IAC Winter School 2016

PLANET FORMATION

UNIVERSITÉ CÔTE D'AZUR

Observatoire de la CÔTE d'AZUR

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The Solar System is flat...

Planets turn around the Sun in the same direction and in the same plane... Therefore, they formed from a disc shape structure around the Sun.

Kant

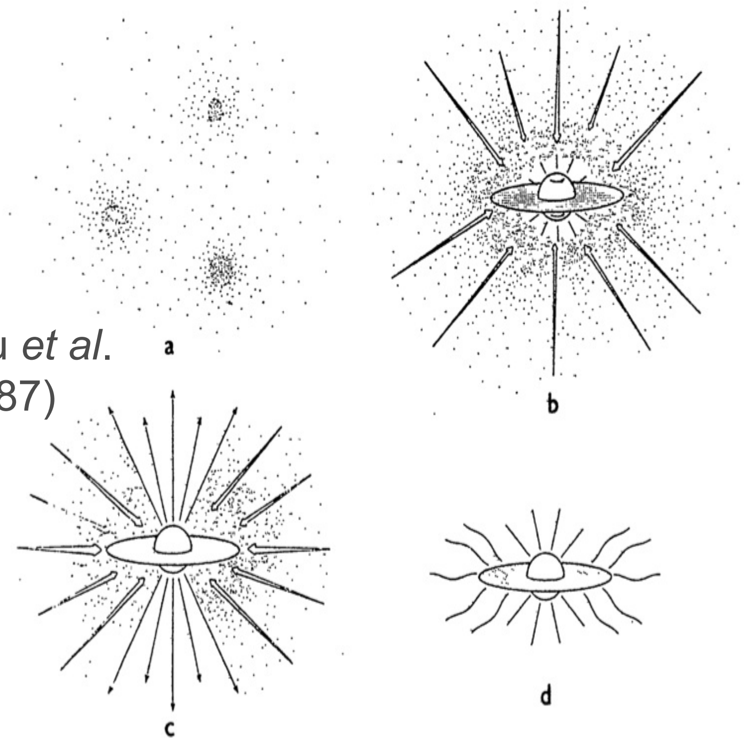
Laplace

THEORY

A star forms by the gravitational collapse of a molecular cloud of interstellar gas.

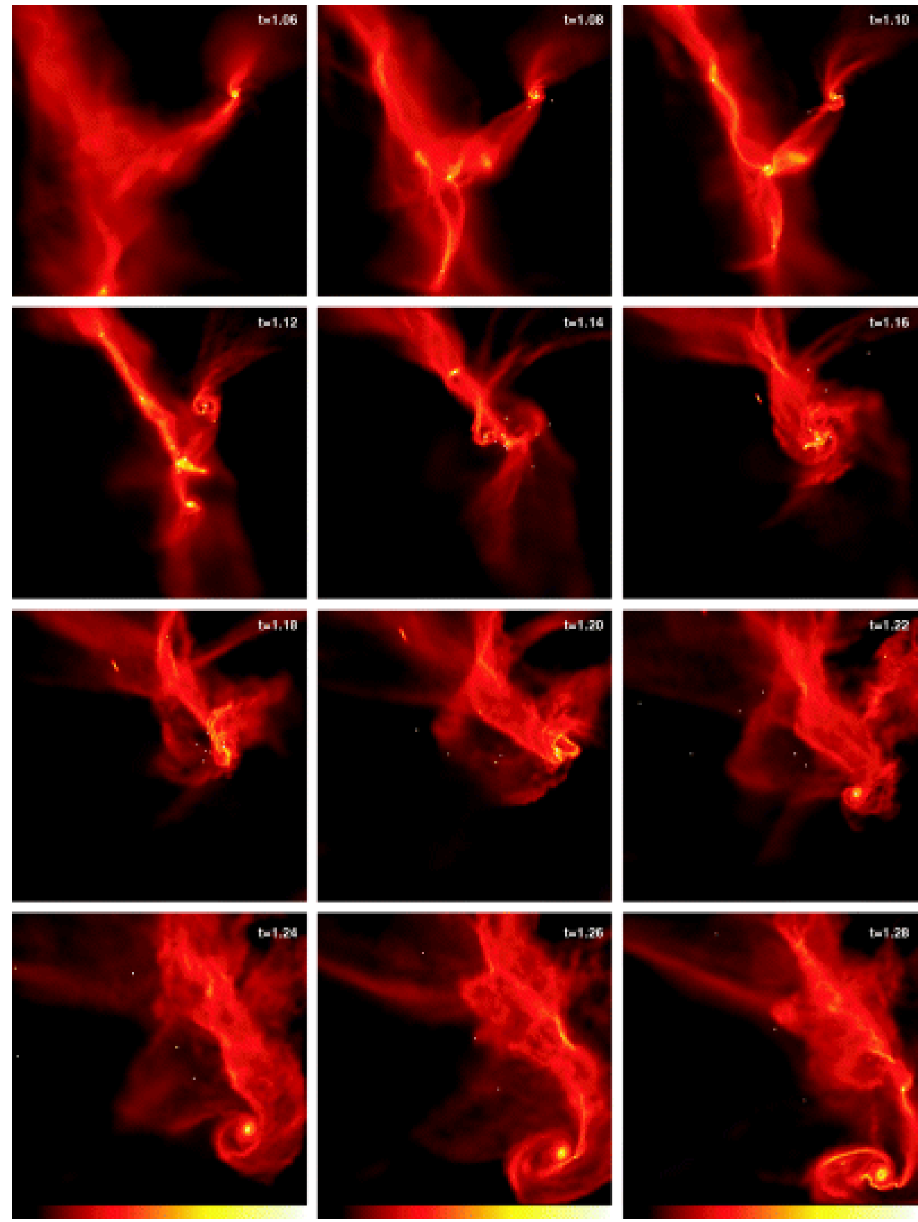
<u>At the centre :</u> Pressure and temperature increase, nuclear fusion begins, the star lights on.

<u>Around :</u> a disc forms.



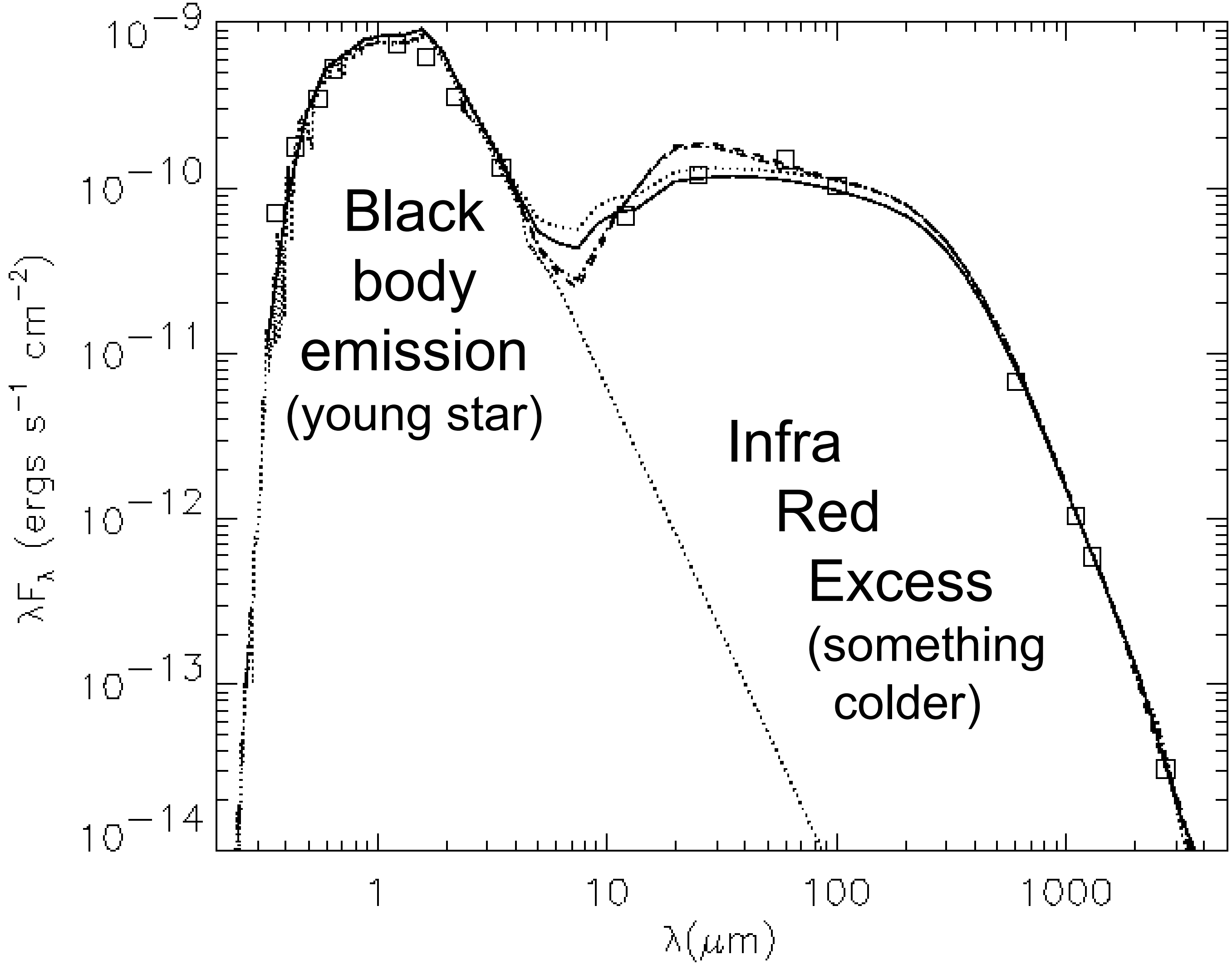
Shu *et al*. (1987)

