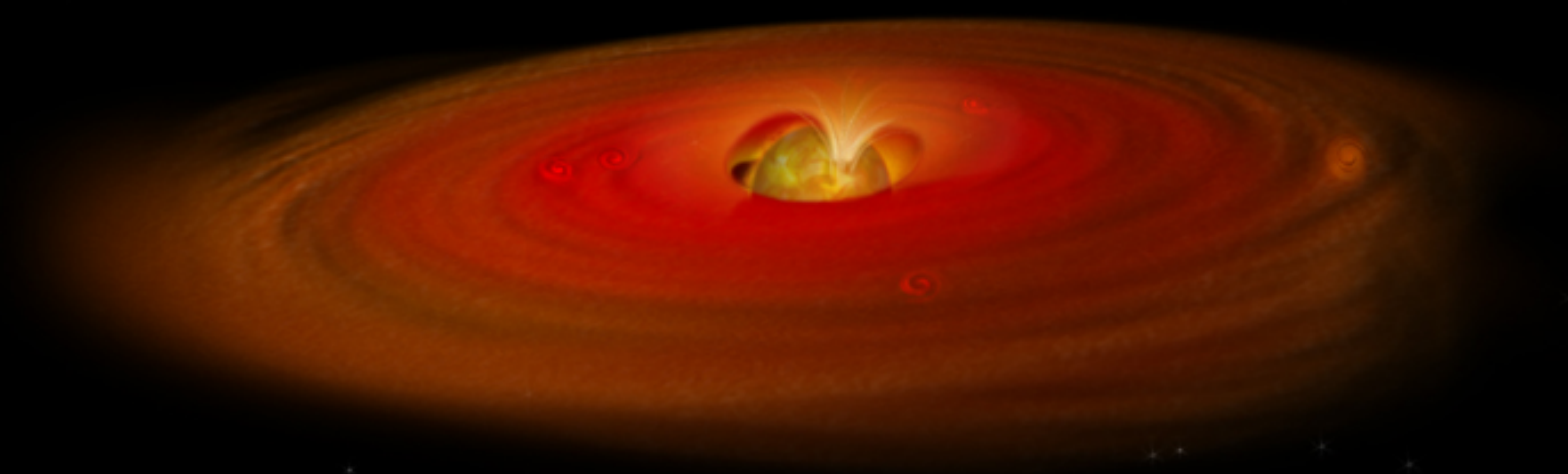
Deserts & pile-ups in the distribution of exoplanets

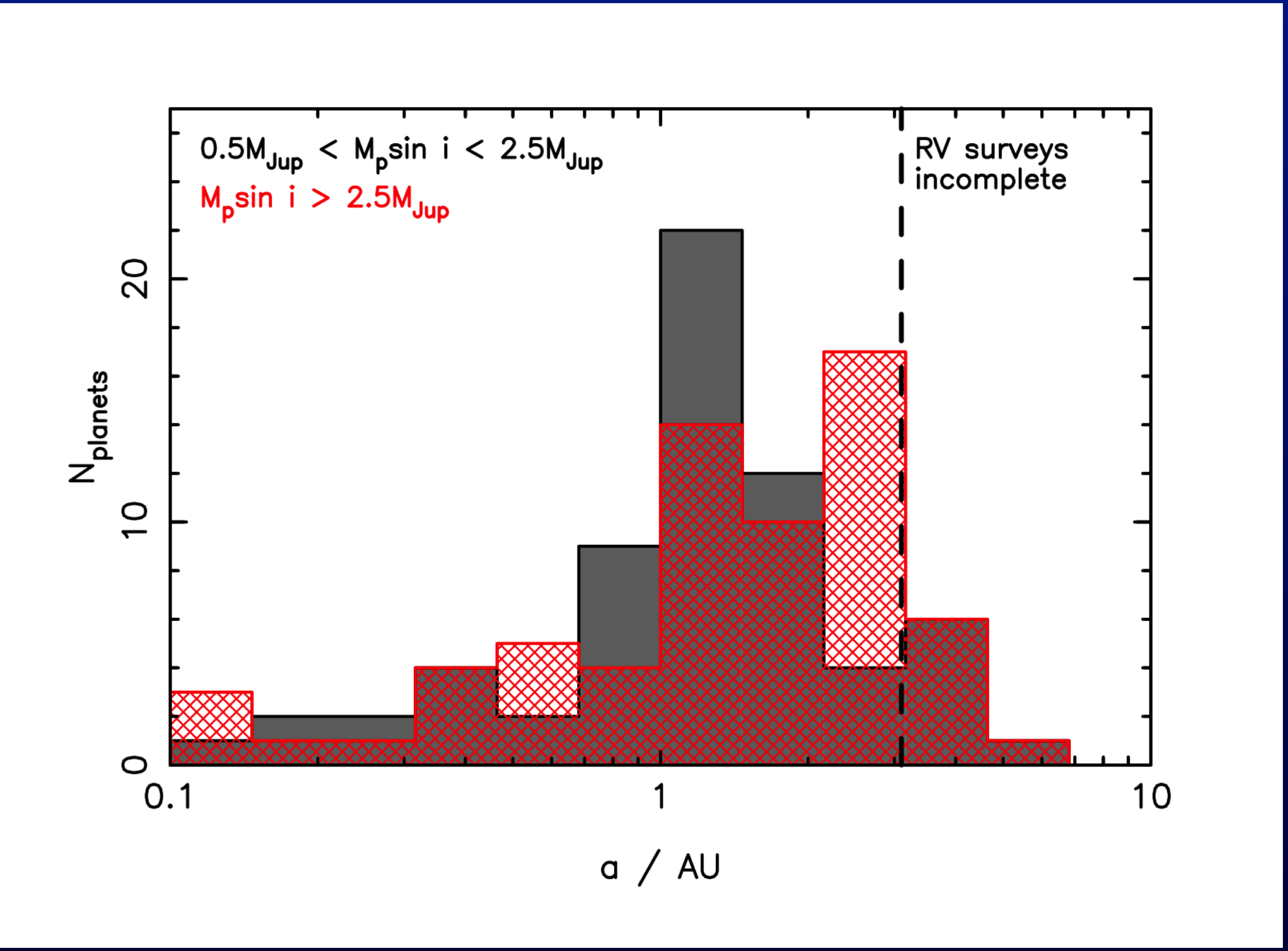


Richard Alexander
Theoretical Astrophyiscs Group, University of Leicester

"Planet Formation & Evolution", Munich, 4th September 2012

Alexander & Pascucci (2012)
(MNRAS, 422, L82 arXiv:1202.5554)

Exoplanets are not smoothly distributed



- Most prominent feature is a "pile-up" of ~Jupiter-mass planets at ~1-2AU in single-planet systems (e.g., Wright et al. 2009).
- We suggest that this is caused by migrating planets interacting with the clearing protoplanetary disc.

Planet migration must be stopped

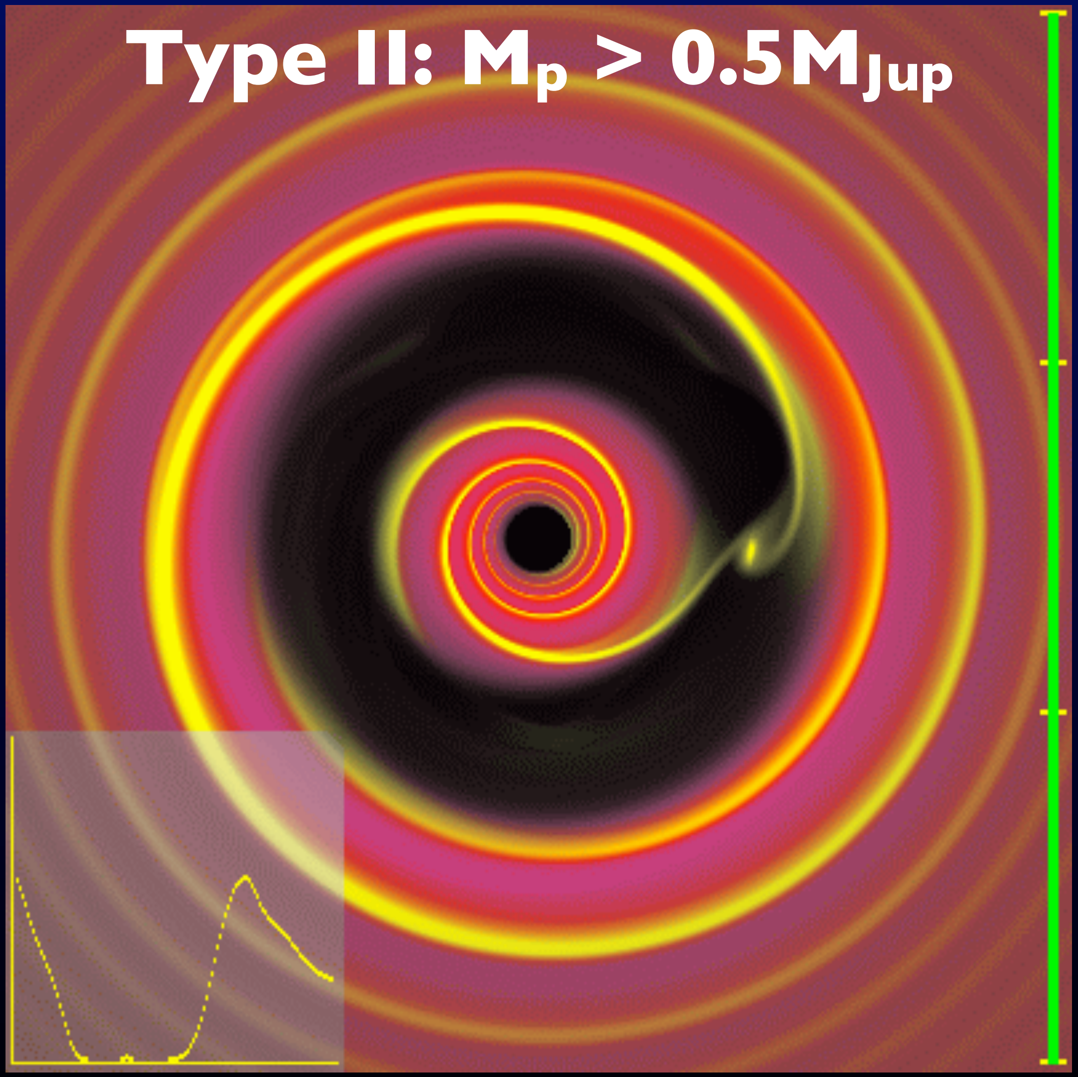
- Planets migrate through their parent protoplanetary discs:

$$t_{\mathrm{migration}} < t_{\mathrm{disc}}$$

- If planets are to survive, migration must be slowed or stopped.

- Type I migration (low-mass planets) can be halted or reversed by local perturbations in the disc structure.

