The Birthplace of Planets

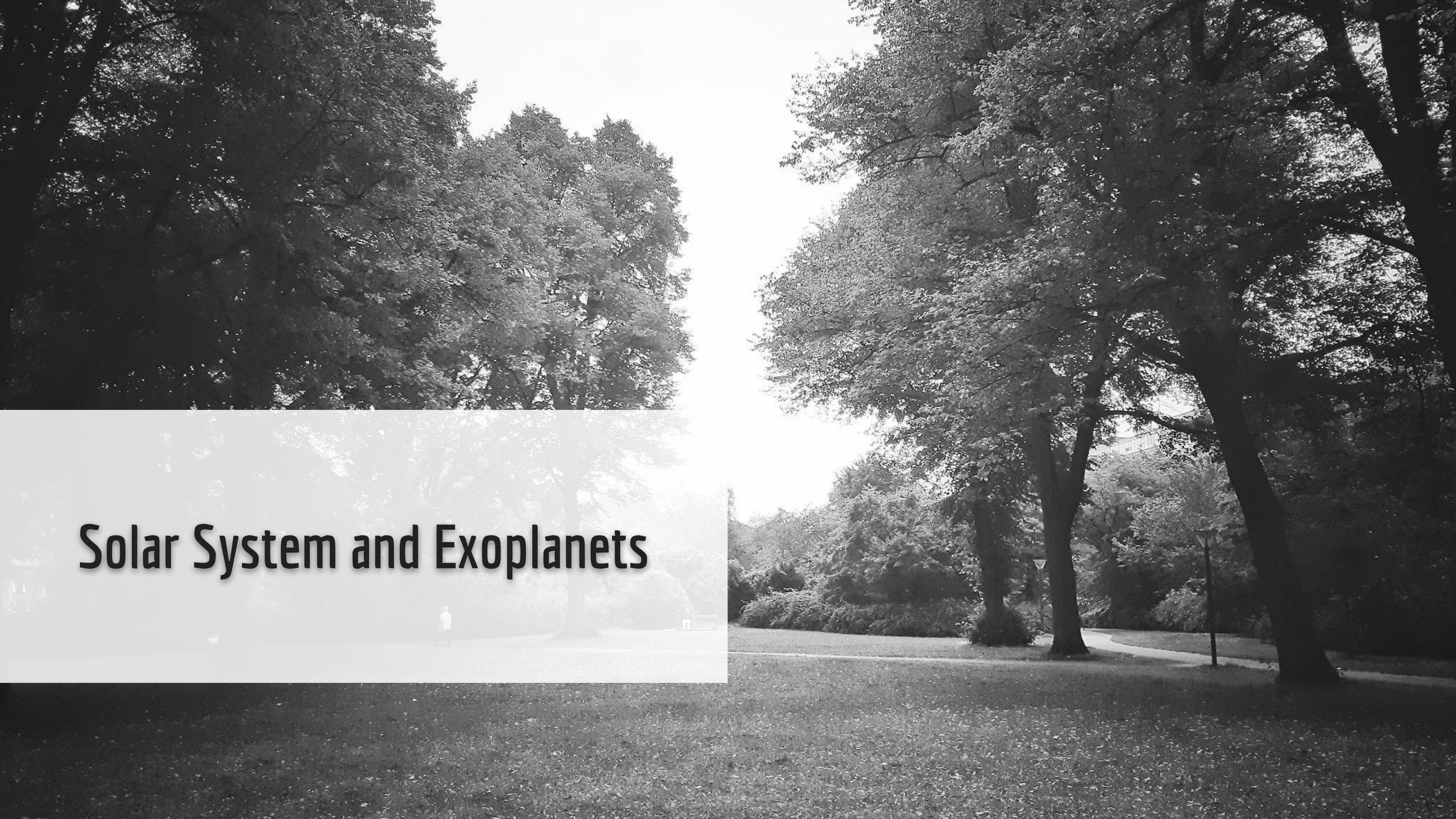
Pablo Benitez-Llambay

Postdoc at

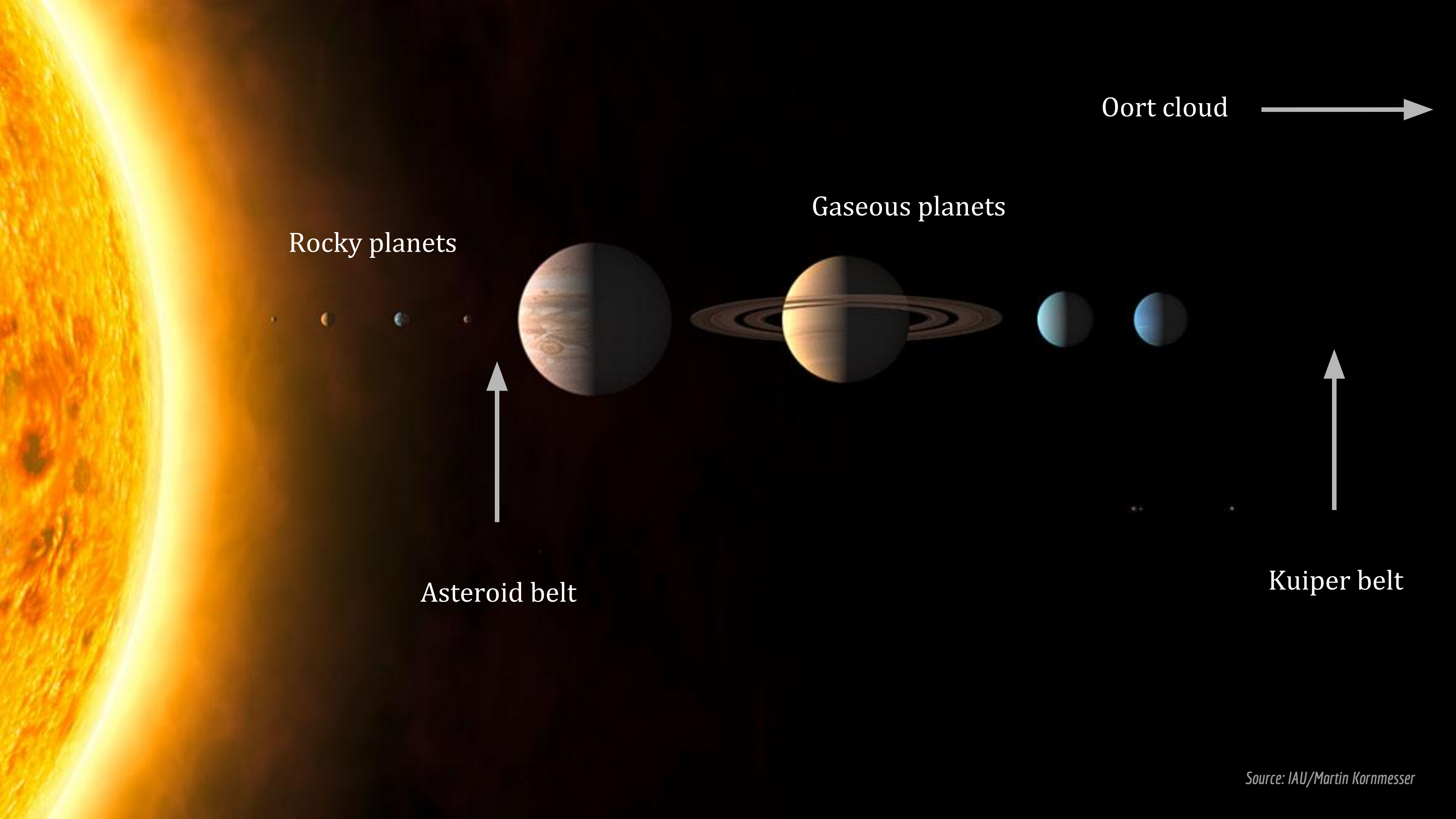
The Niels Bohr International Academy

Outline of the talk

1. Solar System and exoplanets
2. Astrophysical context of planet formation
3. Protoplanetary disks
4. Building blocks of planets
5. Planet formation
6. Planet migration
7. Lessons from the Solar System
8. Summary



Solar System and Exoplanets


Oort cloud
Gaseous planets
Rocky planets
Asteroid belt
Kuiper belt
Source: IAU/Martin Kornmesser

It wasn't always like that…

2000 BC
- Babylonian
- Earth/Moon, Mercury, Venus, Mars, Jupiter, Saturn
