Bridging the gap between the core accretion and gravitational instability planet formation theories

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Swiss Commission for Astronomy (SCFA)

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Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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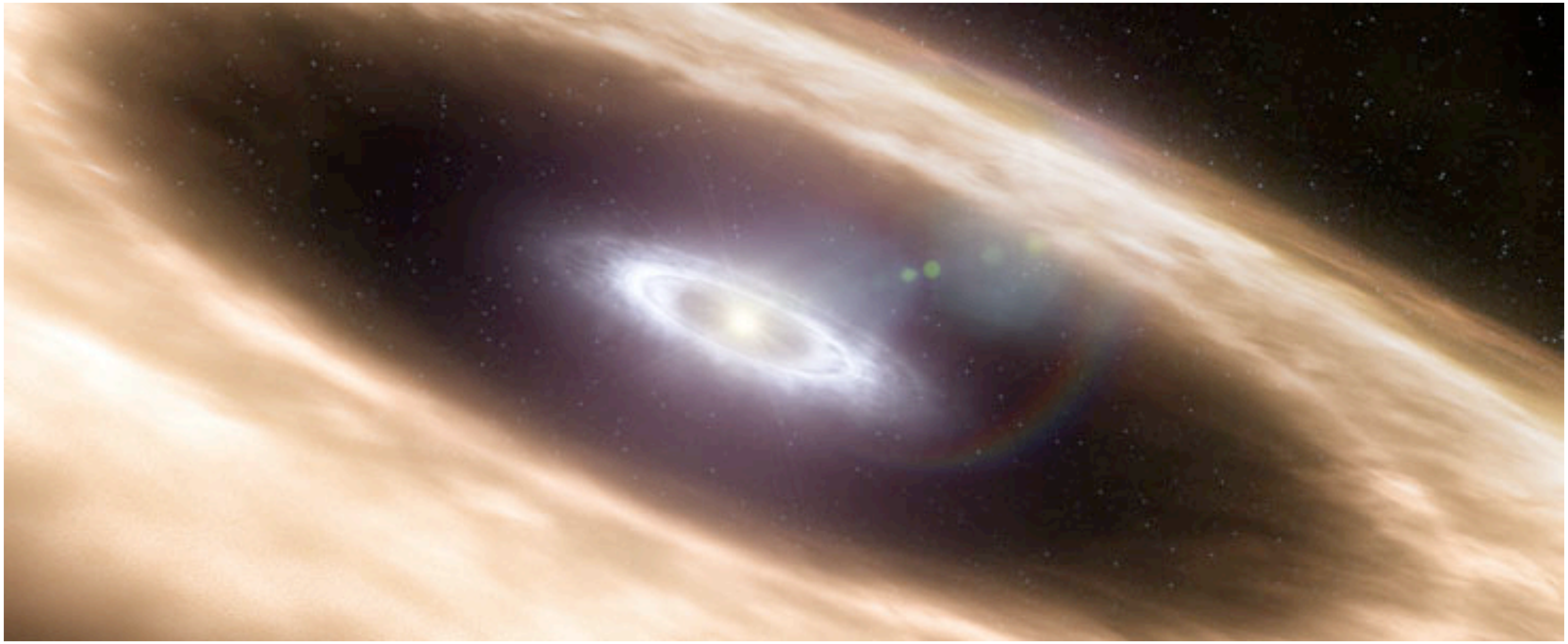
  - Planet formation mechanisms
  - The gap between the formation mechanisms
- Recent developments on planet formation
  - core accretion
  - gravitational instability

Introduction

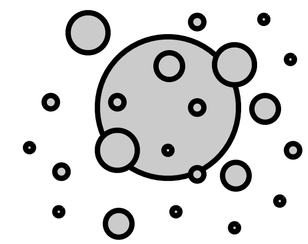
Planets form in circumstellar discs made of gas and dust



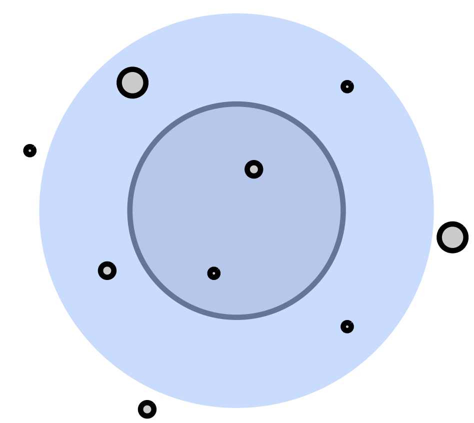
Artist's impression, ESO

Planets may form by dust growth followed by gas accretion

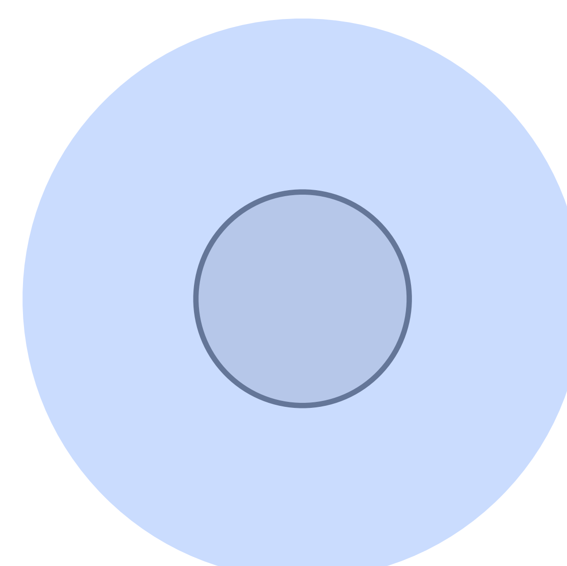
1. Dust coagulates to form a solid core



2. Core starts to accrete gas



3. Runaway gas accretion forms giant planet



Can in principle occur at any time

Posters & talks:
Venturini, Yang, Picogna, Drazkowska

Safronov 1969; Goldreich & Ward 1973; Pollack et al 1996; Hubickyj et al 1995

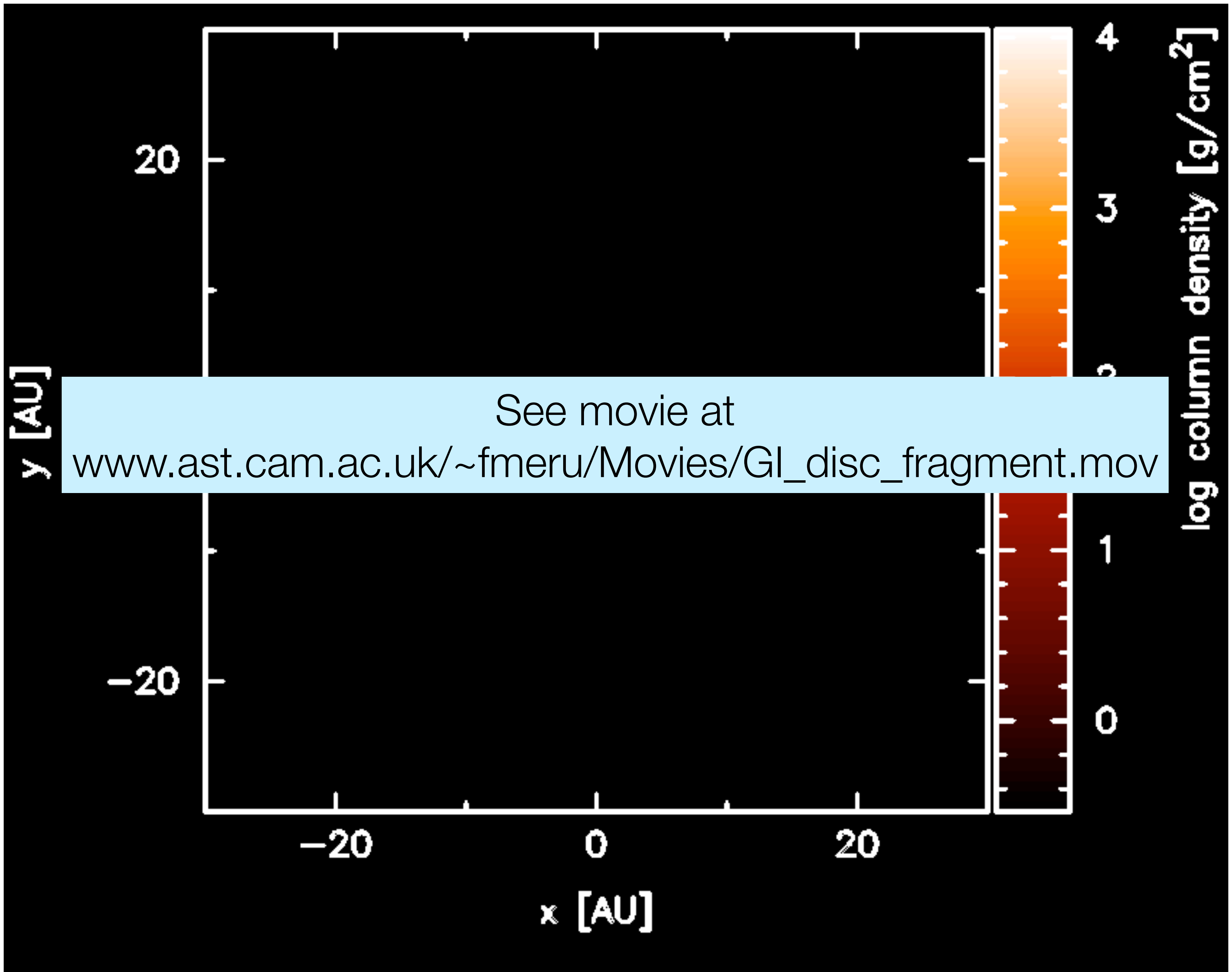
Planets form by core accretion in the inner disc

Formation timescales too long at large radii

$$\frac{\mathrm{d}M_\mathrm{p}}{\mathrm{d}t} \propto \Sigma\Omega$$

Planetesimal accretion rate too long at large radii

Gravitational Instability involves the fragmentation of massive discs



See movie at
www.ast.cam.ac.uk/~fmeru/Movies/GI_disc_fragment.mov

Meru & Bate 2010

Self-gravity drives the evolution of massive discs
(spiral structures form)

Spirals collapse and fragment under the "right" conditions

Poster and talk:
Stoyanovska, Vorobyov

Cameron 1978; Boss 1997

Fragmentation occurs locally if the disc is unstable

Stability determined by:

$$Q = \frac{c_s \kappa}{\pi \Sigma G}$$

For an infinitesimally thin disc:

$$Q > 1 \equiv \text{stable}$$
$$Q < 1 \equiv \text{unstable}$$

Toomre 1964

A fast cooling is also needed for fragmentation

Cooling needs to be faster than a critical value

Gammie 2001; Rice et al 2005; Meru & Bate 2011b,2012

$$t_{cool} < \frac{\beta_{crit}}{\Omega}$$

Fragmentation is more likely at larger radii

Toomre parameter generally decreases with radius

$$Q = \frac{c_s \kappa}{\pi \Sigma G}$$

Cooling condition more likely to be satisfied at large radii - longer orbital timescale