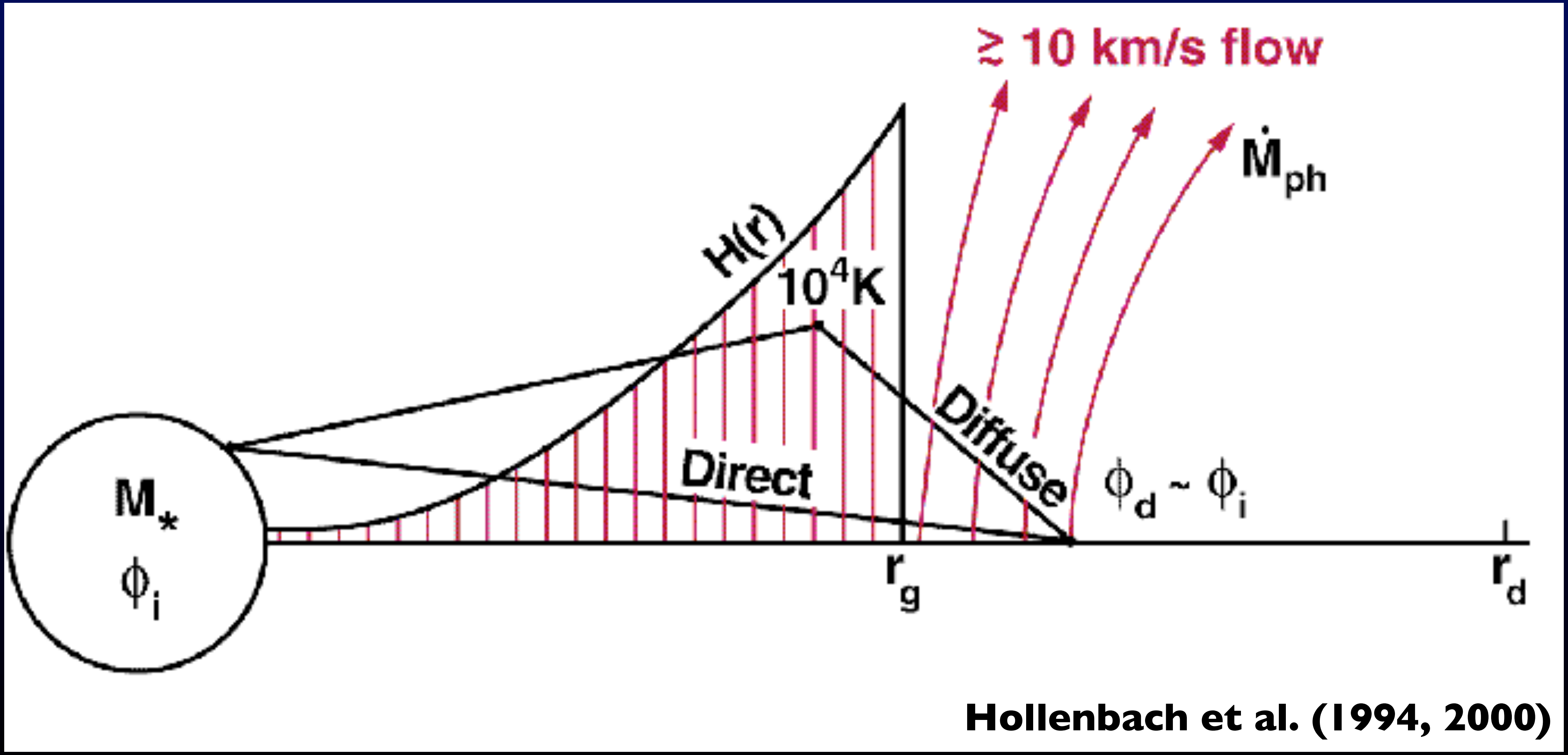
- Type II migration (giant planets) is driven by viscosity, and can only be halted if the disc gas is dispersed.



Armitage (2005)

Disc clearing is not scale-free

- Most plausible mechanism for final disc clearing is photoevaporation.
- High-energy radiation (UV/X-rays) from central star heats disc surface layers and drives a thermal wind.



Disc clearing is not scale-free

- Most plausible mechanism for final disc clearing is photoevaporation.
- High-energy radiation (UV/X-rays) from central star heats disc surface layers and drives a thermal wind.
- Wind has a characteristic radius:

$$R_{\rm g} \simeq \frac{0.2 G M_*}{c_s^2} \simeq 1 - 2\,{\rm AU}$$

- Photoevaporative winds now observed directly, through blue-shifted forbidden lines ([NeII], etc.). Good agreement with models (e.g., RDA 2008; Pascucci & Sterzik 2009; Ercolano & Owen 2010; Pascucci et al. 2011; see also talks by Sacco, Rigliaco).

The model

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{R}\frac{\partial}{\partial R}\left[3R^{1/2}\frac{\partial}{\partial R}\left(\nu \Sigma R^{1/2}\right) - \frac{2\Lambda \Sigma R^{3/2}}{(GM_*)^{1/2}}\right] - \dot{\Sigma}_{\rm w}(R,t)$$

