Dust evolution in protoplanetary discs and the formation of planetesimals

What have we learned from laboratory experiments?

Outline

- From dust to planetesimals
- A collision model of protoplanetary dust
- Pathways to planetesimals

What are we dealing with?

- Protoplanetary dust:
  - Aggregates consisting of $\sim\mu m$-grains
  - For this purpose mainly silicates
  - Behaviour of water-ice has also been researched, but to a far lesser degree
  - There is only very little data for other materials

What are we dealing with?

- Planetesimals
  - Solid object that is dominated by self-gravity
  - Size: $\gtrsim 1\ km$
  - Orbital dynamics not significantly impacted by gas drag

From dust to planetesimals

- $0.1 - 1\ \mu m \rightarrow 1 - 1000\ km$
- Gravitational accretion impossible for bodys smaller than planetesimals
- Radial drift between dust and gas

From dust to planetesimals

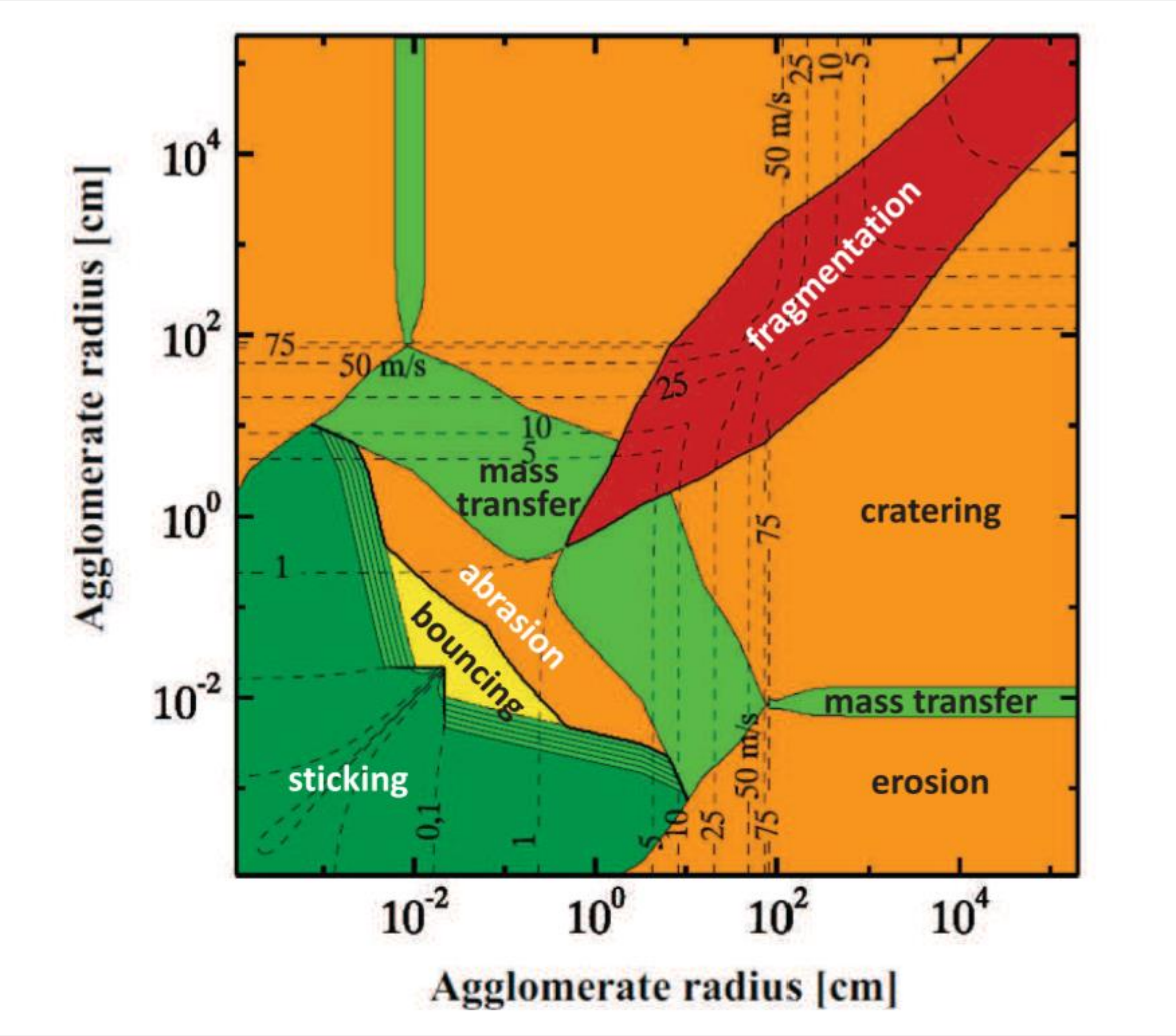
- Gas rotates sub-Keplerian $\Delta v \approx \frac{c^2}{v_K}$, but is pressure-supported
- Small dust aggregates are coupled to the gas → dust drifts inward
- Radial drift velocity increases with increasing aggregate size

From dust to planetesimals

- Aggregates larger than $\sim 1m$ are not coupled to the gas
- Travel at Keplerian speed
- Headwind leads to inward drift
- Radial drift velocity decreases with increasing aggregate size

A collision model of protoplanetary dust

Outcomes of laboratory experiments


Agglomerate radius [cm]
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Agglomerate radius [cm]
fragmentation
mass transfer
cratering
abrasion
bouncing
mass transfer
erosion
sticking
75
50 m/s
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25
50 m/s
75
50 m/s
25
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1
25
75

Blum, 2018

Similarly sized collision partners Sticking

- Collision energy < Van-der-Waals binding energy → sticking occurs
- For higher energies the degree of inelasticity of the collision determines the outcome

