

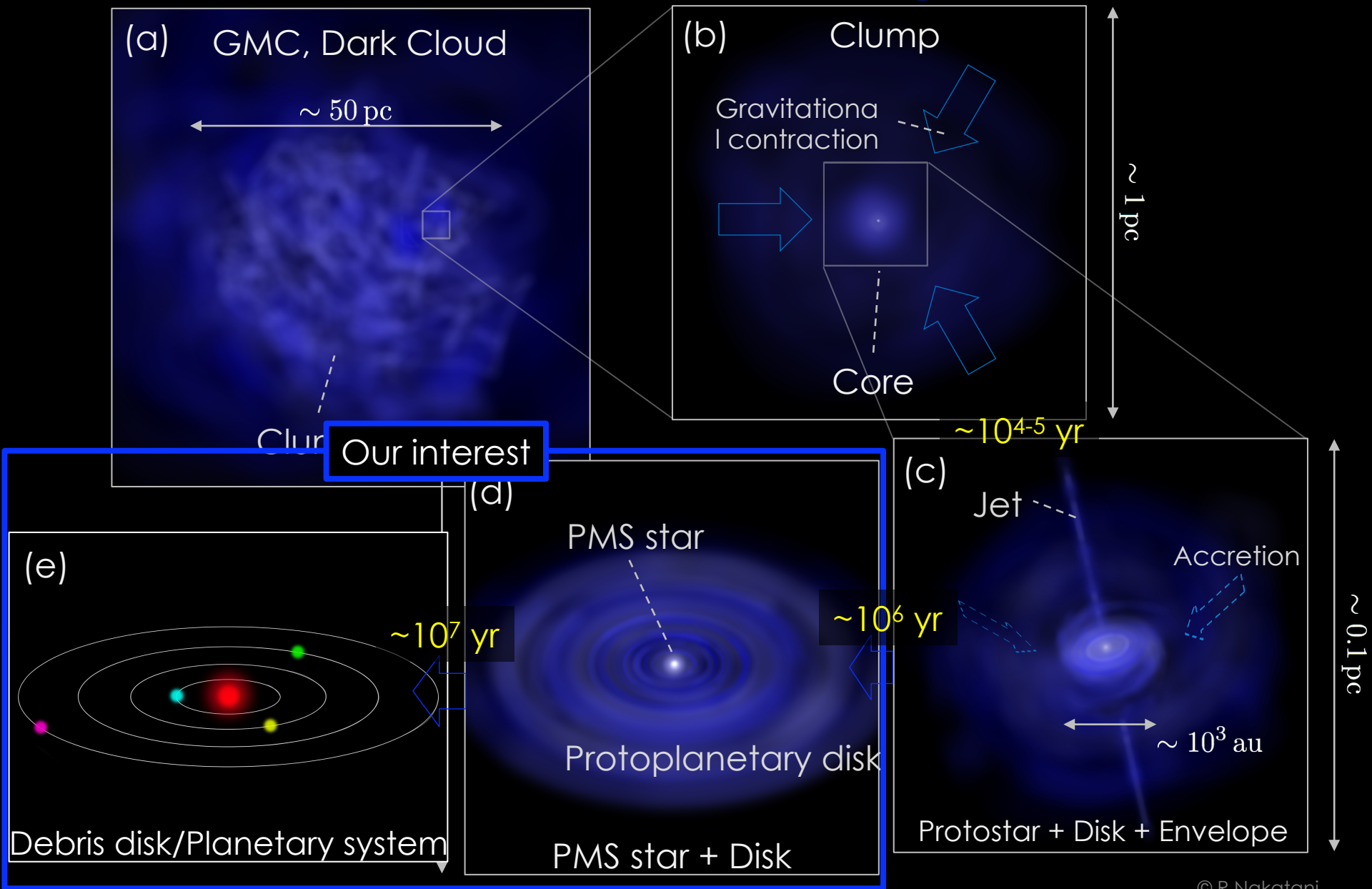
Radiation Hydrodynamics Simulations of Photoevaporating Protoplanetary Disks: Implications to Metallicity Dependence of Disk Lifetimes

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Collaborators: **Takashi. Hosokawa, Naoki Yoshida, Hideko Nomura, Rolf Kuiper**

Papers: **Nakatani et al. (2018a,b)**

Standard Scenario of Low-Mass Stellar-system Formation

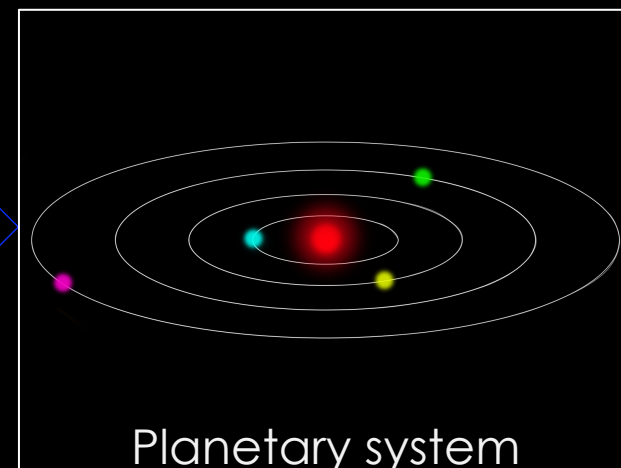
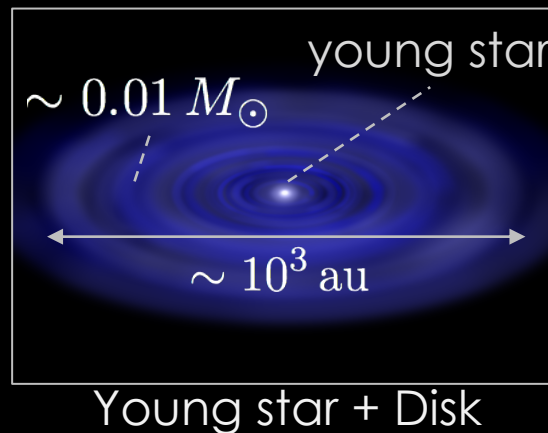
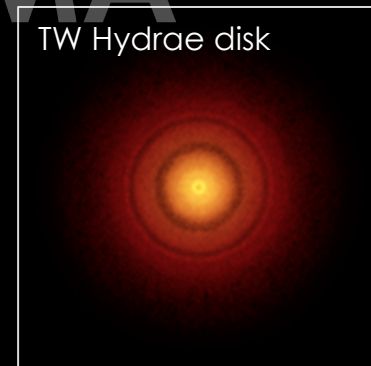