Viscous accretion → $\frac{\partial}{\partial R}$

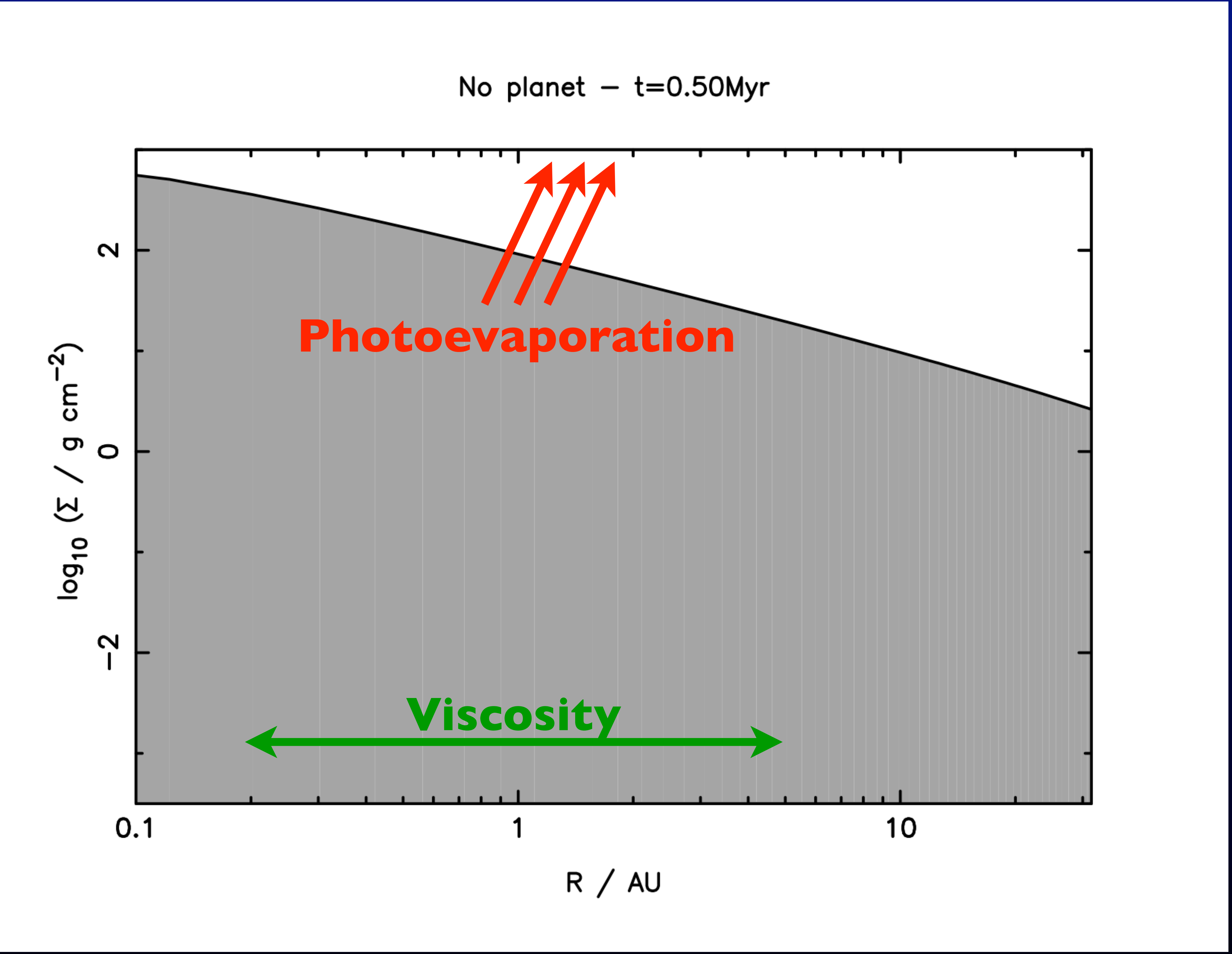
Planetary torque → $(GM_*)^{1/2}$

Photo-evaporation → $\dot{\Sigma}_{\rm w}$

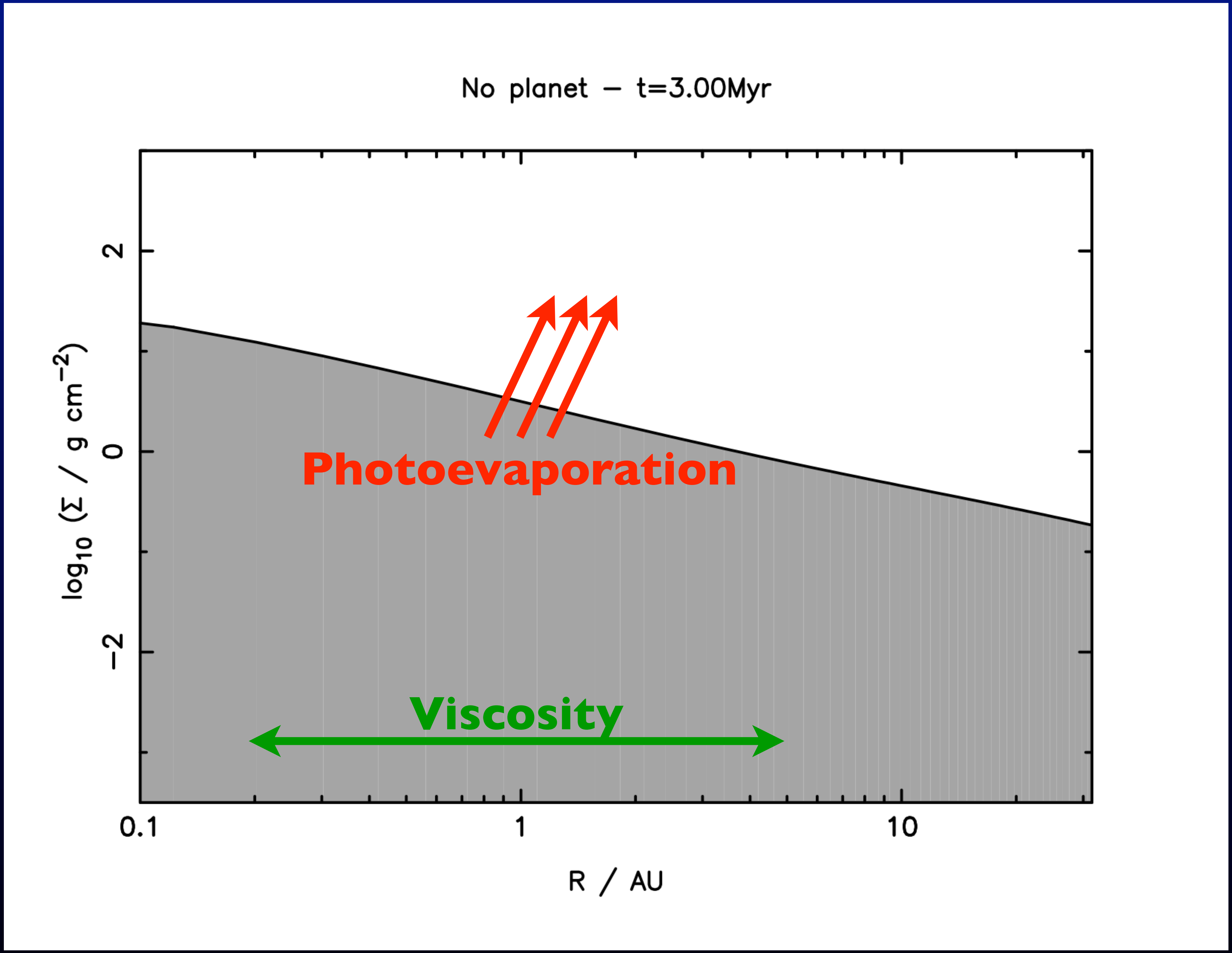
Planet migration →

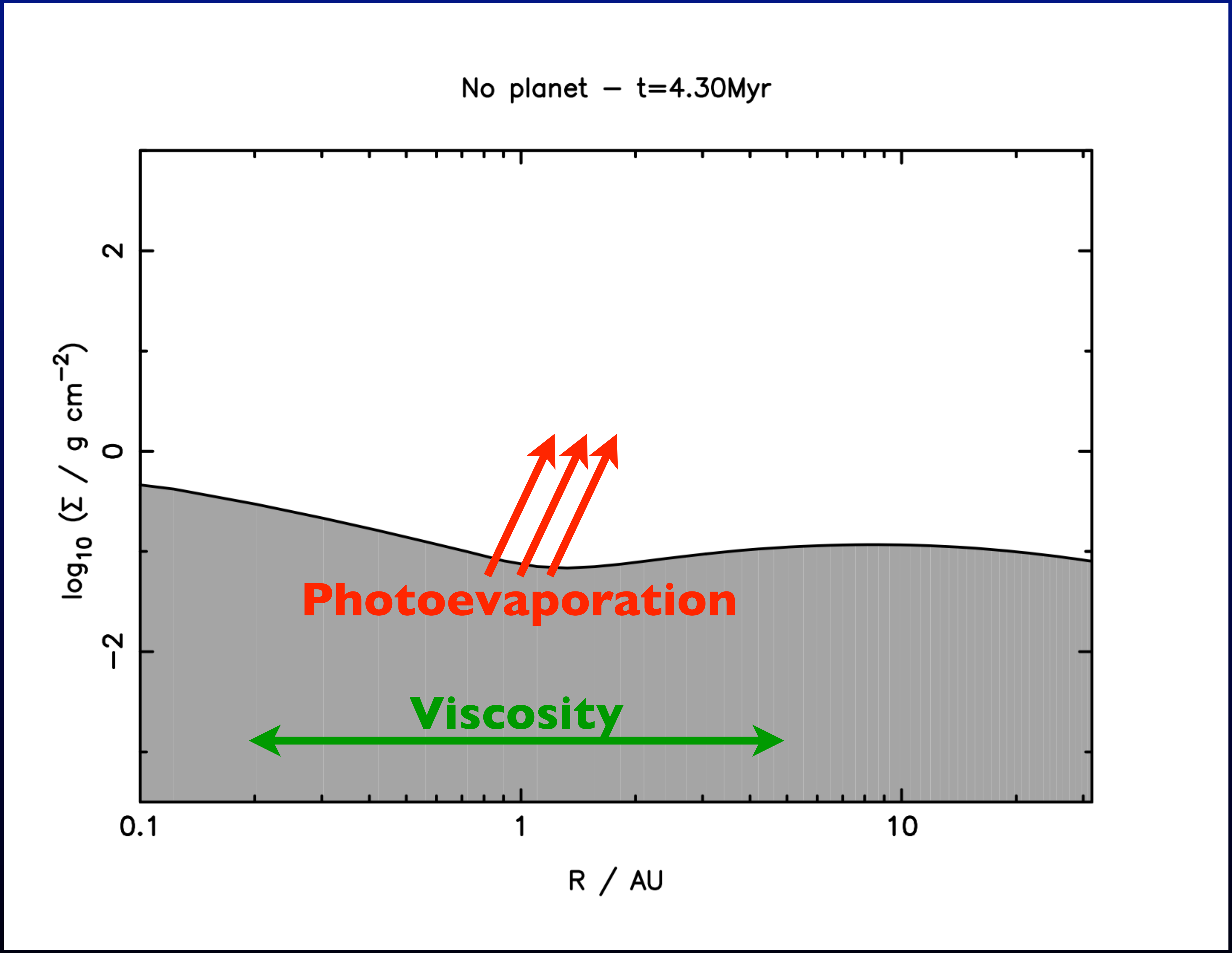
$$\frac{da}{dt} = -\left(\frac{a}{GM_*}\right)^{1/2}\left(\frac{4\pi}{M_{\rm p}}\right)\int R\Lambda\Sigma dR$$

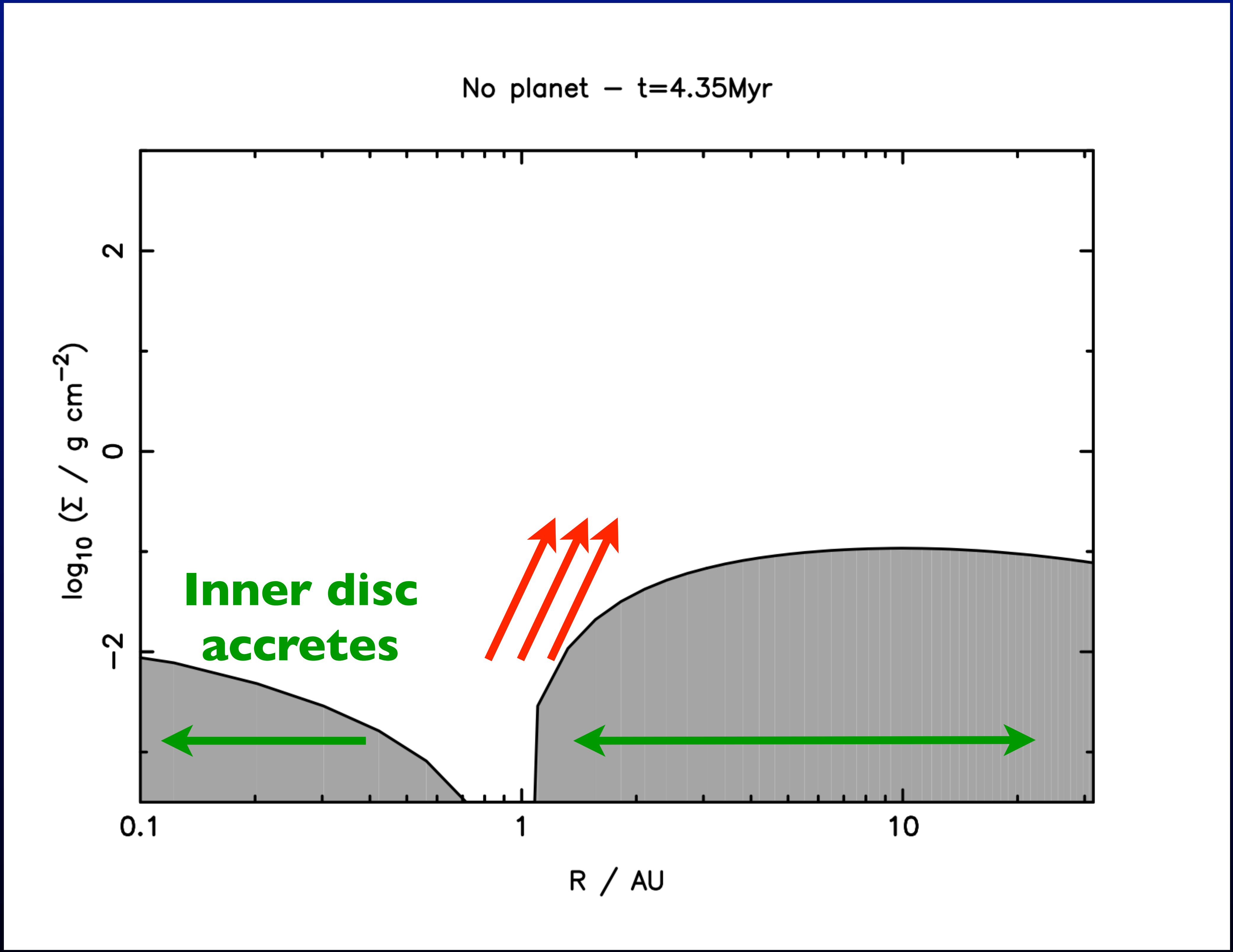
- α-prescription for viscosity.
- Standard Type II migration torque (Lin & Papaloizou 1986).
- Prescribed planetary accretion flow (Lubow & d'Angelo 2006).
- EUV photoevaporation (Hollenbach et al. 1994; RDA et al. 2006).



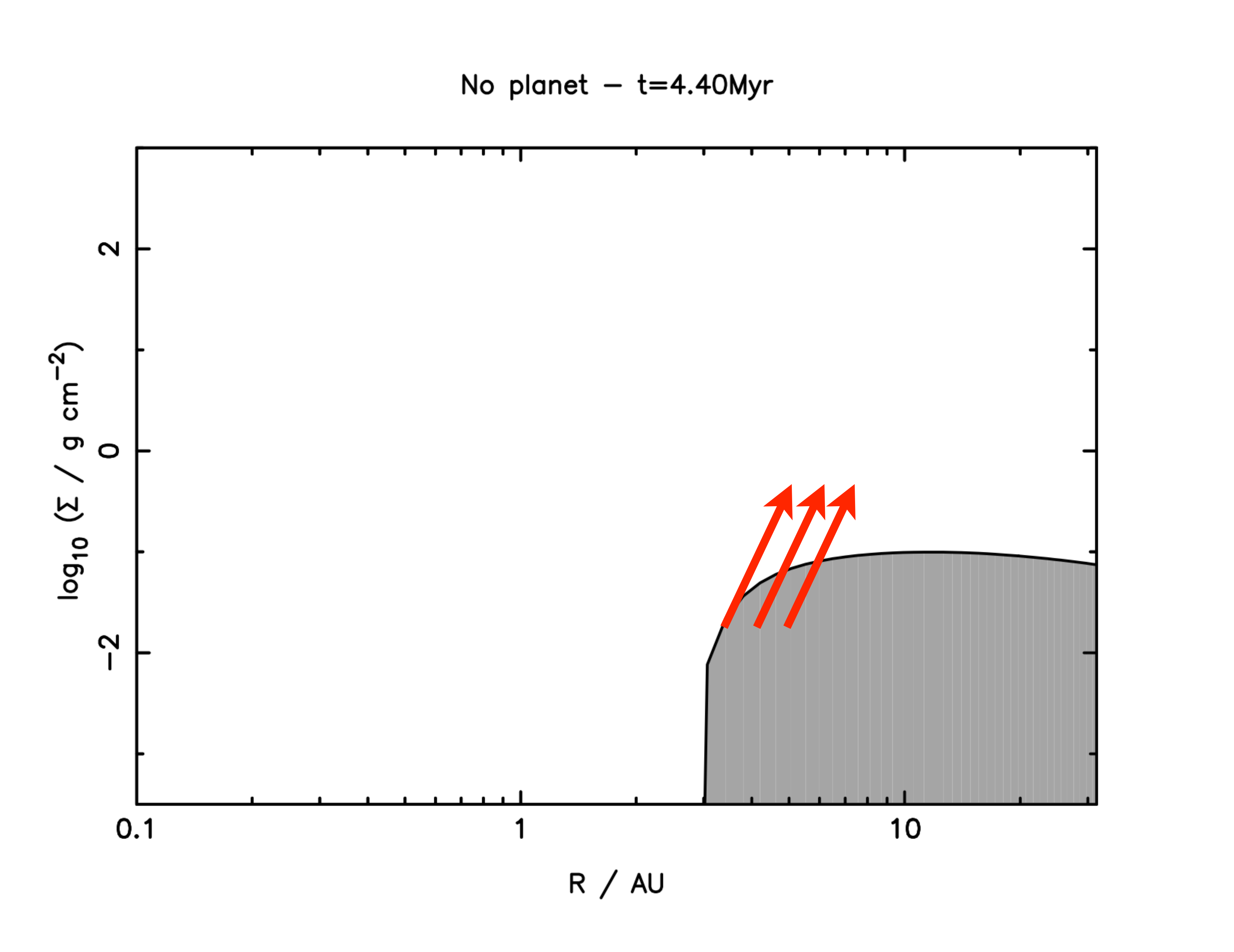
No planet – t=0.50Myr
Photoevaporation
Viscosity
log10 (Σ / g cm−2)
2
0
−2
0.1
1
10
R / AU