Similarly sized collision partners
Sticking

- Three processes lead to complete transfer into one more massive aggregate:
  - Hit-and-stick (very small impact velocities)
  - Sticking with deformation / compaction
  - Deep penetration (size difference needed)

Similarly sized collision partners Bouncing

- Minimal energy dissipation
- Neither sticking nor disruption of colliding bodies
- Leads to gradual compaction of aggregates

Similarly sized collision partners Fragmentation

- High collision speed
- The higher the impact speed, the smaller the largest fragment in relation to the initial aggregate mass

Similarly sized collision partners
Abrasion

- cm-sized dust aggregates
- Low velocity ($\gtrsim 0.1 m s^{-1}$) collisions, too low to lead to fragmentation
- Weak efficiency
- ~ 1000 collisions to destroy particle completely

Small projectile hits large target
Mass transfer

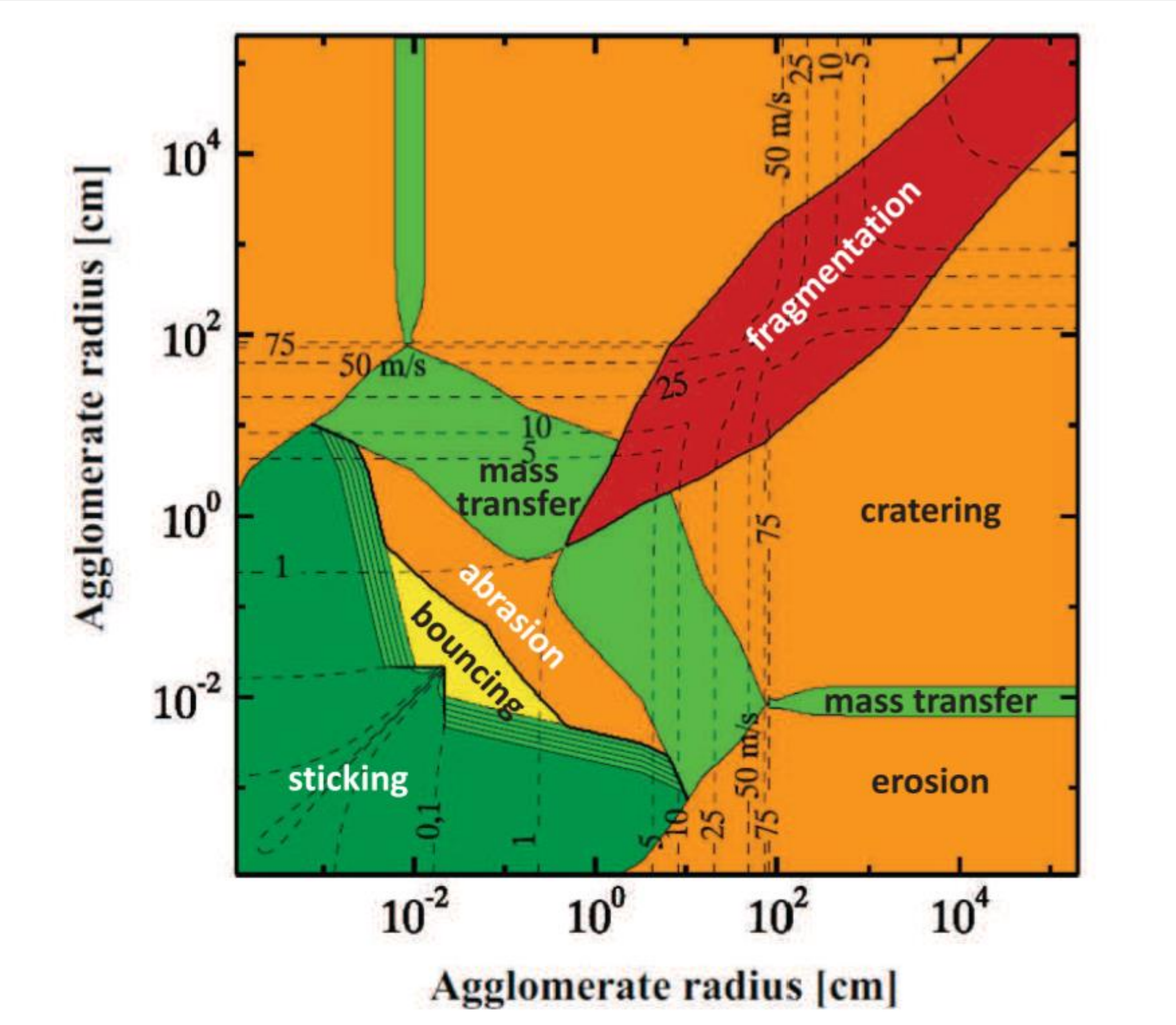
- Smaller aggregate fragments and transfers a part of its mass to the target aggregate
- Up to 50% of projectile mass gets transfered

Small projectile hits large target Cratering

- Same impact velocity range as mass transfer
- Larger projectile mass
- More mass gets excavated than transfered → Target loses mass
- Up to 35 times the projectile mass can be excavated

Small projectile hits large target Erosion

- Similar impact velocity as cratering
- Smaller projectile mass than for mass transfer
- Efficiency increases with increasing impact velocity and decreasing projectile mass


Agglomerate radius [cm]
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Blum, 2018

