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Internal Disk Photoevaporation
Stellar Mass Dependence

The role of magnetic fields in disk formation, evolution, and planet formation

Core2Disk III - 5th October 2023

X-RAY PHOTOEVAPORATION AS A FUNCTION OF STELLAR MASS

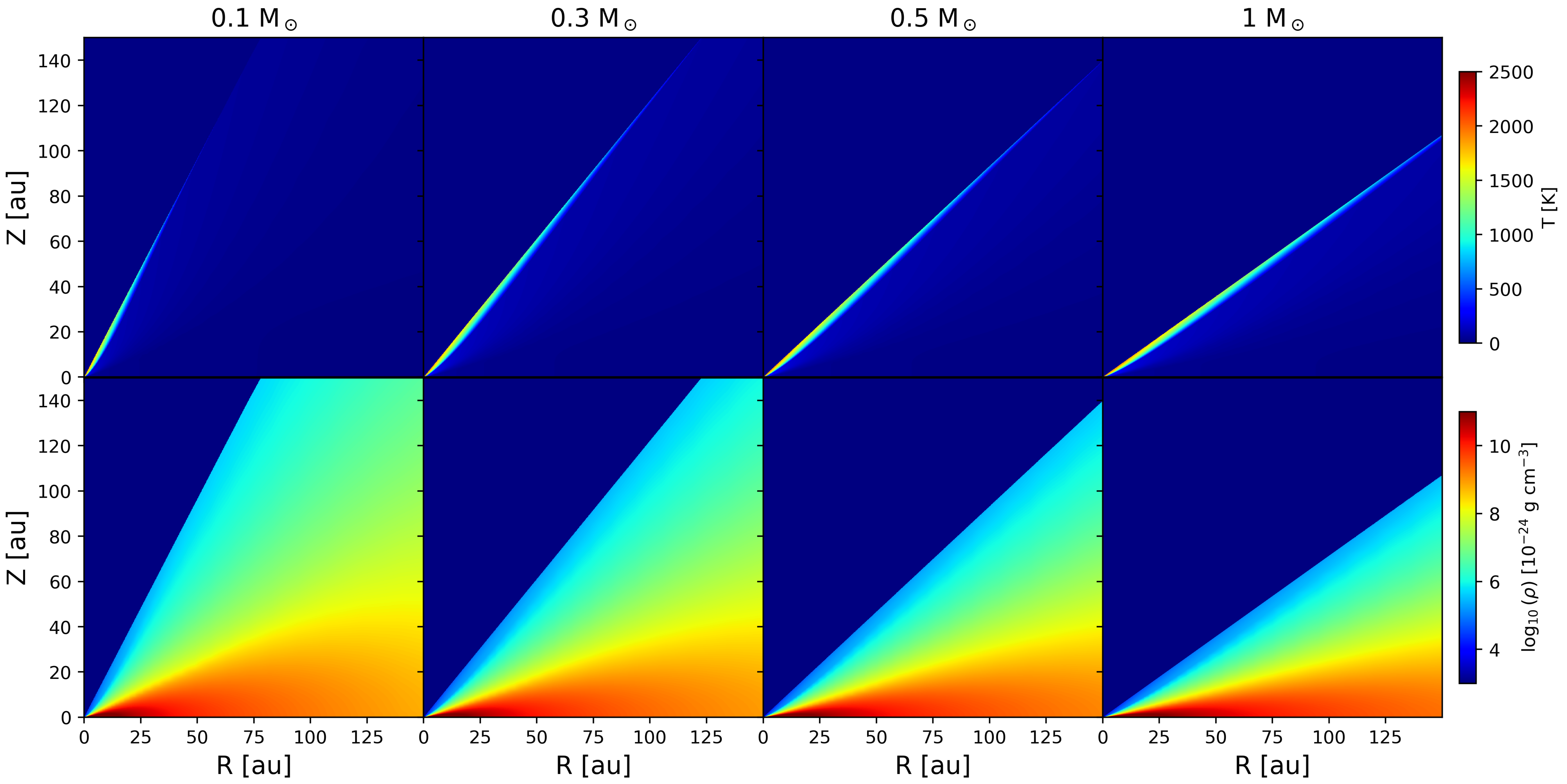
STELLAR PROPERTIES

Stellar parameters from Siess et al. 2000 with age 1 Myr and metallicity Z=0.02, no overshooting

$M_\star$ [$M_\odot$]	$R_\star$ [$R_\odot$]	ST	$L_\star$ [$L_\odot$]	L_X [10^{29} erg/s]	$T_\star$ [K]	M_d [$M_\odot$]
1	2,615	K6	2,335	20,4	4278	0,045
0.5	2,125	M1	0,929	7,02	3771	0,0369
0.3	2,310	M5	0,689	3,20	3360	0,0296
0.1	1,055	M6	0,086	0,59	2928	0,0267

DISK PROPERTIES

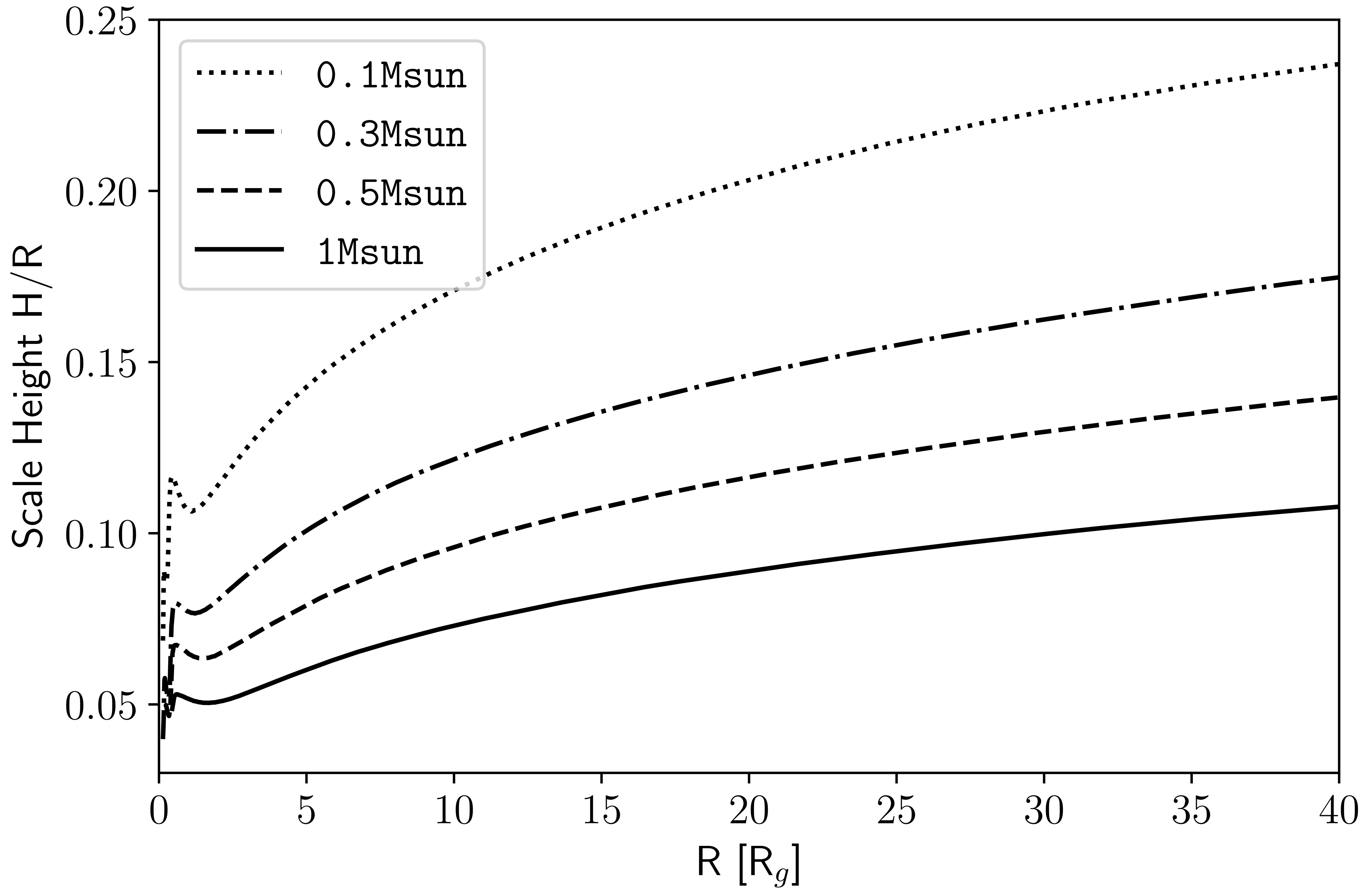
DIAD (D'Alessio Irradiated Accretion Disks)



Picogna et al., 2021

- $R_{\text{out}} = 400$ au
- $\dot{M}_{\text{acc}} = 10^{-8}\ M_\odot yr^{-1}$
- $i = 60^{\text{o}}$
- Disk atmosphere:
  - Minimum grain size: 0.005 μm
  - Maximum grain size: 0.25 μm
- Disk midplane:
  - Minimum grain size: 0.005 μm
  - Maximum grain size: 1 mm
- $\epsilon = 1$ (well-mixed dust)

DISK ASPECT RATIO



Picogna et al., 2021

- The disk aspect ratio depends strongly on the stellar luminosity, thus on the stellar mass