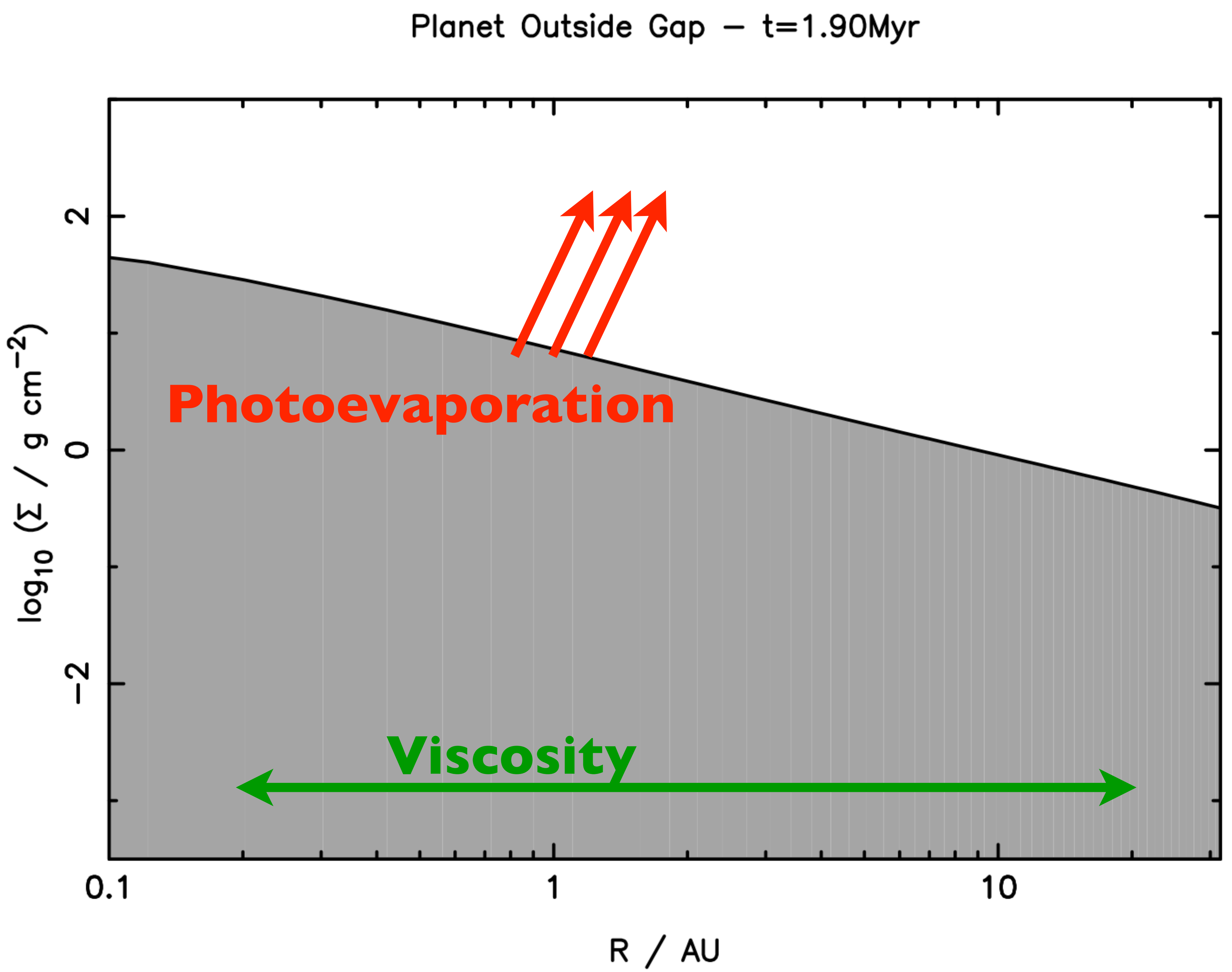

No planet – t=3.00Myr
$\log_{10}$ (Σ / g cm^{-2})
2
0
−2
0.1
1
10
R / AU
Photoevaporation
Viscosity


No planet – t=4.30Myr
$\log_{10}(\Sigma$ / g cm$^{-2})$
2
0
−2
0.1
1
10
R / AU
Photoevaporation
Viscosity

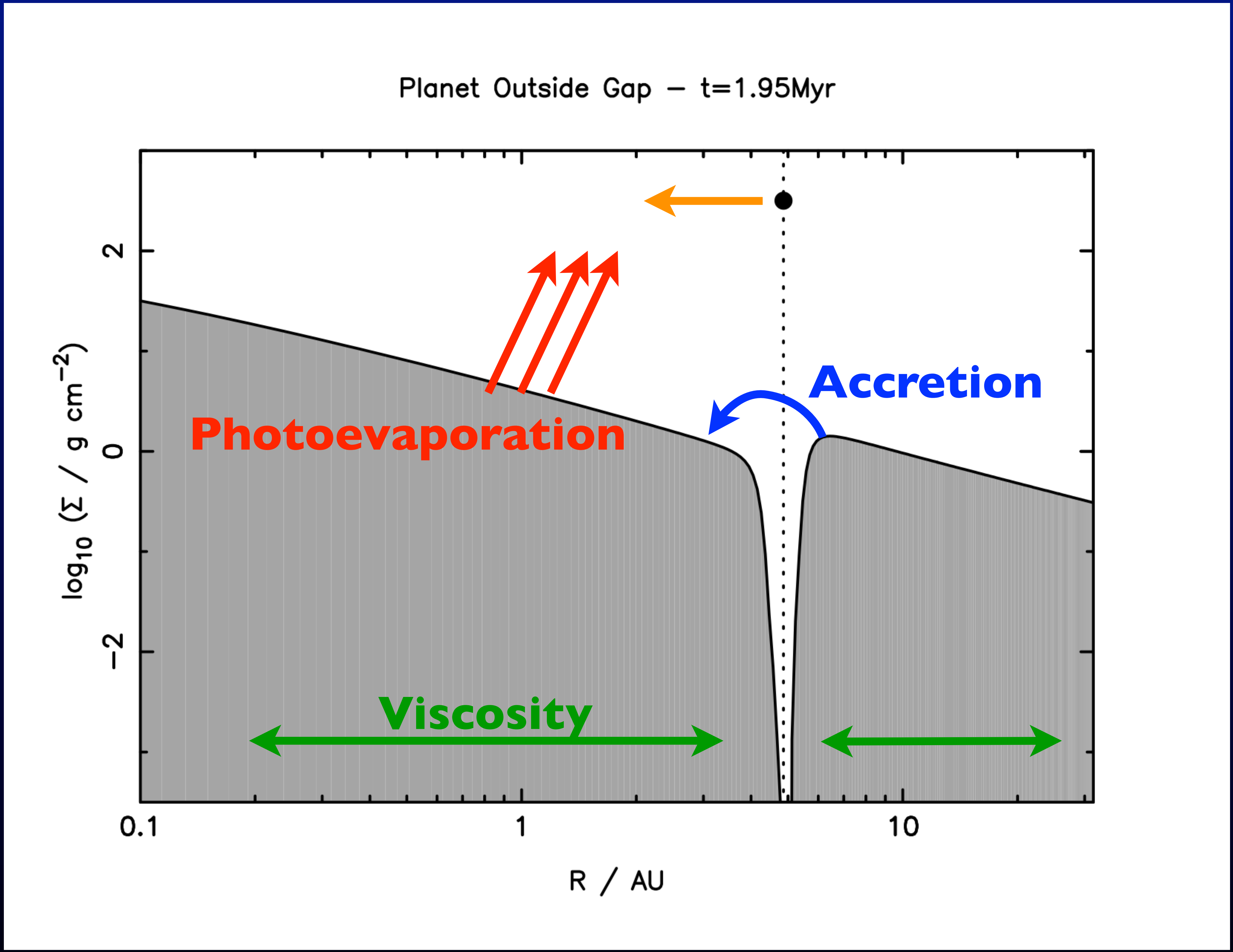


No planet – t=4.35Myr
$\log_{10}(\Sigma$ / g cm$^{-2})$
2
0
−2
0.1
1
10
R / AU
Inner disc
accretes

