How can dust aggregates *really* grow by collisions in protoplanetary disks?

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CAROLO-WILHELMINA BRAUNSCHWEIG

DFG Research Group Planet Formation

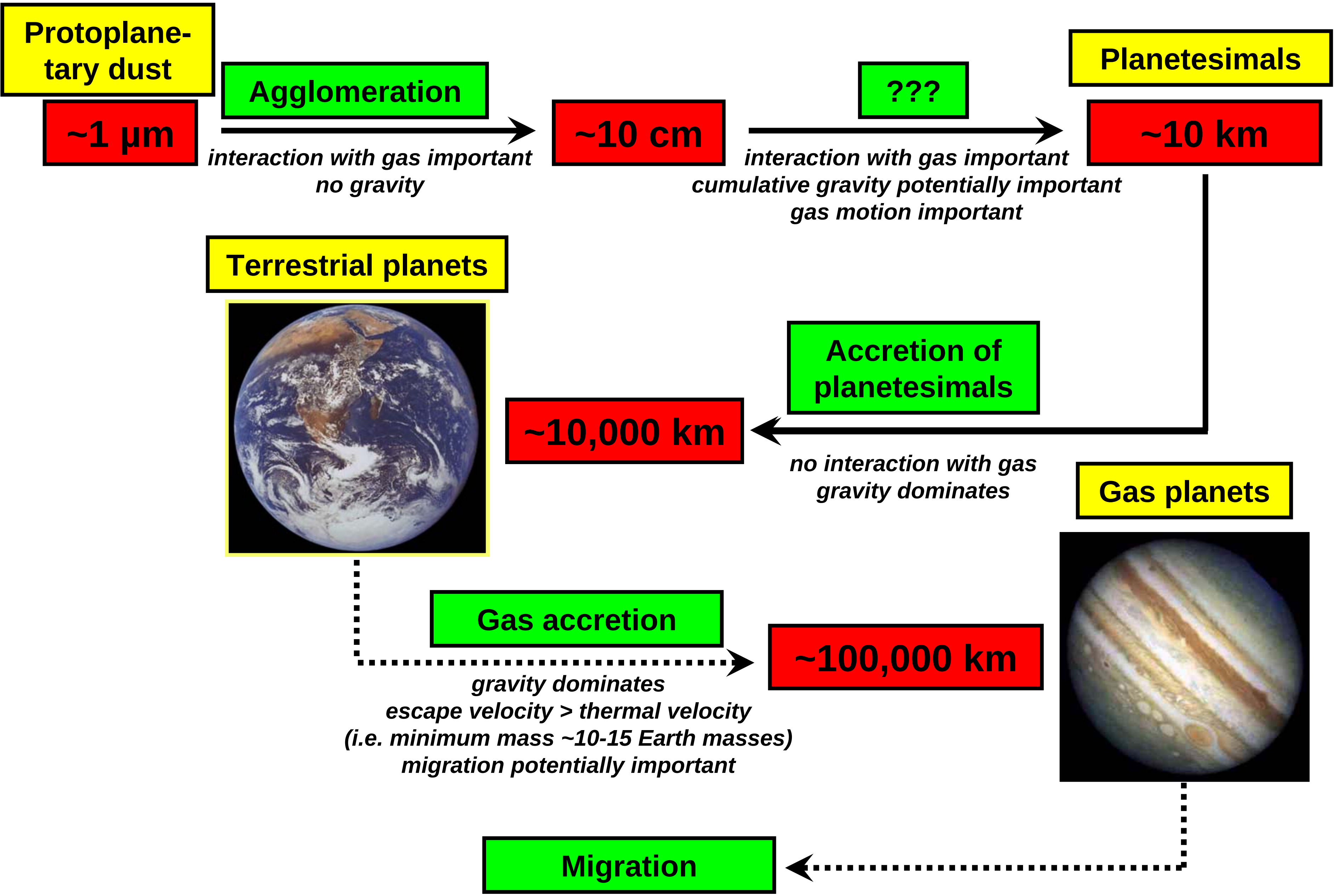
Contents

1.
An overview on planet formation

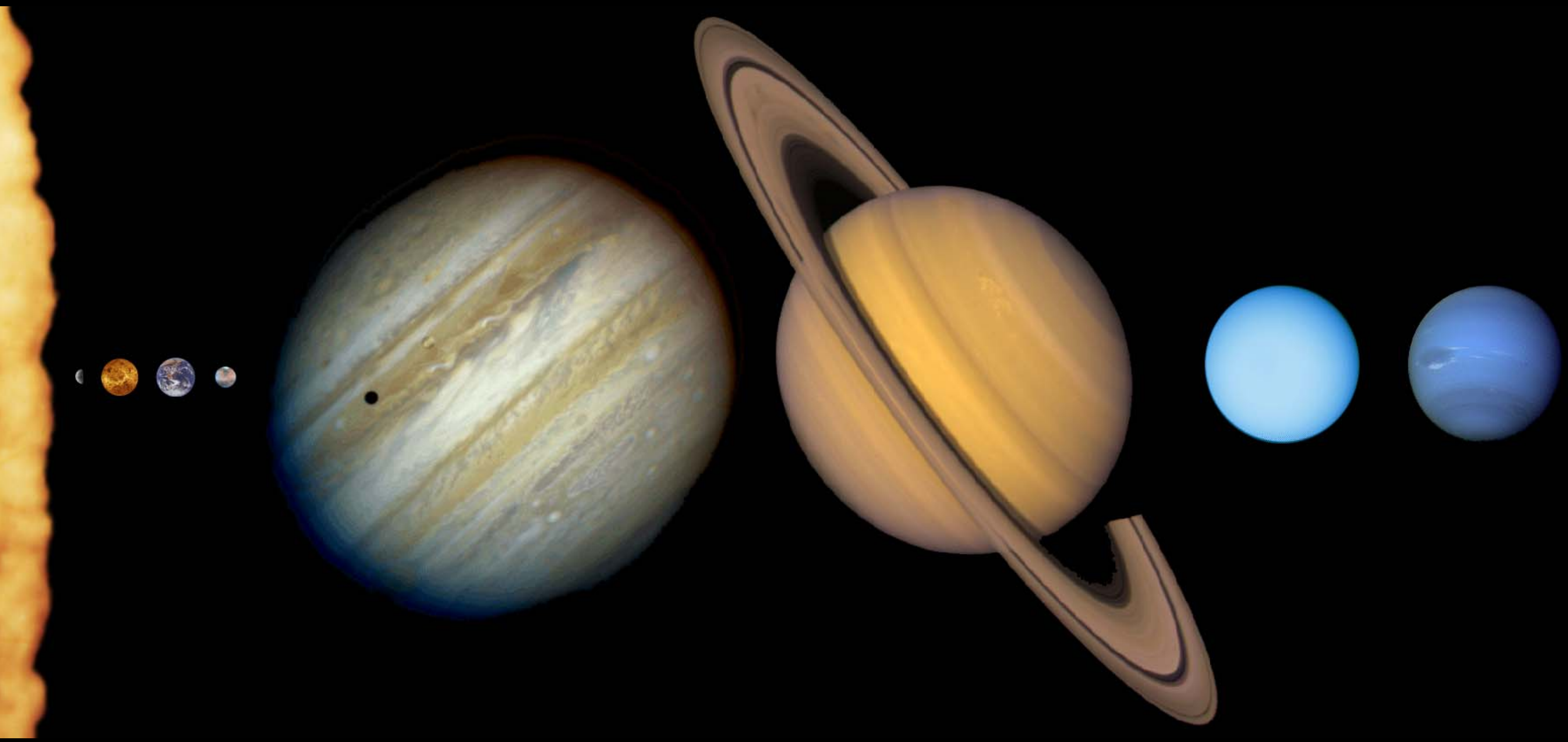
A small chronology of the world

13,7 Gyr	Big bang; formation of the elements H and He
13,4 Gyr	First stars and galaxies; first supernova explosions produce the heavy elements (C,N,O,Si,Fe,…)
12 Gyr	Formation of the milky way
4,567 Gyr	Formation of the solar system; at this point in time the interstellar medium has been enriched with 1% heavy elements
4,5 Gyr	Formation of the earth and the moon
4,45 Gyr	Layer structure of the earth
4,4 Gyr	Solid earth crust
4,2 Gyr	Early ocean
4 Gyr	Plate tectonics
>3,5 Gyr	Earth's magnetic field
>3,5 Gyr	Origin of life
2,3 Gyr	Formation of oxygen-rich atmosphere; formation of ozone
1 Gyr	"Freeze-out" of inner earth core
0 Gyr	Today

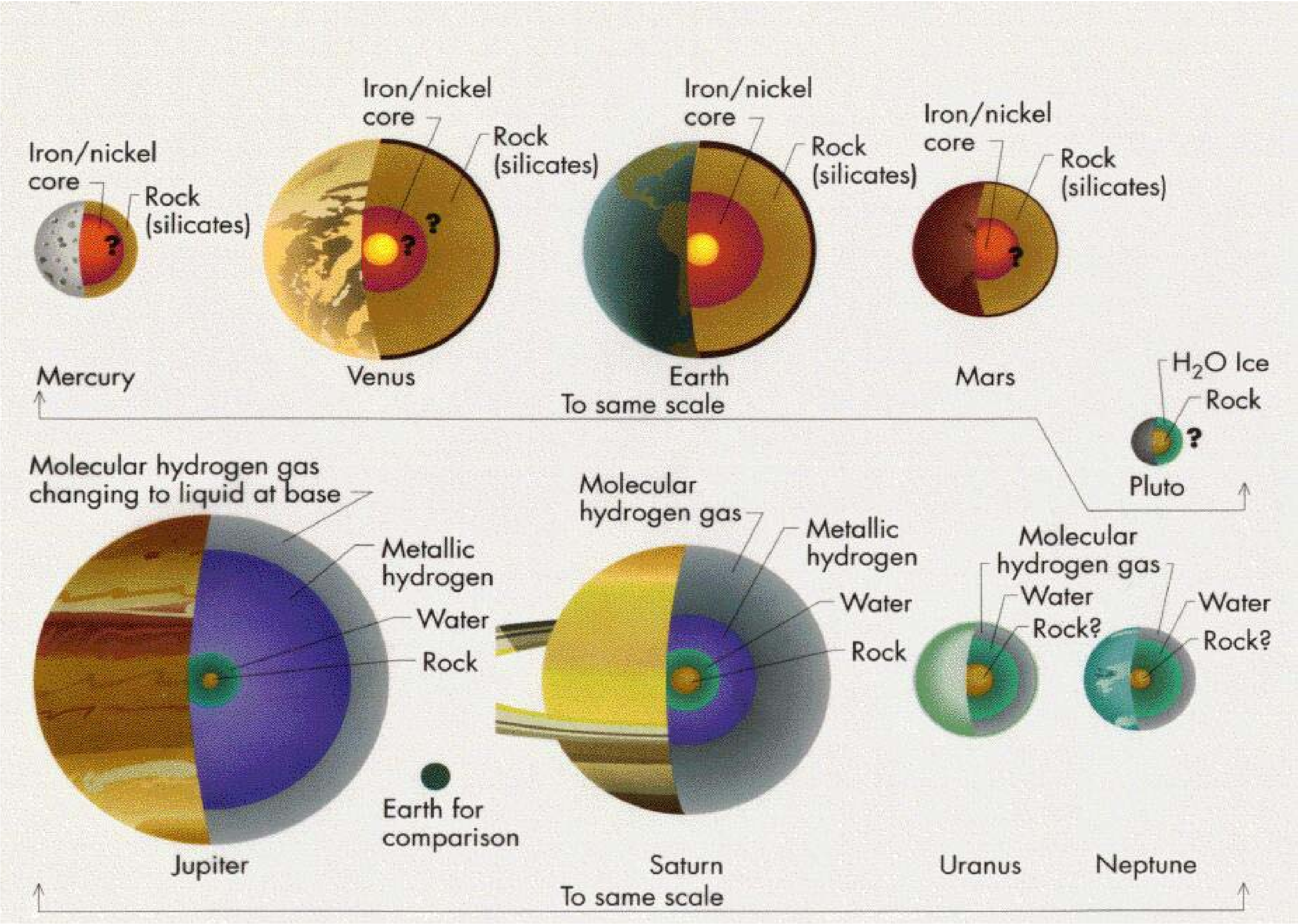
The five-stage process of planet formation



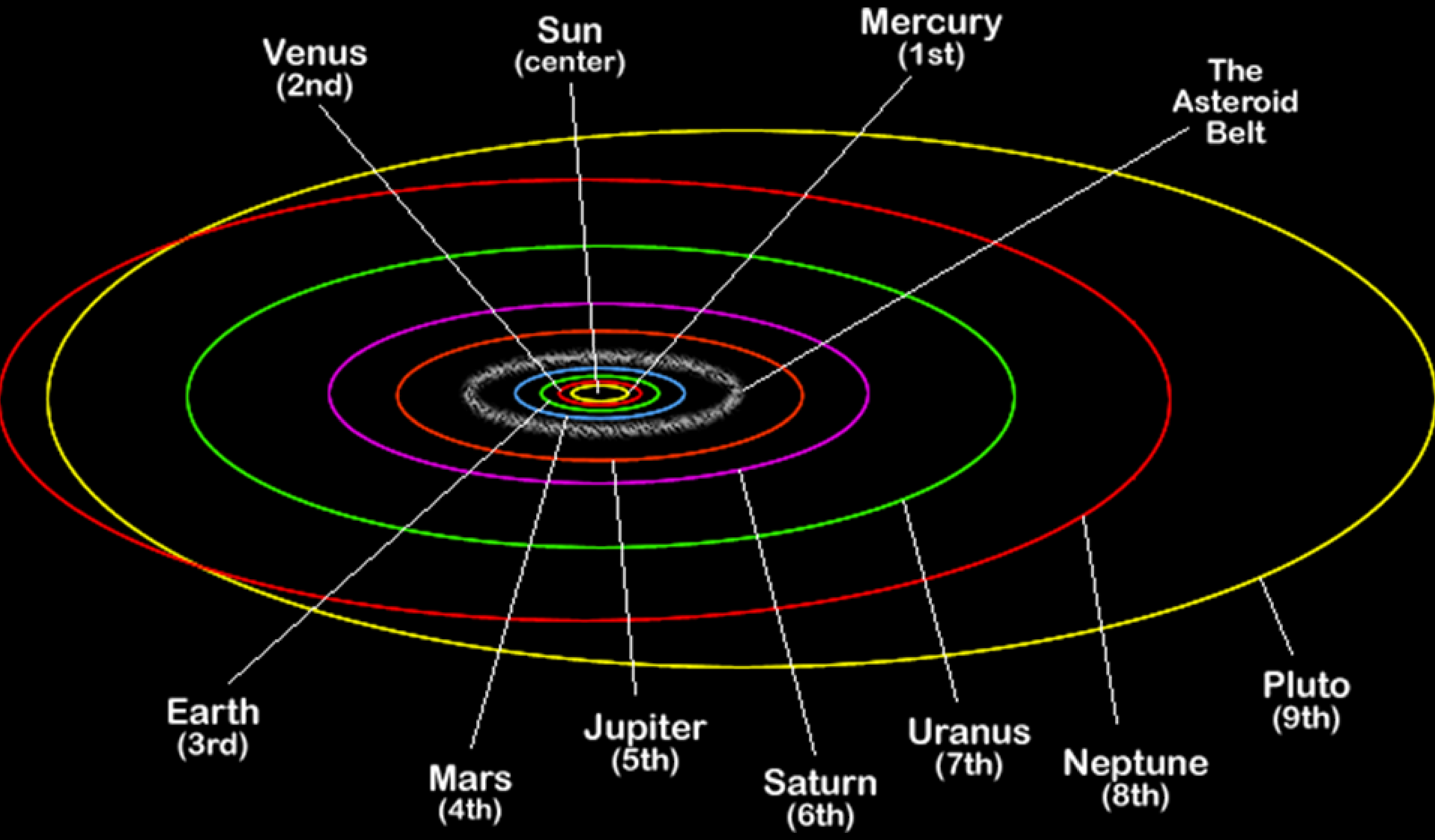
The planets of the solar system



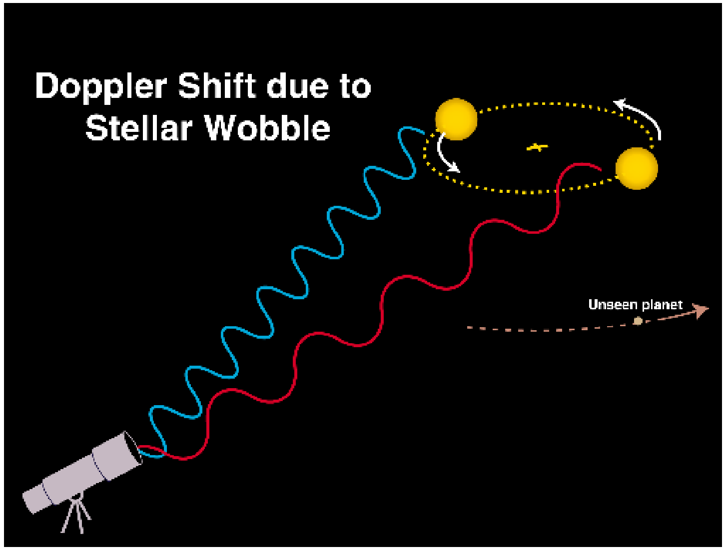
Terrestrial vs. gaseous planets



The planets of the solar system

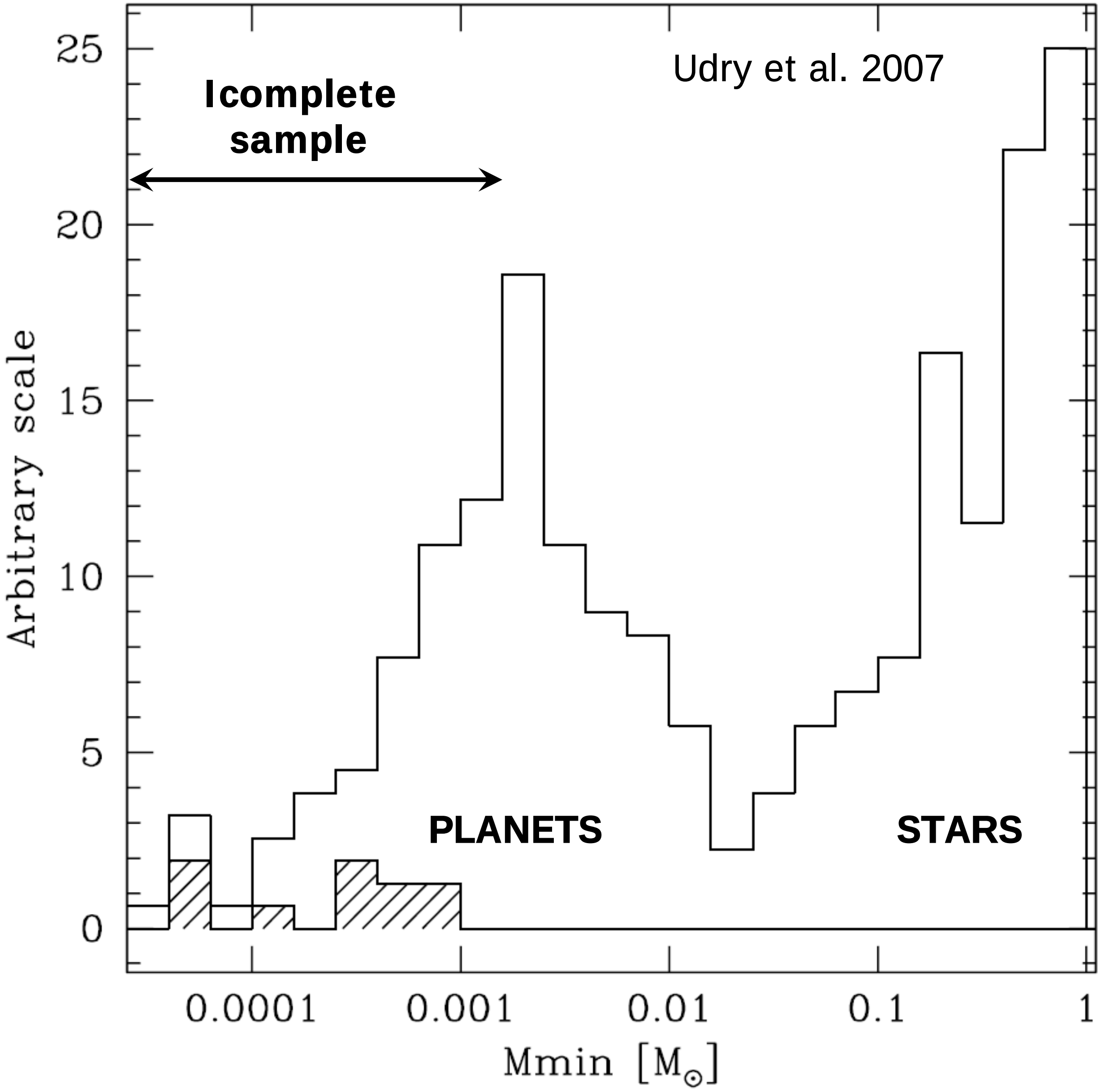


Extrasolar planets

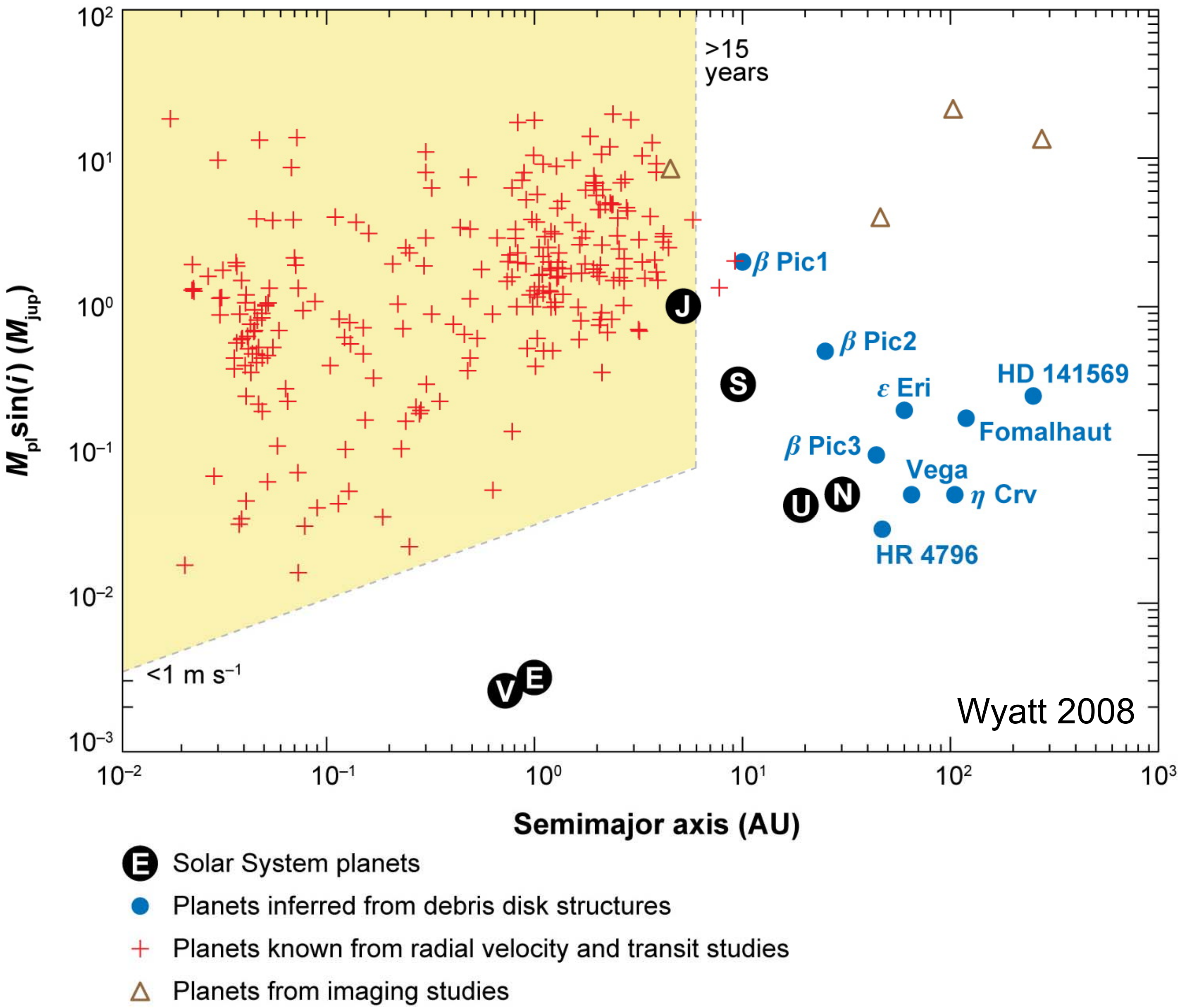


- Planets around solar-type stars
- Total of 333 extrasolar-planet candidates (17 Dec 2008)
  - Spectroscopically detected: 307
  - Transits: 54
- System with 2 or more planets: 31
- Planetary systems in double stars: 30
- Planetary systems in resonance: 5-7
- Fraction of stars with planets: 0-25% (depending on metallicity of the star)

Mass distribution of extrasolar planets



Orbits of extrasolar planets

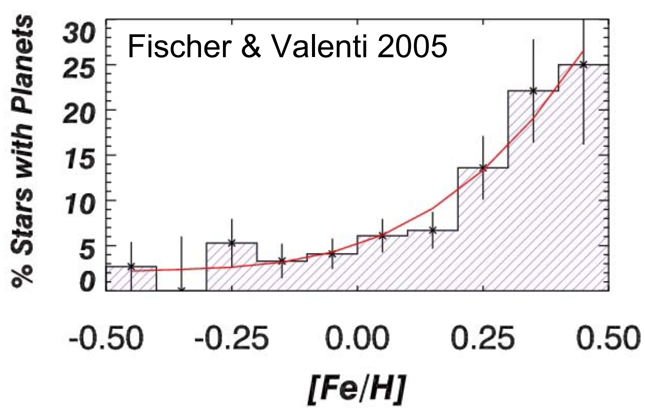


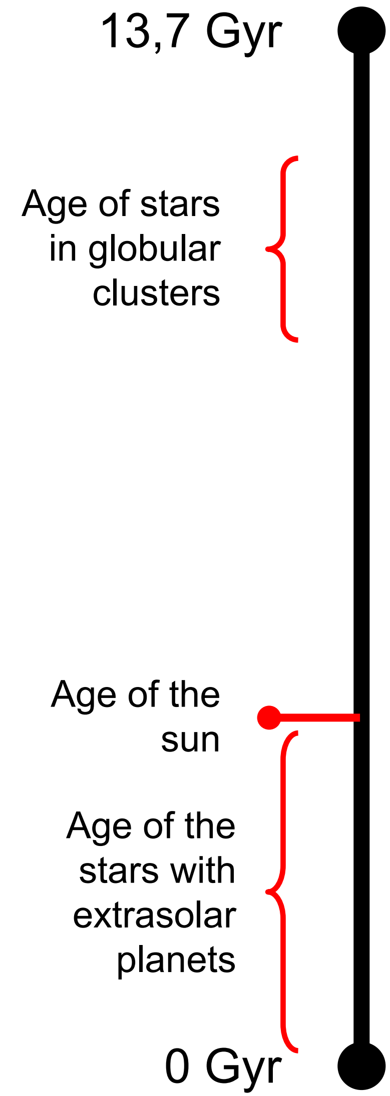
About the metallicity of stars and the connection to planets

▷ The search for planets around stars in globular cluster has so far been unsuccessful; stars in globular clusters possess metallicities «1%.

▷ The sun possesses a metallicity of ~1%.

▷ The mean metallicity of stars with extrasolar planets is >1%.

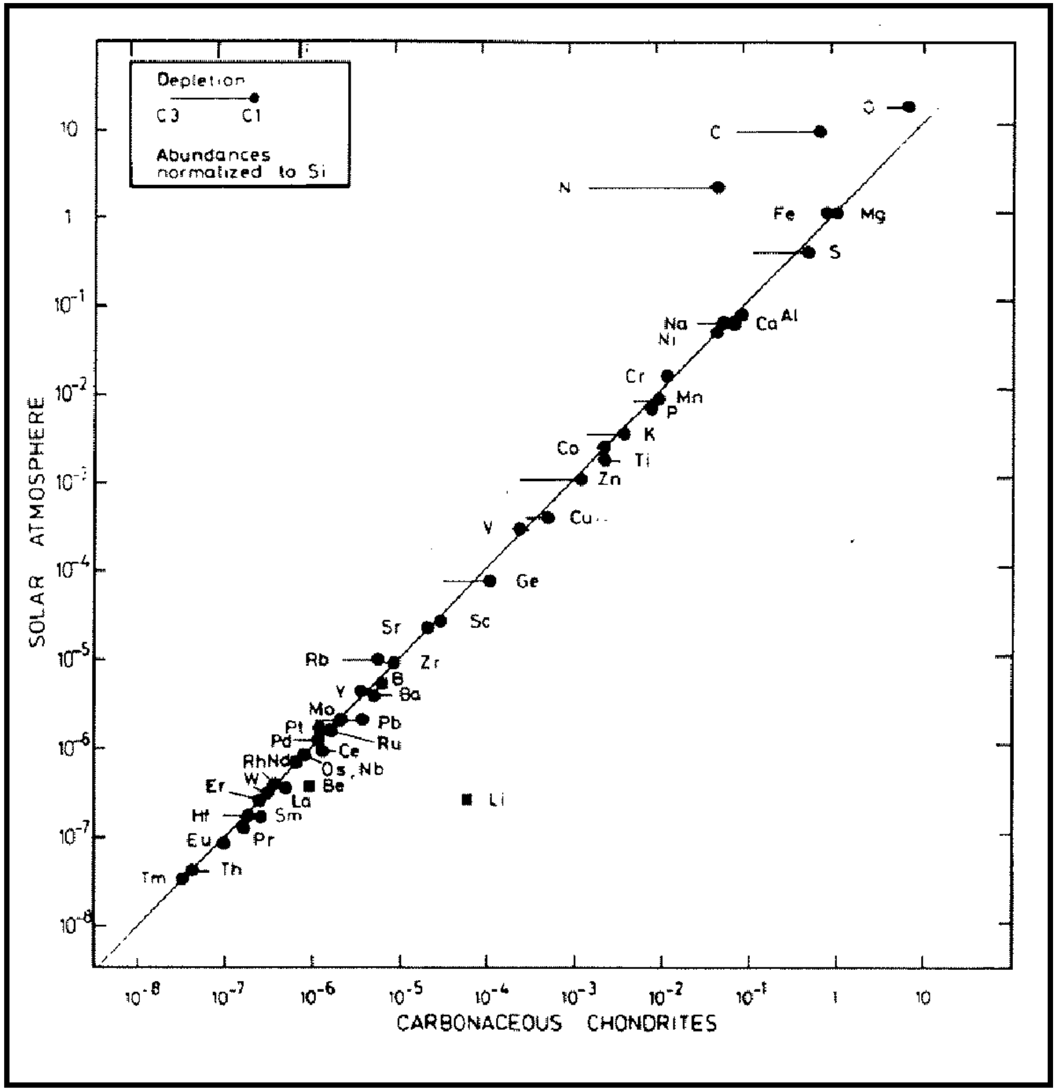




Star and planet formation belong together!

The sun and the planets of our solar system formed at the same time and from the same material reservoir:

- ▷ Elementary abundances
- ▷ Age of the meteorites = age of the sun
- ▷ Parallel angular momentum of sun and planets



Cowley 1995

Star and planet formation belong together!

