Planetesimal Formation —
Snow line & "No-drift" mechanism

Highlights

- Various “runaway” pile-up (instability) modes of pebbles/dust are reported.
- These occur around the snow line and beyond the snow line.
- Beyond the snow line, the “no-drift” mechanism can stop pebble drift, leading to a runaway pile-up.

Ryuki Hyodo

JAXA

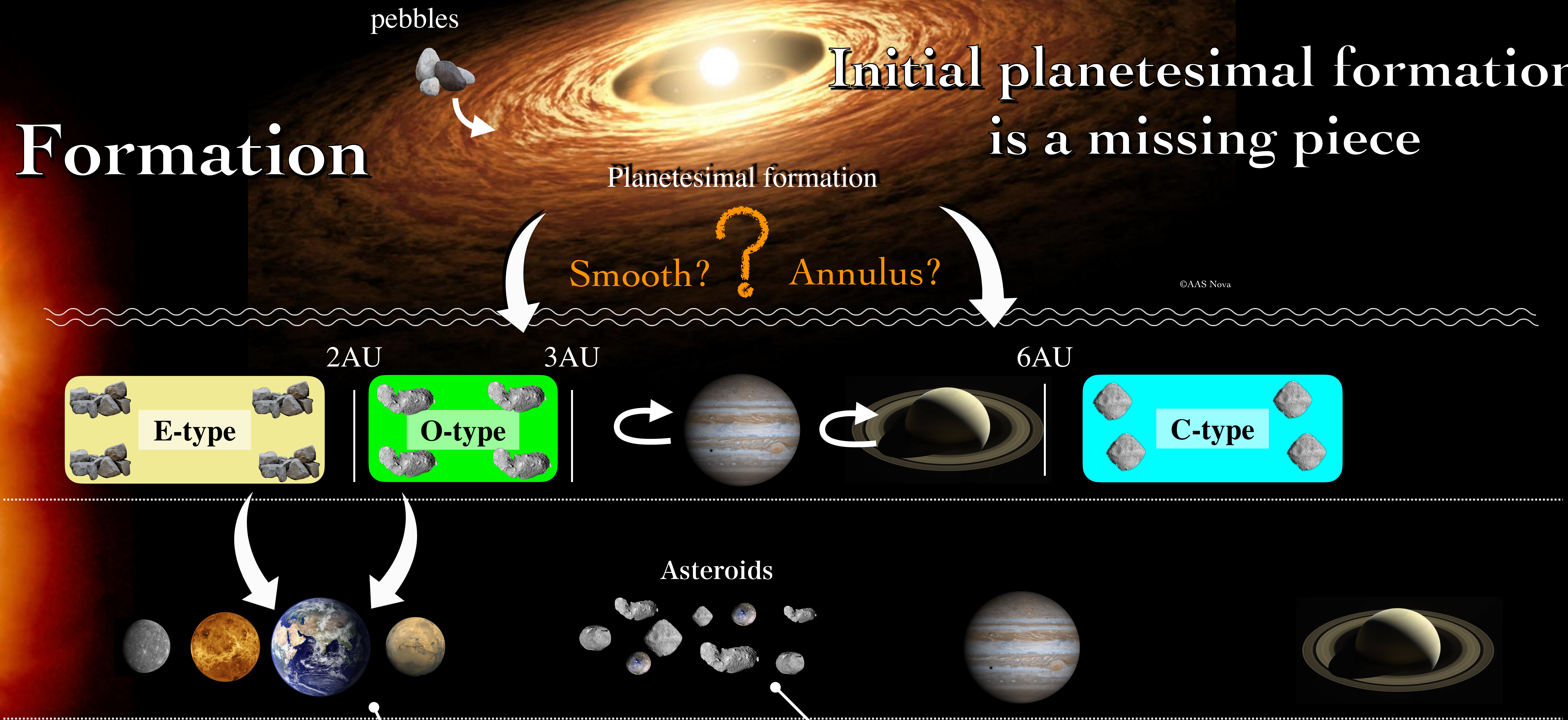
Ida S., Guillot T., Hyodo R., et al. (2021) A&A, 646, A13
Hyodo R., Guillot T., Ida S., et al. (2021) A&A, 646, A14
Hyodo R., Ida S., Guillot T. (2021) A&A, 645, L9

Today’s Contents

- Introduction
    - Importance of planetesimal formation study
- Consequences of pebble drift
    - Pile-up around the snow line
    - Pile-up by “no-drift” mechanism
- Overall results
    - Dependence on the disk structure & pebble mass flux
- Discussion
    - Diverse disk evolutions & diverse planetesimal formations
    - Snow line “fossilized”
- Summary

Planet Formation

Initial planetesimal formation is a missing piece



pebbles

Planetesimal formation

Smooth? ? Annulus?

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2AU

3AU

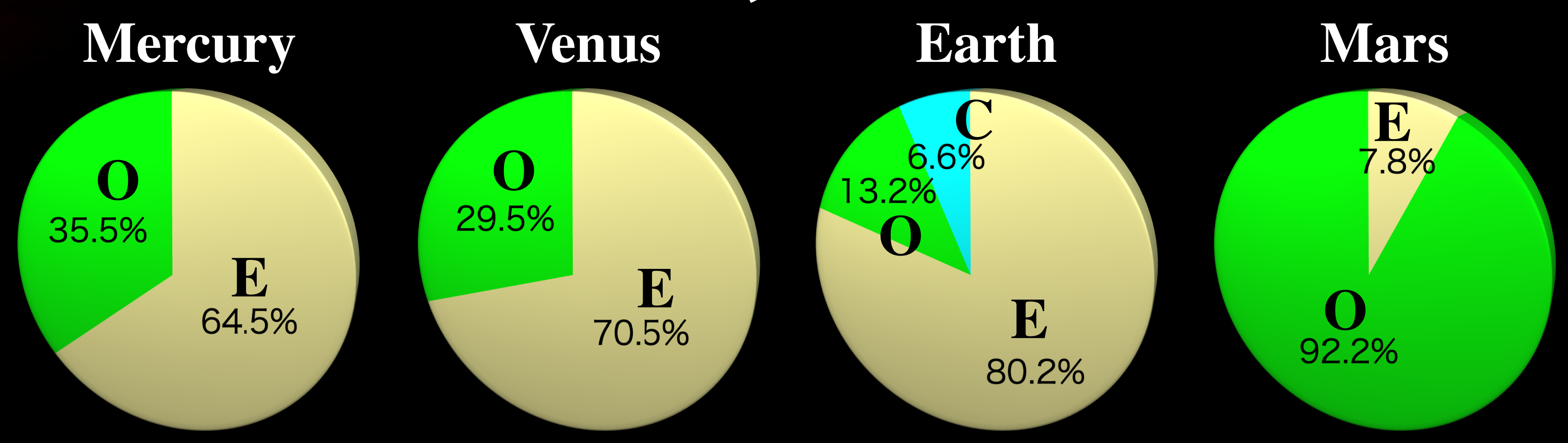
6AU

E-type

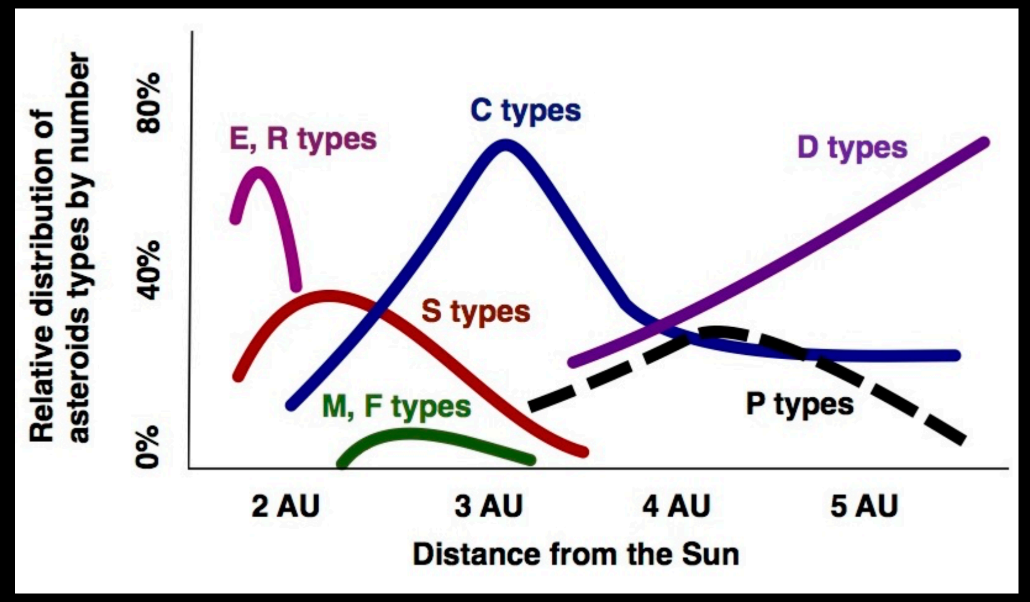
O-type

C-type

Asteroids



*Just example values

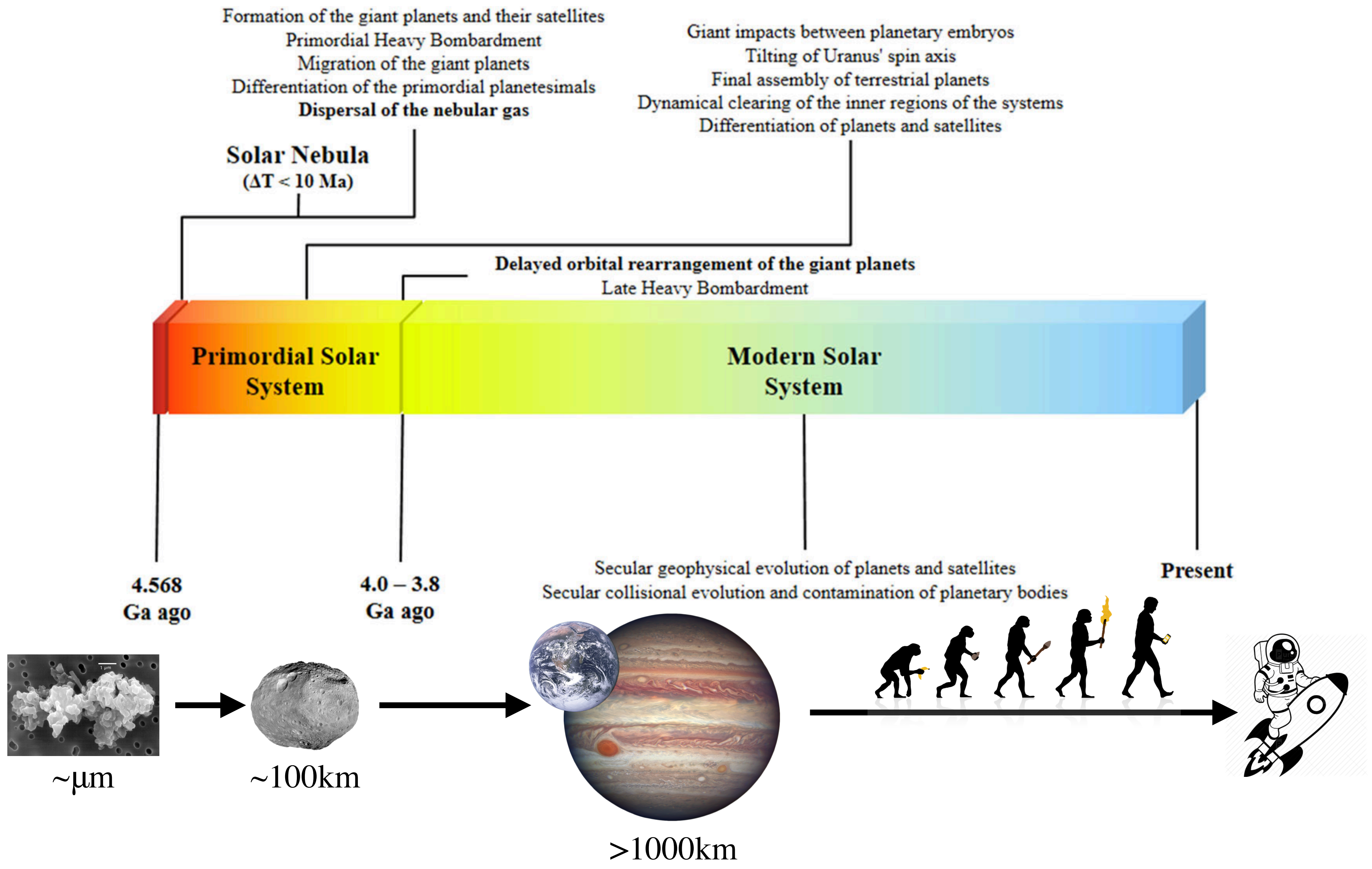


Gradie & Tedesco 1982

Initial planetesimal formation is a missing piece

Smooth or Annulus?

The initial planetesimal distribution borns smooth, or borns in an annulus?



modified from Turrini et al. (2014)
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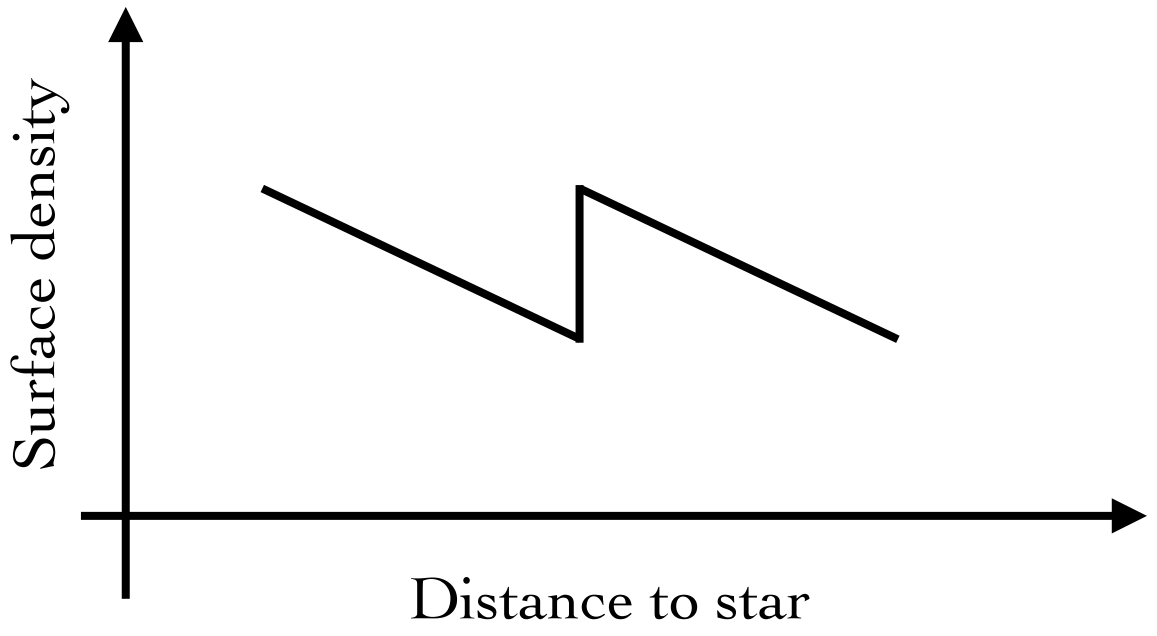
A smooth distribution

The classical view



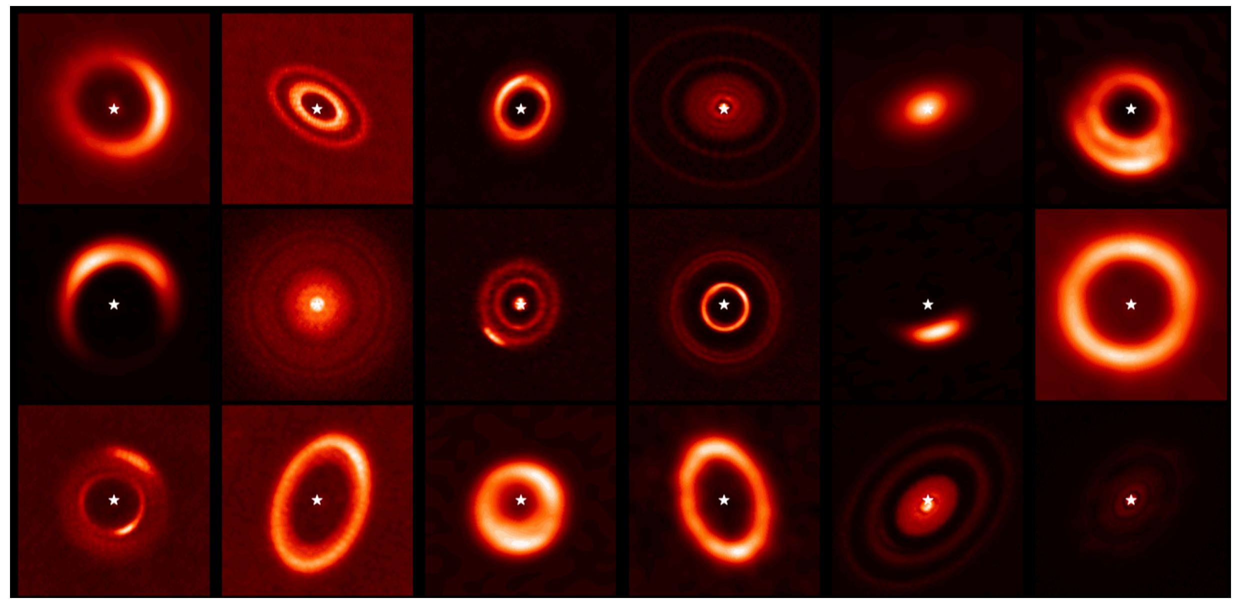
e.g., Weidenschilling 1977

Asteroid belt depleted (e.g., ~1/1000)