photoevaporation opens a gap near the gravitational radius

$$r_g = \frac{GM_*}{c_s^2}$$

TEMPERATURE PRESCRIPTION

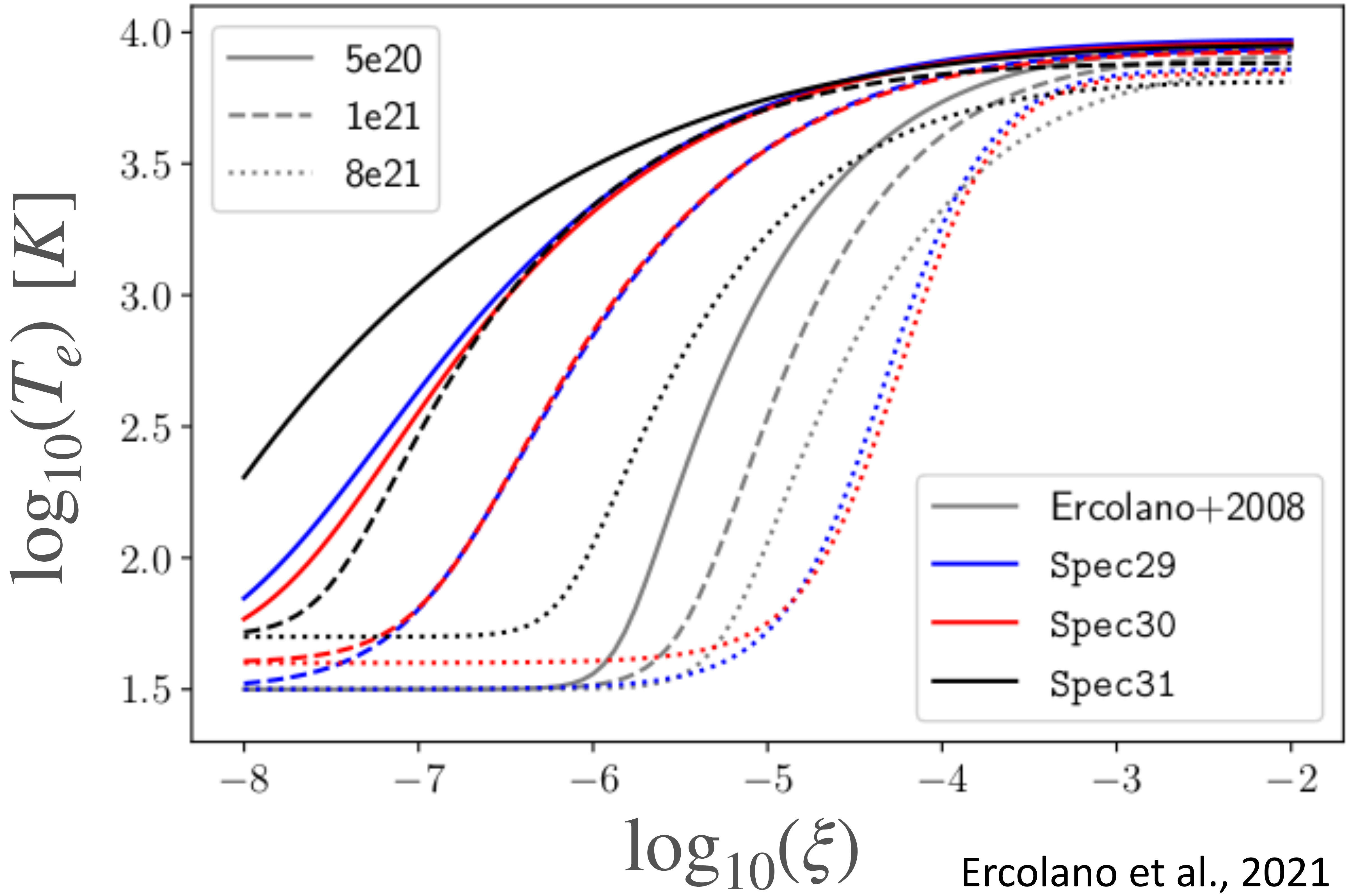
$$\xi = L_X/nr^2$$

MOCASSIN → **T_{gas}**

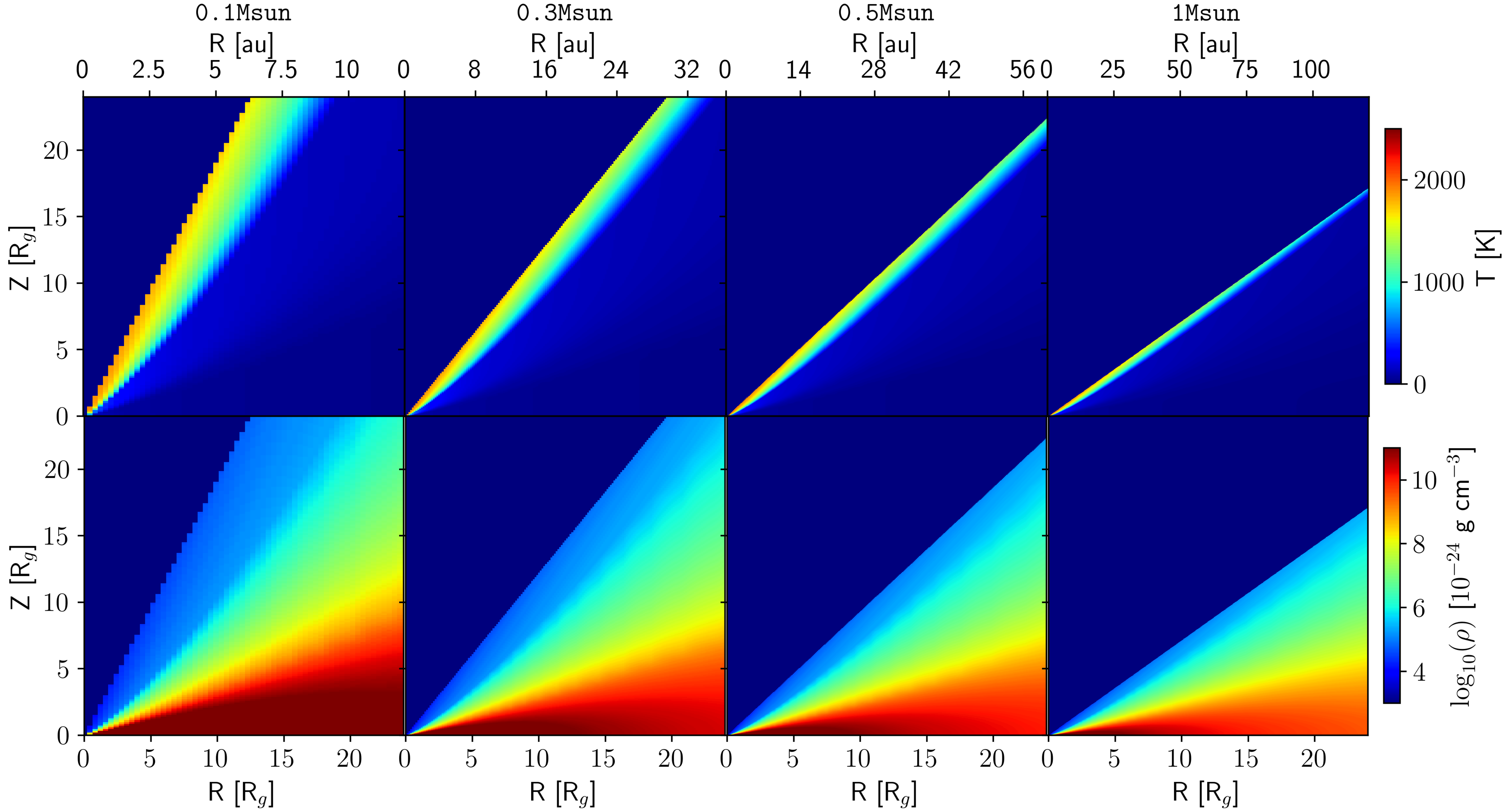
+ column density

+ stellar spectra

T_{dust} ← **DIAD**

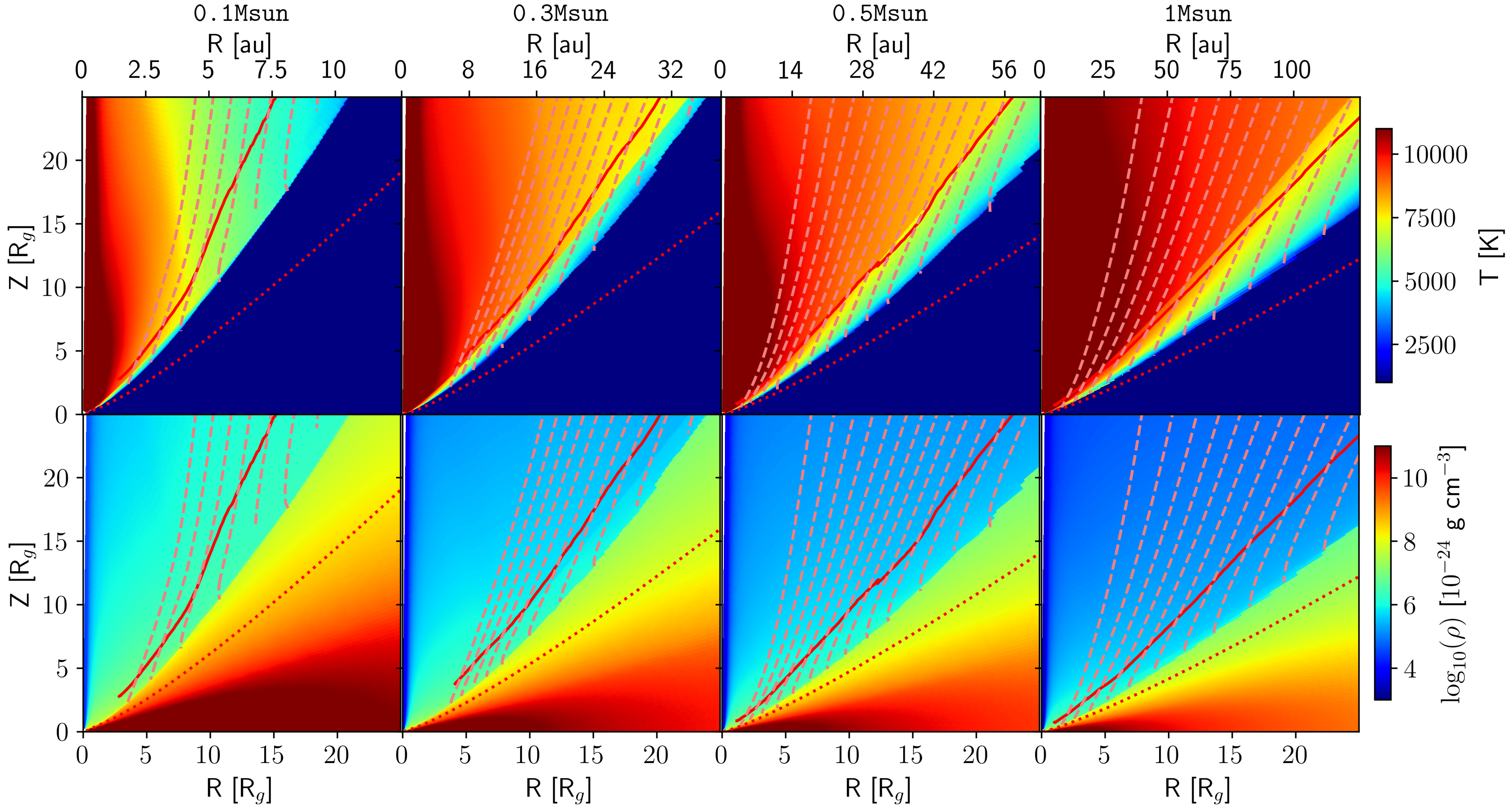


Ercolano et al., 2021



Picogna et al., 2021

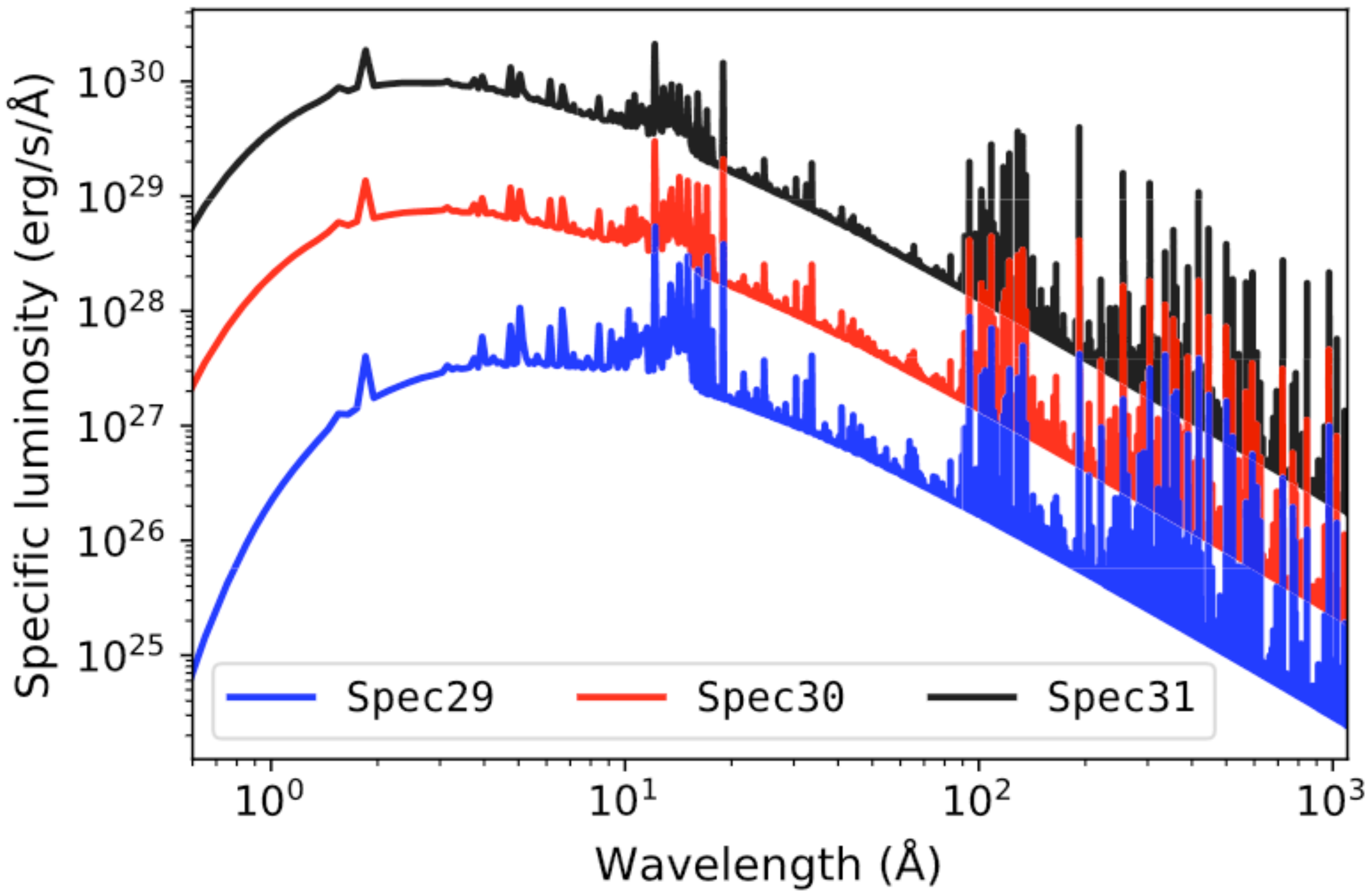
DISK STRUCTURE

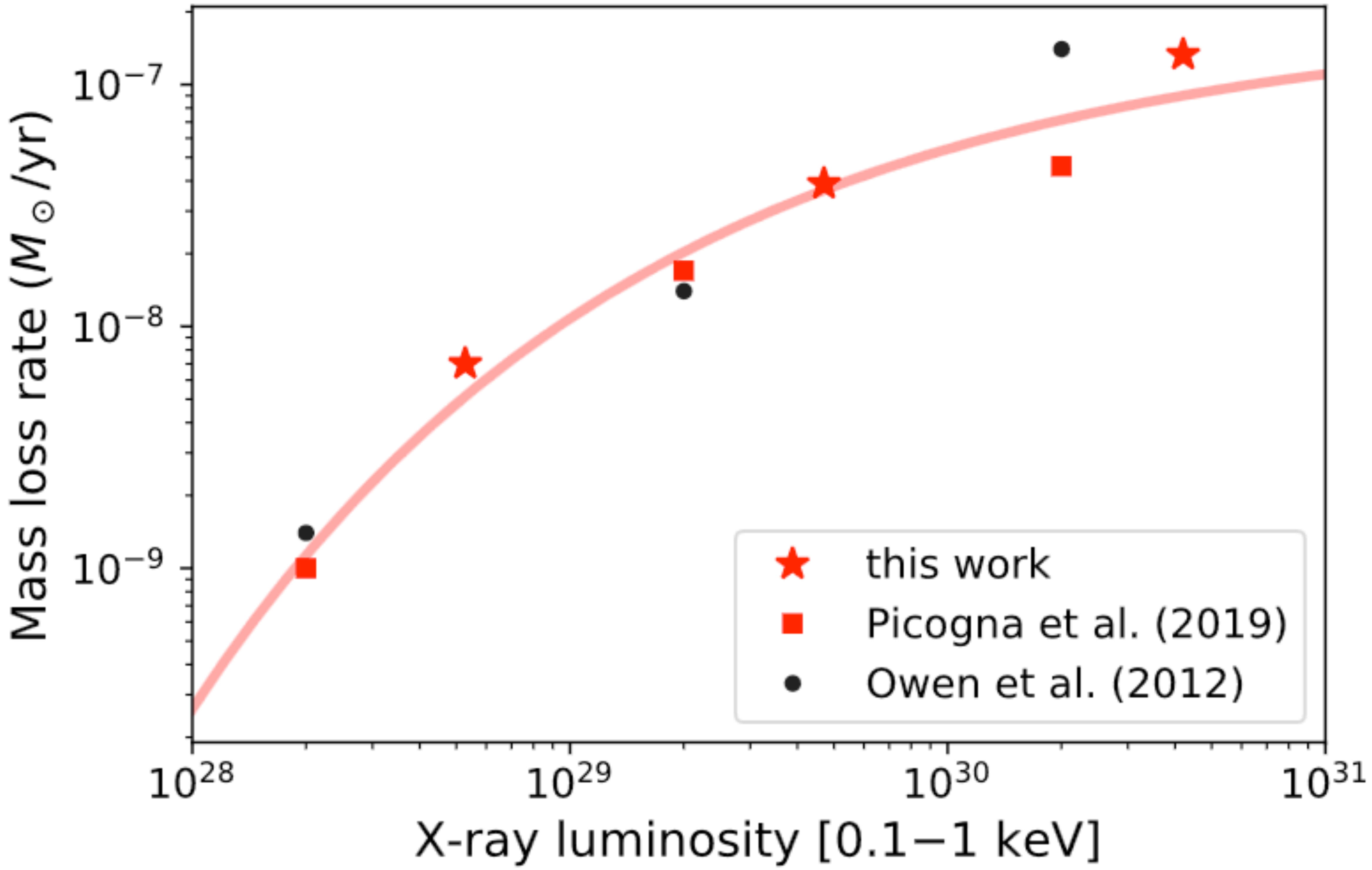


Picogna et al., 2021

- modelled for several hundreds of orbits at 10 au, until a stable disk profile and wind streamlines were obtained
- grid domain extends out to 1000 au to prevent numerical reflections to affect the wind mass-loss rates
- grid inner boundary has been tested for several values (going down to 0.05 au)

