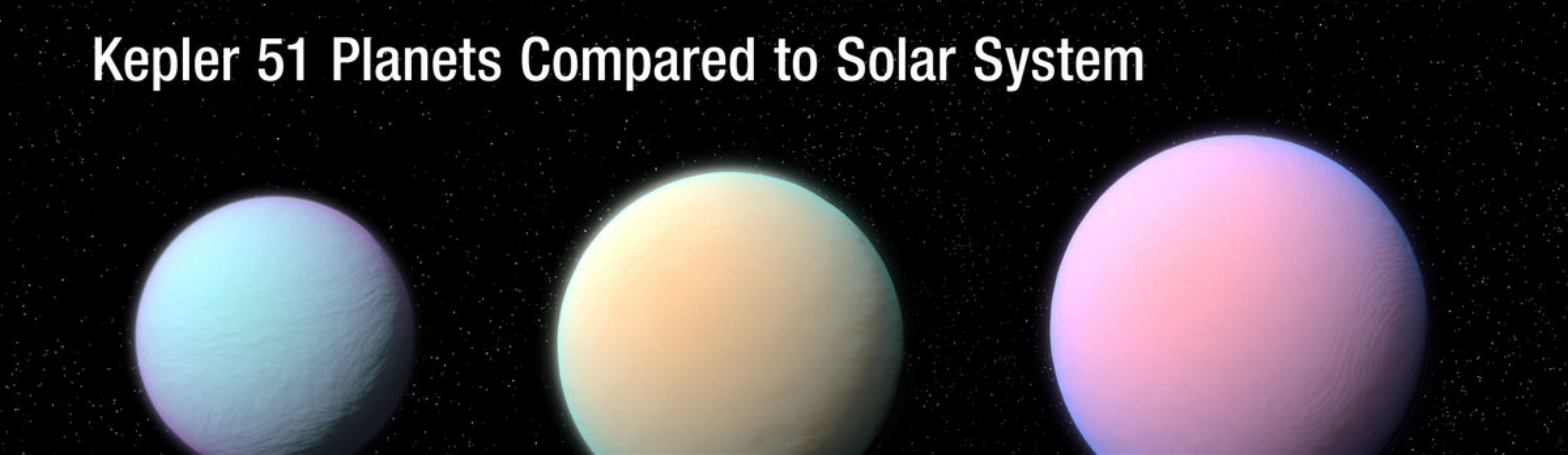

Aerosols in escaping atmospheres:
Implication for Transmission Spectra and Origin of Super-puffs

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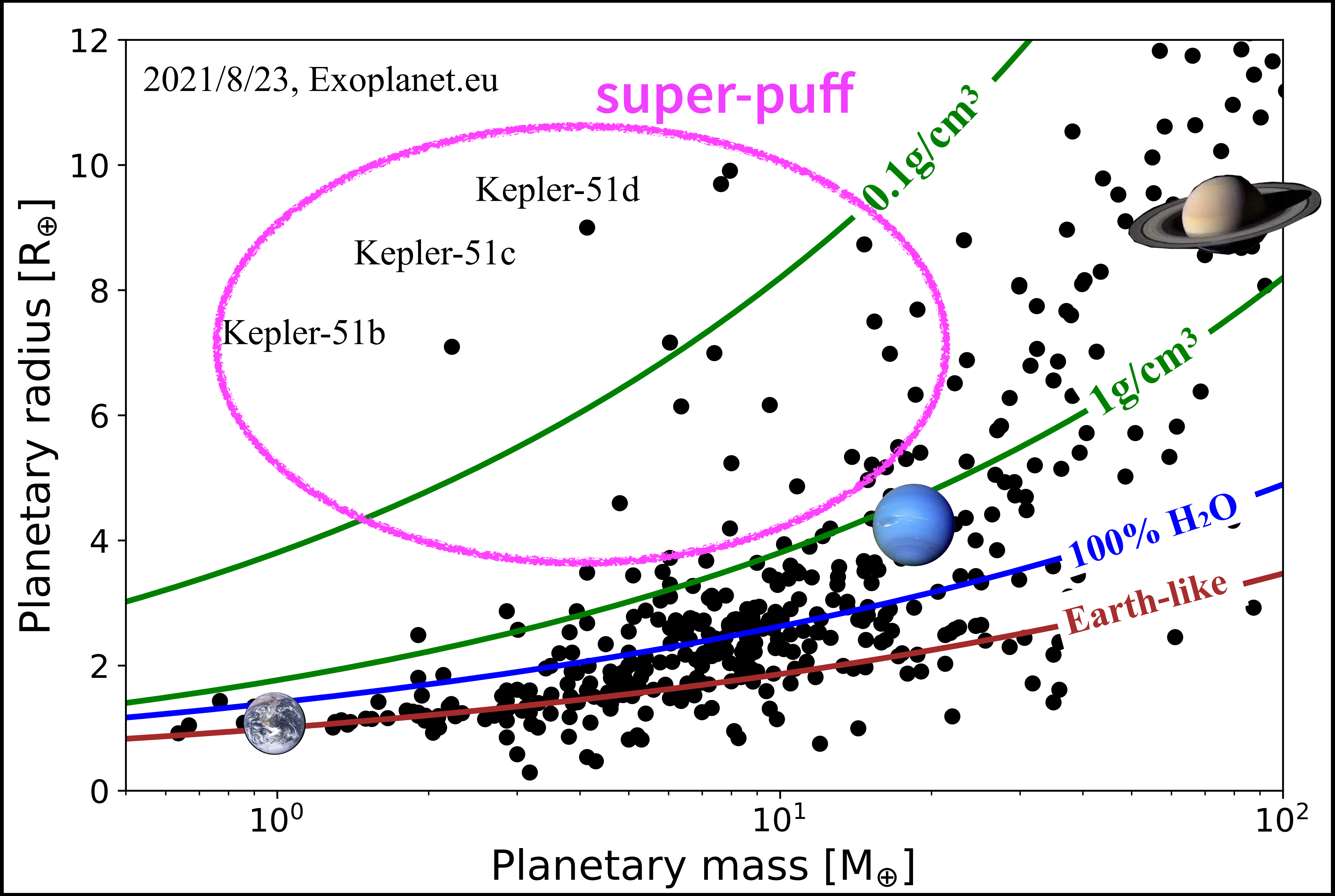
Atmospheres on Sub-Neptunes

- ✓ Some planets have extremely low-density, called super-puffs
  (e.g., Masuda 2014, Jontof-Hutter+2014, Ofir+2014)
- ✓ Large radii may imply massive atmospheres with ~0.1–0.3 Mp (Lopez & Fortney 2014)

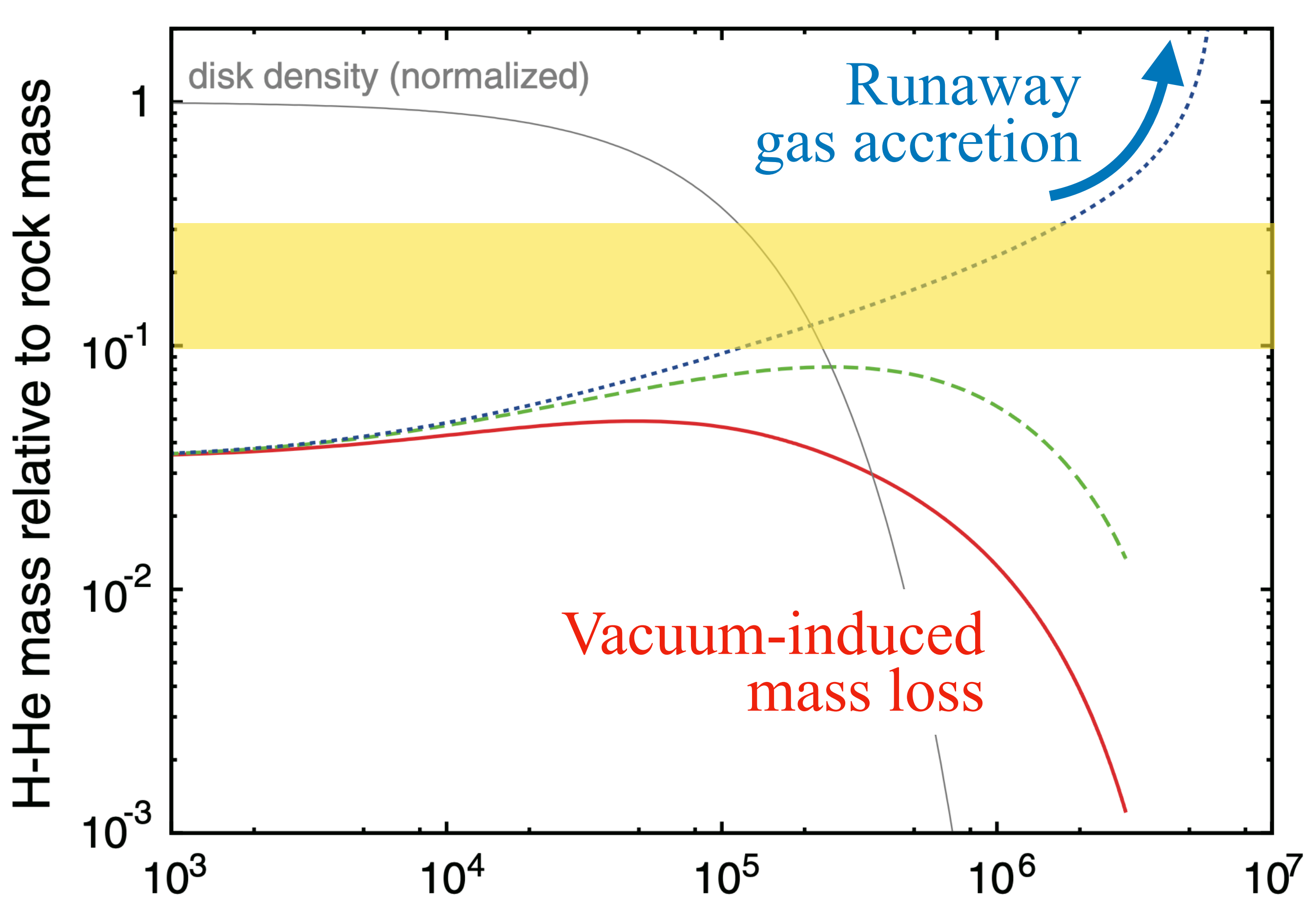


Attractive target to study their atmospheres and formation history

Puzzle of Super-puff Atmospheres (1)

