

# Dispersal of protoplanetary disks: Effects of photoevaporation with stellar evolution and MHD winds

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## Take-home messages

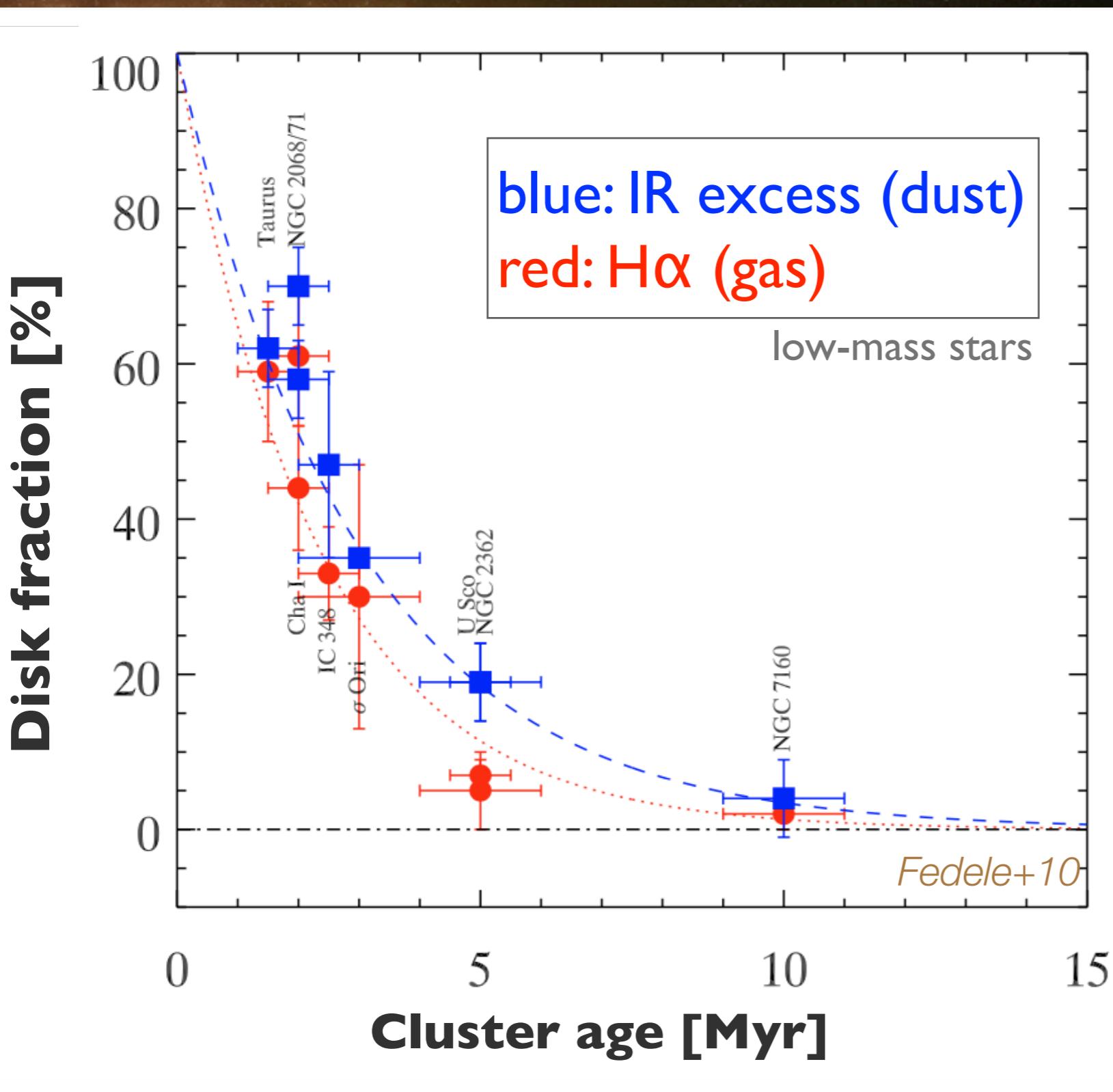
- Can disks with weak turbulence disperse within  $\sim$  Myr?  
— Yes, if both **photoevaporative and MHD winds are considered**

*Kunitomo, Suzuki & Inutsuka (2020), MNRAS*  
<https://doi.org/10.1093/mnras/staa087>

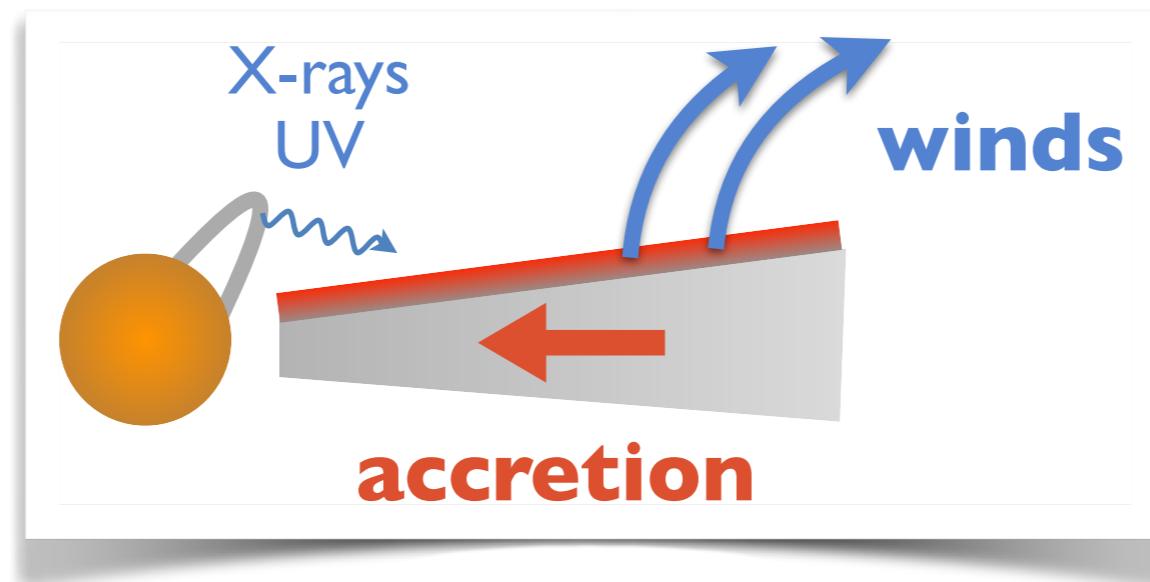
- Does stellar evolution affect disk evolution?  
— Yes, especially around intermediate-mass stars

*Kunitomo, Ida, Takeuchi, Panić, Miley & Suzuki (2021), ApJ, accepted*  
<https://kunitomomasanobu.wixsite.com/home/publications>

# Disk lifetime $\sim 6$ Myr



# Standard picture of disk evolution



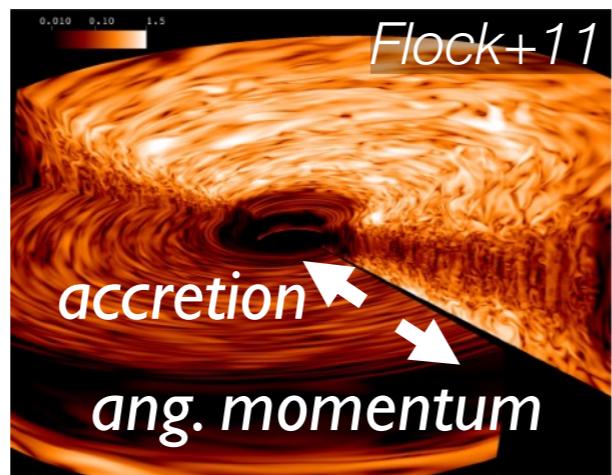
e.g., Alexander+14,  
Clarke+01, Gorti+09,  
Owen+12, Morishima12,  
Kimura+16

## Accretion

- turbulent viscosity

- Radial angular momentum transport
- Origin of turbulence: MRI etc.
- Viscosity:  $\alpha$

Shakura+Sunyaev73



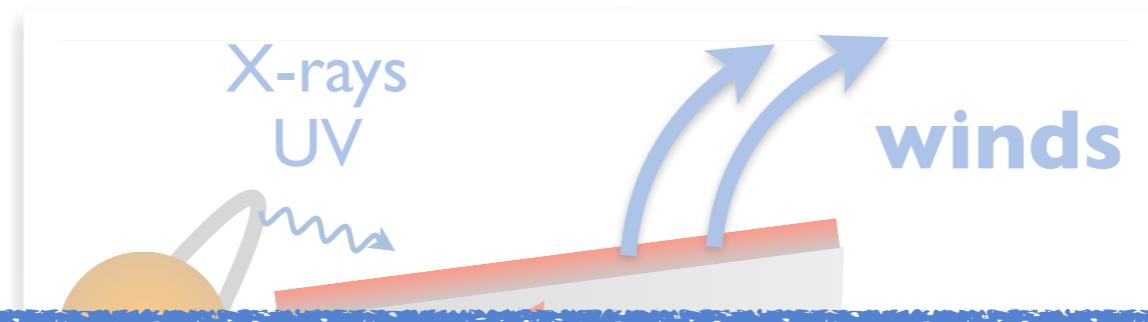
## Winds

- thermal (photoevaporation)

high-energy photons (XUV) heat up the disk surface ( $\sim 10^3$ – $10^4$  K)  
→ gas flows out from the outer  
( $\gtrsim 1$  au) disk where  
*the thermal energy > gravity*

Hollenbach+94, Liffman+03, Alexander+06,  
Gorti+09, Owen+10, Tanaka+13,  
Wang+Goodman17, Nakatani+18ab

# Disk evolution mechanisms



e.g., Alexander+14,  
Clarke+01, Gorti+09,  
Owen+12, Morishima12,  
Kimura+16

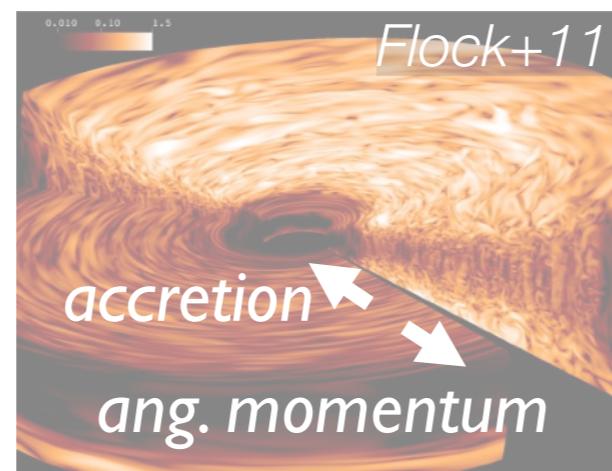
## Two questions:

Kunitomo+21, ApJ

- Does **stellar evolution** affect disk evolution?
- Can disks with **weak turbulence** disperse within  $\sim$ Myr?