Today

An annulus distribution

ALMA observations & planetesimal formation



e.g., Marel et al. 2019

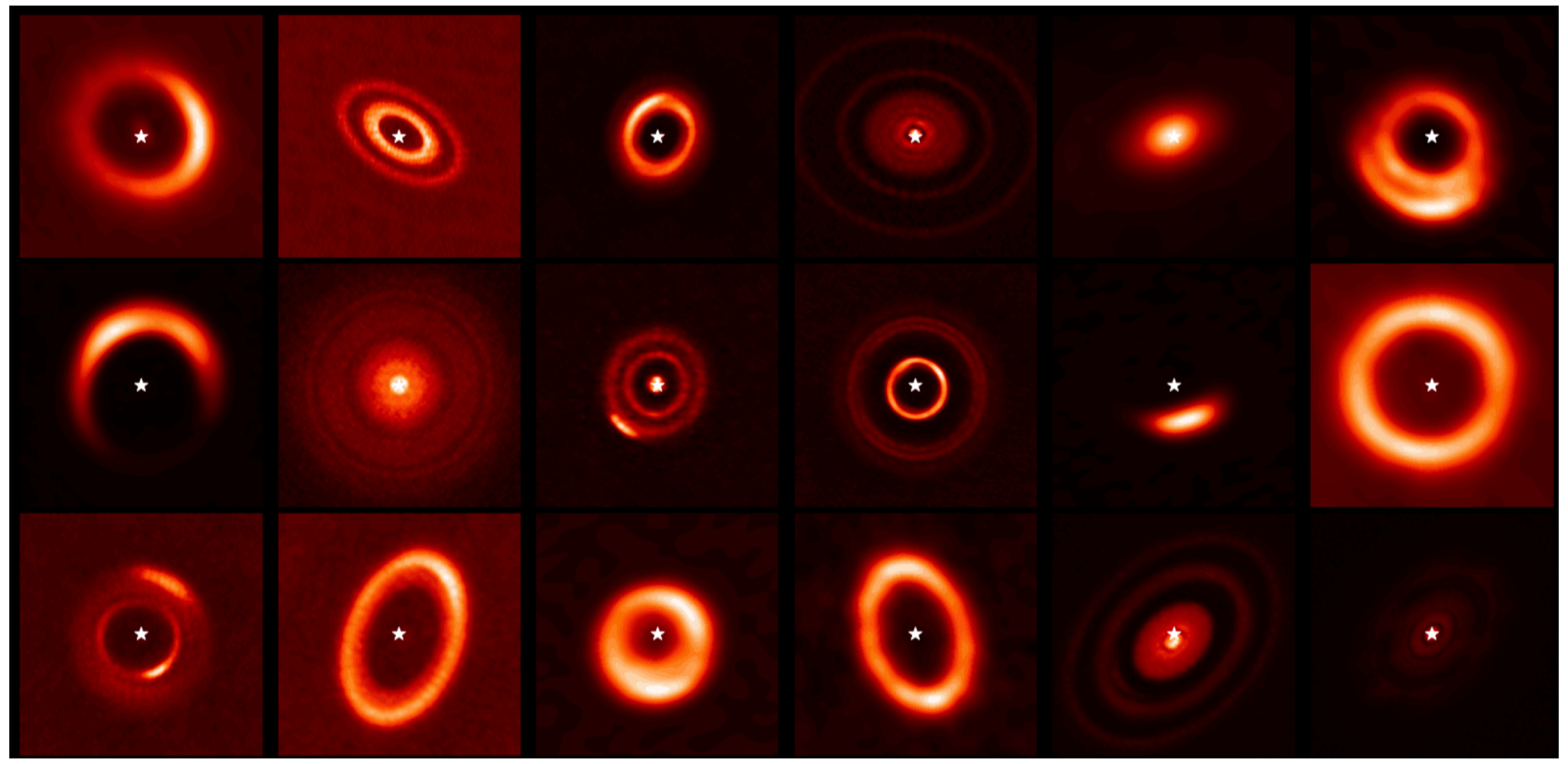
Asteroid belt implanted?

Today

Planetesimal Formation

A (local) elevated concentration of solids may be a favorable condition for planetesimal formation, followed by streaming instability and/or gravitational instability.

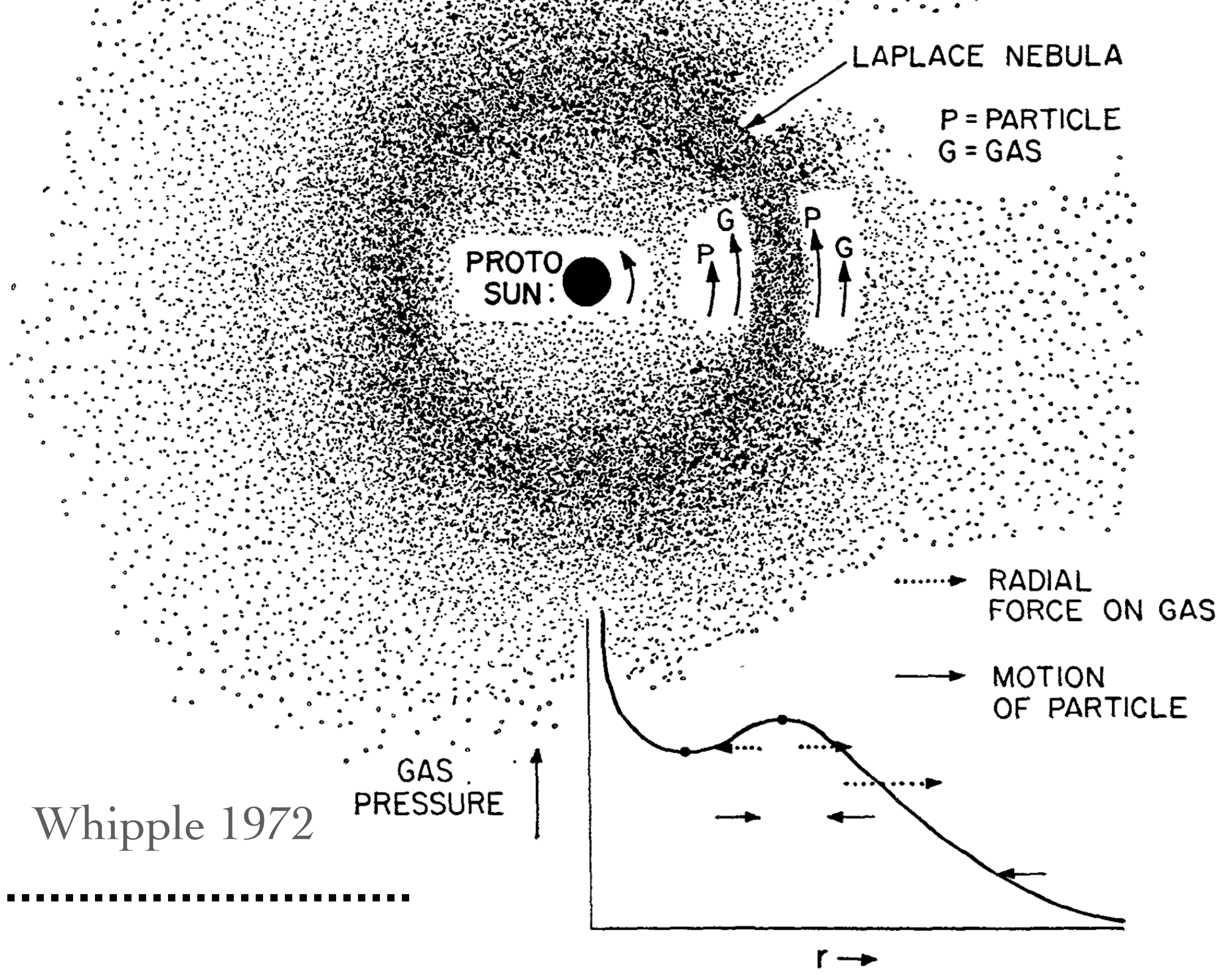
e.g., Johansen et al. 2009
Carrera et al. 2015
Yang et al. 2017



Marel et al. 2019

Pressure Bump

- edges of dead zones
  (e.g., Chatterjee & Tan 2014; Charnoz+2019)
- curved by planet gravity
  (e.g., Pinilla+2012; Kanagawa+ 2015, 2016)
- etc.



Whipple 1972

Snow Line

Stevenson & Lunine 1988
Ciesla & Cuzzi 2006
Birnstiel et al. 2010
Saito & Sirono 2011
Ros & Johansen 2013
Morbidelli et al. 2015
Bitsch et al., 2015
Estrada et al. 2016
Ida & Guillot 2016
Okuzumi et al. 2016
Schoonenberg & Ormel 2017
Drazkowska & Alibert 2017
Hyodo et al. 2019b

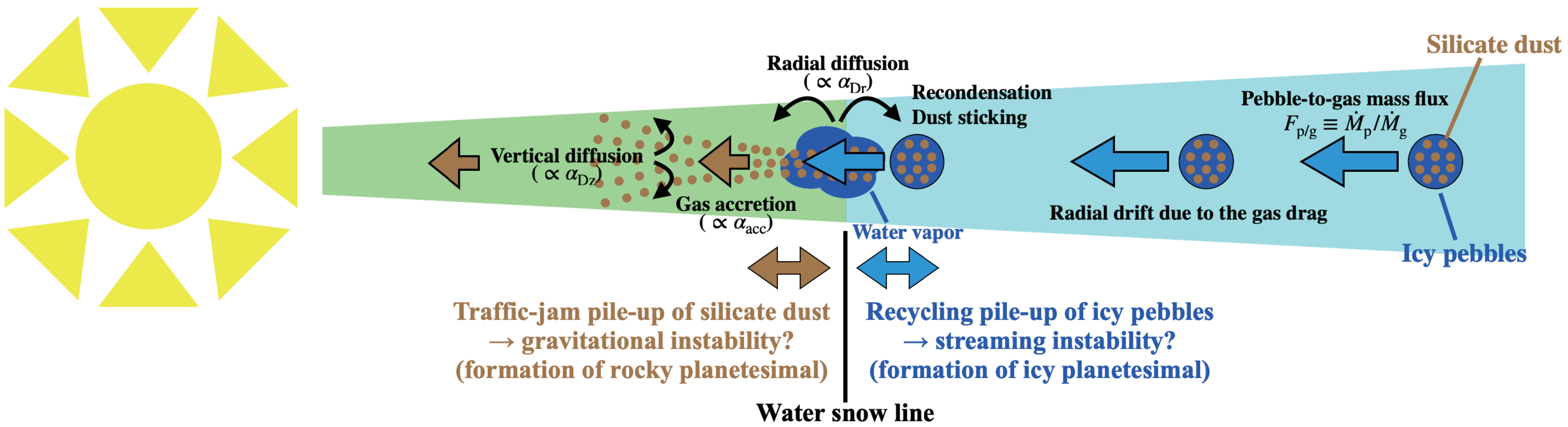


Fig. of Hyodo et al. 2021c

Others

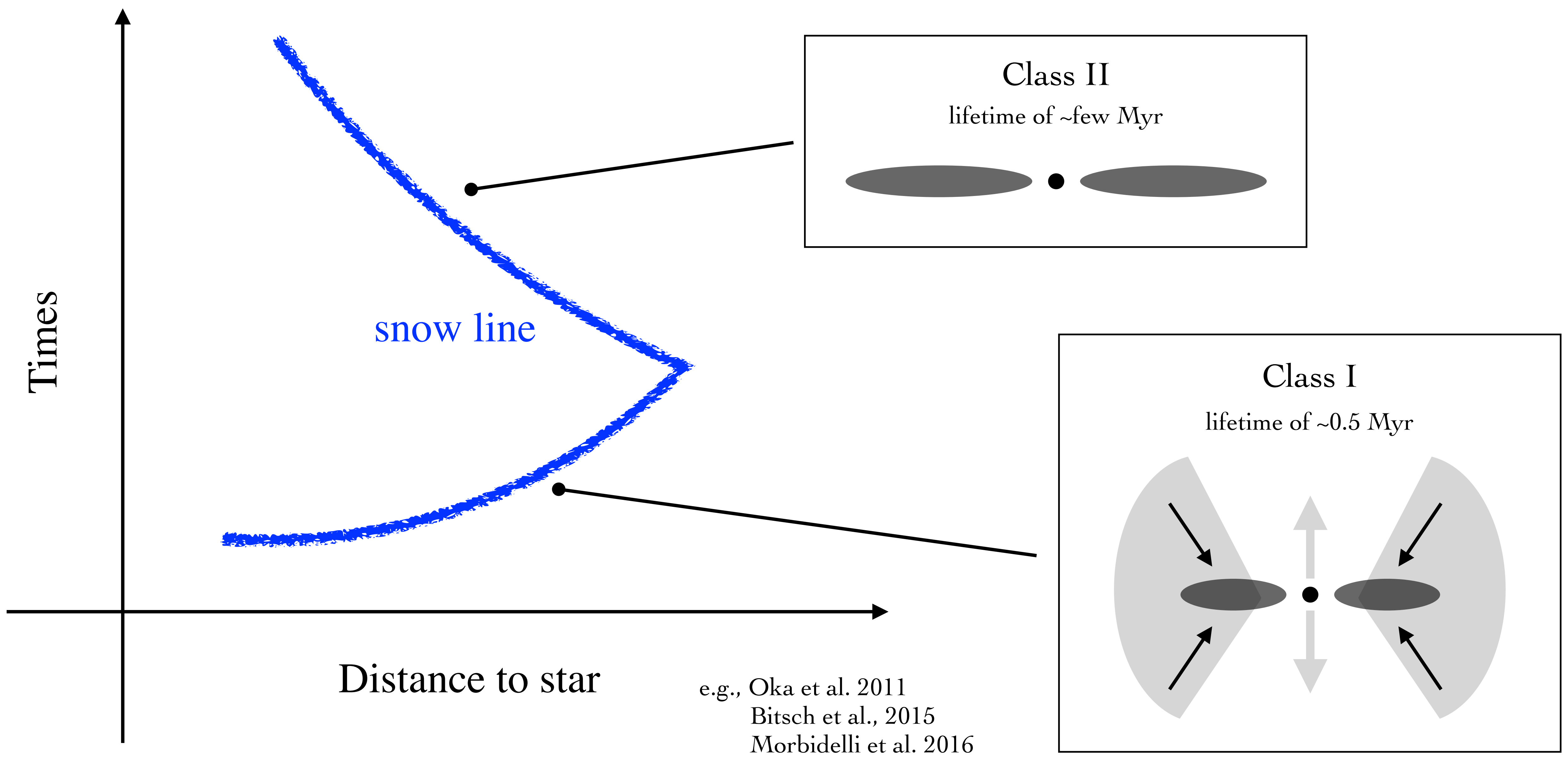
- Dust evolution (e.g., Wada et al, 2009; Okuzumi et al. 2012; Zhang et al. 2015)
- Secular GI (e.g., Ward 1976, 2000; Youdin 2011; Takahashi & Inutsuka 2014)
- Anti-cyclonic vortex (e.g., Barge & Sommeria 1995; Inaba & Barge 2006)
- “No-Drift” mechanism (e.g., Hyodo et al. 2021b)
- etc.

Snow Line Evolution

Snow line migrates, depending on the build-up and/or evolution stages of the disk.

