Photoevaporating Disk Dispersal around Intermediate-Mass Stars

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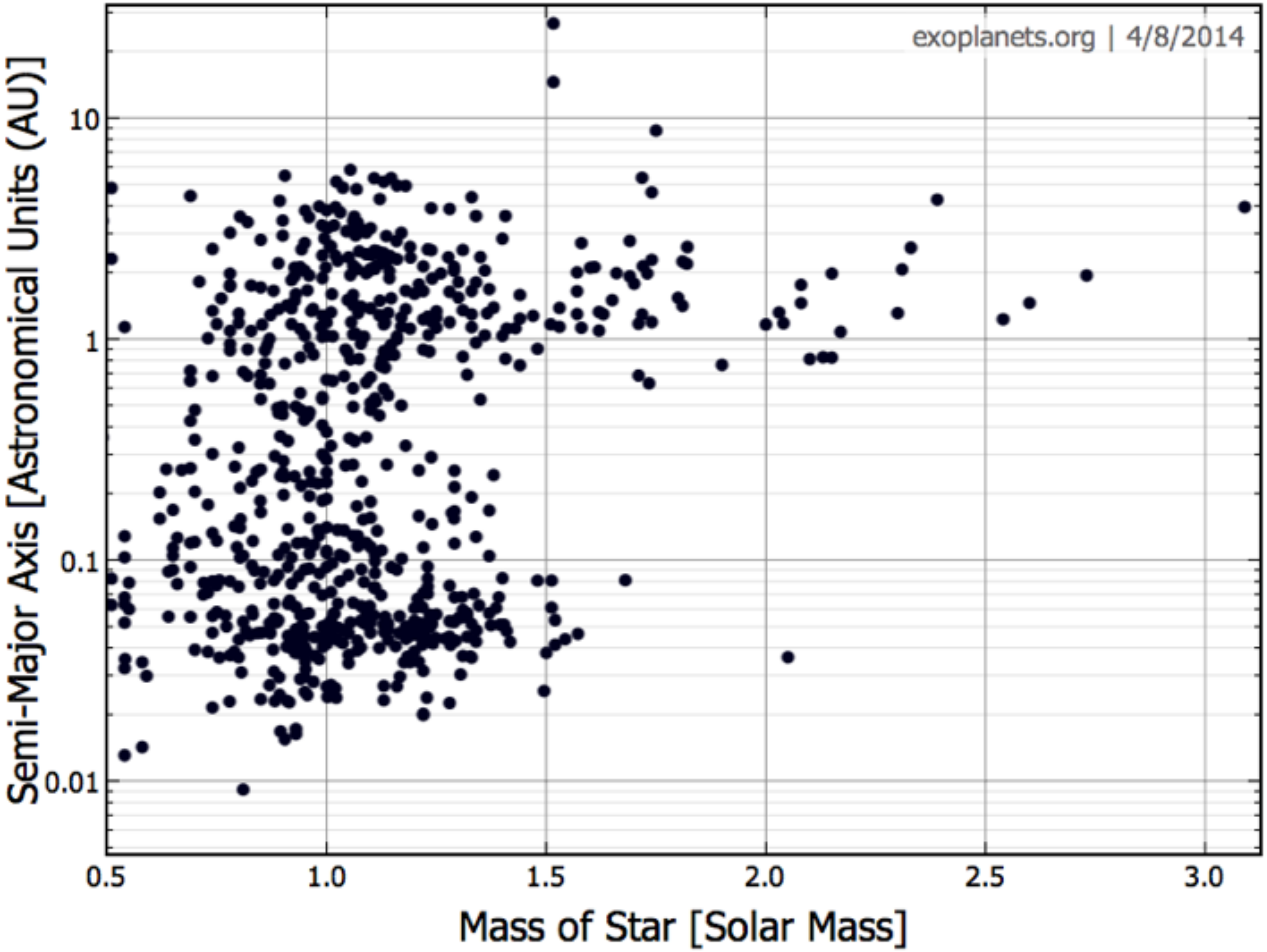
Masanobu Kunitomo,
Taku Takeuchi, Shigeru Ida (*Tokyo Tech*)

“Herbig Ae/Be Stars”@Santiago
Apr. 10, 2014

planets around intermediate-mass stars

- more than 1000 planets have found so far



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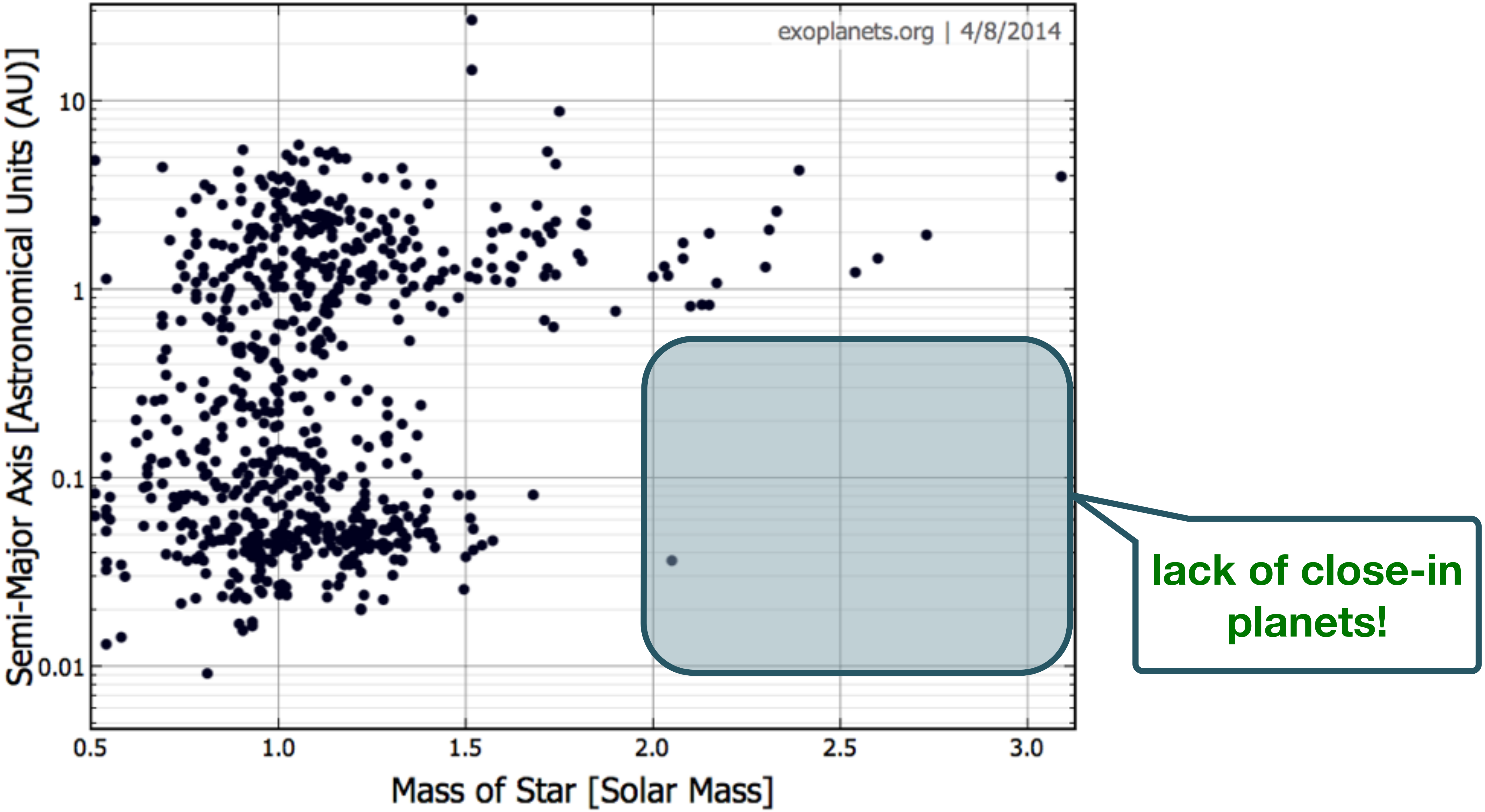

lack of close-in planets!

planets around intermediate-mass stars

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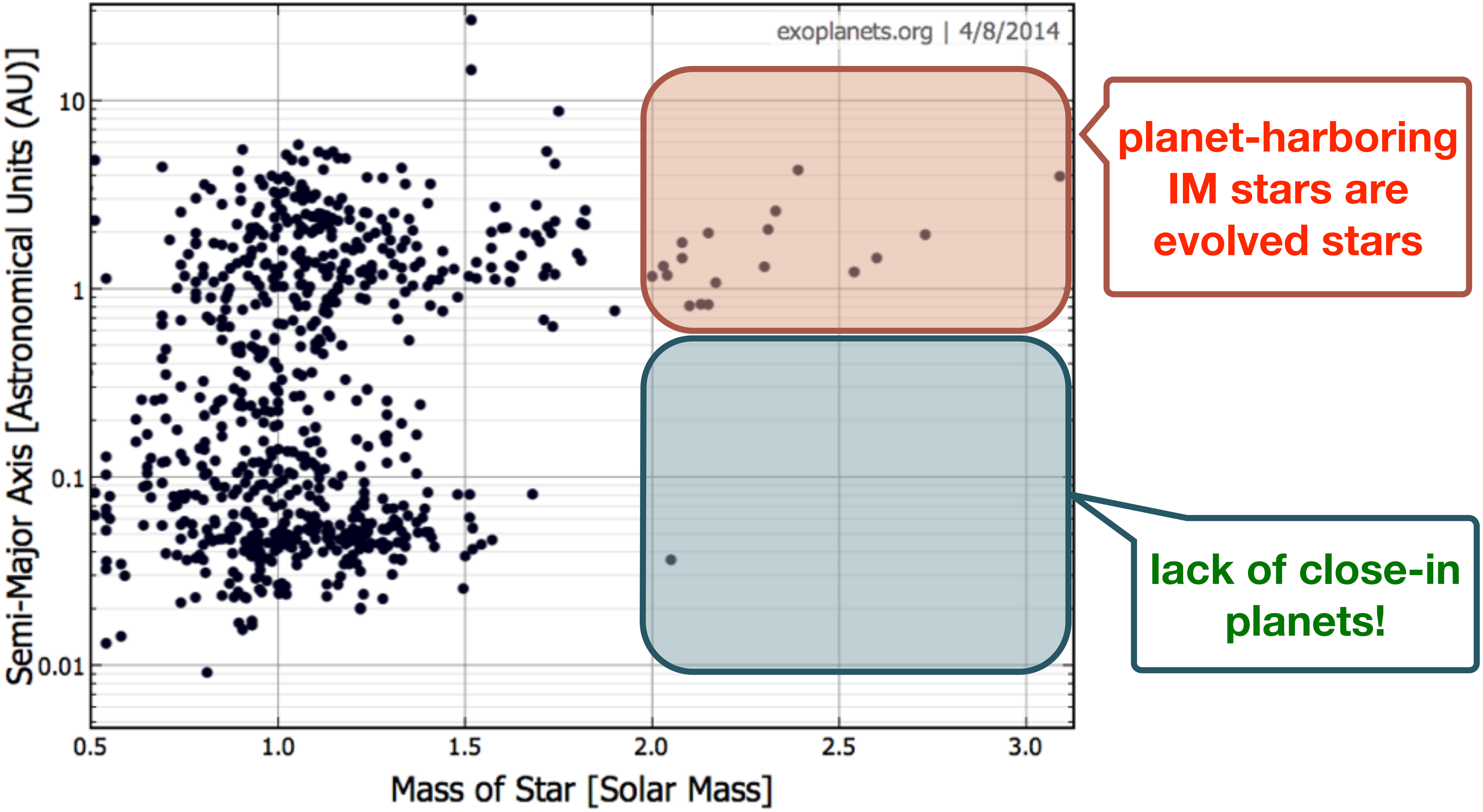
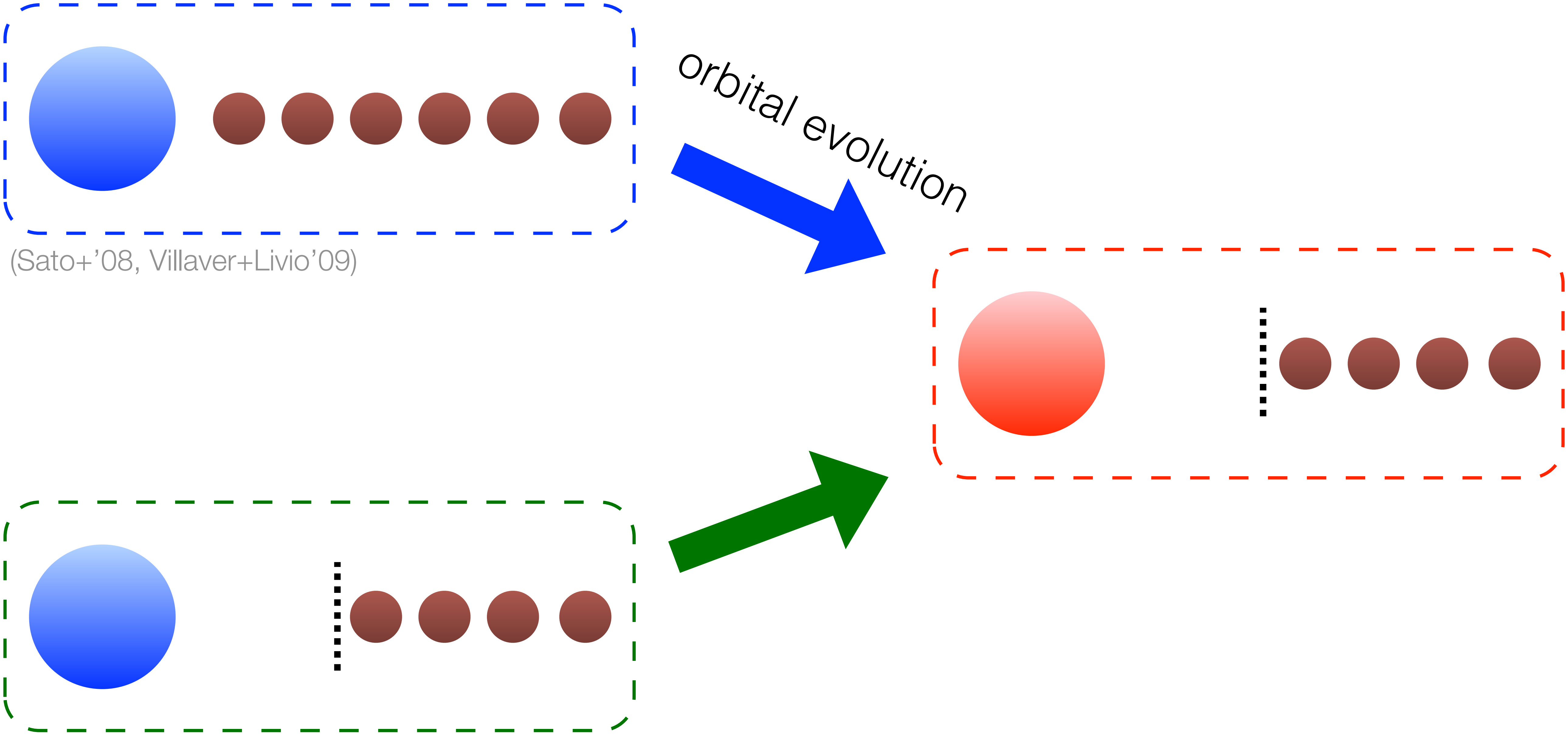


planet-harboring IM stars are evolved stars

lack of close-in planets!

possible origins of the lack of close-in planets

- MS stars
- red giants

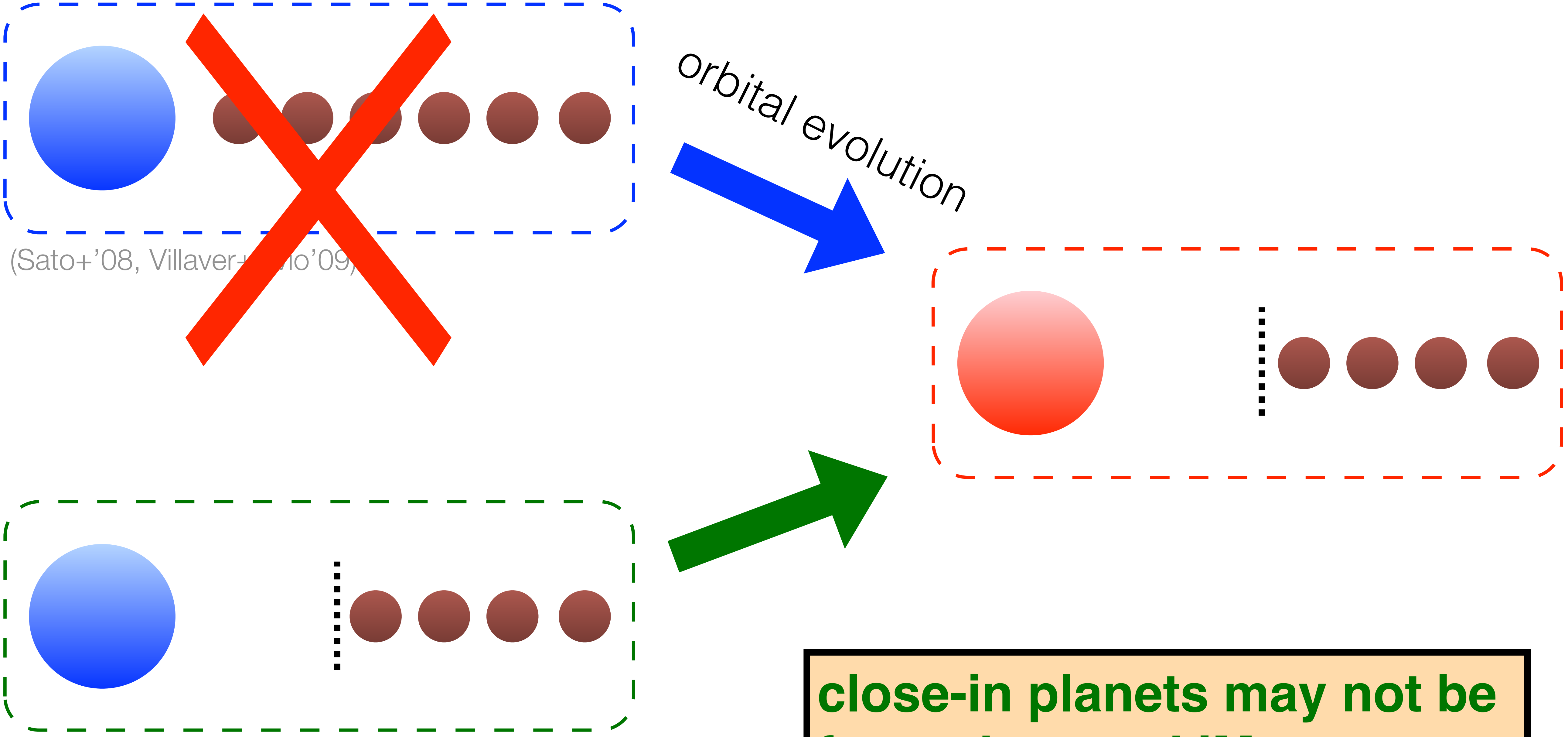


orbital evolution

(Sato+’08, Villaver+Livio’09)