STELLAR SPECTRA DEPENDENCE



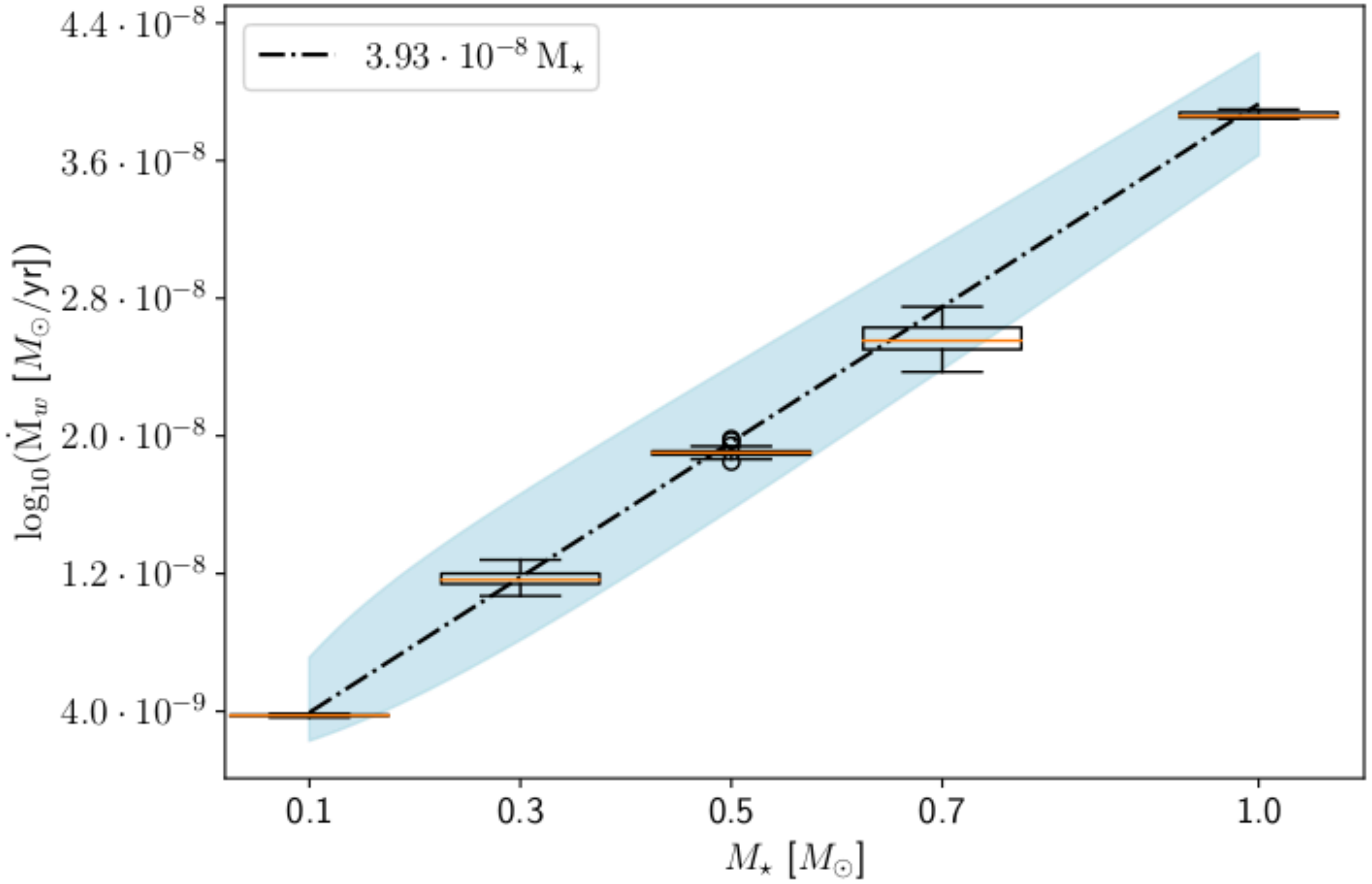


Ercolano et al., 2021

$$\log \dot{M}_{\rm w}(L_{\rm X,soft}) = a_{\rm S} \exp\left(\frac{(\ln(\log L_{\rm X,soft}) - b_{\rm S})^2}{c_{\rm S}}\right) + d_{\rm S},$$

with $a_S=-1.947 \times 10^{17}$, $b_S=-1.572 \times 10^{-4}$, $c_S=-0.2866$, $d_S=-6.694$

STELLAR MASS DEPENDENCE



Picogna et al., 2021

- we modelled stars with mass ranging from 0.1 to 1 Solar mass star
- we changed accordingly the stellar X-ray and bolometric luminosity, and spectral hardness
- the resulting wind mass-loss rate increase linearly with stellar mass

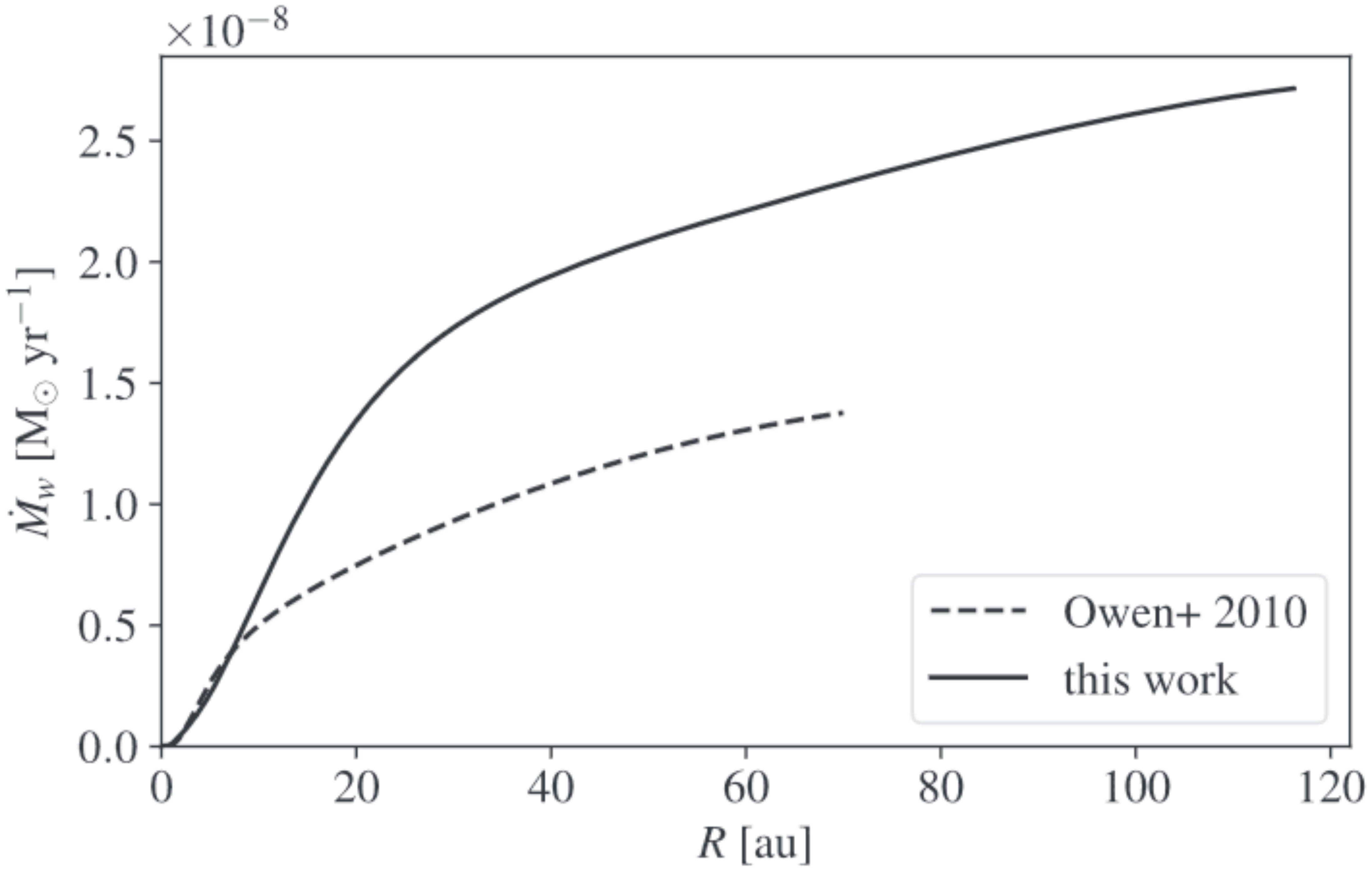
$$\dot{\mathrm{M}}_w = 3.93 \times 10^{-8} \left(\frac{\mathrm{M}_\star}{\mathrm{M}_\odot}\right) [\mathrm{M}_\odot\,\mathrm{yr}^{-1}]$$

$$\dot{M}_{\mathrm{XEUV}}(M_\star, L_{\mathrm{X,soft}}) = \dot{M}_{\mathrm{XEUV}}(M_\star) \frac{\dot{M}_{\mathrm{XEUV}}(L_{\mathrm{X,soft}})}{\dot{M}_{\mathrm{XEUV}}(L_{\mathrm{X,soft,mean}})},$$

Güdel et al., 2007

$$\log_{10}(\mathrm{L}_X) = (1.54 \pm 0.12)\log_{10}(\mathrm{M}_\star) + (30.31 \mp 0.06)$$

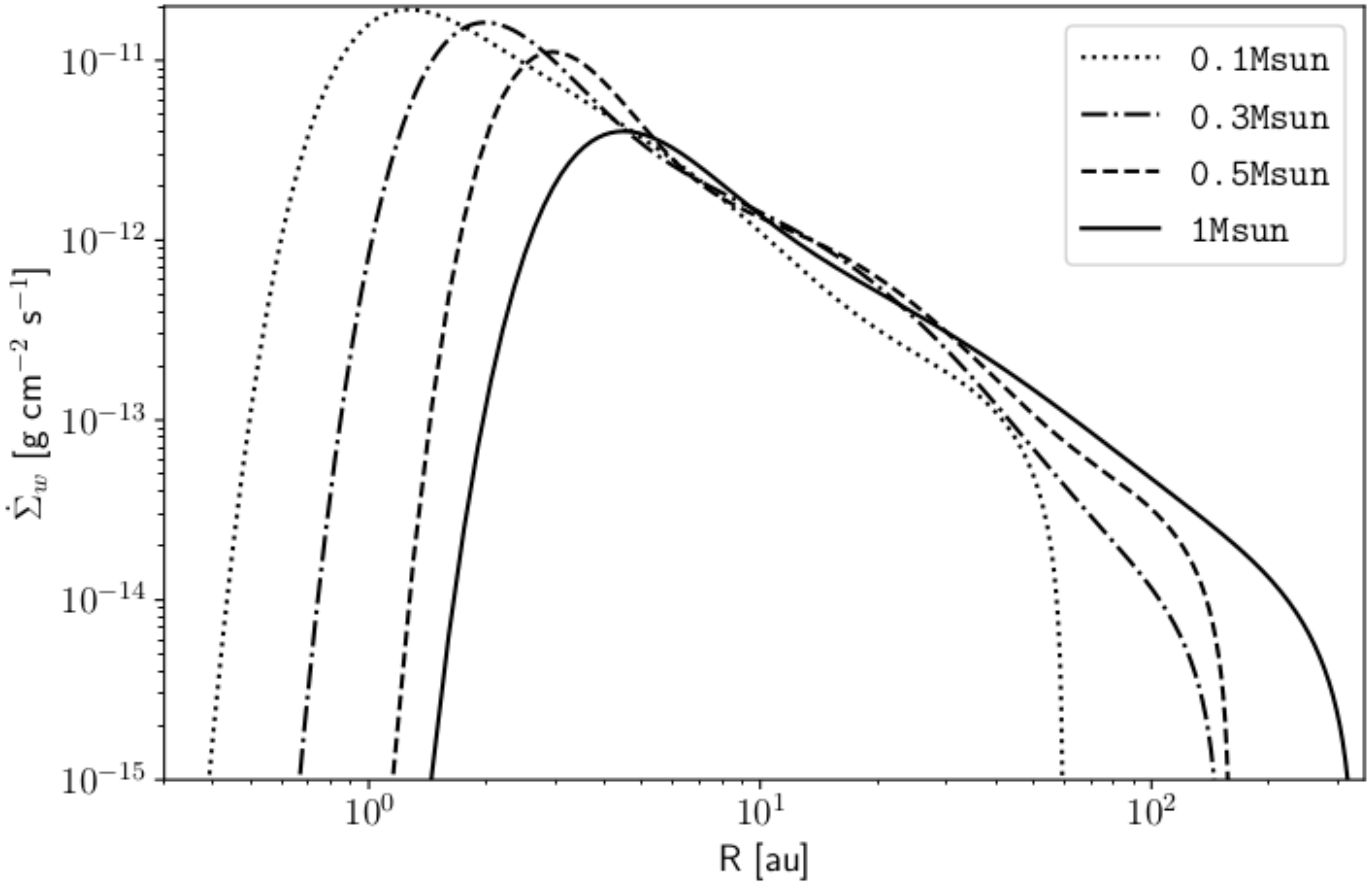
CAVEAT



Picogna et al., 2019

- If the disks extend to ~20 au, then the calculated mass-loss rates are a factor 2 to 3 lower depending on L_X and stellar mass

