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DUST GRAIN EVOLUTION

— FROM SUB-MICRON GRAINS TO PEBBLES TO PLANETESIMALS —

Myriam Benisty & Til Birnstiel

Sagan Exoplanet Summer Virtual Workshop

2021

Credit: ESO/L. Calçada

Why care about solids?

Dust …

… is the **planet forming** material

… is surface area for **chemistry** & means of **transportation**

… affects temperature/ionization → **MHD/chemistry**

… is by far the dominant opacity → **observations**

Outline – Part 1

1. Dust Dynamics
2. Dust Growth
3. Dynamics + Growth
4. Planetesimal Formation

Follow – up talks

Observations → Myriam Benisty

Structure Formation → Jaehan Bae

Gives more citations or relevant key words to look into. Will be skipped in the talk.

In depth

Gives estimates, time scales, or rules-of-tump that are good for back-of-the-evelope calculations.

Quick Estimate

Dust Dynamics

Dust Evolution

Solids & Gas Evolve ***Differently***

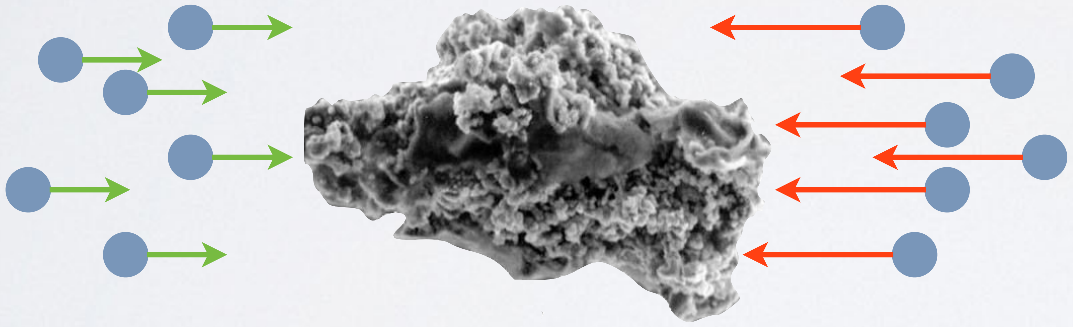
But Not ***Independently****!*

https://youtu.be/p_f6lWWc9jQ

Epstein Drag Regime:

if particle size ≲ gas mean free path

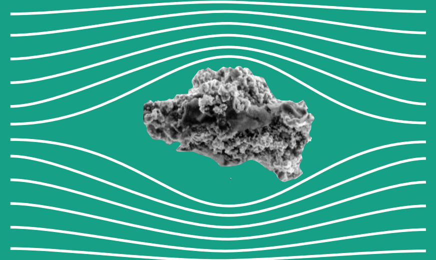
$$\vec{F}_{\mathrm{drag}} = -\frac{4\pi}{3}\rho_g a^2 v_{\mathrm{th}}\vec{v}$$



Inner disk: Stokes drag can become relevant:

if particle size > gas m.f.p.:

$$\vec{F}_{\mathrm{drag}} = -\frac{C_D}{2}\pi a^2 \rho_g v\,\vec{v}$$



In depth

a	grain radius
v_{th}	mean thermal speed
C_D	drag coefficient
v	dust-gas rel. velocity
ρ_g	gas volume density

Stopping Time

Estimate the time scale of adapting to the gas speed:

$$t_{\mathrm{stop}} = \frac{v}{\dot{v}} = \frac{m\,v}{\left|F_{\mathrm{drag}}\right|} \overset{\substack{\text{Epstein regime}\\ \downarrow}}{=} \frac{\rho_s\,a}{\rho_g\,v_{\mathrm{th}}}$$

Example at 1 au: 1 µm: 4 s
1 m: 0.2 yr

More useful: Stokes number – the "aerodynamic size":

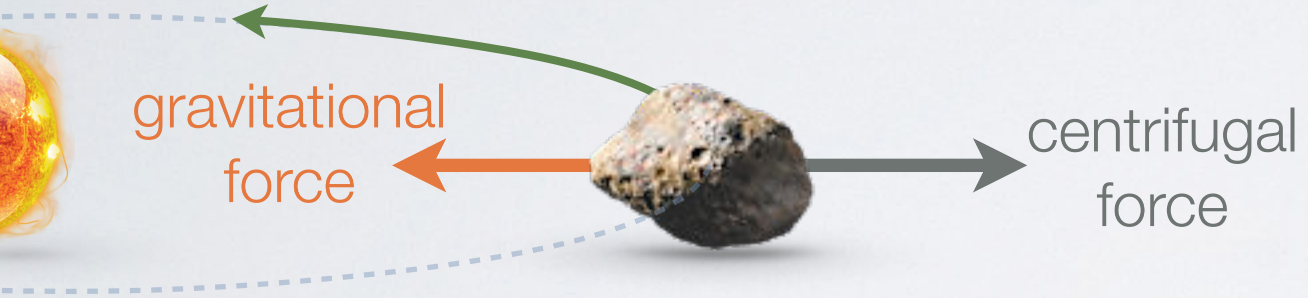
$$\mathrm{St} = t_{\mathrm{stop}}\Omega \overset{\substack{\text{disk mid-plane}\\ \downarrow}}{=} \frac{a\,\rho_s}{\Sigma_g}\frac{\pi}{2}$$

$\mathrm{St} \ll 1$: coupling faster than 1 orbit
$\mathrm{St} \gg 1$: coupling longer than 1 orbit

Radial Drift

Solids

Keplerian
velocity

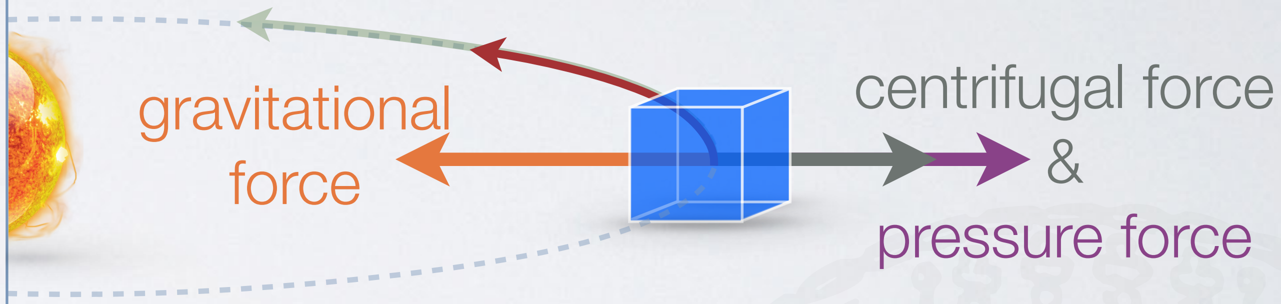


gravitational
force

centrifugal
force

Gas

sub-Keplerian
velocity



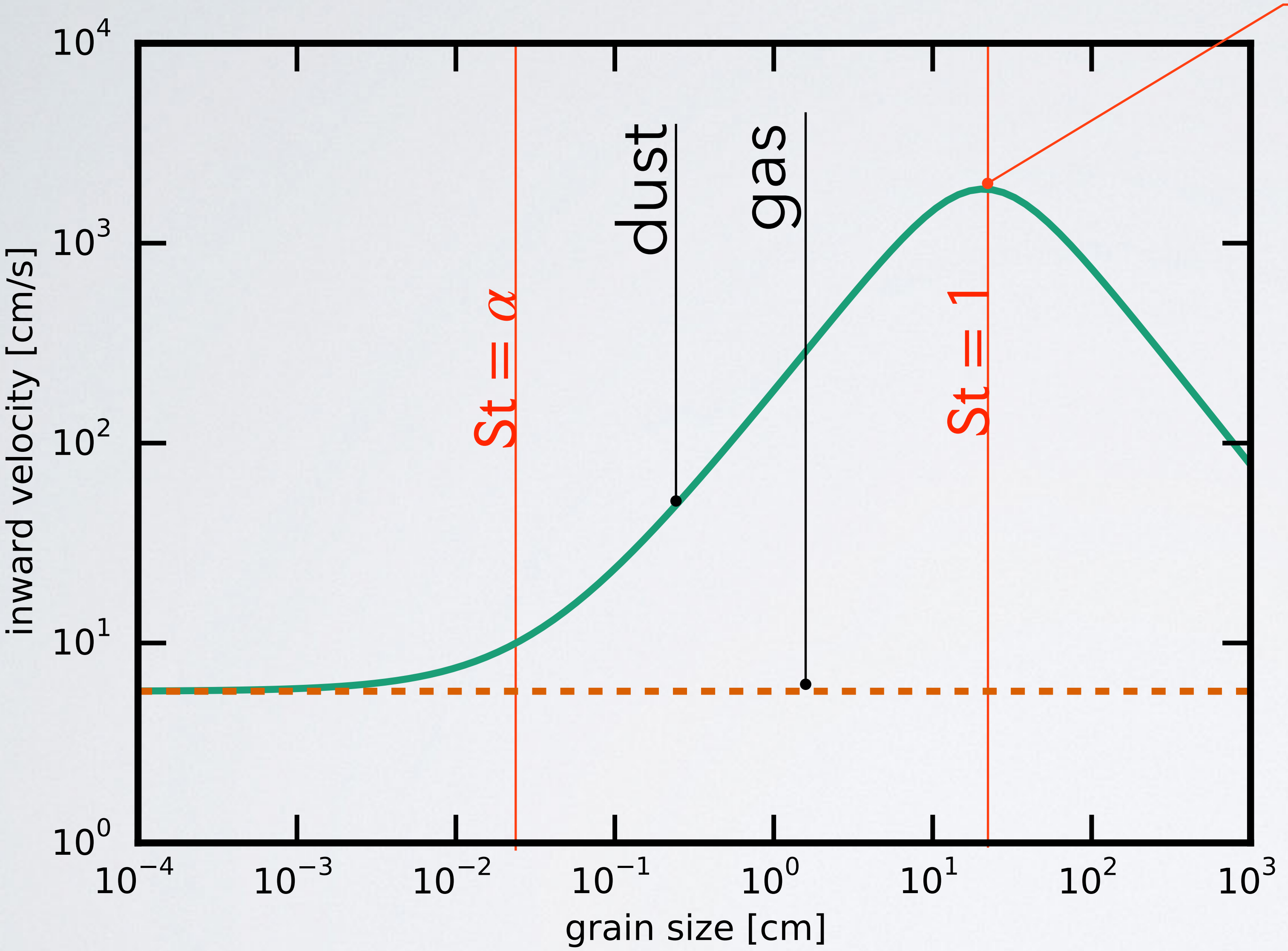
gravitational
force

centrifugal force
&
pressure force

$$\frac{v_{\phi,\mathrm{gas}}^2}{r} = \frac{G\,M_\star}{r^2} + \frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}r} \xrightarrow{P = P_0 \left(\frac{r}{r_0}\right)^{-\gamma_\mathrm{P}}} v_{\phi,\mathrm{gas}} = v_\mathrm{K}\sqrt{1-\gamma_\mathrm{p}\left(\frac{h}{r}\right)^2}$$

typically ~ 0.1% slower than Kepler

Radial drift



80 mph

130 km/h

1.

Large grains (= pebbles = "$St \gtrsim \alpha$)

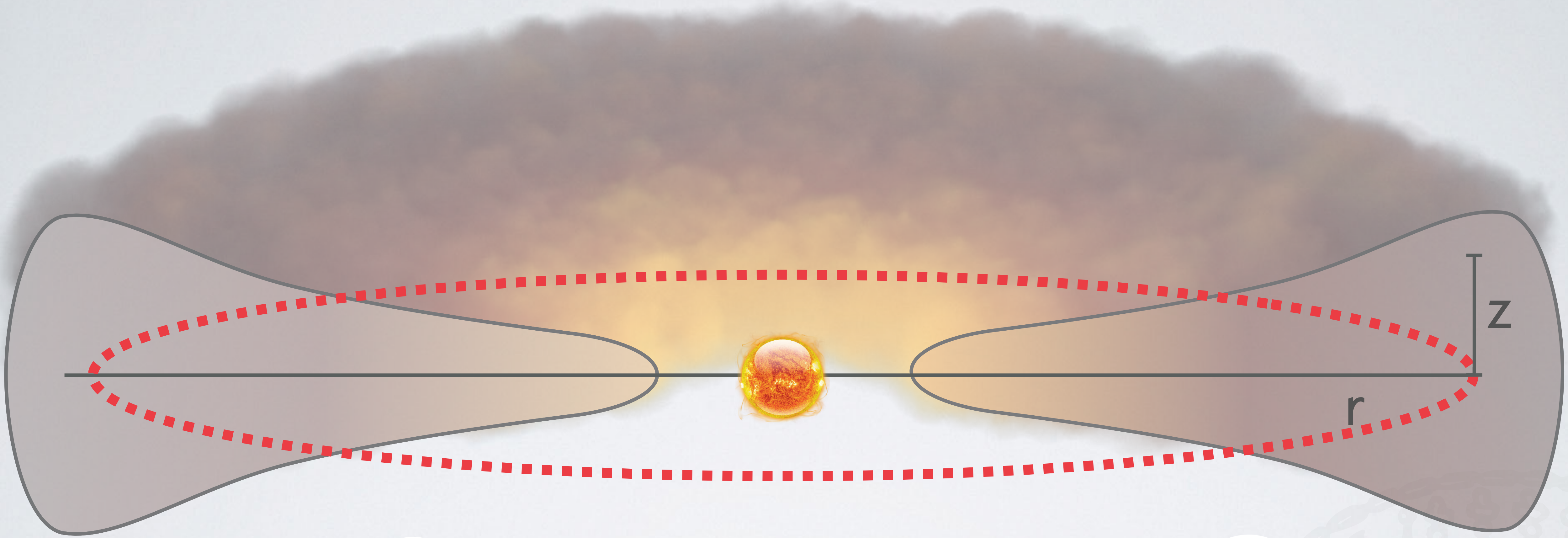
drift to **higher pressure**

2.

$v_{drift} \propto St \propto$ particle size

Quick Estimate

Vertical Settling



$$\underbrace{\ddot{z} = -z\,\Omega_K^2}_{\text{oszillator}} \; \underbrace{-\frac{\dot{z}}{t_s}}_{\text{damping}}$$

$$v_{\text{settling}} = -z\,\Omega^2\,t_s$$

(e.g. Fromang & Nelson 2009 + refs. Inside)

In depth

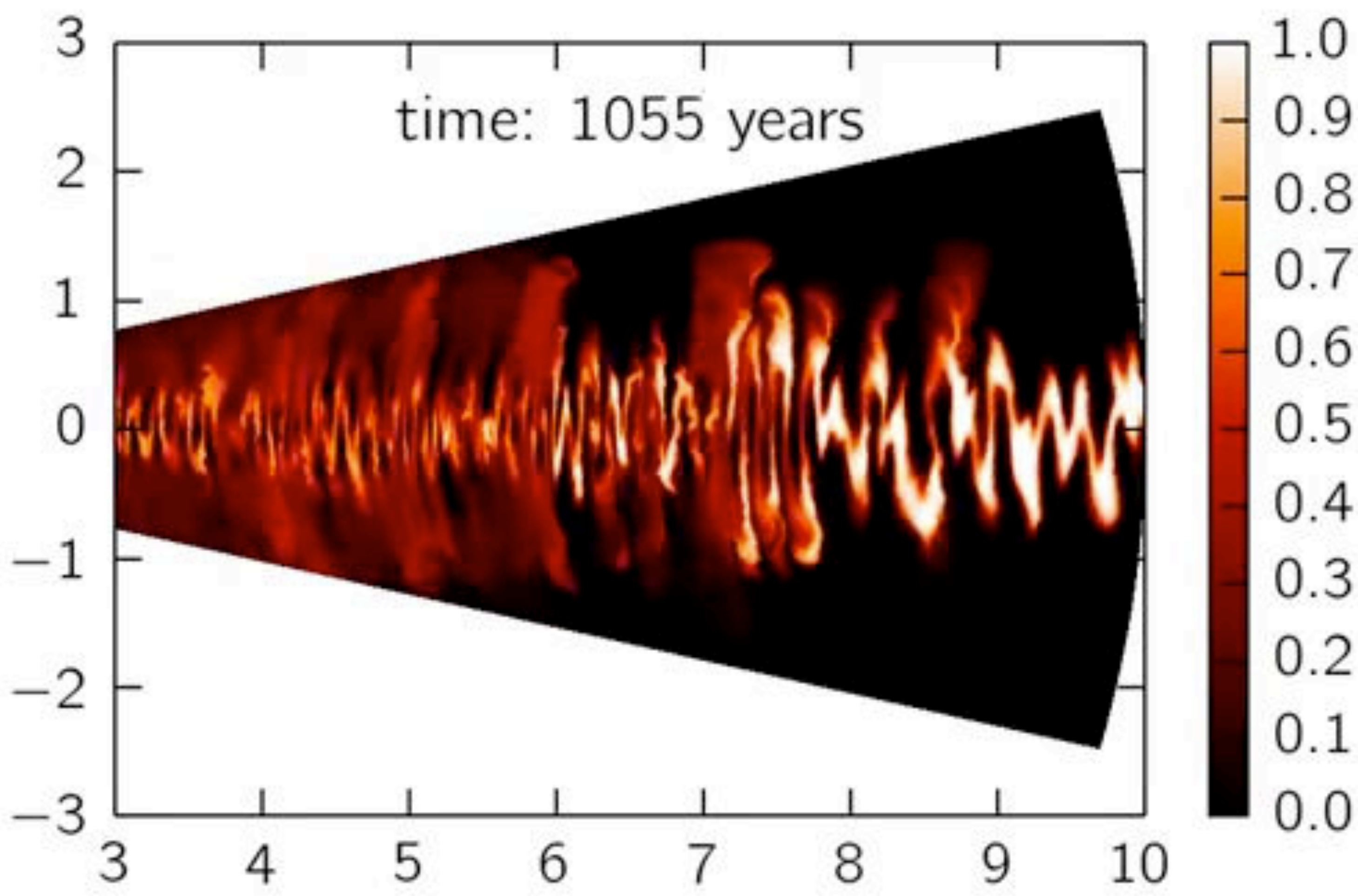
Large grains ($\mathrm{St} \gtrsim \alpha$) sediment

$$t_{\text{set}} \sim \frac{1}{\mathrm{St}\,\Omega}$$

Quick Estimate

Vertical Mixing

Turbulence mixes the solids in all directions!



This animation shows the Vertical Shear Instability (VSI) mixing a tracer fluid, a recently (re-)discovered instability that might drive turbulence in disks.

see: Nelson et al. 2013
Stoll & Kley 2016 (this video)
and others

In depth

Vertical Mixing

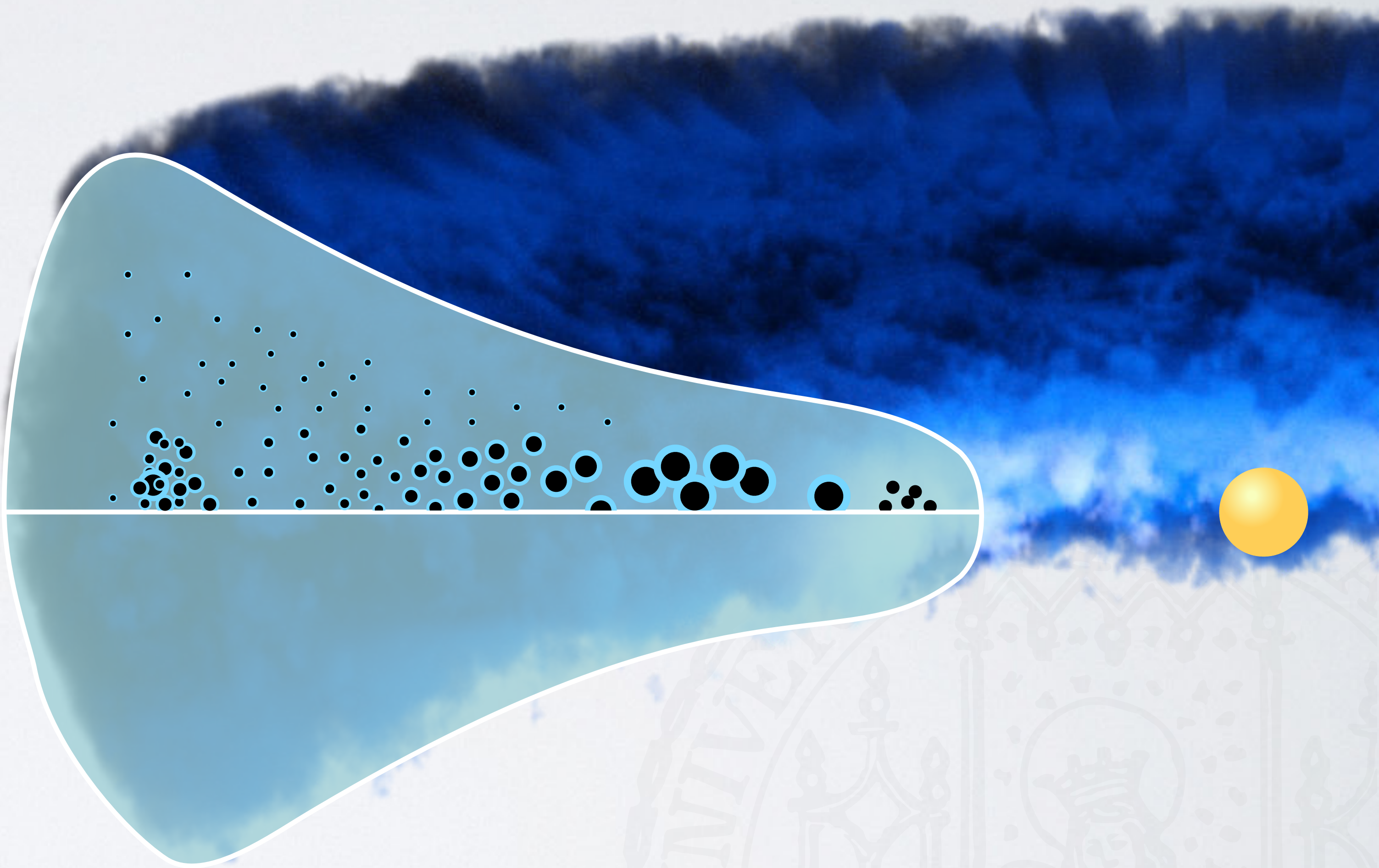
Diffusion acts on the diffusion time scale

$$t_{\mathrm{diff}} \sim \frac{\text{length scale}^2}{\text{Diffusion coefficient}}$$

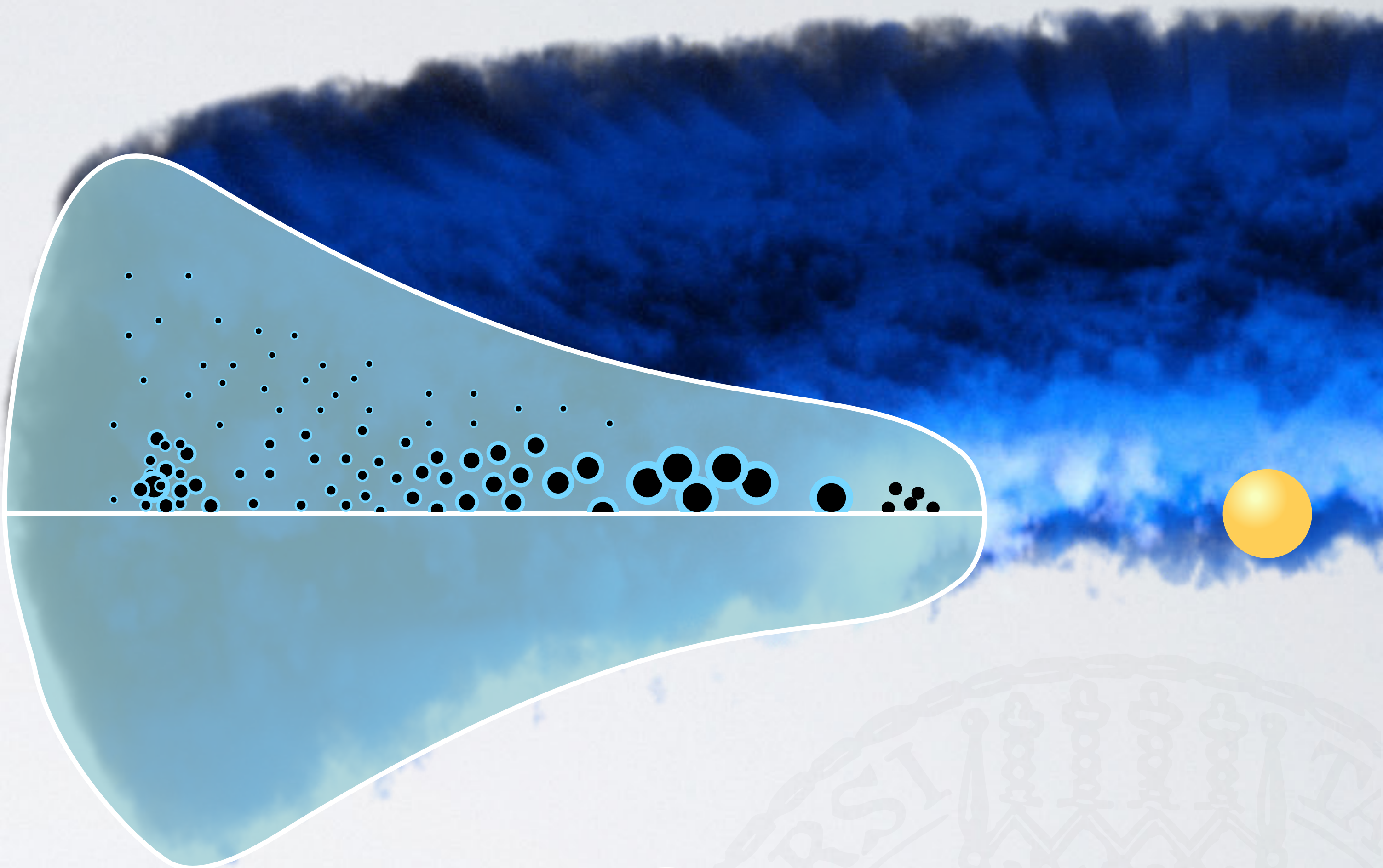
which in our case works out to

$$t_{\mathrm{diff}} = \frac{1}{\alpha\,\Omega}$$

Quick Estimate



Vertical Mixing



Settling vs. Mixing shows sets dust scale height of

$$h_{\mathrm{dust}} \simeq h_{\mathrm{gas}} \sqrt{\frac{\alpha}{\mathrm{St} + \alpha}}$$

The value $\frac{\mathrm{St}}{\alpha}$ also determines radial and azimuthal trapping.