SIMULATION

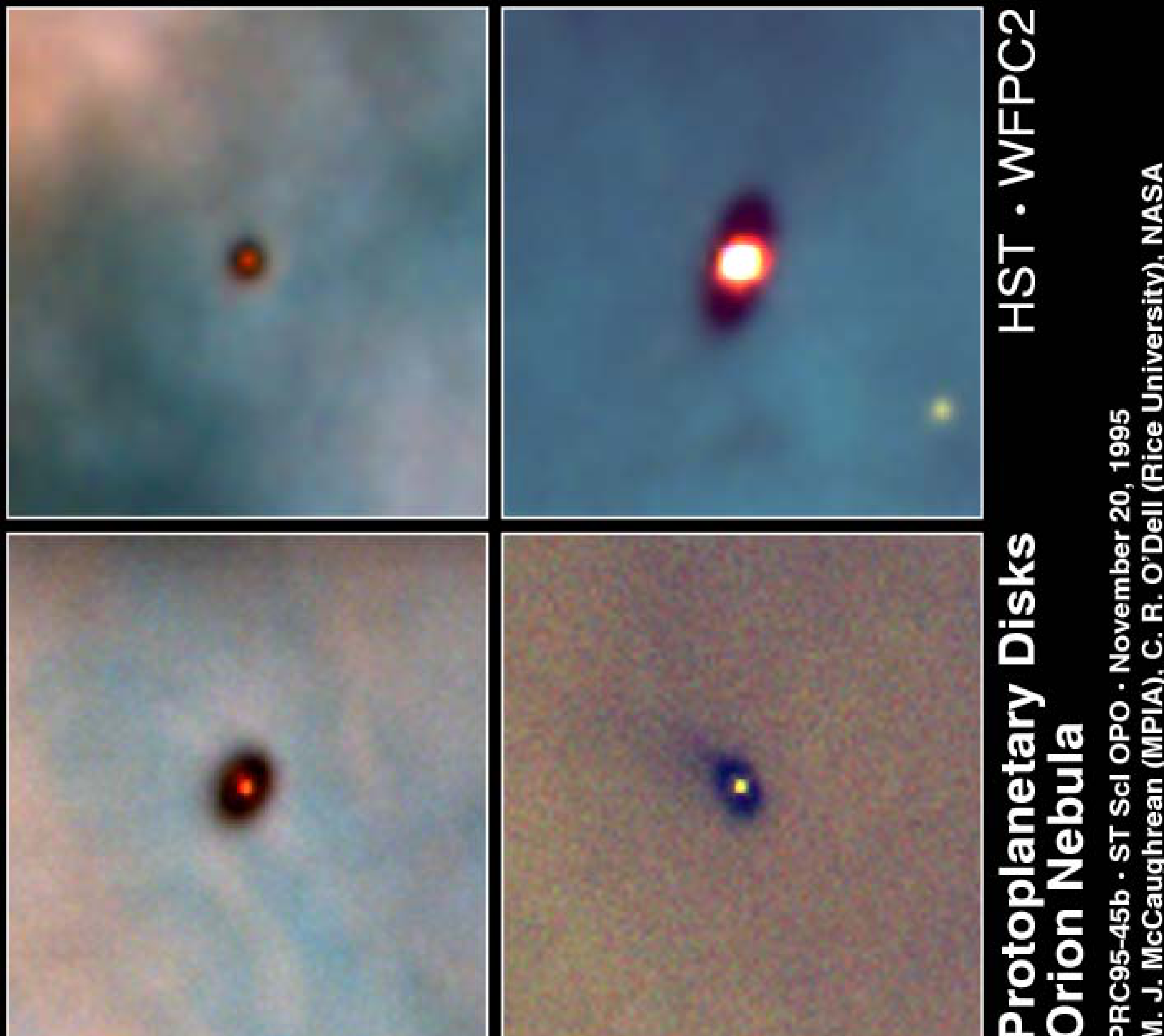


OBSERVATIONS (1)

Spectral Energy Distribution (SED) :



OBSERVATIONS (2)



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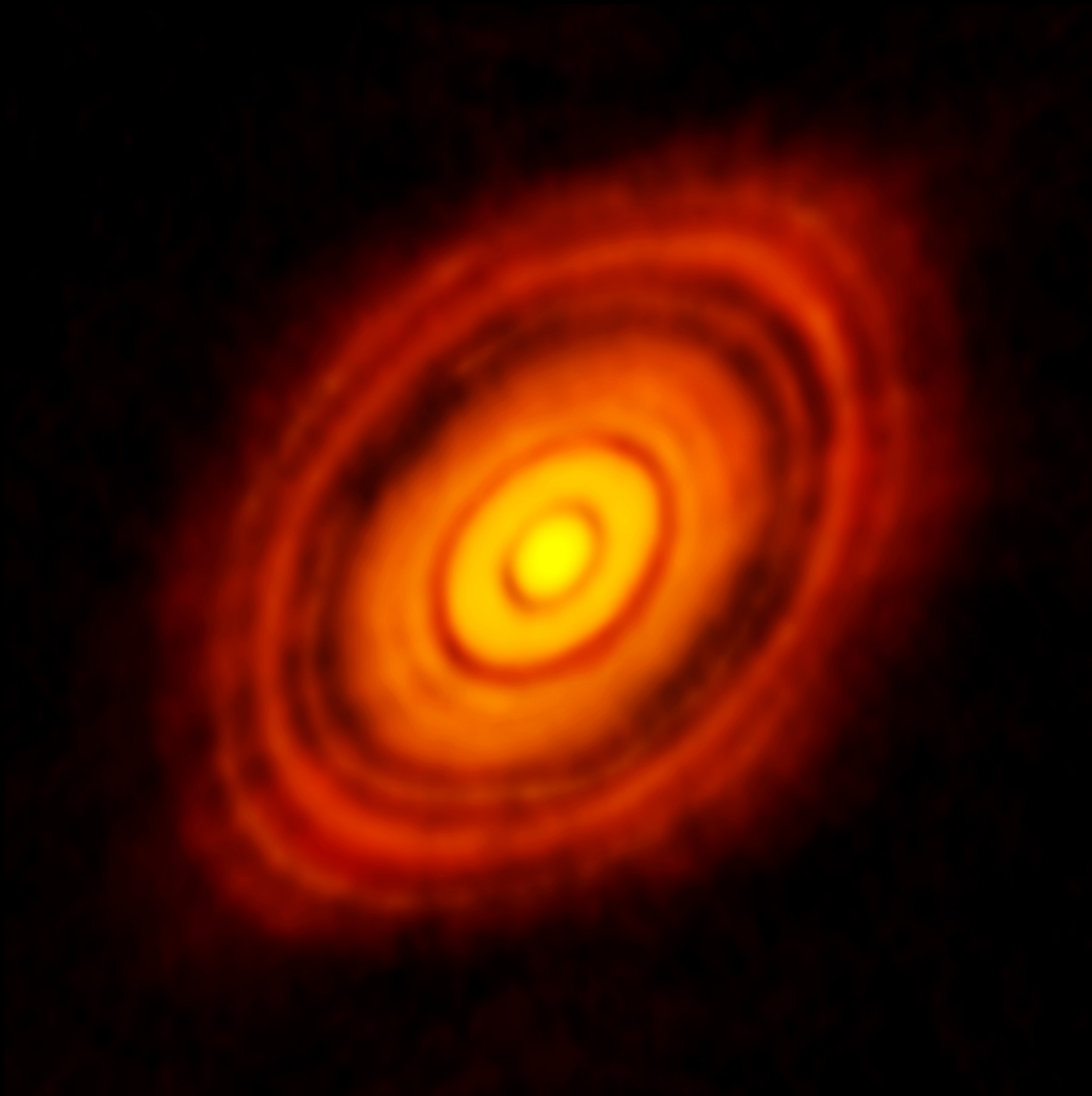
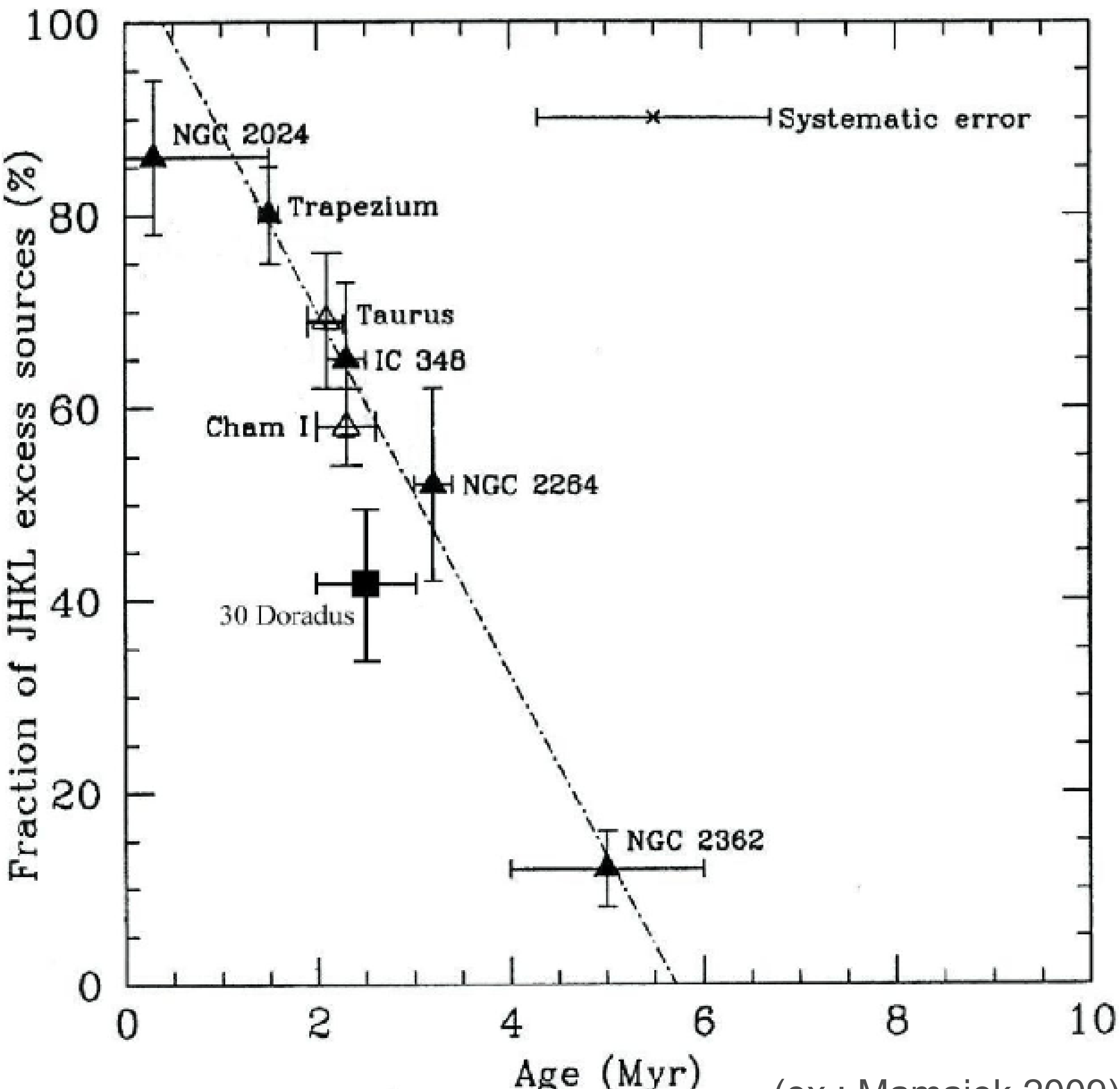