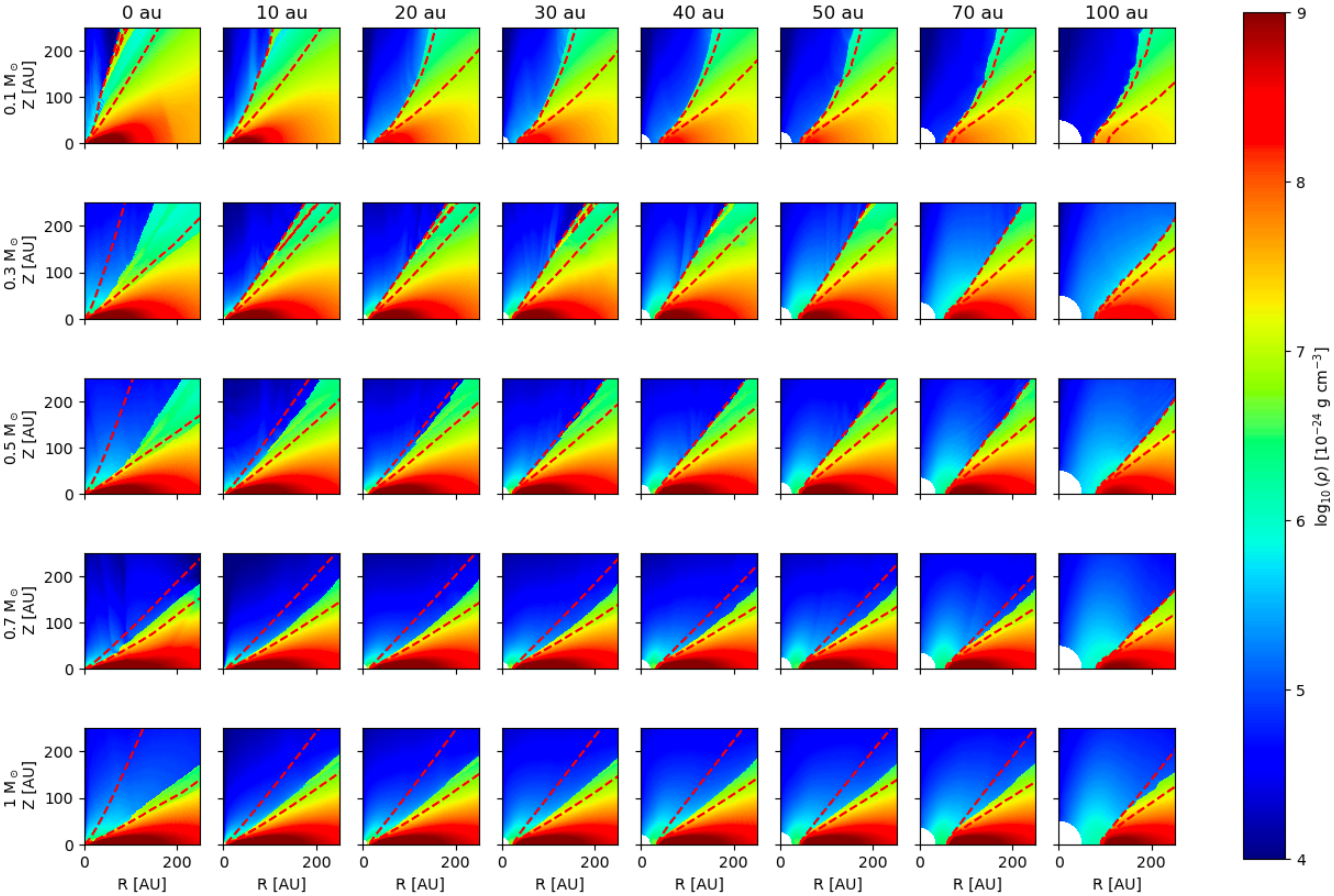
STELLAR MASS DEPENDENCE



Picogna et al., 2021

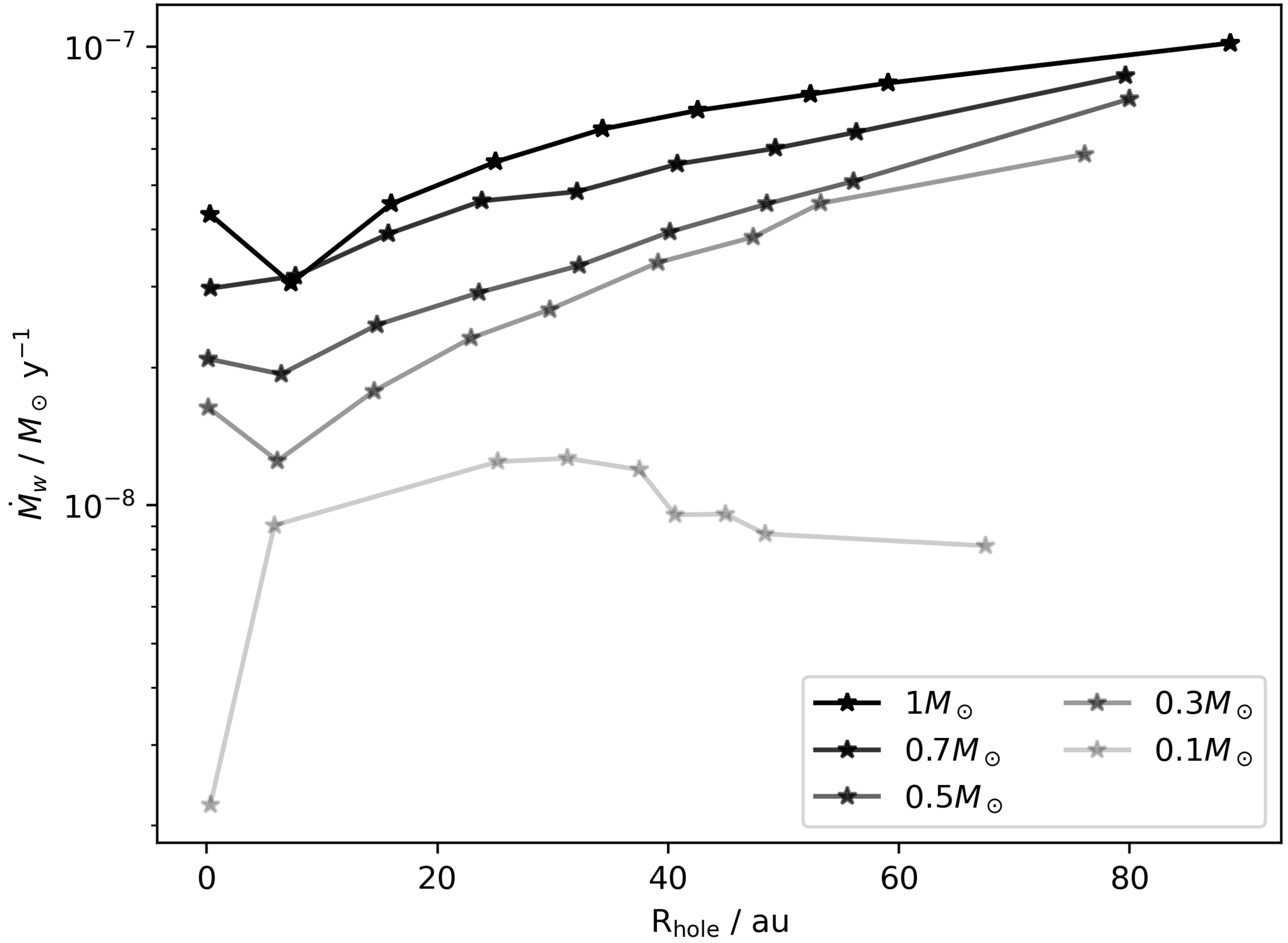
- Integrating the gas stream flows in the wind we derive a Surface mass-loss rate as a function of cylindrical radii, which can be used to study the disc evolution over long time-scale
- changing only the stellar mass we see an increase in the peak radius of the surface density mass-loss rate profile due to the larger gravitational radius
- at the same time the maximum reach of the wind increases as a function of the stellar mass because of the change in the disc aspect ratio

CAVITY SIZE DEPENDENCE



Picogna et al., in prep.

CAVITY SIZE DEPENDENCE



Picogna et al., in prep.

Is this the solution for relic disks?

HOW TO TEST PHOTOEVAPORATIVE MODELS?

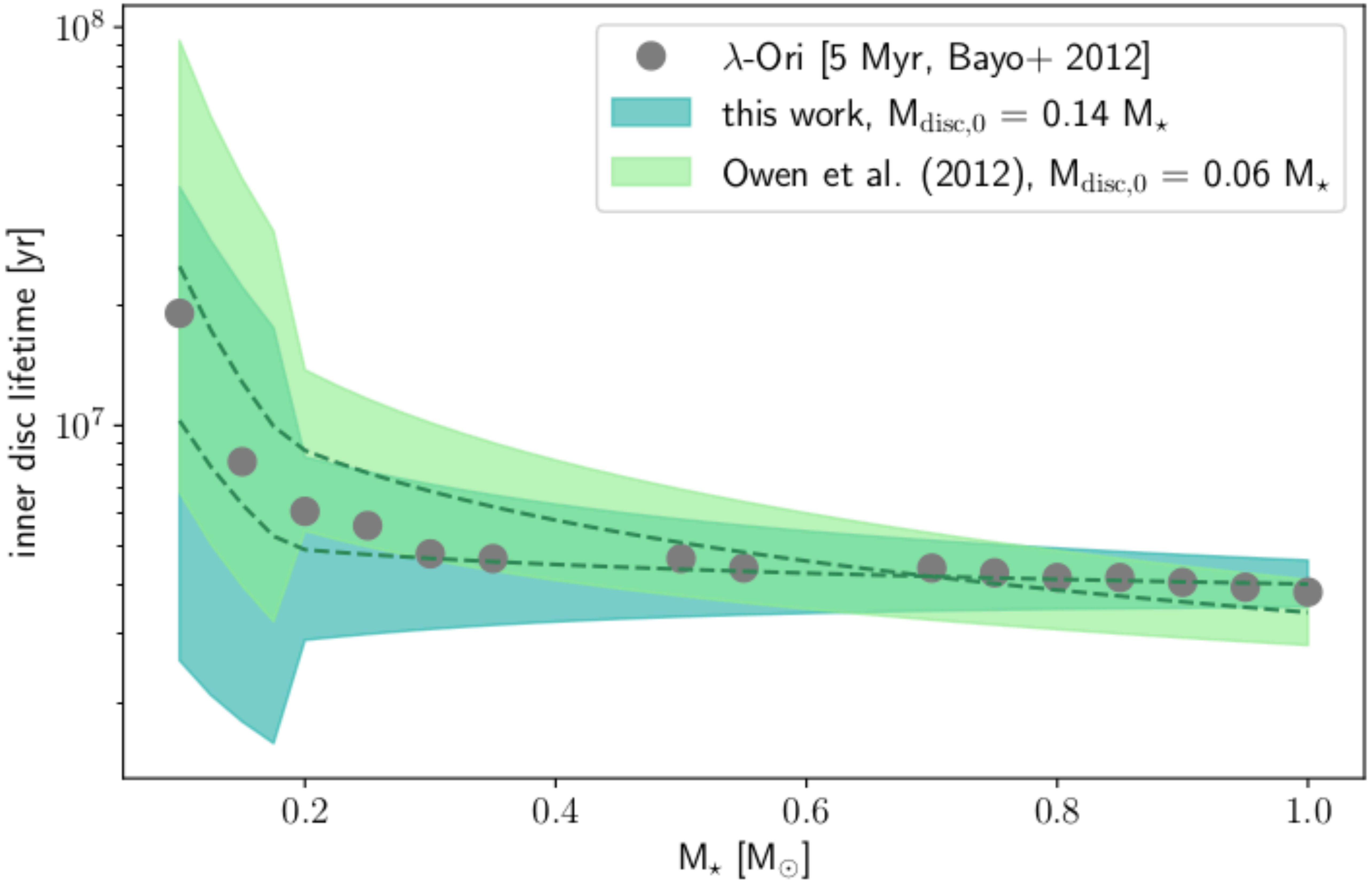
Indirect Tests:

- Disk dispersal timescales
- Metallicity dependence of disk lifetimes
- Inside out dispersal from colour-colour diagrams

Direct Tests:

- High-resolution spectroscopy of blue-shifted gas emission lines
- Dust entrainment from scattered light observations of inclined transition disks

(INNER) DISK LIFE-TIME



Picogna et al. 2021

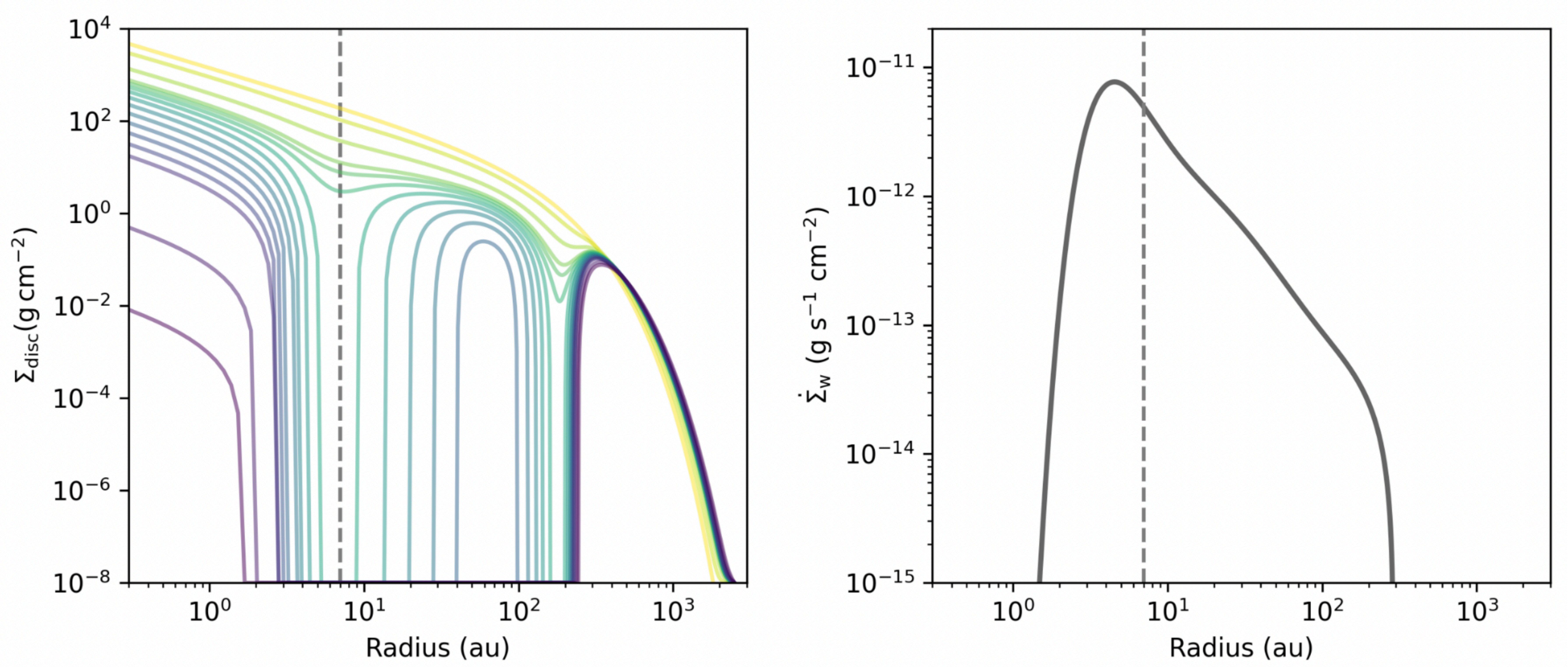
- we compared the derived inner disk life-time from a 5 Myr old star forming region as a function of stellar mass with the prediction from our model finding good agreement for a constant disc-to-star mass ratio

$$
\begin{aligned}
t_{\rm life} &= t_\nu \left(\frac{\dot{M}_{\rm acc,0}}{\dot{M}_w}\right)^{2/3} = \frac{M_{\rm disc,0}}{2\dot{M}_{\rm acc}} \left(\frac{\dot{M}_{\rm acc}}{\dot{M}_w}\right)^{2/3} \\
&= \frac{1}{2}\left(\frac{M_{\rm disc,0}}{\dot{M}^{1/3}_{\rm acc,0}\,\dot{M}^{2/3}_w}\right),
\end{aligned}
$$

$$
\log(\dot{M}_{\rm acc}) = \begin{cases} 4.58(\pm0.68)\ \log(M_\star) - 6.11(\mp0.61), & \leqslant 0.2\,M_\odot \\ 1.37(\pm0.24)\ \log(M_\star) - 8.46(\mp0.11), & \text{otherwise.} \end{cases}
$$

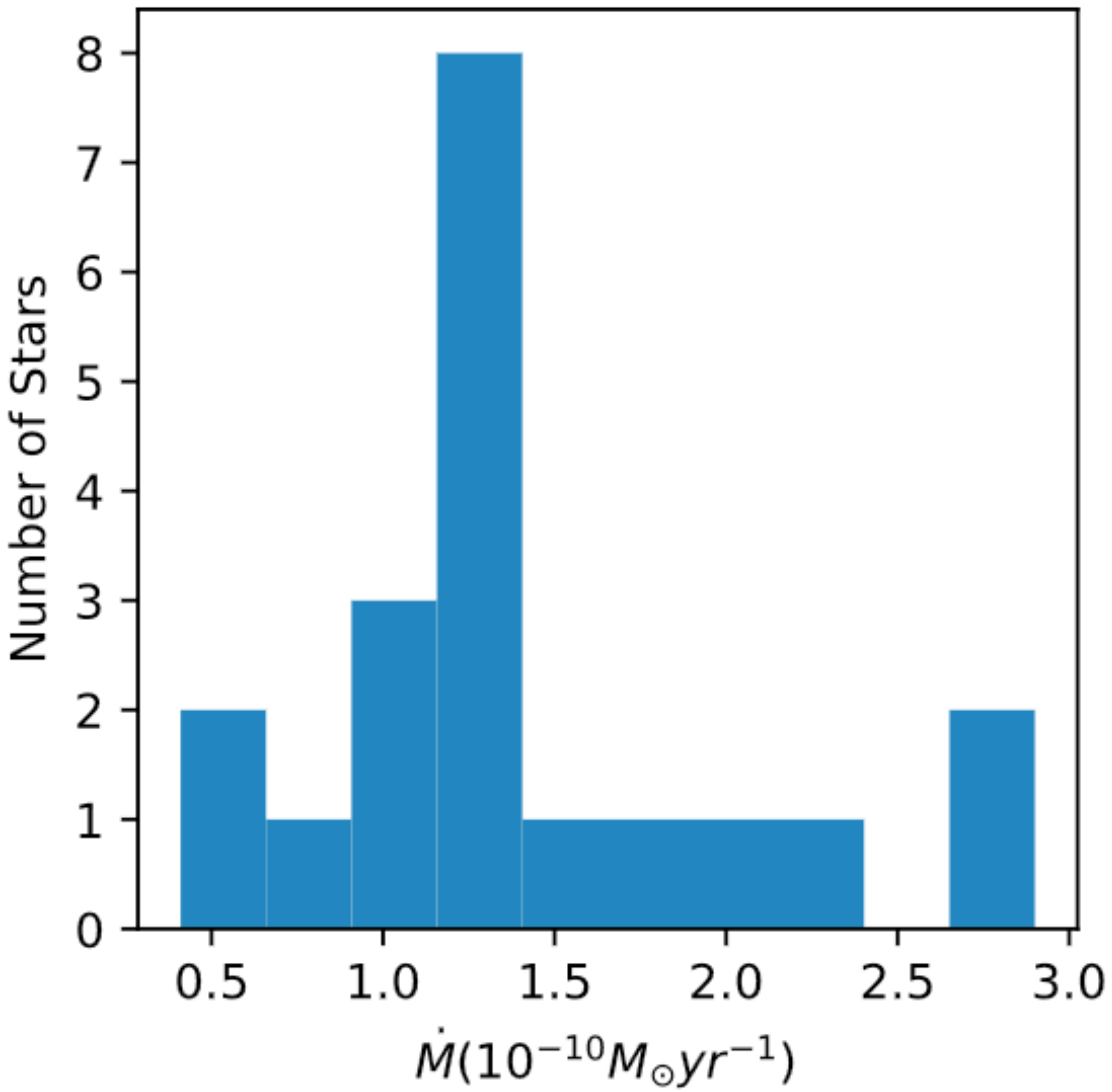
Alcala et al. 2017

DISK EVOLUTION



Left: 1D Surface density evolution as a function of disk radius. Right: Surface density mass-loss rate for a 0.1 Solar mass disk orbiting a 1 Solar mass star with $L_X = 2.04 \cdot 10^{30}$ erg/s. Ercolano & Picogna (2022)