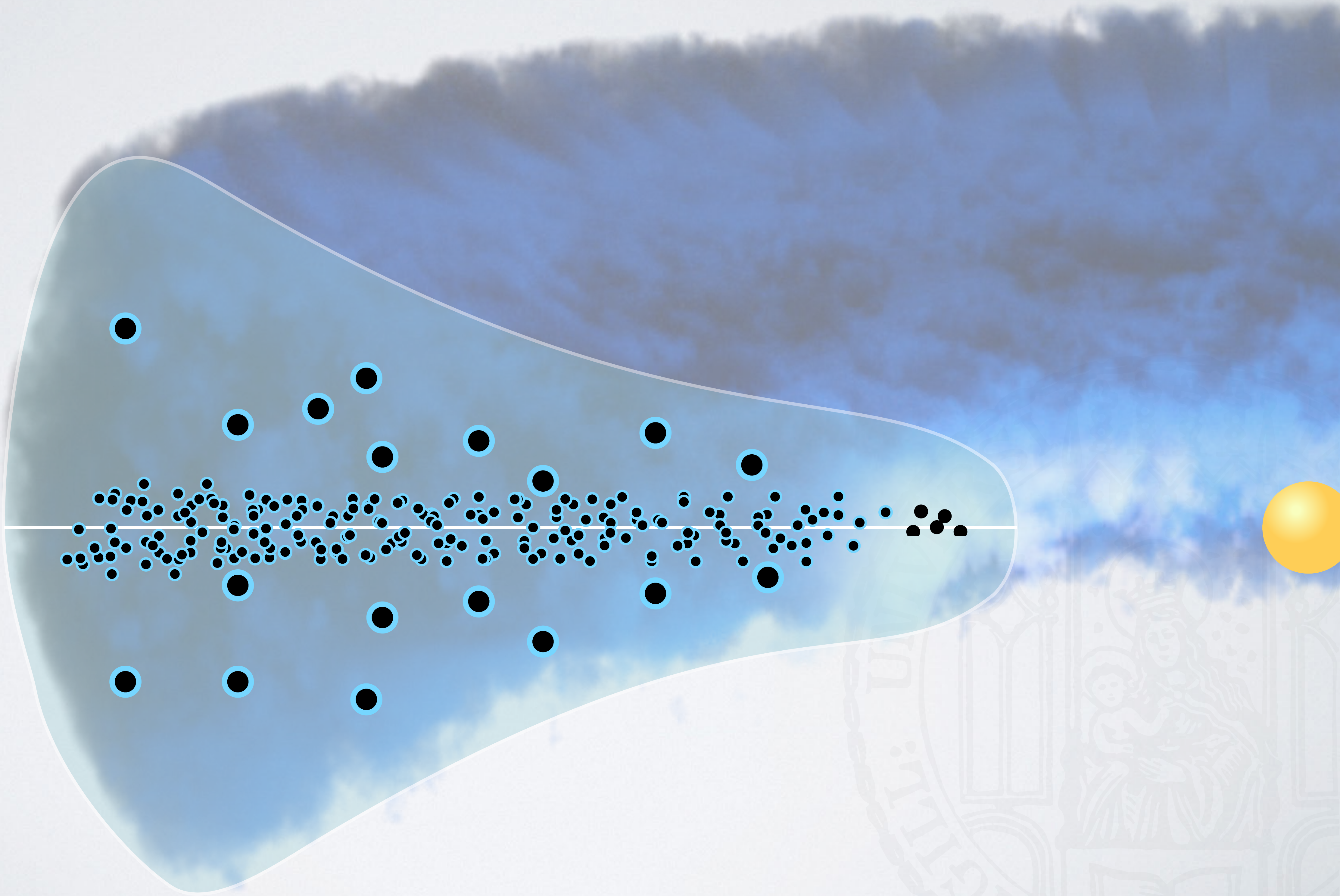
Quick Estimate

Vertical:	Fromang & Nelson 2009
Radial:	Dullemond et al. 2018
Azimuthal:	Birnstiel et al. 2013, Lyra & Lin 2013

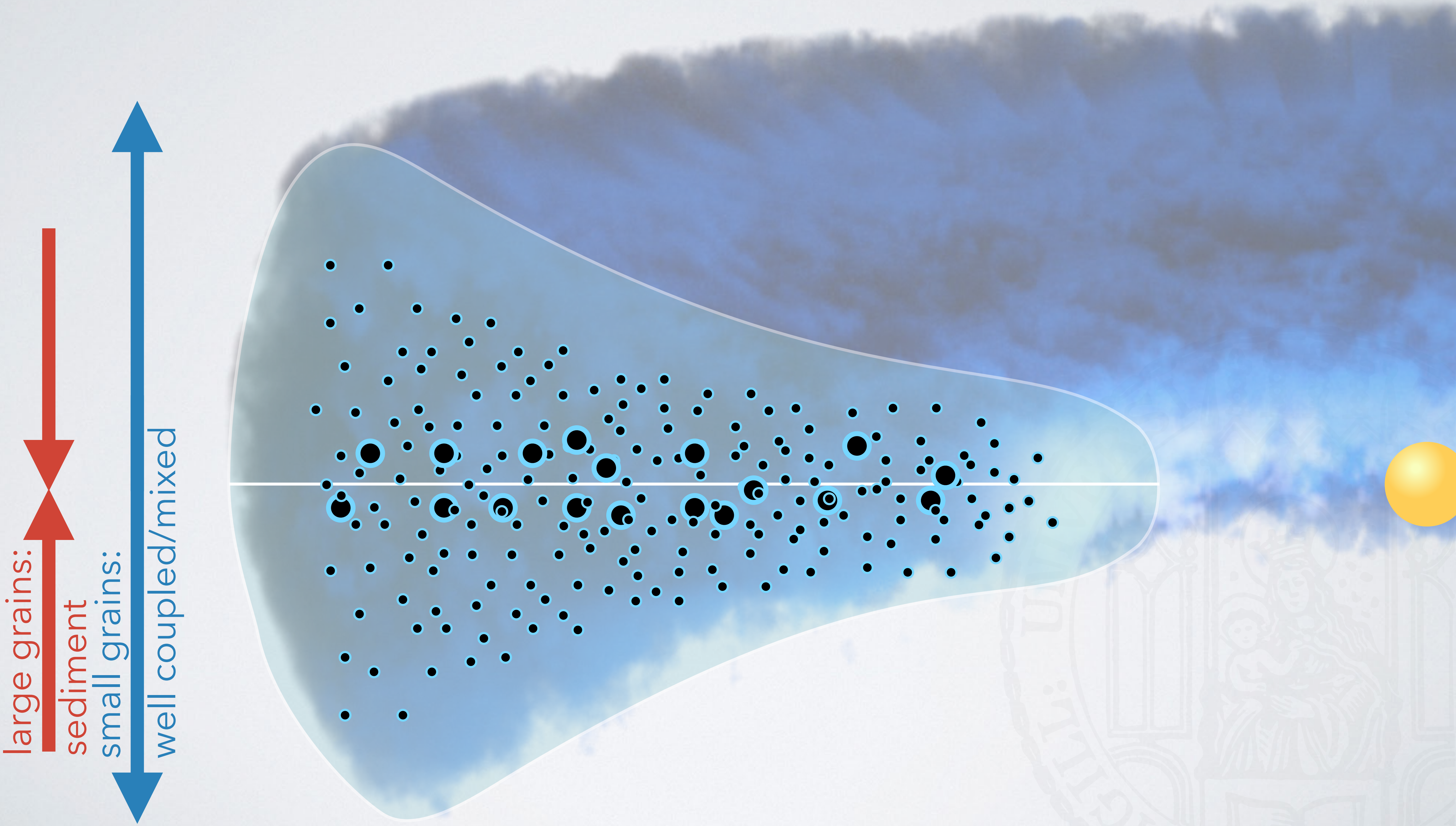
... and references therein

In depth

Vertical Mixing & Drift



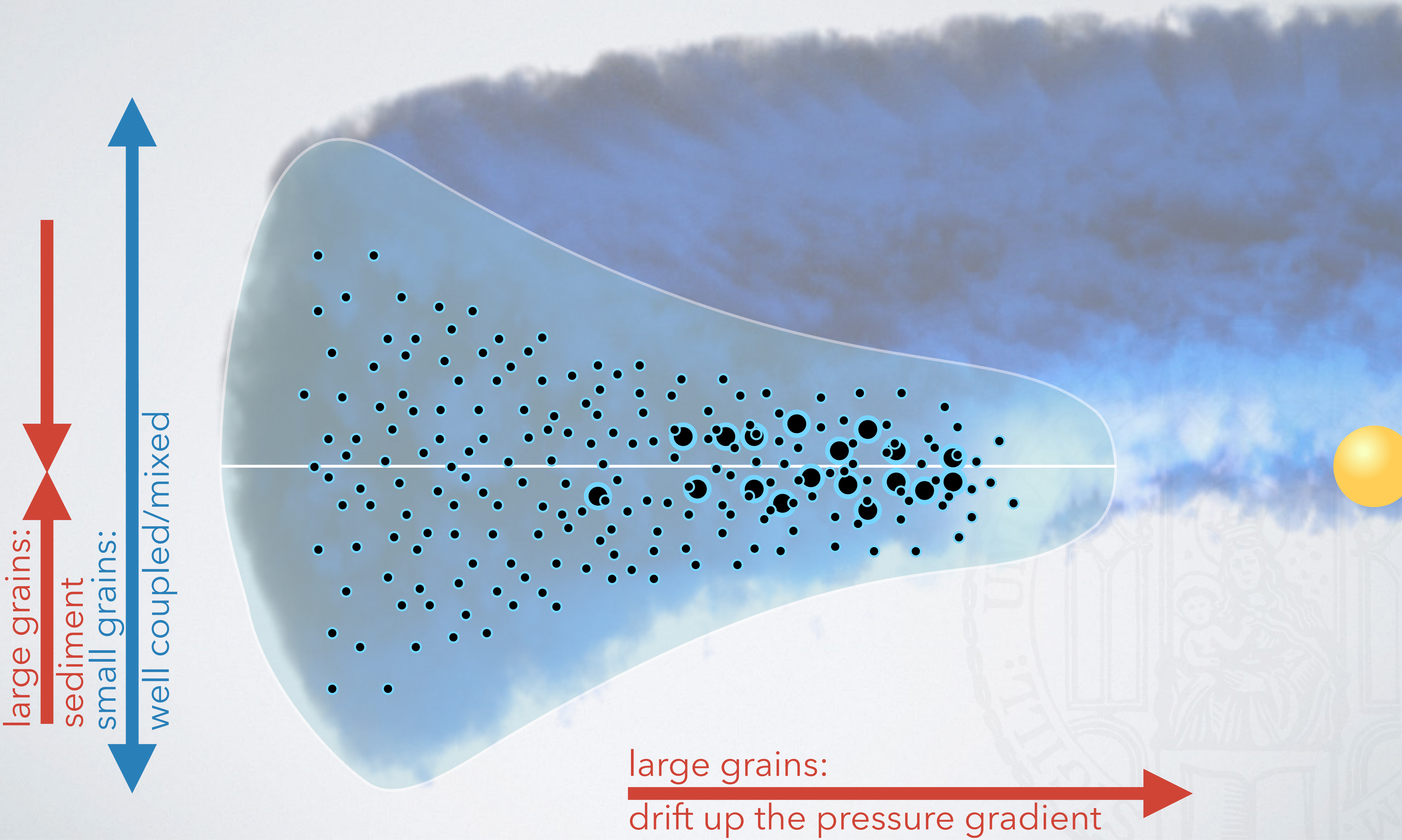
Vertical Mixing & Drift



large grains:
sediment

small grains:
well coupled/mixed

Vertical Mixing & Drift

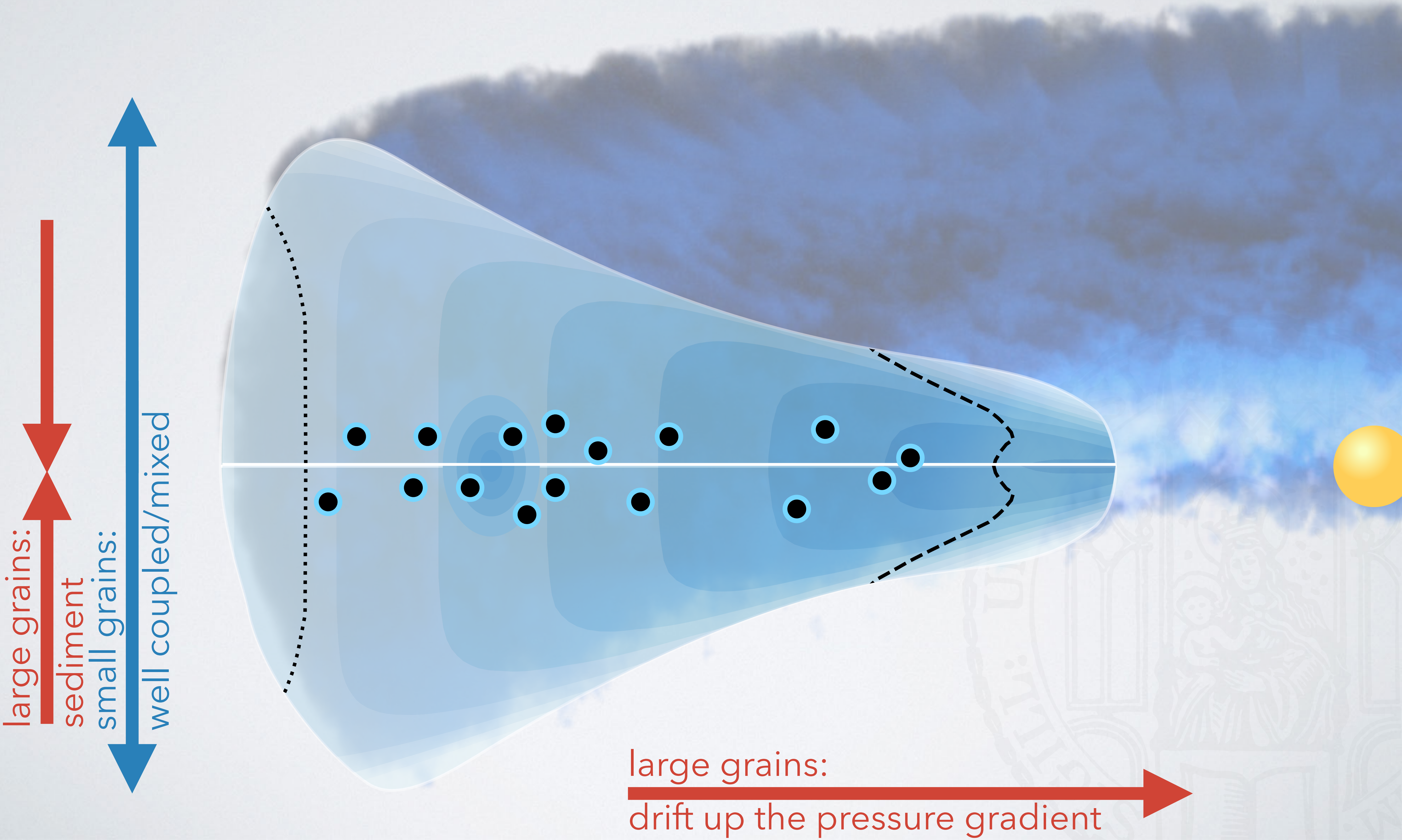


large grains:
sediment

small grains:
well coupled/mixed

large grains:
drift up the pressure gradient

Vertical Mixing & Drift



large grains:
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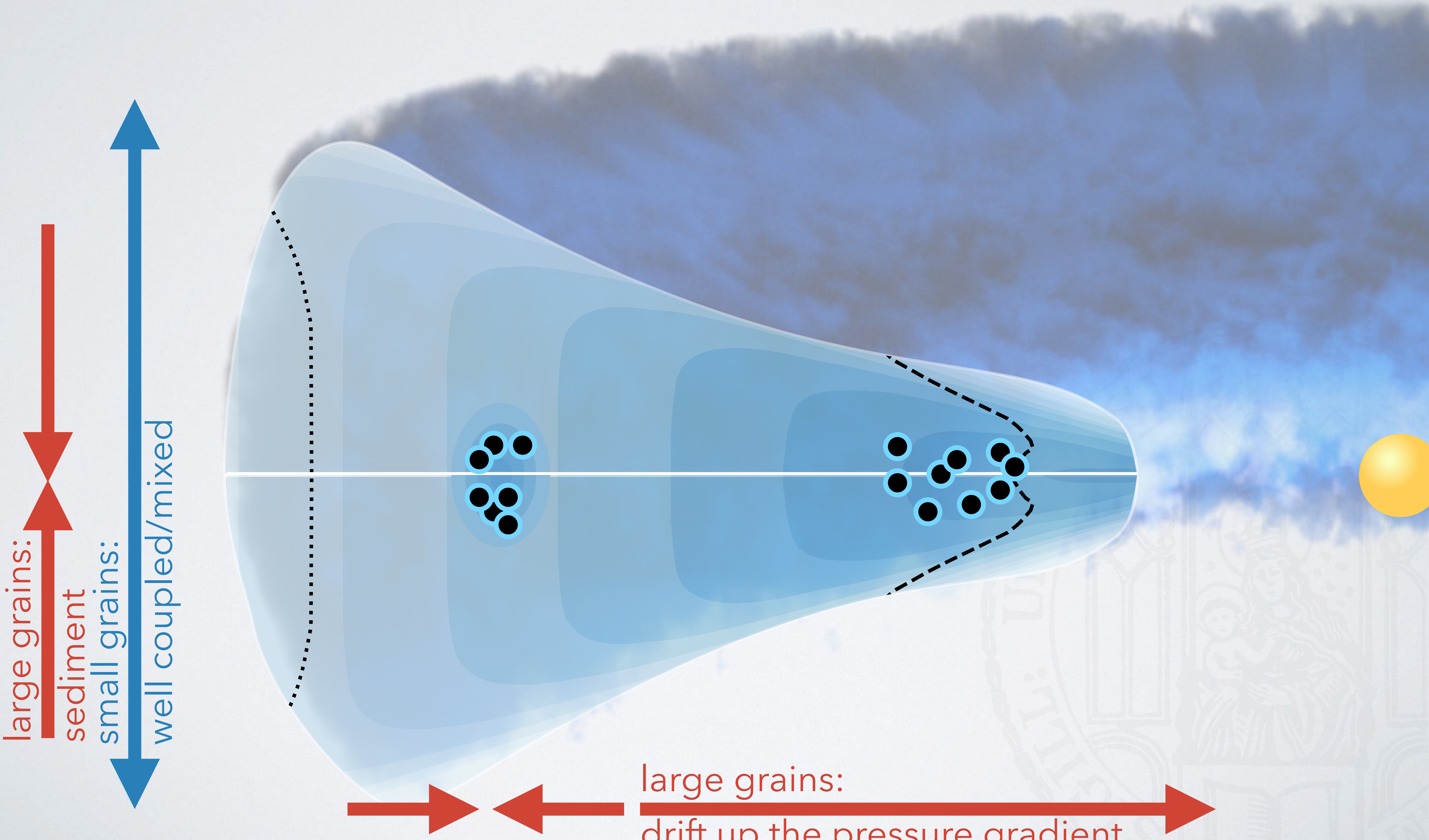
Vertical Mixing & Drift



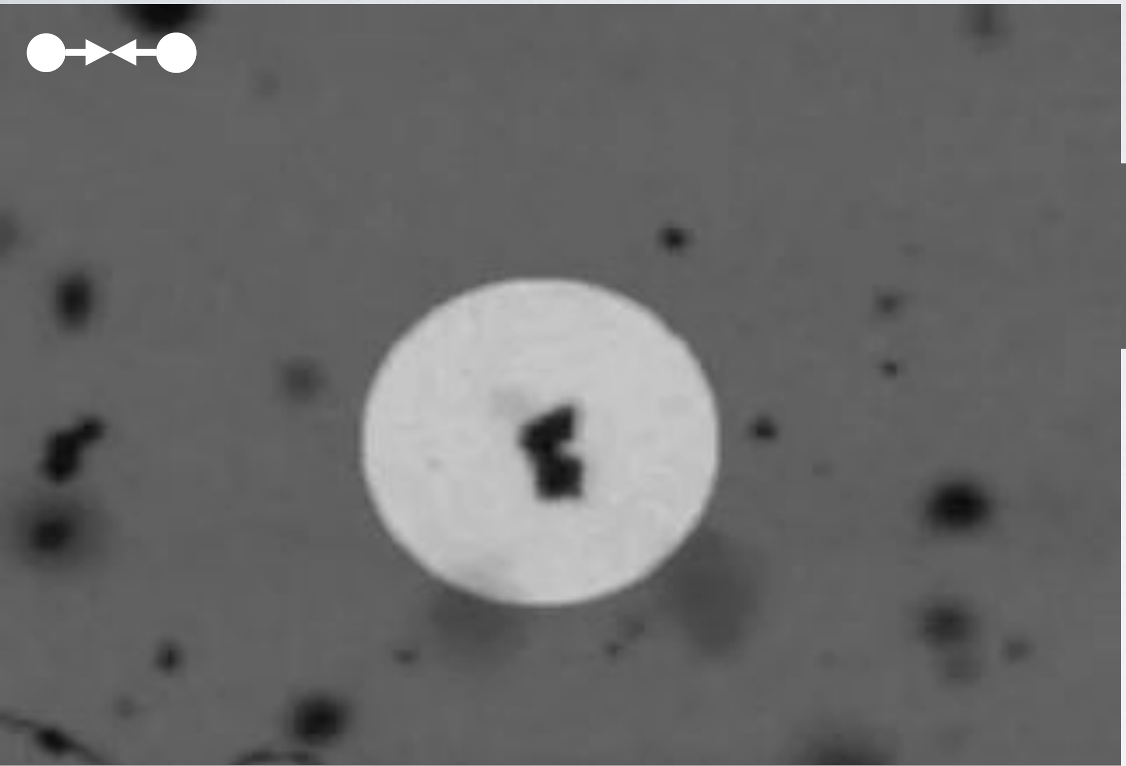
large grains:
sediment

small grains:
well coupled/mixed

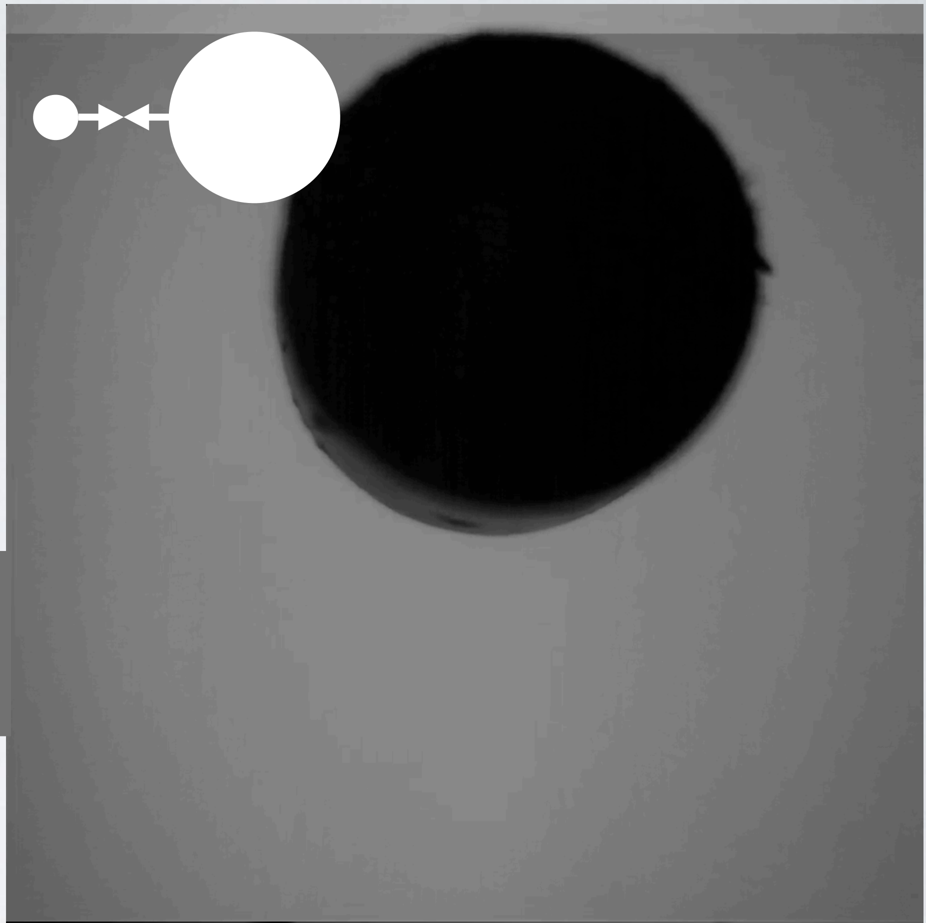
large grains:
drift up the pressure gradient

DUST GROWTH

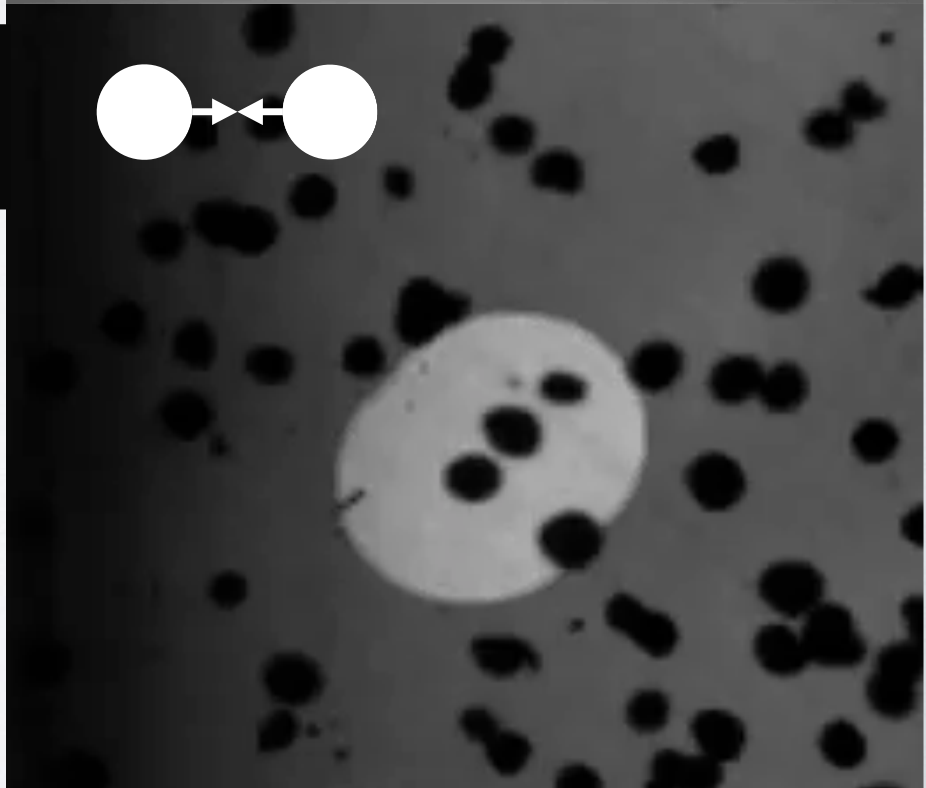
Collisional Effects



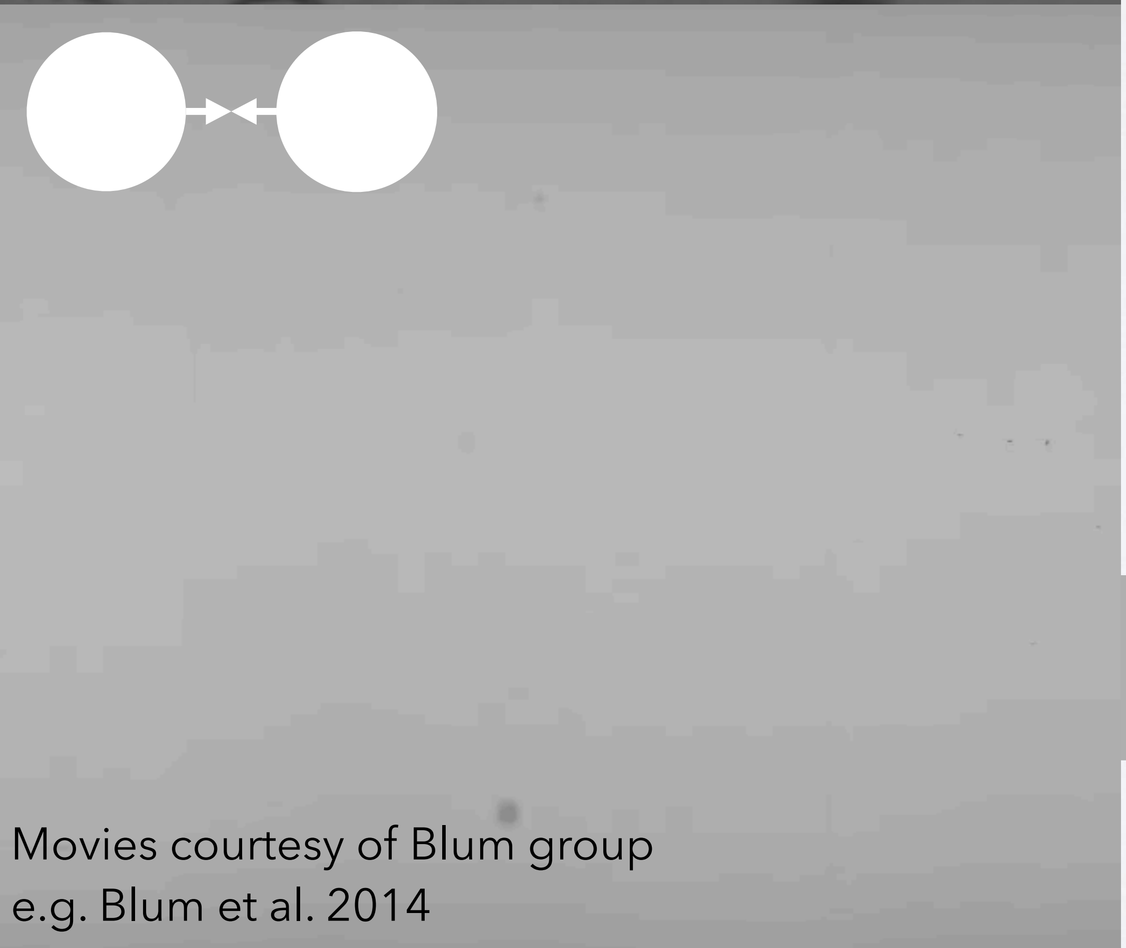
←Sticking



Mass Transfer→



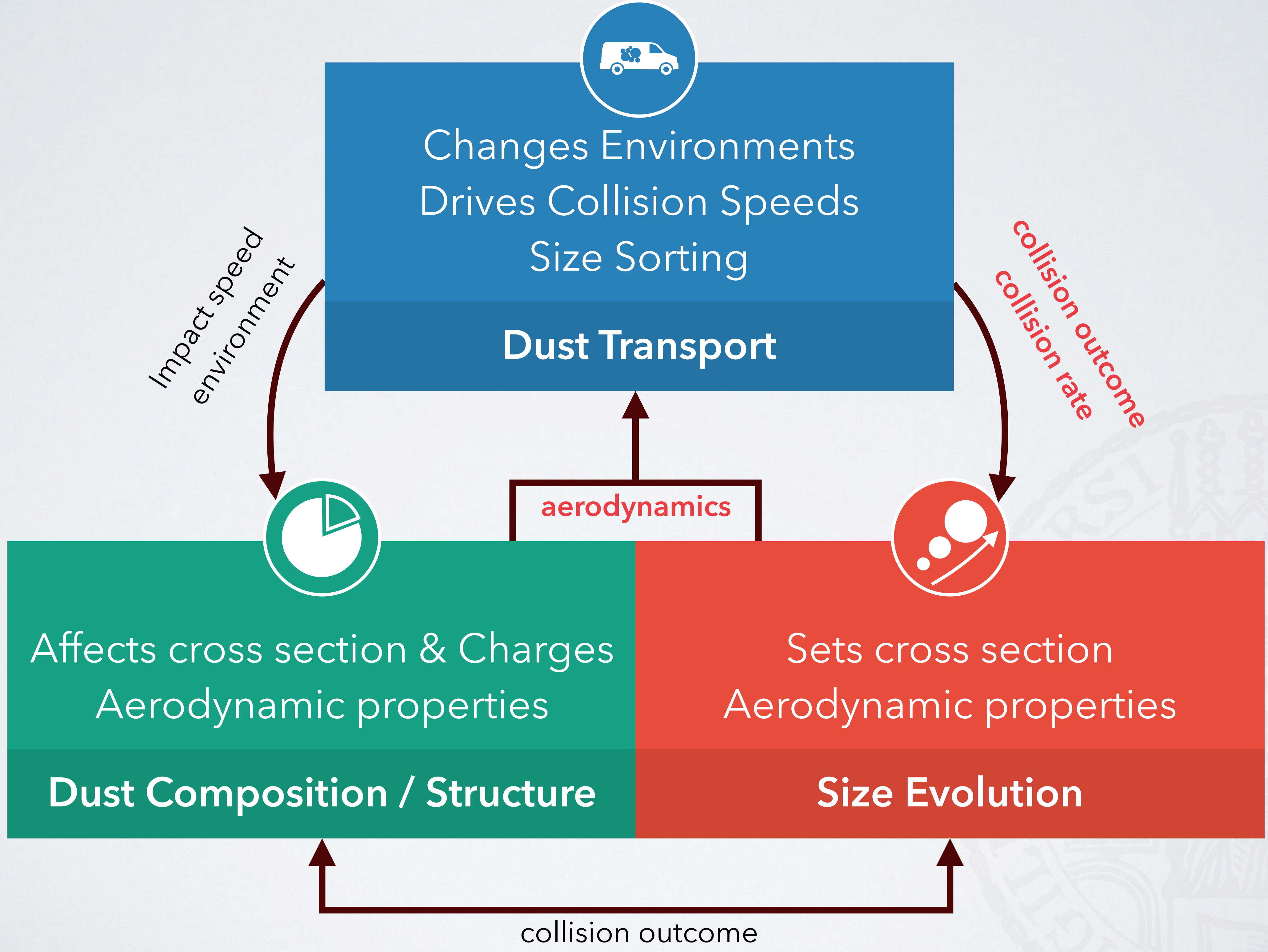
Bouncing→



←Fragmentation

Movies courtesy of Blum group
e.g. Blum et al. 2014

Transport ↔ Collisions



Changes Environments
Drives Collision Speeds
Size Sorting

Dust Transport

Impact speed
environment

collision outcome
collision rate

aerodynamics

Affects cross section & Charges
Aerodynamic properties

Dust Composition / Structure

Sets cross section
Aerodynamic properties

Size Evolution

collision outcome

Transport ↔ Collisions

Despite all these complications:

$$t_{\mathrm{grow}} \sim \frac{1}{\epsilon\,\Omega}$$

(size doubling time scale)
works surprisingly well

Quick Estimate

This estimate assumes turbulent velocities to dominate. Derivation in

Brauer et al. 2008
Birnstiel et al. 2012

In Depth

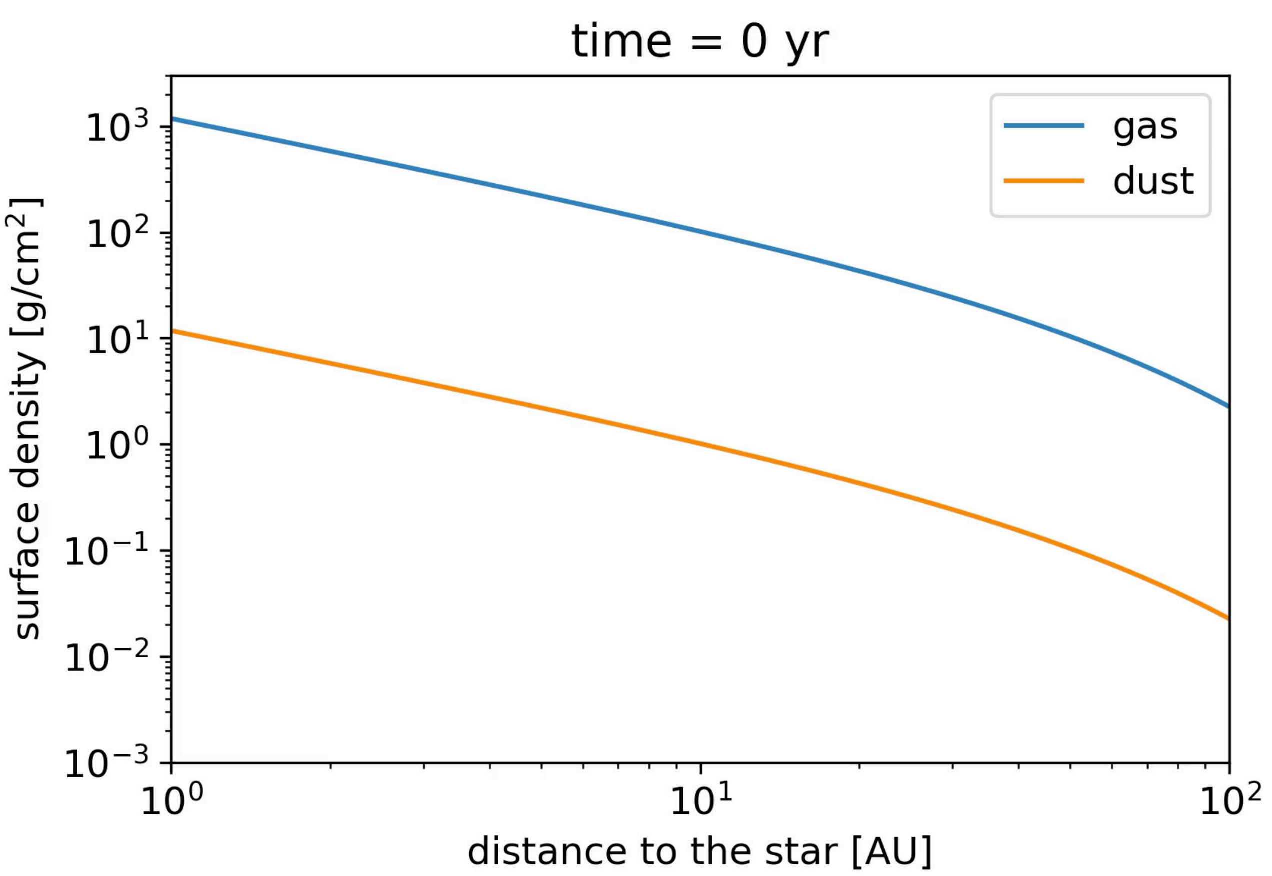
ϵ dust-to-gas ratio $= \frac{\Sigma_\mathrm{d}}{\Sigma_\mathrm{g}}$

Dust Growth
+
Dynamics

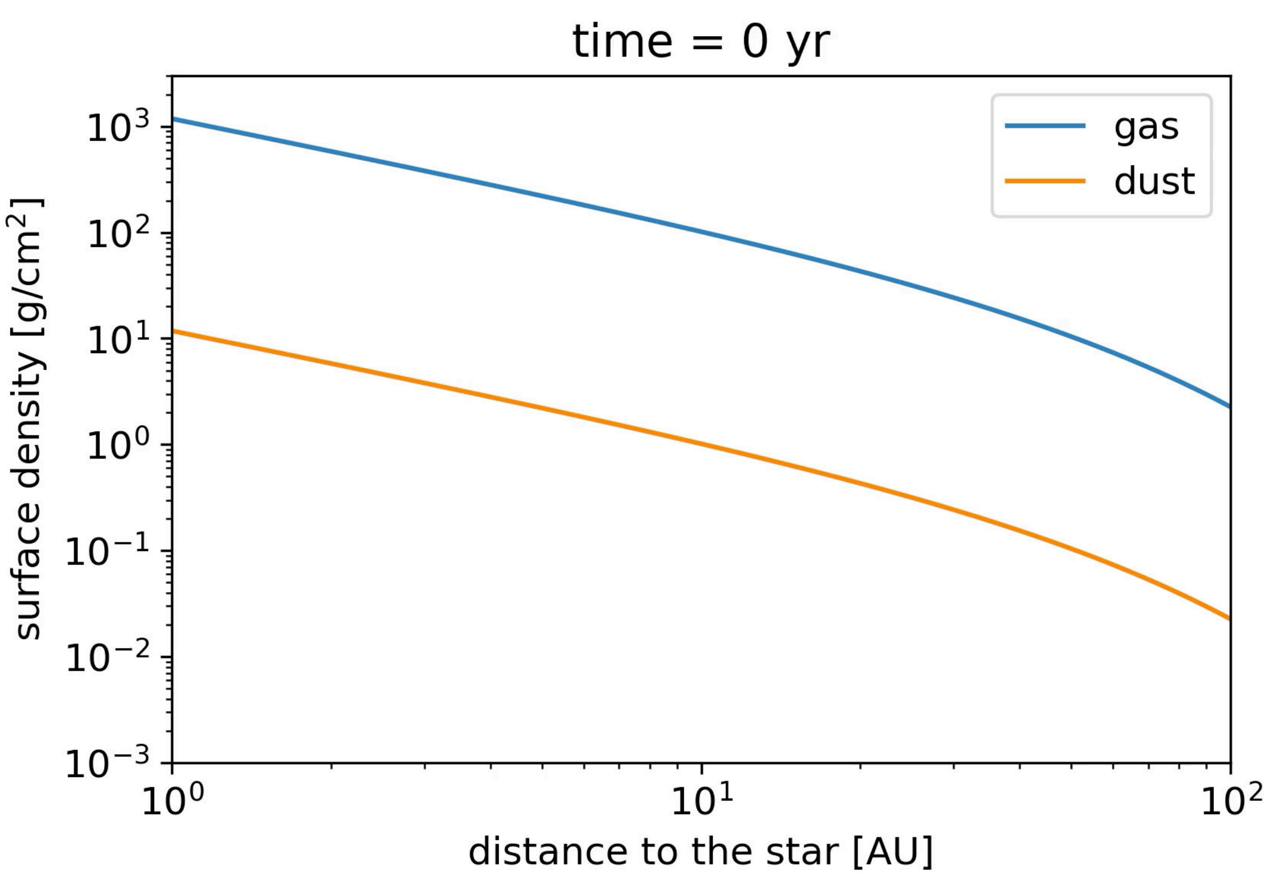
Crash Course: Theory

Size matters! ⇒ Size evolution matters!

fixed size



evolving size



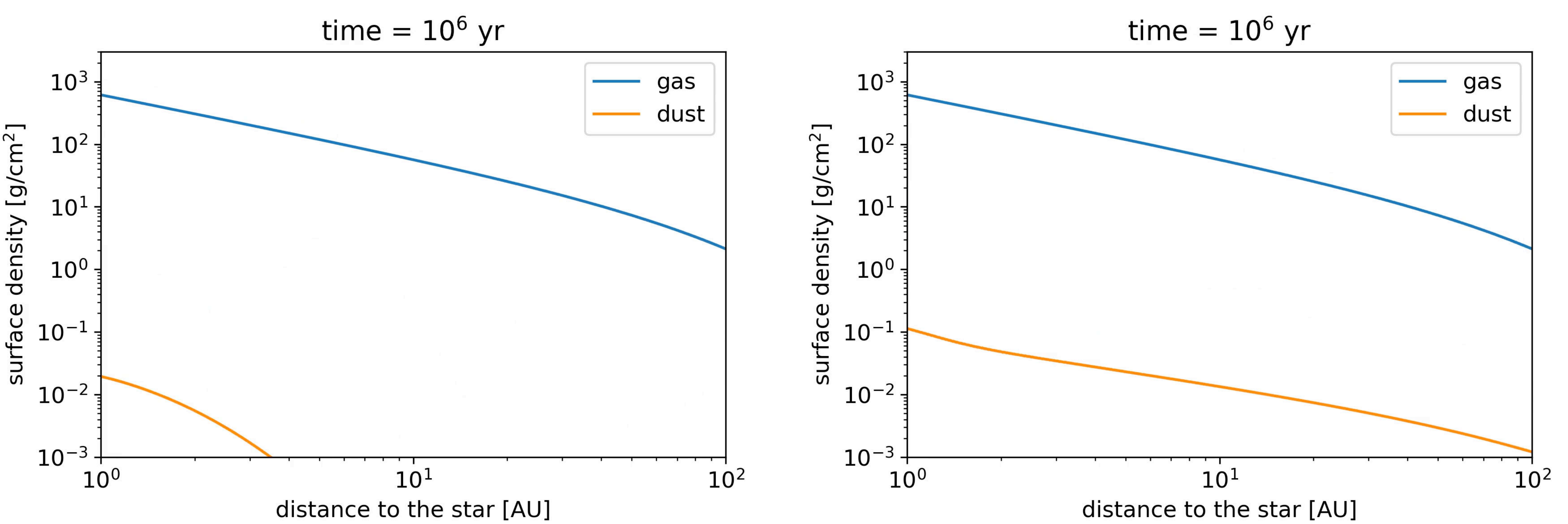
Movies by J. Drążkowska with DUSTPY code (Stammler & Birnstiel in prep.)

Crash Course: Theory

Size matters! ⇒ Size evolution matters!

fixed size

evolving size



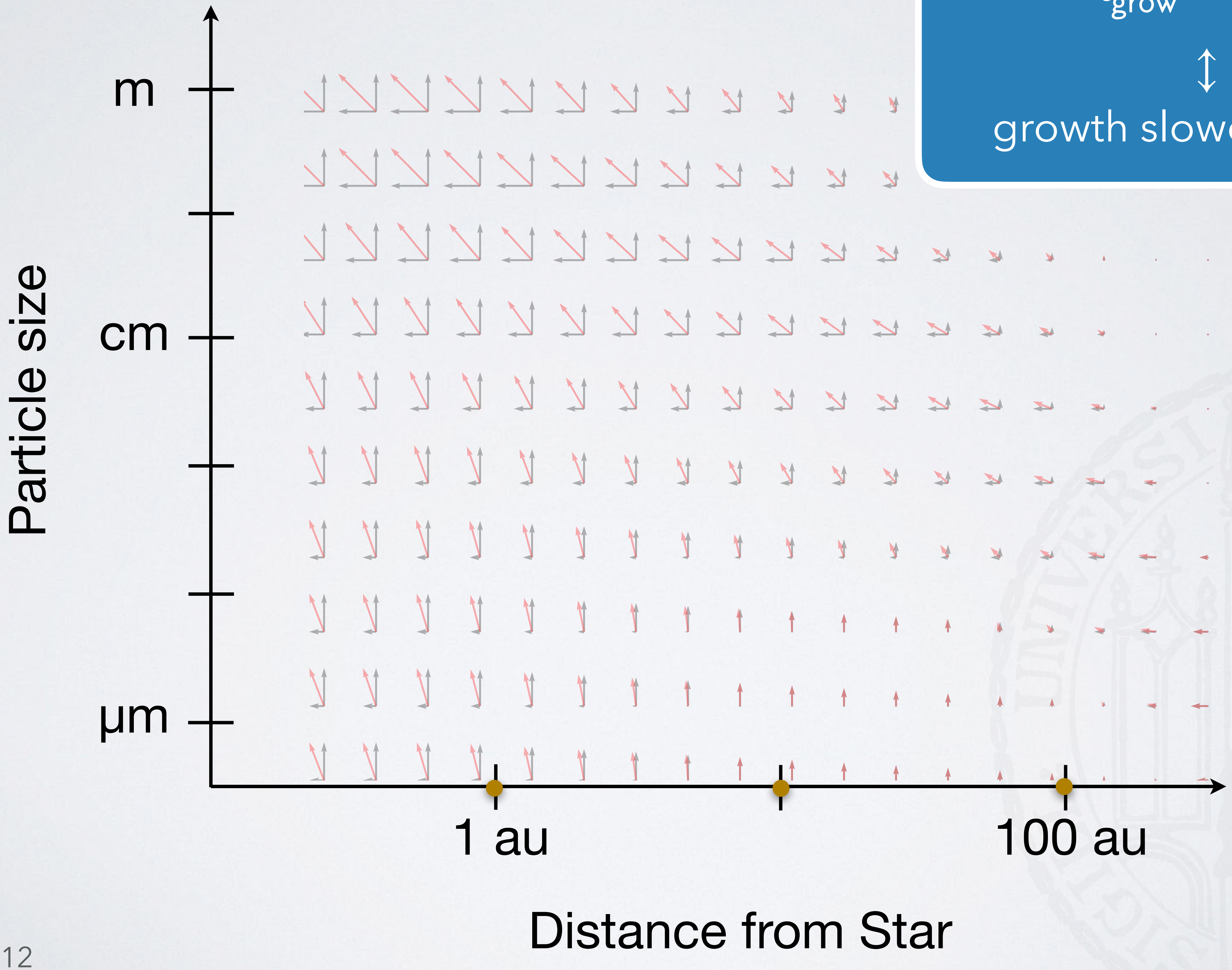
Movies by J. Drążkowska with DUSTPY code (Stammler & Birnstiel in prep.)

Dust Evolution in a Nutshell

$$t_{\text{grow}} \sim \frac{1}{\epsilon\,\Omega}$$

$$\updownarrow$$

growth slower outside



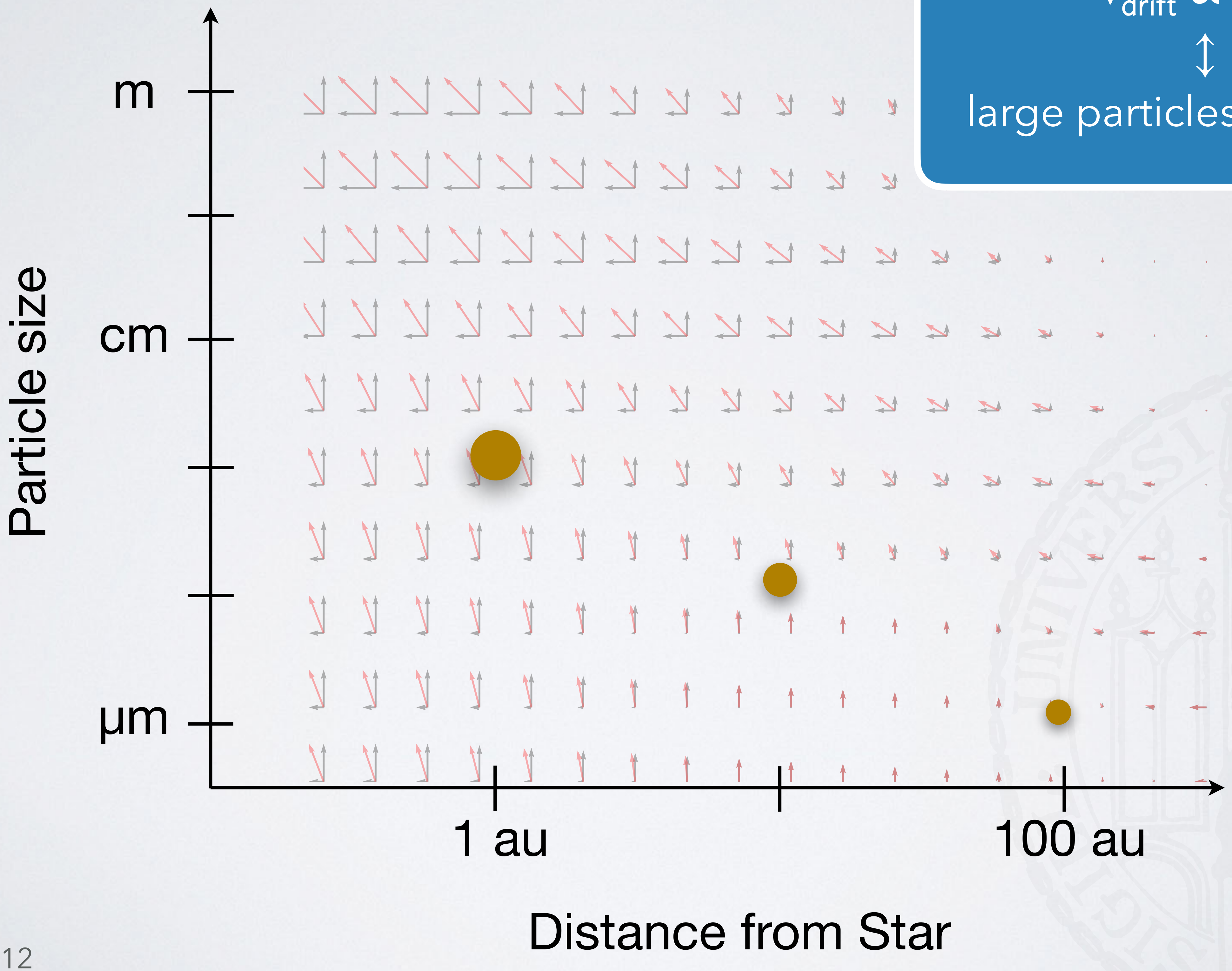
Birnstiel et al. 2012

Dust Evolution in a Nutshell

$v_{drift} \propto a$

$\updownarrow$

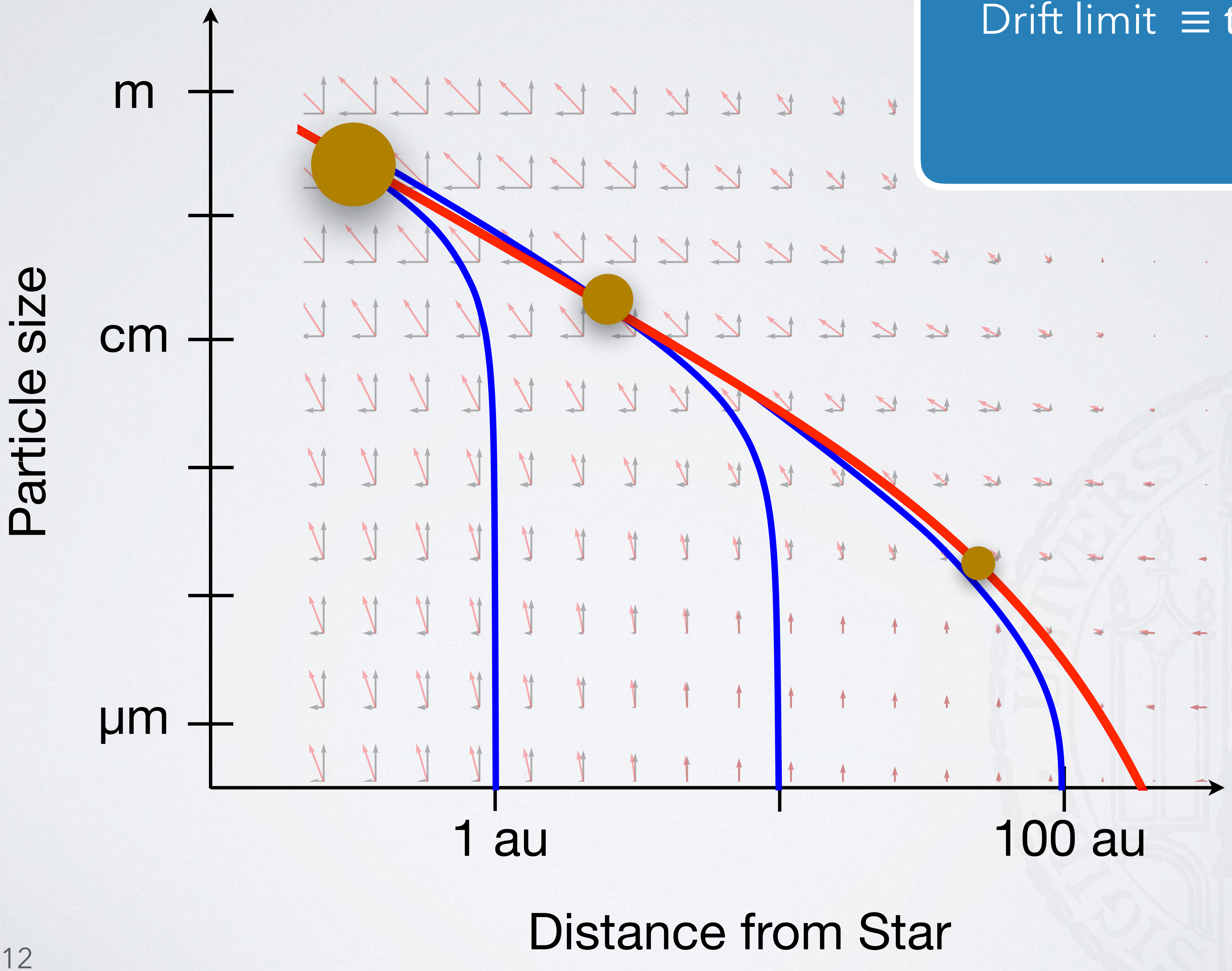
large particles drift faster



Birnstiel et al. 2012

Dust Evolution in a Nutshell

Drift limit $\equiv t_{grow} = t_{drift}$



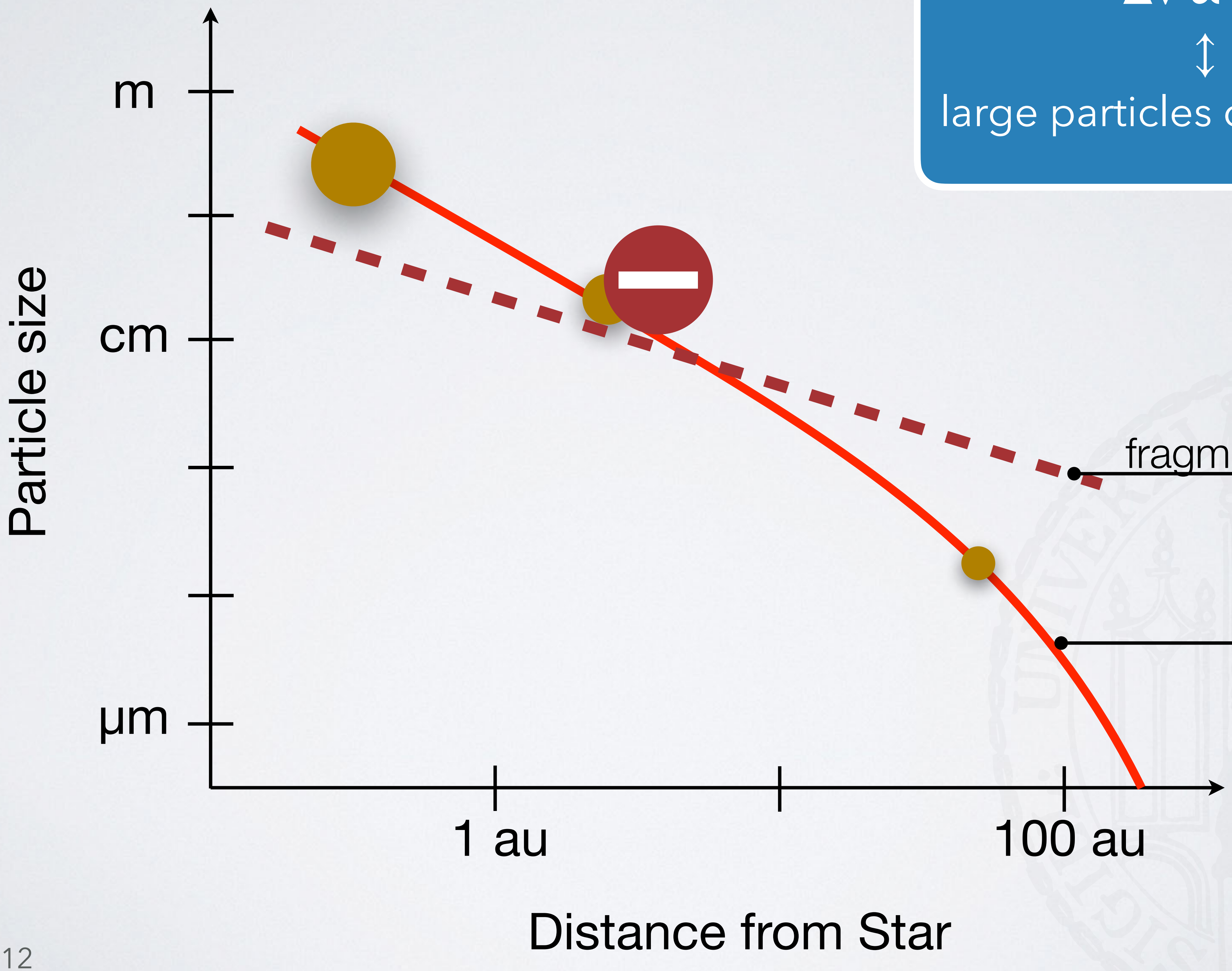
Birnstiel et al. 2012

Dust Evolution in a Nutshell

$\Delta v \propto a$

$\updownarrow$

large particles collide faster



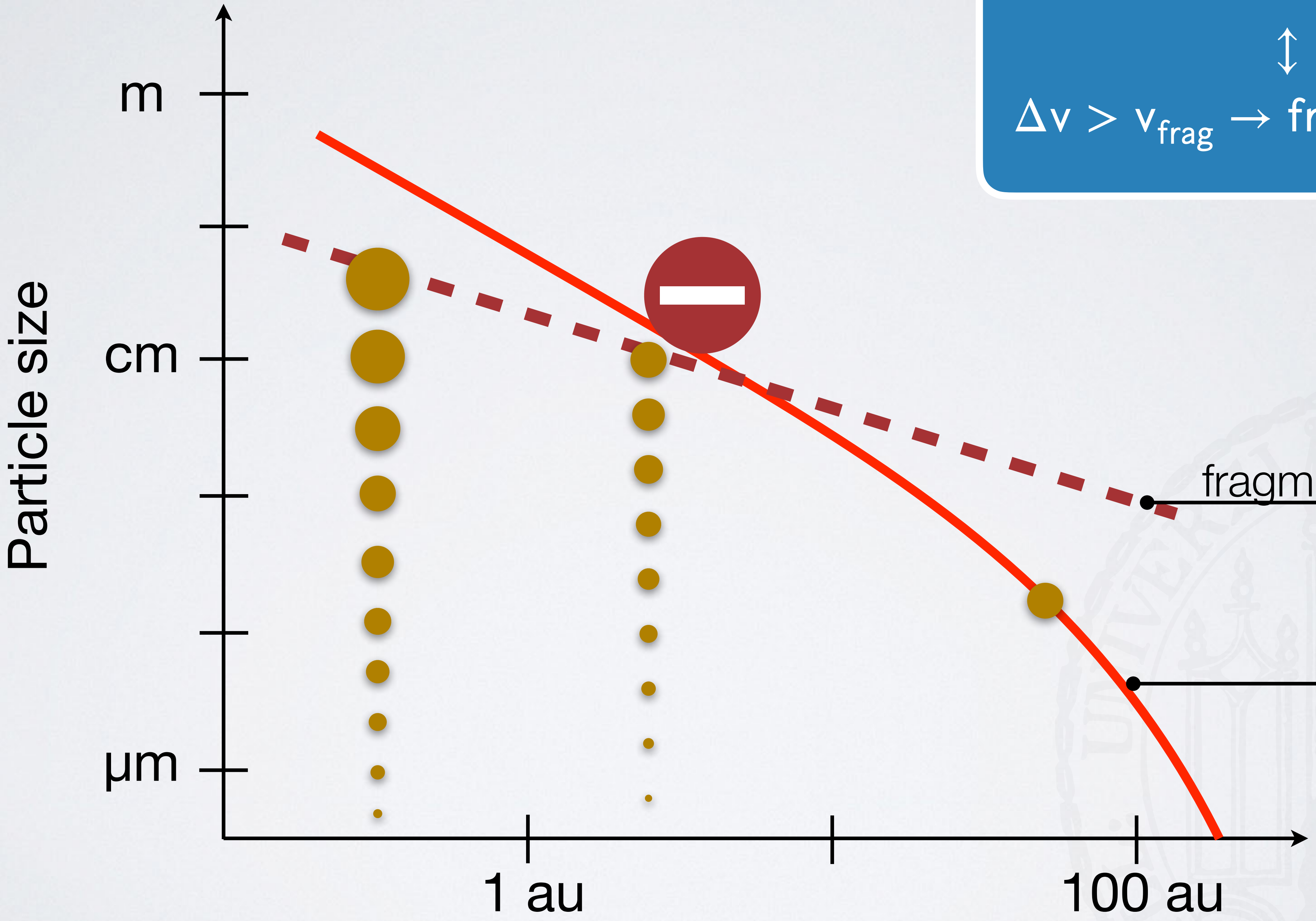
Birnstiel et al. 2012

Dust Evolution in a Nutshell

$\Delta v \propto a$

$\updownarrow$

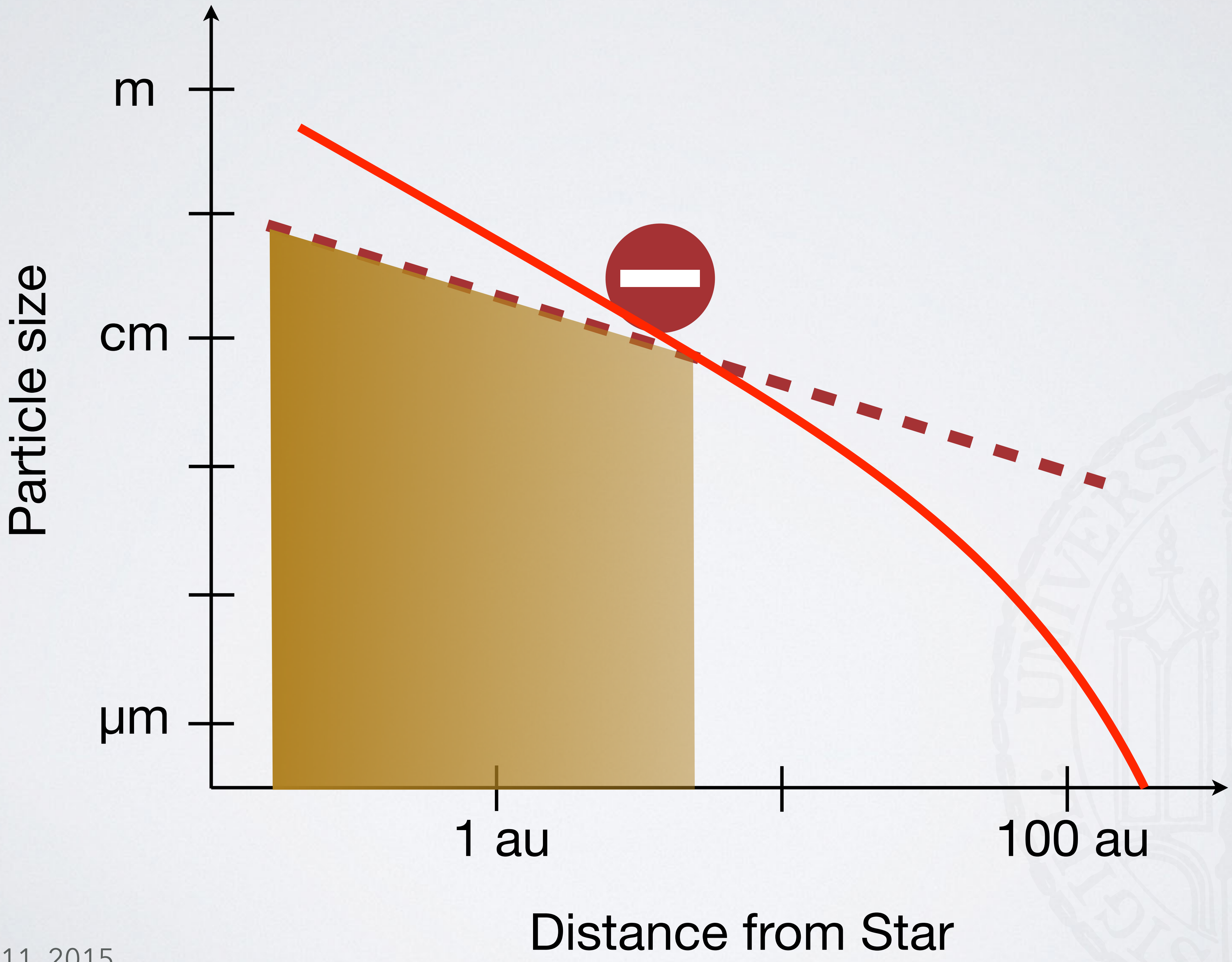
$\Delta v > v_{frag} \rightarrow$ fragmentation



