Radiation-Hydrodynamical Simulations of Photoevaporating Protoplanetary Disks with Various Metallicities

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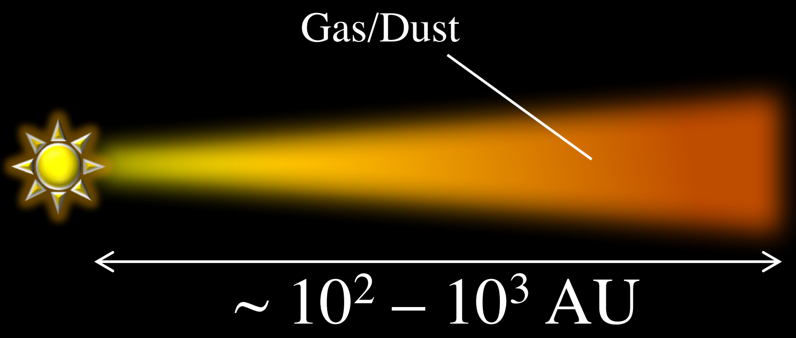
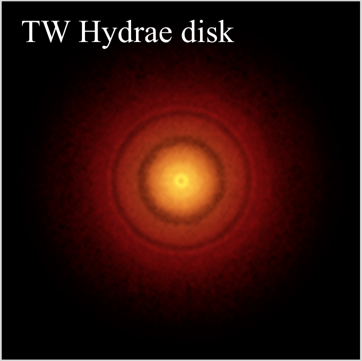
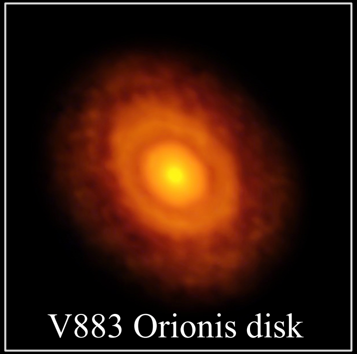
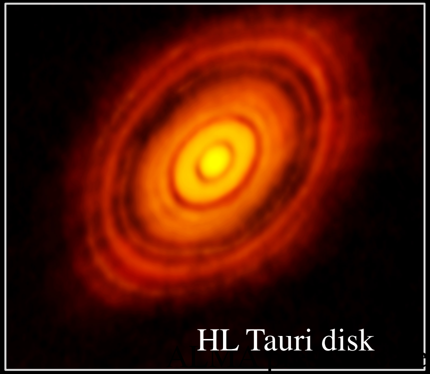
Protoplanetary Disk

- Geometrically thin Keplerian disk around a pre-main-sequence star
- Main components ; Gas/Dust
- Birthplace of planets




TW Hydrae disk


V883 Orionis disk


HL Tauri disk

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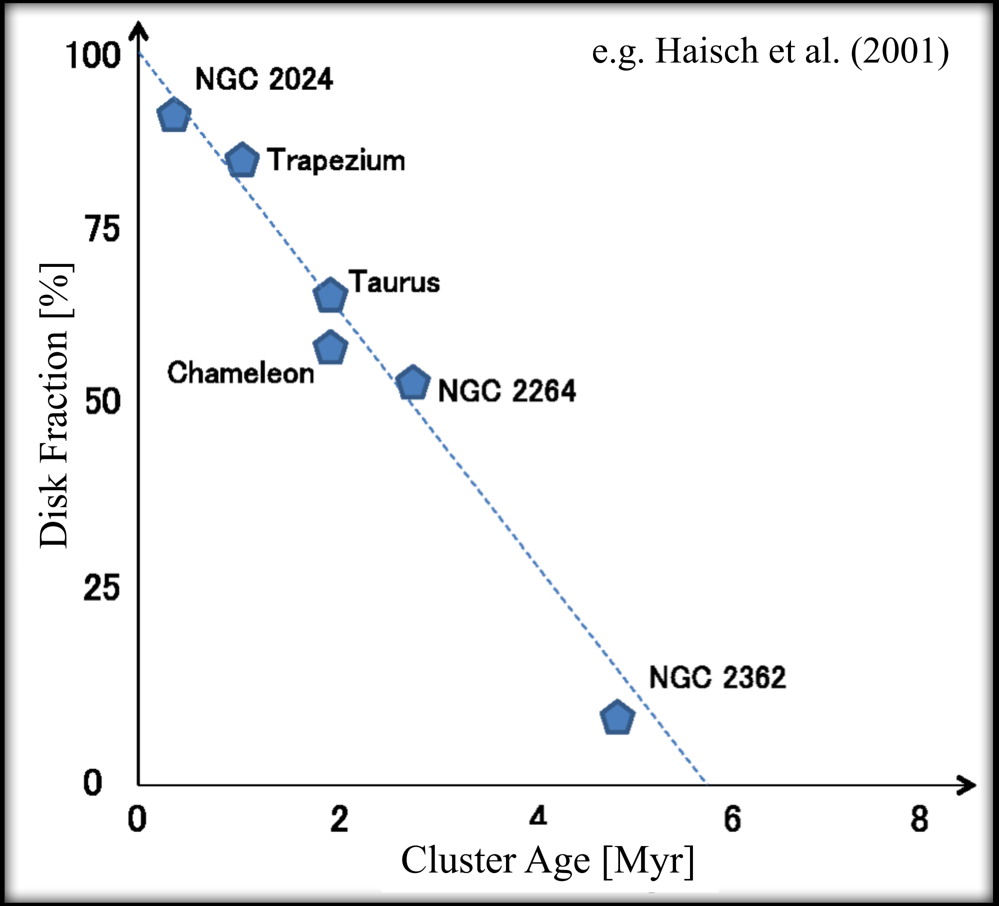
Lifetimes of Protoplanetary Disks

