原始惑星系円盤における紫外線/X線光蒸発の輻射流体シミュレーション: 金属量依存性

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(Nakatani et al. submitted to ApJ; arXiv: 1706.04570)

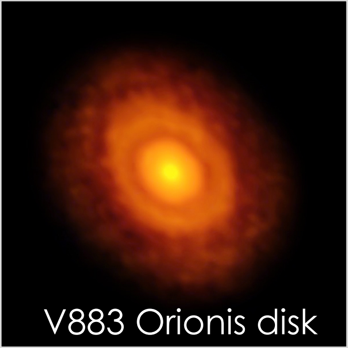
第30回理論懇シンポジウム @ 小柴ホール, 12/26/2017

Protoplanetary Disk

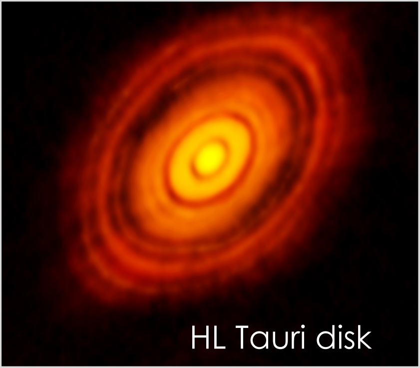
- Geometrically thin Keplerian disk around a pre-main-sequence star

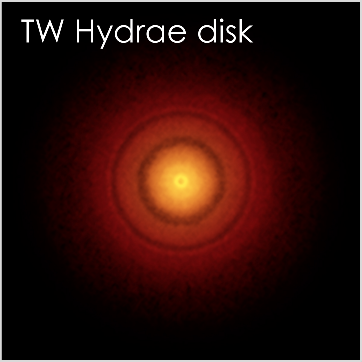
  Main components ; Gas/Dust

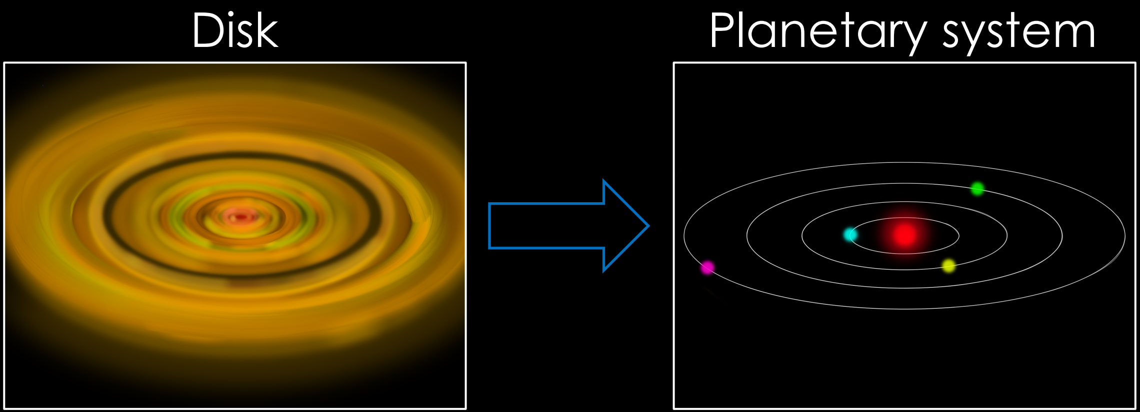
- Birthplace of planets



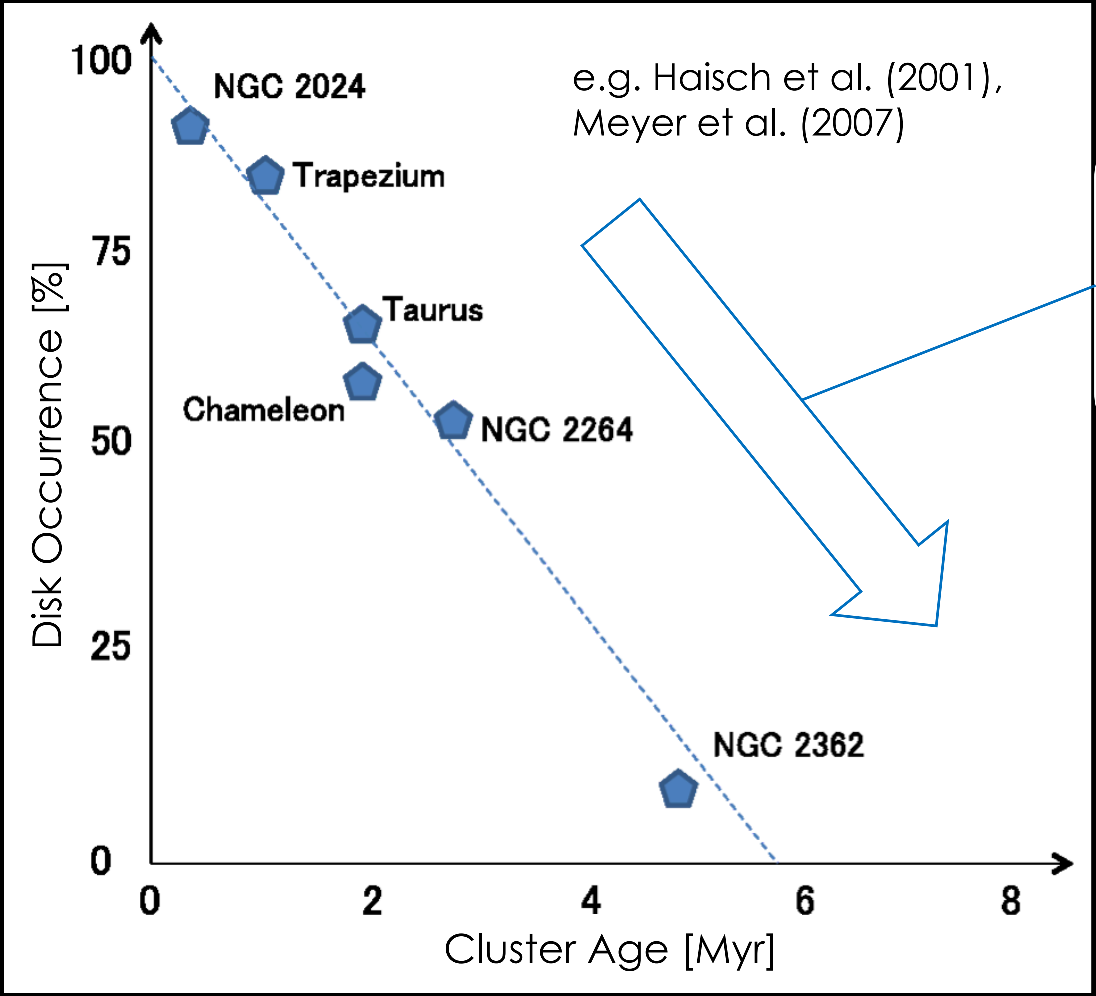
http://www.almaobservatory.org/press-room/press-releases/