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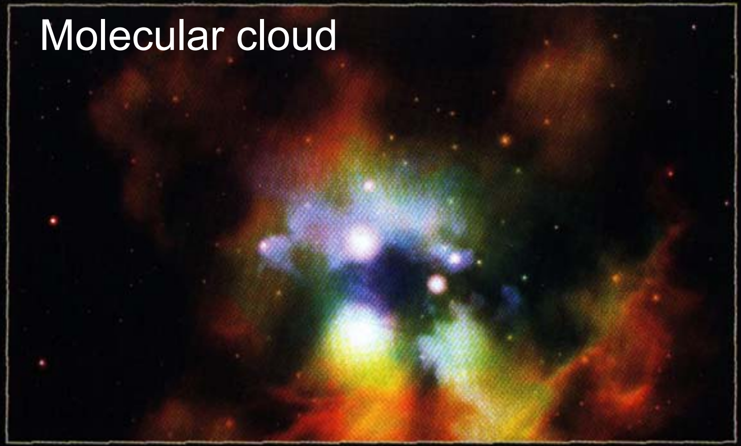
Radiometric dating:

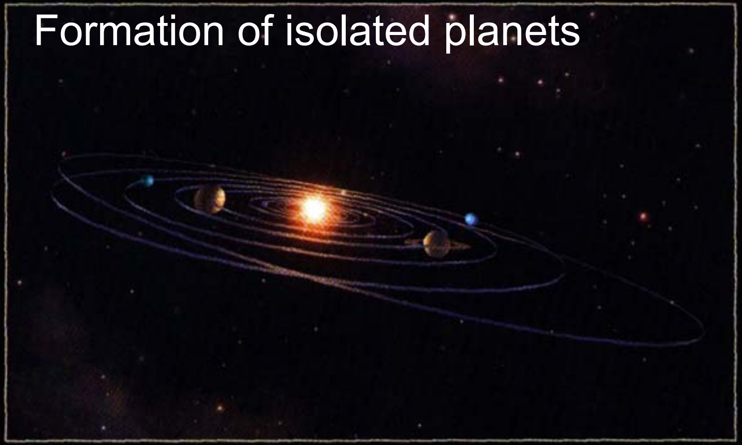
Material	Age
Earth (Zircon, Australia)	4.40 Gyr
Moon (highland rocks)	4.1-4.4 Gyr
Meteorite (oldest from Mars)	4.5 Gyr
Meteorite (chondrules)	4.564 Gyr
Meteorite (CAI)	4.567 Gyr

Age determination of the sun (evolutionary models and helioseismology data):

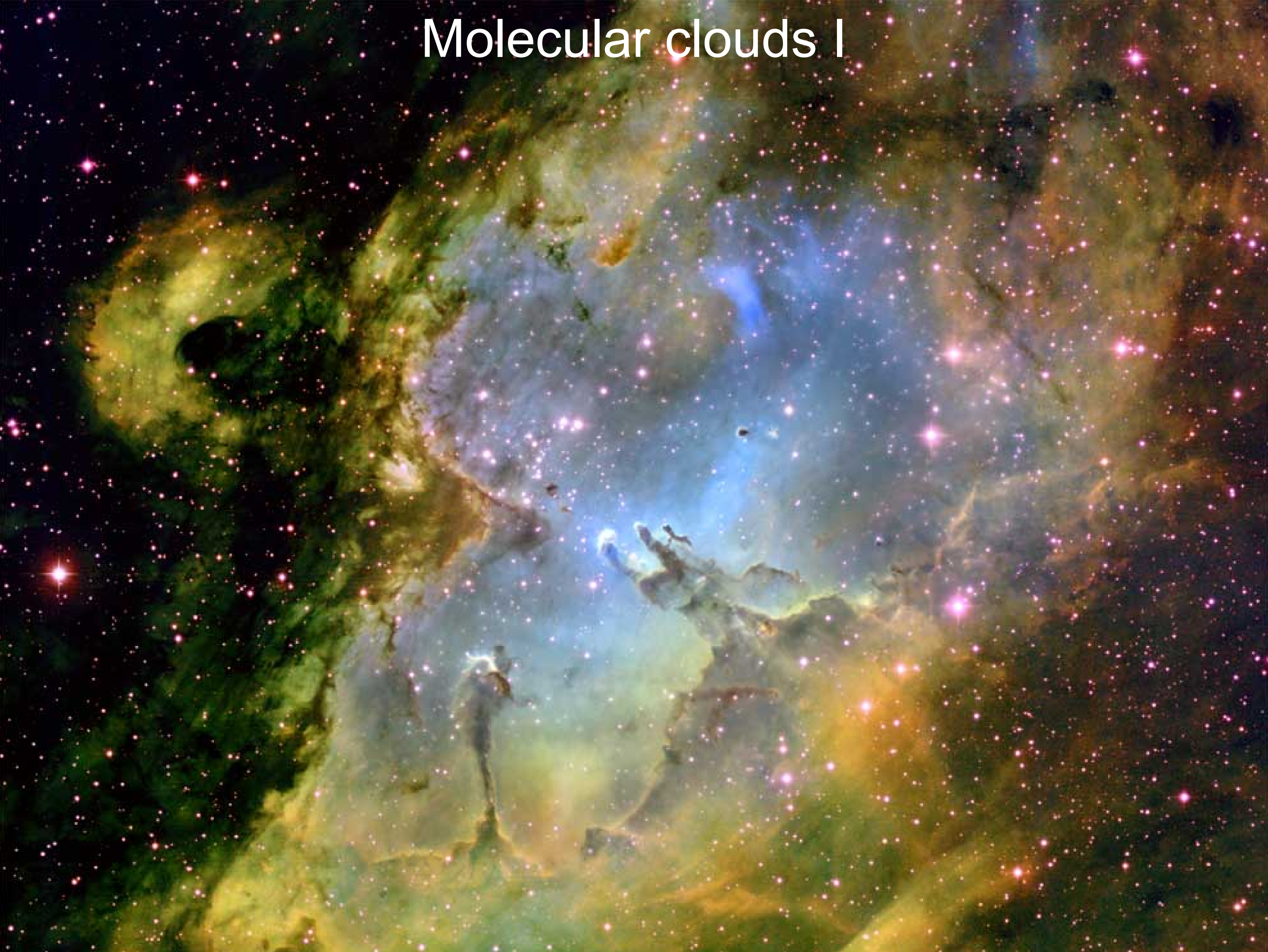
Authors	Age
Guenther & Demarque 1997	4.5±0.1 Gyr
Bonnano, Schlattl & Paterno 2002	4.57±0.11 Gyr
Houdek & Gough 2007	4.68±0.02 Gyr

Star formation – an overview



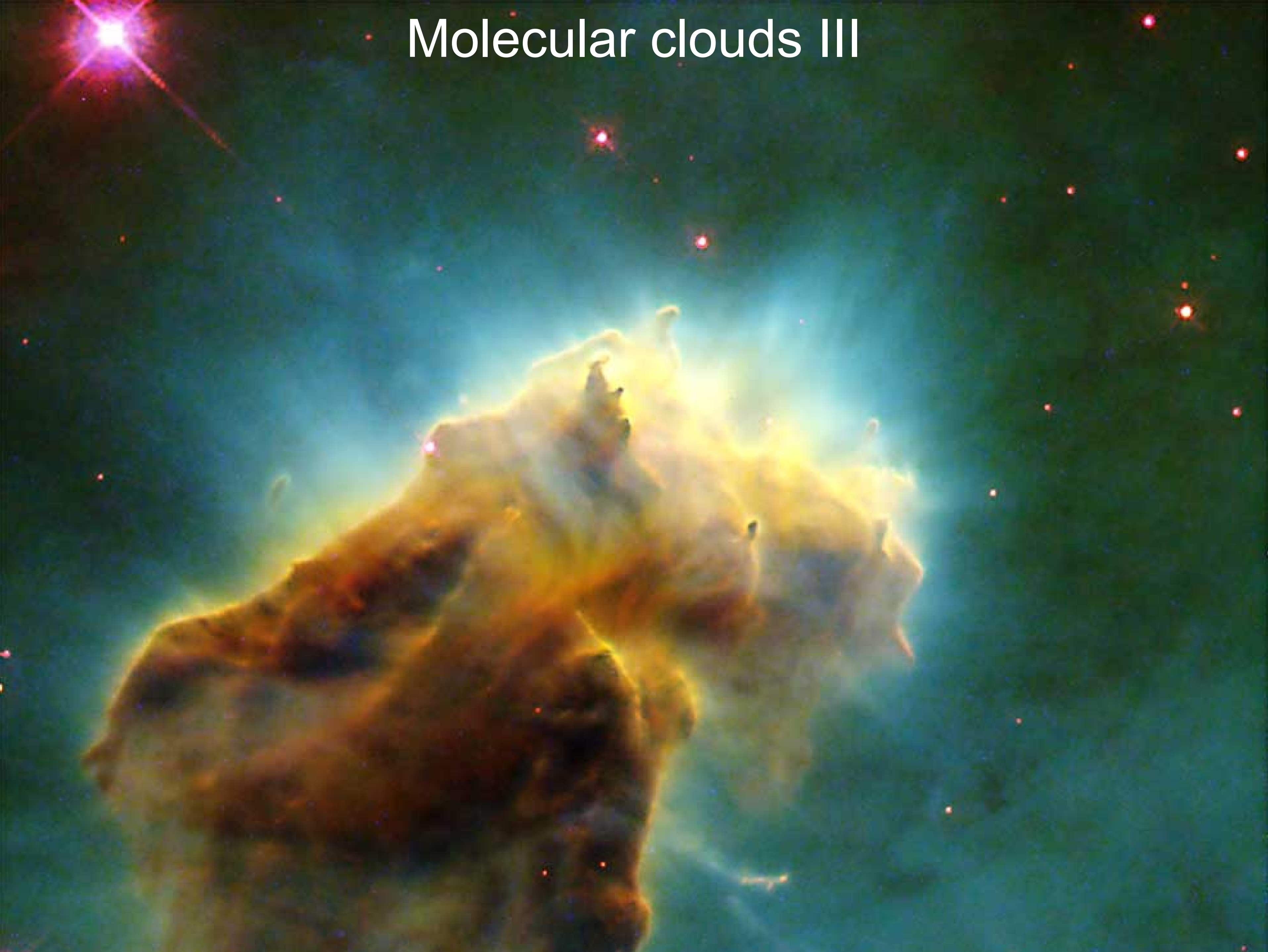


Molecular clouds I



Molecular clouds II

Molecular clouds III



Molecular clouds IV: dust and gas

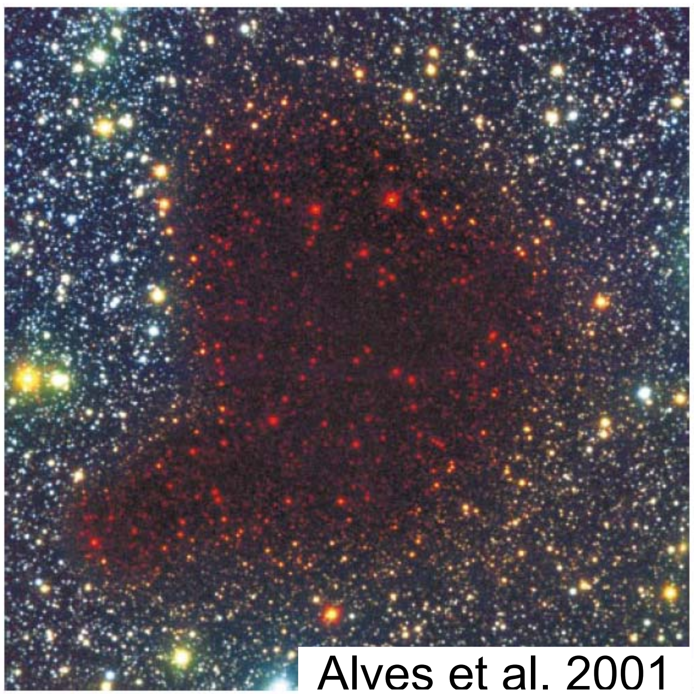
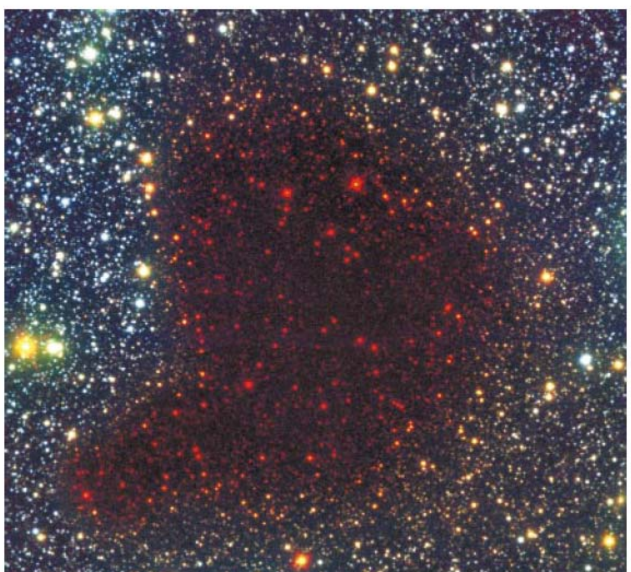


Figure 1 Visible and near-infrared images of Barnard 68. Top, deep B,V,I band (0.44 μm, 0.55 μm, 0.90 μm) image (~7′ × 7′) of the dark molecular cloud Barnard 68 taken with ESO's Very Large Telescope (VLT) located in the Chilean Andes. The cloud is seen in projection against the Galactic bulge. At these optical wavelengths the cloud is completely opaque owing to extinction of background starlight caused by small interstellar dust particles that permeate the cloud. The complete absence of foreground stars projected onto the cloud is a result of the proximity of the cloud to the Solar System (125 pc). The outer radius of the cloud is comparable to the inner size of the Oort cloud of comets that surround the Sun (~10^4 AU). The mass of the cloud is about twice that of the Sun. Bottom, deep B,I,K band image of the cloud constructed by combining an infrared K band (2.2 μm wavelength) image with the B and I images. The K band image was obtained with ESO's New Technology Telescope (NTT) in the Chilean Andes. At near-infrared wavelengths the cloud becomes transparent and the stars located behind the cloud clearly appear in the image. Because these stars are observed only in the longest of the three wavelength bands, they appear very red in this three-colour image. These are the stars that provide measurements of dust extinction directly through the cloud.

Molecular clouds V: the interior



Alves et al. 2001

Bianchi et al. 2003

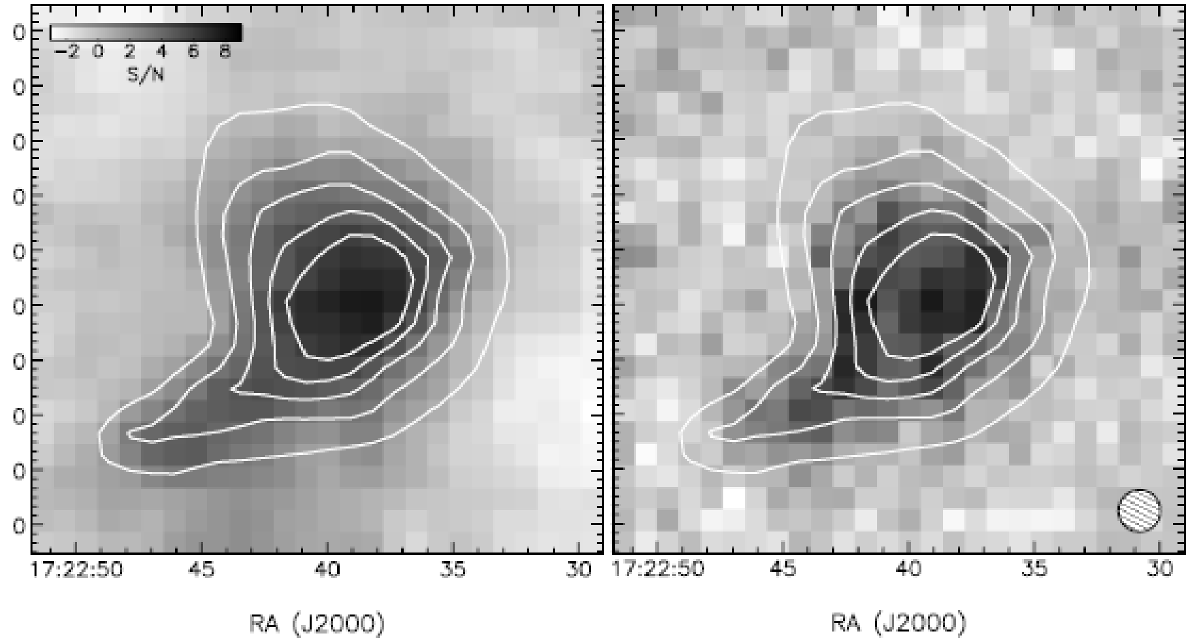
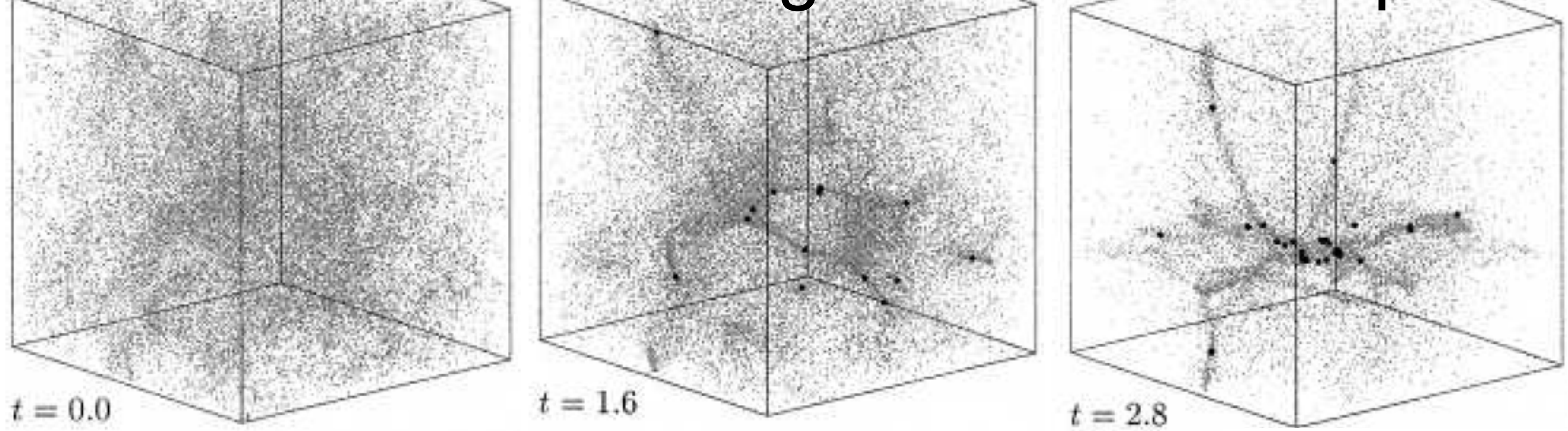


Fig. 1. SCUBA map at 850 μm (left) and SIMBA map at 1.2 mm (right) of Barnard 68, with superimposed A_V contours. The A_V and SCUBA maps have been smoothed to match the SIMBA resolution ($FWHM$ = 24″; the beamsize is shown on the right image). All images have been resampled to a pixel size of 12″. The field of view is 5′ × 5′. A_V contours start at 4 mag and are spaced by 4 mag. For both images, the grayscale in units of S/N.

Molecular clouds VI: gravitational collapse



Bonnell et al. 2007

Fig. 2.— The gravitational fragmentation of molecular cloud is shown from a simulation containing initial structure (*Klessen et al.*, 1998). The gravitational collapse enhances this structure producing filaments which fragment to form individual stars. The time t is given in units of the free-fall time.

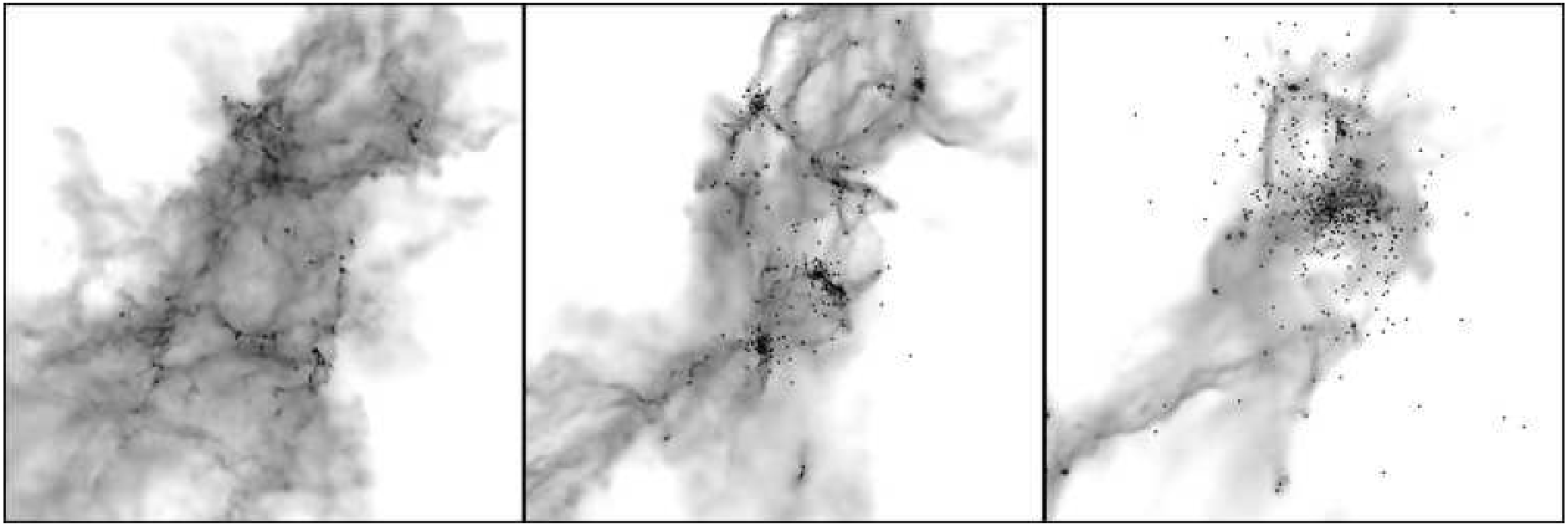
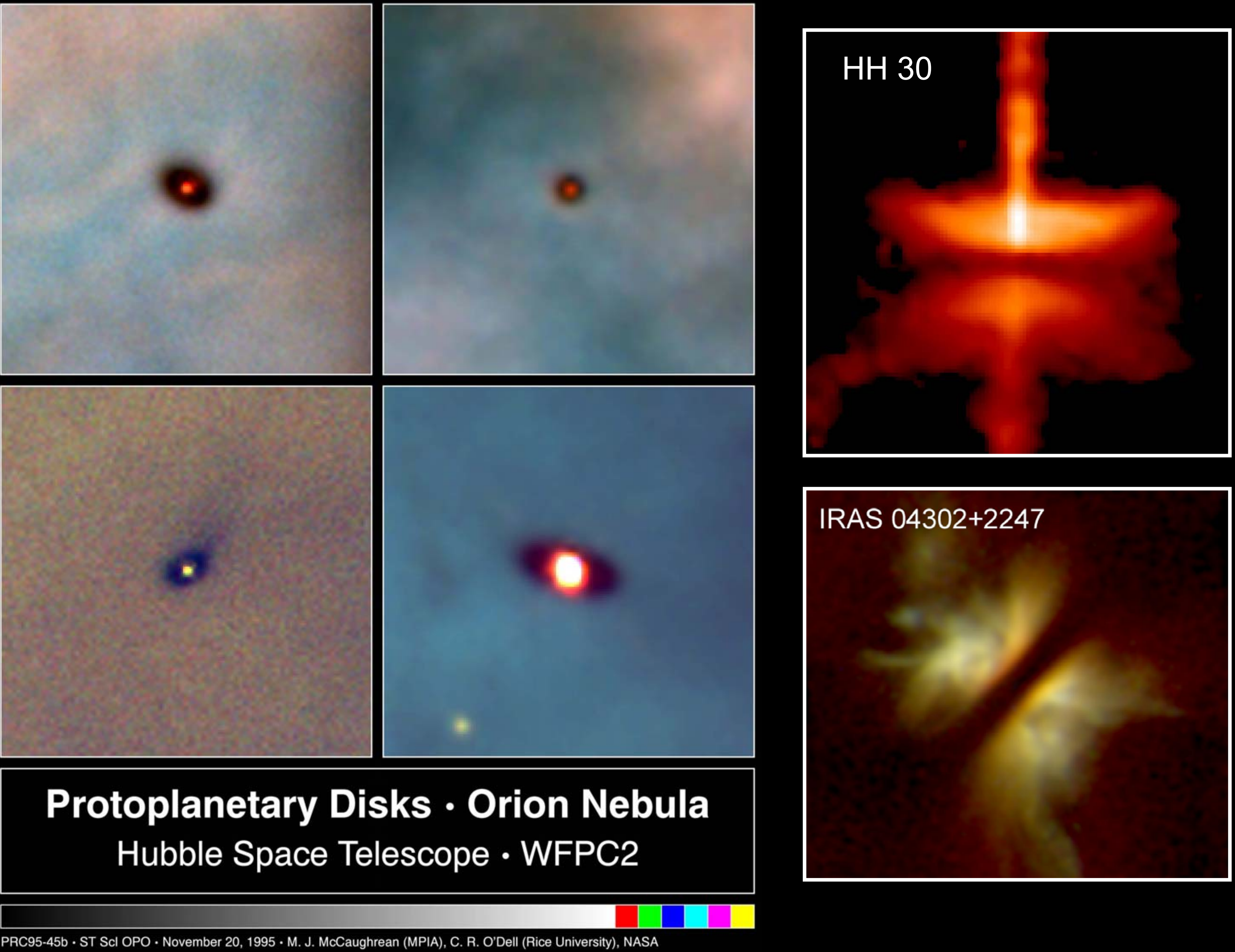


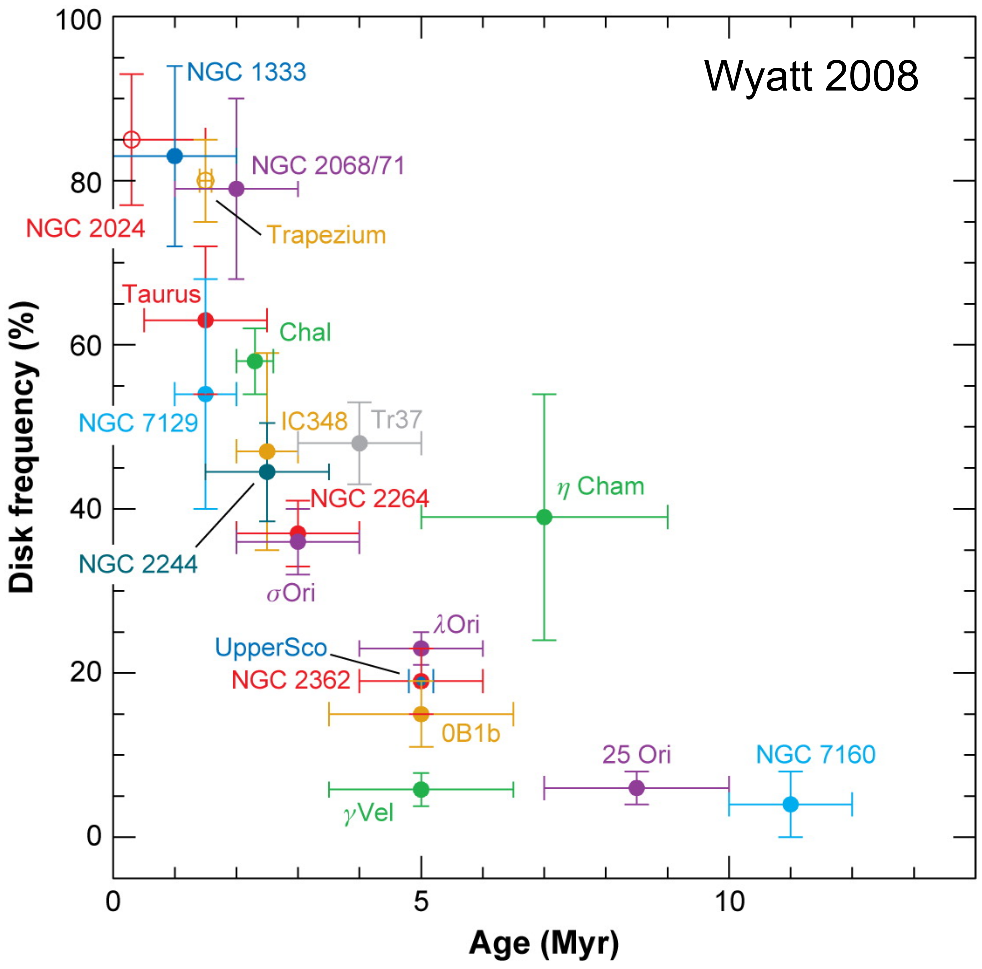
Fig. 8.— The fragmentation of a 1000 $M_\odot$ turbulent molecular cloud and the formation of a stellar cluster (*Bonnell et al.*, 2003). Note the merging of the smaller subclusters to a single big cluster.

Stars form in clusters: the open clusters h und χ Persei


HH 30
IRAS 04302+2247
Protoplanetary Disks • Orion Nebula
Hubble Space Telescope • WFPC2
PRC95-45b • ST ScI OPO • November 20, 1995 • M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

Planet formation must be a (relatively) fast process!

Maximum lifetime of protoplanetary disks 10^7 years



What have we learned so far?

- ▷ The sun and our planets formed concurrently 4.567 billion years ago.
- ▷ Extrasolar planetary systems can be similar to or different from the solar system.
- ▷ Dust plays a decisive role in the formation of the planets.
- ▷ The lifetime of protoplanetary disks, the birthplaces of planets, is a few million years.

2.
The minimum mass solar nebula model

Solar-system data

Planetary zones: masses and surface densities

	Mass ($M_\oplus$)	Fe mass fraction	Solar comp. mass ($M_\oplus$)	Zone limits (AU)	Surface density (g cm^{-2})
Mercury	0.053	0.62	27	0.22	880
Venus	0.815	0.35	235	0.56	4750
Earth	1	0.38	320	0.86	3200
Mars	0.107	0.30	27	1.26	95
Asteroids					
present	0.0005	0.25	0.1	2.0	0.13
original	0.15?		30		40
				3.3	
Jupiter	318	–	600–12 000	7.4	120–2400
Saturn	95	–	1000–6000	14.4	55–330
Uranus	14.6	–	700–2000	24.7	15–40
Neptune	17.2	–	800–2000	35.5	10–25

Weidenschilling 1977

Inferred surface densities

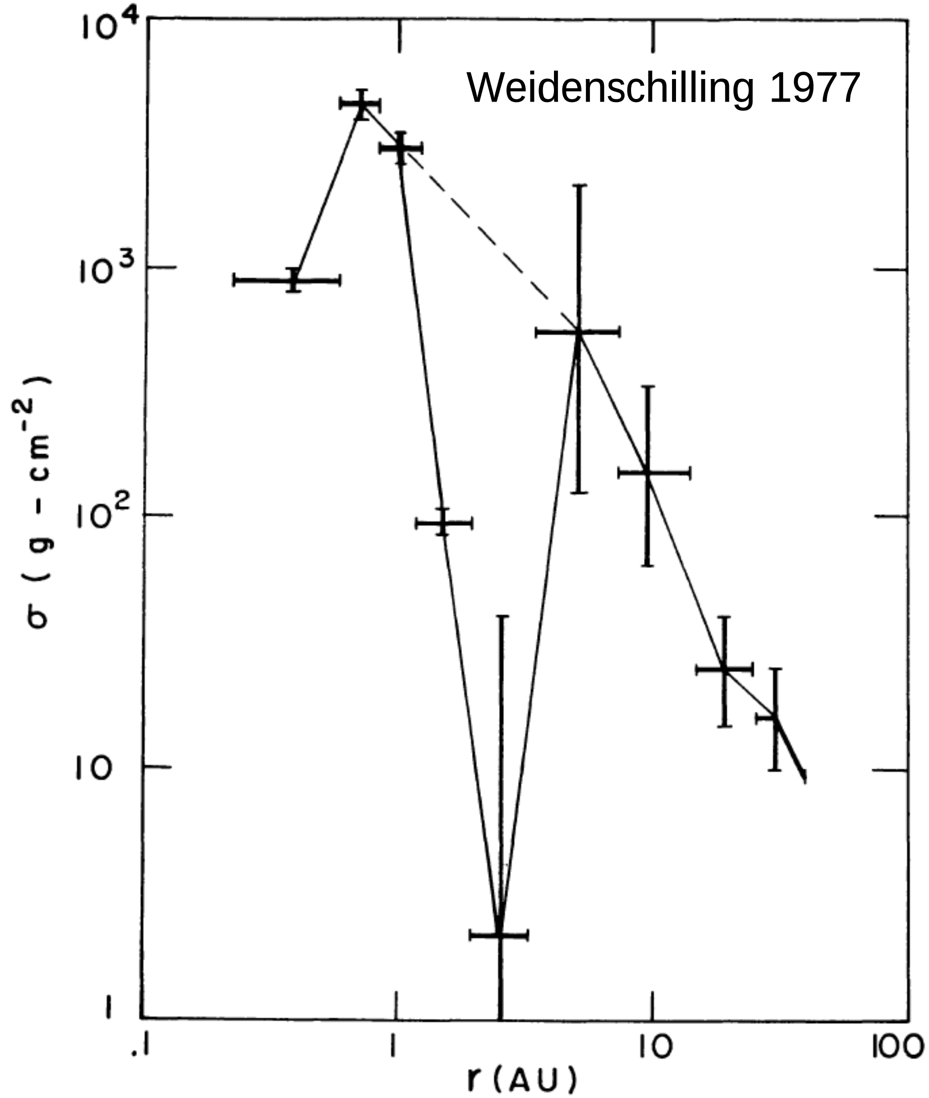


Fig. 1. Surface densities, σ, obtained by restoring the planets to solar composition and spreading the resulting masses through contiguous zones surrounding their orbits. The meaning of the 'error bars' is discussed in the text.

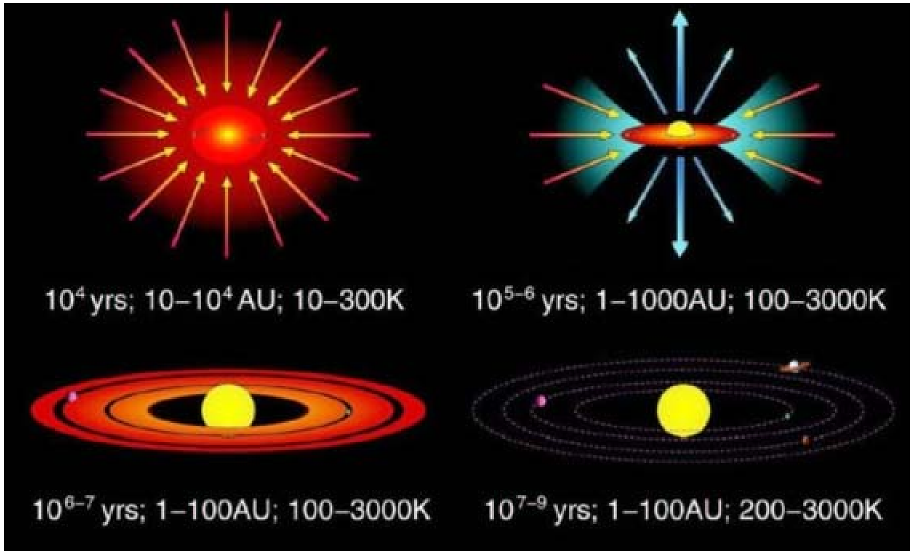
A power-law approximation:

$$\Sigma_s(r) = 1700\ \mathrm{g/cm^2} \cdot \left(\frac{r}{1\,\mathrm{AU}}\right)^{-3/2}$$

3.
Dust-particle condensation

The condensation sequence

© NASA, after Shu et al. 1987



- ▷ Formation of an accretion disk.
- ▷ The disk is initially hot
  → few dust grains.
- ▷ As the disk cools down, dust particles condense.
- ▷ Dust materials: oxides, silicates, organics, ices.
- ▷ Particle sizes: sub-μm - μm.

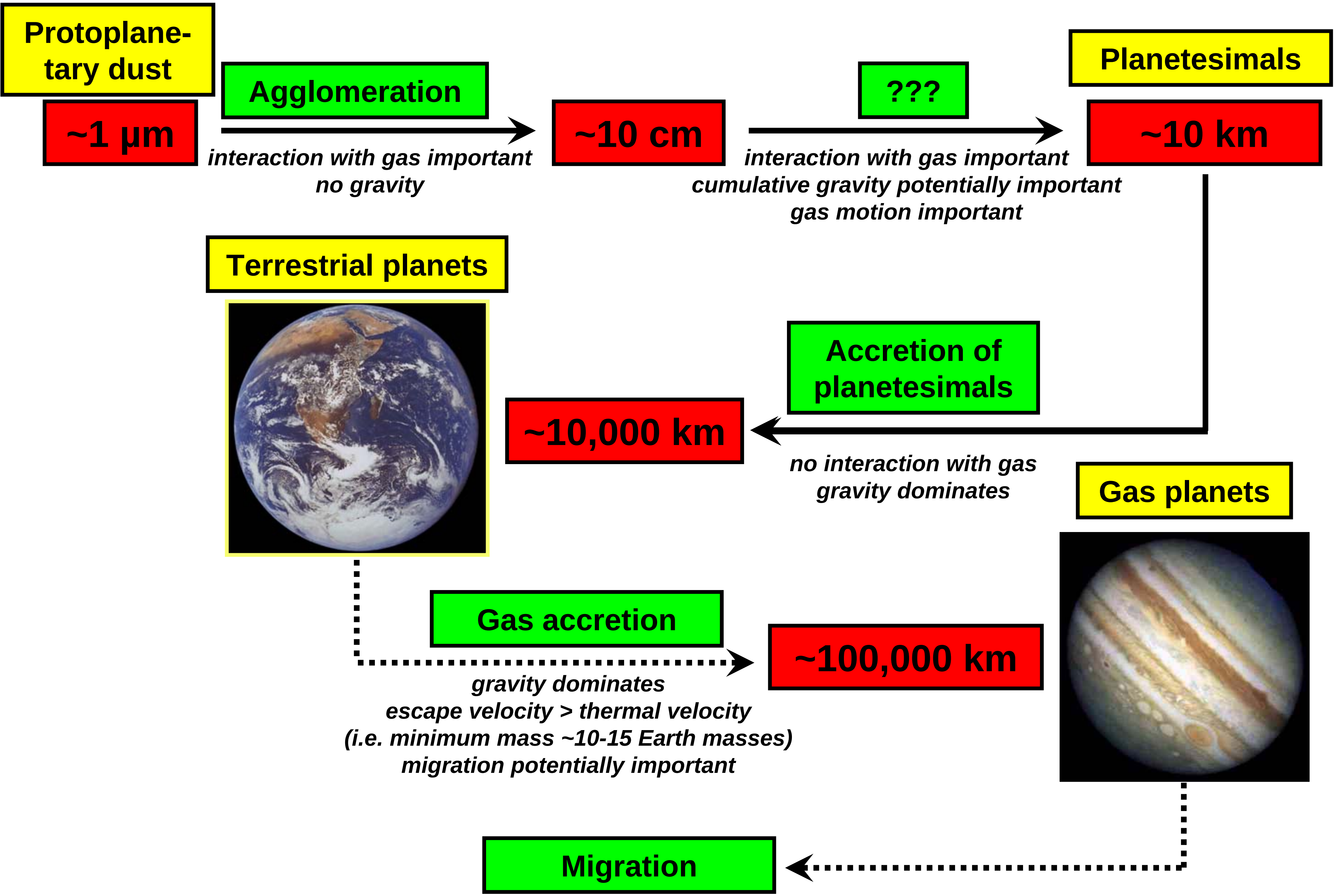
TABLE II Condensation temperatures for selected materials

T	Material
1680 K	Al_2O_3
1590 K	$CaTiO_3$
1400 K	$MgAl_2O_4$
1350 K	Mg_2SiO_4, iron alloys
370 K	Fe_3O_4
180 K	water ice
130 K	$NH_3 \cdot H_2O$
40 K – 80 K	methane, methane ices
50 K	argon

Armitage 2007

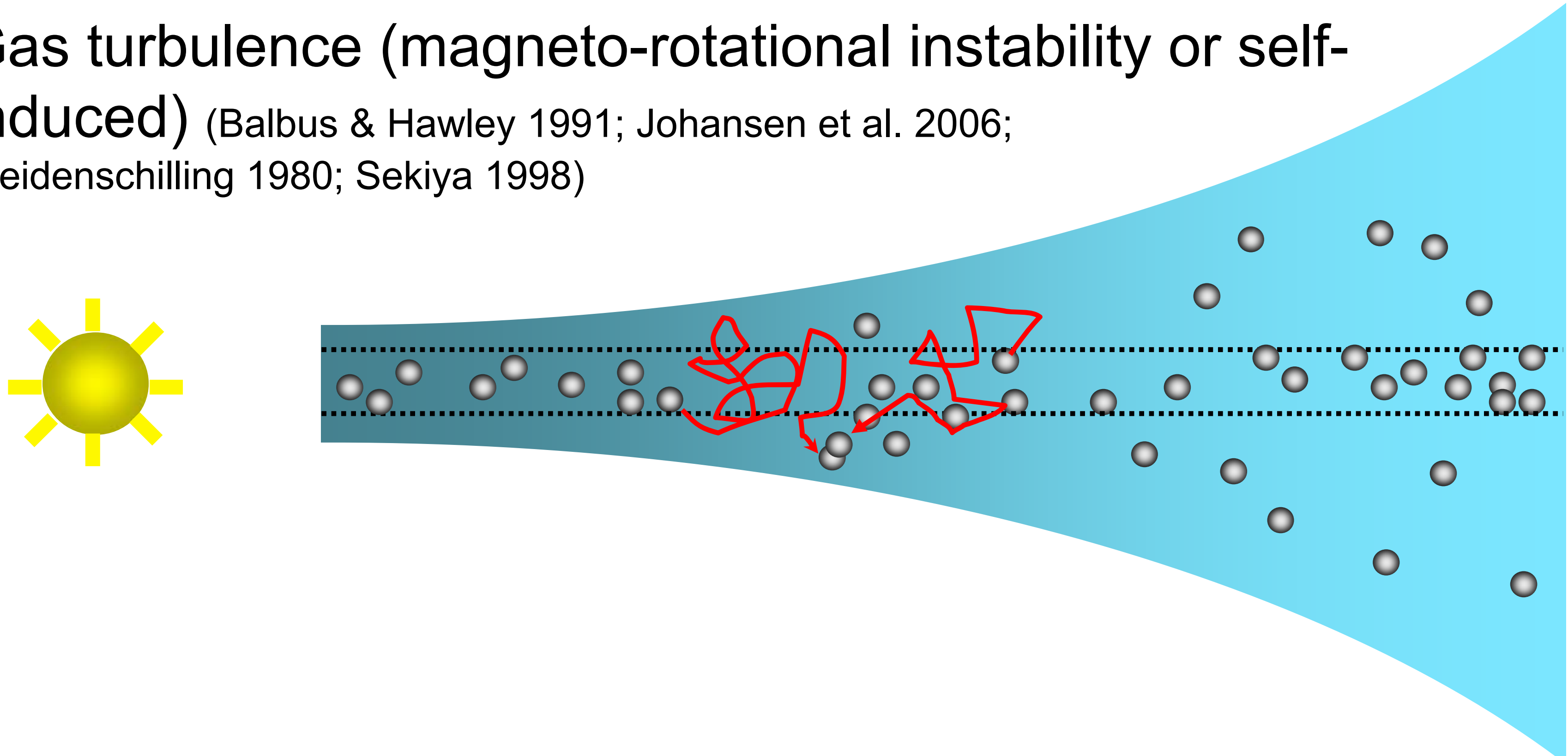
4.
What causes the dust grains to move (and to collide)?

