

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

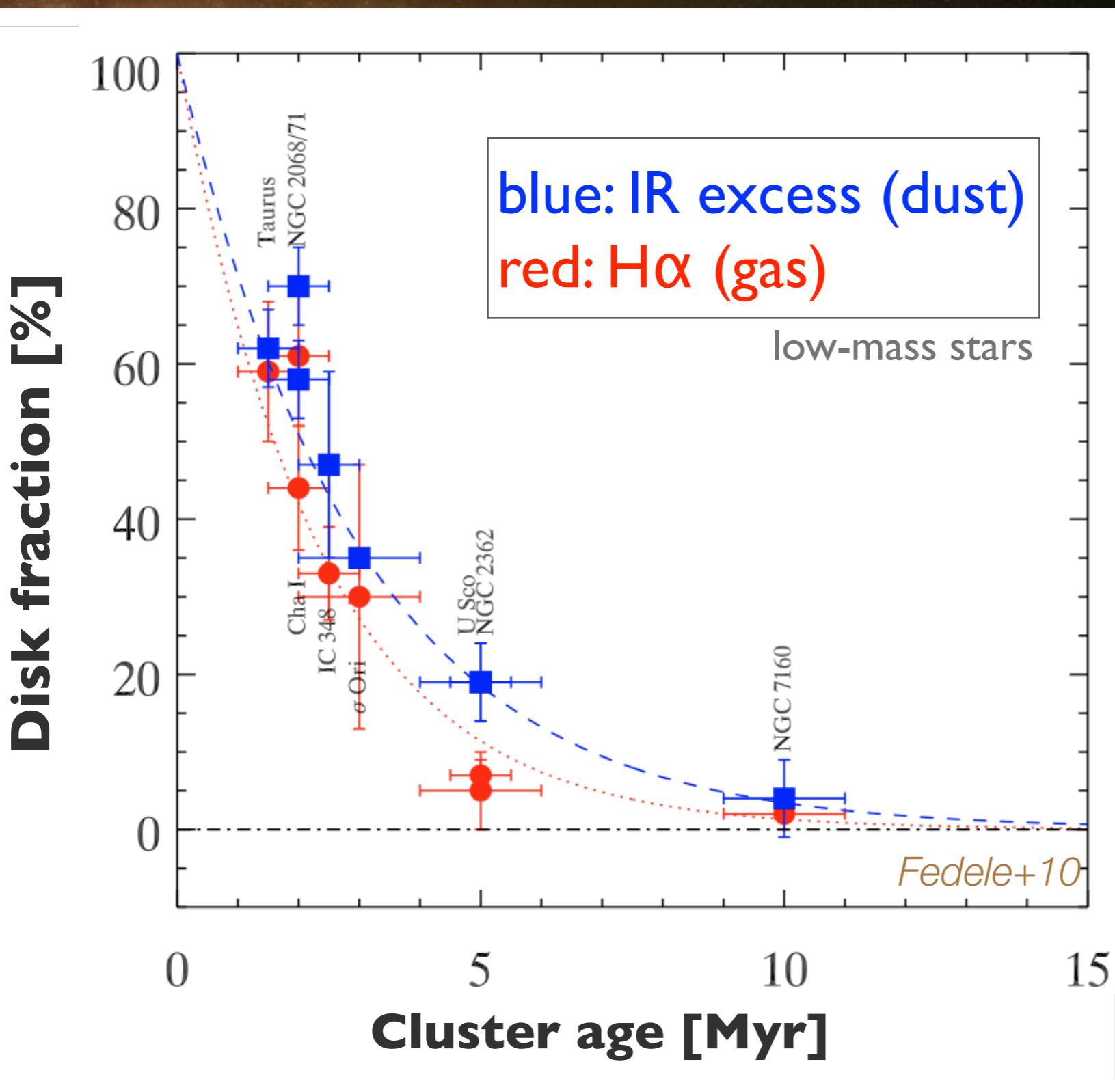
**Masanobu Kunitomo** (*Kurume Univ.*)

Takeru Suzuki (*U.Tokyo*), Shu-ichiro Inutsuka (*Nagoya U*),  
Shigeru Ida, Taku Takeuchi (*Tokyo Tech*),  
Olja Panić, James Miley (*U. Leeds*)

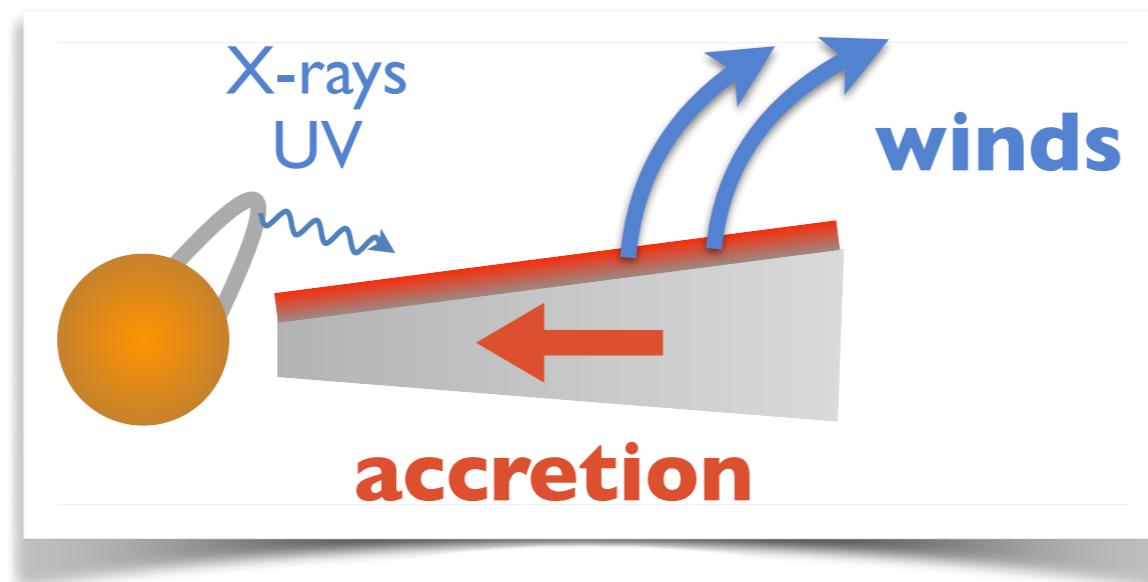
## **References:**

*Kunitomo, Suzuki & Inutsuka (2020), MNRAS,*  
*Kunitomo, Ida, Takeuchi, Panić, Miley & Suzuki, submitted*

# Disk lifetime $\sim 6$ Myr



# Disk evolution mechanisms



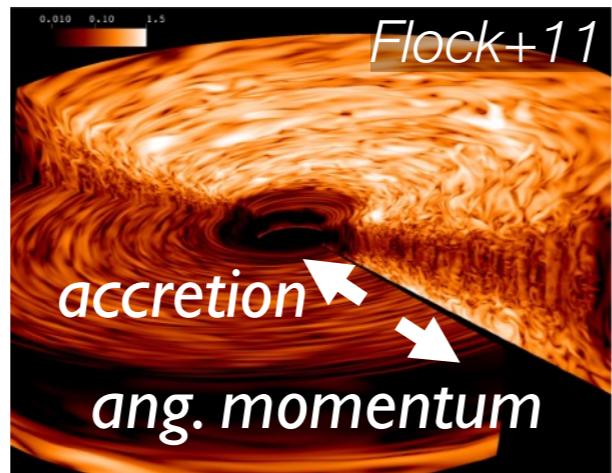
e.g., Alexander+14,  
Clarke+01, Gorti+09,  
Owen+12, Morishima12,  
Kimura+16

## Accretion

- turbulent viscosity

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

Shakura+Sunyaev73



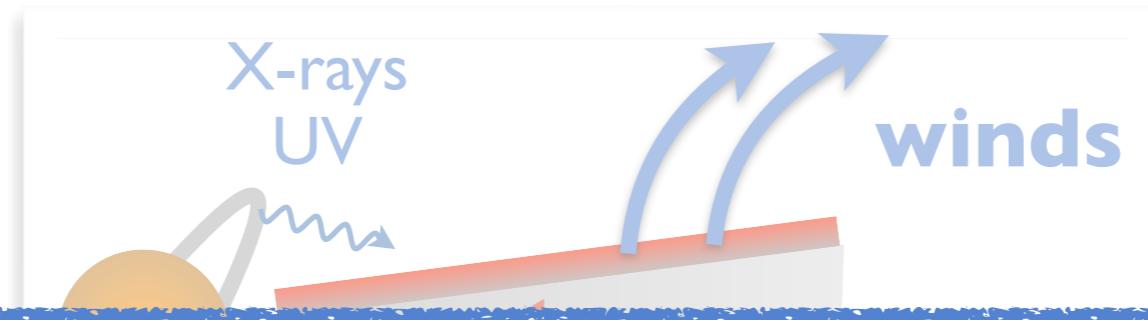
## Winds

- 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



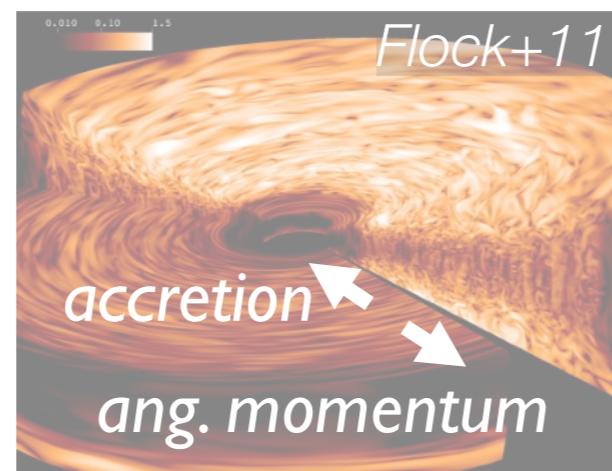
e.g., Alexander+14,  
Clarke+01, Gorti+09,  
Owen+12, Morishima12,  
Kimura+16

## Two questions:

- How does **stellar evolution** affect disk evolution?
- How do disks with **weak turbulence** disperse?