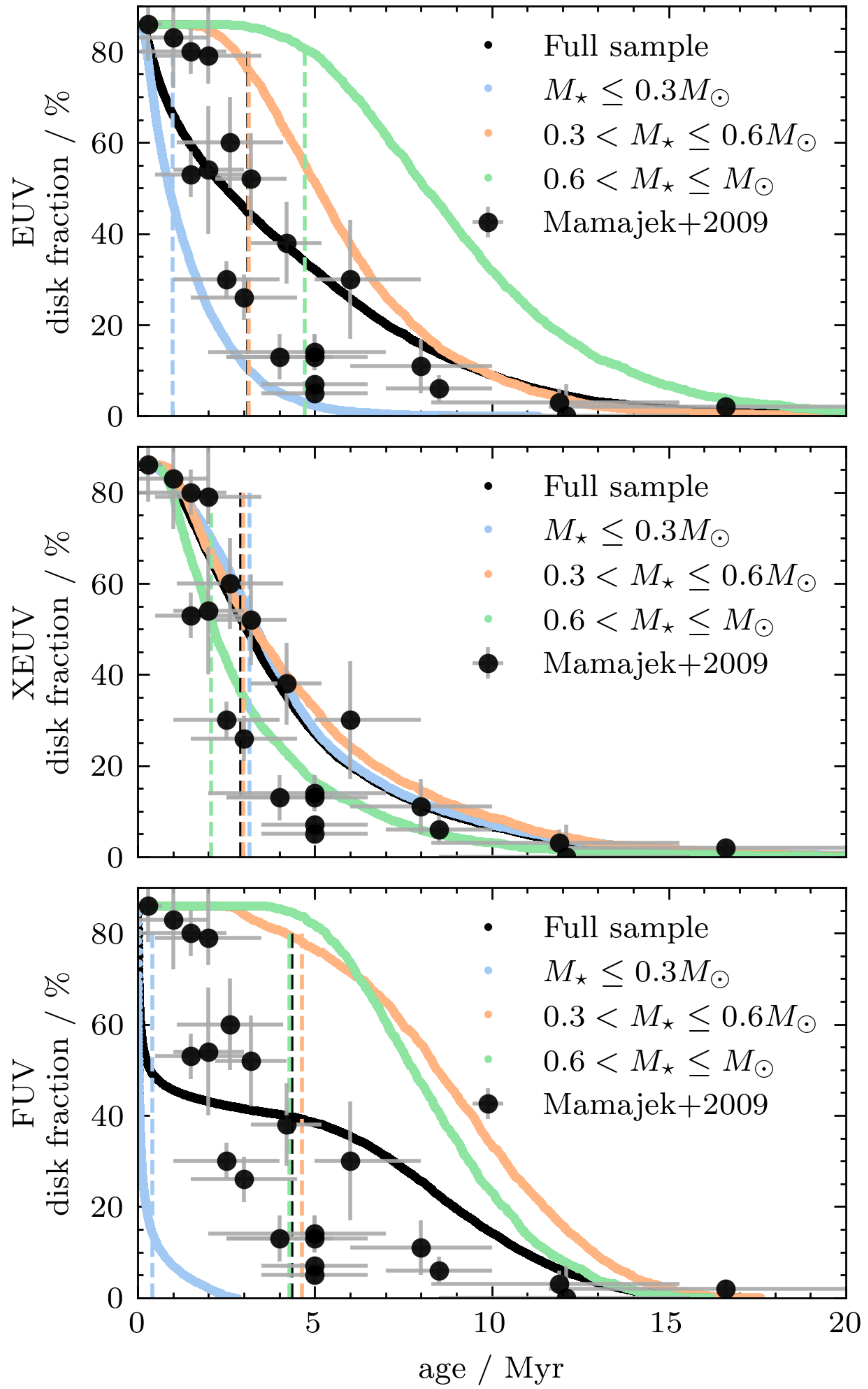
LOW ACCRETORS



Thanathibodee et al. 2023

- Thanathibodee et al. (2022) looked for an accretion signature in disc-bearing stars previously thought to be non-accretors, using the He I λ10830Å line
- In Thanathibodee et al. (2023) they analyse a sub-sample (24 sources) calculating the mass accretion rates
- they derived a minimum accretion rate of the order of 10^{-10} M⊙ / yr, which is roughly one order of magnitude above the detection limit for their sample
- They claimed that this was an evidence that EUV photoevaporation was dispersing these disks

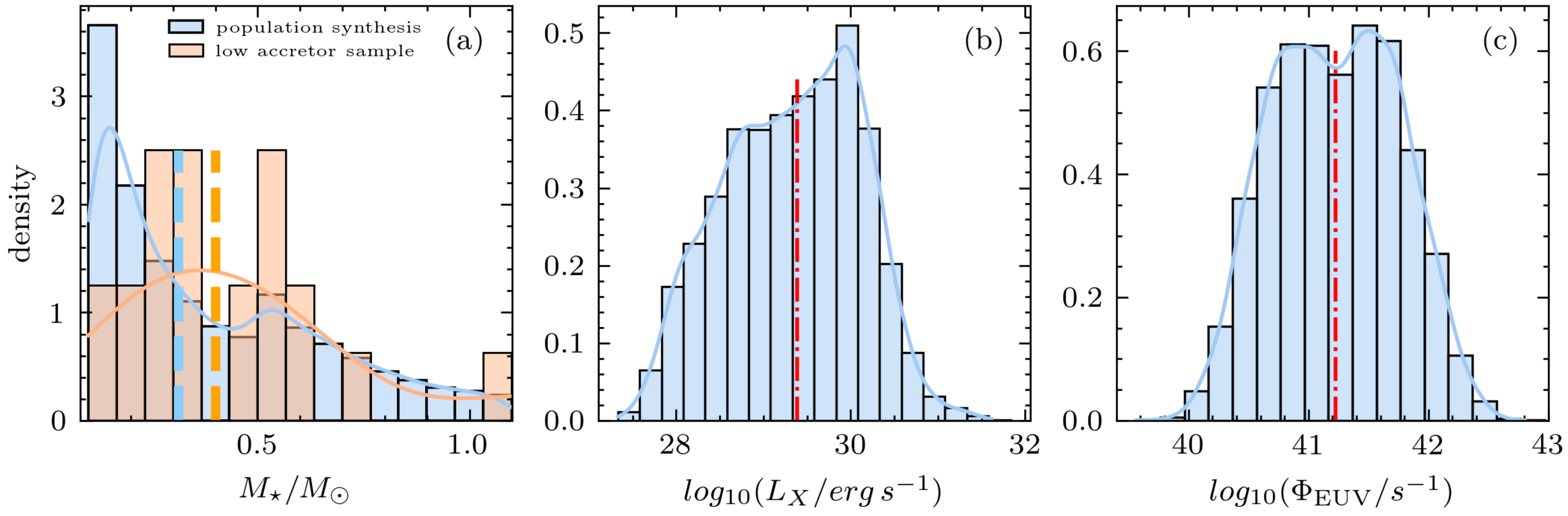
LOW ACCRETORS



- EUV (Alexander & Armitage, 2007)
- X-ray (Picogna et al. 2021, Ercolano et al. 2021)
- FUV (Komaki et al. 2021)

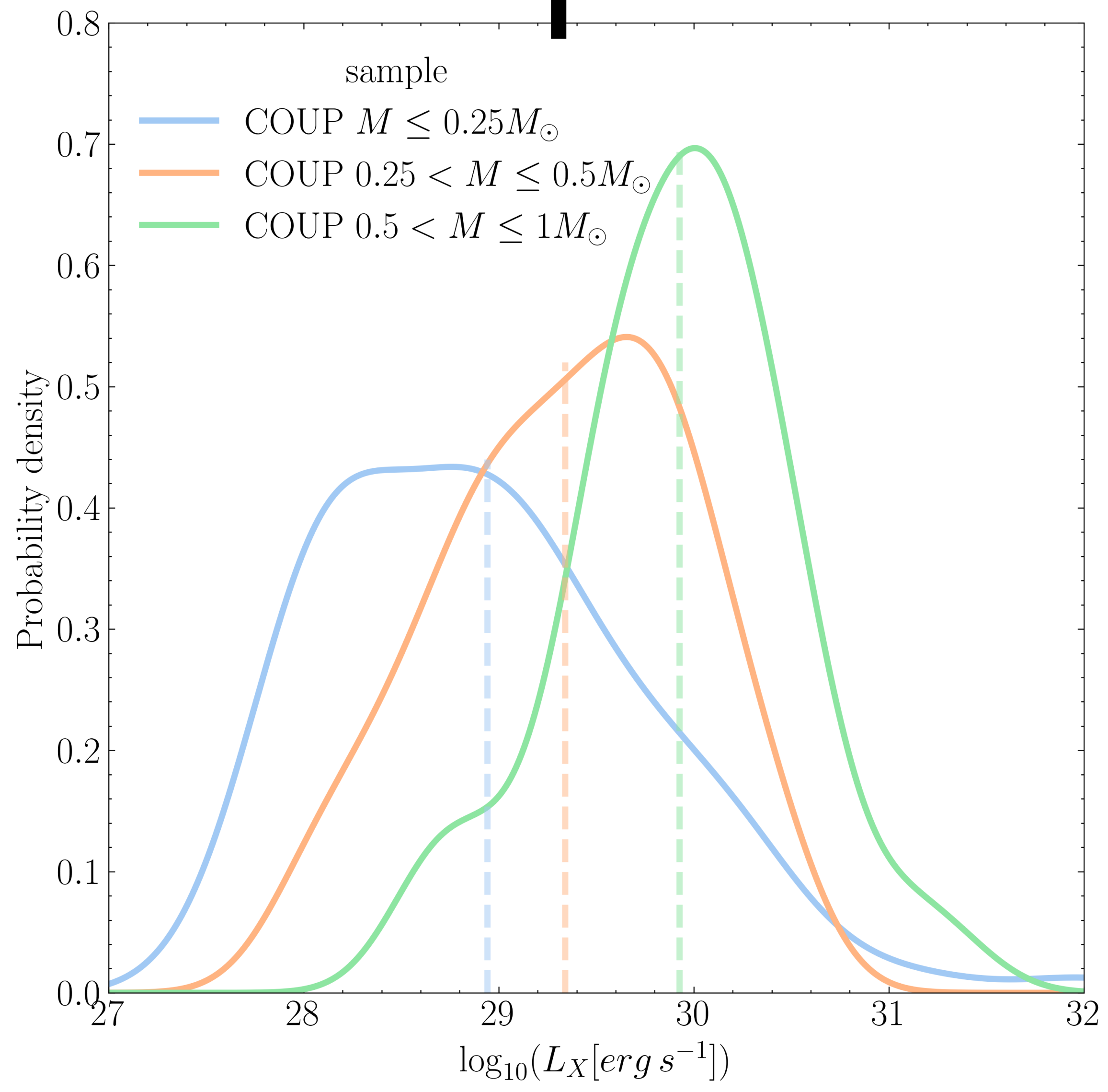
Ercolano et al. 2023

Low Accretors



IMF, Lx, and EUV initial distribution

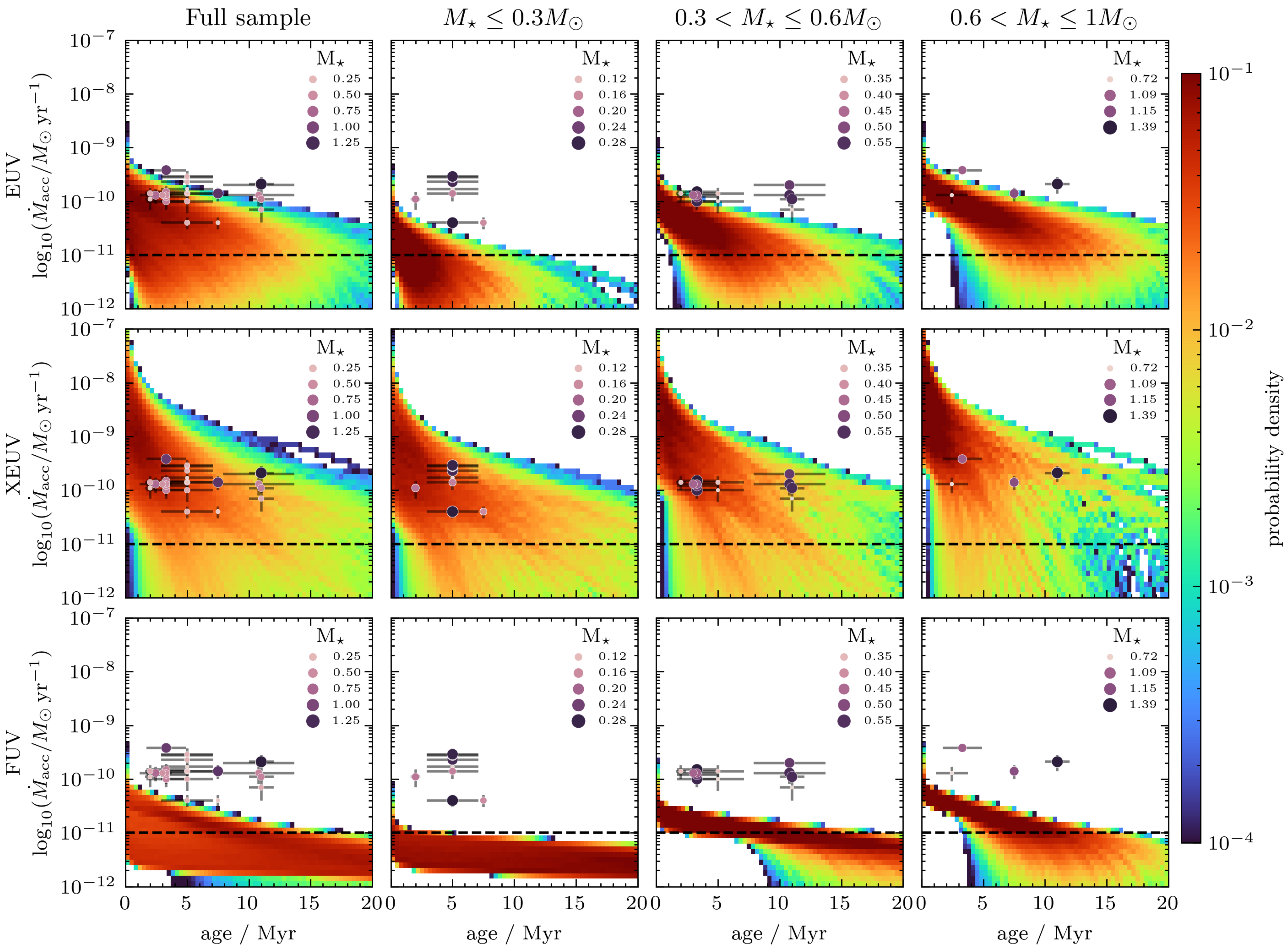
We adopted a IMF from Kroupa (2001)