Pathways to planetesimals

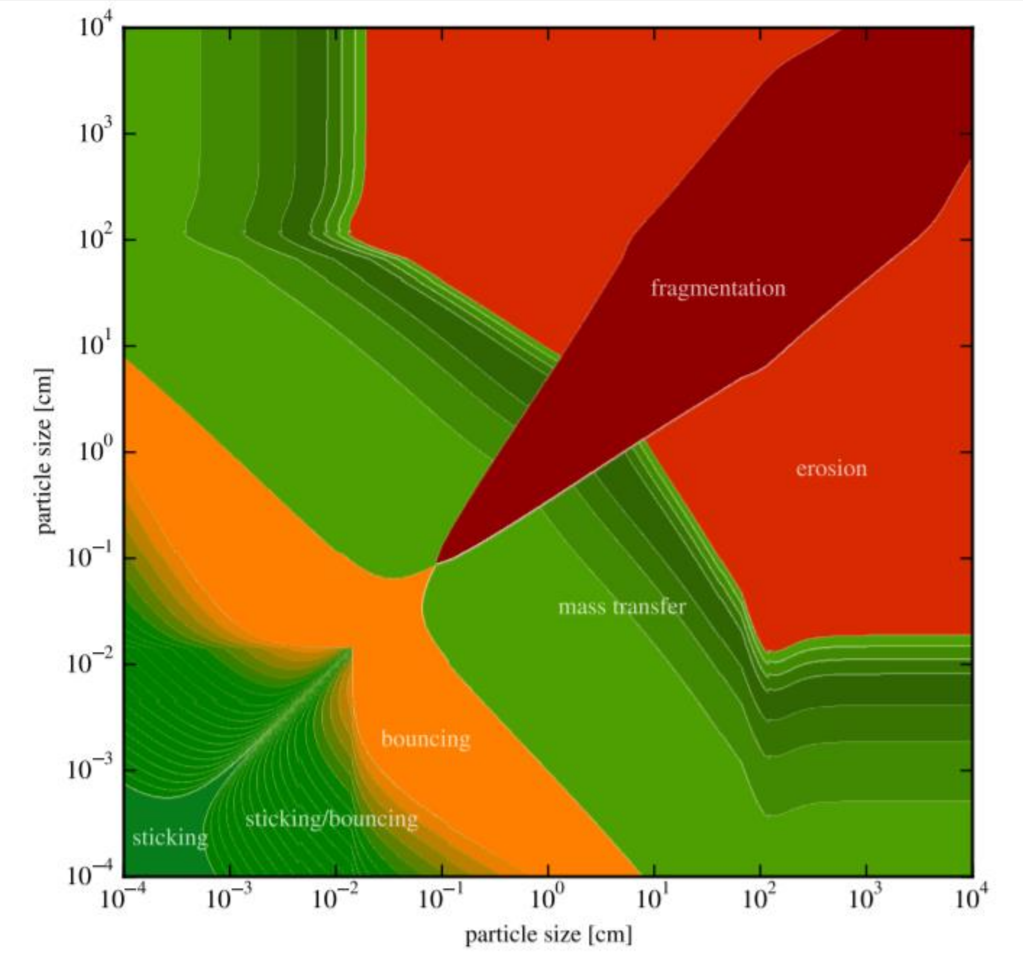
Planetesimal formation scenarios and insights from empirical evidence

Starting from protoplanetary dust, multiple scenarios explain planetesimal formation

- Two scenarios based on „pebbles“ (mm-cm dust aggregates):
  - Gravitational-collapse scenario
  - Mass-transfer scenario
- Additional scenario based on sub-µm water-ice monomers

Dust aggregates (mm-cm sized) called pebbles serve as basis for first two models

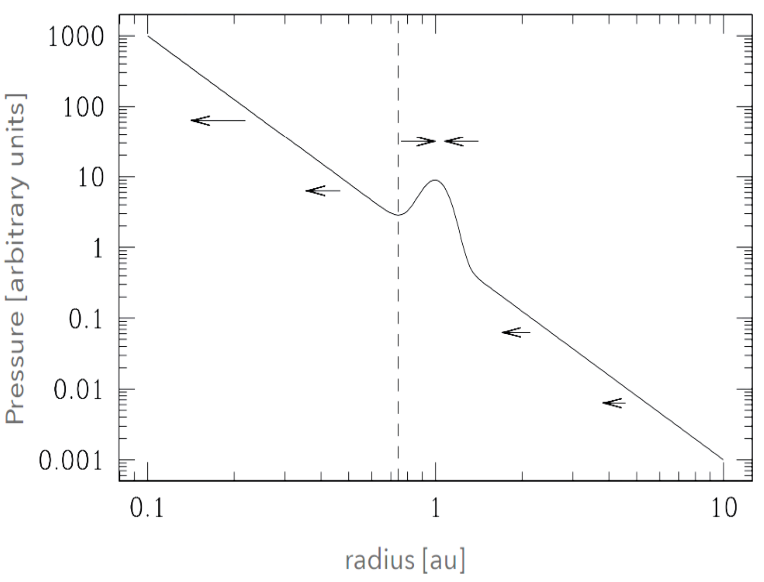
- Fractal growth, sticking and bouncing lead to compaction of siliceous materials into mm-cm-sized pebbles within 10^4 orbital time scales
- Further growth stopped at bouncing barrier
- Maximum size depends on: i) Protoplanetary disk model, ii) distance to star, iii) dust composition



Birnstiel et al., 2016

High pebble density for gravitational collapse can be achieved by pressure bumps, …