— Other Parameters —

Pebble-to-gas mass flux ($F_{\mathrm{p/g}} \equiv \dot{M}_{\mathrm{p}}/\dot{M}_{\mathrm{g}}$)



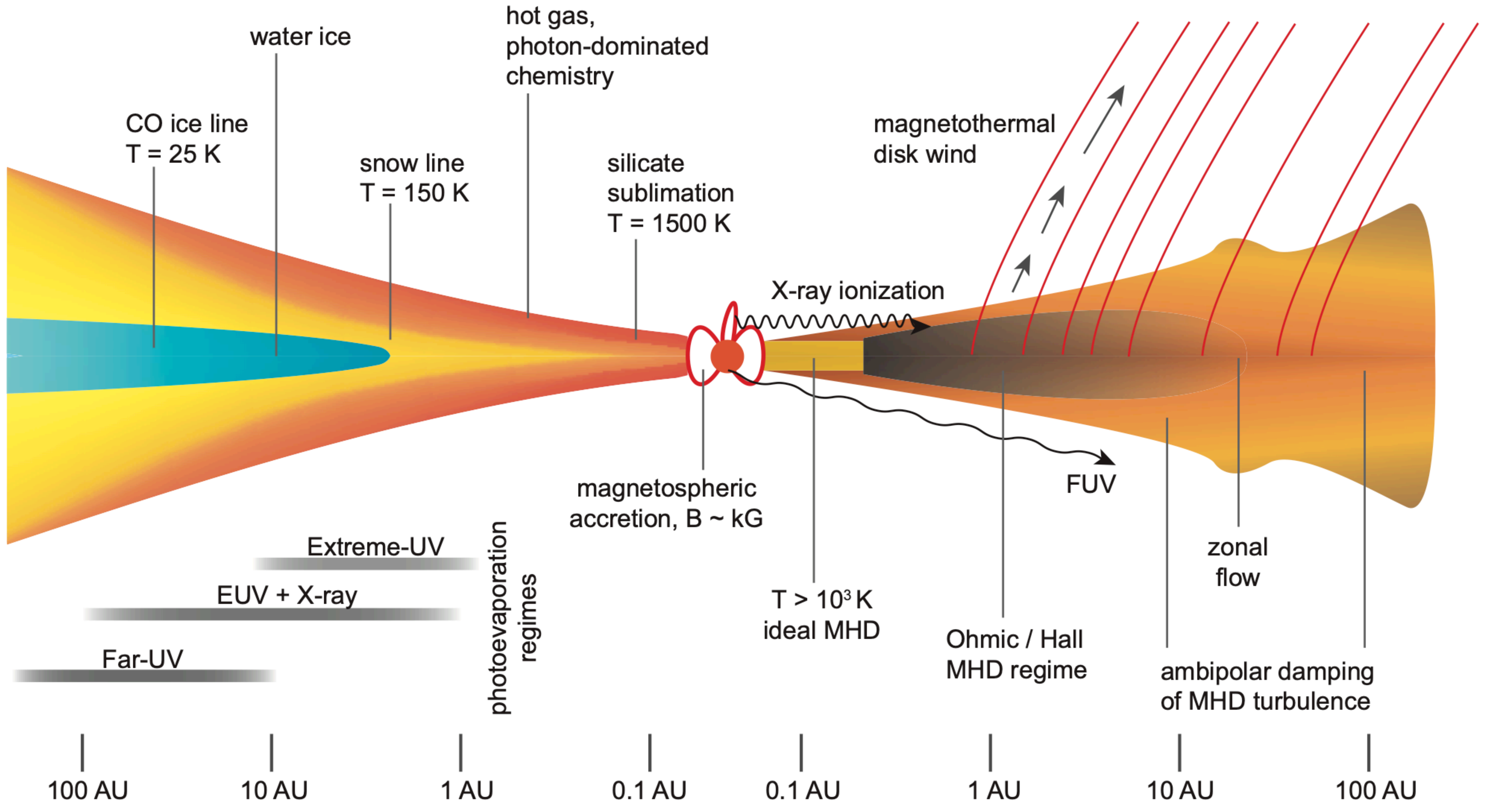
e.g., Oka et al. 2011
Bitsch et al., 2015
Morbidelli et al. 2016
Lichtenberg et al. 2021

Nonuniform Turbulence

A nonuniform turbulence structure may be ubiquitous.

— Parameters —

α_{acc} : α-parameter for disk gas accretion
α_{Dr} : α-parameter for radial mixing
α_{Dz} : α-parameter for vertical stirring



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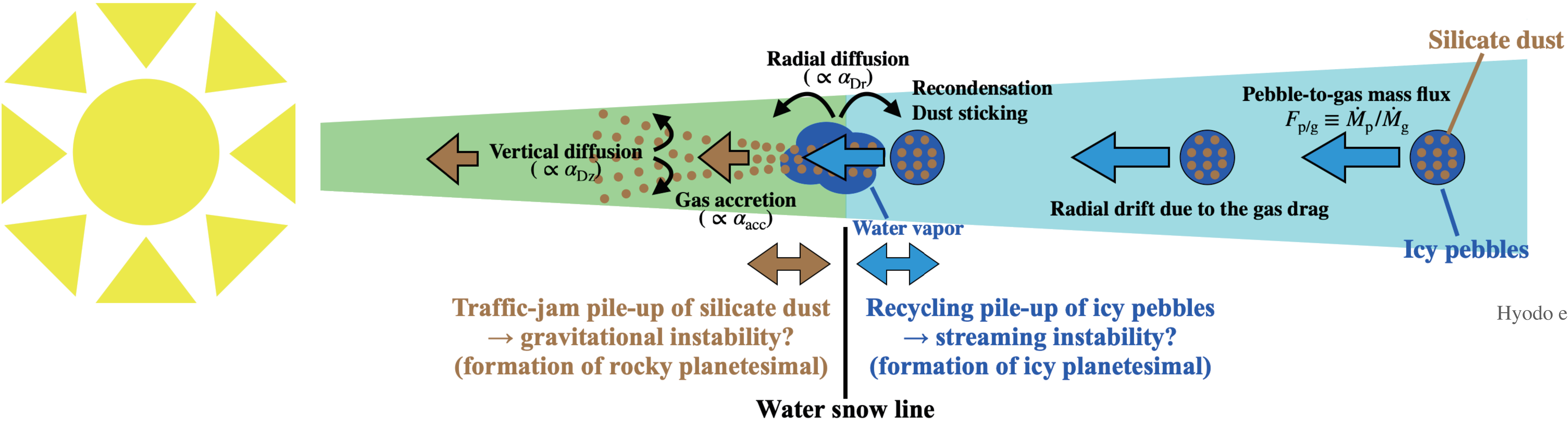
Things around the Snow Line — Qualitative



Hyodo et al. 2021b

- Pebbles ($\tau_s \simeq 0.1$) quickly drift due to gas drag (e.g., Garaud 2007; Lambrechts et al. 2014).
- Silicate dust ($\tau_s \ll 1$) well couples to the gas and drift with the gas (Brnstiel et al. 2010; Morbidelli et al. 2015)
  → causing traffic-jam (e.g., Ida et al. 2016; Hyodo et al. 2019).

- Diffused water vapor outside the snow line re-condense onto icy pebbles.
  (Schoonenberg & Ormel 2017; Drazkowska & Alibert 2017; Ros et al. 2019; Hyodo et al. 2019; Garate et al. 2020)
- Diffused silicate dust outside the snow line can stick to icy pebbles.

- Released silicate dust would initially have a small scale height (similar to pebbles?)
  and would be vertically stirred up as being away from the snow line?

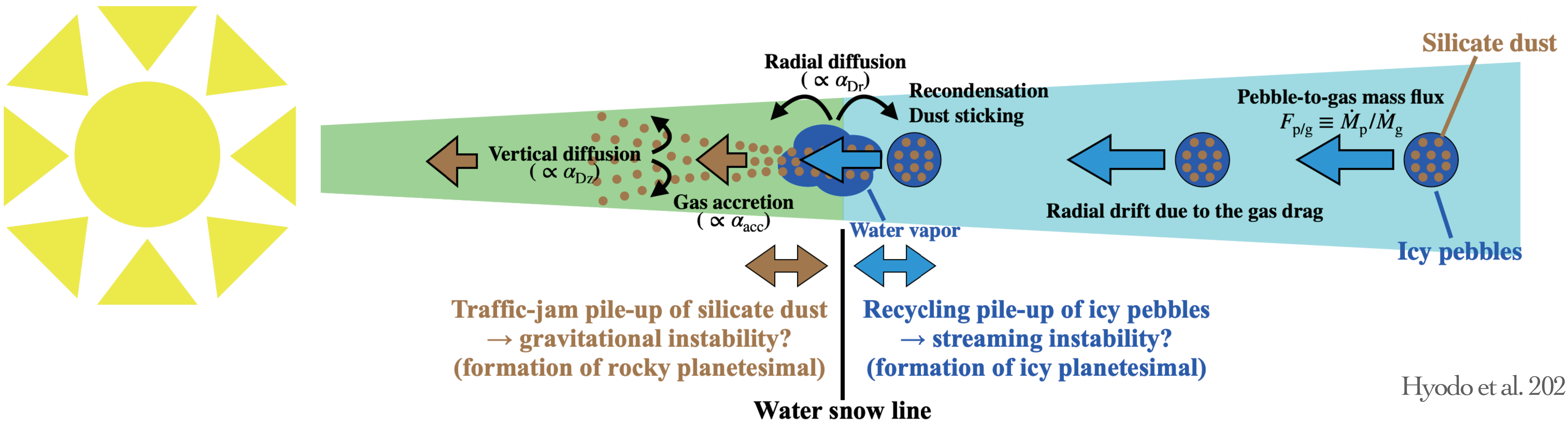
See also
Stevenson & Lunine 1988
Ciesla & Cuzzi 2006
Birnstiel et al. 2010
Saito & Sirono 2011
Ros & Johansen 2013
Estrada et al. 2016

Aimes

Previous studies did not correctly include the back-reaction (dust-gas inertia).
Also, the dependence on the disk structures is unclear.

- Better understanding the consequences of pebble drift to the snow line.
  (silicate dust or icy pebbles?, effects of back-reaction, and scale height, etc)
- It’s dependence on $F_{\mathrm{p/g}} \equiv \dot{M}_{\mathrm{p}}/\dot{M}_{\mathrm{g}}$
- It’s dependence on the turbulent structures (α_{acc}, α_{Dr}, α_{Dz})

A local 1D advection-diffusion simulation



Hyodo et al. 2021c, Fig.1

Models

- Three distinct non-dimensional parameters;
  gas accretion $\propto \alpha_{\rm acc}$
  radial and vertical diffusions $\propto \alpha_{\rm Dr}, \alpha_{\rm Dz}$ $(\alpha_{\rm Dr} = \alpha_{\rm Dz})$
- A realistic scale height of dust (Ida, Guillot, Hyodo et al. 2021)
- The back-reaction (BR) of solids onto gas
  (radial drift and diffusion)
- Recycling of silicate dust and water vapor, included

Parameters

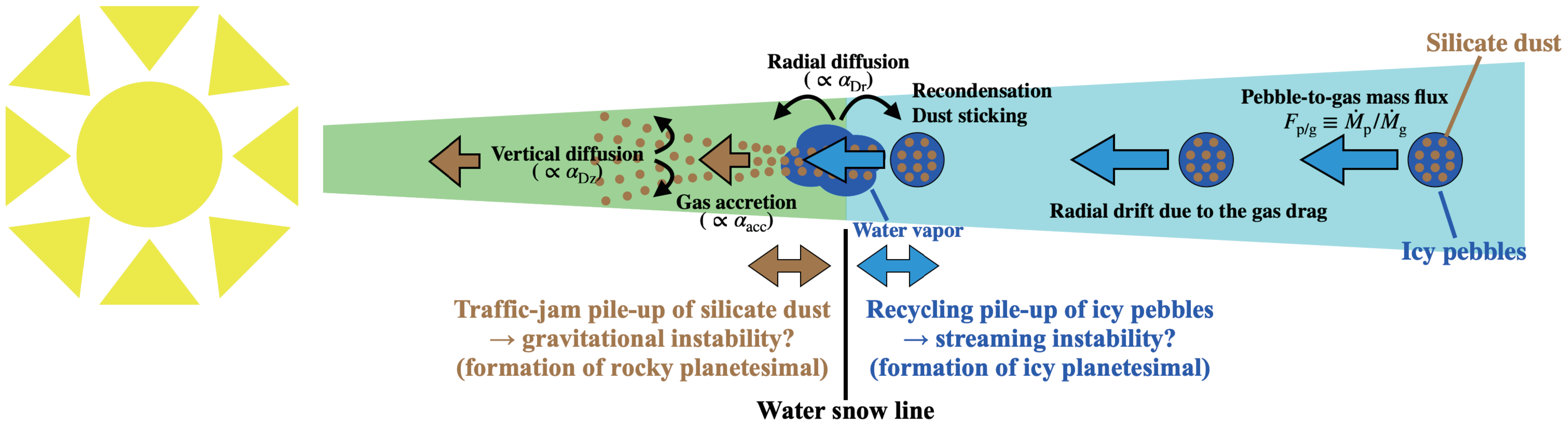
- Pebble-to-gas mass flux $F_{\rm p/g} = \dot{M}_{\rm p}/\dot{M}_g$
  $(\dot{M}_g = 10^{-8} M_\odot {\rm yr}^{-1})$
- The temperature profile $T_{\rm d} = 150\,(r/3{\rm au})^{-1/2}$ K
- Stokes number of pebbles $\tau_{\rm s} \sim 0.1$
- Stokes number of silicate dust $\tau_{\rm s} \ll 0.1$
- Initially, 50:50 rock-to-ice ratio.

A local 1D advection-diffusion simulation

We are looking at Z_p & Z_d around the snow line.

$$Z_{\rm p} \equiv \rho_{\rm p}/\rho_{\rm g}$$

$$Z_{\rm d} \equiv \rho_{\rm d}/\rho_{\rm g}$$



Traffic-jam pile-up of silicate dust
→ gravitational instability?
(formation of rocky planetesimal)

Recycling pile-up of icy pebbles
→ streaming instability?
(formation of icy planetesimal)

Midplane spatial density

gas surface density
gas scale height

Gas: $\rho_{\rm g} = \boxed{\Sigma_{\rm g}}/\sqrt{2\pi}\boxed{H_{\rm g}}$

pebble surface density
pebble scale height

Pebble: $\rho_{\rm p} = \boxed{\Sigma_{\rm p}}/\sqrt{2\pi}\boxed{H_{\rm p}}$

Silicate dust: $\rho_{\rm d} = \boxed{\Sigma_{\rm d}}/\sqrt{2\pi}\boxed{H_{\rm d}}$

silicate dust scale height
silicate dust surface density

Pebble scale height

Stokes number
pebble-to-gas ratio ($Z \equiv \rho_{\rm p}/\rho_{\rm g}$)
coefficient for diffusion back-reaction (K=0,1,2)
gas scale height

Turbulence-regulated H_p

$$H_{\rm p,tur} = \left(1 + \frac{\boxed{\tau_{\rm s,p}}}{\alpha_{\rm Dz}\left(1+\boxed{Z_{\rm p}}\right)^{\boxed{-K}}}\right)^{-1/2} \boxed{H_{\rm g}}$$

Richardson number
(0.5 here)

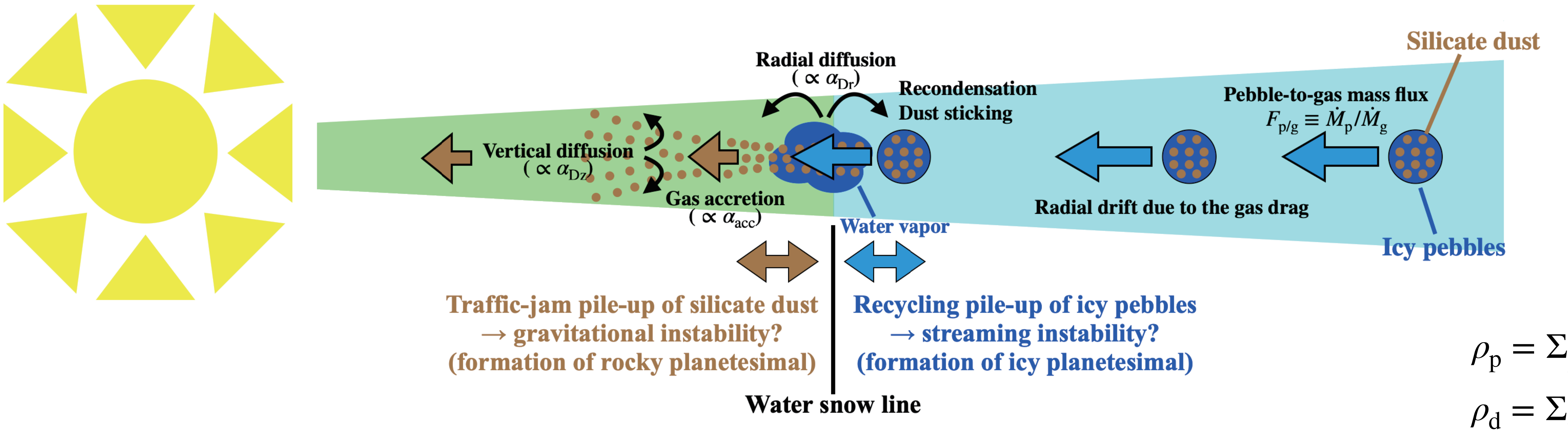
KH-regulated H_p

$$H_{\rm p,KH} \simeq Ri^{1/2}\frac{Z^{1/2}}{(1+Z)^{3/2}}C_\eta\left(\frac{H_{\rm g}}{r}\right)H_{\rm g} = \boxed{Ri}^{1/2}\frac{Z^{1/2}}{(1+Z)^{3/2}}\eta r$$

Larger one used

$$H_{\rm p} = \max\left\{H_{\rm p,tur}, H_{\rm p,KH}\right\}$$

Snow Line - Critical Considerations



$$\rho_p = \Sigma_p/\sqrt{2\pi}H_p$$

$$\rho_d = \Sigma_d/\sqrt{2\pi}H_d$$

Back-reaction

Radial drift (Drift-BR)

ρ_p/ρ_g

$\Lambda \equiv \rho_g/(\rho_g+\rho_p) = 1/(1+\boxed{Z})$

Stokes number

$$v_p = -\frac{\boxed{\Lambda}}{1+\Lambda^2\tau_s^2}\left(2\boxed{\tau_s}\Lambda\eta v_K - \boxed{v_g}\right)$$

gas velocity

gas orbital frequency

gas pressure

$$\eta \equiv \frac{\boxed{\Omega_K}-\boxed{\Omega}}{\Omega_K} = -\frac{1}{2}\frac{\partial \ln \boxed{P_g}}{\partial \ln r}\left(\frac{H_g}{r}\right)^2$$

Keplerin orbital frequency

As pile-up occurs, drift velocity decreases.