- Origin of turbulence: MRI etc.
- Viscosity:  $\alpha$

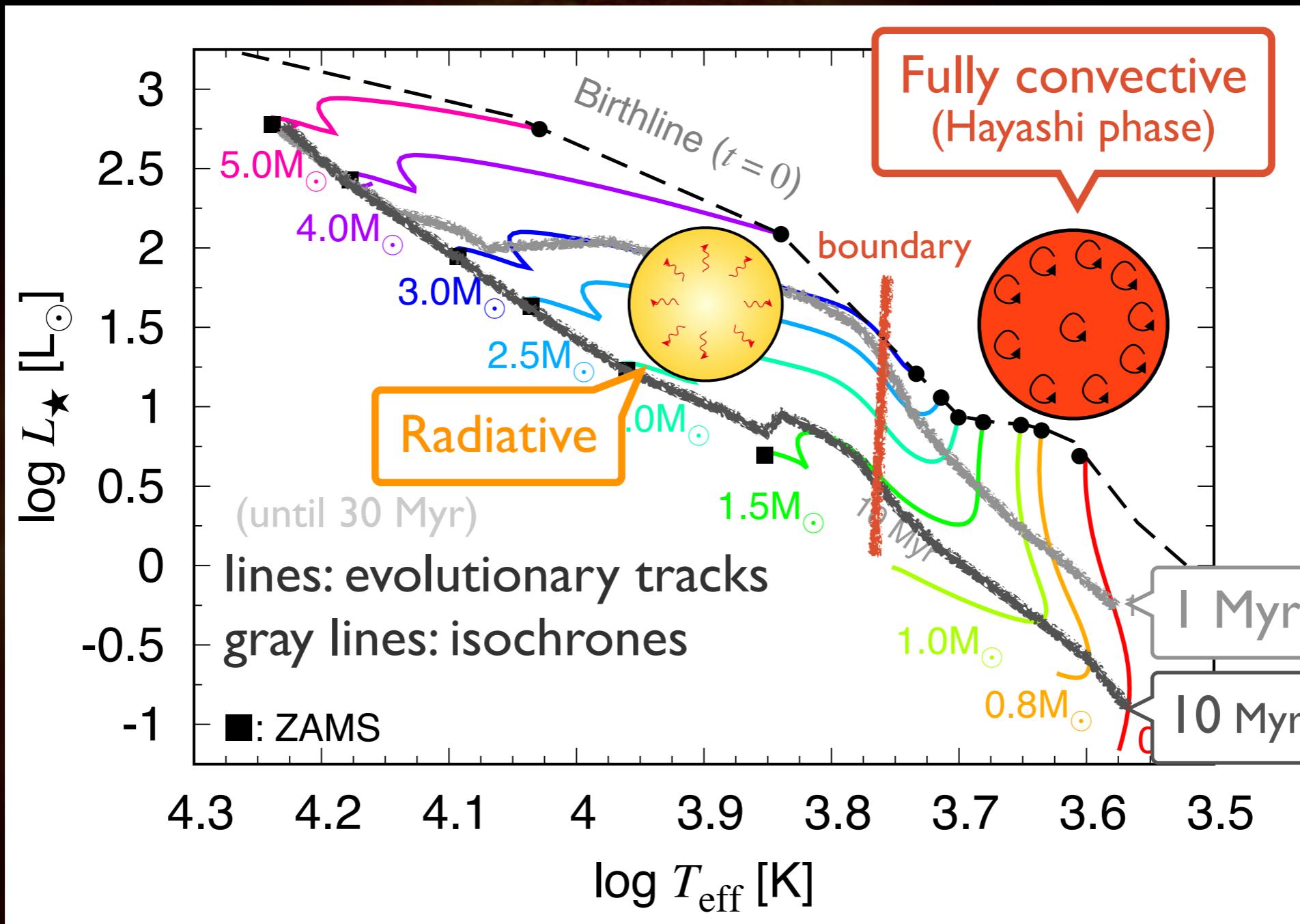
Shakura+Sunyaev73



→ gas flows out from the outer ( $\gtrsim 1$  au) disk where  
the thermal energy > gravity

Hollenbach+94, Liffman+03, Alexander+06,  
Gorti+09, Owen+10, Tanaka+13,  
Wang+Goodman17, Nakatani+18ab

# Young stars evolve



- Pre-MS stars are formed at the birthline
- $T_{\text{eff}}$  increases on the Henyey track
- Stellar structure changes: fully convective to radiative
- Higher-mass stars evolve more quickly

# Stellar XUV luminosity evolves

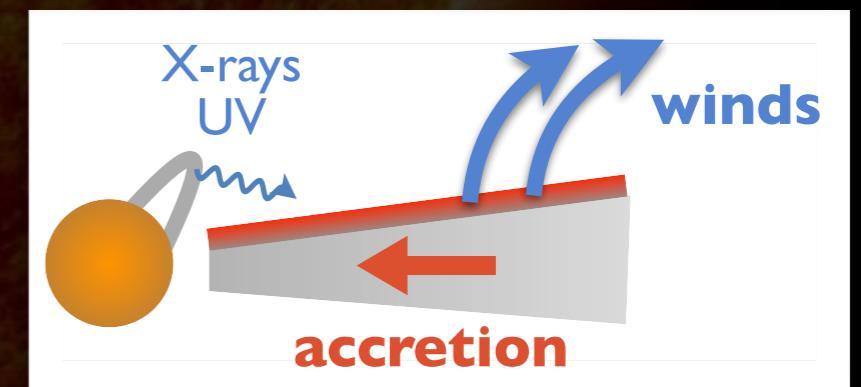
Three components of XUV radiation of young stars:

- magnetic activity
- accretion shock
- photospheric radiation

**stellar structure**  
(thickness of convective envelope)

**stellar  $T_{\text{eff}}$**

XUV luminosity determines the photoevaporation rate  
→ Question: How does stellar evolution affect the disk evolution?

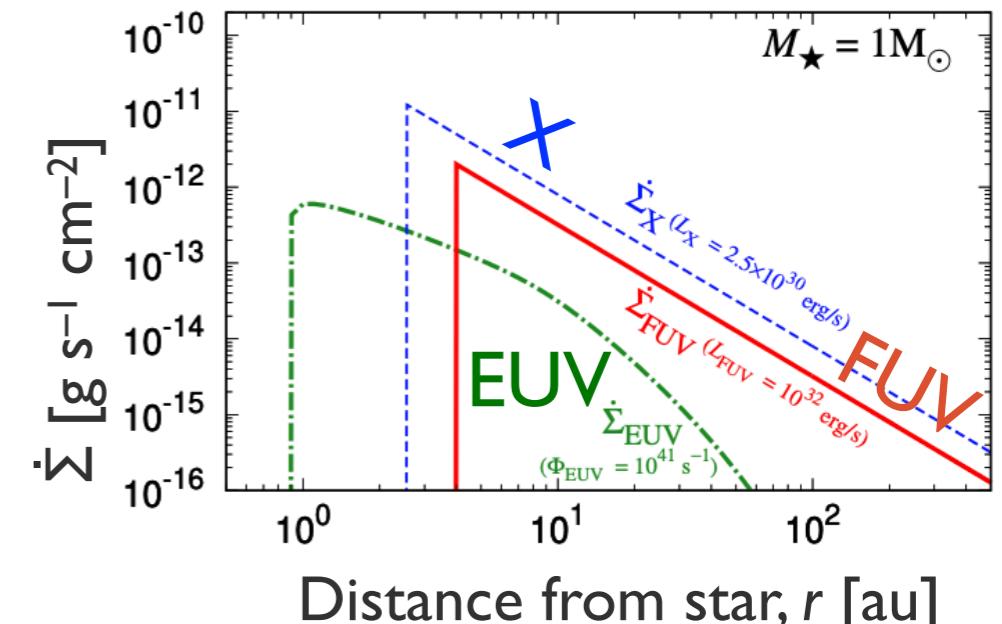


# Method: 1D diffusion equation

$$\frac{\partial \Sigma}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left[ \frac{2}{r\Omega} \frac{\partial}{\partial r} (r^2 \Sigma \alpha c_s^2) \right] + \dot{\Sigma}_{\text{PEW}} = 0$$

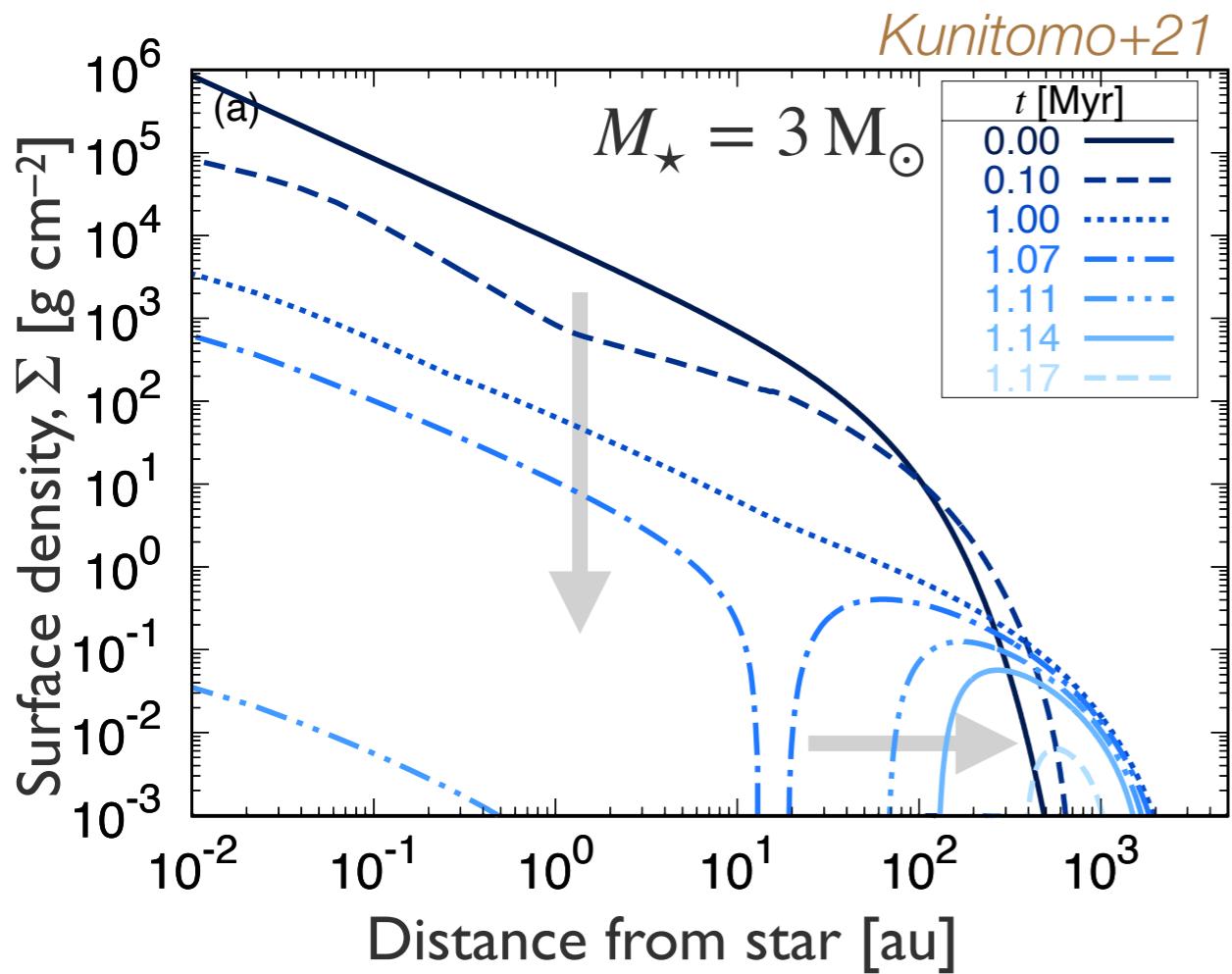


- Photoevaporative wind rate  $\dot{\Sigma}_{\text{PEW}}$ :  
FUV: Gorti+Hollenbach09, Wang+Goodman17,  
EUV: Alexander+Armitage07, X-ray: Owen+12
- $\dot{\Sigma}_{\text{PEW}}$  changes along with the evolution of stellar XUV luminosity
- XUV luminosities: stellar evolution and atmosphere models, empirical relations  
*Paxton+11, Castelli+Kurucz03, Wright+11, Calvet+Gullbring98, etc.*

