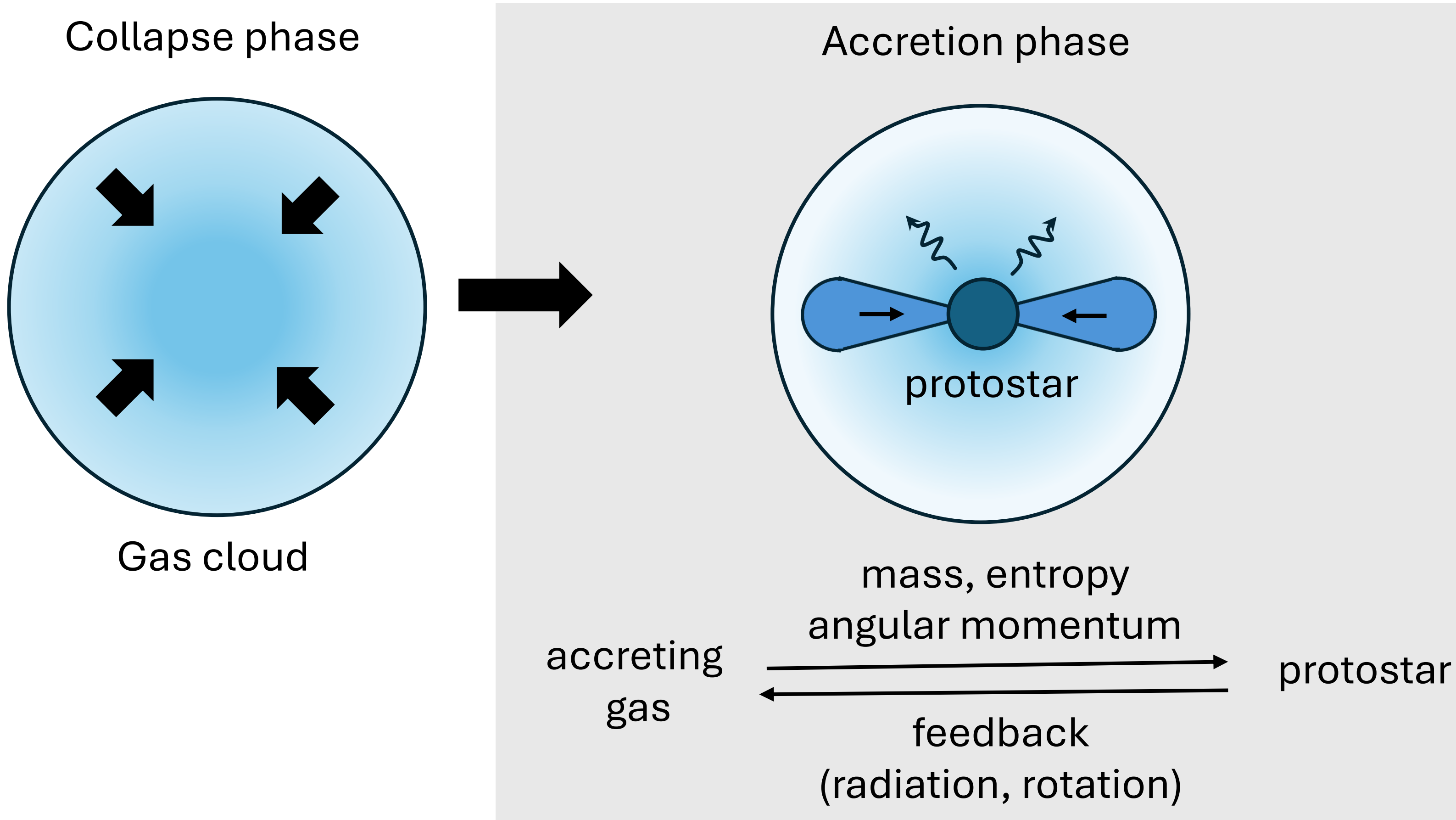
Star Formation

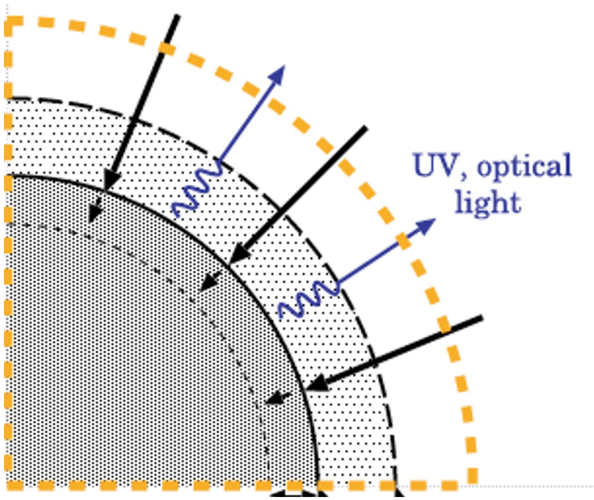


The protostar and the accretion flow evolve while interacting with each other.

The final stellar properties are determined during the accretion phase.

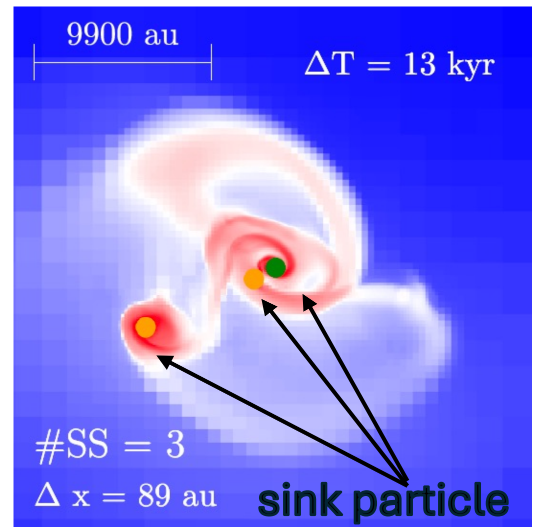
1D Protostar and 3D Accretion Flow

1D Stellar Evolution Calculation



(Hosokawa & Omukai 09)

3D RHD simulation



(Regan & Downes 18)

While accretion flows have been extensively studied in 3D, protostellar evolution is still mainly treated in 1D.

Key Question and Our Approach

How do protostars and accretion flows evolve in 3D while interacting with each other?

⬇

3D RHD simulation resolving both accretion flow and protostars

- a **new RHD solver** for solving radiative transfer down to protostellar interior based on an explicit M1 closure.
- application to **primordial high-mass star formation**

Today’s talk highlights the scientific results.

(Related work : Luo+18, Ahmad+24,scheme and context are different from ours)

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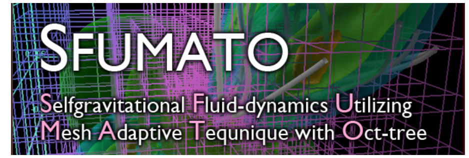
3D RHD Code based on SFUMATO-RT

- Self-gravity
- Adaptive Mesh Refinement



(Matsumoto 07, Sugimura+20,23)

- Chemistry network and thermal processes for primordial gas

  Chemical species : $\mathrm{H}, \mathrm{H_2}, \mathrm{H^+}, \mathrm{H^-}, \mathrm{H^{2+}}, \mathrm{e}$

- **Newly developed RHD solver**

We solve the radiative processes consistently with gas evolution all the way to the protostellar interior in our simulations.

➢ explicit M1-closure method w/ reduced speed of light
(Fukushima & Yajima 20)

➢ modified scheme for the very dense medium
(Rosdahl & Teyssier 15)

➢ Separately solve radiation energy density & photon number density to approximately get the spectrum

Setup : Primordial Star Formation

- Cosmological initial condition from GADGET2 (Chon+18)