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

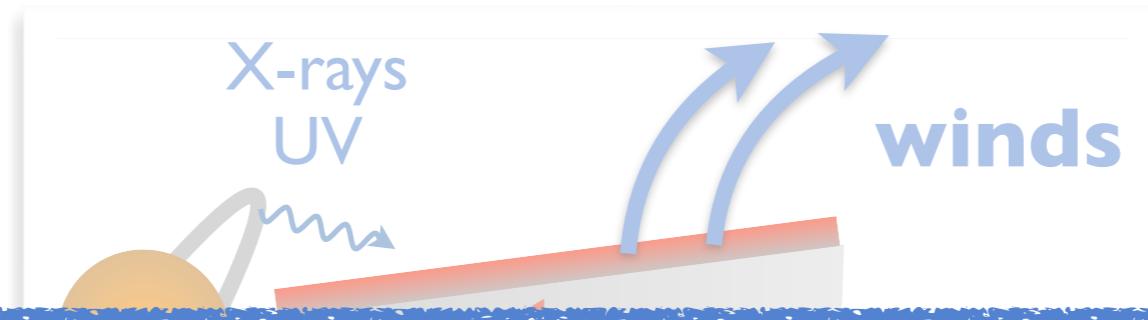
Shakura+Sunyaev73



→ 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

# Disk evolution mechanisms



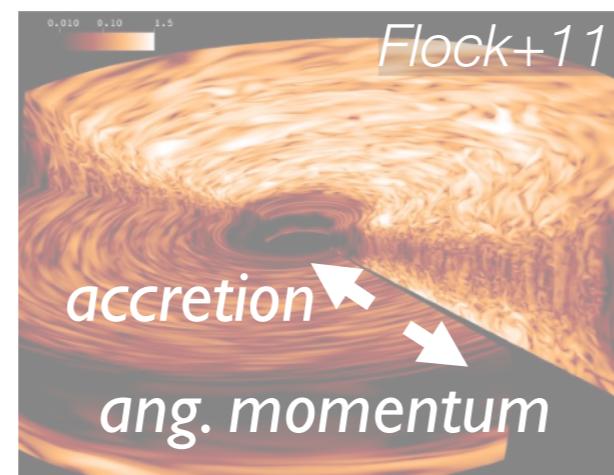
e.g., Alexander+14,  
Clarke+01, Gorti+09,  
Owen+12, Morishima12,  
Kimura+16

## Two questions:

**Kunitomo+, submitted**

- How does **stellar evolution** affect disk evolution?
- How do disks with **weak turbulence** disperse?
- Origin of turbulence: MRI etc.
- Viscosity:  $\alpha$

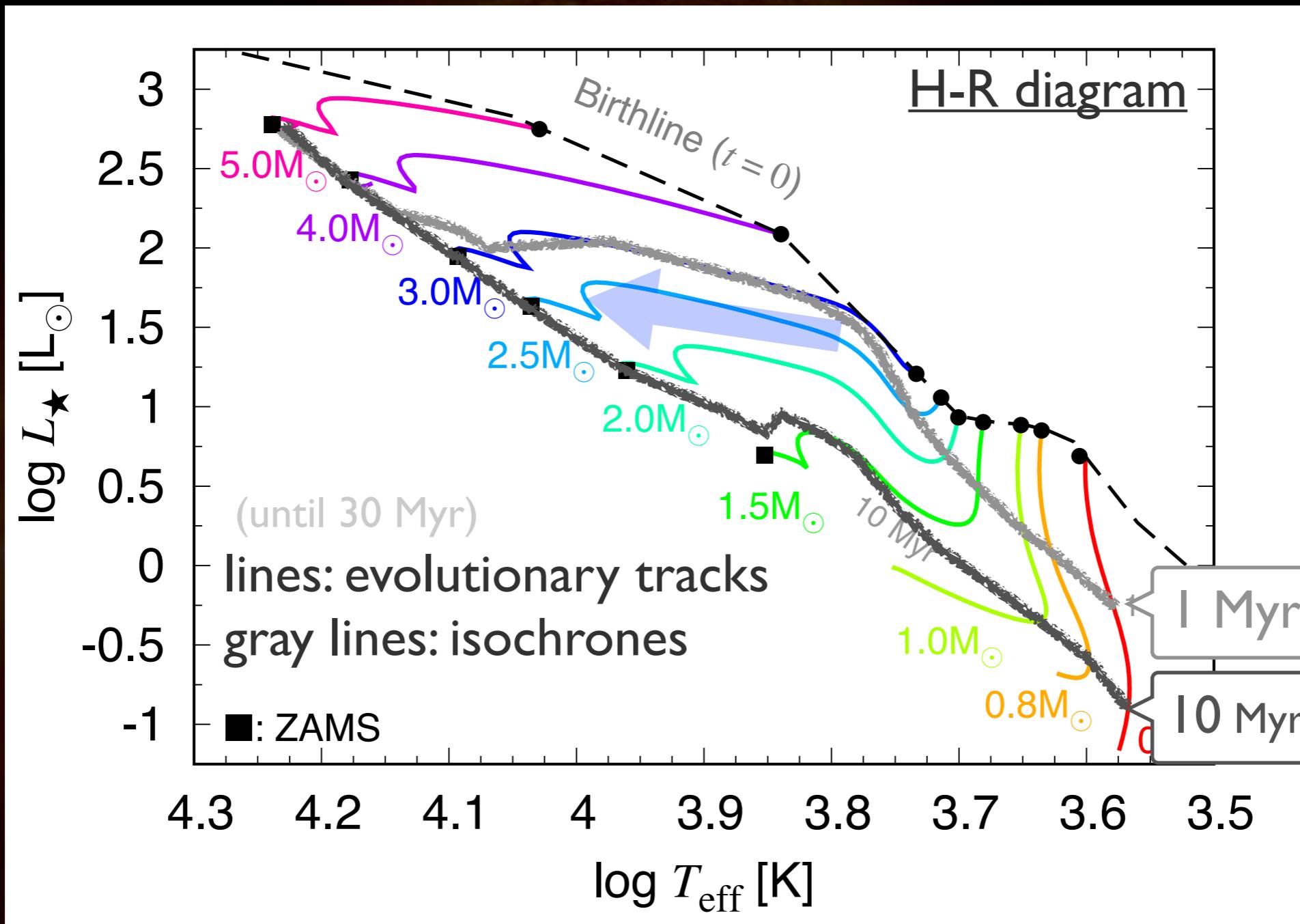
Shakura+Sunyaev73



→ 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

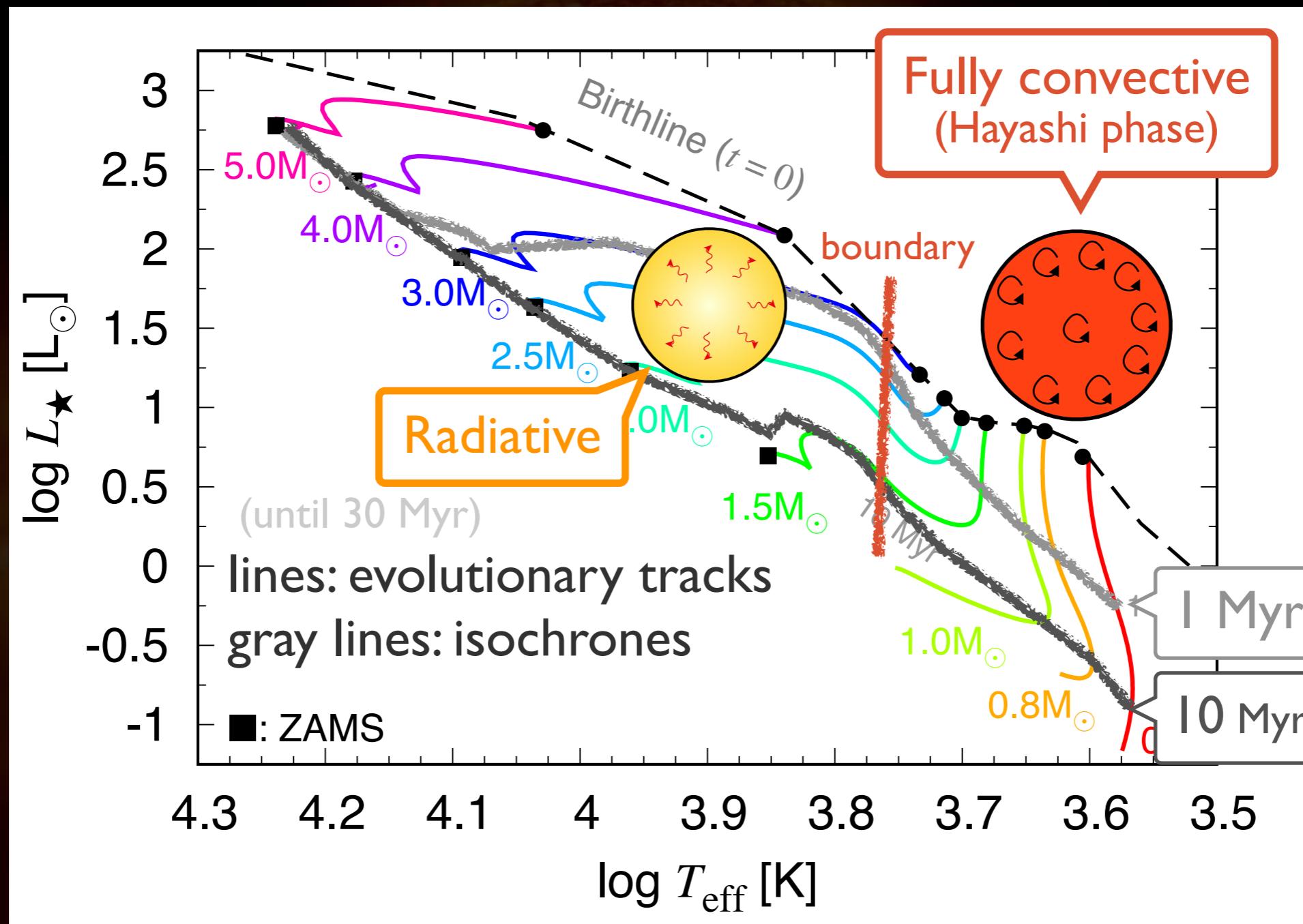
# Young stars evolve



Higher-mass stars evolve more rapidly

- The **effective temperature** increases with time

# Young stars evolve



# Higher-mass stars evolve more rapidly

- The **effective temperature**  $T_{\text{eff}}$  increases with time
  - The surface **convective envelope** is lost