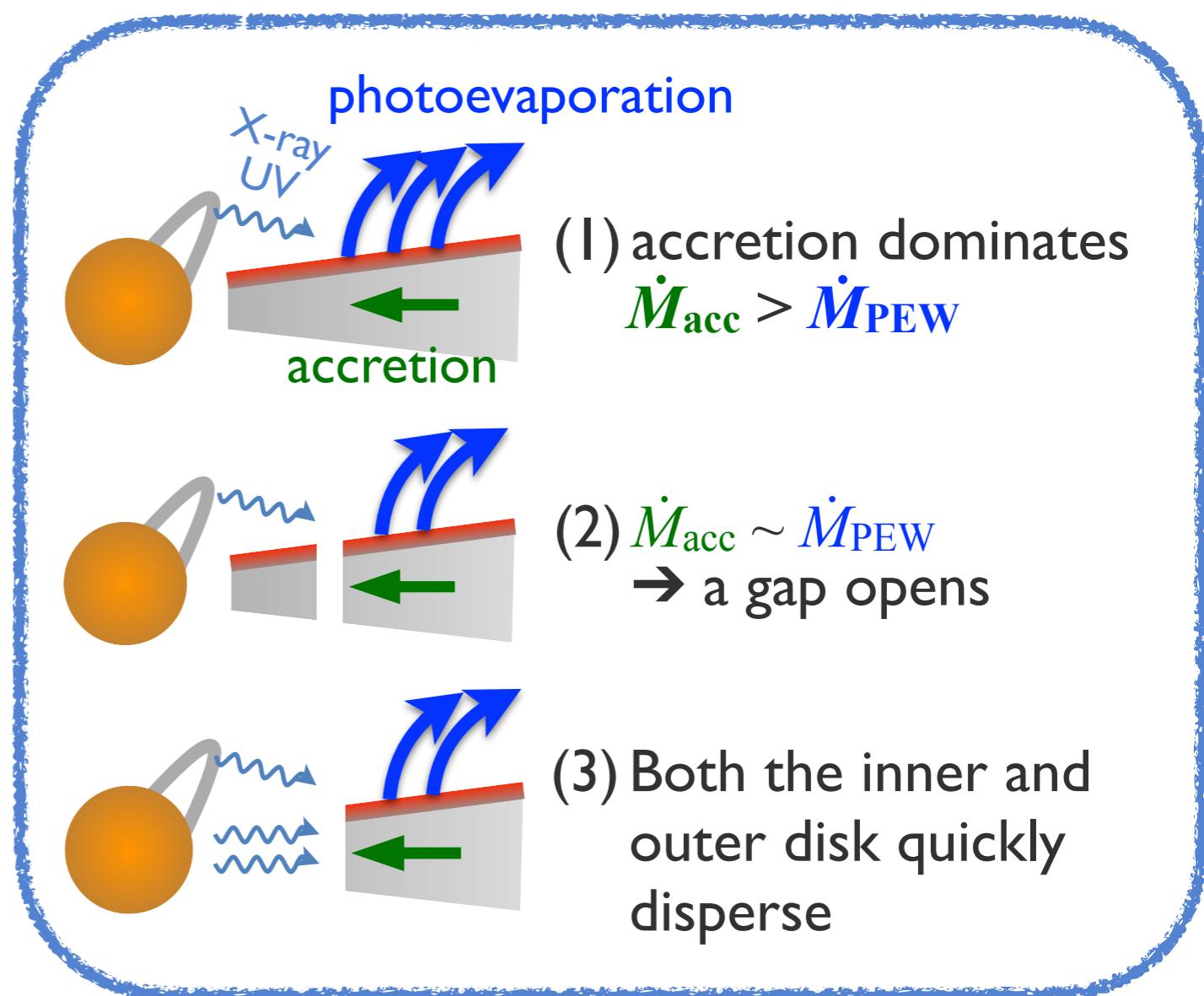


- **Settings:**
  - Stellar mass  $M_\star = 0.5 - 5 M_\odot$ , Disk initial condition: 50 au,  $0.1 M_\star$
  - Temp. structure: stellar irradiation + viscous heating *Nakamoto+Nakagawa94*
  - Viscosity parameter  $\alpha = 10^{-2} (M_\star/M_\odot)$  (from observations  $\dot{M} \propto M_\star^2$ ) *Muzerolle+05*

# Surface density evolution around a $3 M_{\odot}$ star

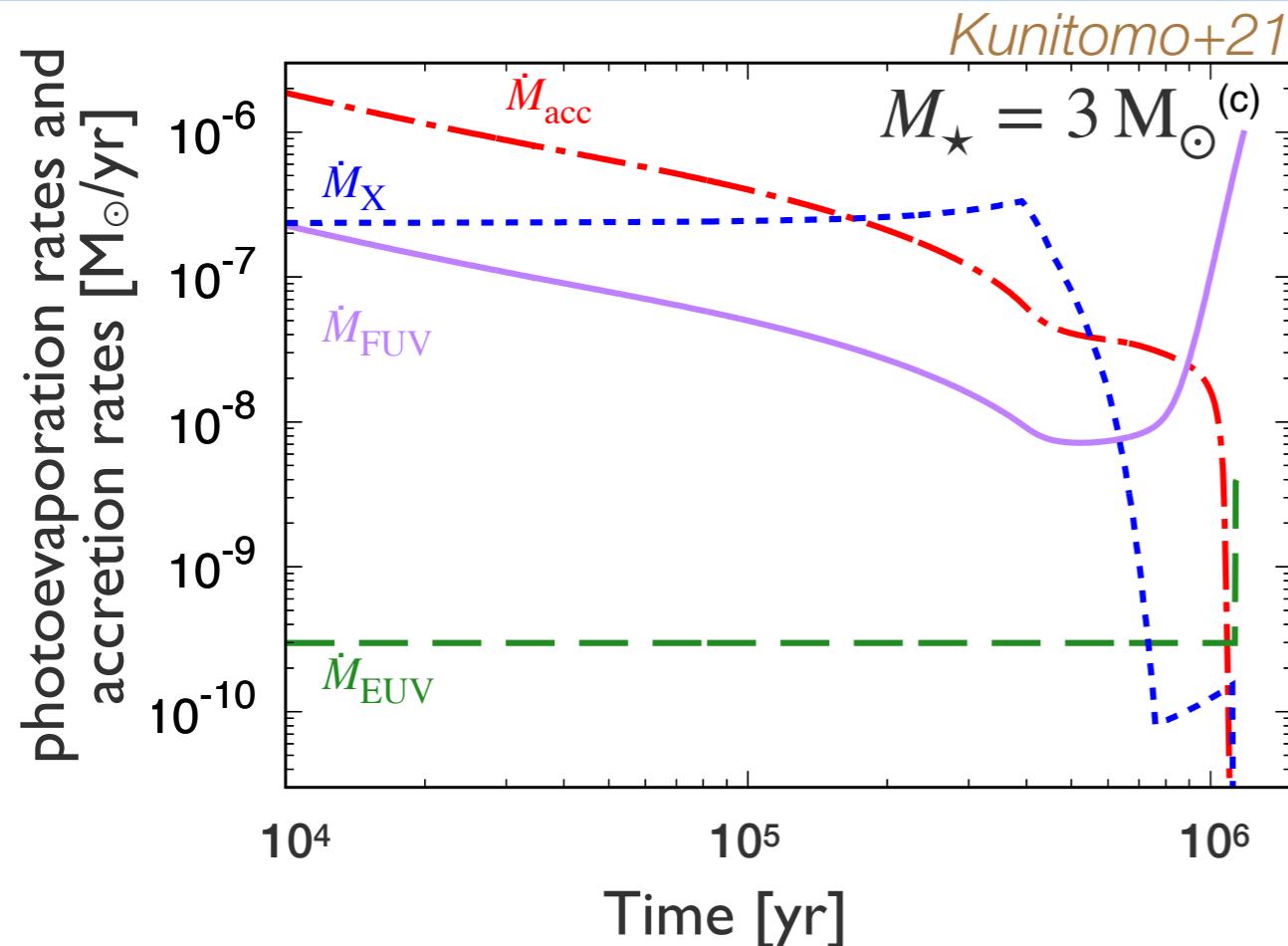


Qualitative behavior looks similar to previous studies



*Clarke+01*

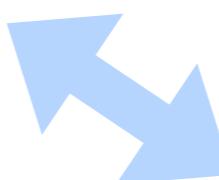
# Accretion & PEW rate evolution around a $3 M_{\odot}$ star



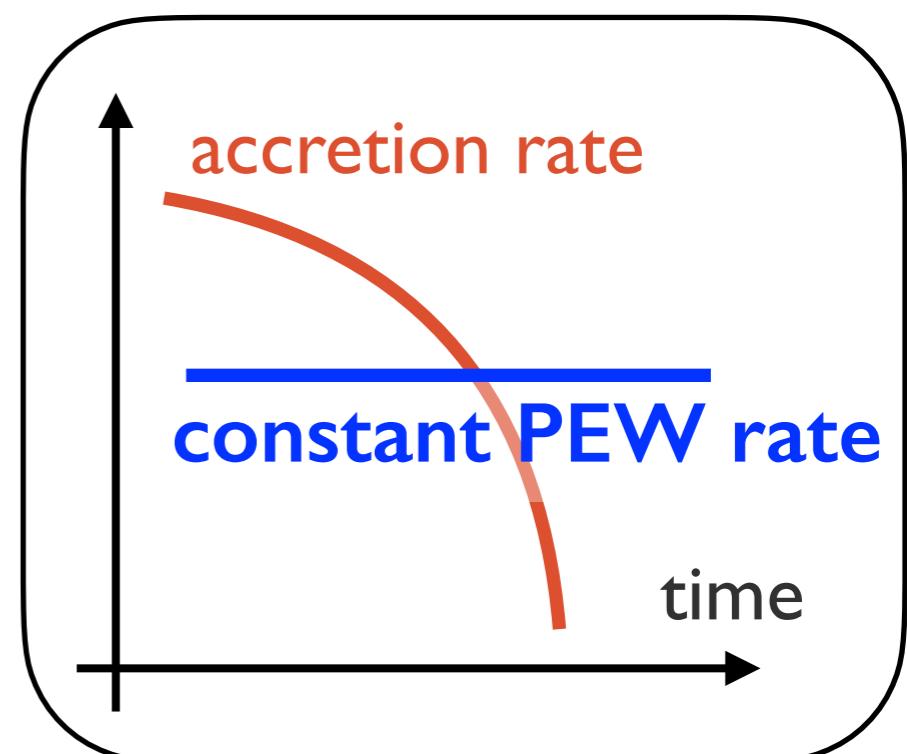
- **Photoevaporation rates evolve with time significantly:**

different from previous studies

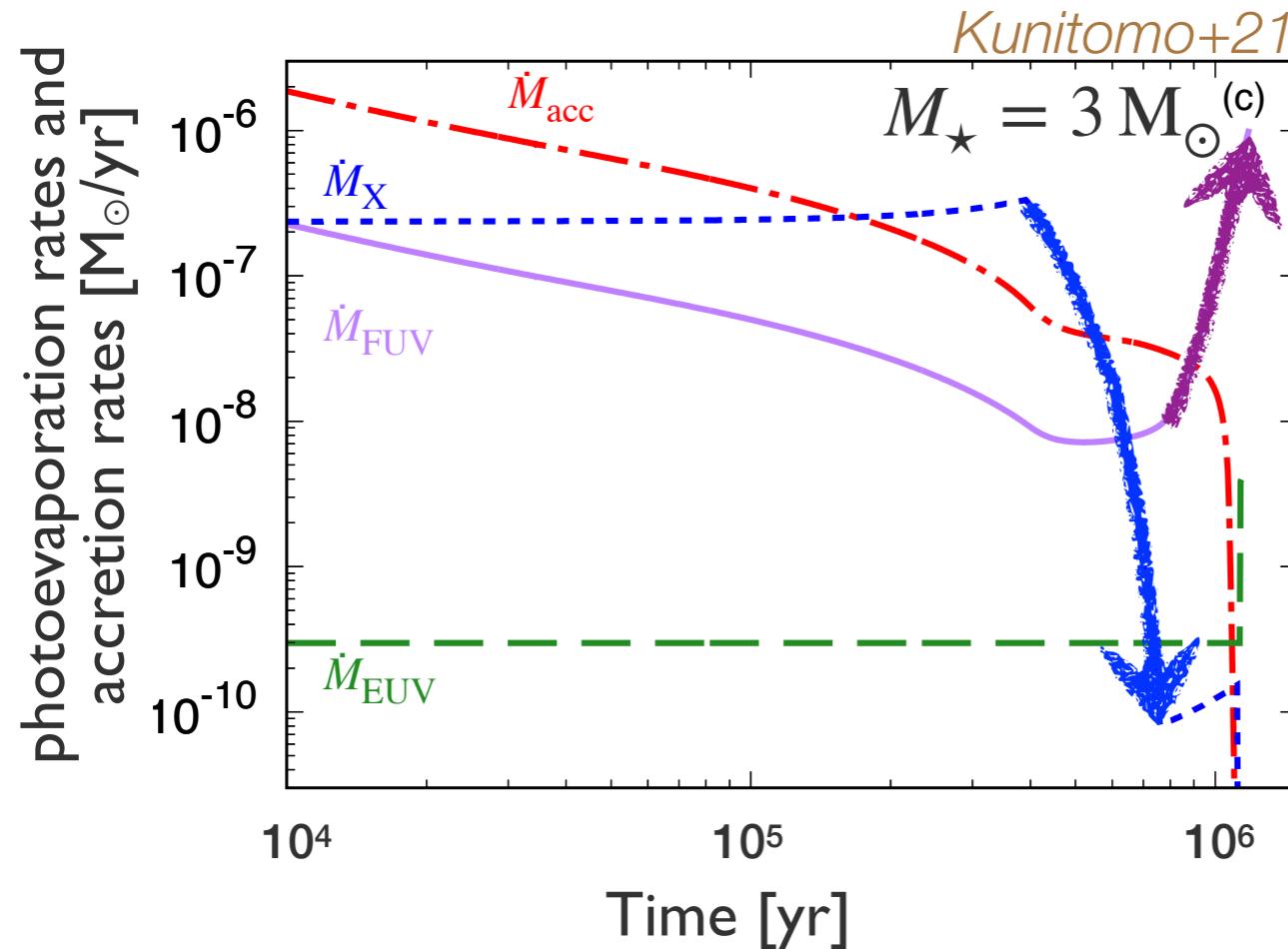
- Dominant mechanism changes from X-rays to FUV PEW



previous studies

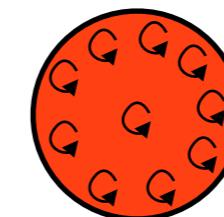


# Accretion & PEW rate evolution around a $3 M_{\odot}$ star

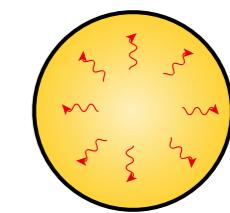


Why?