(Burkert+Ida’07,Currie’09)

possible origins of the lack of close-in planets



- MS stars
- red giants

Kunitomo+'11

orbital evolution

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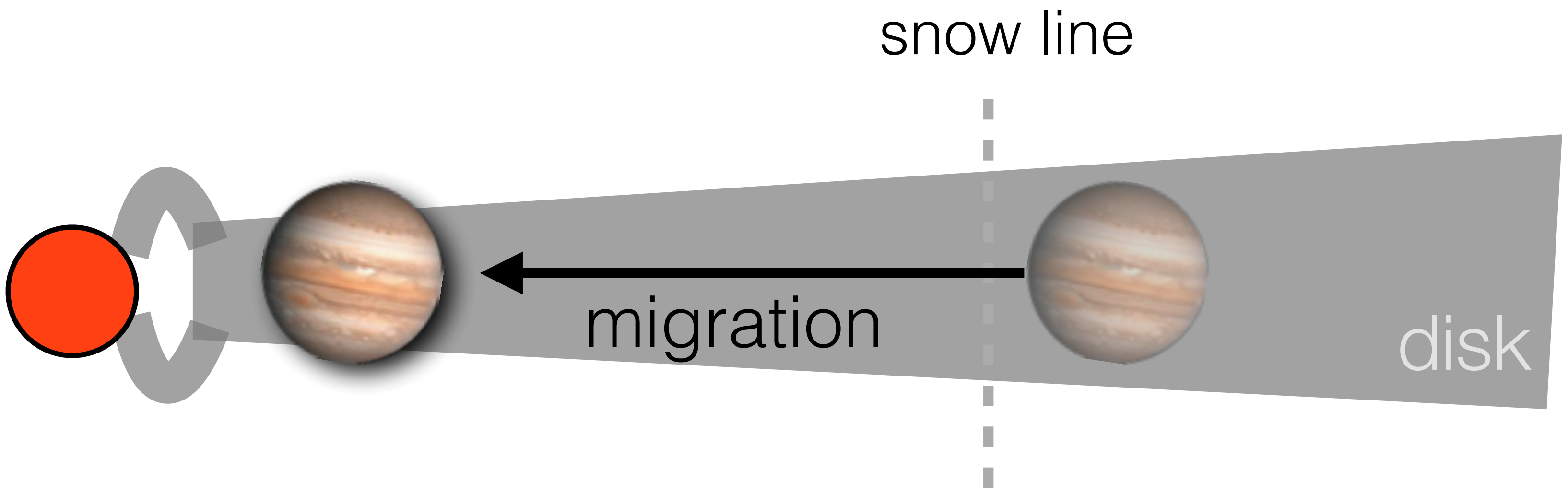
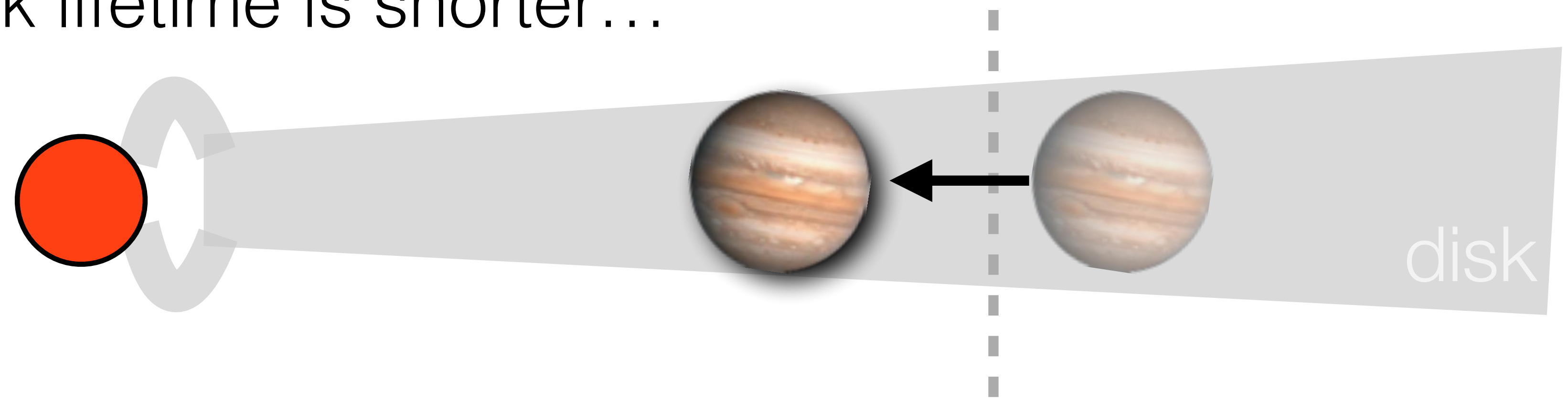
close-in planets may not be formed around IM stars

why close-in planets are not formed



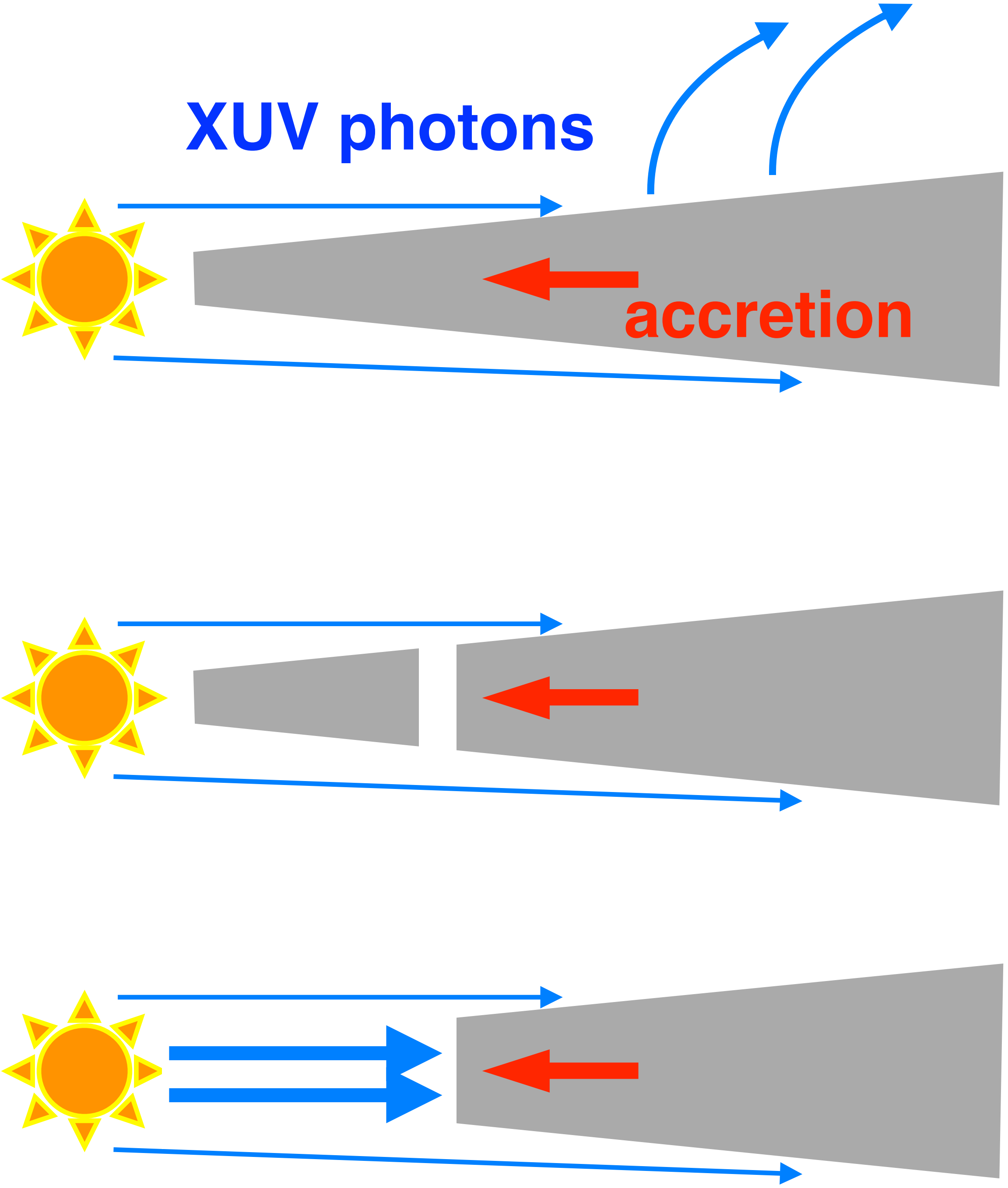
- if the disk lifetime is shorter…

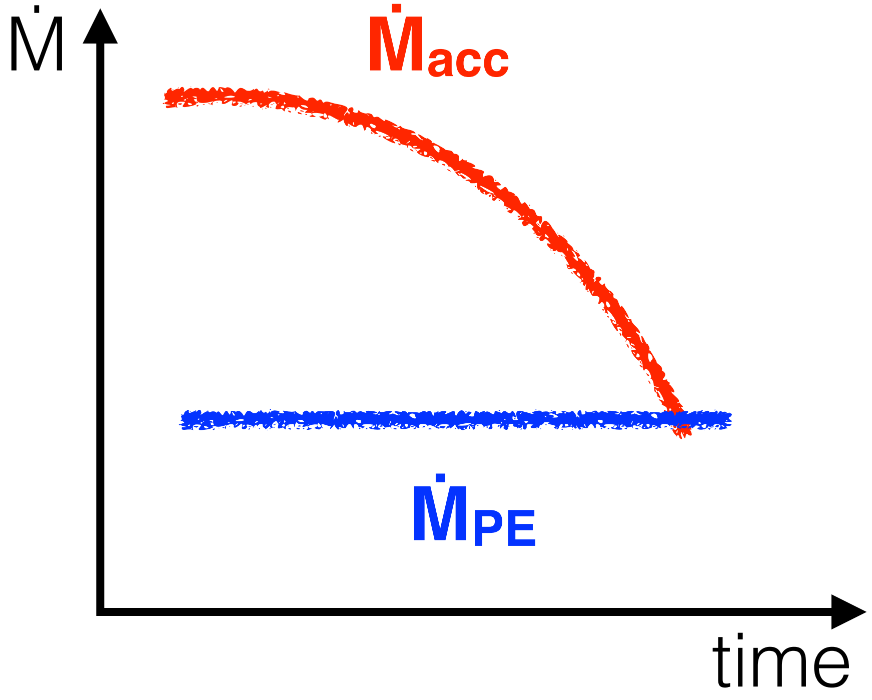


(Burkert+Ida'07,Currie'09)

the disk lifetime is important
for the distribution of planets

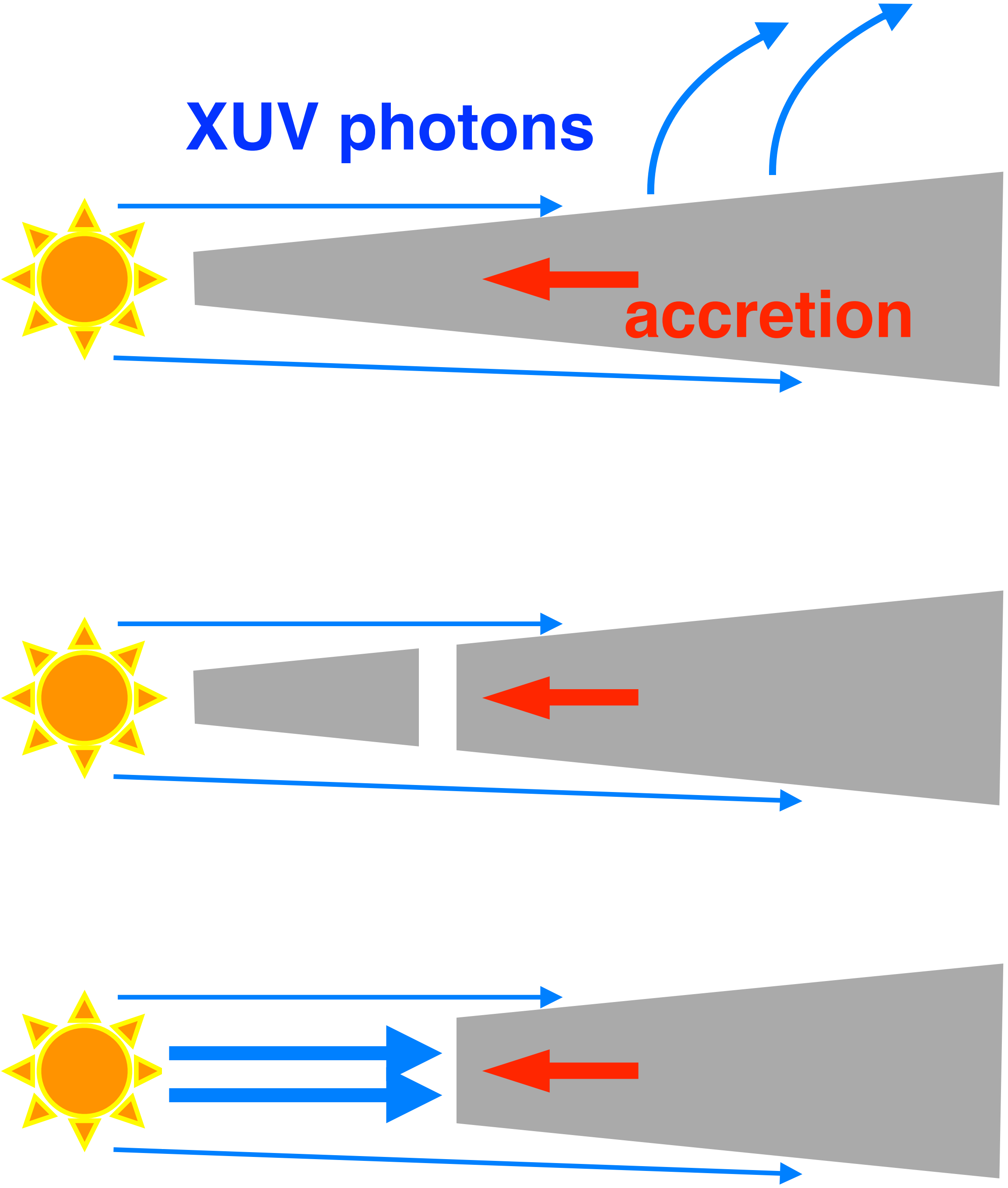
dispersal of protoplanetary disks

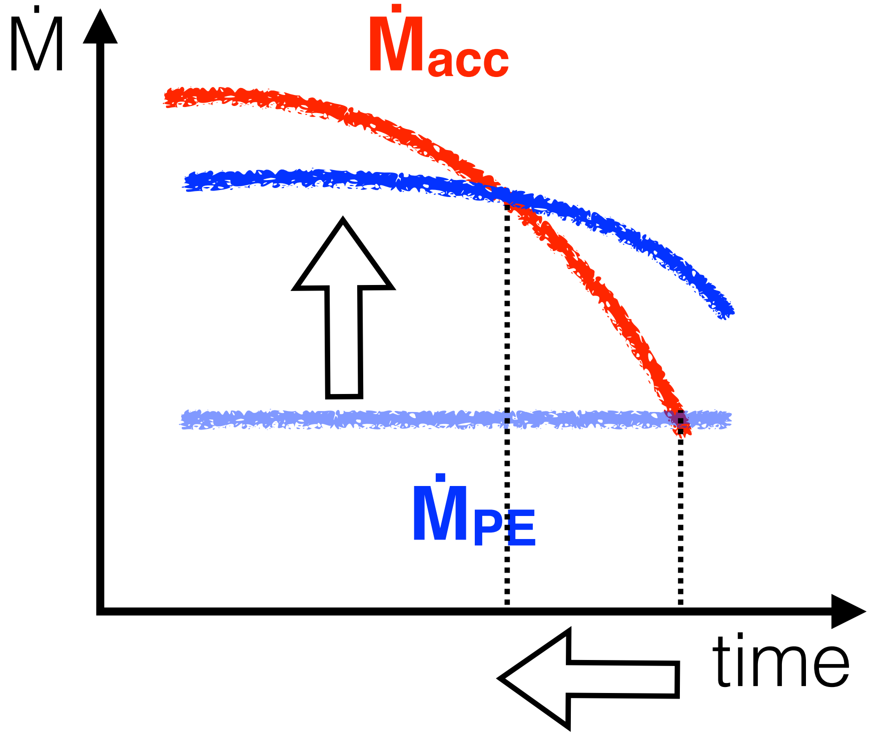




photoevaporation rate ($\dot{M}_{\rm PE}$) is important for the disk lifetime

dispersal of protoplanetary disks

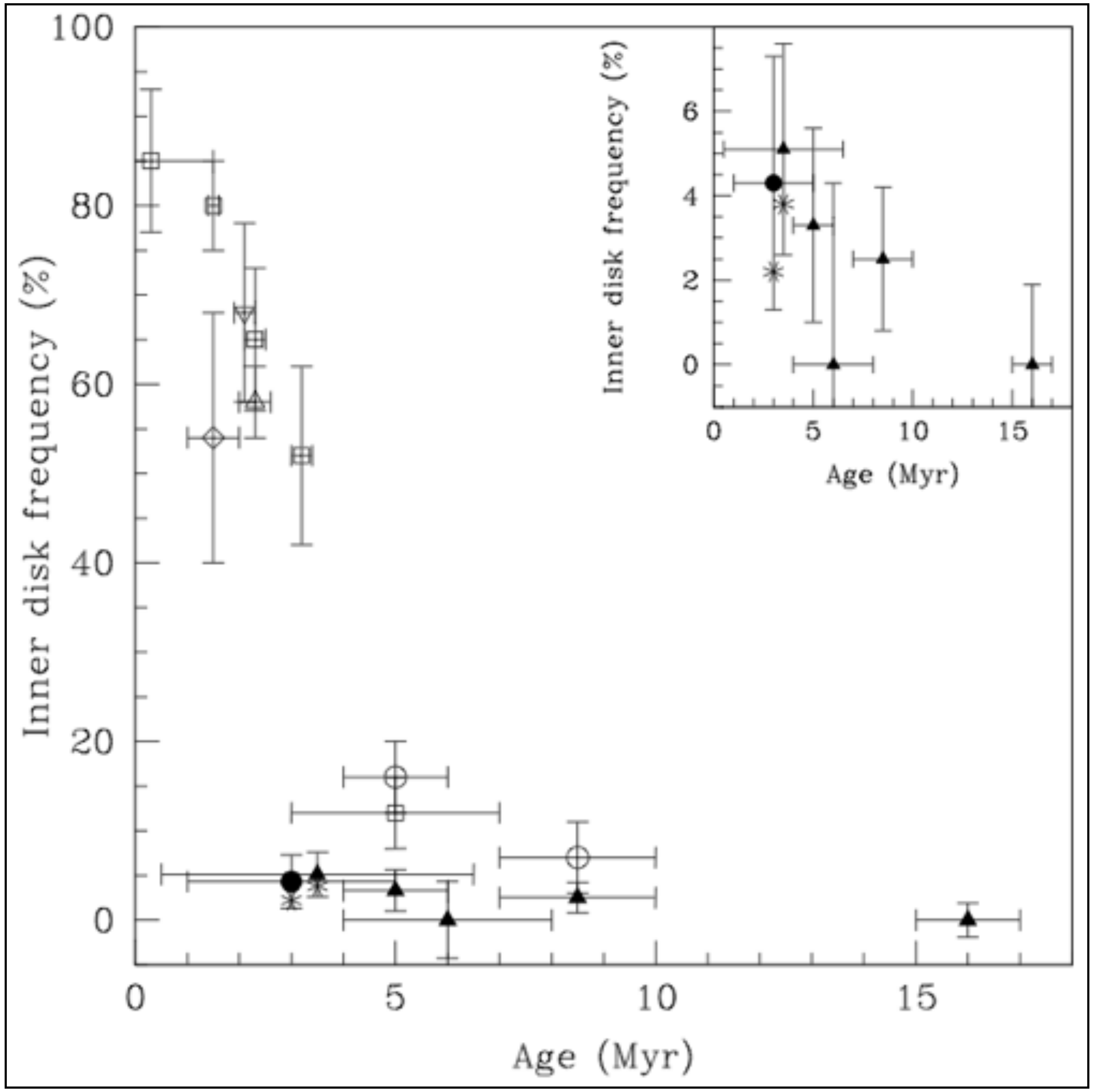




photoevaporation rate ($\dot{M}_{PE}$) is important for the disk lifetime

higher L_{XUV} (X-ray and UV luminosity) **and then higher $\dot{M}_{PE}$ can make the disk lifetime shorter**