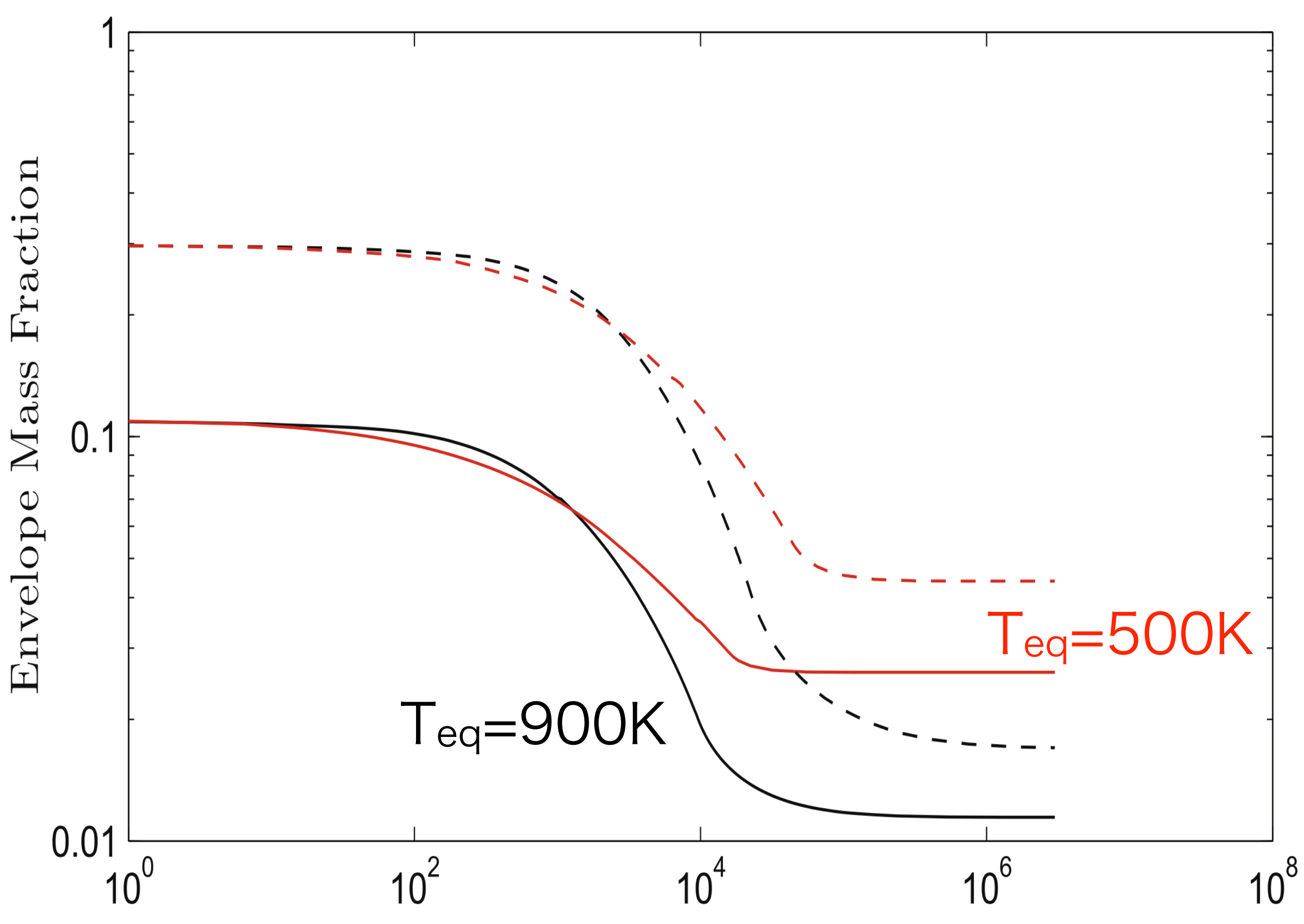
It is not easy to explain
why low-mass planets have massive atmospheres

Difficulty for acquiring atmosphere in situ
(e.g., Lee & Chiang 2016, Ginzburg+2016)



(Ikoma & Hori 2012)

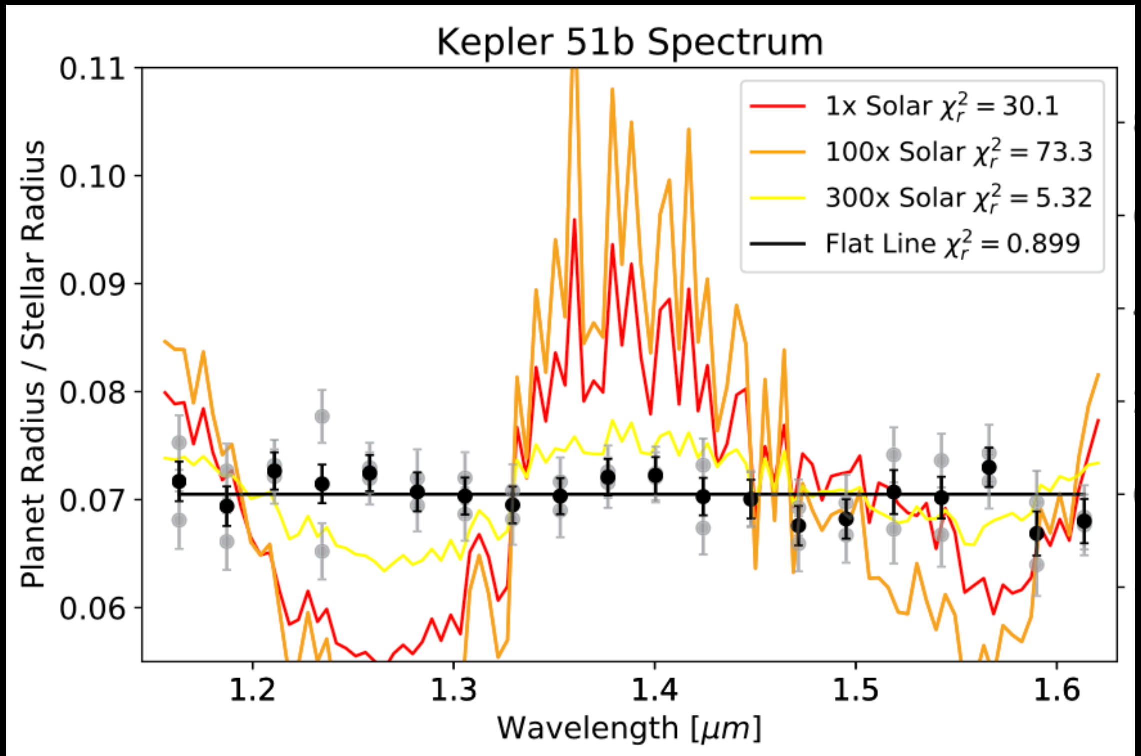
Atmospheric loss after disk dissipation
(e.g., Owen & Wu 2016, 2017, Wang & Dai 2018)

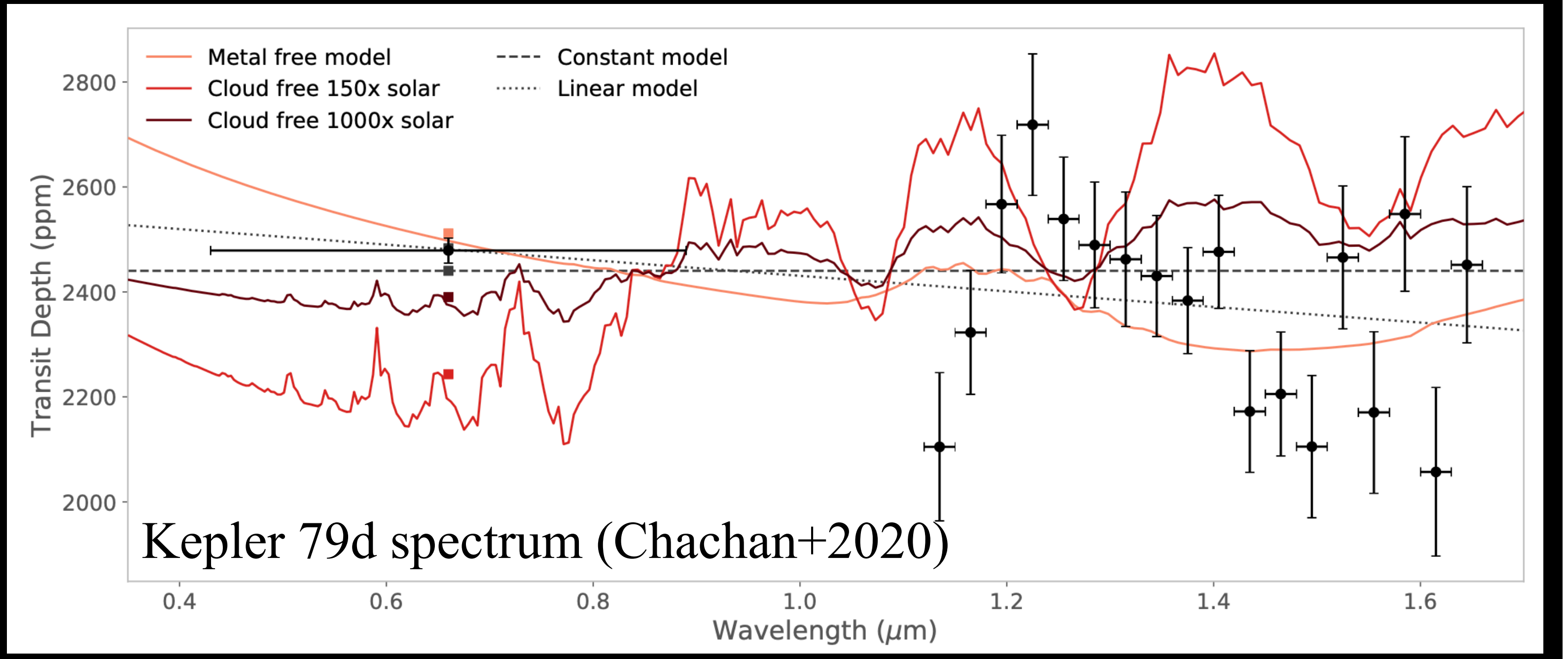


(Owen & Wu 2016)

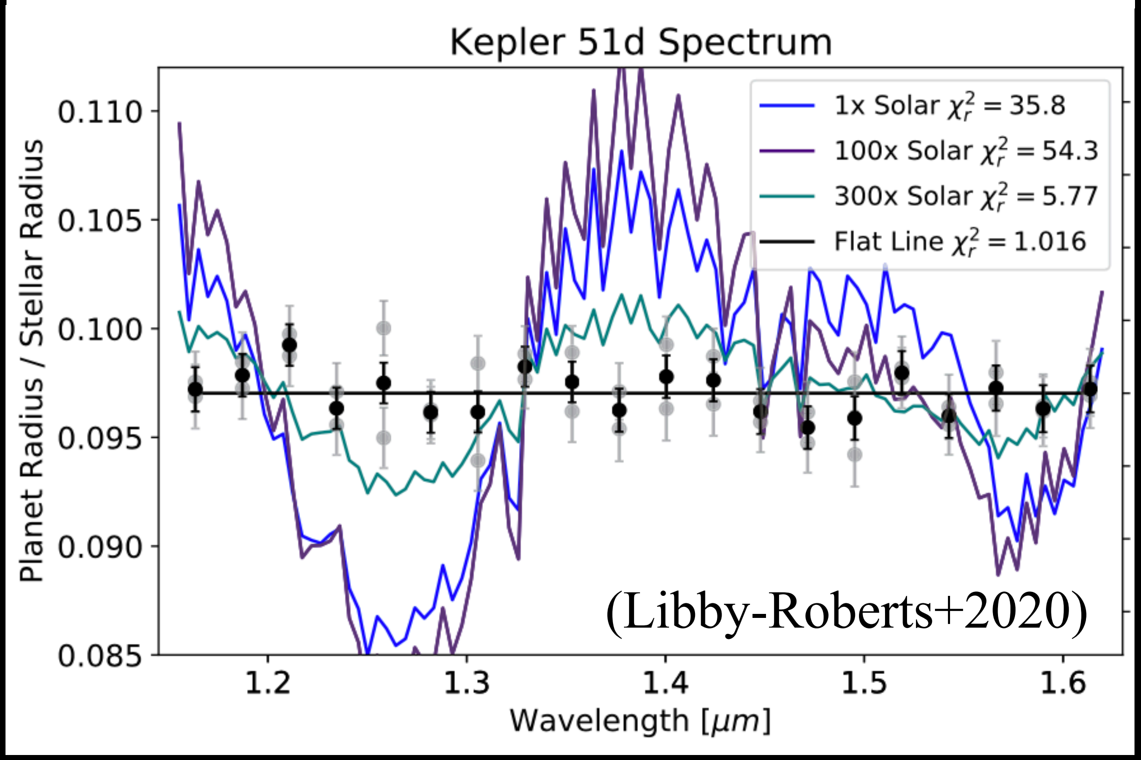
Puzzle of Super-puff Atmospheres (2)

- ✓ Low planetary gravity should cause large spectral features in transmission spectra
- ✓ However, the spectra are mostly featureless