X-ray PEW:  
Stellar structure evolution



convective

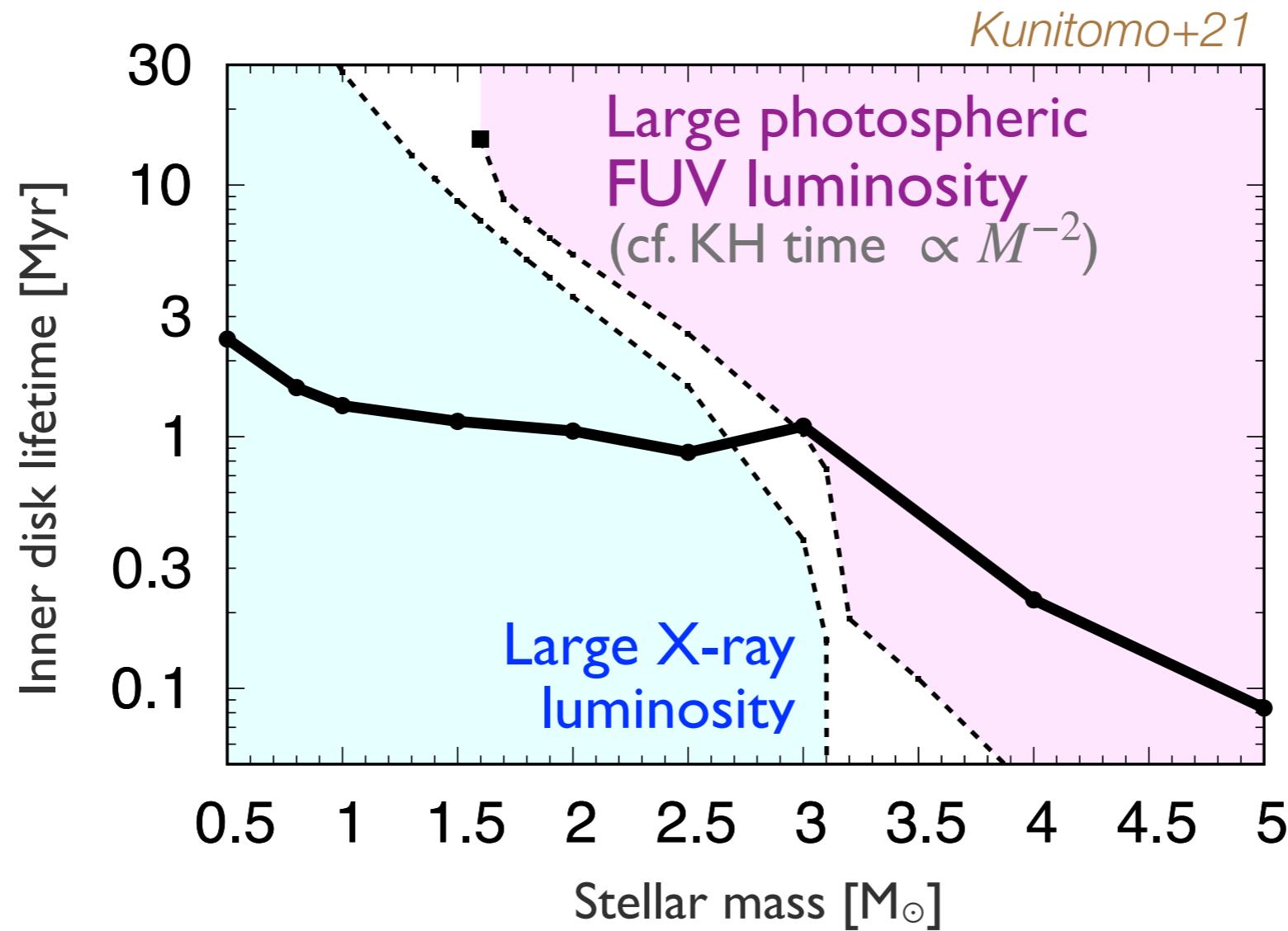


radiative

FUV PEW:  
 $T_{\text{eff}}$  increases  
→ photospheric FUV increases

**Stellar evolution** determines the disk lifetime  
around **intermediate-mass stars**

# Disk lifetime vs stellar mass



- **Disk lifetime decreases with stellar mass**

- consistent with observations

Hillenbrand+92, Hernandez+05,  
Carpenter+06, Yasui+14, Ribas+15

Why?

- $\geq 3 M_{\odot}$ : increase of **FUV** luminosity
- low-mass stars: X-ray photoevaporation and viscous timescale ( $\propto M_{\star}^{-1}$ )

## Two questions:

- Does **stellar evolution** affect disk evolution?
- Can disks with **weak turbulence** disperse within ~Myr?

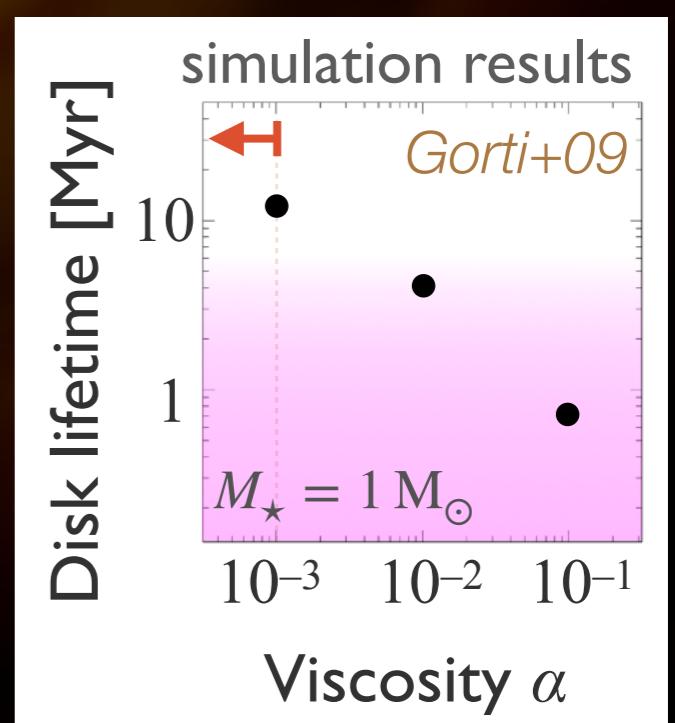
**Kunitomo+20, MNRAS**

# Disks are not turbulent ( $\alpha \lesssim 10^{-3}$ )

- Observations:
  - clear multiple gaps in the inclined disk  
→ geometrically thin
  - velocity dispersion
  - HL Tau:  $\alpha < \text{a few } 10^{-4}$  *Pinte+16*
  - HD163296:  $\alpha < 3 \times 10^{-3}$  *Flaherty+17*
  - (TW Hya: uncertain) *Flaherty+18*
- Theoretical studies
  - non-ideal MHD effects suppress MRI  
e.g., *Sano+Miyama99, Turner+14, Mori+17*

Only with *viscous accretion* and *photoevaporation*,  
**disk lifetime  $> 10\text{Myr}$**   
**→ inconsistent with obs.**  
 $(\sim 6\text{Myr})$

see also *Morishima12*

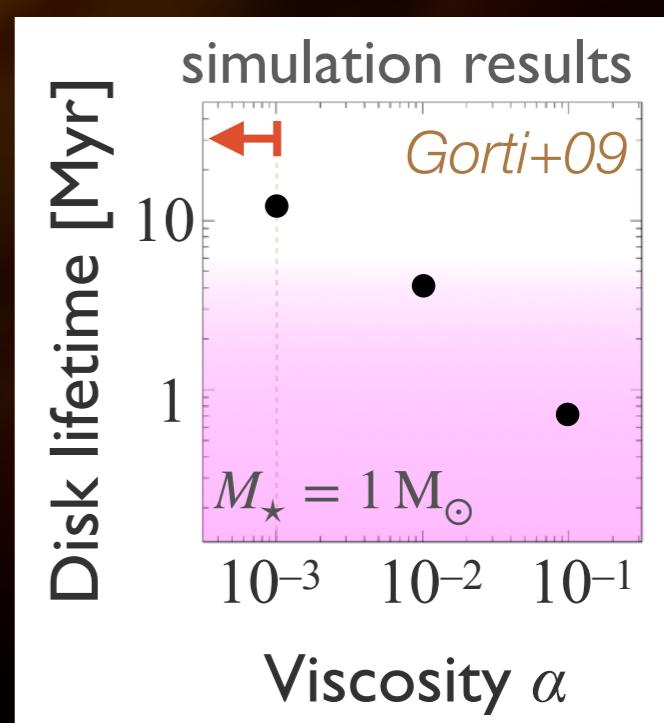


# Disks are not turbulent ( $\alpha \lesssim 10^{-3}$ )

- Observations:
  - clear multiple gaps in the inclined disk  
→ **geometrically thin**
  - **velocity dispersion**
- **+ Magnetic winds and accretion**
- Theory
  - non-ideal MHD effects supported  
e.g., Sano+Miyama99, Turner+14, Mori+17

Only with viscous accretion and photoevaporation,  
**disk lifetime > 10Myr**  
**→ inconsistent with obs.**  
 (~6Myr)

see also Morishima12



# 1D advection-diffusion equation w/ magnetic acc. & winds

$$\frac{\partial \Sigma}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left[ \frac{2}{r\Omega} \left\{ \frac{\partial}{\partial r} (r^2 \Sigma \alpha c_s^2) + r^2 \overline{\alpha_{\phi z}} (\rho c_s^2)_{\text{mid}} \right\} \right] + \dot{\Sigma}_{\text{MDW}} + \dot{\Sigma}_{\text{PEW}} = 0$$