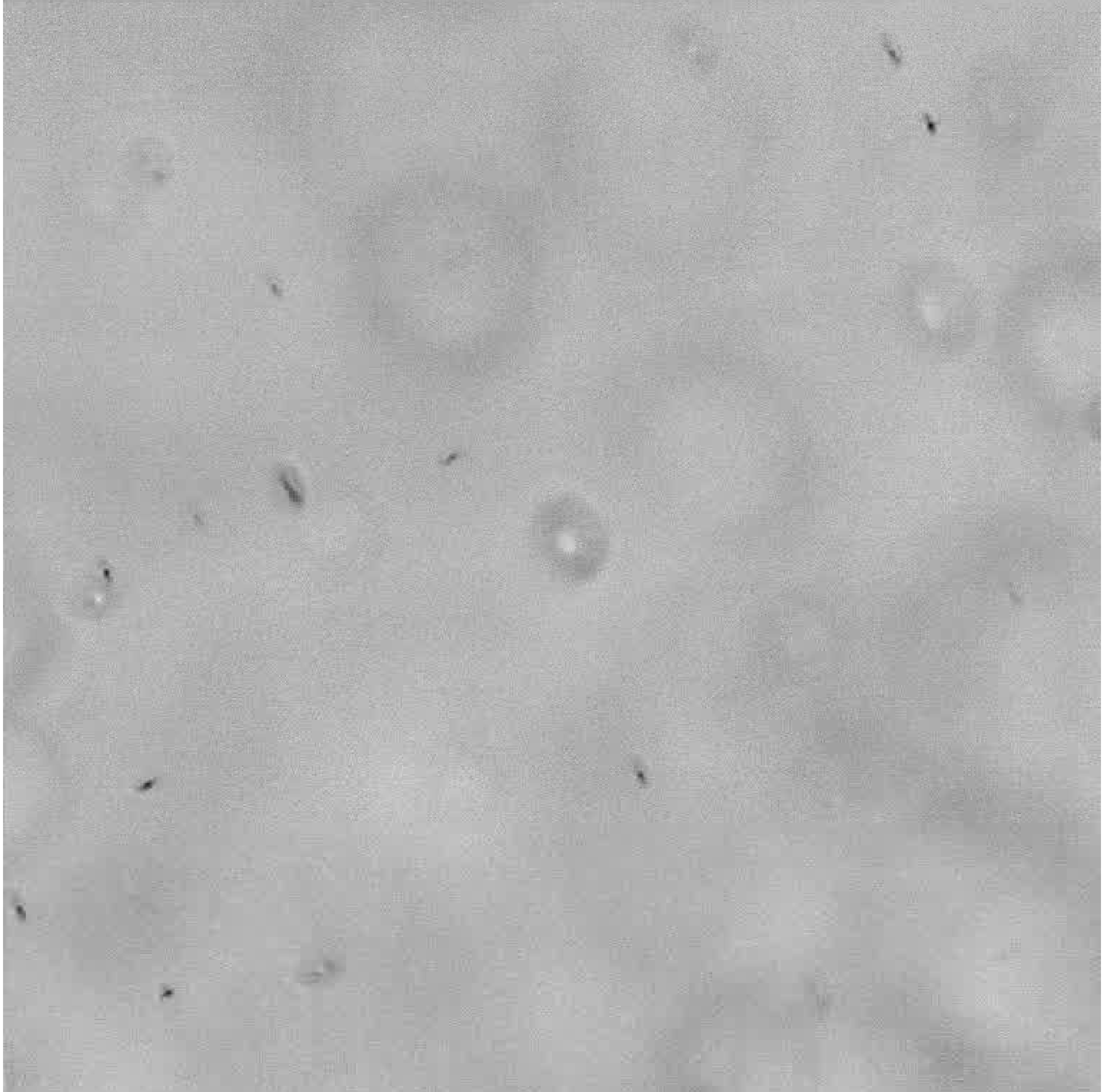
The five-stage process of planet formation



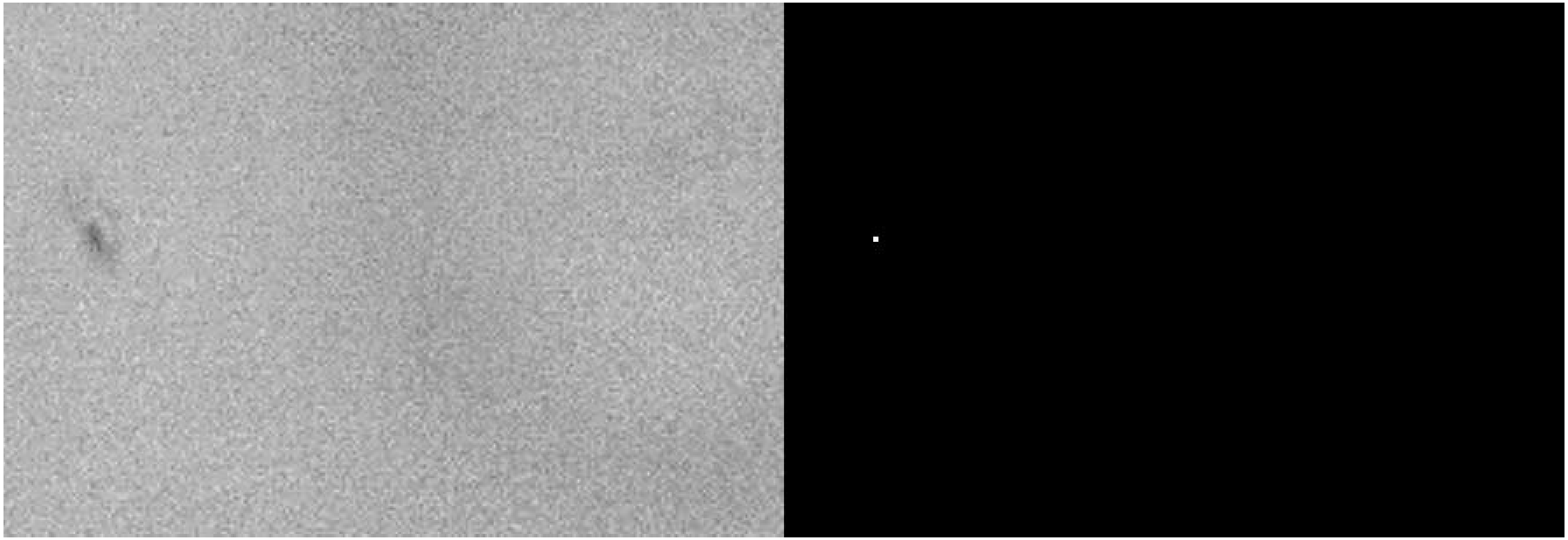
What causes the dust grains to move (and to collide)?

- Brownian motion (Weidenschilling 1984)
- Vertical sedimentation, radial drift, azimuthal velocity differences (Weidenschilling 1984)
- Gas turbulence (magneto-rotational instability or self-induced) (Balbus & Hawley 1991; Johansen et al. 2006; Weidenschilling 1980; Sekiya 1998)





Blum et al. 2006



Blum et al. 2006

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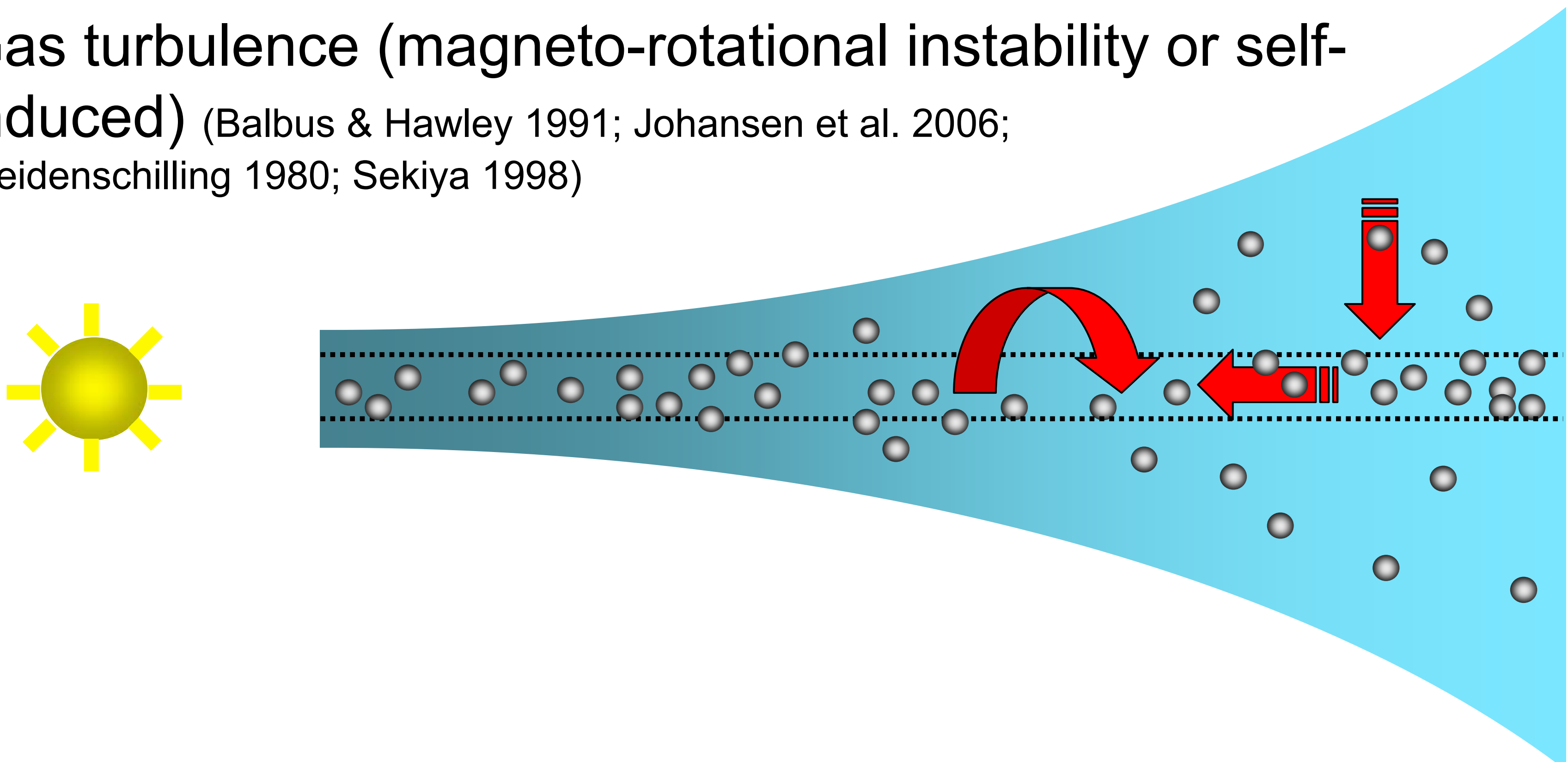
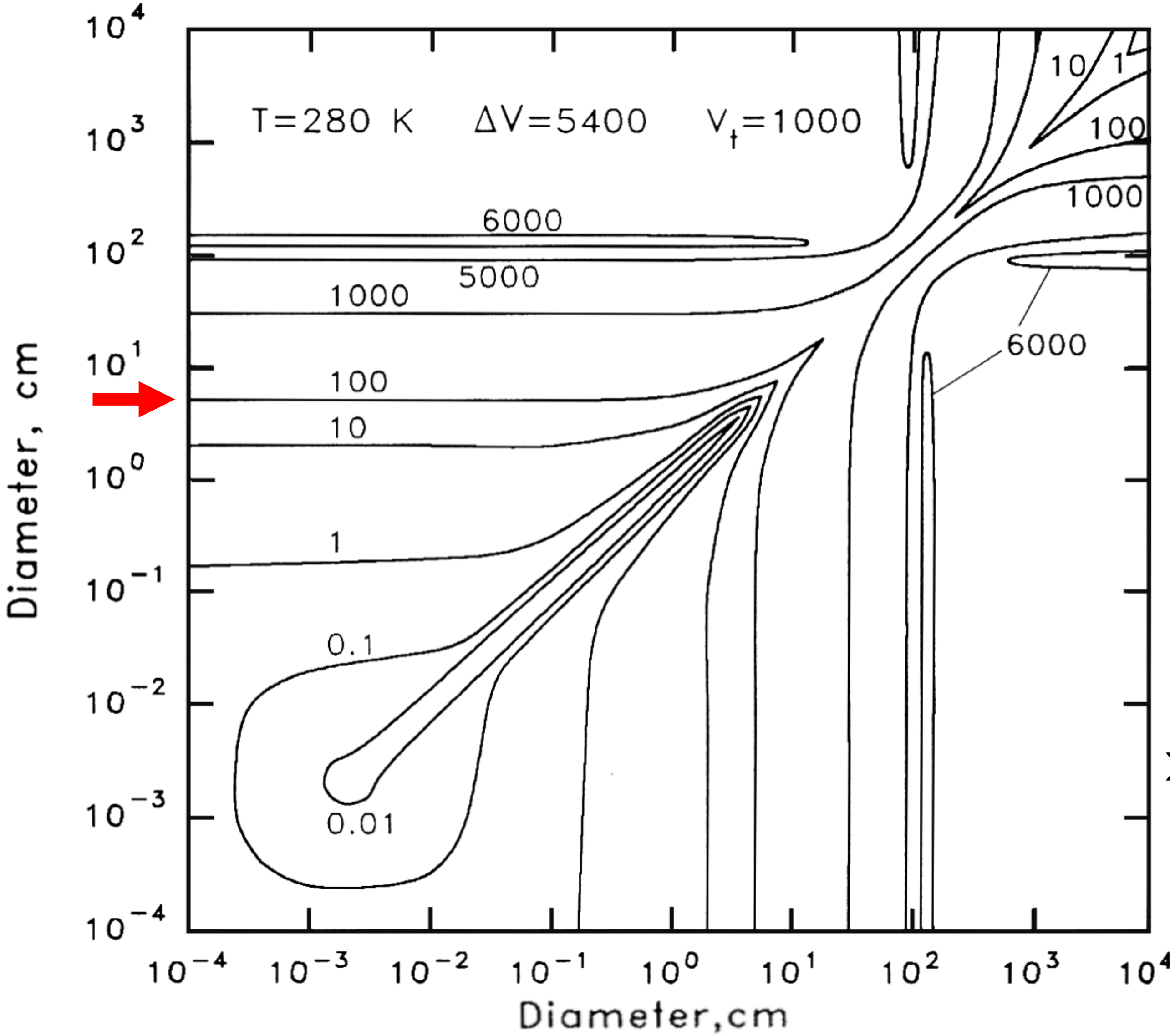


A MMSN model for the collision velocities between protoplanetary dust grains



1 AU

Velocity contours in cm/s

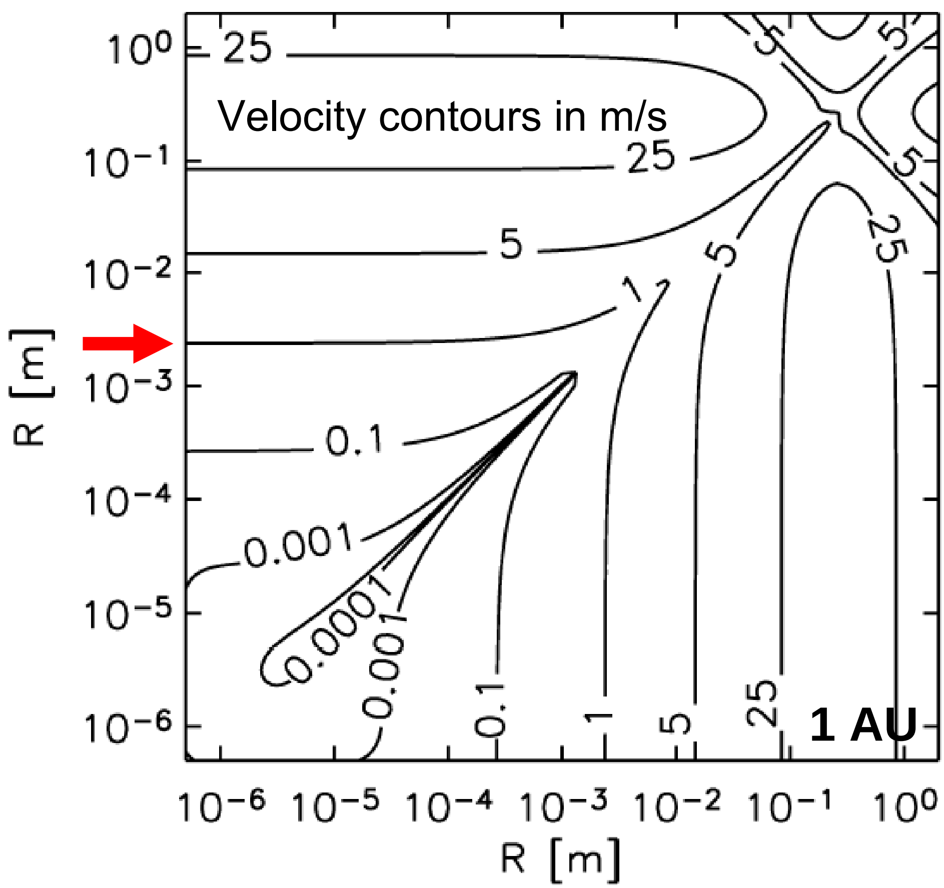
Critical velocity of 1 m/s ➡ reached for 5-cm particles

$$\Sigma_s(r) = 1700\ \mathrm{g/cm^2} \cdot \left(\frac{r}{1\ \mathrm{AU}}\right)^{-3/2}$$

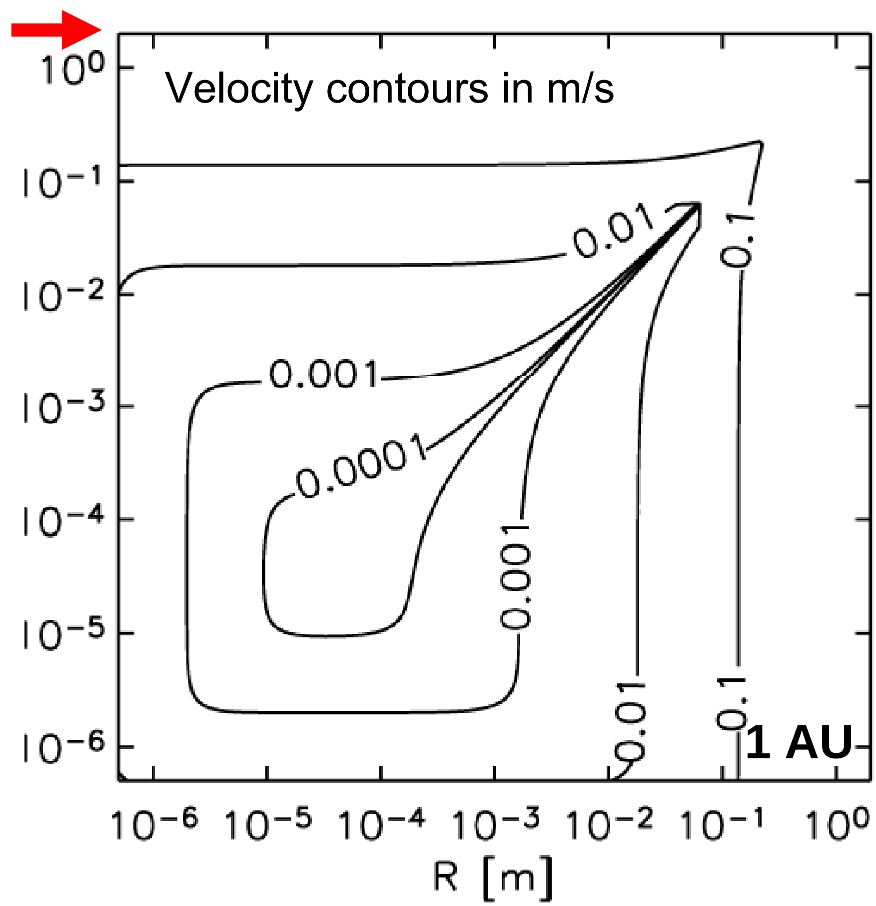
Weidenschilling & Cuzzi 1993

Alternative models

Andrews & Williams 2007



Desch 2007



$$\Sigma_s(r) = 20\,\mathrm{g/cm^2} \cdot \left(\frac{r}{1\,\mathrm{AU}}\right)^{-0.8}$$

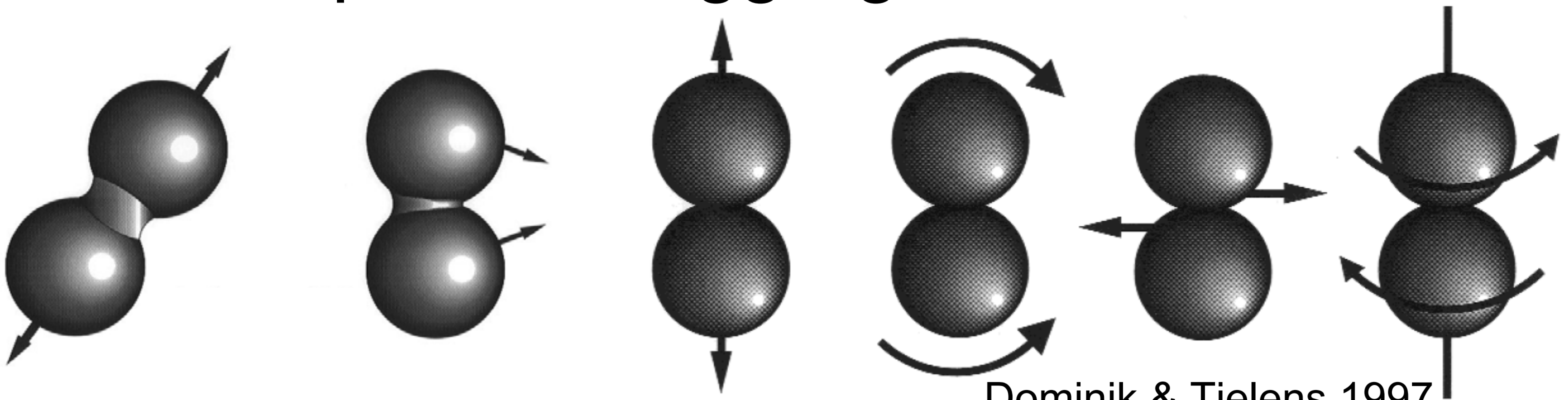
$$\Sigma_s(r) = 50500\,\mathrm{g/cm^2} \cdot \left(\frac{r}{1\,\mathrm{AU}}\right)^{-2.17}$$

Critical velocity of 1 m/s → reached for 4-mm particles

Critical velocity of 1 m/s → reached for >1-m particles

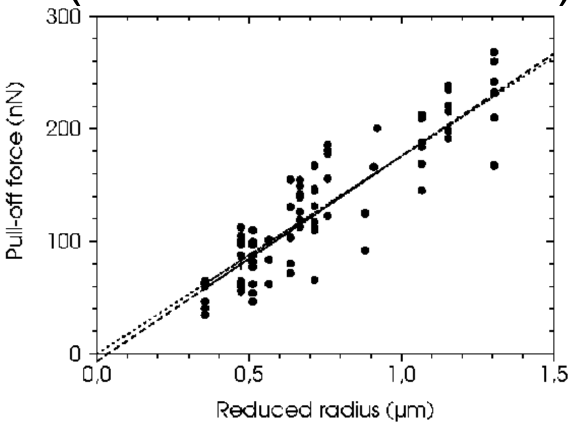
5.
What happens in a collision between two dust particles/aggregates?

What happens in a collision between two dust particles/aggregates?



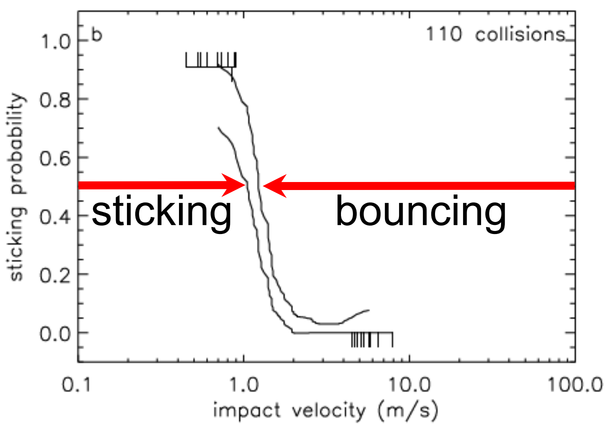
Dominik & Tielens 1997

Adhesion force (van der Waals force)



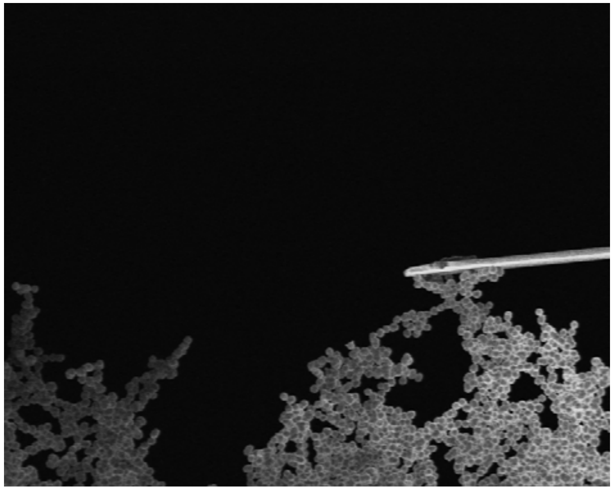
Heim et al. 1999

Threshold velocity for sticking



Poppe et al. 2000

Restructuring

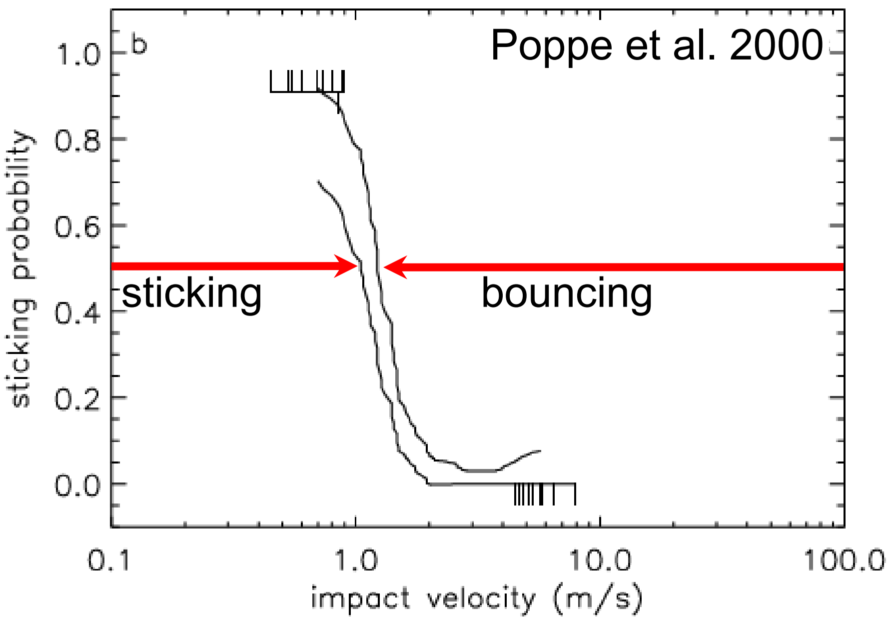


Heim et al. 2005

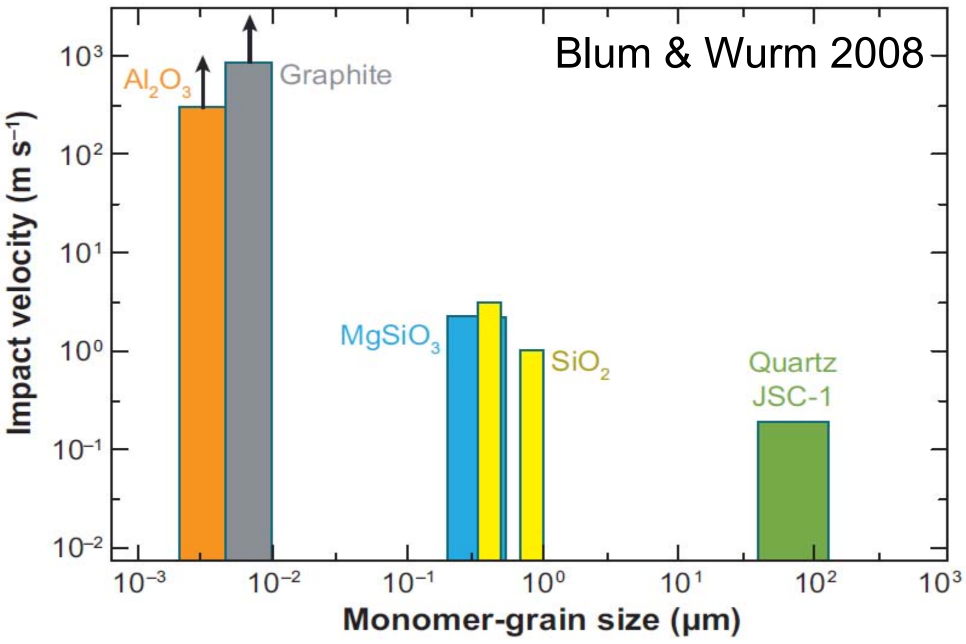
The importance of the threshold velocity for sticking

- ▷ $v_{SG} \approx v_{AG} \approx v_{FR}$
  v_{SG}: threshold velocity for single-grain sticking
  v_{AG}: threshold velocity for fractal-dust-aggregate sticking
  v_{FR}: threshold velocity for dust-aggregate fragmentation.
- ▷ The threshold velocity for dust-aggregate sticking is dependent on the monomer size.