# Stellar XUV luminosity evolves

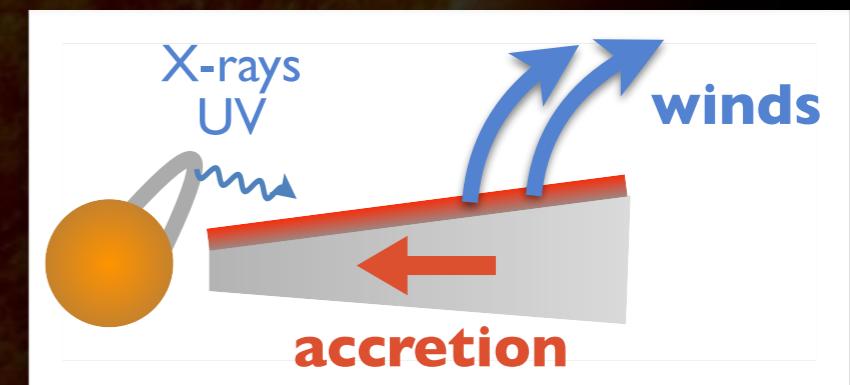
Three components of XUV radiation of young stars:

- magnetic activity
- accretion shock
- photospheric radiation

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

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

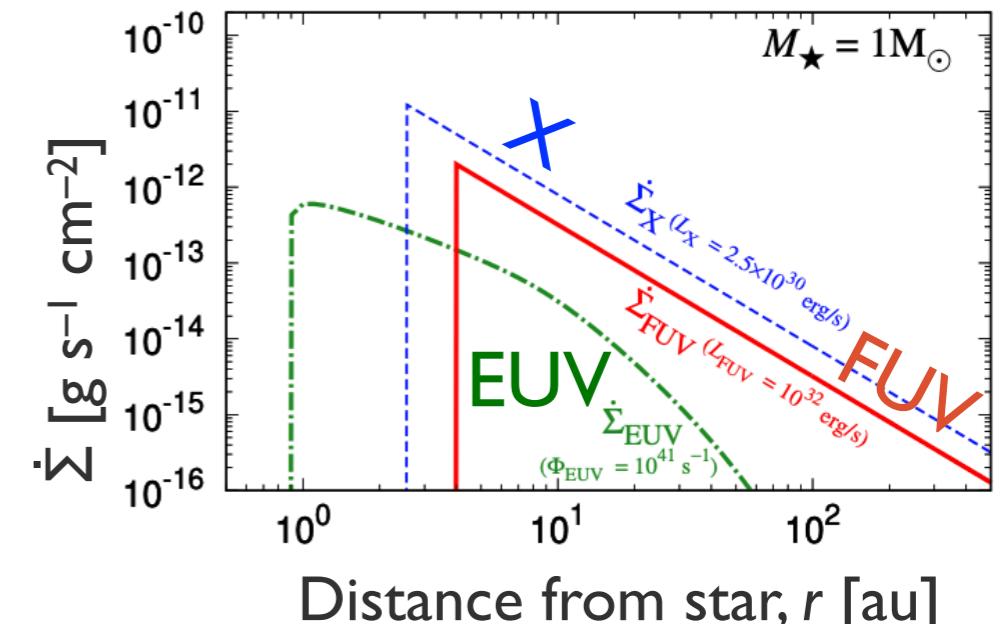
XUV luminosity determines the photoevaporation rate  
→ Question: How does stellar evolution affect the disk evolution?



# Method: 1D diffusion equation

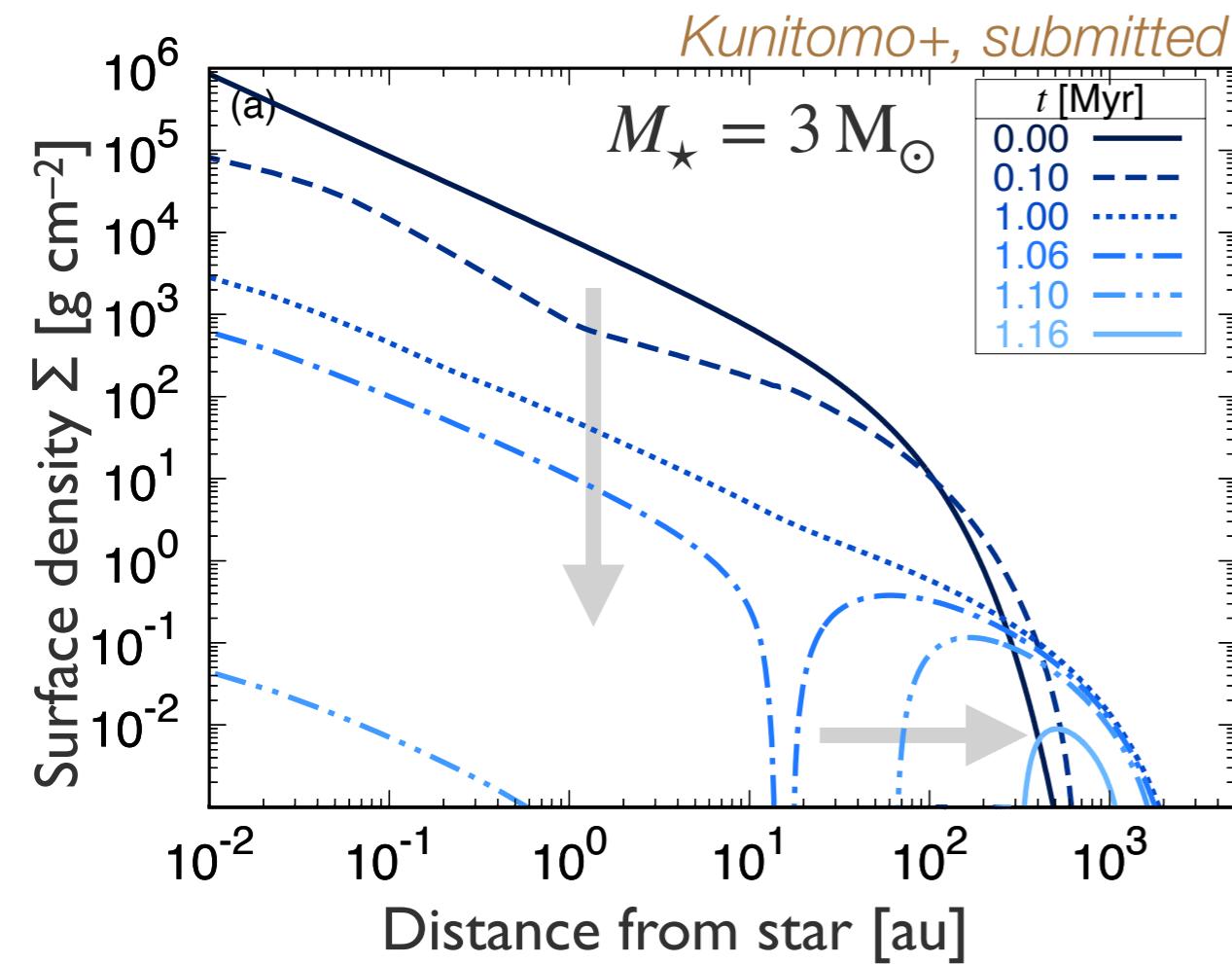
$$\frac{\partial \Sigma}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left[ \frac{2}{r\Omega} \frac{\partial}{\partial r} (r^2 \Sigma \alpha c_s^2) \right] + \dot{\Sigma}_{\text{PEW}} = 0$$