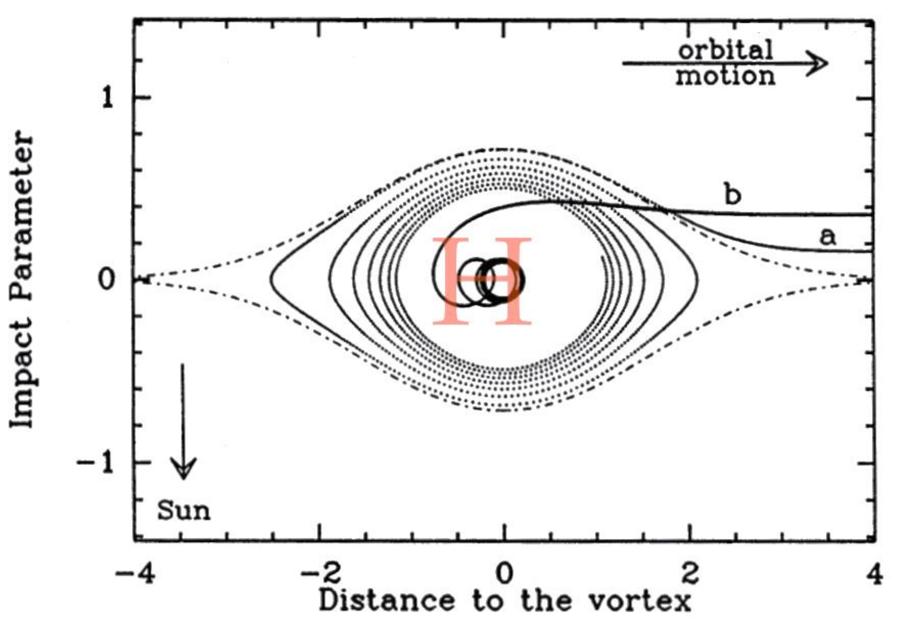
- Gravitational collapse scenario requires high spatial concentration of pebbles, e.g. by:
  - Pressure bumps: axisymmetric overpressure region prevailing in balance between pressure gradient and Coriolis force; surrounding zonal flow envelope is super-/sub-Keplerian on in-/ outside → dust migration to center of pressure bump
  - Downside: turbulence may lead to high collision speeds (ca. 10-100 m/s) between m-sized particles



Birnstiel, 2019

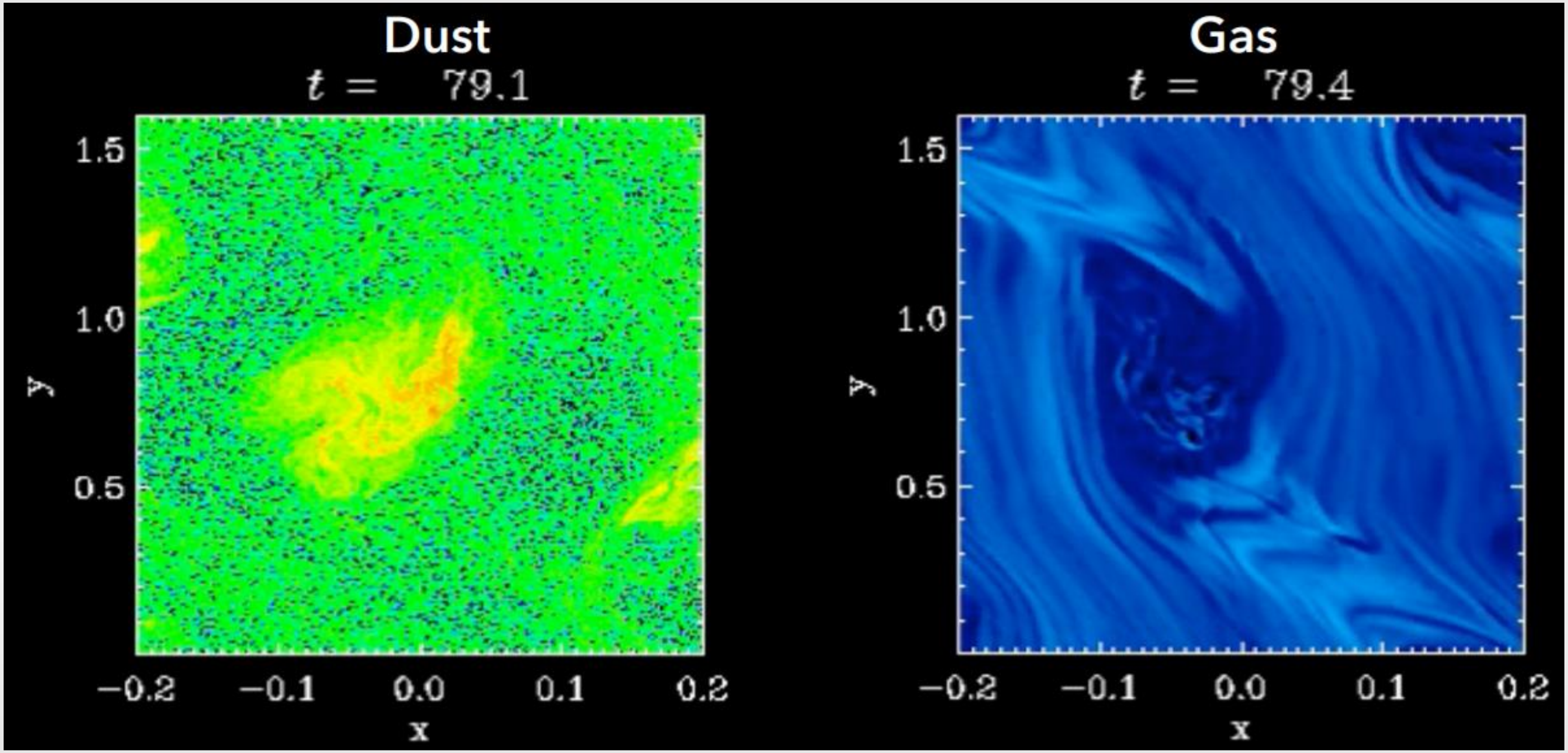
… high pressure vortices induced by flow instabilities …