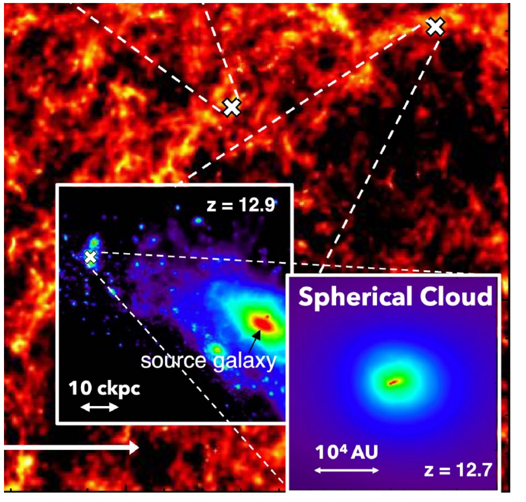
  Gas cloud at redshift $z \sim 13$

  irradiated by strong FUV radiation from a nearby galaxy

  ⬇

  Atomic cooling halo

  Accretion rate $\dot{M} \sim 1\, M_{\odot}\, \mathrm{yr}^{-1}$



(Chon+18)

- Box Size ~ 100 pc

- Resolution

  Resolve Jeans length with 8 cells.

  The maximum resolution = 4.7×10^{-3} au.

  (c.f. radius of primordial protostar $\gtrsim 0.5$ au, Hosokawa+12)

- We follow collapse and accretion phases of the system until **7 years** after the protostar formation.

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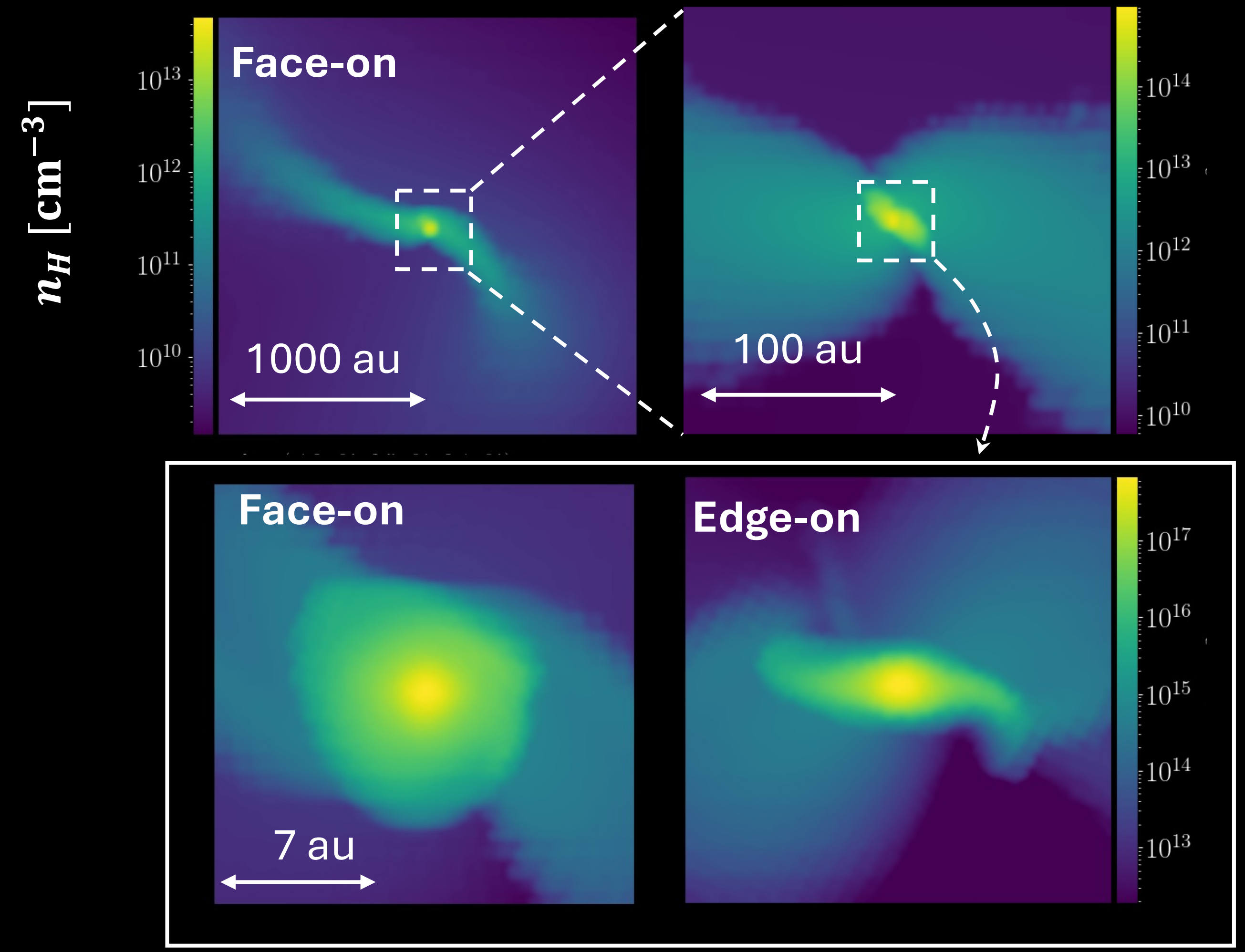
Final Snapshot