disk lifetime around IM stars — **Observation**



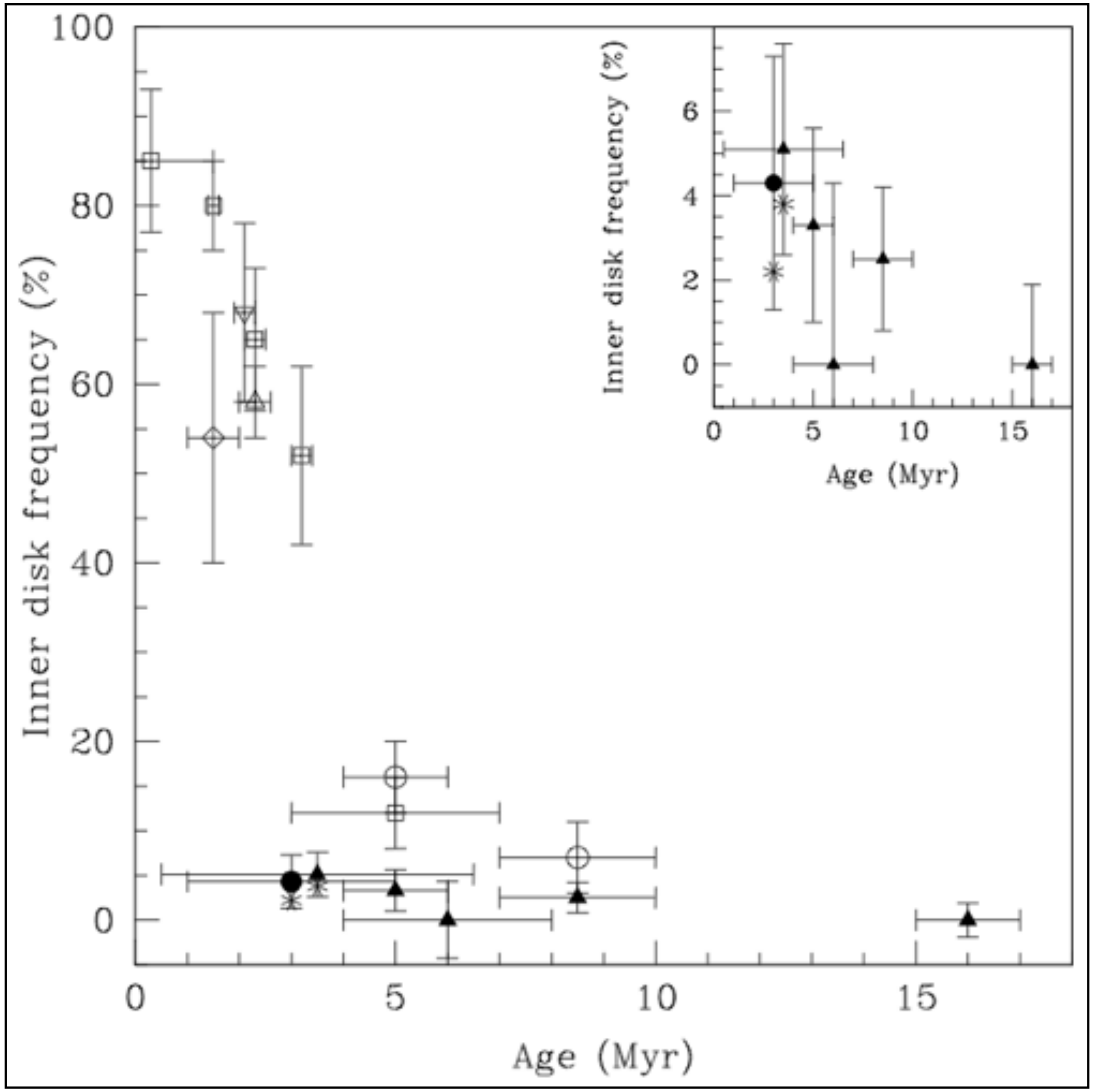
(Hernandez et al. 2005)

○□△◇: low-mass stars(<~1M☉)

●▲＊: IM stars(~2–7M☉)

the disk lifetime of IM stars is shorter than that of low-mass stars by Near-IR observation

disk lifetime around IM stars — **Observation**



(Hernandez et al. 2005)

○□△◇: low-mass stars(<~1$M_\odot$)

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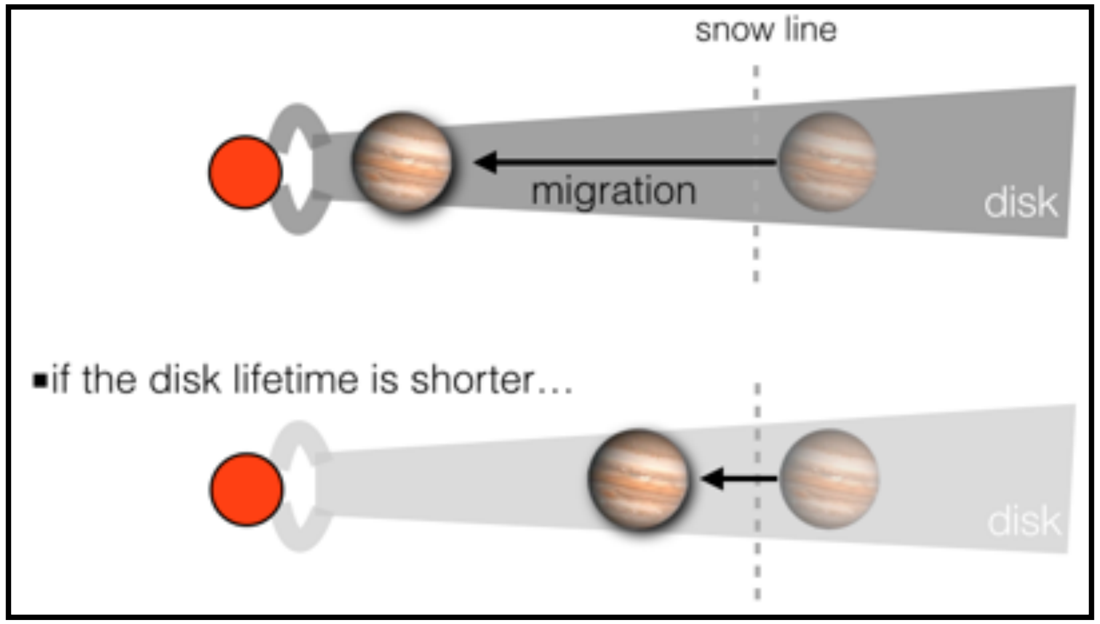
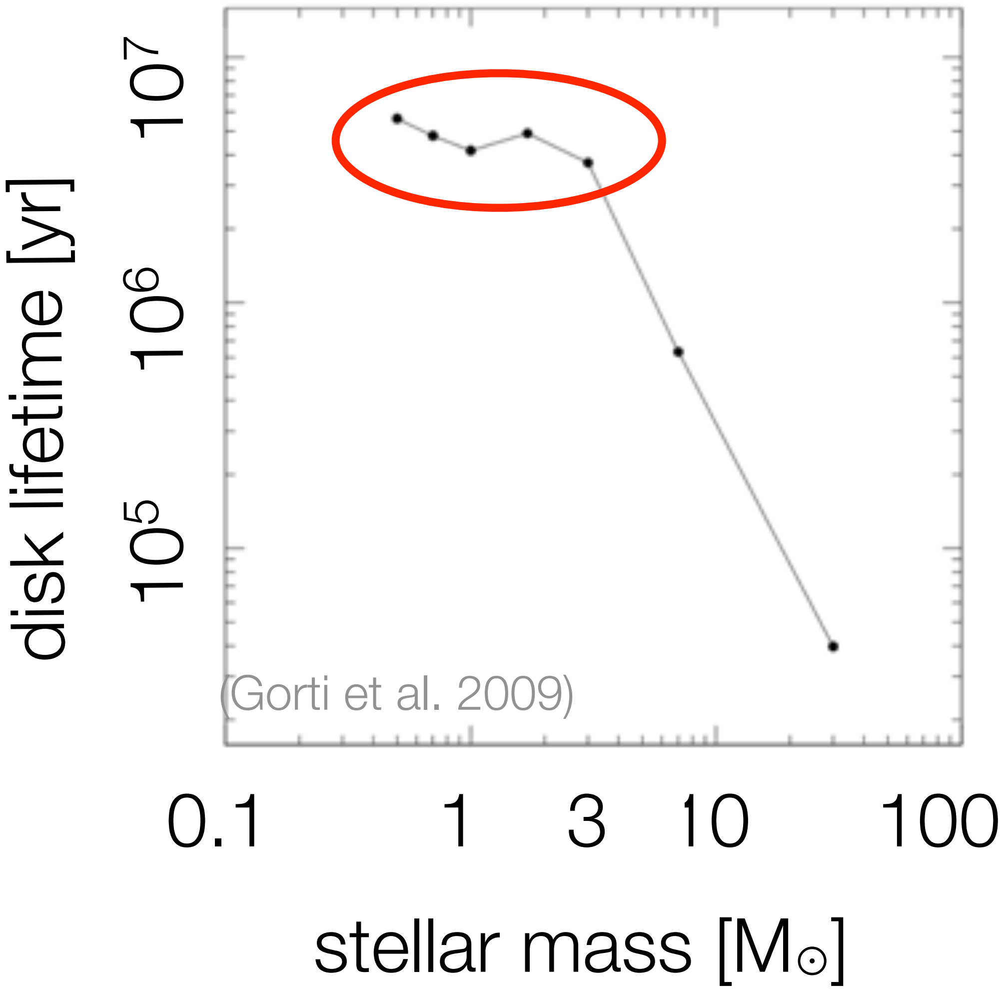


disk lifetime around IM stars — **Theory**

- **Gorti et al. (2009):** calculated the disk evolution including **X, EUV & FUV**

  →**“the disk lifetime almost constant from low-mass to IM stars”**

  →**inconsistent with observed feature**



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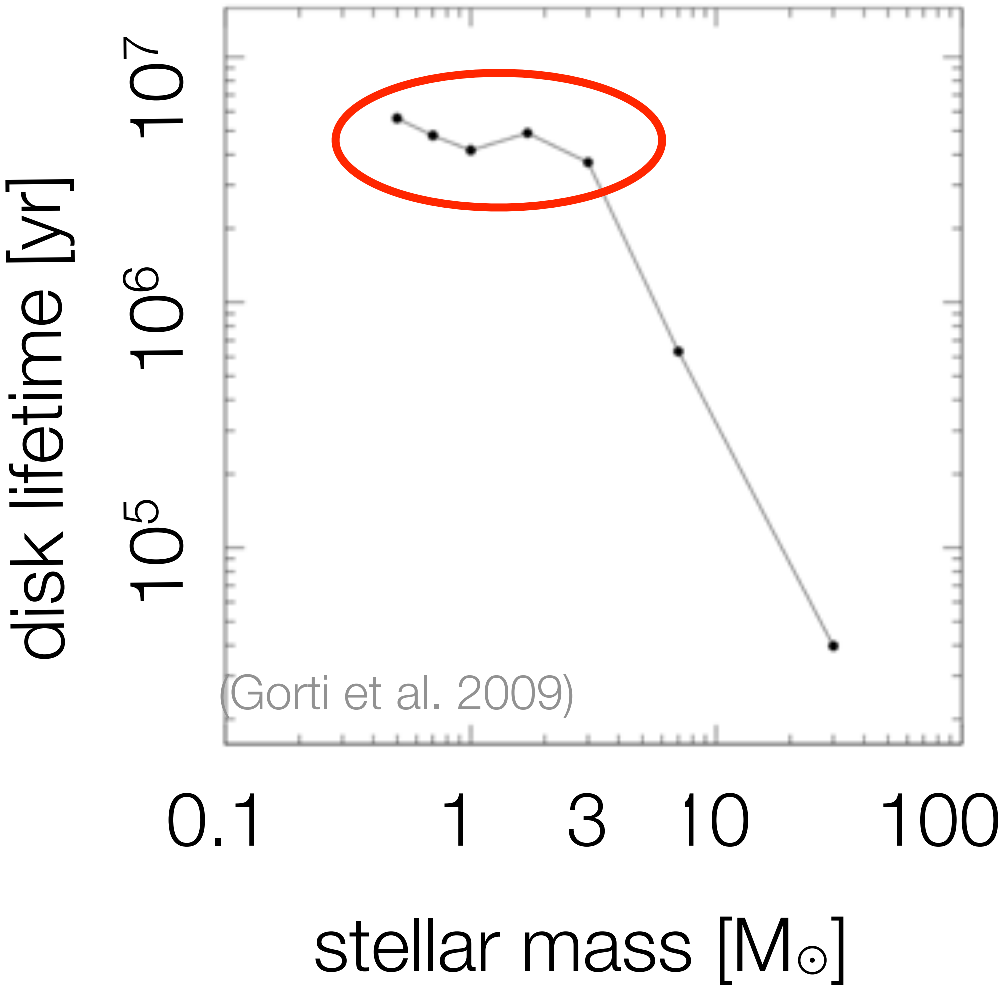
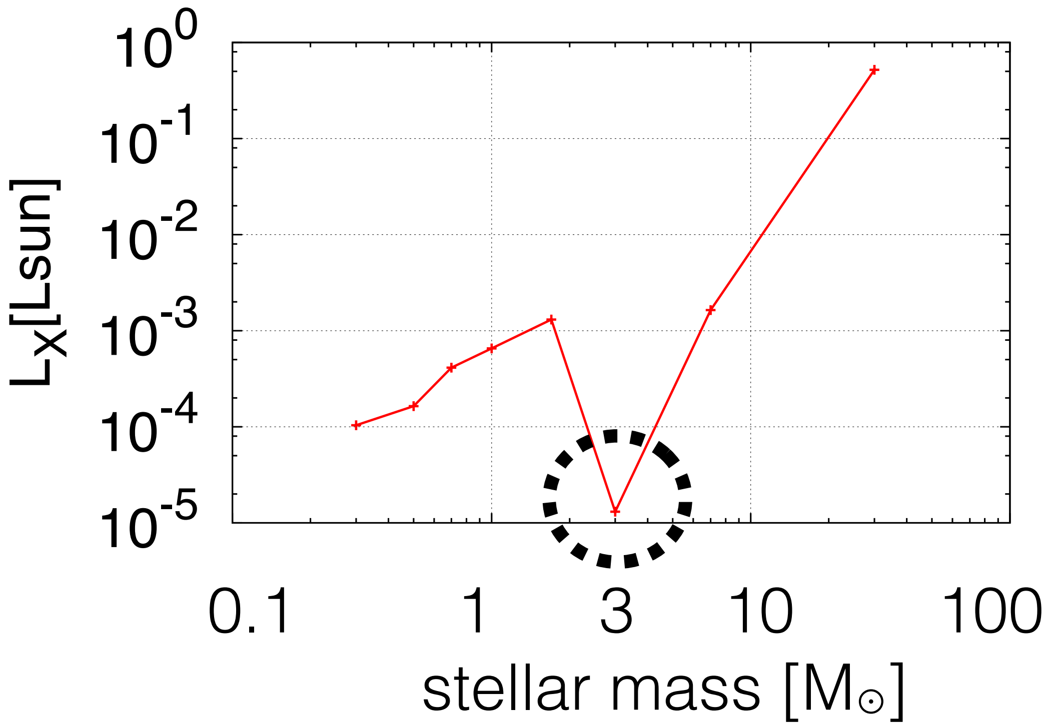


(Gorti et al. 2009)

- cause: small and constant L_{EUV}, L_X



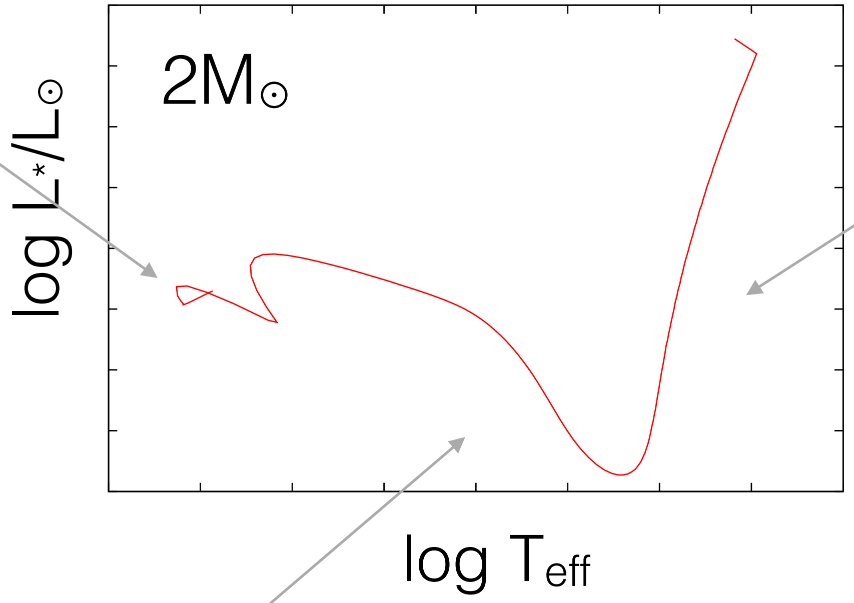
aim of this study

MS

no convective envelope

$L_X \sim 10^{-9} L_\star$

(e.g., Cassinelli+'94)



on Hayashi track

fully convective

"X-ray saturation"