- Vortex trapping: Formation by flow instability such as baroclinic instability (radial convection) → emergence of large-scale slowly turning
  vortices (high pressure) trapping dust particles
- Downside: Dust feedback destroys vortex flow for dust-to-gas ratio > 1



Barge & Sommeria, 1995

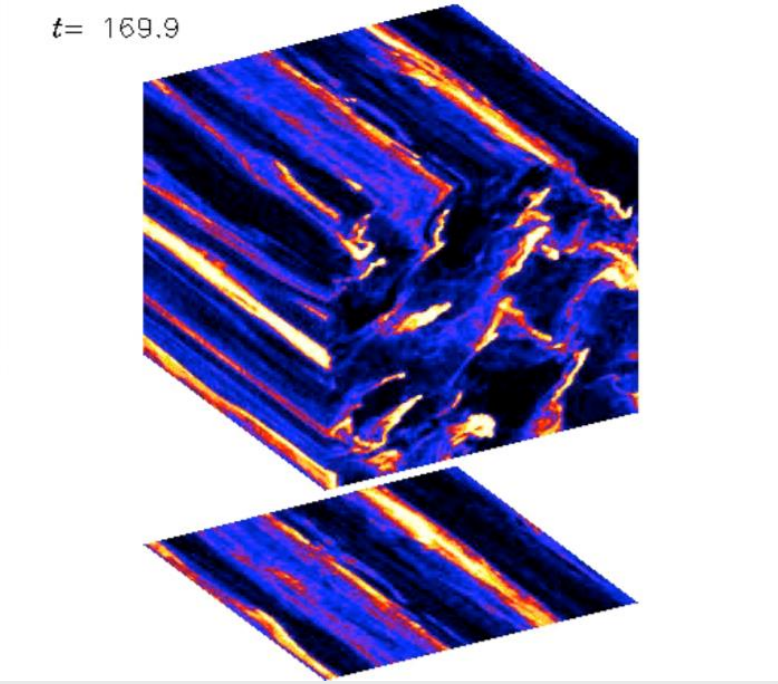
Small particles (St=0.01) get trapped in vortex created by convective overstability



Klahr et al., 2013

… and streaming instability

- Streaming instability: Dust-to-gas ratio in the mid-plane approaches unity → dust feedback accelerates gas → less headwind leads to reduced radial drift → run-away process leads to pile-up in filament; intensified effect for concentrated dust region due to reduced effective aerodynamic drag → higher azimuthal speed leads to dust „clean-up“ in orbit



Johansen et al., 2007

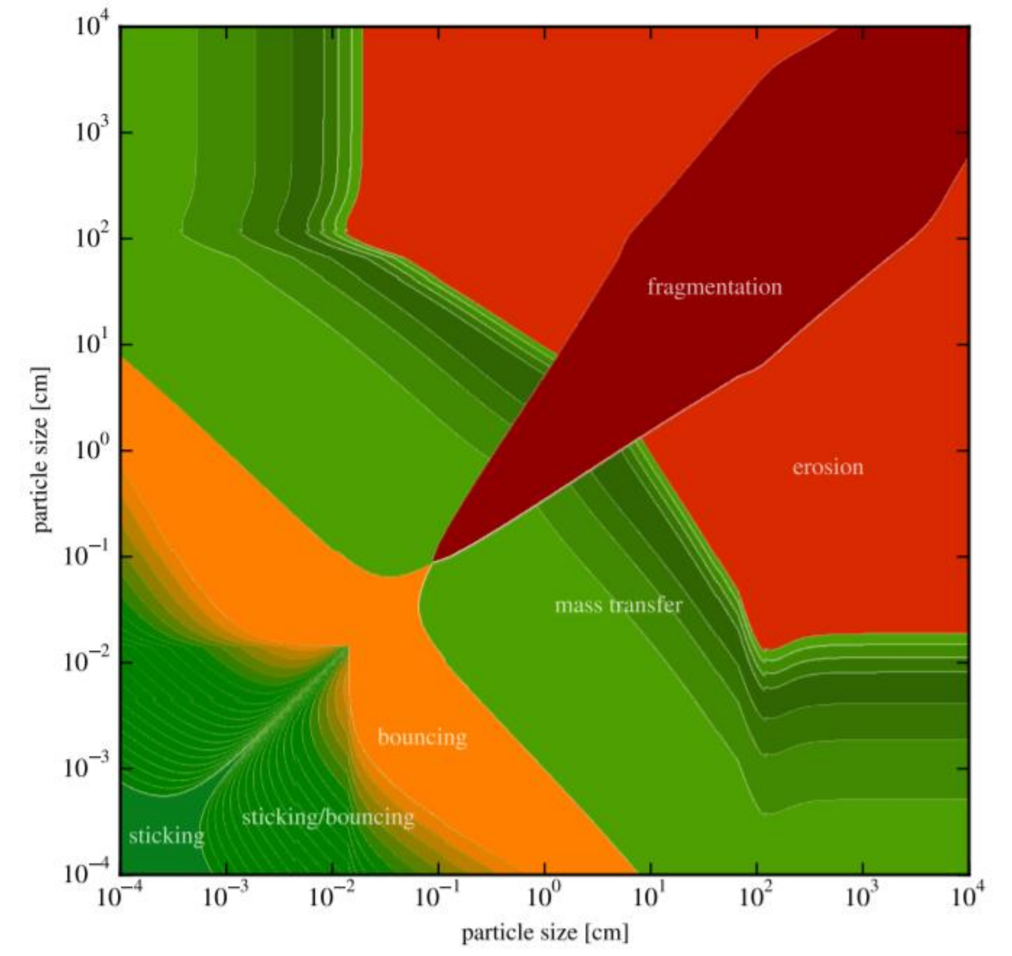
- Downside: St ca. 10^{-3} … 5, high metallicity (> 0.03), dust-to-gas ratio >1 required