At 7 years after the protostellar formation.



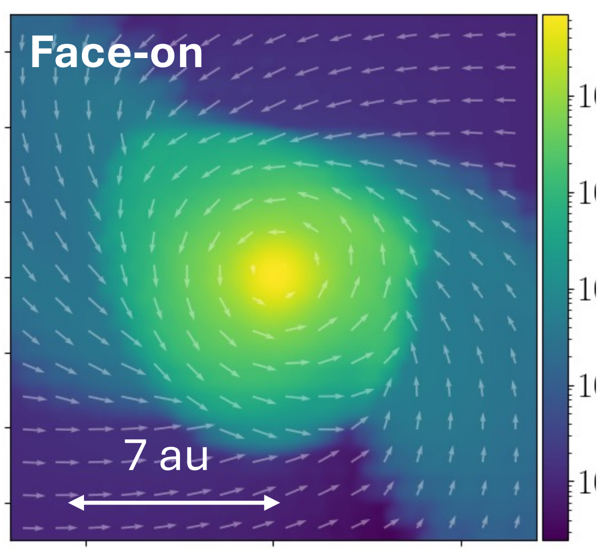
large-scale filament → small-scale protostar + disk

Smooth Protostar–Disk Transition

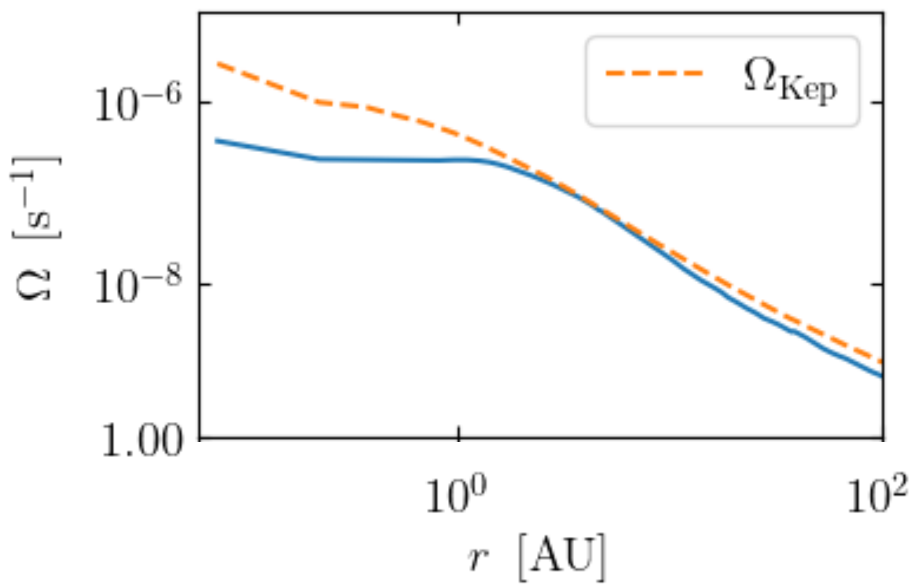
The protostar is no longer a stand-alone object defined by an accretion shock, but smoothly connected to the disk.