OBSERVATIONS (3)



(ex : Mamajek 2009)

Discs have a life time of ~5 Myrs.

SCHEMA: planetary formation

1) Condensation of solids.

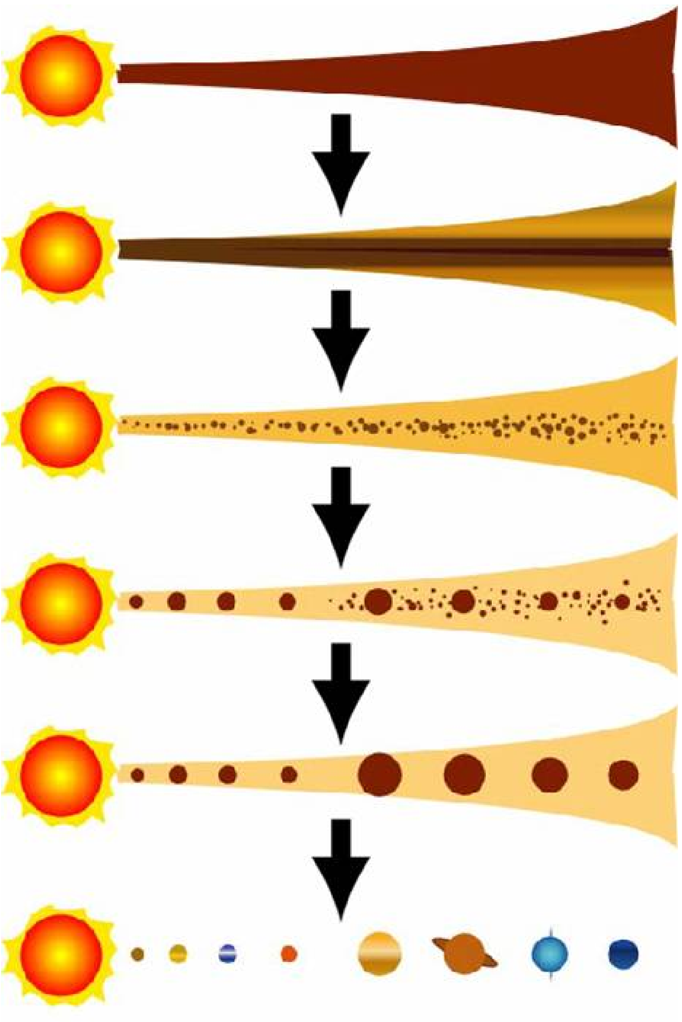
2) Sedimentation of grains
towards the midplane.

3) Aggregation upto ~1cm.

4) Formation of planetesimals
(10km)

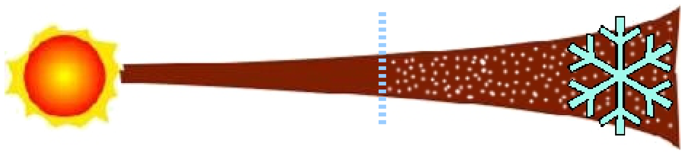
5) Protoplanets and cores.
(100 – 1000 km)

6) Dissipation of the gas.



Remark: Step N lasts ~10^N years.

CONDENSATION: the ice-line



Temperature in the proto-planetary disc is inversely proportional to the distance to the Sun.

Close to the Sun, it's hot, H_20 is in vapor form.

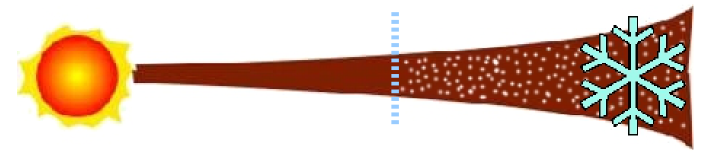
Far from the Sun, H_20 is in solid form : it snows !

The limit is called, the *iceline* (or snowline).
It is at typically 3-4 AU.

Beyond the iceline, planetesimals are made of half ice =>
comets vs dry asteroids, made inside the iceline.

Also, there is more solids beyond the iceline and they are more sticky, so one can make bigger embryos.

CONDENSATION: the ice-line

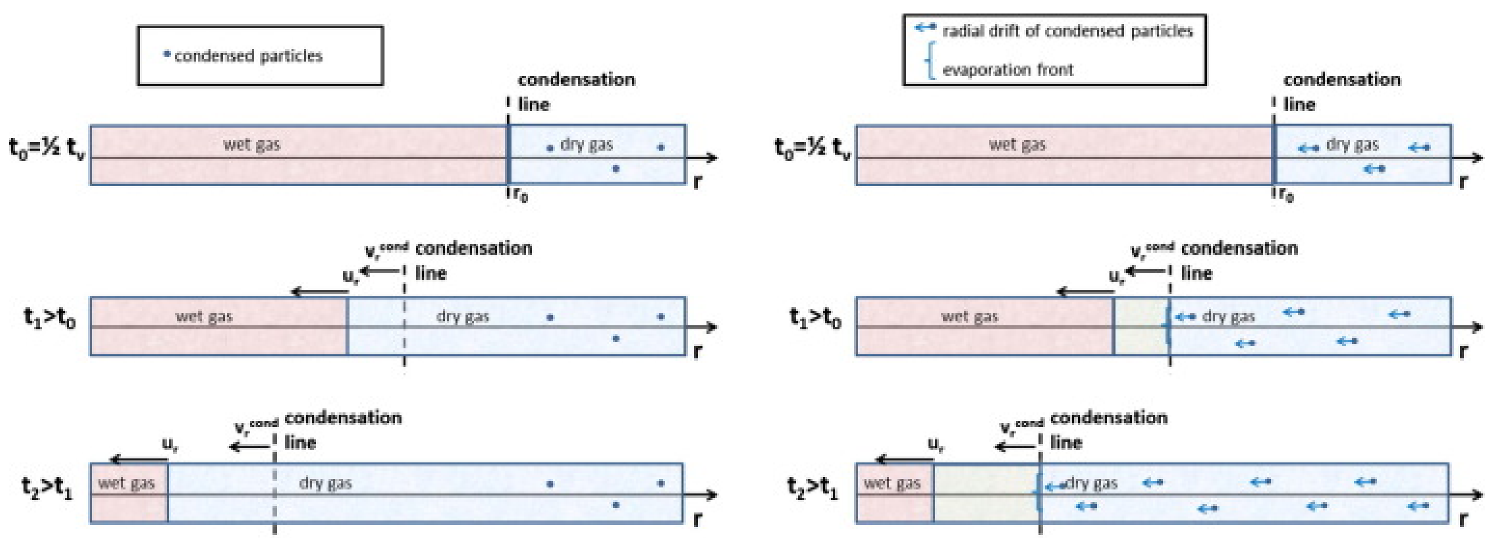


True for other species as well.