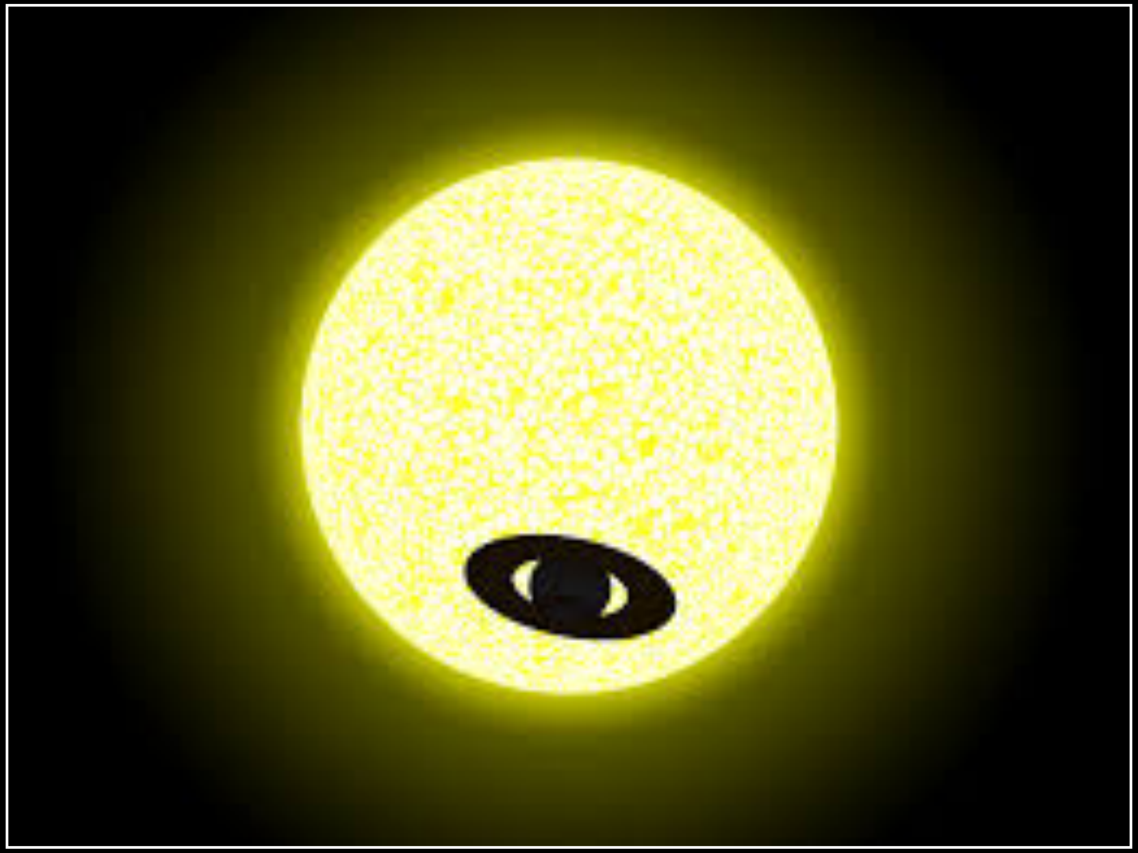
Kepler 79d spectrum (Chachan+2020)



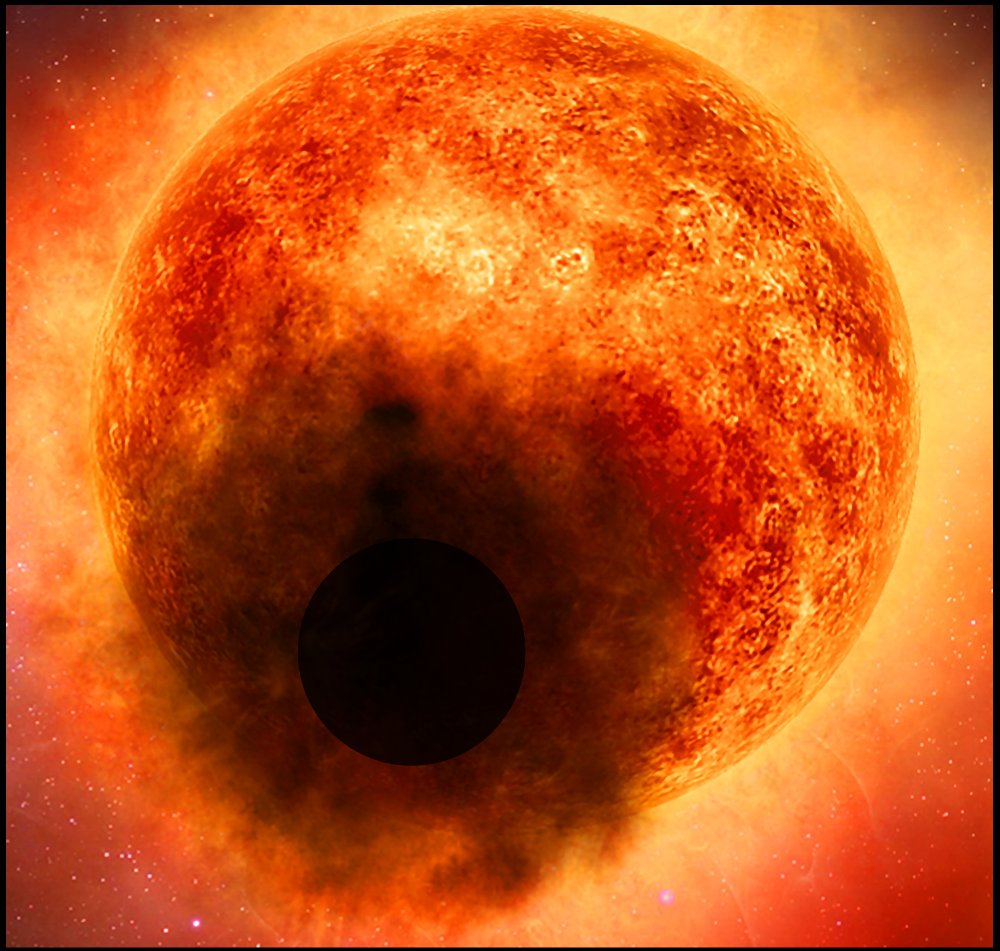
(Libby-Roberts+2020)

Some Mechanisms may Inflate Observable Sizes

Circumplanetary ring?
(Zuluaga et al. 2015, Piro & Vissapragada 2019)



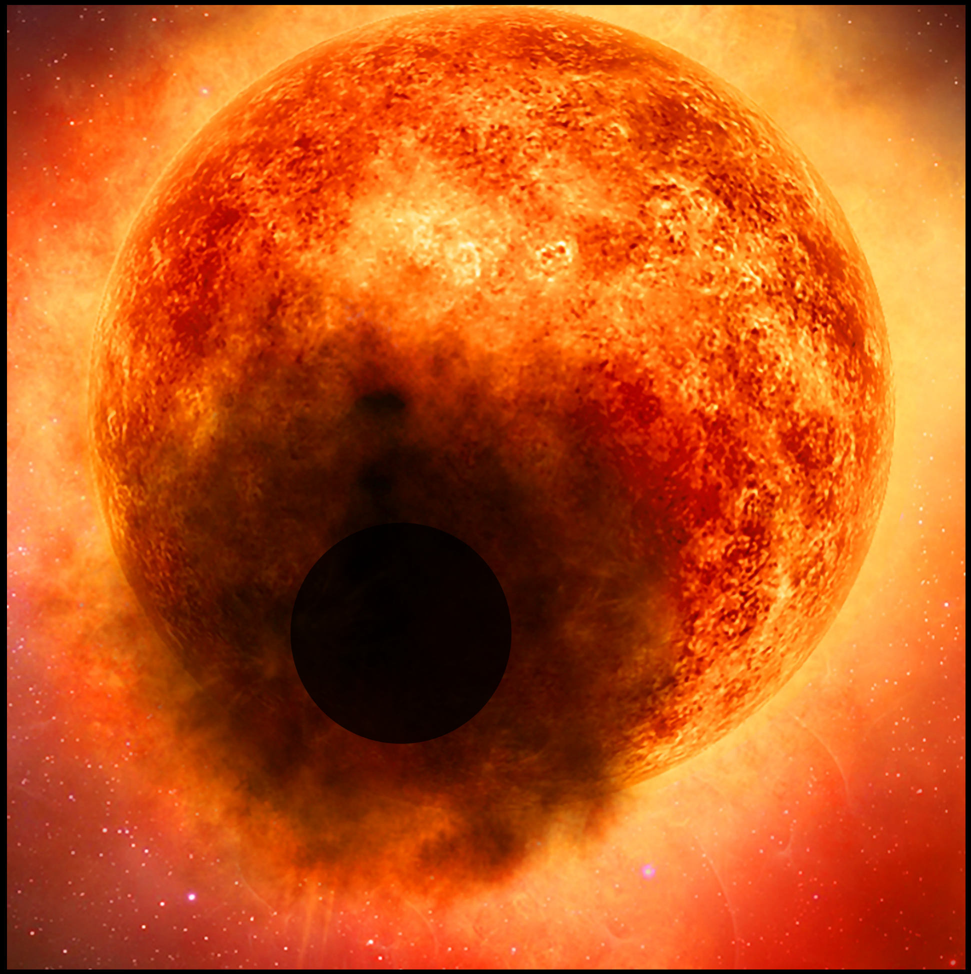
Atmospheric dust (aerosols)?
(Wang & Dai 2019, Kawashima et al. 2019, Gao & Zhang 2020)

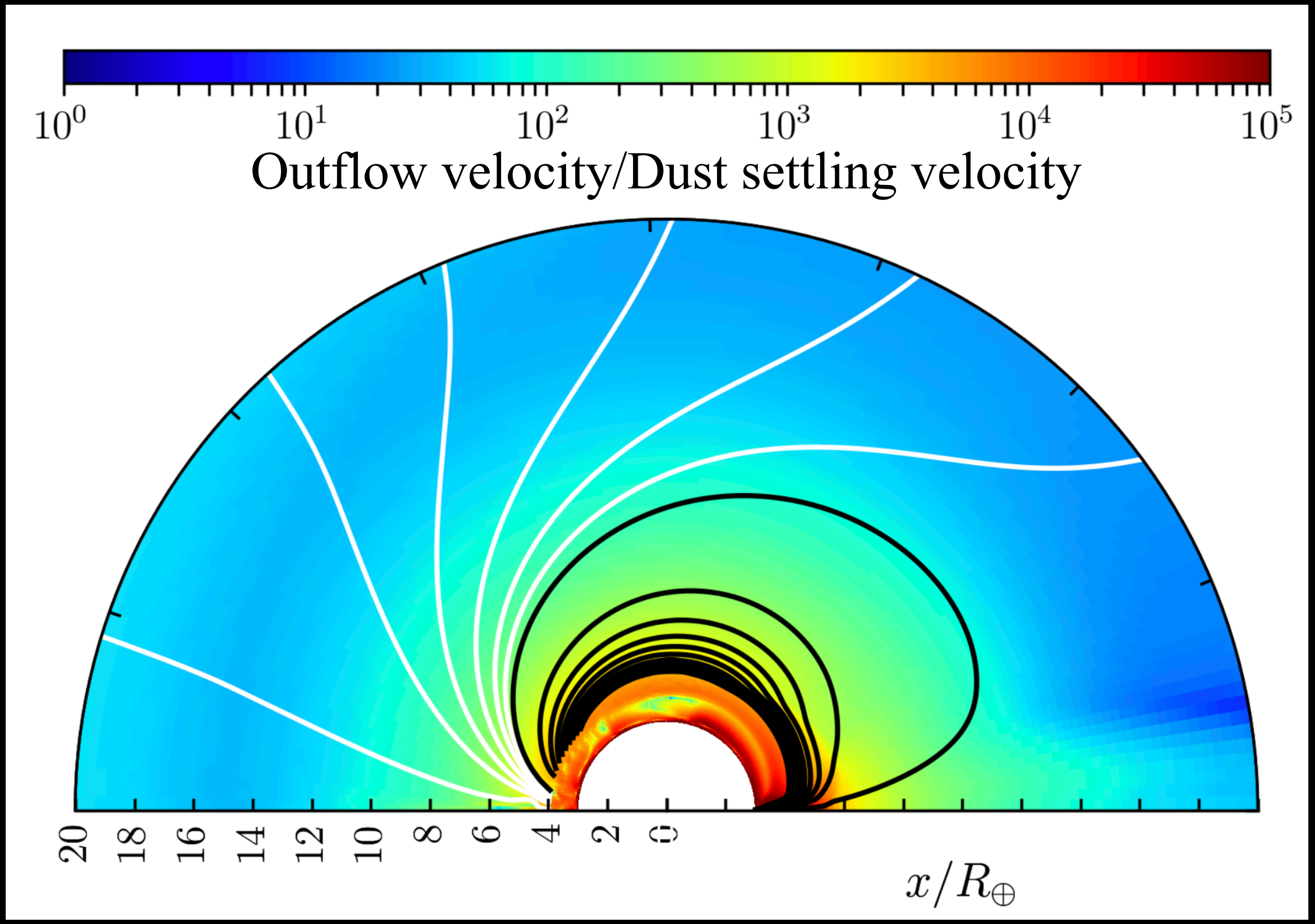


Strong interior heating is also proposed to cause inflated radii
(Millholland 2019)