Planetesimal formation by gravitational collapse of pebble clouds avoids particle growth barriers

- Advantages:
    - Problems associated with dust aggregates larger than pebbles, e.g. bouncing barrier (> mm-cm), fragmentation limit (> 1 m/s), erosion barrier and drift barrier, can be avoided
    - Fast process (t_{grow} ca. $10^1 – 10^3$ t_{orb})
- Disadvantages:
    - High density scenarios require specific parameters, e.g. streaming instability only for metallicity > 0.03 in case of minimal St 1.5×10^{-3} (merely after dissipation of gaseous protoplanetary disc in later stages of disc evolution)

Assumption of velocity distribution of dust aggregates enables growth by mass transfer

- Figure on the right is based on mean collision velocities between particles
- Mass-neutral bouncing gap can be overcome by assumption of velocity distribution of dust aggregates
- Growth to planetesimals by mass transfer post destructive processes



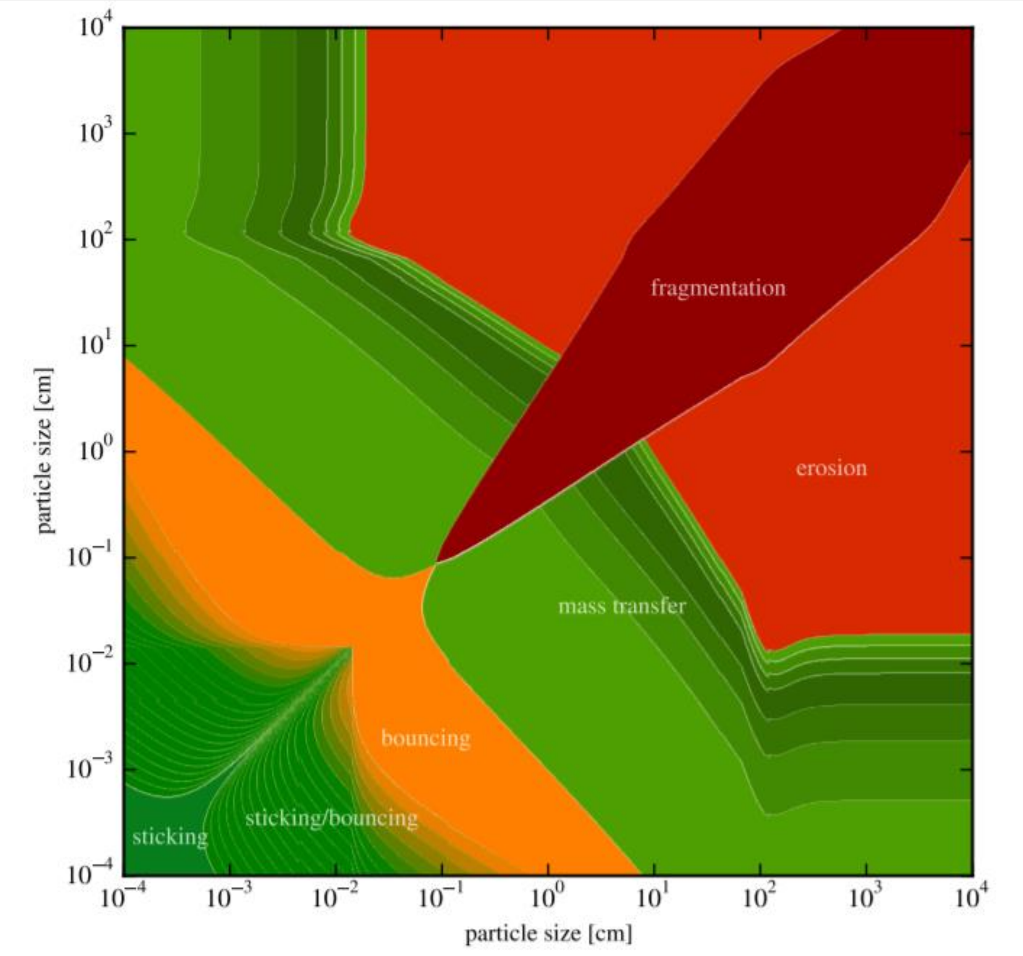
Birnstiel et al., 2016

Empirical basis for formation by mass transfer robust, but efficiency highly region-dependent

- Advantages:
  - Fragmentation, cratering and mass transfer proven to exist for dust aggregates
  - Variations in mass density and stochastic nature of turbulence → assumption of velocity dispersion
  - 100 m-sized aggregates could form in 1 … 5×10^4 yrs at 1 AU
- Disadvantages:
  - Growth time scales/maximum aggregate sizes significantly increase/decrease outwards in disc (6×10^5 yrs/ ca. m-sized at 30 AU), limited by radial drift without dust traps
  - No aggregates > 0.1 m can form due to erosion

Agglomeration of sub-μm water-ice monomers solves major direct collisional growth issues

- Major obstacles: i) low velocity for transition from sticking to bouncing, ii) low collision energies required for compaction
- Smaller stickier ca. 0.1 μm water-ice grains exhibit initial fractal growth before experiencing compaction, due to collisions, gas pressure and self-gravity



Birnstiel et al., 2016

Formation with sub-µm water-ice monomers highly efficient, but only for certain parameters

- Advantages:
  - High restructuring impedance and high collisional threshold → bouncing barrier never reached
  - High porosity and capture cross section → short time scales ca. 10^4 yrs → radial drift negligible
- Disadvantages:
  - Relaxing high stickiness or high resistance to compaction → smaller aggregates significantly experiencing radial drift
  - Erosion may play larger role
  - In general empirical data is incomplete