The composition of the solids
and of the gas component depends
on the location in the protoplanetary disc.

The temperature depends on r, but also on z and t...

<u>Time evolution:</u> what drifts faster ? Dry gas or hydrated solids ? (Morbidelli et al. 2016)

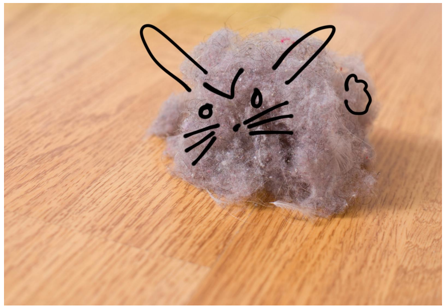


SEDIMENTATION, AGGREGATION

Like at home !

Dust can't stay in the air.

It makes little dust bunnies, dust aggregates



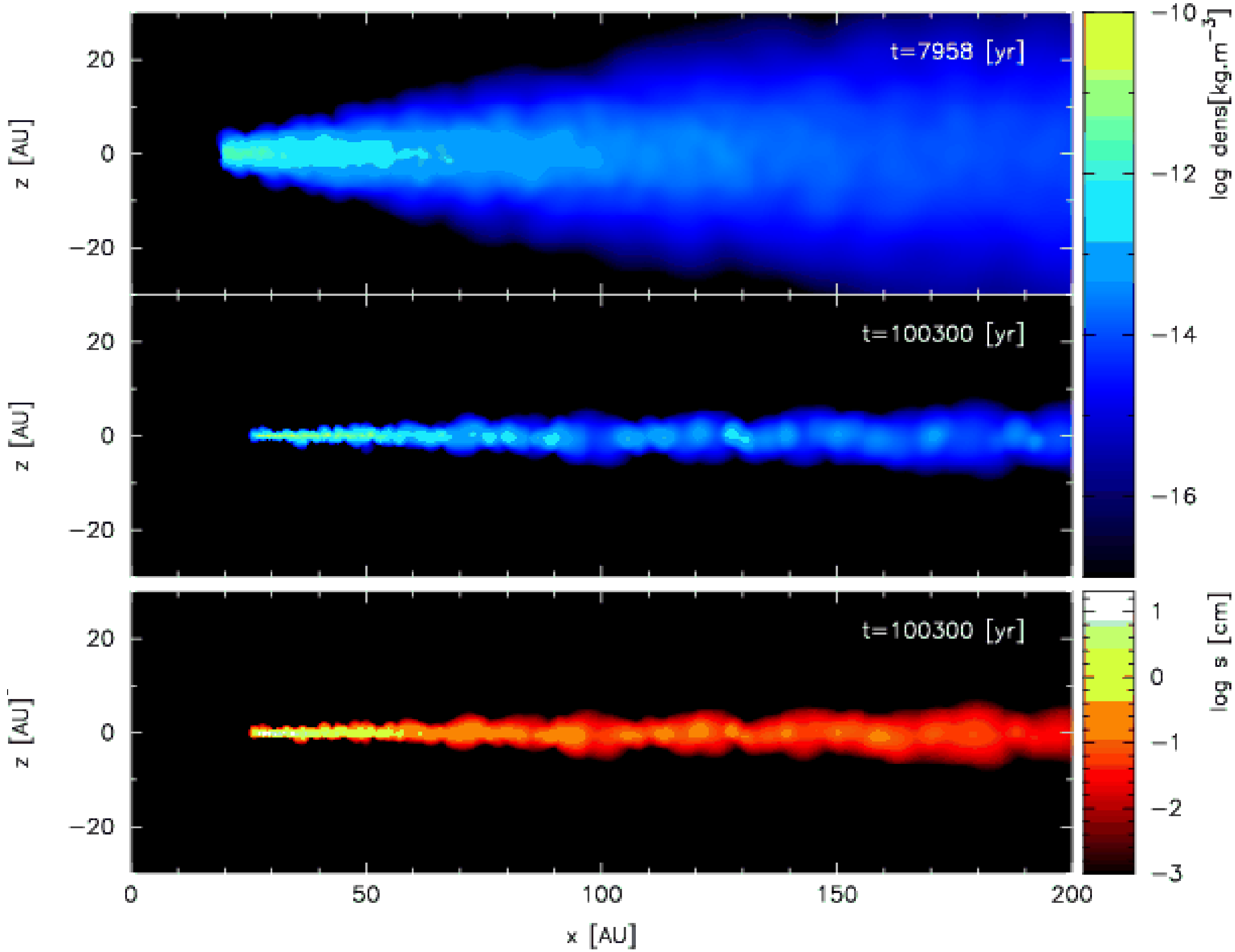


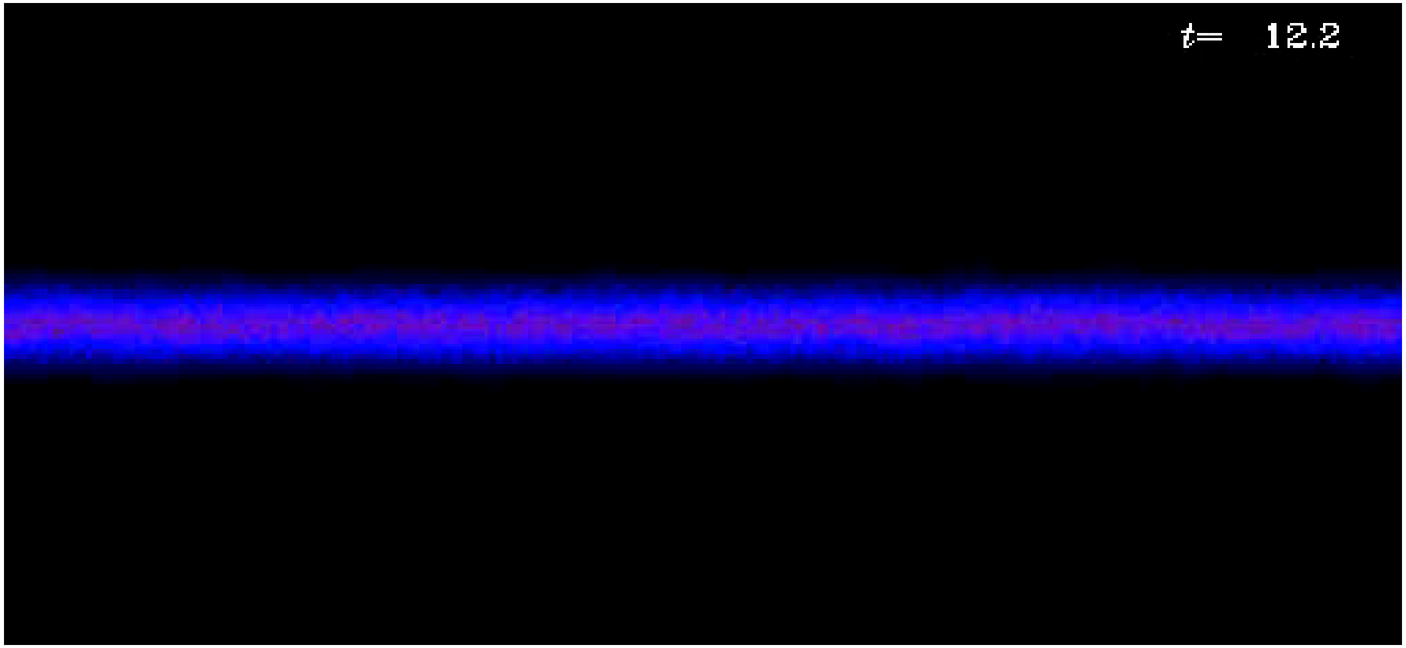
Image : Laibe *et al.* (2008)

SEDIMENTATION, AGGREGATION

Possibly high concentrations of solids in the midplane.

Turbulence ?