$$t_{cool} < \frac{\beta_{crit}}{\Omega}$$

There appears to be a formation gap in protoplanetary discs

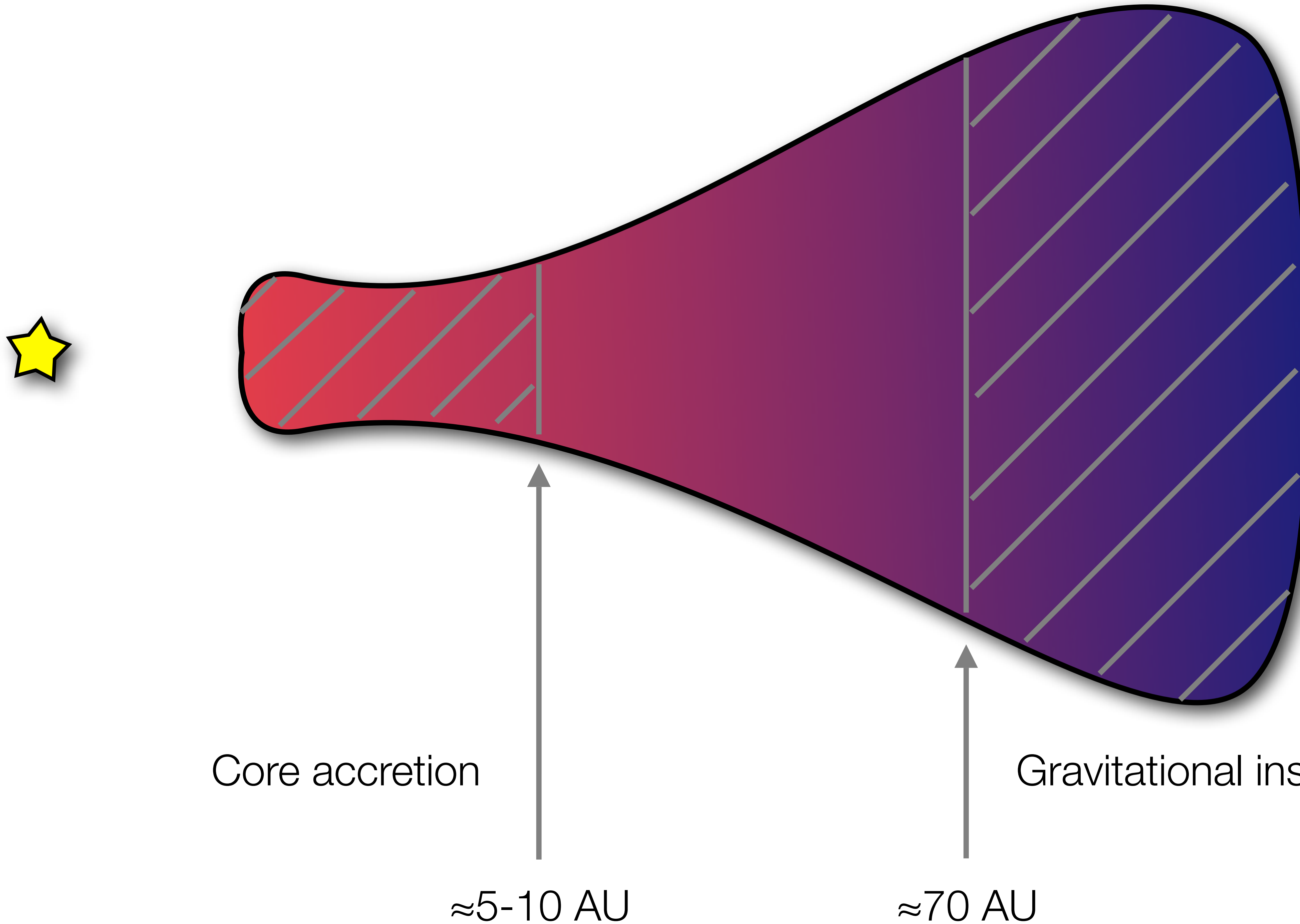


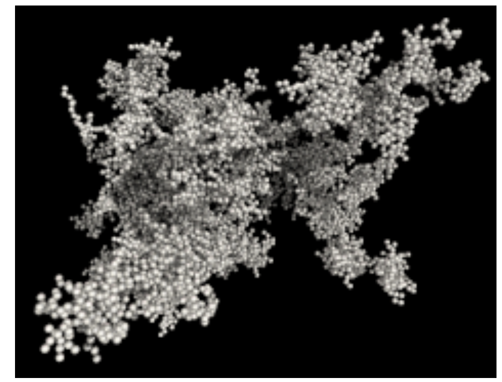
Image reproduced with permission from A. Banzatti

Core accretion

There are different methods used to understand dust growth at small sizes

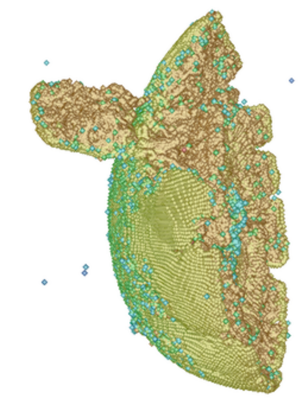
Scale

Molecular dynamics (particles)



A. Seizinger

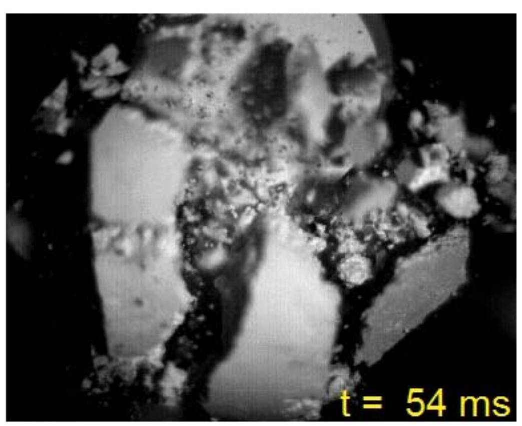
Talk: Gonzalez



Meru et al 2013

Laboratory experiments (~10 μm - 10 cm)

SPH simulations (cm-dm)



Beitz et al 2011

Posters and talks:
Capelo, De Beule, Schywek, Kothe, Deckers, Teiser, Blum, Bukhari, Kelling, Weidling, Wurm

Monte Carlo (considers background disc)

Smoluchowski equation (considers background disc)

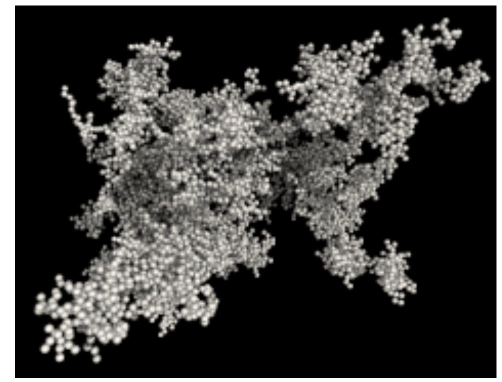
Poster: Stammler

Gravity-dominated regime

There are different methods used to understand dust growth at small sizes

Scale

Molecular dynamics (particles)



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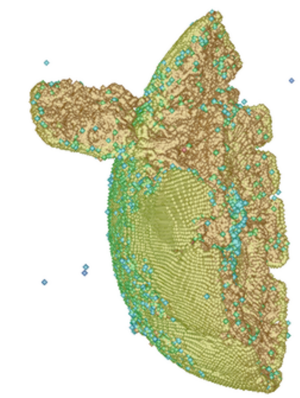

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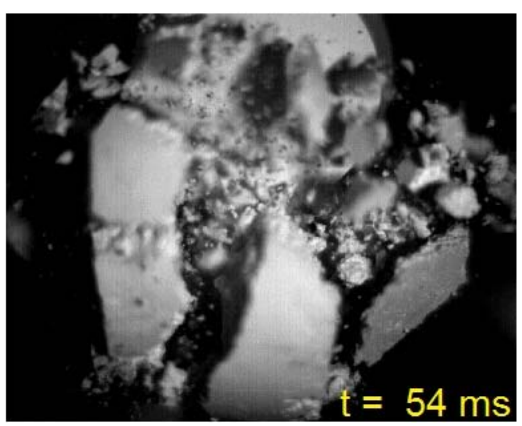

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Monte Carlo
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Smoluchowski equation
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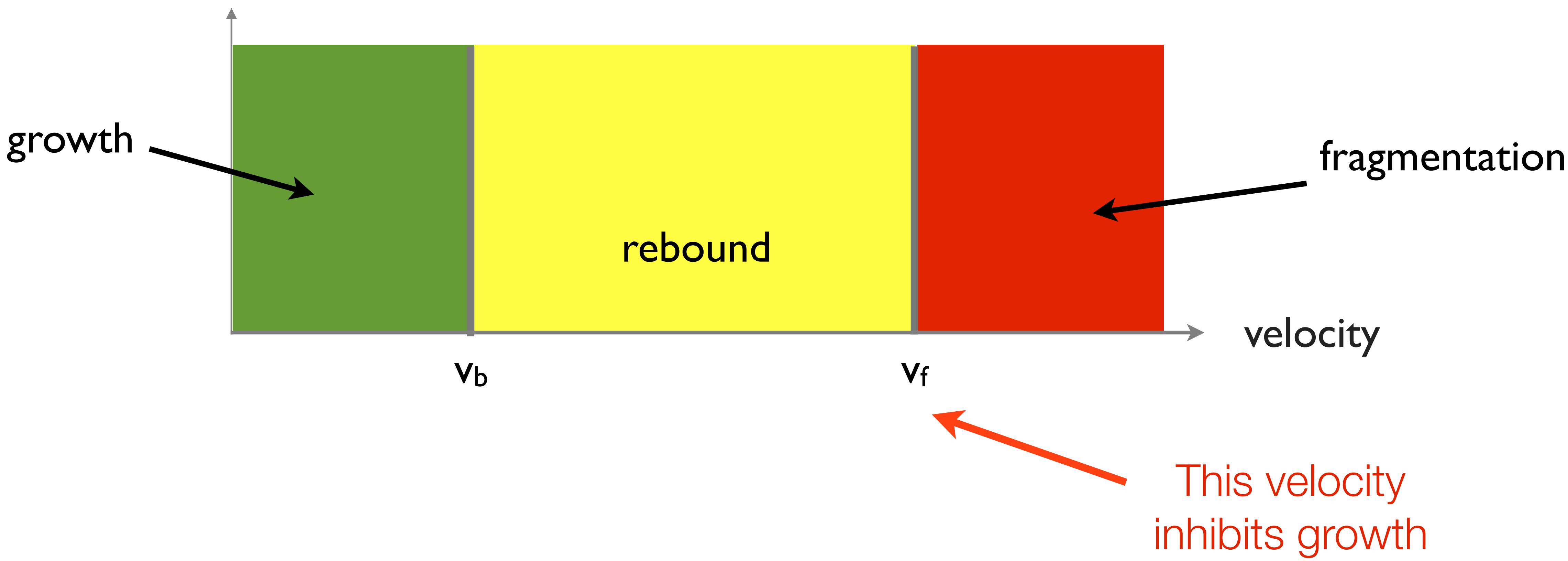
Poster:
Stammler

Gravity-dominated regime

The velocity at which the aggregates collide determines their collisional outcome

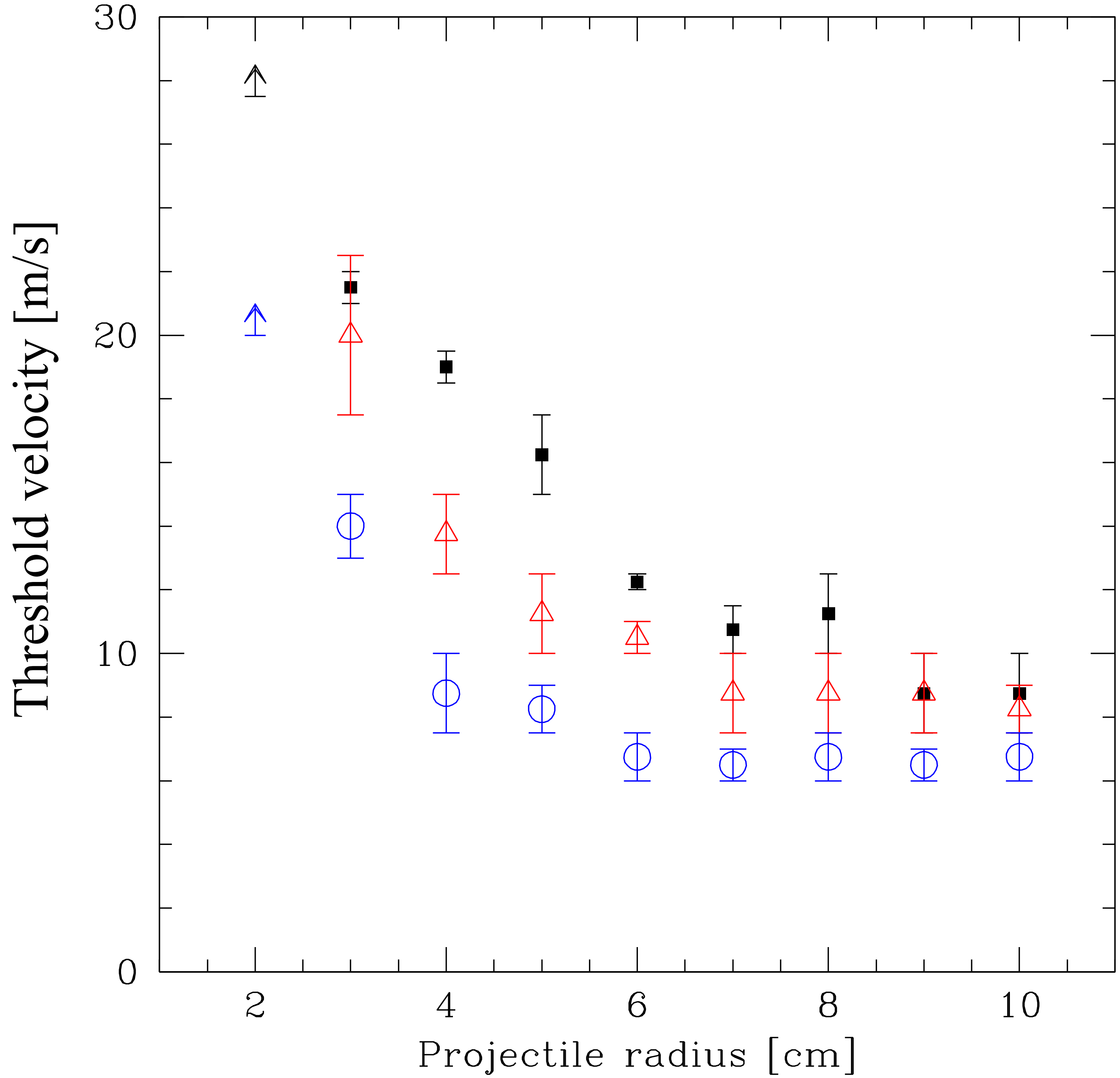


How high can the collision velocities be before aggregates will fragment?