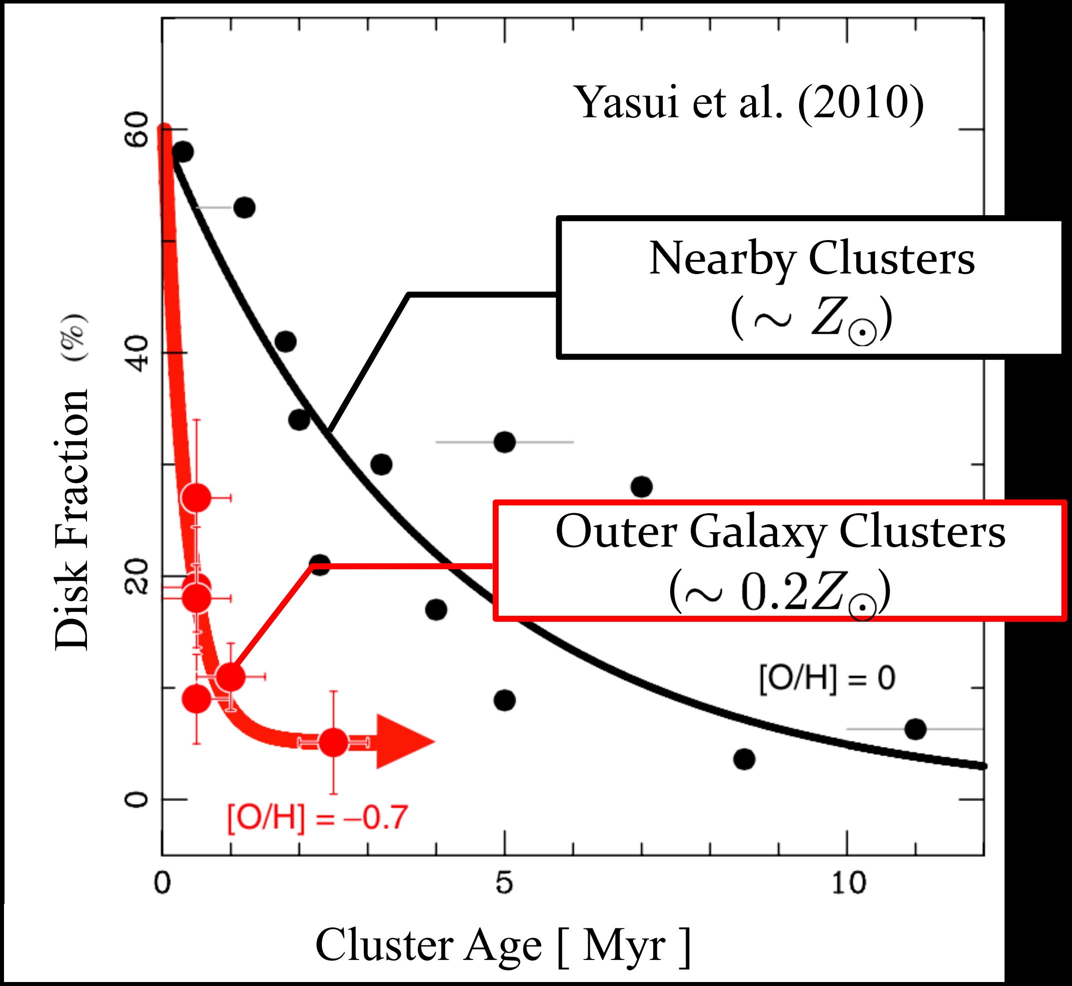


Older stars have
Lesser number of disks

Typical lifetime of a disk
~ 3-6 Myr

* Disk Fraction =
(disk-bearing members in a cluster) / (total number of members)

Metallicity Dependence of Lifetimes



With Low Z, earlier/faster dispersal.

(Low $Z \rightarrow$ small amount of metals/dust)

Lifetime (low Z) ~ 1 Myr

Low Z environments may affect disk dispersal.