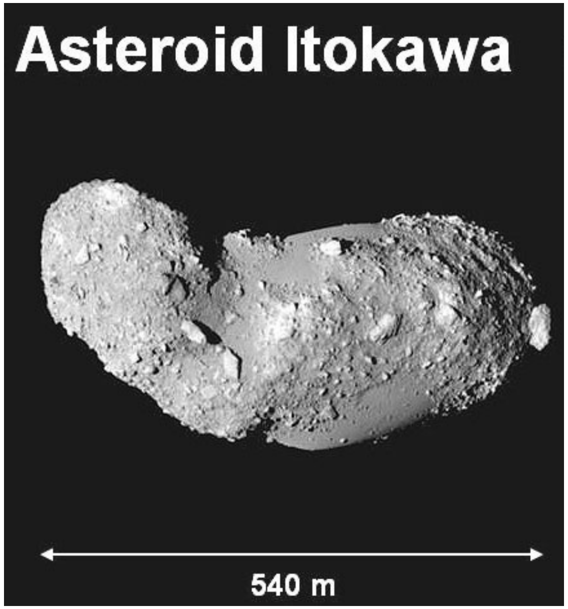
Formation of large clumps / bodies ?



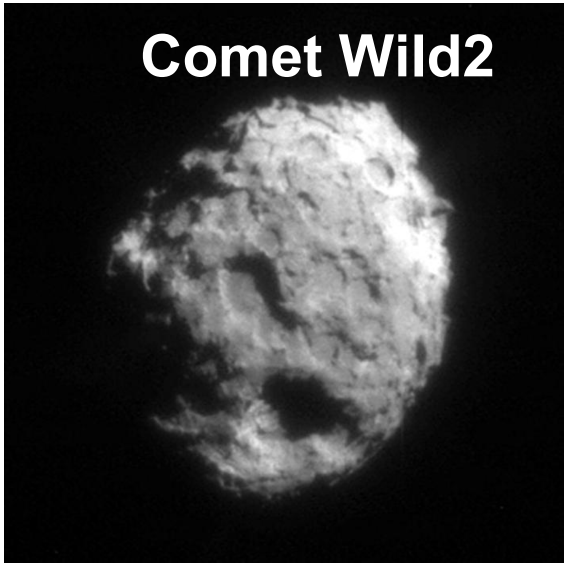
Film : Anders Johansen

PLANETESIMALS

Objects > 100m, hold together by **gravity**.



Inside 3 AU, rocky and metal rich bodies, devoid of water :
the ancestors of terrestrial planets and asteroids.

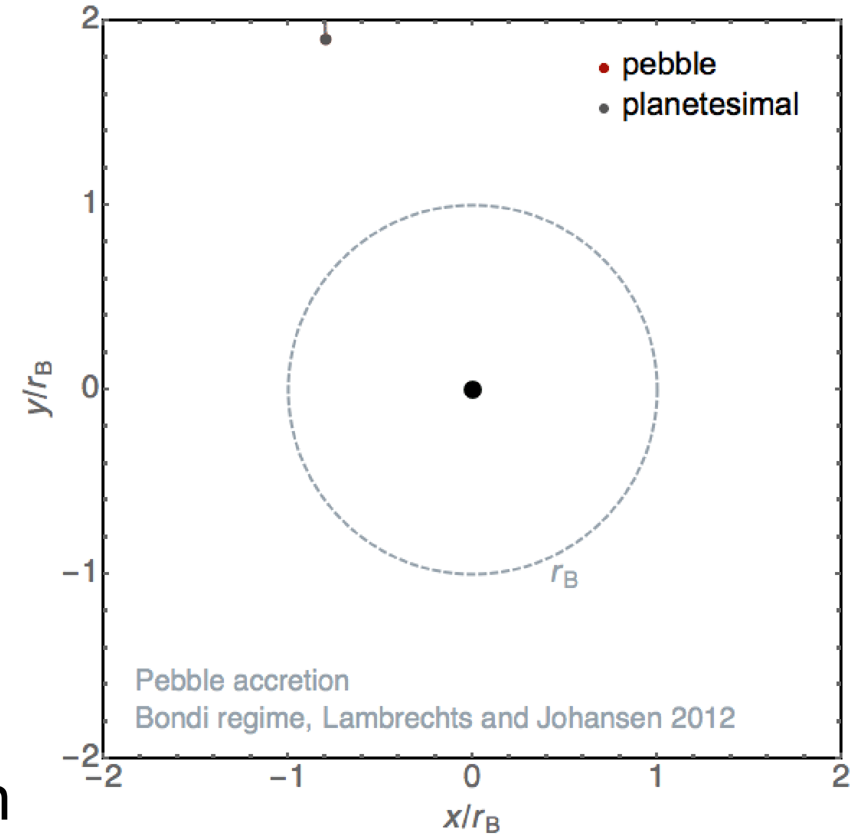


Beyond 3 AU, objects made of rocks, metals, and ~50 ices (water, $C0_2$, methane).

The smaller will become comets, the larger will constitute the core of giant planets.

PEBBLE ACCRETION

Solids of ~1-10cm are slightly decoupled from the gas, but very sensitive to friction.



Their trajectories are bend by the gravity of a planetesimal → friction → energy loss → accretion.

Much larger cross section than pure graviational focussing.
Extremely efficient, runaway growth of bodies, until they perturb the gas so much that the flux of pebbles stops (~20 M_{Earth}).

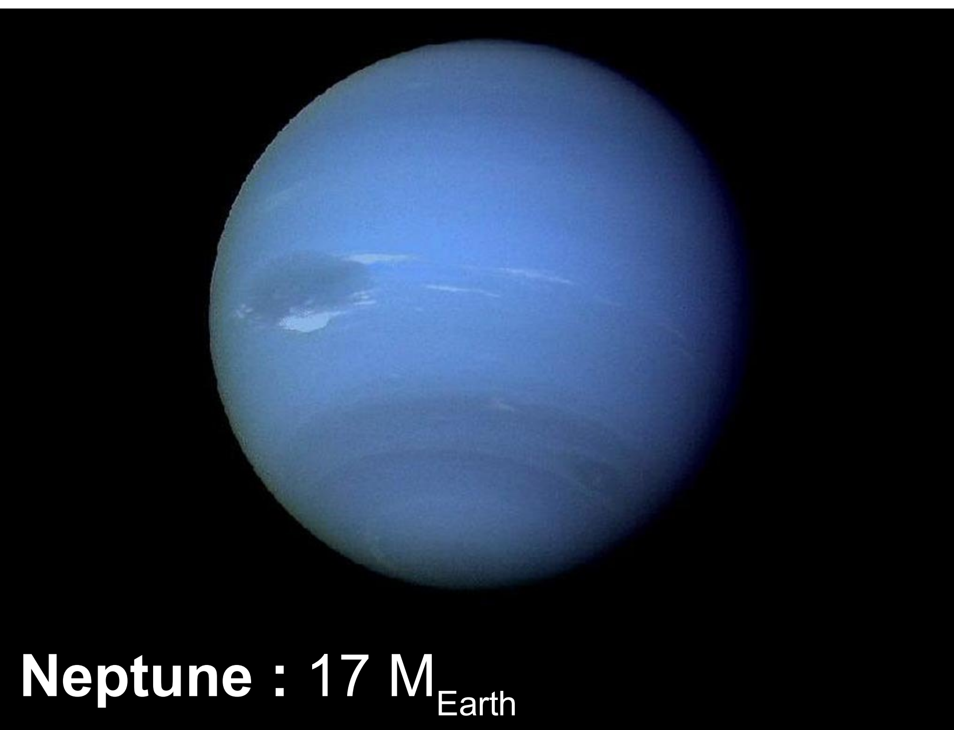
More efficient beyond the ice line → formation of big cores there, and only tiny embryos closer to the Sun.
(Lambrechts, Johansen & Morbidelli 2014)