Distance from Star

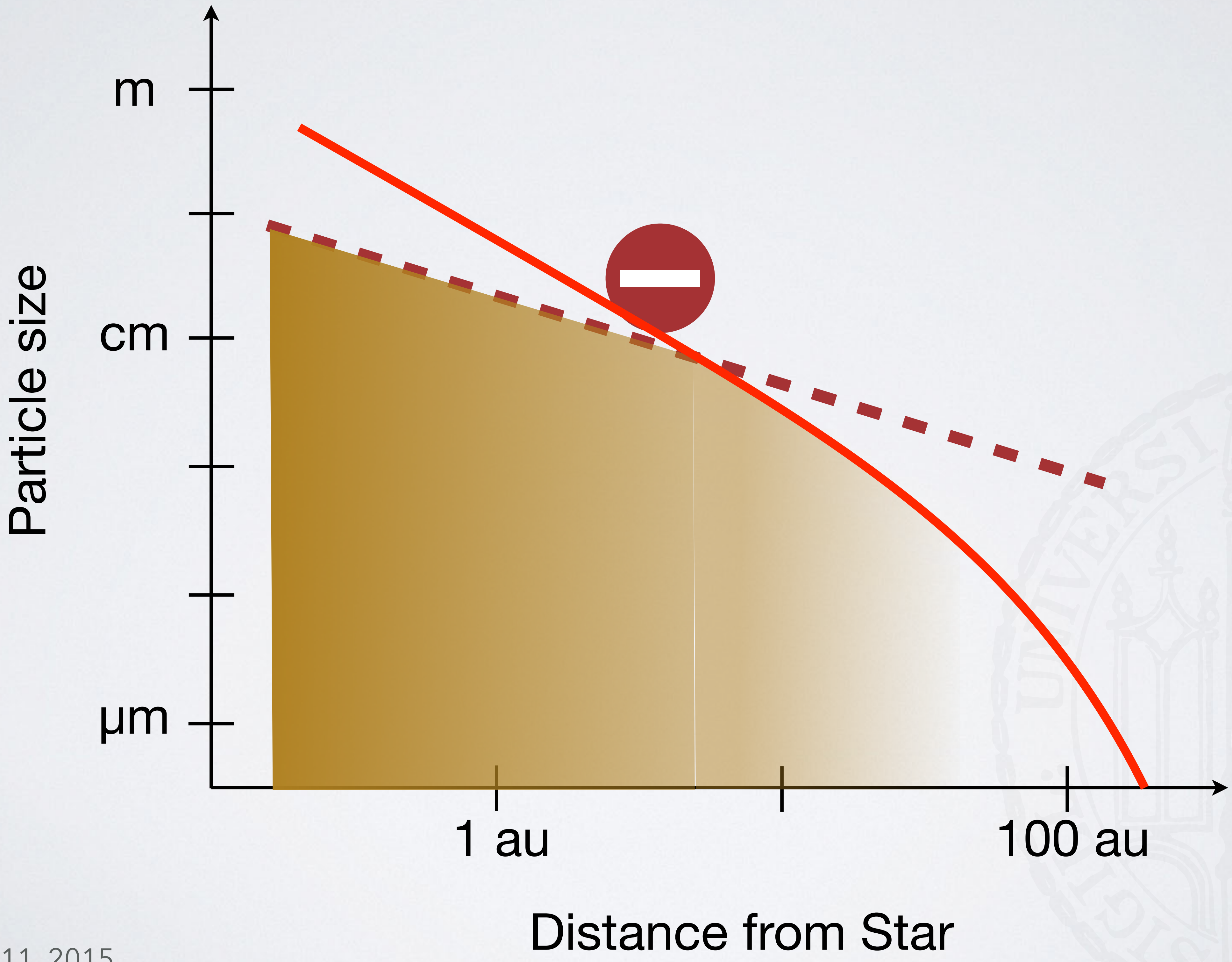
Birnstiel et al. 2012

Dust Evolution in a Nutshell



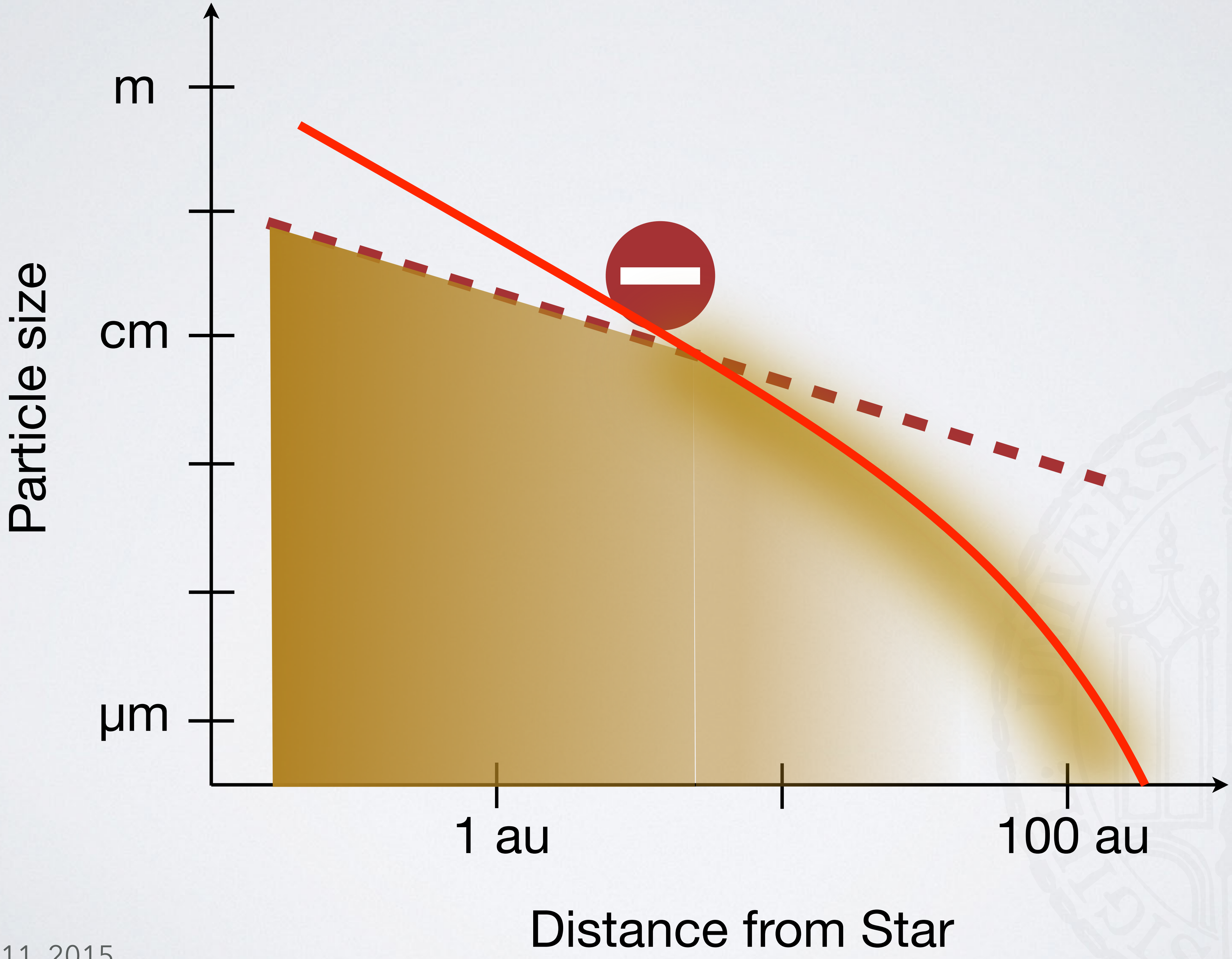
Birnstiel et al. 2011, 2015

Dust Evolution in a Nutshell



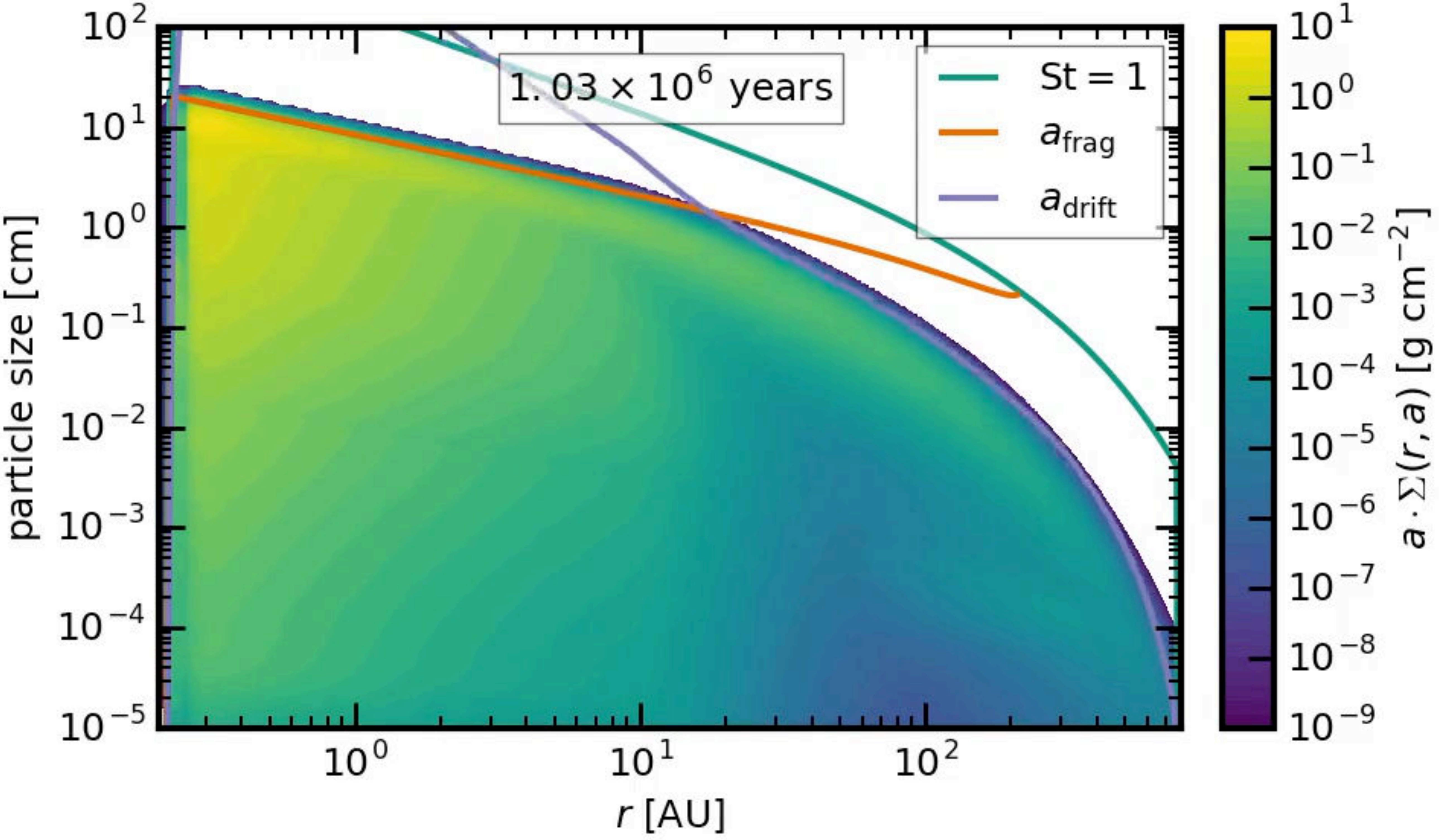
Birnstiel et al. 2011, 2015

Dust Evolution in a Nutshell



Birnstiel et al. 2011, 2015

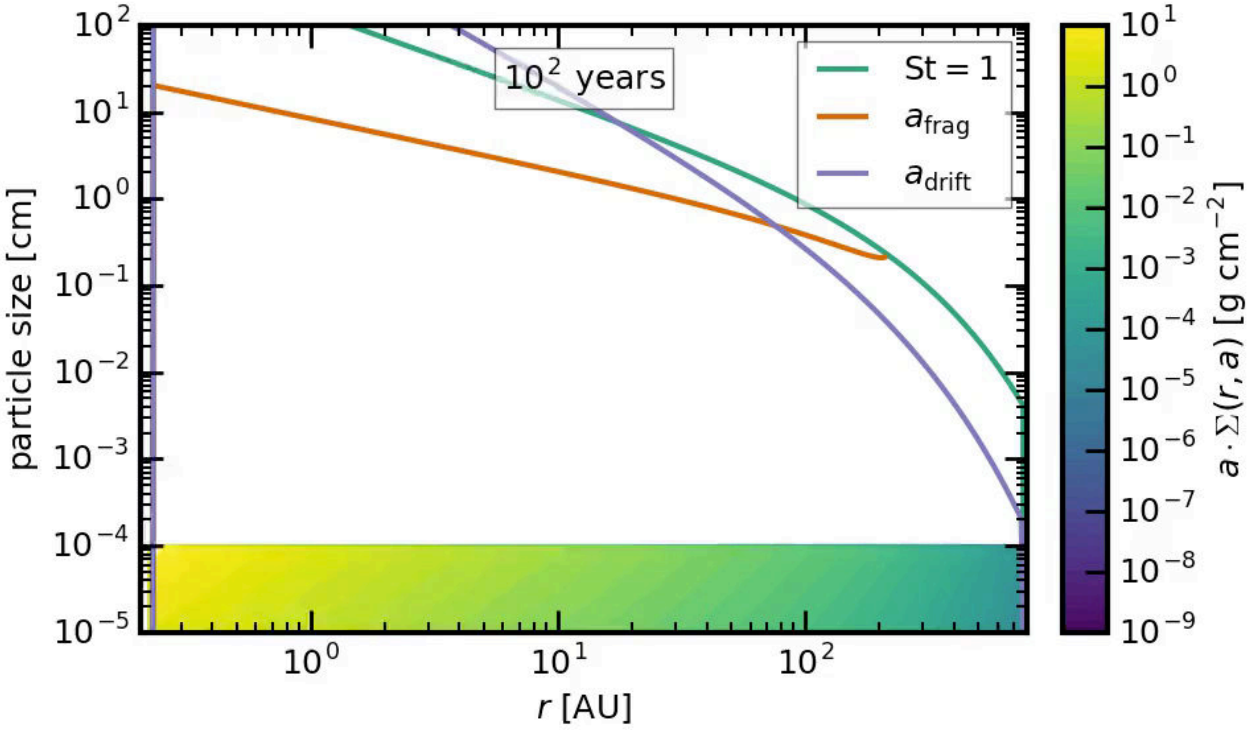
Dust Evolution in a Nutshell



Birnstiel et al. 2012

PLANETESIMAL FORMATION

Dust Evolution in a Nutshell



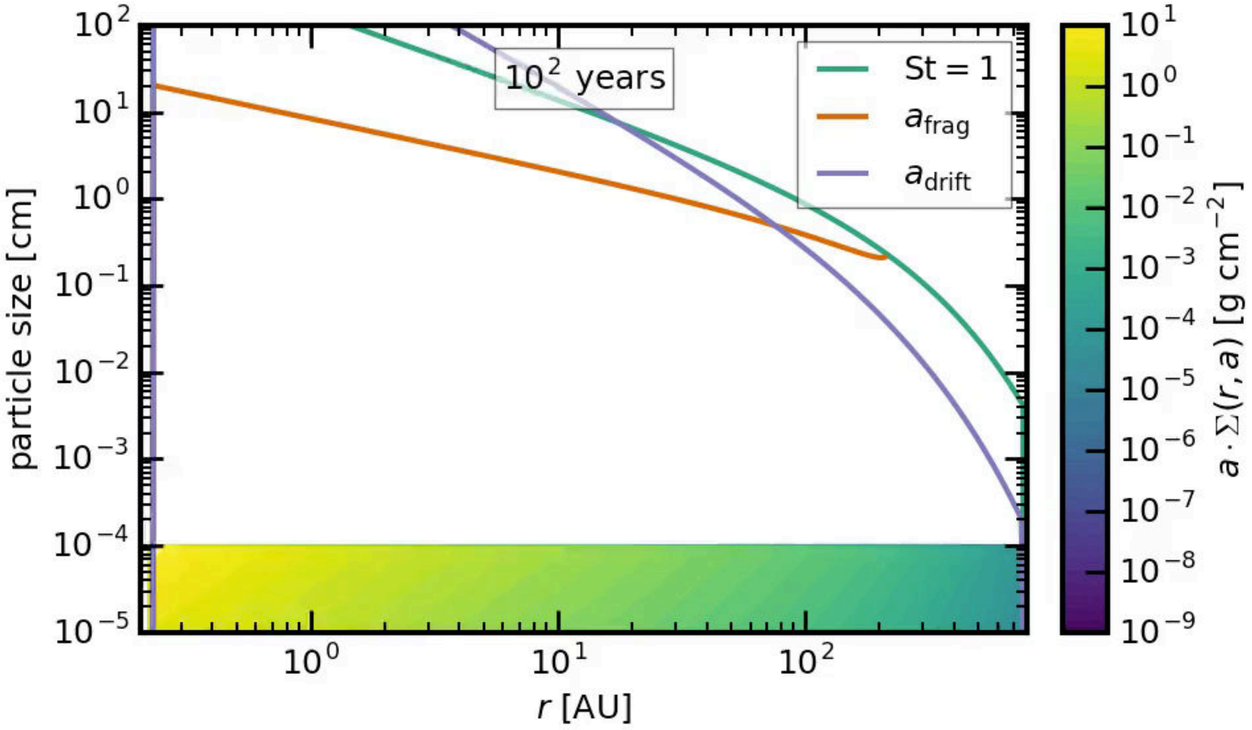
→ All particles drift onto the star

→ No planetesimals are formed

→ There shouldn't be any planets

Birnstiel et al. 2012

Dust Evolution in a Nutshell



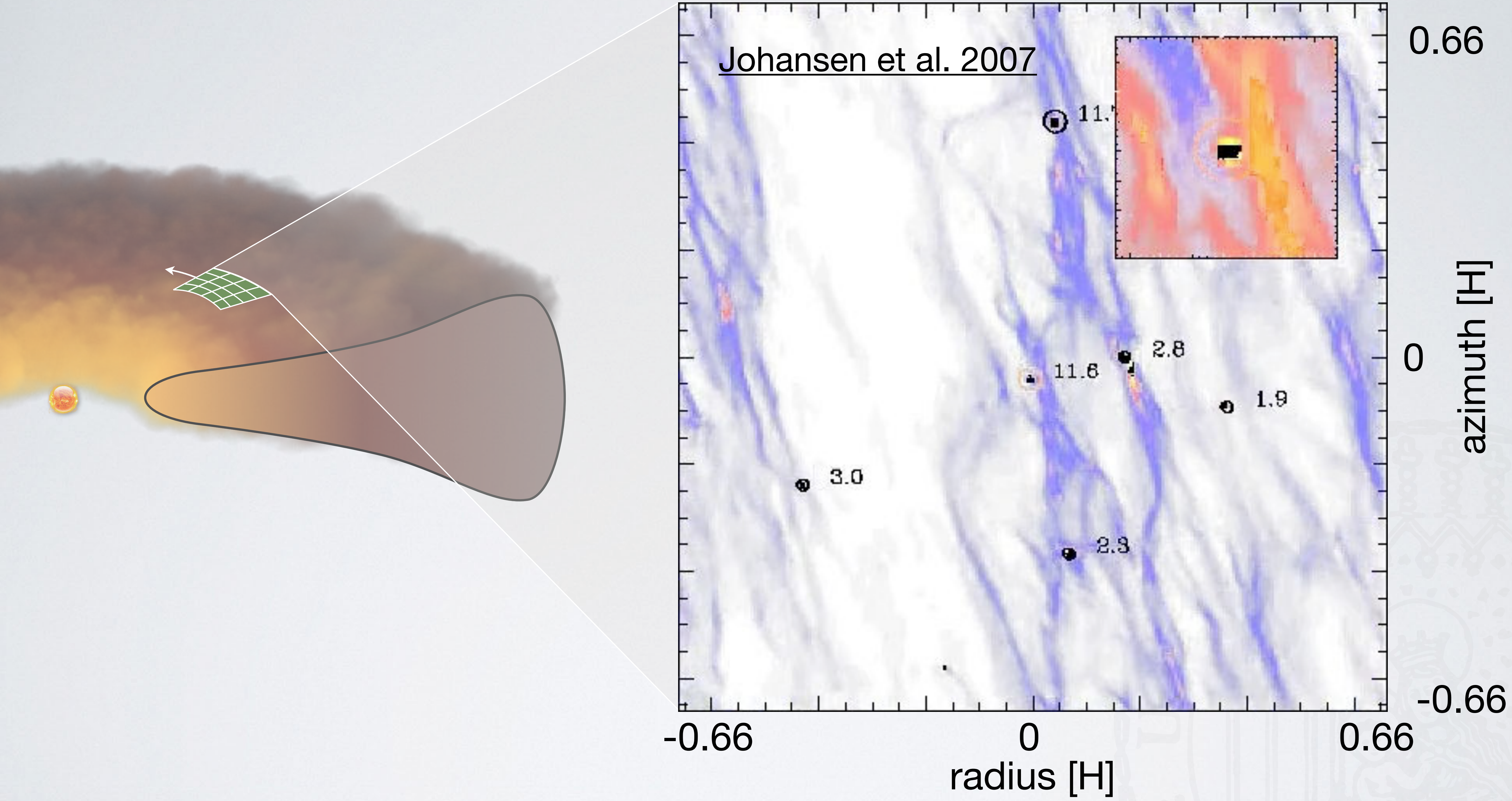
Some **collisional pathways** have been suggested:

- "lucky particles":
  e.g. Windmark et al. 2012
  too inefficient
- "porous growth":
  e.g. Kataoka et al. 2013
  inner disk only, porosity too high?

In Depth

Birnstiel et al. 2012

Gravoturbulent Planetesimal Formation

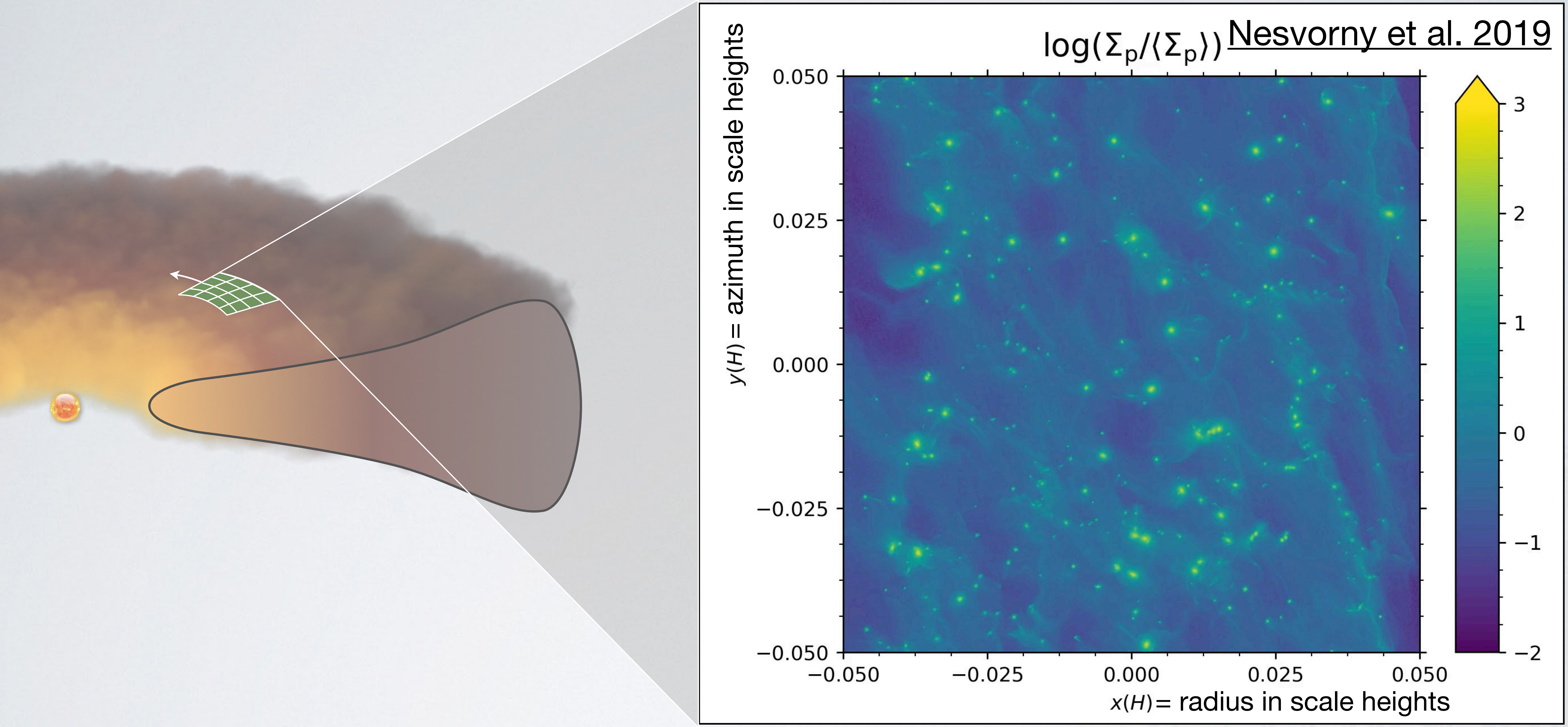


Johansen et al. 2007

Requires:
- "large" particles
- dust overdensities (~3% instead of 1%)

see also: Youdin & Goodman 2005, Bai & Stone 2010 and others

Gravoturbulent Planetesimal Formation



Requires: - "large" particles

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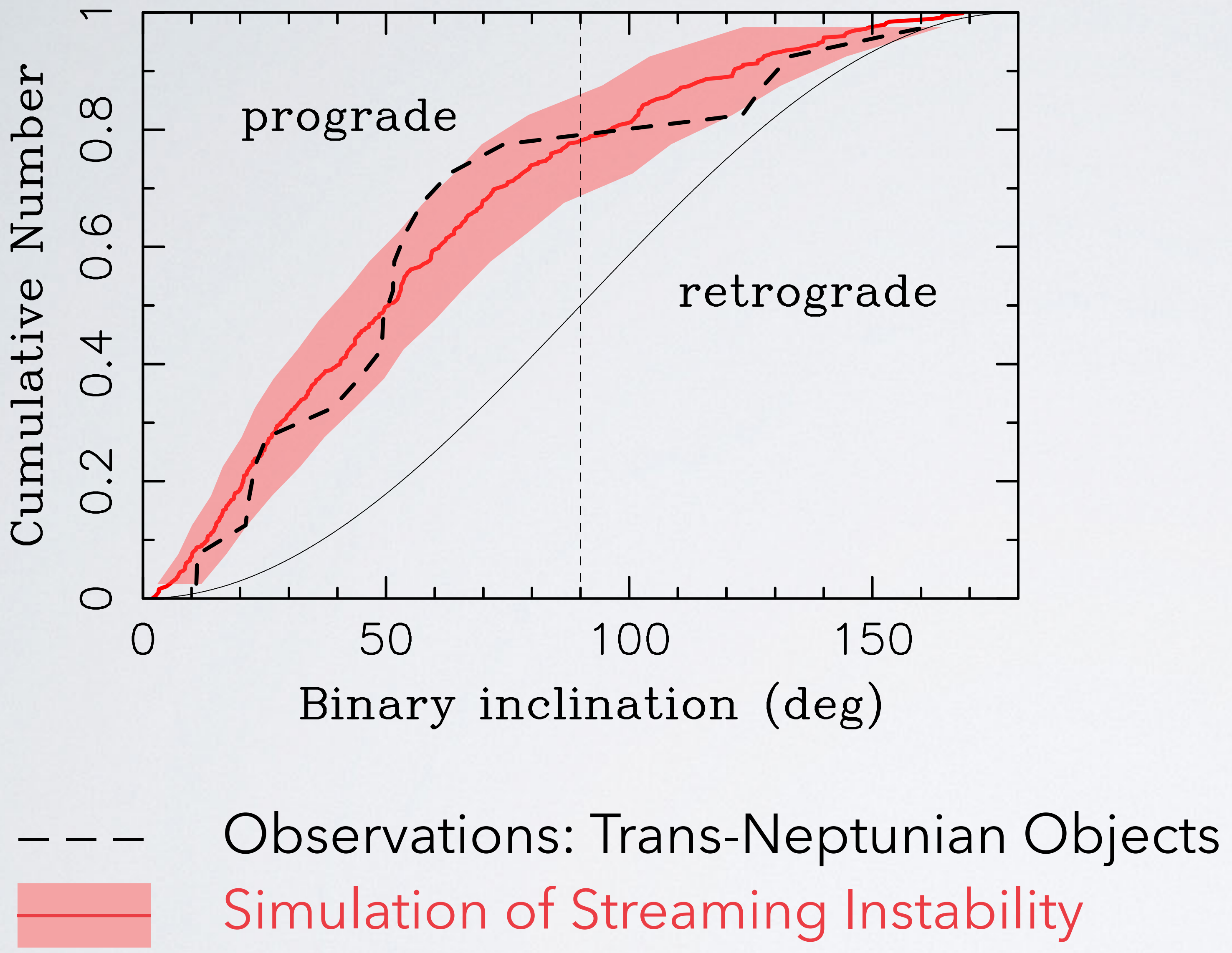
see also: Youdin & Goodman 2005, Johansen et al. 2007, Bai & Stone 2010 and others

Gravoturbulent Planetesimal Formation

Nesvorny et al. 2019



– – – Observations: Trans-Neptunian Objects

🟥 Simulation of Streaming Instability


NASA / JHUAPL / SwRI / Roman Tkachenko

SI explains fraction of binary objects & their size range!