Protoplanetary Disk (PPD)

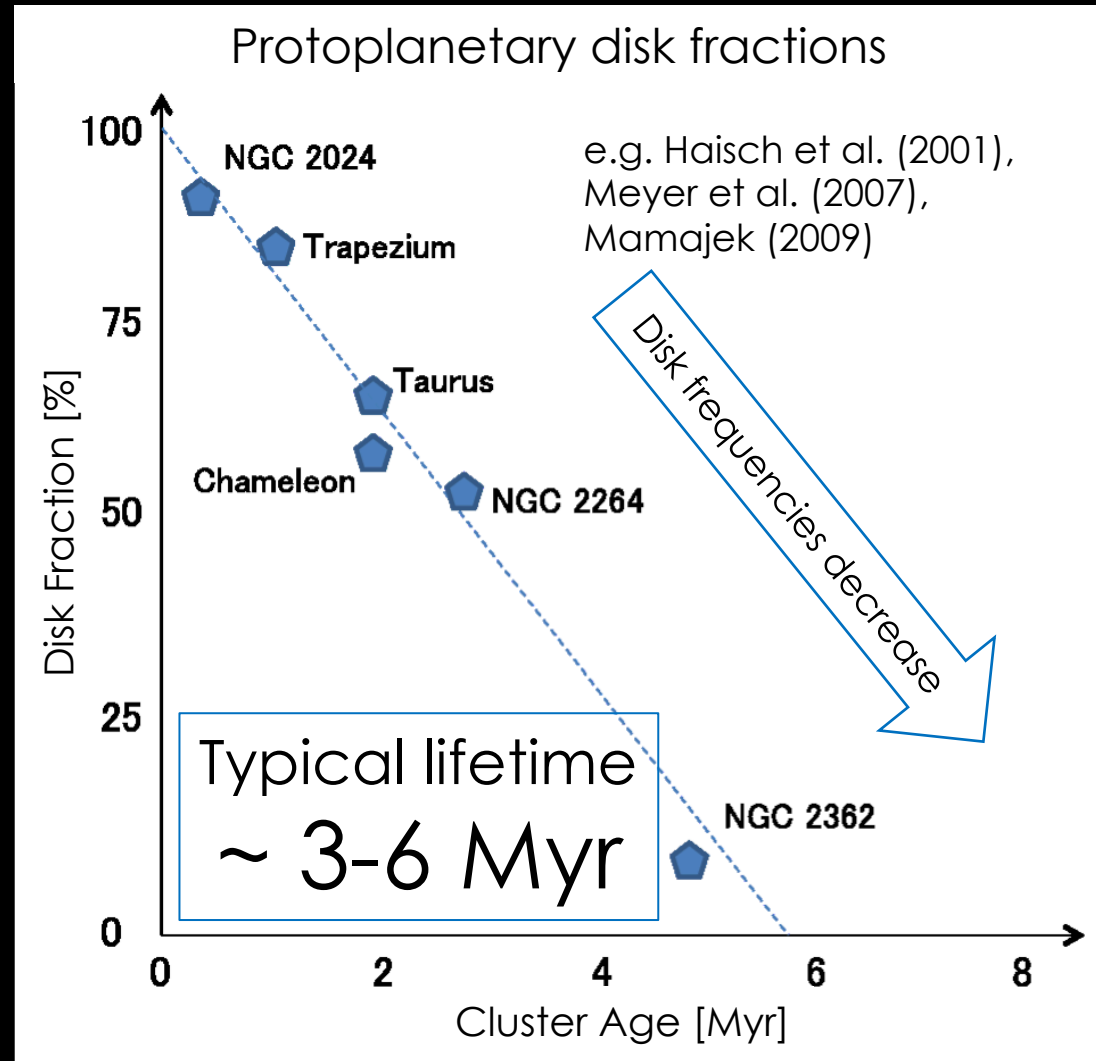
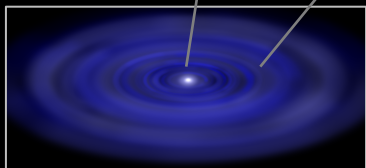
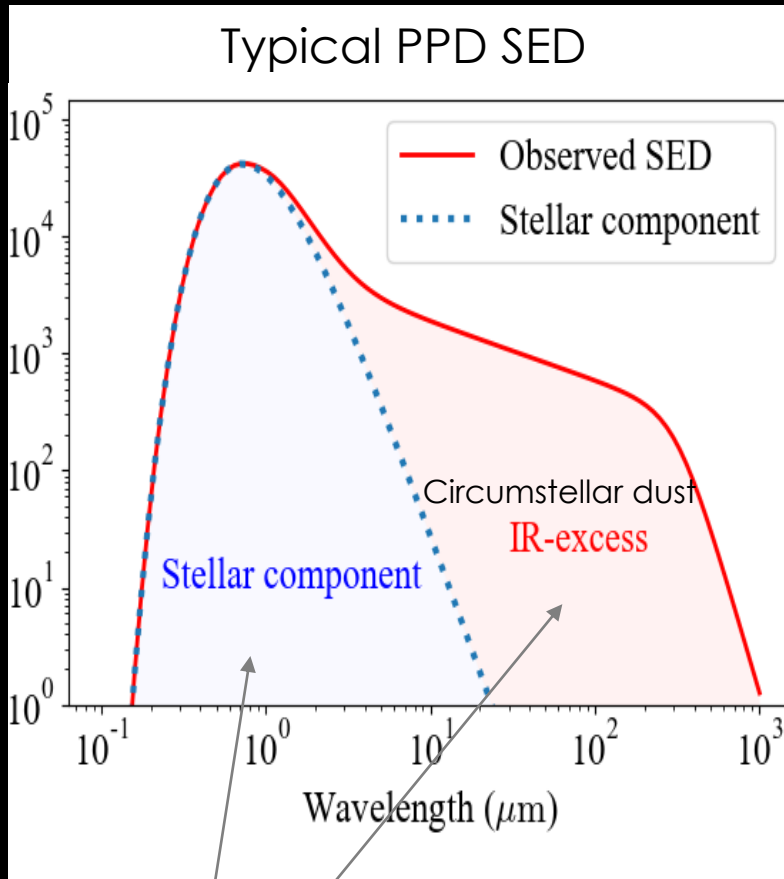
- Geometrically thin Keplerian disk around a young star
- Main components: Gas/Dust
- Birthplace of planets
→ **disk dispersal time characterizes planet formation timescale.**