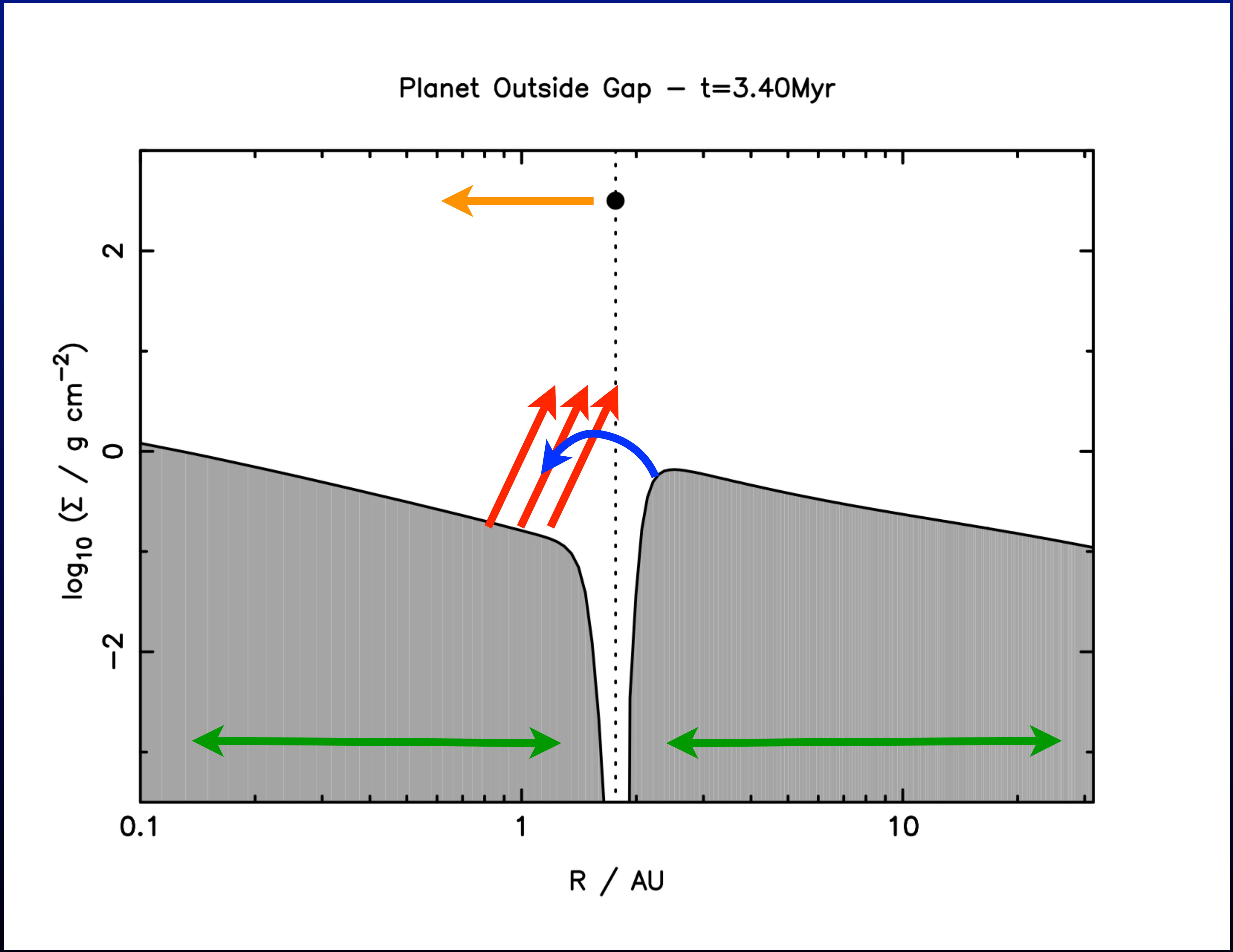

No planet – t=4.40Myr
log10 (Σ / g cm−2)
2
0
−2
0.1
1
10
R / AU



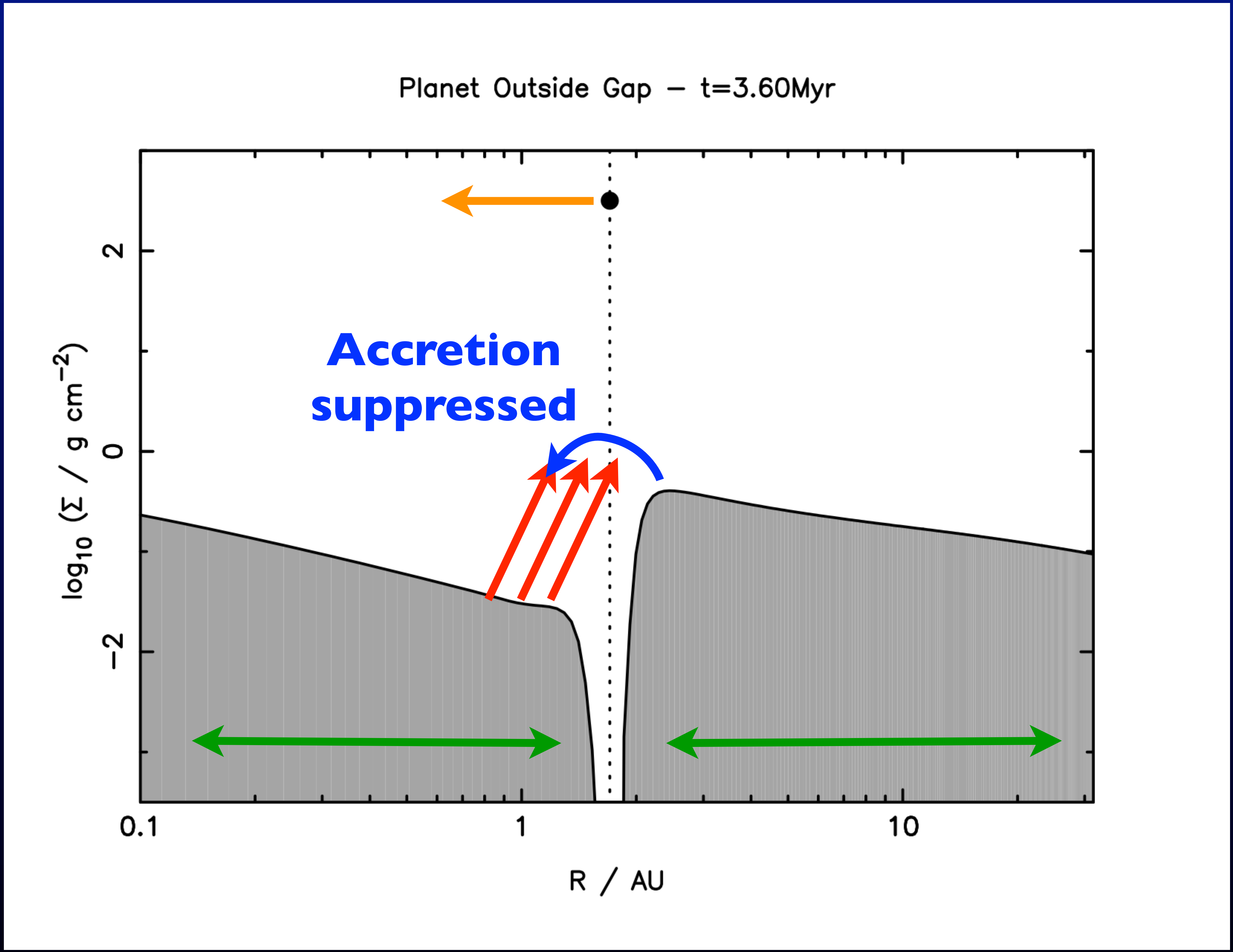
Planet Outside Gap – t=1.90Myr
Photoevaporation
Viscosity
log10 (Σ / g cm−2)
2
0
−2
0.1
1
10
R / AU



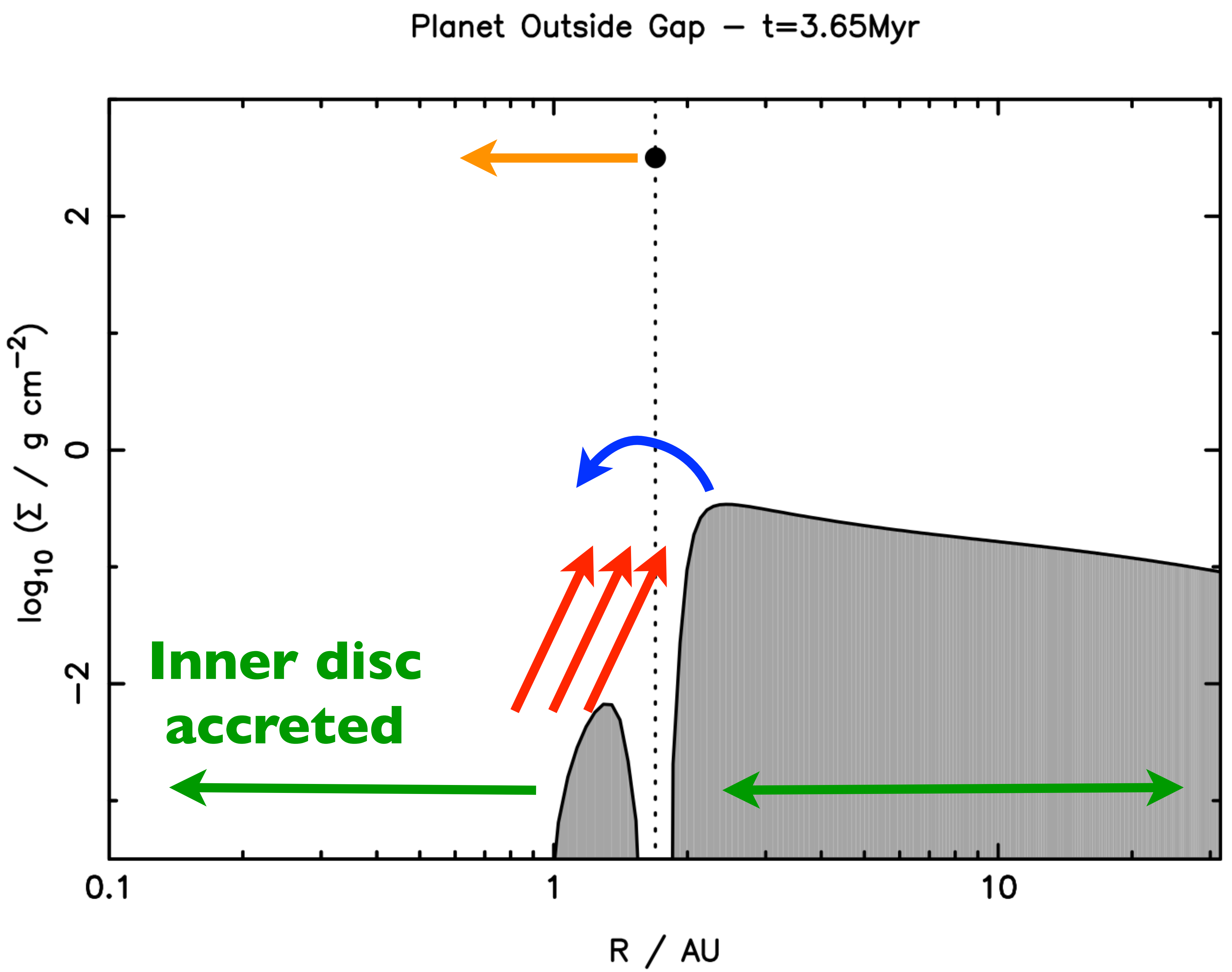
Planet Outside Gap – t=1.95Myr
log10 (Σ / g cm−2)
2
0
−2
0.1
1
10
R / AU
Photoevaporation
Accretion
Viscosity



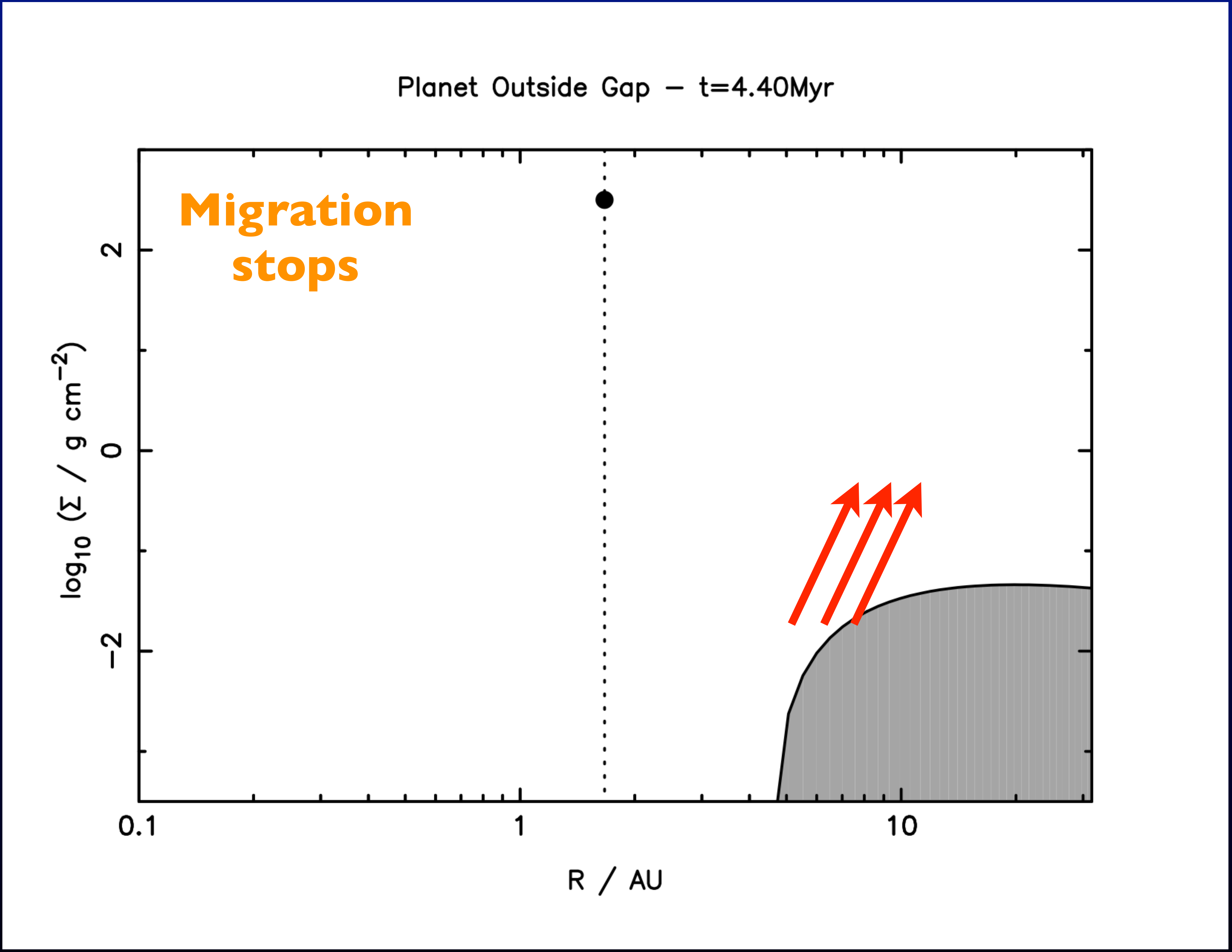
Planet Outside Gap – t=3.40Myr
log10 (Σ / g cm−2)
2
0
−2
0.1
1
10
R / AU