How is the fragmentation velocity affected by aggregate size and porosity ?

Knowing the collisional outcome is essential to model the growth evolution of many dust aggregates

As the mass ratio increases the aggregates are more likely to stick



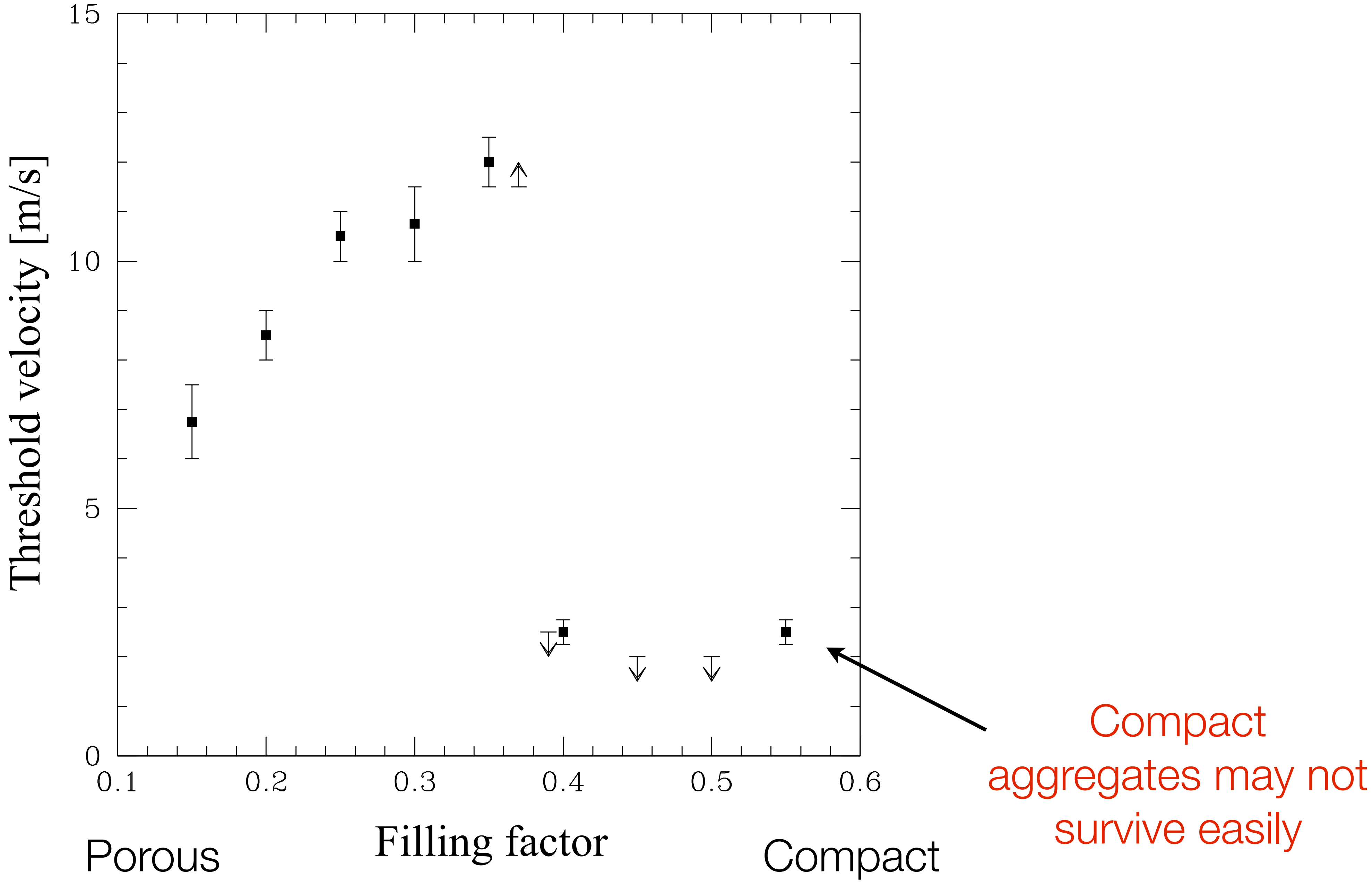
filling factor = 35%
filling factor = 25%
filling factor = 15%

← Mass ratio

Also seen in laboratory experiments
e.g. Wurm et al 2005, Teiser & Wurm 2009

Meru et al 2013

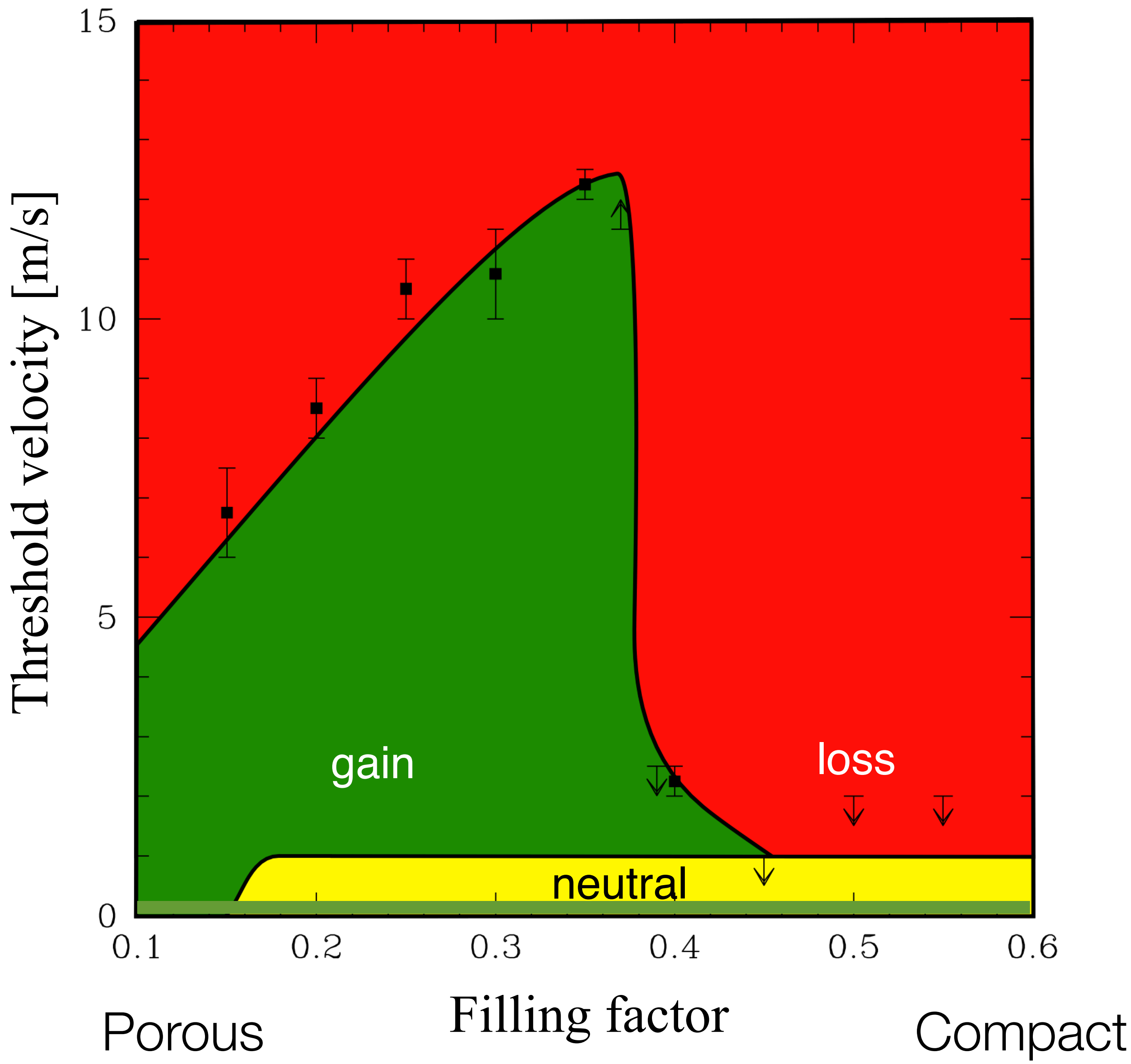
Porous aggregates become stronger with filling factor but compact aggregates break easily

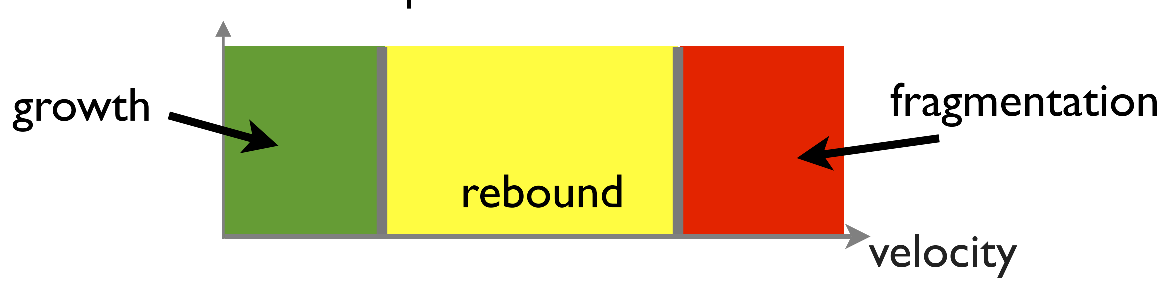


Meru et al 2013

Porous aggregates become stronger with filling factor but compact aggregates break easily

Also combines results of Beitz et al 2011, Geretshauser, Meru et al 2011, Geretshauser et al 2012