$L_X \sim 10^{-3.5} L_\star$

(e.g., Flaccomio+'03; Hamaguchi+'05)

on Henyey track

radiative core develops

$L_X \sim 10^{-6} L_\star$ (e.g., Hubrig+'09; Zinnecker+Preibisch'94)

→L_X and then $\dot{M}_{PE}$ can be very large at first and evolve

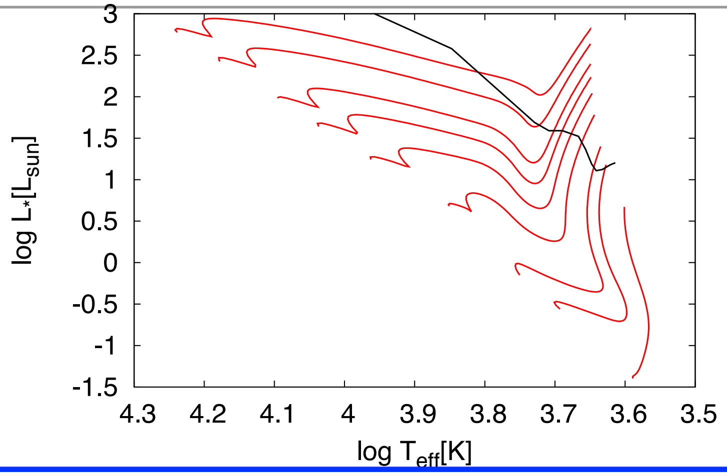
investigate the impact of the evolution of L_X on the P.E. rate and the disk evolution

method

1. stellar evolution: MESA

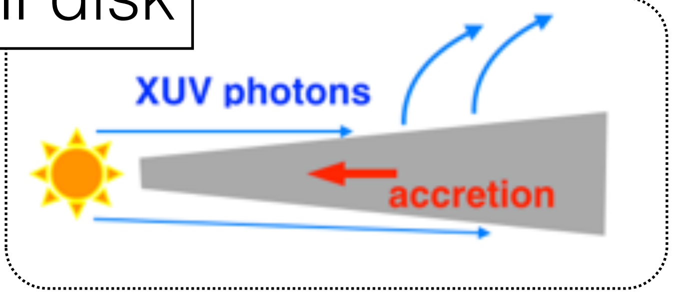
(Paxton+’11)

- $L_\bigstar(t)$, $M_{\rm conv}(t)$
- $M_\bigstar=0.5\text{-}5M_\odot$
- t=0: birthline (Behrend+Maeder’01)



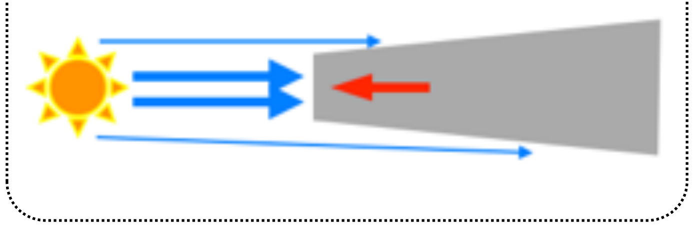
2. P.E. model

full disk



X: Owen+’12
EUV: Hollenbach+’94

disks w/ inner-holes



X: Owen+’12
EUV: Alexander+’06

- $\Phi_{\rm EUV}=10^{41}$ [1/s]
- L_X is calculated using $L_\bigstar$ and $M_{\rm conv}$ to reproduce “saturation” relation

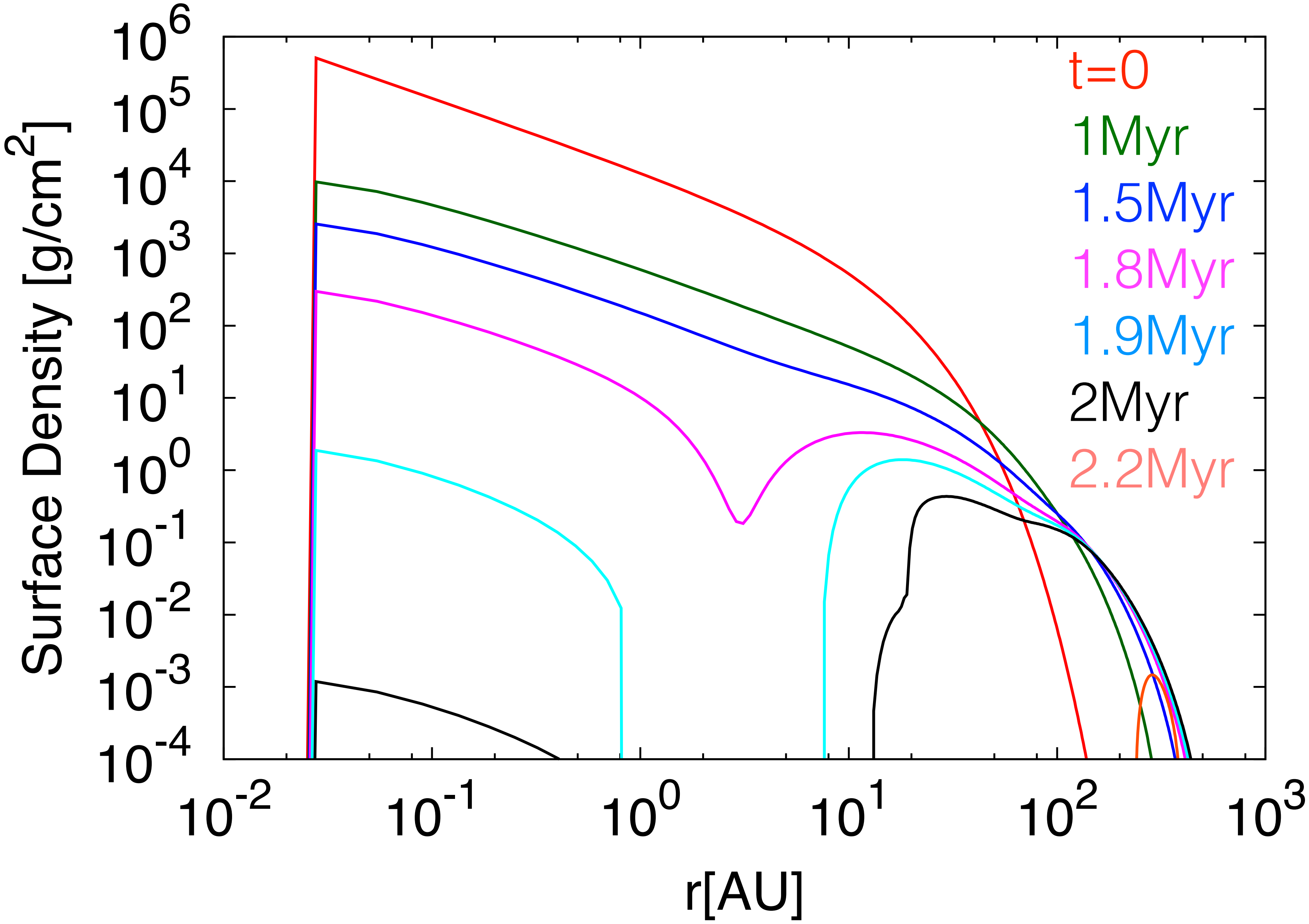
3. disk evolution

$$\frac{\partial\Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left(\sqrt{r}\frac{\partial}{\partial r}\left(\nu\Sigma\sqrt{r}\right)\right) - \dot{\Sigma}_{\rm PE}$$

- initial surface-density profile：self-similar solution, $r_1=10$AU
- from the observed relation, $\mathbf{M_{d,ini}\propto M_\bigstar}$, $\boldsymbol{\alpha\propto M_\bigstar}$ (from $\dot{M}\propto M_\bigstar^2$ and $L_\bigstar\propto M_\bigstar^2$)

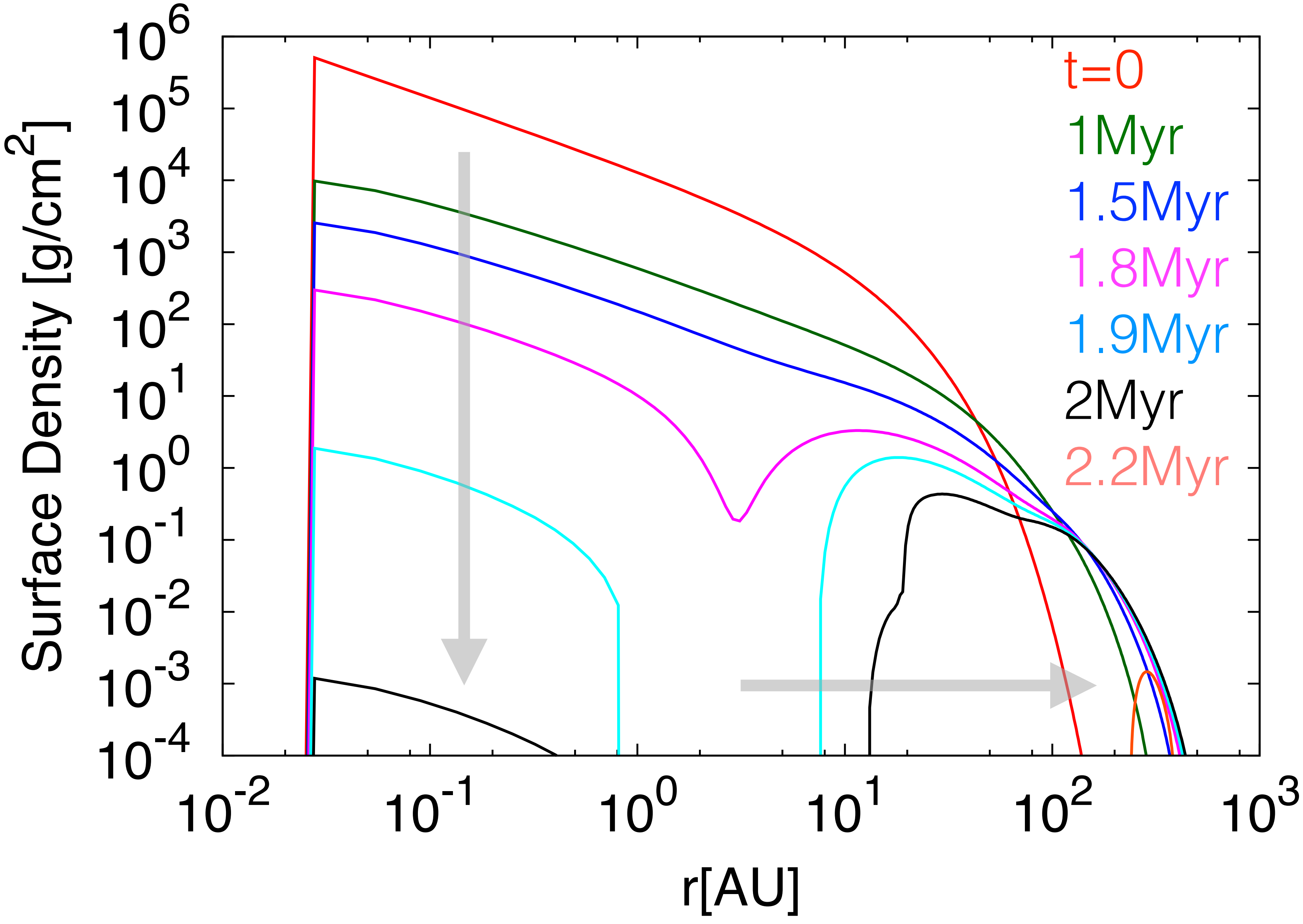
(Williams+Cieza’11, Calvet+’04, Muzerolle+’05)

Result: example of the disk evolution around $1M_\odot$



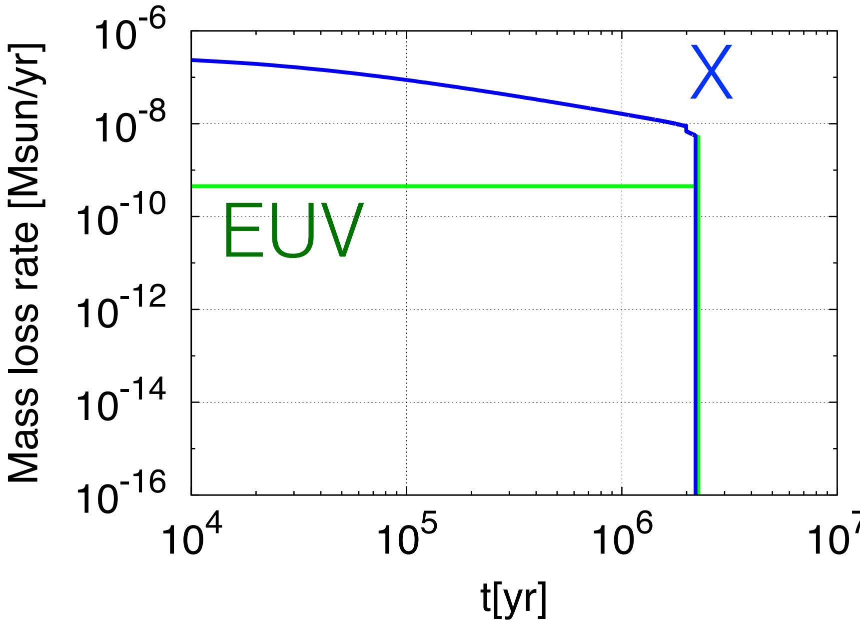
- $M_\bigstar = 1M_\odot$
- $M_{\mathrm{disk,ini}} = 0.1M_\odot$
- $\alpha = 1\times10^{-3}$

Result: example of the disk evolution around 1M⊙



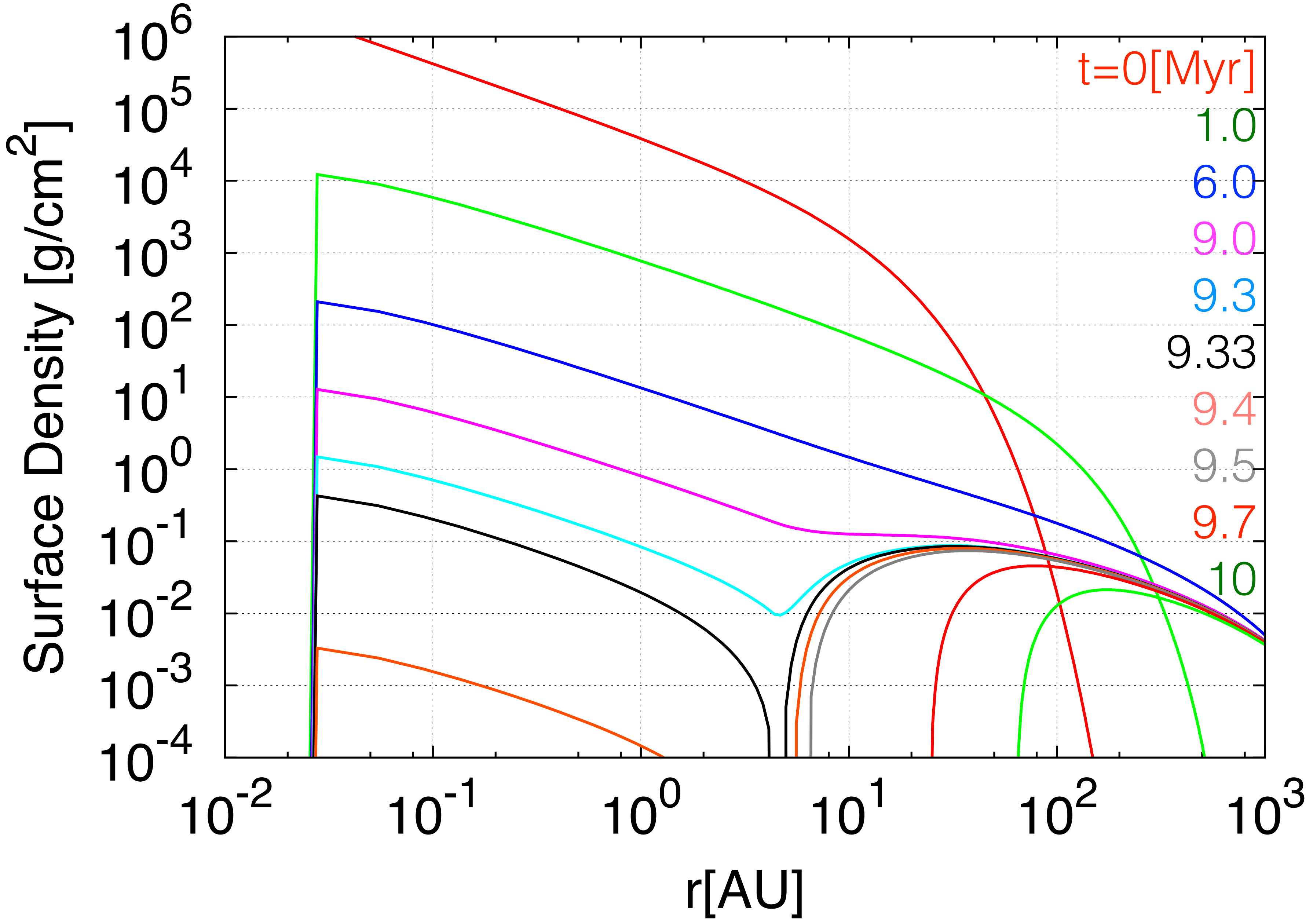
- $M_{\bigstar}$=1M⊙
- $M_{disk,ini}$=0.1M⊙
- α=1×10^{-3}

- a gap opens at ~2Myr
- the disk completely dissipates in 0.2Myr after gap opens