- Protostar = pressure support, $M_* \sim 5M_\odot$
- Accretion disk = centrifugal support, $M_{\text{disk}} \sim 6M_\odot$

Density snapshot



Rotation profile



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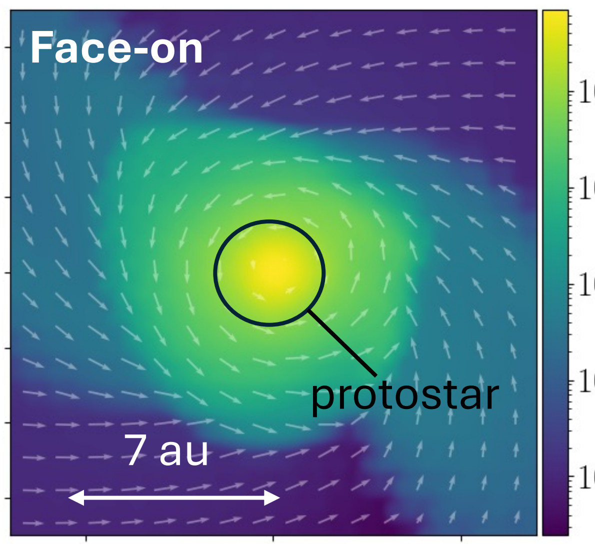