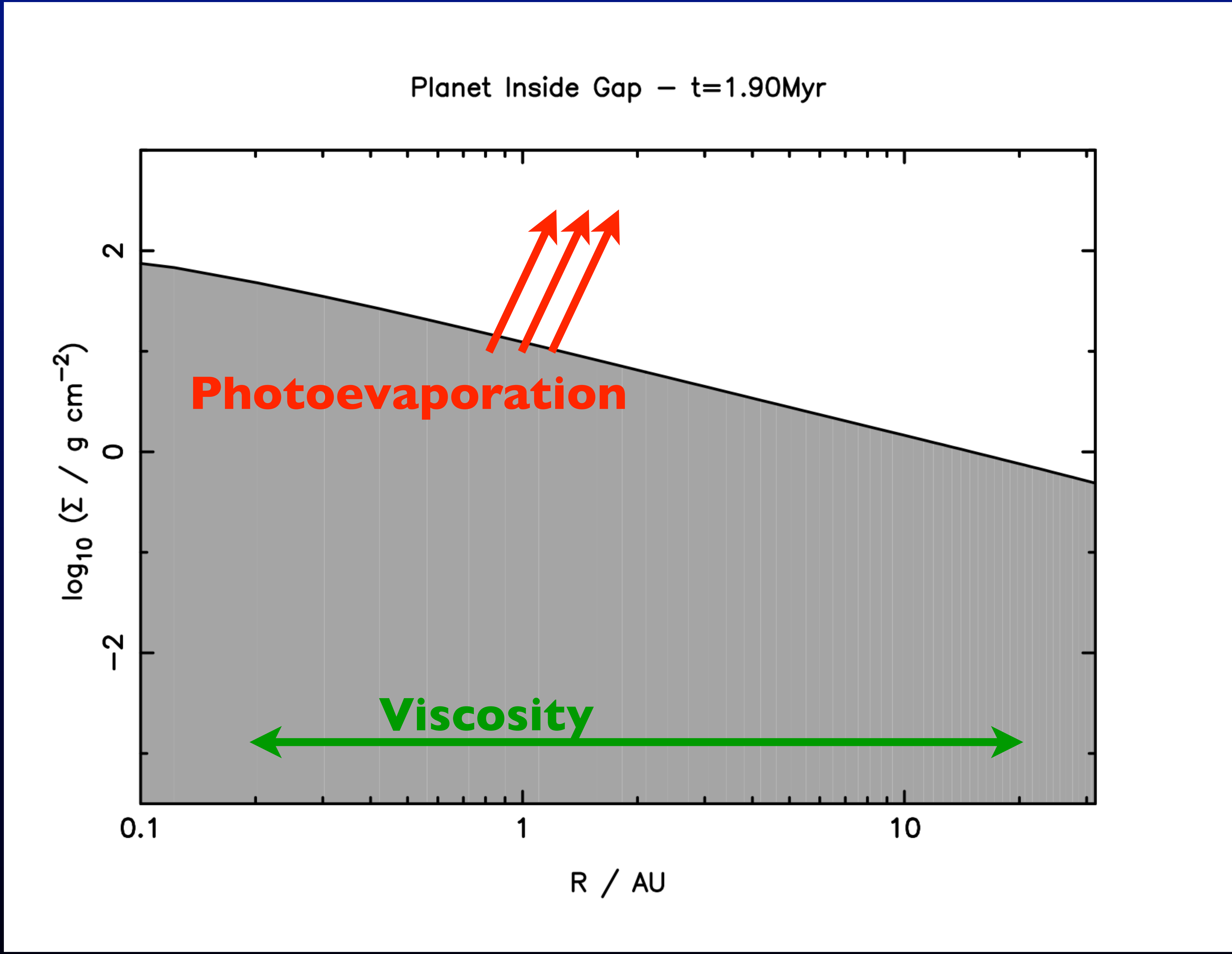


Planet Outside Gap – t=3.60Myr
Accretion suppressed
$\log_{10} (\Sigma / g\ cm^{-2})$
2
0
−2
0.1
1
10
R / AU

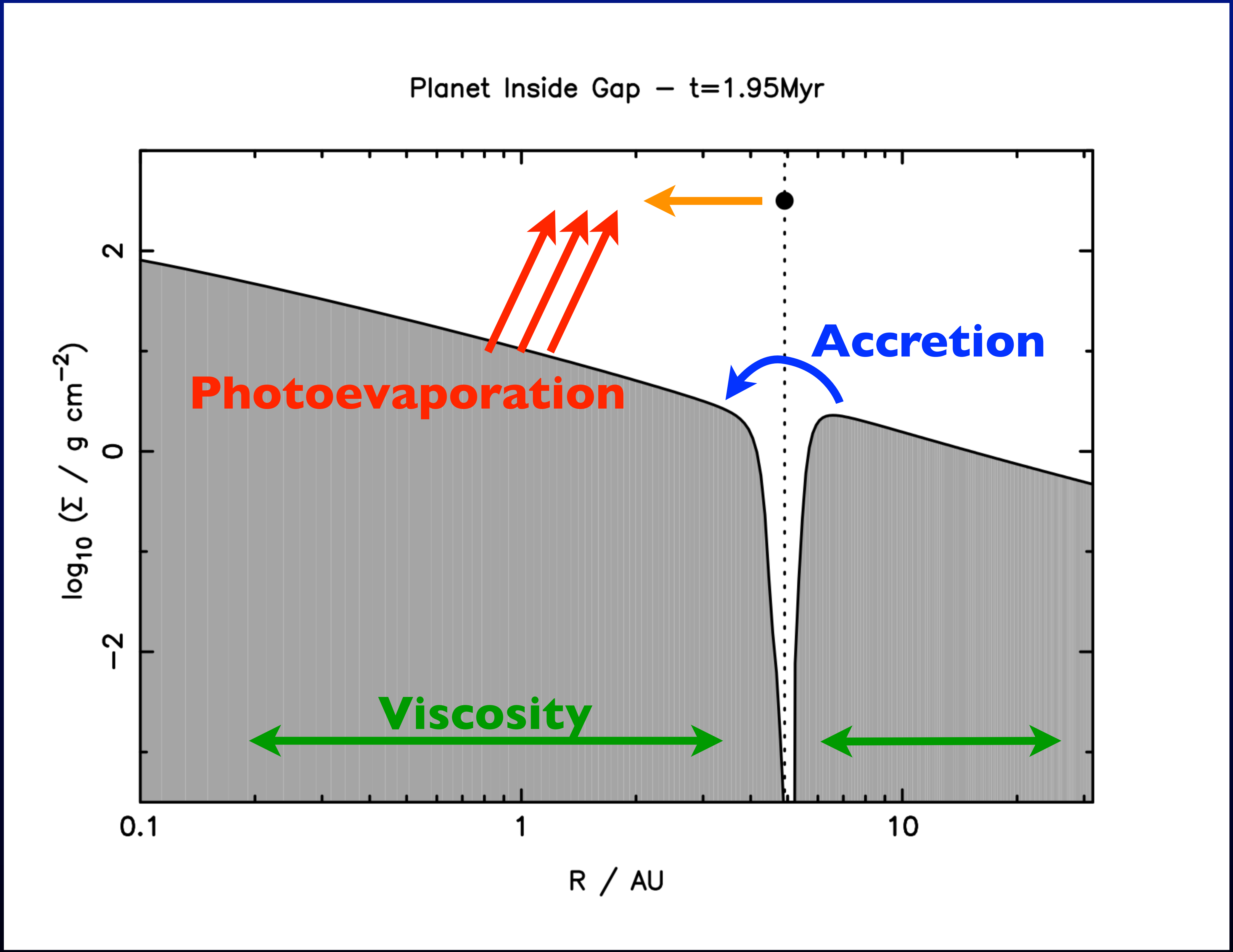


Planet Outside Gap – t=3.65Myr
log10 (Σ / g cm−2)
2
0
−2
0.1
1
10
R / AU
Inner disc
accreted

