Radiation-hydrodynamical simulations of photoevaporating protoplanetary disks with various metallicities

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Abstract: Recent studies show that a protoplanetary disk lifetime is shorter in the low metallicity environments than the solar neighborhood. Photoevaporation is suggested as an important mechanism to explain it. We perform radiation hydrodynamics simulations of photoevaporation of a protoplanetary disk. We simultaneously solve hydrodynamics, self-consistent EUV/FUV radiative transfer, and non-equilibrium chemistry. Grain temperatures are also calculated by solving the radiative transfer of the stellar irradiation and grain (re-)emission. For our fiducial configuration, the resulting photoevaporation rate is $1.38 \times 10^{-8}\, M_\odot\, \mathrm{yr}^{-1}$ for solar metallicity. It becomes low as metallicity increases in the range of $10^{-0.5} Z_\odot \lesssim Z \lesssim 10\, Z_\odot$ and sharply declines towards lower metallicity in the range of $10^{-1} Z_\odot \lesssim Z \lesssim 10^{-0.5} Z_\odot$. It is almost constant in the lowermost range $10^{-4} Z_\odot \lesssim Z \lesssim 10^{-1} Z_\odot$. We develop a semi-analytic model. It can well explains the metallicity dependence of the photoevaporation rates and the radial distribution of them. Our results are consistent with the observed lifetimes.

