Evolution of silicate/volatile accretion disks originating from solid planetary bodies around white dwarfs

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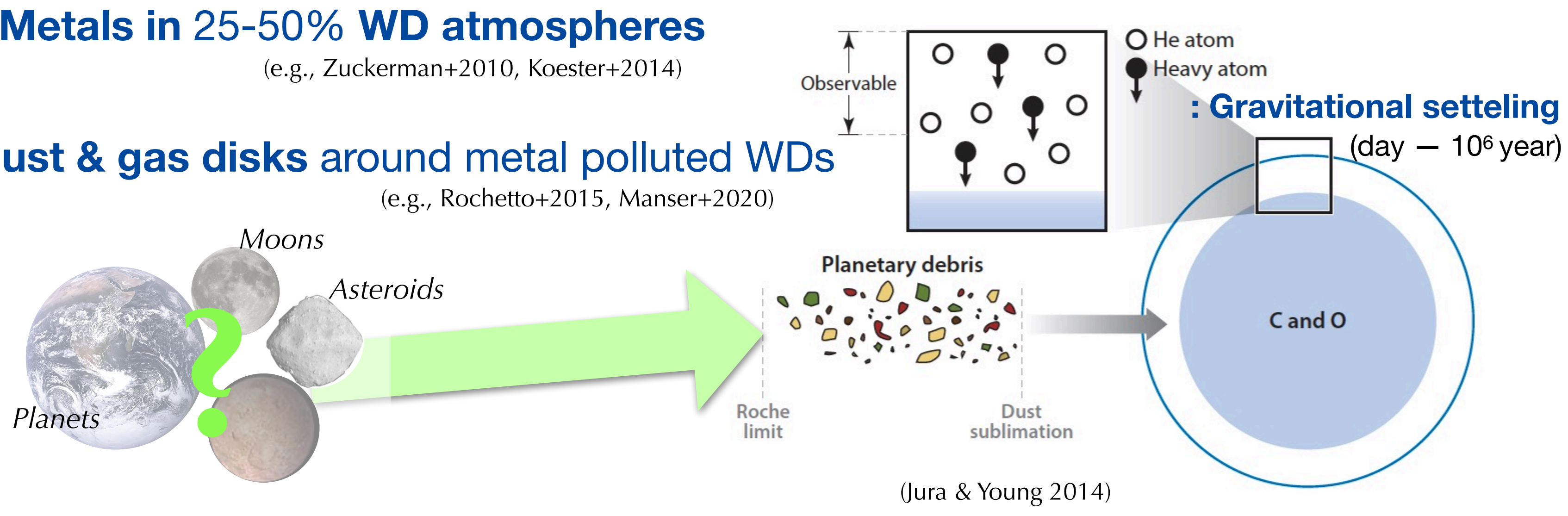
Context. Debris disks around white dwarfs are thought to originate from tidally disrupted planetary bodies and are responsible for metal accretion onto host WDs. Observations have inferred that (1) WDs with disks tend to have accretion rates higher than that induced by Poynting-Robertson drag and that (2) their photospheres show refractory-rich composition.

Aims. We revisit (1) the high-accretion rate problem to consider the simultaneous reproduction of (2) for the disks originating from rocky bodies and ice-bearing bodies.

Methods. We perform 1D advection/diffusion simulations that consistently incorporate sublimation/condensation and back-reaction to particle drift due to gas drag in solid-rich disks.

Results. We find the mono-compositional silicate disks cannot reproduce the observed high accretion rate due to the quick re-condensation of diffused vapor beyond the sublimation line. Alternatively, for the disks with volatile gas (e.g. water vapor), it enhances the silicate accretion to rates larger than PR-drag flux through gas drag. The refractory-rich accretion is simultaneously reproduced when the initial volatile fraction of the disk is $\lesssim$ 10 wt% because of the suppression of volatile accretion due to the efficient back-reaction of solid to gas.