<http://www.almaobservatory.org/press-room/press-releases/>

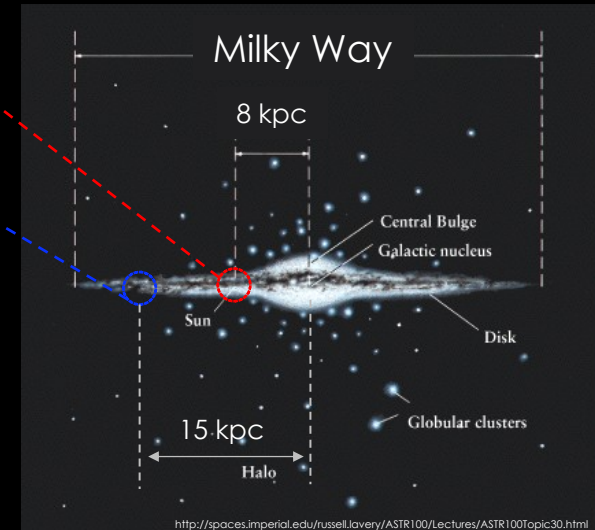
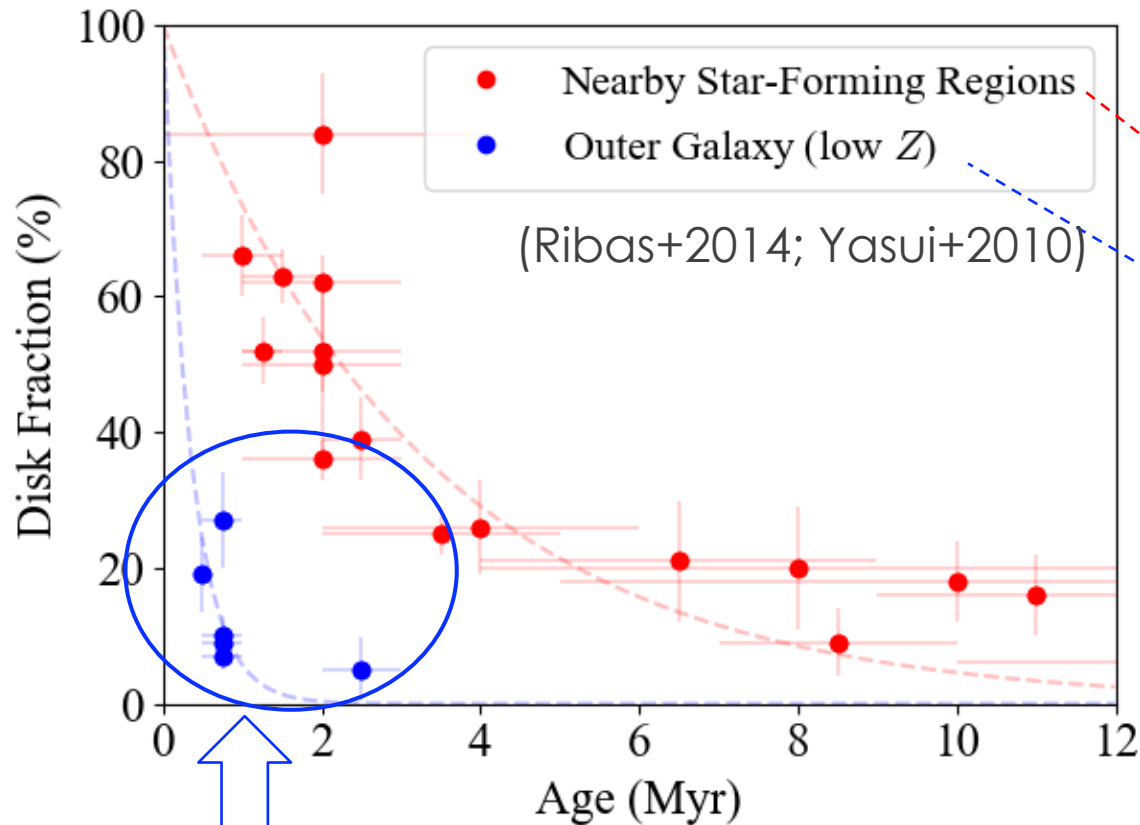


