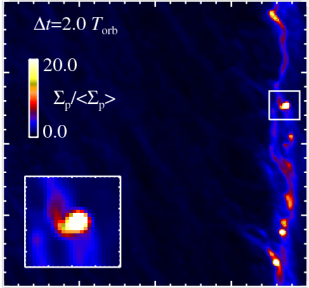
Planetesimal growth and planet formation



Anders Johansen (Leiden University→ Lund**)**

"Exoplanets Rising: Astronomy and Planetary Science at the Crossroads"
Kavli Institute for Theoretical Physics, March–April 2010

Collaborators: **Andrew Youdin**, *Thomas Henning, Hubert Klahr, Wlad Lyra, Mordecai-Mark Mac Low, Jeff Oishi*

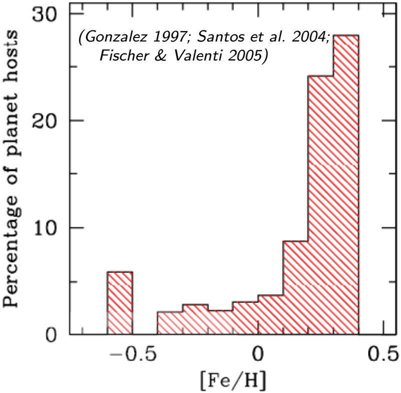
Exoplanet-metallicity connection

- First planet around solar-type star found in 1995

  (Mayor & Queloz 1995)

- Today more than 400 exoplanets known

⇒ Exoplanet probability increases sharply with metallicity of host star



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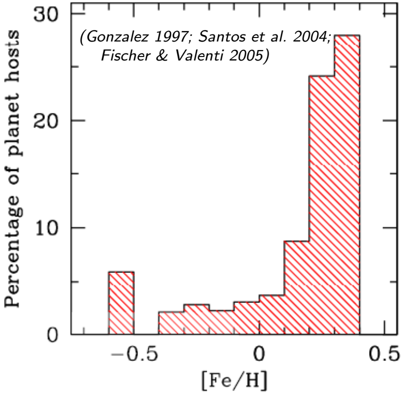

Hydrodynamical models of planetesimal formation exhibit similar sharp dependence on metallicity

Planet formation

Planetesimal hypothesis of Safronov 1969:

Planets form in protoplanetary discs from dust grains that collide and stick together

1. Dust to planetesimals
   μm → cm: contact forces during collision lead to sticking
   cm → km : ???
2. Planetesimals to protoplanets
   km → 1,000 km: gravity
3. Protoplanets to planets
   Gas giants: 10 $M_\oplus$ core accretes gas ($< 10^6$–10^7 years)
   Terrestrial planets: protoplanets collide (10^7–10^8 years)

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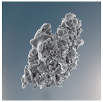

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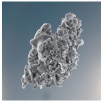

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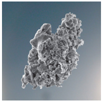

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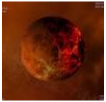

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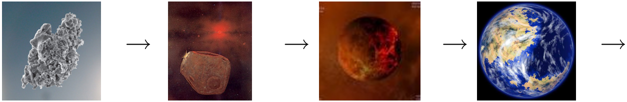

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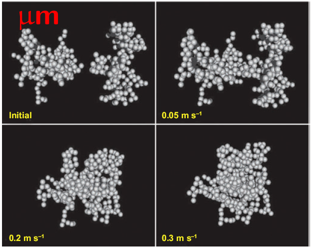
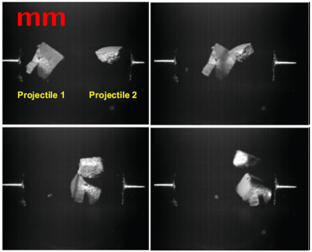
Recipe for making planets?

- Hydrogen and Helium (98,5%)
- Dust and ice (1,5%)
- Coagulation (dust growth)

⇒ Planets?



(Paszun & Dominik)



(Blum & Wurm 2008)

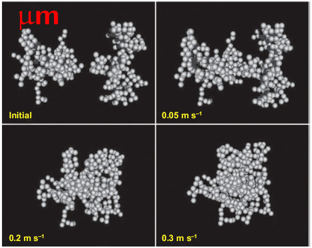
Recipe for making planets?