GIANT PLANETS

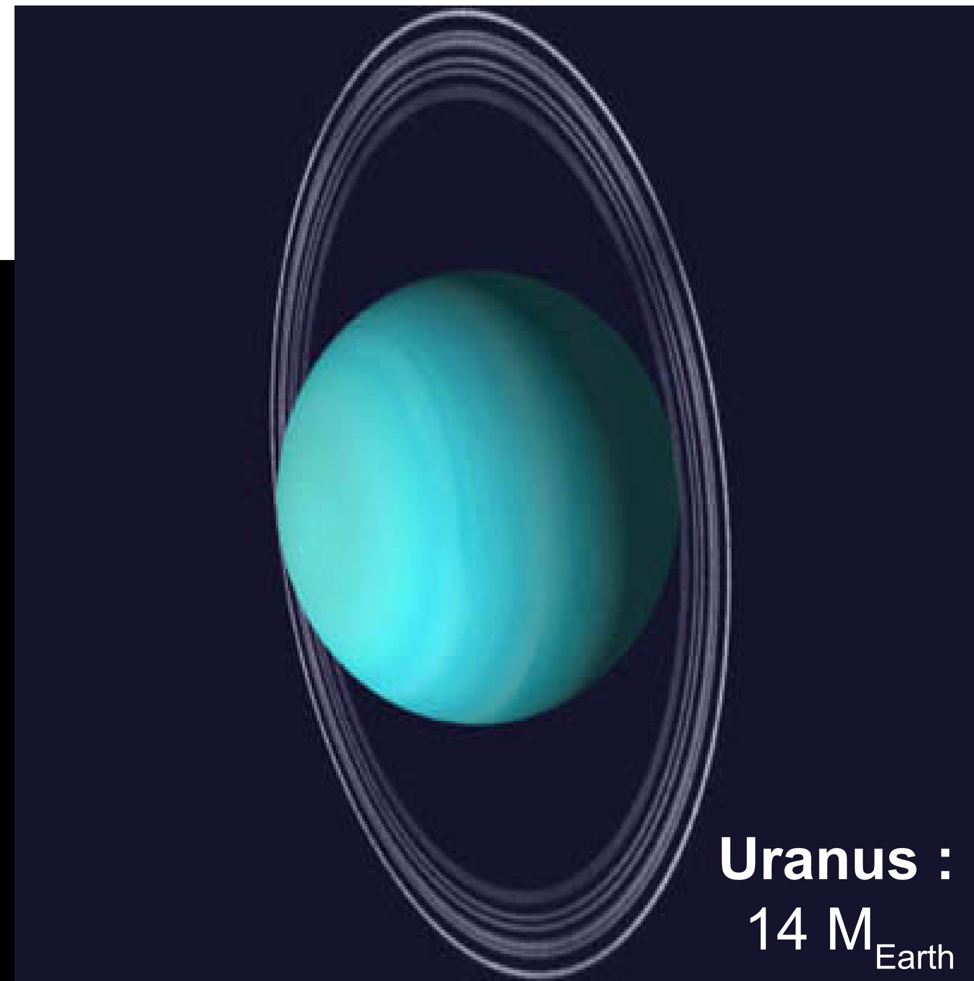
<u>Core accretion model :</u>

A very massive body (10 M_{Earth}) holds gas from the disc, becomes surrounded by a spherical envelope, which cools and contracts slowly...

→ ice giants.



Neptune : 17 M_{Earth}



Uranus : 14 M_{Earth}

GIANT PLANETS

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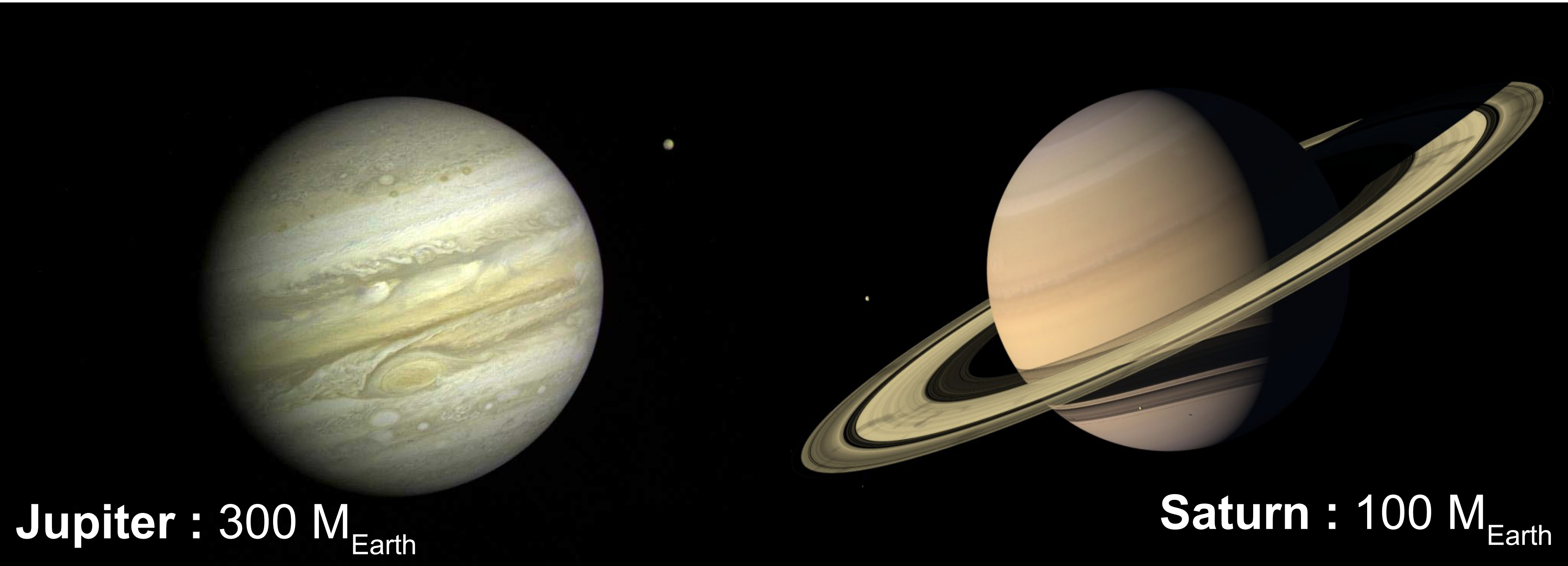
If the mass of gas exceeds that of the core, or accretion solids stops, **collapse**. The planet becomes a gas giant.



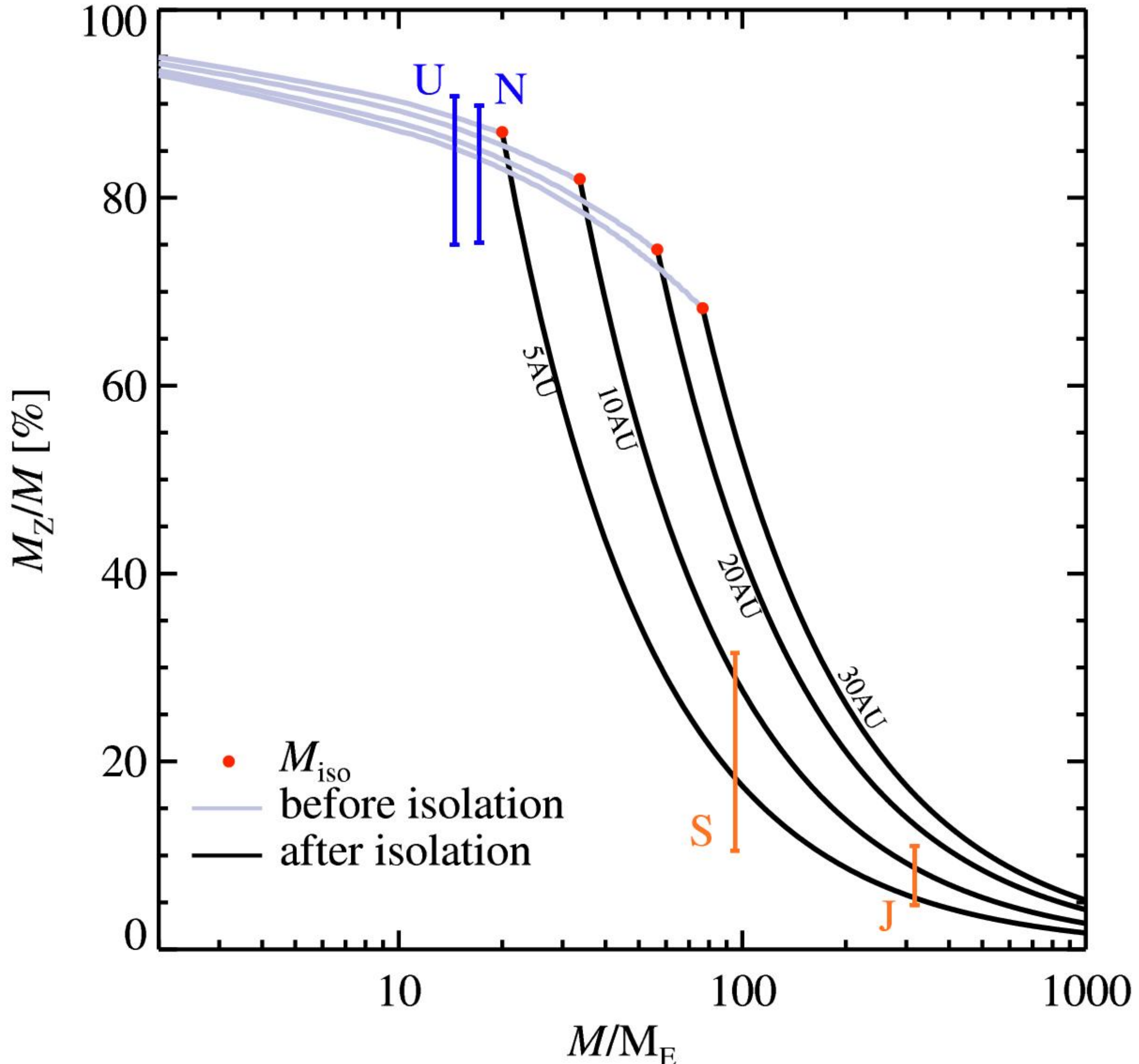
Jupiter : 300 M_{Earth}

Saturn : 100 M_{Earth}

GIANT PLANETS

Lambrechts et al. (2014) :