The lifetimes have been estimated with IR observations.



*** Disk Fraction = $\frac{\text{(disk-bearing members in a cluster)}}{\text{(total number of members)}}$

Subaru NIR observations have revealed metallicity dependence in disk lifetimes.



Low Z environments may **faster** disk dispersal **for some reason**.

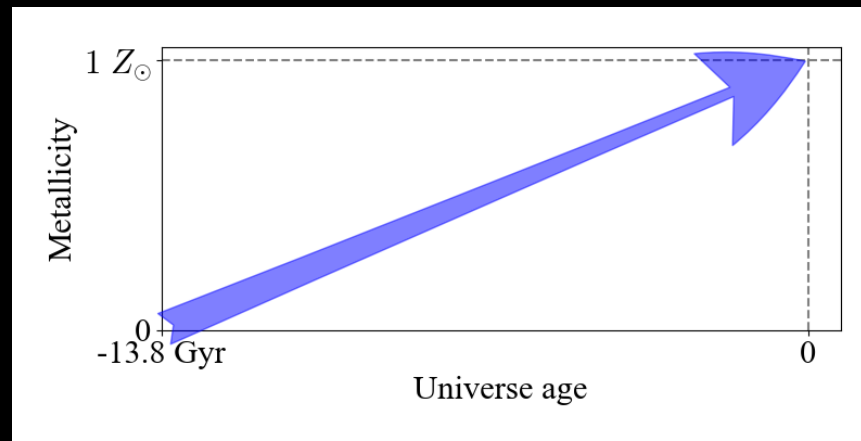
Significances of the metallicity dependence.

<< Lifetime – planet formation >>

- Time limit to gaseous **planet formation**
- Set **initial configuration**
- Influence on **chemical states**

<< The metallicity dependence – planet formation >>

- Suggest **planet-formable environments**
- Disk evolution/planet **formation in general metallicity environments**



Photoevaporation

- a disk-dispersing mechanism -

e.g., Bally & Scoville (1982); Shu et al. (1993), Hollenbach et al. (1994)

FUV: ($6 \text{ eV} \lesssim h\nu \lesssim 13.6 \text{ eV}$)
 EUV: ($13.6 \text{ eV} \lesssim h\nu \lesssim 0.1 \text{ keV}$)
 X-rays: ($0.1 \text{ keV} \lesssim h\nu \lesssim 10 \text{ keV}$)



Surface gas heating

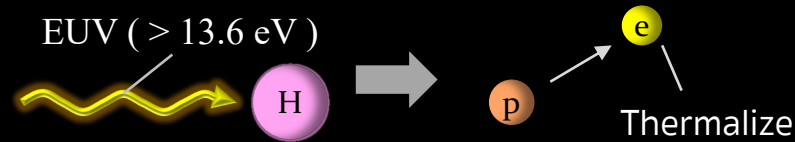
Unbound, hot
 Photoevaporative flow

$$\frac{(\text{gravitational energy})}{(\text{thermal energy})} = \frac{GM_*}{rc_s^2} \lesssim 1$$

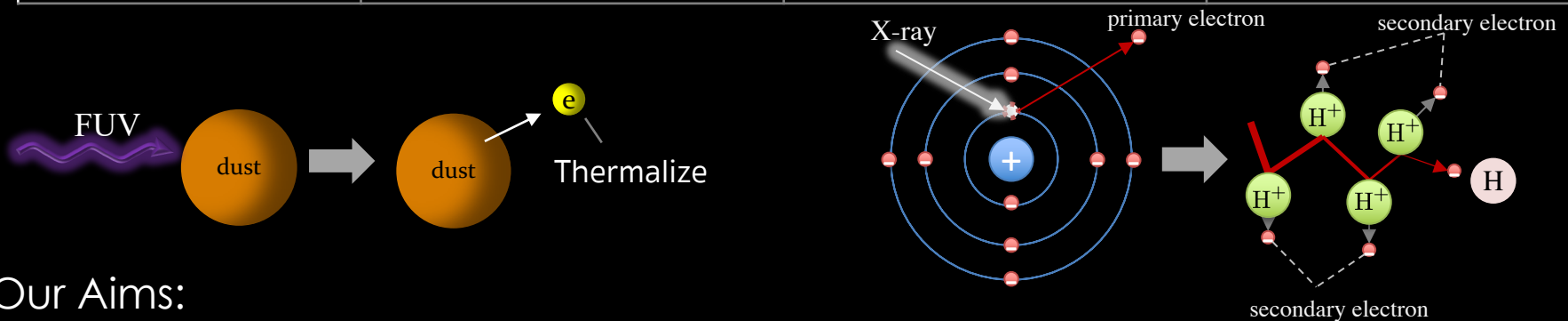
$$\Leftrightarrow r \gtrsim \frac{GM_*}{c_s^2} \sim 10 \text{ AU} \left(\frac{M_*}{M_\odot} \right) \left(\frac{T}{10^4 \text{ K}} \right)^{-1}$$