About Drift-BR	pebbles	dust
Ida & Guillot 2016		✔
Schoonenreg&Ormel 2017	✔	
Hyodo et al. 2019	✔	✔
Ida et al. 2021, Hyodo et al. 2021	✔	✔

*Including back-reaction onto the gas motion does not qualitatively change the results. (see Garate et al. 2020)

Diffusions (Diff-BR)

a coefficient to characterize the strength of the diffusion back-reaction (K=1 or 2 as examples; Hyodo et al. 2019)

$$D_r = \alpha_{Dr}H_g^2\Omega\Lambda^{\boxed{K}}$$

$$D_z = \alpha_{Dz}H_g^2\Omega\Lambda^{K}$$

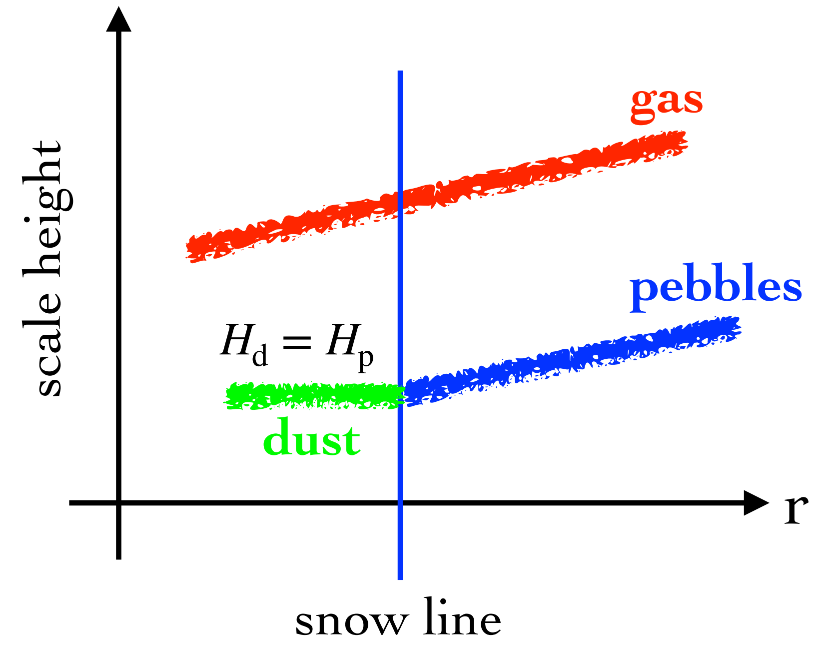
As pile-up occurs, the diffusivity decreases.

About Diff-BR	pebbles	dust
Ida & Guillot 2016		
Schoonenreg&Ormel 2017		
Hyodo et al. 2019	✔	✔
Ida et al. 2021, Hyodo et al. 2021	✔	✔

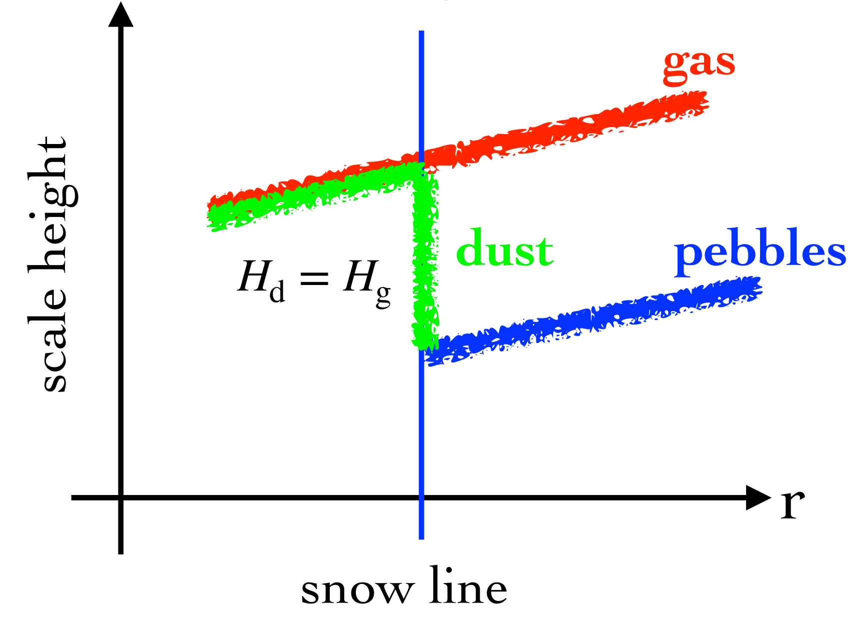
*As long as $K \neq 0$, the results do not qualitatively change.

Scale height of silicate dust H_d

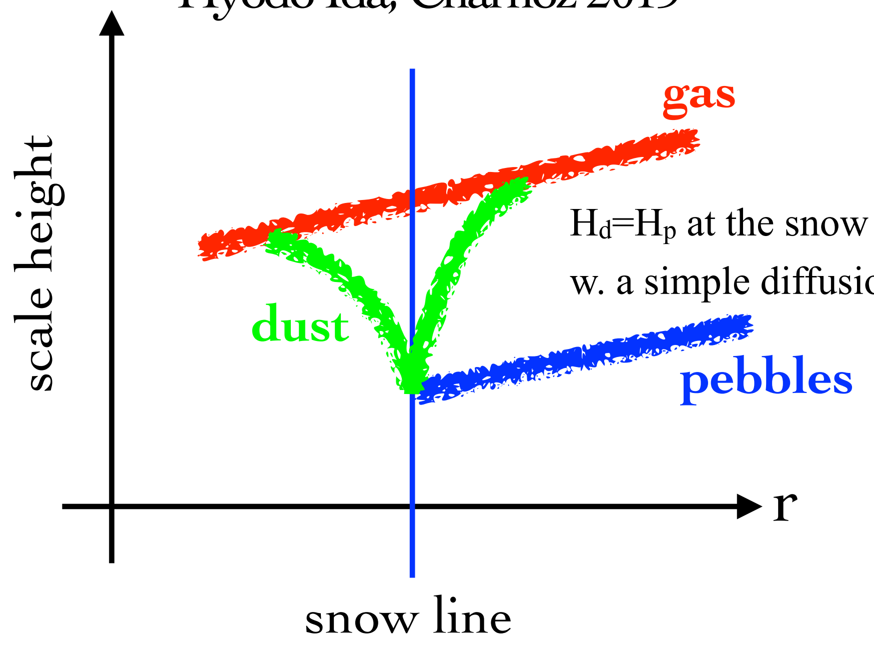
Ida&Guillot 2016



Schoonenberg&Ormel 2017

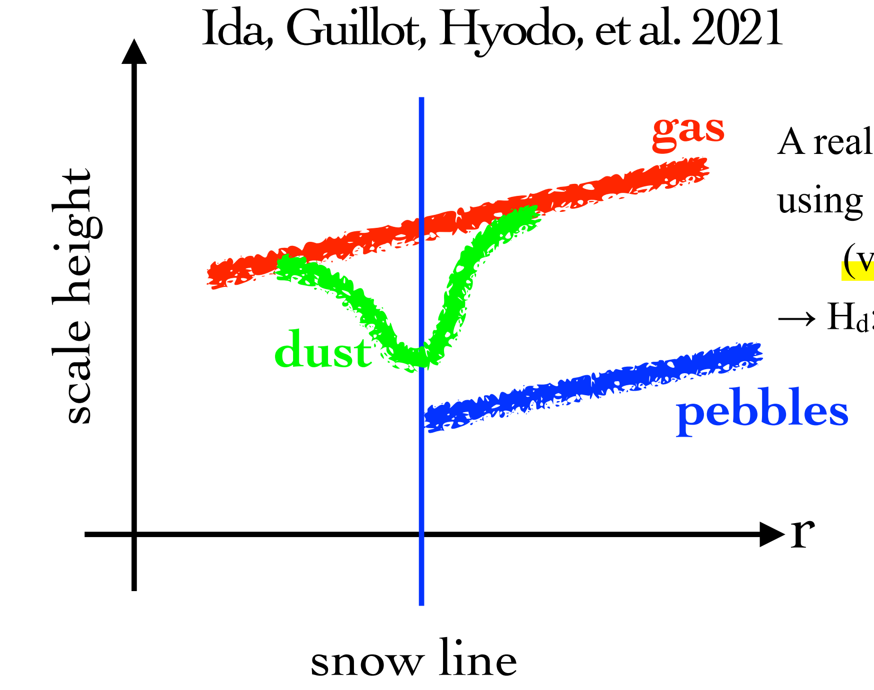


Hyodo Ida, Charnoz 2019



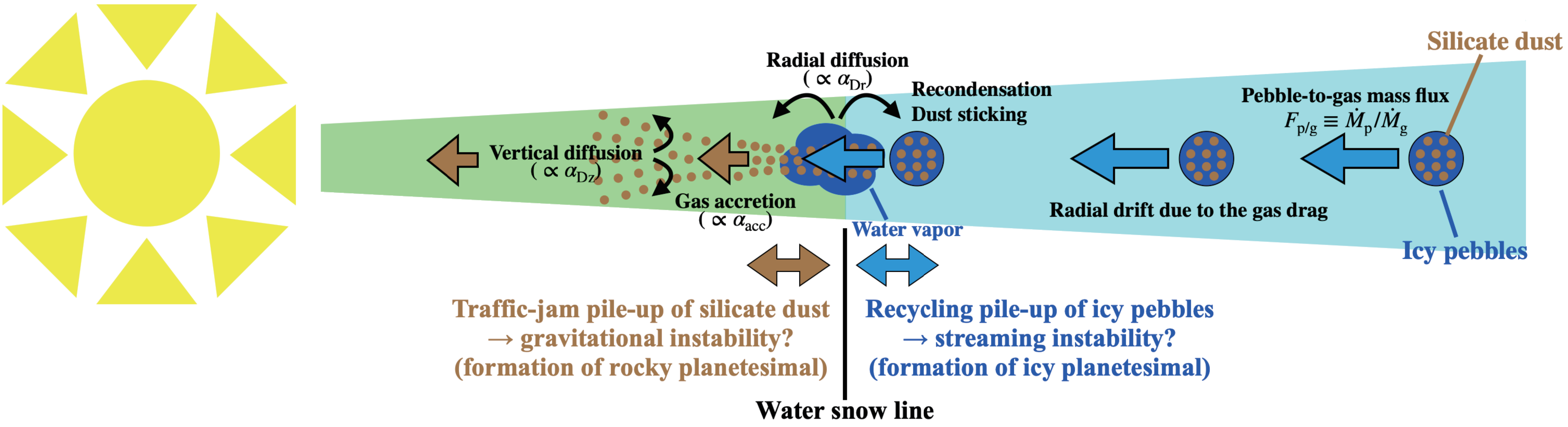
Hd=Hp at the snow line w. a simple diffusion model.

Ida, Guillot, Hyodo, et al. 2021

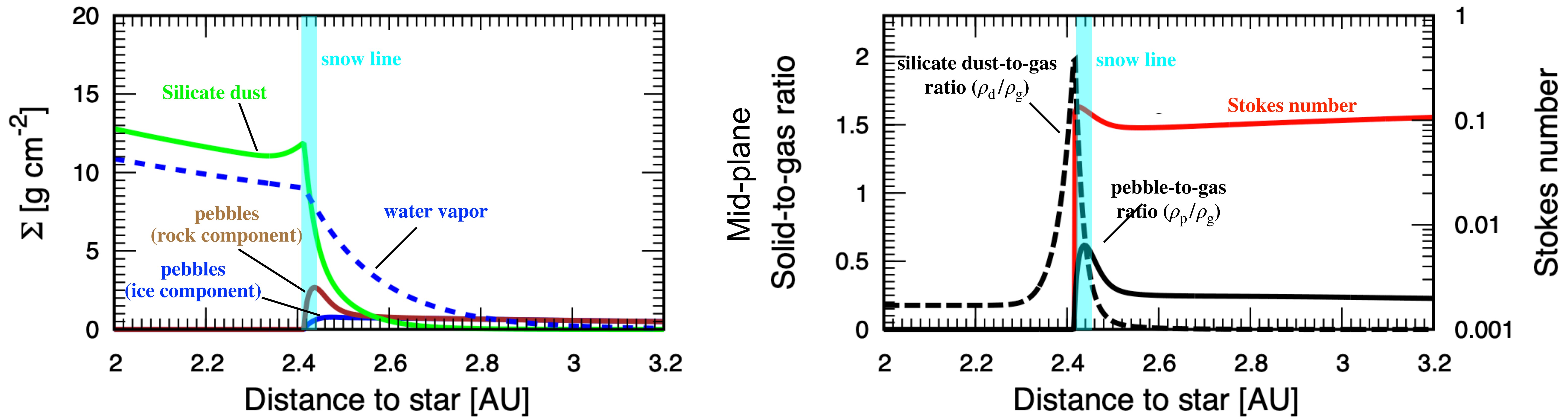


A realistic H_d is derived using Monte-Carlo simulations. (via a Lagrangian method)
→ H_d: a function of disk structure. (i.e., α_{acc}, α_{Dr}, α_{Dz})

An Example Result



$\alpha_{acc} = 1 \times 10^{-2}$, $\alpha_{Dr}=\alpha_{Dz} = 1 \times 10^{-3}$, $F_{p/g} = 0.3$ with $K = 0$ (Hyodo et al. 2019)



Here, the resultant pile-up is a steady-state.

By changing disk structures (α_{acc}, α_{Dr}, α_{Dz}) and $F_{p/g}$,
a "runaway" pile-up occurs (a key point of this study).