- 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.*

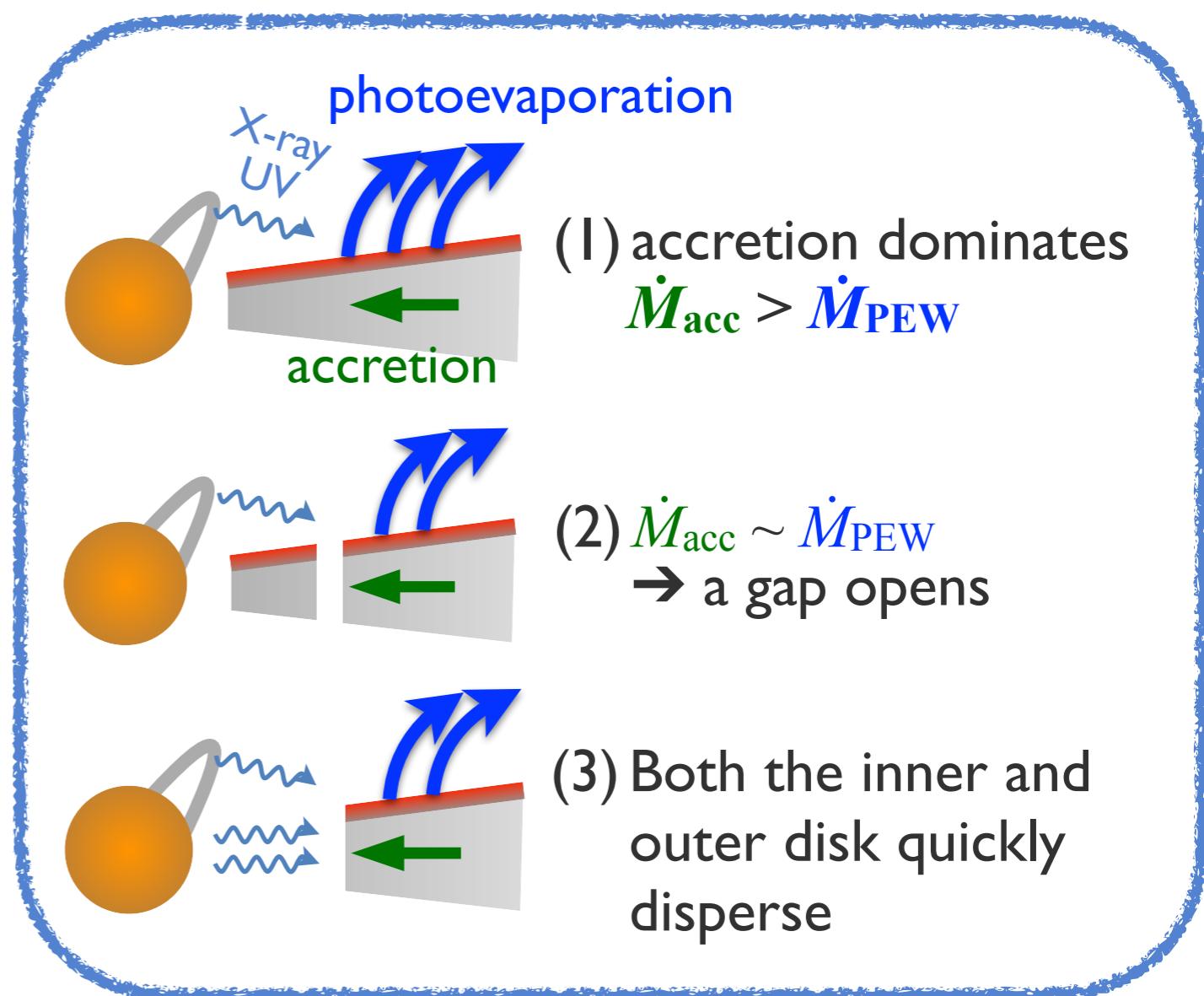


- **Settings:**
  - Stellar mass  $M_\star = 0.5 - 5 M_\odot$ , Disk initial condition: 50 au,  $0.1 M_\star$
  - Temp. structure: stellar irradiation + viscous heating *Nakamoto+Nakagawa94*
  - Viscosity parameter  $\alpha = 10^{-2} (M_\star / M_\odot)$  (from observations  $\dot{M} \propto M_\star^2$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

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

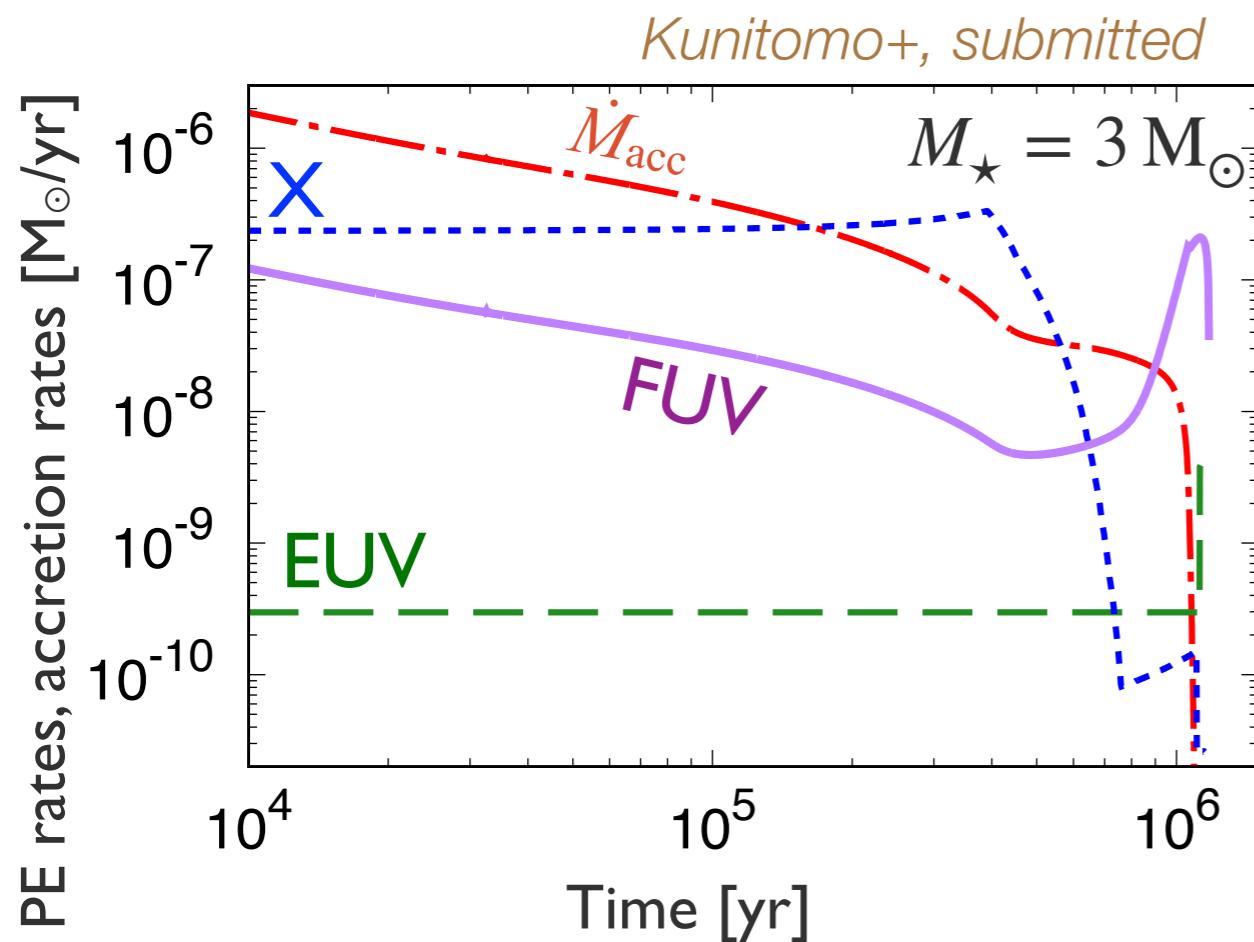


Qualitative behavior looks similar to previous studies



Clarke+01

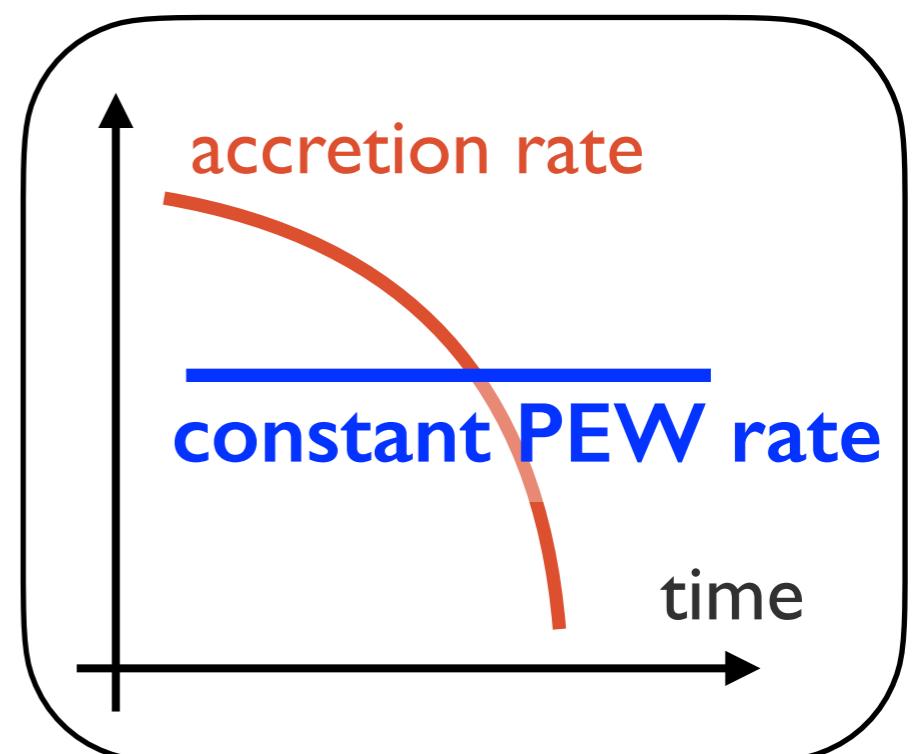
# Accretion & PEW rate evolution around a $3 M_{\odot}$ star