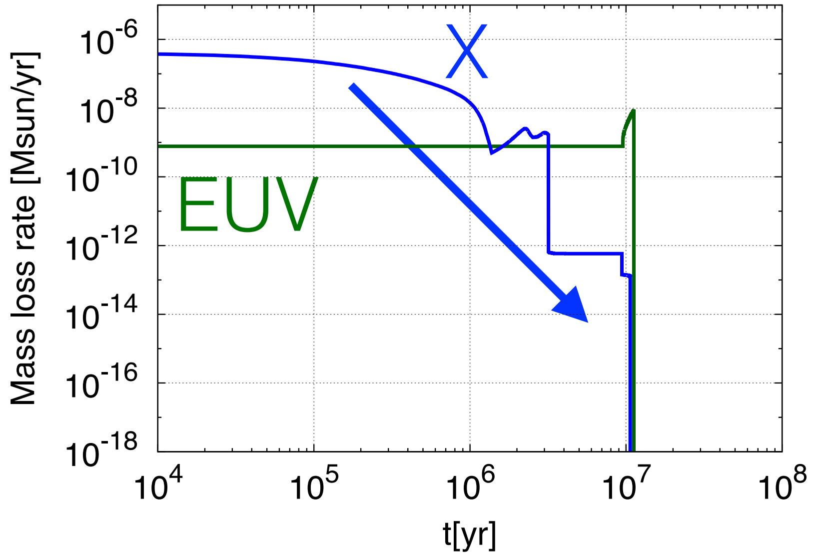


the P.E. rate is dominated by X-ray

Result: example of the disk evolution around $3M_\odot$

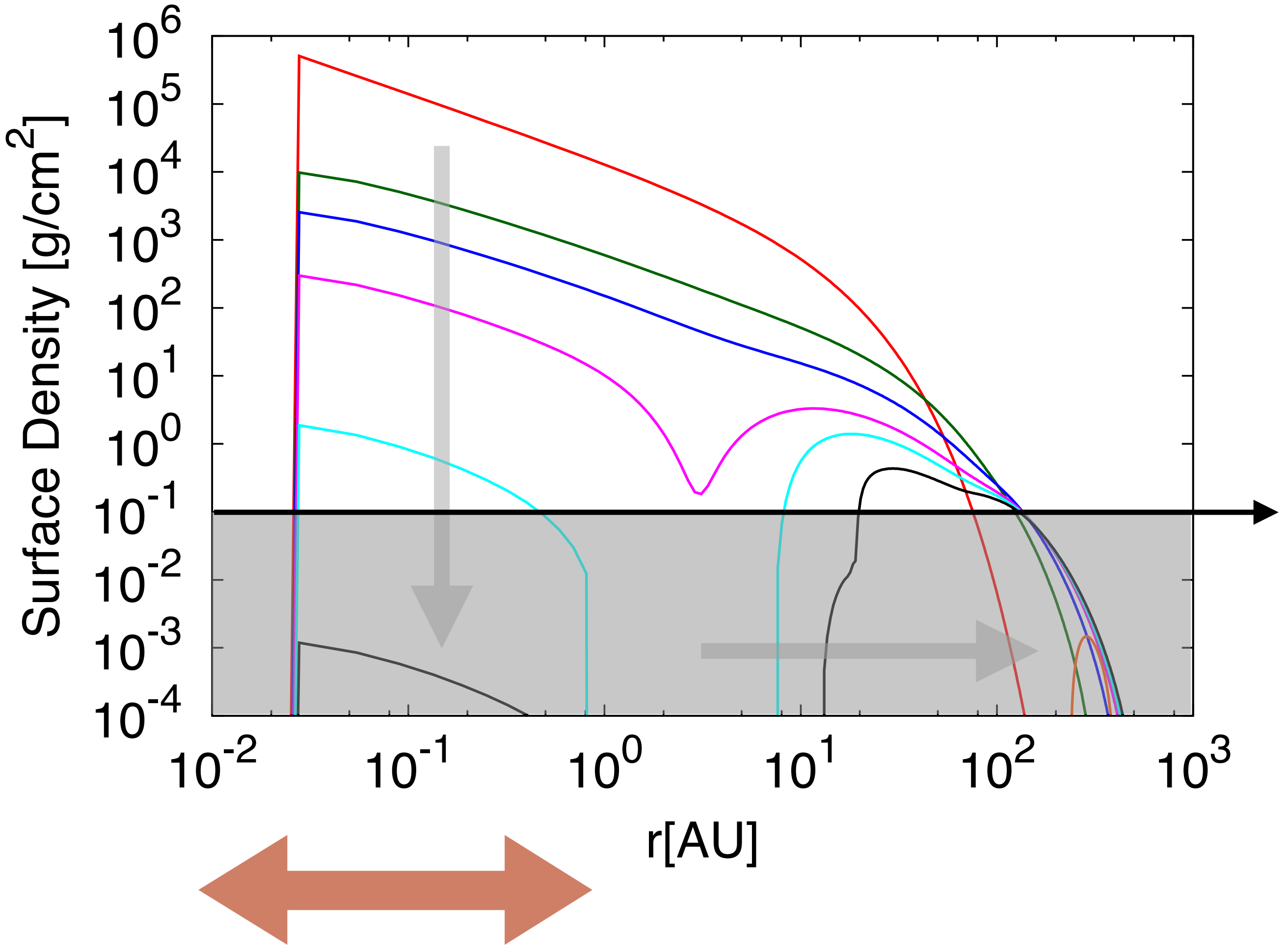


- $M_\star=3M_\odot$
- $M_{disk,ini}=0.3M_\odot$
- $\alpha=3\times10^{-3}$



- after leaving the Hayashi track, L_X becomes smaller
- at last, **the dominant source of P.E. is changed to EUV**

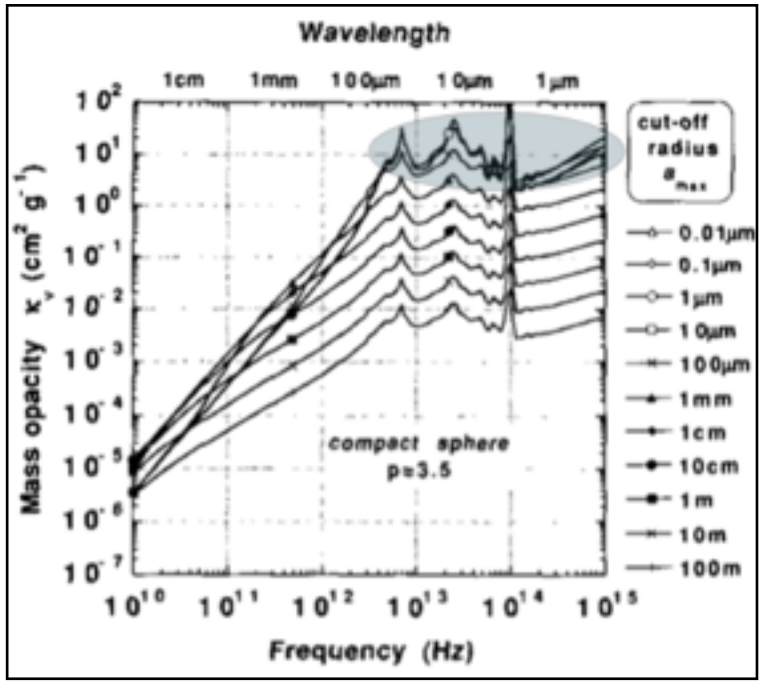
Result: example of the disk evolution



detection limit:
0.1g/cm^2

Near-IR emitting region

κ~10cm^2/g
Nakagawa & Miyake (1993)

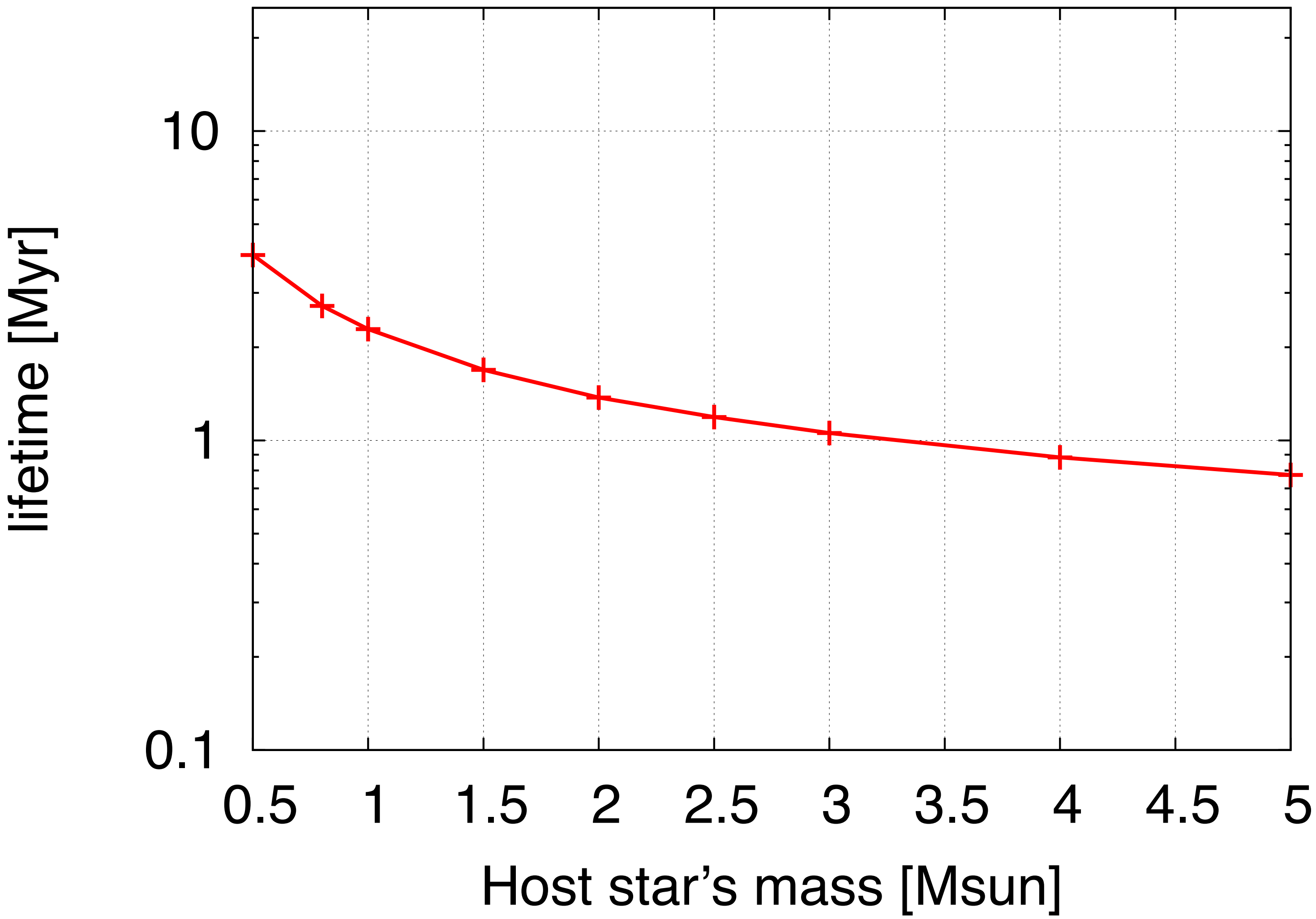


we define disk lifetime as "*the surface density in the NIR emitting region falls below the detection limit*"

Result: the disk lifetime as a function of $M_\bigstar$

▪**L_X=const. with time** $L_X=10^{-3.5}L_\bigstar$, $L_\bigstar=2L_\odot(M_\bigstar/M_\odot)^2$

- $M_{disk,ini}=0.1M_\bigstar$
- $\alpha=10^{-3}\times(M_\bigstar/M_\odot)$



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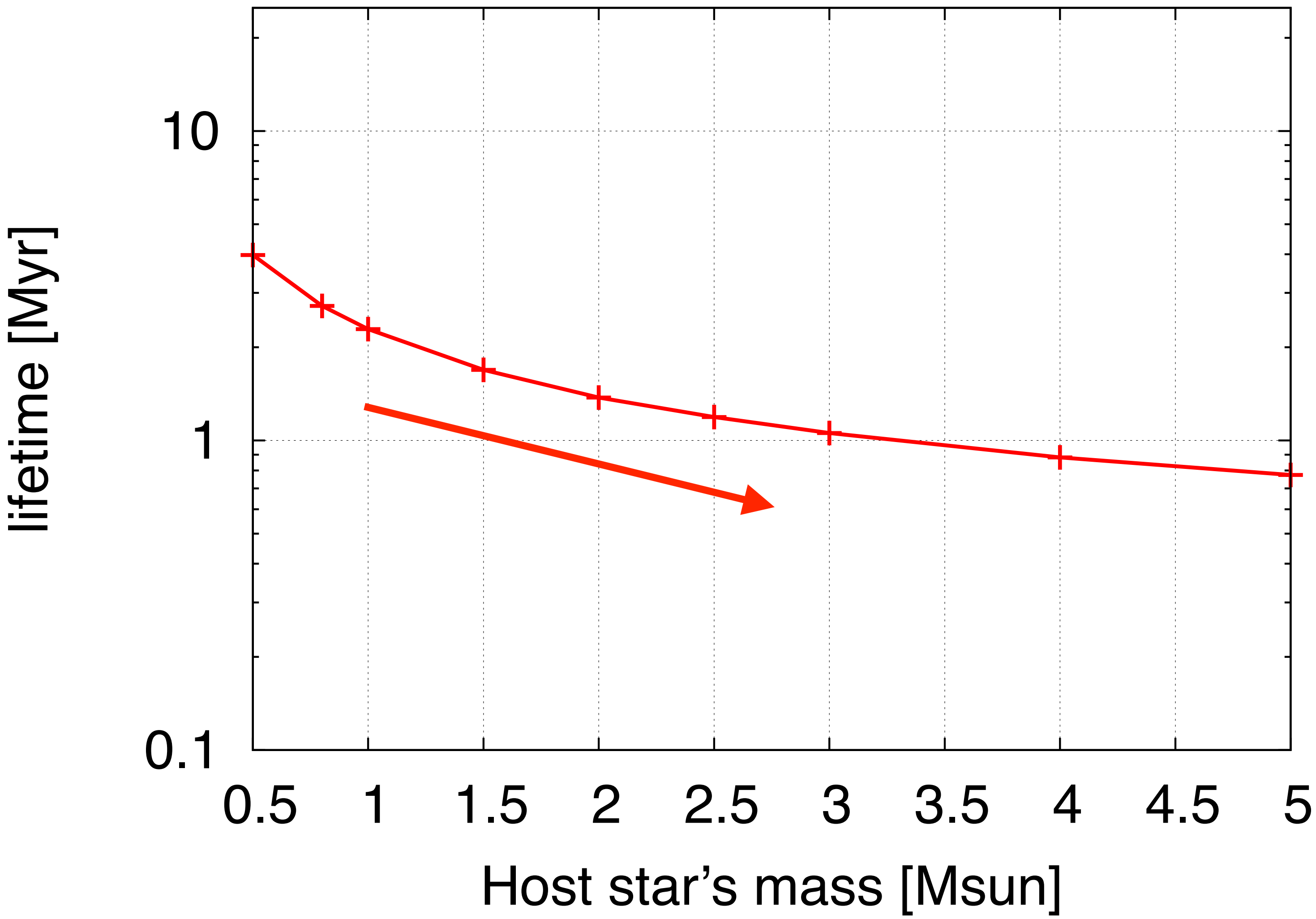

- If the L_X increases with $M_\bigstar$, the disk lifetime decreases with $M_\bigstar$ contrary to Gorti et al. (2009)

Result: the disk lifetime as a function of $M_\star$

■L_X=const. with time $L_X=10^{-3.5}L_\star$, $L_\star=2L_\odot(M_\star/M_\odot)^2$

■L_X=$L_X(t)$

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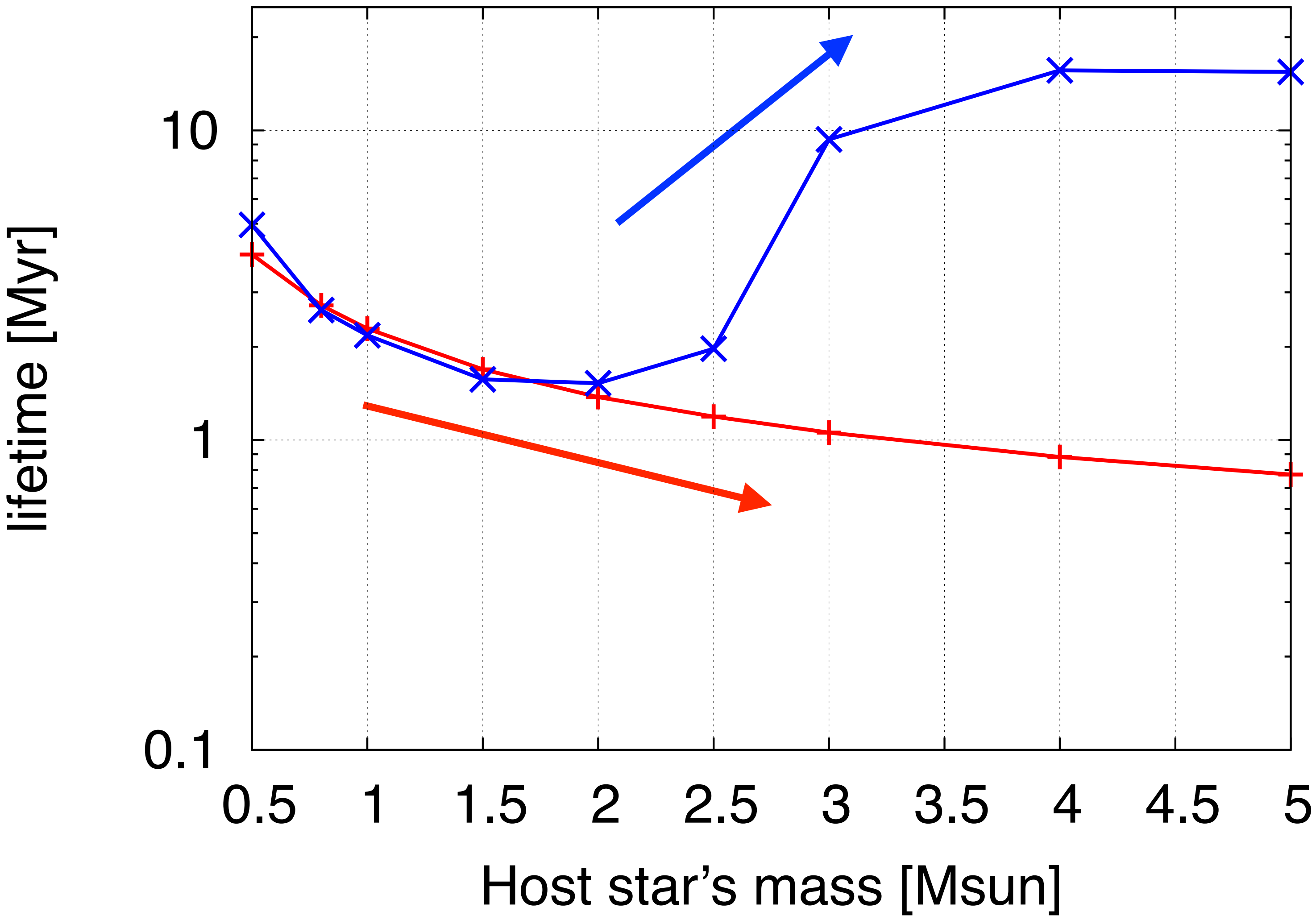

- If the L_X increases with $M_\star$, the disk lifetime decreases with $M_\star$ contrary to Gorti et al. (2009)
- However, the evolution of L_X makes the disk lifetime longer on the high-mass side