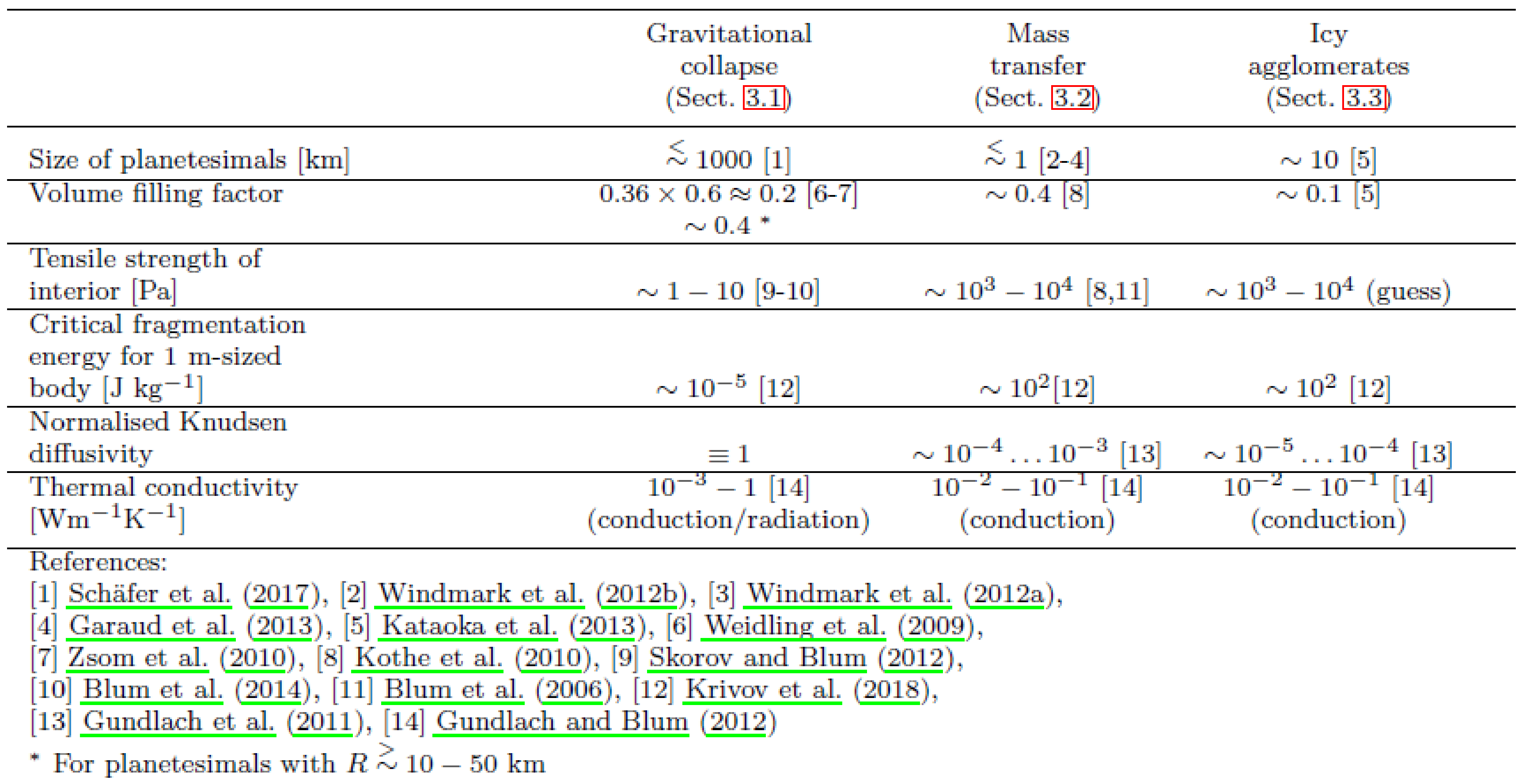
The three formation scenarios imply certain predictions for properties of planetesimals

- Parameters for distinguishing three scenarios:
  - Size
  - Volume filling factor (fraction of planetesimal volume actually filled by matter)
  - Tensile strength (internal cohesion of material)
  - Collisional strength (energy required to fragment colliding bodies so that biggest surviving mass equals half of original mass)
  - Knudsen diffusivity (resistance to gas flow)
  - Thermal conductivity

Some aspects have to be considered when analyzing the planetesimal parameters

- Planetesimals >10 km formed in gravitational collapse scenario are expected to approach mass transfer scenario parameters (R = 50 km, ρ = 1000 kg/m3 → $p = 4/15 \times \pi G \rho^2 R^2 = 1.4 \times 10^5$ Pa > crushing strength of pebbles)
- Mass transfer and icy agglomerates models not physically distinct (both rely on intrinsic stickiness of grains, differ merely by material and particle size or rather protoplanetary disc region
- Not suitable for scenario distinction: thermal conductivity, due to uncertainties and overlaps, and volume filling factor for large planetesimals affected by lithostatic compression

While gravitational collapse leads to largest aggregates, icy agglomerates are least dense