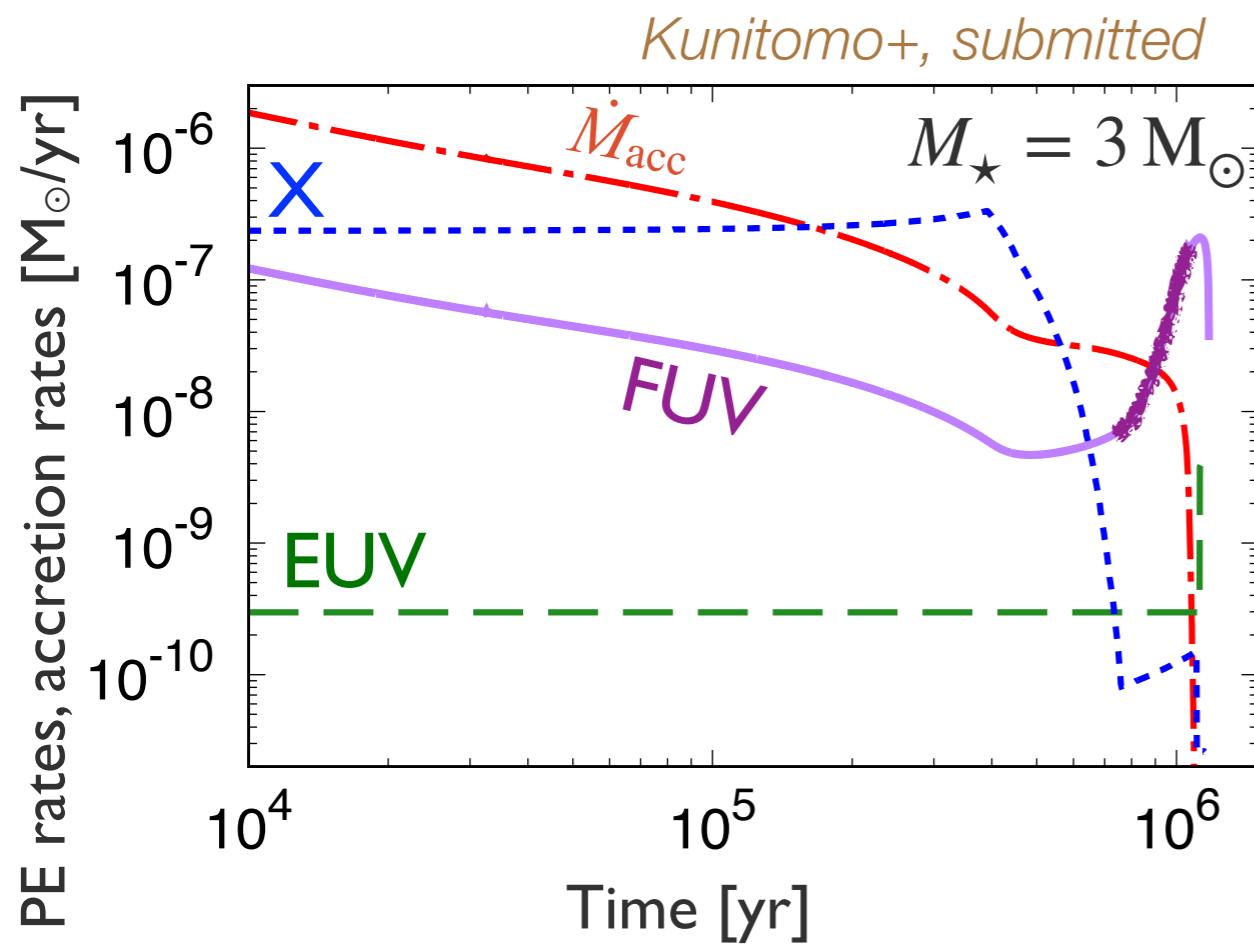
- PEW rates evolve with time significantly: different from previous studies
- Dominant mechanism changes from X-rays to FUV PEW



previous studies

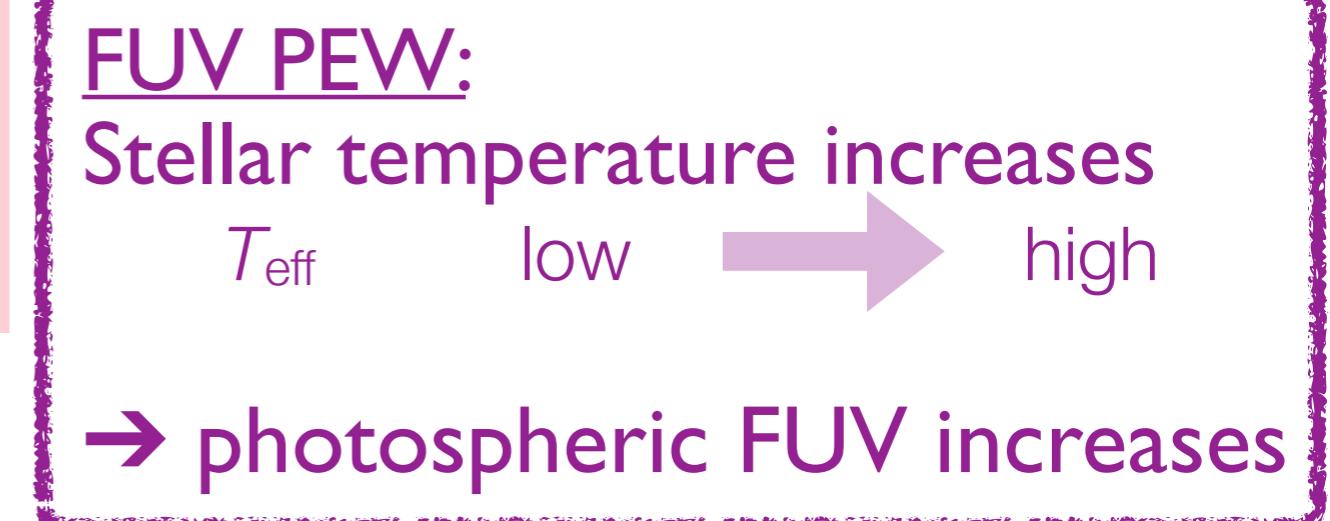
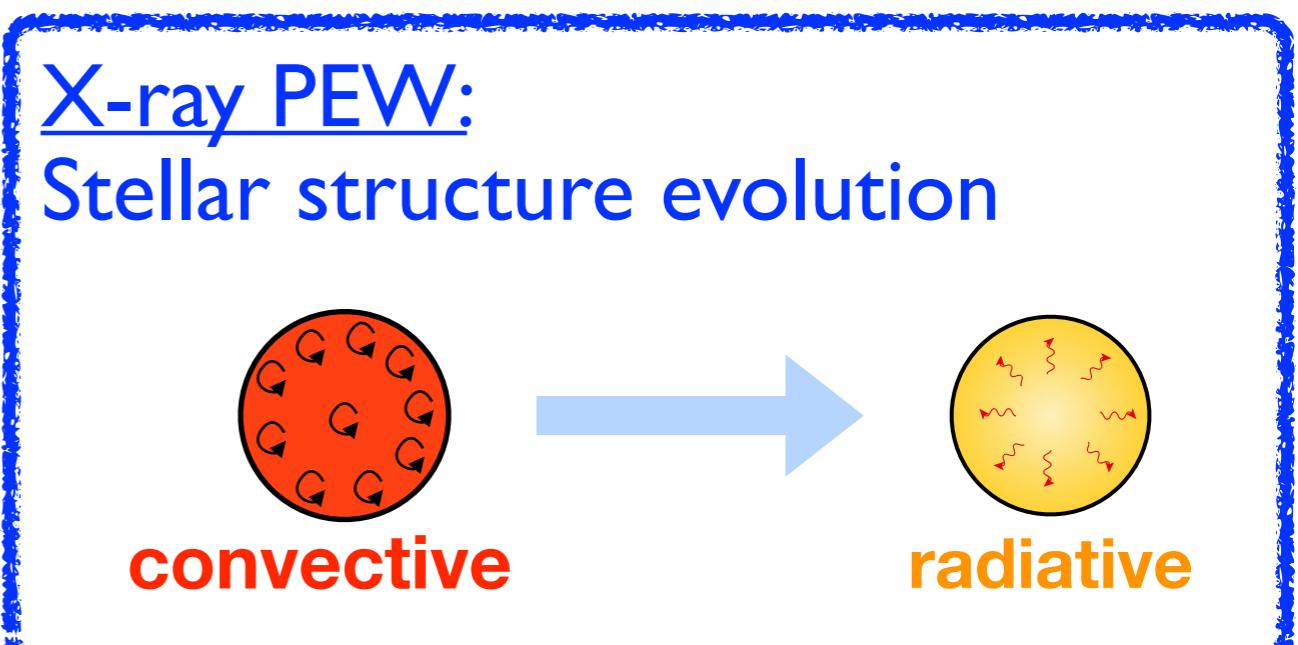