I. Motivation

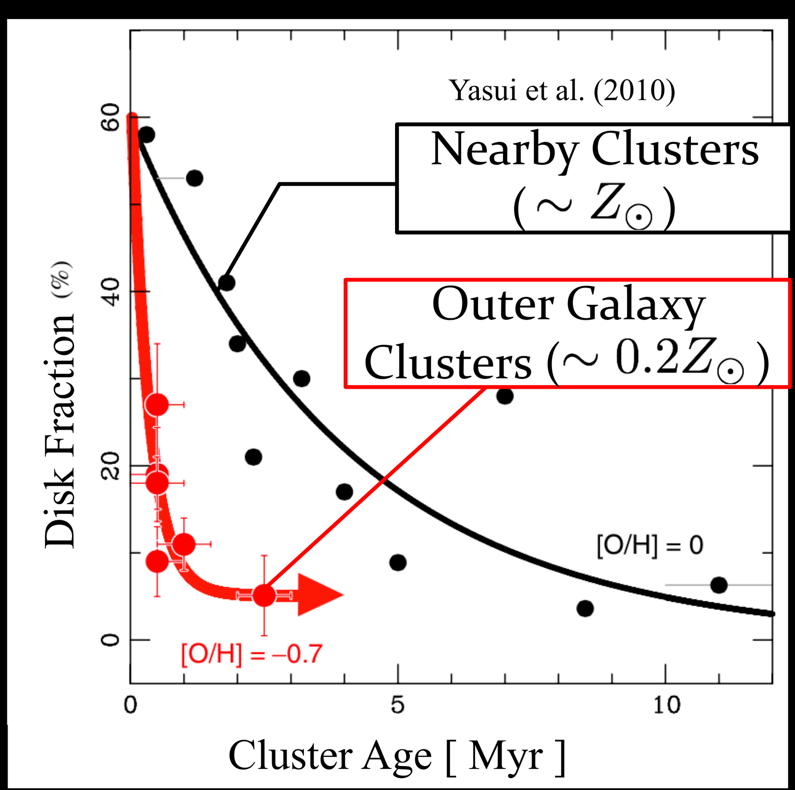


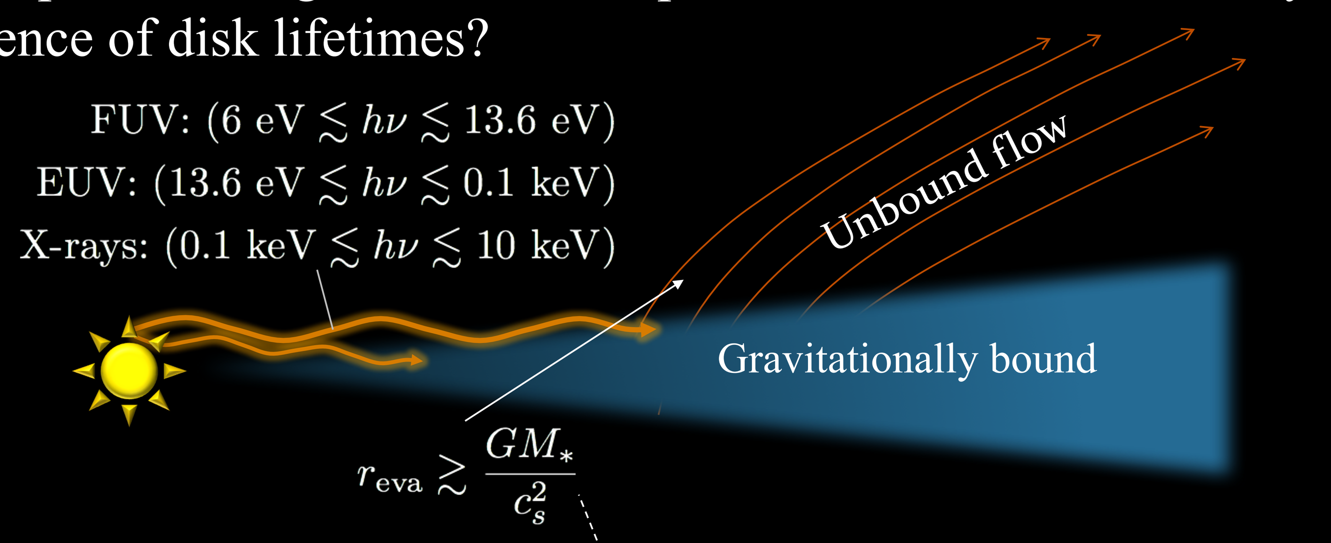
Figure 1. ; Disk fractions

- A protoplanetary disk has the lifetime estimated to be 3 – 6 Myr [1] (see the black line of Fig.1).
- Extreme outer Galaxy clusters suggest a short disk lifetime estimated to be ≲ 1 Myr [2]. A lifetime is shorter in lower metallicity environments. (see the red line of Fig.1)

References: [1] Haisch et al. (2001), [2] Yasui et al. (2009, 2010)

Photoevaporation

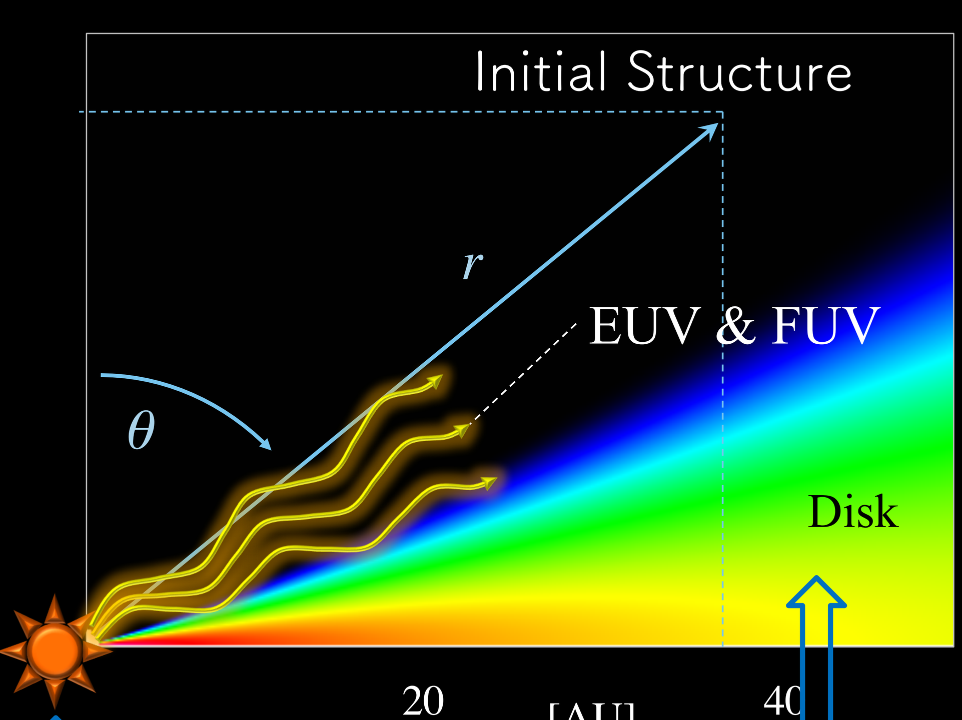
- Photoevaporation might be able to explain the observed metallicity dependence of disk lifetimes?