Another Topic…

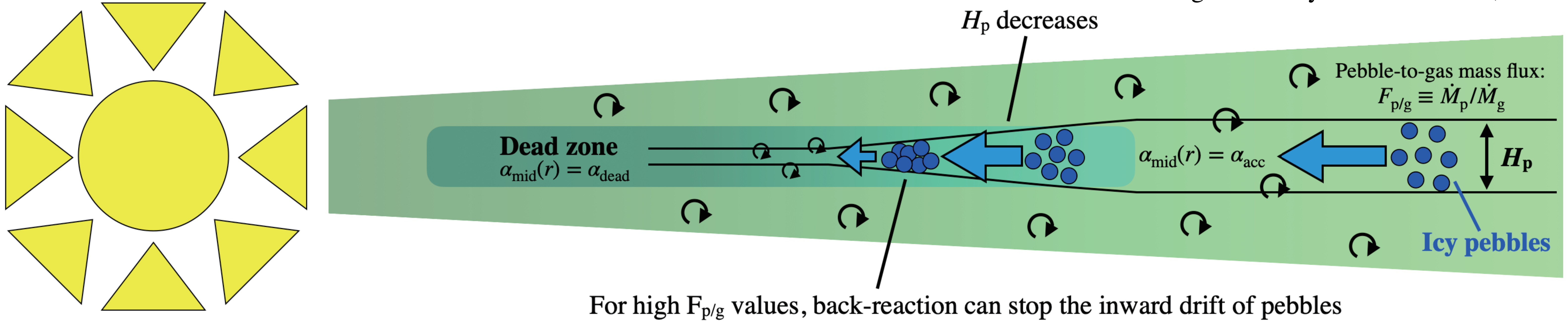
“Before reaching the snow line,
the ‘No-drift’ mode may occur.”

Hyodo, Ida, Guillot (2021c), A&A Letters

*This process does not require snow line, pressure bump, and/or pebble growth.

“No-drift” runaway pile-up — A consequence of drift back-reaction

Fig.1 from Hyodo et al. 2021b, A&A Letters



α_{acc}: α-parameter for gas accretion
α_{mid}: α-parameter for vertical (radial) mixing

Case example settings

- Vertical layered gas disk (e.g., due to the disk wind) accretes onto the star ($\propto \alpha_{acc}$)
- The inner disk midplane is MRI-dead ($\alpha_{mid} = \alpha_{dead}$). The outer disk is MRI-active ($\alpha_{mid} = \alpha_{acc}$).
- The scale height of pebbles (H_p) depends on the midplane turbulent stirring ($\propto \alpha_{mid}$).

Pebble scale height

Stokes number
pebble-to-gas ratio ($Z \equiv \rho_p/\rho_g$)
coefficient for diffusion back-reaction
gas scale height

Turbulence-regulated H_p

$$H_{p,tur} = \left(1 + \frac{\boxed{\tau_s}}{\alpha_{mid}\,(1+\boxed{Z})^{\boxed{-K}}}\right)^{-1/2} \boxed{H_g}$$

Richardson number
(0.5 here)

KH-regulated H_p

$$H_{p,KH} \simeq Ri^{1/2}\frac{Z^{1/2}}{(1+Z)^{3/2}}C_\eta\left(\frac{H_g}{r}\right)H_g = \boxed{Ri}^{1/2}\frac{Z^{1/2}}{(1+Z)^{3/2}}\eta r$$

Larger one used

$$H_p = \max\left\{H_{p,tur}, H_{p,KH}\right\}$$

Pebble drift velocity

$\Lambda \equiv \rho_g/(\rho_g+\rho_p)$
$= 1/(1+Z)$

Drift velocity decreases as pile-up proceeds (drift back-reaction)
→ the “No-drift” mode induced

$$v_p = -\boxed{\frac{\boxed{\Lambda}}{1+\Lambda^2\tau_s^2}}\left(2\tau_s\Lambda\eta v_K - \boxed{v_g}\right)$$

gas accretion velocity

gas pressure

gas orbital frequency

$$C_\eta \equiv -\frac{1}{2}\frac{\partial \ln \boxed{P_g}}{\partial \ln r}$$

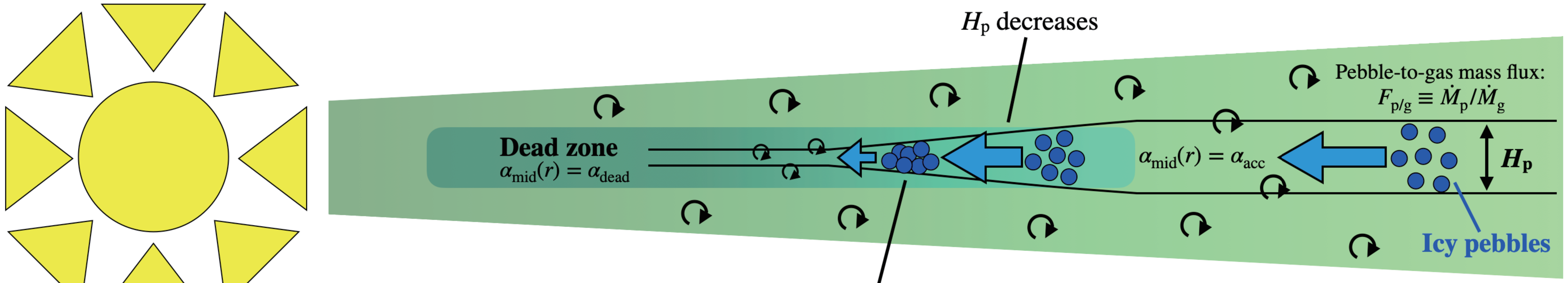
$$\eta \equiv \frac{\boxed{\Omega_K} - \boxed{\Omega}}{\Omega_K} = -\frac{1}{2}\frac{\partial \ln P_g}{\partial \ln r}\left(\frac{H_g}{r}\right)^2 = C_\eta\left(\frac{H_g}{r}\right)^2$$

Keplerin orbital frequency

$$v_g = -\frac{3\nu_{acc}}{2r} = -\frac{3\alpha_{acc}H_g^2\Omega_K}{2r} = -\frac{3\alpha_{acc}}{2}\left(\frac{H_g}{r}\right)^2 v_K,$$

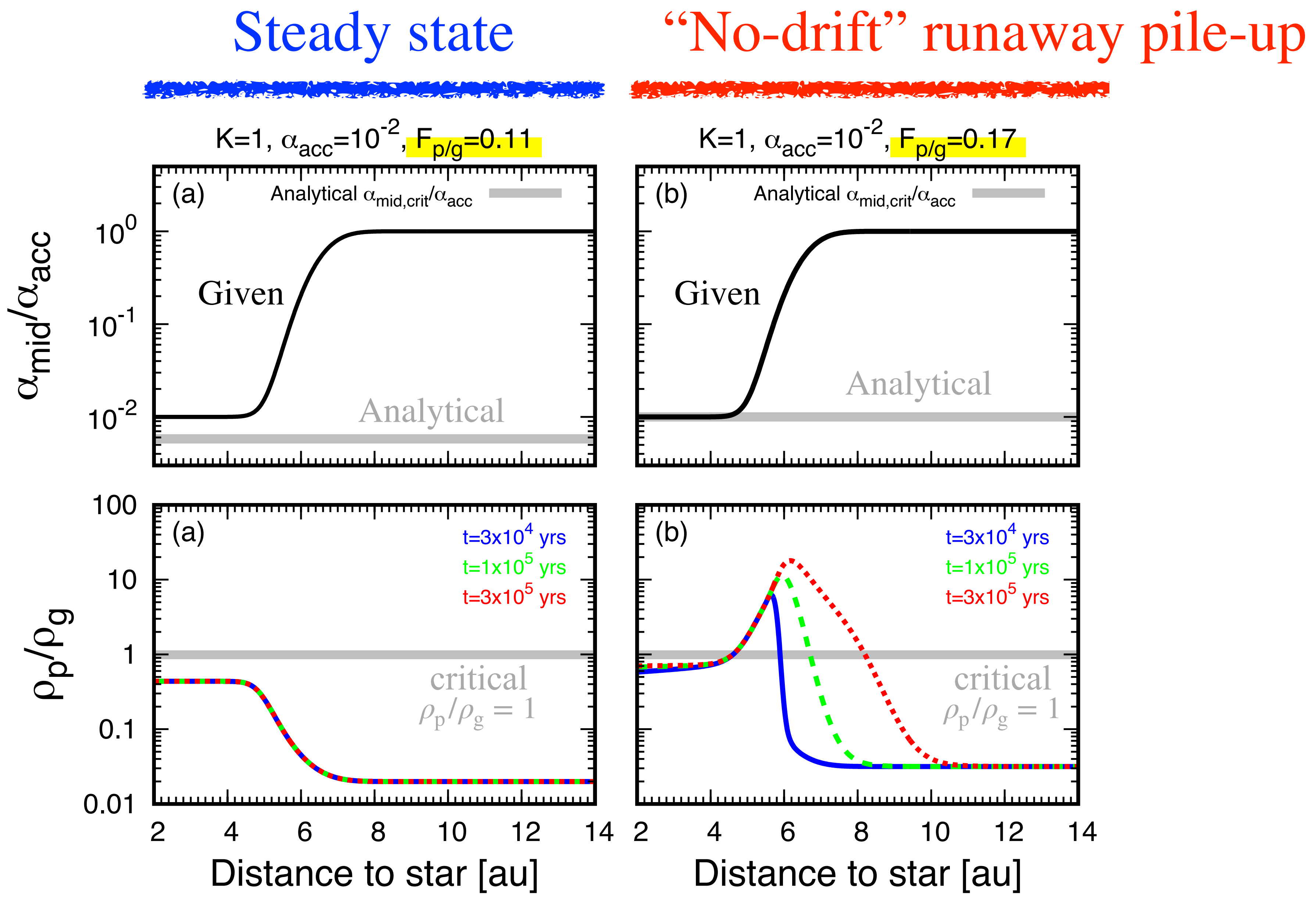
$$\simeq -\frac{3}{2}\alpha_{acc}\eta v_K\left(-\frac{1}{2}\frac{d\ln P_g}{d\ln r}\right)^{-1} = -\frac{3}{2}\alpha_{acc}\eta v_K C_\eta^{-1},$$

"No-drift" runaway pile-up — Numerical



For high $F_\mathrm{p/g}$ values, back-reaction can stop the inward drift of pebbles

"No-drift" occurs
for "given" ≤ "Analytical"



Analytical — A critical value

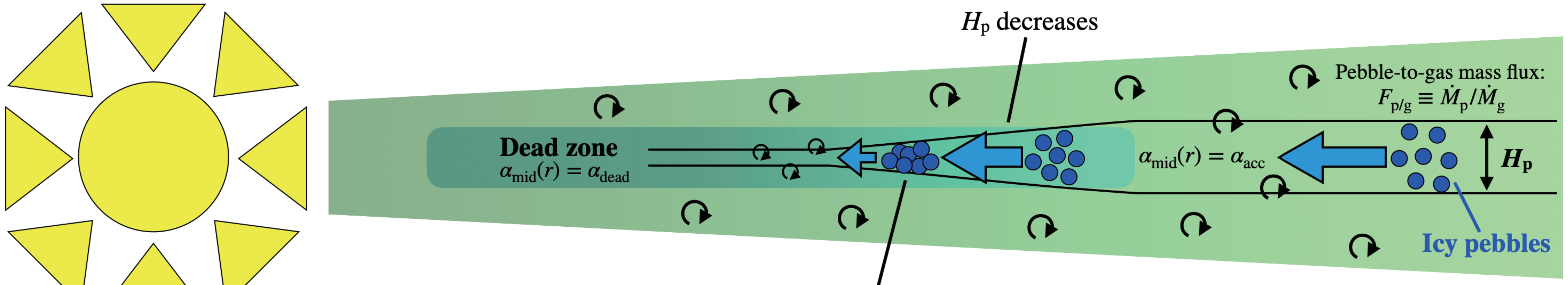
Below which the "No-drift" mode occurs

$$\frac{\alpha_\mathrm{mid,crit}}{\alpha_\mathrm{acc}} \equiv \left(\frac{3F_\mathrm{p/g}}{C_\eta}\right)^2 \alpha_\mathrm{acc}\tau_\mathrm{s}^{-1},$$

$$\simeq 4.76 \times 10^{-3} \left(\frac{F_\mathrm{p/g}}{0.1}\right)^2 \left(\frac{C_\eta}{11/8}\right)^{-2} \left(\frac{\alpha_\mathrm{acc}}{10^{-2}}\right)\left(\frac{\tau_\mathrm{s}}{0.1}\right)^{-1}$$

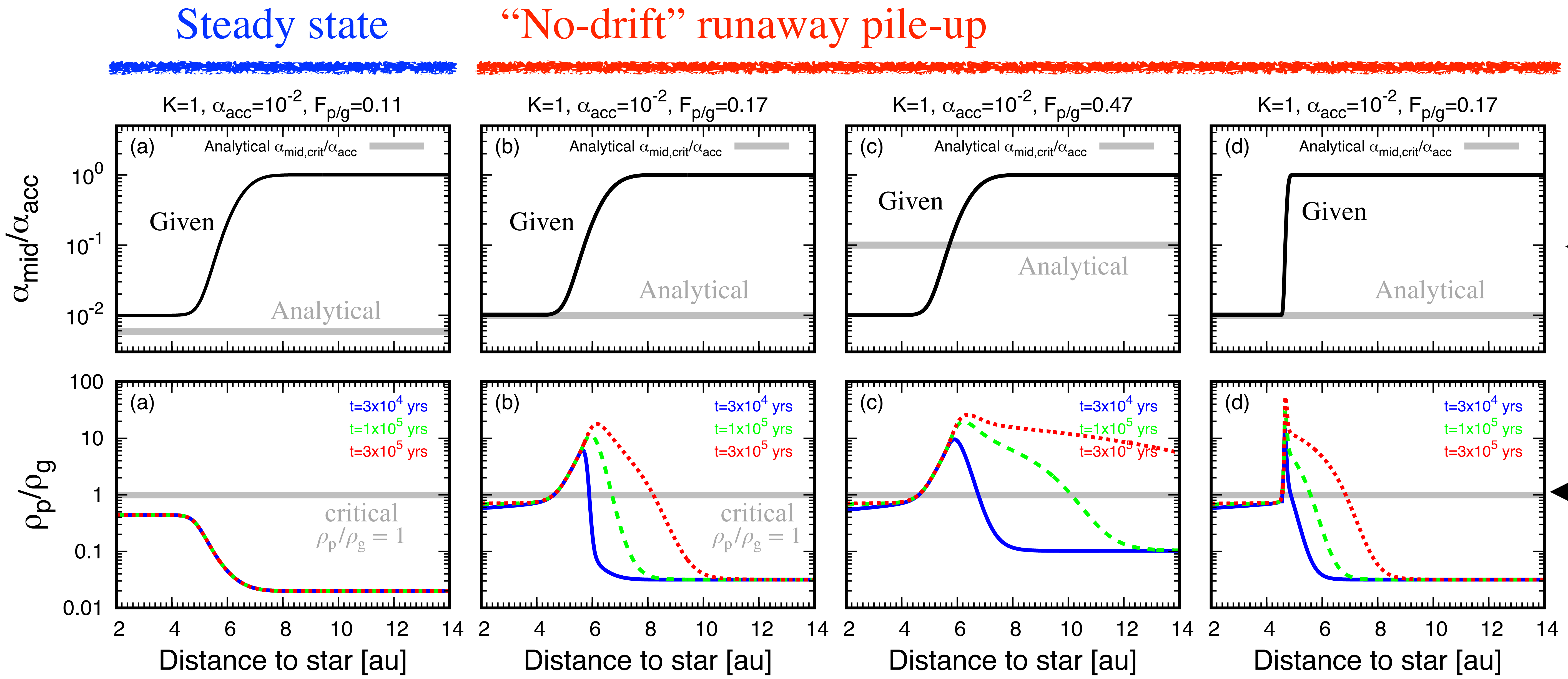
$$C_\eta \equiv -\frac{1}{2}\frac{\partial \ln P_\mathrm{g}}{\partial \ln r}$$

“No-drift” runaway pile-up — Numerical



For high $F_{p/g}$ values, back-reaction can stop the inward drift of pebbles

“No-drift” occurs
for “given” ≤ “Analytical”



Steady state

“No-drift” runaway pile-up

No dependence on the architecture of the dead zone

Once the “no-drift” takes place at a specific heliocentric distance, runaway pile-up propagates outward!