Not all is good!


NASA / JHUAPL / SwRI / Roman Tkachenko

Recent issues:
the streaming instability might not work if

- external turbulence is present:
  Auffinger & Laibe 2018
  Umurhan et al. 2020
  Gole et al. 2020
  Klahr & Schreiber 2021
- particles not of single sizes
  Krapp et al. 2019
  Zhu & Yang 2021
  Paardekooper et al. 2020

In Depth

A New Paradigm

Growing planetesimals is hard
(bouncing, fragmentation, drift)

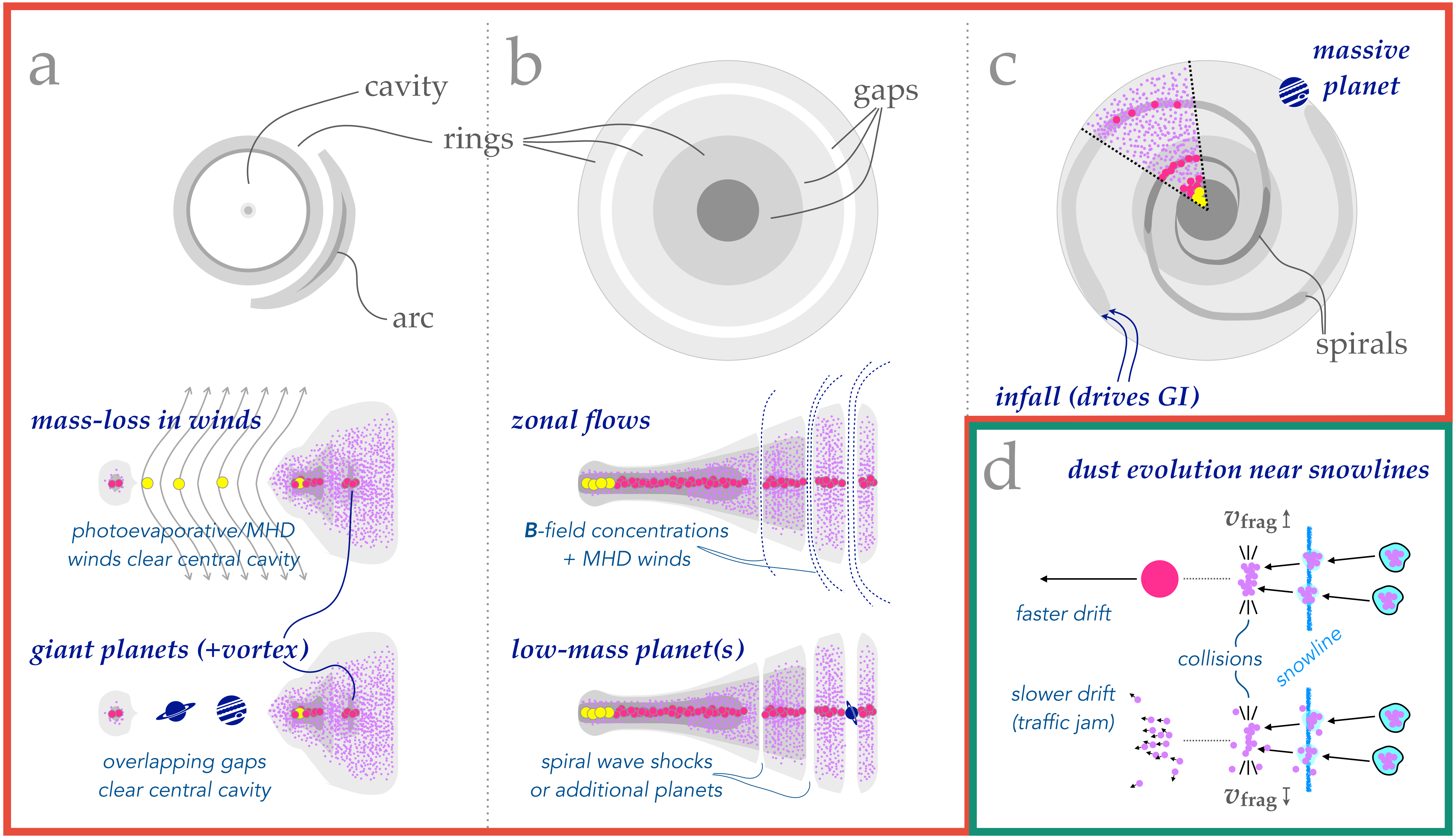
Collapsing small dust is impossible
(small grains coupled to gas)

Growing pebbles is easy
(up to one of the growth barriers)

Collapsing pebbles is easy
if dust is accumulated

…
Dead Zone Edge
Zonal Flows
Dust Evolution + Convective Overstability = Planetesimals
GSF Instability
Rossby Vortices
…

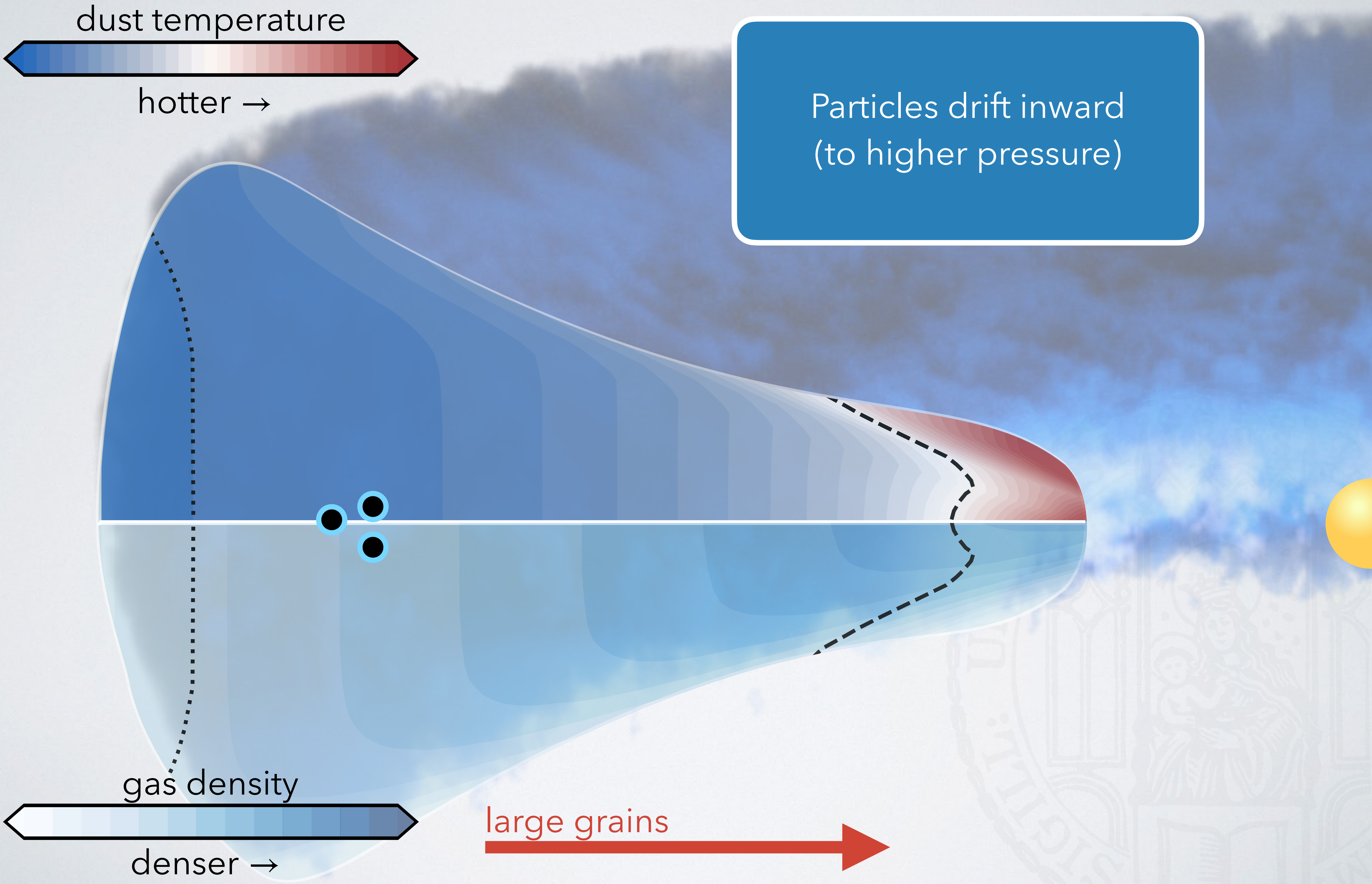
What causes the trapping?



See talk by Jaehan Bae

Andrews et al. 2020

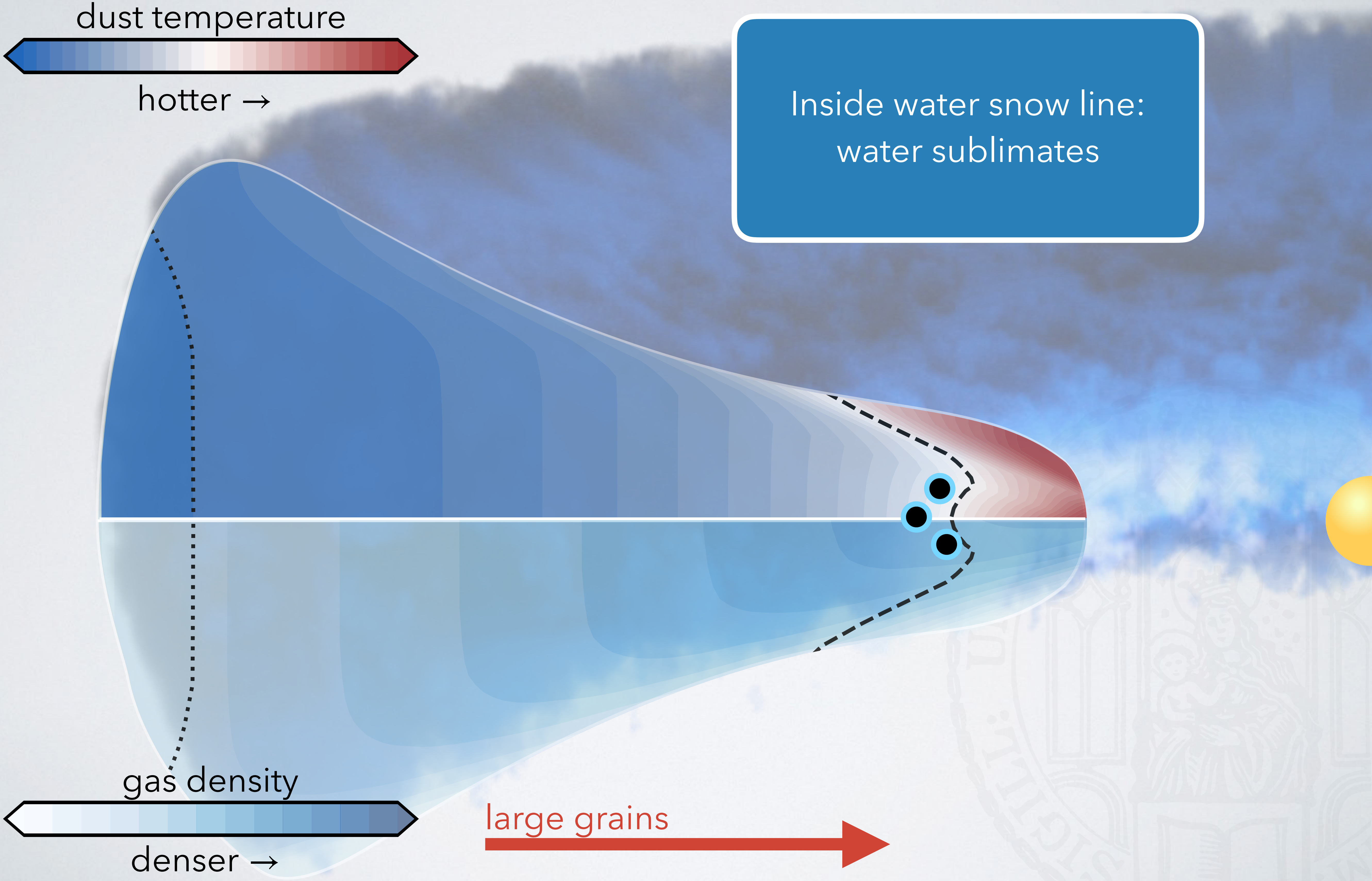
Snow Lines: Complicated



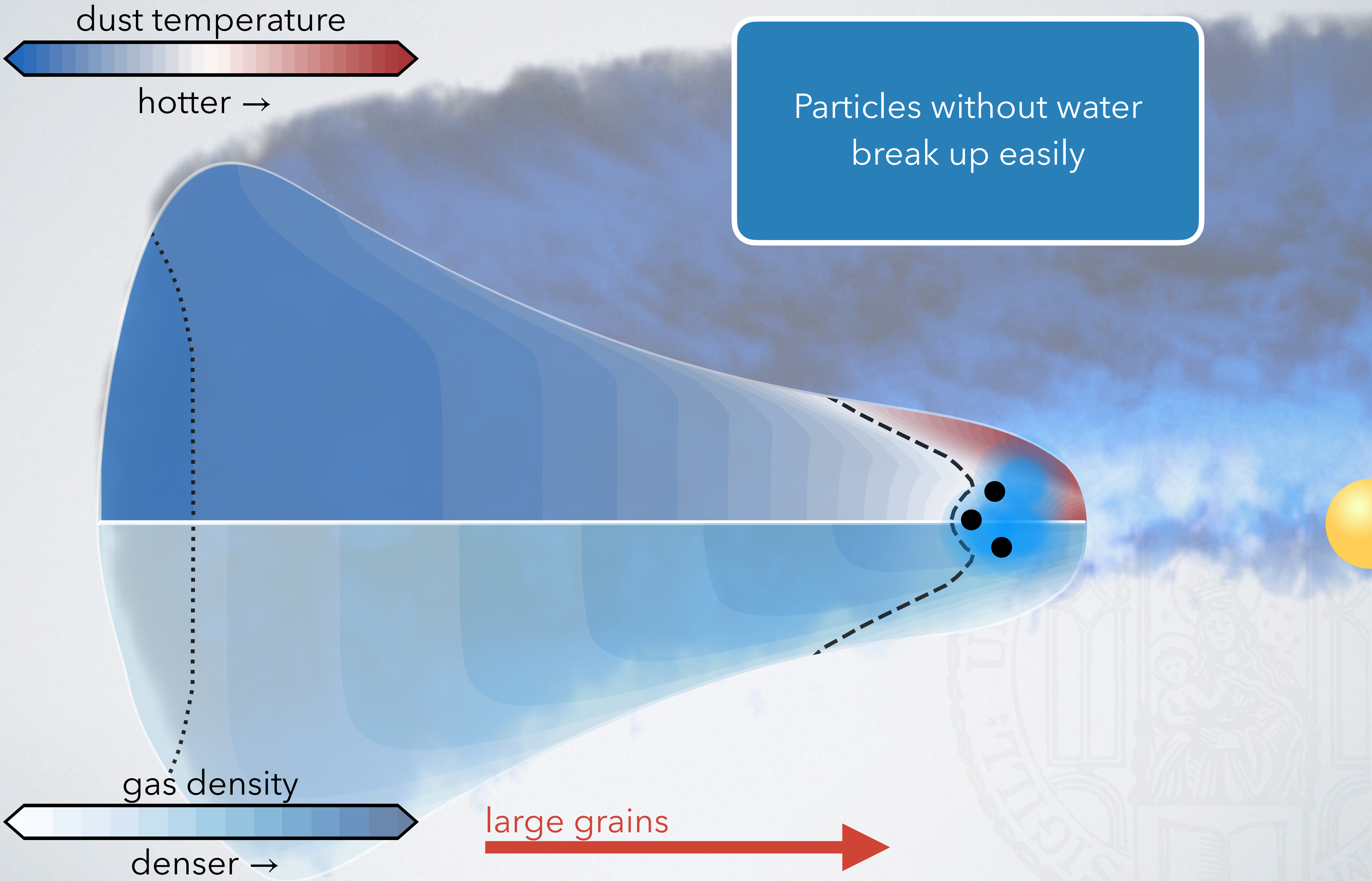
Particles drift inward
(to higher pressure)

Snow Lines: Complicated

Inside water snow line:
water sublimates

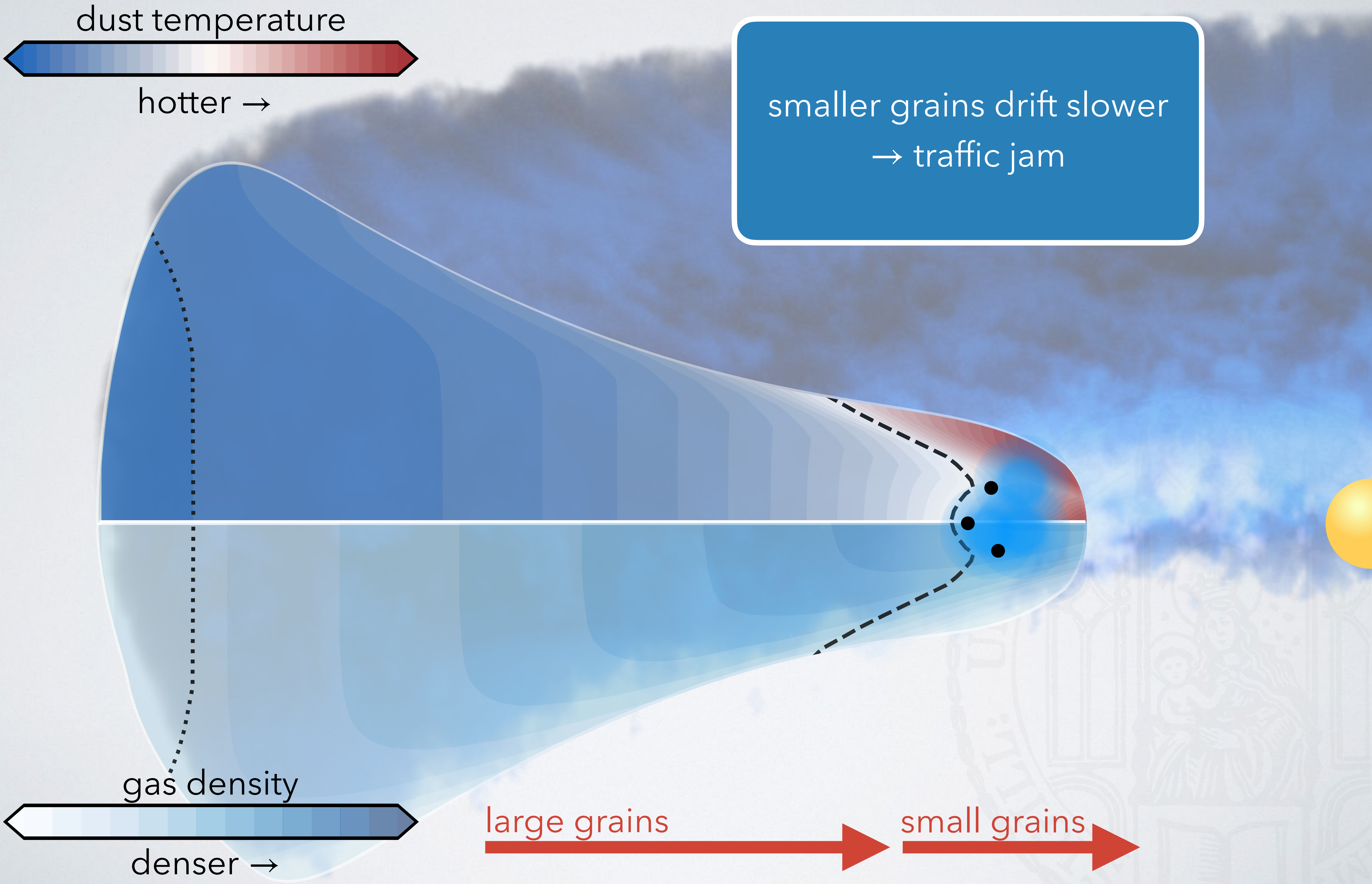


Snow Lines: Complicated



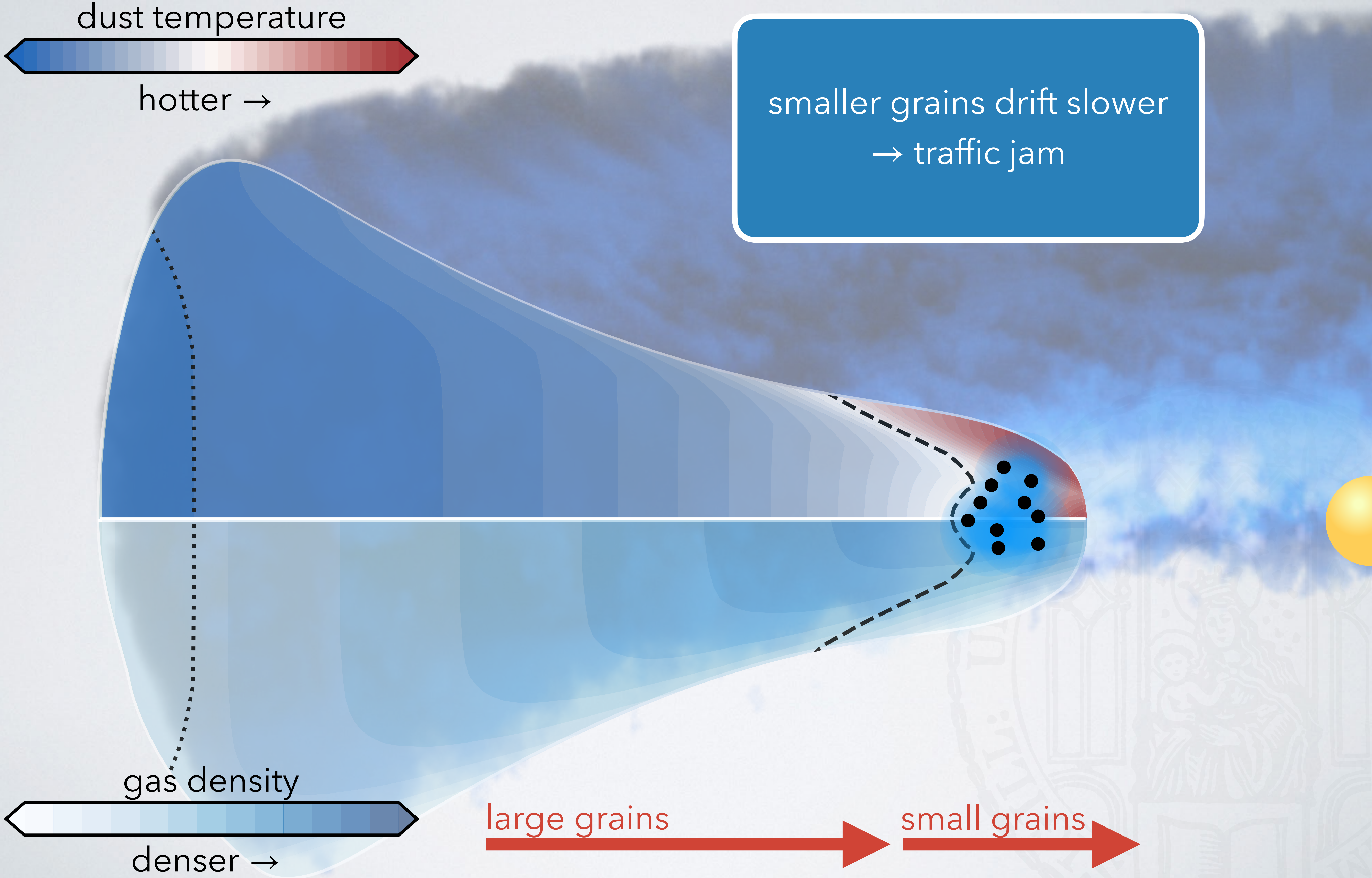
Particles without water break up easily

Snow Lines: Complicated



smaller grains drift slower
→ traffic jam

Snow Lines: Complicated



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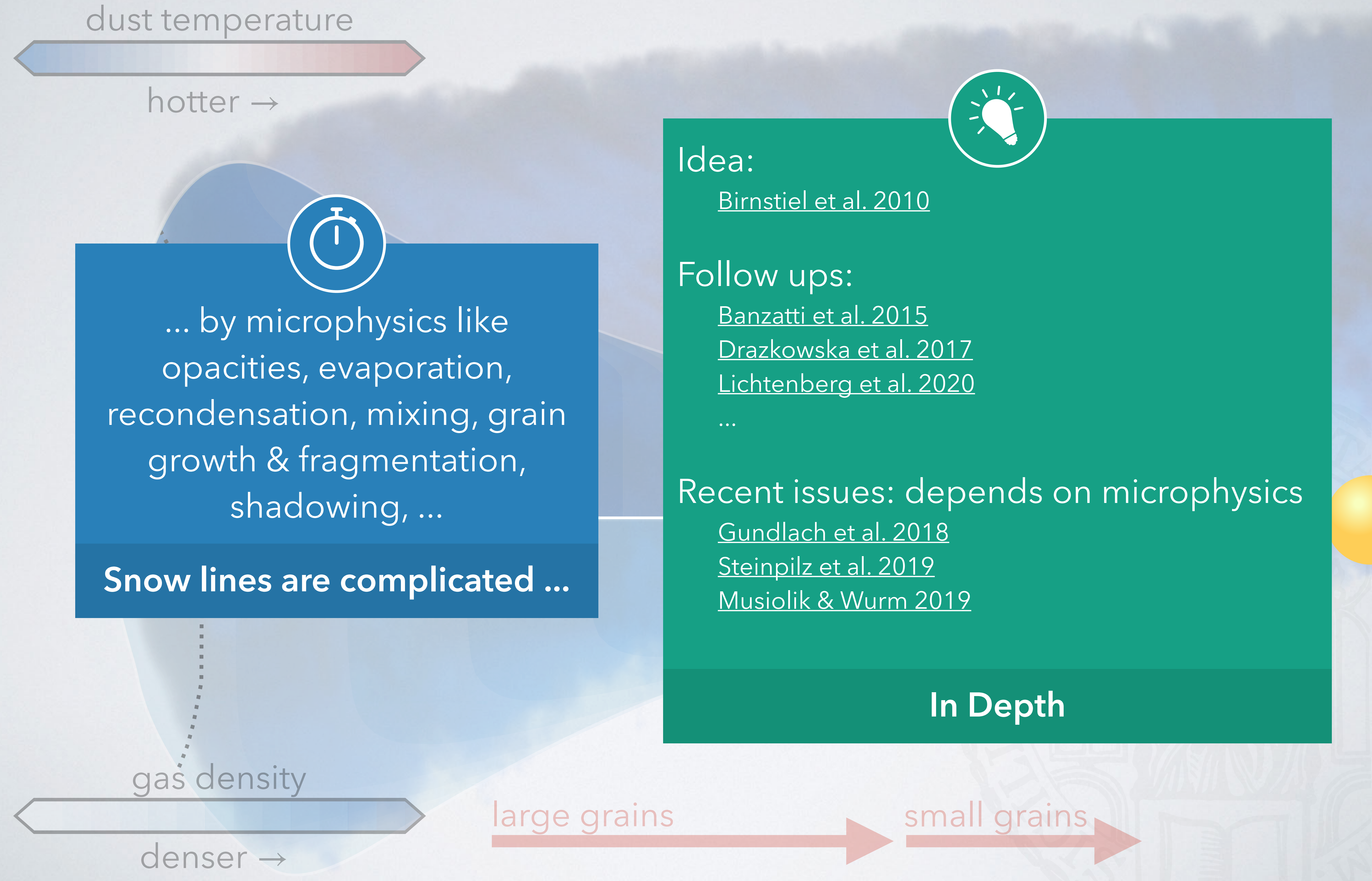
Snow Lines: Complicated



... by microphysics like opacities, evaporation, recondensation, mixing, grain growth & fragmentation, shadowing, ...