Lifetimes of Protoplanetary Disks



e.g. Haisch et al. (2001), Meyer et al. (2007)

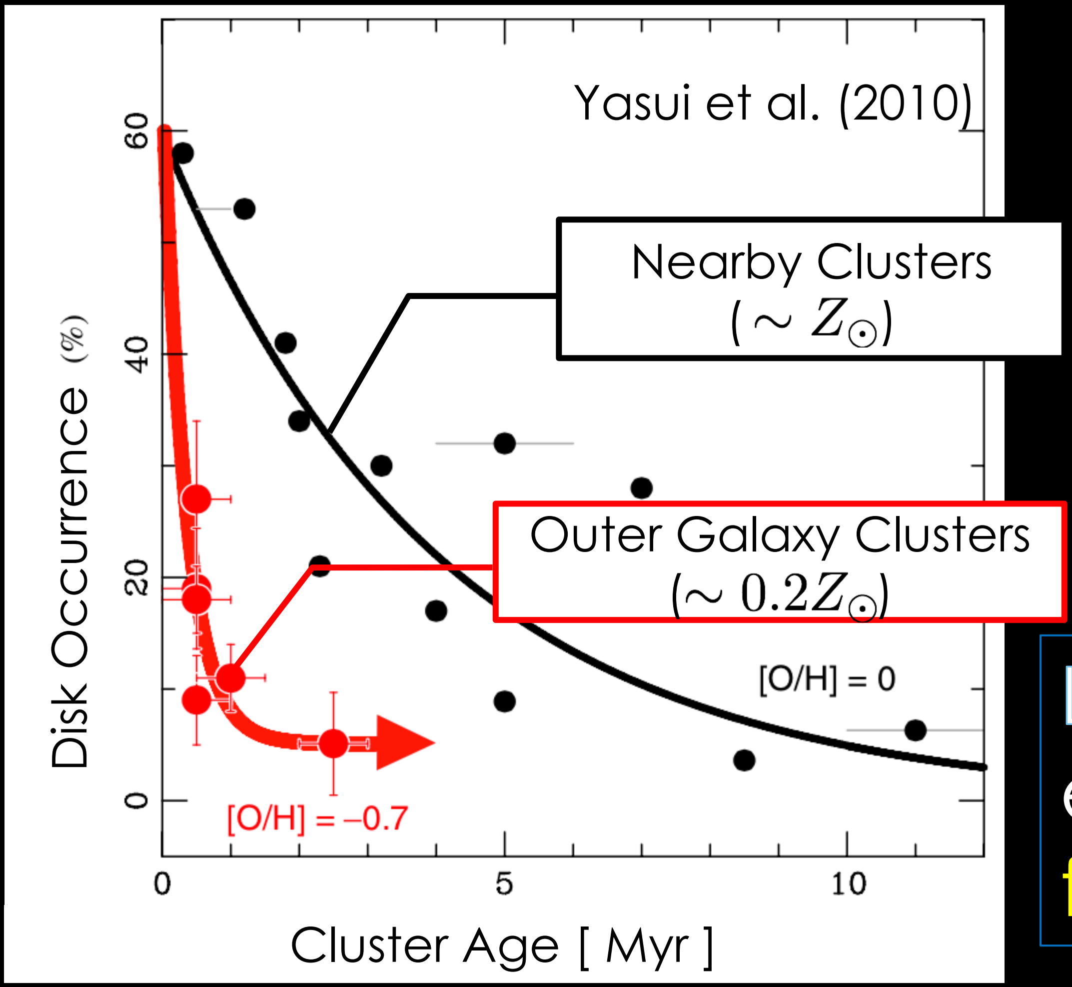
Disk Occurrence decreases as a cluster ages

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.

Lifetime (low Z) ~ 1 Myr

Low Z
environments may
faster disk dispersal.

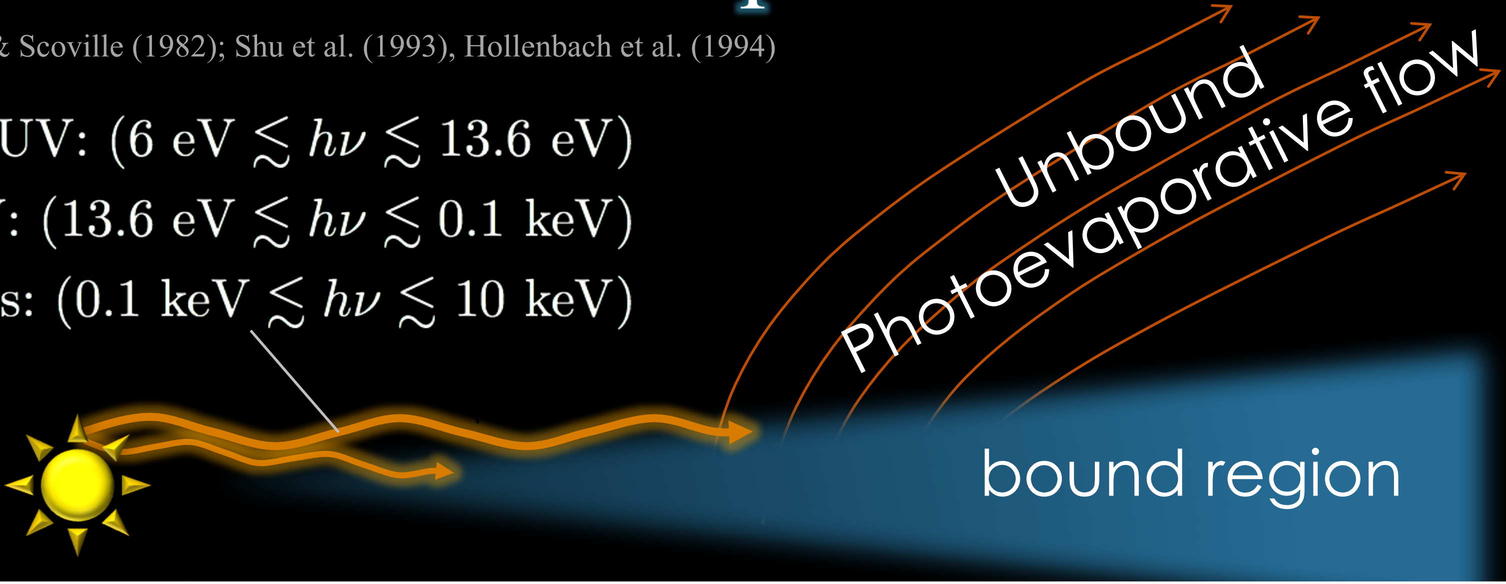
What mechanism makes a disk disperse?
– Photoevaporation –