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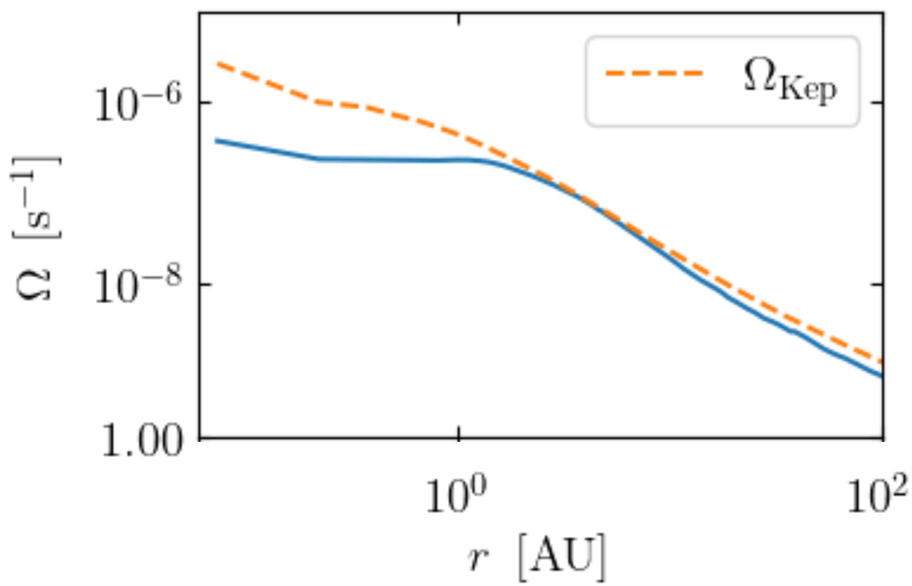