Snow lines are complicated ...

Idea:

Birnstiel et al. 2010

Follow ups:

Banzatti et al. 2015
Drazkowska et al. 2017
Lichtenberg et al. 2020
...

Recent issues: depends on microphysics

Gundlach et al. 2018
Steinpilz et al. 2019
Musiolik & Wurm 2019

In Depth

Summary

... **slower** in the outer disk
... **faster** in higher dust-to-gas ratio
... until they don't stick (but bounce/fragment)
... depending on microphysics

Dust Particles grow ...

... **drift faster** if they are larger
... are **diffused** by turbulence
... form planetesimals if **St** & ϵ large enough

Dust Particles ...

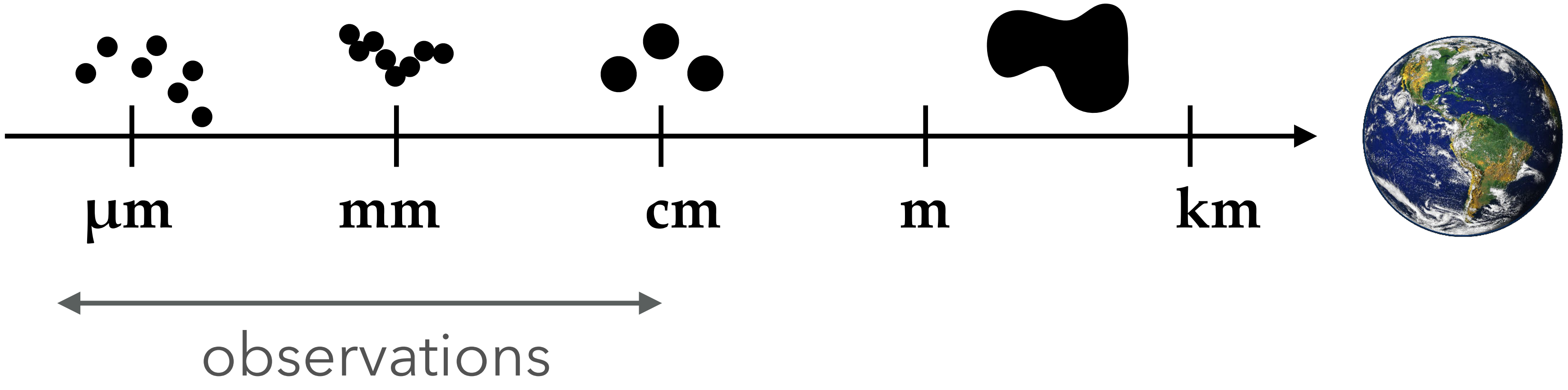
... now it's time for a reality check!

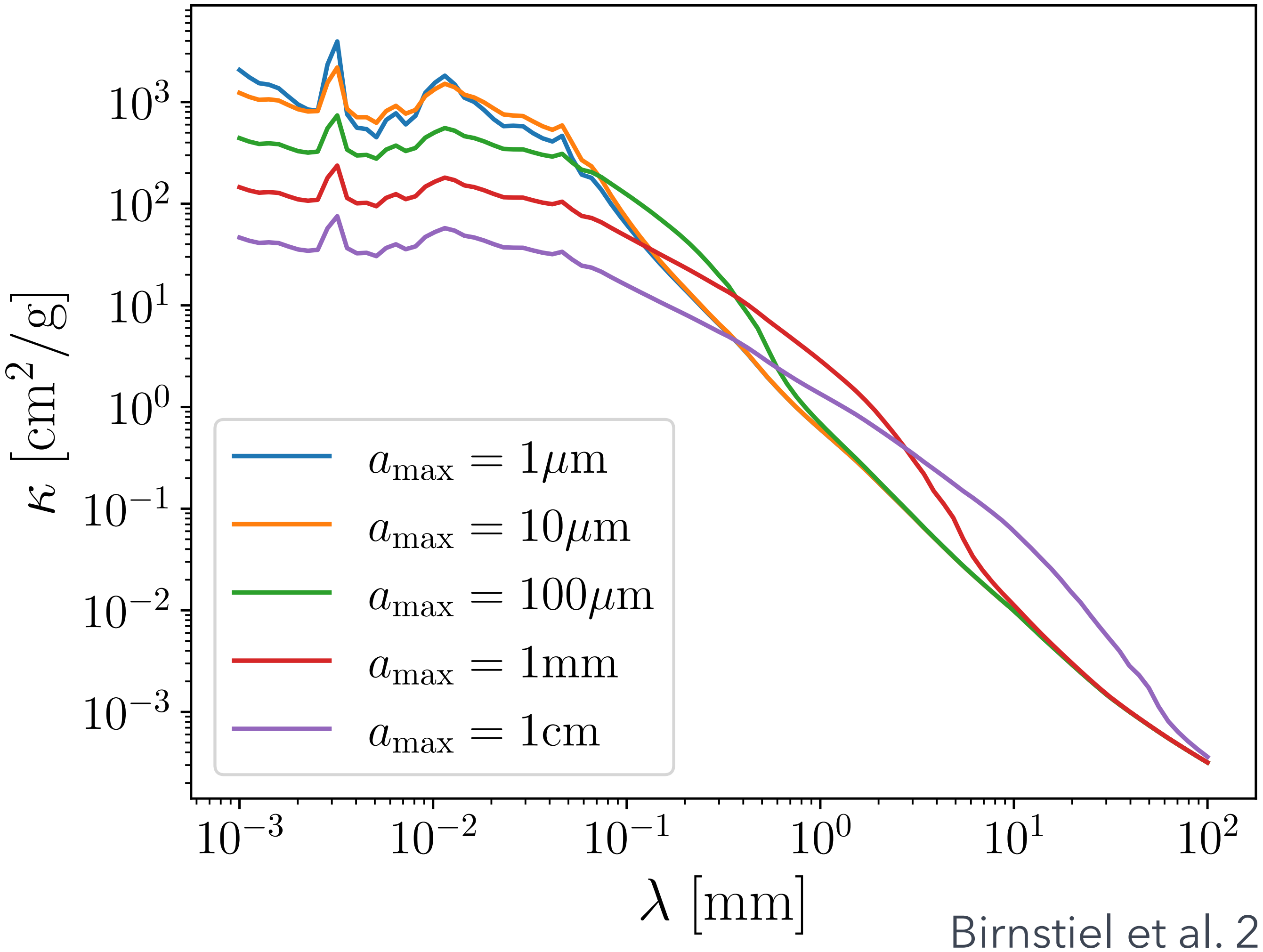
→ Observations

Outline – Part 2

1. Observations of dust grains
2. Evidence for dust growth
3. Evidence for dust trapping
4. Evidence for dust dynamics

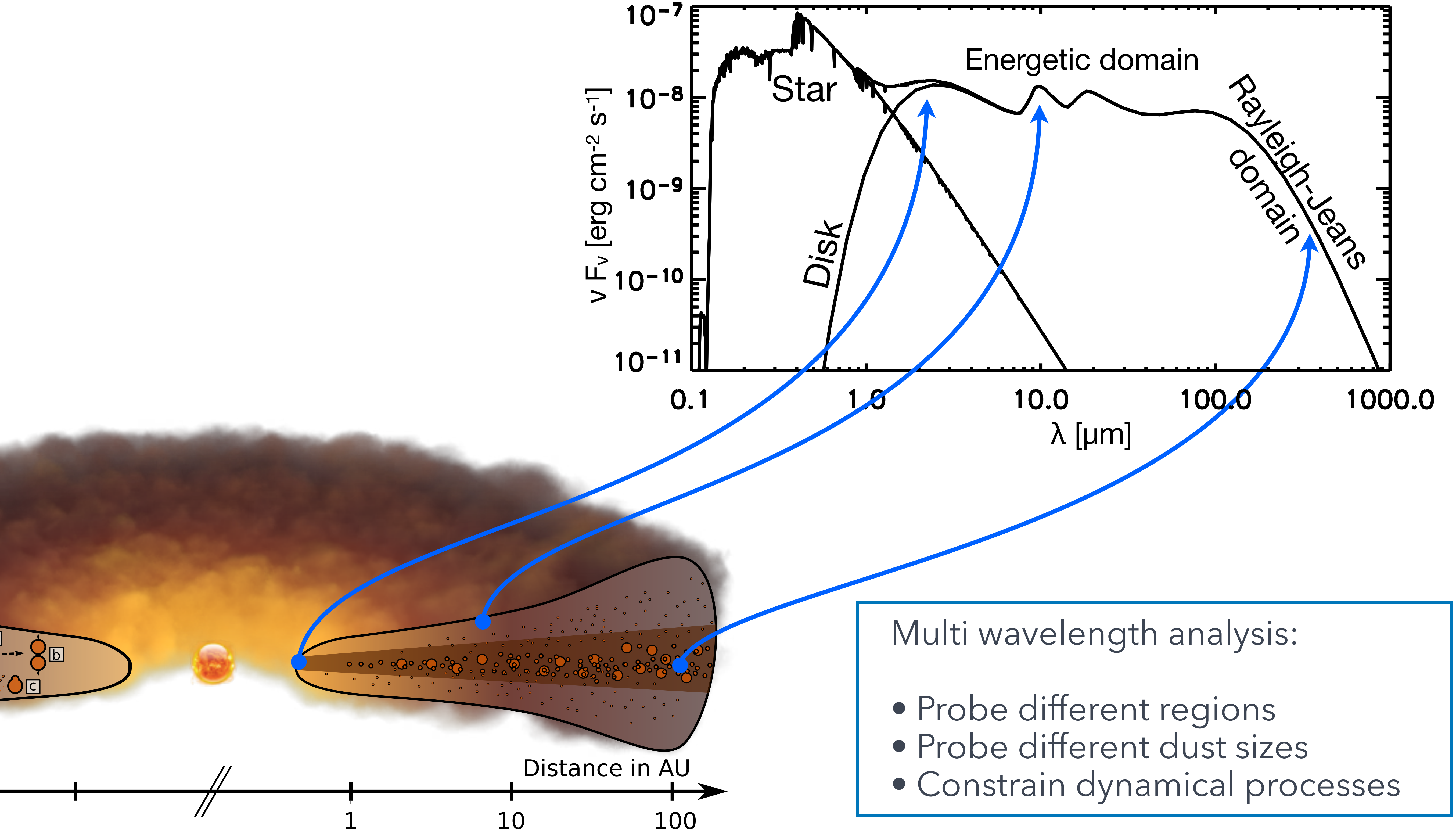
Dust observations





Birnstiel et al. 2018

Dust observations

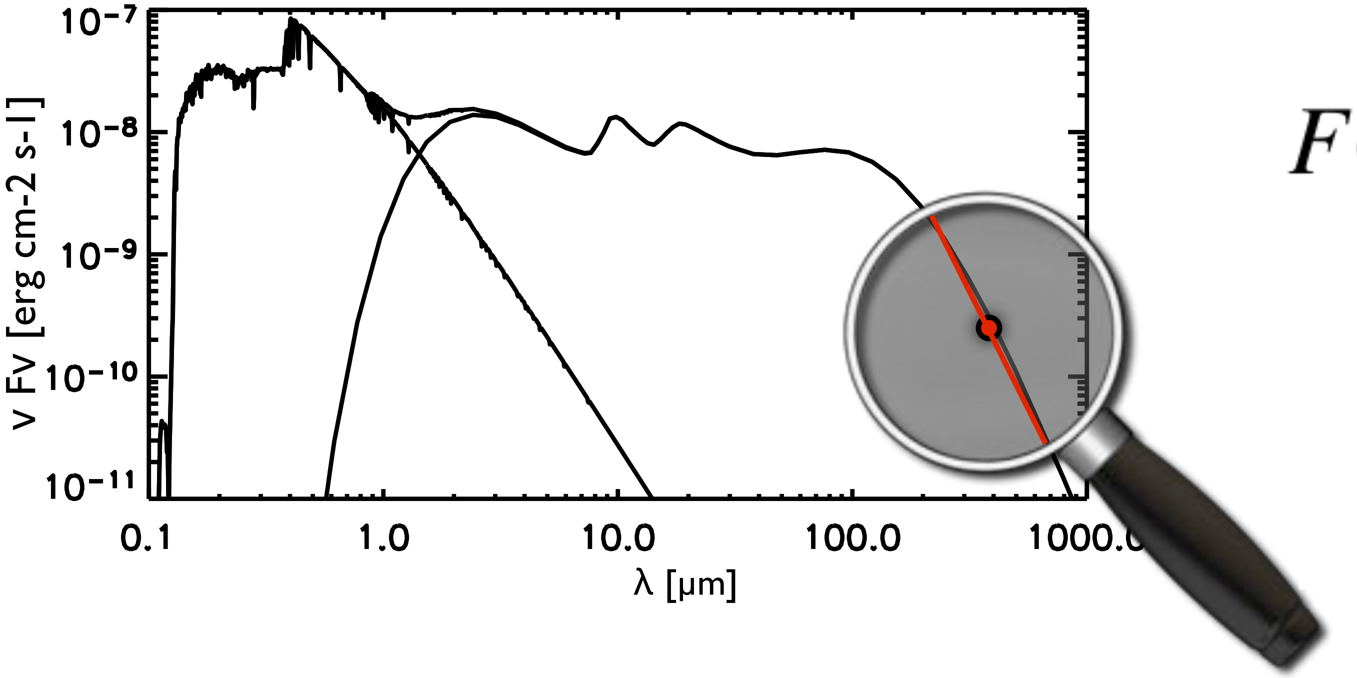


©Dullemond

Multi wavelength analysis:

- Probe different regions
- Probe different dust sizes
- Constrain dynamical processes

Evidence for grain growth



In the optically *thin* regime

$$F(\nu) \propto M_{\rm dust} \cdot B_\nu(T) \cdot \kappa(\nu)$$

$$\kappa(\nu) \propto \nu^{\beta}$$ → **Maximum dust size**

$$B_\nu \propto \nu^{2}$$

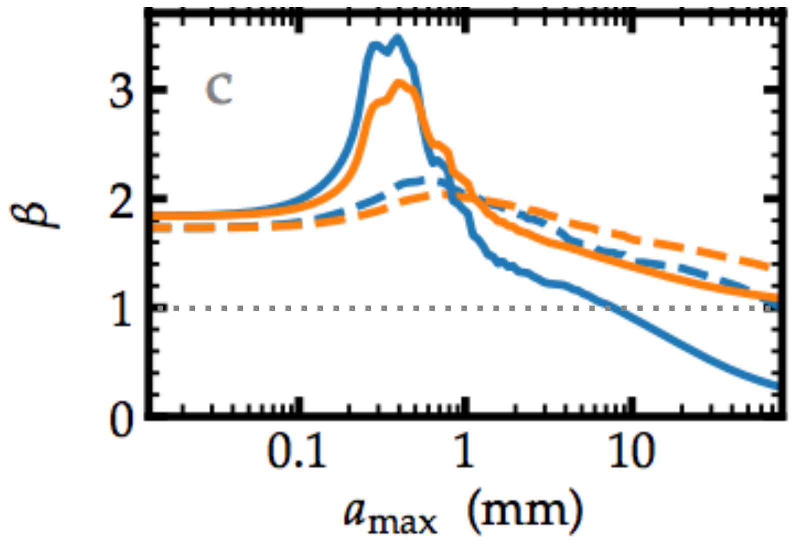
If β <1 (or α<3) :
large dust grains

$$F(\nu) \propto M_{\rm dust} \cdot \nu^{2+\beta}$$

$$\propto M_{\rm dust} \cdot \nu^{\alpha}$$

→ **Maximum dust size**

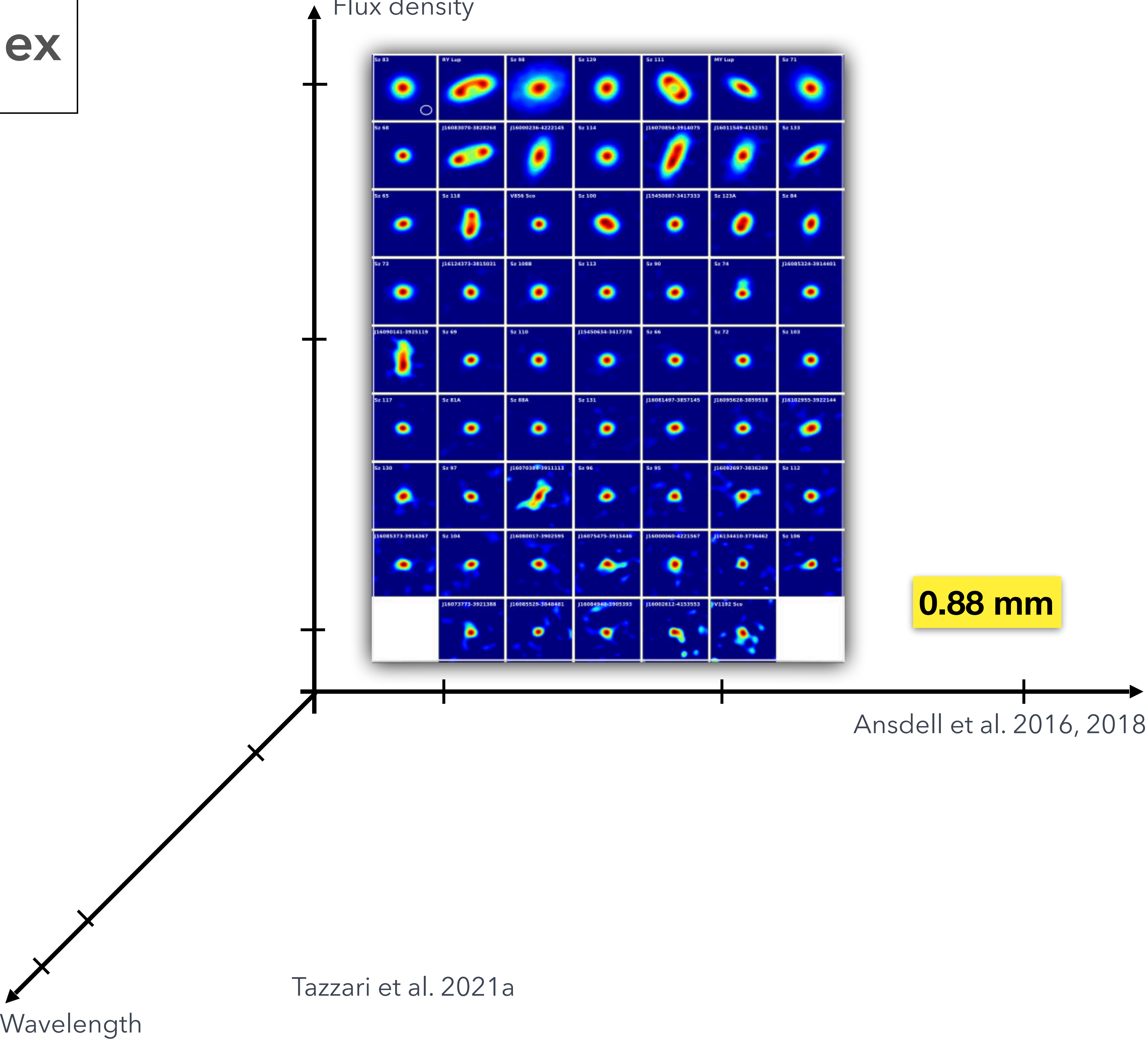
- Spectral slope gives a_{max}
- A low spectral index could be due to high optical depth regions



Andrews et al. 2020

In the optically *thick* regime $F(\nu) \propto B_\nu(T) \cdot$ Disk Area

Spectral index



Ansdell et al. 2016, 2018

Tazzari et al. 2021a

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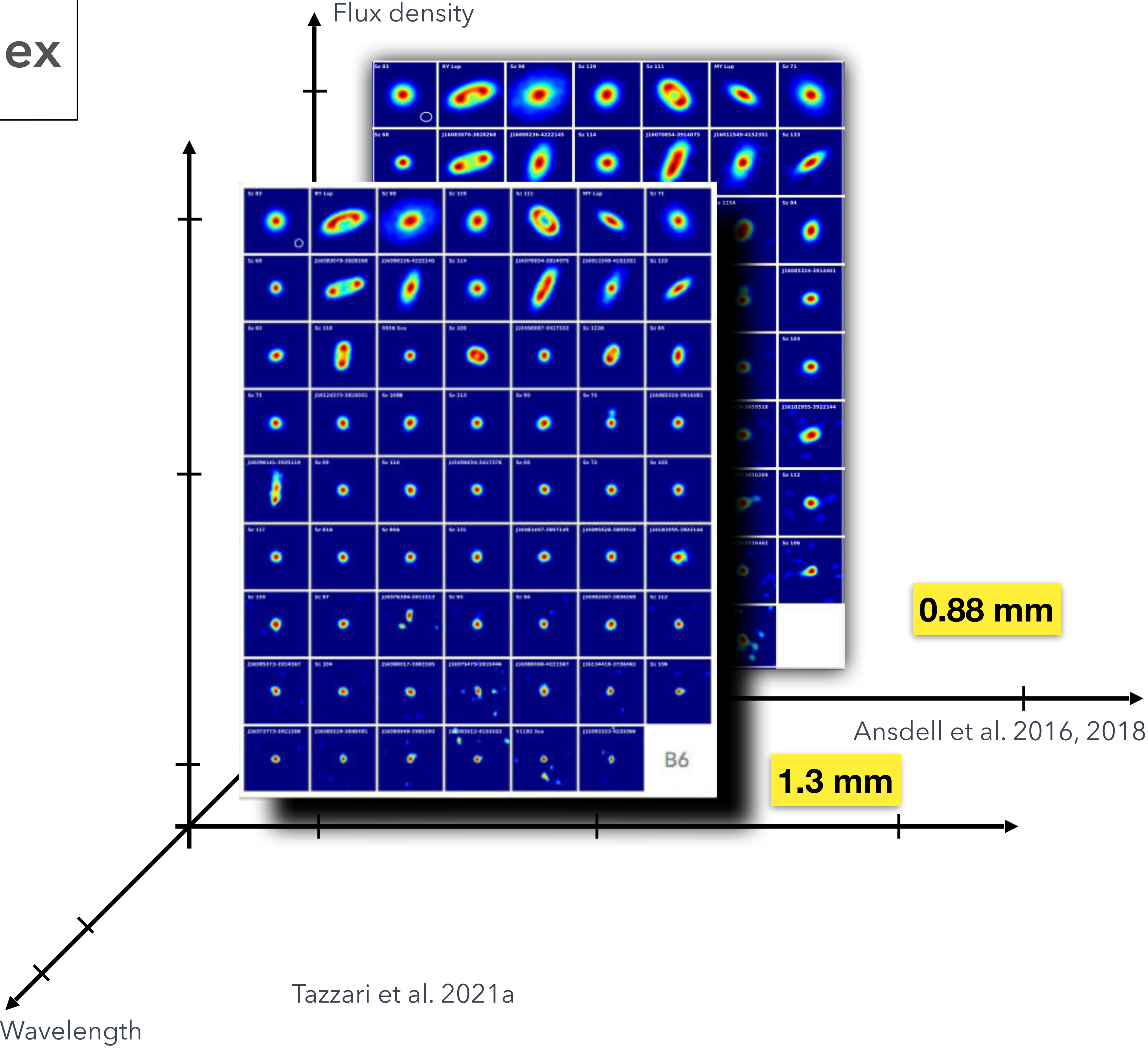
Spectral index



Ansdell et al. 2016, 2018

Tazzari et al. 2021a

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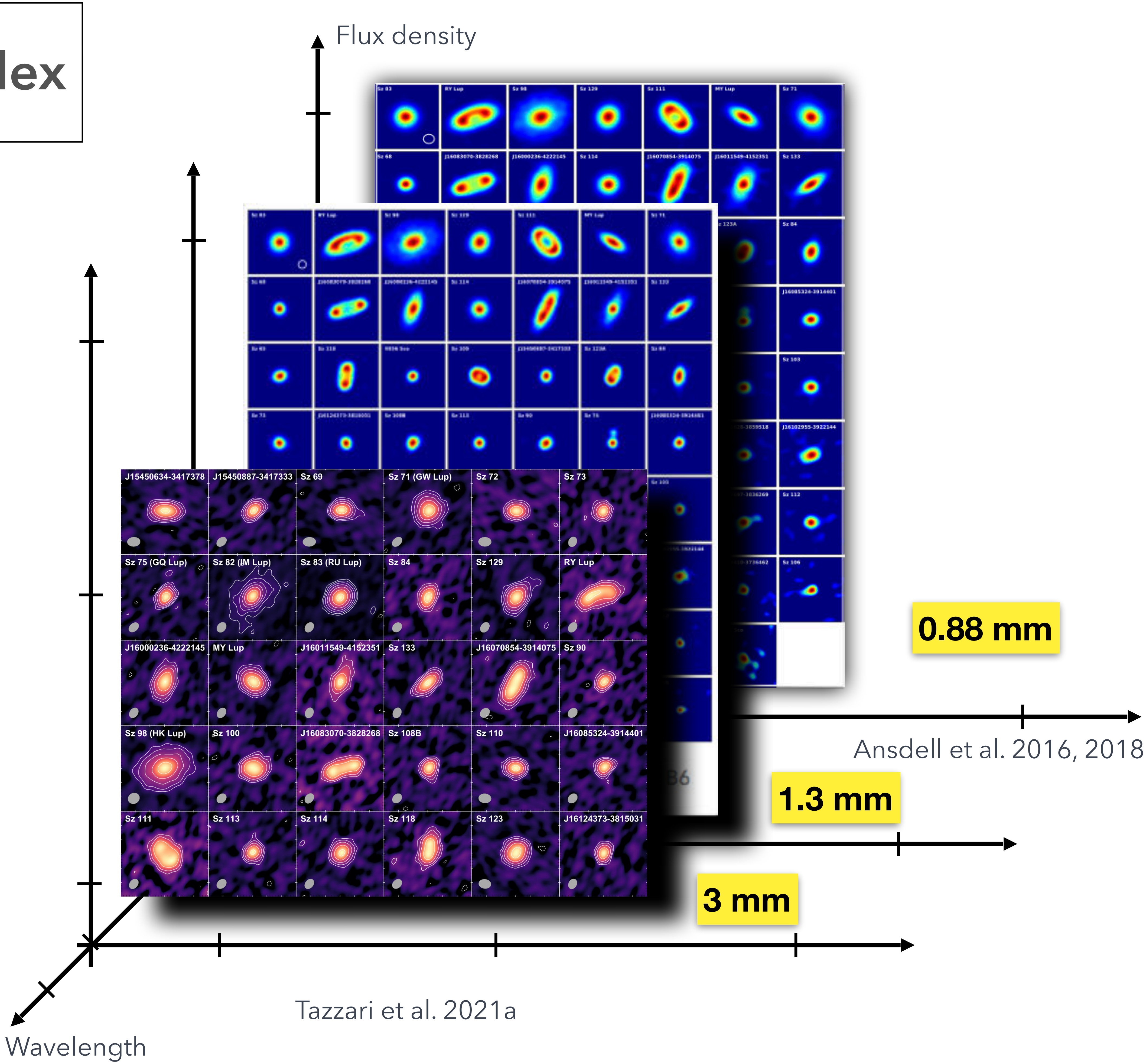
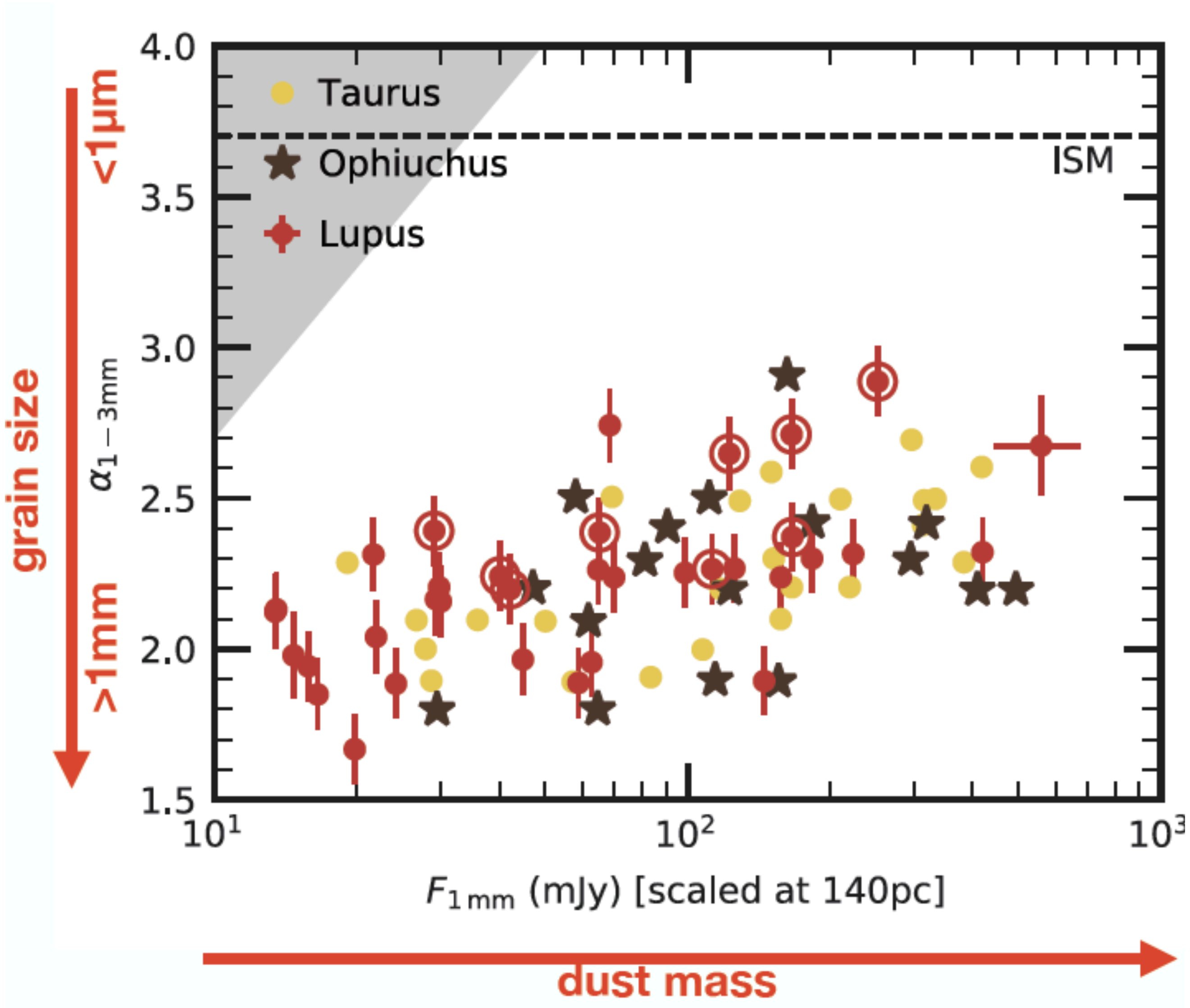
Spectral index