Meru et al 2013

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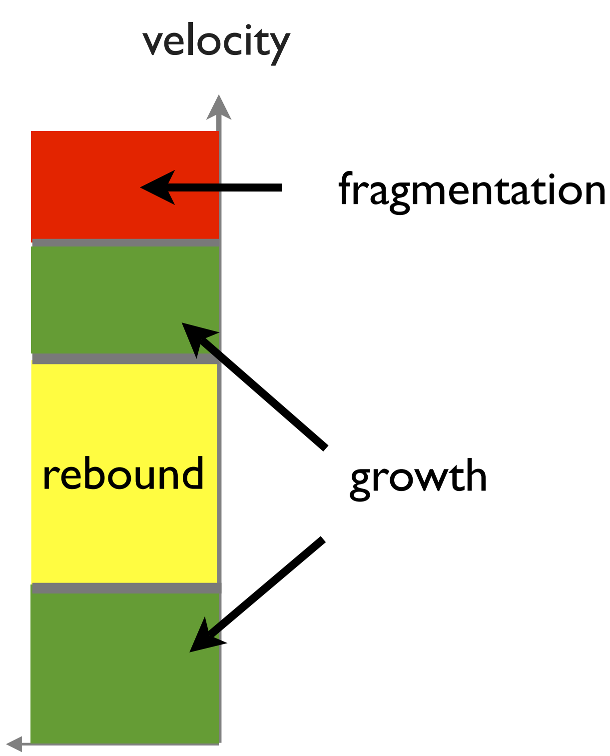
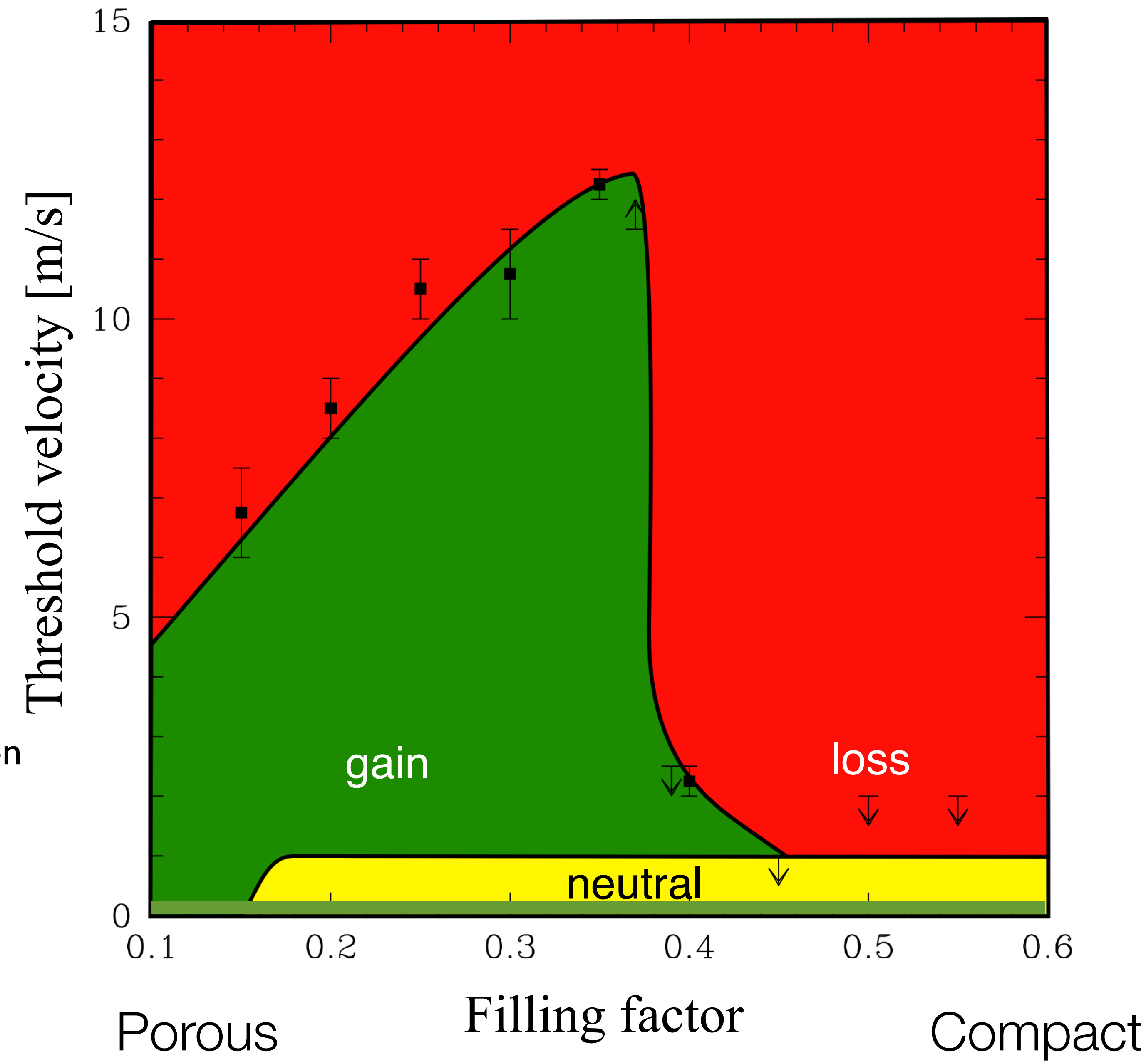
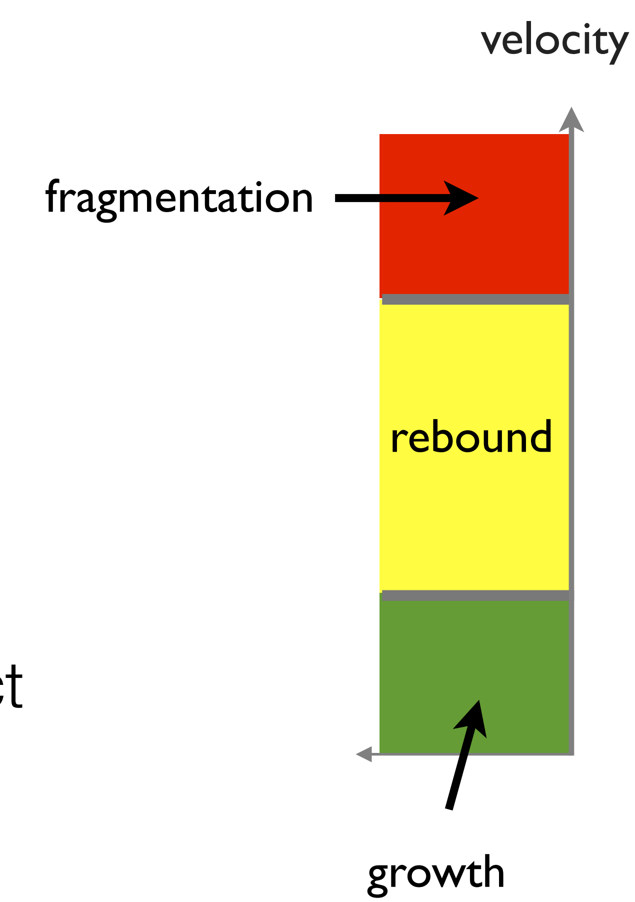


Meru et al 2013





There are different methods used to understand dust growth at small sizes

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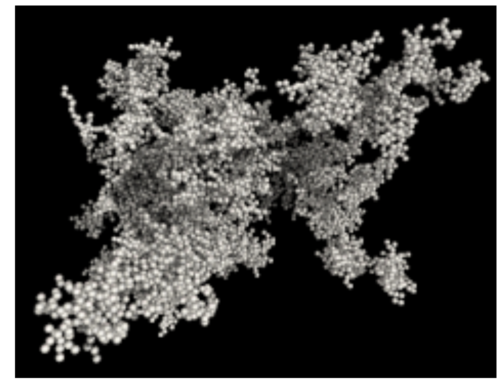
Molecular dynamics (particles)



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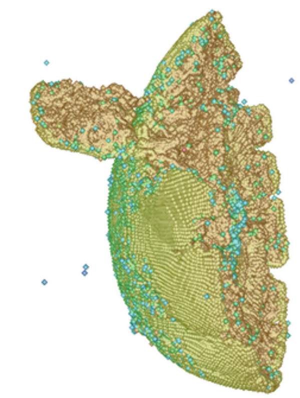
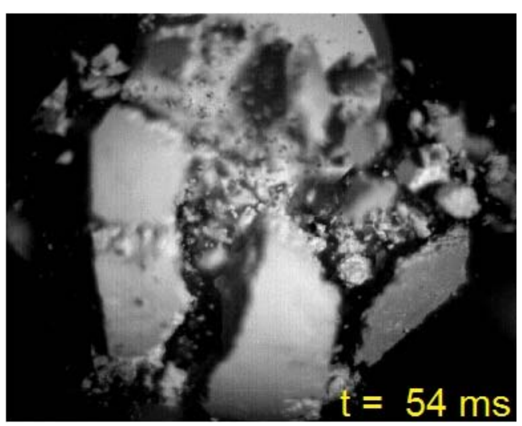


Meru et al 2013

Laboratory experiments
(~10 μm - 10 cm)

SPH simulations (cm-dm)



Beitz et al 2011

Monte Carlo
(considers background
disc)

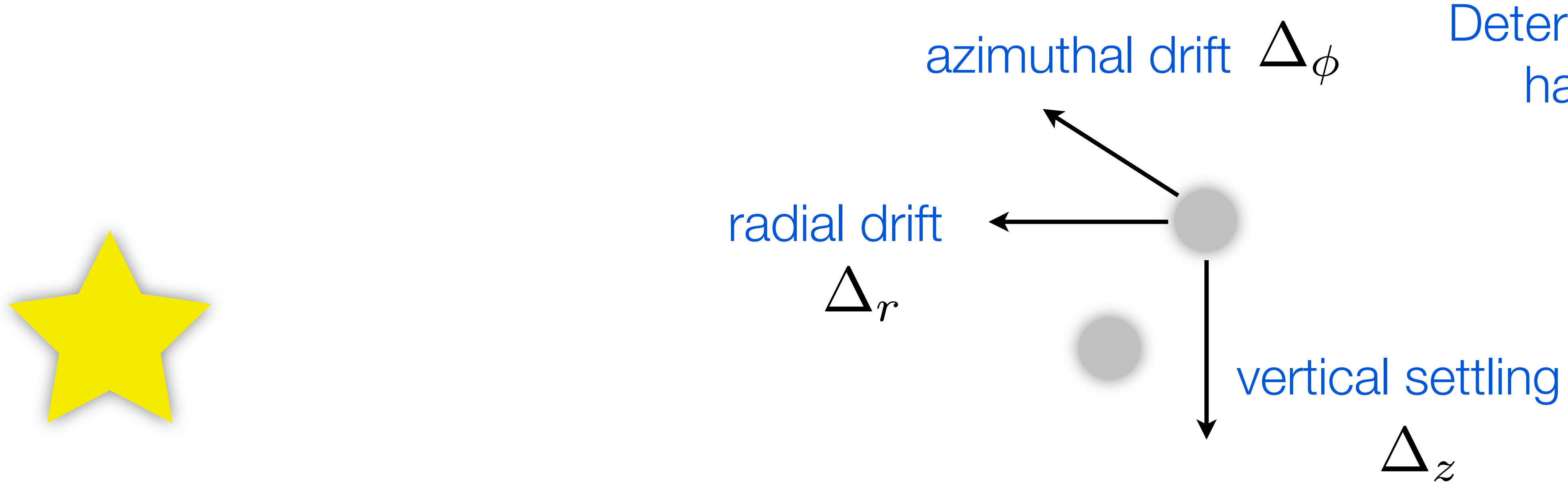
Smoluchowski equation (considers background disc)

Gravity-dominated regime

The collision velocity was previously single-valued, determined by aggregate sizes and disc properties

Contributions to collision velocity:

Deterministic velocities have a direction



Stochastic velocities:	Turbulence	Δ_T
	Brownian motion	Δ_B

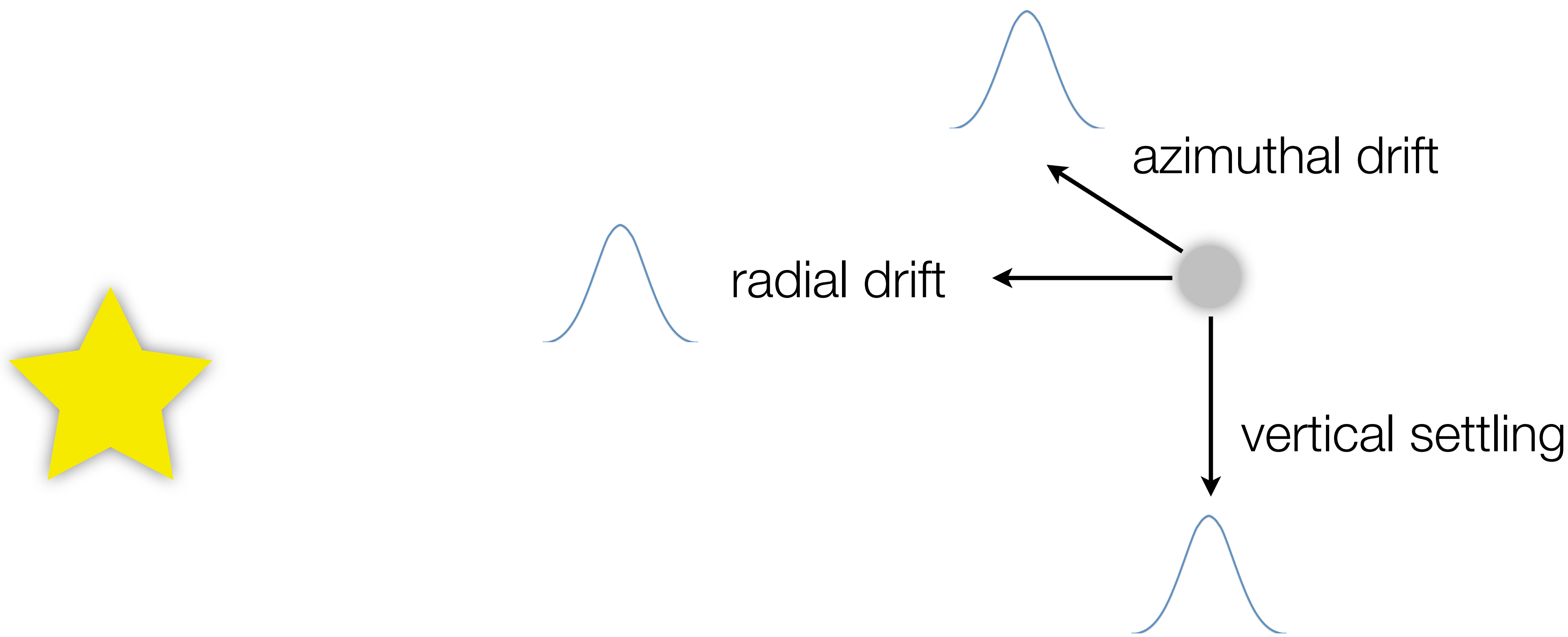
Collision velocity = $\sqrt{\Delta_r^2 + \Delta_\phi^2 + \Delta_z^2 + \Delta_T^2 + \Delta_B^2}$

Tanaka, Dullemond, Brauer et al 2007, 2008; Birnstiel et al 2010; Zsom et al 2010

Two aggregates of particular sizes at a particular disc location will always collide at the same velocity. Realistic?