Dusty Outflow Scenario (Wang & Dai 2019)

- ✓ Atmospheric escape may blow atmospheric dust to upper atmospheres
- ✓ With sufficiently abundant and small dust,
  the dusty outflow can enhance the observable radius by a factor of ~3





Constant particle size and abundance were assumed
→ Use microphysical model in this study

Modeling Grain Growth in Escaping Atmospheres

Simulate size distributions of aerosols in outflow with a microphysical model

(Using a model used for haze formation on solar system objects (Ohno, Zhang, Tazaki, & Okuzumi 2021))

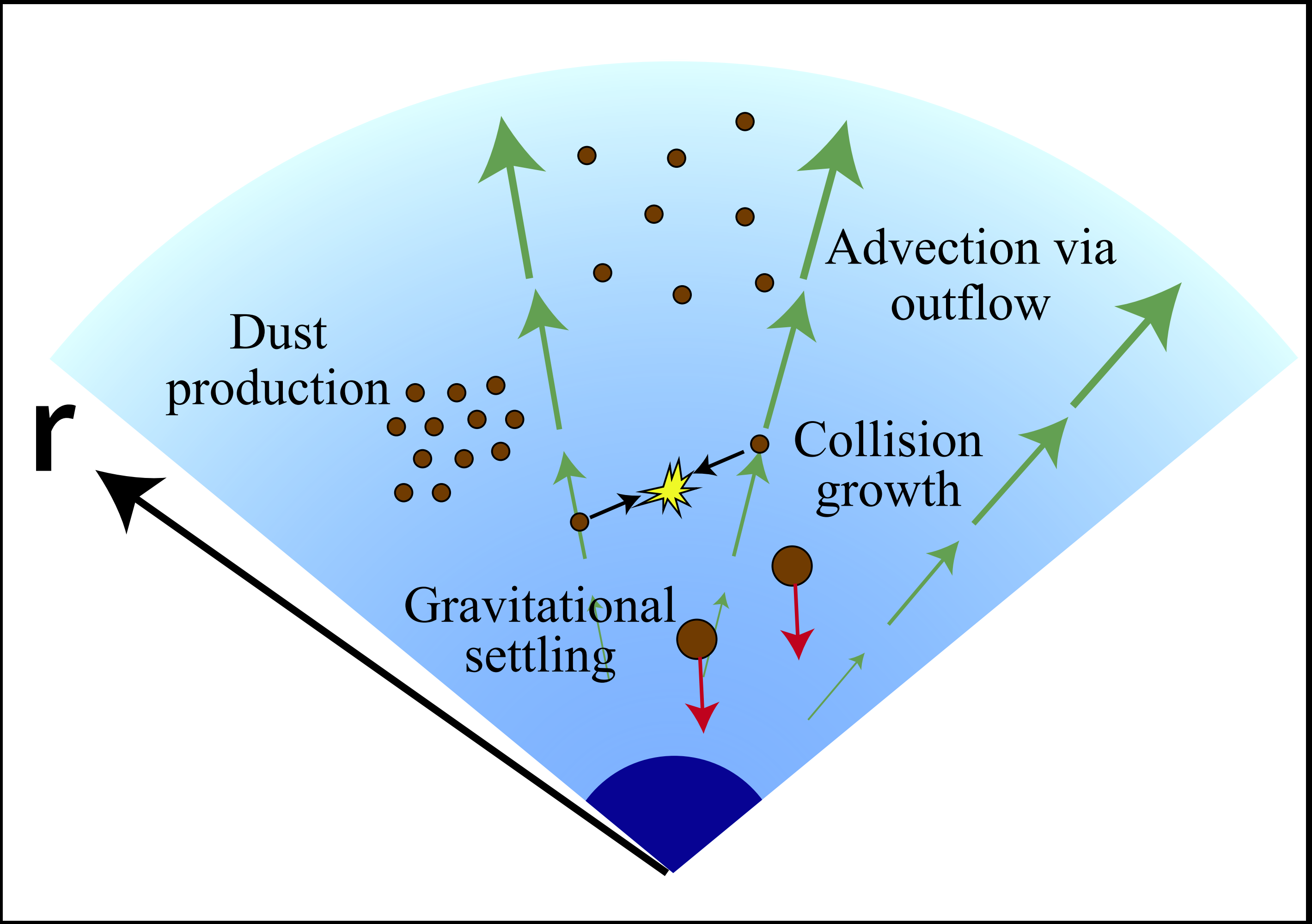
$$\frac{\partial n(m)}{\partial t} = \frac{1}{2}\int_0^{m} K(m', m-m')n(m')n(m-m')dm' - n(m)\int_0^{\infty} K(m,m')n(m')dm' + \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left(\rho_g K_z \frac{\partial}{\partial r}\left(\frac{n(m)}{\rho_g}\right) - (v_g - v_d)n(m)\right)\right] + S(m)$$

Settling velocity (v_d)

Outflow velocity (v_g)

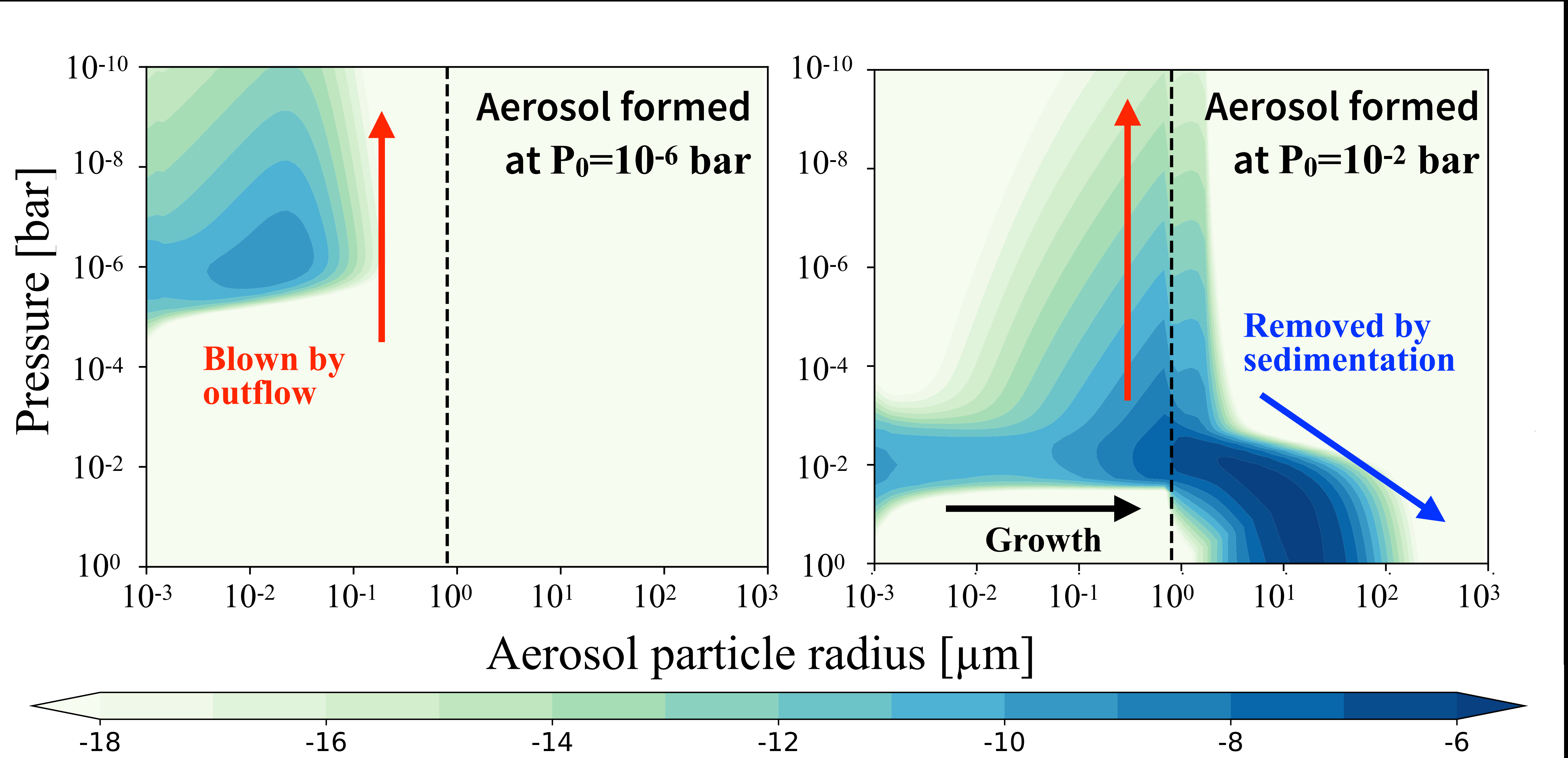
Parameterize aerosol production by log-normal distribution ($S(m)$)

$$S = -\frac{dP}{dr}\frac{f_{dust}\dot{M}/4\pi r^2 m_0}{\sigma P\sqrt{2\pi}}\exp\left(-\frac{(\log(P/P_0))^2}{2\sigma^2}\right)$$



- ✓ Assume spherical particles and neglect condensation for simplicity
- ✓ Isothermal Parker wind model (Parker 1958)
- ✓ Vary aerosol production rate f_{dust} and pressure level of aerosol production P_0