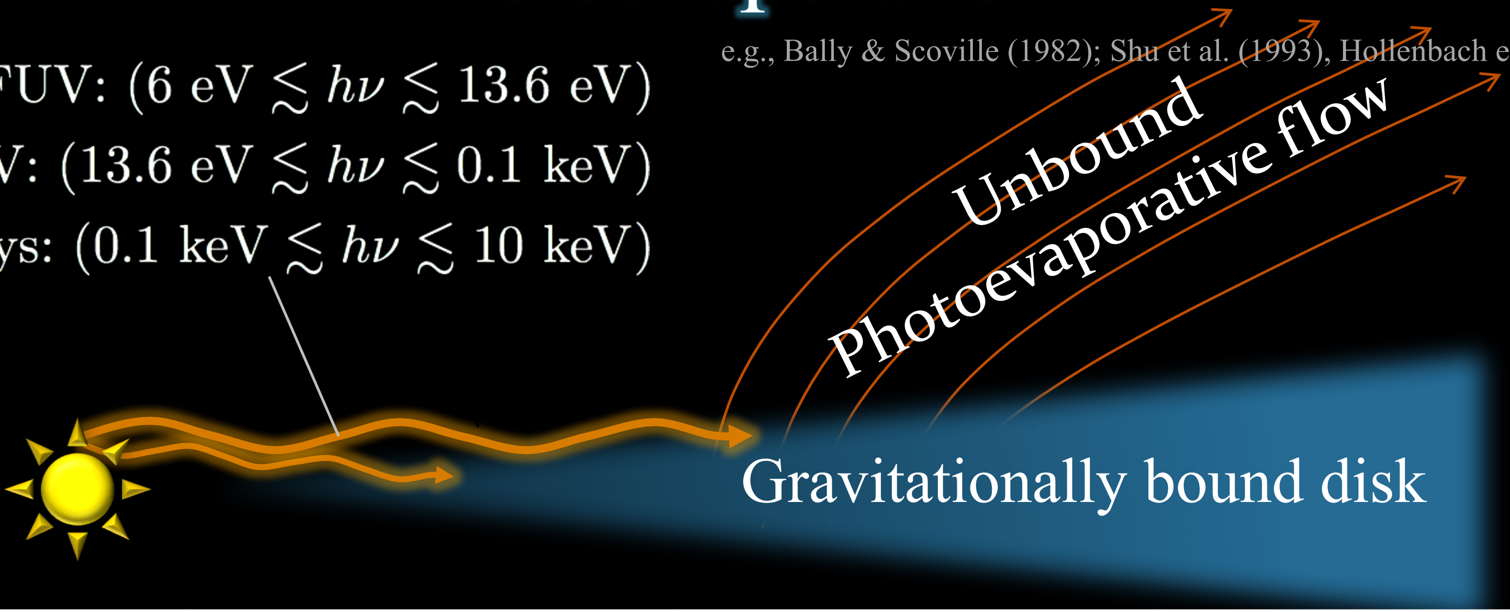
What mechanism makes a disk disperse?
– Photoevaporation –

FUV: $(6\ \mathrm{eV} \lesssim h\nu \lesssim 13.6\ \mathrm{eV})$

EUV: $(13.6\ \mathrm{eV} \lesssim h\nu \lesssim 0.1\ \mathrm{keV})$

X-rays: $(0.1\ \mathrm{keV} \lesssim h\nu \lesssim 10\ \mathrm{keV})$

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



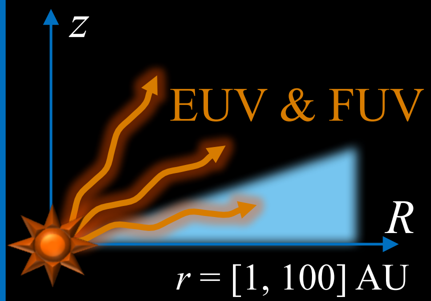
	FUV	EUV	X-rays
Main absorber	Dust	Atomic hydrogen	Metal elements
Attenuation column (solar metallicity)	$N_{\mathrm{H}} \sim 10^{21}\ \mathrm{cm}^{-2}$	$N_{\mathrm{HI}} \sim 10^{17}\ \mathrm{cm}^{-2}$	$N_{\mathrm{H}} \sim 10^{21}\ \mathrm{cm}^{-2}$

Our Aims:

- To examine Z dependence of FUV/EUV photoevaporation rates to give implications to the Z dependence of the lifetimes

Methods (dust/metals are proportional to Z)

Hydrodynamics (PLUTO ver. 4.1)
+ EUV & FUV transfer (developed by RN)
+ dust IR transfer (developed by Rolf)
+ non-equilibrium Chemistry (developed by RN)



r = [1, 100] AU
θ = [0, π/2]

Basic Equations

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

$$\frac{\partial \rho v_r}{\partial t} + \nabla \cdot (\rho v_r \boldsymbol{v}) = -\frac{\partial P}{\partial r} - \rho \frac{GM_*}{r^2} + \rho \frac{v_\theta^2 + v_\phi^2}{r}$$

$$\frac{\partial \rho v_\theta}{\partial t} + \nabla \cdot (\rho v_\theta \boldsymbol{v}) = -\frac{1}{r}\frac{\partial P}{\partial \theta} - \rho \frac{v_\theta v_r}{r} + \frac{\rho v_\phi^2}{r} \cot\theta$$

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

$$\frac{\partial E}{\partial t} + \nabla \cdot (H \boldsymbol{v}) = -\rho v_r \frac{GM_*}{r^2} + \rho (\Gamma - \Lambda)$$

$$\frac{\partial n_{\mathrm{H}} y_i}{\partial t} + \nabla \cdot (n_{\mathrm{H}} y_i \boldsymbol{v}) = n_{\mathrm{H}} R_i$$

$$e = \frac{P}{\rho(\gamma - 1)} = \frac{kT}{\mu m_{\mathrm{H}}(\gamma - 1)}$$

$$\boldsymbol{F}_{\mathrm{local}} = \boldsymbol{F}_{\mathrm{local}}(\boldsymbol{r}, t)$$

Heating/Cooling processes

< Photo-Heating >

- photoionization (EUV)
- photoelectric effect (FUV)

< Line cooling >

- H_2, CO,
- CII, OI, HI (Lyα)