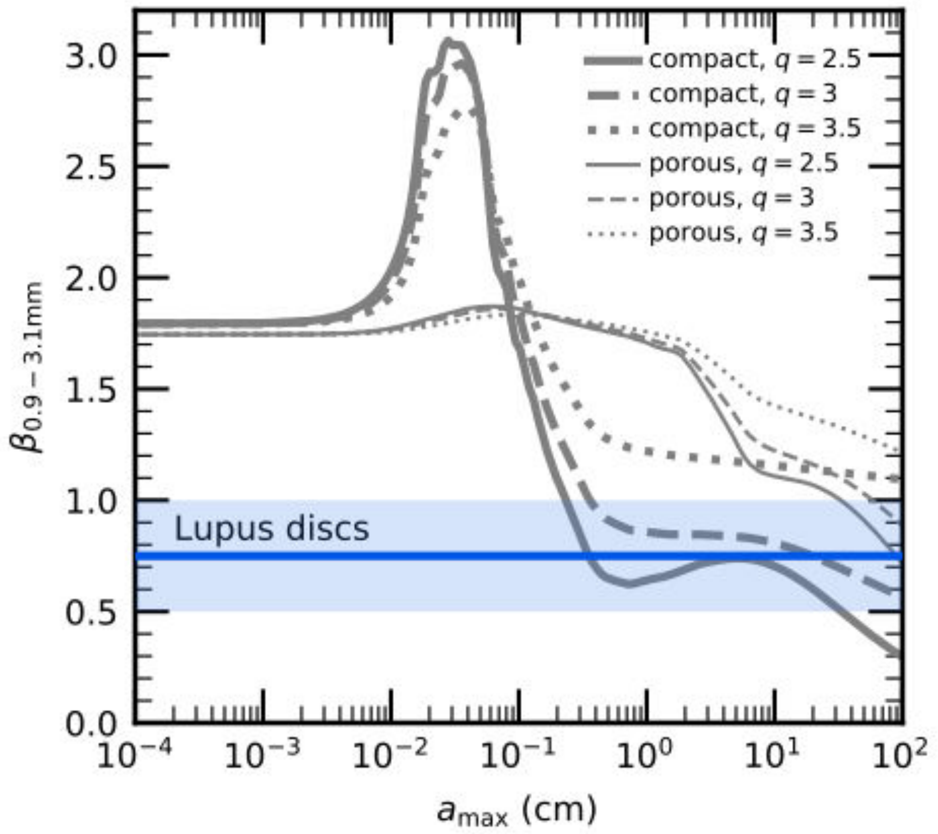


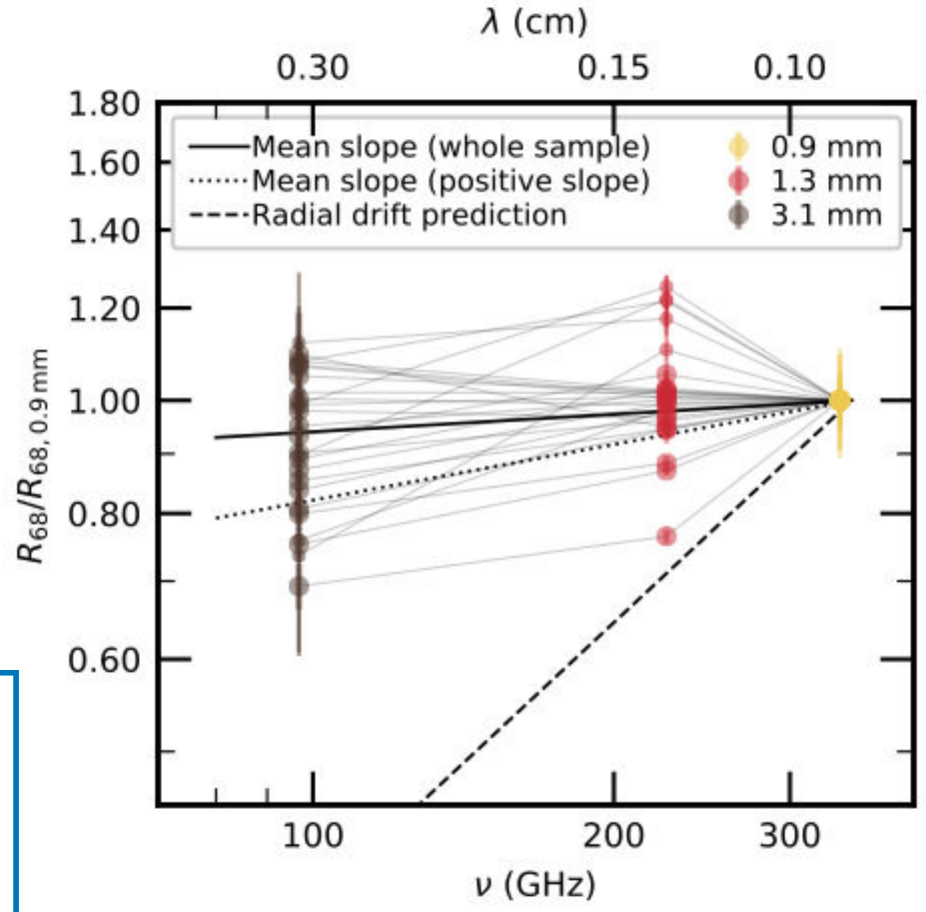
© Tazzari

Evidence for grain growth



Tazzari et al. 2021a

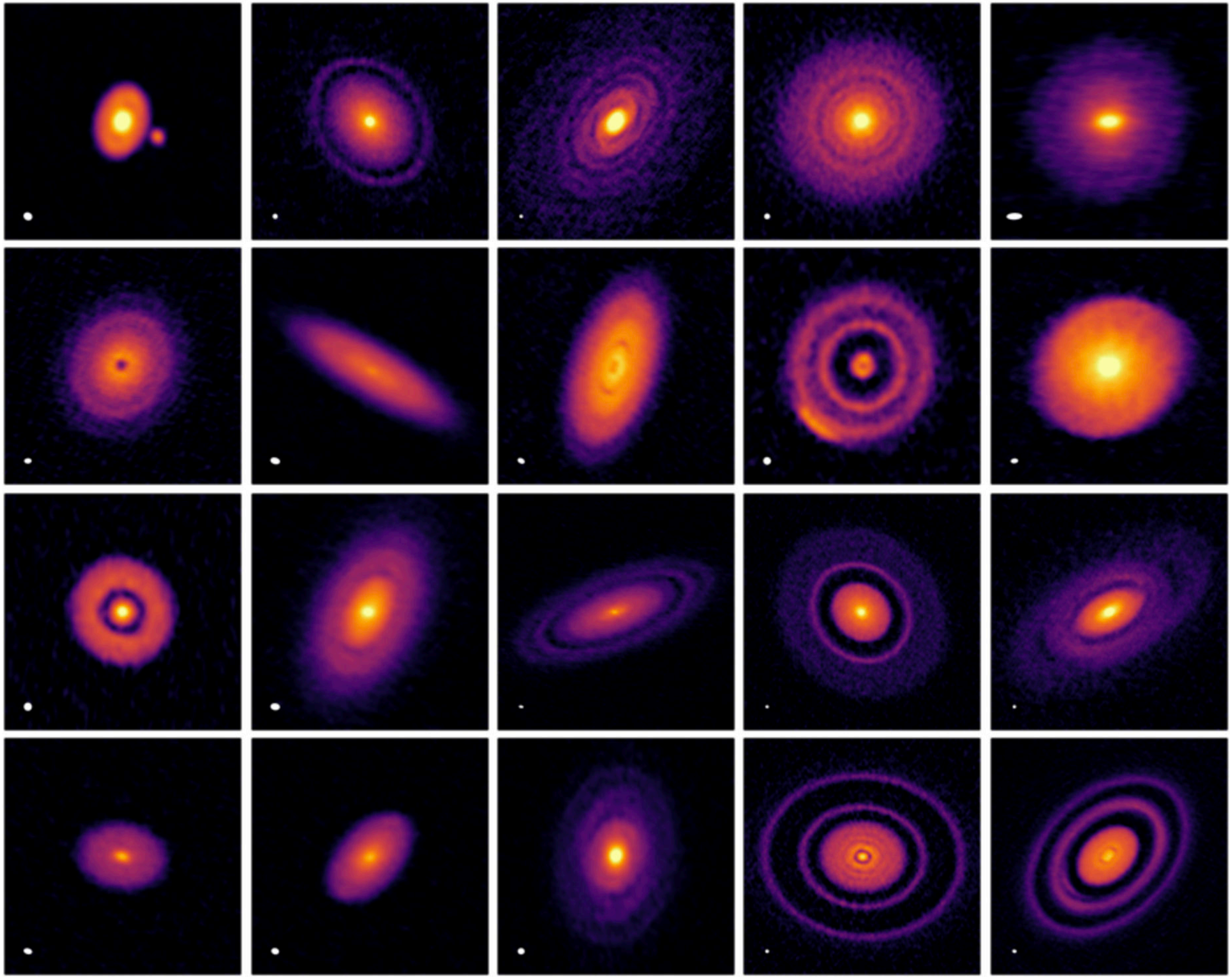




- Pebbles (mm) are found in disks
- Optically thin regions require grain growth
- Pebbles survive the fast inward drift and fragmentation
- Require the presence of dust traps

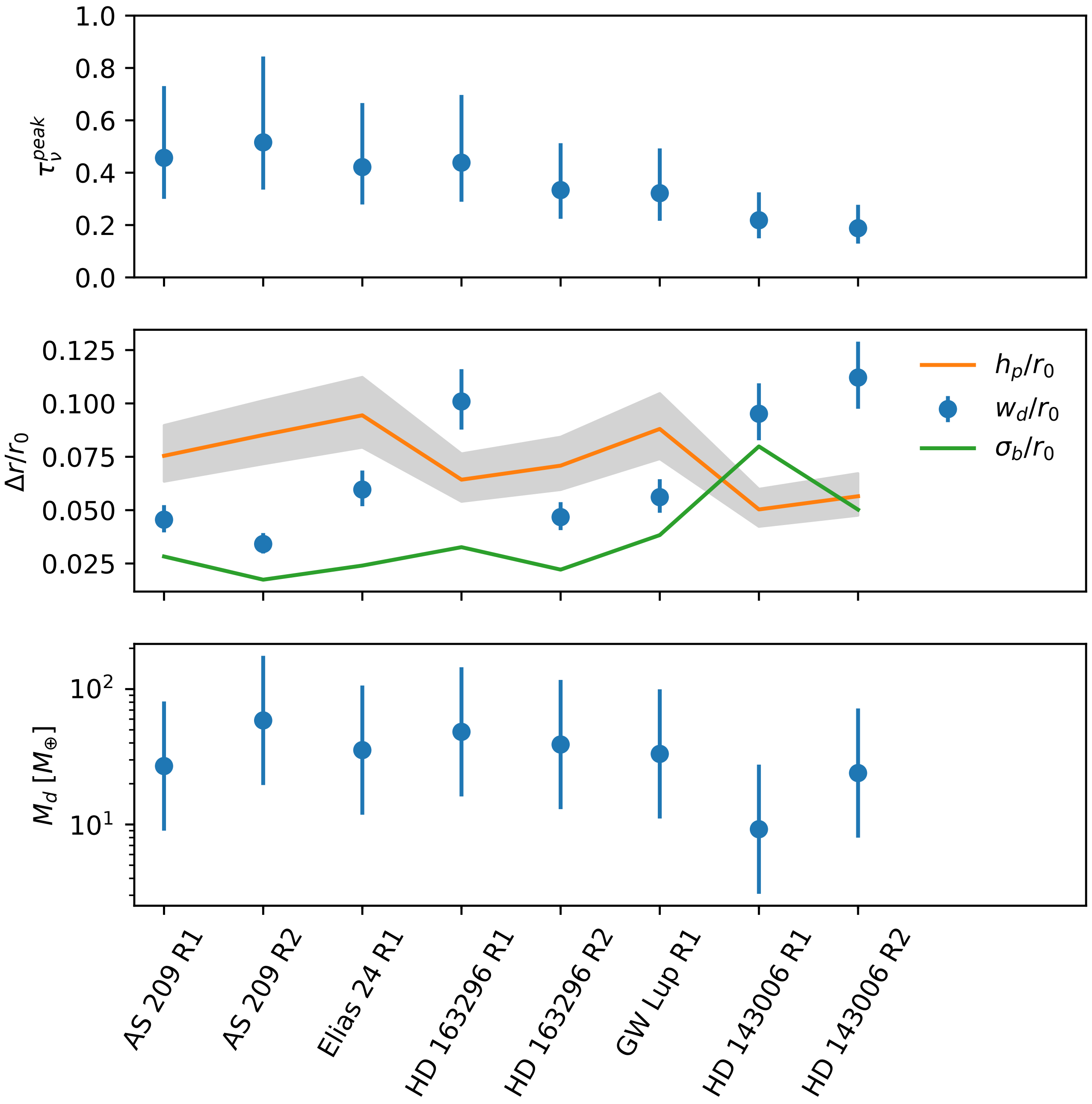
Tazzari et al. 2021b

Substructures in dust

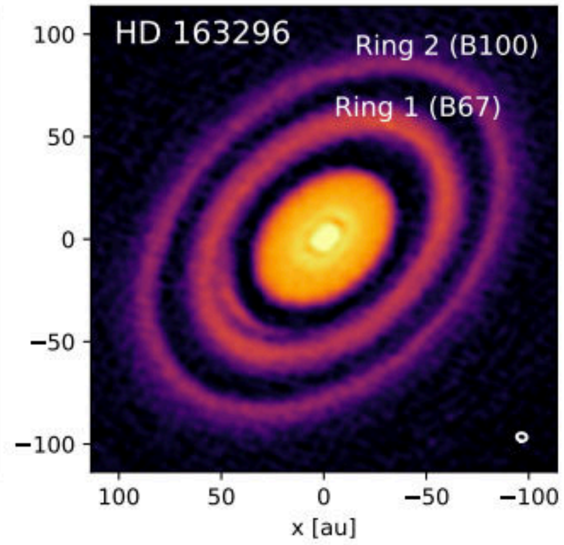


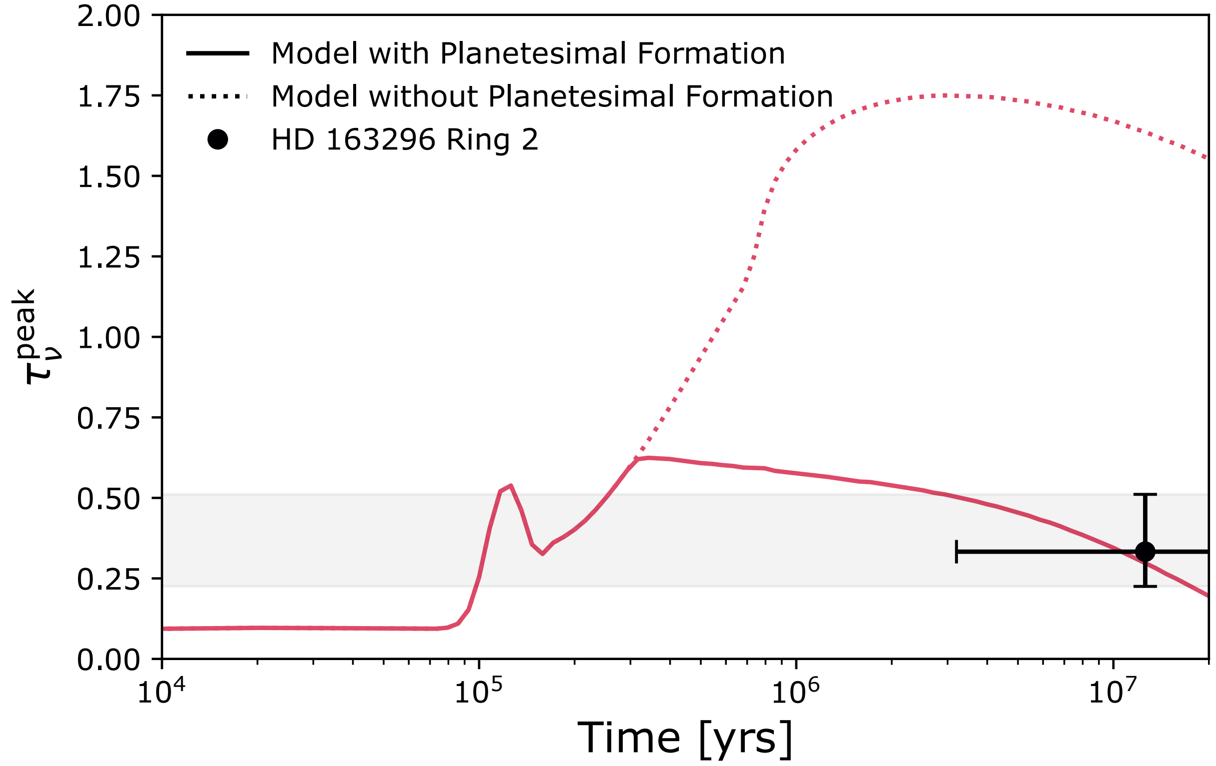
Andrews et al. 2018

Evidence for dust trapping



Dullemond et al. 2018

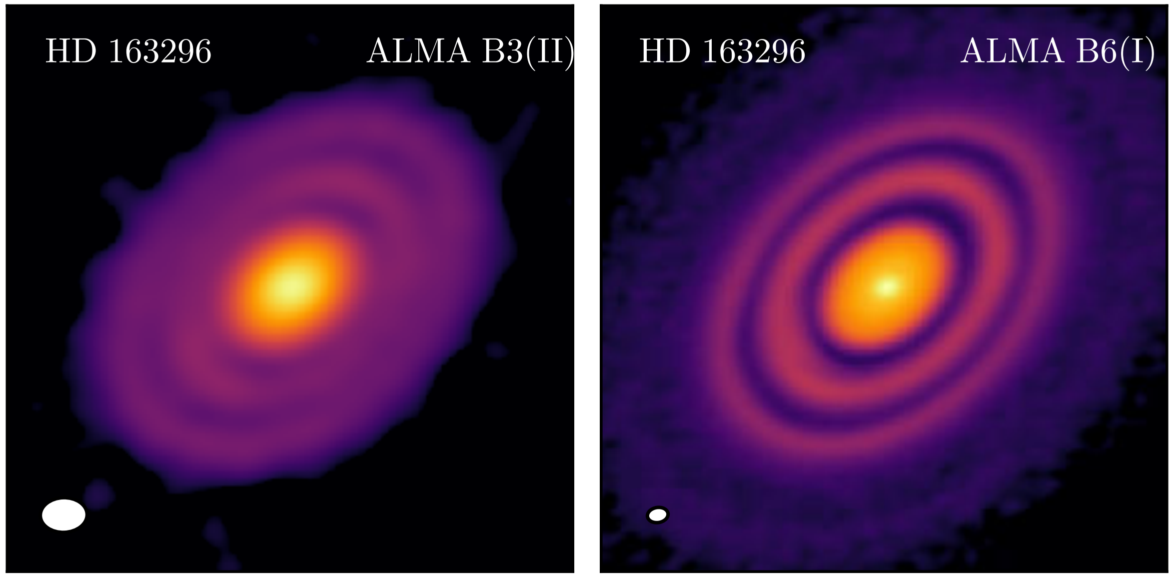




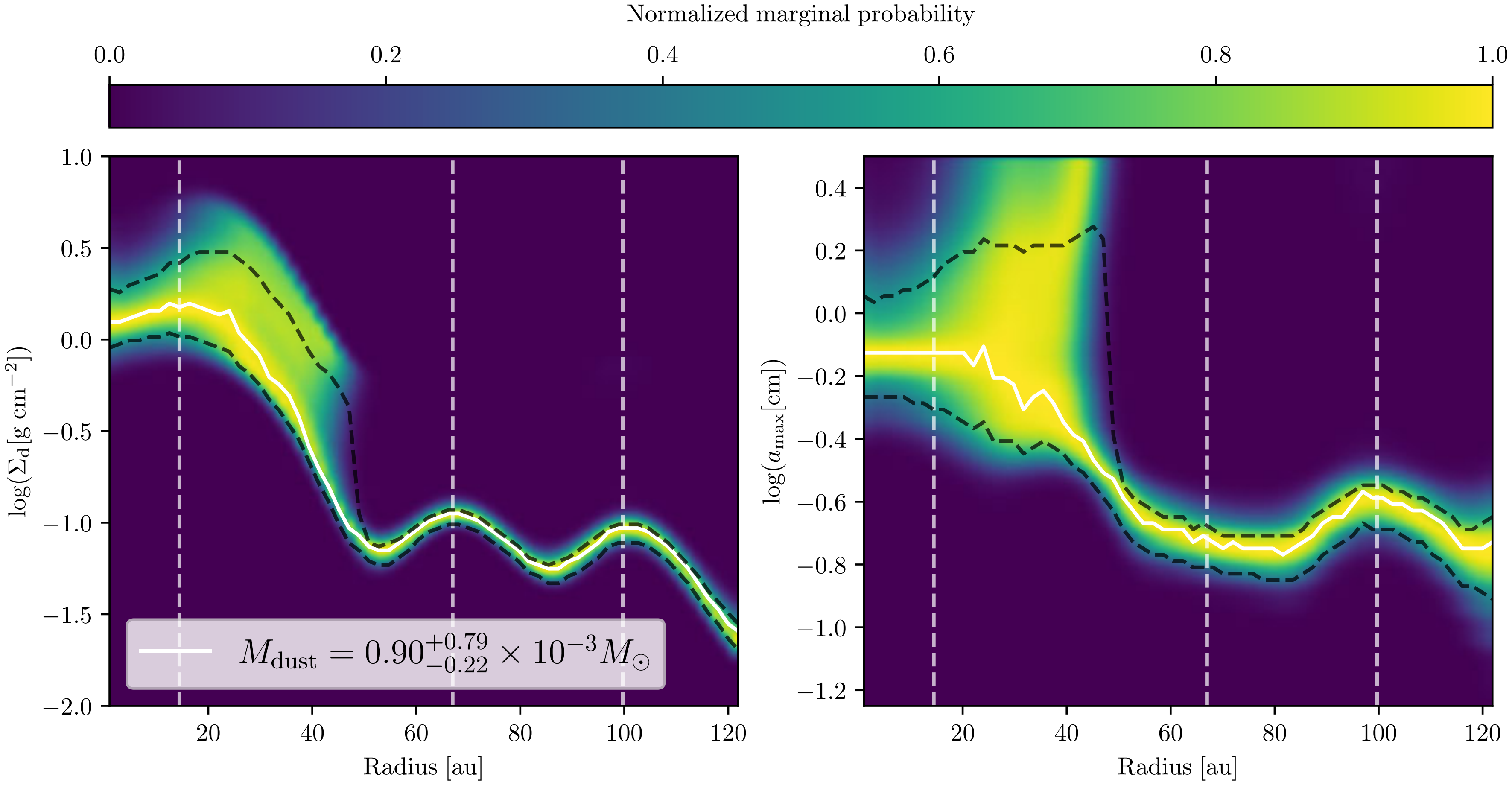
Stammler et al. 2019

- Rings properties consistent with dust trapping
- Almost constant optical depth possibly indicating planetesimal formation

Evidence for growth in dust traps



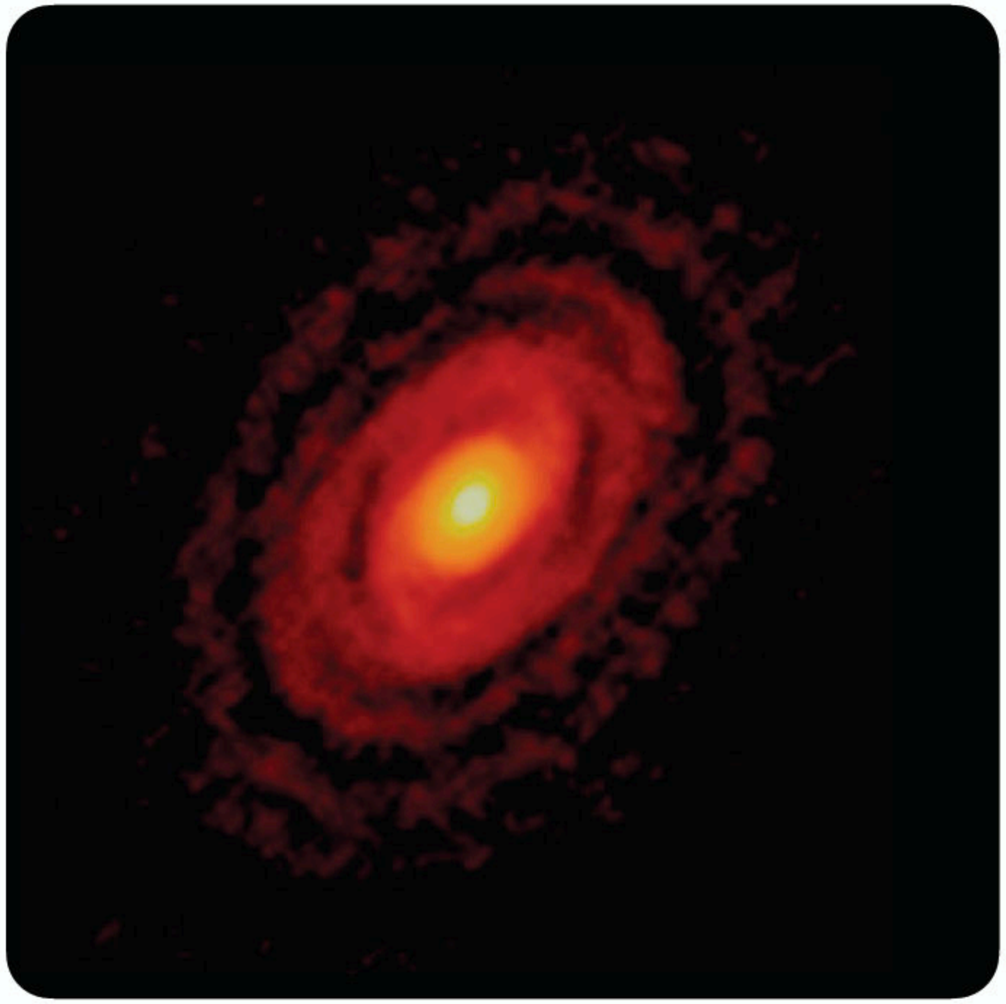
- Rings observed at various wavelengths
- Dust surface density and a_{max} constrained
- Traffic jam and dust traps can be identified