Result: the disk lifetime as a function of $M_\bigstar$

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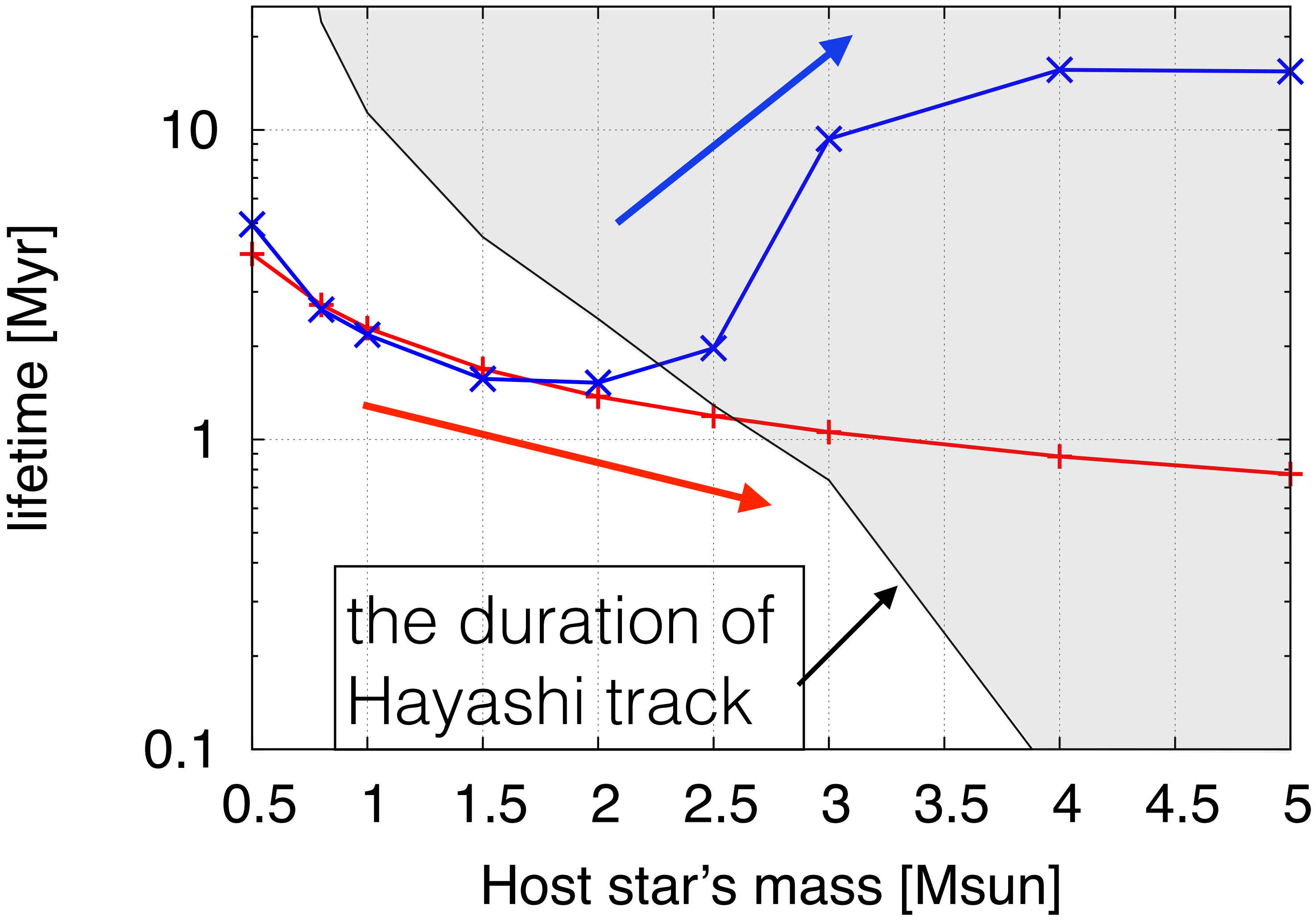
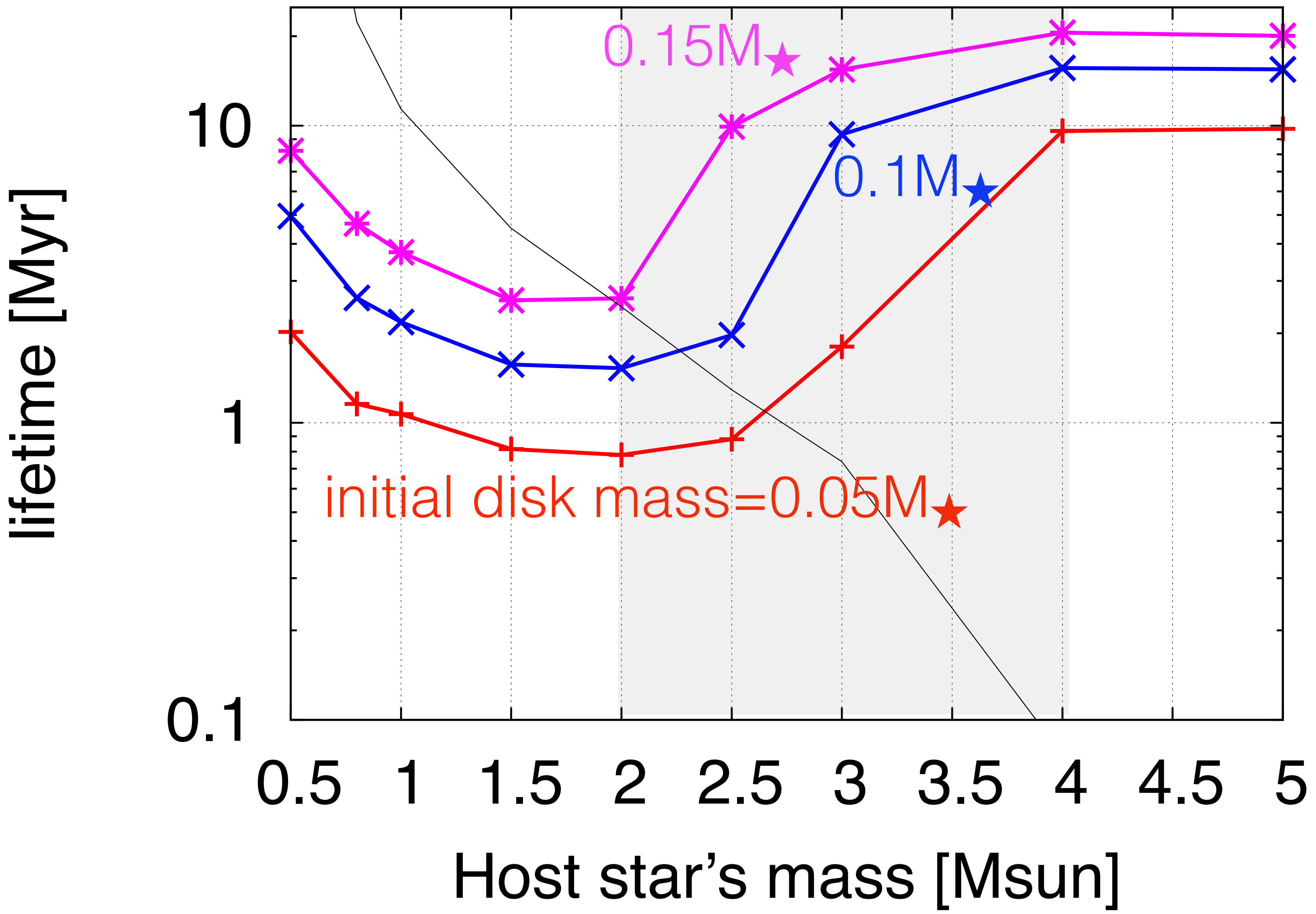
- $\alpha = 10^{-3} \times (M_\bigstar/M_\odot)$



- If the L_X increases with $M_\bigstar$, the disk lifetime decreases with $M_\bigstar$ contrary to Gorti et al. (2009)

- However, the evolution of L_X makes the disk lifetime longer on the high-mass side
- this increase is caused by leaving the Hayashi track
- the large L_X at the beginning does not play an important role

Discussion: dependence on the initial disk mass

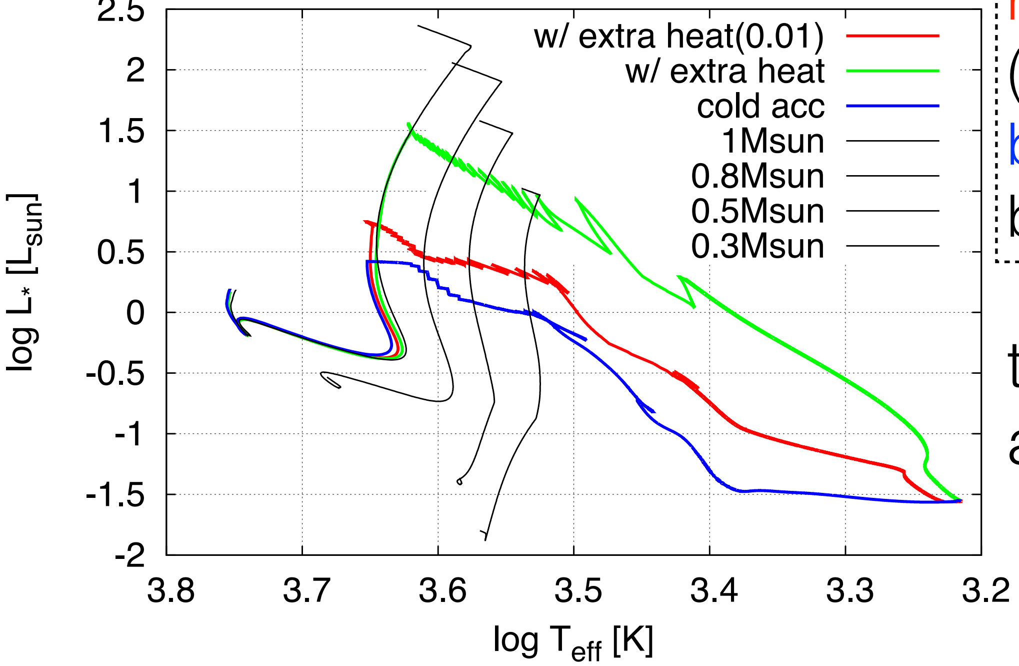


- $\alpha = 1 \times 10^{-3} \times M_\star$

▪the disk lifetime of 2-4$M_\odot$ stars can be sensitive to the initial condition

▪the qualitative behavior is not changed

Discussion: PMS evolution



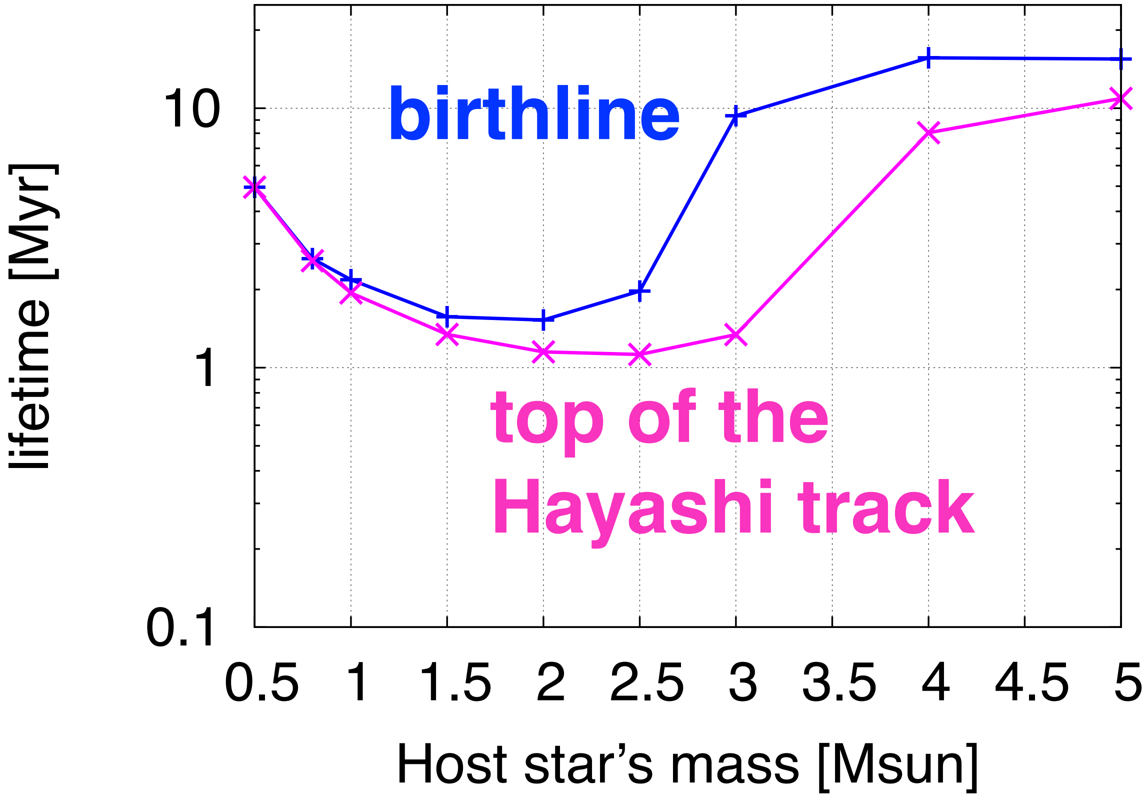
Kunitomo, Guillot & Ida (in prep.)

red& green: w/ accretion & extra heat (ξ=0.01, 0.5)
blue: w accretion & w/o extra heat
black lines: non-accreting model

$$L_{\rm add}= \xi GM\dot{M}/R$$

the efficiency of the energy injection into the star by the accreting material **can change the evolution track largely**

(e.g., Baraffe+Chabrier'10; Hosokawa+'11)



- if the disk evolution is calculated from the top of the Hayashi track, the lifetime can become shorter by the initial larger L_X and the loner Hayashi track duration

- however, again the qualitative behavior is not changed

Summary

The distribution of planets around IM stars may be affected by the disk lifetime.
We investigated the disk lifetime around IMs including the photoevaporation by X-rays and EUV photons.
In particular, we focused on the effect of L_X evolution.
As a result, we find

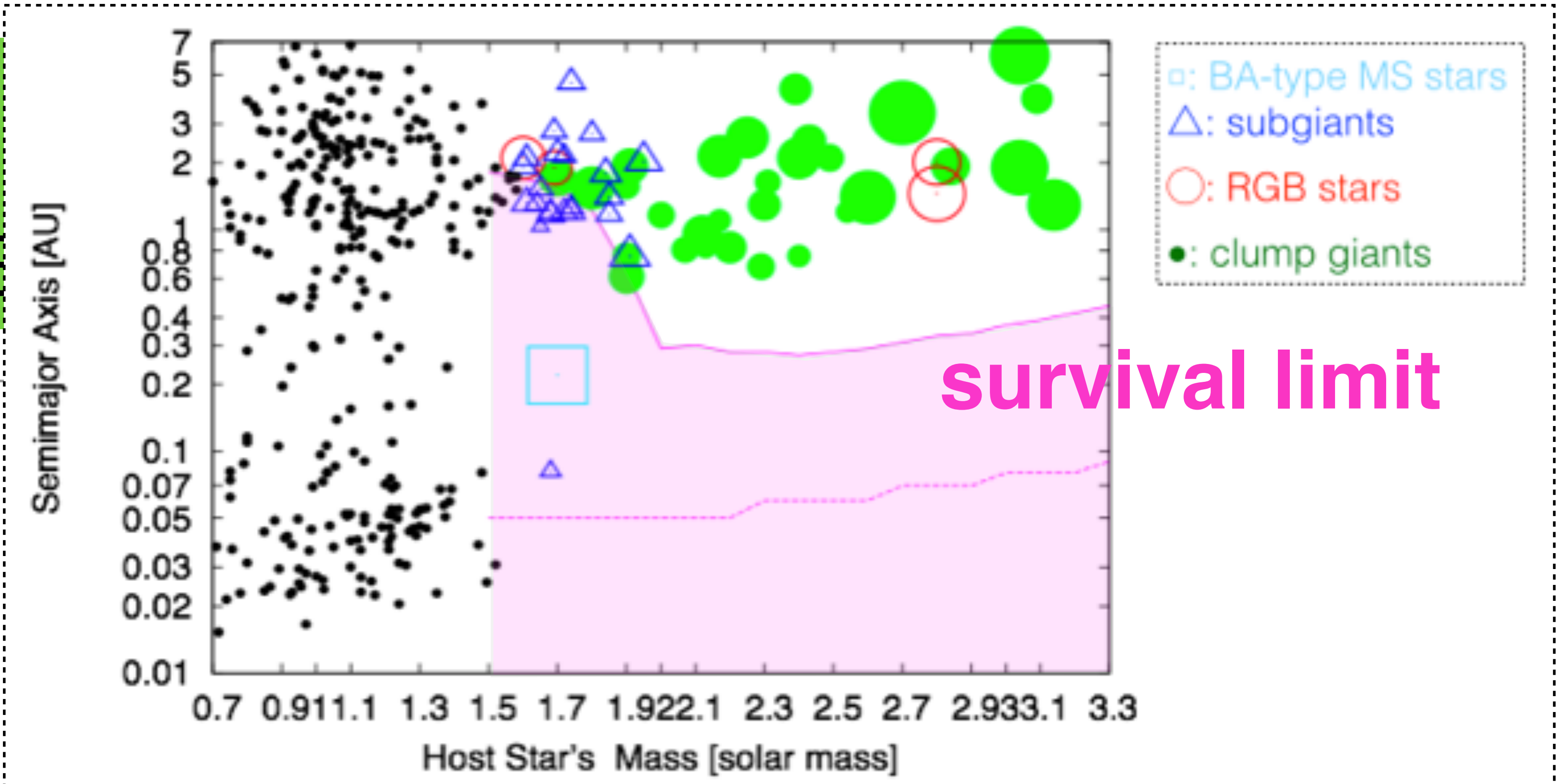
- the dominant source of P.E. can be changed to UV around IM stars
- the disk lifetime around IM stars can increase by the evolution of L_X
- only the evolution of L_X may not explain the observed disk lifetime

future work:

- including another effect (e.g., FUV P.E.) would be needed especially for the high-mass stars