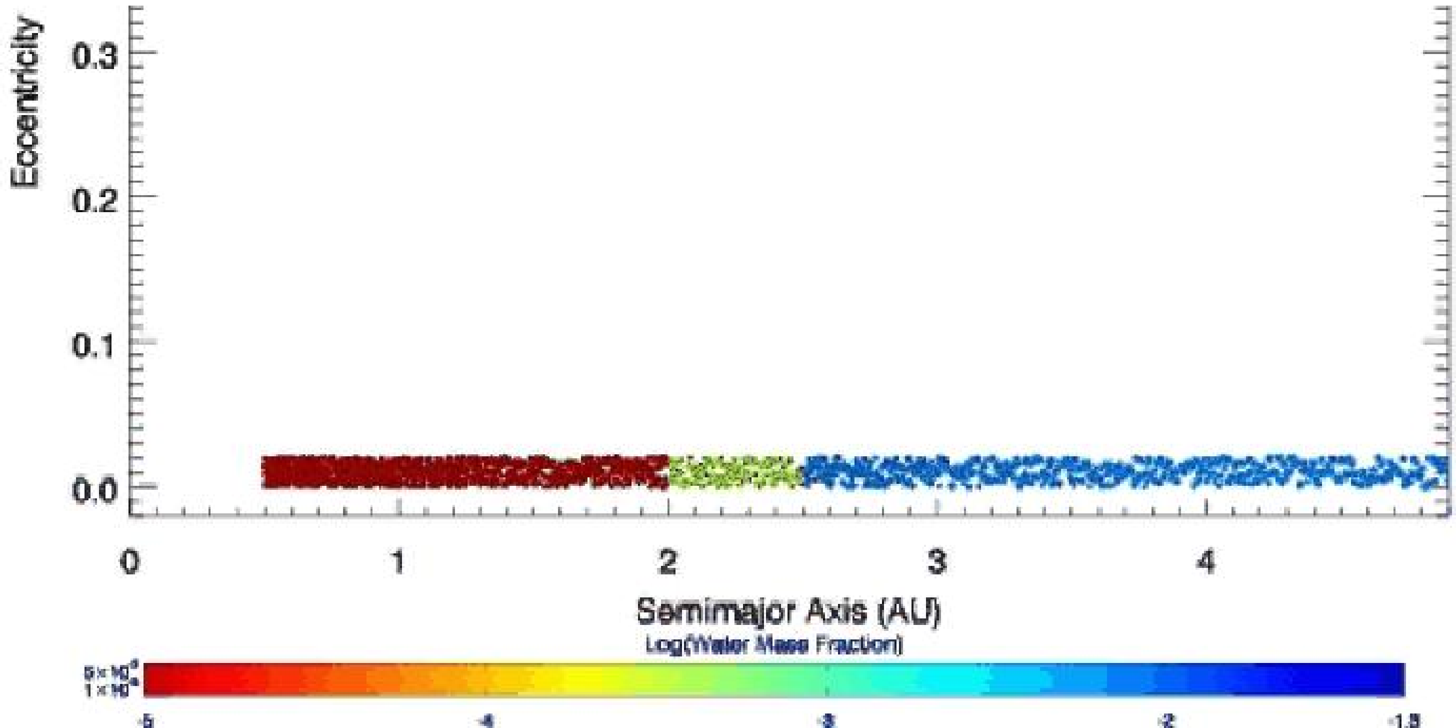
The isolation from pebbles triggers the runaway gas accretion. Easier and faster to reach closer to the Sun → U & N never reached it, contrary to J & S.



TERRESTRIAL PLANETS

Inside ~4 AU, the proto-planets are ~1/100 to 1/10 M_{Earth} .
There are ~50 of them between 0,3 and 2 AU, surrounded by a disc of planetesimals...

This dense system is unstable → as soon as gas dissipates, **giant impacts** among proto-planets, until only 3 or 4 planets remain, far enough from each other.



Film : Sean Raymond

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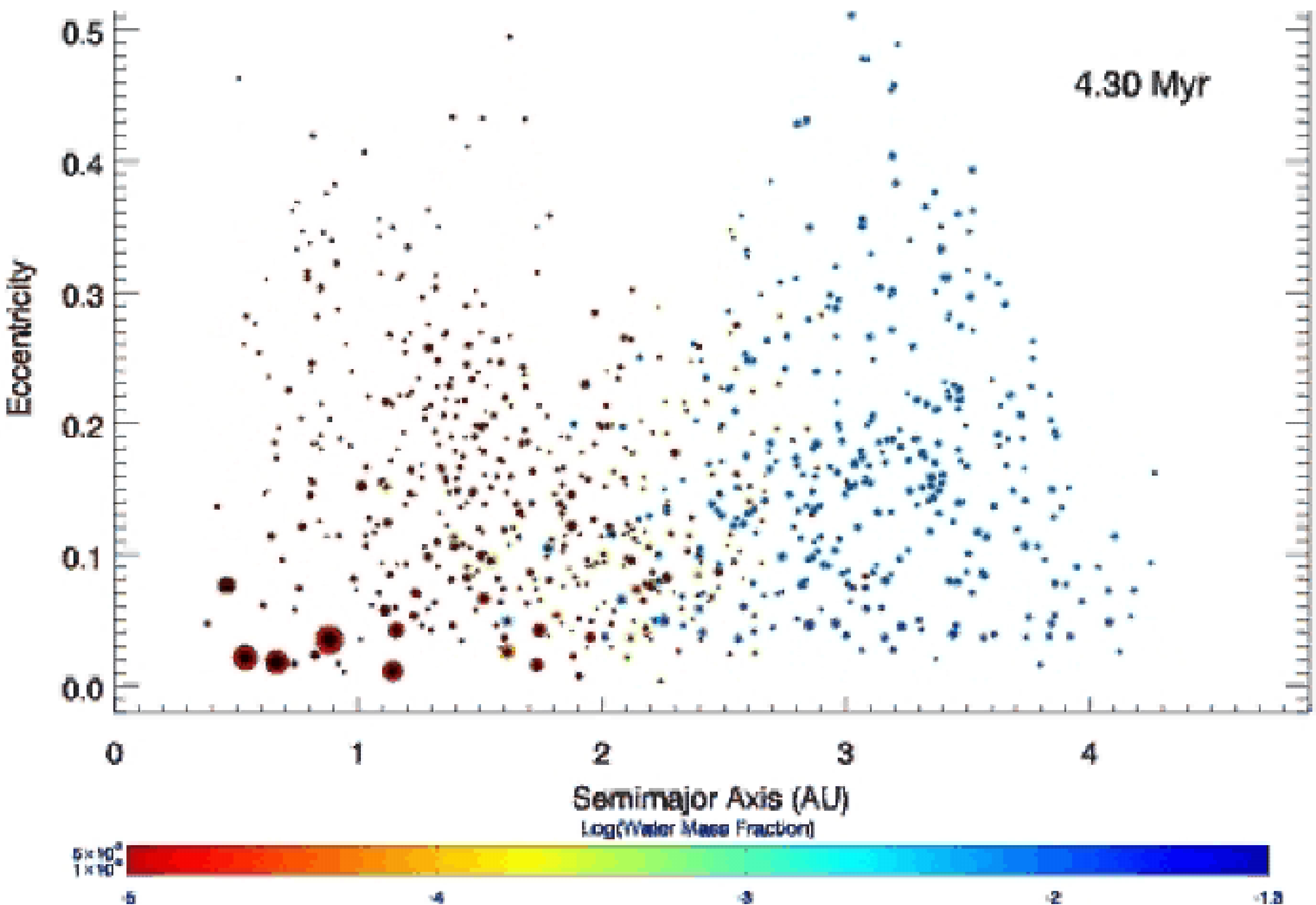
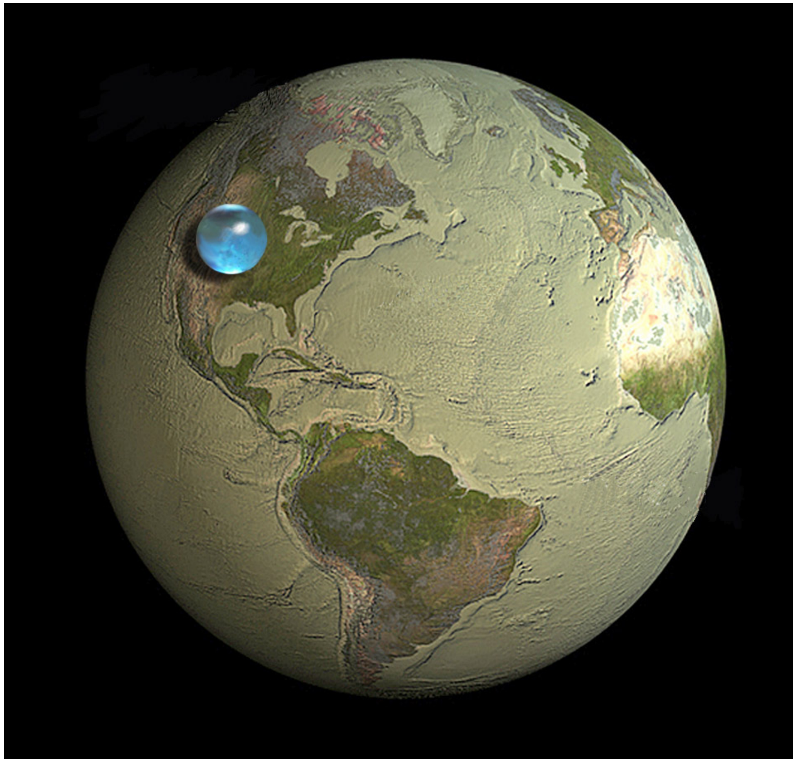


Film : Sean Raymond

TERRESTRIAL PLANETS

Duration of this phase: ~100 millons years.