Analytical — A critical value

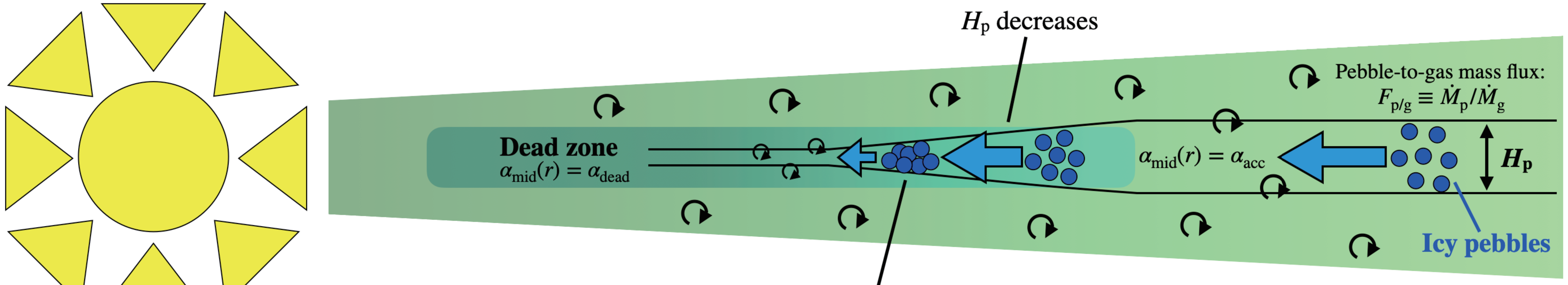
Below which the “No-drift” mode occurs

$$\frac{\alpha_{\rm mid,crit}}{\alpha_{\rm acc}} \equiv \left(\frac{3F_{\rm p/g}}{C_\eta}\right)^2 \alpha_{\rm acc}\tau_{\rm s}^{-1},$$

$$\simeq 4.76\times10^{-3}\left(\frac{F_{\rm p/g}}{0.1}\right)^2\left(\frac{C_\eta}{11/8}\right)^{-2}\left(\frac{\alpha_{\rm acc}}{10^{-2}}\right)\left(\frac{\tau_{\rm s}}{0.1}\right)^{-1}$$

$$C_\eta \equiv -\frac{1}{2}\frac{\partial \ln P_{\rm g}}{\partial \ln r}$$

“No-drift” runaway pile-up — Parameter map



For high $F_{p/g}$ values, back-reaction can stop the inward drift of pebbles

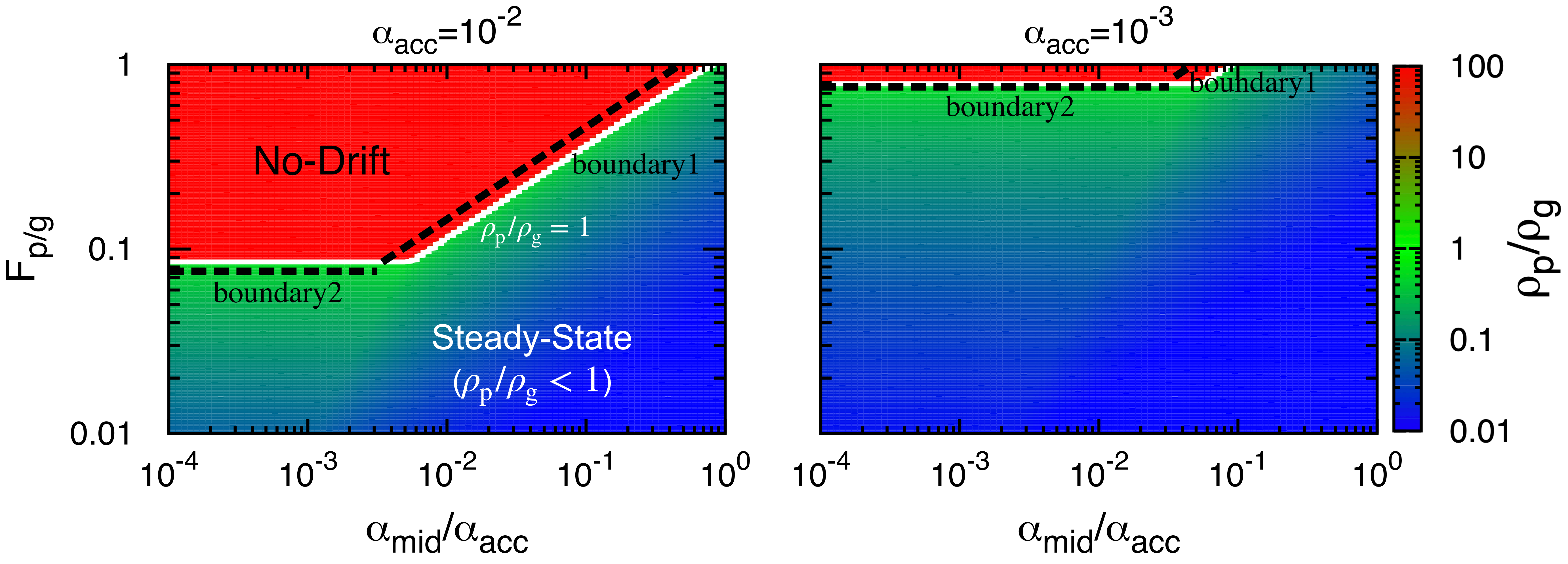
Hyodo et al. 2021b, A&A Letters

Analytical — Critical boundary1

Above which the “No-drift” mode occurs

$$F_{p/g,crit1} = \frac{C_\eta}{3}\frac{\tau_s}{\alpha_{acc}} h_{p/g} \simeq \frac{(\alpha_{mid}\tau_s)^{1/2} C_\eta}{3\alpha_{acc}},$$

$$\simeq 0.15 \times \left(\frac{\alpha_{acc}}{10^{-2}}\right)^{-1} \left(\frac{\alpha_{mid}}{10^{-4}}\right)^{1/2} \left(\frac{\tau_s}{0.1}\right)^{1/2} \left(\frac{C_\eta}{11/8}\right)$$



Analytical — Critical boundary2

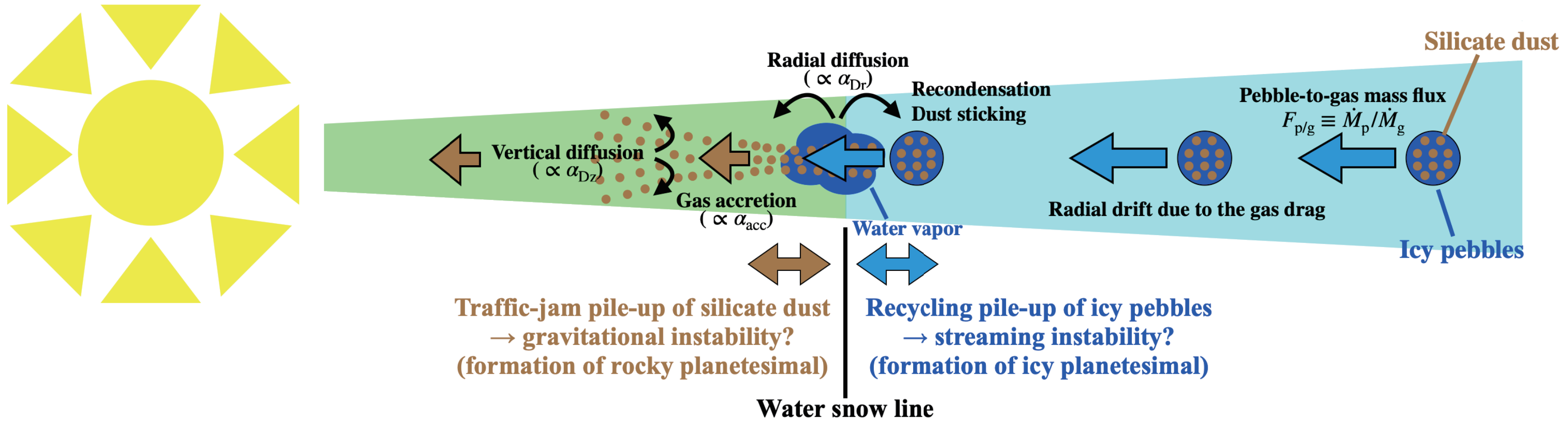
Above which the “No-drift” mode occurs

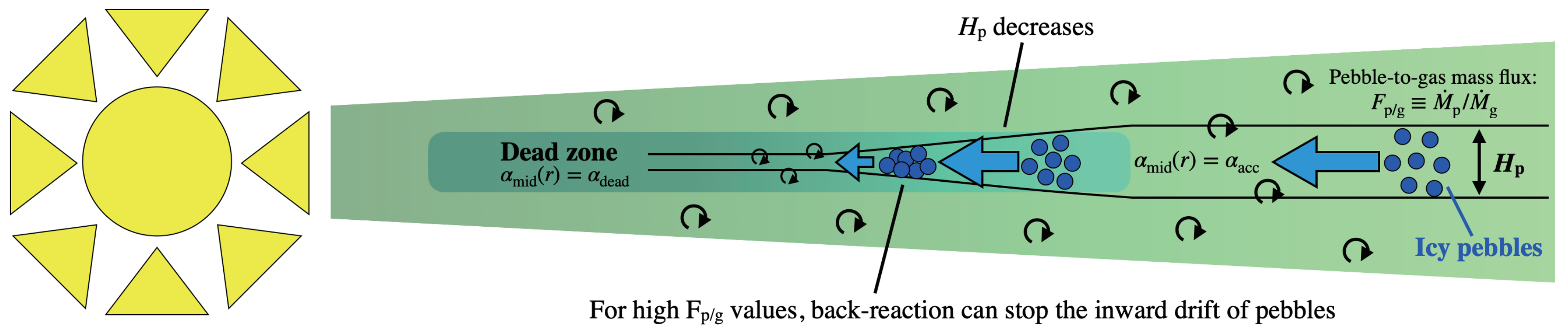
$$F_{p/g,crit2} = \frac{C_\eta}{3}\left(\frac{\tau_s}{\alpha_{acc}}\right) h^{Z=1}_{p/g,KH} = \frac{11}{24}\left(\frac{\tau_s}{\alpha_{acc}}\right) h^{Z=1}_{p/g,KH},$$

$$\simeq 0.06 \times \left(\frac{\alpha_{acc}}{10^{-2}}\right)^{-1} \left(\frac{\tau_s}{0.1}\right) \left(\frac{Ri}{0.5}\right)^{1/2} \left(\frac{H_g/r}{0.04}\right)$$

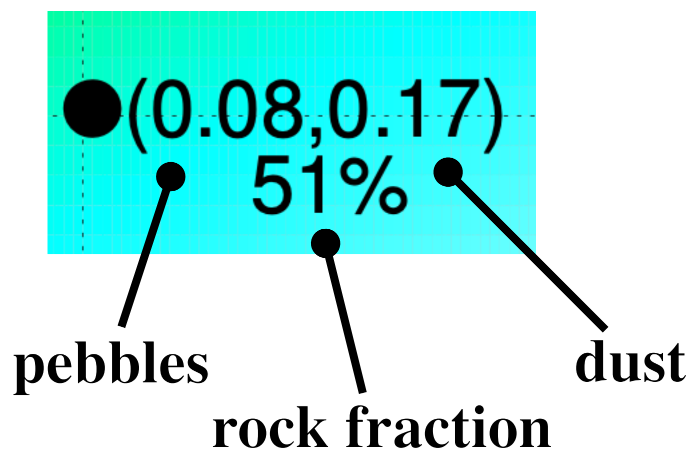
Resultant pile-up mode —

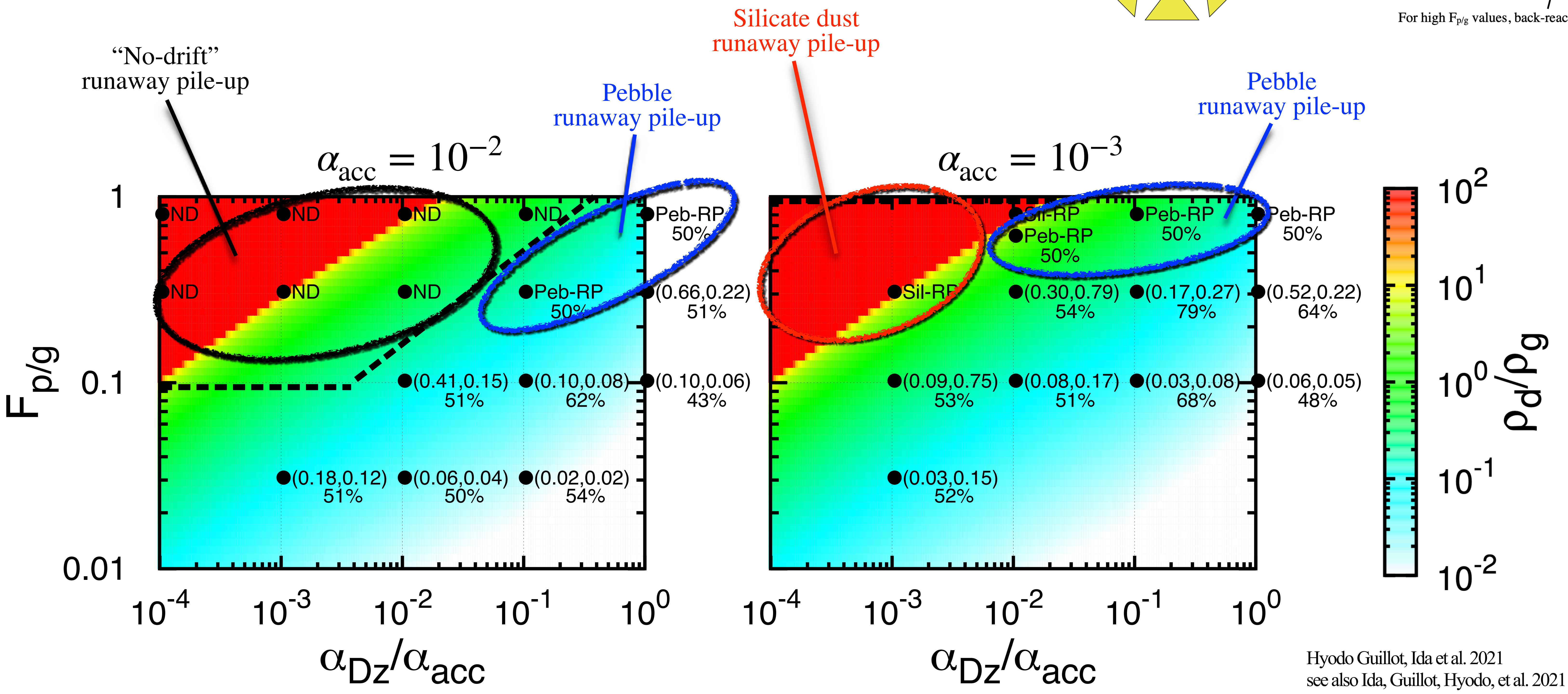
Dependence on α_{acc}, $\alpha_{\mathrm{Dz}}(\alpha_{\mathrm{Dr}})$, and $\mathrm{F}_{\mathrm{p/g}}$





Midplane solid-to-gas ratio
($\rho_{\mathrm{p}}/\rho_{\mathrm{g}}$, $\rho_{\mathrm{d}}/\rho_{\mathrm{g}}$)

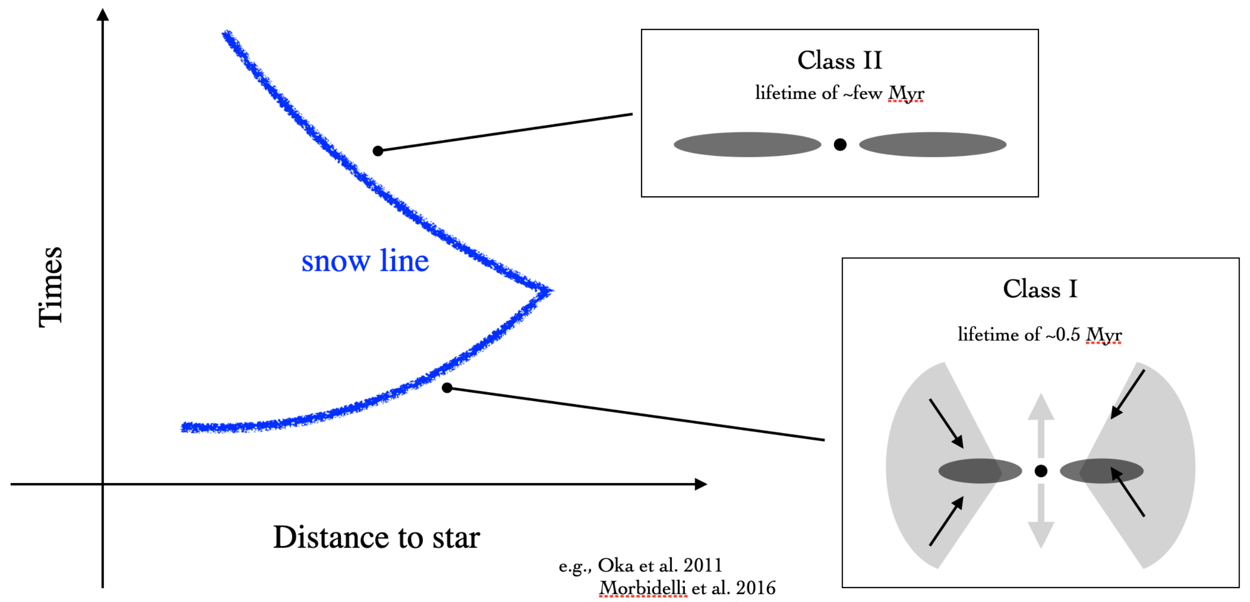




Hyodo Guillot, Ida et al. 2021
see also Ida, Guillot, Hyodo, et al. 2021

- For $\alpha_{\mathrm{Dz}}/\alpha_{\mathrm{acc}} \ll 1$, a pile-up of silicate dust preferred.
- For $\alpha_{\mathrm{Dz}}/\alpha_{\mathrm{acc}} > 0.1$ with $F_{\mathrm{p/g}} > 0.3$ a pile-up of pebbles preferred.
- For $\alpha_{\mathrm{acc}} = 10^{-2}$, the "No-drift" mode widely appears.