Supplement slides

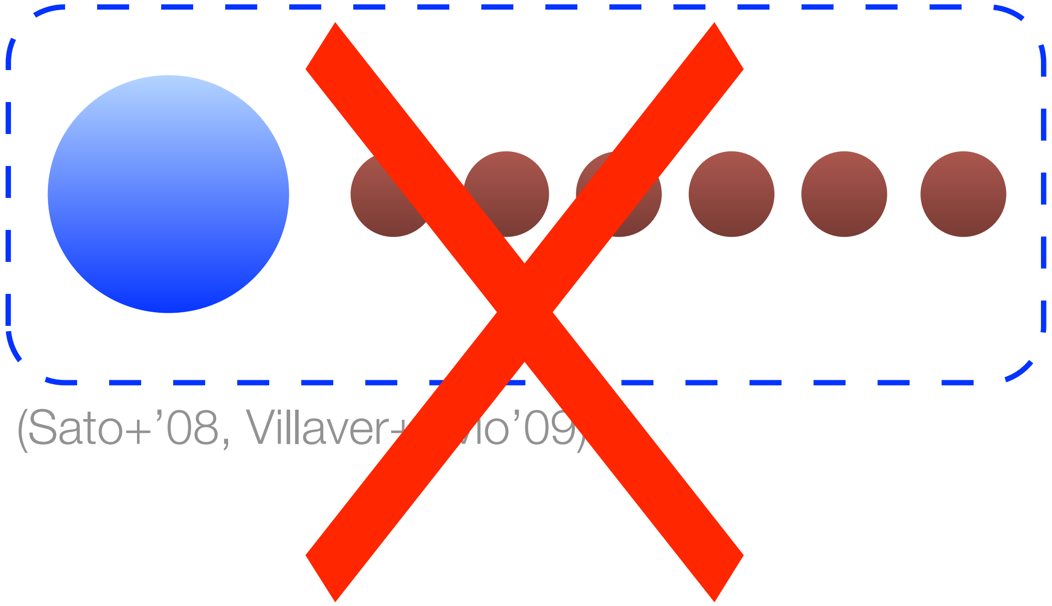
possible origins of the



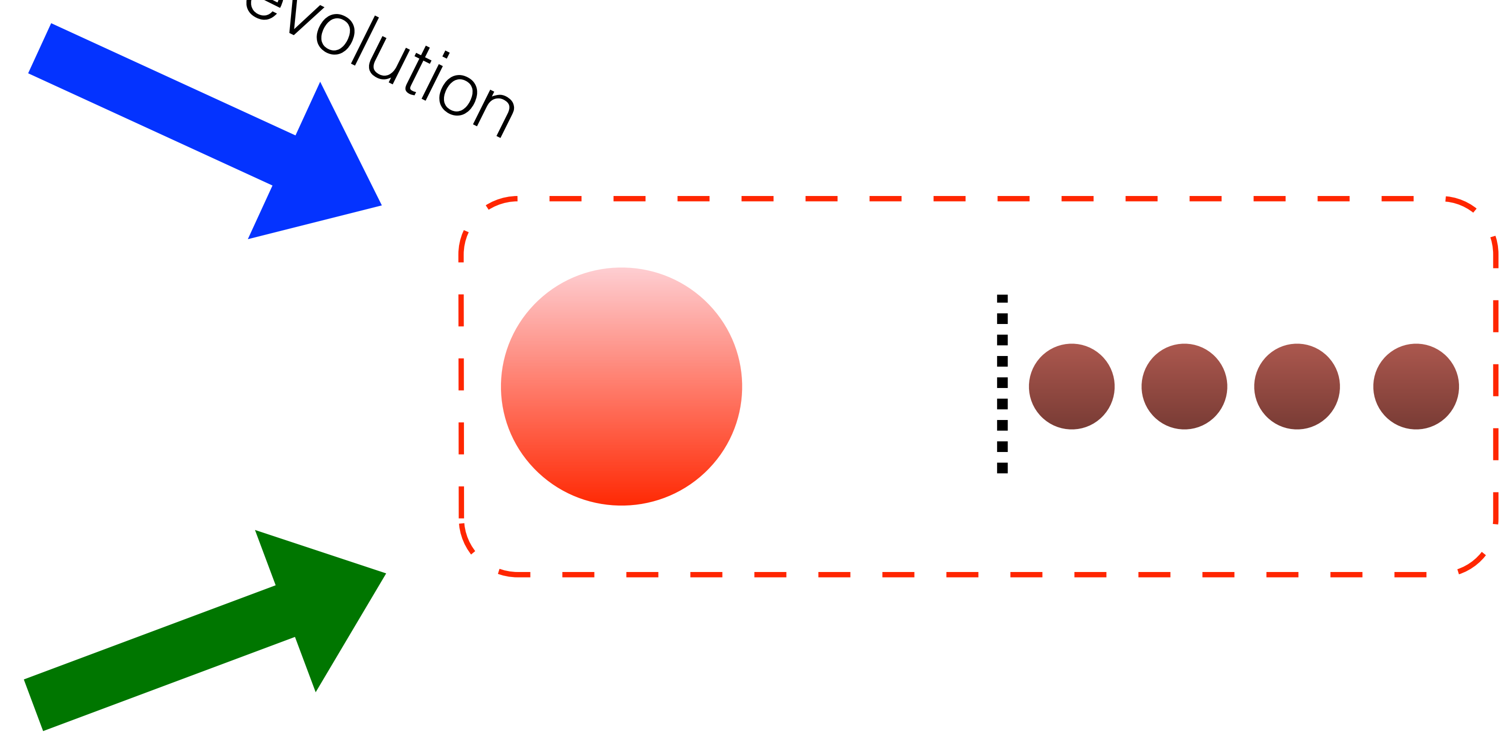
survival limit

- MS stars

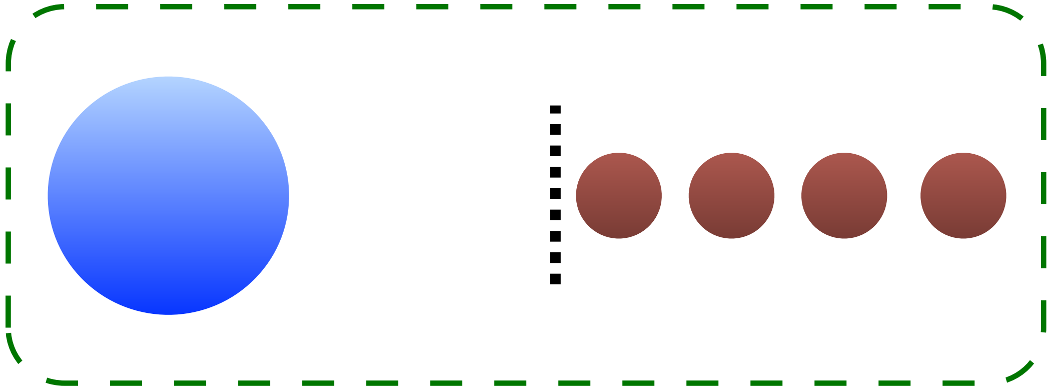
Kunitomo+'11



(Sato+'08, Villaver+ io'09)



al evolution



(Burkert+Ida'07,Currie'09)

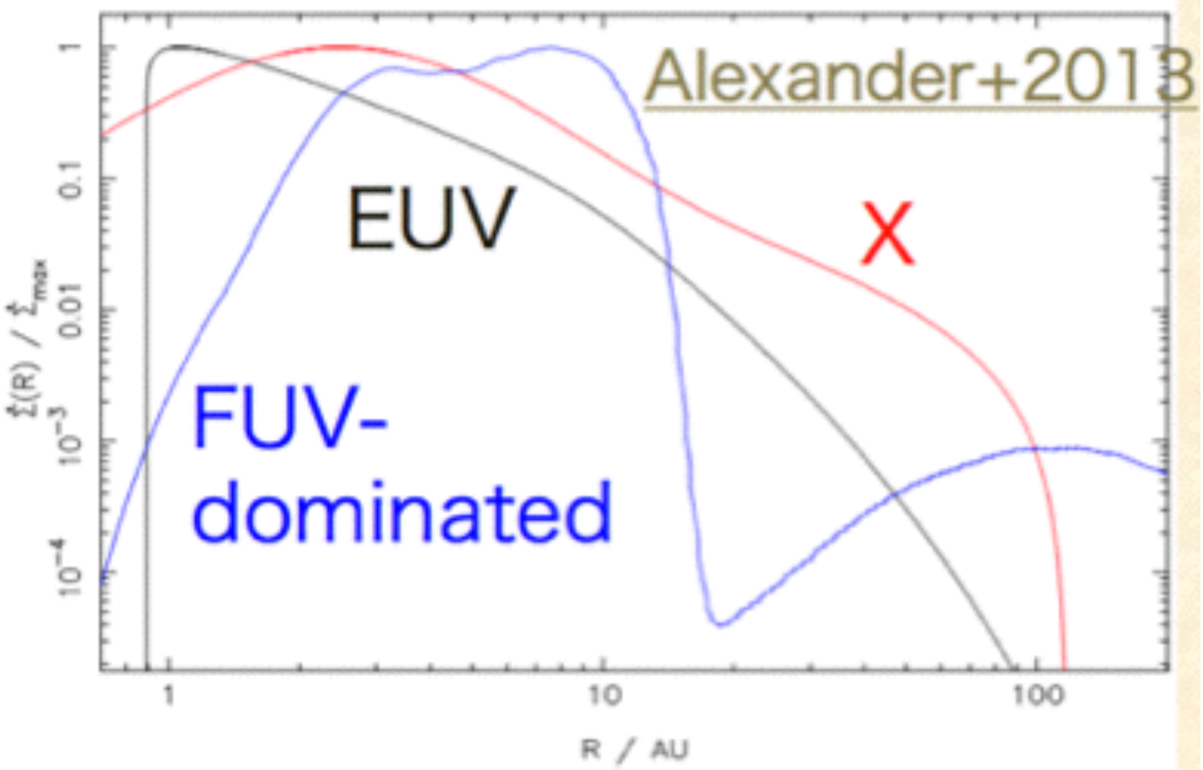
close-in planets may not be formed around IM stars

Photoevaporation Model

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left(\sqrt{r}\frac{\partial}{\partial r}\left(\nu\Sigma\sqrt{r}\right)\right) - \dot{\Sigma}_{\mathrm{PE}}$$

- $\dot{\Sigma}_{\mathrm{PE}}$ can be the combination of the four $\dot{\Sigma}$

	w/o gap	w/ gap
EUV	Hollenbach+94	Alexander+06
X	Owen+12	Owen+12


Alexander+2013

$$\dot{M}_w = 6.25 \times 10^{-9} \left(\frac{M_*}{1\,\mathrm{M}_\odot}\right)^{-0.068} \left(\frac{L_{\mathrm{X}}}{10^{30}\,\mathrm{erg\,s^{-1}}}\right)^{1.14} \mathrm{M}_\odot\,\mathrm{yr}^{-1}$$

$$\dot{M}_{\mathrm{EUV}} = 3.439 \times 10^{-10}\,[M_\odot\ \mathrm{yr}^{-1}] \left(\frac{\Phi_{\mathrm{EUV}}}{10^{41}\ \mathrm{s}^{-1}}\right)^{1/2} \left(\frac{M_*}{M_\odot}\right)^{1/2}$$

Lx

$$L_X = \max\left(10^{-3.5} L_\star \left(\frac{M_{\rm conv}}{M_\star}\right), 10^{-6}\right)$$

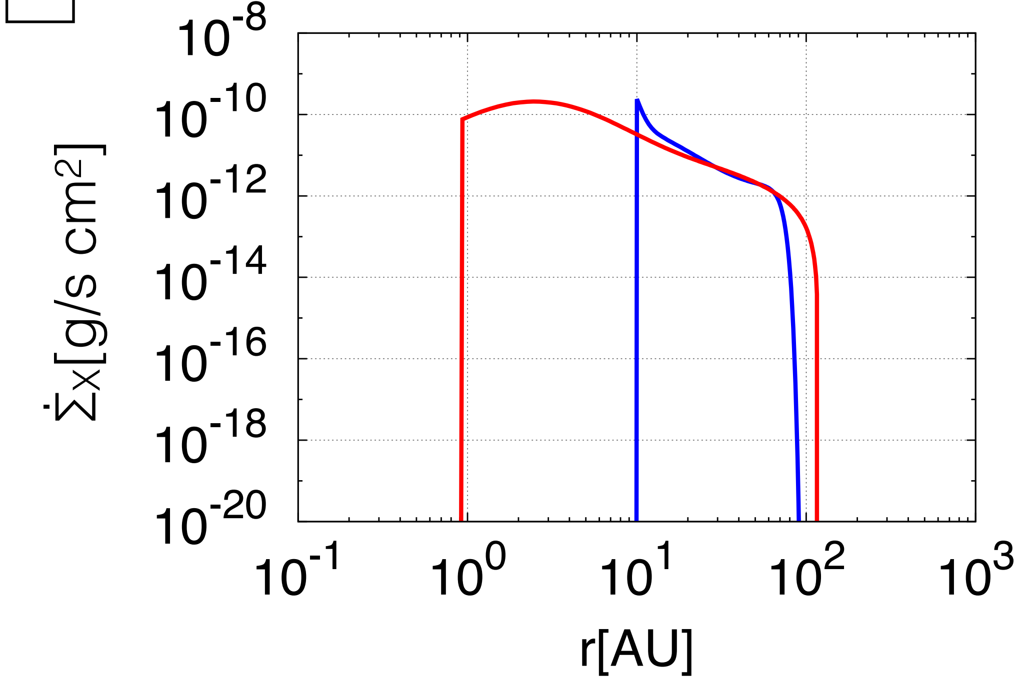
before ZAMS

$$L_X = \max\left(10^{-3.5} L_\star \left(\frac{M_{\rm conv}}{M_\star}\right), 10^{-9}\right)$$

after ZAMS

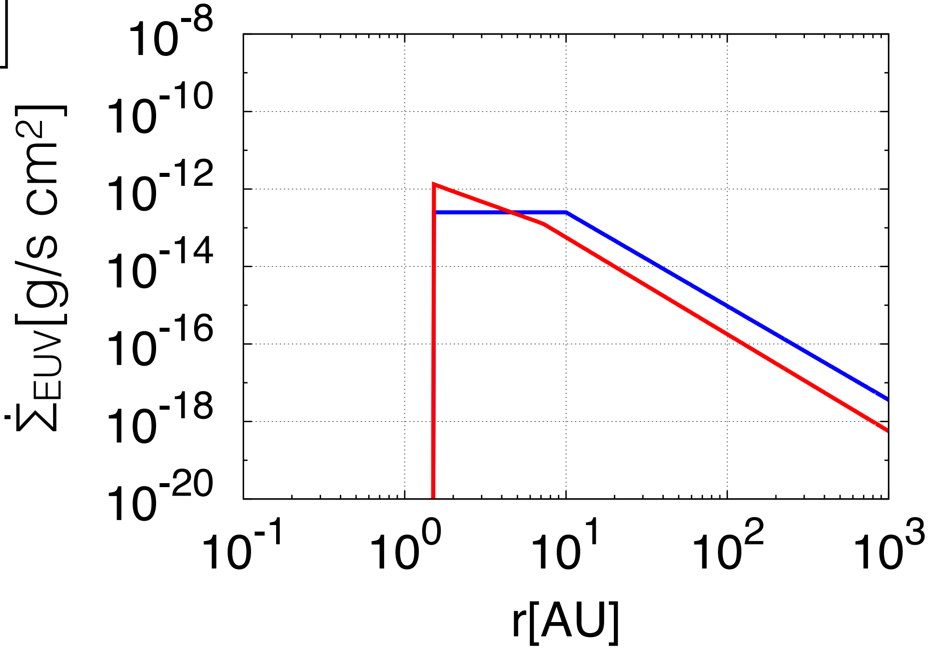
mass loss profile by photoevaporation

X



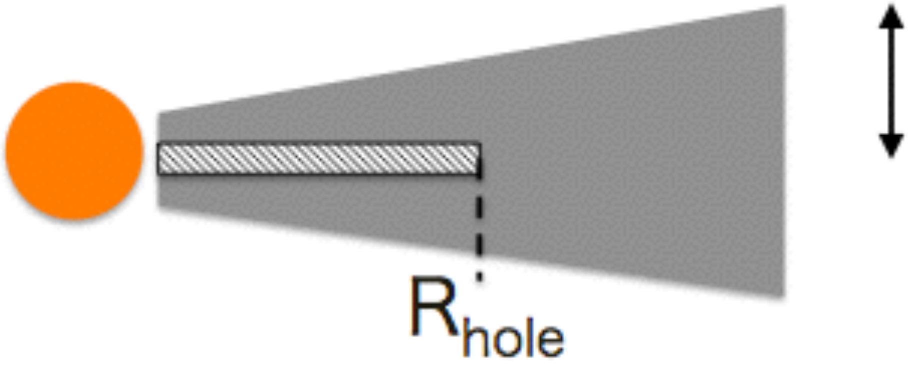
blue: w/ inner hole @10AU
Owen et al. (2012) (both)

EUV



blue: w/ inner hole @10AU
Hollenbach+(1994), Alexander+(2006)

hole radius

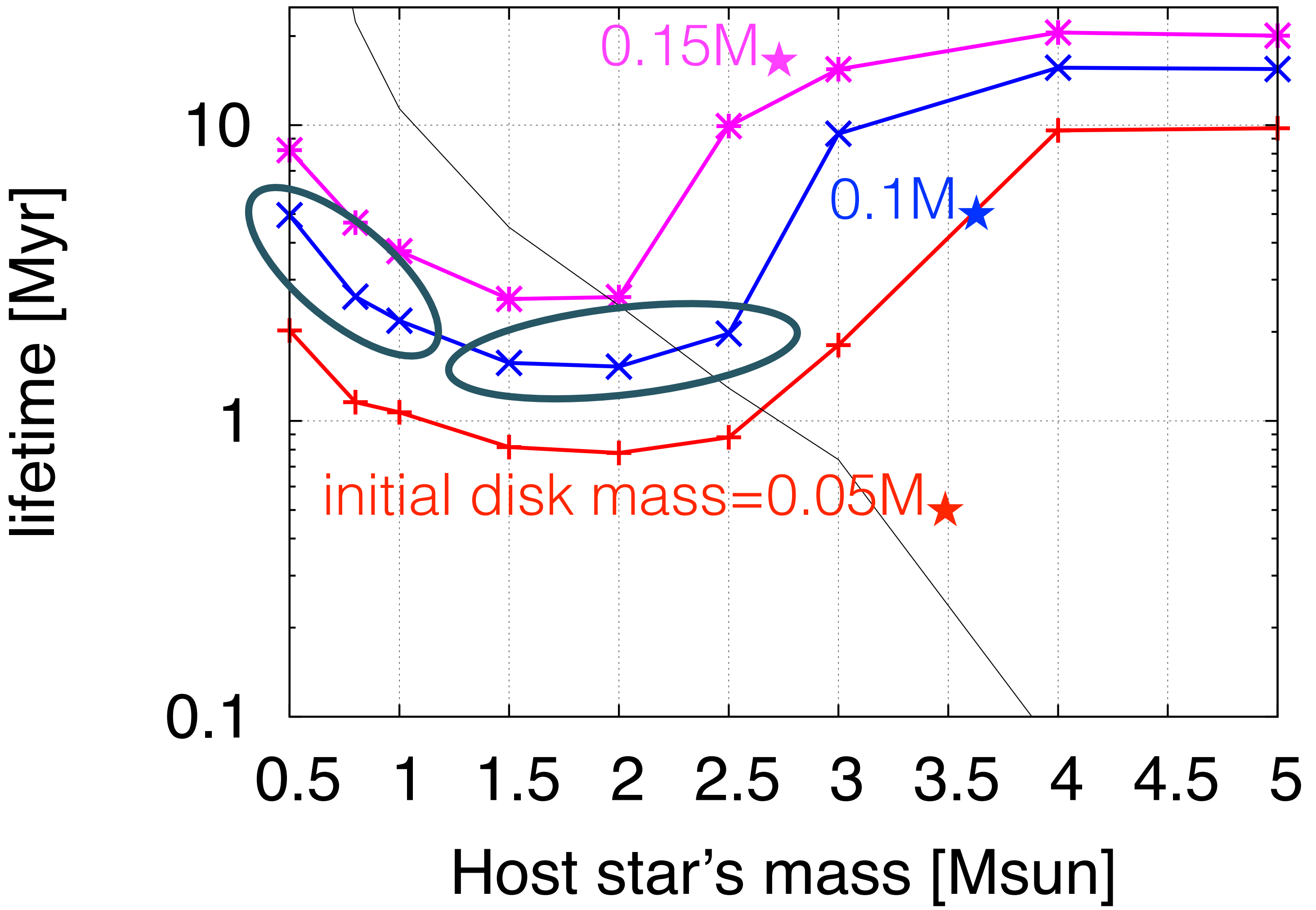


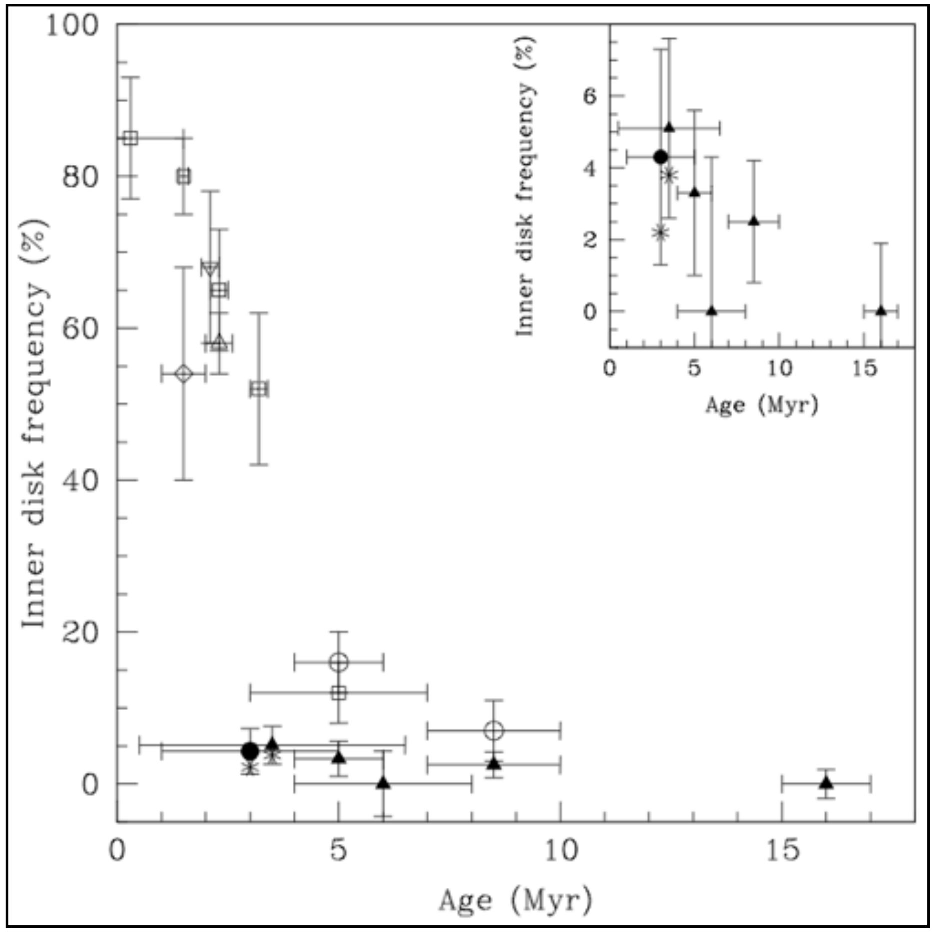
$$h = 0.05\ \mathrm{AU}\left(\frac{r}{1\ \mathrm{AU}}\right)$$