The new approach assumes each particle has a distribution of velocities

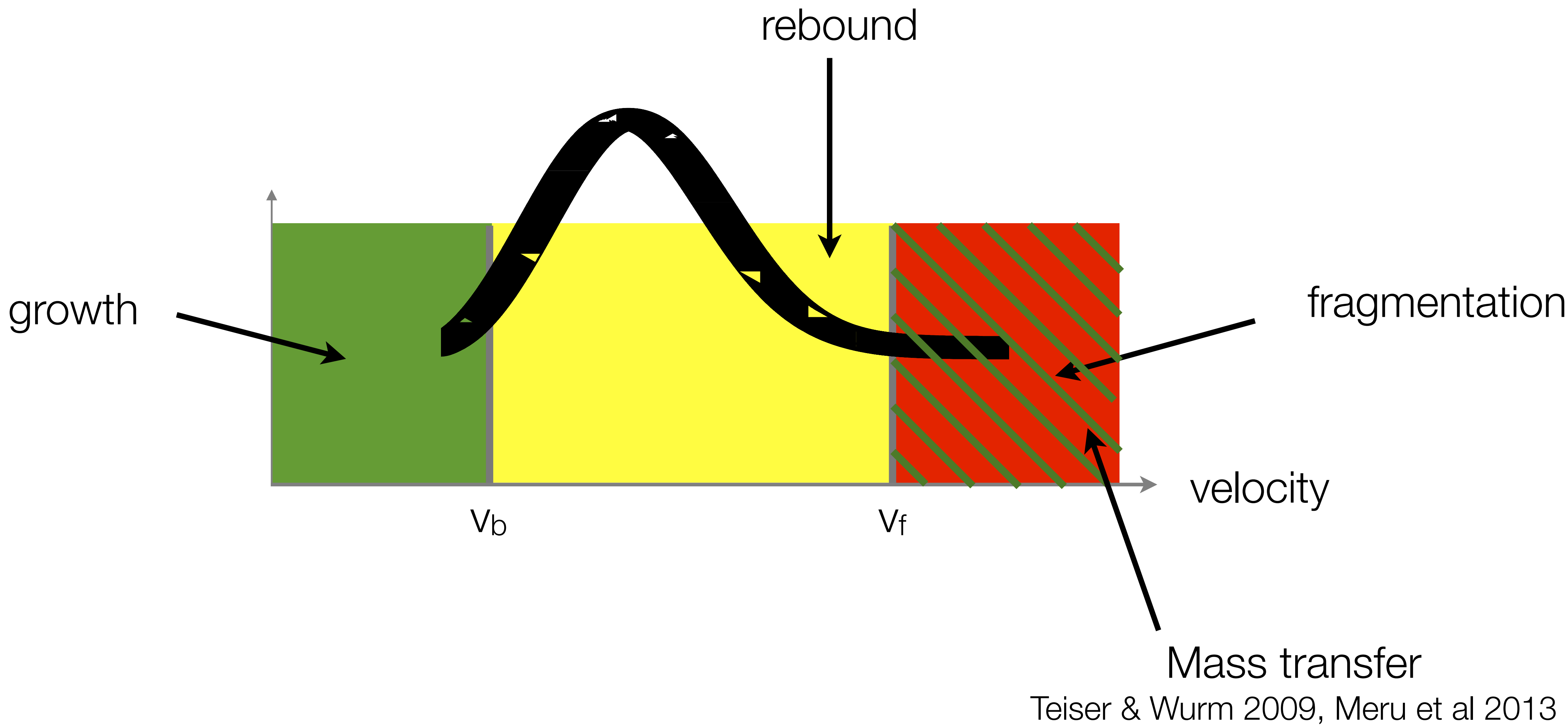
Peak given by deterministic velocity in each direction



Spread in each direction given by stochastic velocities (turbulence & brownian motion)

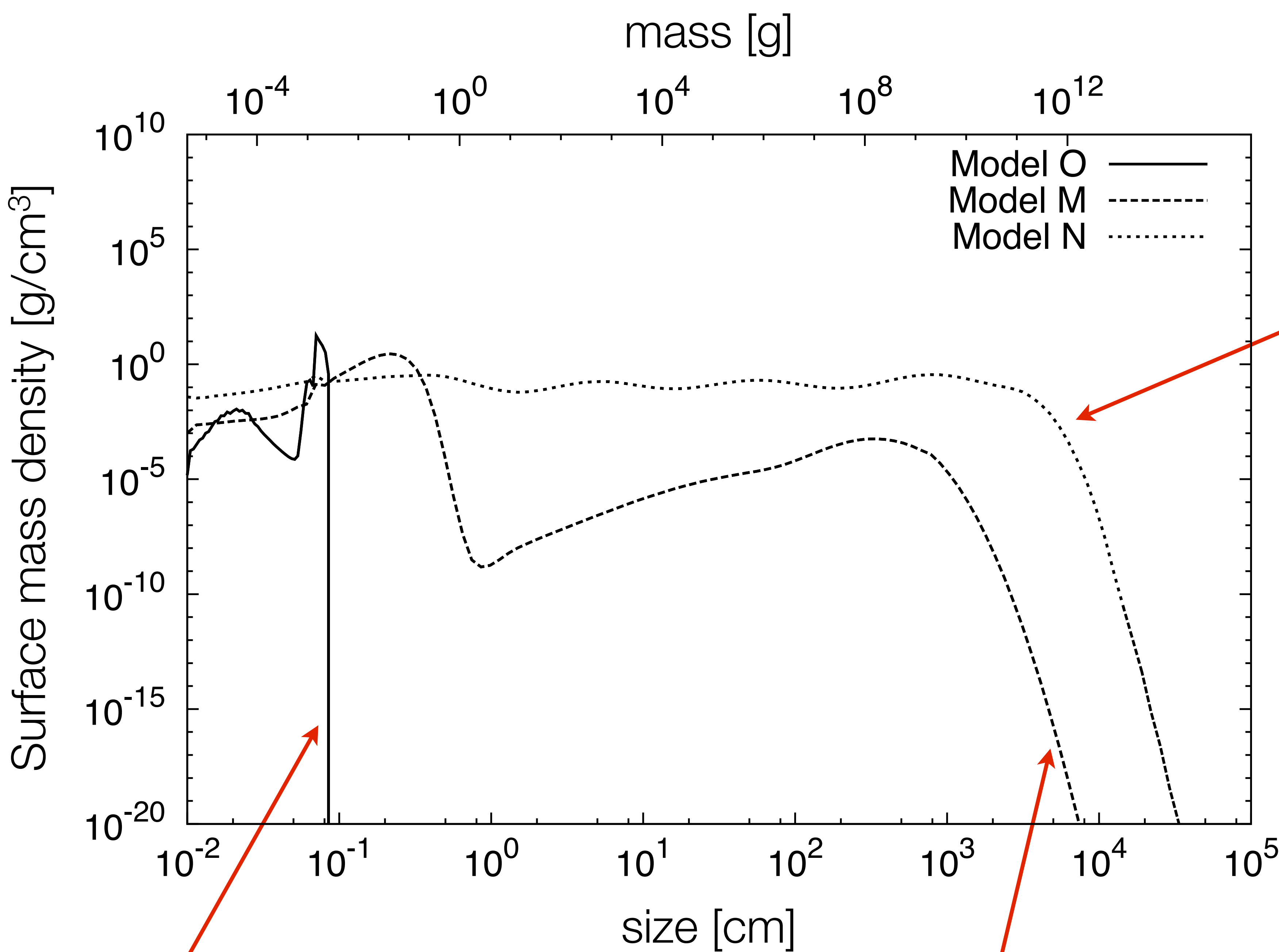
Garaud, Meru et al 2013 (also see Okuzumi et al 2011, Galvagni et al 2012, Windmark et al 2013)