Single-grain collisions



Dust-aggregate collisions

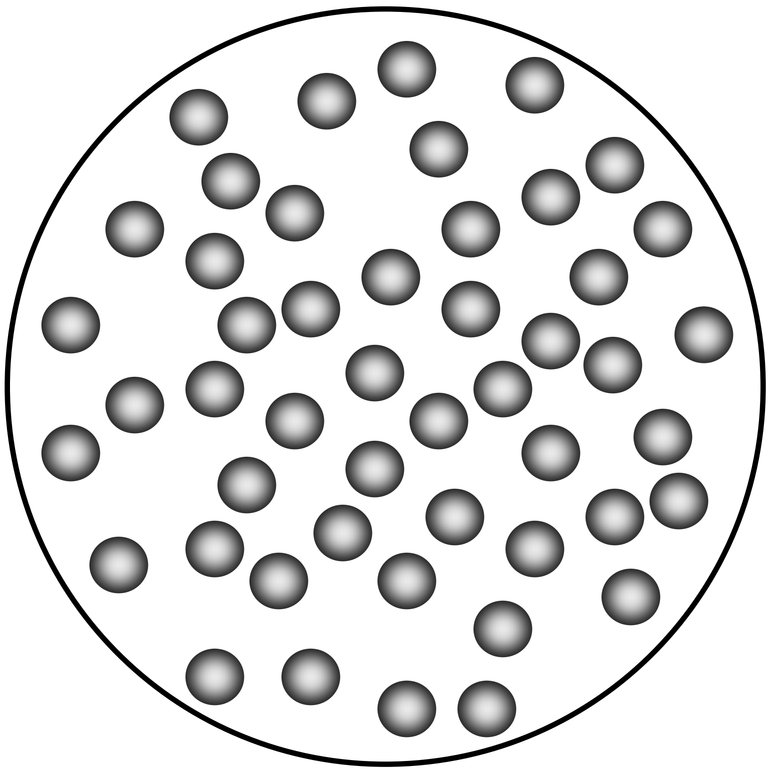


6.
How does dust agglomeration start?

The initial growth

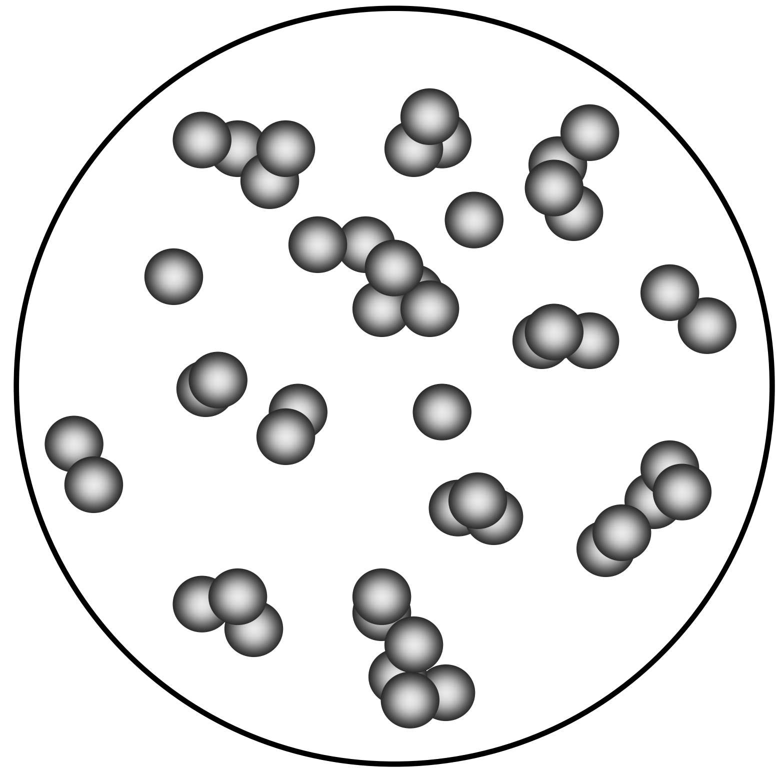
P R I N C I P L E

Start with monomers at $t_0 = 0$



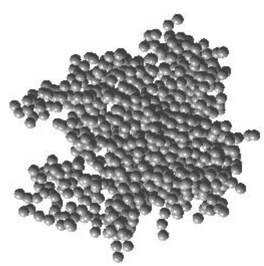
Relative velocities due to Brownian motion, drift, gas turbulence

Observe aggregate mass (distribution) and structure at $t > t_0$

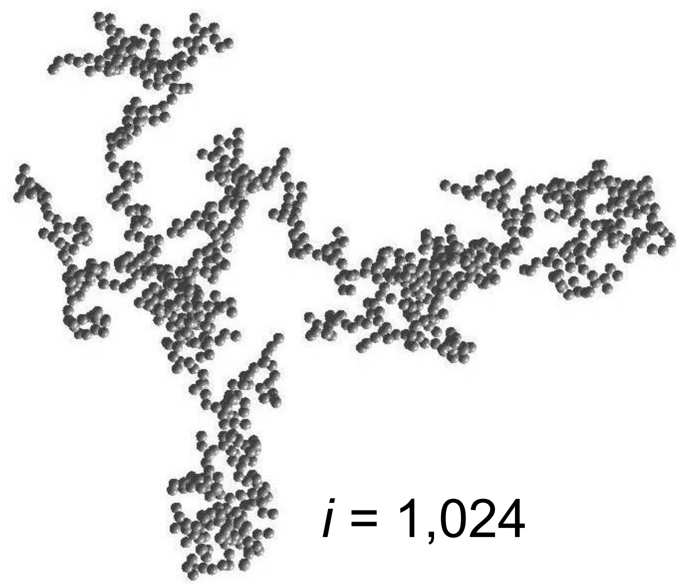


Consider the simplest cases

BPCA	BCCA
Ballistic Particle-Cluster Agglomeration	Ballistic Cluster-Cluster Agglomeration
⇓	⇓
ballistic hit-and-stick impacts of single dust particles into growing dust agglomerate	ballistic hit-and-stick collisions between equal-mass dust agglomerates



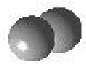
i = 1,024



i = 1,024

BPCA

N=2

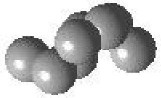


BPCA

N=4

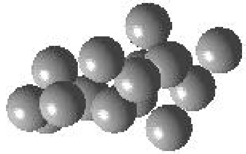
BPCA

N=8



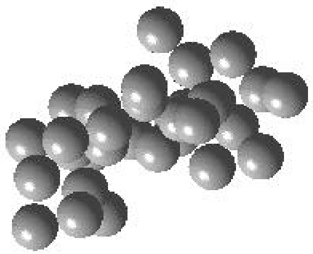
BPCA

N=16



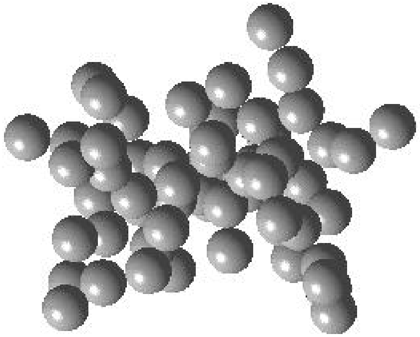
BPCA

N=32



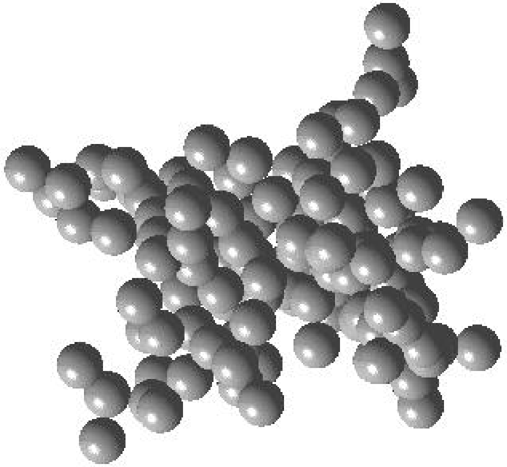
BPCA

N=64



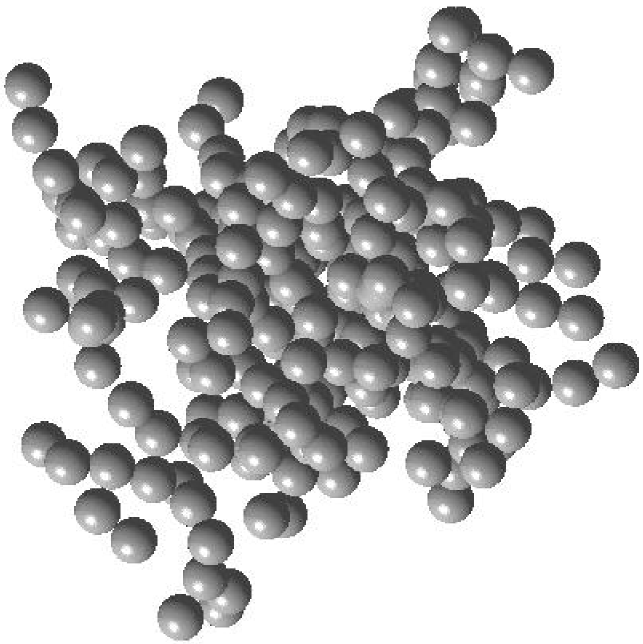
BPCA

N=128



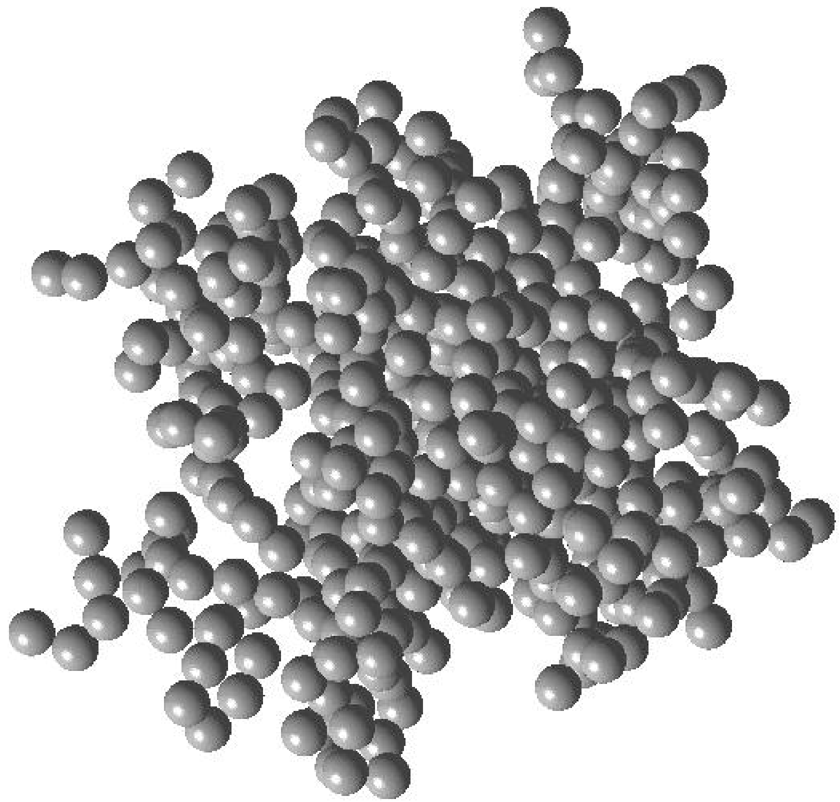
BPCA

N=256



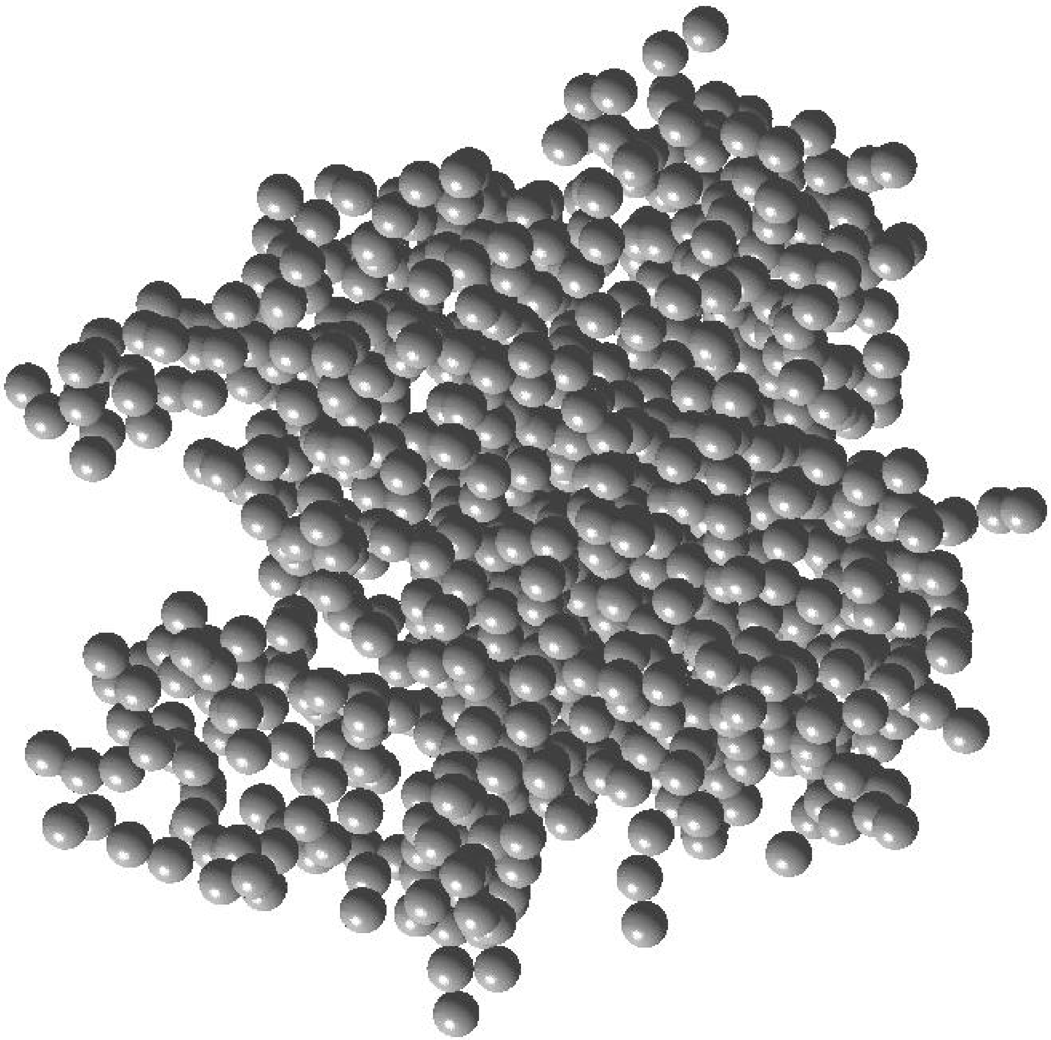
BPCA

N=512



BPCA

N=1024

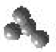


BCCA

N=2

BCCA

N=4

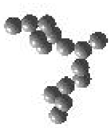


<u>BCCA</u>

N=8

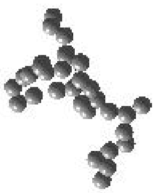
BCCA

N=16



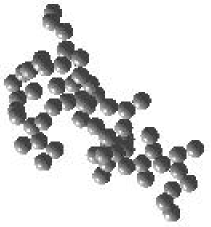
BCCA

N=32



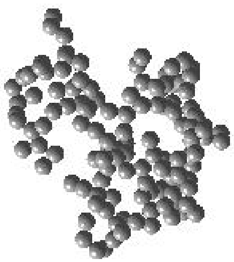
BCCA

N=64



BCCA

N=128



BCCA

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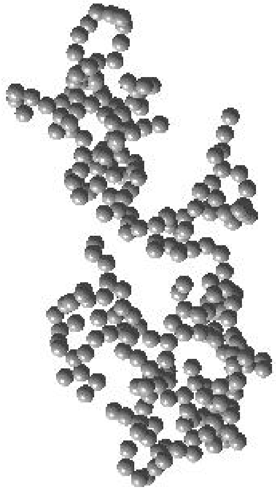
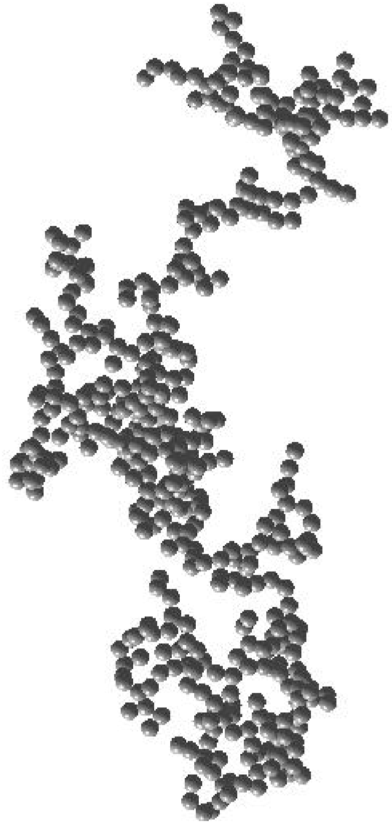


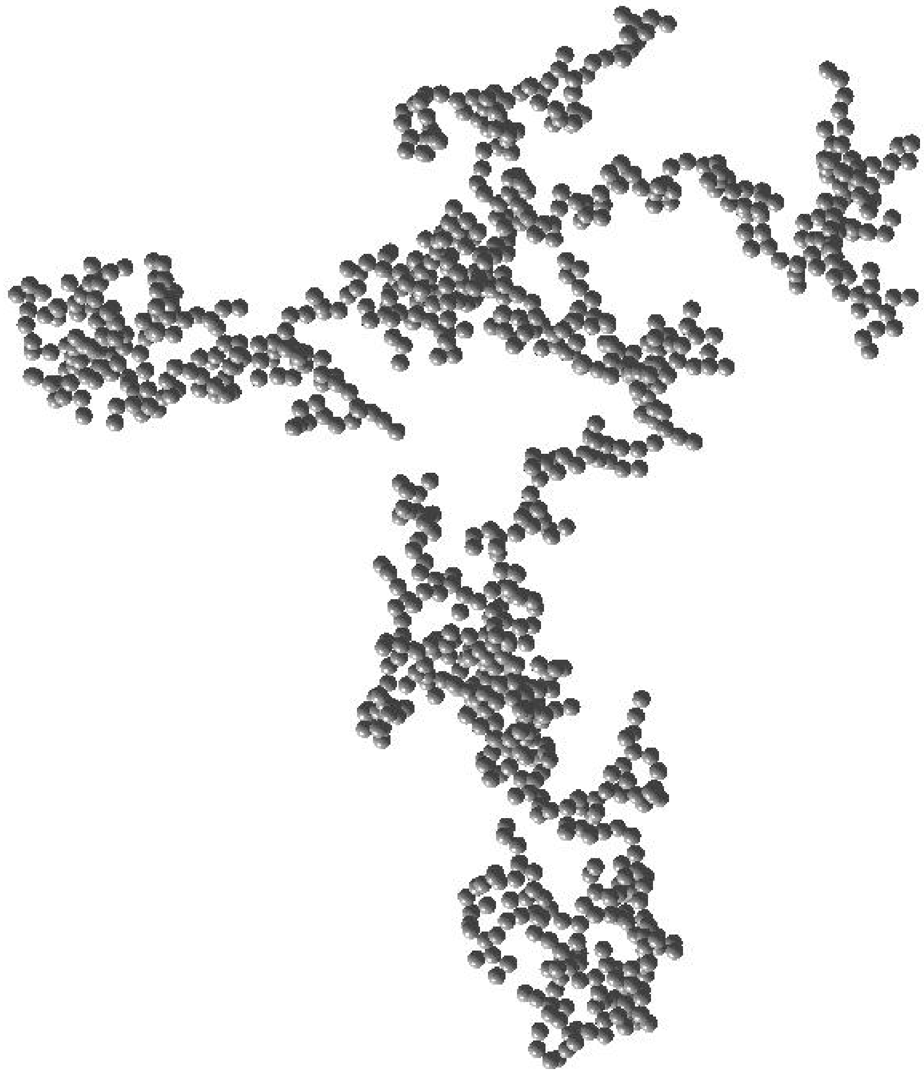
BCCA

N=512



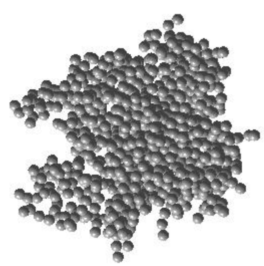
BCCA

N=1024

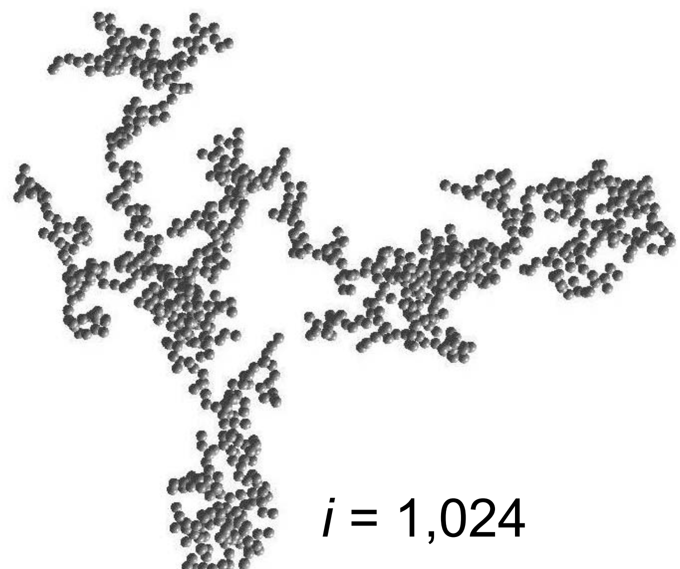


Consider the simplest cases

<u>BPCA</u>	<u>BCCA</u>
Ballistic Particle-Cluster Agglomeration	Ballistic Cluster-Cluster Agglomeration
⇓	⇓
ballistic hit-and-stick impacts of single dust particles into growing dust agglomerate	ballistic hit-and-stick collisions between equal-mass dust agglomerates



i = 1,024

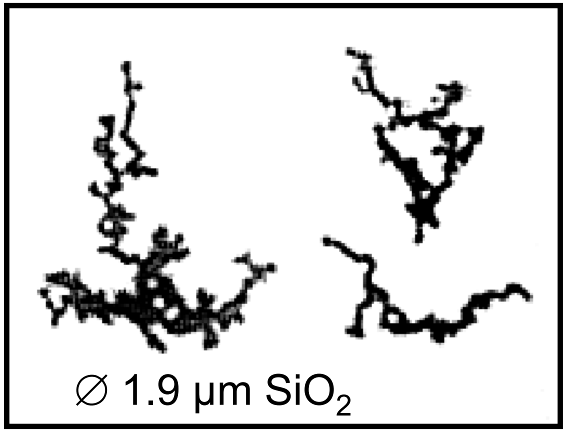


i = 1,024

The initial growth

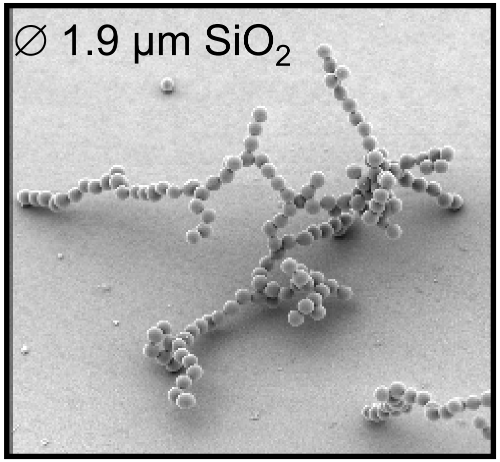
EXPERIMENTS

Gas turbulence



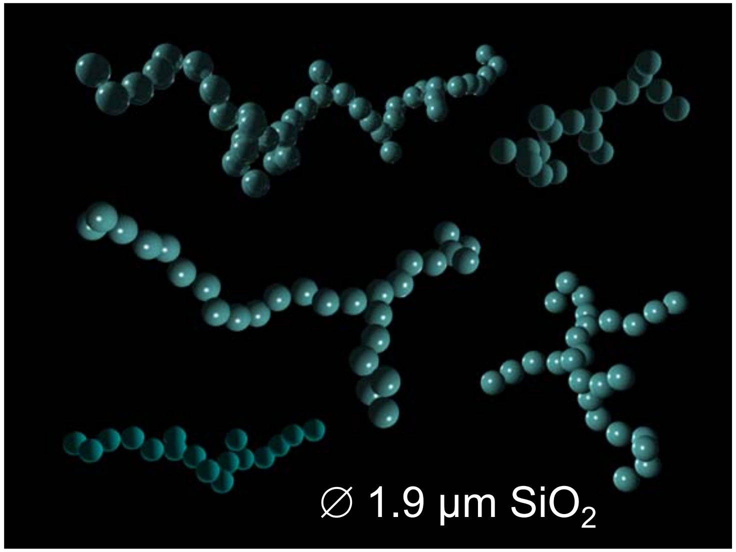
Wurm & Blum 1998

Differential sedimentation



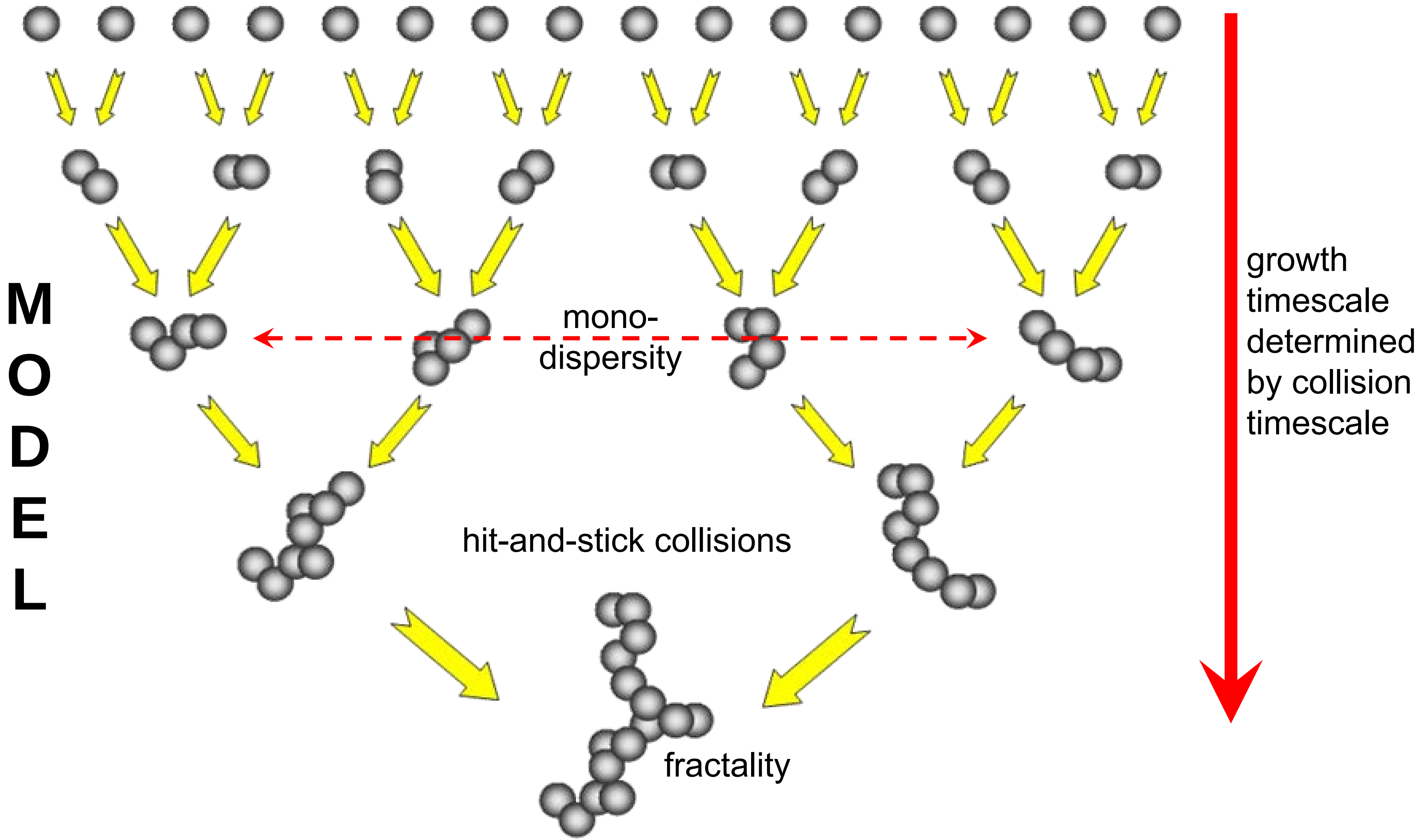
Blum et al. 1998

Brownian motion



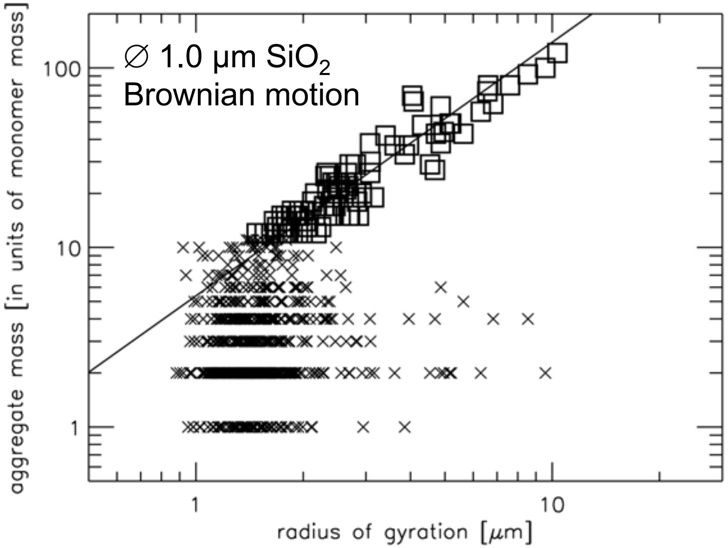
Blum et al. 2000

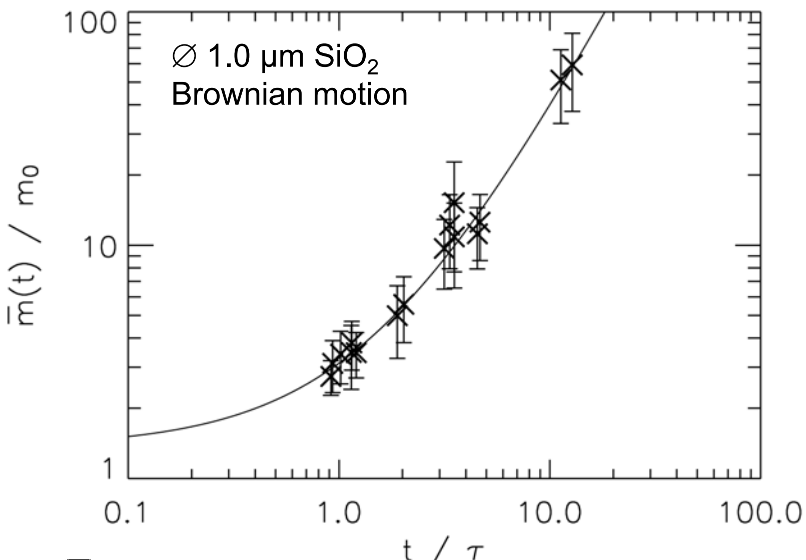
The initial growth

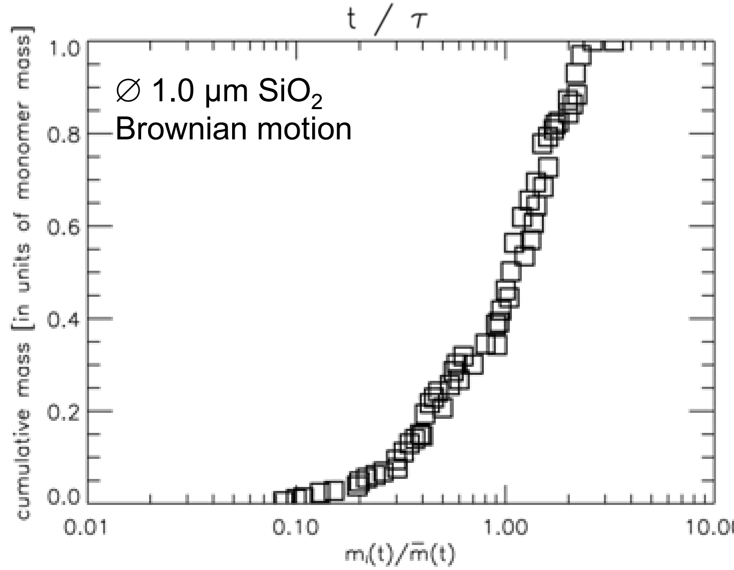


The initial growth

E X P E R I M E N T S







- ▷ Hit-and-stick collisions
- ▷ Mass-size relation $m \propto s^D$ with $D \leq 2$ (fractal aggregates)
- ▷ Narrow (quasi-monodisperse) mass spectra
- ▷ Temporal mass growth follows a power law

$$\frac{\bar{m}(t)}{m_0} = \left[(1-\gamma)\left(a\frac{t}{\tau} + c \right) \right]^{1/1-\gamma}$$

Krause & Blum 2004

The initial growth

S
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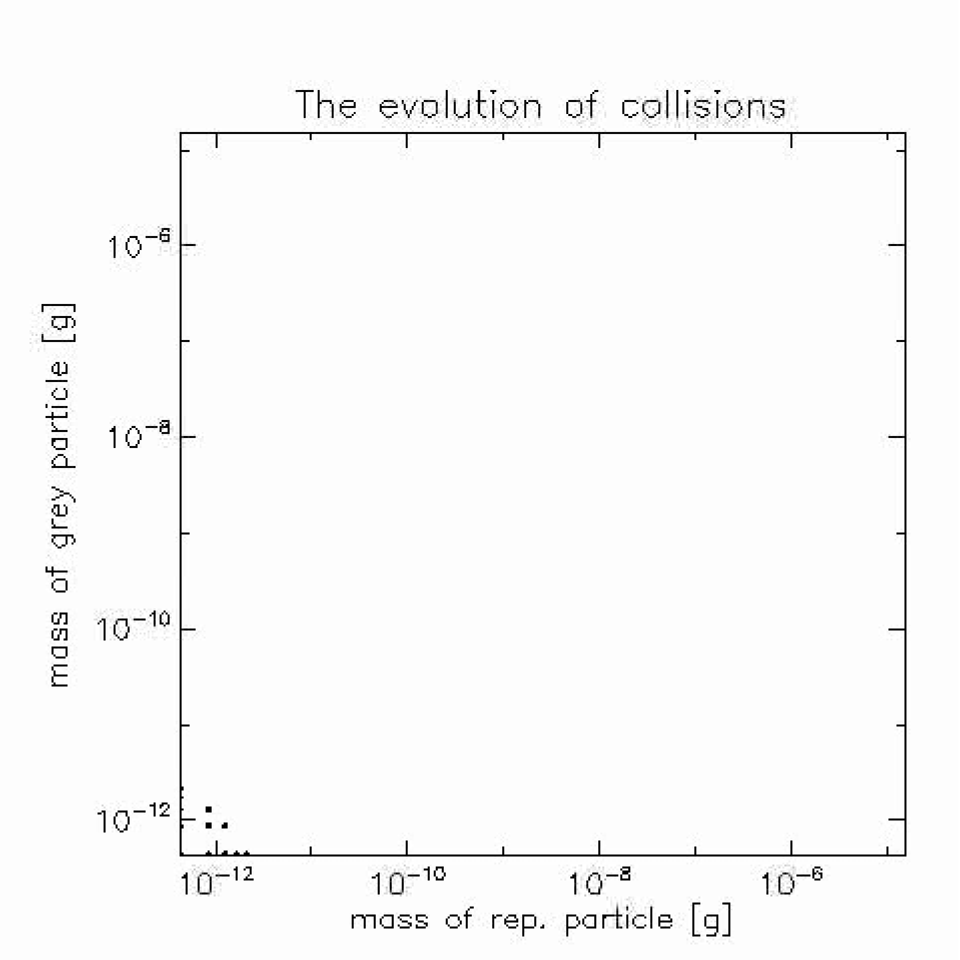
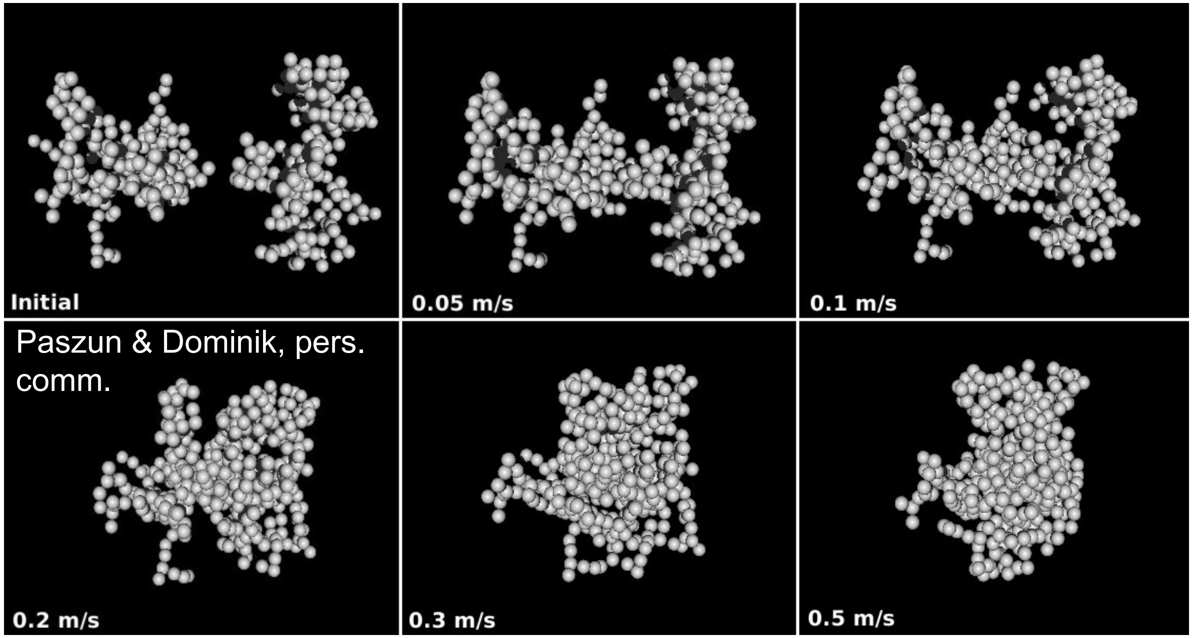


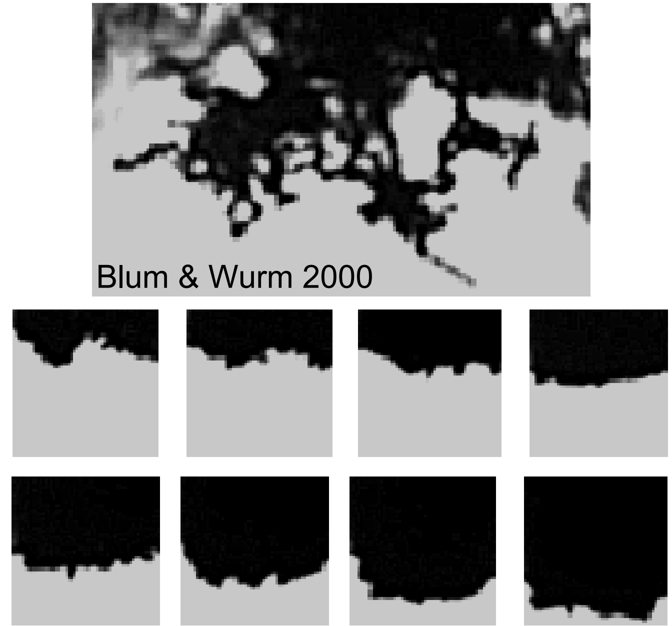
- ▷ "Minimum Mass Solar Nebula" model
- ▷ Hit-and-stick collisions
- ▷ Brownian motion + turbulence
- ▷ t = 0…30 yrs

7.
Why do the dust aggregates not continue to grow the “fractal” way?

The restructuring/compaction growth regime

Low impact energy: hit-and-stick collisions



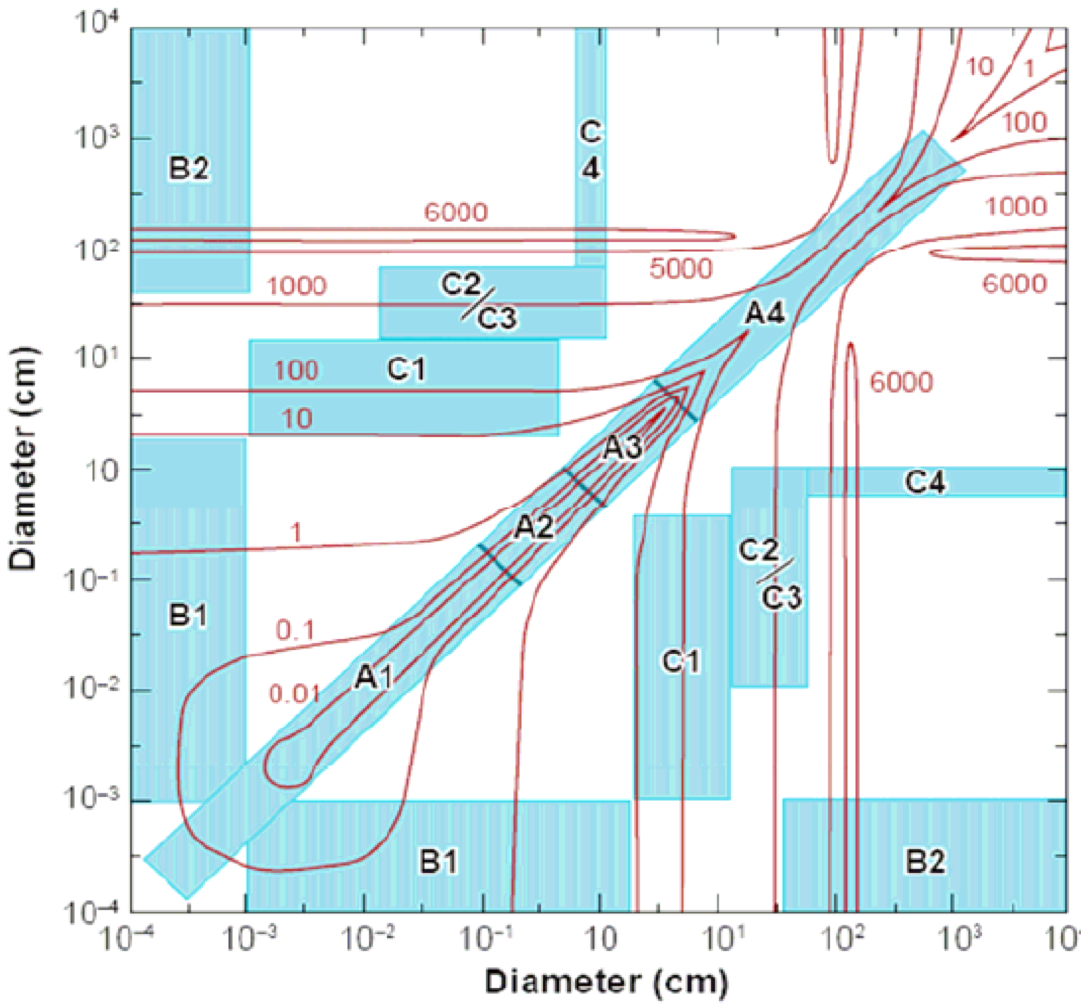


Intermediate impact energy: compaction

- ▷ Collisions result in sticking.
- ▷ Impact energy exceeds energy to overcome rolling friction (Dominik and Tielens 1997; Wada et al. 2007).
- ▷ Dust aggregates become non-fractal (?) but are still highly porous.