- Hydrogen and Helium (98,5%)
- Dust and ice (1,5%)
- Coagulation (dust growth)

⇒ Planets? *No*

“Meter barrier”:

- Growth to mm or cm, but not larger
- The problem: *small dust grains stick readily with each other – sand, pebbles and rocks do not*



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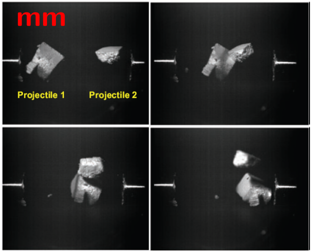

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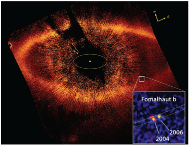
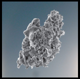
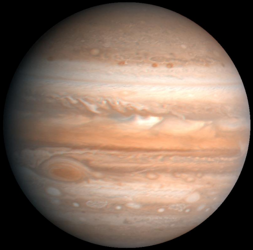
Overview of planets

Protoplanetary discs





Dust grains



Gas giants and ice giants

Pebbles

Terrestrial planets

Dwarf planets

\+ More than 400 exoplanets
\+ Countless asteroids and Kuiper belt objects
\+ Moons of giant planets

Planetesimals

- Kilometer-sized objects massive enough to attract each other by gravity (two-body encounters)
- Assembled from colliding dust grains
- *Building blocks of planets*
- Problems:
  - Pebbles, rocks and boulders:
    - drift rapidly through the disc
    - have terrible sticking properties
  - Protoplanetary discs are turbulent

William K. Hartmann

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William K. Hartmann

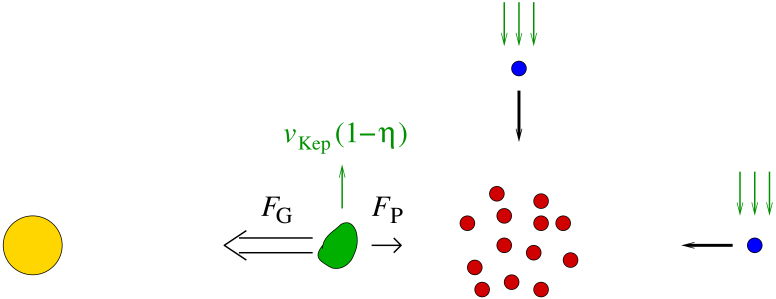
Planetesimal formation must

1. proceed quickly
2. not rely on sticking between large solids
3. operate in a turbulent environment

Streaming instability

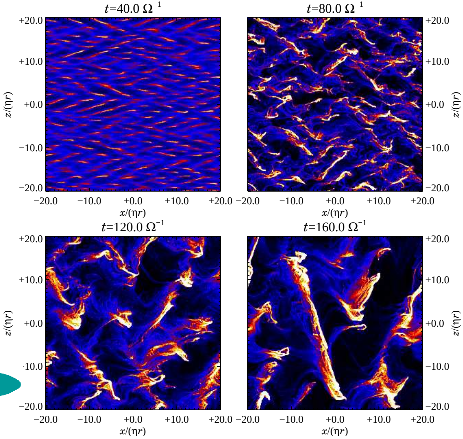
Youdin & Goodman 2005: *(see also Goodman & Pindor 2000)*

- Gas orbits slightly slower than Keplerian
- Particles lose angular momentum due to headwind
- Particle clumps locally reduce headwind and are fed by isolated particles



Clumping

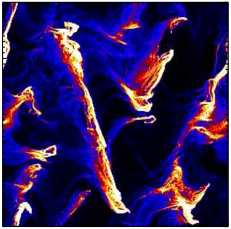
Linear and non-linear evolution of radial drift flow of meter-sized boulders:



Strong clumping in non-linear state of the streaming instability

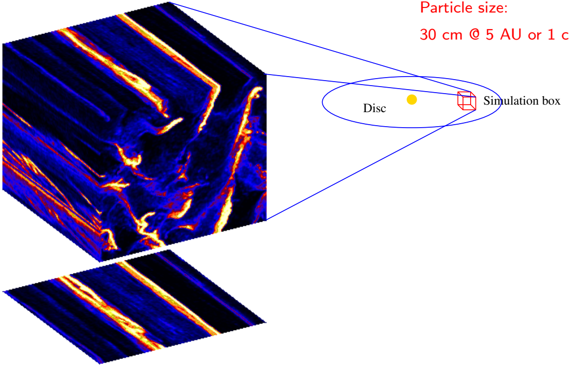
(Youdin & Johansen 2007; Johansen & Youdin 2007; also Bai & Stone in preparation)

Why clump?