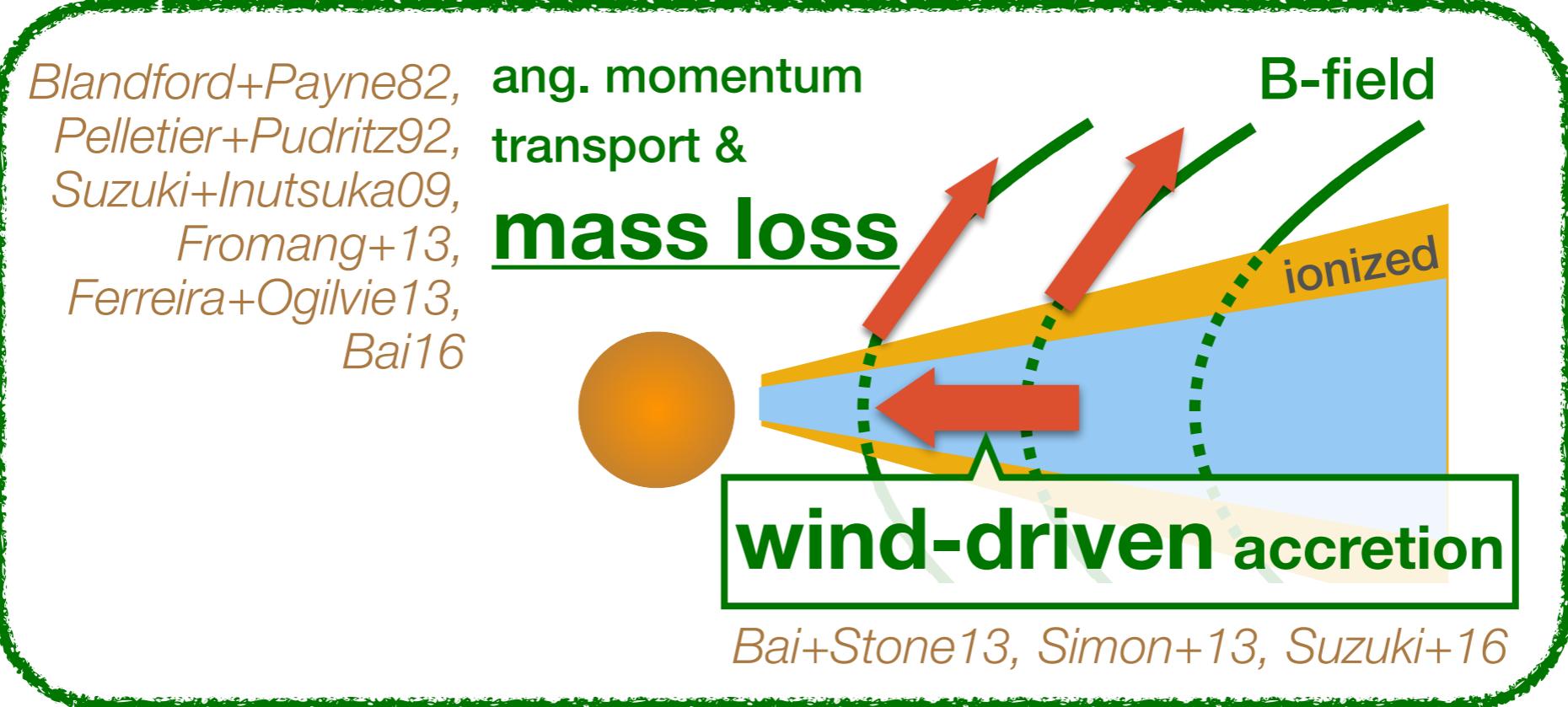
viscous accretion    **wind-driven accretion**    **magnetic disk winds**

$\alpha \simeq 10^{-4}$

photoevaporation

X-ray:  
Owen+12

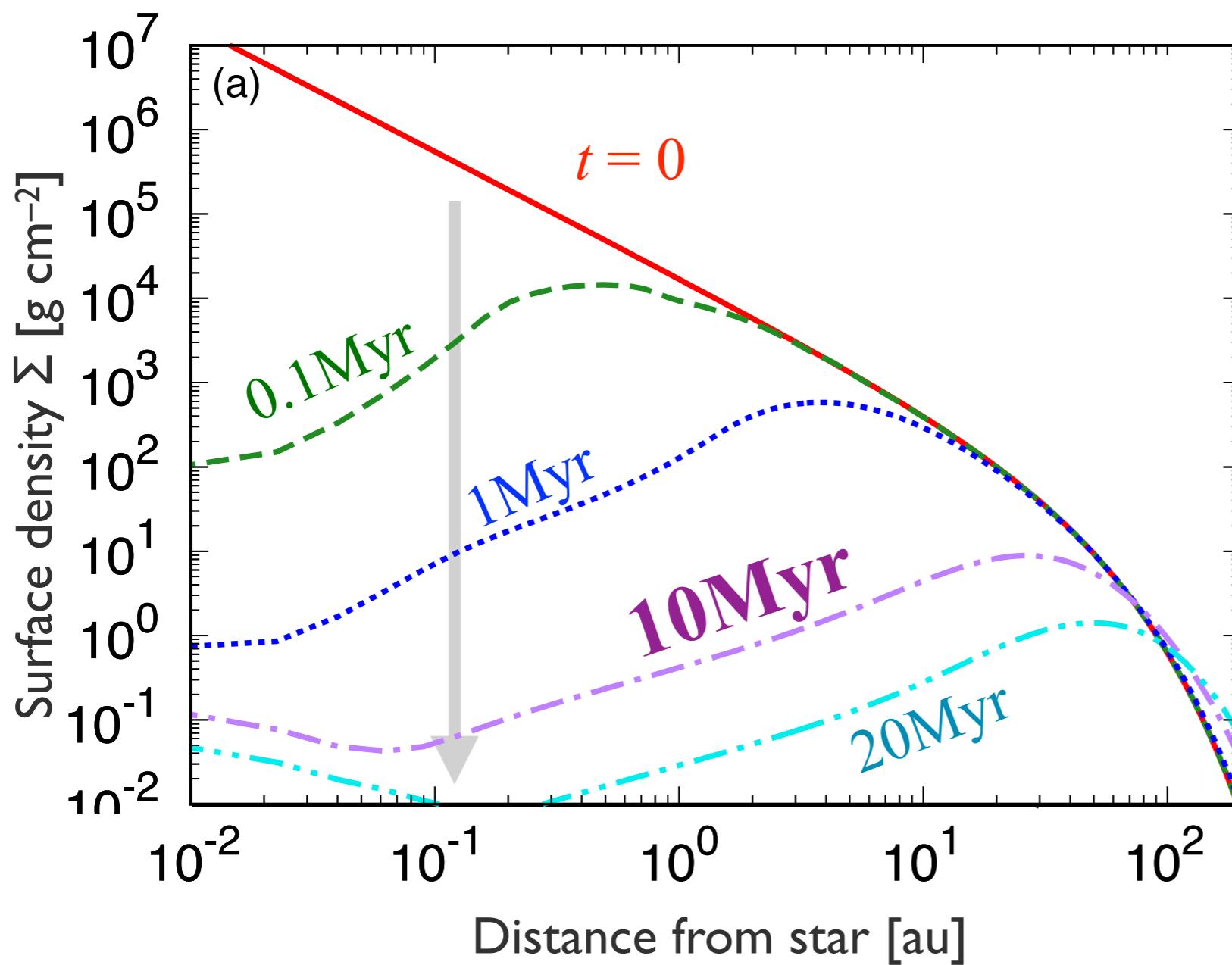
EUV:  
Alexander+06



- **Settings:**

- Stellar mass  $M_\star = 1 M_\odot$ , Disk initial condition: 30 au,  $0.1 M_\star$
- Temp. structure: stellar irradiation + viscous heating Nakamoto+Nakagawa94

# Result1: No photoevaporation case



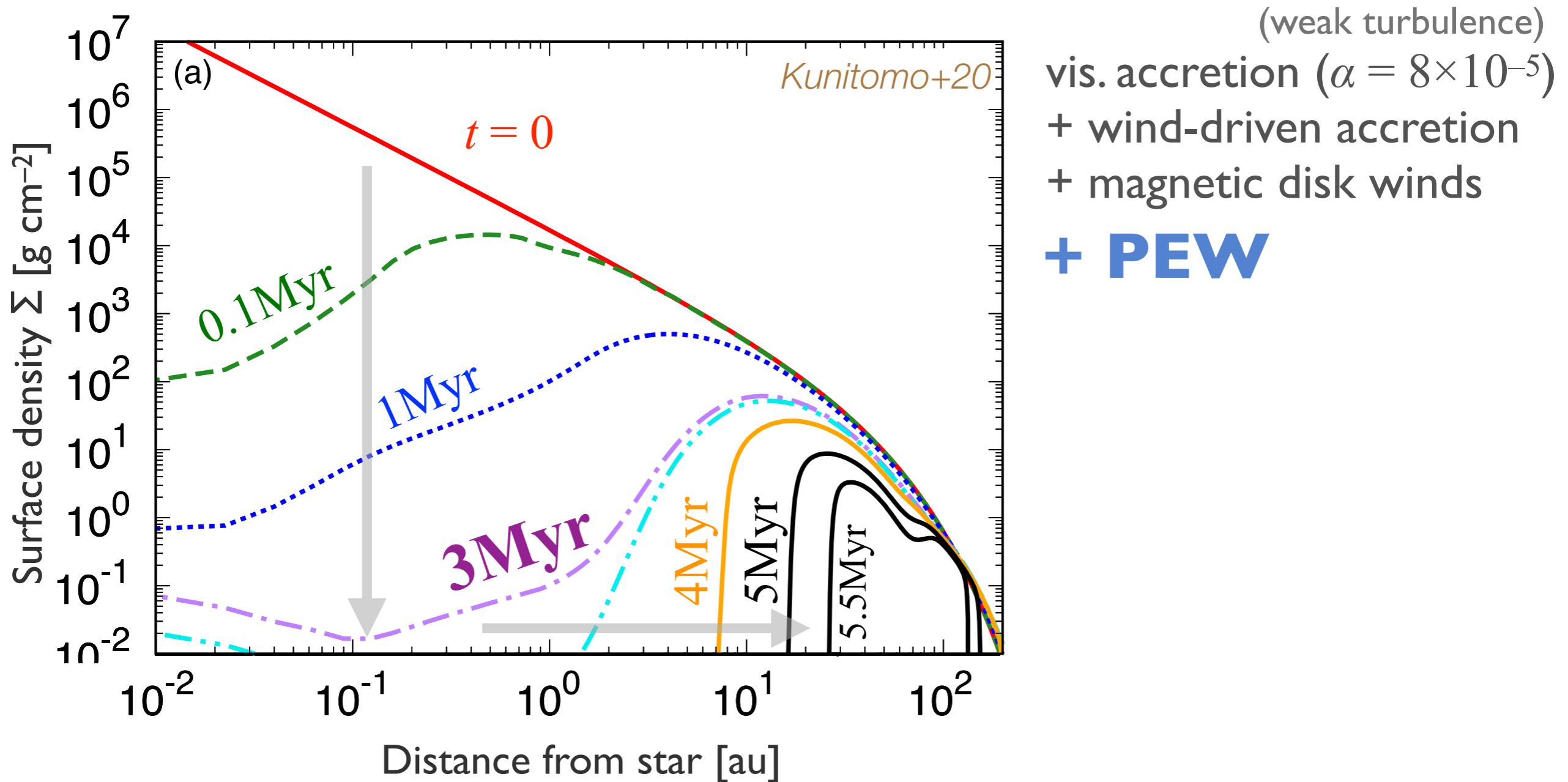
(weak turbulence)  
vis. accretion ( $\alpha = 8 \times 10^{-5}$ )  
+ wind-driven accretion  
+ magnetic disk winds  
**(w/o PEW)**  
see *Suzuki+16, Bai16*

**Accretion energy**  
drives **MHD winds**

- Disk structure changes especially in the **inner disk**
- however the disk is **long-lived** ( $\gtrsim 10$  Myr)  
→ **inconsistent with obs.** only with magnetic acc. and winds

$\dot{M}_{\text{acc}}$  decreases with time  
→ **wind mass loss also decreases**