8.
Collisions between high-porosity non-fractal dust aggregates

The experimental range



Blum & Wurm 2008

Background contours by Weidenschilling & Cuzzi 1993

▷ Sizes of protoplanetary dust aggregates:

1 µm	1 mm	1 m	1 km

▷ Collision velocities of protoplanetary dust aggregates:

10^{-4} m/s	10^{-2} m/s	1 m/s	10^{+2} m/s

▷ Protoplanetary dust materials:

oxides	silicates	organics	ices

no expt's	expt's

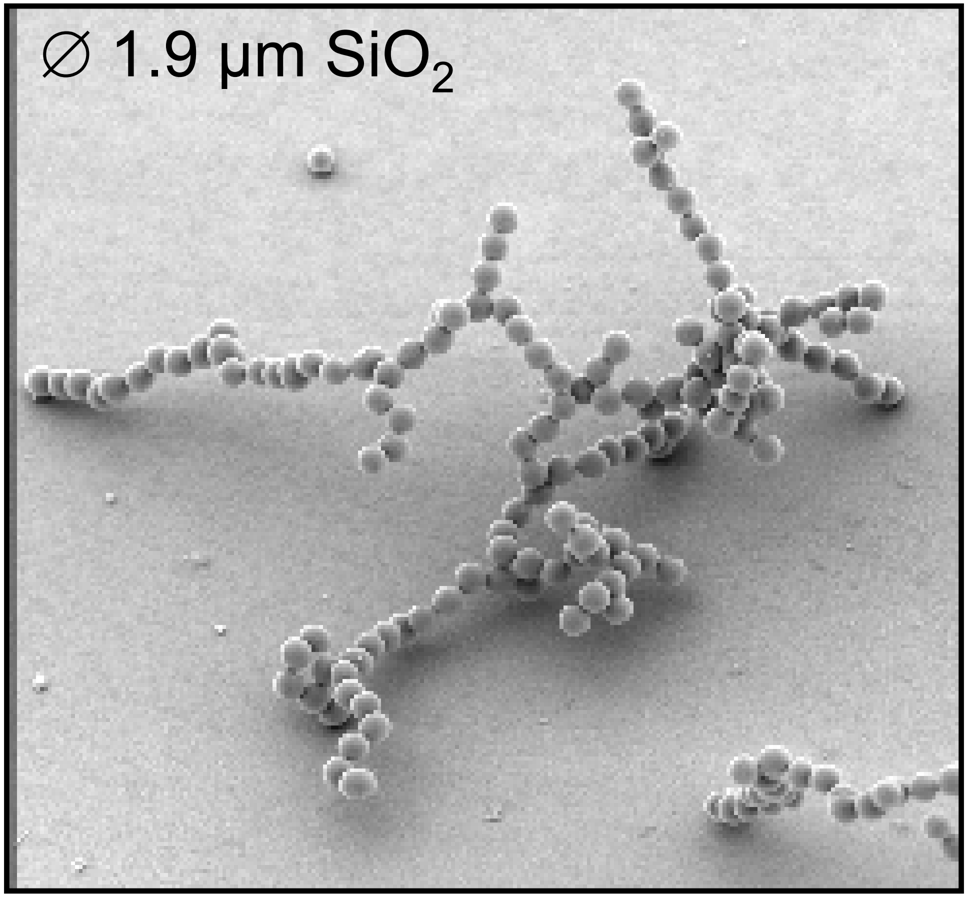
Experimental outcomes in dust-aggregate collisions

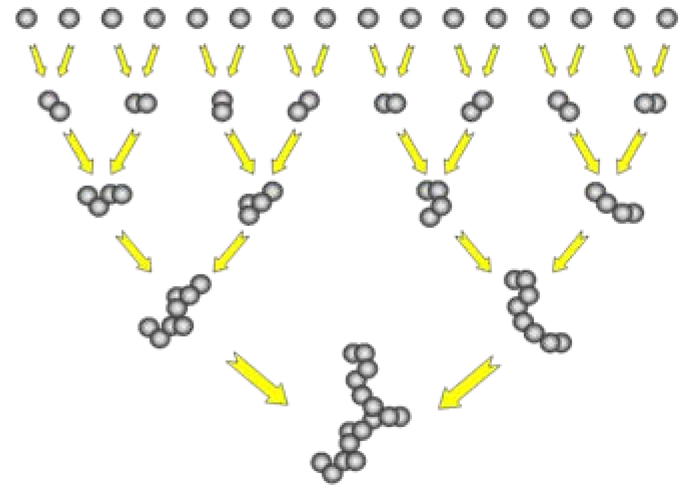
STICKING + NO COMPACTION	**STICKING + COMPACTION**	**BOUNCING + COMPACTION**	**BOUNCING + FRAGMENTATION**	**BOUNCING + (PARTIAL) STICKING + FRAGMENTATION**
Wurm & Blum 1998	Blum & Wurm 2000	Blum & Münch 1993	Blum & Münch 1993	Wurm et al. 2005b
Blum et al. 1998	Langowski et al. 2008	Heißelmann et al. (in prep.)	Schräpler & Blum (in prep.)	Paraskov et al. 2007
Blum & Wurm 2000	Teiser & Blum (in prep.)	Weidling et al. (subm.)	Wurm et al. 2005a	Teiser & Wurm ~~2008~~
Blum et al. 2000		Güttler & Blum (in prep.)	Paraskov et al. 2007	Güttler & Blum (in prep.)
Blum et al. 2002			Teiser & Wurm (in prep.)	
Blum & Schräpler 2004			Lammel et al. (in prep.)	
Krause & Blum 2004				
Blum et al. 2006				

Experimental outcomes in dust-aggregate collisions

STICKING + NO COMPACTION	STICKING + COMPACTION	BOUNCING + COMPACTION	BOUNCING + FRAGMENTATION	BOUNCING + (PARTIAL) STICKING + FRAGMENTATION

An example of a fractal dust aggregate grown in a laboratory experiment





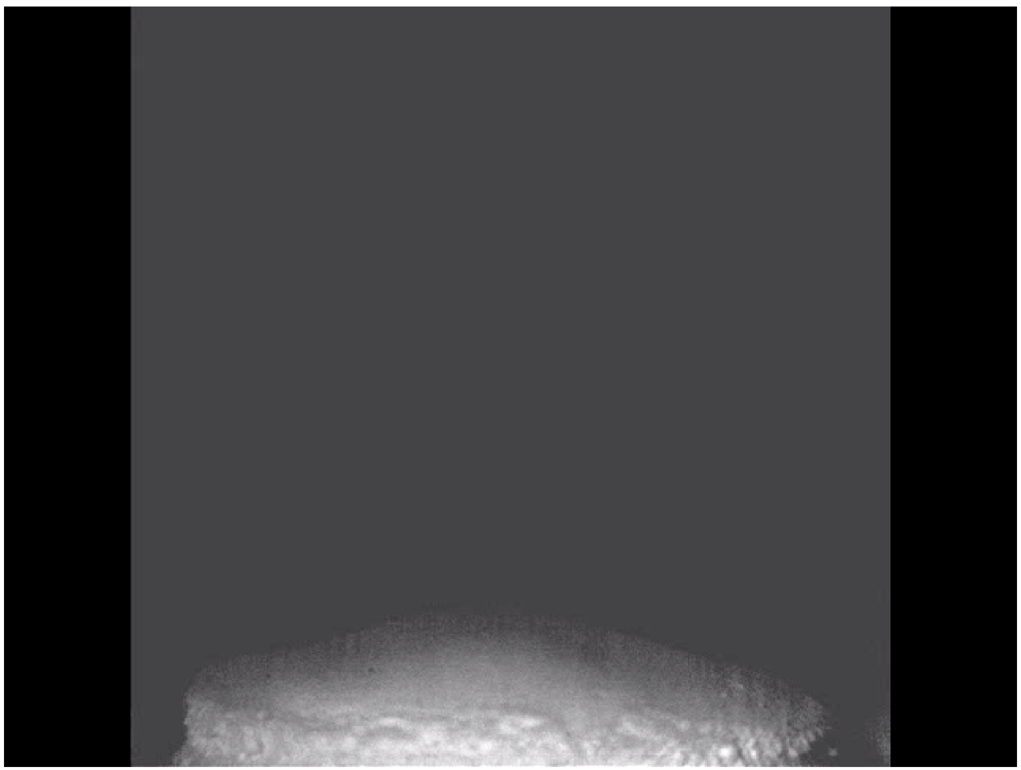
Blum et al. 1998

Experimental outcomes in dust-aggregate collisions

STICKING + NO COMPACTION	STICKING + COMPACTION	BOUNCING + COMPACTION	BOUNCING + FRAGMENTATION	BOUNCING + (PARTIAL) STICKING + FRAGMENTATION

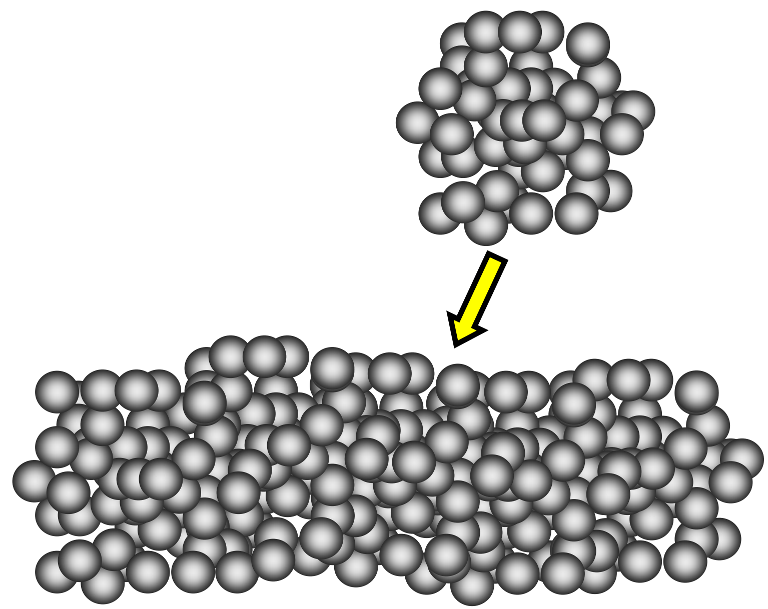
Sticking due to deep penetration

PROJECTILES: v = 0.9 m/s; ∅ = 2-3 mm; φ = 0.07



TARGET:
dust particles: ∅ 0.1-10 μm SiO_2 (irr.)
target ∅ = 25 mm; φ = 0.07

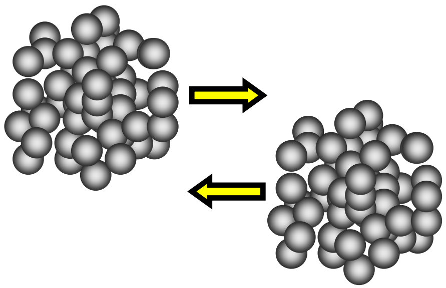
Langkowski et al. 2008



Experimental outcomes in dust-aggregate collisions

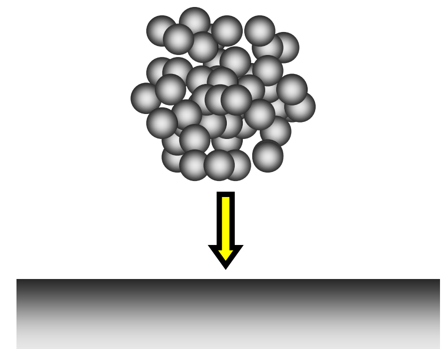
STICKING + NO COMPACTION	STICKING + COMPACTION	BOUNCING + COMPACTION	BOUNCING + FRAGMENTATION	BOUNCING + (PARTIAL) STICKING + FRAGMENTATION

Low coefficient of restitution as indication for compaction

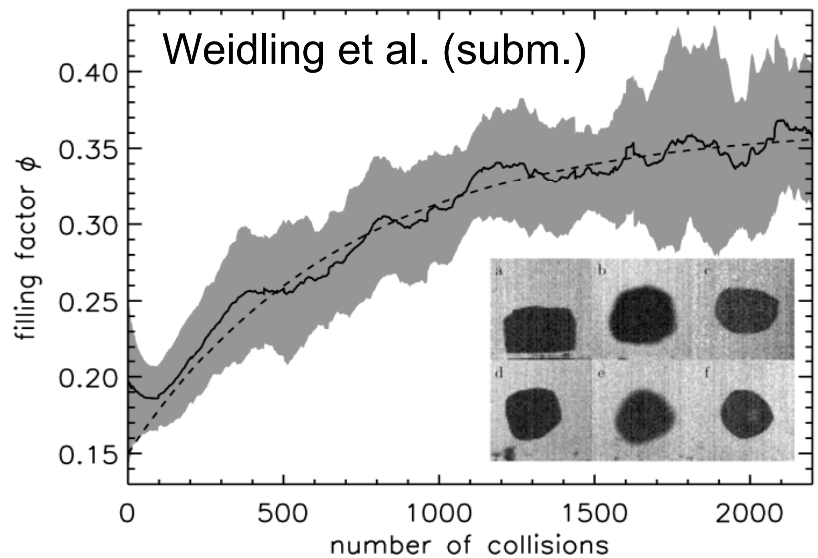


v = 0.4 m/s
∅ = 3-5 mm
φ = 0.15
SiO_2 (sph.)

Heißelmann et al. (in prep.)



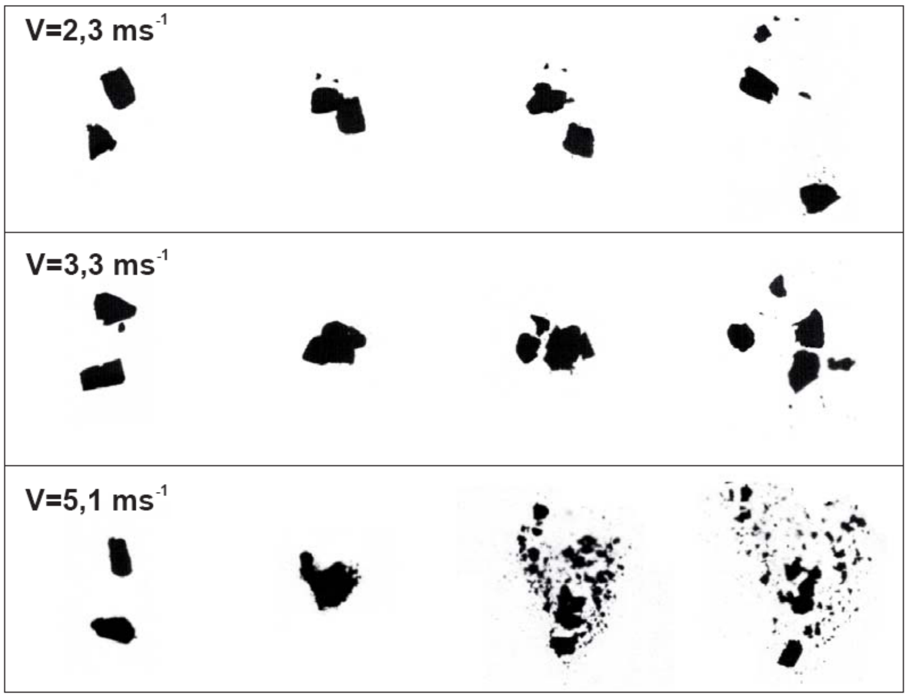
v = 0.2 m/s
∅ = 2.5 mm
φ = 0.15
SiO_2 (sph.)



Experimental outcomes in dust-aggregate collisions

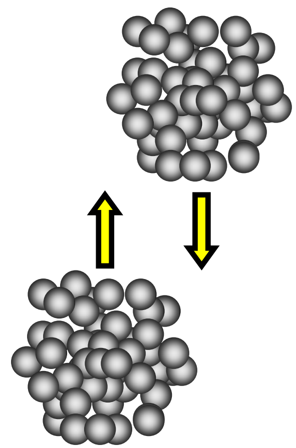
STICKING + NO COMPACTION	STICKING + COMPACTION	BOUNCING + COMPACTION	BOUNCING + FRAGMENTATION	BOUNCING + (PARTIAL) STICKING + FRAGMENTATION

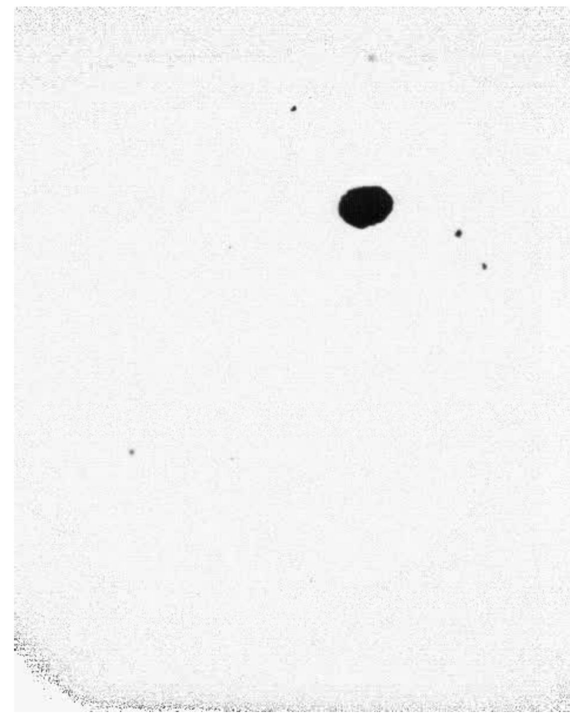
Breaking of inter-particle bonds



PROJECTILES:
dust particles: ∅ 1.5 µm SiO_2 (sph.)
∅ ~ 2 mm; φ = 0.15

Lammel et al.
(in prep.)





3D

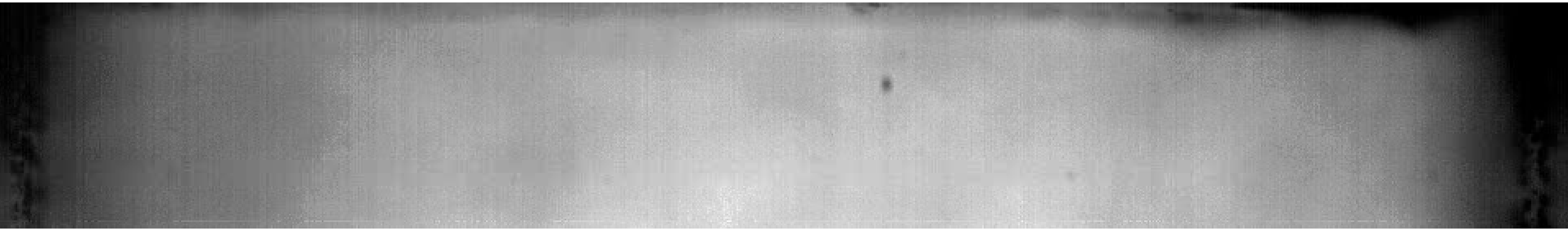
2D

Lammel et al. (in prep.)
SiO_2, φ = 0.15; v = 5.1 m/s

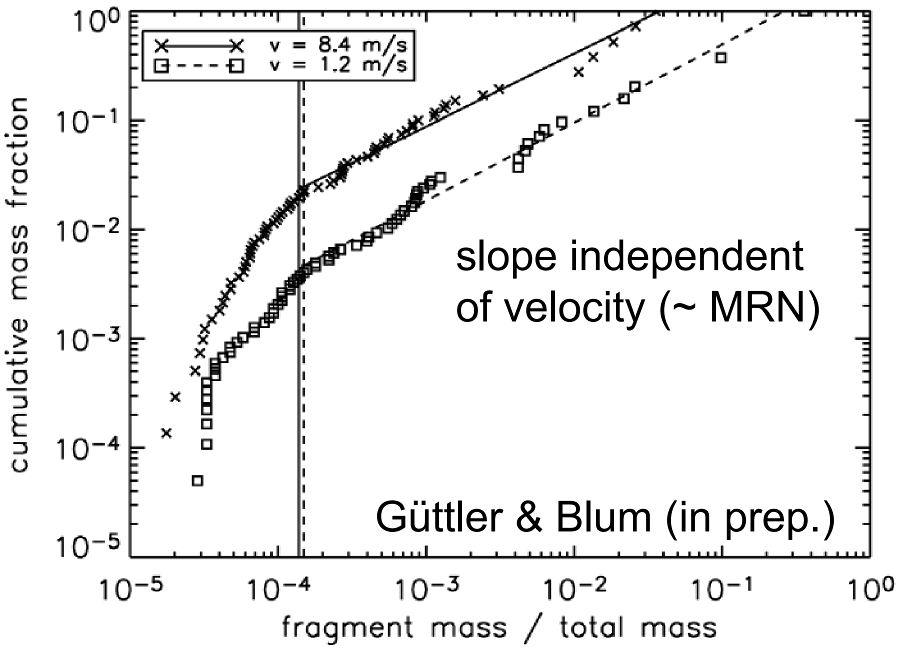
Experimental outcomes in dust-aggregate collisions

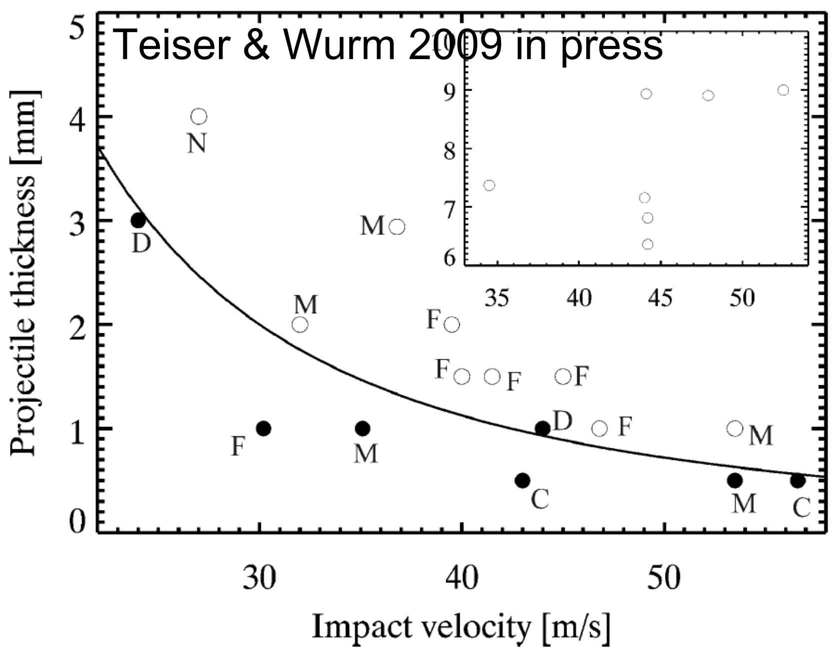
STICKING + NO COMPACTION	STICKING + COMPACTION	BOUNCING + COMPACTION	BOUNCING + FRAGMENTATION	BOUNCING + (PARTIAL) STICKING + FRAGMENTATION

"High-velocity" impacts of dust aggregates

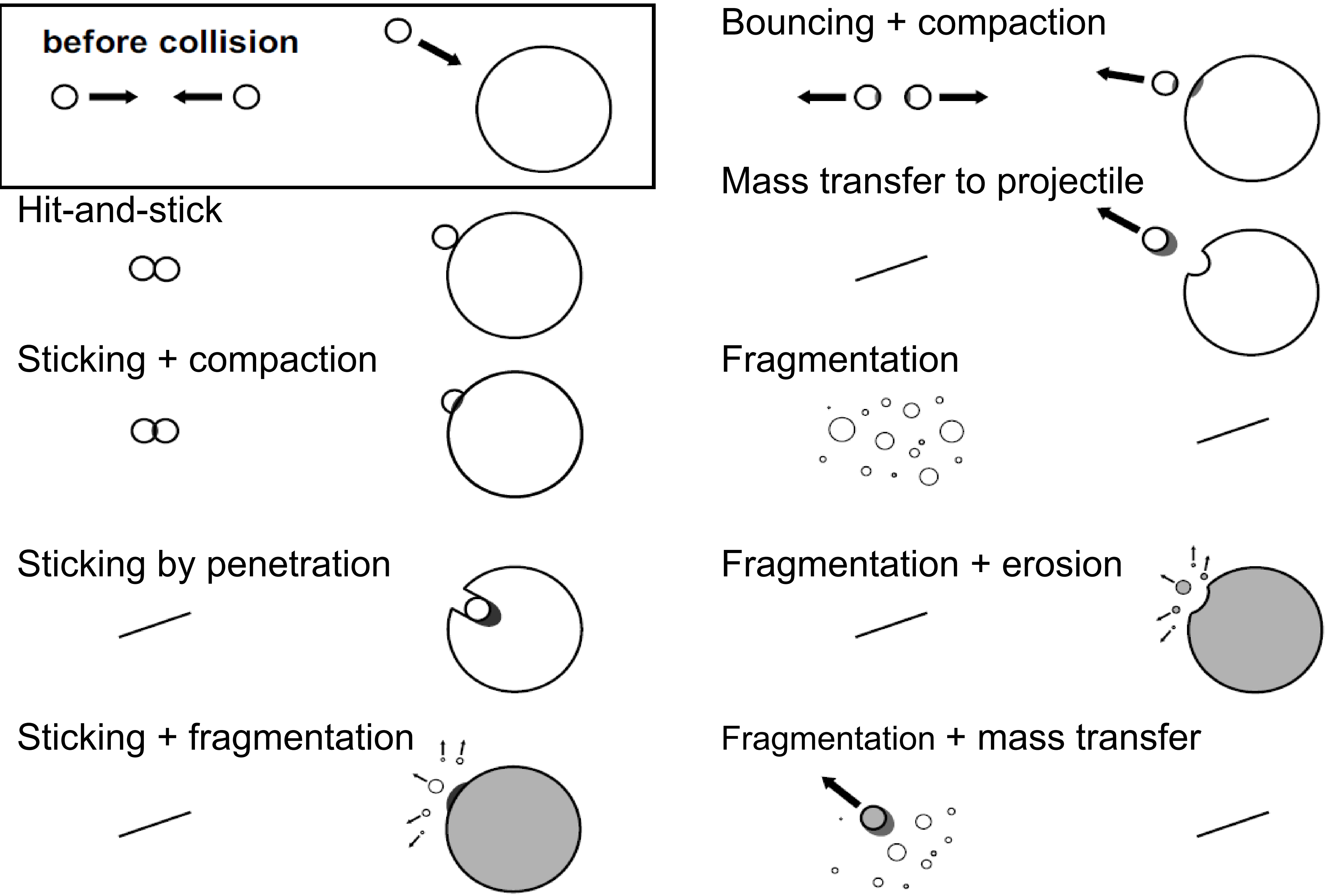


∅ 0.6 mm SiO_2 aggregate (φ = 0.35) projectile @ 8.4 m/s impact velocity onto solid SiO_2 target





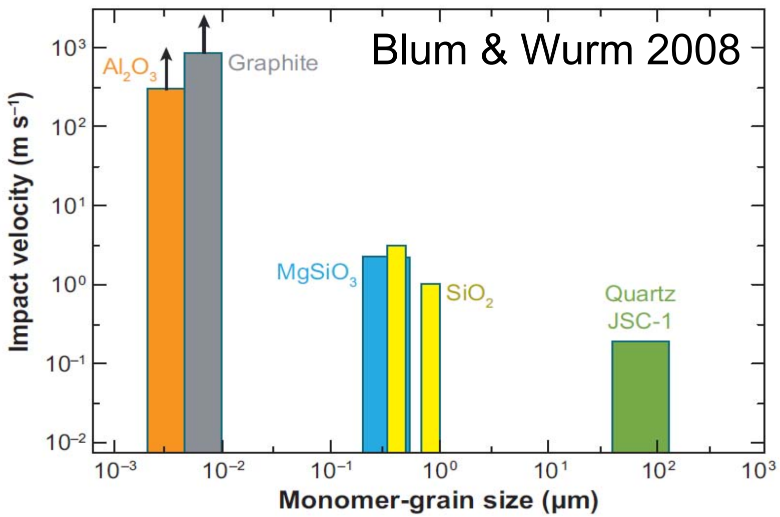
An attempt for categorization



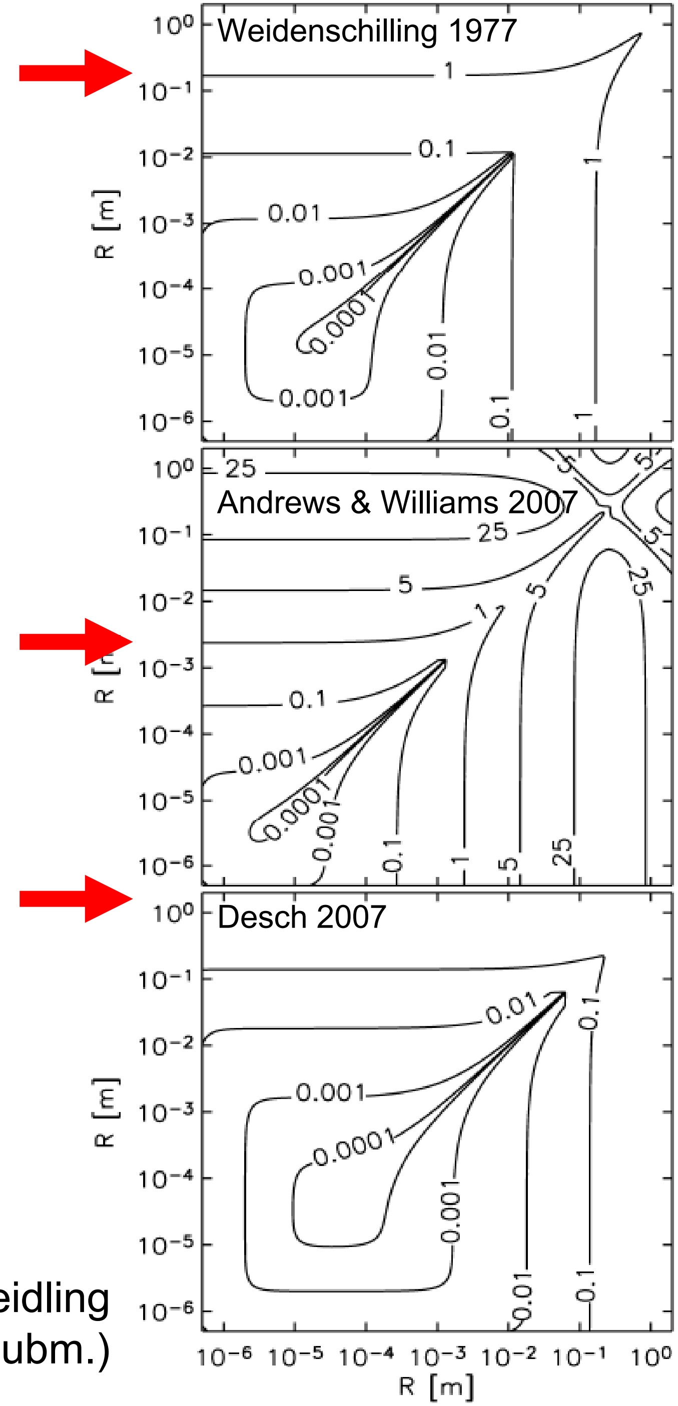
9.
How large can dust aggregates *really* grow by direct sticking?

The "facts"

- Collision velocity increases with increasing aggregate size in all solar-nebula models.
- Growth is limited by fragmentation.
- Fragmentation threshold $v_{th} \approx 1$ m/s, but depends on monomer size.

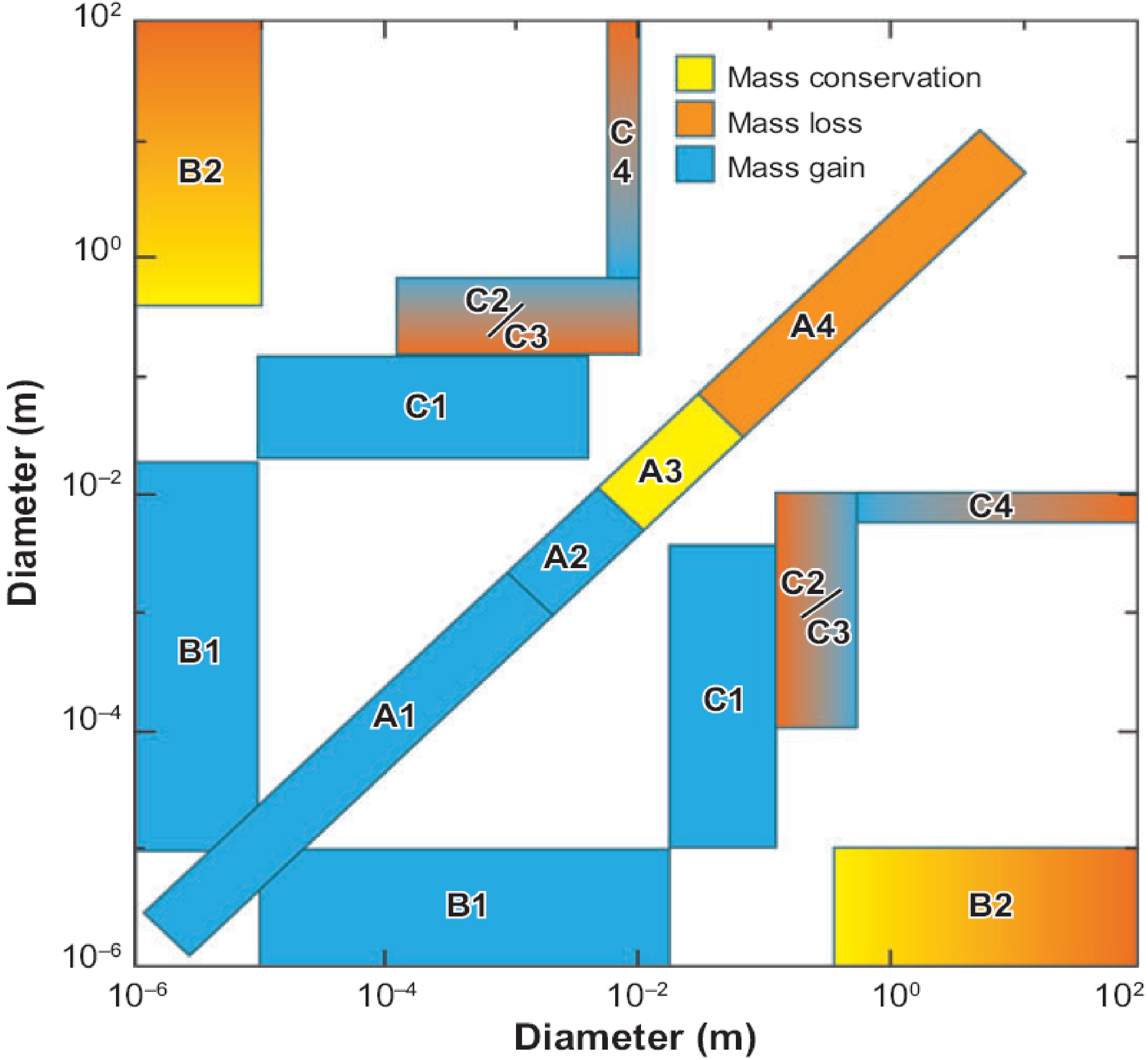


- Maximum aggregate size → achievable by direct collisional sticking:
  ~ 1 dm for MMSN (Weidenschilling 1977)
  ~ 1 mm for Andrews & Williams 2007 model
  ~ 1 m for Desch 2007 model.