Clumping in 3-D

3-D evolution of the streaming instability:



Particle size:

30 cm @ 5 AU or 1 cm @ 40 AU

- Particle clumps have up to 100 times the gas density
- Clumps dense enough to be gravitationally unstable
- But still too simplified:
  - ⇒ no vertical gravity and no self-gravity
  - ⇒ single-sized particles

This talk

⇒ 3-D hydrodynamical simulations of particle sedimentation, including multiple sizes, clumping and self-gravity

I will show that:

This talk

⇒ 3-D hydrodynamical simulations of particle sedimentation, including multiple sizes, clumping and self-gravity

I will show that:

- The streaming instability can provide the necessary ingredients for planetesimal formation
- Clumps readily contract gravitationally to form 100 km radius planetesimals

This talk

⇒ 3-D hydrodynamical simulations of particle sedimentation, including multiple sizes, clumping and self-gravity

I will show that:

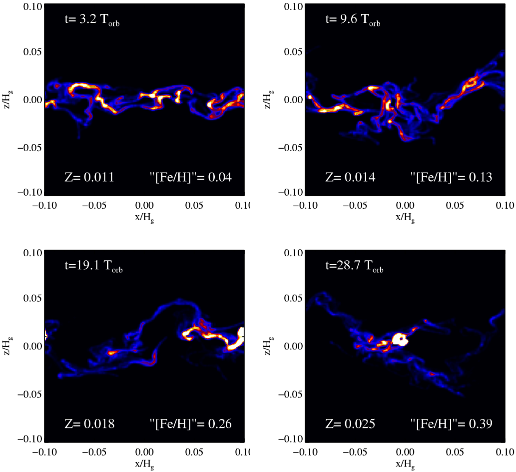
- The streaming instability can provide the necessary ingredients for planetesimal formation
- Clumps readily contract gravitationally to form 100 km radius planetesimals

Clumping depends on metallicity in a way that matches observed correlation between host star metallicity and exoplanets

Sedimentation and clumping

Sedimentation of 10 cm rocks:

- Gas mass decreases with time
- Solar metallicity: puffed up mid-plane layer
- Clumping above $Z \approx 0.02$



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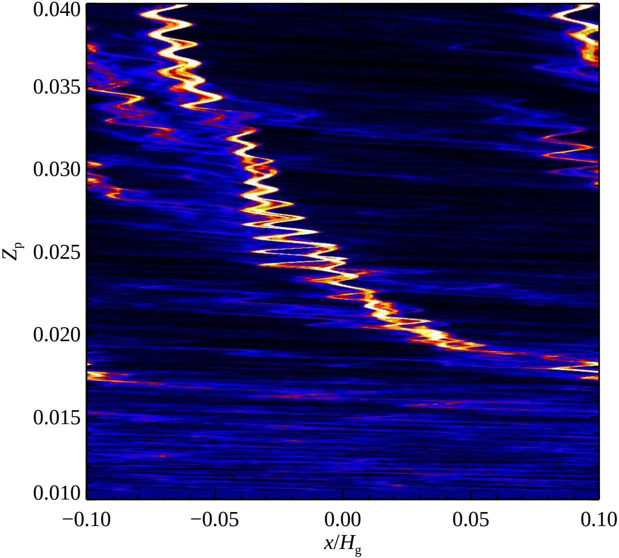

Why is metallicity important?