The end result is a distribution with non-zero sticking probability



Growth achieved to larger sizes than before

1 AU



Separation of deterministic and stochastic velocities

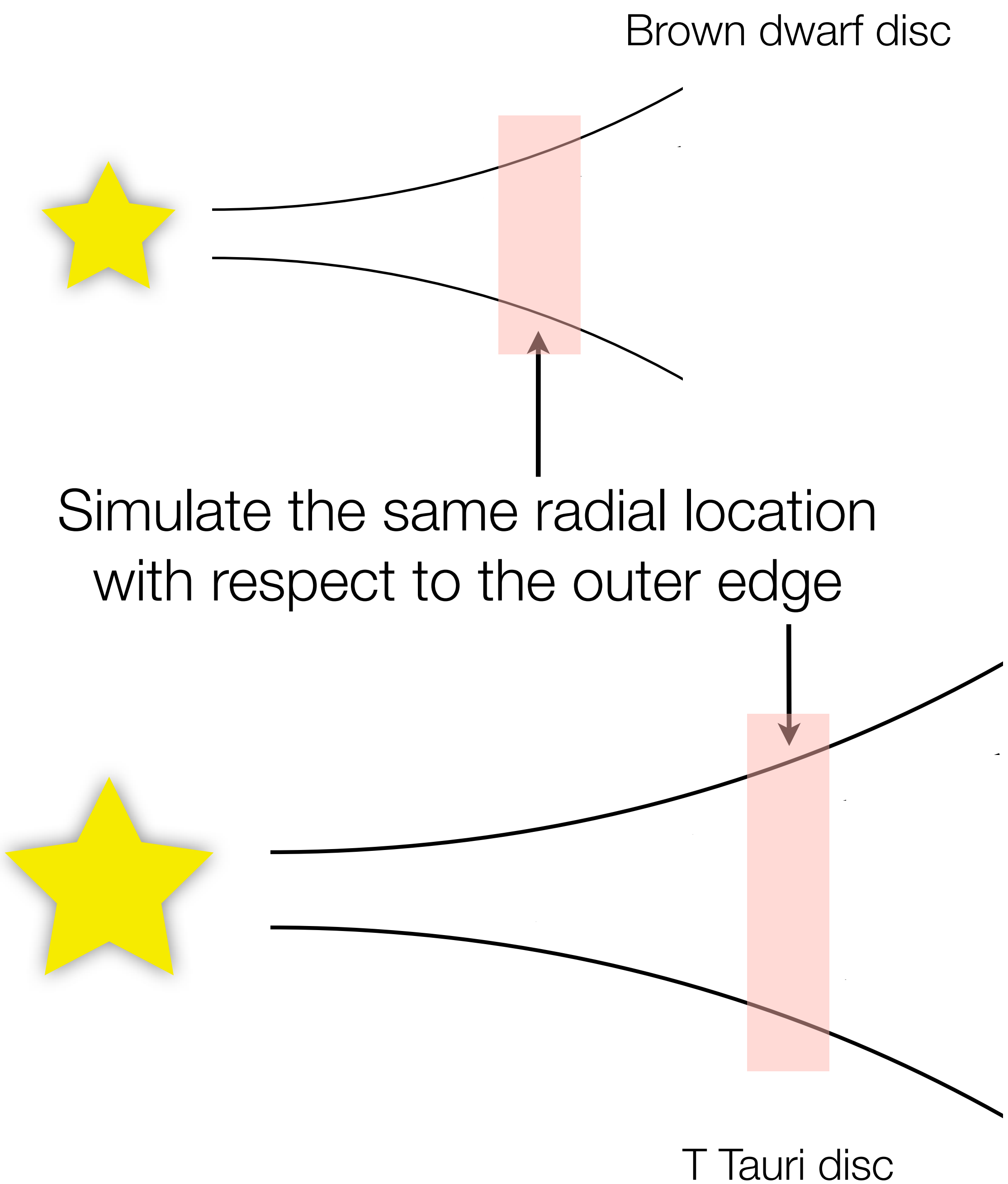
No velocity pdf

Turbulence-dominated regime

Galvagni et al 2011, Windmark et al 2012

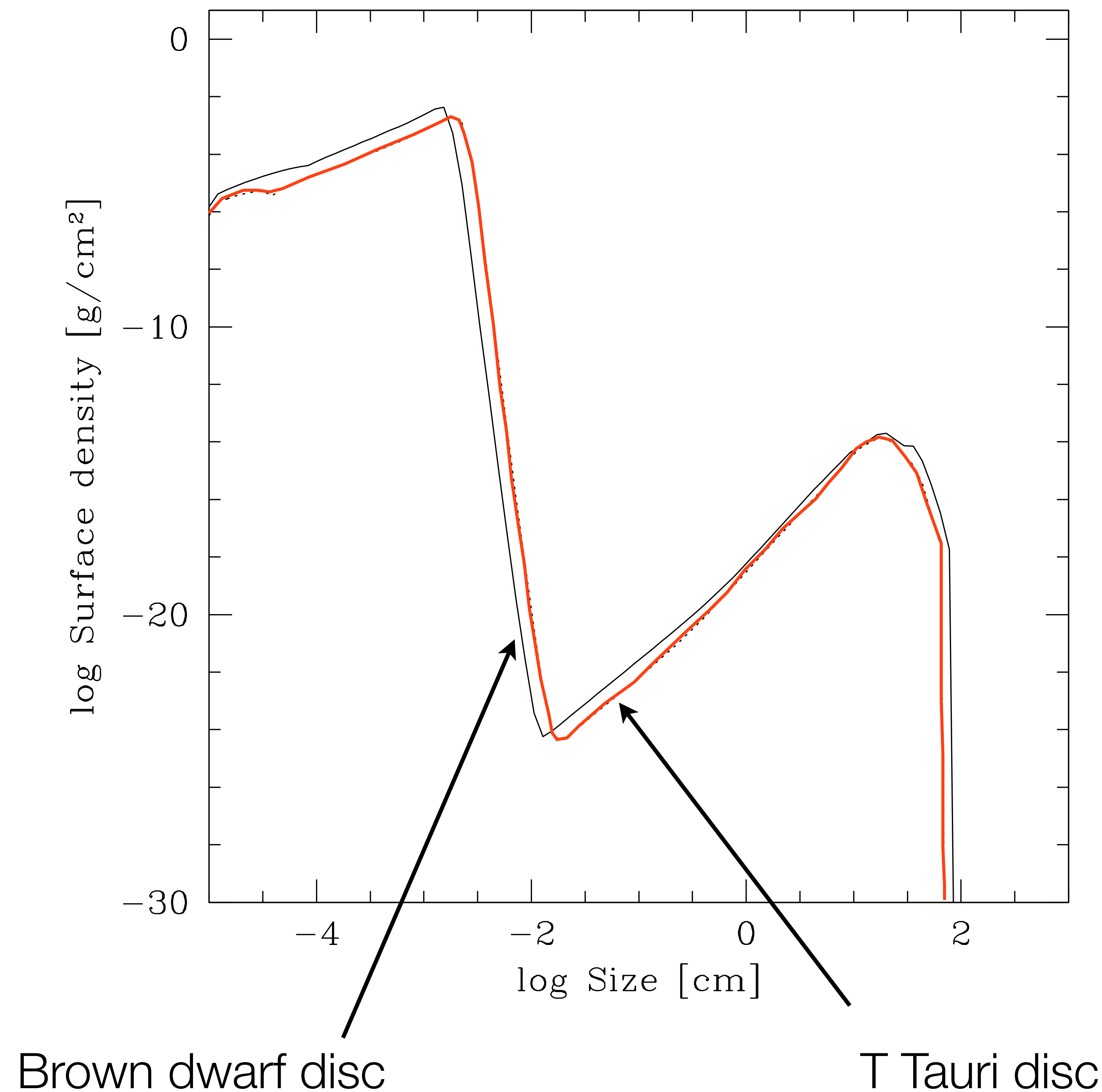
Garaud, Meru et al 2013

Growth in brown dwarf and T Tauri discs occurs to the same maximum size



Simulate the same radial location with respect to the outer edge

T Tauri disc is scaled-up
(disc mass, radius and stellar mass)



Meru et al 2013

Gravitational instability

A fast cooling is also needed for fragmentation

Cooling needs to be faster than a critical value

Gammie 2001; Rice et al 2005; Meru & Bate 2011b,2012

$$t_{\text{cool}} < \frac{\beta_{\text{crit}}}{\Omega}$$

Fast cooling implies high turbulent stresses

Gammie 2001; Rice et al 2005

$$\alpha_{\mathrm{GI}} = \frac{4}{9}\frac{1}{\gamma(\gamma-1)}\frac{1}{\beta}$$

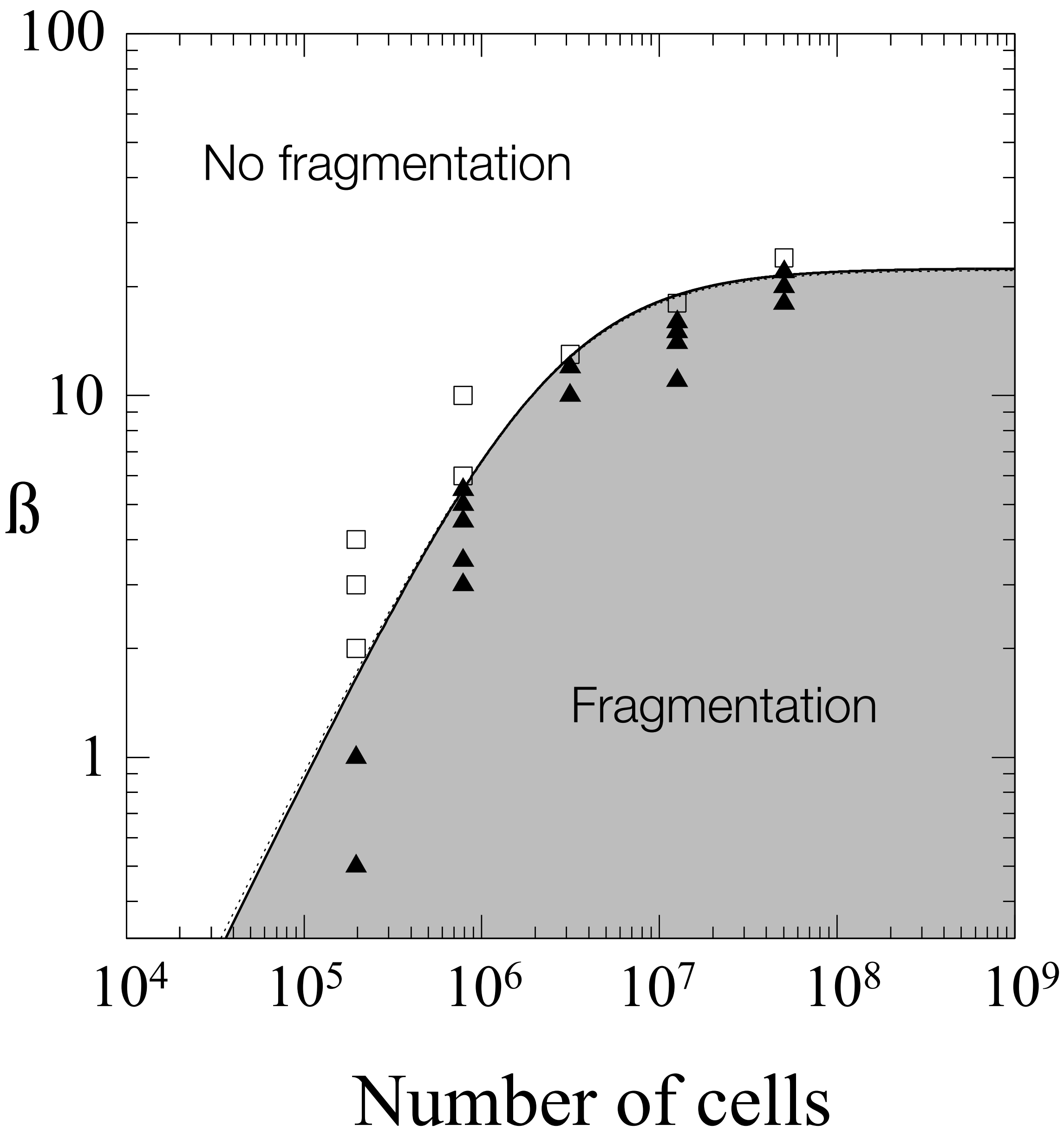
Turbulent stresses vary with radius

Clarke 2009

$$\alpha_{\mathrm{GI}} = 0.4\left(\frac{R}{100\mathrm{AU}}\right)^{\frac{9}{2}}$$

There is a critical radius outside of which fragmentation occurs

New results show fragmentation is easier than previously thought



Meru & Bate 2012

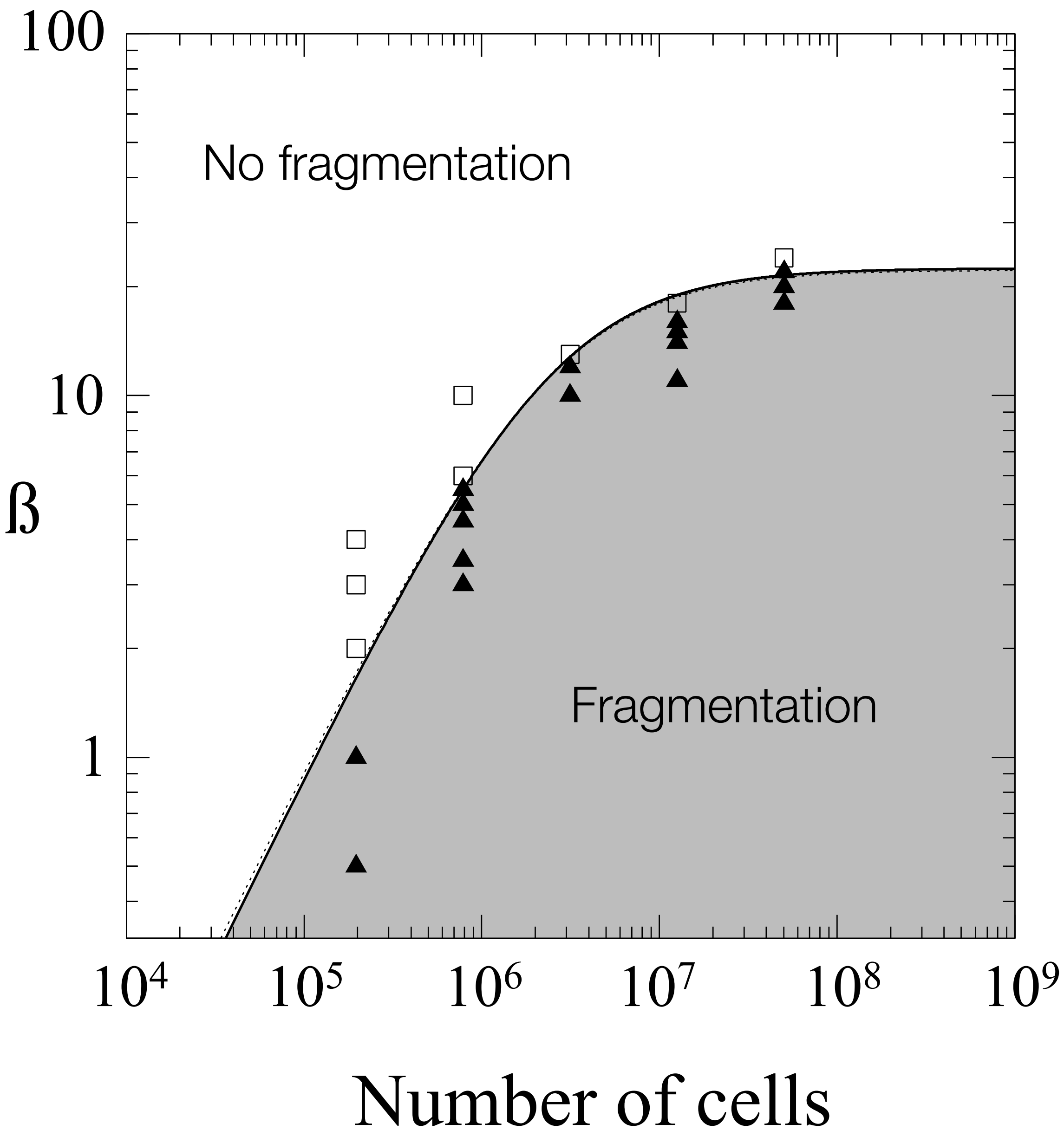
Previous results:

$$\beta_{\rm crit} \approx 6 - 7 \quad \text{for} \quad \gamma = \frac{5}{3}$$

Rice et al 2005

$\beta_{\rm crit}$	$R_{\rm crit}$ $(M_\star = 1 M_\odot)$
6.5	**66 au**

New results show fragmentation is easier than previously thought



Meru & Bate 2012

Previous results:

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Rice et al 2005

$\beta_{\rm crit}$	$R_{\rm crit}$ $(M_\star = 1 M_\odot)$
6.5	66 au
20.0	51 au
30.0	47 au