Typical mass loss rate (photoevaporation rate): $10^{-10} - 10^{-8} M_\odot \text{ yr}^{-1}$

Metallicity affects the disk opacity to FUV and X-ray.



| | FUV | EUV | X-rays |
|------------------------|---|---|---|
| Photon energy | $6 \text{ eV} \leq h\nu \leq 13.6 \text{ eV}$ | $13.6 \text{ eV} \leq h\nu \leq 100 \text{ eV}$ | $0.1 \text{ keV} \leq h\nu \leq 10 \text{ keV}$ |
| Main absorber | Dust | Atomic hydrogen | Metal elements ($\geq 0.3 \text{ keV}$) |
| Penetrability | High | Low | High |
| Metallicity dependence | Dependent | Independent | Dependent |



Our Aims:

- Understand metallicity dependence of mass-loss rates
 - Give implications to the observational lifetimes

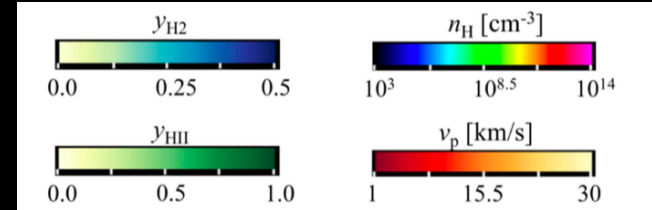
We performed the first self-consistent rad.-hydro. simulations

| | Hollenbach+94 | Gorti+09 | Owen+10 | Ercolano+10 | Wang+17 | Nakatani+18a | Nakatani+18b |
|----------------------|---------------|----------|---------|-------------|---------|--------------|--------------|
| Hydrodynamics | No | No | Yes | No | Yes | Yes | Yes |
| Radiative transfer | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Thermal processes | Yes | Yes | No | Yes | Yes | Yes | Yes |
| (Detailed) Chemistry | No | Yes | No | Yes | Yes | Yes | Yes |
| FUV heating | No | Yes | No | No | Yes | Yes | Yes |
| EUV heating | Yes | Yes | No | Yes | Yes | Yes | Yes |
| X-ray heating | No | Yes | Yes | Yes | Yes | No | Yes |
| Dust IR transfer | No | Yes | No | No | No | Yes | Yes |
| Multi-metallicity | No | No | No | Yes | No | Yes | Yes |

Photoevaporating Disk = Cold disk + Hot wind

(Nakatani +18a)

DB: Rz.vtr

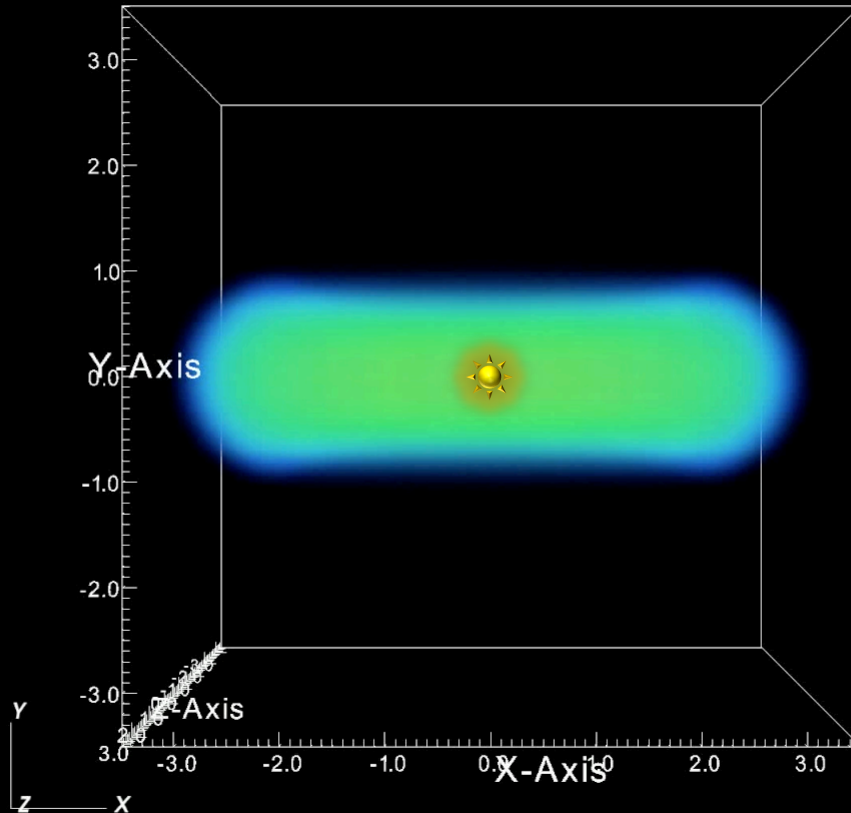


Color Scales

UV- & X-ray-heated region
= Wind region

Optically thick region
= Steady disk region

Photoevaporating disk
||
Cold disk ($\sim 10 - 100 \text{ K}$)
+
Hot winds ($> 10^3 \text{ K}$)