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

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

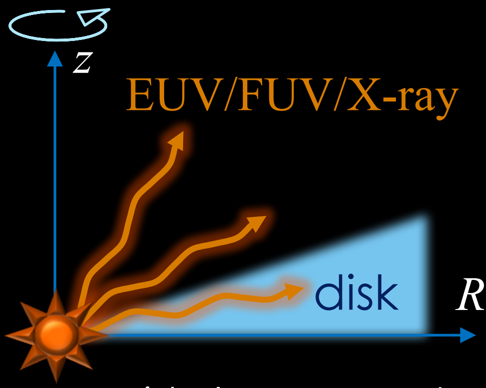


	FUV	EUV	X-rays
Reaction	Dust + FUV → Dust + e	H + EUV → H^+ + e	M + X → M^+ + e
Main absorber	Dust grains	Atomic hydrogen	Metal elements
Penetrability	High	Low	High

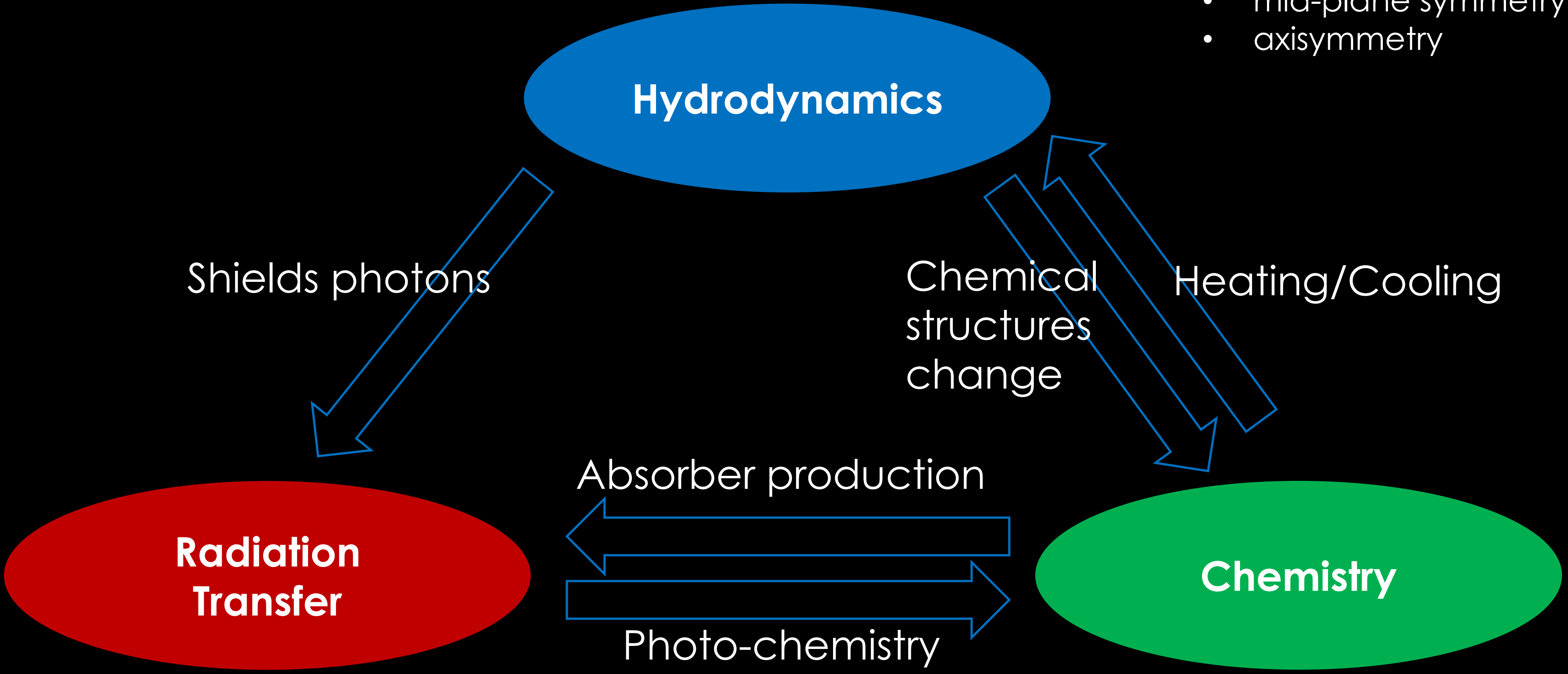
Our Work:
- What roles UV/X-ray play in photoevaporation
- examine Z dependence of photoevaporation

Methods:

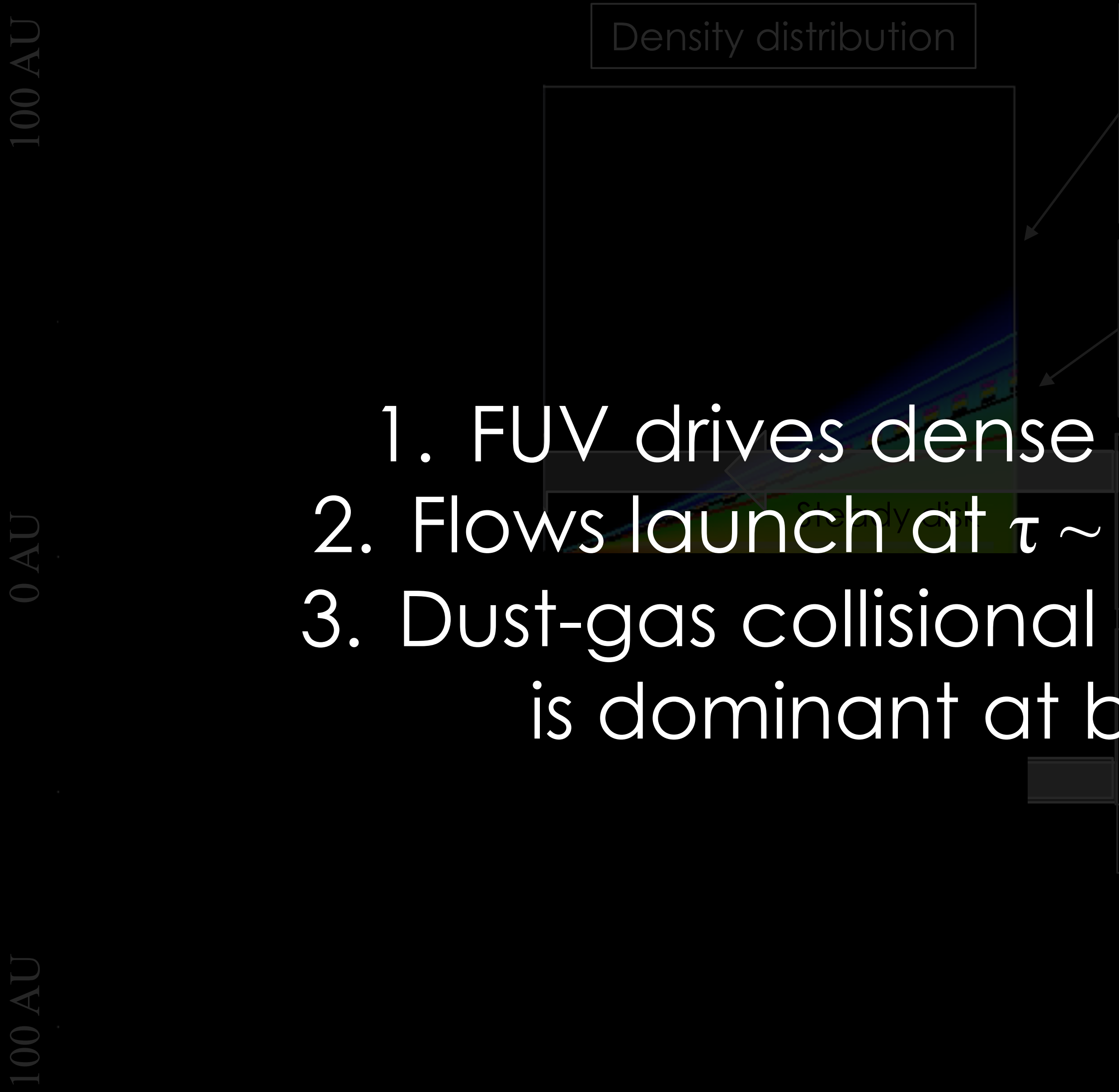
Hydrodynamics (2D; spherical polar coord.)
\+ **Radiation transfer** (FUV/EUV/X-ray, dust IR)
\+ **Non-equilibrium Chemistry** ,
Varying disk metallicity (dust/metal $\propto Z$)



- mid-plane symmetry
- axisymmetry



UV Photoevaporation in Solar Metallicity Disk



Dashed lines (τ_{FUV})

Magenta: 0.5
Yellow: 1
Black : 2

Solid lines (n_{H} /cm^{-3})

Cyan: 10^5 Blue: 10^6
Black: 10^7 Red: 10^8

1. FUV drives dense winds
2. Flows launch at $\tau \sim 1$: base
3. Dust-gas collisional cooling is dominant at base

Photoevaporative flows launch at $\tau_{\mathrm{FUV}} \sim 1$ (base) (yellow dashed line)

EUV-driven ionized flow

$n_{\mathrm{H}} \sim 10^5\ \mathrm{cm}^{-3}$

$v_{\mathrm{p}} \sim 5 - 30\ \mathrm{km/s}$

Dust-gas collisional cooling (blue region) is dominant at the base

FUV-driven neutral flow

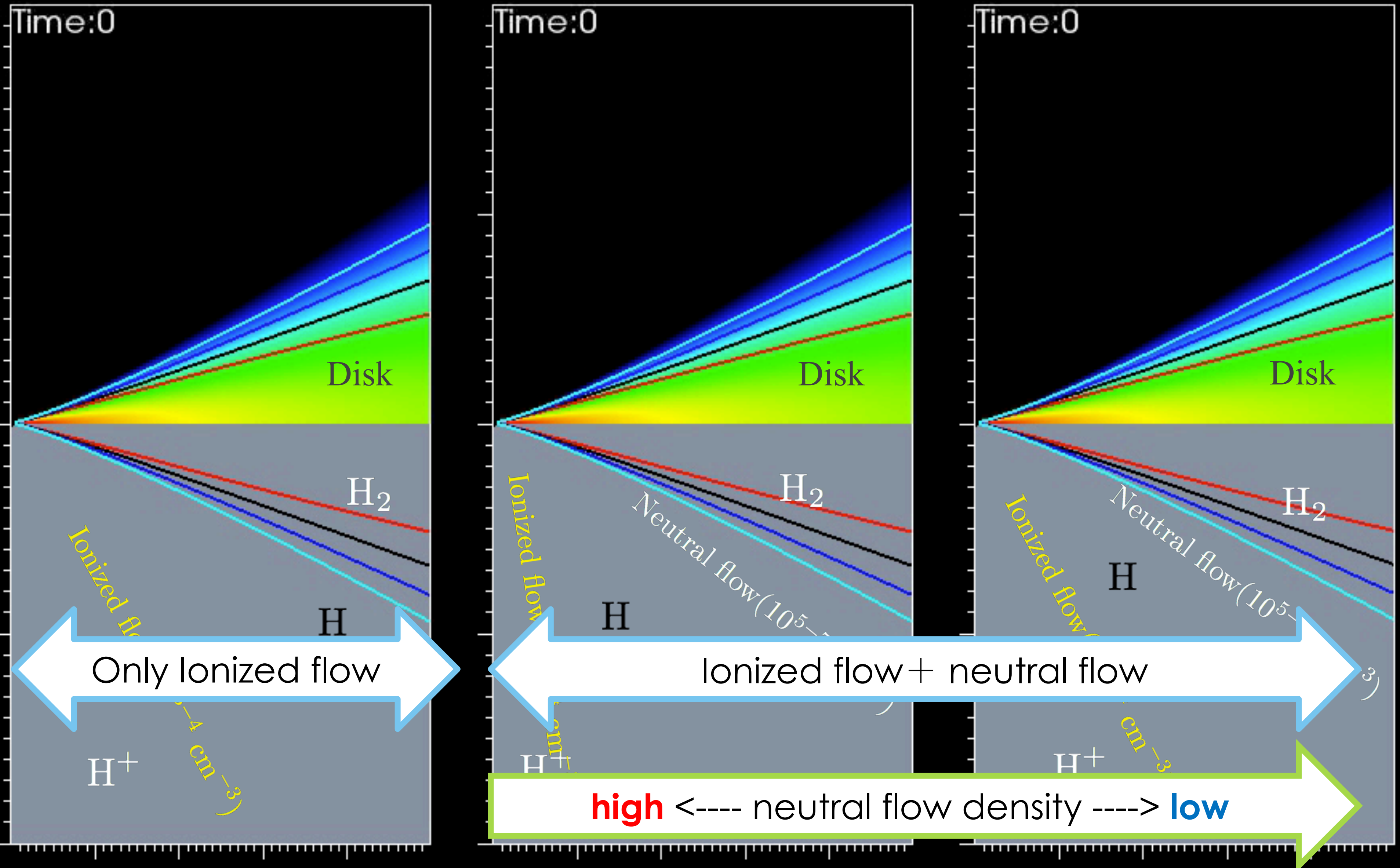
$n_{\mathrm{H}} \sim 10^{5-7}\ \mathrm{cm}^{-3}$