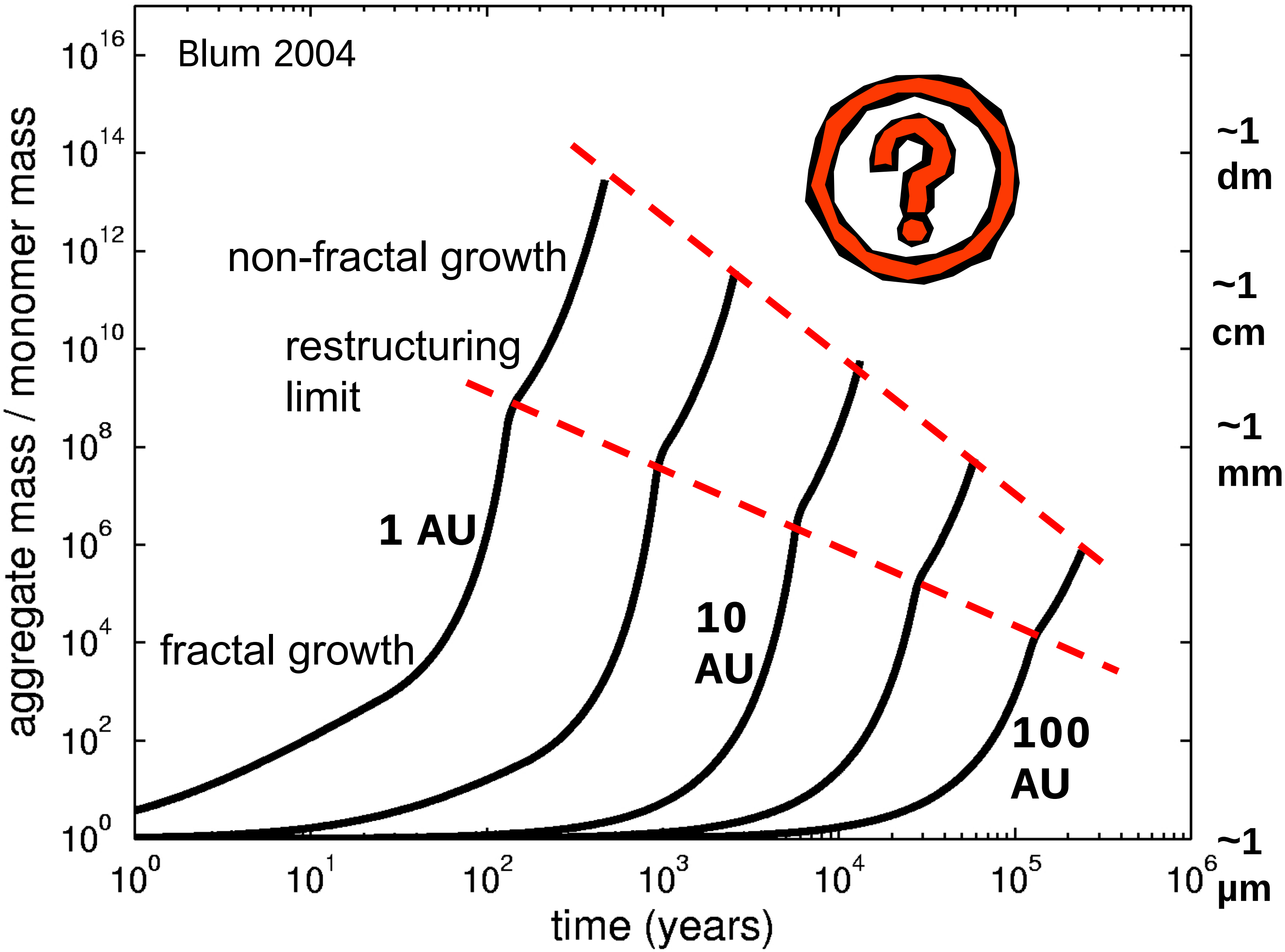
Weidling et al.(subm.)

The growth range in the MMSN model



Blum & Wurm 2008

How fast can we reach the decimeter size ?



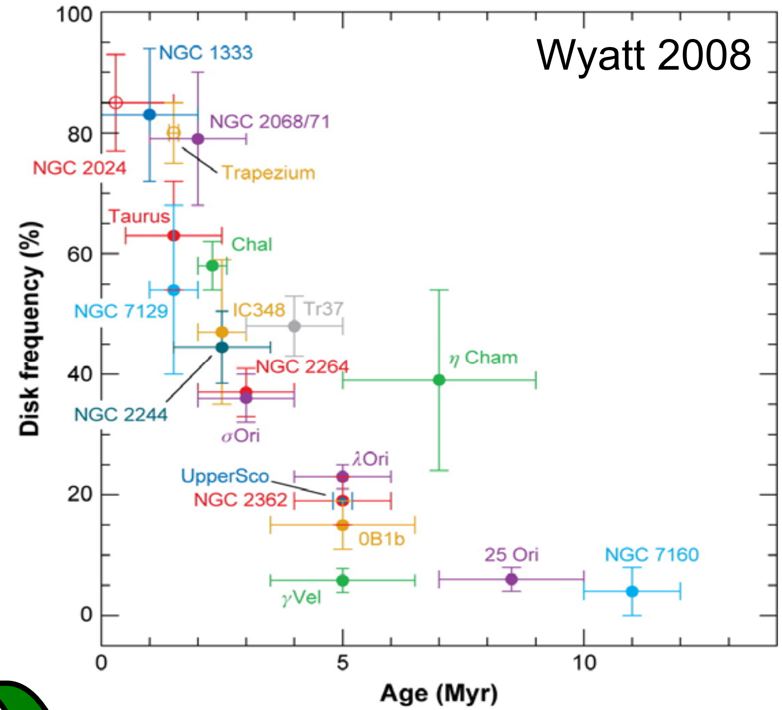
Minimum-mass solar nebula model taken from: Hayashi et al. 1985

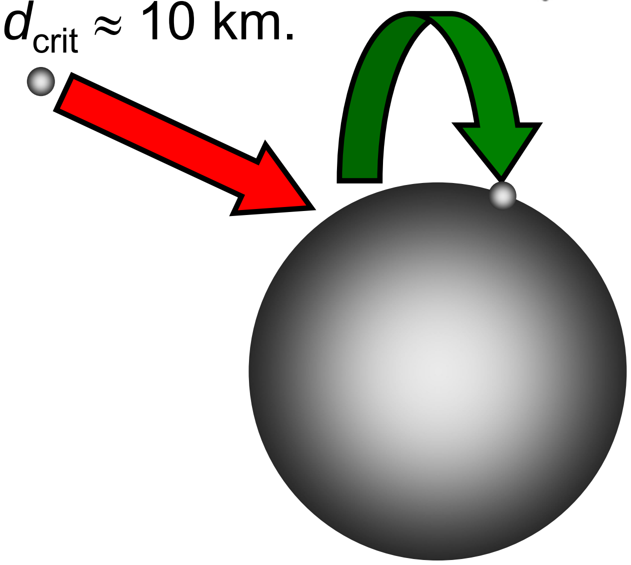
Growth timescale to dm size of ~10^3 years confirmed by more sophisticated model of Dullemond & Dominik 2005

10.
Is a dust-aggregate size of ~1 dm sufficient for the later formation of planets?

At which size becomes gravity important ?

- As long as the nebular gas is around (10^6 – 10^7 yrs), relative velocities between (≤ km-sized) protoplanetary bodies are ≤ 50 m/s.
- Escape velocity v_{esc} [m/s] ≈ d [km].
- Typical rebound velocity of bouncing or fragmenting projectile ~$0.2 \times v_{imp}$ (i.e. coefficient of restitution ~0.2).
- Size above which impacting dust aggregate *must* stick: $d_{crit} \approx 10$ km.



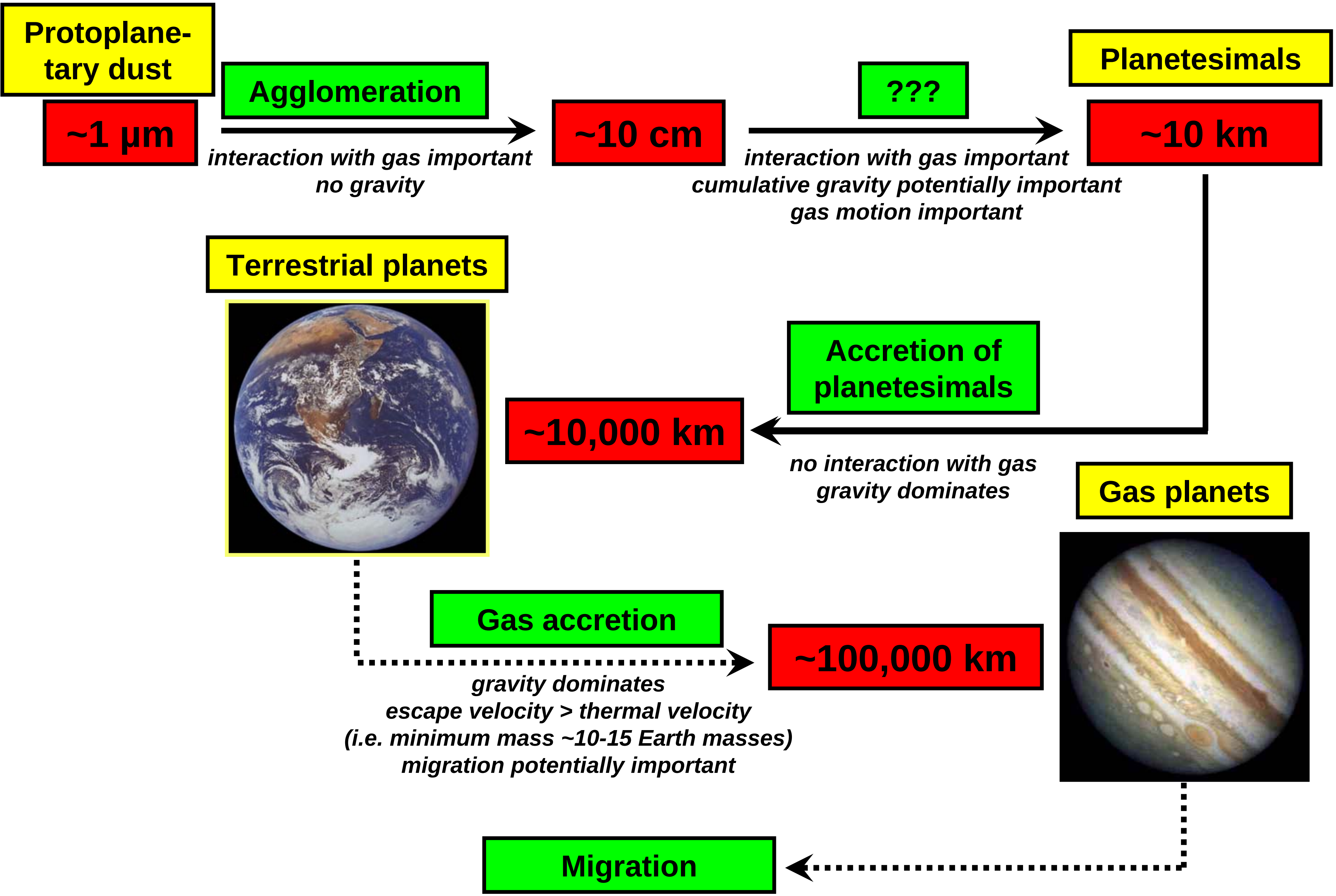


The growth range 1 dm … 1 km

Basically unsolved, due to the following problems:

- ▷ Radial drift: radial velocity peaks at ~1 m bodies; drift timescale ~100 yr (“meter-size barrier“); smaller and larger bodies need longer times ($\tau \propto s^{-1}$ for $s \leq$ 1m; $\tau \propto s$ for $s \geq$ 1m).
- ▷ High collision velocities: experiments suggest no direct sticking, but rather compaction and fragmentation.

The five-stage process of planet formation

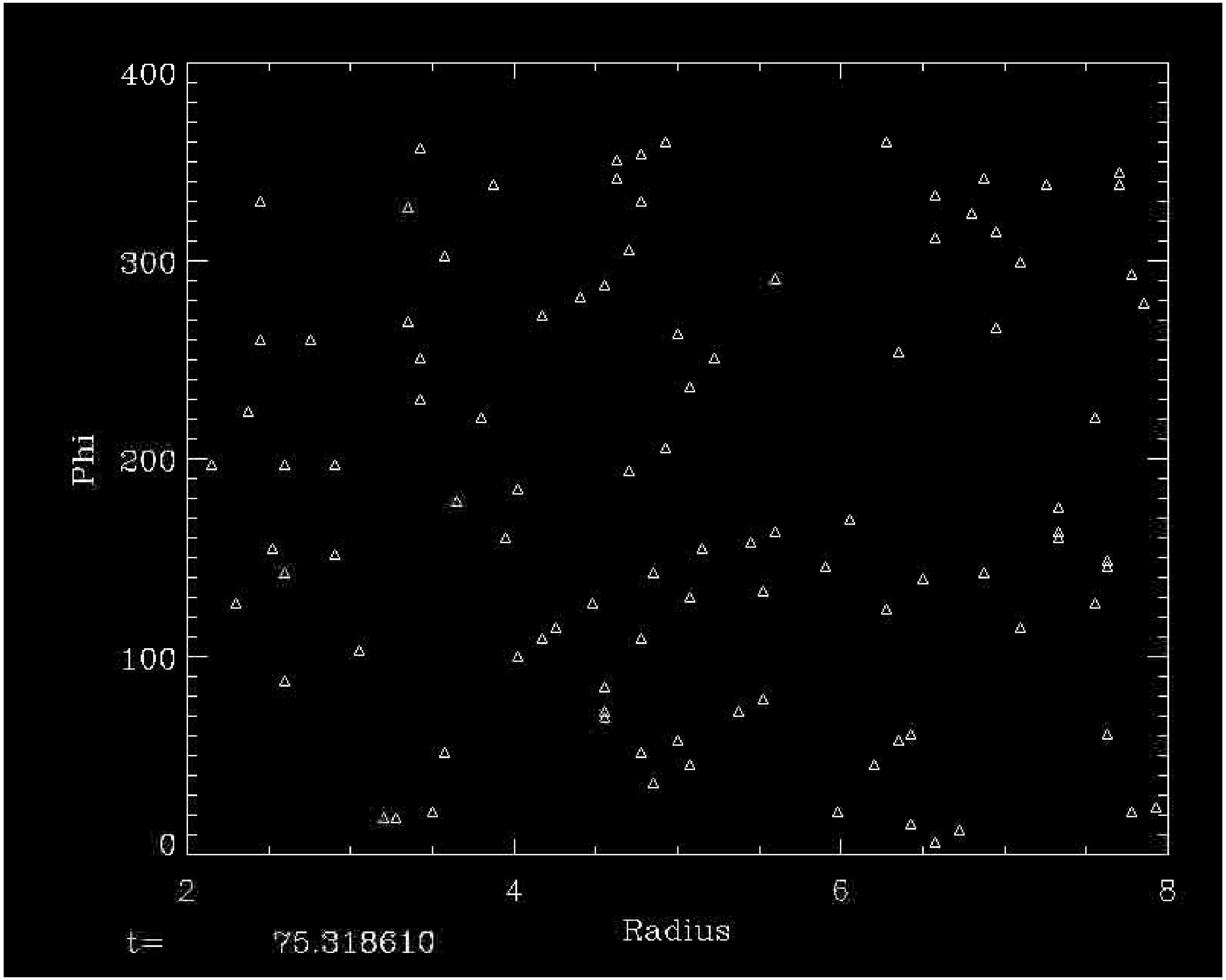


11.
Can the dm-size barrier be shifted to larger sizes?

Ways around the radial drift problem and/or the fragmentation threshold

- Capture of m-sized bodies in turbulent eddies
  (Klahr & Bodenheimer 2006; Johansen et al. 2006a)
- Suppressed radial drift in dust-dominated sub-disk
- Fast growth of m-sized bodies in dust-dominated sub-disk due to high number densities, low relative velocities, and/or gravitational instability
  (Schräpler & Henning 2004; Johansen et al. 2006b; Johansen et al. 2007)
- Fast growth of m-sized bodies by secondary accretion mechanisms
  (Wurm et al. 2001; Blum 2004)
- Photophoresis at the inner edge of the (dust) disk
  (Krauß & Wurm 2005)
- …

Capture of macroscopic particles by long-living gas vortices



- ▷ Trapping of solid objects in pressure maxima and/or in anticyclonic vortices.
- ▷ Basically all solid bodies with sizes 0.1-10 m are efficiently captured.
- ▷ No escape of dust with sizes 0.1-1000 m from vortices.
- ▷ Low relative velocities within the vortices $\Rightarrow$ collisional growth ?
- ▷ No shear inside vortices.
- ▷ Concentration of the dust particles in the centers of the vortices $\Rightarrow$ gravitational instability ?

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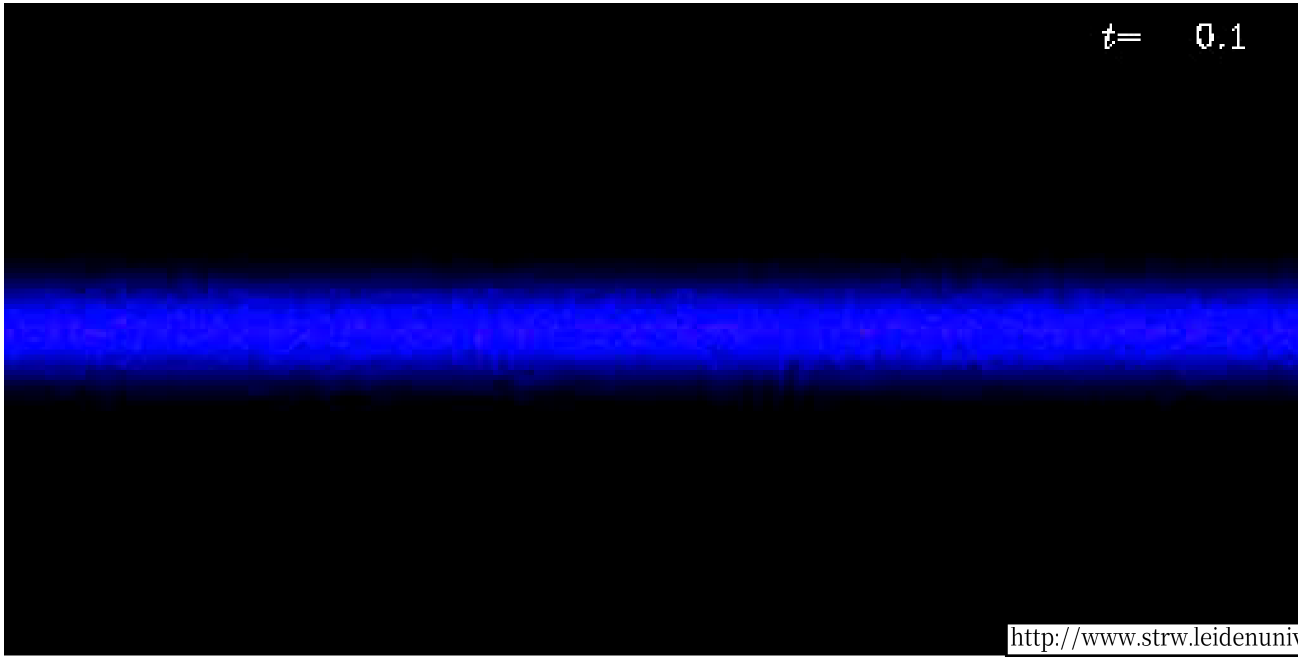
Δ: 1m dust particle

Ways around the radial drift problem and/or the fragmentation threshold

- ▷ Capture of m-sized bodies in turbulent eddies
  (Klahr & Bodenheimer 2006; Johansen et al. 2006a)
- ▷ Suppressed radial drift in dust-dominated sub-disk
- ▶ Fast growth of m-sized bodies in dust-dominated sub-disk due to high number densities, low relative velocities, and/or gravitational instability
  (Schräpler & Henning 2004; Johansen et al. 2006b; Johansen et al. 2007)
- ▷ Fast growth of m-sized bodies by secondary accretion mechanisms
  (Wurm et al. 2001; Blum 2004)
- ▷ Photophoresis at the inner edge of the (dust) disk
  (Krauß & Wurm 2005)
- ▷ …

Gravitational instability (Johansen et al. 2007)



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http://www.strw.leidenuniv.nl/~ajohan/research.php#movies

- In absence of turbulence, >cm-sized dust aggregates sediment towards the midplane of the protoplanetary disk.
- When the dust density exceeds the gas density, the gas in the midplane is forced to rotate at Keplerian velocity. Due to the shearing between the midplane rotation and the layers above/below the midplane, a Kelvin-Helmholtz instability forms.
- Due to a local variation of the dust-to-gas ratio and, thus, the rotation speed, a "clumping instability" occurs.
- Gravitationally-bound dust ensembles are formed when the dust size exceeds ~0.1 m.
- Direct formation of planetesimals with sizes up to 100-1 000 km, if fragmentation is negligible.
- However, if collisions results in fragmentation, no net growth occurs (Johansen et al. 2008).

Ways around the radial drift problem and/or the fragmentation threshold

- Capture of m-sized bodies in turbulent eddies
  (Klahr & Bodenheimer 2006; Johansen et al. 2006a)
- Suppressed radial drift in dust-dominated sub-disk
- Fast growth of m-sized bodies in dust-dominated sub-disk due to high number densities, low relative velocities, and/or gravitational instability
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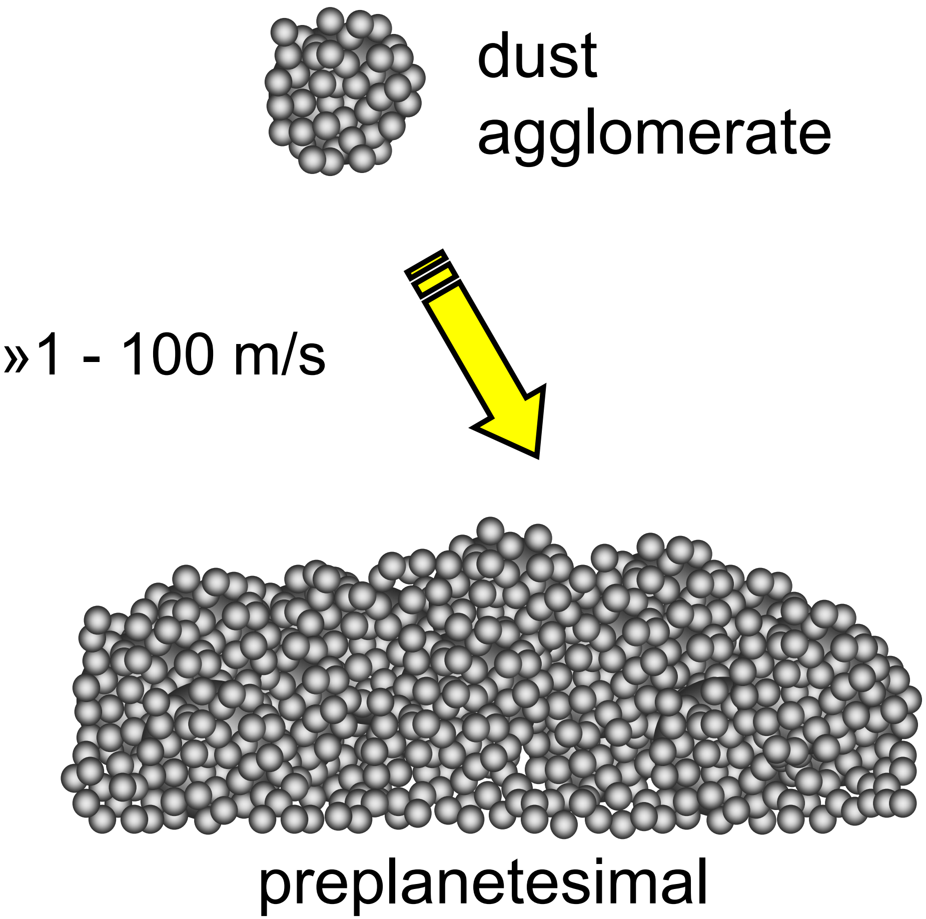
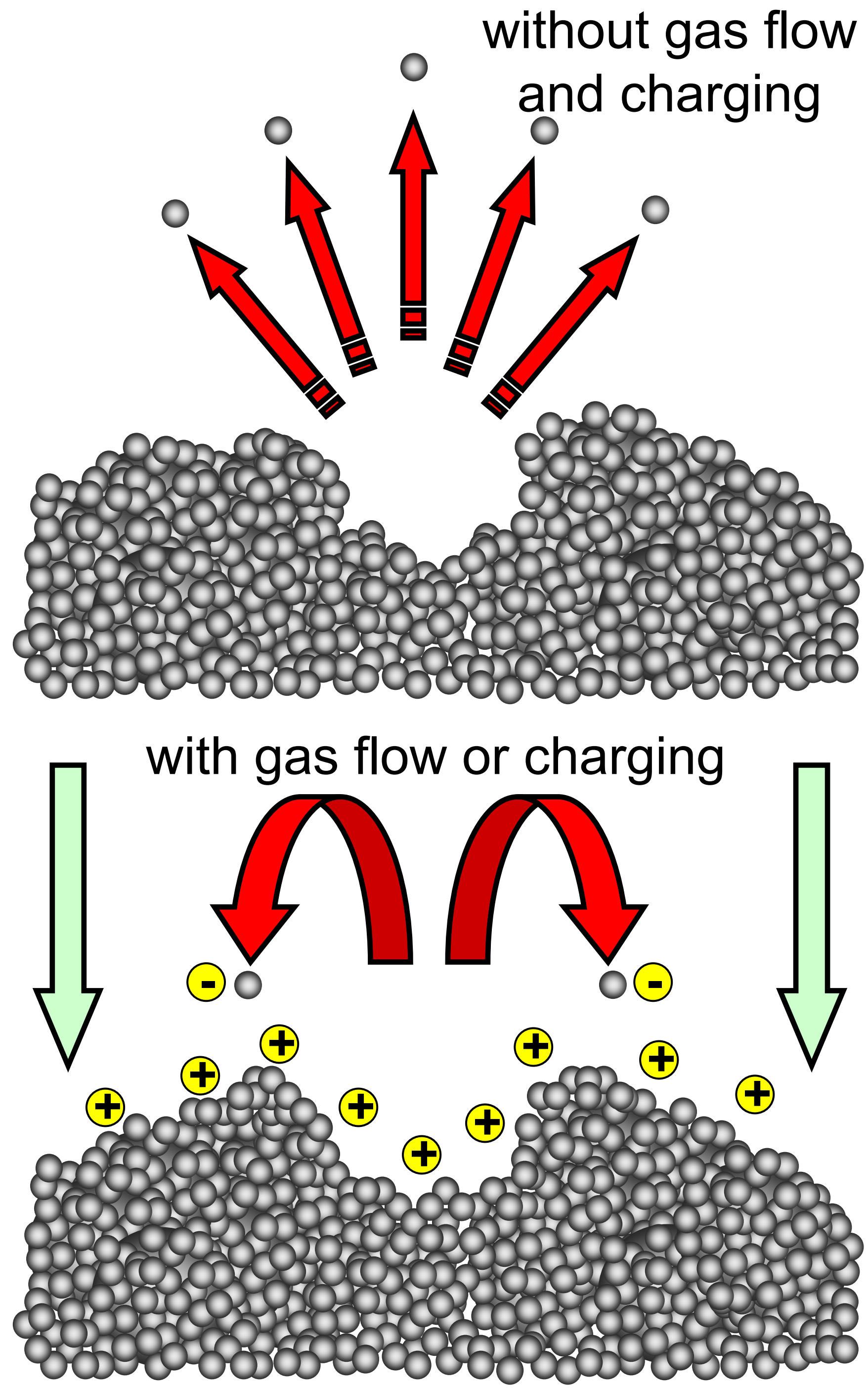
  (Wurm et al. 2001; Blum 2004)
- Photophoresis at the inner edge of the (dust) disk
  (Krauß & Wurm 2005)
- …

Fast growth of m-sized bodies by secondary accretion mechanisms

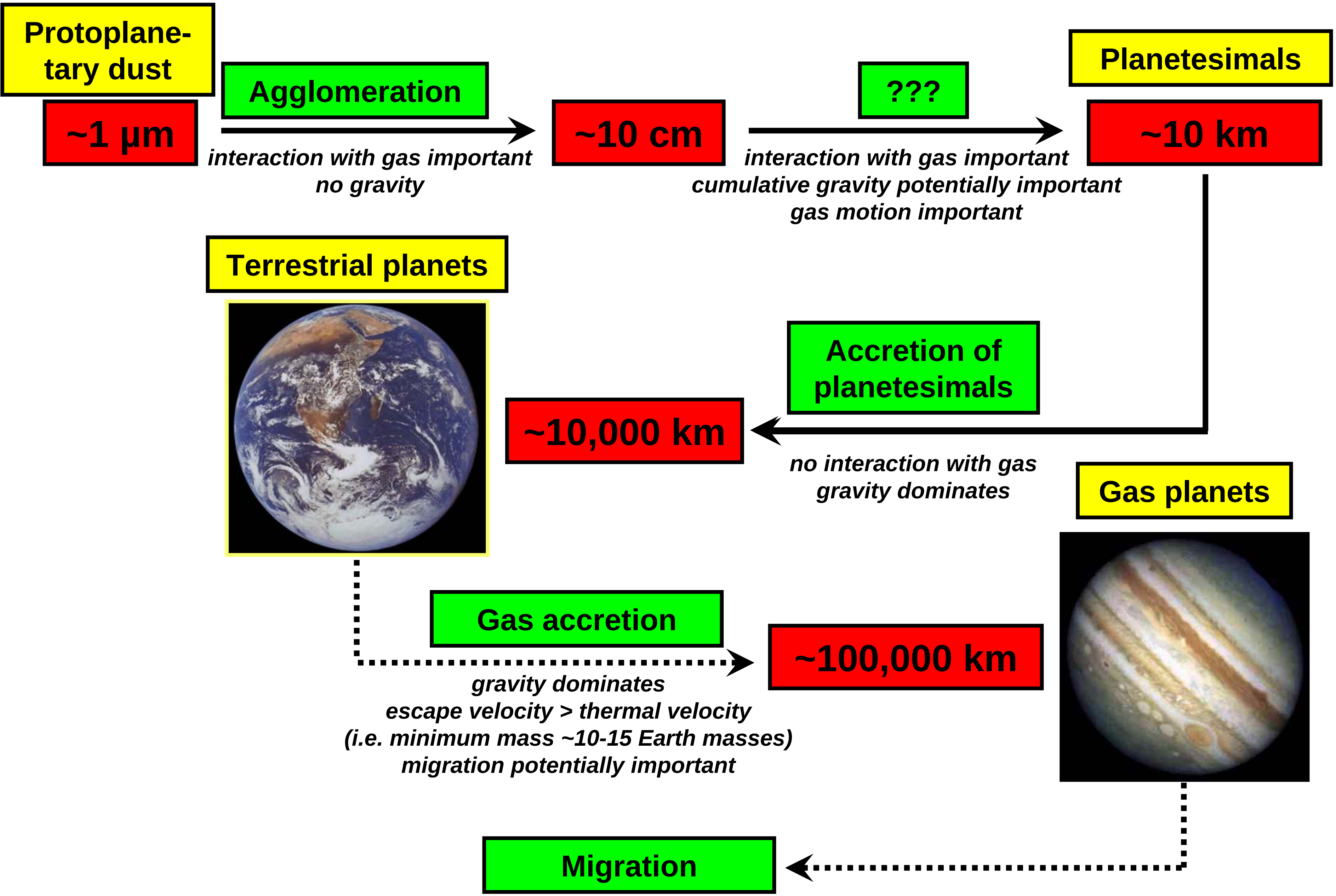
(Wurm, Blum & Colwell 2001; Blum 2004)





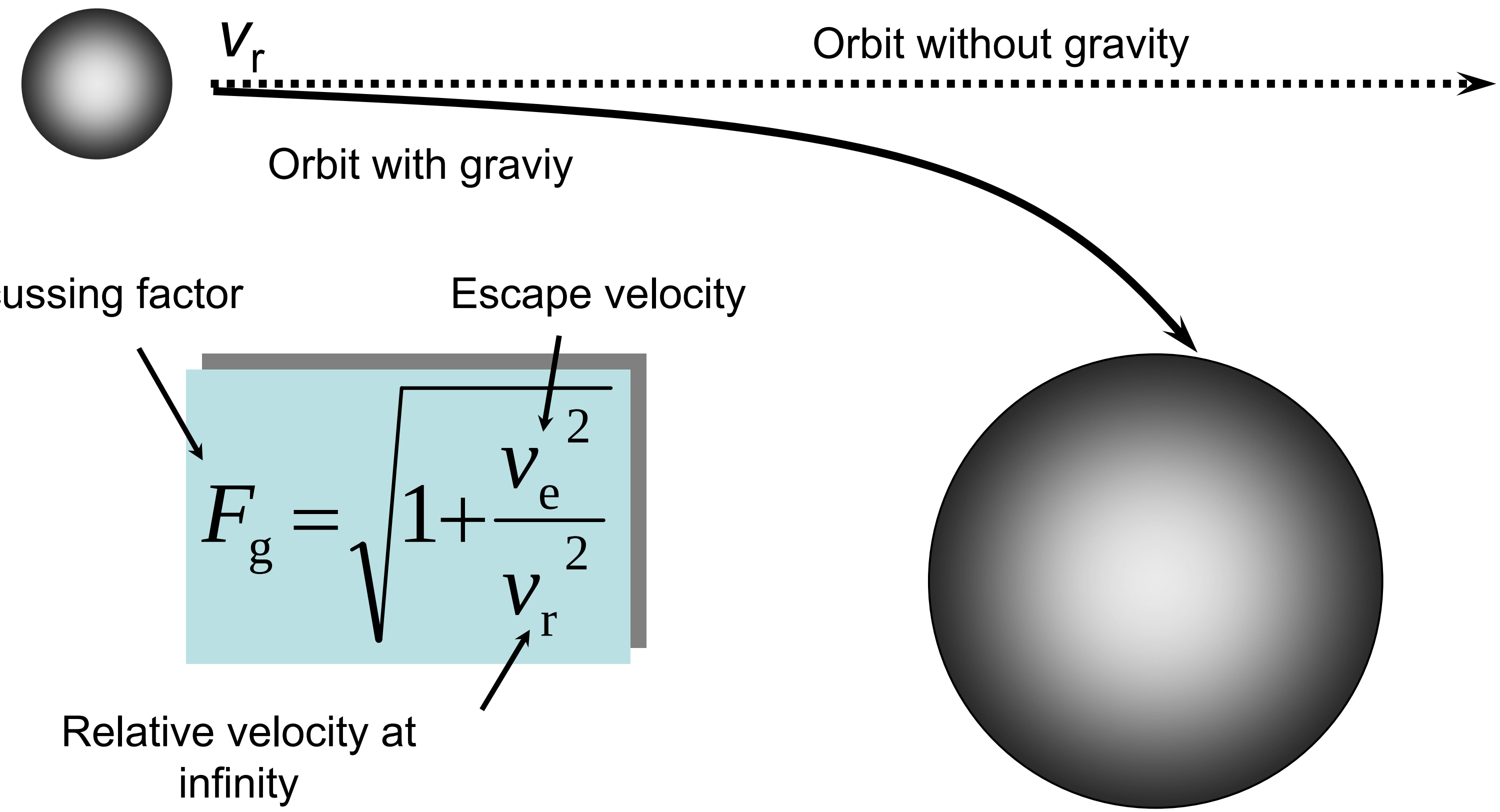
12.
The next steps towards planetary-system formation