Planetary materials in/around white dwarfs



Metals in 25-50% WD atmospheres (e.g., Zuckerman+2010, Koester+2014)

Dust & gas disks around metal polluted WDs (e.g., Rochetto+2015, Manser+2020)

: **Gravitational setteling** (day — 10^6 year)

(Jura & Young 2014)

Continuous Metal supply from external sources: Planetary accretion scenario

- The surviving asteroids/planets: scattered into star-grazing orbits (Debes & Sigurdsson, 2002; Bonsor+ 2011; Mustill+ 2018)
- Tidal disruption → Accretion through dust & gas disks (e.g., Farihi 2016) (*can explain metals in short $t_{\rm sink}$)

A disk model is needed to link WD observations to planetary composition/evolution

Observationally inferred trends to be reproduced in a model

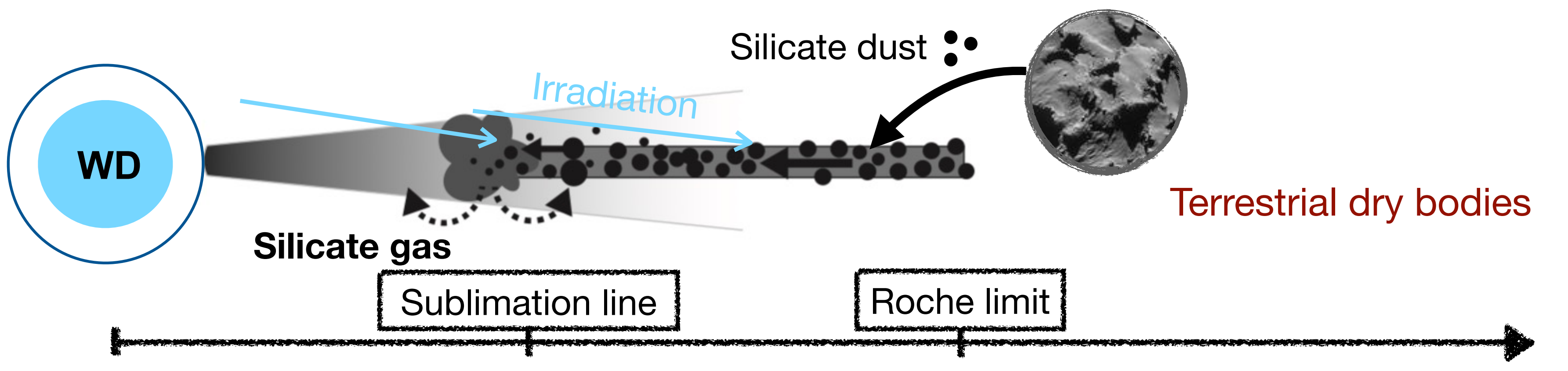
1) WD atmospheric composition：rocky-rich (Jura & Young 2014)

2) Accretion rate：$10^6 - 10^{11}$ g/s (Farihi+2009, 2010)

↑ Cannot be produced only by Poynting-Robertson drag ($\lesssim 10^8$ g/s) (Rafikov 2011)

Coupled evolution model of silicate dust and gas (Metzger et al. 2012)

- Accelerating silicate particle drift by gas drag of silicate gas → ✓(1) & ✓?(2)
- However, re-condensation of silicate gas is not included.



*Geometrically thin disk → WD irradiation from above

*As the disk becomes optically thick, radiation received by particles decreases.

We revisit the (1) high-$\dot{M}$ problem to consider the simultaneous reproduction of (2) refractory-rich photospheres.

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Coupled-evolution model of multiple components

Simulate 1D advection and diffusion of silicate particles/gas (and volatile gas)

(Modify the code of Hyodo+2019 Hyodo+2021, which is adopted for the icy snow line in PPD)

- Consistently incorporating sublimation/condensation calculation as source/sink term in equations.