< Collisional cooling >

- recombination (HII + e → HI)
- dust-gas heat transfer

Chemical species

H H^+ H_2 e CO CII OI

Chemical reactions

$\mathrm{H} + \mathrm{e} \longrightarrow \mathrm{H}^+ + 2\,\mathrm{e}$

$\mathrm{H}^+ + \mathrm{e} \longrightarrow \mathrm{H} + h\nu$

$\mathrm{H}_2 + \mathrm{e} \longrightarrow 2\,\mathrm{H} + \mathrm{e}$

$\mathrm{H}_2 + \mathrm{H} \longrightarrow 3\,\mathrm{H}$

$3\,\mathrm{H} \longrightarrow \mathrm{H}_2 + \mathrm{H}$

$2\,\mathrm{H} + \mathrm{H}_2 \longrightarrow 2\,\mathrm{H}_2$

$2\,\mathrm{H}_2 \longrightarrow \mathrm{H}_2 + 2\,\mathrm{H}$

$2\,\mathrm{H} \longrightarrow \mathrm{H}^+ + \mathrm{e} + \mathrm{H}$

$2\,\mathrm{H} \xrightarrow{\mathrm{dust}} \mathrm{H}_2$

$\mathrm{EUV} + \mathrm{H} \longrightarrow \mathrm{H}^+ + \mathrm{e}$

$\mathrm{FUV} + \mathrm{H}_2 \longrightarrow 2\,\mathrm{H}$

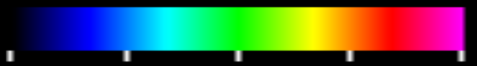
$\mathrm{FUV} + \mathrm{CO} \longrightarrow \mathrm{C}^+ + \mathrm{O}$

$\mathrm{C}^+ + \mathrm{O} \xrightarrow{\mathrm{CHx}} \mathrm{CO}$

Solar Metallicity Disk

Density

n_H [cm^{-3}]



Velocity(arrow; >1km/s)

v_p [km/s]

Abundances

H ; white

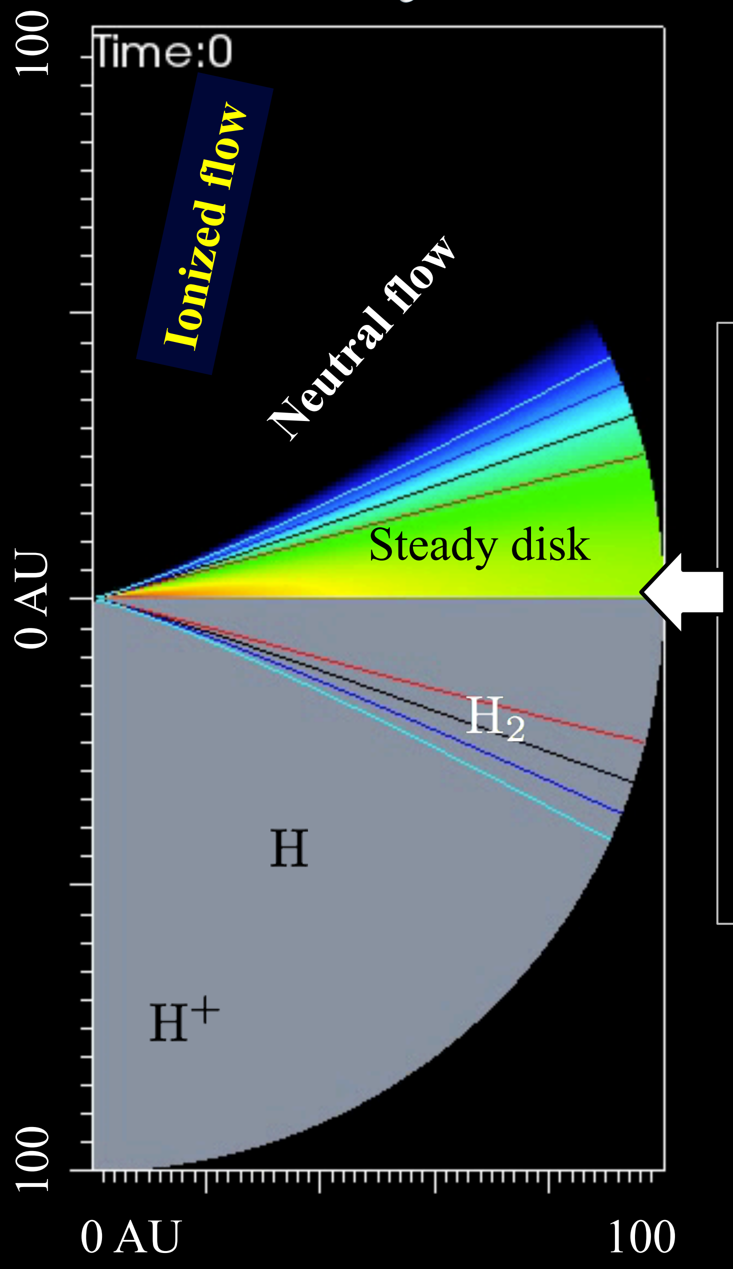
H^+ ; green

H_2 ; blue

Solid lines (n_H)

Cyan : 10^5 /cm^3 Blue : 10^6 /cm^3

Black: 10^7 /cm^3 Red : 10^8 /cm^3



Ionized flow (EUV-driven)