An approximate criterion for evaporation. (thermal energy) ≧ (gravitational energy)

II. Numerical Simulation & Methods

Consistent radiation-hydrodynamics with non-equilibrium chemistry



Simulation setup

- 2D spherical polar coord.
- Symmetry
  - Axis ($\theta = 0$)
  - mid-plane ($\theta = \pi/2$)
- Computational domain
  - r = [1 , 100] AU
  - θ = [0 , π/2] rad

Stellar parameters (a low-mass PMS star)

$\Phi_{\mathrm{EUV}} = 6 \times 10^{41}\ \mathrm{s}^{-1}$

$L_{\mathrm{FUV}} = 4 \times 10^{31}\ \mathrm{erg\ s}^{-1}$

$R_* = 2\ R_\odot \quad M_* = 0.5\ M_\odot$

(e.g., Clarke+01; Alexander+04; Gorti+09; Owen+12)

Chemical Reactions

- Photoionization,
- H_2 photodissociation
- CO photodissociation
- collisional reactions

- The amounts of dust/metals are proportional to metallicity (e.g., Omukai 2000)
  - *Species* H, H^+, H_2, C^+, O, CO, e
  - *Dust-to-gas-mass ratio* $0.01\ Z/Z_\odot$
  - *Elemental abundances* $y_C = 0.927 \times 10^{-4}\ Z/Z_\odot$, $y_O = 3.568 \times 10^{-4}\ Z/Z_\odot$
  - *Metallicity* $10^{-4}\ Z_\odot \leq Z \leq 10\ Z_\odot$
- Hydrostatic equilibrium disk as the initial structure

Heating/Cooling Processes

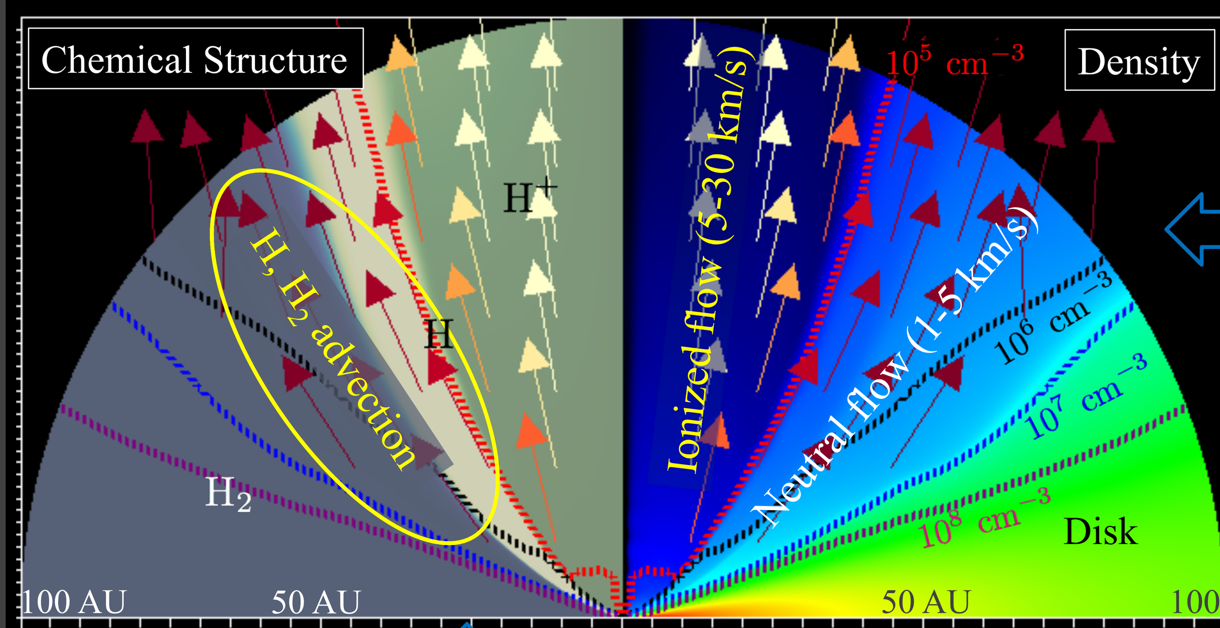
- *Line cooling*
  - H2 & CO (rovibration)
  - CII & OI (fine-structure)
  - HI (Lyman α)
- *Photo-heating*
  - EUV (photoionization)
  - FUV (photoelectric effect)
- *Other cooling*
  - Recombination
  - Dust-gas heat transfer