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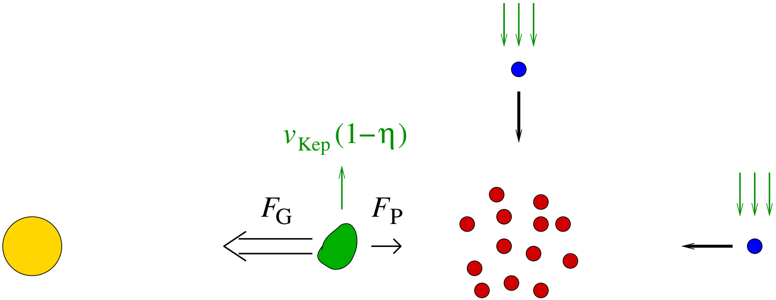
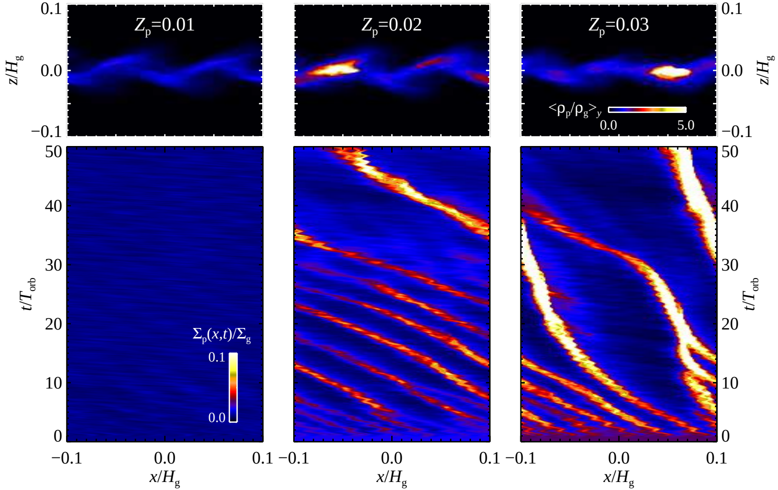


- *Clumping relies on particles being able to accelerate the gas towards Keplerian speed*

Dependence on metallicity

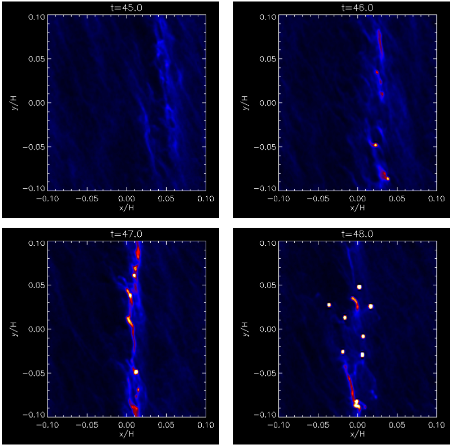
- Particles sizes 3–12 cm at 5 AU, 1–4 cm at 10 AU
- Increase pebble abundance $\Sigma_{\rm par}/\Sigma_{\rm gas}$ from 0.01 to 0.03



Planetesimal formation movie

Time is in Keplerian orbits (1 orbit $\approx$ 10 years)

Keplerian flow



Keplerian flow

Johansen, Youdin, & Mac Low (2009)

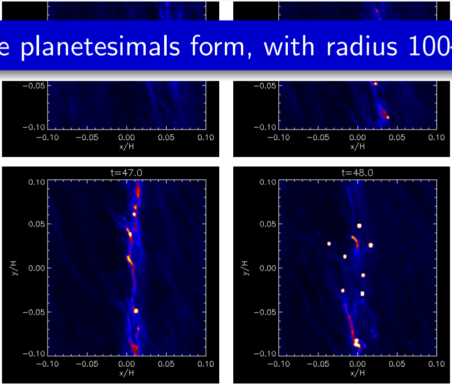
Planetesimal formation movie

Time is in Keplerian orbits (1 orbit $\approx$ 10 years)

Collapse happens much faster than the radial drift time-scale

Massive planetesimals form, with radius 100–200 km

Keplerian flow



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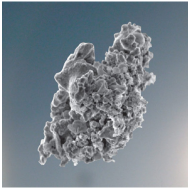
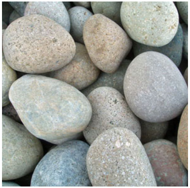
The "clumping scenario" for planetesimal formation

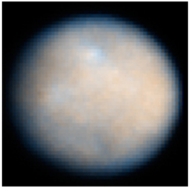
1. Dust growth by coagulation to a few cm



2. Spontaneous clumping through streaming instabilities



3. Gravitational collapse to 100 km radius planetesimals



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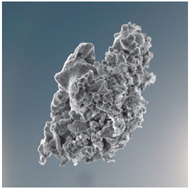