Updated simulation results suggest $\beta_{\rm crit} > 20$

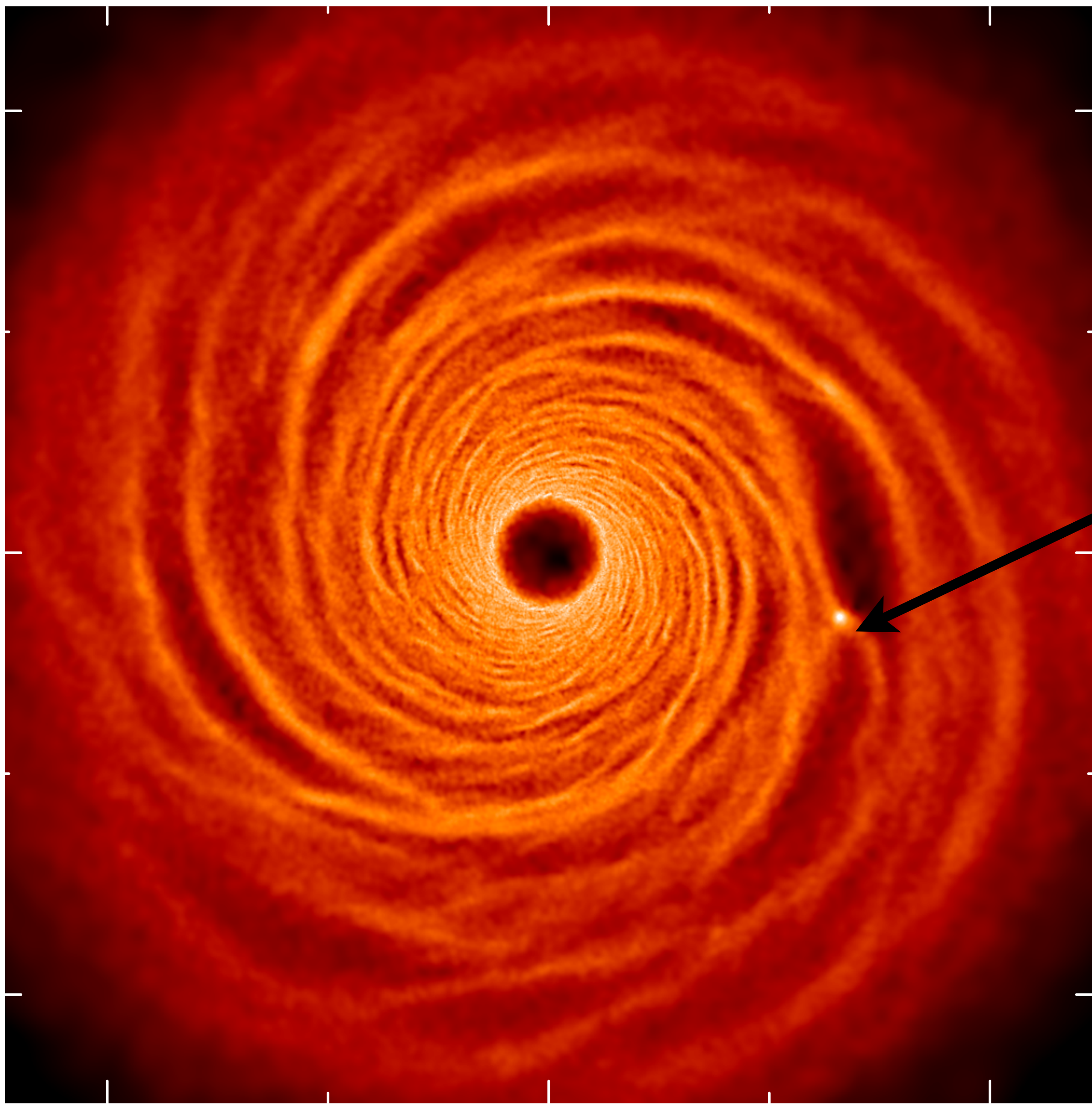
Paardekooper 2012, Meru & Bate 2012

The story isn’t quite over yet

Stochastic fragmentation makes assessing when fragmention occurs harder
Paardekooper 2012; Hopkins & Christiansen 2013

Different ways of modelling cooling can affect the results
Rice et al 2014

What happens in a gravitationally unstable disc after the first fragment forms?

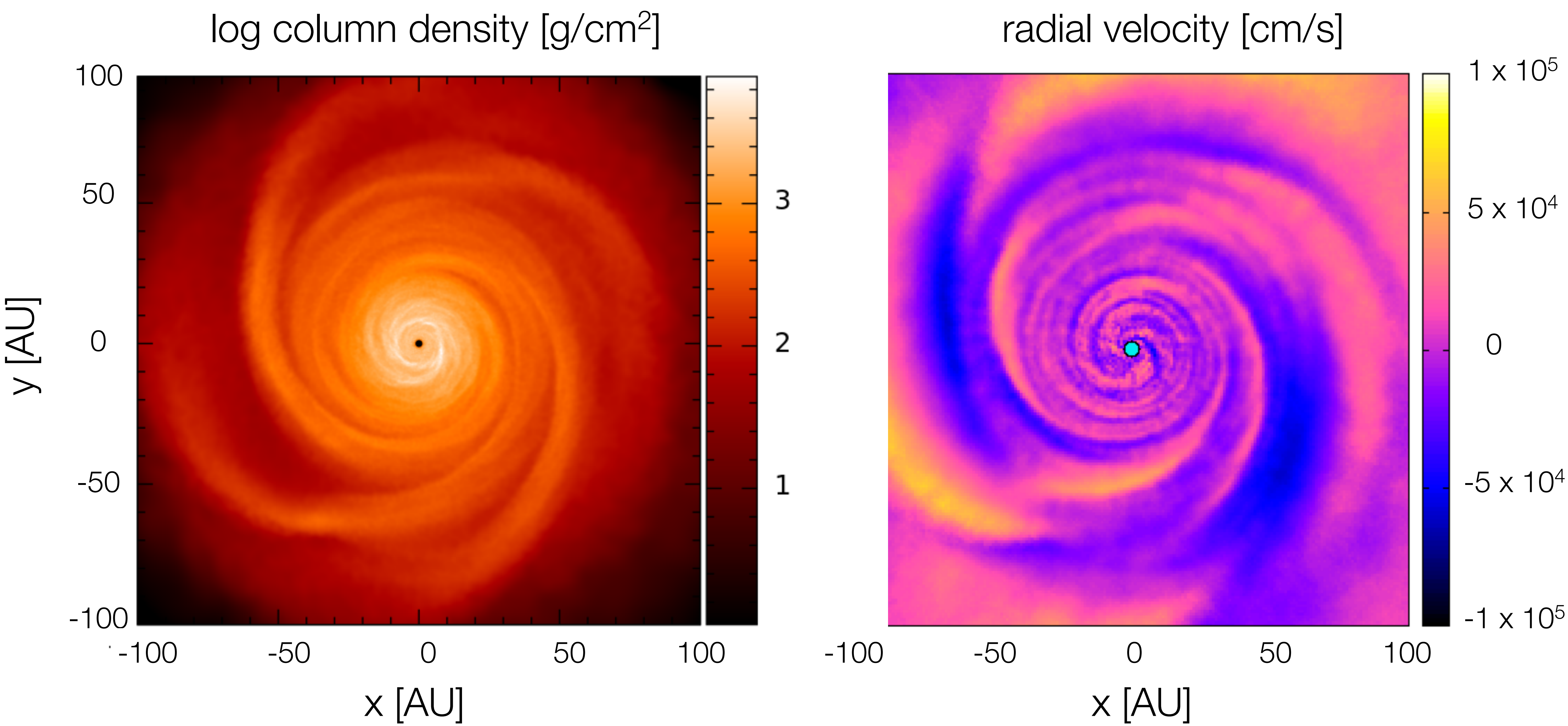


The fragment will have an effect on the surrounding disc material

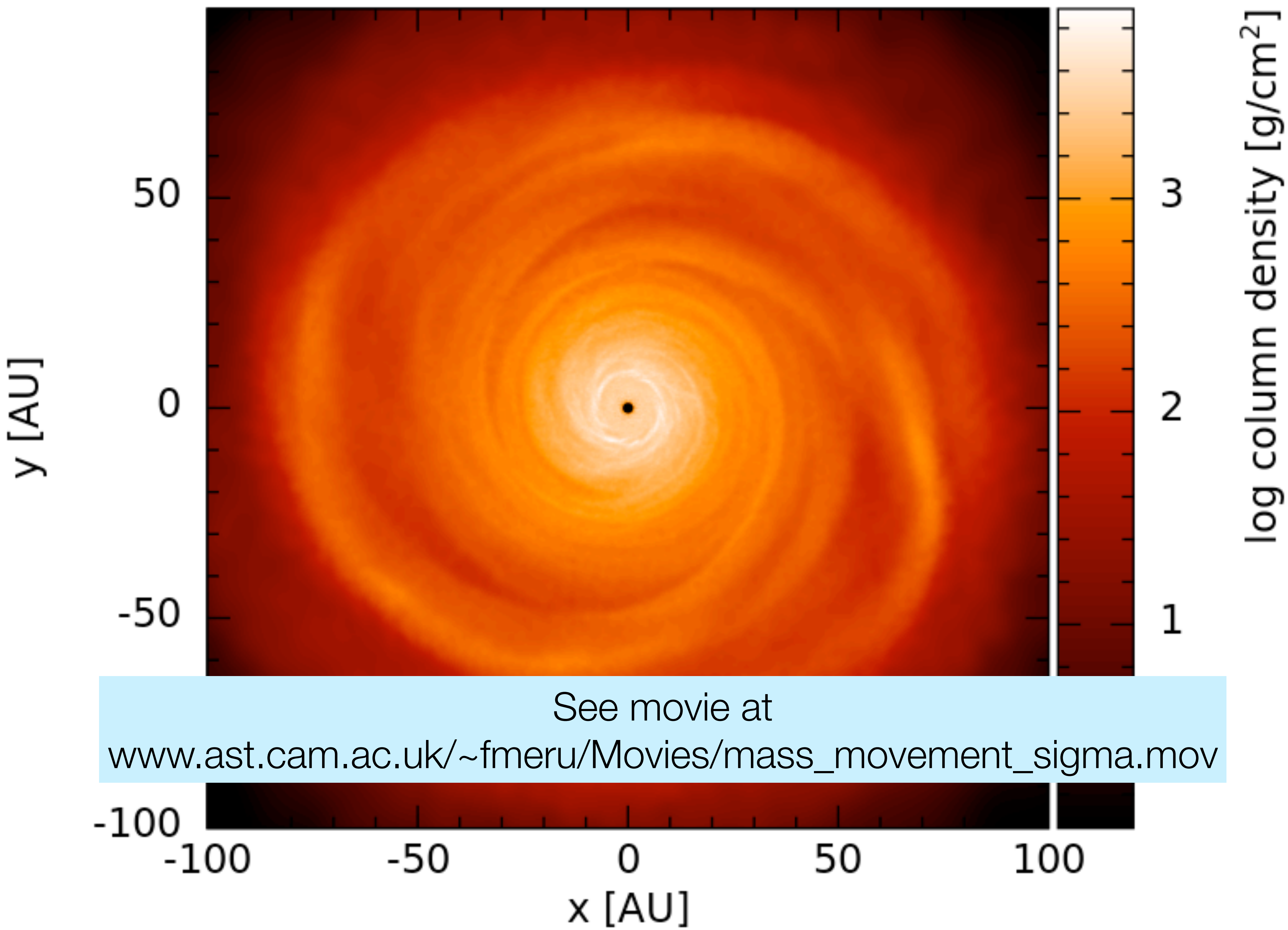
3D SPH simulations with radiative transfer