Particles/gas velocities considering angular momentum exchange through gas drag

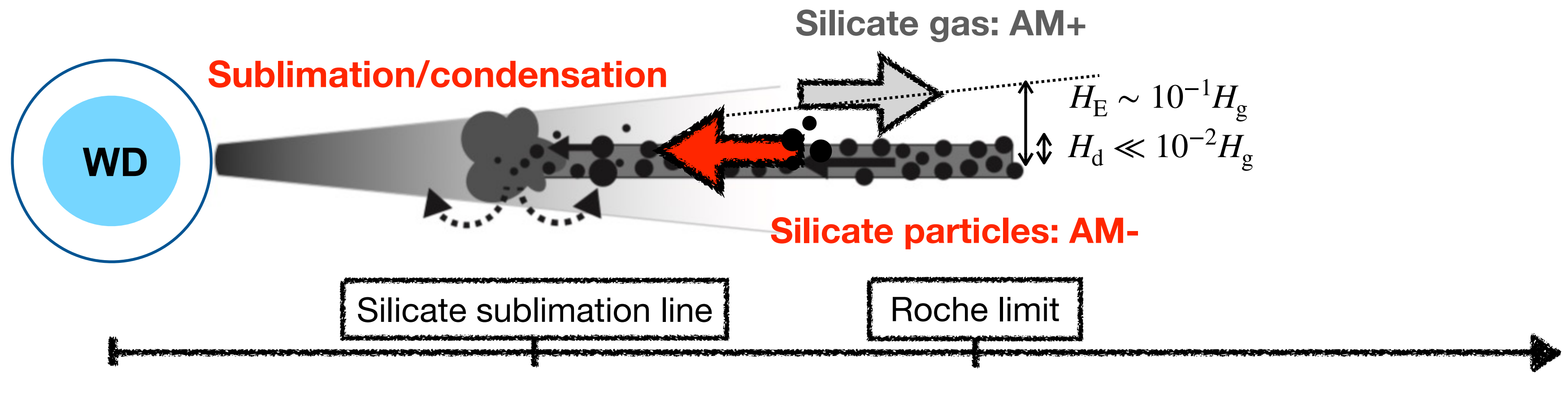
- Dust & gas exchange their AM on the surface of settled dust plates (Metzger+2012)
- Assuming the vertical turbulence of gas transports AM within to the Ekman layer

➡ Back-reaction force strength Z (below) determines the efficiency of AM exchange

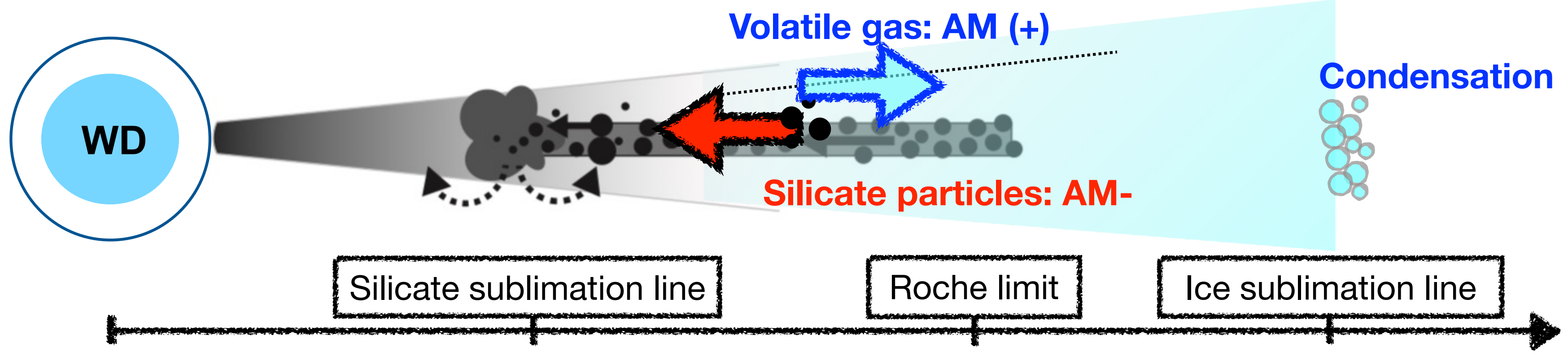
$$Z = \frac{\int_{-H_{\rm E}}^{H_{\rm E}} \rho_{\rm d}(z)\,dz}{\int_{-H_{\rm E}}^{H_{\rm E}} \rho_{\rm g}(z)\,dz} \simeq \frac{\Sigma_{\rm d}}{f\Sigma_{\rm g}^{\rm all}} \qquad f = H_{\rm E}/H_{\rm g}$$