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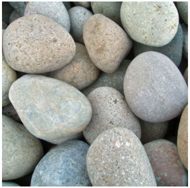

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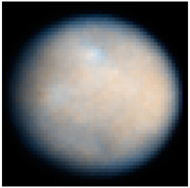
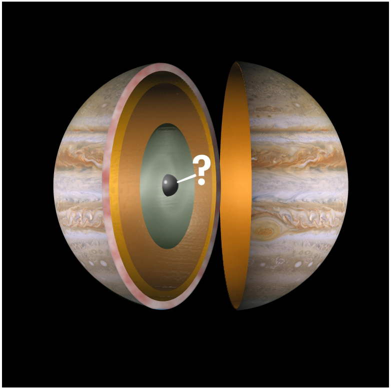


(see John Chambers's talk today for alternative turbulent concentration scenario)

From planetesimals to giant planets

1. Form km-scale planetesimals from dust grains
2. Planetesimals collide and build 10 $M_\oplus$ core
3. Run-away accretion of several hundred Earth masses of gas



(talks by David Stevenson, Jack Lissauer)

Metallicity of host star

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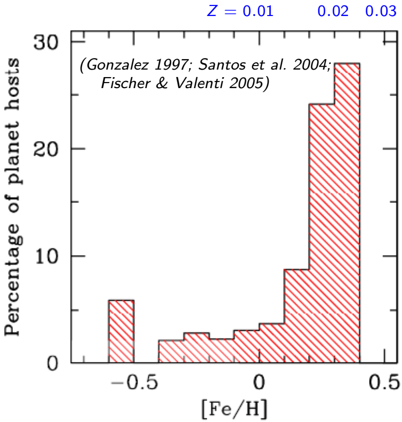
- Today more than 400 exoplanets known
- Exoplanet probability increases sharply with metallicity of host star



⇒ Expected due to efficiency of core accretion
(Ida & Lin 2004; Mordasini et al. 2009)

⇒ . . . but planetesimal formation may play equally big part
(Johansen, Youdin, & Mac Low 2009)

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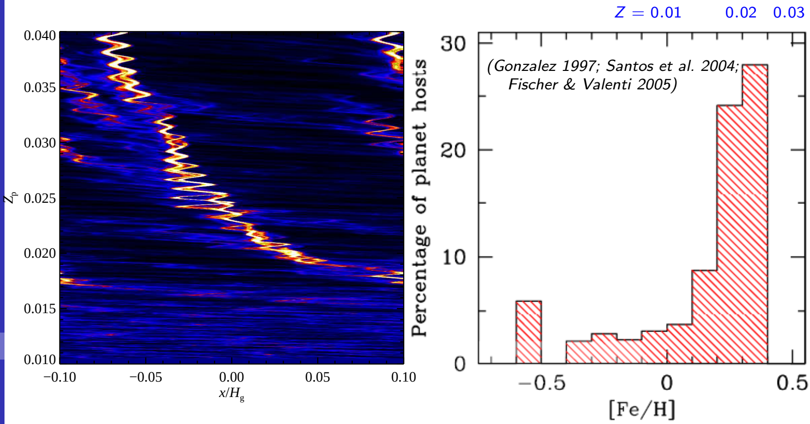

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Several modes of planet formation

- Clumping through streaming instabilities depends *only* on mid-plane dust-to-gas ratio (metallicity), *not* on absolute column density
- However, metallicity is not a constant of a given protoplanetary disc

Protoplanetary discs can obtain critical metallicity by:

1. starting out with high metallicity

   ⇒

2. photoevaporating the gas

   ⇒

3. transport solids radially

   ⇒

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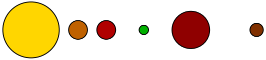
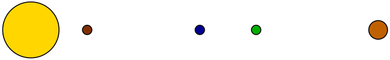
3. transport solids radially
   $\Rightarrow$ restructure debt/mortgage

Low and high metallicity planet formation



High metallicity systems

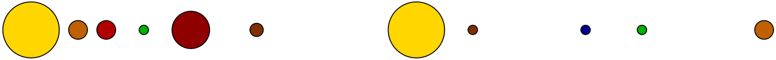
- Planet formation is rapid
- Lots of time to accrete gas
- Moderate mass planets migrate and become hot Jupiters