We assumed a chromospheric origin for EUV, adopting the same stellar mass scaling as the X-rays with a dispersion of 0.25 dex

Ercolano et al. 2023

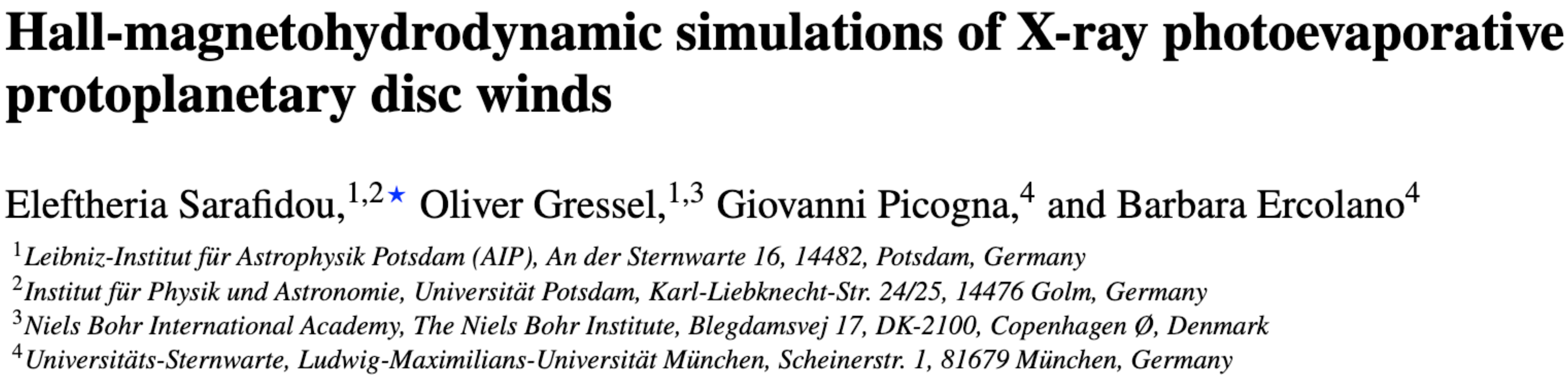
LOW ACCRETORS



Ercolano et al. 2023

DISK WIND INTERACTION

MAGNETO-THERMAL WINDS



Hall-magnetohydrodynamic simulations of X-ray photoevaporative protoplanetary disc winds

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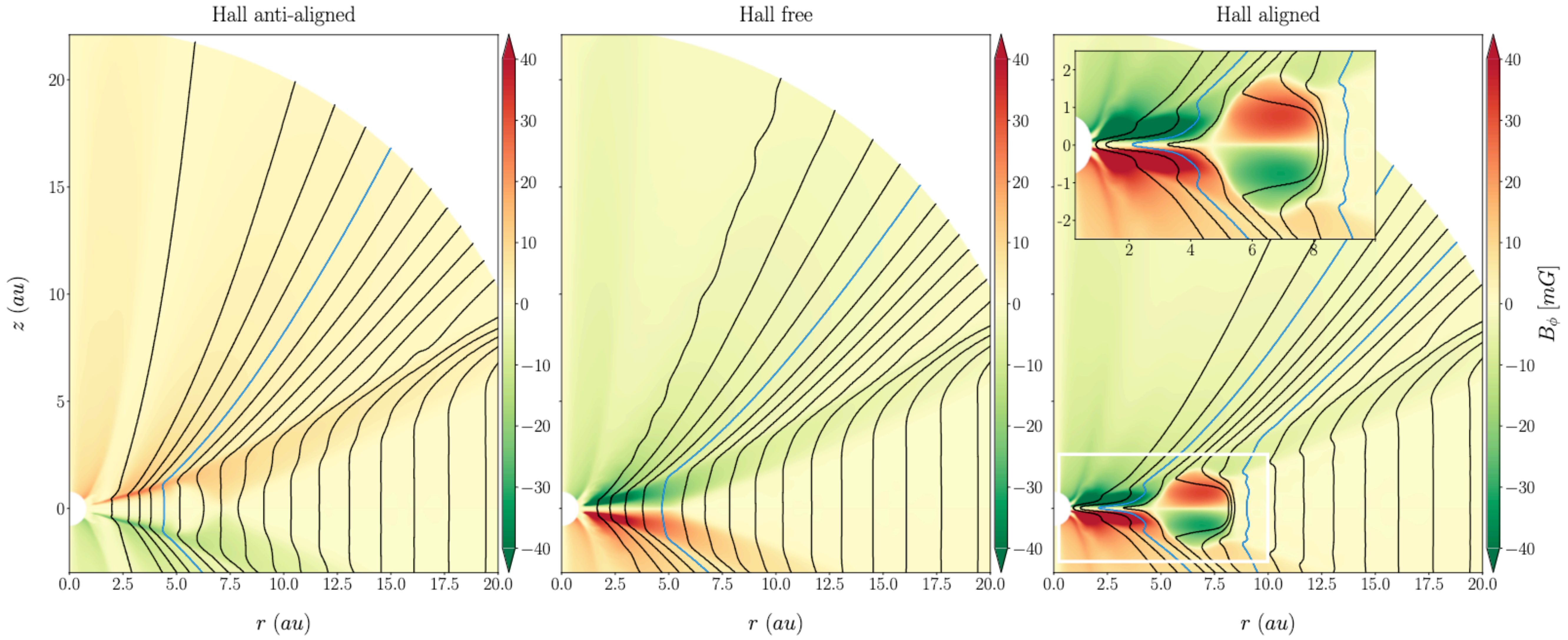
[2] *Institut für Physik und Astronomie, Universität Potsdam, Karl-Liebknecht-Str. 24/25, 14476 Golm, Germany*
[3] *Niels Bohr International Academy, The Niels Bohr Institute, Blegdamsvej 17, DK-2100, Copenhagen Ø, Denmark*
[4] *Universitäts-Sternwarte, Ludwig-Maximilians-Universität München, Scheinerstr. 1, 81679 München, Germany*

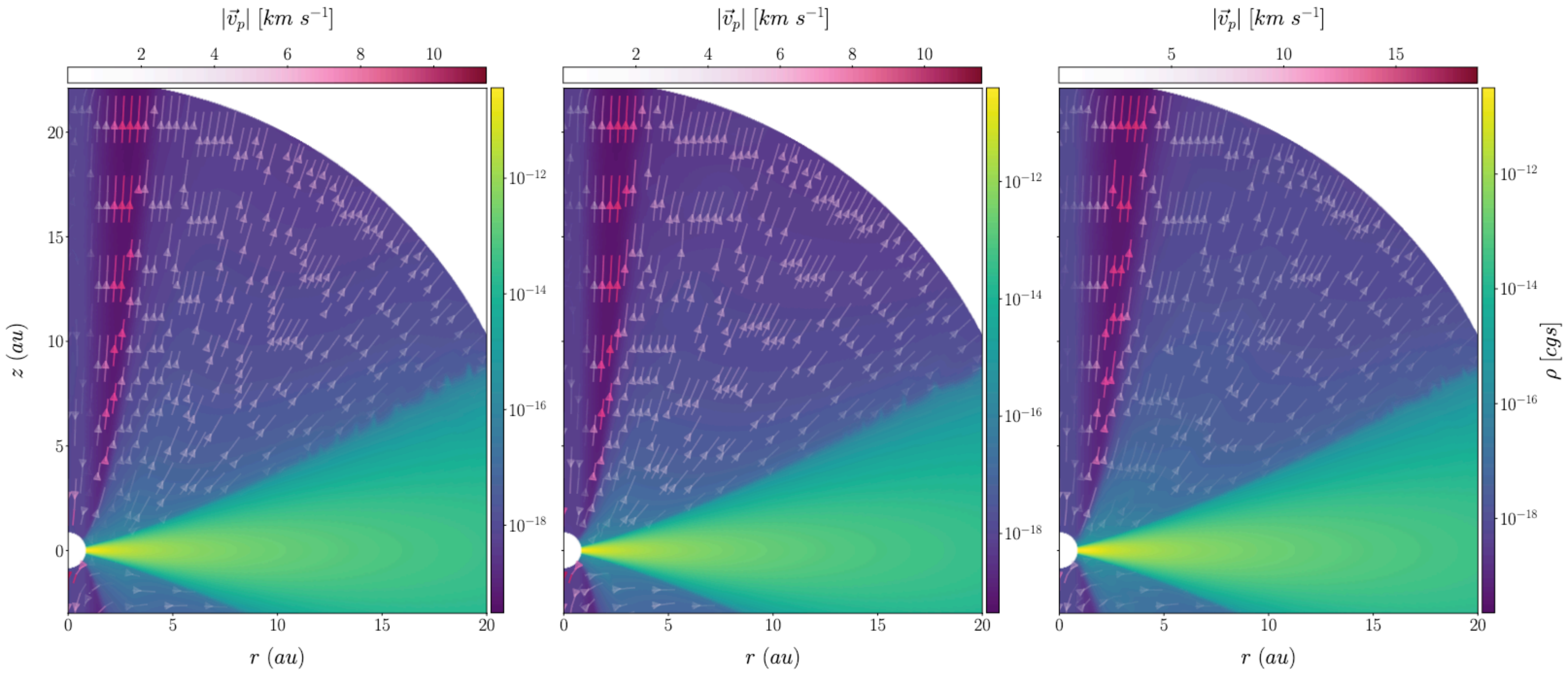
- Aims:
  - Effect of Hall-effect on the field-topology and mass loss/accretion rates
  - Including internal X-ray photoevaporation in non-ideal MHD simulations
- Results:
  - in the aligned orientation, the HE causes prominent inward displacement of the poloidal field lines that can increase the accretion rate through a laminar Maxwell stress
  - outflows are mainly driven by photoevaporation – unless the magnetic field strength is considerable (i.e., $\beta_P \leq 10^3$) or the X-ray luminosity low enough (i.e., $\log(L_X) \leq 29.3$)

MAGNETO-THERMAL WINDS



(a) Toroidal magnetic field snapshots

Time averaged snapshots of the toroidal magnetic field with poloidal field lines



(b) Density snapshots

Time averaged snapshots of the density with the poloidal velocity streamlines

MAGNETO-THERMAL WINDS

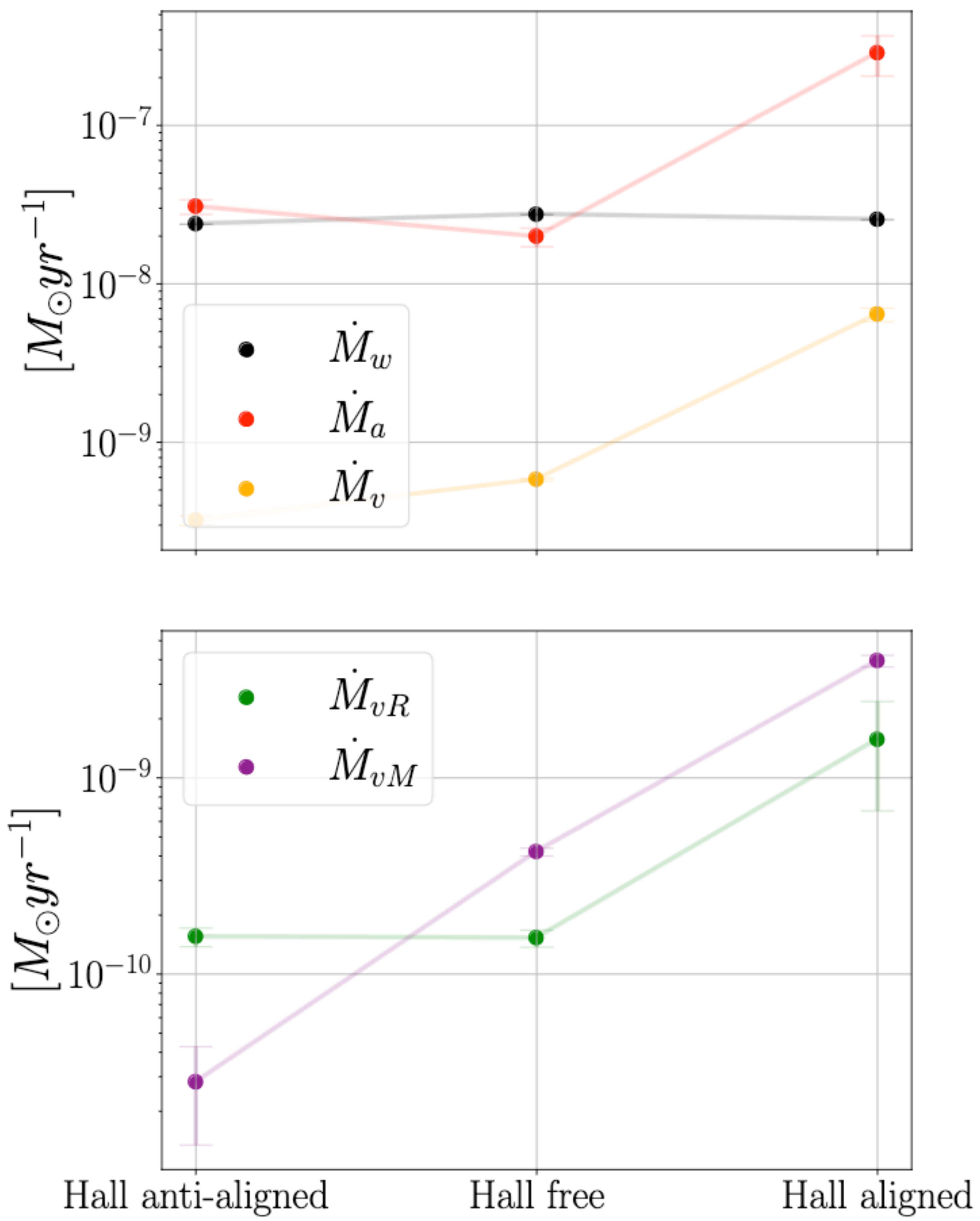


Figure 3. Total wind mass loss rate ($\dot{M}_{\rm w}$), accretion accretion rate ($\dot{M}_{\rm a}$) and viscous accretion rates (i.e., $\dot{M}_{\rm v}$, consisting of $\dot{M}_{vR}$ and $\dot{M}_{vM}$) of the three fiducial cases – Hall free, anti-aligned and aligned HE. The error bars indicate the uncertainty in the time and volume averaging of the quantities.