Vertical thickness of Ekman layer：

$$H_{\rm E} \sim (\nu/\Omega)^{1/2} \sim 0.1(\alpha/10^{-3})^{1/2} H_{\rm g}$$

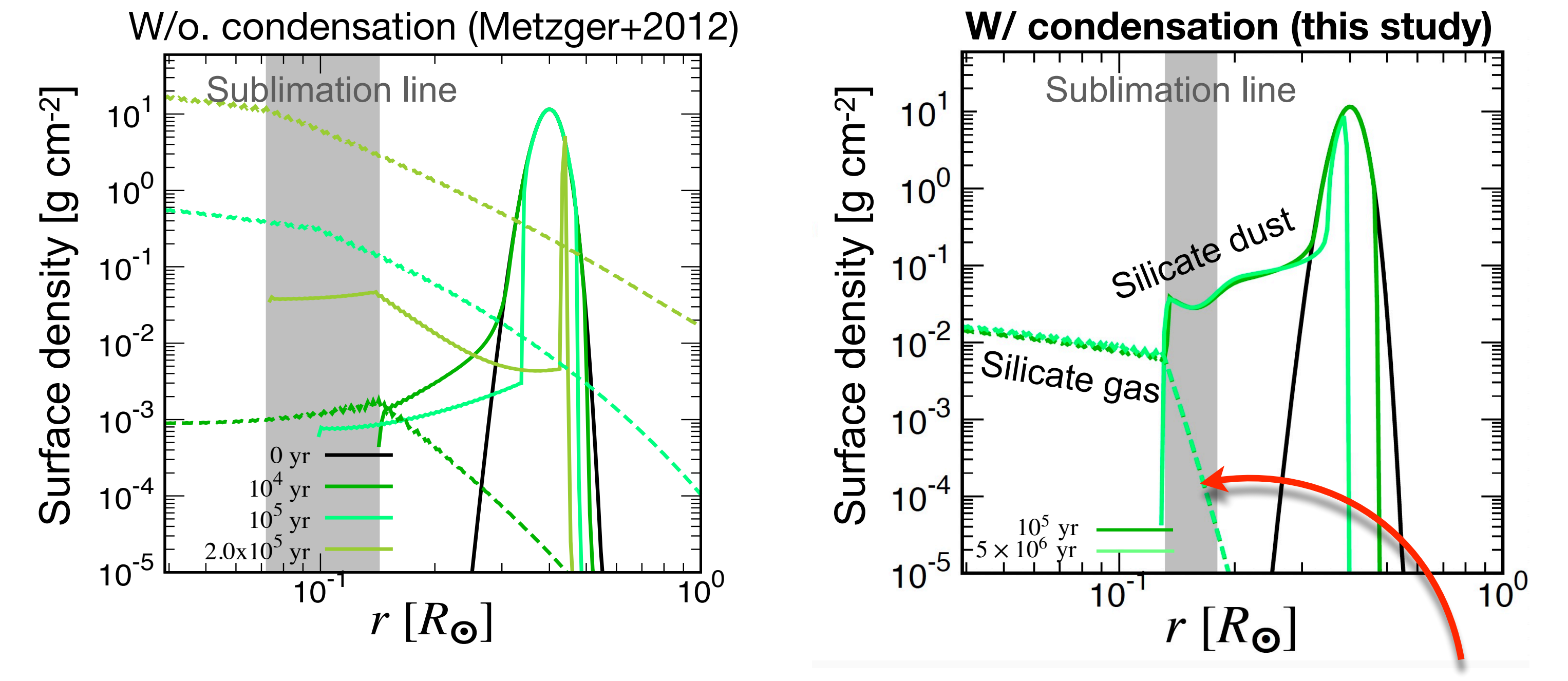


Disks originating from Ice-bearing bodies (silicate + volatile gas)