Solar (or lower) metallicity systems

- Planet formation triggered by photoevaporation
  (Throop & Bally 2005; Alexander & Armitage 2007)
- Little gas when planets form, so gas giants rare and no strong migration

Low and high metallicity planet formation



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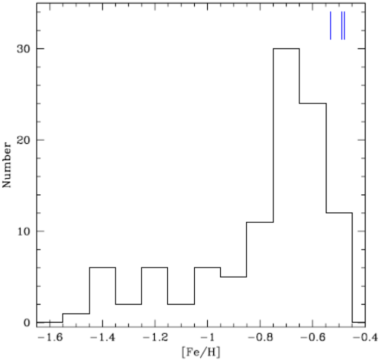
⇒ Predict fewer close in planets in low metallicity systems and that low mass planets can form around low metallicity stars

⇒ Need better statistics of low metallicity systems and low mass planets

Low metallicity planets

Santos et al. (A&A accepted): monitored 100 metal poor stars for planets.



- ⇒ Three planets found
- ⇒ All three planets orbit the most metal rich stars of the sample
- ⇒ *No hot Jupiters* ($a = 1.76, 1.78, 5.5$ AU)

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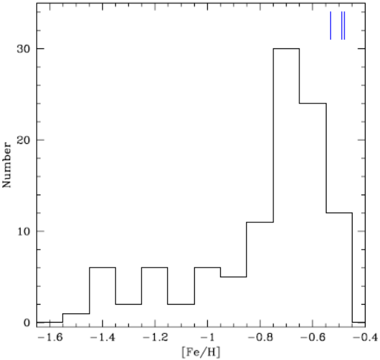

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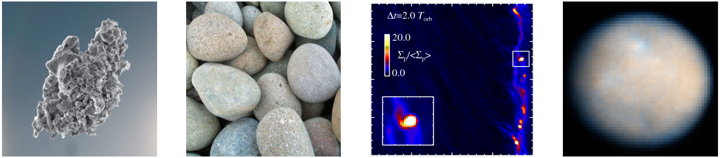
This is a spectacular confirmation that metallicity matters even for systems of intrinsically low metallicity

Conclusions

Clumping through streaming instability relevant because:

1. Based on first principles hydrodynamical calculations
2. Allows formation of planetesimals from pebbles and rocks
3. Efficiency depends very strongly on metallicity and increases sharply above solar metallicity
4. Can be trigged by photoevaporation, opening a new mode of planet formation around metal poor stars

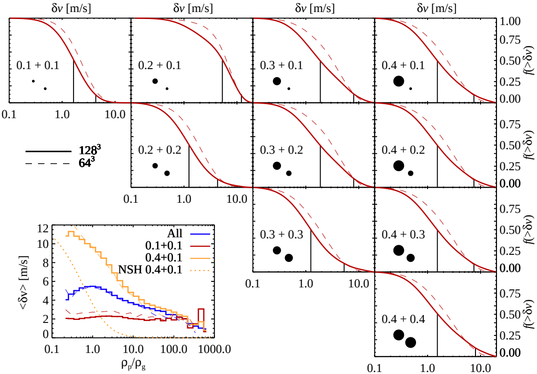
(Johansen, Youdin, & Mac Low 2009)



Collision speeds

Relative speeds of particles measured in single grid cells:

- Typical collision speed 2–5 m/s
- Only 5% of collisions faster than 10 m/s
- Collision speed in dense clumps below 2 m/s



Laundry list

- How do cm-sized pebbles and rocks form out of dust grains?
  (Brauer et al. 2008; Zsom et al. 2010)
- How do pebbles survive radial drift in low metallicity discs?
  (Takeuchi & Lin 2002; Brauer et al. 2007)
- What is the role of collisional fragmentation and coagulation during gravitational collapse
- What is the relative role of small scale turbulent concentrations and large scale streaming instabilities?
  (Cuzzi et al. 2008; John Chambers's talk at this meeting)
- What is the size spectrum of newly formed planetesimals?
  Morbidelli et al. 2009: Asteroids were born big
  Core accretion and certain debris discs: Planetesimals should be small