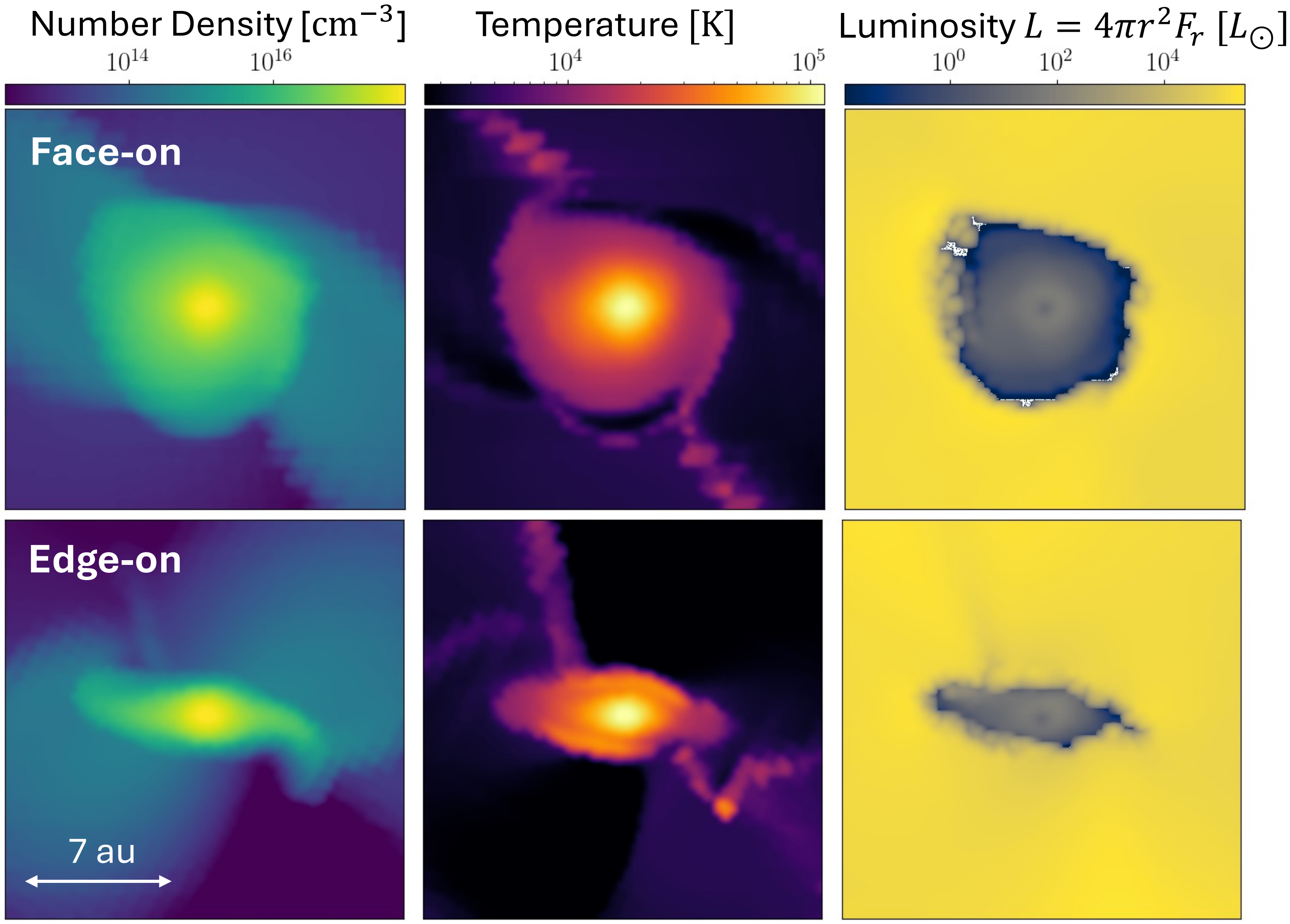
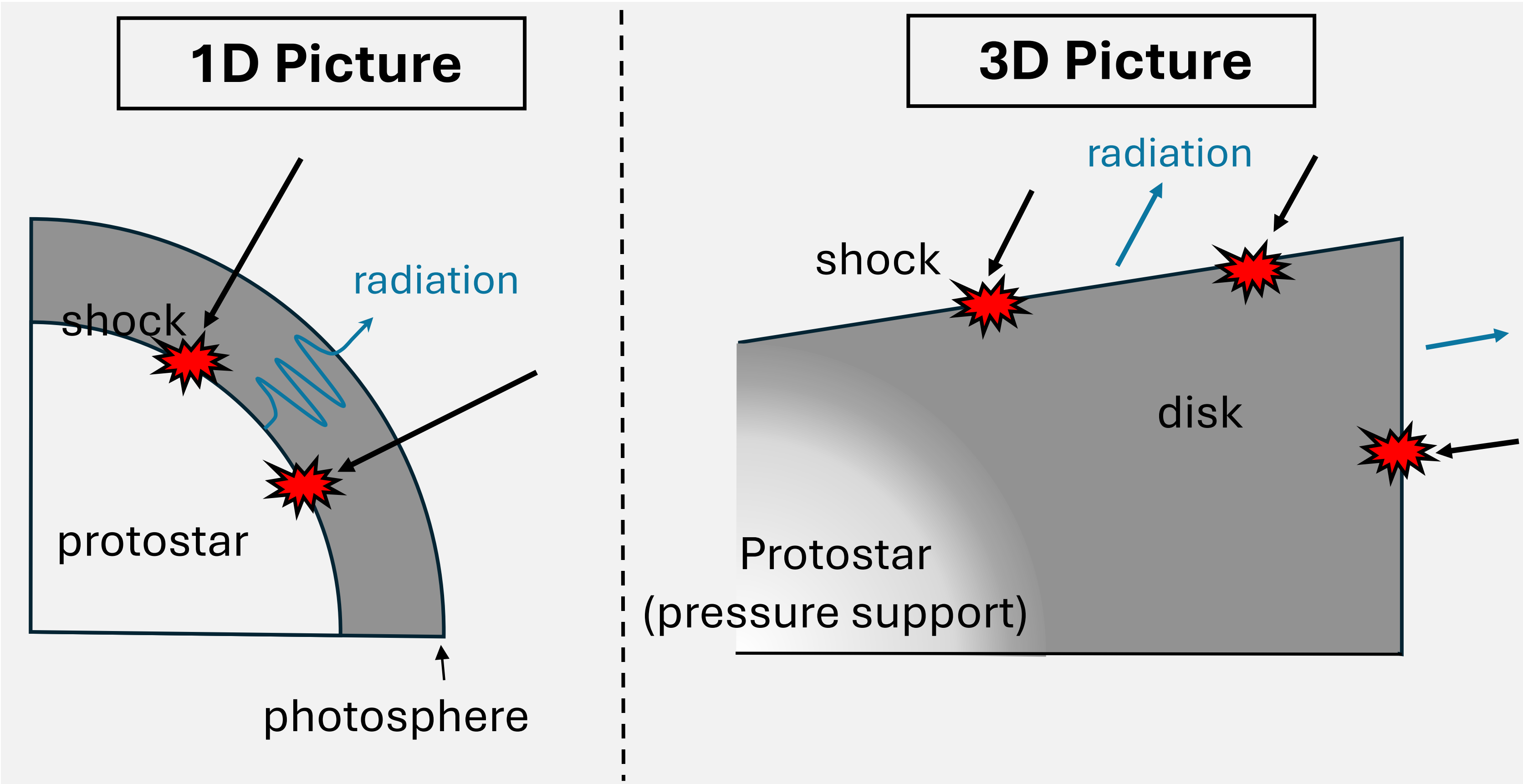