$v_{\mathrm{p}} \sim 0.5 - 5\ \mathrm{km/s}$

Various metallicities

low Z → high Z

$Z = 10^{-3}\ Z_{\odot}$ $Z = 10^{-0.5} Z_{\odot}$ $Z = 10^{+0.5} Z_{\odot}$

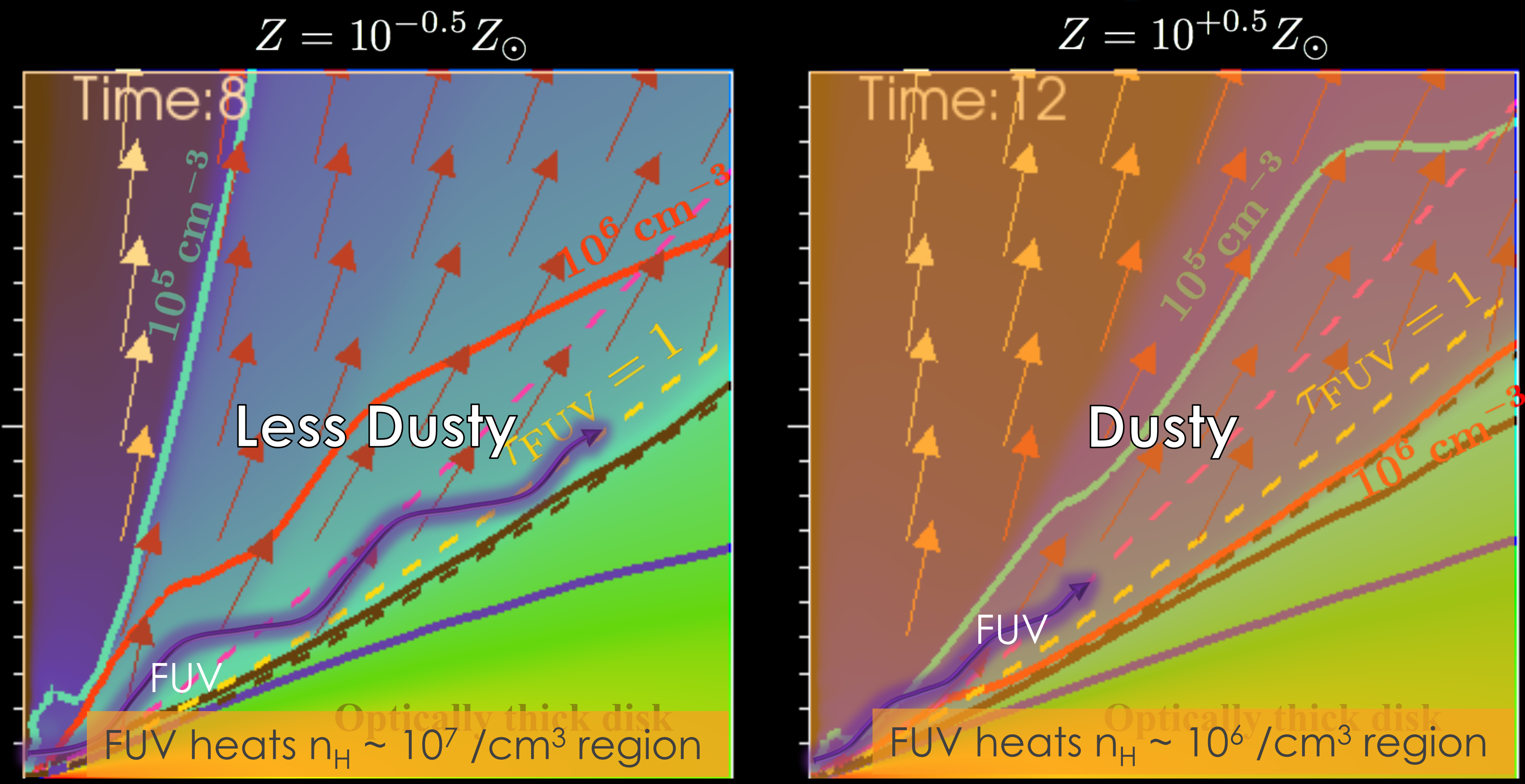


Only Ionized flow

Ionized flow + neutral flow

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

1. Denser flow in lower metallicity



$Z = 10^{-0.5} Z_\odot$

$Z = 10^{+0.5} Z_\odot$

FUV heats $n_H \sim 10^7$ /cm^3 region

FUV heats $n_H \sim 10^6$ /cm^3 region

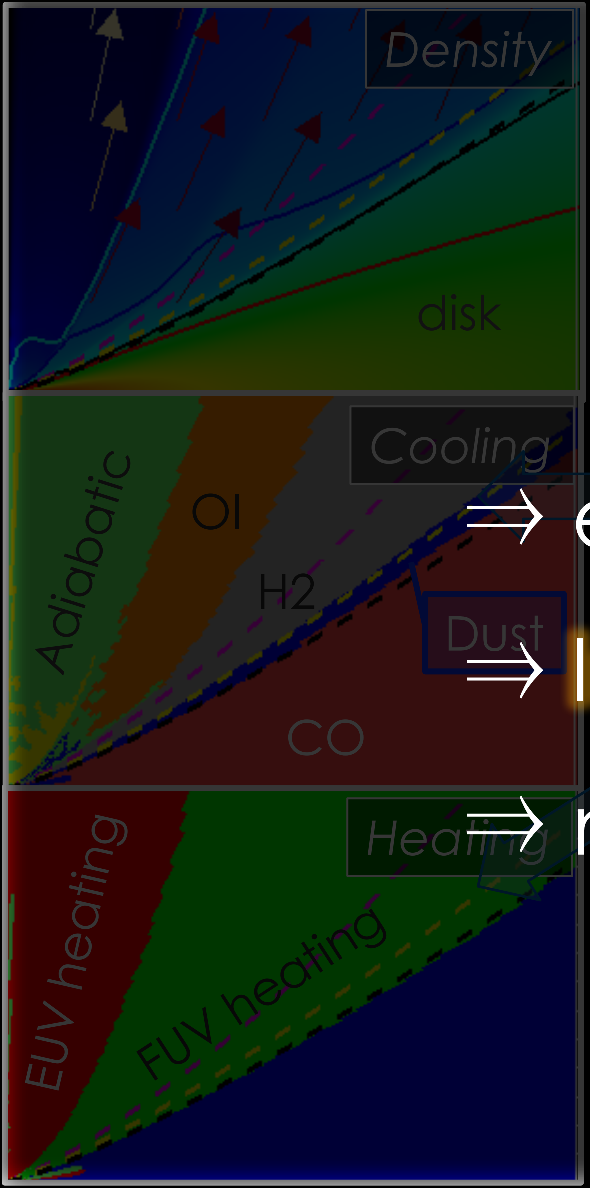
See the yellow dashed line ($\tau_{FUV} = 1$) and the red solid line ($n_H = 10^6$ cm^{-3})

lower metallicity → less amount of the absorbers

→ FUV can reach denser regions.