# Result2: Case with photoevaporation

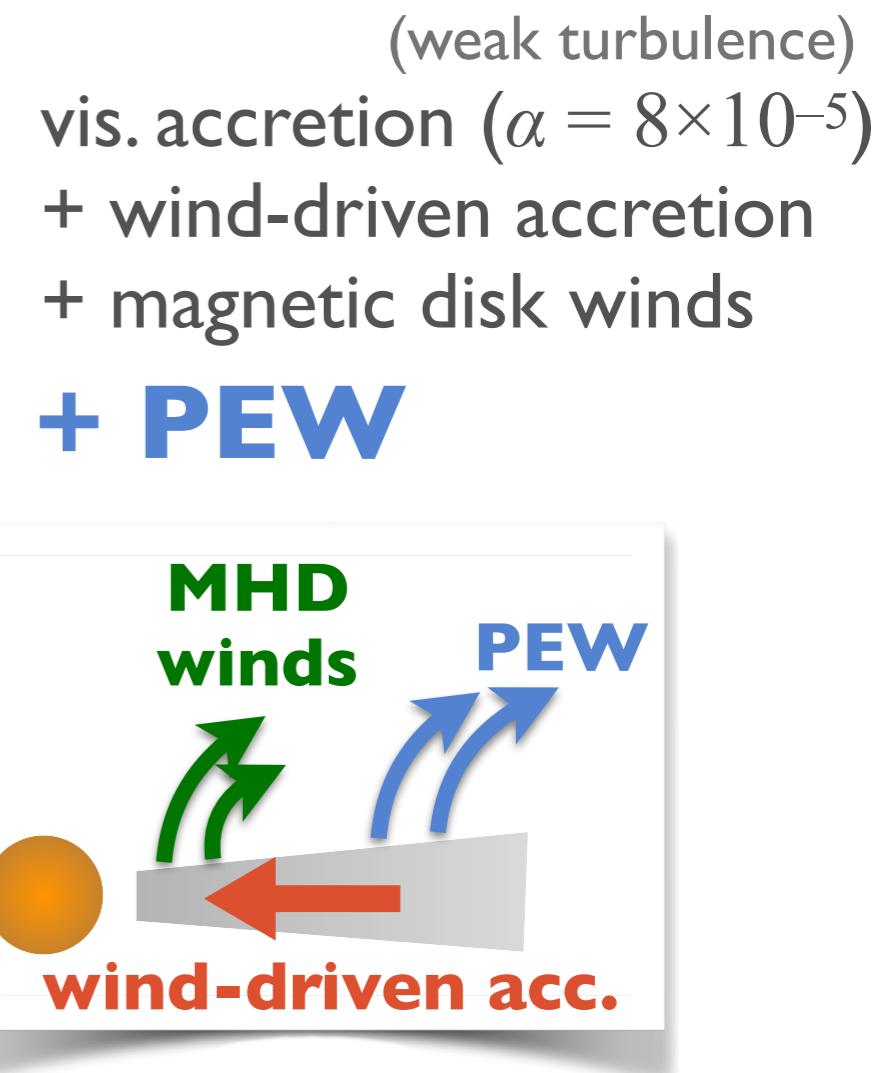
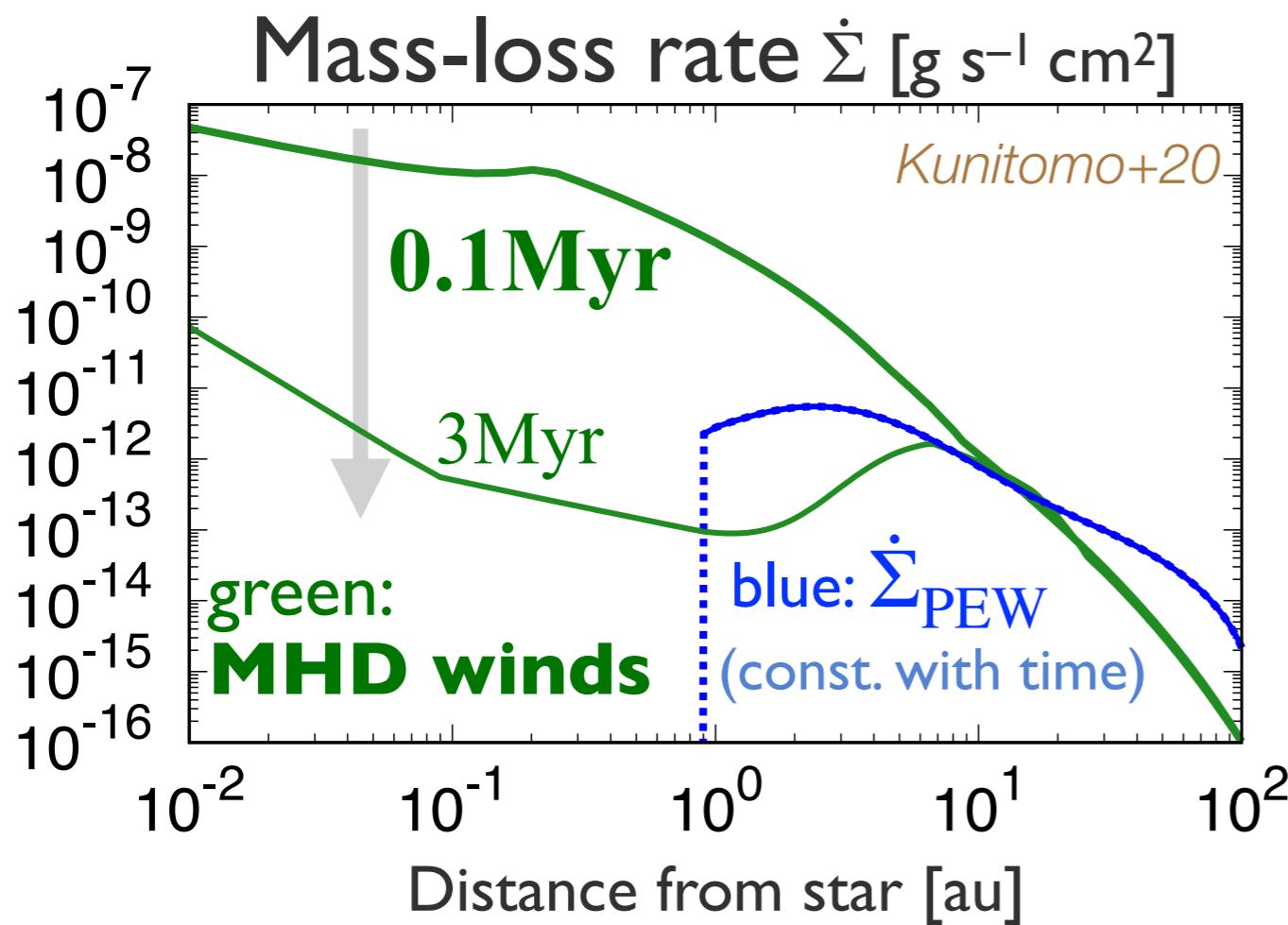


Inner disk lifetime **~3 Myr** if both winds are considered

→ **consistent with observations**

Why? PEW rate does **not** change with time around low-mass stars (unlike MHD winds)

# Result2: Two winds are cooperative



- **MHD winds** dominate in the **early** phase in the **inner** disk
- **PEW** dominates in the **late** phase in the **outer** disk
- **Wind-driven acc.** also plays an important role

larger accretion energy release

# Summary

- The dominant mechanism of photoevaporation changes from X-rays to FUV  
→ **Stellar evolution** must be considered for the disk evolution models around **intermediate-mass stars** *Kunitomo+21, ApJ*
- **MHD winds** dominates in the **early** phase in the **inner** disk, whereas **photoevaporation** does in the **late** phase in the **outer** disk
- If both winds and wind-driven accretion are considered, **weak-turbulence** disks can disperse **within several Myr** *Kunitomo+20, MNRAS*
- **Future work:**
  - disk evolutions with both winds with varying stellar mass
  - dependence on initial conditions *Alexander+Armitage07, Kimura+16*
  - long-term evolution of two fluids (gas & dust) *Takeuchi+05, Gorti+15, Taki+21*

# Thank you for your attention!

For more details, please ...

- send a message on Slack
- send an email: [kunitomo.masanobu@gmail.com](mailto:kunitomo.masanobu@gmail.com)
- read our papers:
  - Kunitomo, Suzuki & Inutsuka (2020), MNRAS ([link](#))
  - Kunitomo, Ida, Takeuchi, Panić, Miley & Suzuki (2021), ApJ, ([link](#))
- watch a YouTube video for another conference ([link](#))

back-up slides for the 1st part

# Evolutionary models of XUV luminosity

**Table 1.** Stellar evolutionary models.

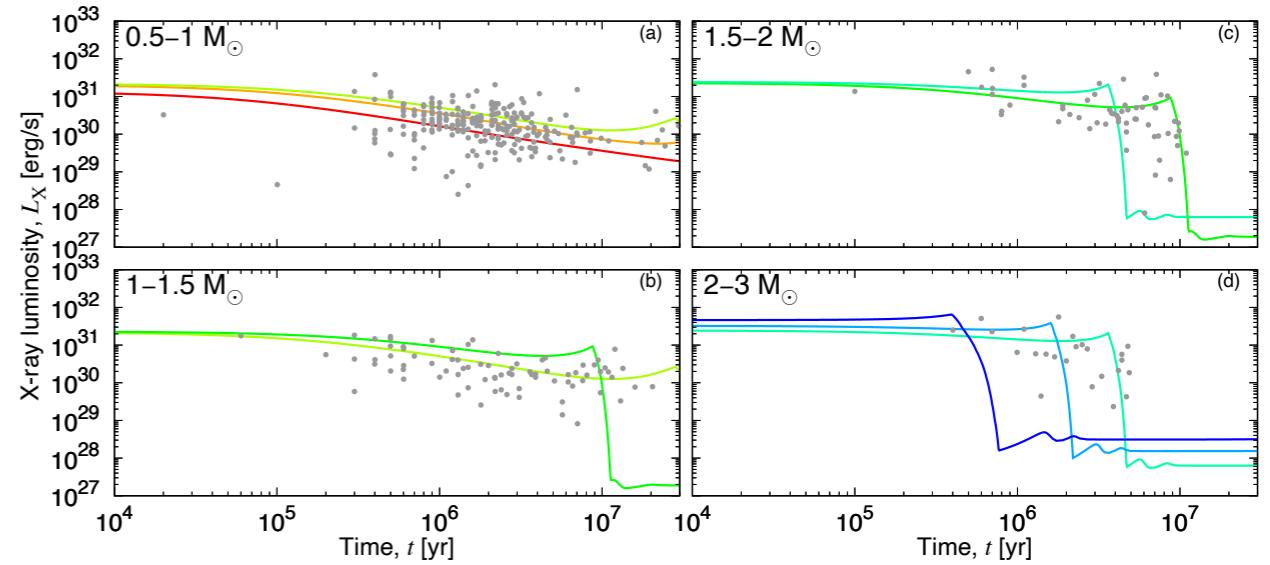
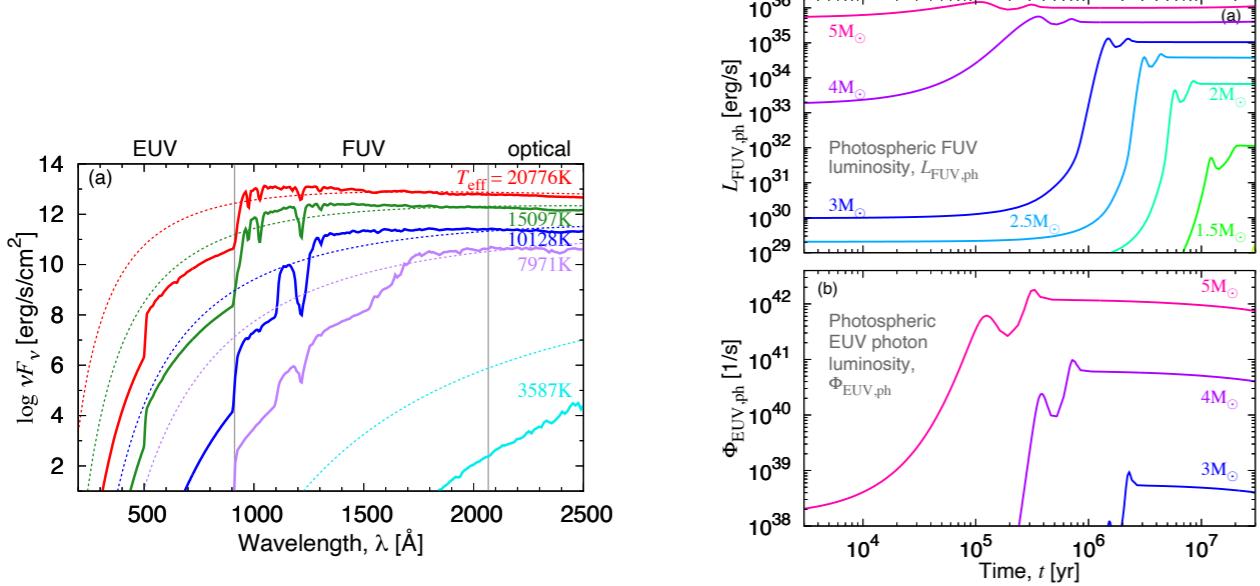
Kunitomo+21

$M_\star$	$\log t$	$R_\star$	$L_\star$	$T_{\text{eff}}$	$M_{\text{conv}}$	$R_{\text{conv}}$	$\tau_{\text{conv}}$	$L_X$	$\Phi_{\text{EUV,ph}}$	$L_{\text{FUV,ph}}$
[M $_\odot$ ]	[yr]	[R $_\odot$ ]	[L $_\odot$ ]	[K]	[M $_\odot$ ]	[R $_\odot$ ]	[day]	[erg/s]	[1/s]	[erg/s]
0.5	0.00	4.537E+00	4.883E+00	4.032E+03	5.000E-01	5.113E-02	1.387E+02	1.391E+31	0.000E+00	1.162E+26
0.5	1.00	4.536E+00	4.686E+00	3.991E+03	4.998E-01	1.858E-01	1.377E+02	1.335E+31	0.000E+00	8.965E+25
0.5	2.00	4.536E+00	4.685E+00	3.991E+03	4.998E-01	1.858E-01	1.377E+02	1.334E+31	0.000E+00	8.964E+25
⋮										