Results for mono-compositional silicate disks

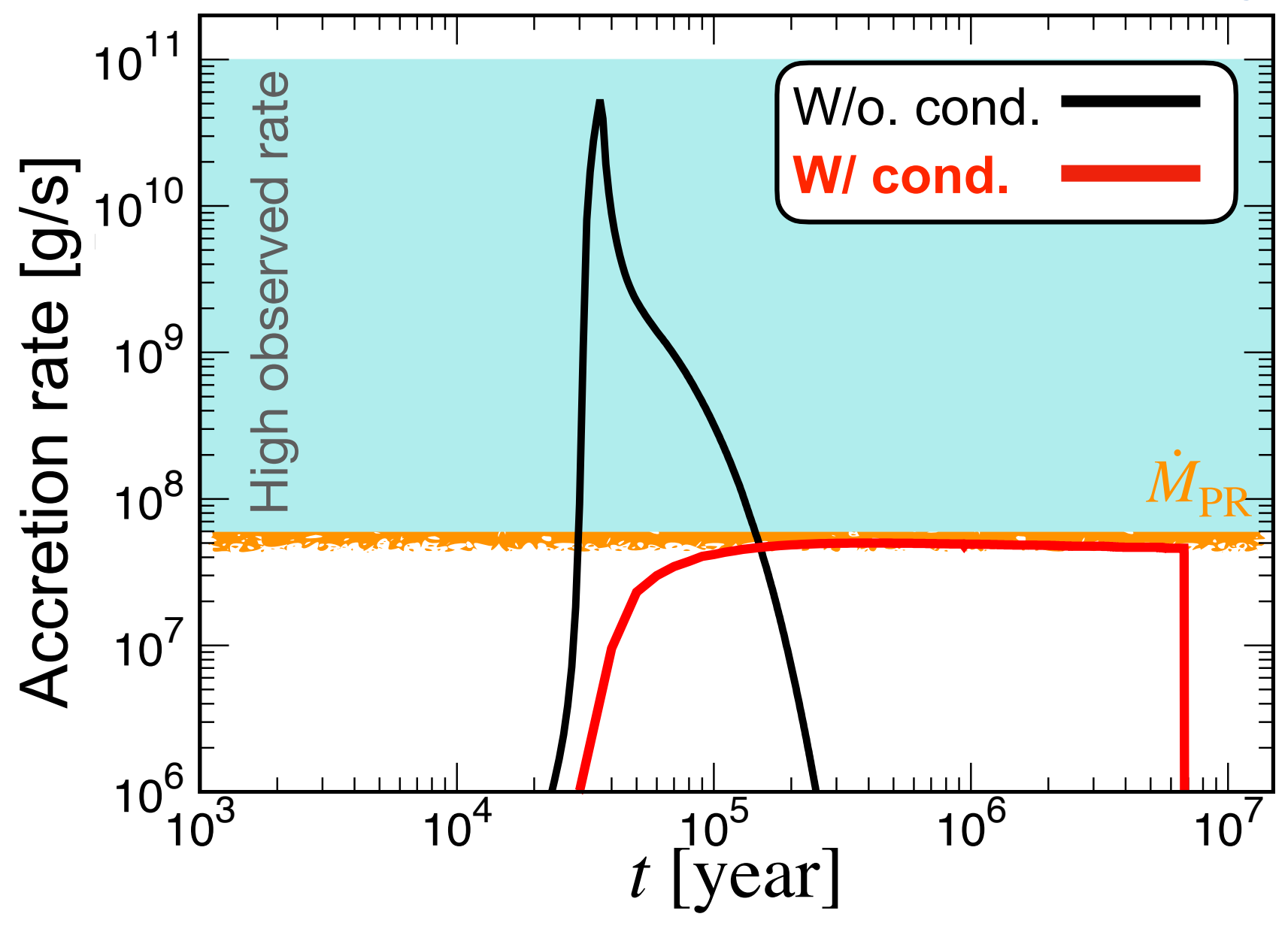
Surface density evolution of silicate dust & gas disks



The gas surface density outside the silicate line exactly follows saturation vapor pressure.