$n_H \sim 10^{3-5}$ cm^{-3}

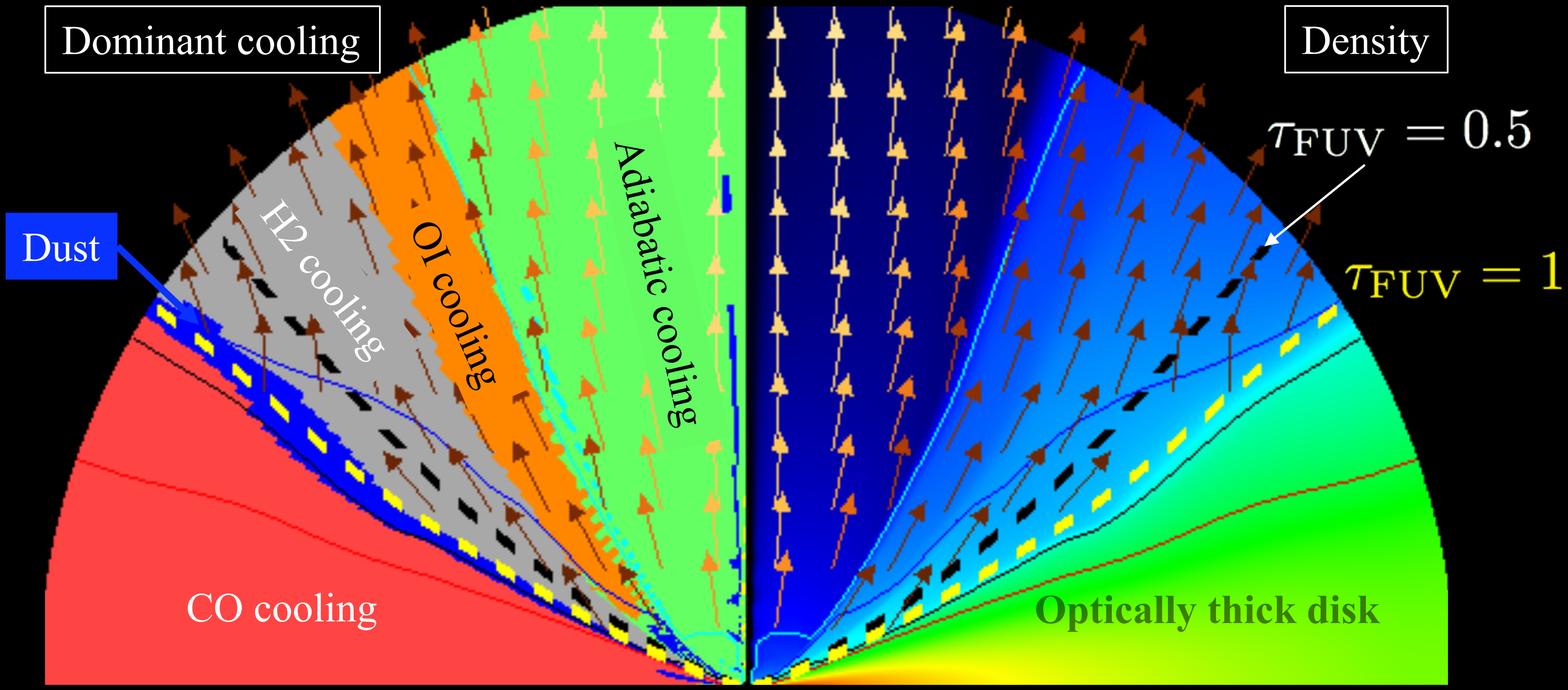
$v_p \sim 5 - 30$ km/s

Neutral flow (FUV-driven)