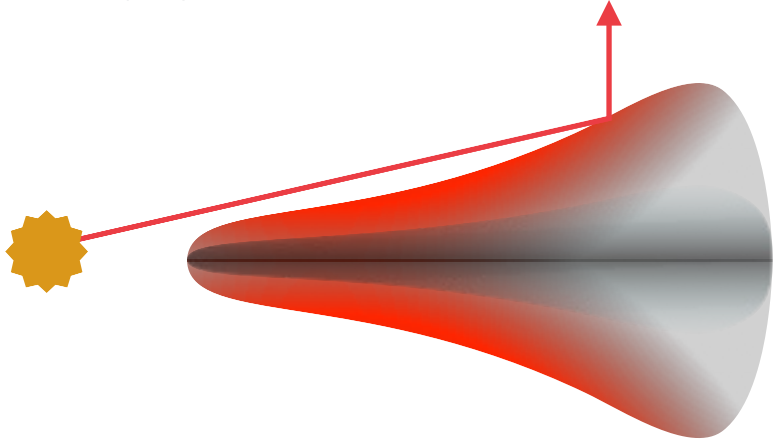
Sierra et al. 2021

Dust dynamics

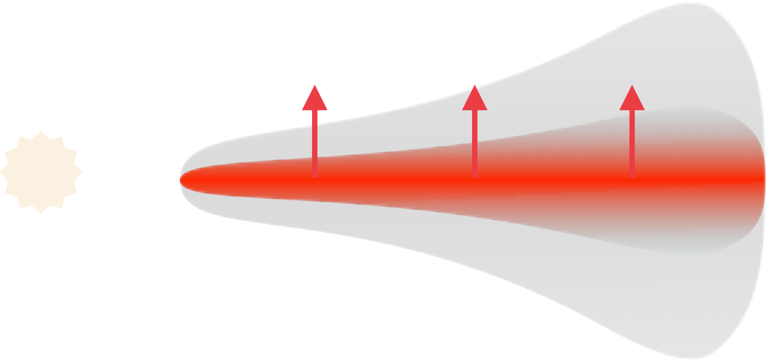
Avenhaus et al. 2018



Andrews et al. 2018

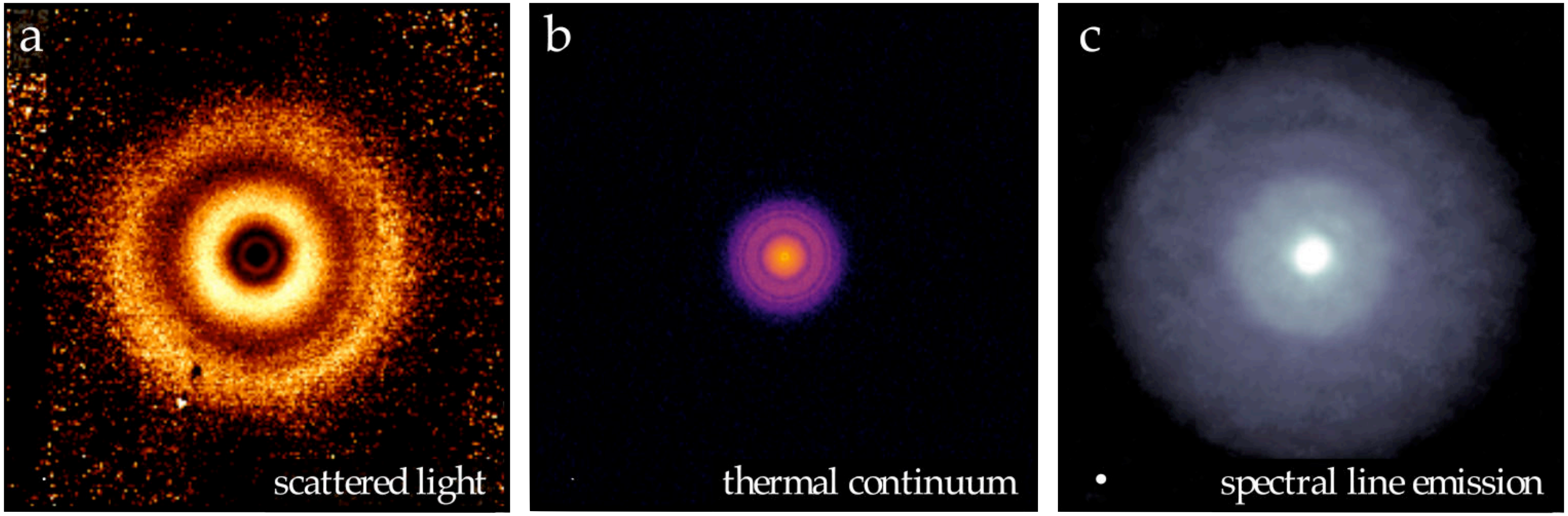


Scattered light

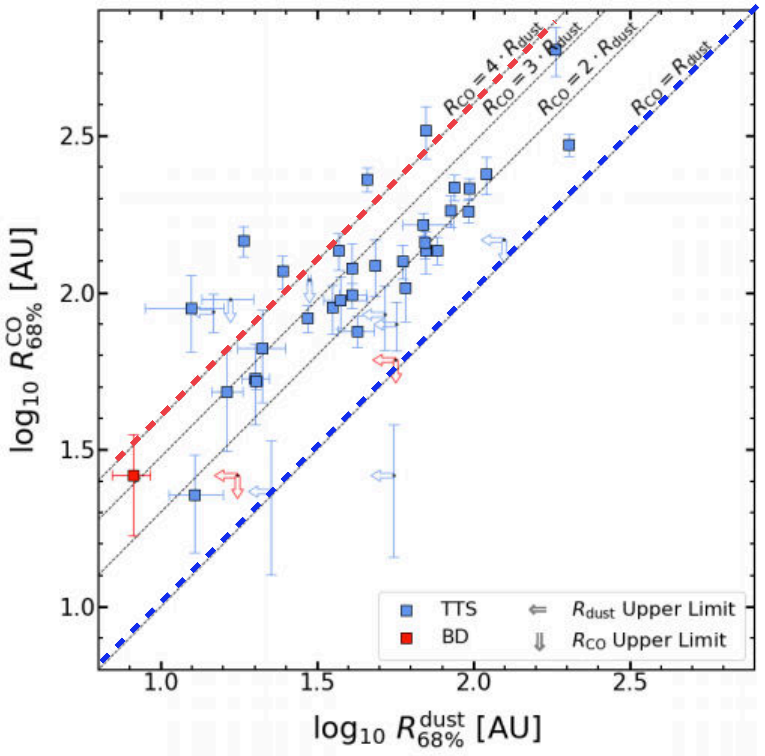


Sub-millimeter continuum

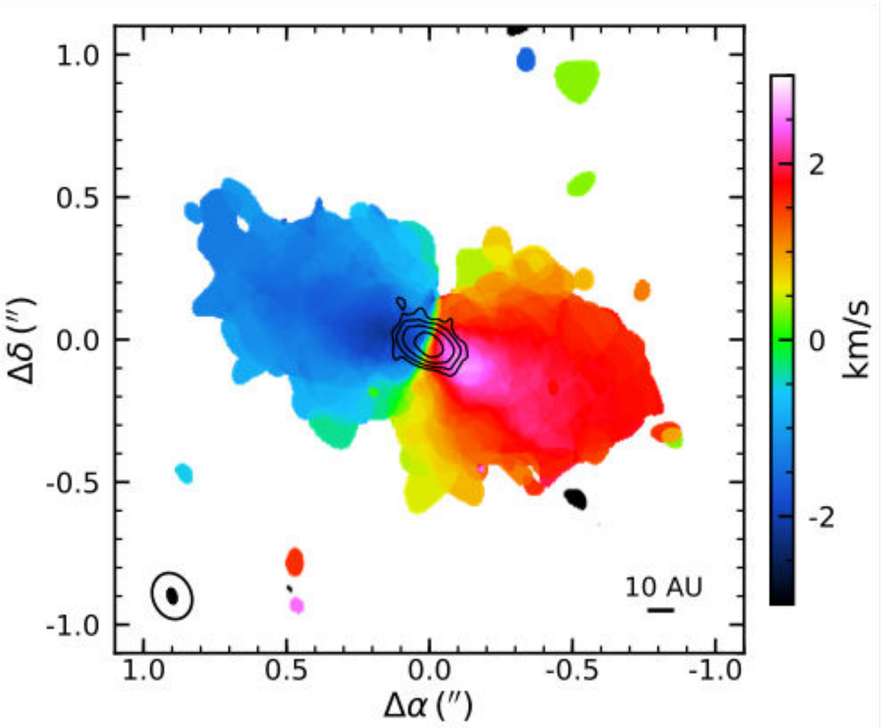
Dust radial drift



Andrews et al. 2020



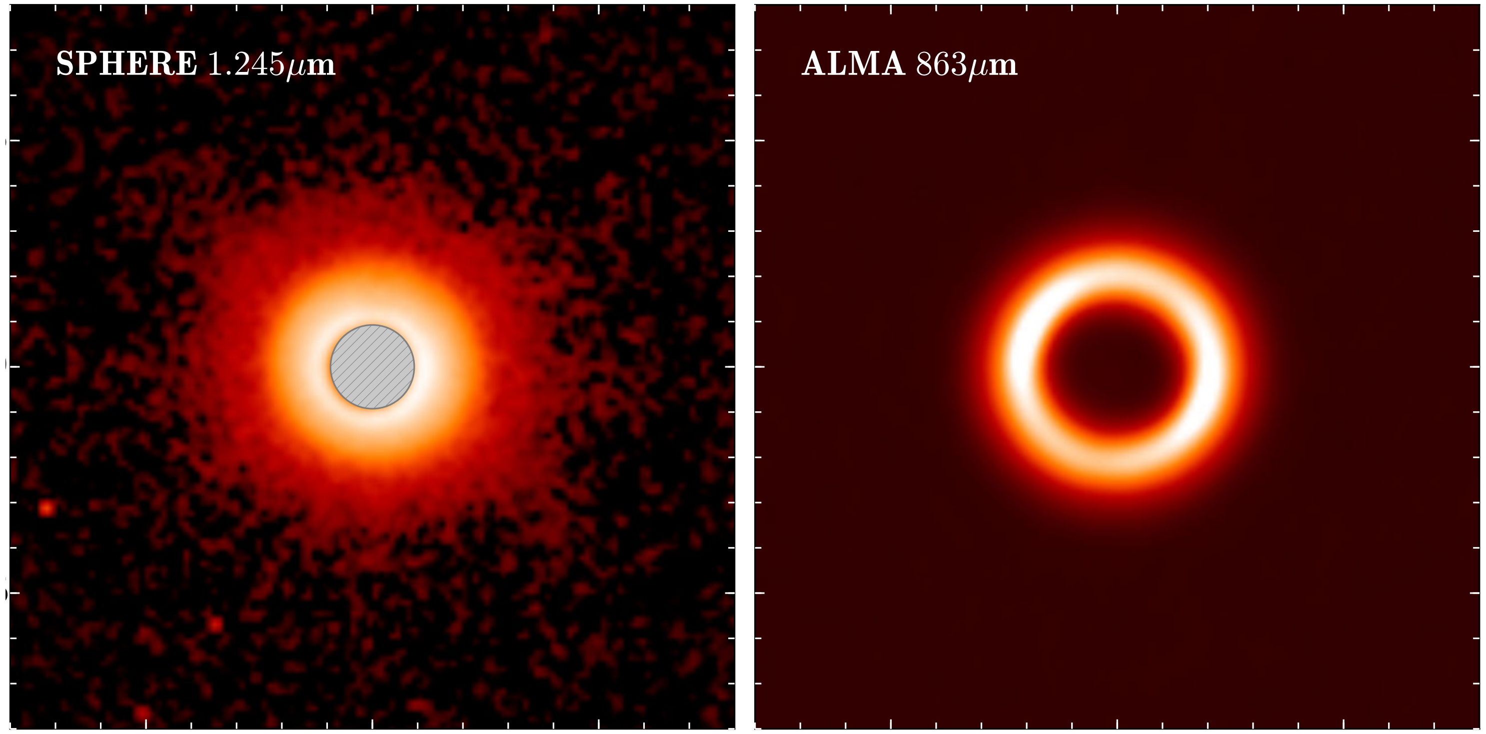
Sanchis et al. 2021



Facchini et al. 2019

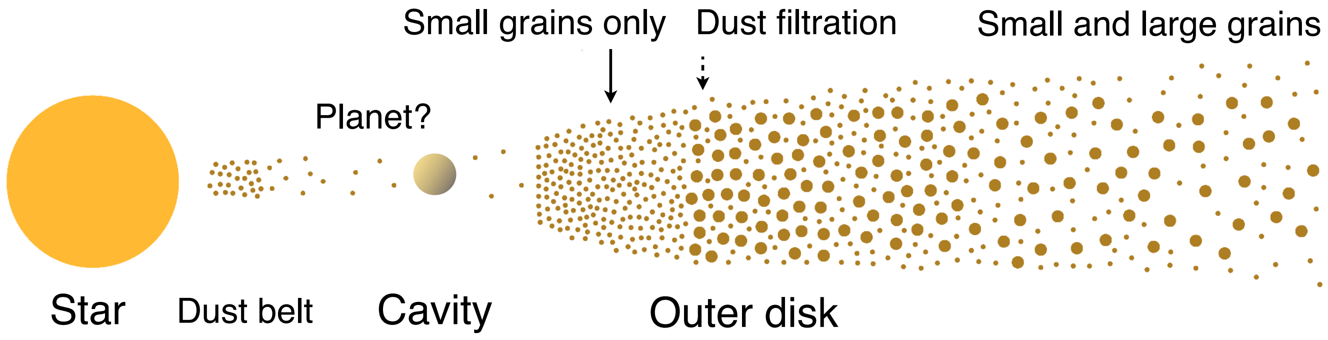
- Disk extents in CO and continuum indicate radial drift
- Require dust traps

Dust radial drift

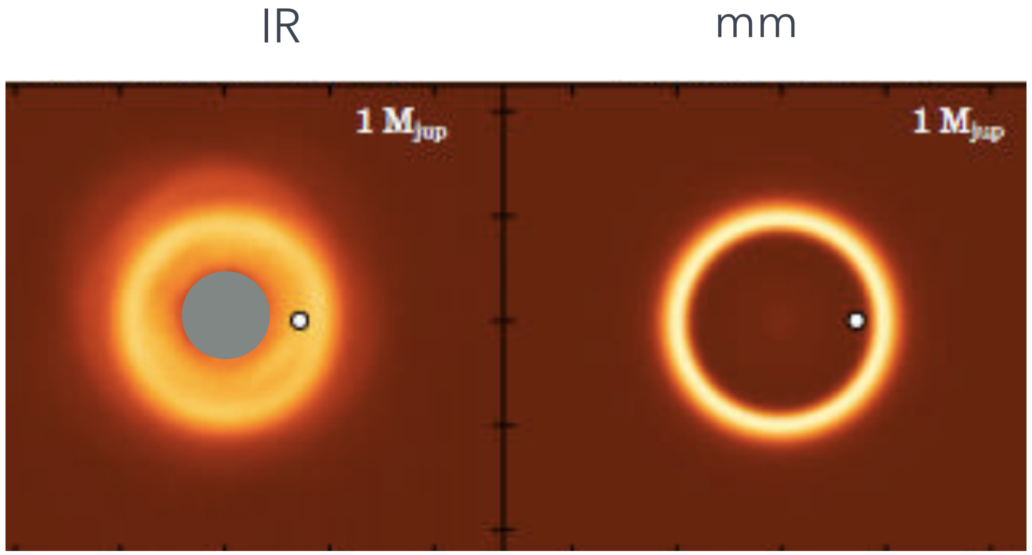


Kurtovic et al. in prep

- Most transition disks show small dust grains within their mm-cavities
- Can be used to constrain the pressure gradient

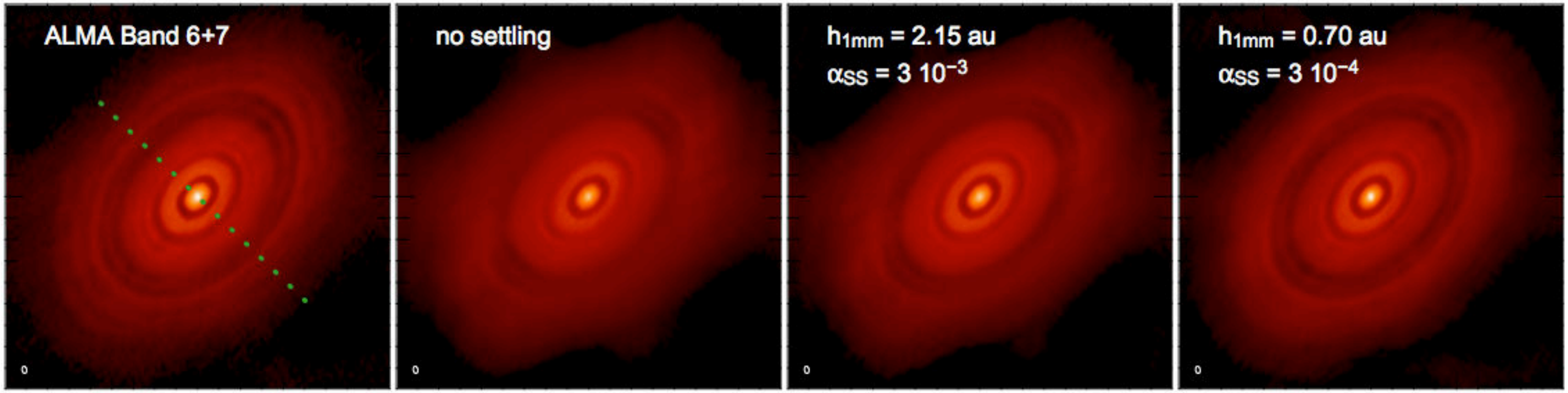


Garufi et al. 2016
Villenave et al. 2019

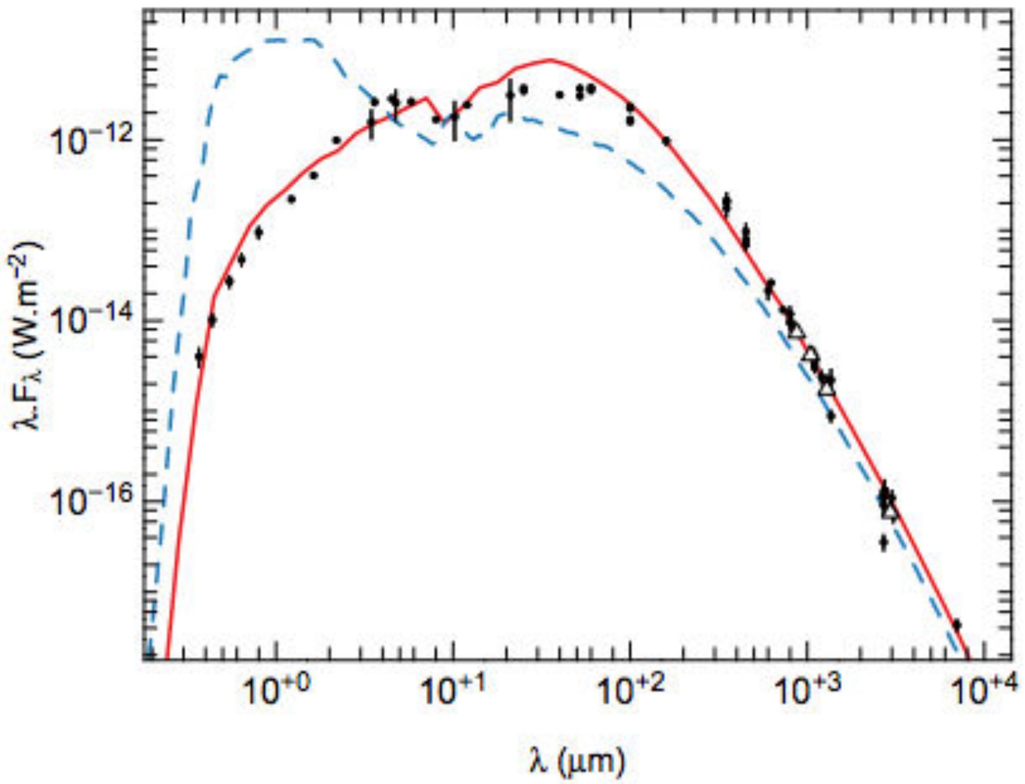


De Juan Ovelar et al. 2013

Dust vertical settling

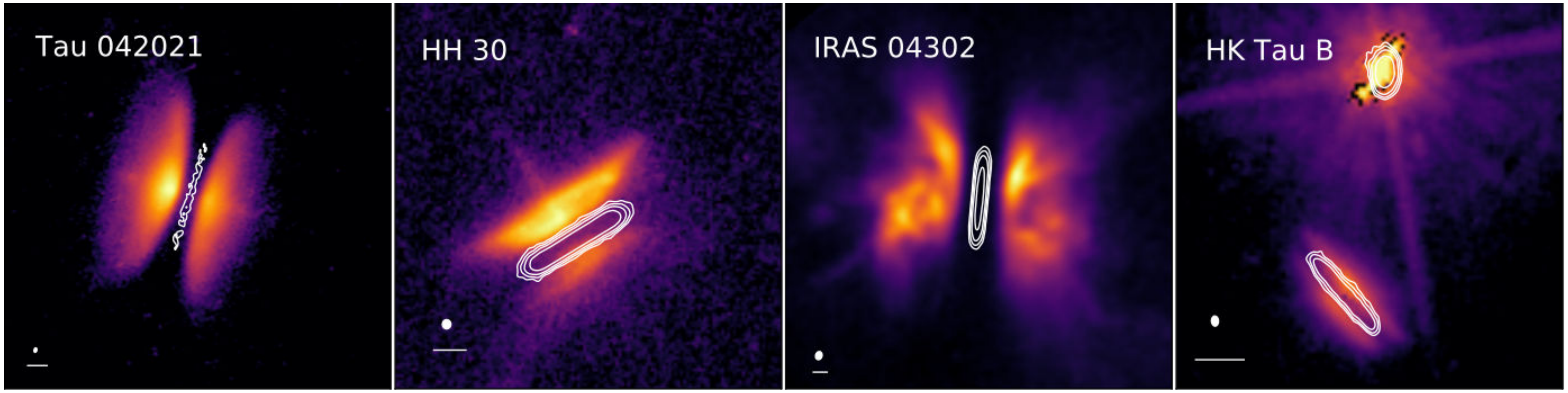


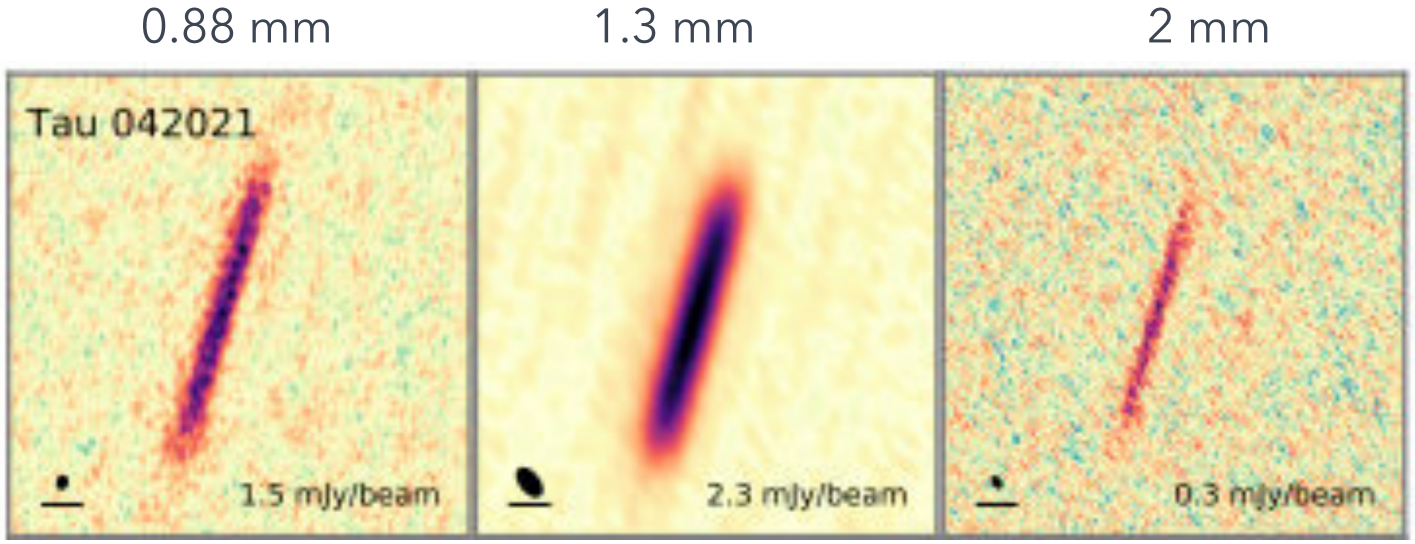
- Symmetric gap widths indicate a geometrically thin, settled, disk
- SED requires small dust grains at high altitudes



Pinte et al. 2018

Dust vertical settling





Villenave et al. 2020

- Effective size-selective vertical settling
- Dust height ~ 1 au at 100 au
- Constrain low turbulence parameter

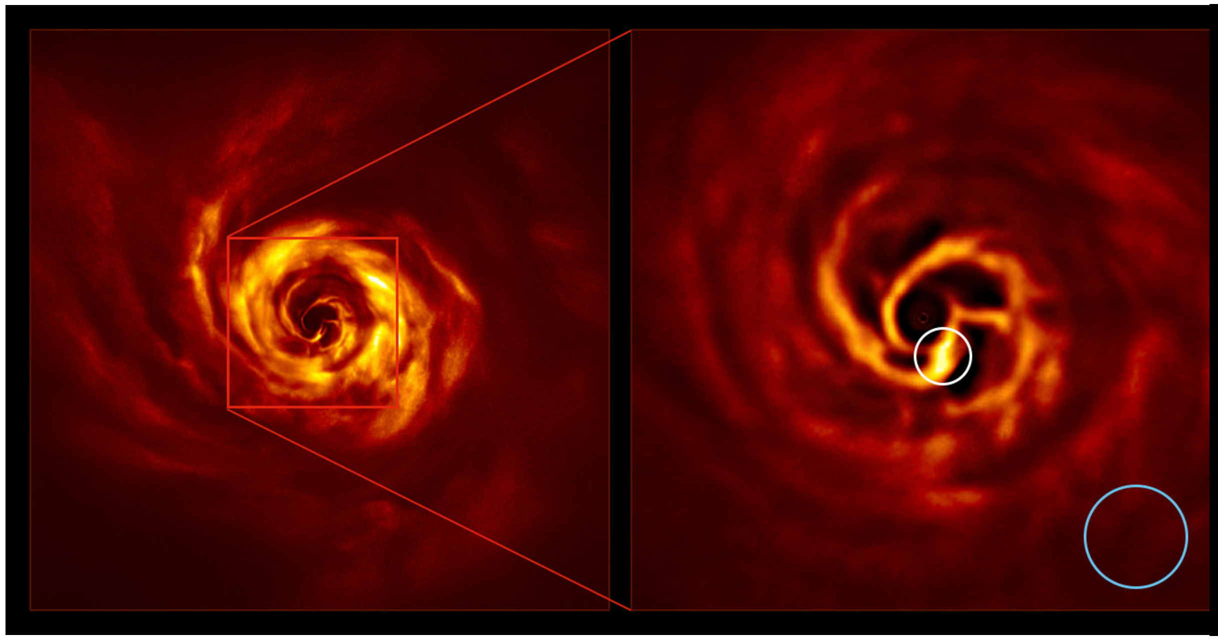
Conclusions

- ***What works?***
  - Dust grains grow and drift to regions of high pressure
  - Pressure bumps are dust traps where grains grow

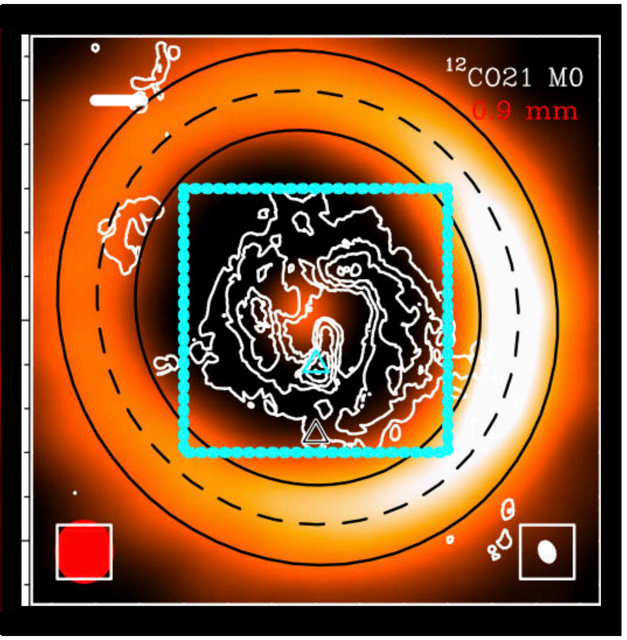
- ***What is missing?***
  - Direct observations of planetesimals in disks is not possible
  - Dust grain sizes are still challenging to measure
  - Porosity is poorly understood
  - Connecting dust growth observed at various stages
  - A global modelling of multiple dust tracers

Coherent understanding on disk evolution

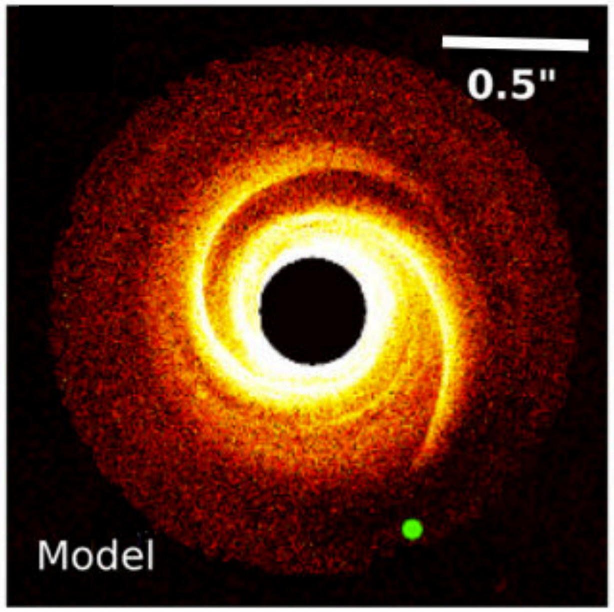
Dust grains of different sizes provide complementary tracers to understand the dynamical processes affecting the disk evolution.



Boccaletti et al. 2020

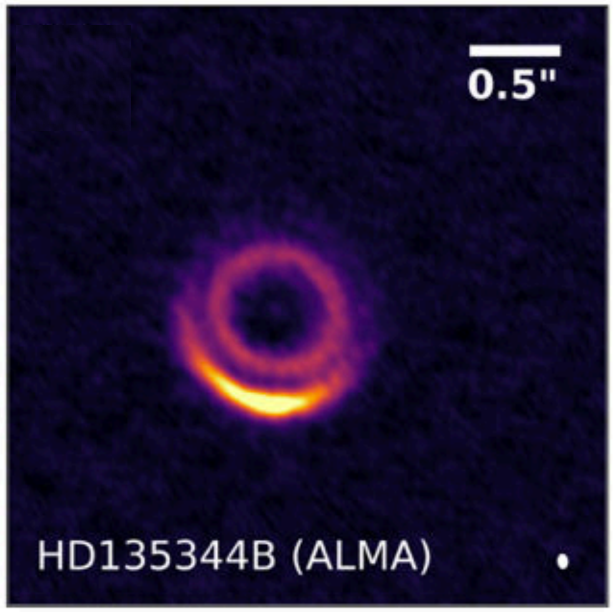


Tang et al. 2017



Dong et al. 2016

Stolker et al. 2016



Cazzoletti et al. 2018