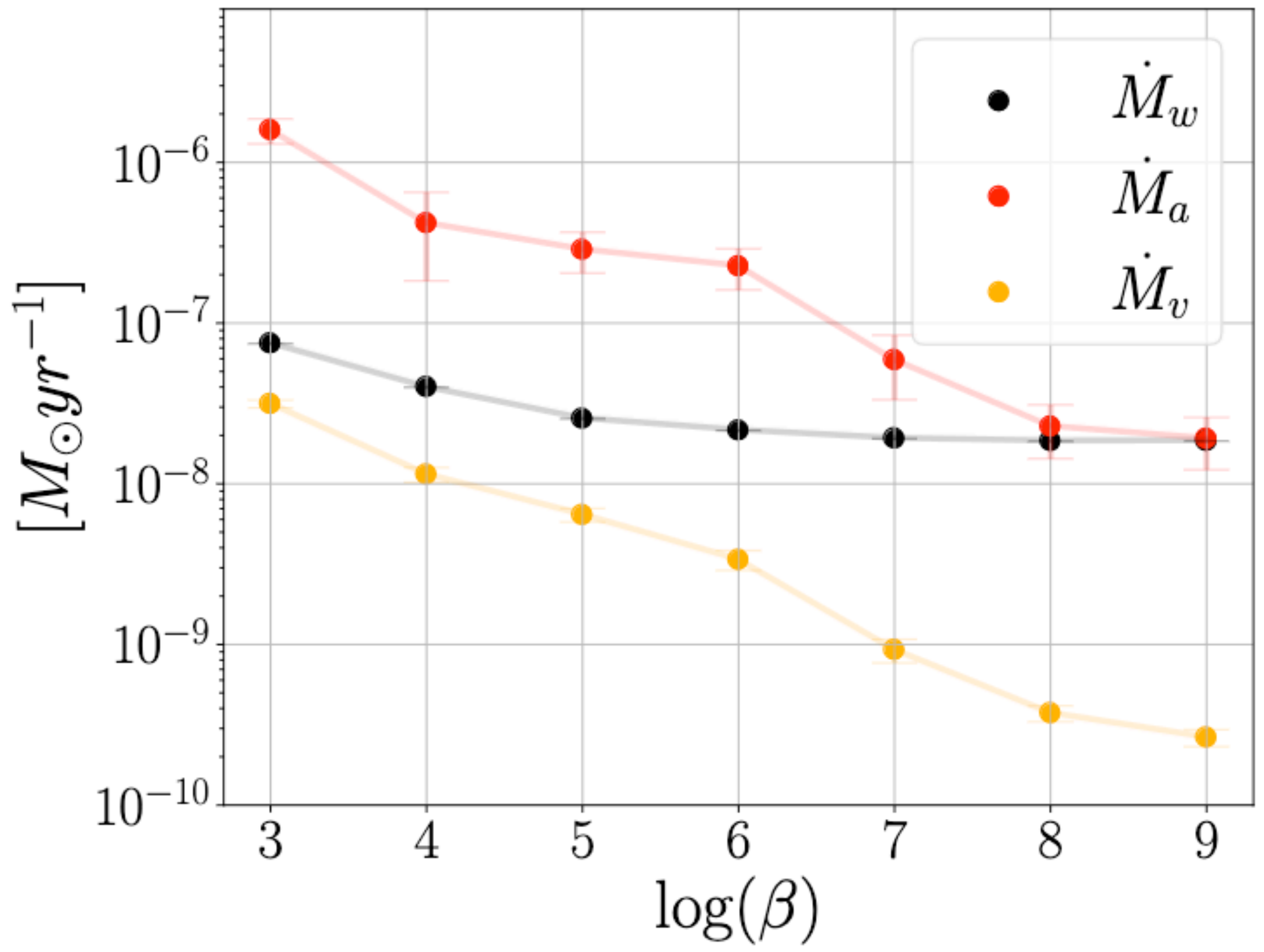


Figure 7. Trends of the total wind mass loss rate ($\dot{M}_{\rm w}$), mass accretion rate ($\dot{M}_{\rm a}$) and viscous accretion rate ($\dot{M}_{\rm v}$). The error bars indicate the uncertainty of the measurements.

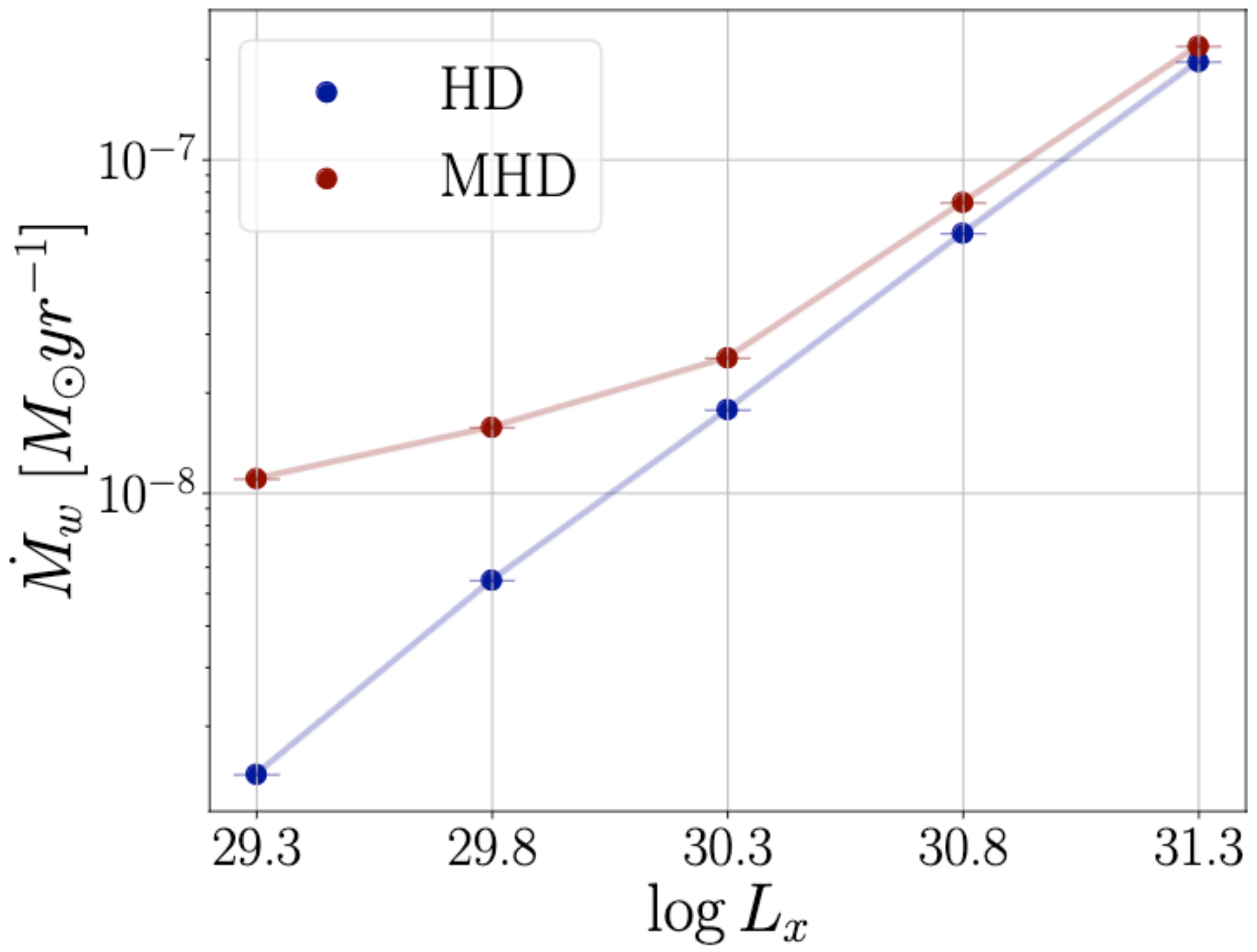
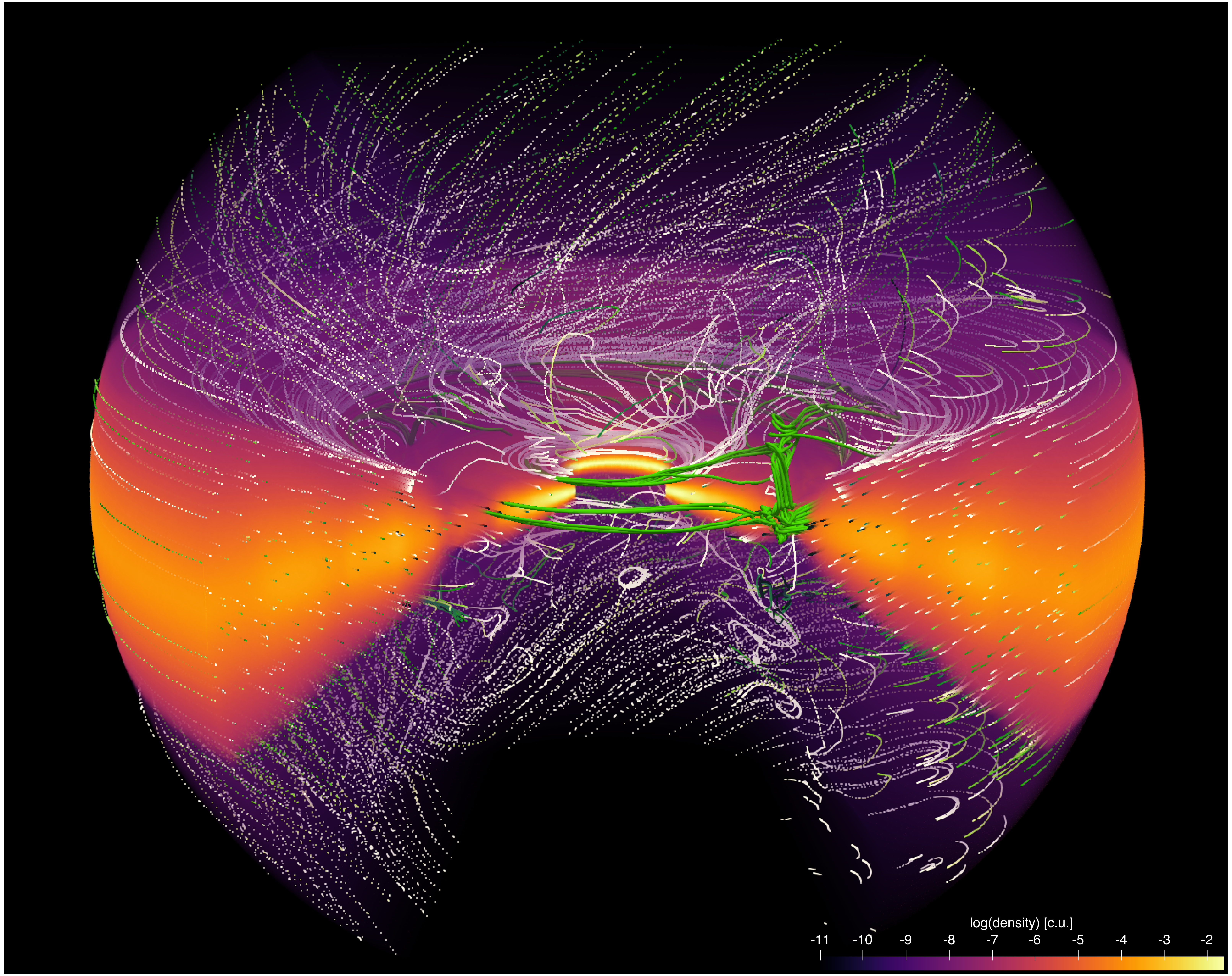


Figure 10. Dependence of the wind mass loss rates ($\dot{M}_{\rm w}$) for runs with several L_X values for a set of runs with MHD and one with only hydro.

$$\beta = 2\mu_0 p / B^2$$ **Plasma parameter**

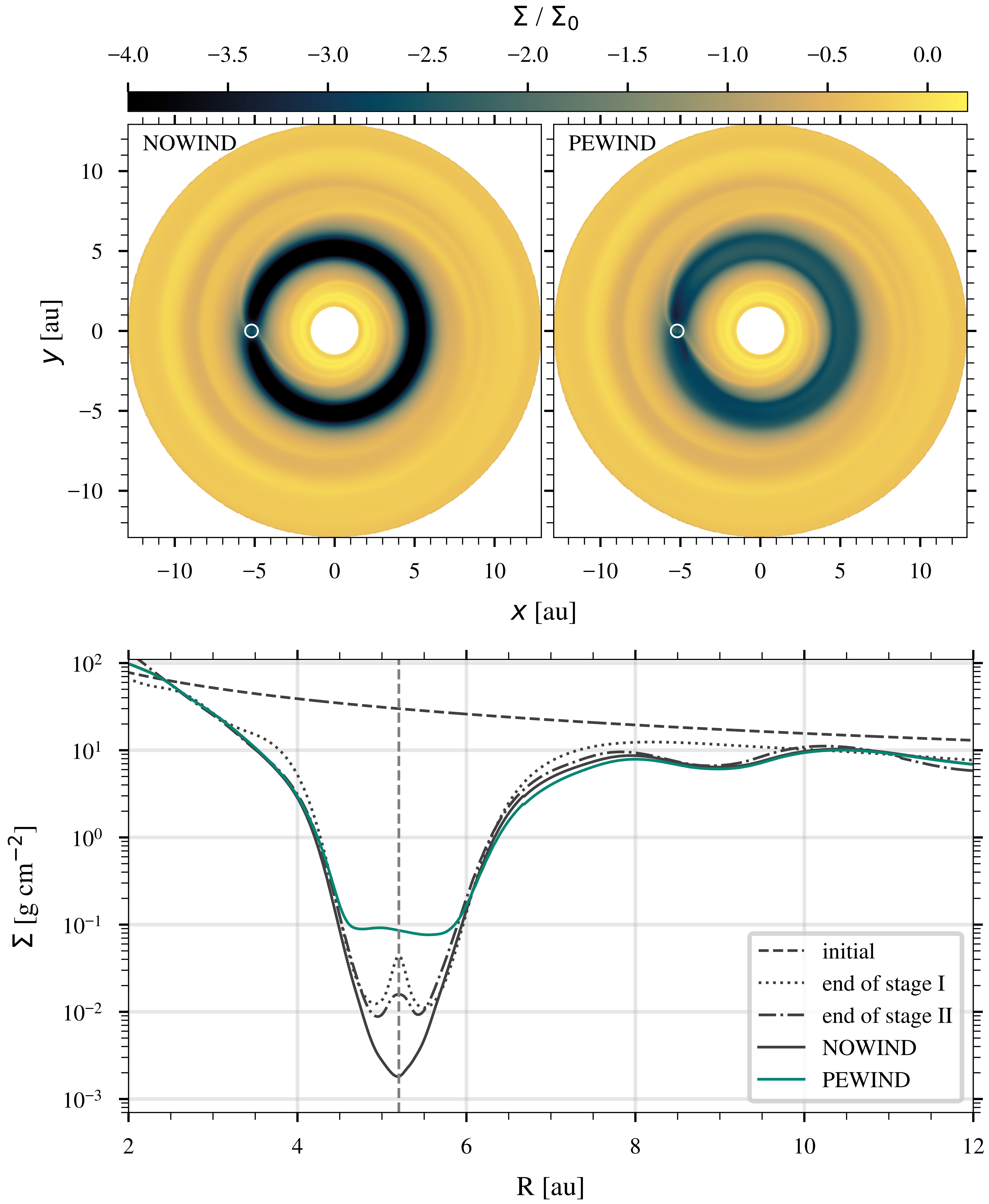
What are the consequences for disk evolution?

PLANET-WIND INTERACTION



Weber, Picogna, Ercolano, in prep.