$n_H \sim 10^{5-7}$ cm^{-3}

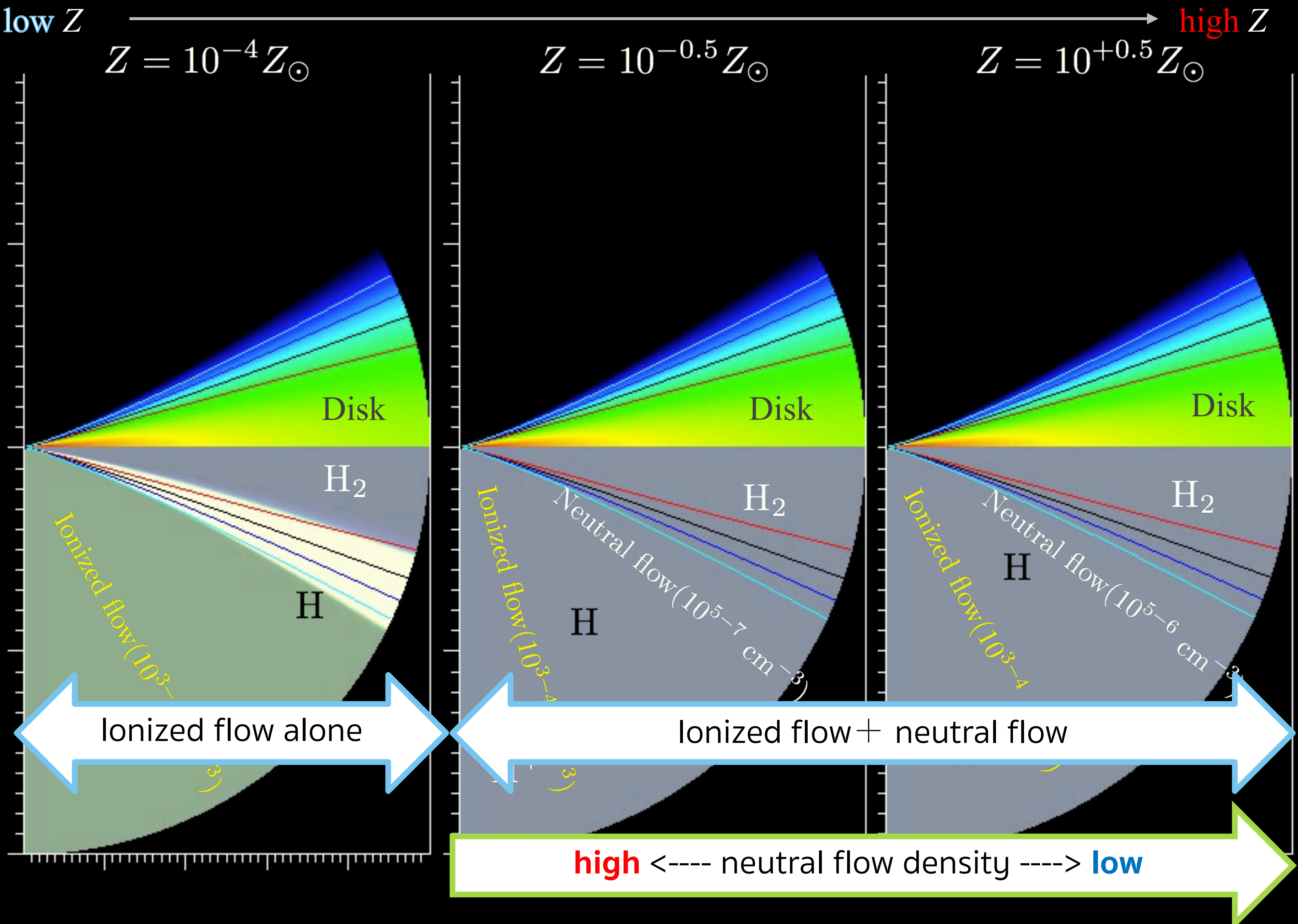
$v_p \sim 0.5 - 5$ km/s

Photoevaporation "base"



Photoevaporative flow is launched from $\tau_{\mathrm{FUV}} = 0.5 - 1$.
The dominant cooling source is dust-gas collisional cooling there.

Various metallicities

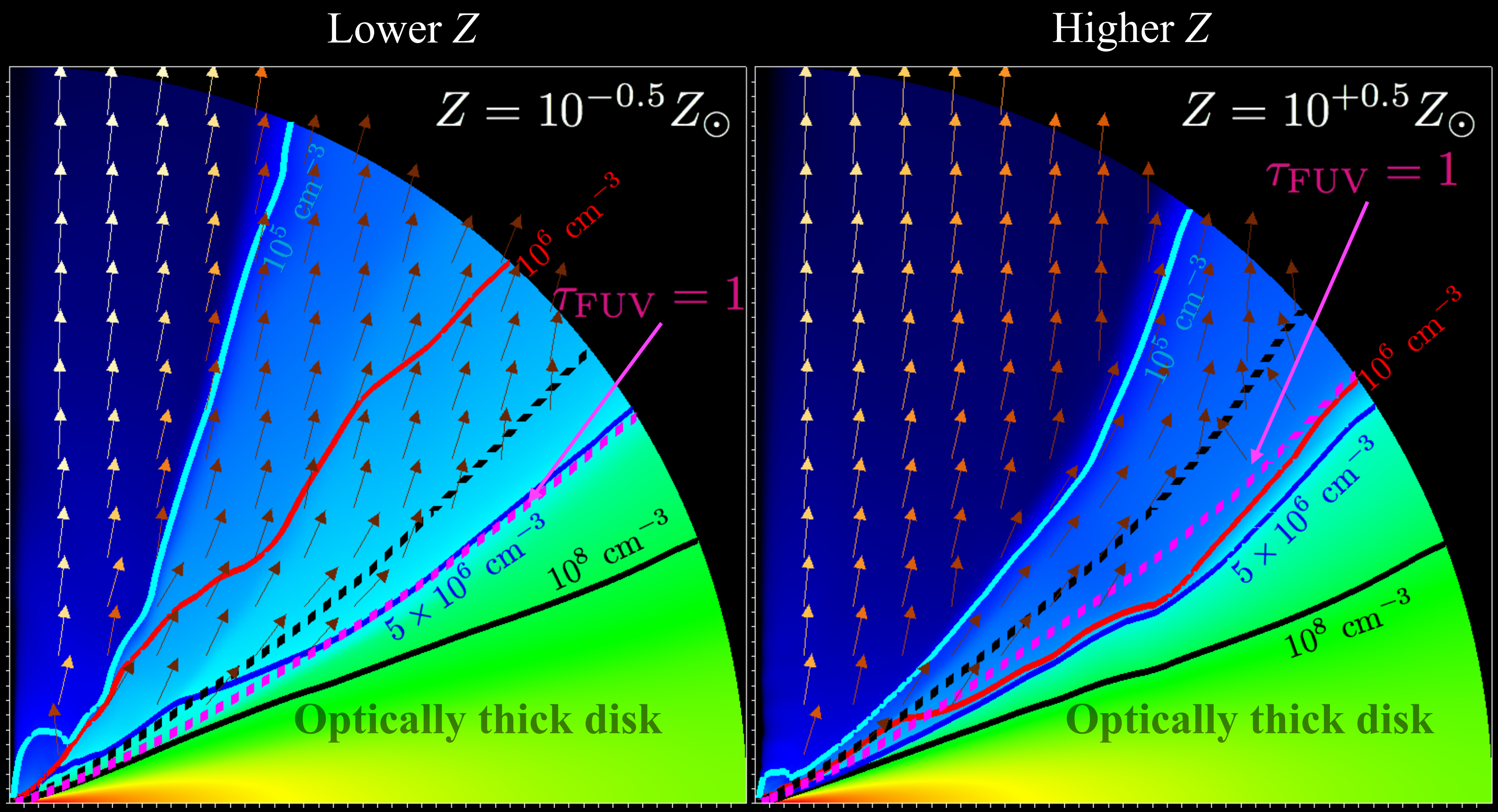


Ionized flow alone

Ionized flow + neutral flow

high <---- neutral flow density ----> **low**

1. Denser flow in lower metallicity



(Optically thick regions = below dashed magenta line, $\tau_{\rm FUV} = 1$)