Dust Temperatures — Kuiper et al. (2010, 2013)

- Radiation transfer (hybrid-scheme) for direct & diffusion component
- T_{dust} → [(re-)emission] = [direct & diffusion components absorption]

III. Results: Solar Metallicity Disk

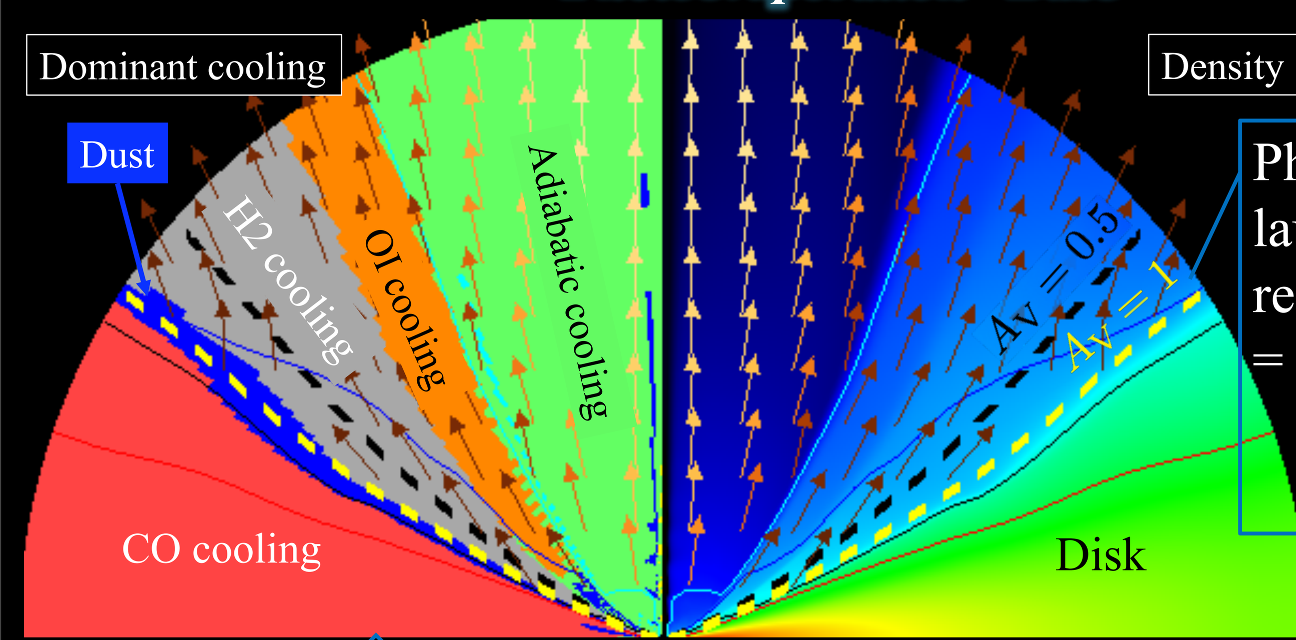
Dense Neutral Flow & H_2 molecular flow



- EUV heating → Ionized flow FUV heating → Neutral flow
- Neutral flow is denser (10^{5-7} cm^{-3}) than ionized flow