Self-consistent formation and evolution

Before it fragments the disc is relatively calm

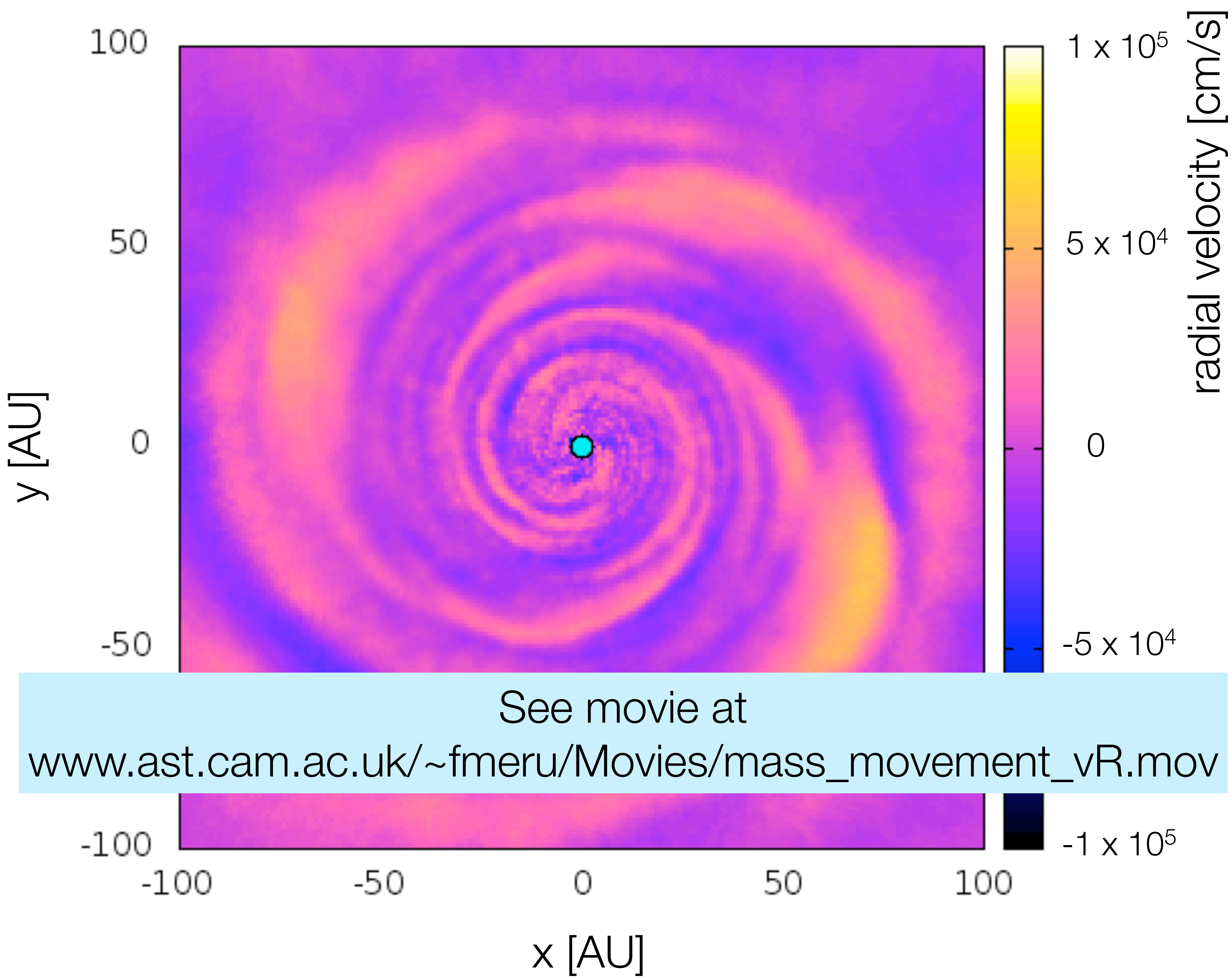


The disc fragments in the outer part and then the inner parts

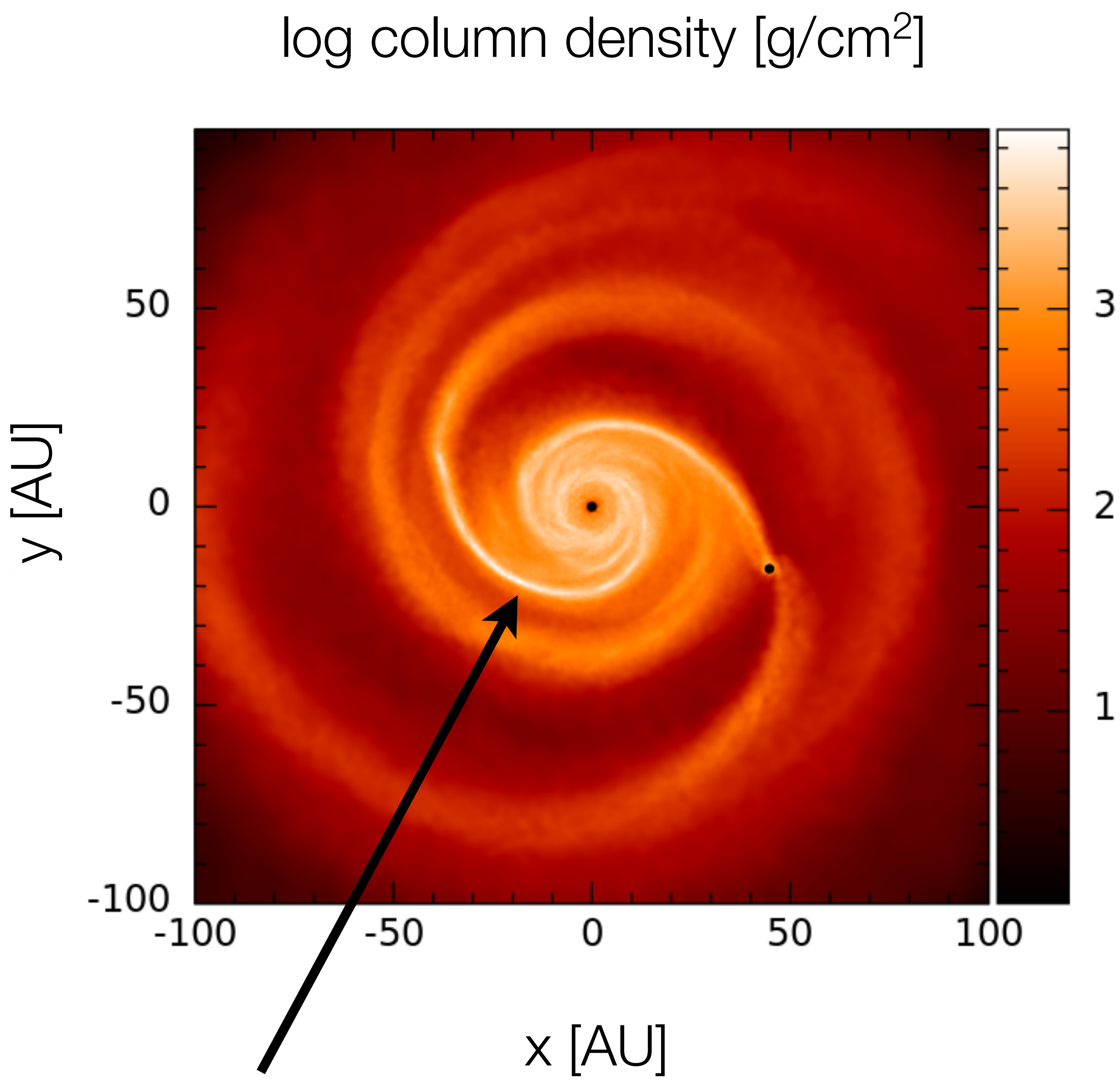


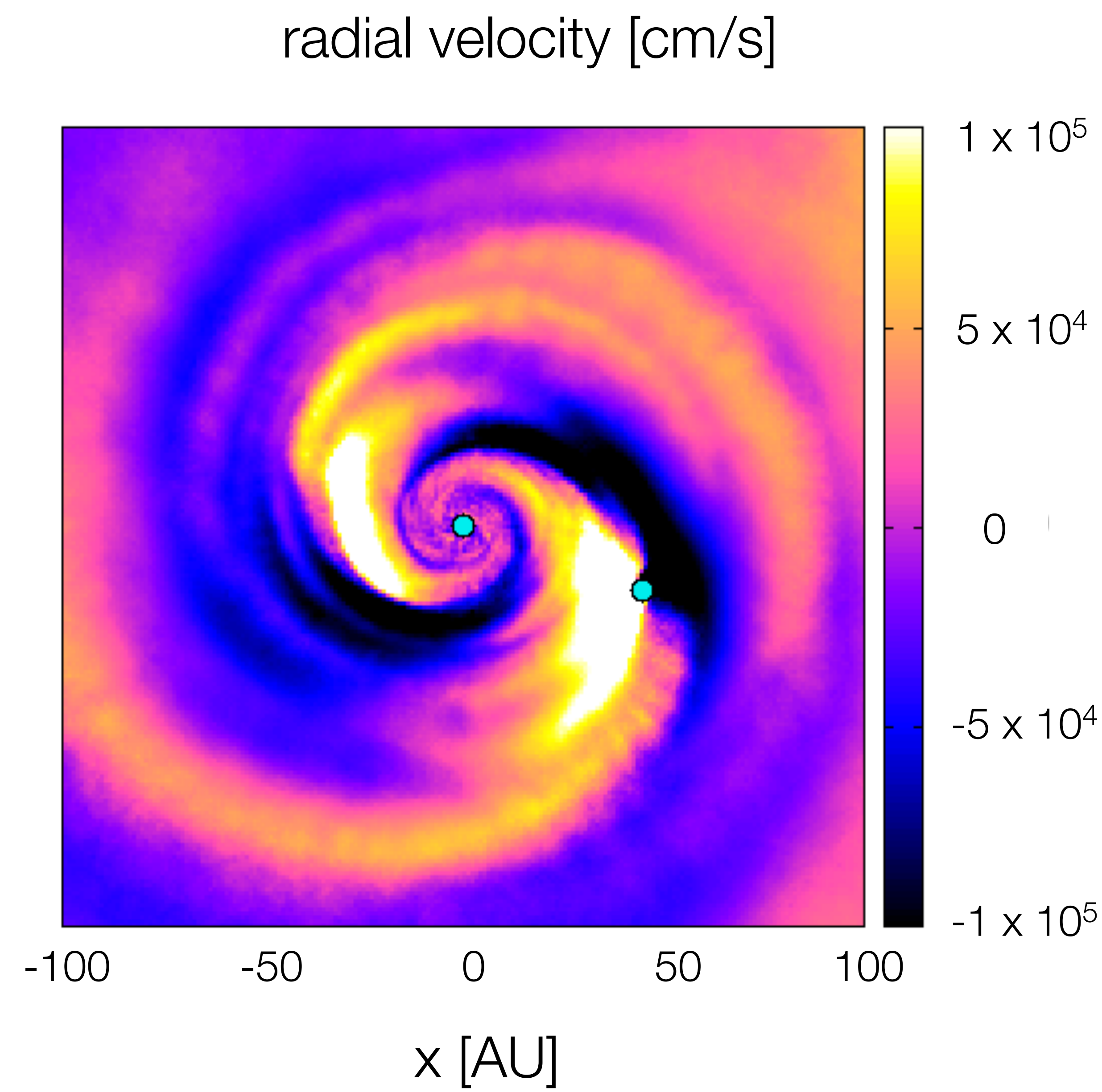
See movie at
www.ast.cam.ac.uk/~fmeru/Movies/mass_movement_sigma.mov

The inwards movement of gas triggers further fragmentation



The gas movement in the disc is more dynamic after fragmentation



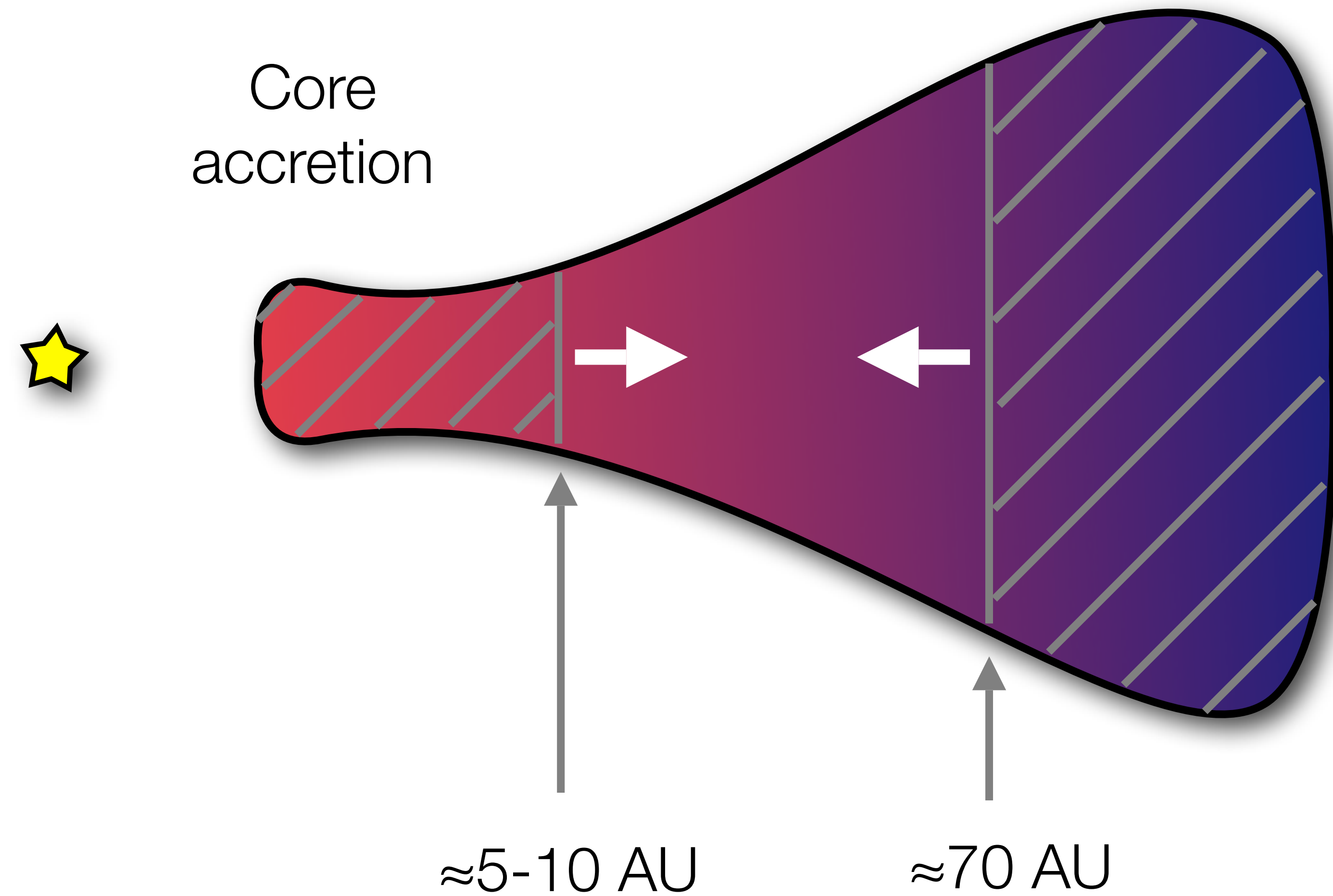


The inwards movement causes the inner spiral to become more dense, lowering the Toomre parameter and allowing further fragmentation

$$Q = \frac{c_s \kappa}{\pi \Sigma G}$$

Meru, in prep
See also Armitage & Hansen 1999

Summary



1. Identified further areas of growth

   Porous aggregates and collisions between high mass ratio aggregates help growth

2. Taking into account velocity distributions significantly helps early stage growth

1. Fragmentation is easier needing slower cooling than previously thought

2. Inwards movement of material due to a fragment can trigger further fragmentation at small radii