# Accretion & PEW rate evolution around a $3 M_{\odot}$ star

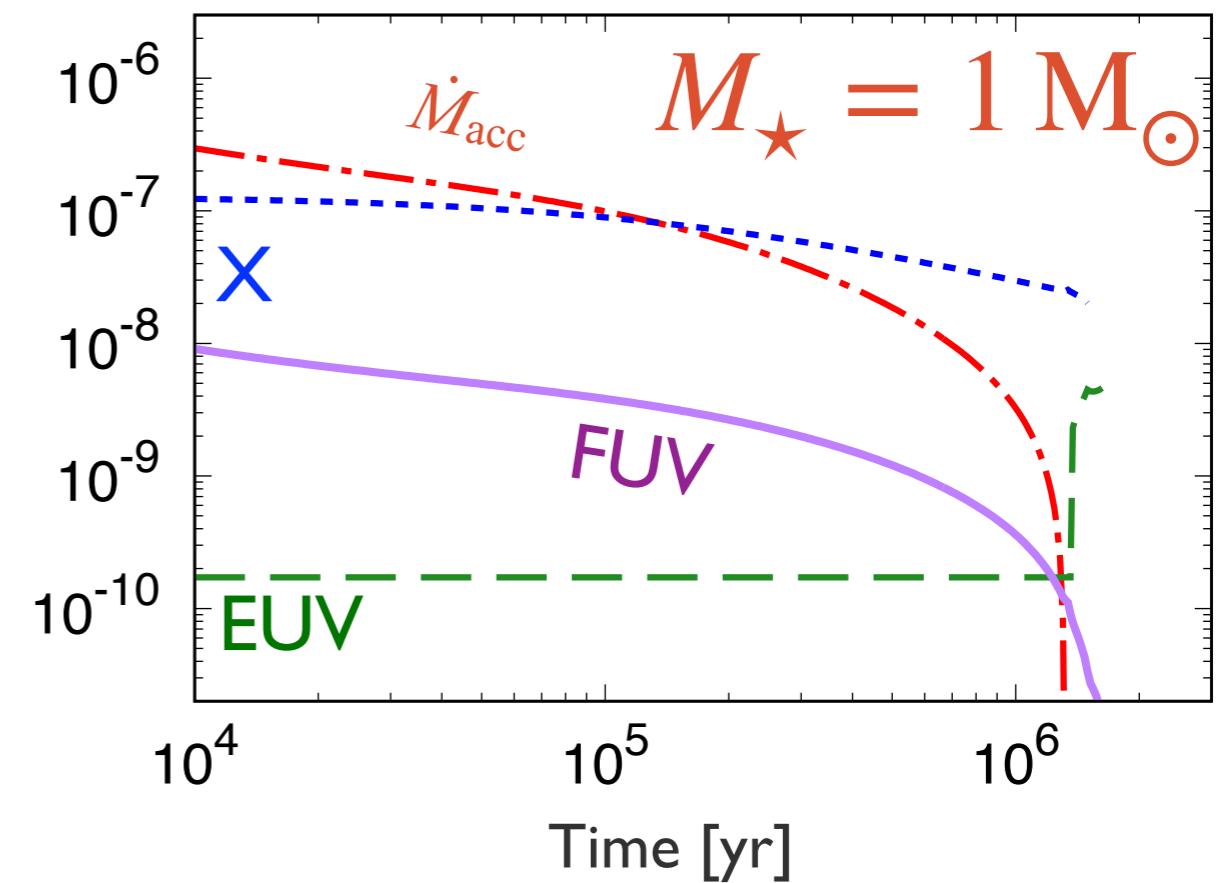
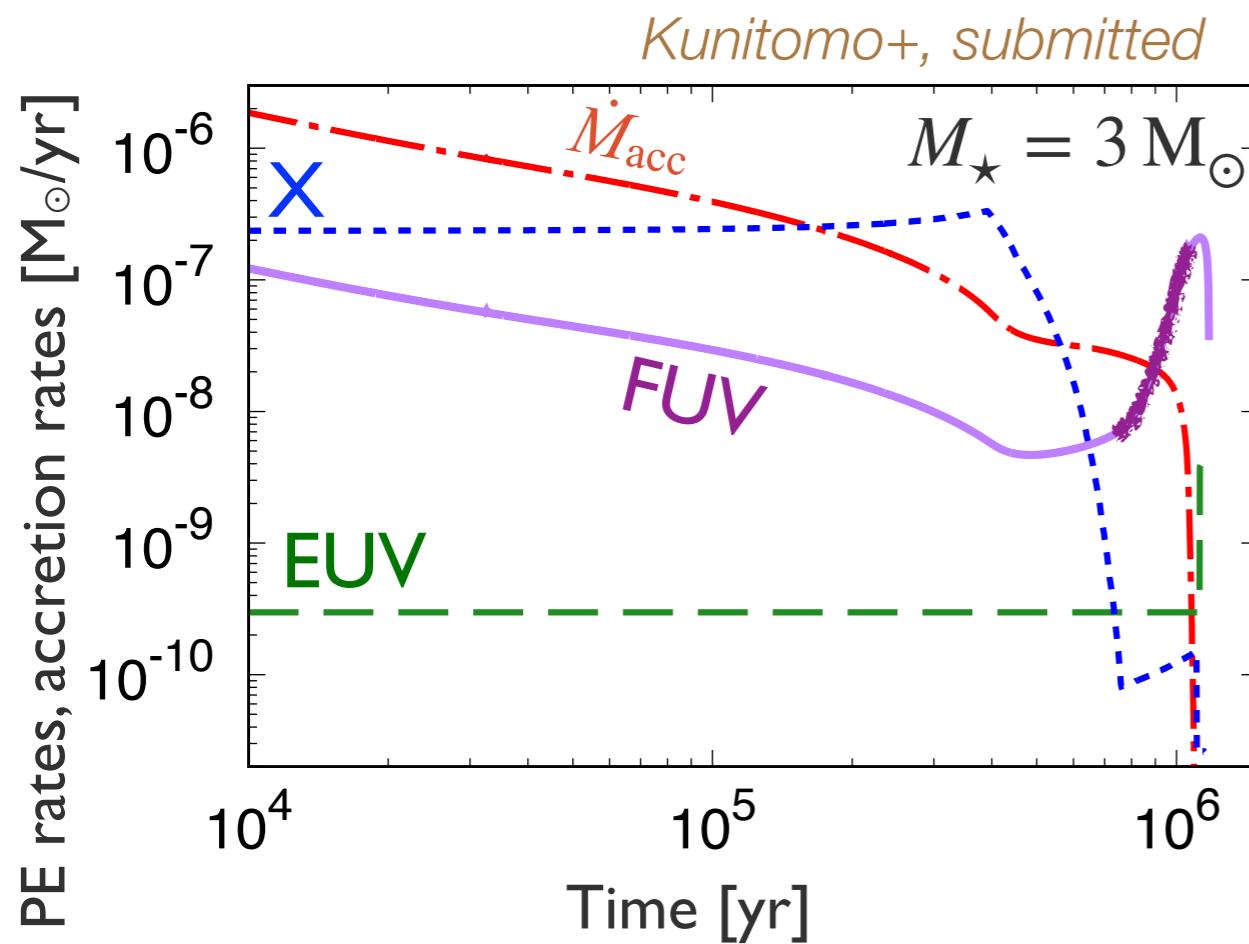


**Stellar evolution**  
determines the disk lifetime around  
**intermediate-mass**  
**stars**

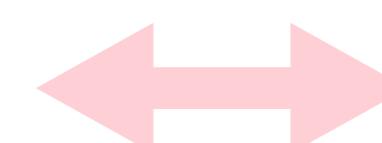
- PEW rates evolve with time significantly: different from previous studies
- Dominant mechanism changes from X-rays to FUV PEW



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



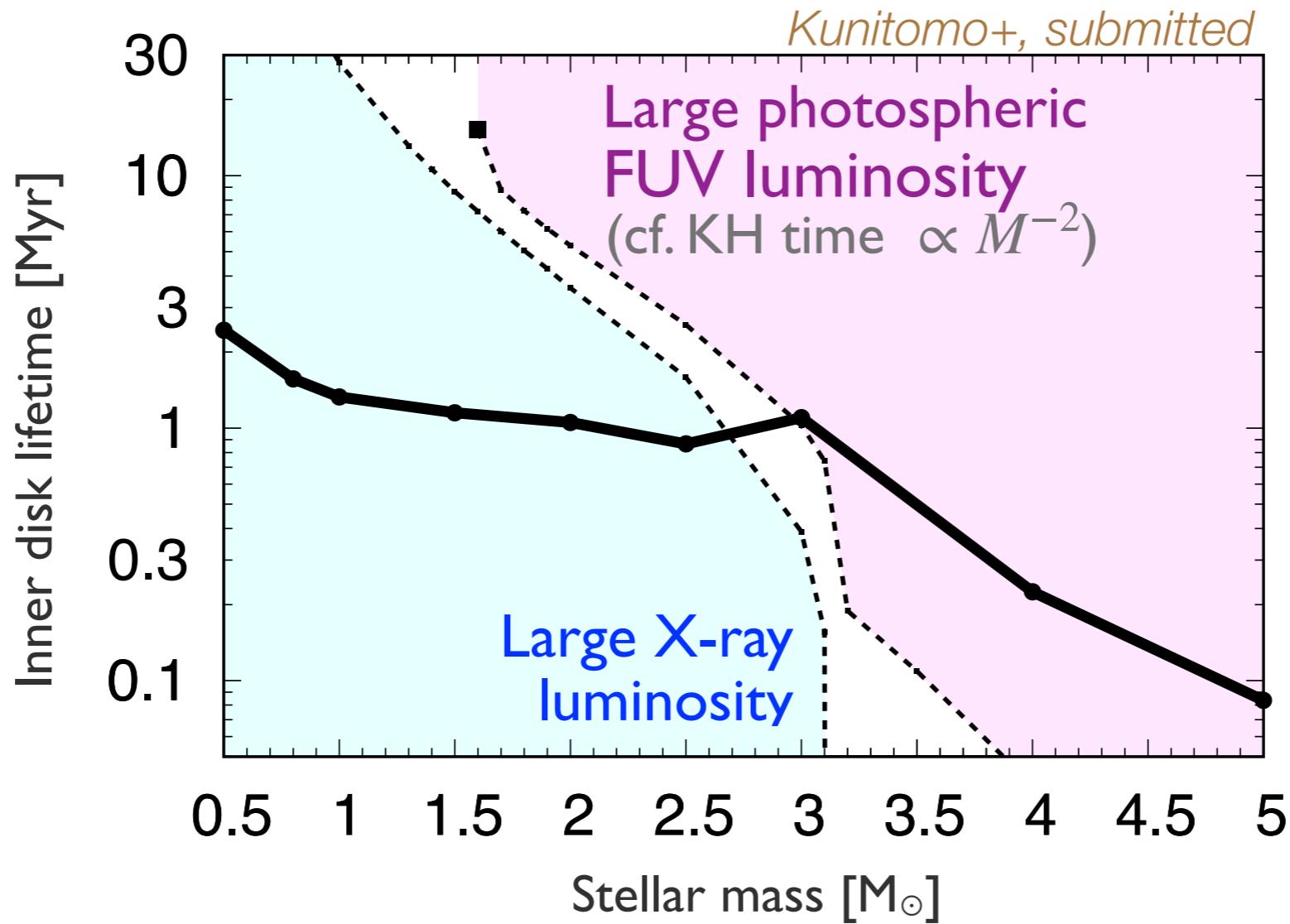
**Stellar evolution**  
determines the disk lifetime around  
**intermediate-mass stars**



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

:: longer stellar  
K-H timescale

# Disk lifetime vs stellar mass



- Disk lifetime decreases with stellar mass
  - consistent with observations
  - $\geq 3 M_{\odot}$ : increase of **FUV** luminosity matters
  - (low-mass stars: viscous timescale ( $\propto M_{\star}^{-1}$ ) matters)

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

## Two questions:

- How does ***stellar evolution*** affect disk evolution?
- How do disks with ***weak turbulence*** disperse?