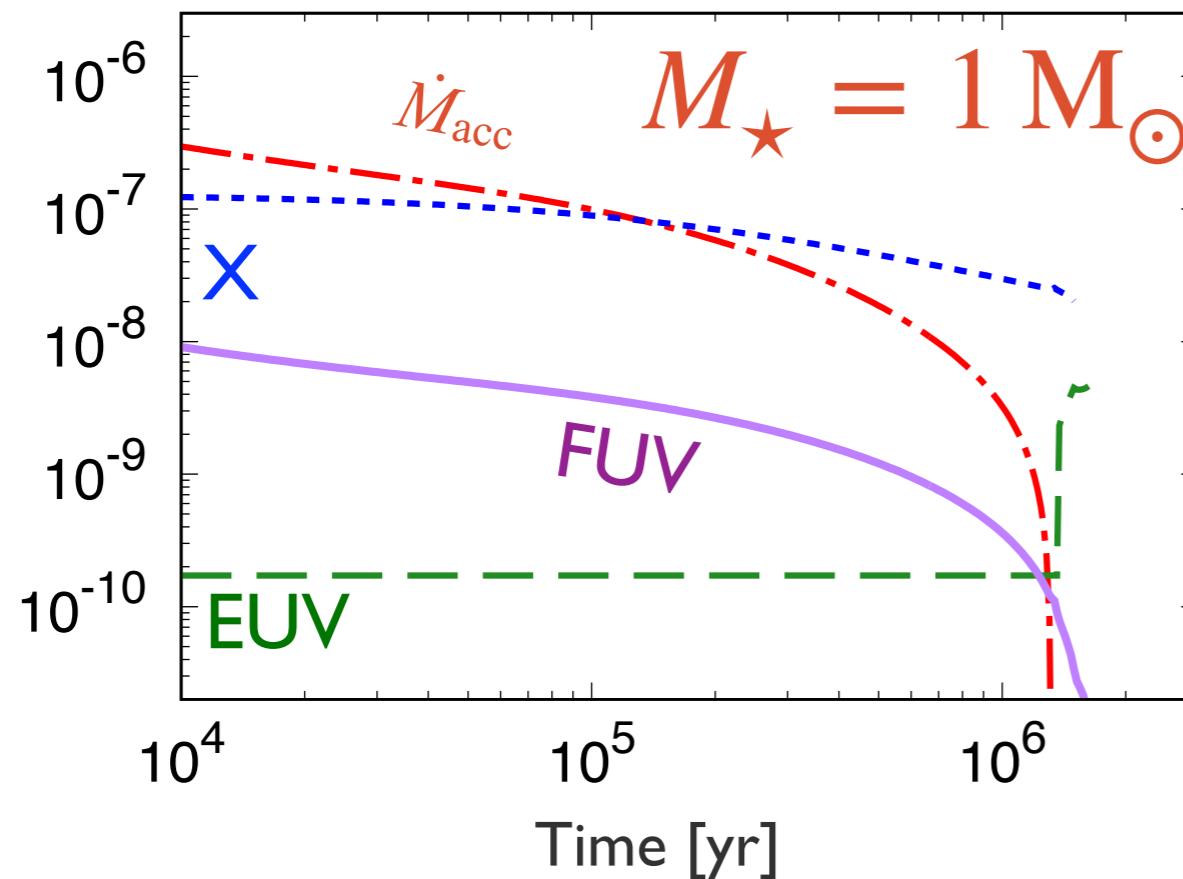
*Continued*

NOTE—Evolutionary models of young 0.5–5 M $_\odot$  stars. Table 1 is published in its entirety in the machine-readable format. A portion is shown here for guidance regarding its form and content.

Available at [this URL](#)



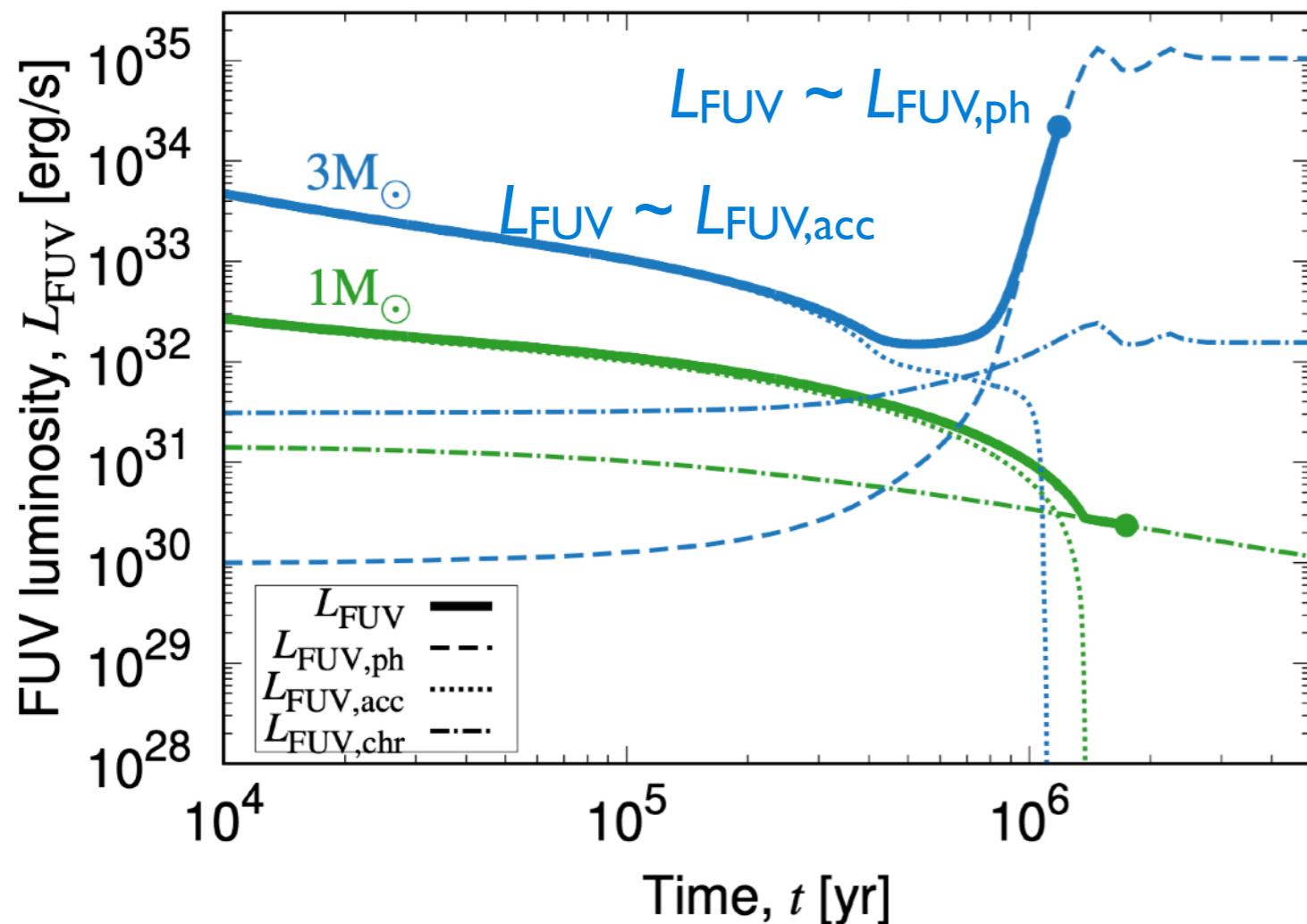
# Accretion & PEW rate evolution around a $1 M_{\odot}$ star



PEW rates around  
**low-mass stars**  
do **not** evolve with  
time significantly

: longer stellar  
K-H timescale

# FUV luminosity evolution



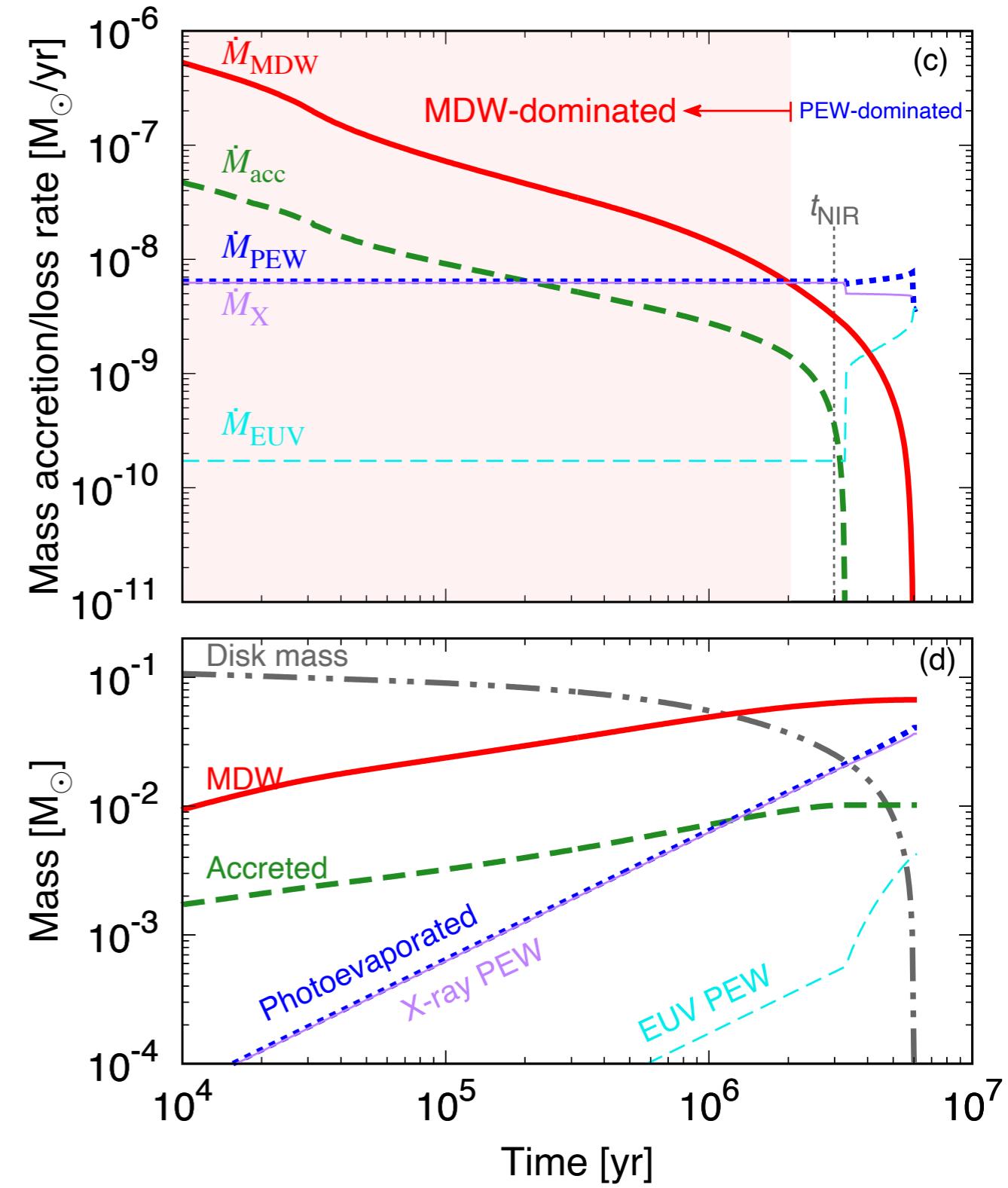
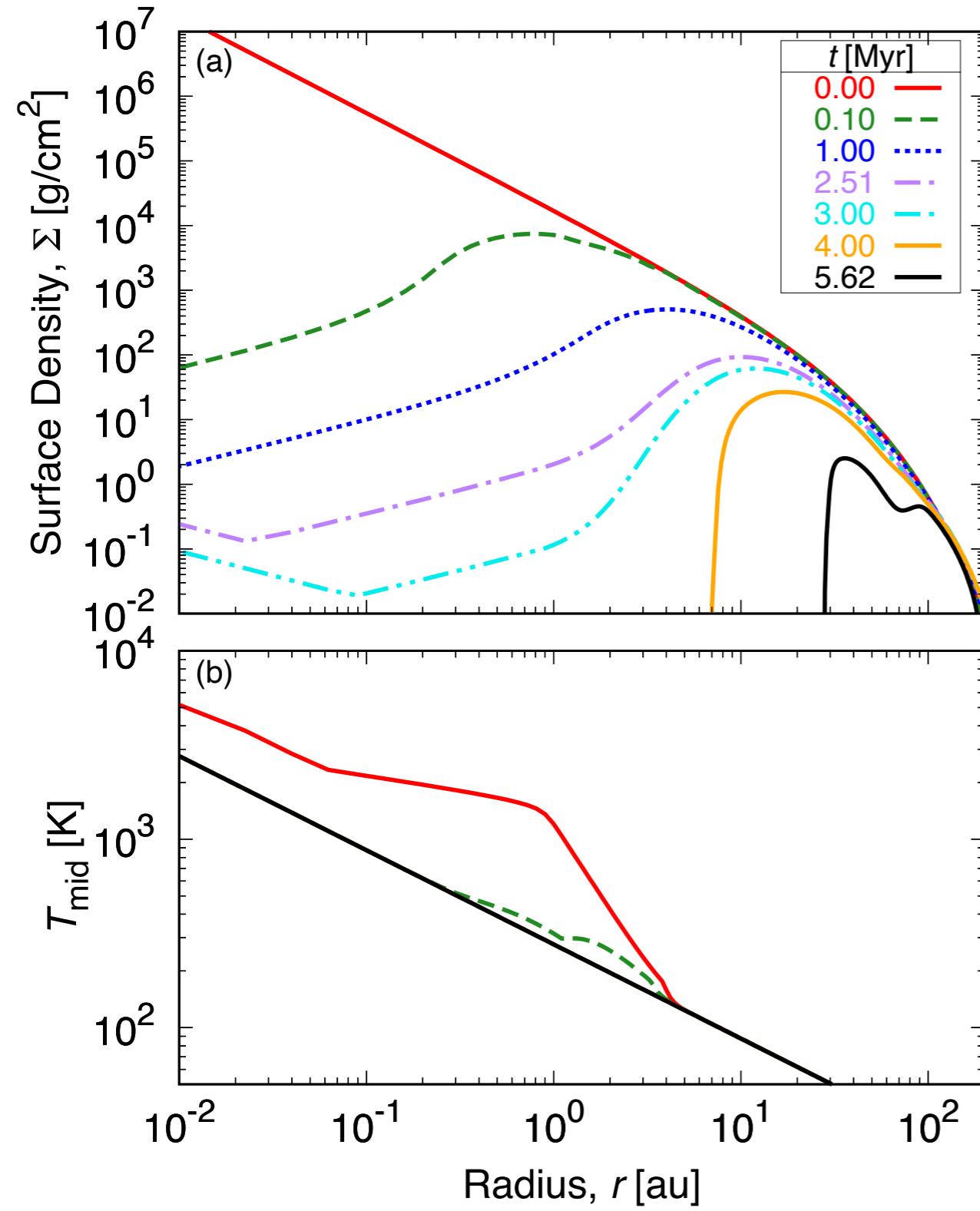
**Figure 9.** Temporal evolution of  $L_{\text{FUV}}$  (the thick solid line),  $L_{\text{FUV,ph}}$  (dashed),  $L_{\text{FUV,acc}}$  (dotted) and  $L_{\text{FUV,chr}}$  (dot-dashed) in the cases of  $M_{\star} = 3M_{\odot}$  (blue) and  $1M_{\odot}$  (green). The disks disperse and the simulations stop at the filled circles. We note that  $L_{\text{FUV,ph}}$  of a  $1M_{\odot}$  star is negligibly low.