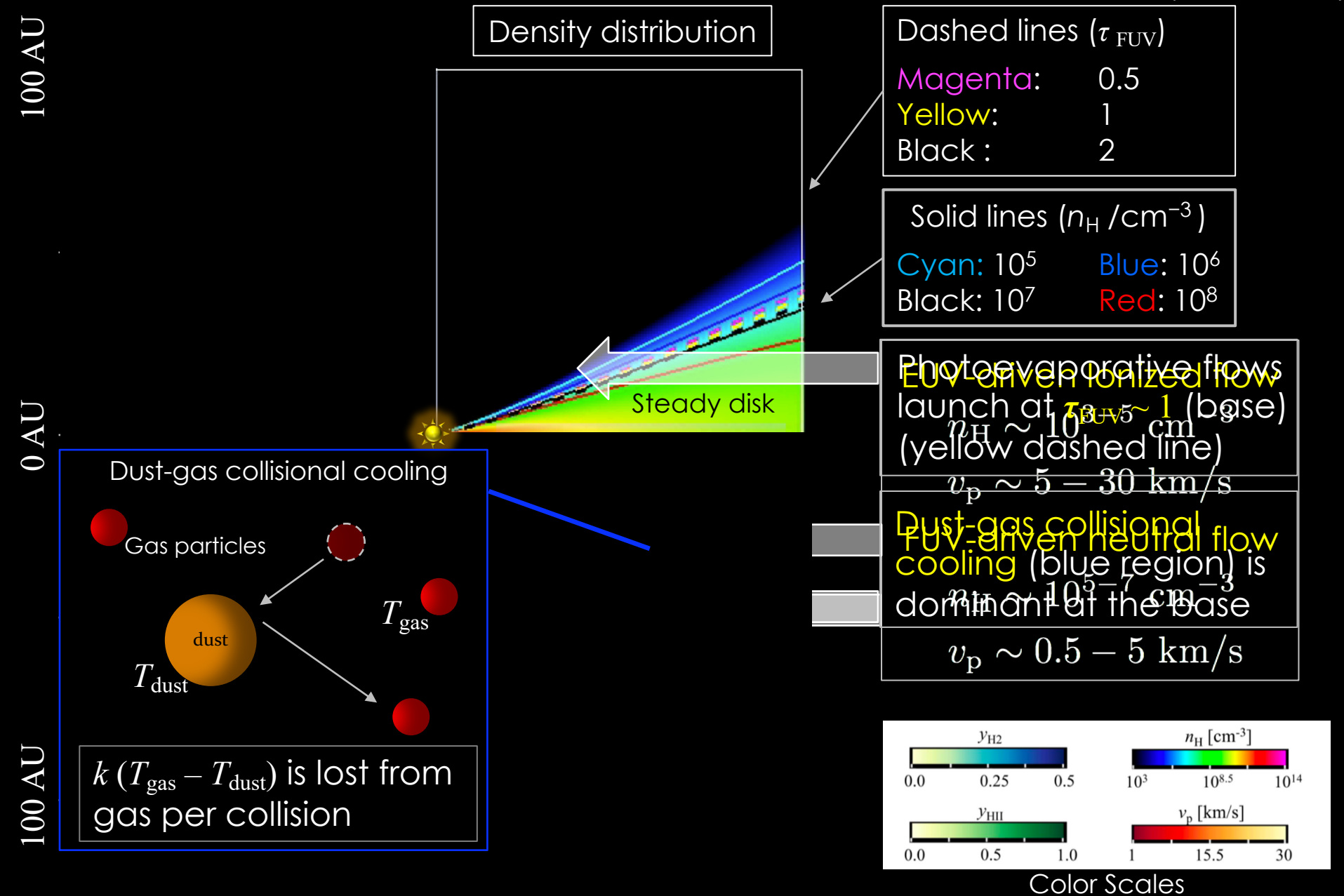
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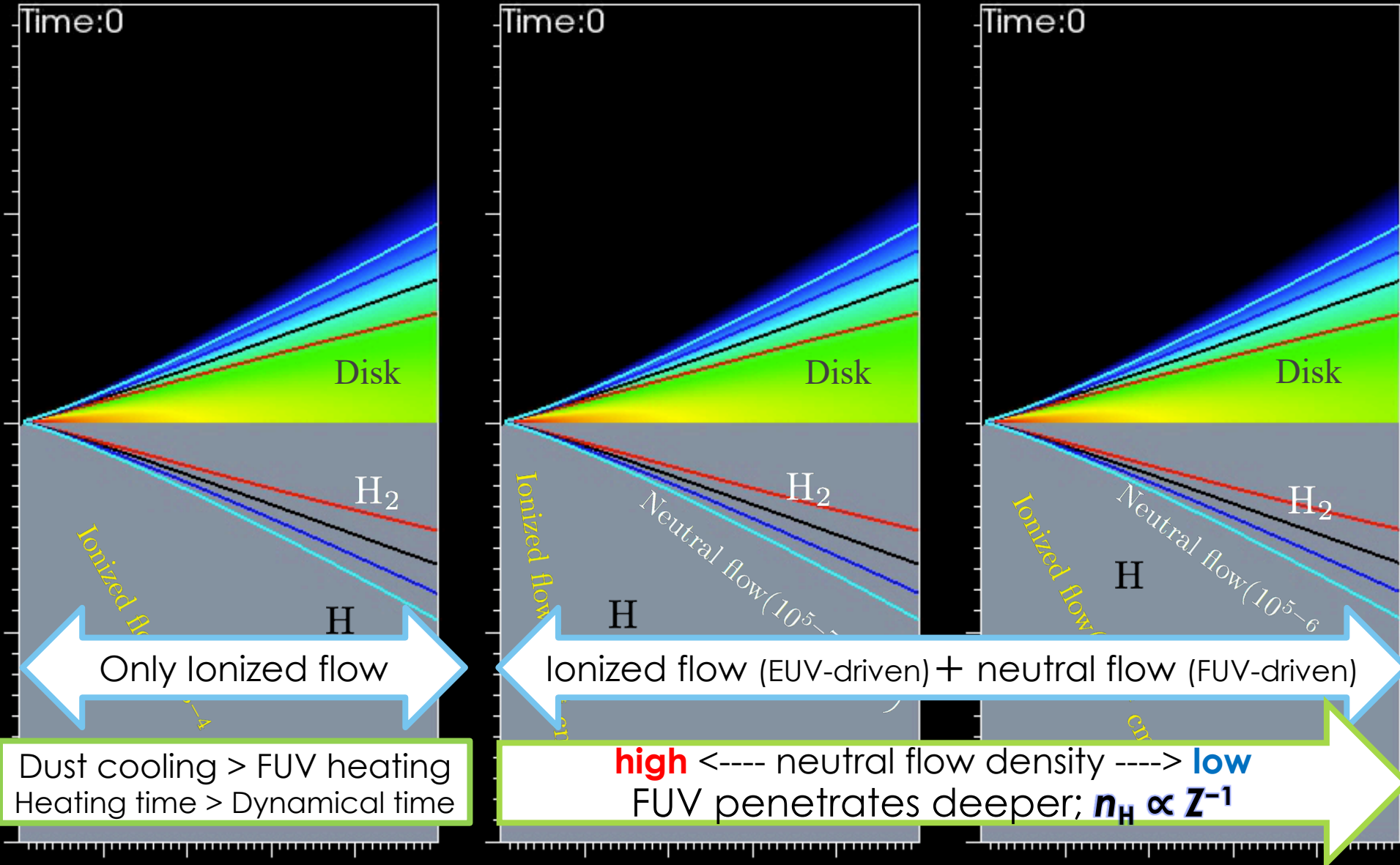
(Our simulations are in 2D spherical polar coordinates.)