→ DENSER winds in LOWER metallicity ($n_{H,base} \propto Z^{-1}$)

2. No neutral flow in very low metallicity



Remember… at the base ($\tau = 1$),
FUV heating VS Dust-gas cooling

metallicity ↘

⇒ effective cooling

⇒ lower temperatures

⇒ no neutral wind

Dust-gas collisional cooling

$$\text{collision rates} = 4\pi a^2 c_s n_\mathrm{H} n_\mathrm{d}$$

FUV heating

$$\text{absorption rates} = F_\mathrm{FUV} \sigma_\mathrm{d} n_\mathrm{d}$$

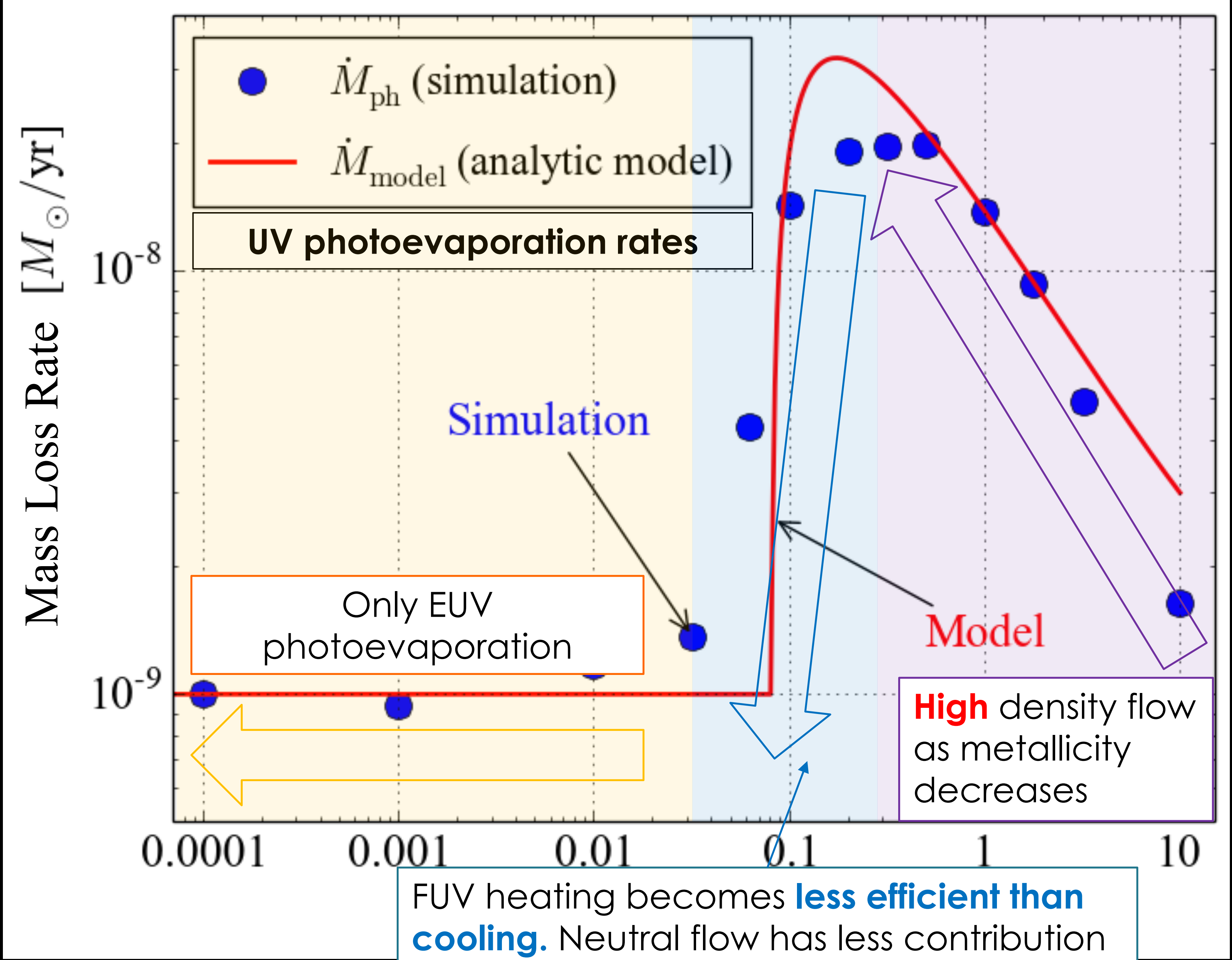
$$n_\mathrm{H,base} \propto Z^{-1}$$

$$r = \frac{\text{Cooling}}{\text{Heating}} \propto \frac{a_\mathrm{d}^2 c_s n_\mathrm{H}}{F_\mathrm{FUV} \sigma_\mathrm{d}} \propto Z^{-1}$$

$$L_\mathrm{FUV} e^{-\tau_\mathrm{FUV}}$$

metallicity ↘ ⇒ r ↗.