Discussion I — Evolving Protoplanetary Disks



e.g., Oka et al. 2011
Morbidelli et al. 2016
Lichtenberg et al. 2021

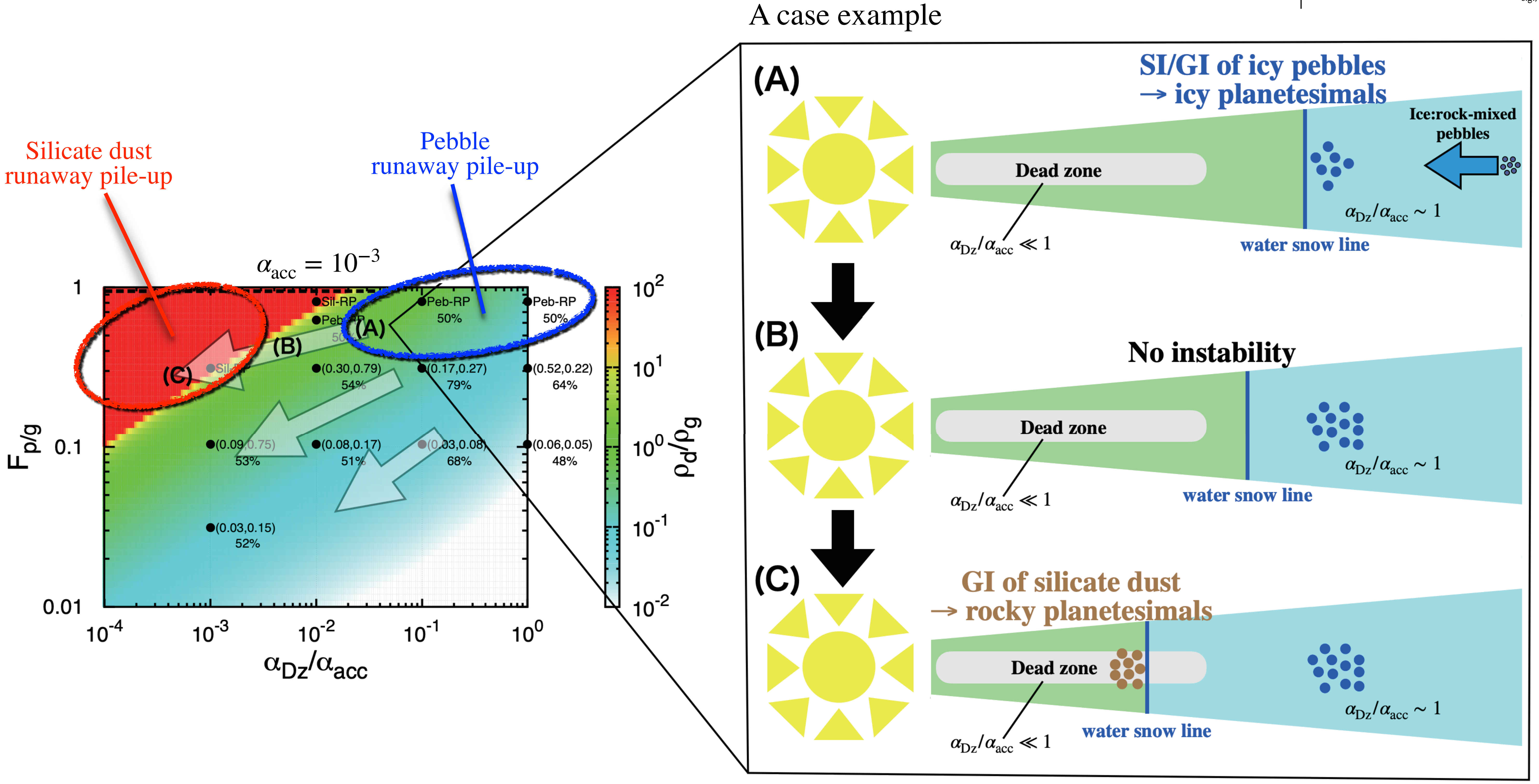


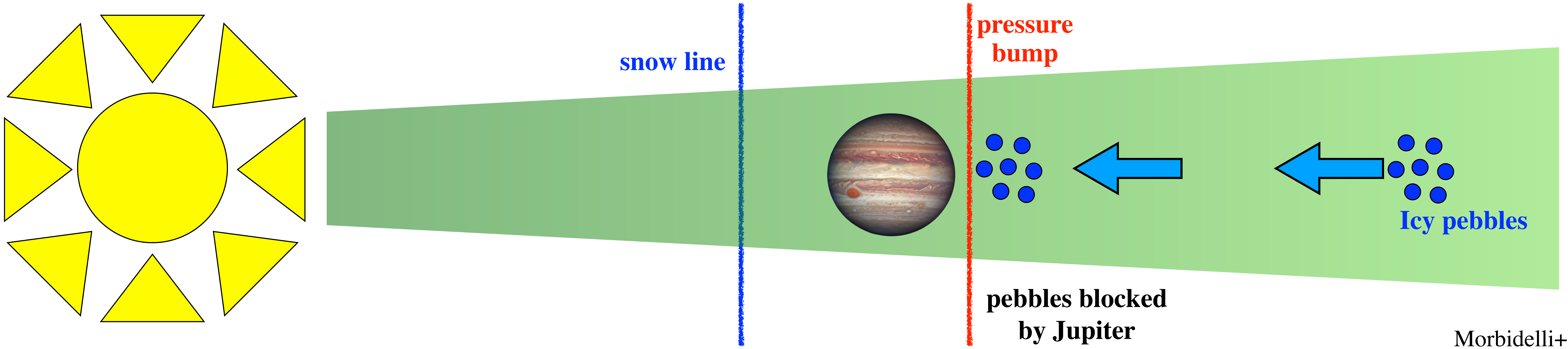
Fig.6 from Hyodo et al. 2021c, A&A

See also Ida et al. 2021, A&A

A diverse distribution of initial planetesimals could be originated from diverse paths of the disk evolution. (i.e., snow line evolution & $\alpha_{\rm acc}$, $\alpha_{\rm Dz}(\alpha_{\rm Dr})$, and $F_{\rm p/g}$)

Discussion II — Snow line "fossilized"

The water ice line can be "fossilized" by the rapid growth of Jupiter's core — The inward flow of icy pebbles halted.


snow line

pressure bump

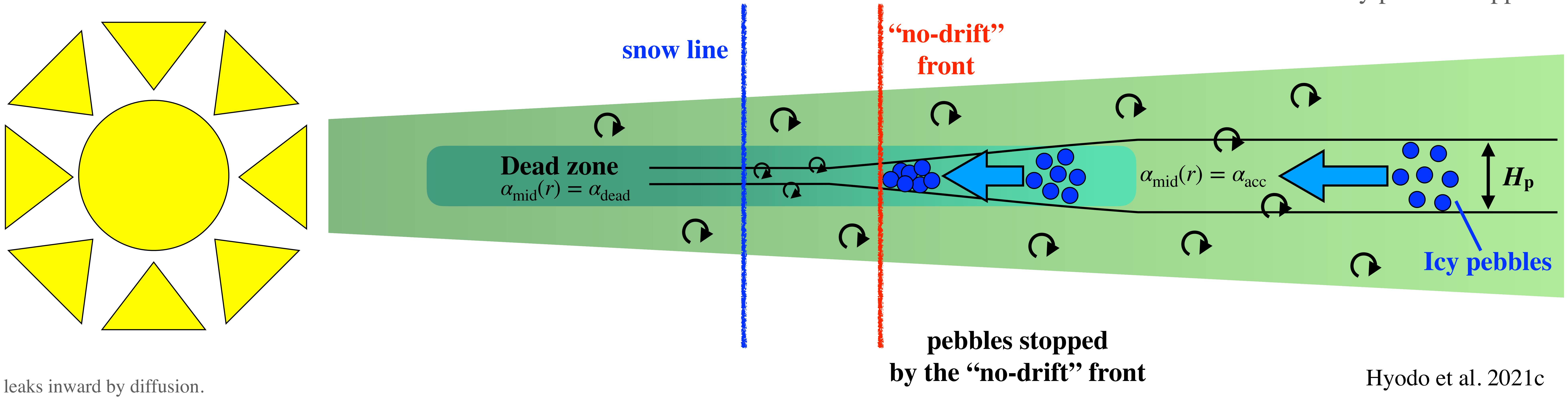
Icy pebbles

pebbles blocked by Jupiter

Morbidelli+2016
see also Bitsch+ 2021

Depending on the size, pebbles can pass through Jupiter.

The water ice line can be "fossilized" by the "no-drift" mechanism— The inward flow of icy pebbles suppressed.


snow line

"no-drift" front

Dead zone
$\alpha_{\mathrm{mid}}(r) = \alpha_{\mathrm{dead}}$

$\alpha_{\mathrm{mid}}(r) = \alpha_{\mathrm{acc}}$

H_p

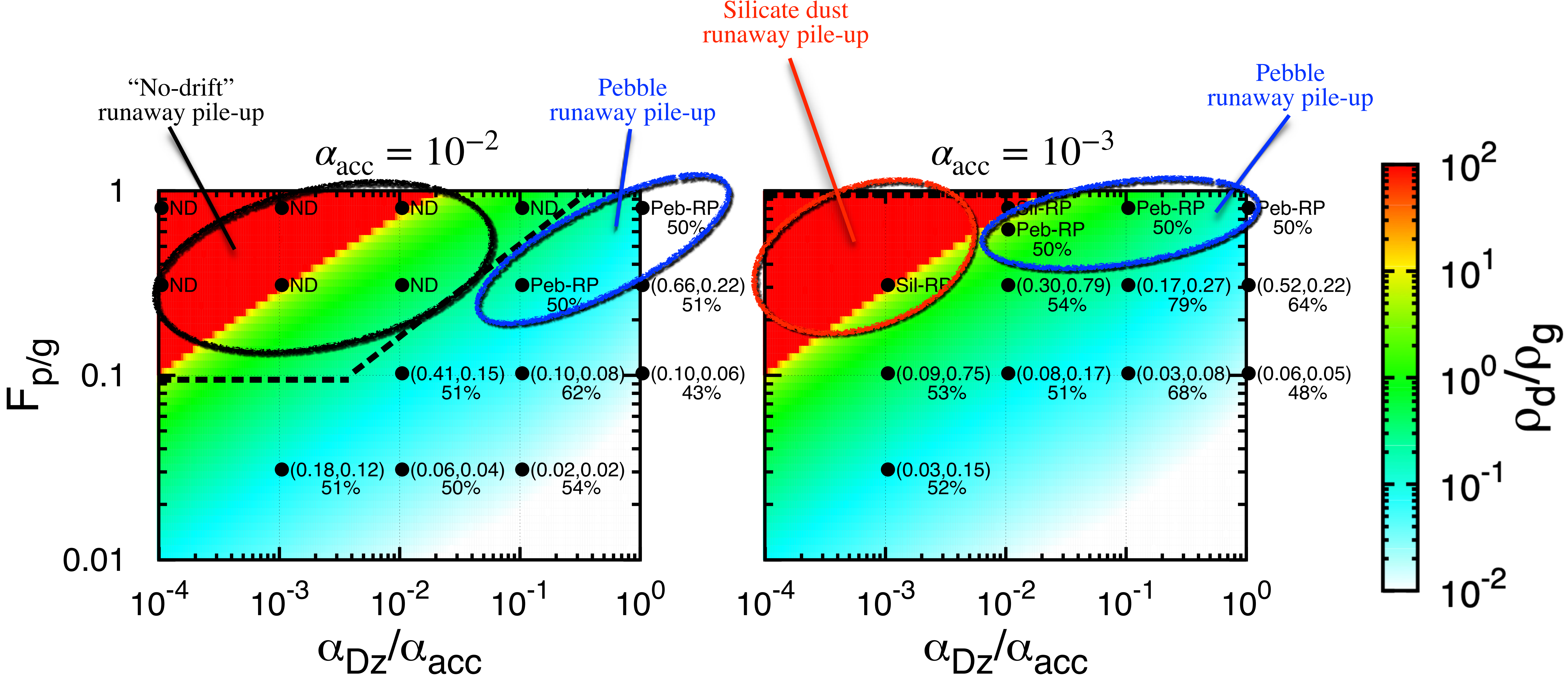
Icy pebbles

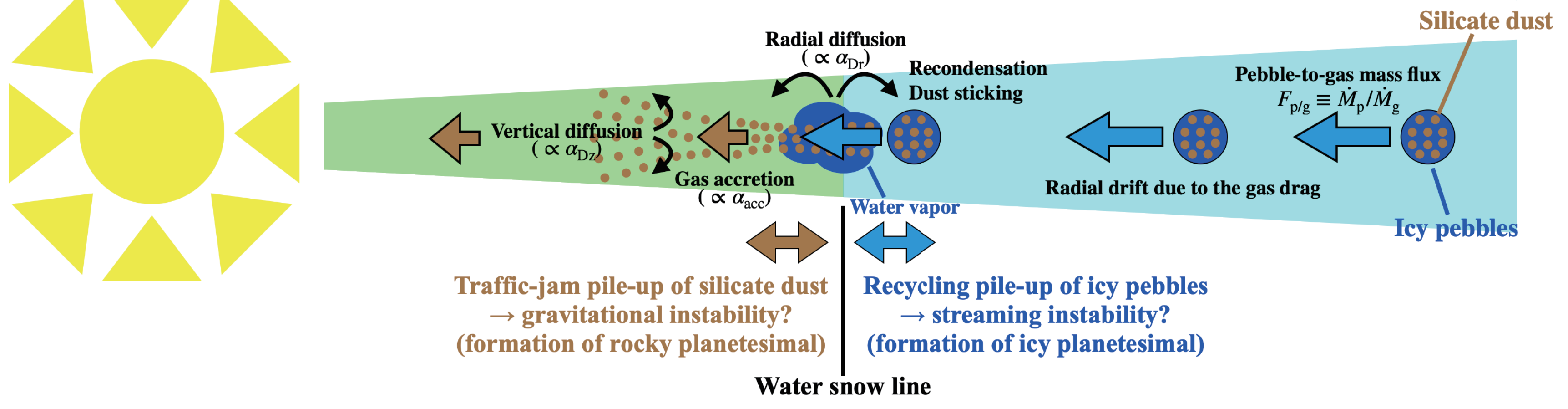
pebbles stopped by the "no-drift" front

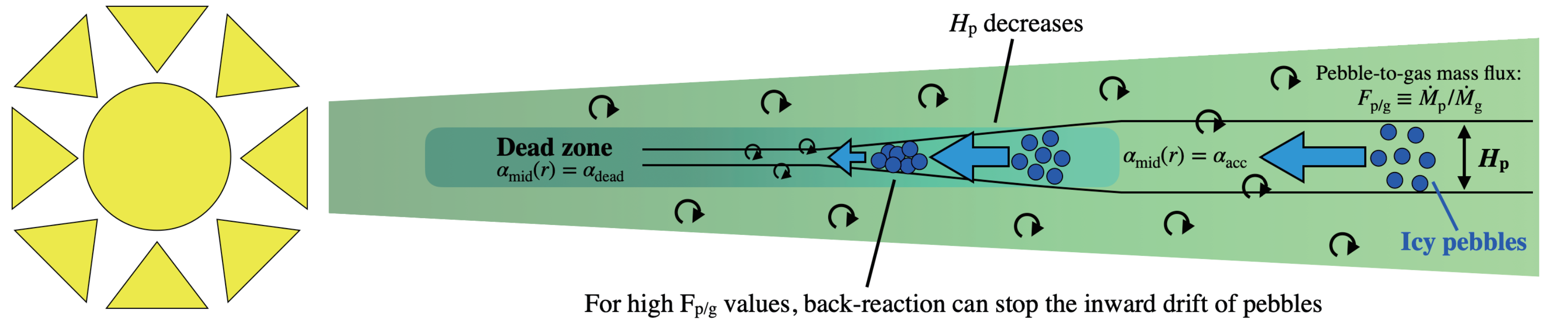
Hyodo et al. 2021c

A fraction of pebbles leaks inward by diffusion.