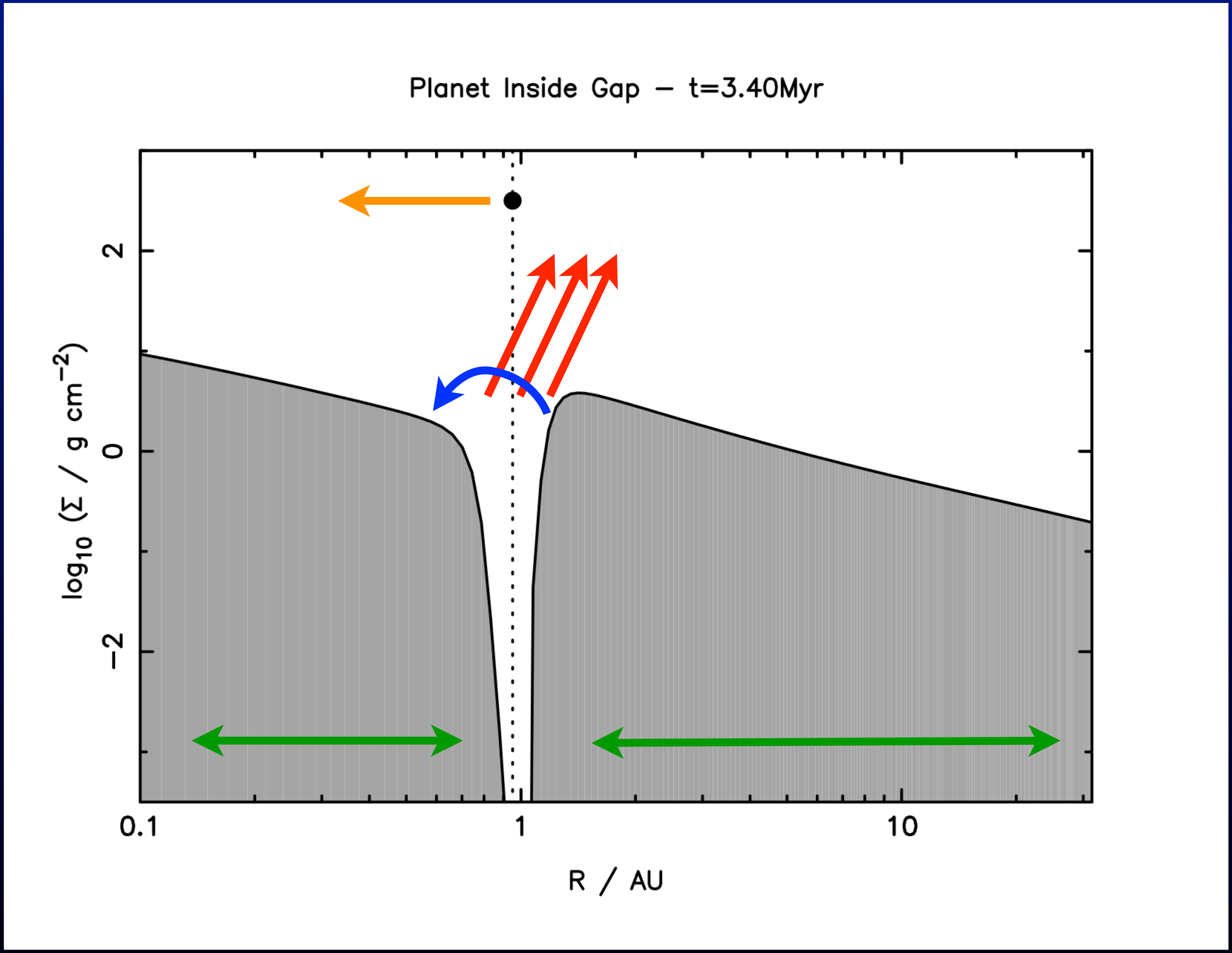

Planet Outside Gap – t=4.40Myr
Migration stops
log10 (Σ / g cm−2)
2
0
−2
0.1
1
10
R / AU



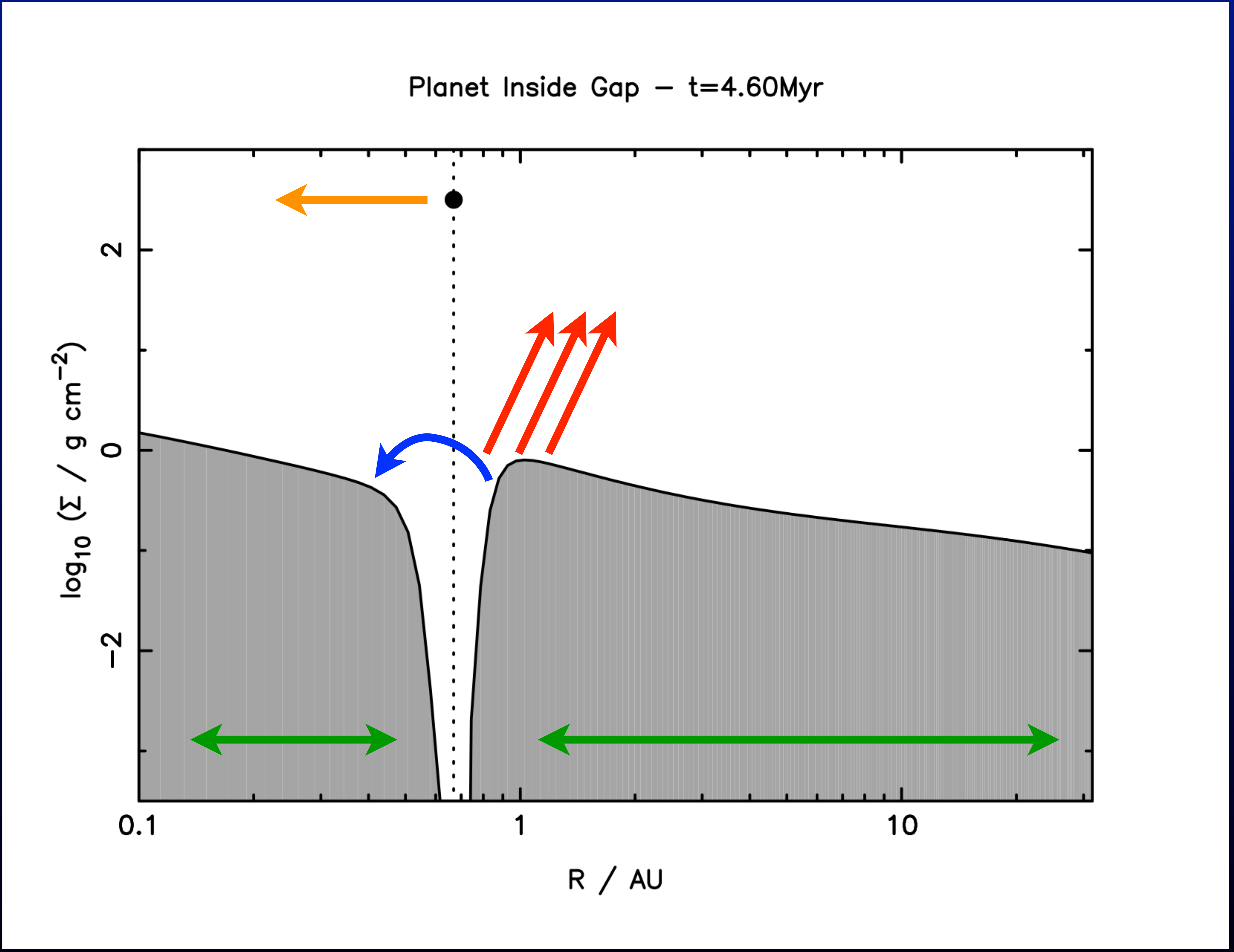
Planet Inside Gap – t=1.90Myr
Photoevaporation
Viscosity
2
0
−2
0.1
1
10
R / AU
log10 (Σ / g cm−2)



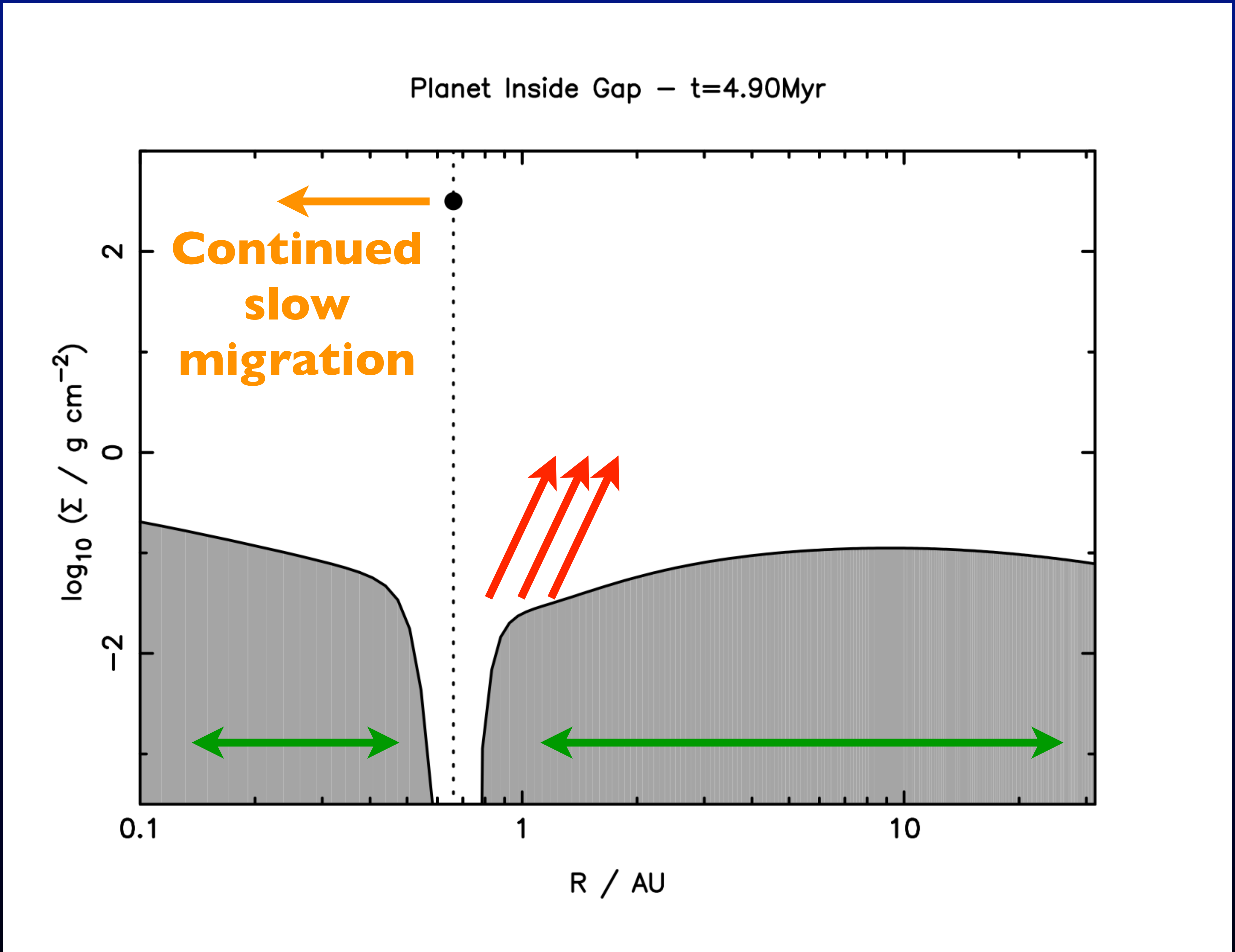
Planet Inside Gap – t=1.95Myr
Photoevaporation
Accretion
Viscosity
$\log_{10}(\Sigma\ /\ \mathrm{g\ cm^{-2}})$
2
0
−2
0.1
1
10
R / AU