Mixing →
bodies formed
beyond the ice line
impact the Earth,
and deliver
the 0,04% water
we observe today...

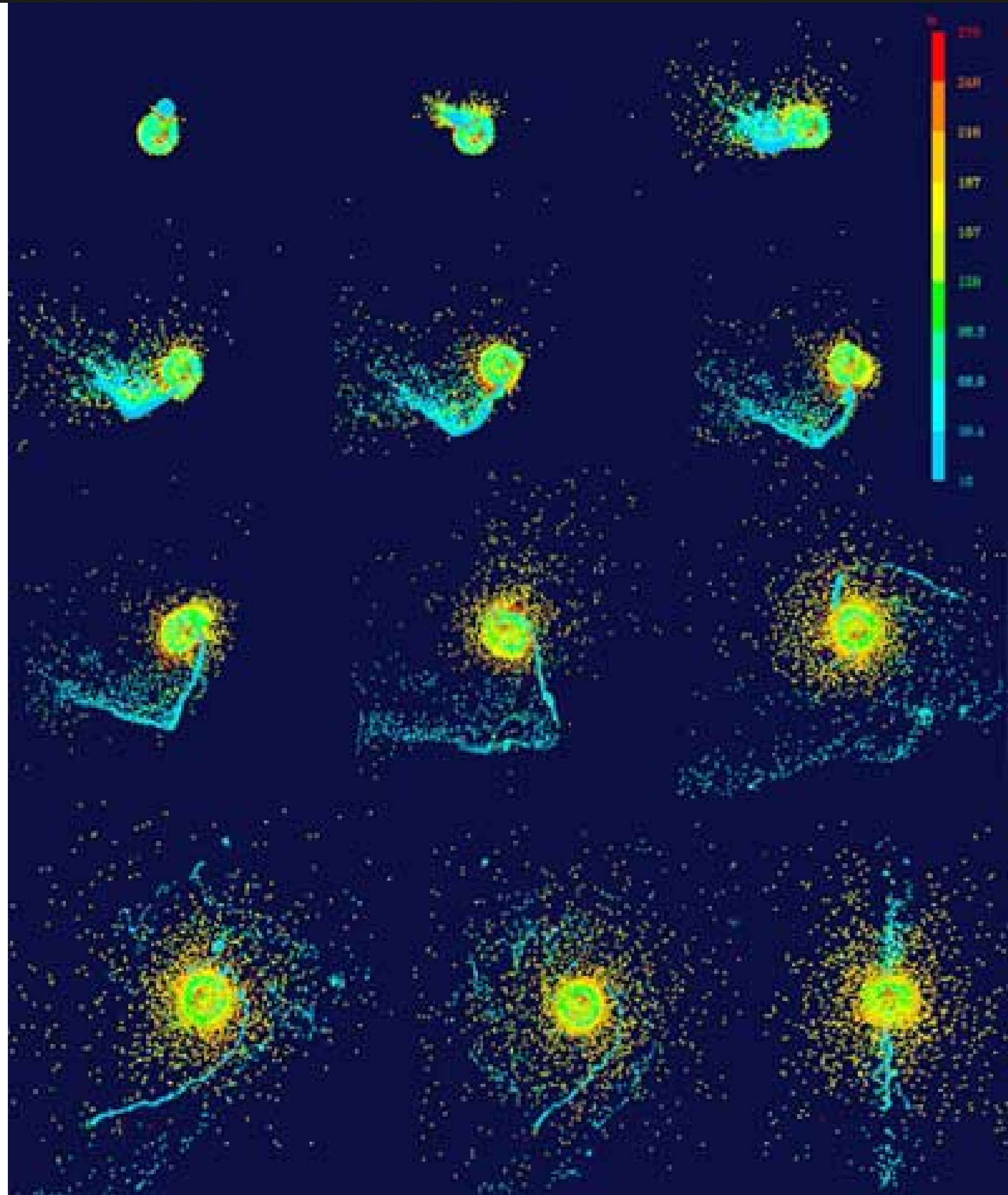


(Problem: Mars always too big in simulations...)

TERRESTRIAL PLANETS

The last of these giant impacts on Earth is the « *moon-forming impact* », by a body the size of Mars, other called Theia.

It has ejected in orbit a ring of matter, coming from the mantle of the Earth, which then engendred the Moon :



CONCLUSION

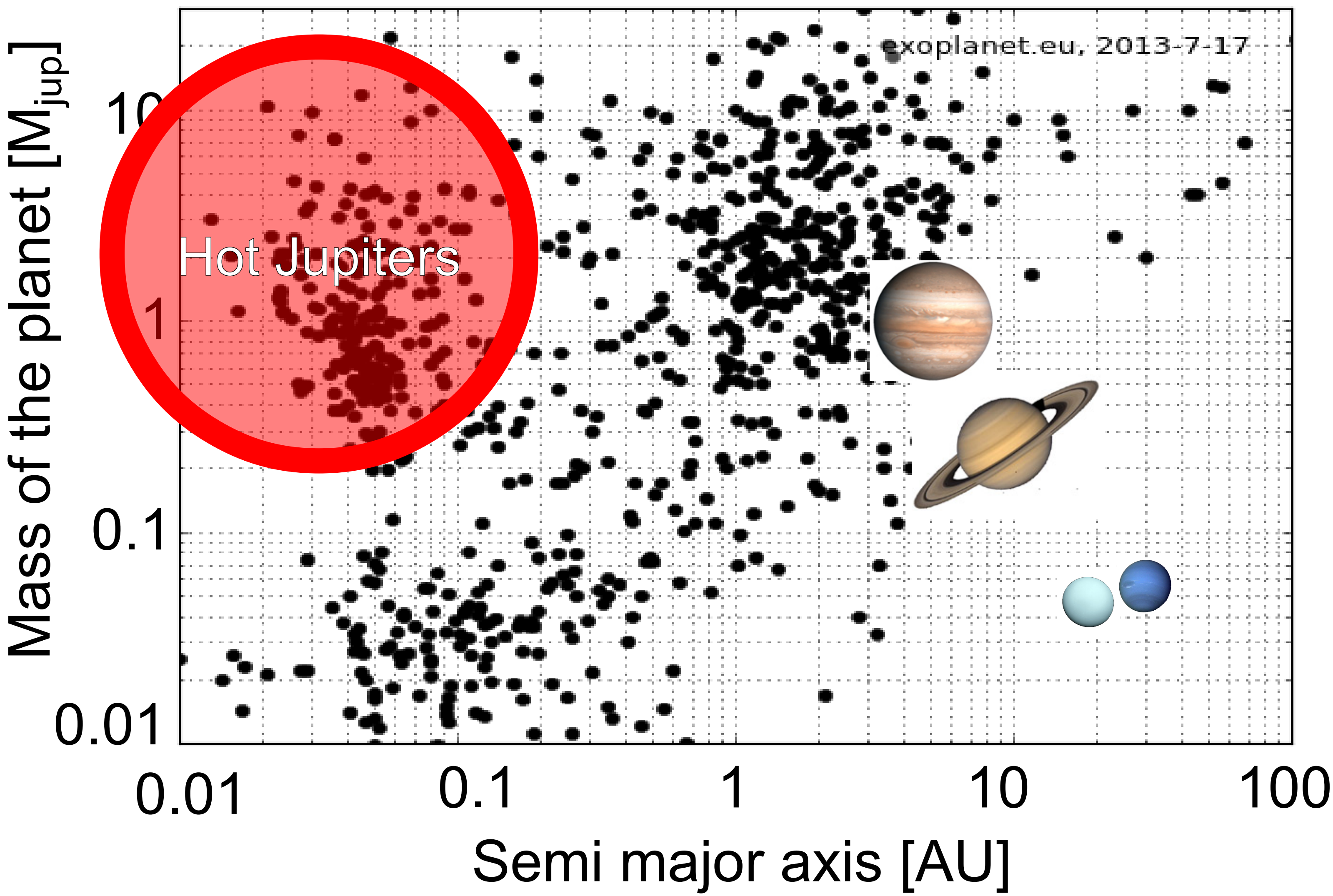
Planets form in proto-planetary discs of gas and dust around young stars
- in a few million years
- in a plane containing the star
- with giant planets far from the star, beyond the ice line, and small dry terrestrial planets close to the star.

Then, the disc dissipates, and the planetary system stays the same for billions of years.

There should be planets around every star, in systems similar to ours.
Pretty theory ! :-)

EXOPLANETS

We know more than 2000 planets outside of the Solar System !



These systems are very different from the Solar System !

Hot Jupiters shouldn't have formed where they are.