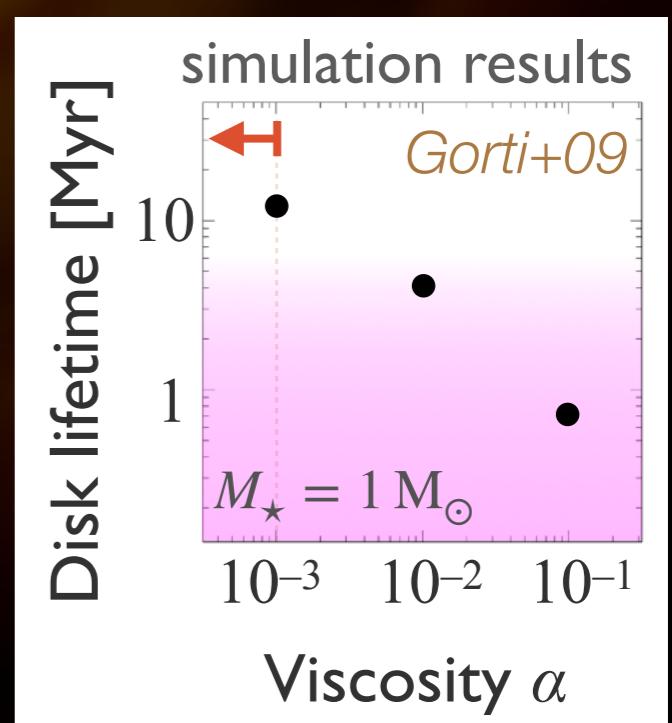
***Kunitomo+20, MNRAS***

# 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 > 10Myr**  
 → **inconsistent with obs.**  
 ( $\sim 6\text{Myr}$ )