The five-stage process of planet formation

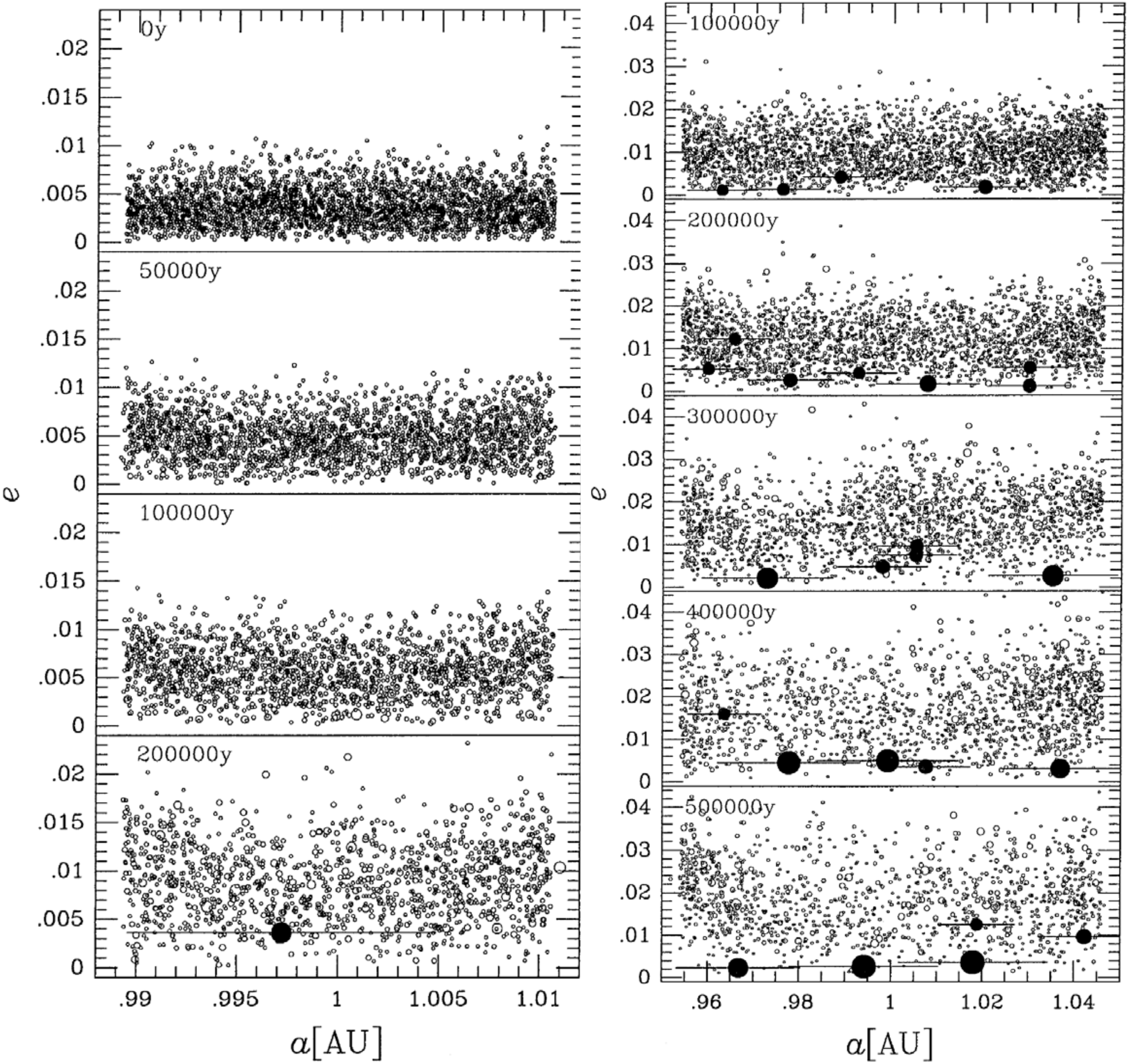


Accretion of planetesimals

- ▷ Gas friction is negligible
- ▷ Typical collision velocity < escape velocity
  - ▶ Gravitational sticking
  - ▶ Collision probability increased due to gravitational focussing → large bodies grow faster than small bodies



$$F_g = \sqrt{1 + \frac{v_e^2}{v_r^2}}$$



Kokubo & Ida 2000

Formation timescales of terrestrial planets

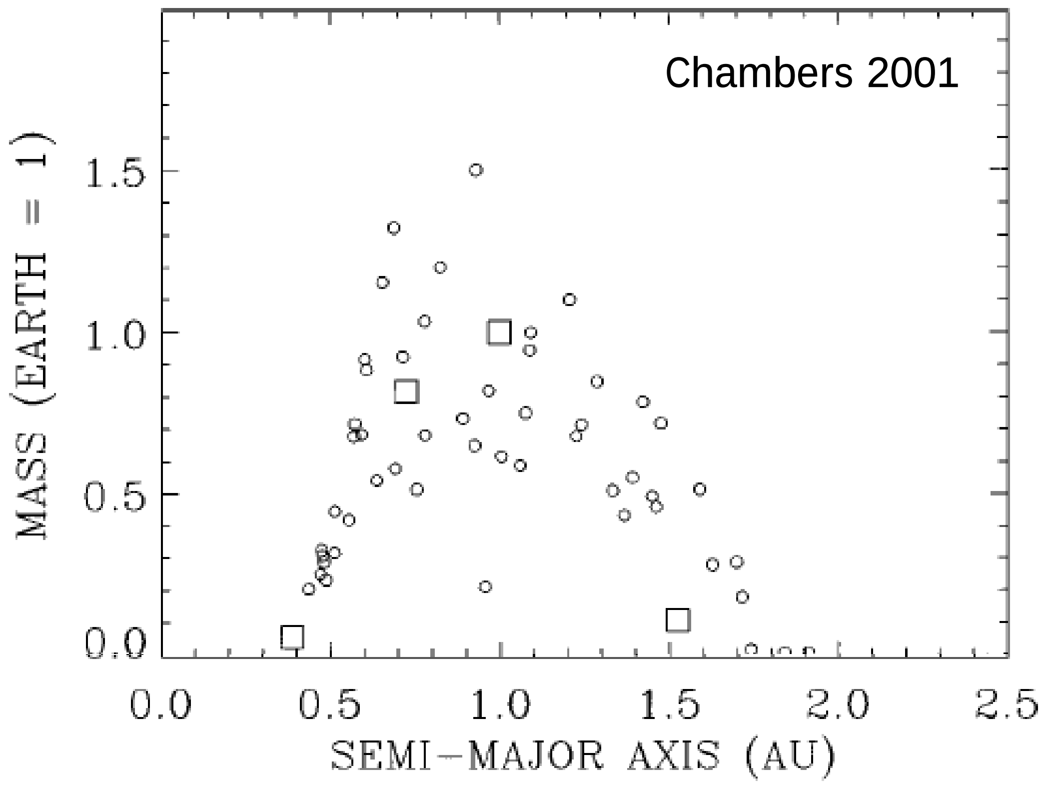
Time[$] *(yr)*	*Size*	*Process*	
0	**10^{-6} m**	**Condensation of dust particles**	Stage 1
~ 10^{3}-10^{4}	**0.1 m**	**Agglomeration with high sticking probability**	Stage 1
? (< 10^{7})[§]	**10 km**	**Planetesimals with mass m_0**	Stage 2
Time[#] ***(yr)***	***Mass***	***Process***	
~ 10^{3}	**30 m_0**		Stage 3
~ 7×10^{3}	**10^{5} m_0**		Stage 3
~ 2×10^{4}	**10^{6} m_0**		Stage 3
~ 6×10^{4}	**10^{7} m_0**		Stage 3
~ 10^{5}	**$10^{7,5}$ m_0; 0,01-0,1 M_E**	**Planetary embryos (isolated)**	Stage 3
~ 10^{6-7}	**0.1-0.5 M_E**	**Protoplanets (+ embryos; embryos are slowly consumed)**	Stage 3
~ 10^{7-8}	**1 M_E**	**Planets on isolated orbits**	Stage 3

[$] Since the formation of the sun

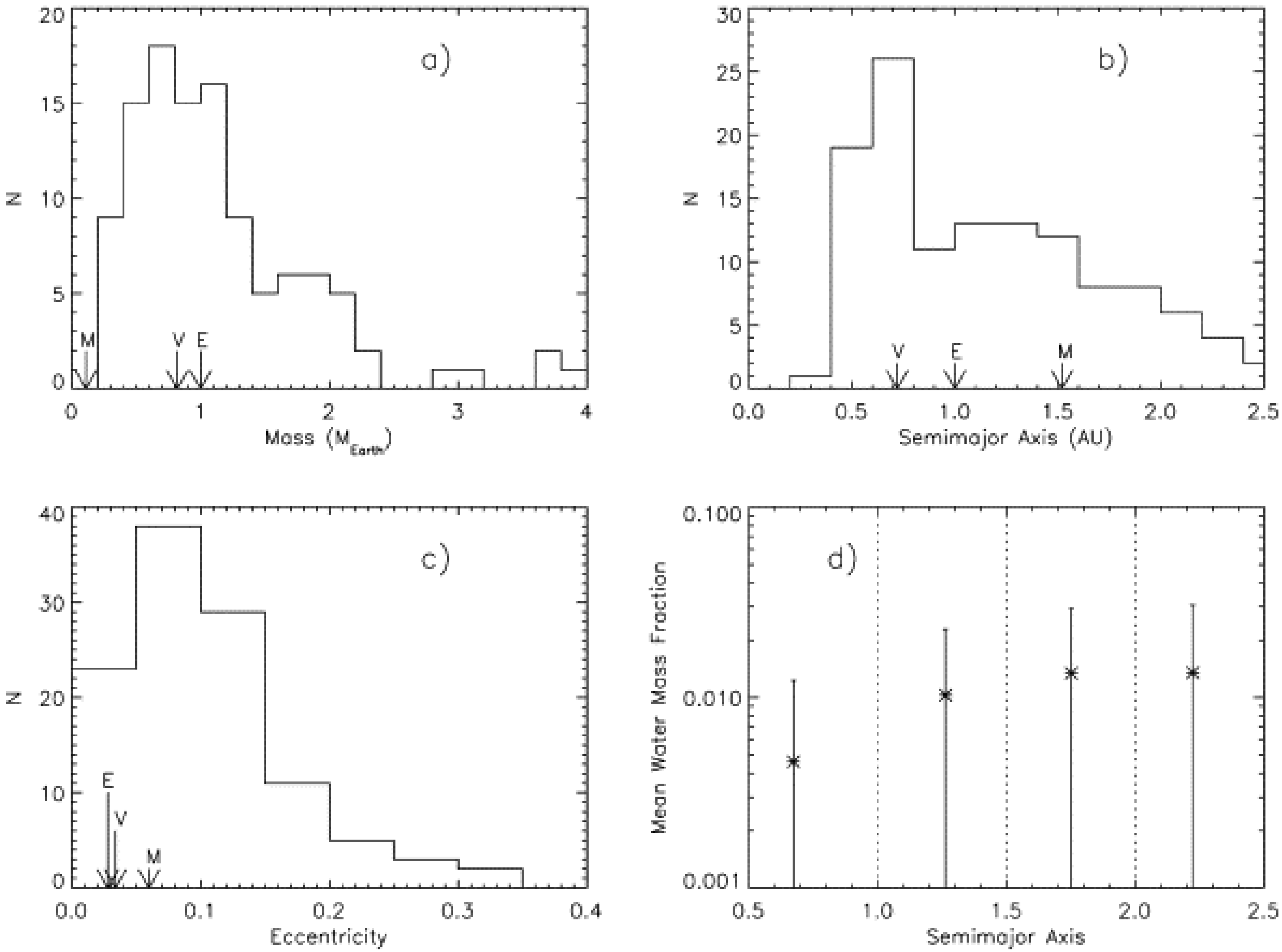
[§] Dispersion of the nebula after ~10^{7} years

[#] Since the formation of planetesimals

Making terrestrial planets

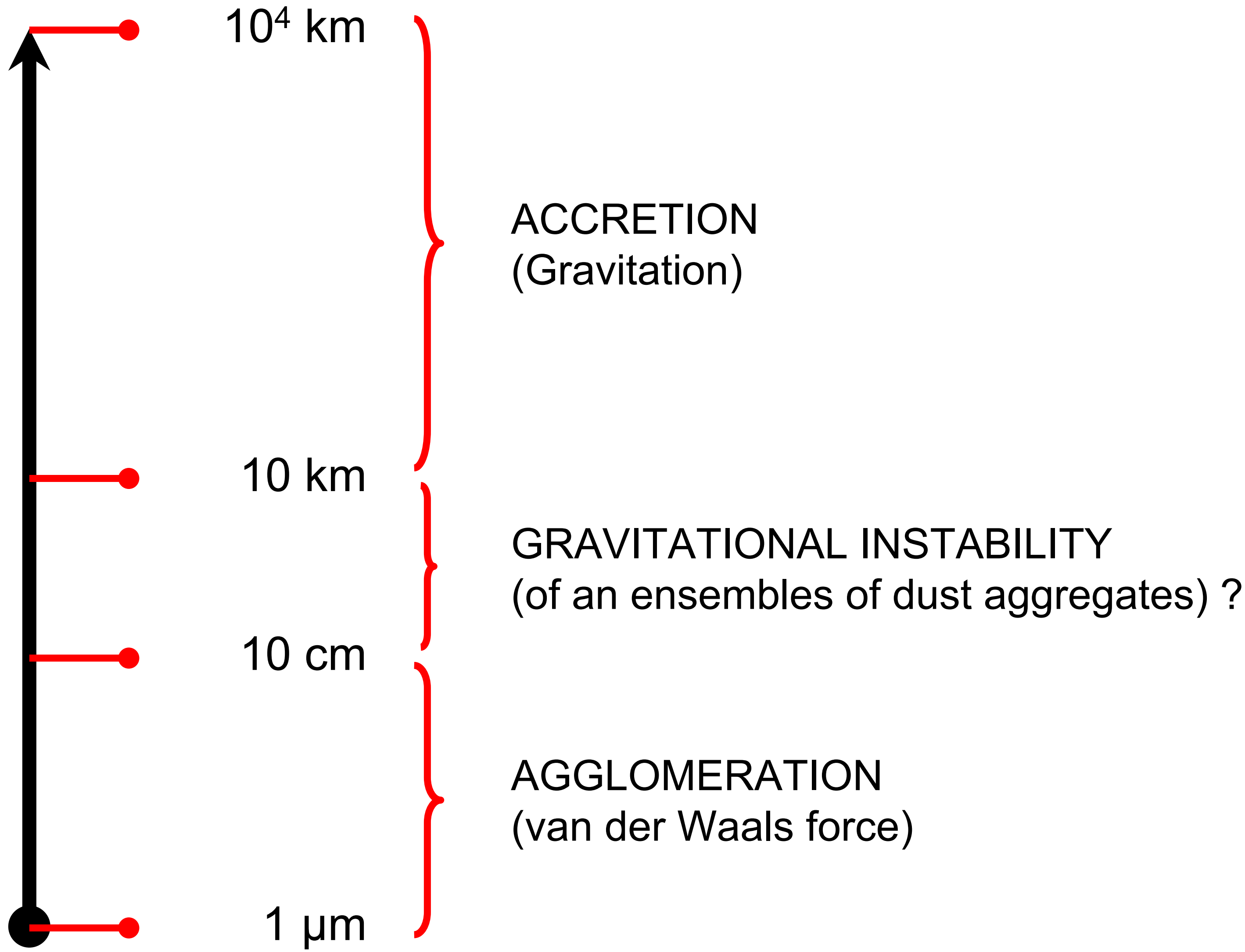


Making terrestrial planets

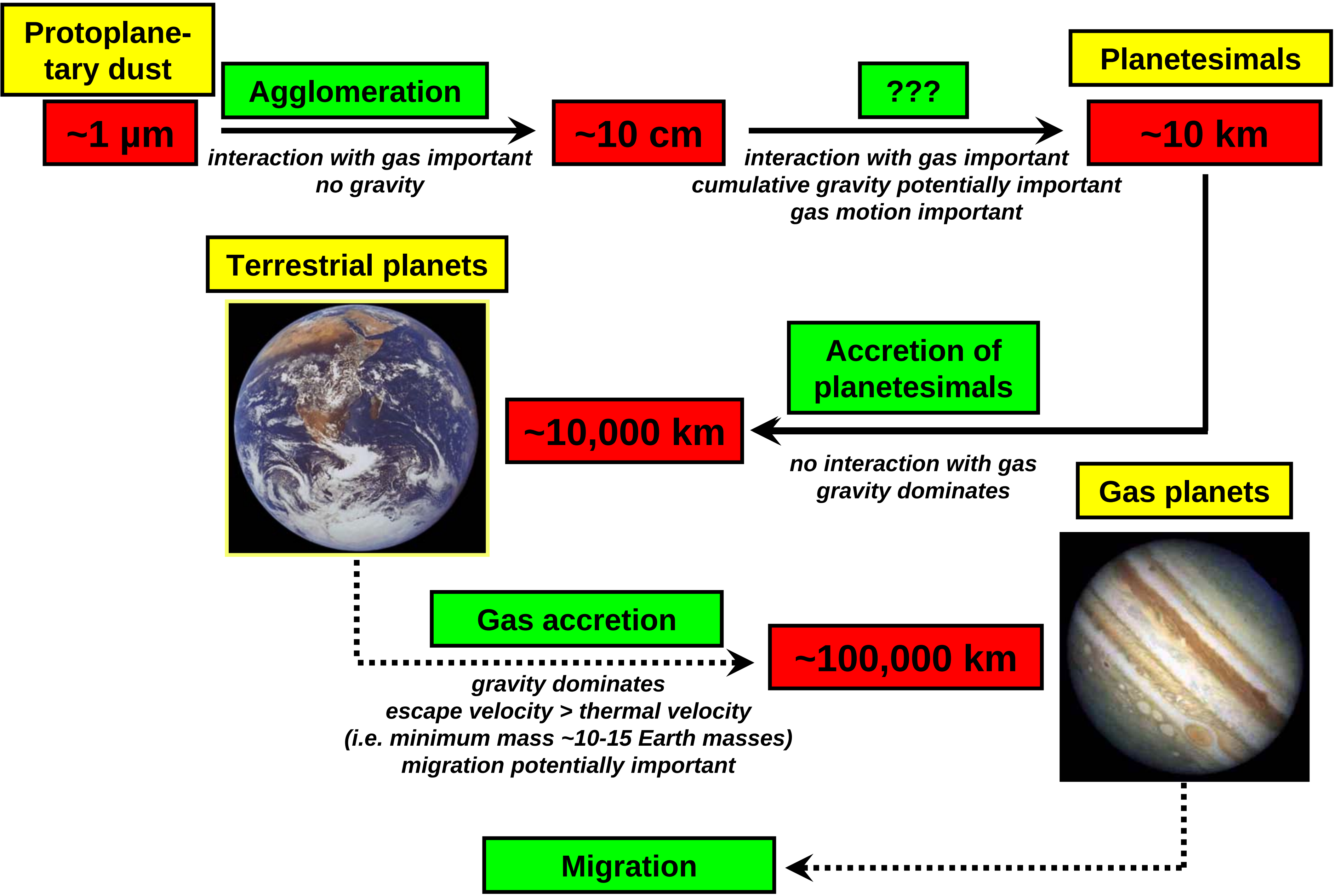


Raymond et al. 2004

Overview of the formation of terrestrial planets

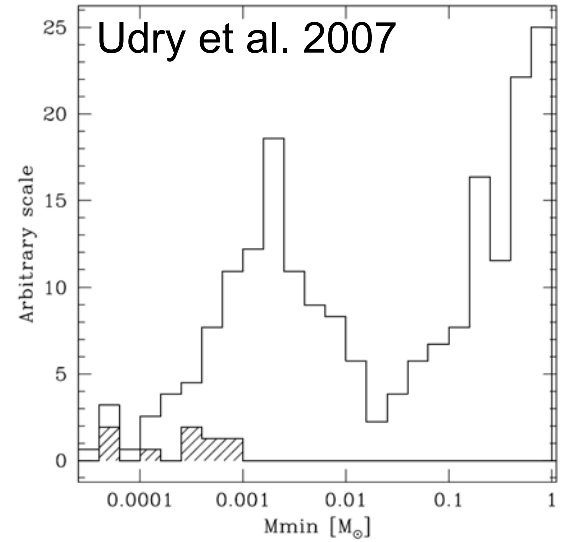


The five-stage process of planet formation



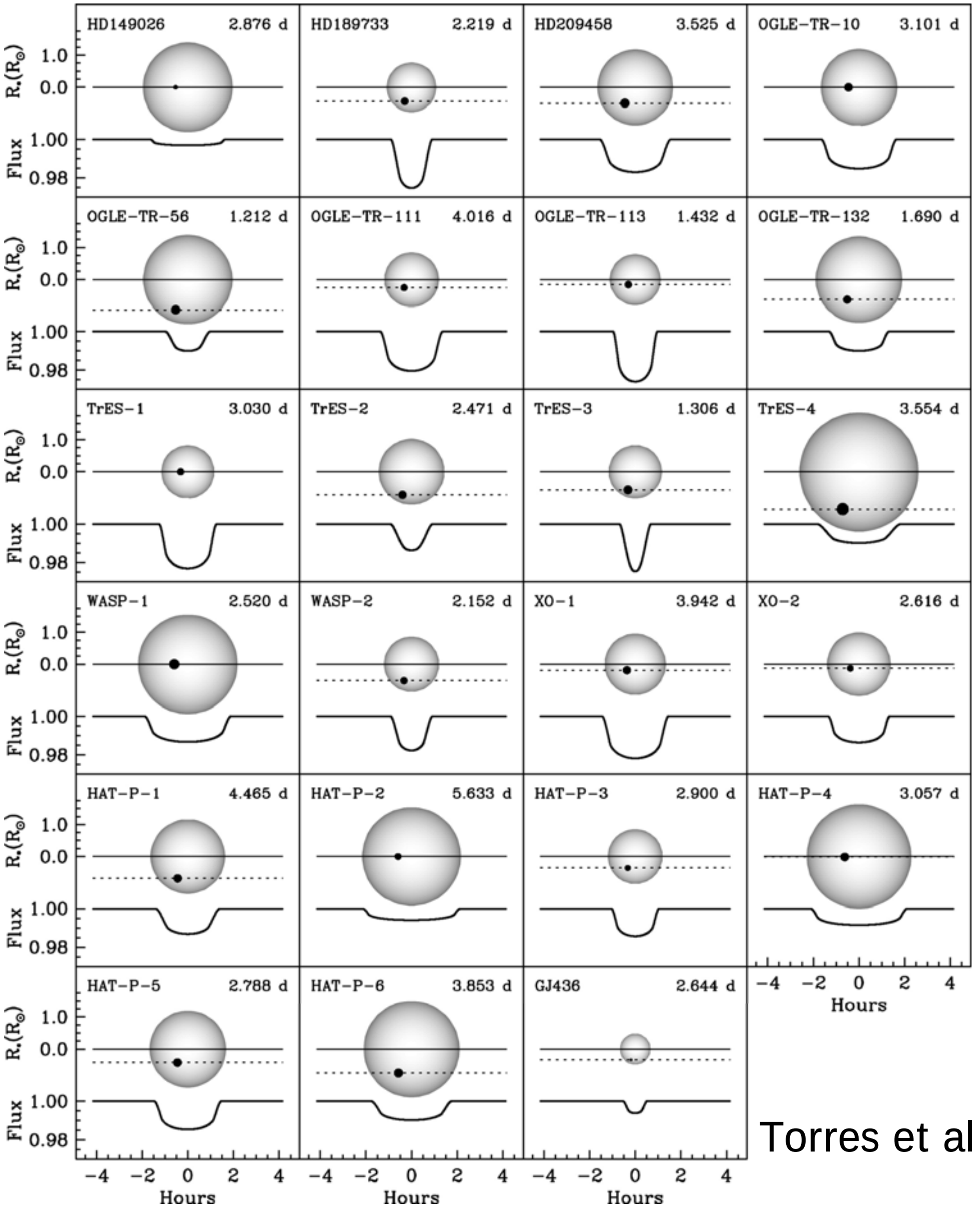
The formation of gas planets

Two hypotheses for the formation of the planets Jupiter, Saturn, Uranus and Neptune:



1. *Gravitational instability* (Boss 2001; 2003; 2007)
   - ▷ Pro: fast process.
   - ▷ Con: unclear whether the process is feasible (problems with radiation transport); "Brown Dwarf Desert".
2. *Formation of a 10-15 M_E solid core; gravitational accretion of gas* (Pollack et al. 1996; Klahr & Bodenheimer 2006; Klahr & Kley 2006)
   - ▷ Pro: gas accretion on solid core well understood and fast (within ~300.000 yrs).
   - ▷ Con: formation of a 10-15 M_E terrestrial planet within < 10^7 yrs difficult; possible if (1) long-living eddies exist in the gas, which can efficiently trap m-sized bodies (in this case, no need for stages 2-3) or (2) if the mass density is sufficiently high.

Masses and sizes of extrasolar planets



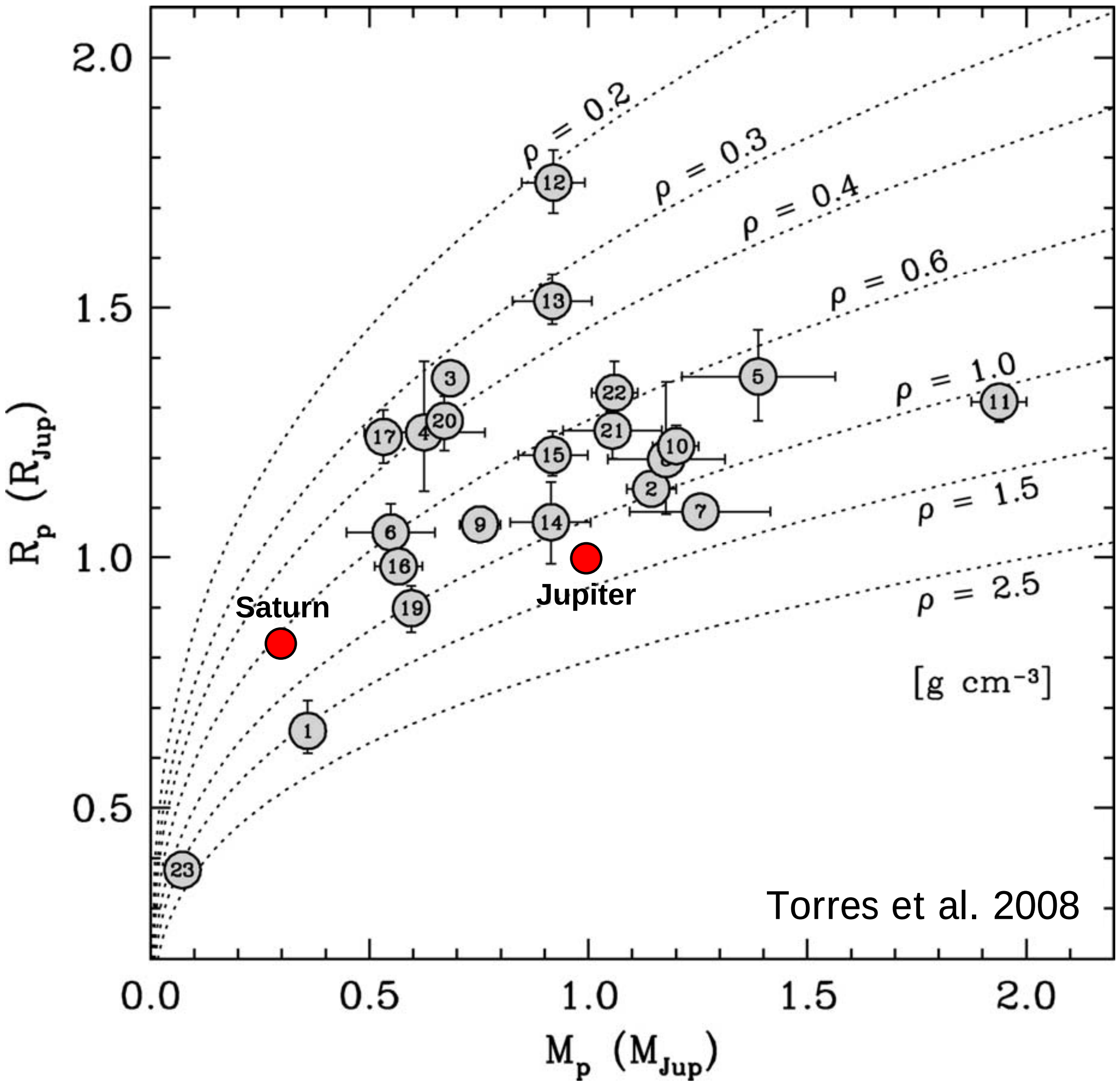
Tests of the formation hypotheses of gas planets:

→ Do extrasolar planets possess a core with more than ~1-2% of the planetary mass?

→ Simultaneous measurement of mass and radius of extrasolar planets.

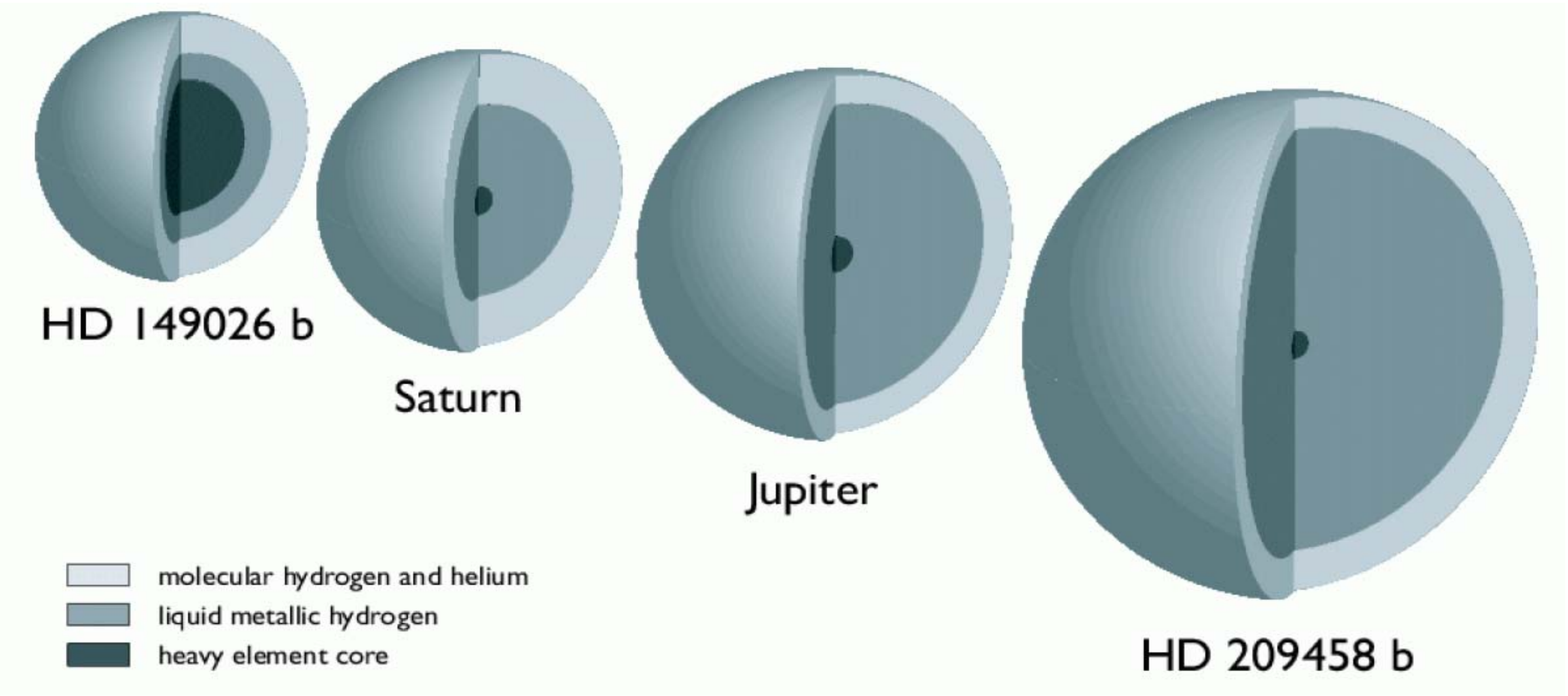
Torres et al. 2008

Masses and sizes of extrasolar planets



Core masses of extrasolar planets

Tests of the formation hypotheses of gas planets

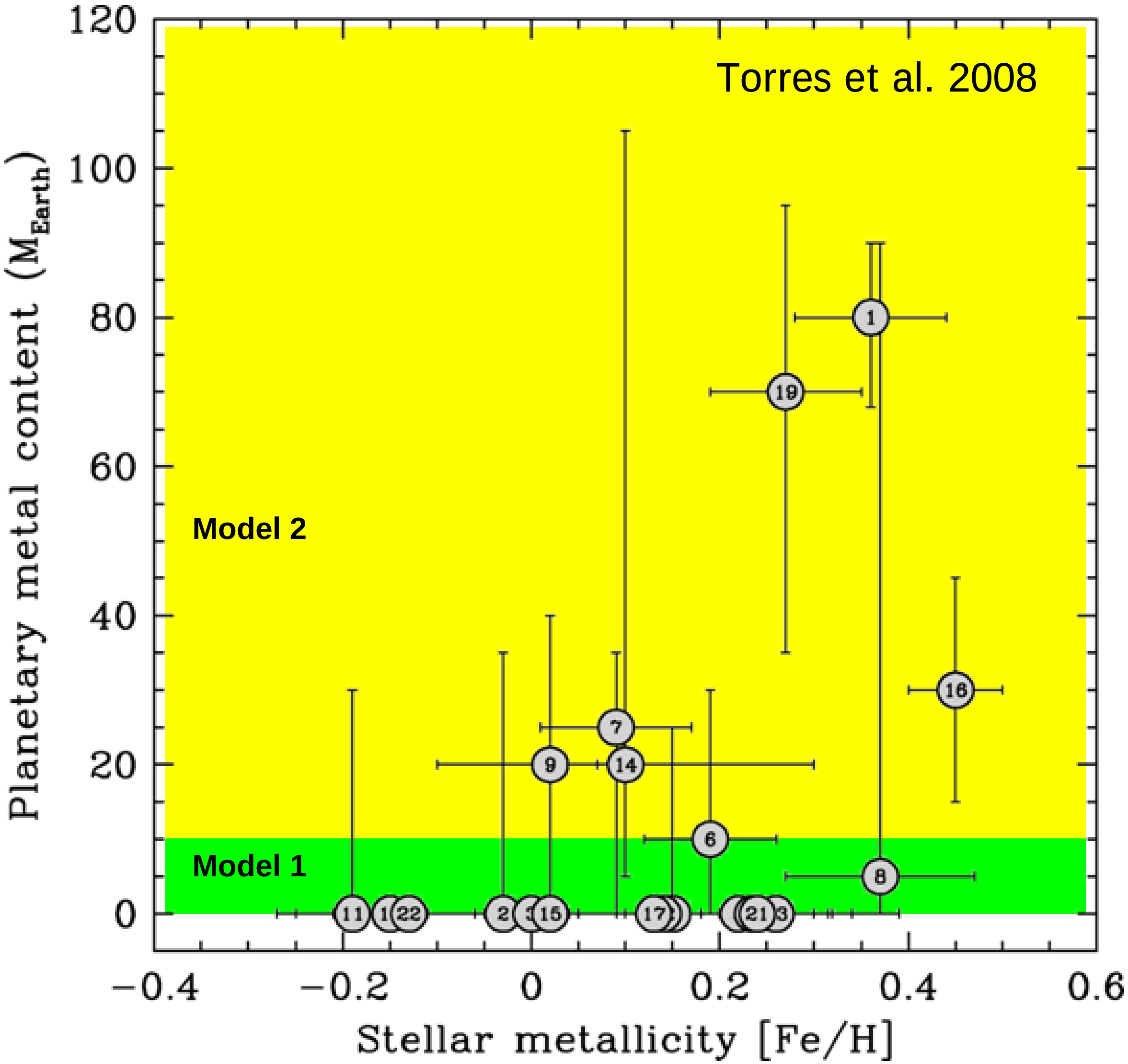


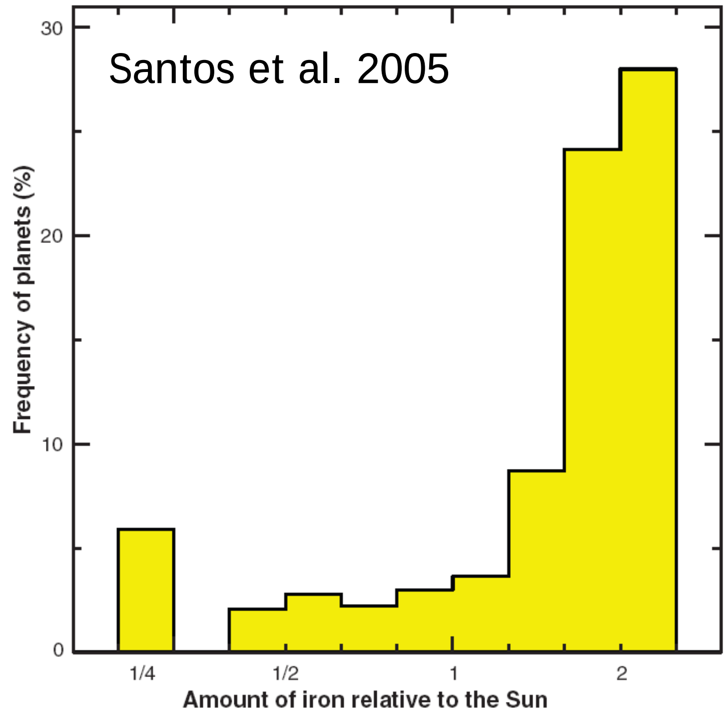
Charbonneau et al. 2007

Prediction model 1: core mass / total mass ~0.01 – 0.02.