Dust largely settle down to planet when they form at deep atmospheres

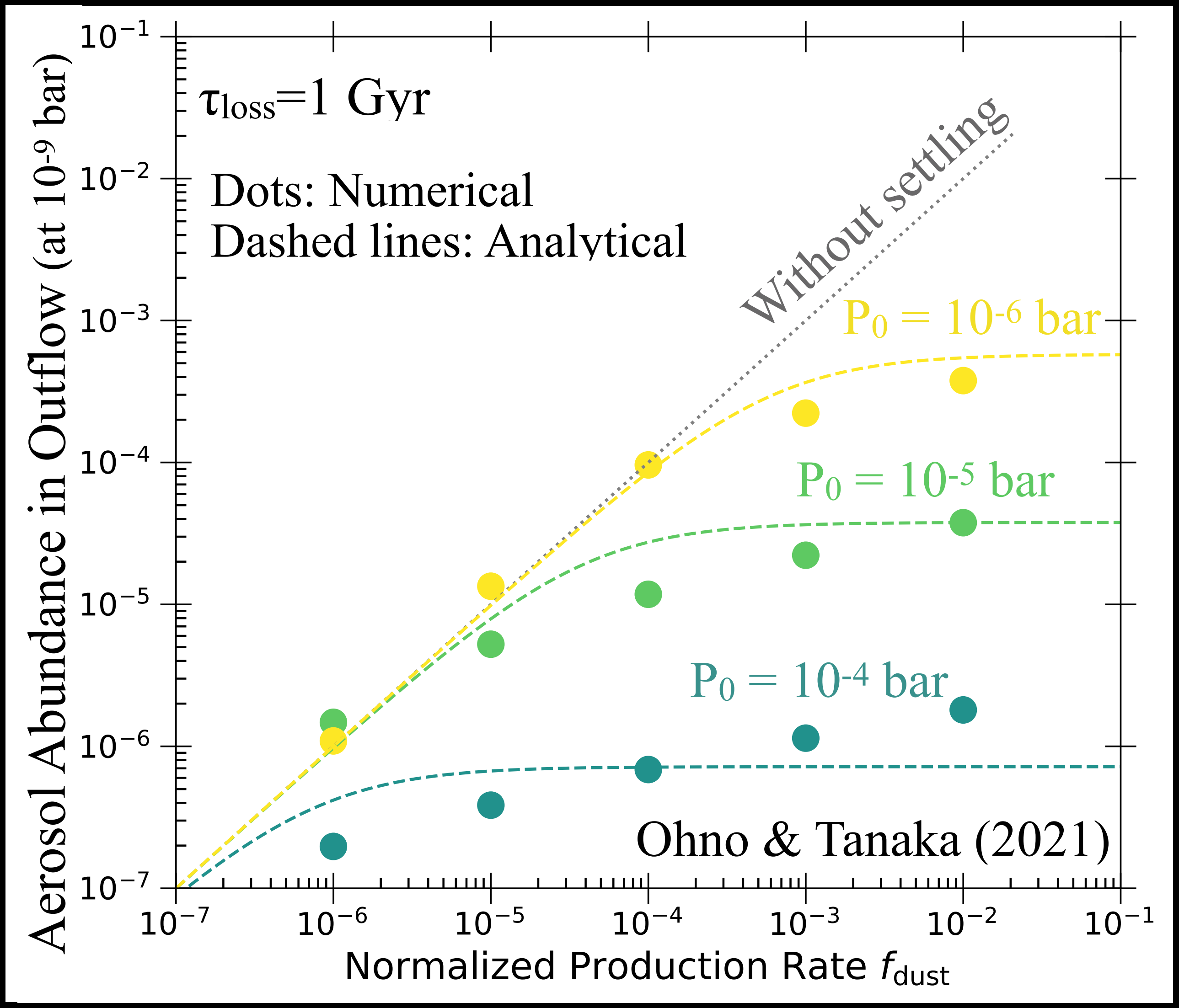


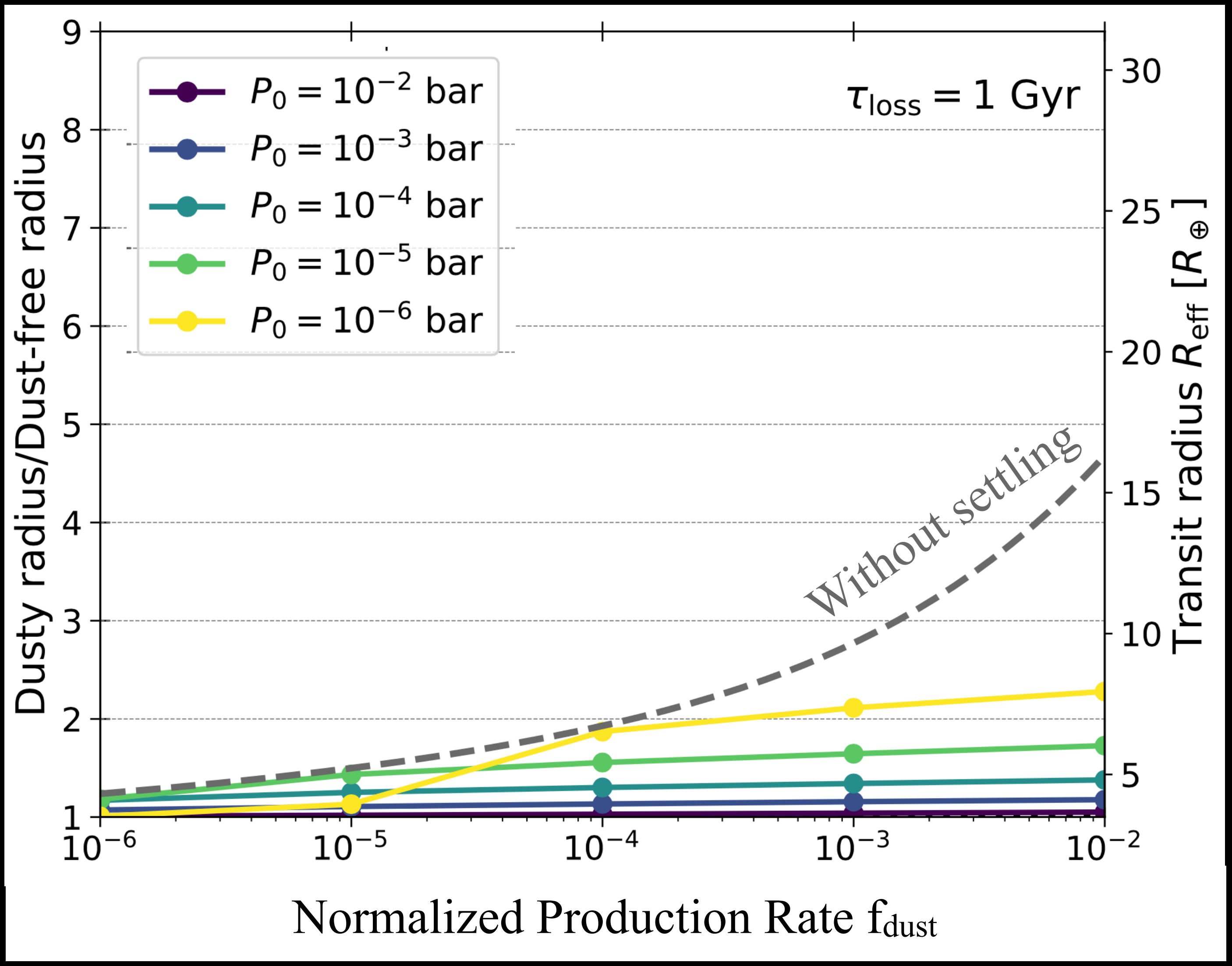
Ohno & Tanaka (2021)

Mass loss timescale here is τ_{loss}=0.1 Gyr

Aerosol Abundance in Outflow

Aerosols are barely transported by outflow
when they are formed in deep atmospheres where the outflow is slow



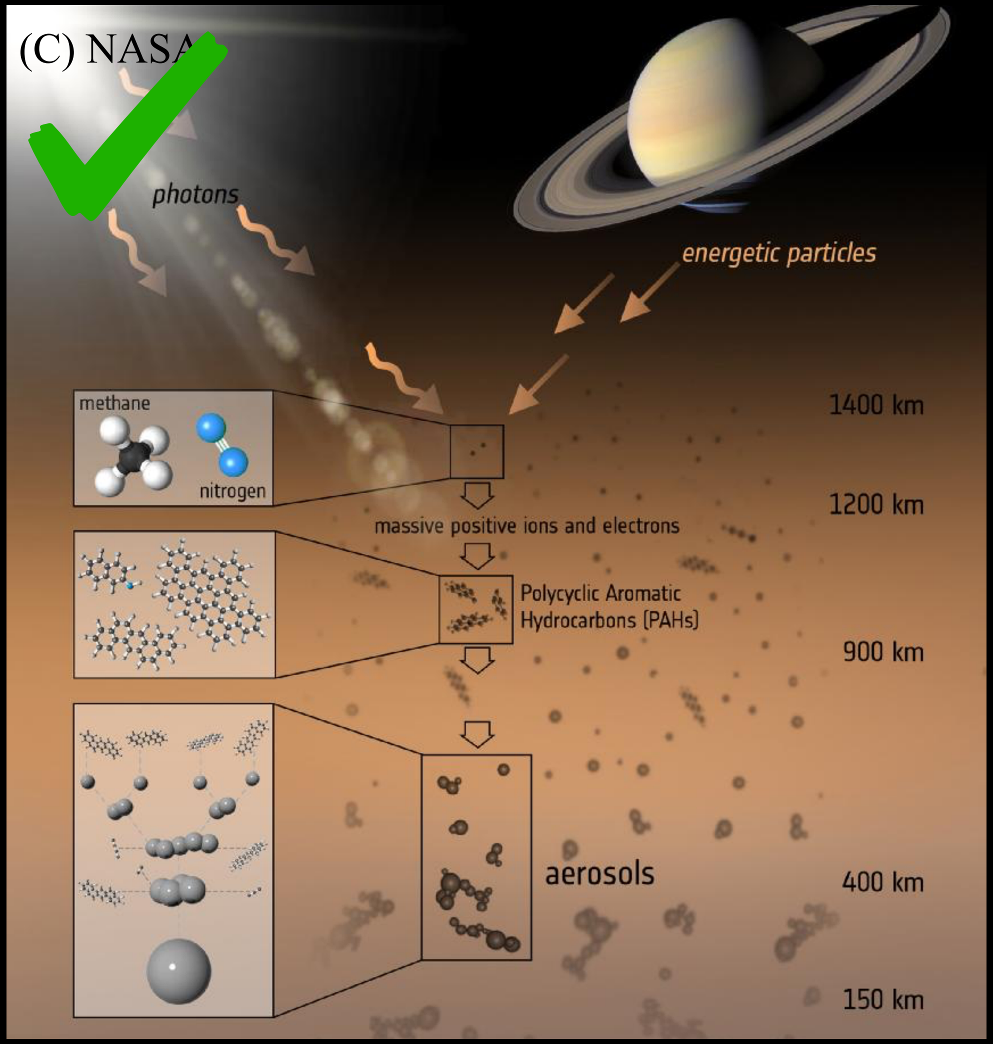


High-altitude aerosols tend to be blown by outflow, potentially leading to enhance the transit radius by a factor of ~2

What kind of aerosols are responsible?

Condensation clouds
(formed at ~10^{-2}–10^{-1} bar)

Photochemical hazes
(formed at ~10^{-6}–10^{-5} bar)



Meteoric dust
(formed at ~10^{-8}–10^{-6} bar)

Photochemical hazes seem ubiquitous in cool exoplanets (Crossfield & Kreidberg 2017, Gao+2020)

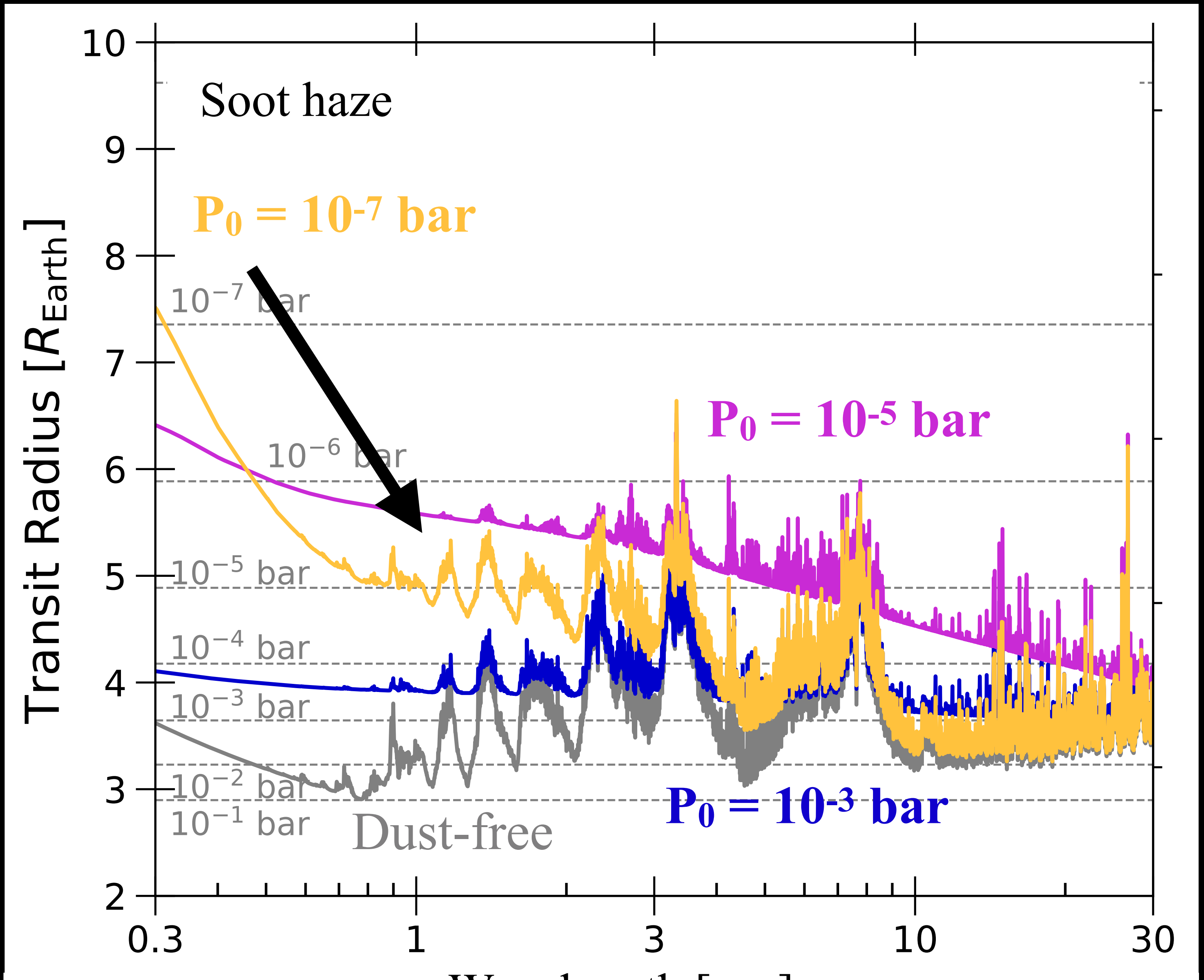
→ Photochemical hazes are promising candidates