	Gravitational collapse (Sect. 3.1)	Mass transfer (Sect. 3.2)	Icy agglomerates (Sect. 3.3)
Size of planetesimals [km]	$\lesssim 1000$ [1]	$\lesssim 1$ [2-4]	~ 10 [5]
Volume filling factor	$0.36 \times 0.6 \approx 0.2$ [6-7] ~ 0.4 *	~ 0.4 [8]	~ 0.1 [5]
Tensile strength of interior [Pa]	$\sim 1 - 10$ [9-10]	$\sim 10^3 - 10^4$ [8,11]	$\sim 10^3 - 10^4$ (guess)
Critical fragmentation energy for 1 m-sized body [J kg^{-1}]	$\sim 10^{-5}$ [12]	$\sim 10^2$[12]	$\sim 10^2$ [12]
Normalised Knudsen diffusivity	$\equiv 1$	$\sim 10^{-4} \dots 10^{-3}$ [13]	$\sim 10^{-5} \dots 10^{-4}$ [13]
Thermal conductivity [Wm^{-1}K^{-1}]	$10^{-3} - 1$ [14] (conduction/radiation)	$10^{-2} - 10^{-1}$ [14] (conduction)	$10^{-2} - 10^{-1}$ [14] (conduction)

References:
[1] Schäfer et al. (2017), [2] Windmark et al. (2012b), [3] Windmark et al. (2012a), [4] Garaud et al. (2013), [5] Kataoka et al. (2013), [6] Weidling et al. (2009), [7] Zsom et al. (2010), [8] Kothe et al. (2010), [9] Skorov and Blum (2012), [10] Blum et al. (2014), [11] Blum et al. (2006), [12] Krivov et al. (2018), [13] Gundlach et al. (2011), [14] Gundlach and Blum (2012)

* For planetesimals with $R \gtrsim 10 - 50$ km

Blum, 2018

Empirical evidence suggests gravitational collapse planetesimal formation scenario

- Size-frequency distribution in asteroid/Kuiper belt
  - „Knee“ at ca. 100 km → smaller = collisional fragments, larger = primordial planetesimals → planetesimals on average born big (gravitational collapse), but also sub-km size reproduction possible
- Debris discs (end of planetesimal collision cascade)
  - Modelling of collision processes and fit to observed debris disc brightness → agreement for gravitational collapse and mass transfer, but number of sub-km-sized bodies makes difference (Solar system indicates gravitational collapse, due to low number of sub-km-sized bodies)

Empirical evidence suggests gravitational collapse planetesimal formation scenario

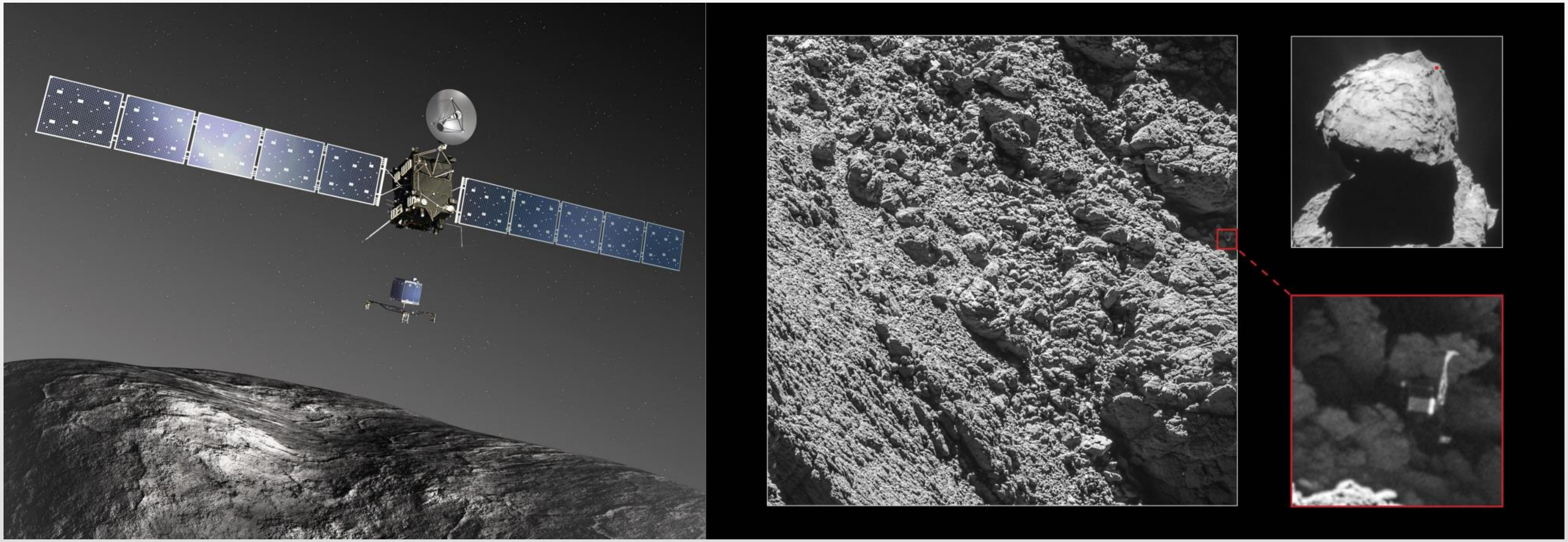
- Fractal particles in comet 67P
    - Explanation: comet consists of larger entities between which primordial fractal dust aggregates are captured
    - Mass transfer model would destroy and compact pebbles, icy aggregates do not provide sufficiently large void spaces
- Physical properties of comet 67P
    - Earlier: formation by gravitational collapse, as dust activity requires gas pressure below dry dust layer > sum of cohesion and gravitational force of dust
    - Rosetta mission: 67P consists of 3-6 mm radius pebbles

Summary

- Three scenarios provide explanation for planetesimal formation:
  - Gravitational-collapse scenario
  - Mass-transfer scenario
  - Water-ice-monomer-agglomeration scenario
- Three formation scenarios provide distinct predictions for certain planetesimal properties
- Comparison to empirical evidence suggests gravitational-collapse scenario to play dominant role in planetesimal formation

Summary

- More empirical work is necessary to answer further questions related to dust evolution/planetesimal growth, e.g. whether gravitational collapse can form km-sized bodies



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