- Geocentric model

16th
- Copernicus
- Brahe
- Heliocentric model
- Comets are not atmospheric phenomena

17th
- Galileo
- Kepler
- Huygens
- Cassini
- Telescope
- Galilean moons
- Saturn's rings and moons

18th
- Halley
- Herschel
- Kant/Laplace
- Halley's comet
- Uranus
- Uranus' moons
- Saturn's moons

19th
- Piazzi
- Olbers
- Adams/Le Verrier
- Ceres
- Pallas
- Neptune

20th
- Wolf
- Tombaugh
- Oort
- Many others
- Trojan asteroid Achilles
- Pluto
- Oort cloud
- Kuiper belt
- Space missions era..

4122

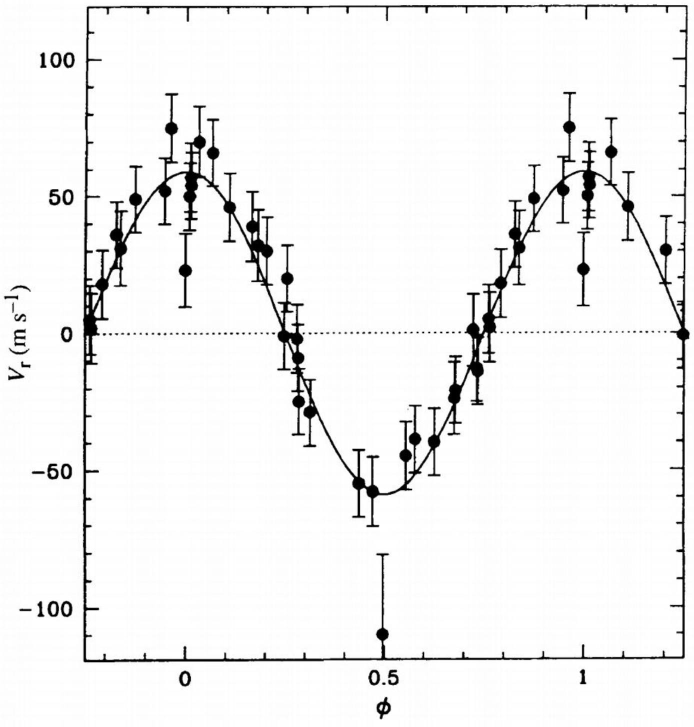
planets and 3063 planetary systems (671 multiple planet systems) detected and confirmed with different methods