UV photoevaporation rates

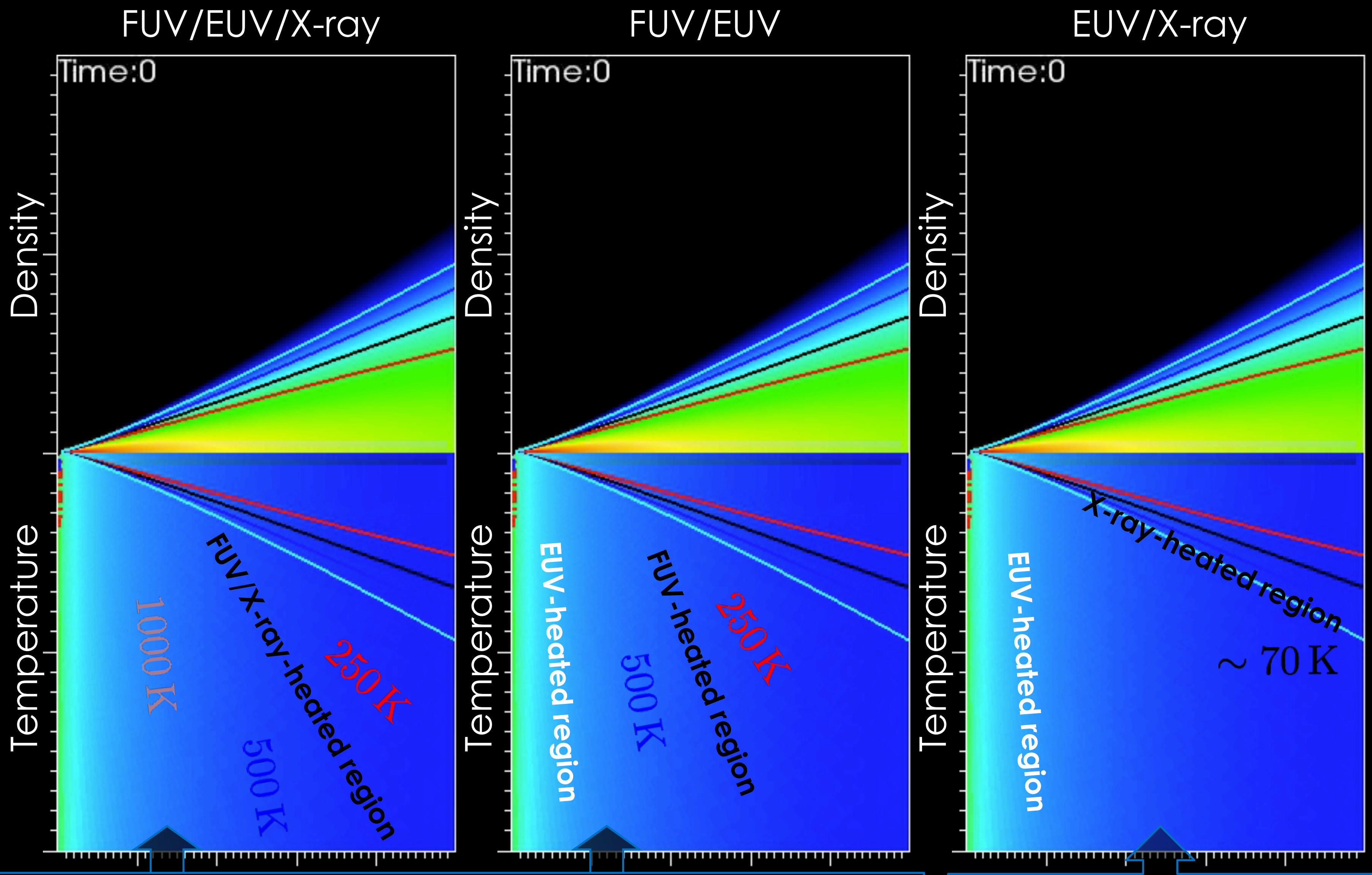


Only EUV photoevaporation

High density flow as metallicity decreases

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

X-ray Effects ($Z = 0.1\,Z_\odot$ disk)