FUV heating VS dust cooling at Wind “base” where $\tau_{\text{FUV}} \sim 1$. (Nakatani +18a)

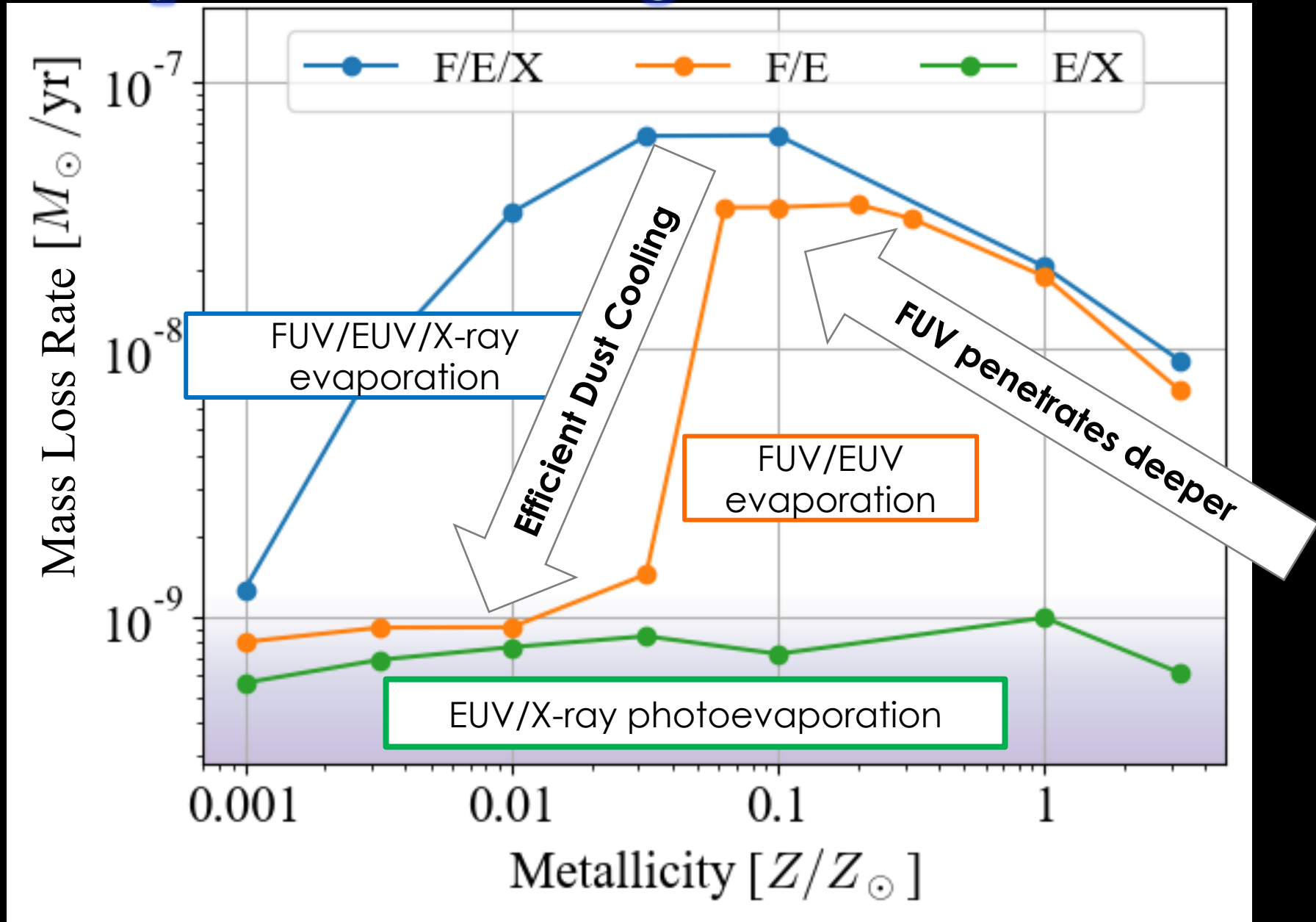


We do find metallicity dependence

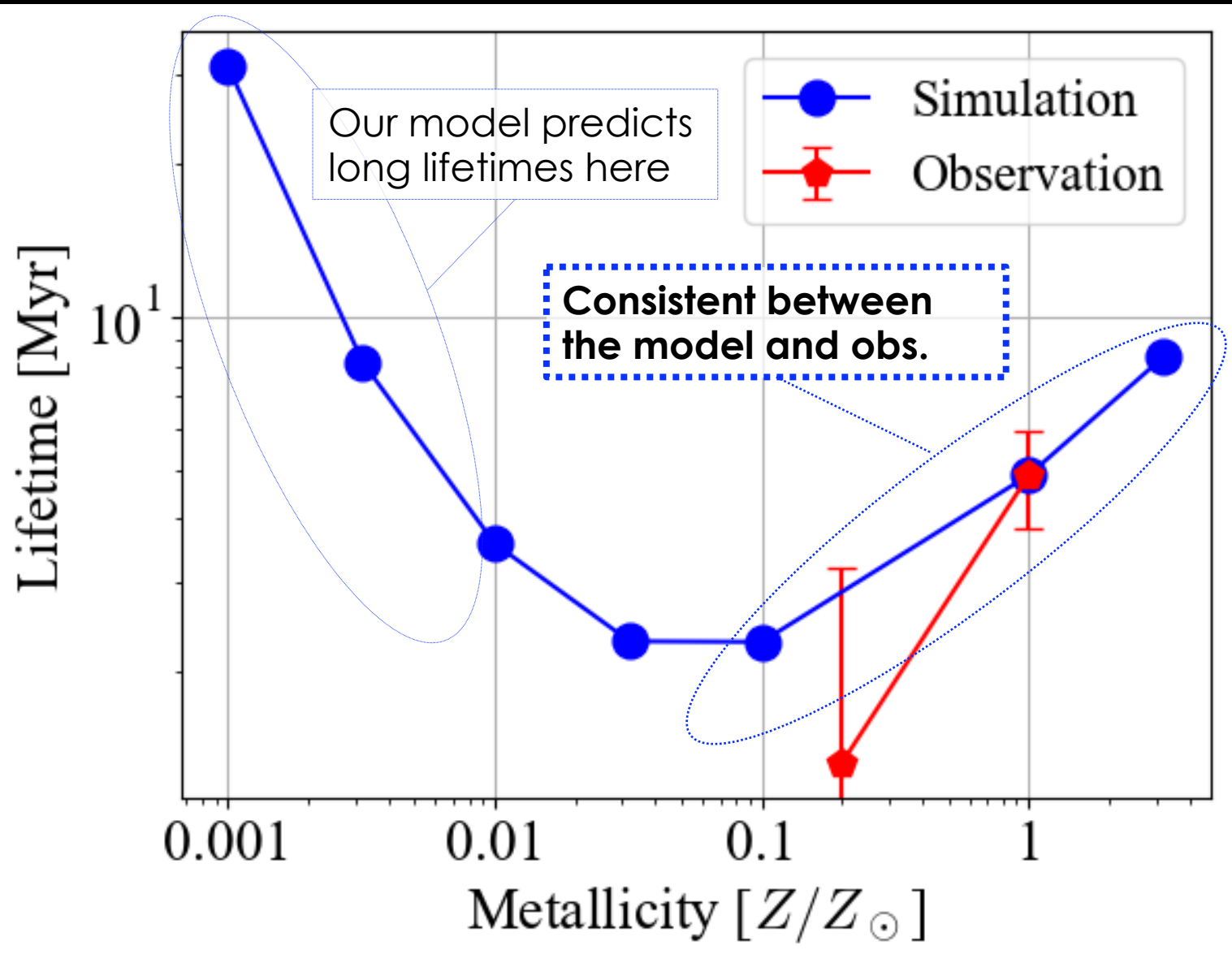
low Z $\xrightarrow{\hspace{10em}}$ high Z
 $Z = 10^{-3} Z_{\odot}$ $Z = 10^{-0.5} Z_{\odot}$ $Z = 10^{+0.5} Z_{\odot}$



Photoevaporation rate is the highest at subsolar metallicities



Photoevaporation can yield the short lifetimes



➤ Summary

1. Motivation: Observational metallicity dependence of lifetimes.
2. Methods: Hydrodynamical simulations with radiative transfer and non-equilibrium chemistry to examine the metallicity dependence of photoevaporation.
3. Results: Photoevaporation rates has a peak at $Z \sim 10^{-1} Z_{\odot}$. X-rays strengthen the FUV heating in the extremely low-metallicity range.
4. Conclusion: Our model gives consistent lifetimes with the observed lifetimes. Our model predicts disks would have even longer lifetimes in the much lower metallicity environments $Z \leq 10^{-2} Z_{\odot}$.