(supporting the idea of Gao & Zhang 2020)

Transmission Spectra with Hazy Outflow

- ✓ Lower P_0 usually obscures spectral features more efficiently
- ✓ Very low P_0 leads to super-Rayleigh slope and noticeable spectral features

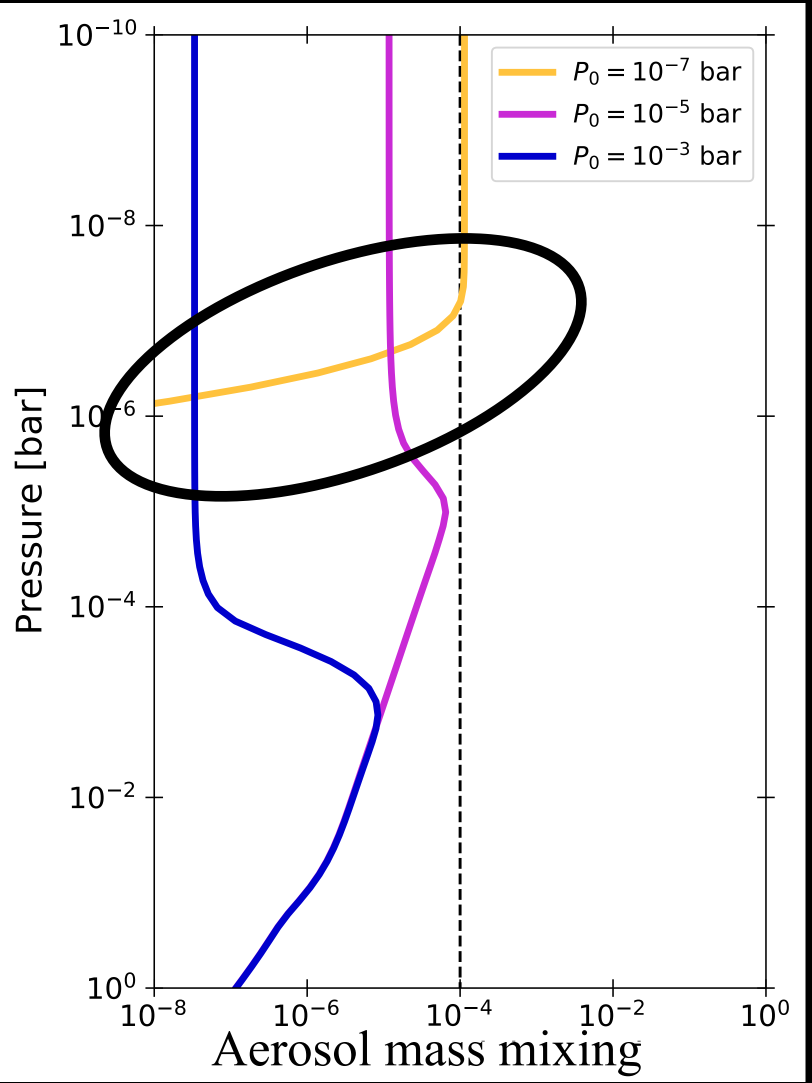
Caused by steep vertical gradient in atmospheric opacity (Ohno & Kawashima 2020)



Ohno & Tanaka (2021)

$$\kappa \propto \lambda^{\alpha} P^{-\beta}$$

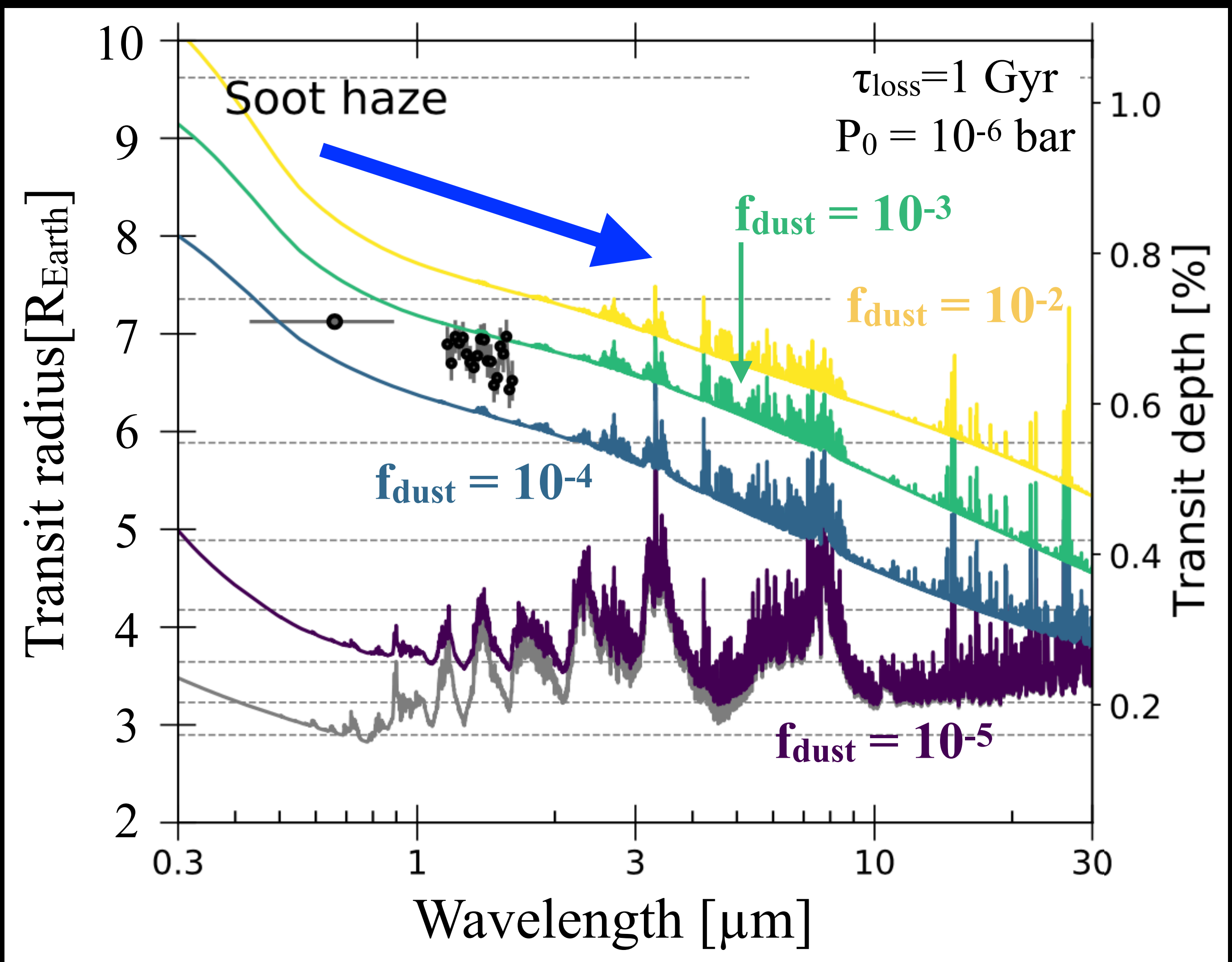
$$\frac{1}{H}\frac{dR_{\mathrm{p}}}{d\ln\lambda} = \frac{\alpha}{1-\beta}$$



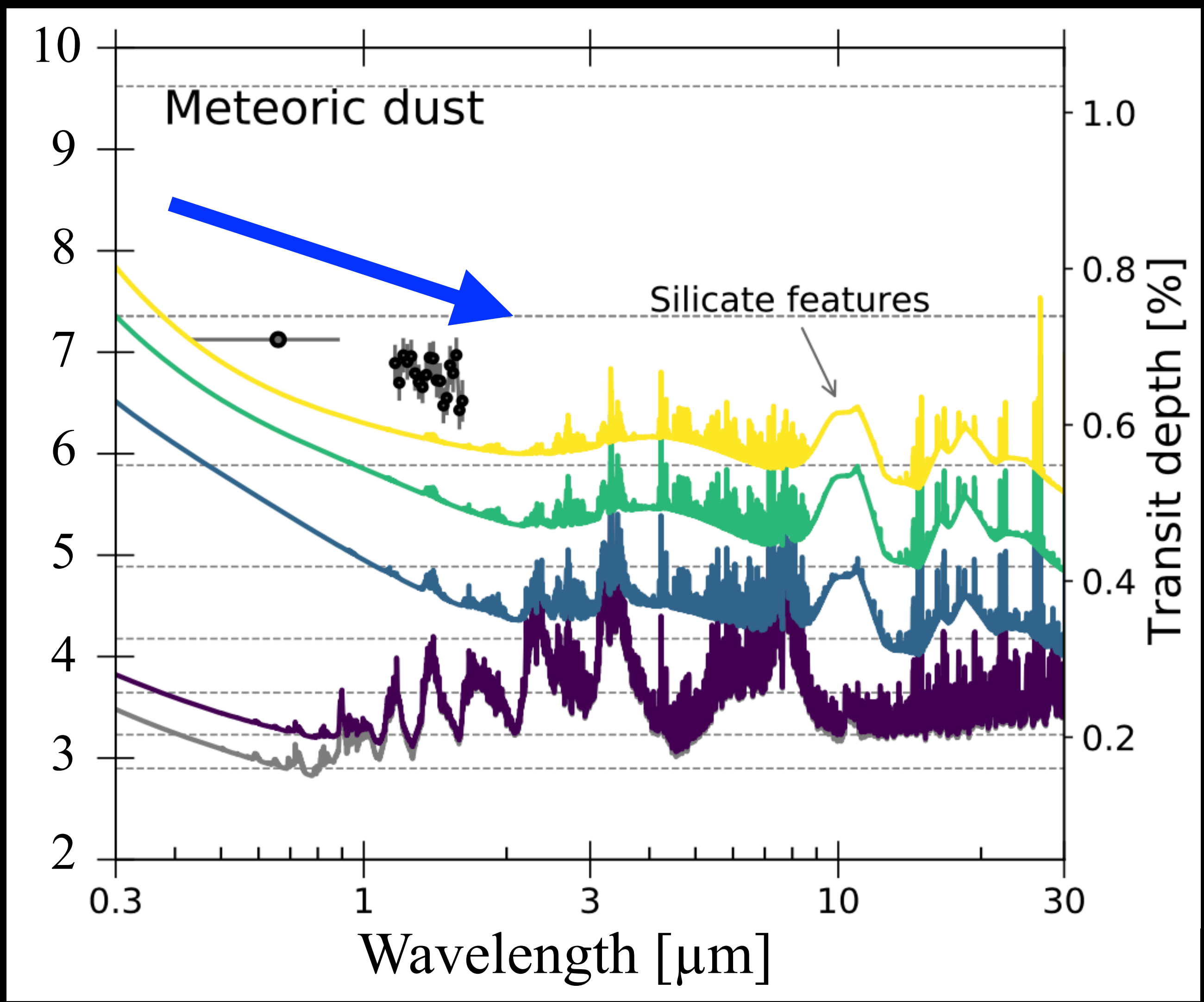
Compared with the Spectrum of Super-puff Kepler-51b

Hazy outflow can explain featureless transmission spectrum of super-puff Kepler-51b

Data from Kepler (Masuda 2014) and HST (Libby-Roberts+2020)