Summary





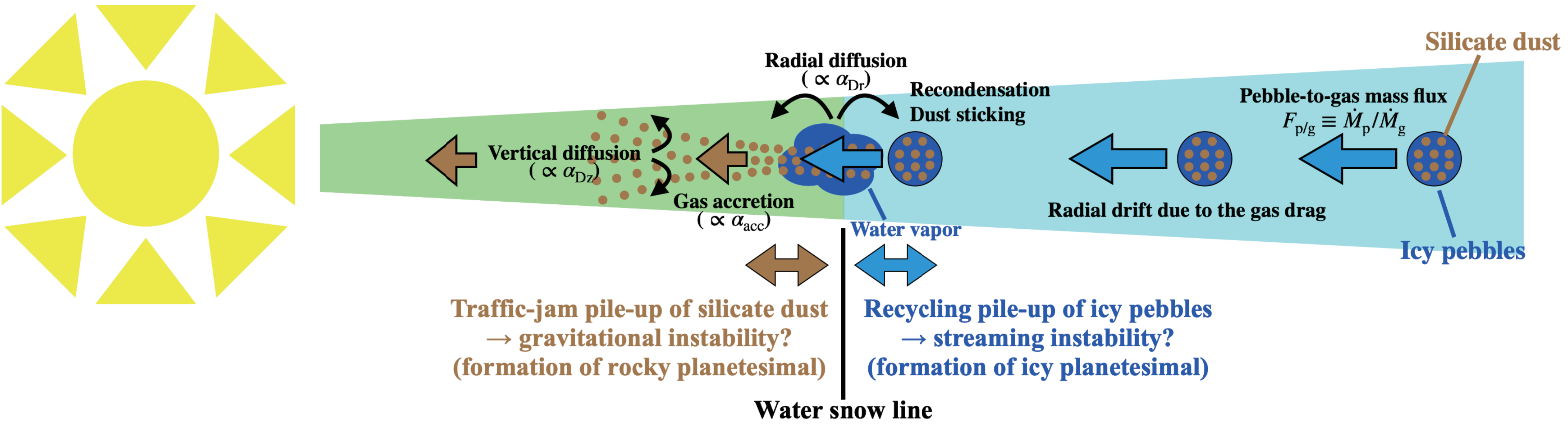


Hyodo, Ida, Charnoz (2019b), A&A
Ida, Guillot, Hyodo, et al. (2021), A&A
Hyodo, Guillot, Ida, et al. (2021b), A&A
Hyodo, Ida, Guillot (2021c), A&A Letters

Pile-up around the snow line and the "No-drift" mode

- **Rocky/icy planetesimal formation just inside/outside the snow line, possible.** → via runaway pile-ups that would lead to SI or/and GI.
- **The resultant modes (dust/pebbles/No-Drift) depend on $F_{p/g}$ & disk structure (α_{acc}, α_{Dr}, α_{Dz}).**
- **Diverse planetesimal formation can be originated from diverse paths of disk evolution.**

A proper description of H_d is very important



Traffic-jam pile-up of silicate dust
→ gravitational instability?
(formation of rocky planetesimal)

Recycling pile-up of icy pebbles
→ streaming instability?
(formation of icy planetesimal)

$$H_d \simeq \left(h_{d/g,0}^{-1} + h_{d/g,*}^{-1}\right)^{-1} H_g$$

$$h_{d/g,0} = \left(1 + \frac{\tau_{s,d}}{\alpha_{Dz}}\right)^{-1/2}$$

$$h_{d/g,*} \simeq \left(h_{p/g,0}^2 + \frac{2}{3}\frac{\alpha_{Dz}}{\alpha_{acc}}\frac{\Delta\tilde{x}}{H_g/r}\right)^{1/2} \times \left(1 + \frac{2}{3}\frac{\alpha_{Dr}/\alpha_{acc}}{1 + (C_{r.diff}\alpha_{Dr}/\alpha_{acc})^2}\frac{1}{\left(H_g/r\right)(\Delta\tilde{x} + \epsilon)}\right)$$

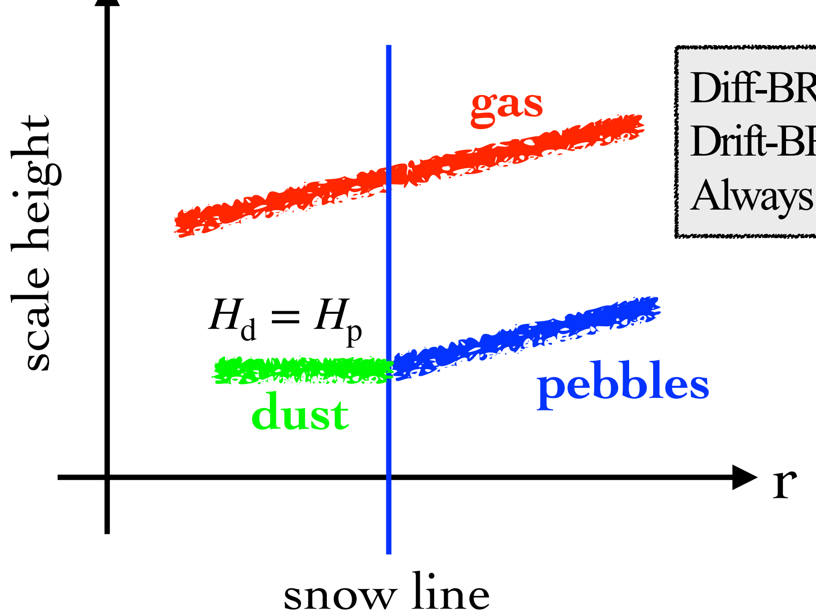
$$\Delta\tilde{x} = \max\{\Delta\tilde{x}_{subl}, \Delta\tilde{x}_{snow}\}$$

Ida, Guillot, Hyodo, et al. 2021

Here “pile up” means “Runaway pile-up”

Dust can piles up inside the snow line

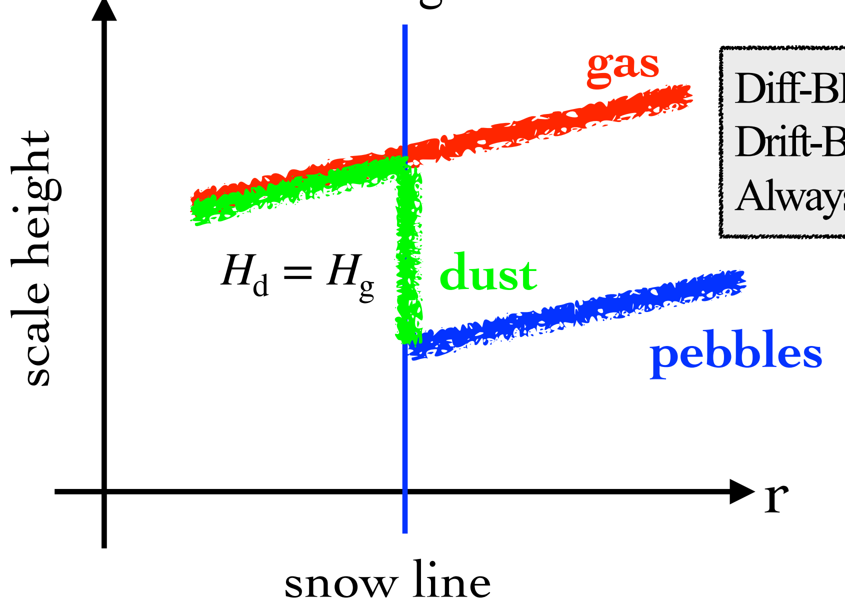
Ida&Guillot 2016



Diff-BR: NOT included (K=0)
Drift-BR for dust: Included
Always $\alpha_{Dz} = \alpha_{acc}$

Dust does not pile up inside the snow line

Schoonenberg&Ormel 2017



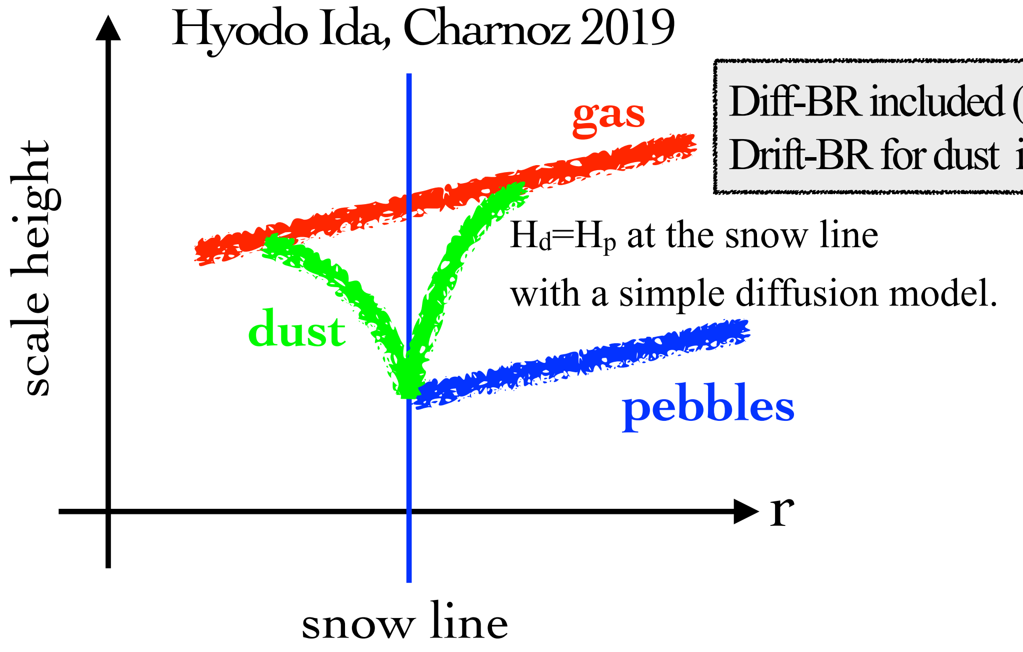
Diff-BR NOT included (K=0)
Drift-BR for dust: NOT included
Always $\alpha_{Dz} = \alpha_{acc}$

Dust can piles up inside the SL depending on the α_{Dz}/α_{acc} value

slightly overestimated at SL

Dust can piles up inside the SL depending on the α_{Dz}/α_{acc} value

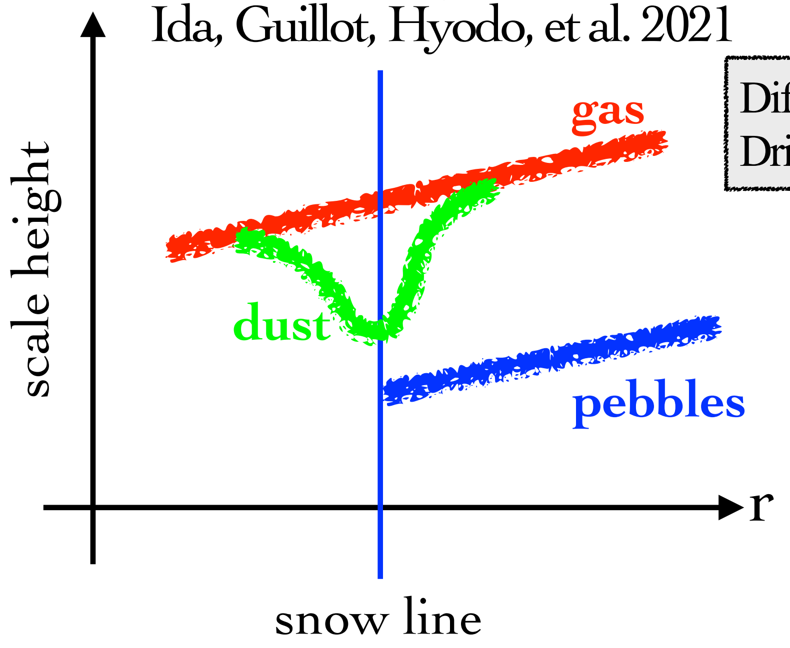
Hyodo Ida, Charnoz 2019



Diff-BR included (K=1 or 2)
Drift-BR for dust included

H_d=H_p at the snow line
with a simple diffusion model.

Ida, Guillot, Hyodo, et al. 2021

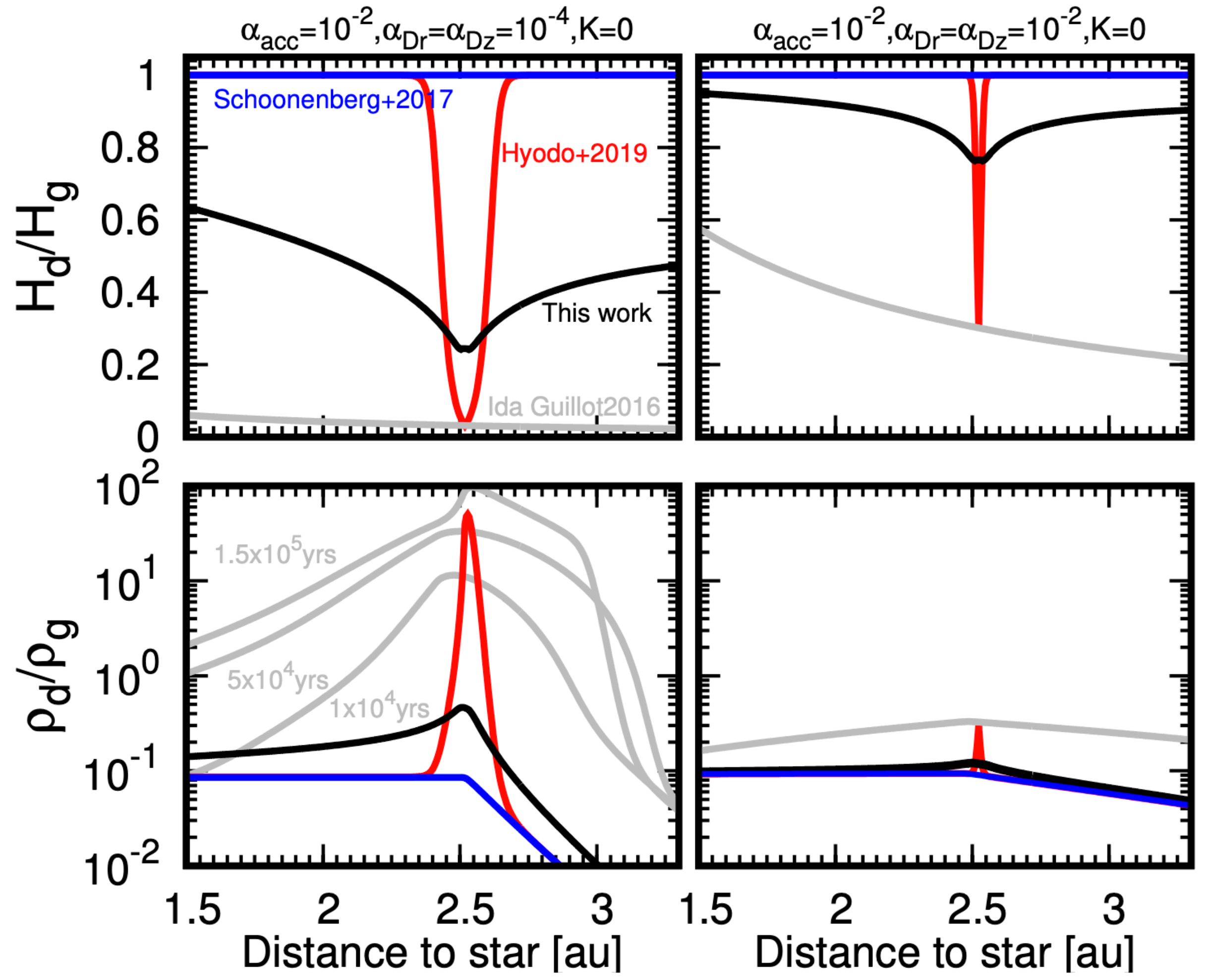


Diff-BR included (K=1 or 2)
Drift-BR for dust: included

What about pebbles outside the SL?
→ Hyodo et al. 2021

Dependence of silicate dust pile-up upon H_d just inside the snow line

Case of $F_{p/g} = 0.3$ and $\tau_{s,p} = 0.1$ at 3 au



Hyodo Guillot, Ida et al. 2021
see also Ida, Guillot, Hyodo, et al. 2021