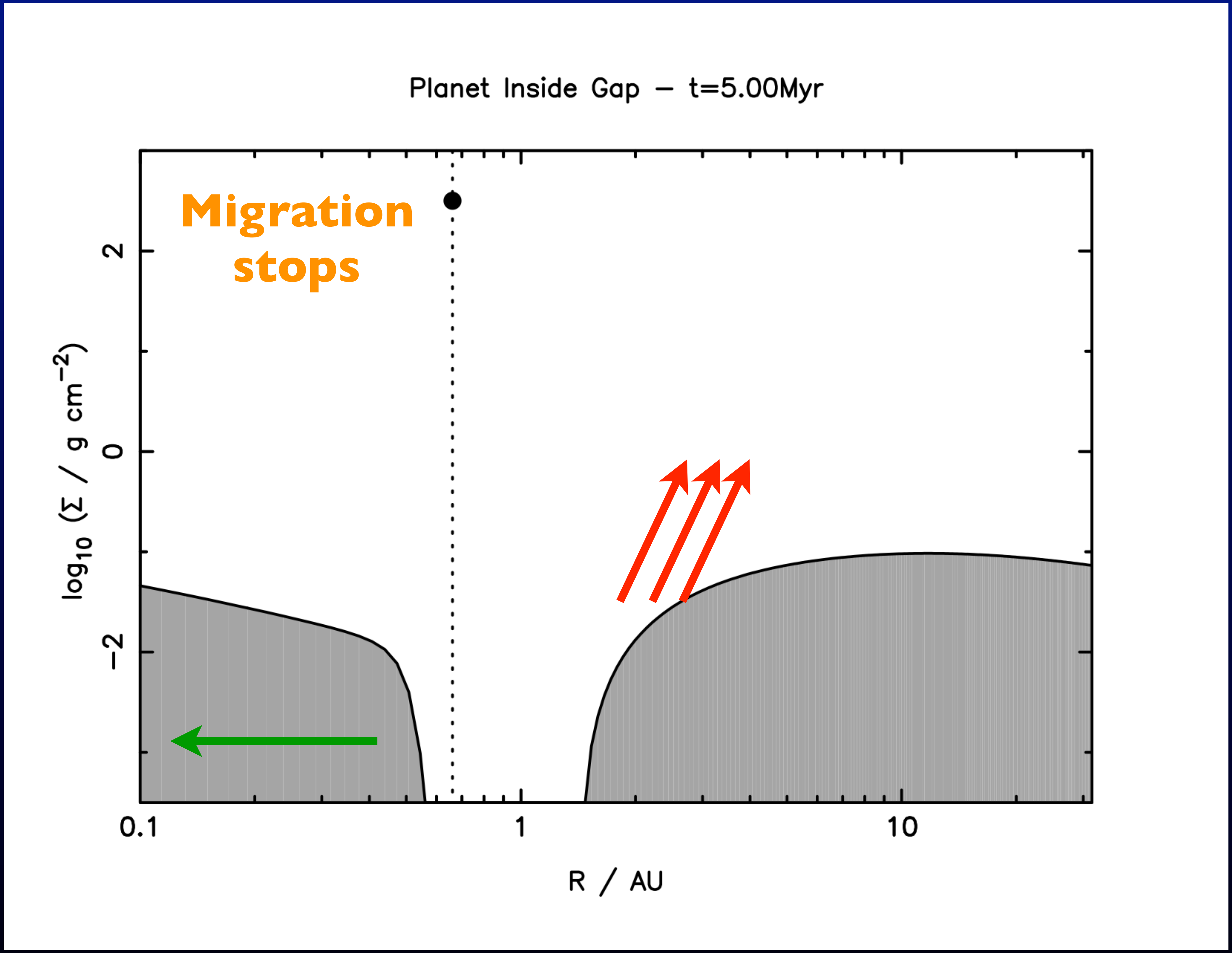
Planet Inside Gap – t=3.40Myr
2
0
−2
$\log_{10}$ (Σ / g cm^{-2})
0.1
1
10
R / AU



Planet Inside Gap – t=4.60Myr
$\log_{10} (\Sigma \ / \ g \ cm^{-2})$
2
0
−2
0.1
1
10
R / AU



Planet Inside Gap – t=4.90Myr
Continued slow migration
$\log_{10}(\Sigma$ / g cm$^{-2})$
2
0
−2
0.1
1
10
R / AU



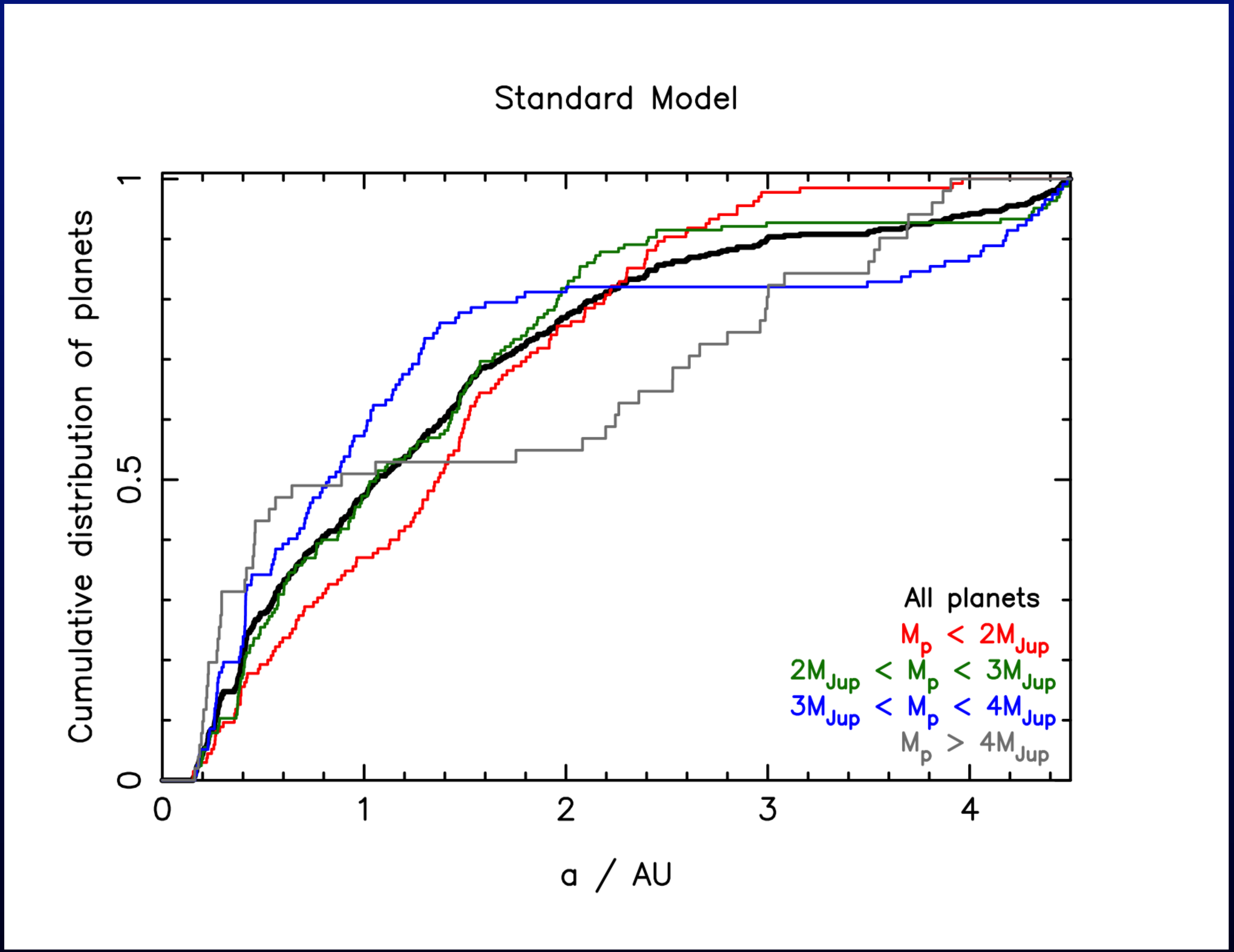
Planet Inside Gap – t=5.00Myr
Migration
stops
log10 (Σ / g cm−2)
2
0
−2
0.1
1
10
R / AU

What happens near R_g?

- Planets *inside* R_g when the gap opens continue migrating for a short time.
- Planets *outside* R_g suppress accretion and can trigger disc clearing, halting their migration.
- Net effect is a *desert* (few planets) close to R_g, and *pile-ups* (lots of planets) at smaller and larger radii.
- Dynamics are non-linear, and very sensitive to migration rate and efficiency of planetary accretion (both of which depend on M_p).
- Use Monte Carlo approach to make predictions: brute-force integration of thousands of planet/disc models.

Distribution of planets: deserts & pile-ups

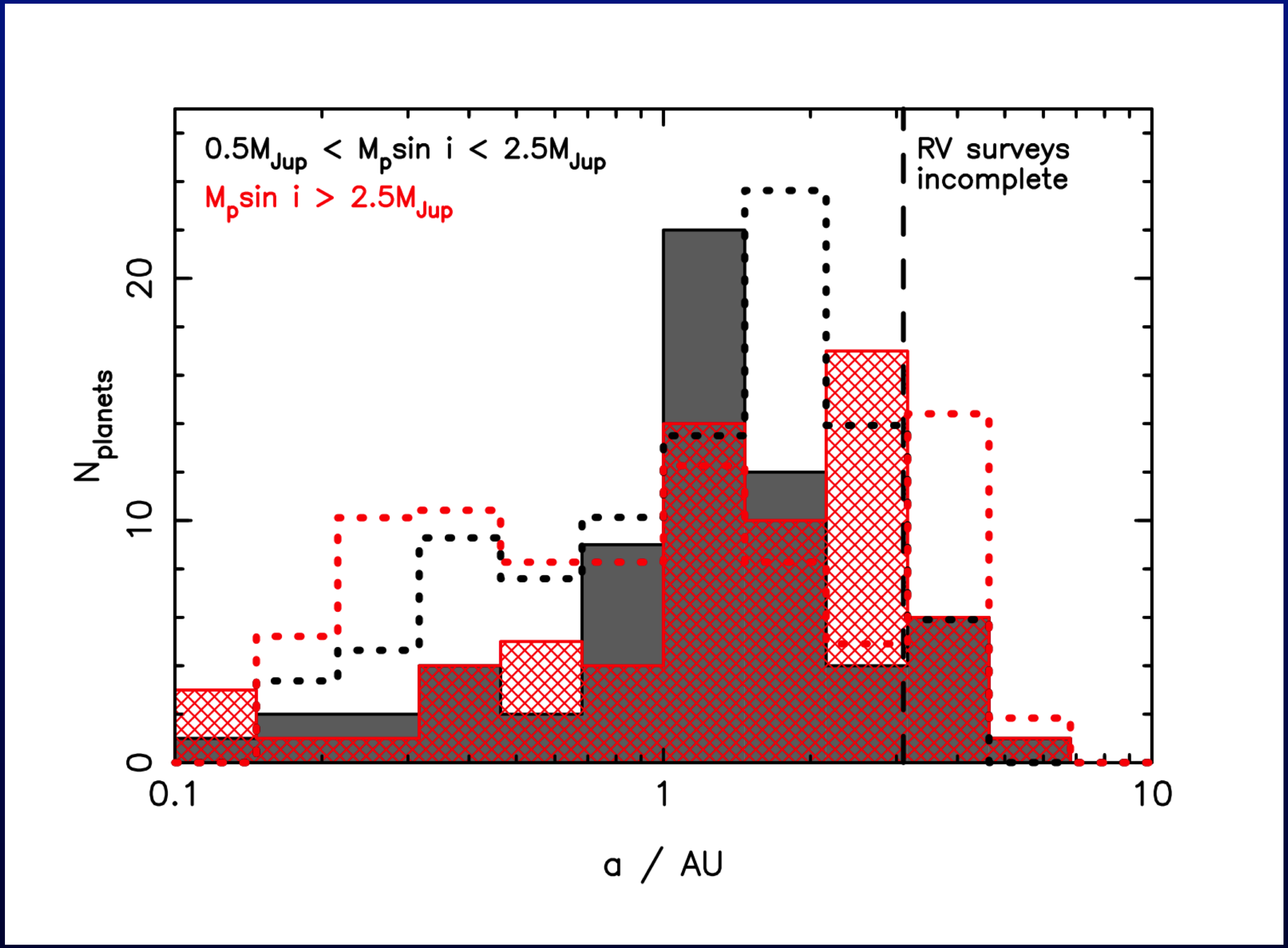
RDA & Pascucci (2012)



- Deserts & pile-ups appear at different locations for planets of different masses.

Distribution of planets: deserts & pile-ups

RDA & Pascucci (2012)



- We predict a pile-up for ~Jupiter-mass planets at ~1-2AU. A similar feature is seen in RV survey data (Wright et al. 2009).
- The observed exoplanet distribution can be used as a diagnostic of both disc clearing and planetary accretion.

Summary

- Giant planet migration (Type II) is halted by disc dispersal.
- Disc clearing by photoevaporation has a characteristic radius.
- Migration is altered close to this radius, when planets encounter the gap in the clearing disc.
- This creates deserts and pile-ups in the exoplanet distribution at ~AU radii.
- Tentative agreement with current data...