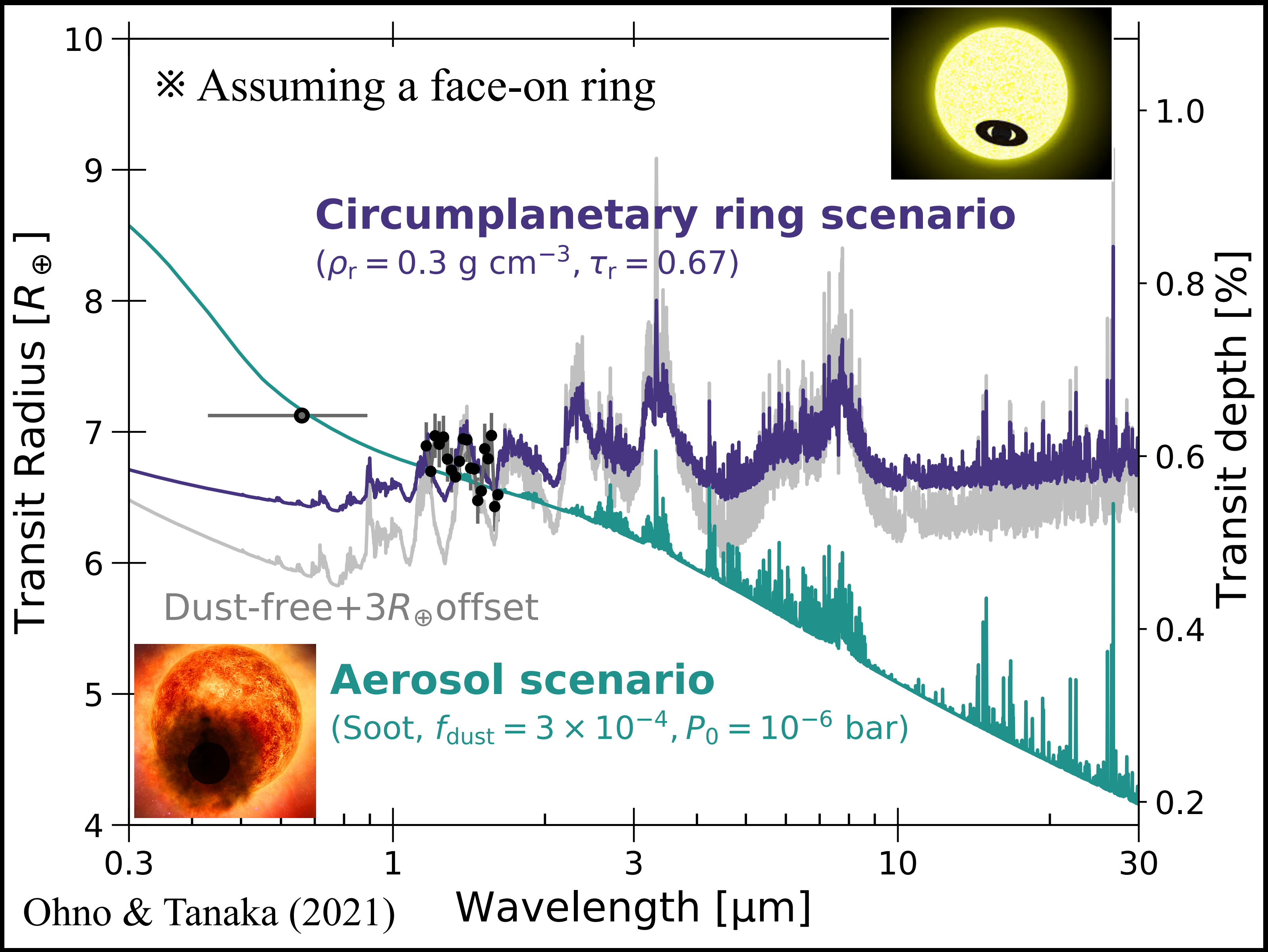


Absorption feature of aerosol may appear



Transit radius drastically decreases with increasing wavelength, testable by observations of JWST

Can We Distinguish Hazy Puffs and Ring Systems?



Atmospheric dust scenario :
Radius decreases with wavelength
because of tiny particle sizes

Ringed planet :
Large radius remains at long wavelength
because of large sizes of ring particles
(>100cm, Schlichting & Chang 2011)

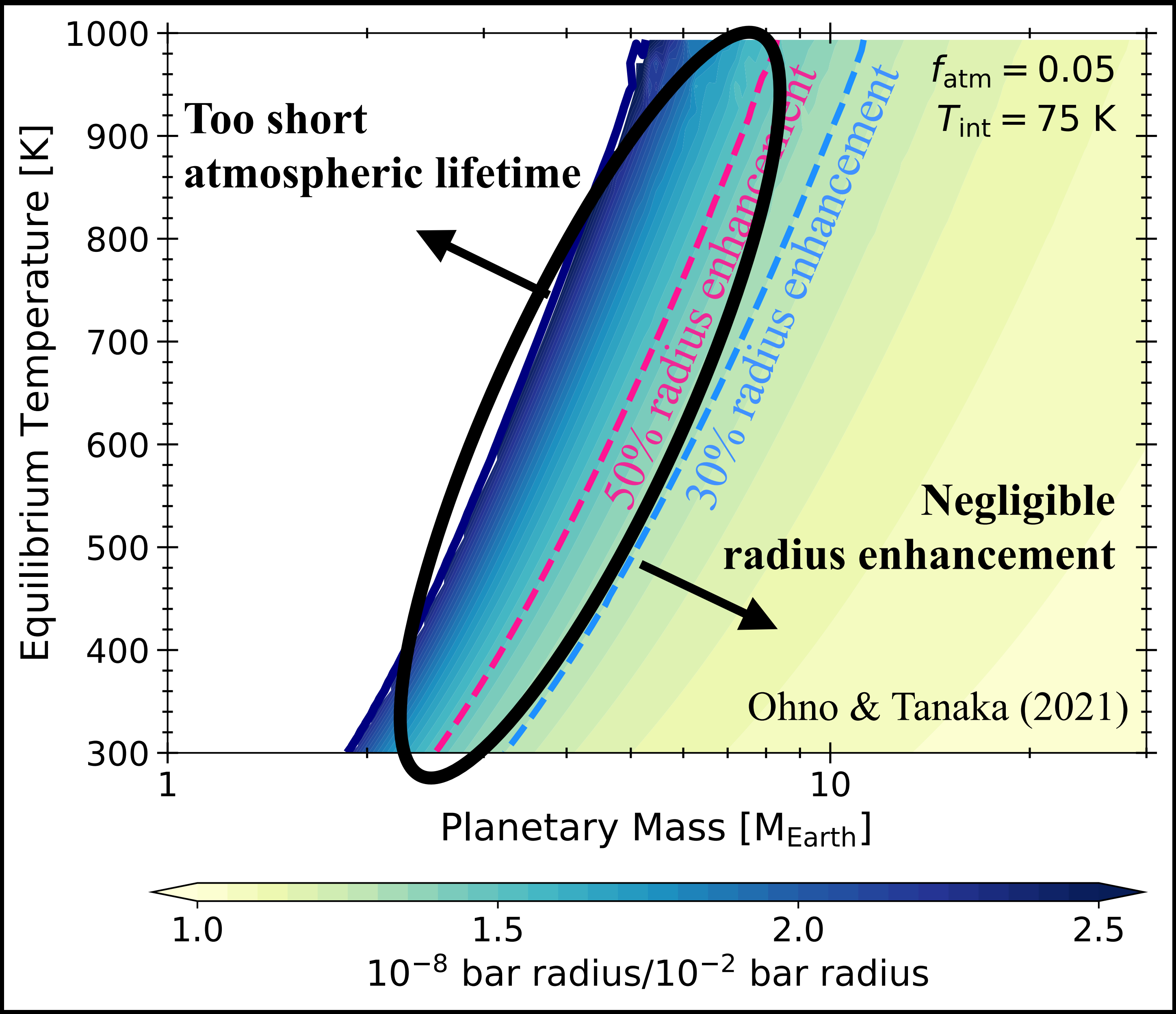
Transmission spectra with wider wavelength coverage help to disentangle different origins of super-puffs

Why are Super-puffs Uncommon?

Photochemical hazes seem ubiquitous in cool exoplanets (Crossfield & Kreidberg 2017, Gao+2020)

Q. Why don't all hazy planets become super-puffs?

A. The radius enhancement can work only for narrow range of planetary mass



High-altitude hazes work only when scale height H is large

$$\frac{R_{10^{-8}\ \rm bar}}{R_{10^{-2}\ \rm bar}} \approx 1 + \frac{14H}{R_{10^{-2}\ \rm bar}}$$

However, planets with $H \geq 0.1R_p$ are vulnerable to atmospheric boil-off (Owen & Wu 2016, Fosatti+2017)

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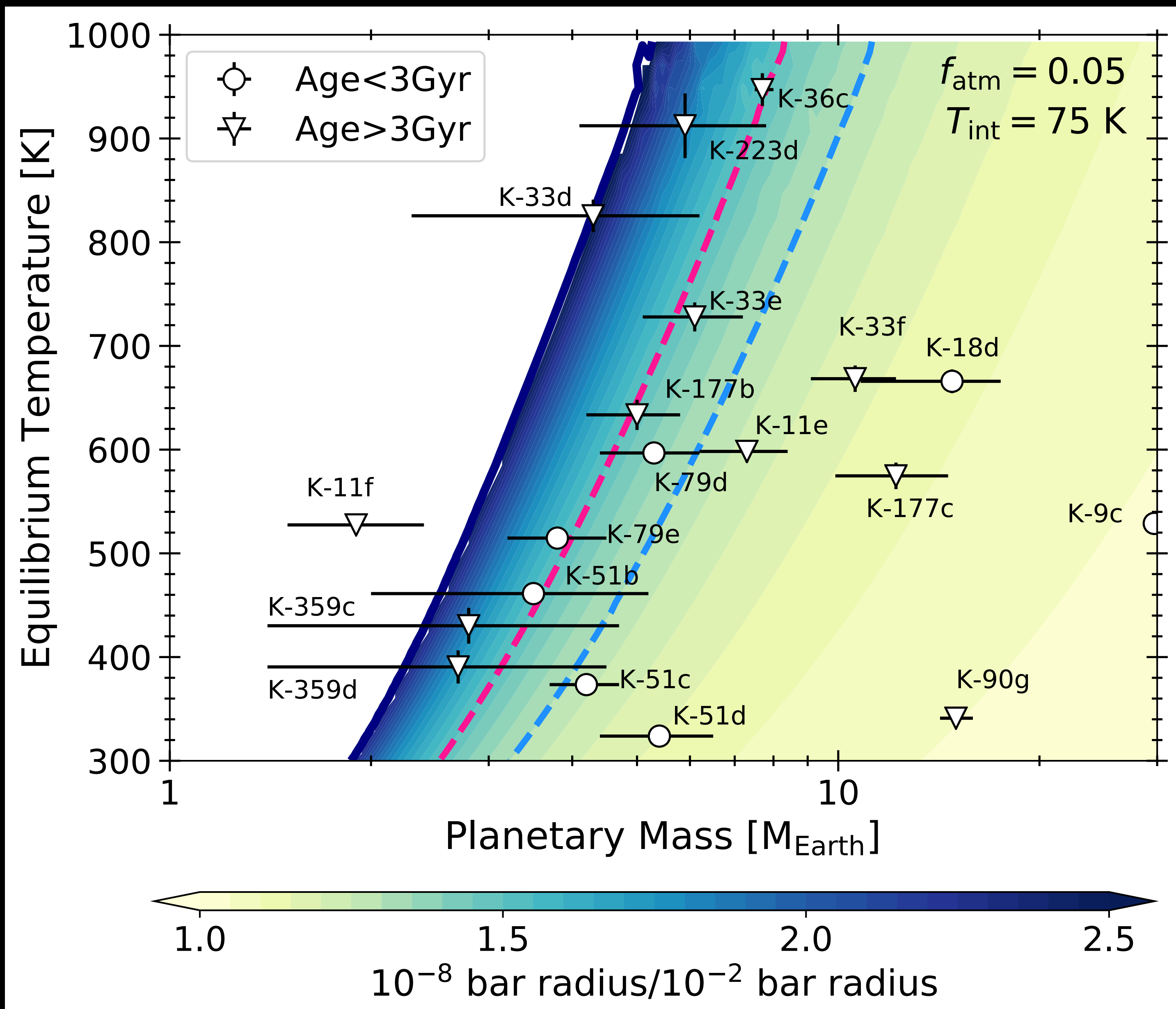

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Super-puff candidates from Chachan+2020

Hazes inflate radius only for planets verge on total atmospheric loss, which may explain why super-puffs are uncommon.