The lower metallicity → the less amount of dust (absorbers)

FUV can reach the denser region.

↓

The flow is DENSER as metallicity becomes LOWER ($n_{\rm H,base} \propto Z^{-1}$)

2. No neutral flow in lowest metallicity

No neutral flow → Gas cannot get sufficient energy at base

Recall that dust-gas collisional cooling is dominant cooling at base.

Since dust cooling is a collisional process $\boxed{n_\mathrm{d} \propto n_\mathrm{H}(Z/Z_\odot)}$ $\boxed{n_\mathrm{H,base} \propto Z^{-1}}$

$$(\text{dust cooling at base}) \propto n_\mathrm{d,base} n_\mathrm{H,base} \propto n_\mathrm{H,base}^2 \frac{Z}{Z_\odot} \propto \left(\frac{Z}{Z_\odot}\right)^{-1}$$

Since FUV heating is a photo-process

$$(\text{FUV heating at base}) \propto L_\mathrm{FUV} e^{-\tau_\mathrm{d}} n_\mathrm{d} \propto n_\mathrm{d} \propto n_\mathrm{H,base} \frac{Z}{Z_\odot} \propto 1$$

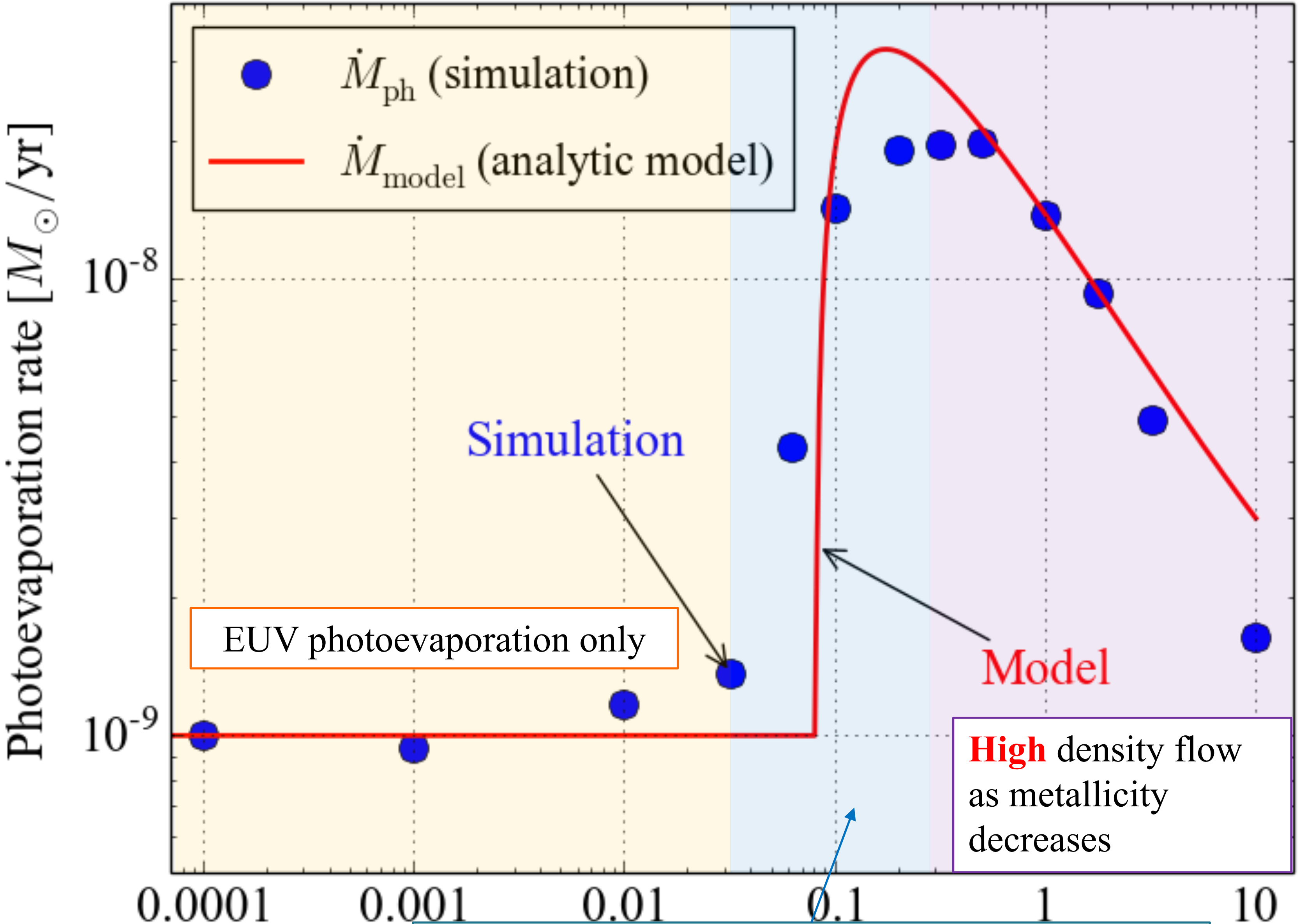
Compared with dust cooling,

FUV heating becomes inefficient as metallicity decreases.