Hot and Optically Thick Disk

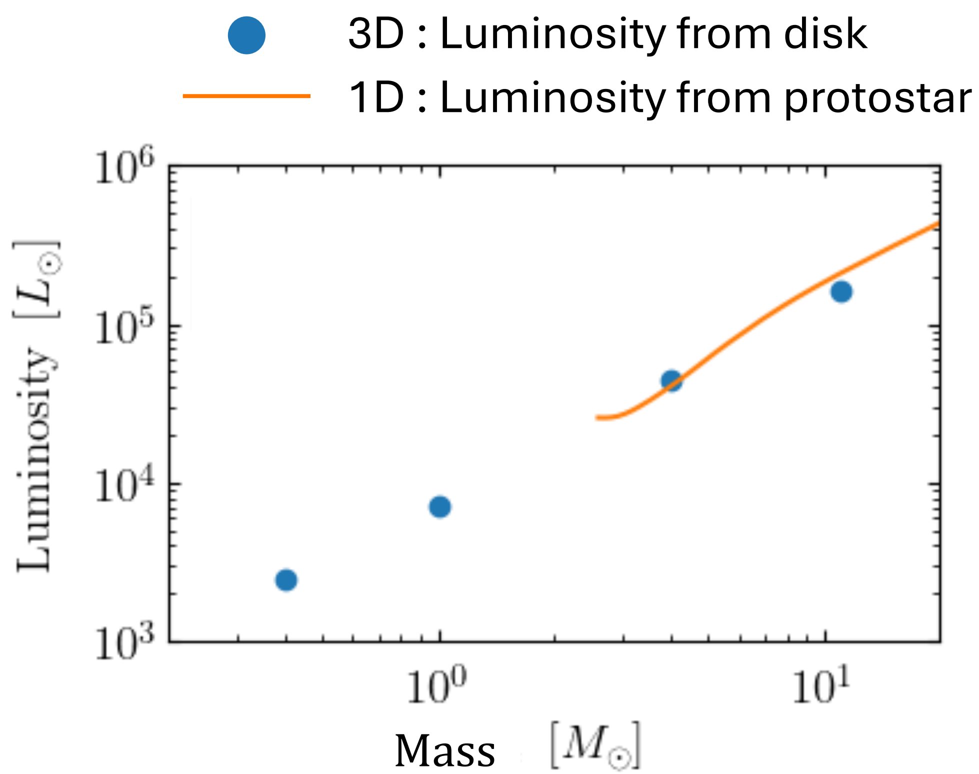


Protostar and Disk Evolution in 3D



- No discontinuity between the protostar and disk.
- Thermal energy generated at the shock surface is stored into the disk.
- Accretion luminosity originates from the disk surface

Luminosity Evolution



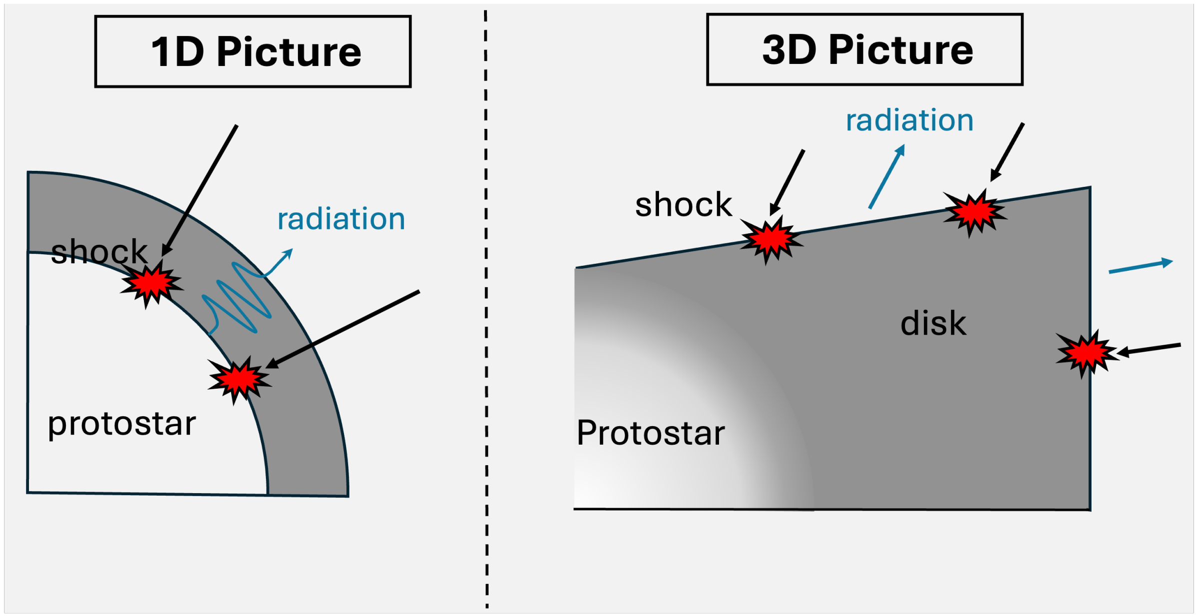
- Disk luminosity in 3D ≈ Protostellar luminosity in 1D
- Disk is in the adiabatic accretion phase and gain entropy due to accretion.

$$t_{\mathrm{acc}} \equiv \frac{M_{\mathrm{disk}}}{\dot{M}} \quad < \quad t_{\mathrm{KH}} = \frac{G M_{\mathrm{disk}}^2}{R_{\mathrm{disk}}} \frac{1}{L_{\mathrm{disk}}}$$

Summary

3D RHD simulation resolving accretion flow and protostellar interior.

- ✓ Smooth Protostar–Disk Transition.
- ✓ Radiation is emitted from the disk surface.
- ✓ Protostellar luminosity in 1D calculation corresponds to disk luminosity in 3D calculation.



Future work : revealing the quantitative impact on the final stellar properties