◆direct P.E. EUV: Alexander+'06, X: Owen+'12

- R_{hole}: the radius where $\tau=\sigma N_0=\sigma\int n_0 dr=1$ **(for EUV, τ=4.61)**
  - $\sigma_{EUV}=6.3\times10^{-18}$cm^2, $\sigma_X=10^{-22}$cm^2
- if $R_{hole}>r_g$, we change the photoevaporation rate into direct P.E.

Discussion: comparison with observation

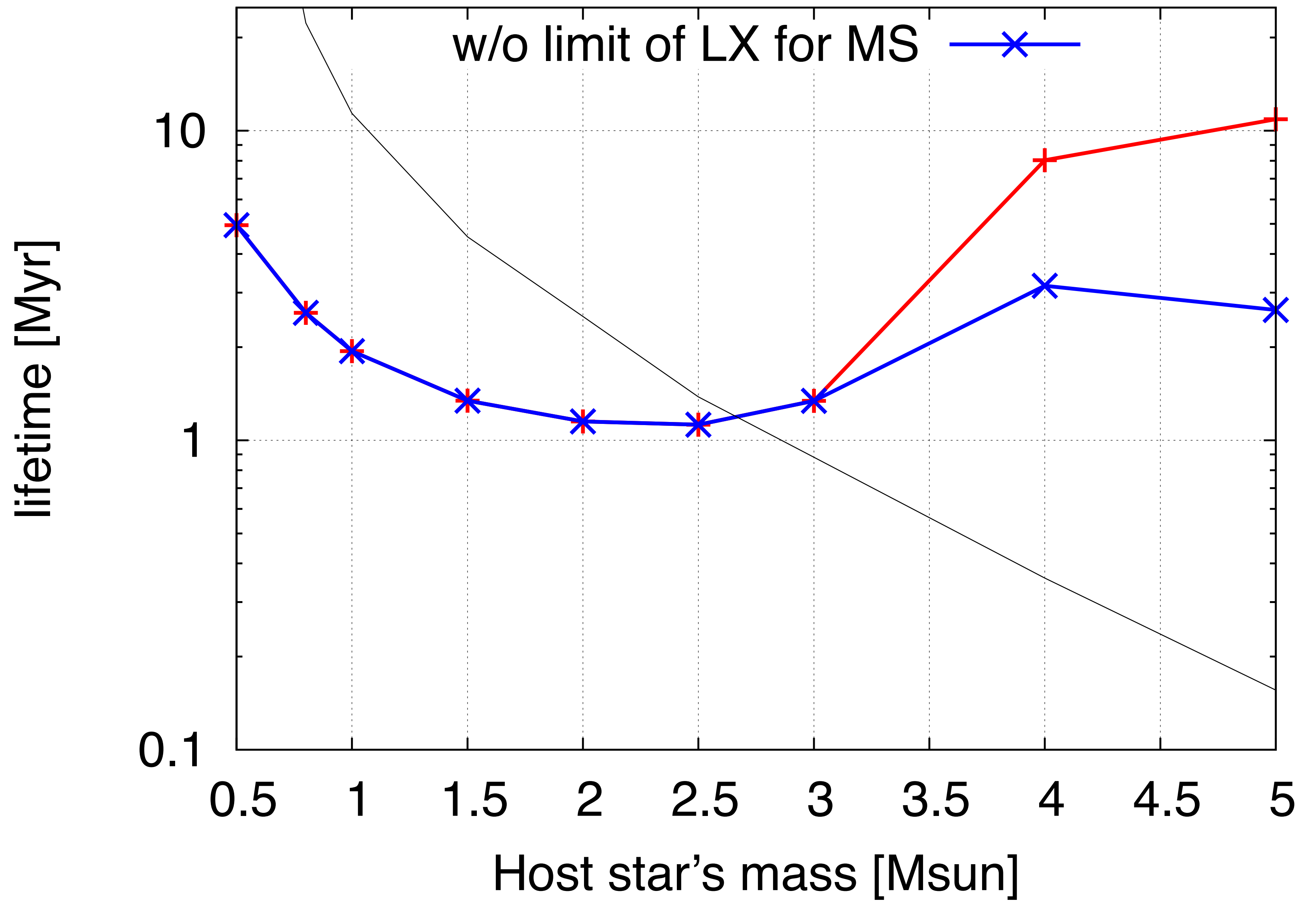




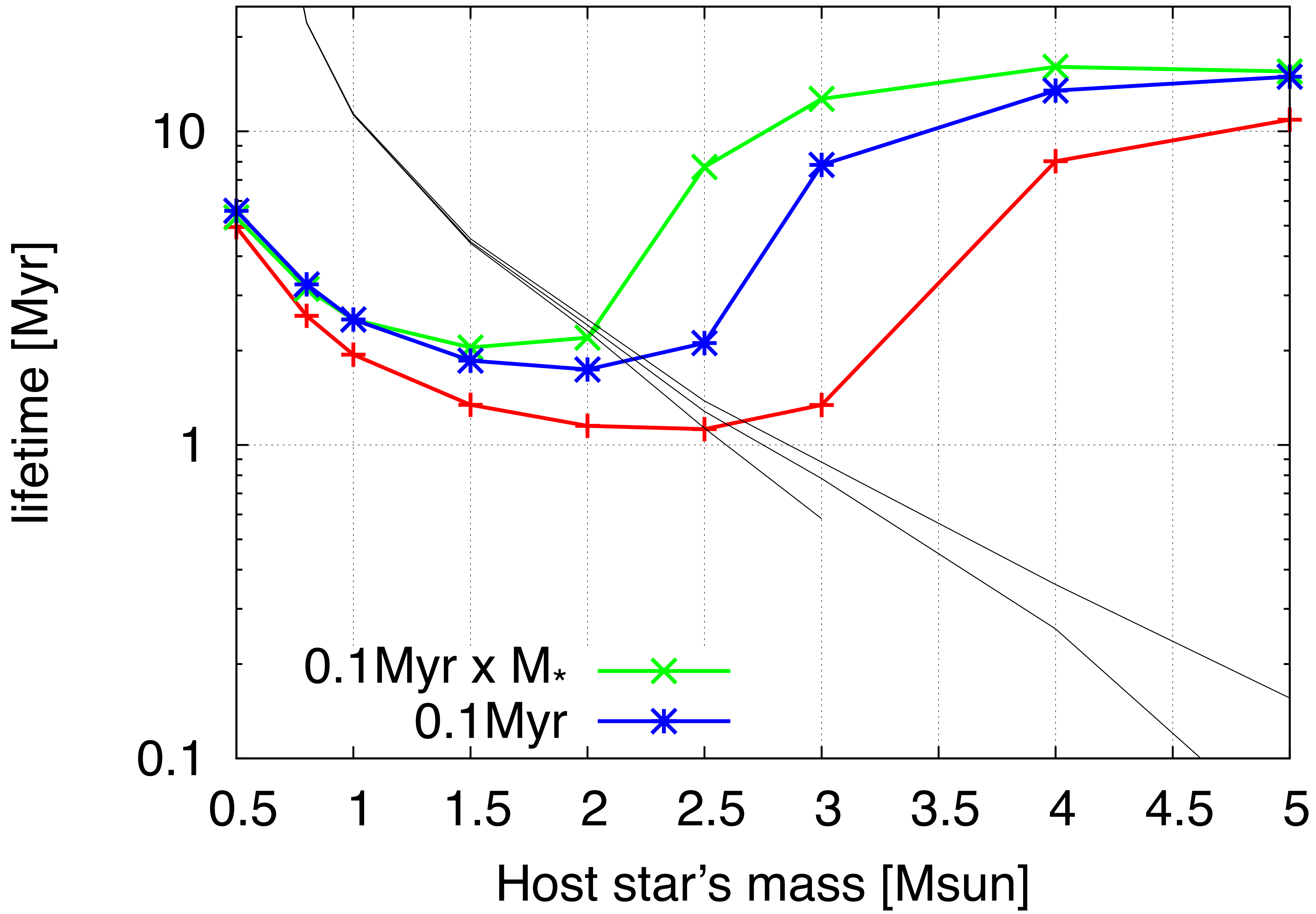
(Hernandez et al. 2005)

- in the case $M_{\rm disk,ini} = 0.1M_\bigstar$, if the most of observed objects are lighter than $3M_\odot$, **only X-ray P.E. can explain** the observed feature. However, it is not promising.
- FUV is needed

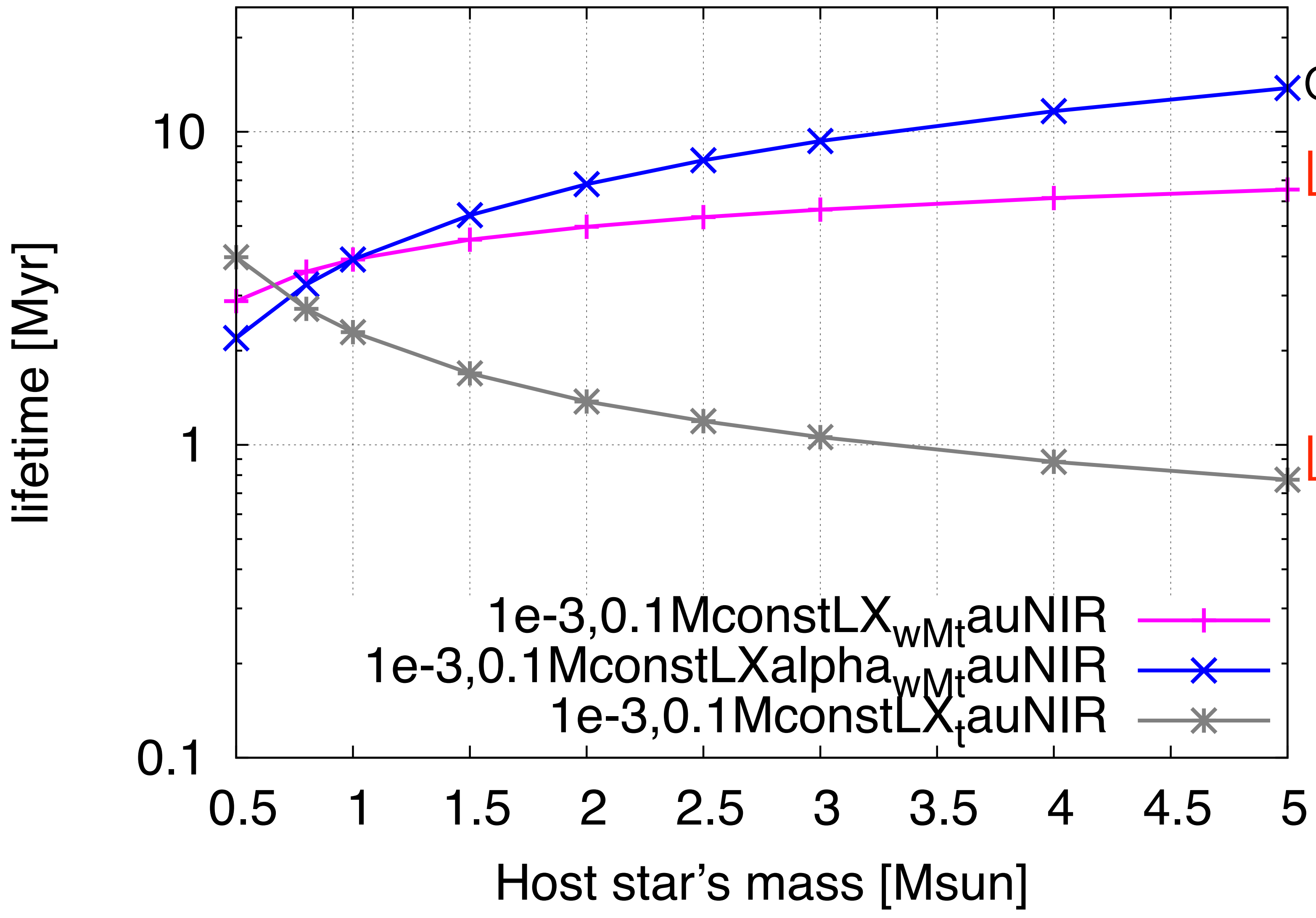
Effect of limit of LX for BA-type MS stars



Effect of birthline



Effect of $L_X(M_\star)$

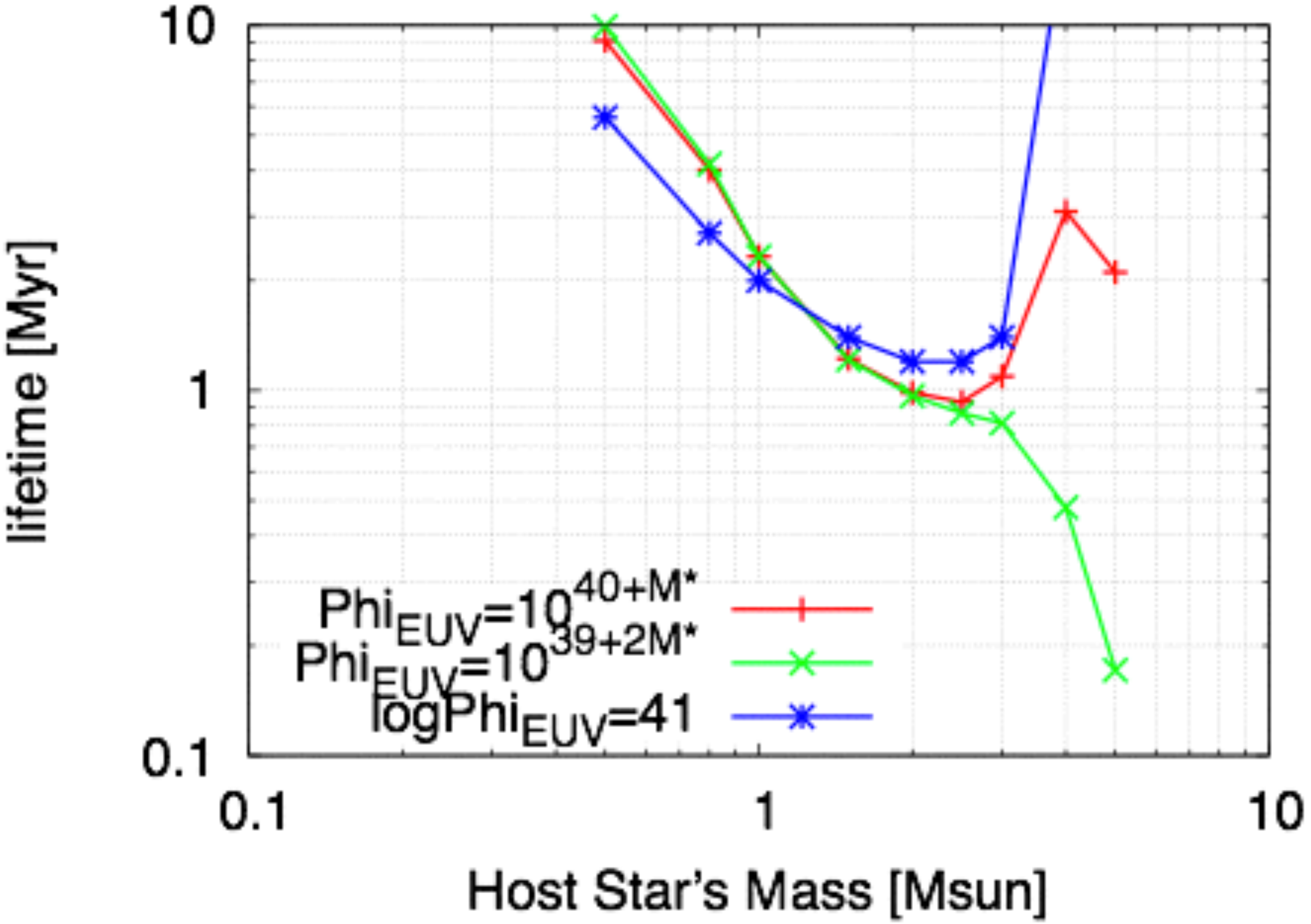


α,L_X=const w/ t,$M_\star$

L_X=const w/ t,$M_\star$, α=α(M*)

L_X=const w/ t, α=α(M*)

Φ_{EUV}


10
1
0.1
0.1
1
10
lifetime [Myr]
Host Star's Mass [Msun]
PhiEUV=10^40+M*
PhiEUV=10^39+2M*
logPhiEUV=41