- H_2 flow → Chemical structures are changed by photo-evaporation

Photoevaporation "Base"

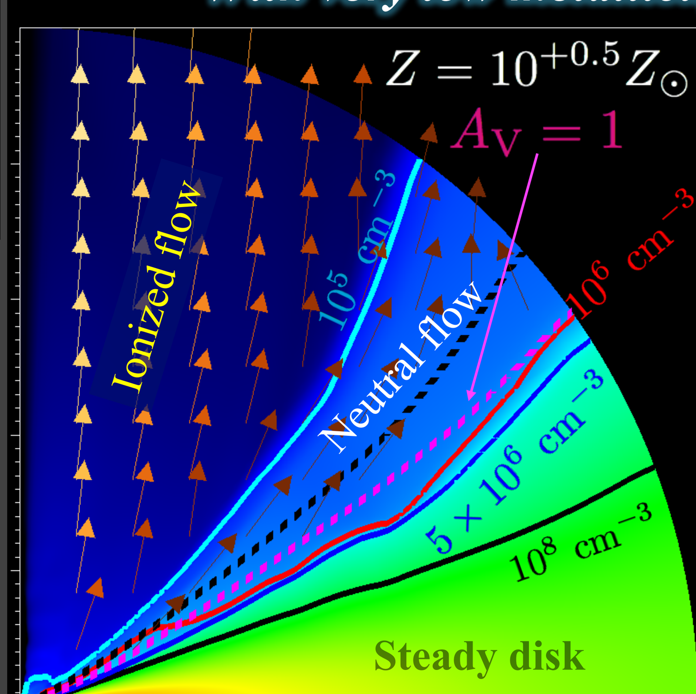


Photoevaporation is launched from the region between $A_V = 0.5$ and $A_V = 1$. ↓ "Base"

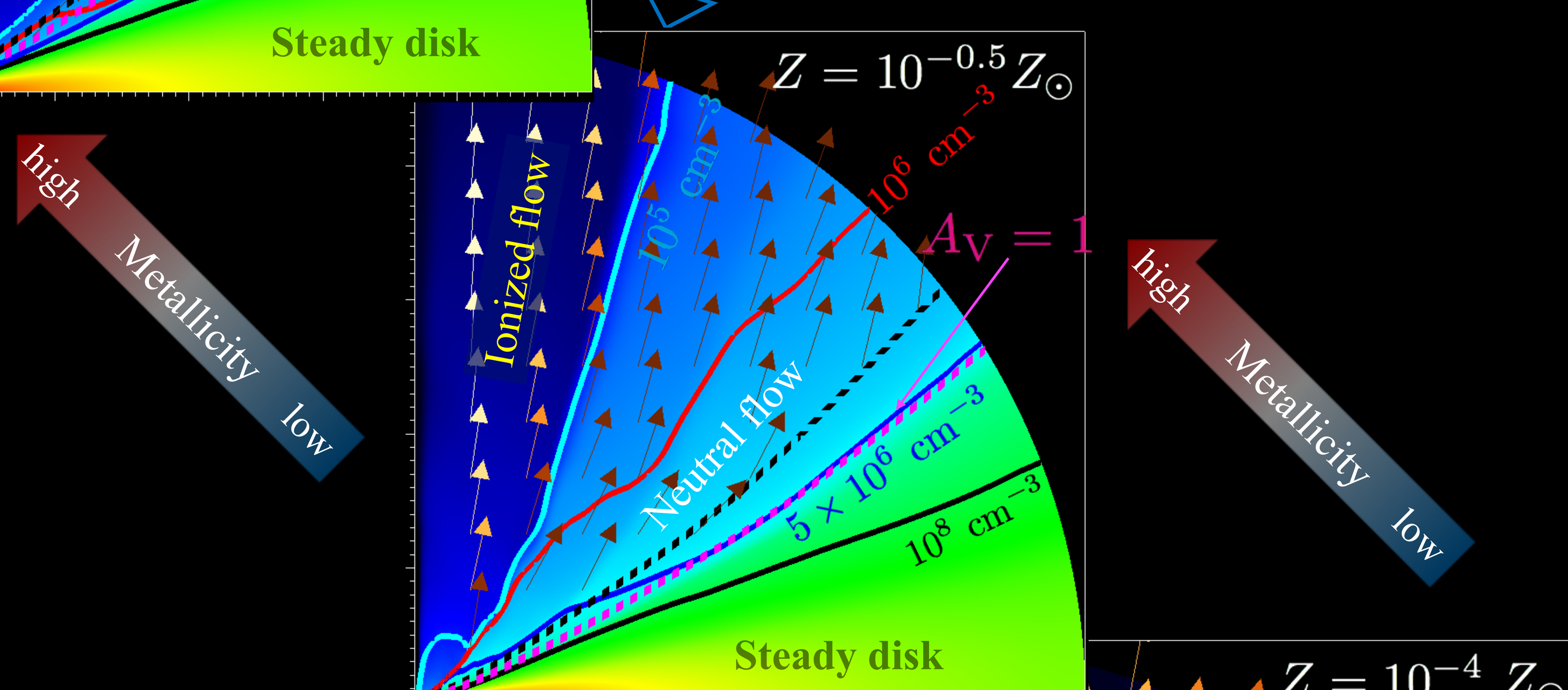
Dominant cooling: dust-gas collisions and H_2 line.