FUV originates from

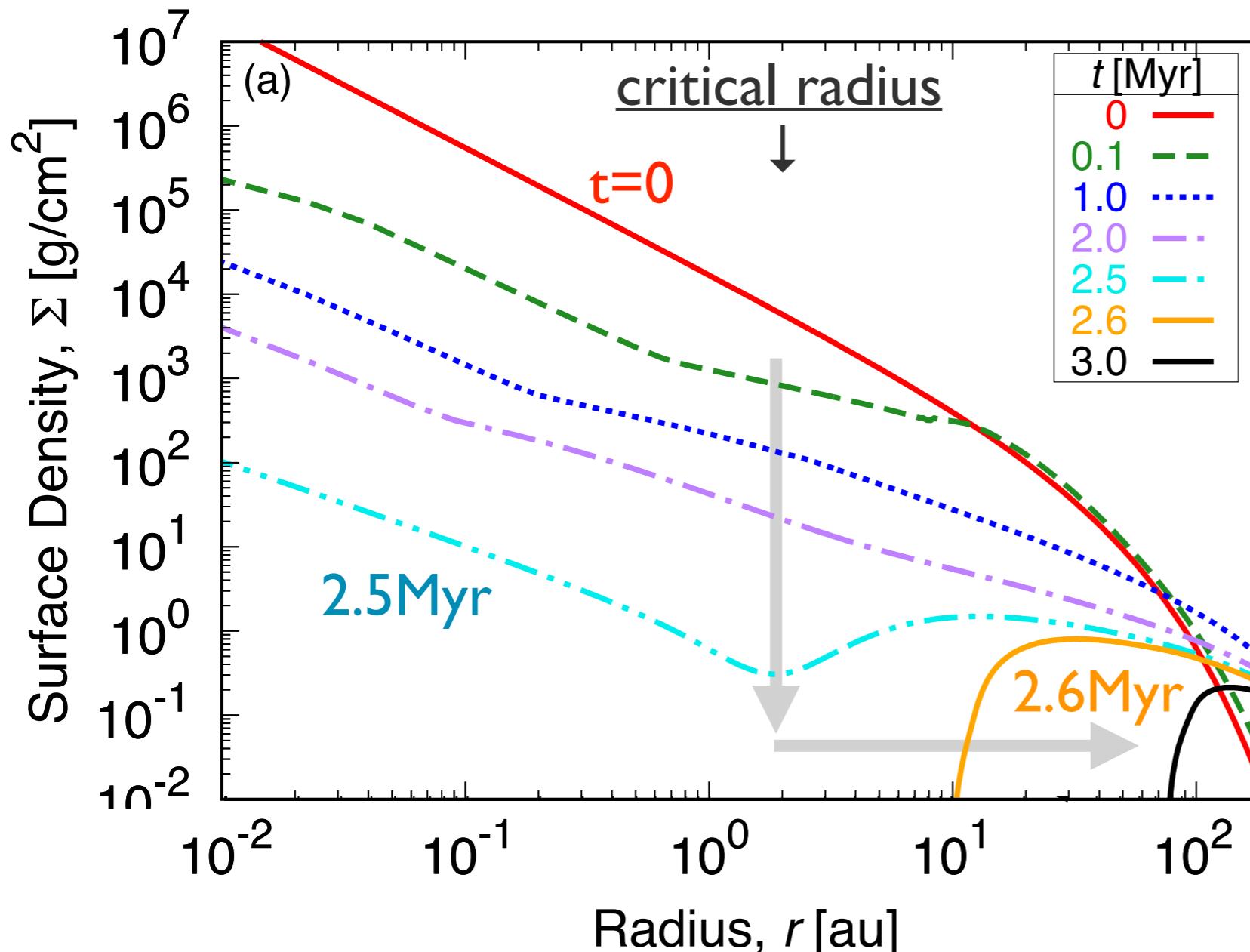
- stellar photosphere
- stellar chromosphere
- accretion

**back-up slides for the 2nd part**

# Result2: Case with photoevaporation



# Disk evolution in the classical picture

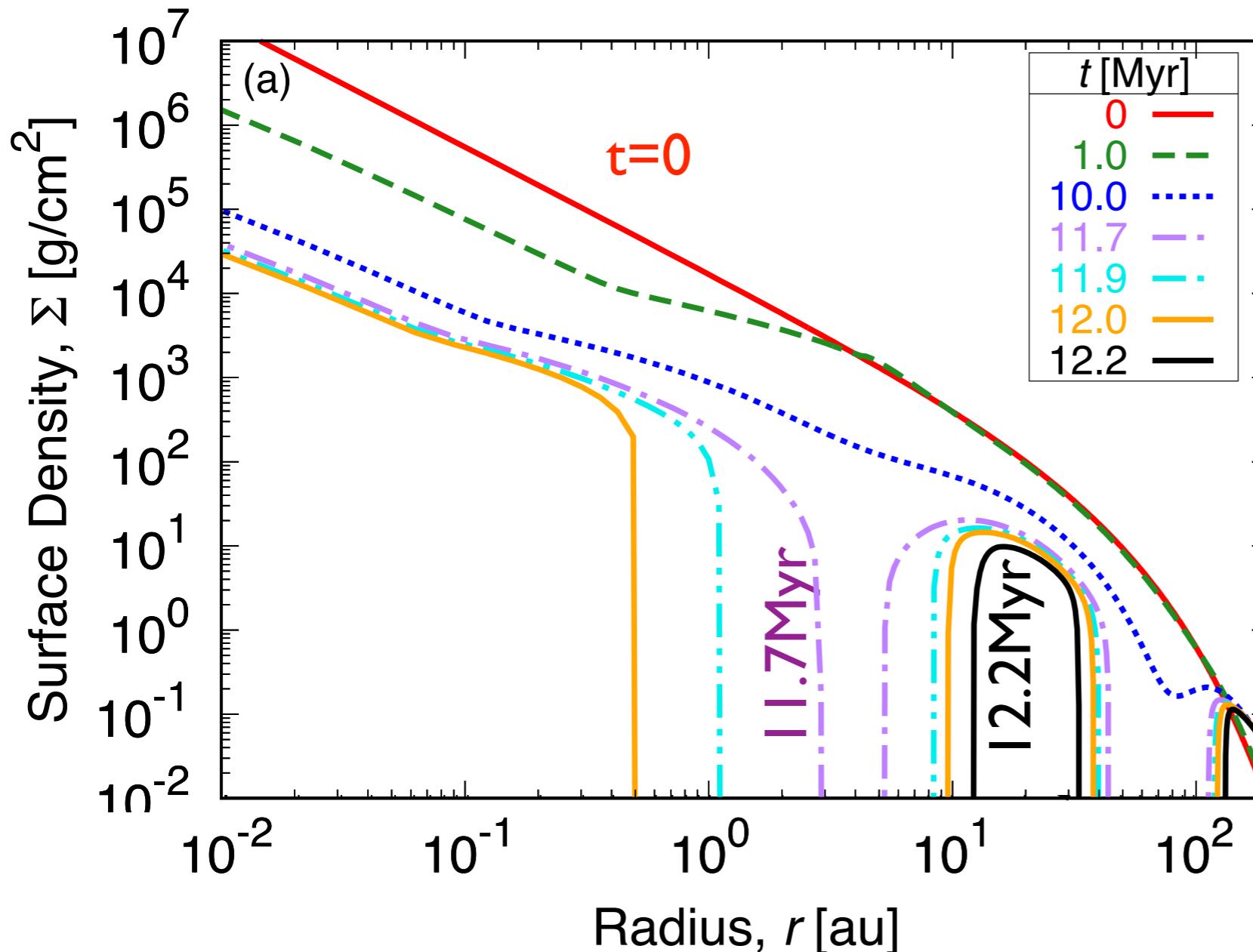


- viscous acc. + photoevaporation (EUV+X)
- $a=8\times 10^{-3}$

see *Alexander+14, PPVI, Clarke+01, Alexander+06, Gorti+09, Owen+10, Morishima12, Bae+13, Kimura+16*

- Disk lifetime = 2.5 Myr if a disk is turbulent

# MRI-inactive case w/o MHD winds



- viscous acc. + photoevaporation (EUV+X)
- $a = 8 \times 10^{-5}$   
(recent obs. suggest)

- Disk lifetime = 12 Myr  
→ Much longer than observation ( $\sim 3\text{--}5$  Myr)

see also Gorti+09, Morishima12

# Discussion (1)

## Monte Carlo simulations

- We performed Monte Carlo simulations varying  $\alpha_{r\varphi}$  and  $\alpha_{\varphi z}$  w/ and w/o MHD winds
- Concerning the half-life period, **the case with MDW matches obs.**