FUV/EUV/X-ray

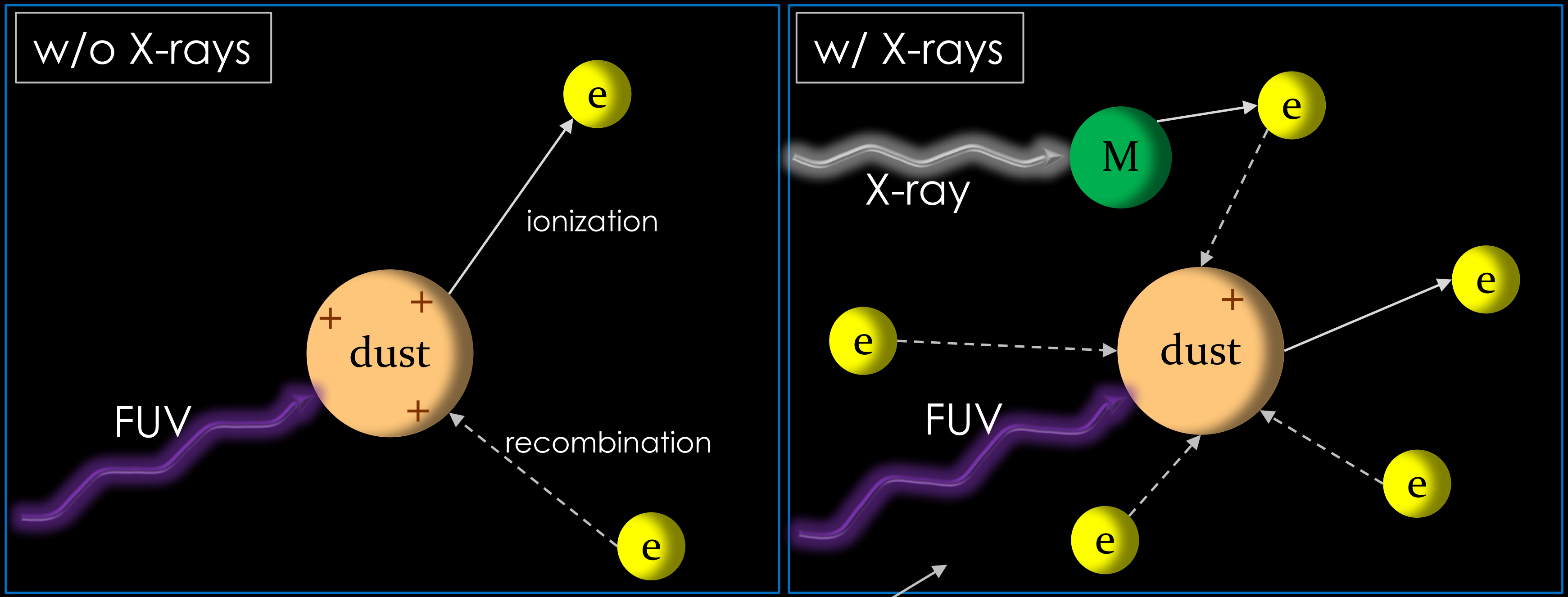
FUV/EUV

EUV/X-ray

- The temperature is higher in the left
- The gas evaporates more vigorously in the left

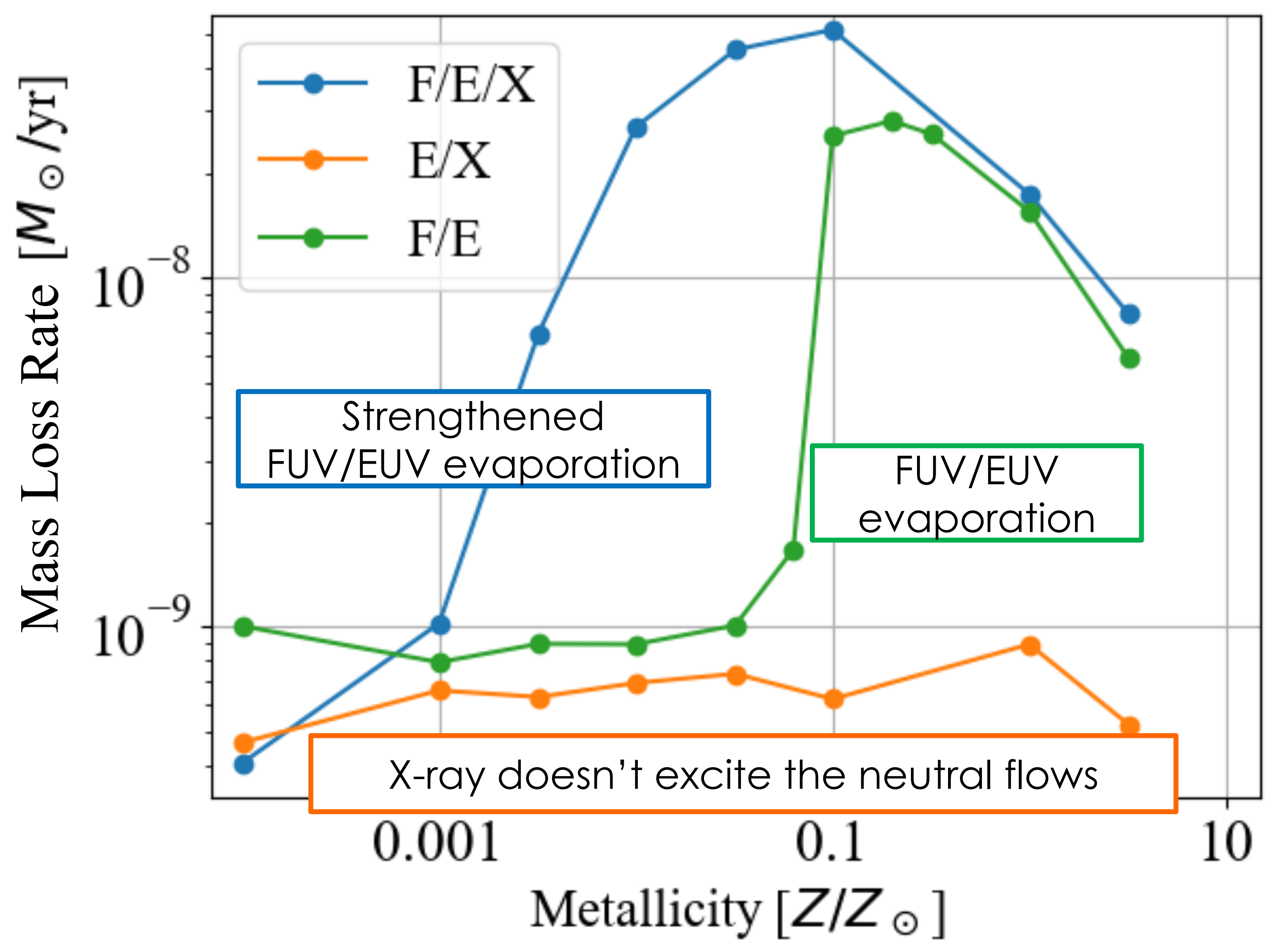
X-ray doesn’t excite flows

X-rays strengthen the FUV heating



Electron rich
→ Efficient recombination
→ Reduced positive charge
→ Efficient photoelectron ejection
→ Strengthened FUV heating

UV/X-ray Photoevaporation Rates



Strengthened FUV/EUV evaporation

FUV/EUV evaporation

X-ray doesn't excite the neutral flows

- 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 $Z \sim 10^{-0.5}\ Z_\odot$. If X-rays are taken into account, the peak moves to $Z \sim 10^{-1}\ Z_\odot$. X-rays strengthen the 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 $Z \lesssim 10^{-3}\ Z_\odot$.

- Future (current) work
  - Modeling dust dynamics in photoevaporating disks.