IV. Results: Various Metallicity Disks

- ***Neutral flow density increases with decreasing metallicity.***
- ***With very low metallicity, the neutral flow is not even excited.***



Lower metallicity
↓
Smaller amount of dust
↓
Less attenuation of FUV
↓
FUV can heat denser region
↓
Higher neutral flow density ($\propto Z^{-1}$)



In (neutral) base regions ($n_H \propto Z^{-1}$),

Dust-gas cooling $\propto n_{\mathrm{dust}}\, n_H \propto Z^{-1}$

FUV heating $\propto n_{\mathrm{dust}} \propto Z \times Z^{-1} = 1$

↓

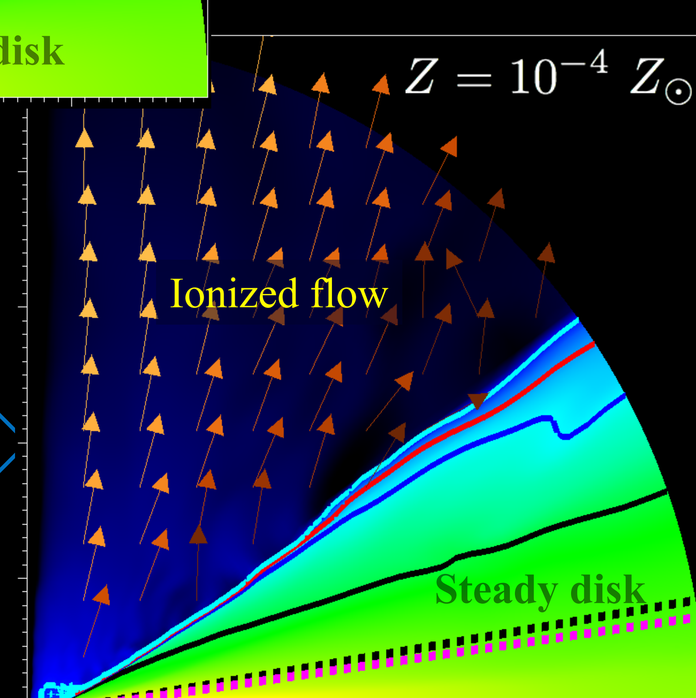
Cooling is effective with lower Z

↓

Temperature becomes lower

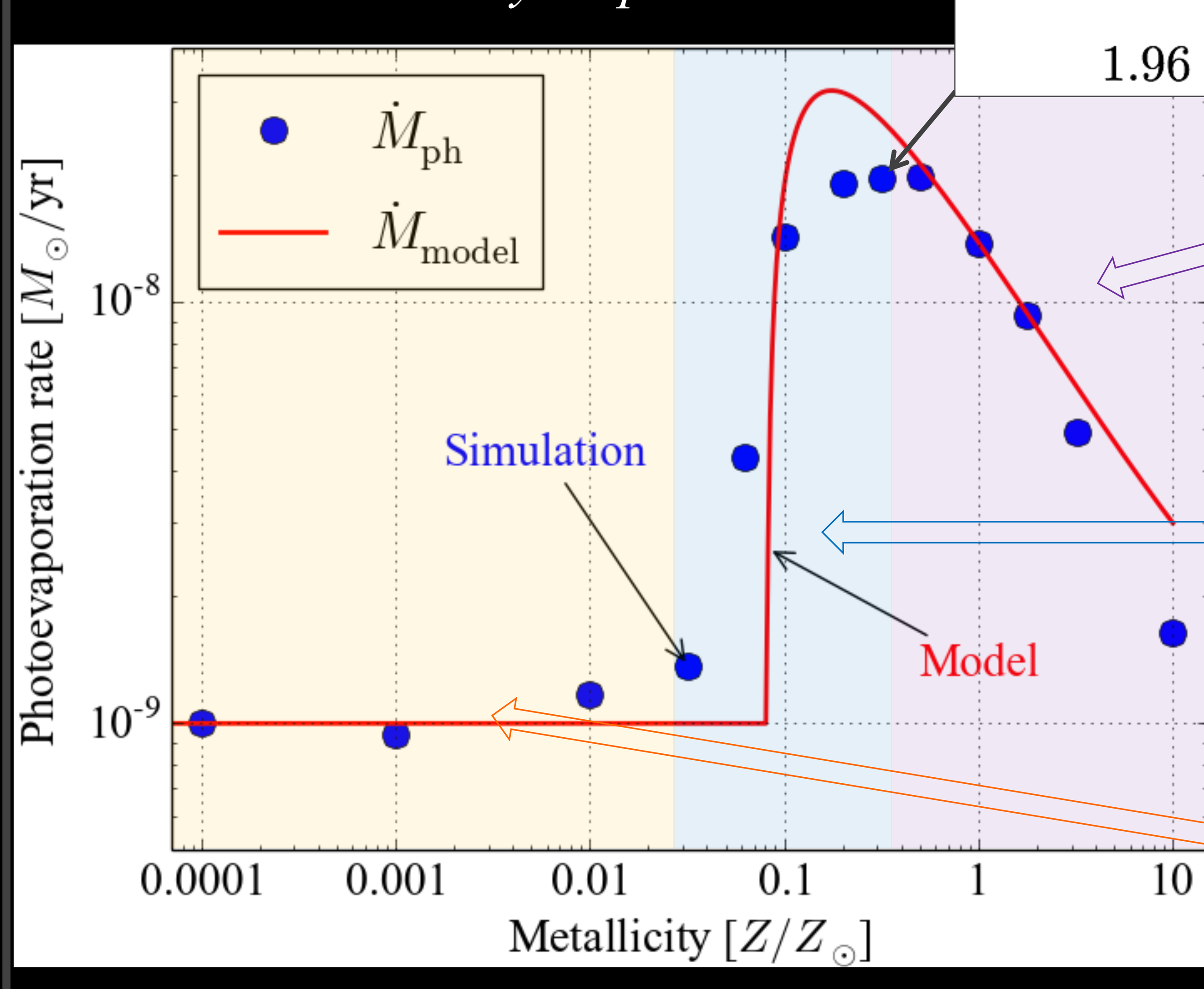
↓

Neutral flow is not excited



V. Results: Metallicity Dependence

Peak: $Z = 10^{-0.5}\ Z_\odot$ $1.96 \times 10^{-8}\ M_\odot/\mathrm{yr}$



High density flow with lower Z

FUV heating is less effective than cooling. It becomes hard to excite neutral flow.

Only ionized flow is excited. It is caused by EUV, so metallicity-independent