Accretion rate

Initial disk mass: 10^{23}g



✗ **Accretion rate higher than $\dot{M}_{\rm PR}$**

(∵Gas density is so low that gas-drag driven acceleration of silicate particles never occurs.)

✓ **Rocky-rich photospheres**

Results for silicate disks with volatile gas

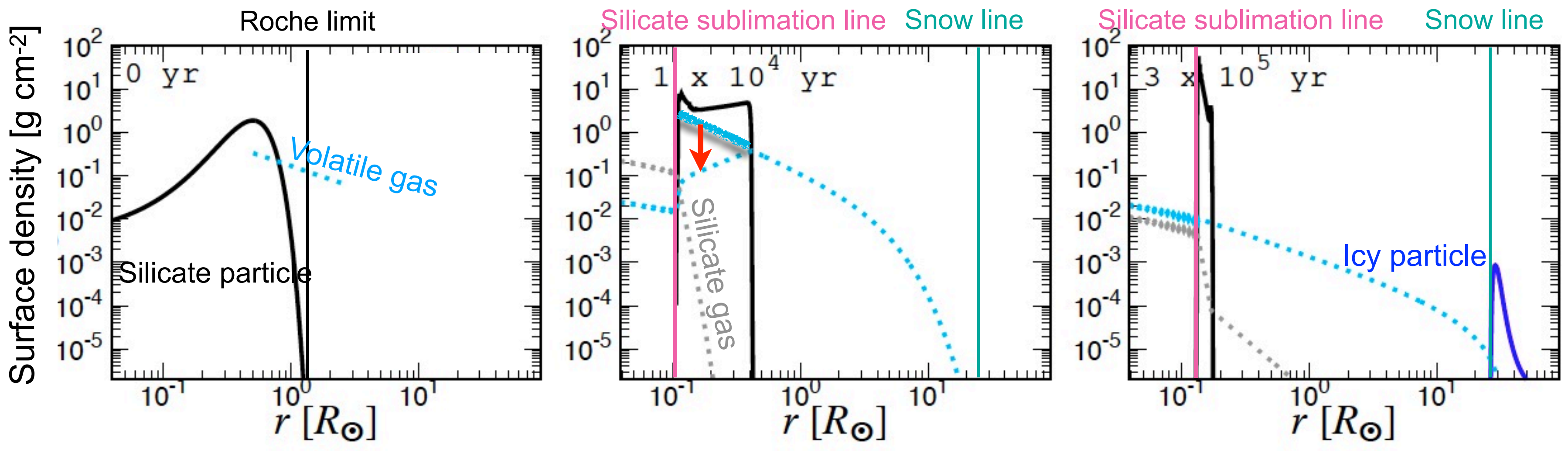
Surface density evolution of silicate gas/dust & volatile gas

*Silicate particles: Gaussian within $r_{\rm Roche}$

*Volatile gas: diffused near $r_{\rm Roche}$

*Initial particle size：1 cm (e.g., Graham+1990)