see also *Morishima12*

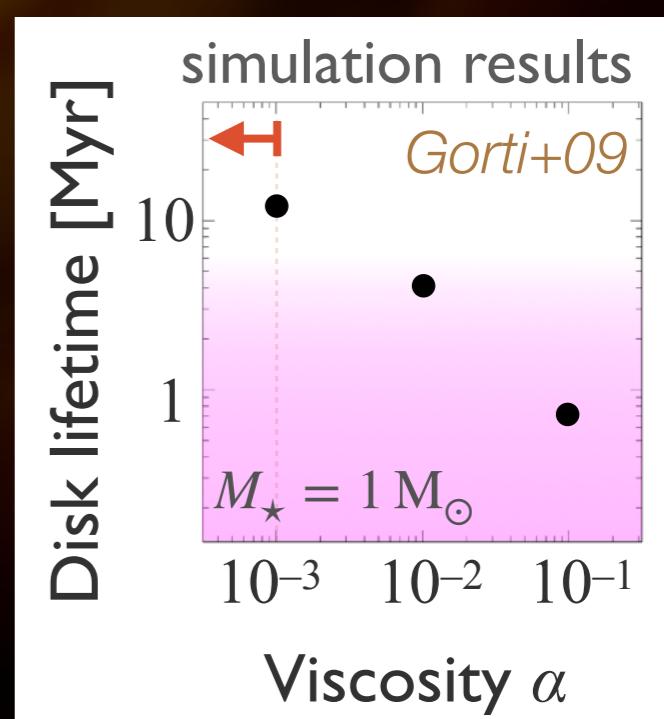


# Disks are not turbulent ( $\alpha \lesssim 10^{-3}$ )

- 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

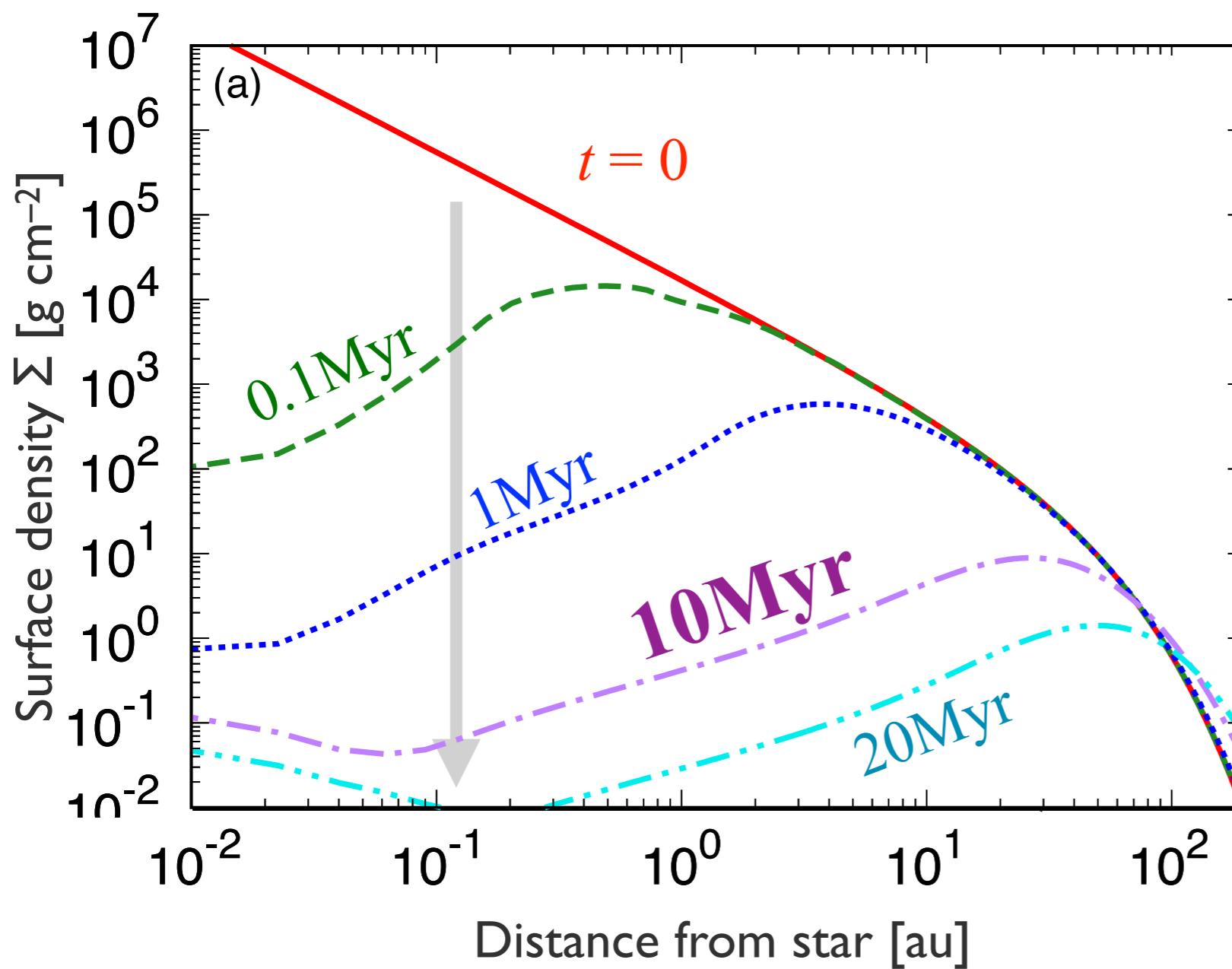
EUV:  
Alexander+06



- **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



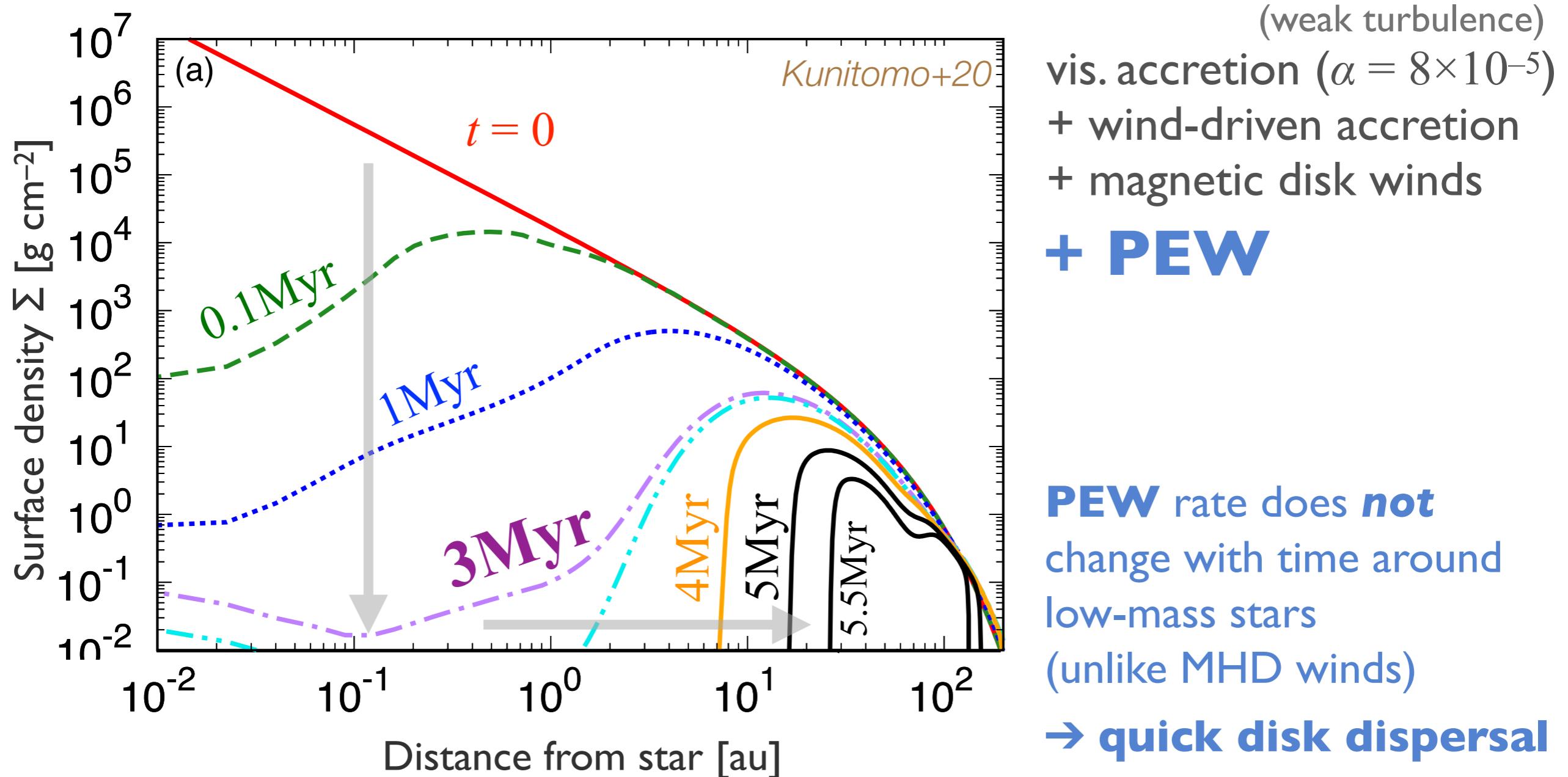
(weak turbulence)  
vis. accretion ( $\alpha = 8 \times 10^{-5}$ )  
+ wind-driven accretion  
+ magnetic disk winds  
**(w/o PEW)**  
see *Suzuki+16, Bai16*

**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**

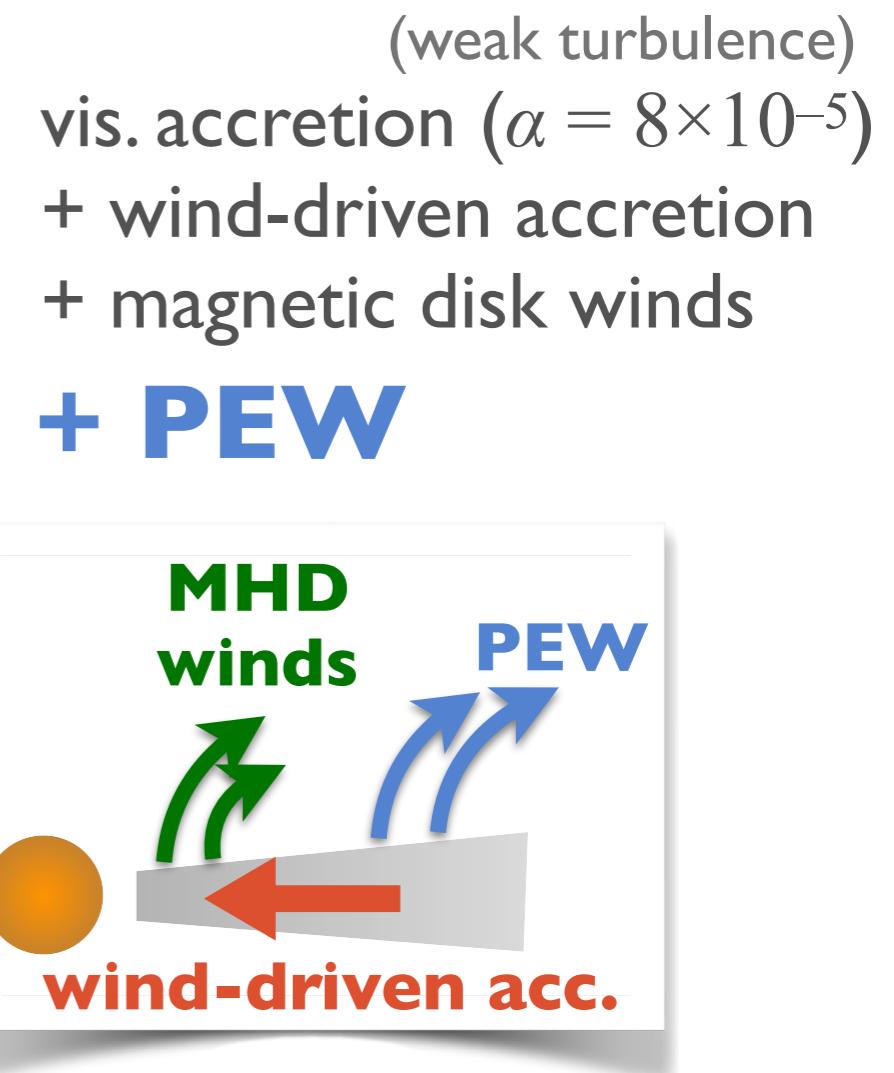
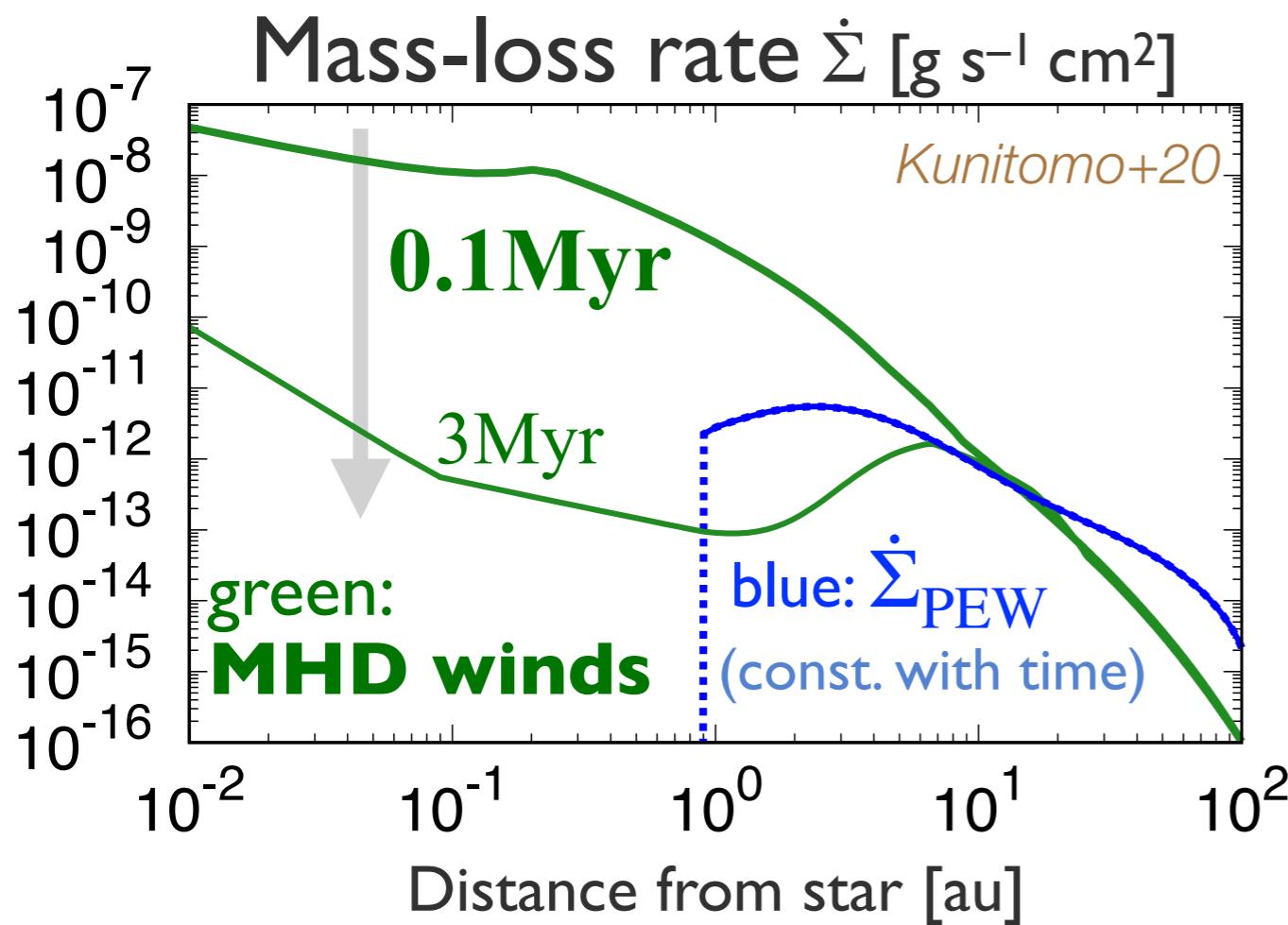
$\dot{M}_{\text{acc}}$  decreases with time  
→ **wind mass loss also decreases**

# Result2: with photoevaporation case



Inner disk lifetime  $\sim 3$  Myr  
→ consistent with observations

# 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

See Kunitomo+20

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+, submitted*
- **MHD winds** dominates in the **early** phase in the **inner** disk, whereas **PEW** 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 PEW & MHD 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+20*