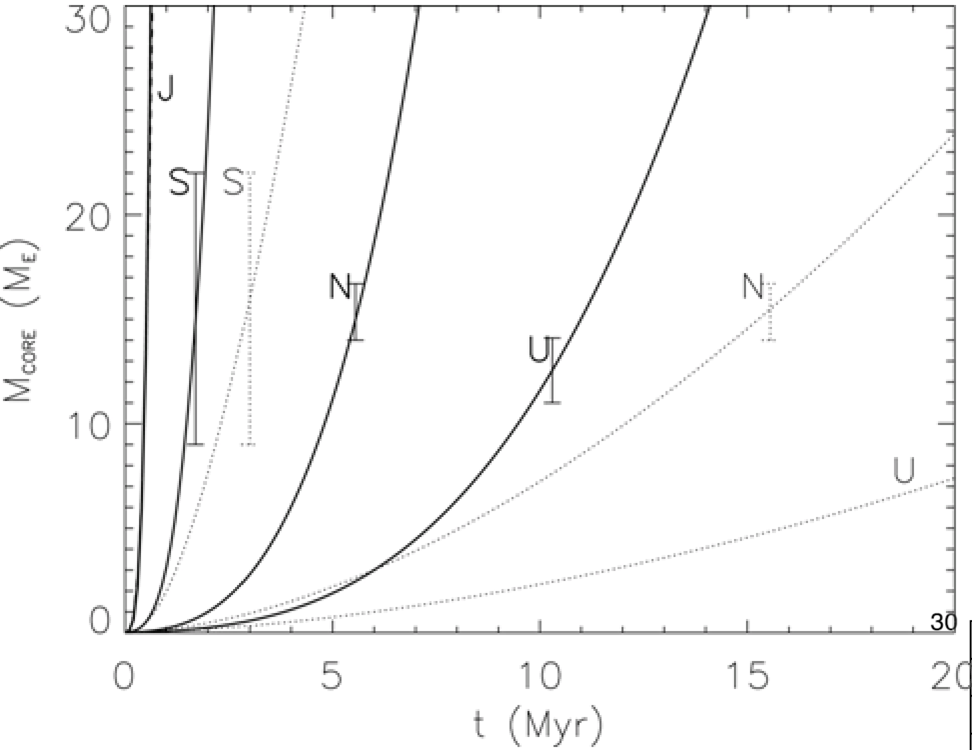
Prediction model 2: core mass ≥10-20 earth masses.

Core masses of extrasolar planets



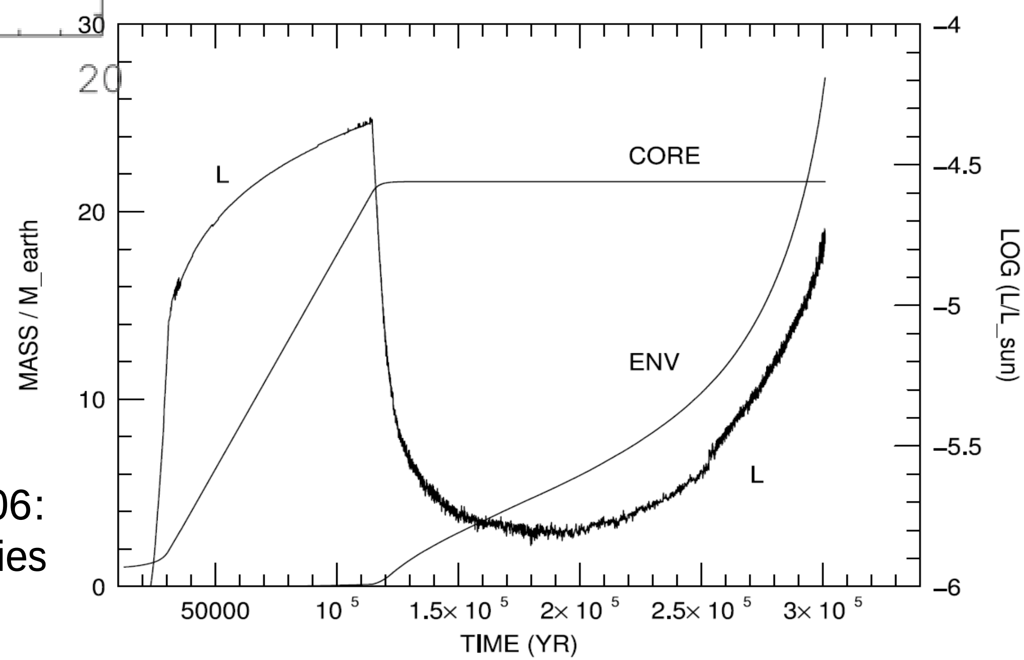


The formation of gas planets within 10^6-10^7 yrs (model 2)

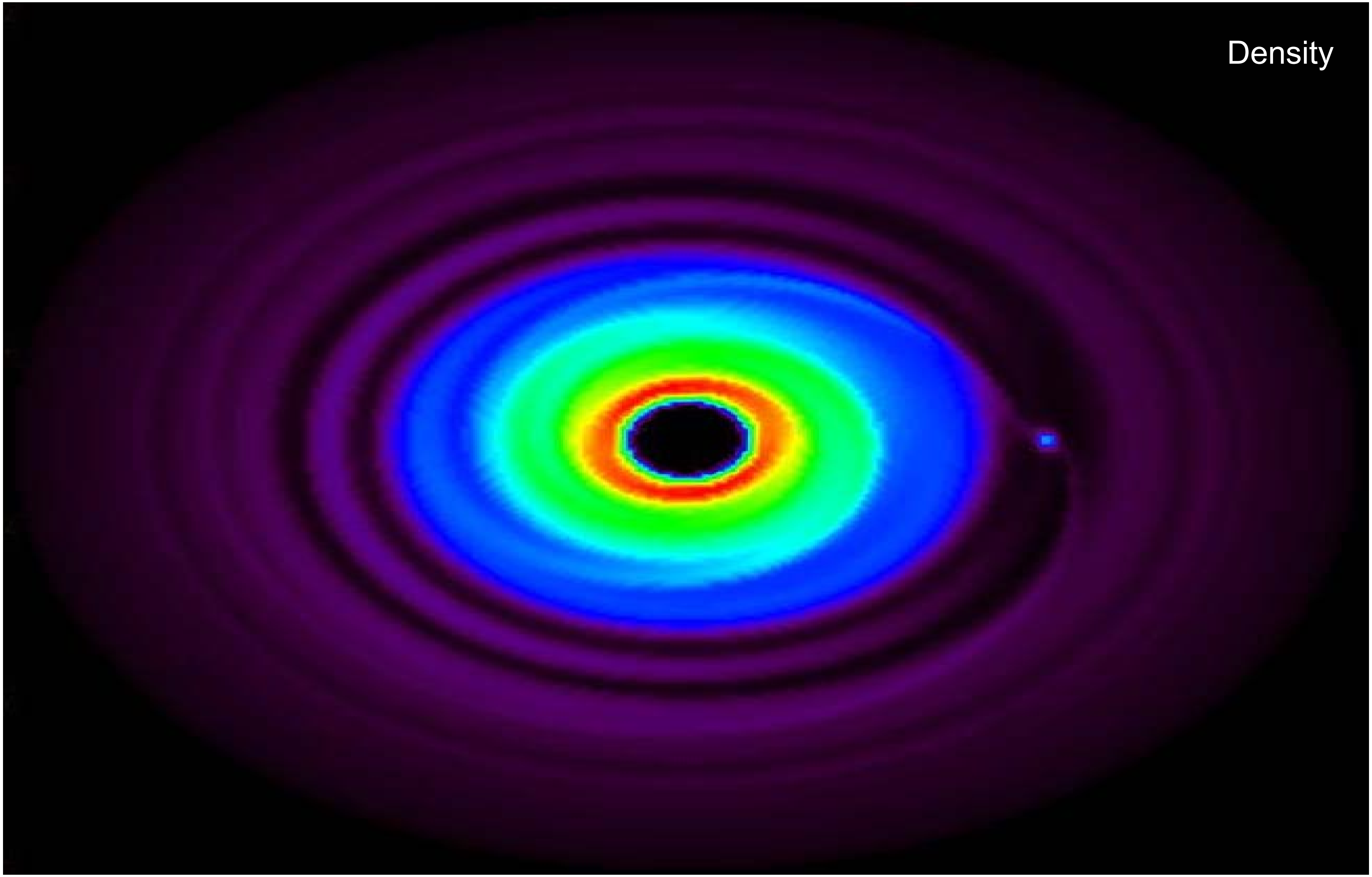


Desch 2007:
modified model of solar nebula,
based on Nice model

Klahr & Bodenheimer 2006:
particle shearing within turbulence eddies

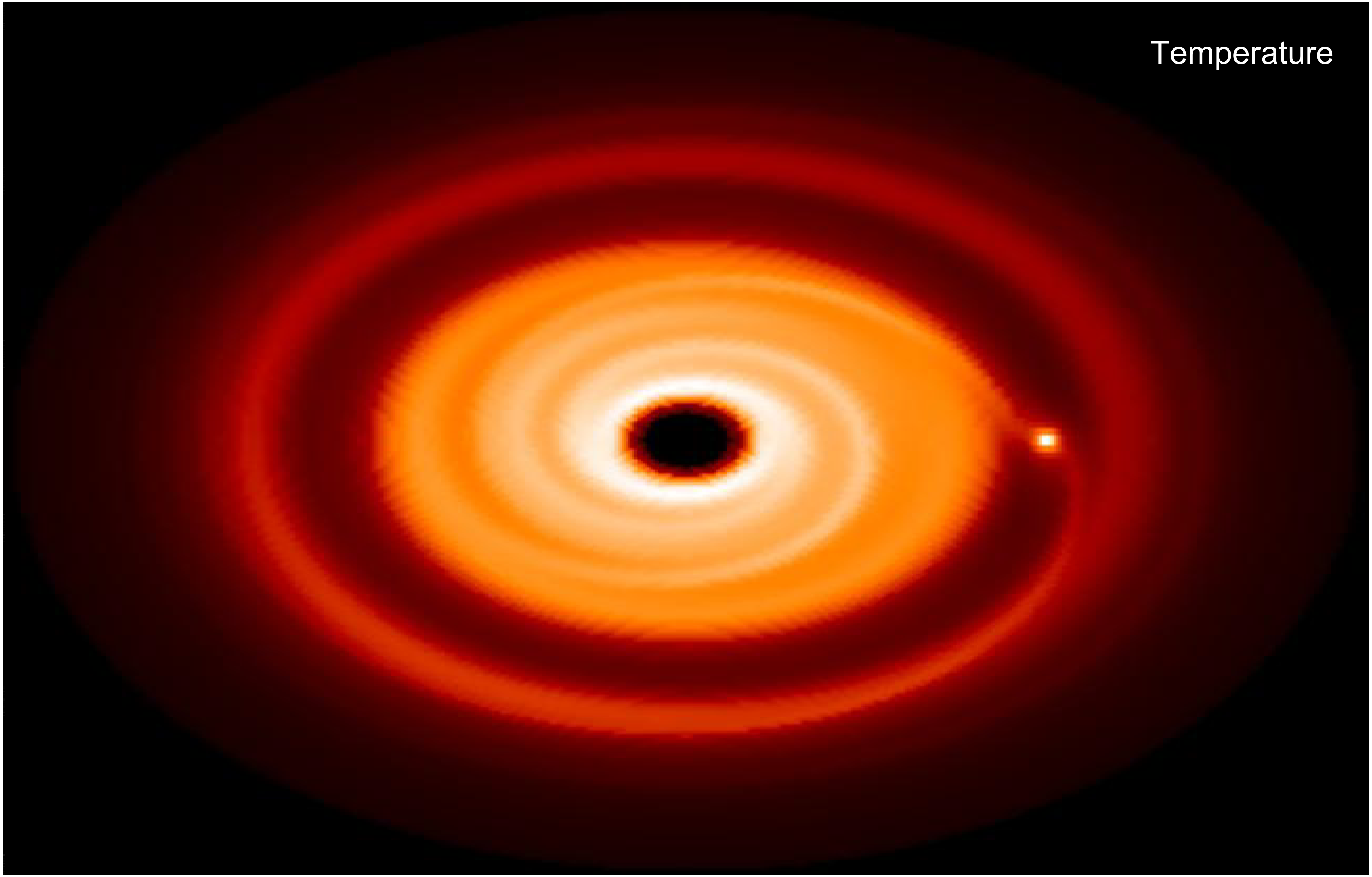


The formation of gas planets within 10^6-10^7 yrs (model 2)



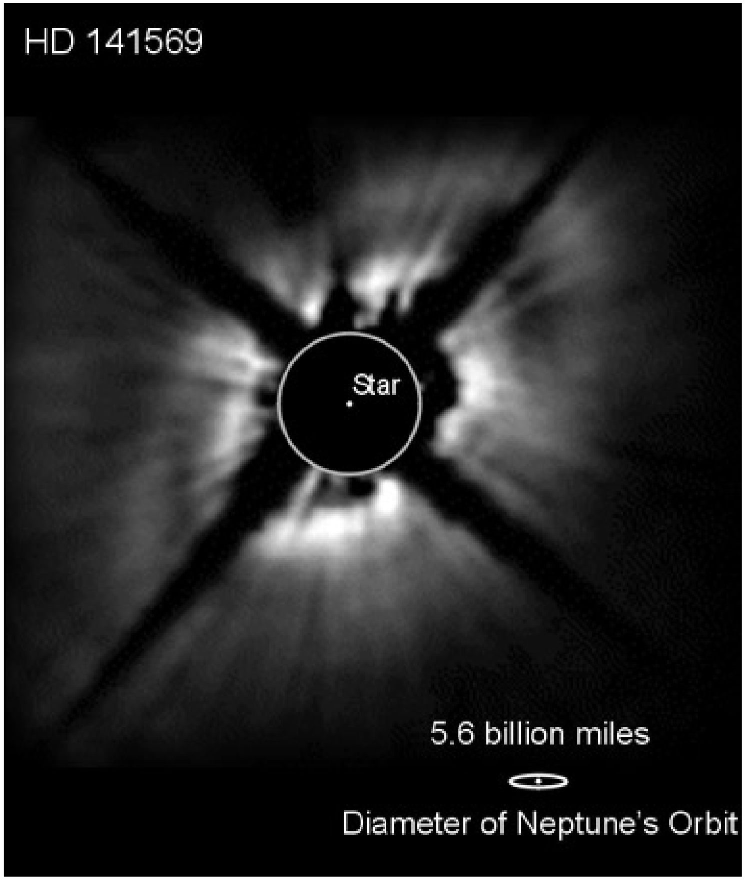
Klahr & Kley 2006

The formation of gas planets within 10^6-10^7 yrs (model 2)

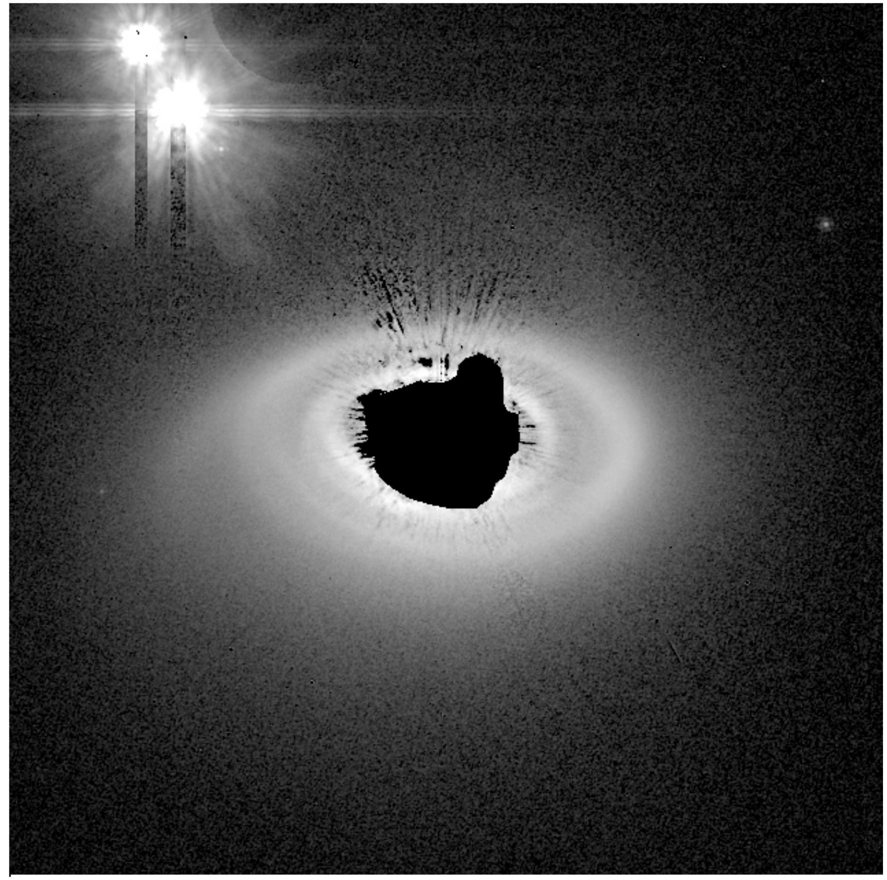


Klahr & Kley 2006

Has the formation of a gas planet been (indirectly) observed *in statu nascendi* ?

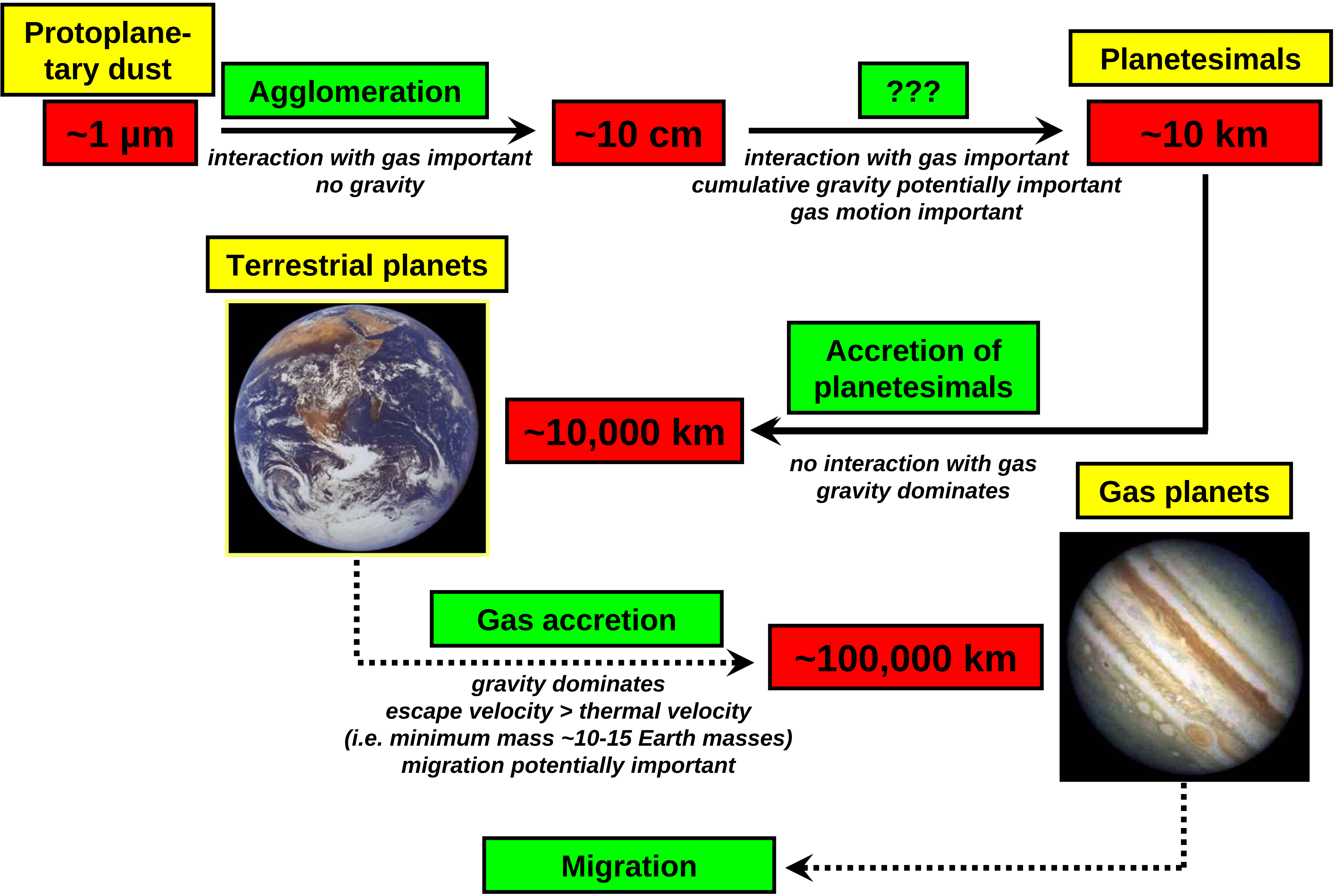


http://hubblesite.org/newscenter/archive/releases/1999/03

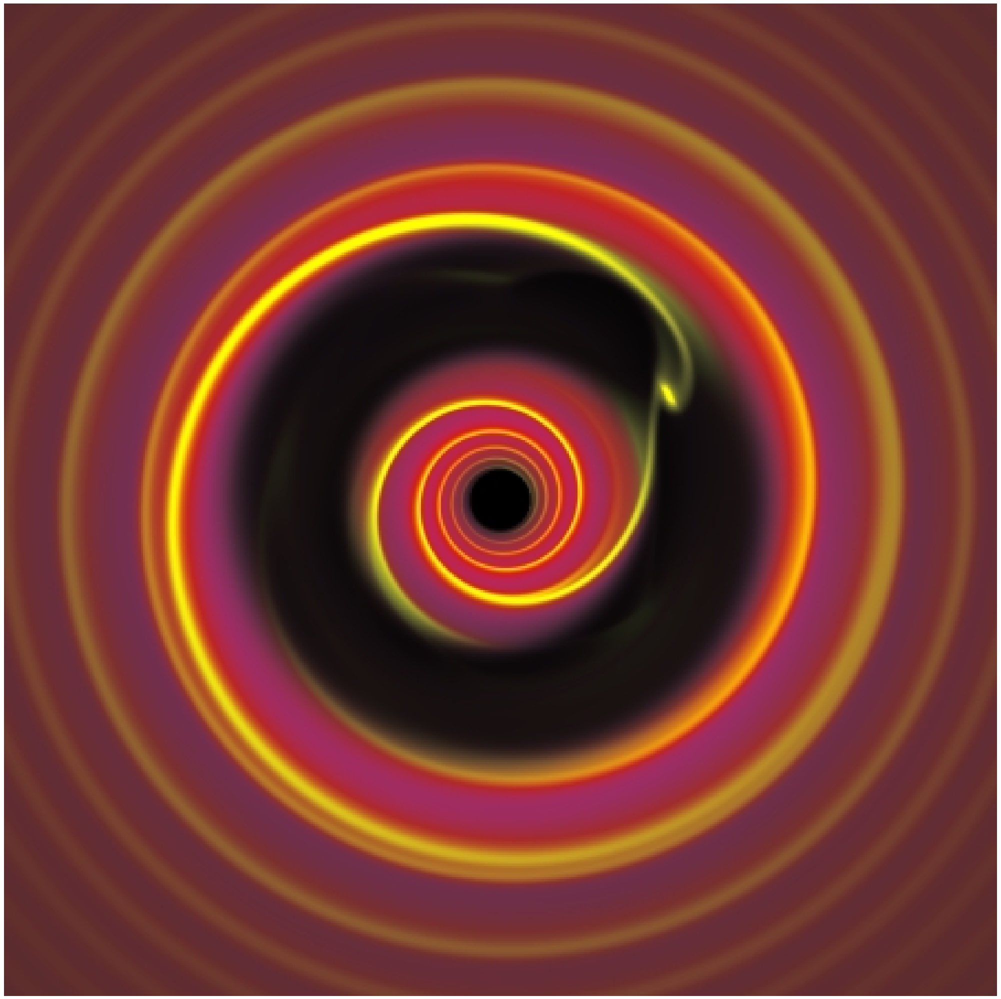


http://hubblesite.org/newscenter/archive/releases/2003/02/image/b/

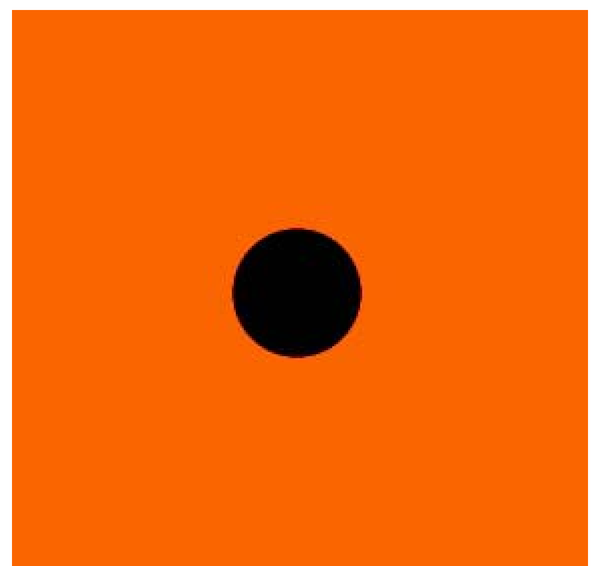
The five-stage process of planet formation



Planet migration und reorganization

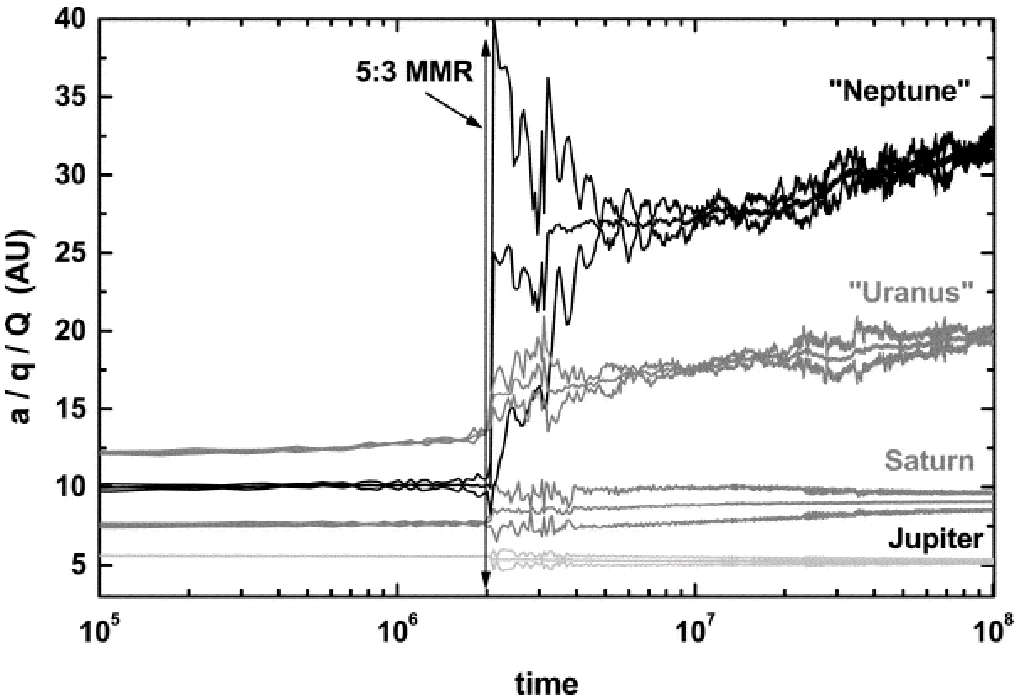


Excitation of spiral density waves in the gas by the planet; torque anisotropy between inner and outer disk; in most cases, the influence of the outer spiral wave dominates so that the planet loses angular momentum and spirals radially inward. Stop of migration by (a) clearing of the nebula or (b) tidal friction with the central star.

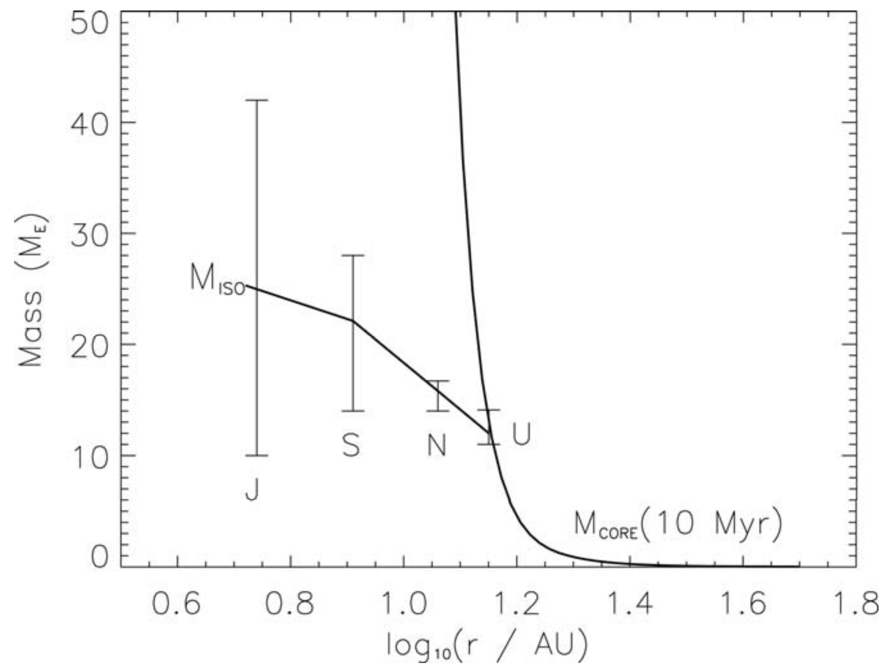


http://www.maths.qmul.ac.uk/~masset/moviesmpegs.html

The Nice model for the dynamic evolution of the giant planets of the solar system



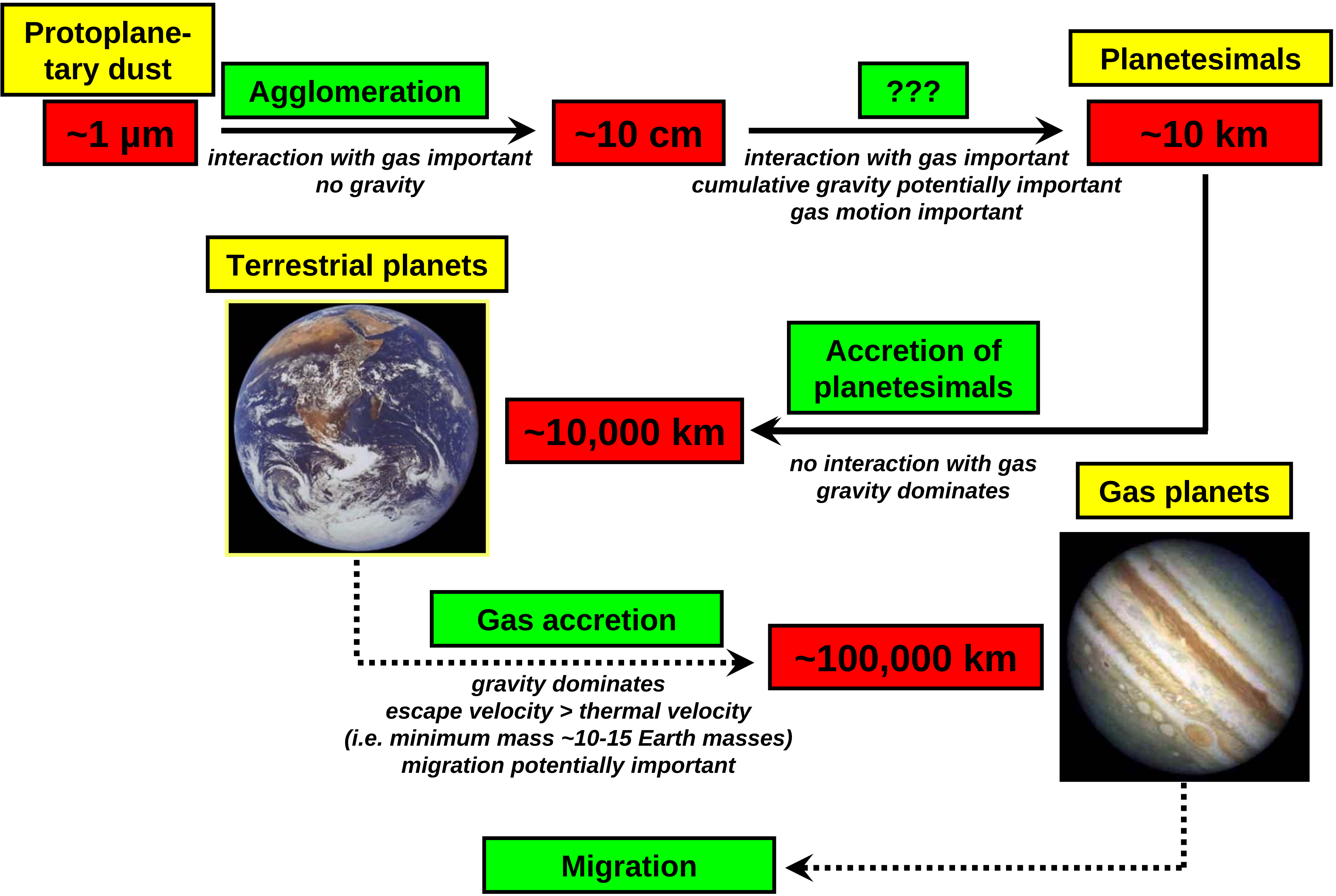
Morbidelli et al. 2007
(Migration, resonances, clearing of nebula)



Desch 2007
(Prediction of the core masses of the giant planets; modified solar-nebula model, based upon Nice model)

13. Conclusions

The five-stage process of planet formation



CONCLUSION ON DUST AGGLOMERATION

- ▷ The growth of protoplanetary dust from (sub-)micrometer to ~10 cm in size (model dependent !) is caused by sticking collisions and is rather well understood.
- ▷ Initial growth timescales from μm to dm size are ~10^3 yrs (@1AU for the MMSN model).
- ▷ However, the further growth is still extremely speculative (and undoubtedly complex); direct collisional growth seems unlikely; secondary growth mechanisms, high-number-density effects and/or gravitational instabilities might be important.

  → work in progress … stay tuned!

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- ▷ Blum, J. 2006. *Dust Agglomeration*. Adv. in Phys. 55 (7-8), 881-947.
- ▷ Blum, J. & Wurm, G. 2008. *The Growth Mechanism of Macroscopic Bodies in Protoplanetary Disks*. Ann. Rev. Astron. Astrophys. 46, 21-56.

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