Summary

We have examined dusty outflow scenario (Wang & Dai 2019) **for explaining large radii of super-puffs using a microphysical model**

Q. How is grain growth of dust going on in escaping atmospheres?

- ✓ Aerosols grow into two populations: outflowing and settling particles
- ✓ Abundance of outflowing aerosol highly depends on where aerosols are formed

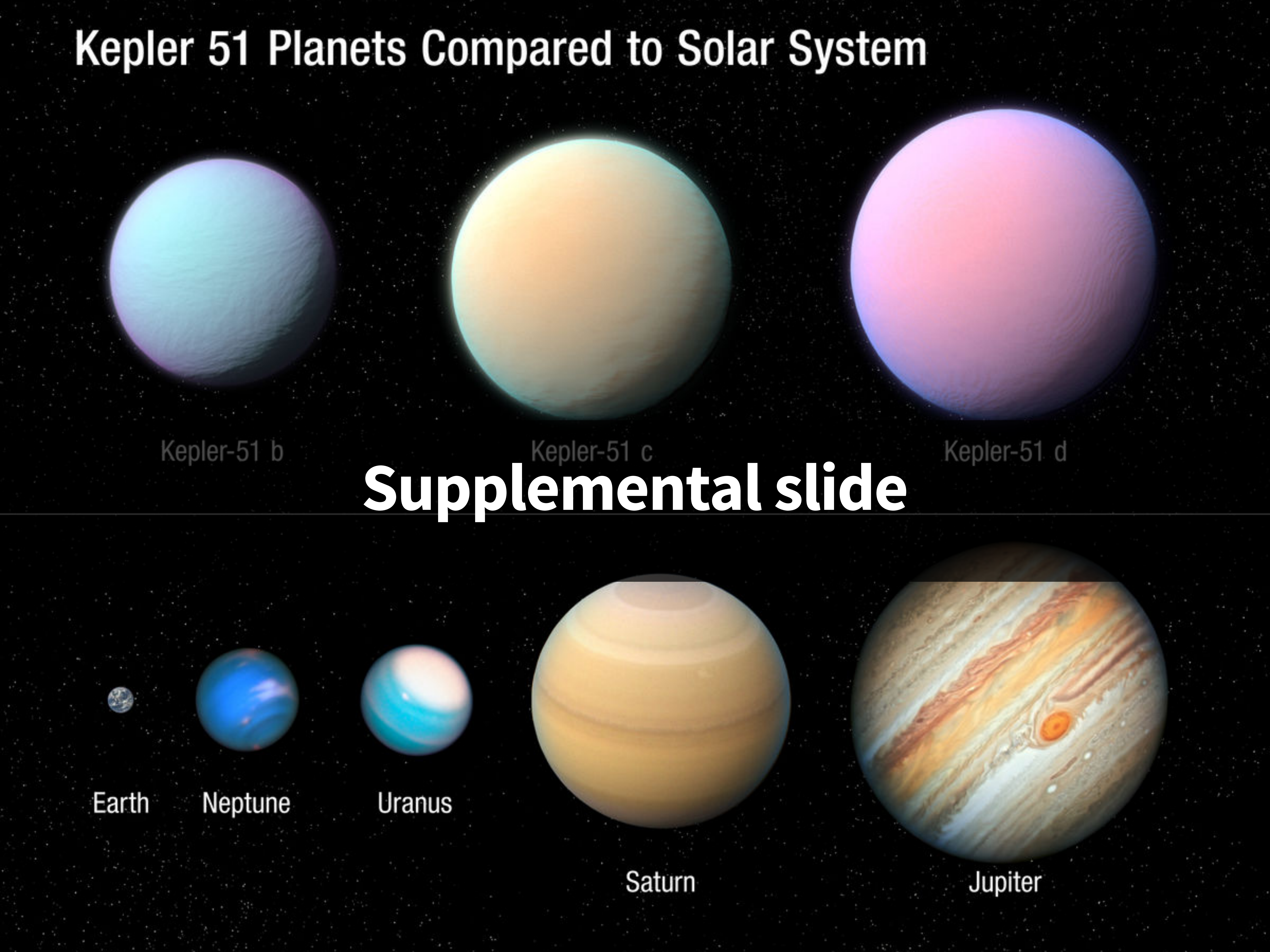
Q. What kind of aerosol is responsible?

- ✓ Aerosols formed at low altitude barely affect transit radius, while high altitude aerosol can enhance the transit radius by a factor of 2–3.
- ✓ Photochemical hazes are promising candidates to explain large radii of super-puffs. Alternatively, meteoric dust might work as well.

Q. How does the hazy outflow influences on transmission spectra?

- ✓ Hazy outflow can explain featureless transmission spectra of super-puffs.
- ✓ Planetary radius decreases with wavelength owing to tiny sizes of outflowing aerosols.
- ✓ Radii of super-puffs with circumplanetary rings does not decrease with wavelength, providing a hint to distinguish from hazy outflow scenario,

Supplemental slide



Vertical opacity gradient alters the spectral slope

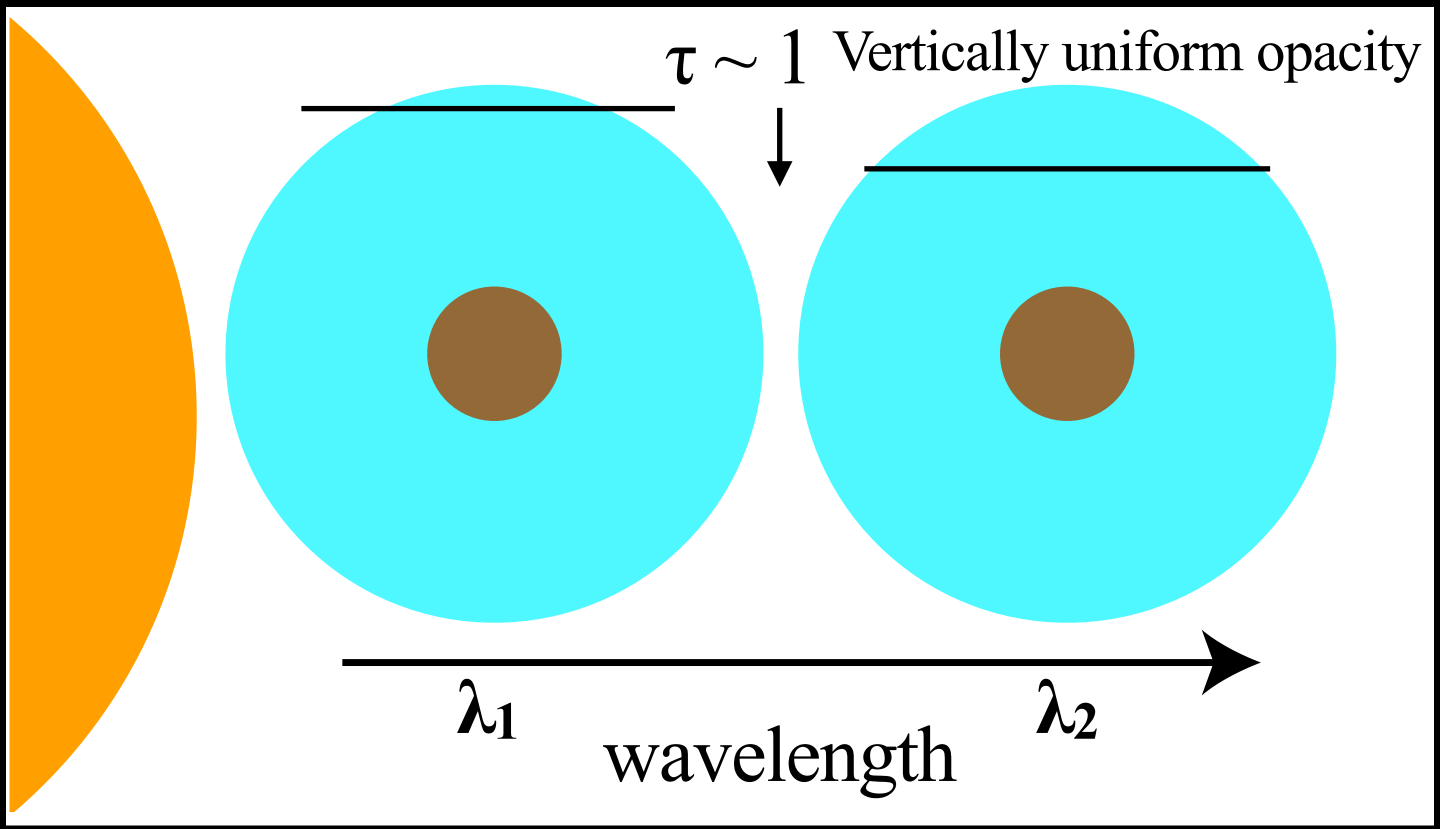
(Ohno & Kawashima 2020)

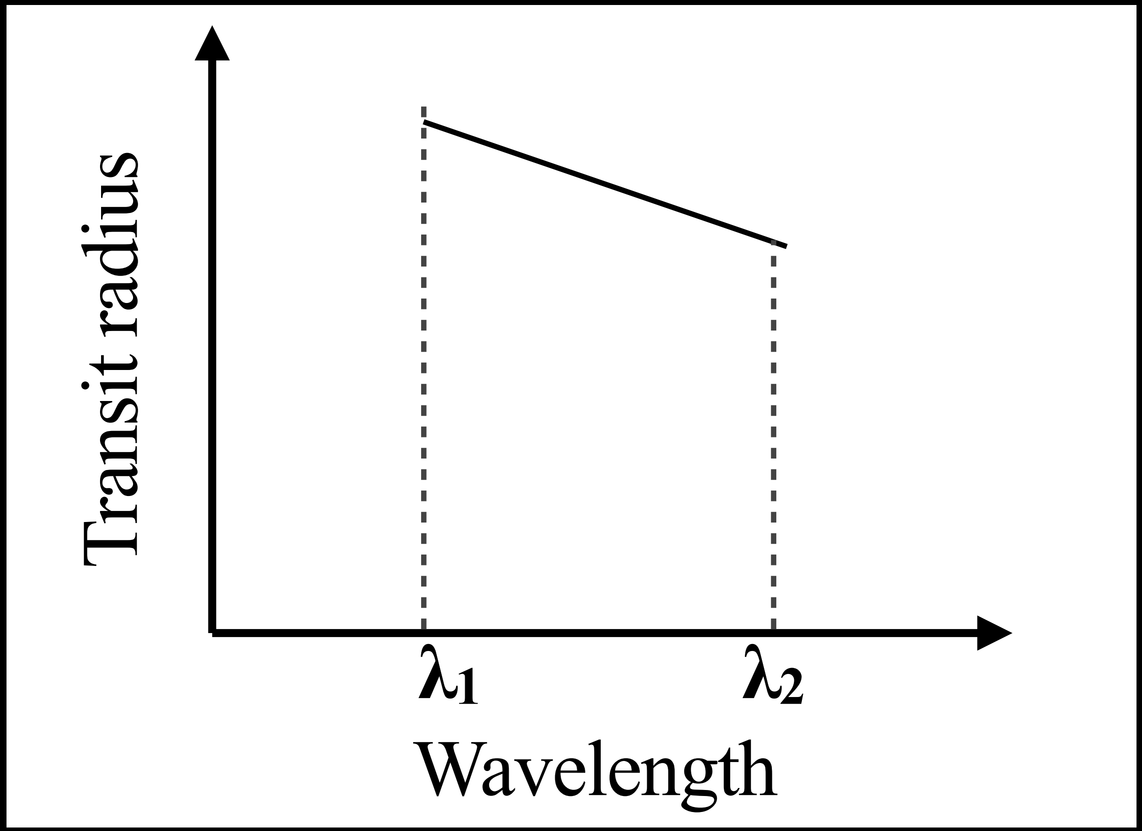
Spectral slopes with vertical opacity gradient

$$\kappa \propto \lambda^{\alpha} P^{-\beta}$$

$$\frac{dR_{\mathrm{p}}}{d\ln\lambda} = \frac{H\alpha}{1-\beta} \quad (\beta < 1)$$

Key point: The slope is steepened if higher altitudes is more opaque (i.e., β>0)





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