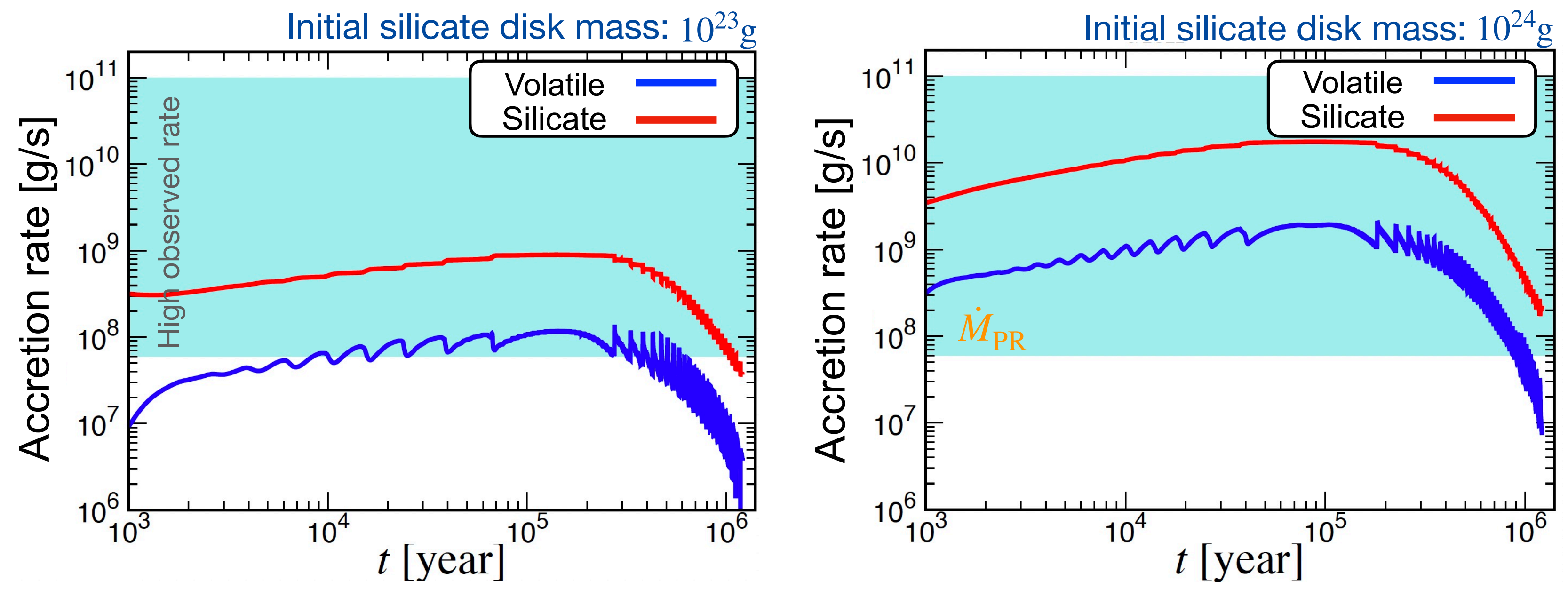
*$\alpha = 10^{-3}$



- Volatile gas disks diffuse out to snow line → **co-exist with silicate particles**
- Due to BKR of silicate dust, volatile gas density is lower in the co-existing regions.

Accretion rate from disks with initial $M_{\rm sil}/M_{\rm vol}$ = 10

Initial silicate disk mass: 10^{23}g　　Initial silicate disk mass: 10^{24}g



✓ **Accretion rate higher than $\dot{M}_{\rm PR}$**

- Due to efficient gas drag from volatile gas even for disks with $M_{\rm sil} > M_{\rm vol}$
- $\dot{M}_{\rm sil}$ can be higher for a higher disk mass. → reproduce a wide range of observed rate

✓ **Rocky-rich photospheres**

- Back-reaction of dust to gas reduces $\dot{M}_{\rm vol}$ to an order of magnitude lower value than $\dot{M}_{\rm sil}$ over all accretion phases.

Ceres-sized bodies with a small amount of ice would be a plausible origin

*To explain observed H fraction in WD atmospheres, $\dot{M}_{\rm vol}$ should decrease by an order of magnitude (Jura & Xu 2012)

→ Possibility of H escape due to XUV irradiation of WDs? (Okuya, Ikoma & Nakayama in progress)