↓

Resulting gas temperature becomes lower as metallicity decreases.

Neutral flow cannot be excited in a very low metallicity range.



Simulation

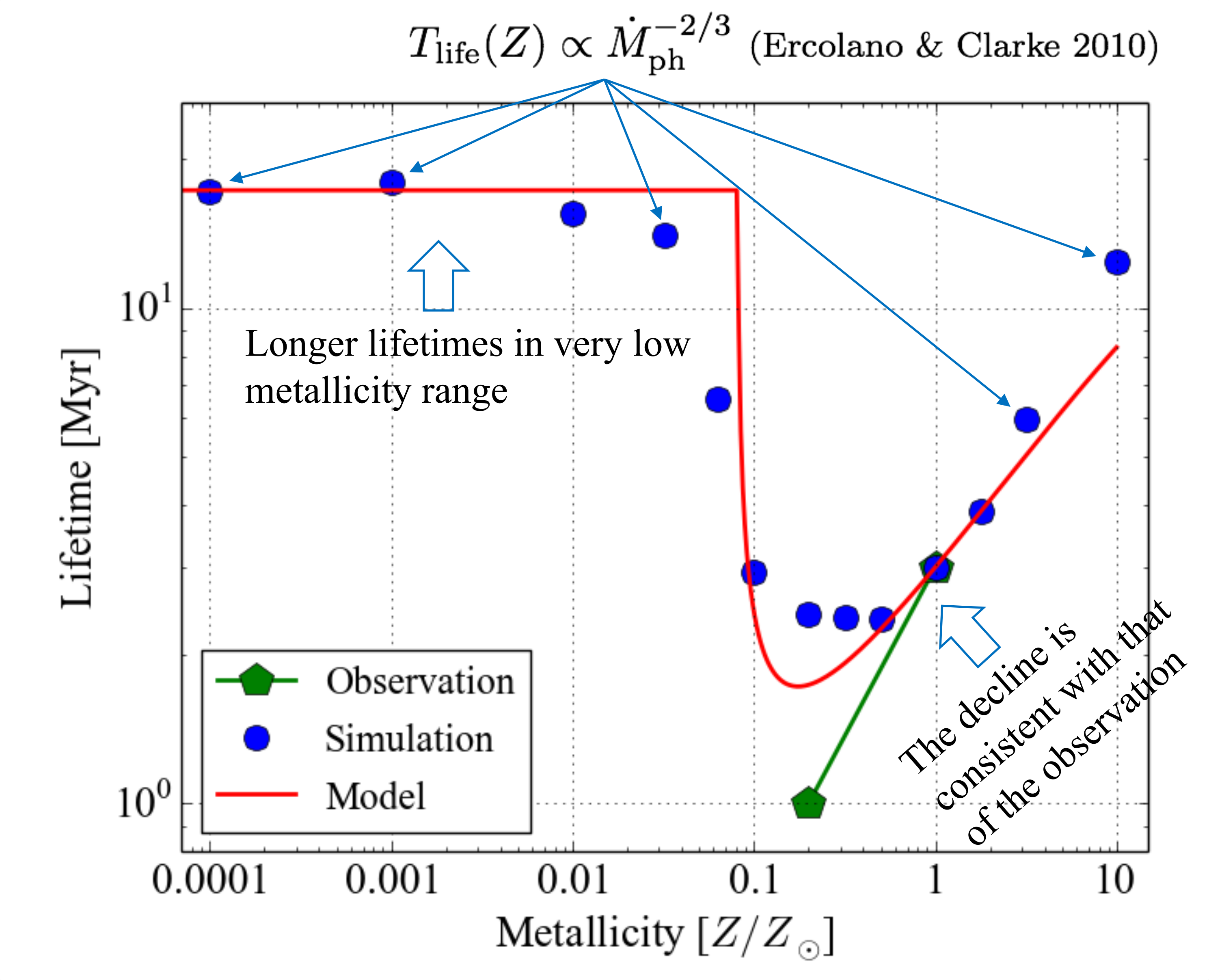
EUV photoevaporation only

Model

High density flow
as metallicity
decreases

FUV heating becomes **less efficient than cooling.**
Neutral flow has less contribution to mass loss.

Estimated lifetimes



$T_{\rm life}(Z) \propto \dot{M}_{\rm ph}^{-2/3}$ (Ercolano & Clarke 2010)

Longer lifetimes in very low metallicity range

The decline is consistent with that of the observation

- 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 $Z \sim 10^{-0.5}\, Z_{\odot}$, which reflects the metallicity dependence of FUV heating.
  4. Conclusion: Our model would be consistent with the observed metallicity dependence of the lifetimes, and it predicts that the disks would have even longer lifetimes in the much lower metallicity environments $Z \leqq 10^{-2}\, Z_{\odot}$.

- Future work
  - FUV/EUV/X-ray photoevaporation
  - Update chemistry and implement dust coagulation/accretion
  - Dust dynamics