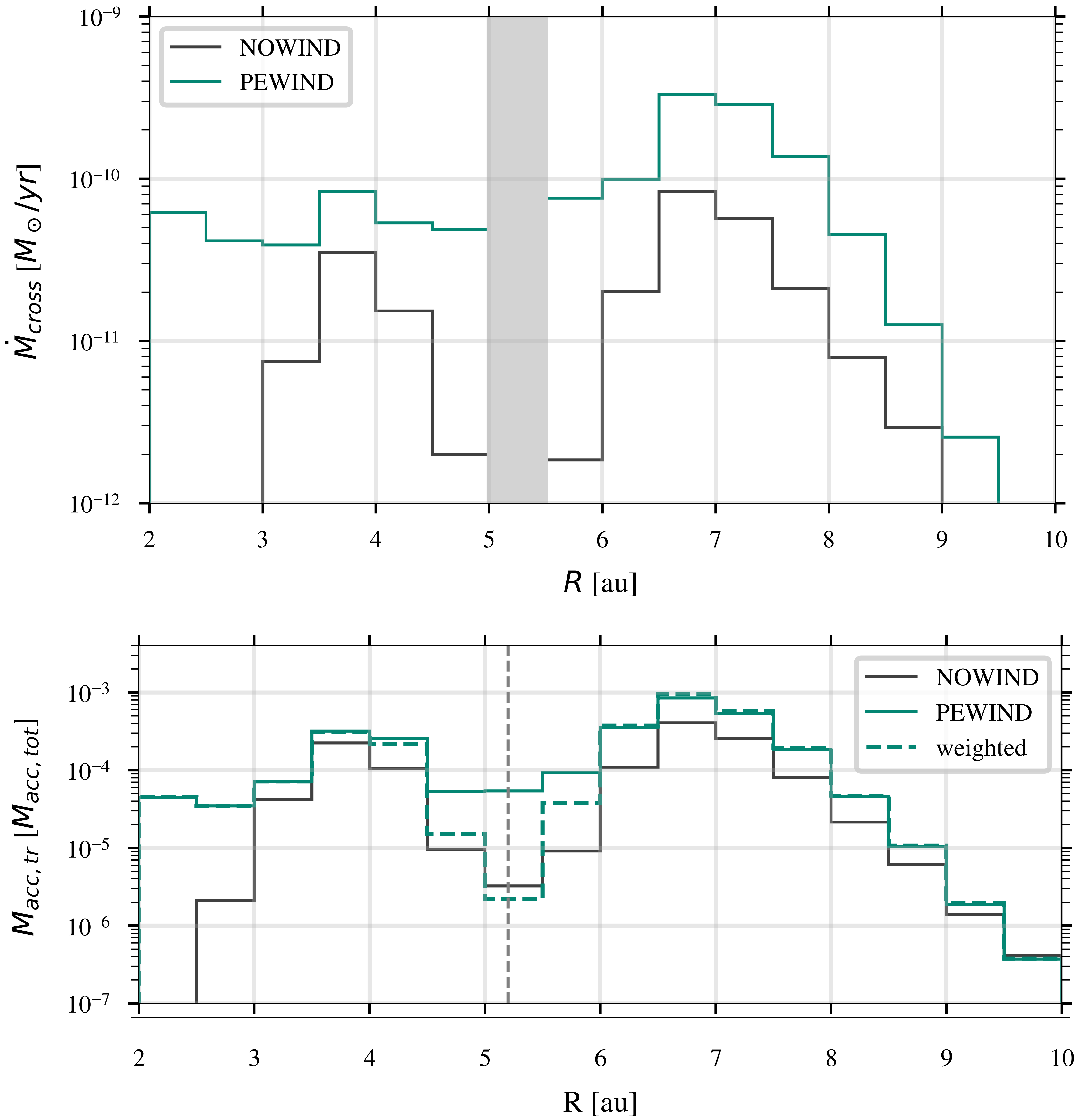
PLANET-WIND INTERACTION



- 1 Jupiter mass planet at 5.2 au
- Orbiting a $0.7\ M_{\odot}$ star with $L_X = 2 \times 10^{30}$ erg/s
- Comparison of the gap with/out the PE wind

Weber, Picogna, Ercolano, in prep.

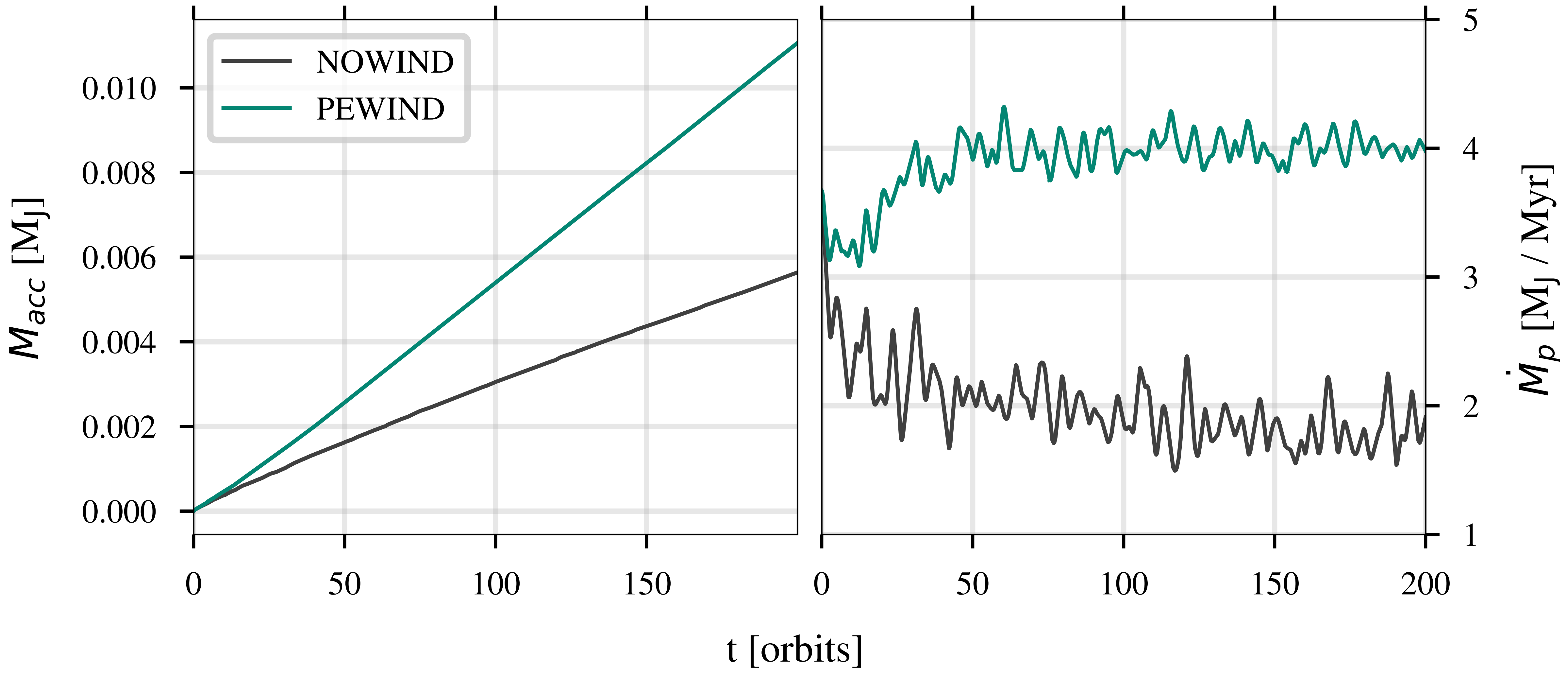
PLANET-WIND INTERACTION

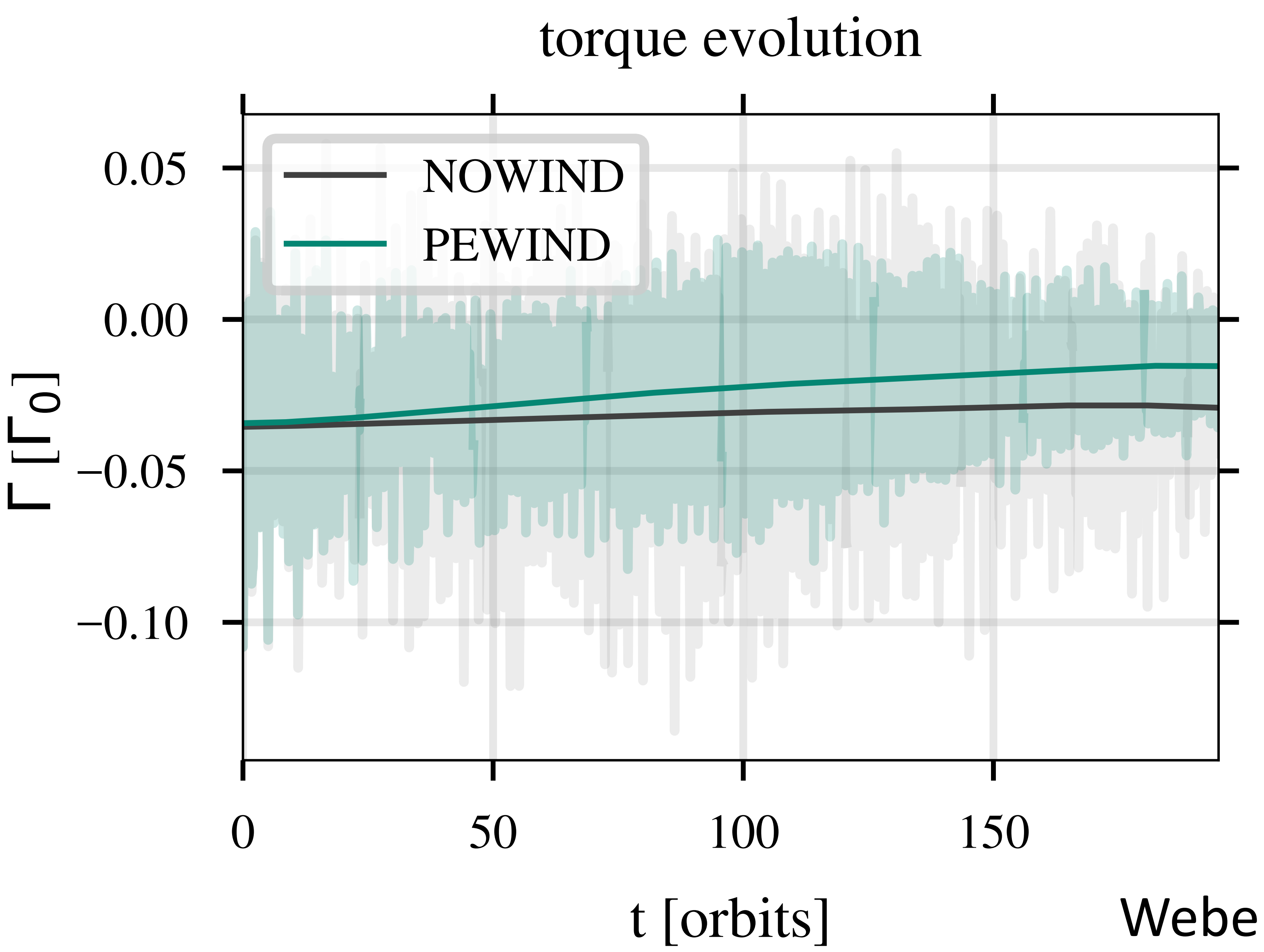


Weber, Picogna, Ercolano, in prep.

- The mass crossing the gap is greatly increased in both direction
- The planet accretes material from an extended region with respect to the wind-less case

PLANET-WIND INTERACTION



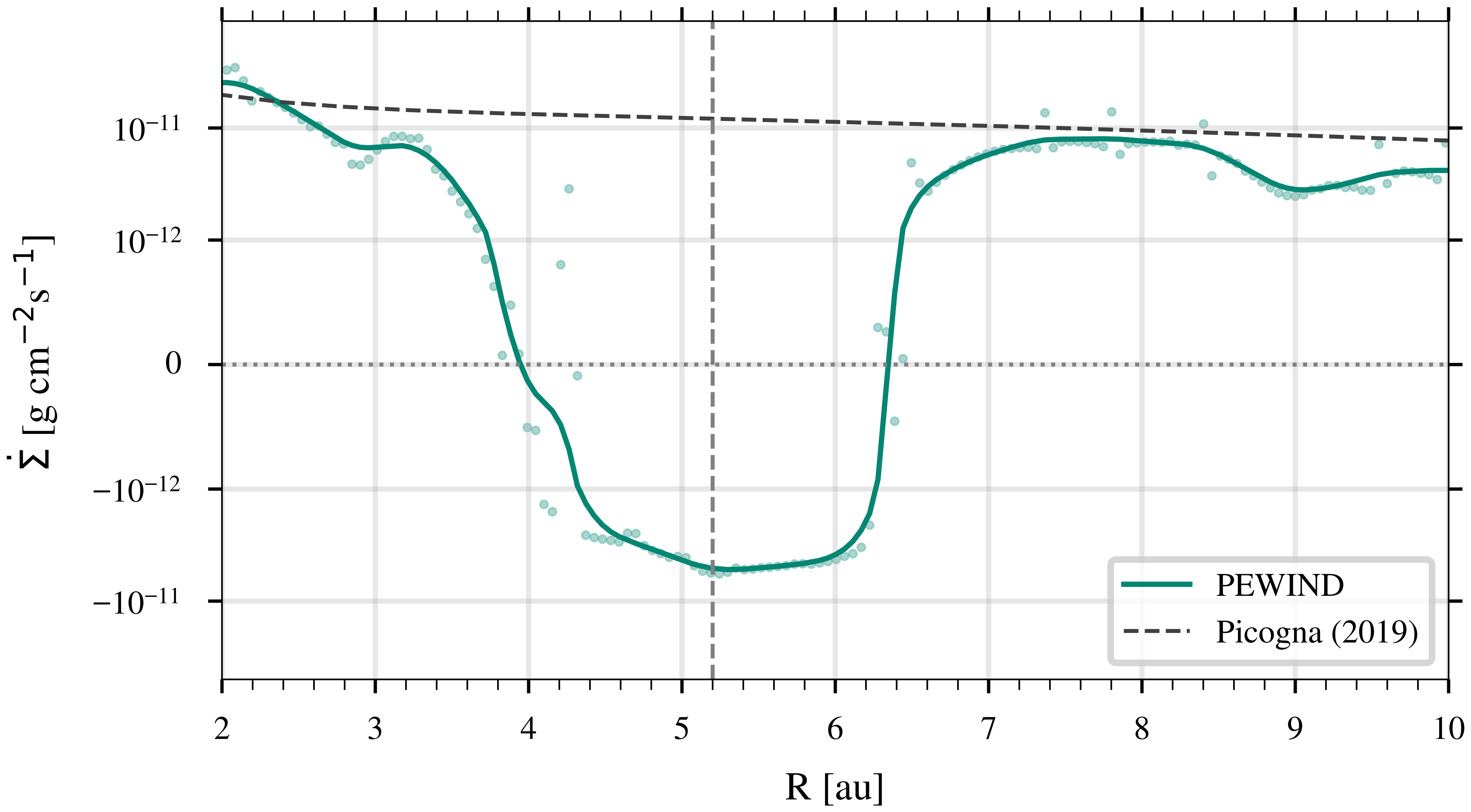


Weber, Picogna, Ercolano, in prep.

- The accretion rate onto the planet doubles when including the PE winds
- The total torque is reduced due to the increased surface density inside the planet location

Is this problematic for planet pop. synthesis models?

PLANET-WIND INTERACTION



Weber, Picogna, Ercolano, in prep.

- The mass-loss rate due to the wind is reduced by a factor 2 due to the planet presence.

Are “cold” Jupiters the solution for long-lived disks?

Few Ideas for discussion

- Do we now agree on PE mass-loss rates?
- Do we still have to worry about relic disks?
- How disk dispersal proceed (in compact disks)?
- What about intermediate mass stars?
- We should start thinking about disk evolution in the magneto-thermal wind scenario (MHD disk winds loaded by thermal winds)
- Are cold Jupiters one possible solution to long-lived disks?