Source: exoplanet.eu, October 2019

51 Pegasi / 51 Pegasi b

- 51 Peg is a the first “main-sequence” star discovered hosting an exoplanet
- 51 Peg b is a giant planet (half the mass of Jupiter)
- Semi-major axis 0.05 AU (Mercury is 0.39 AU)
- Orbital period of 4 days

Hot Jupiter



Mayor & Queloz (1995)

Different to our Solar System

Orbital migration of the planetary companion of 51 Pegasi to its present location

D. N. C. Lin*, P. Bodenheimer* & D. C. Richardson†

* UCO/Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064, USA
† Canadian Institute for Theoretical Astrophysics, McLennan Laboratories, University of Toronto, 60 St George Street, Toronto, Ontario, Canada M5S 1A7

Here we show that, if the companion is indeed a gas-giant planet, it is extremely unlikely to have formed at its present location. We suggest instead that the planet probably formed by gradual accretion of solids and capture of gas at a much larger distance from the star (~5 AU), and that it subsequently migrated inwards through interactions with the remnants of the circumstellar disk.

Nobel prize in Physics 2019

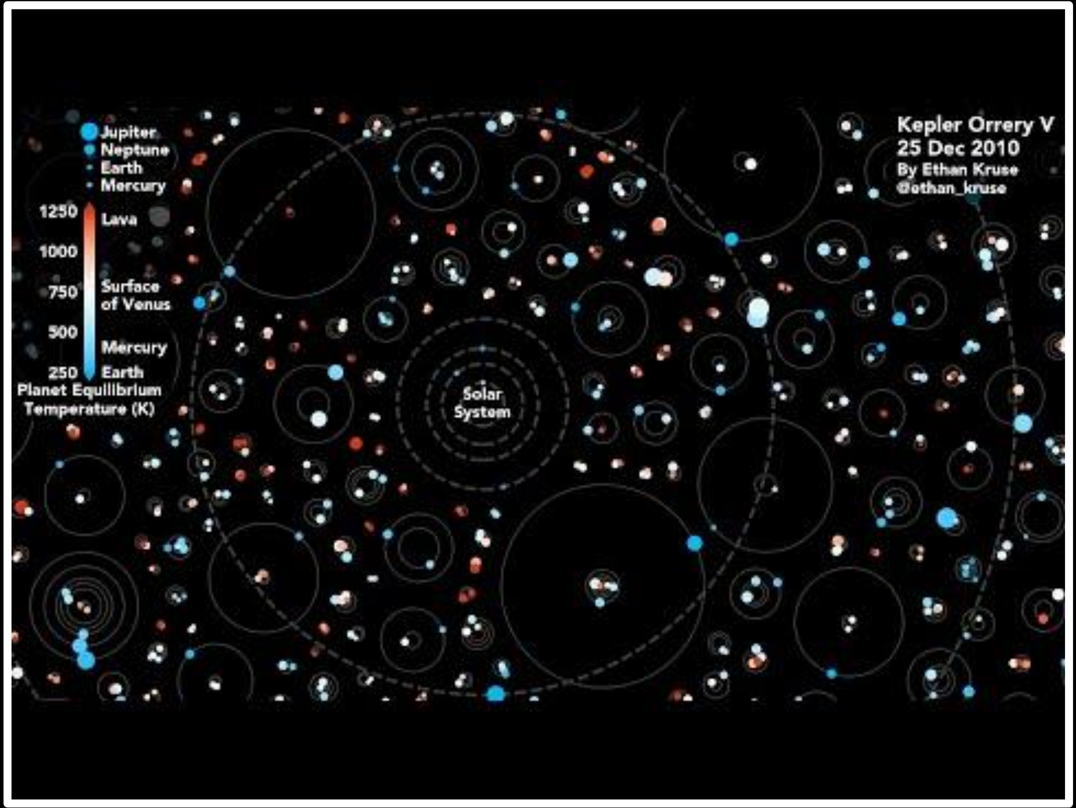
For the discovery of an exoplanet orbiting a solar-type star

Ill. Niklas Elmehed. © Nobel Media.
Michel Mayor
Prize share: 1/4

Ill. Niklas Elmehed. © Nobel Media.
Didier Queloz
Prize share: 1/4

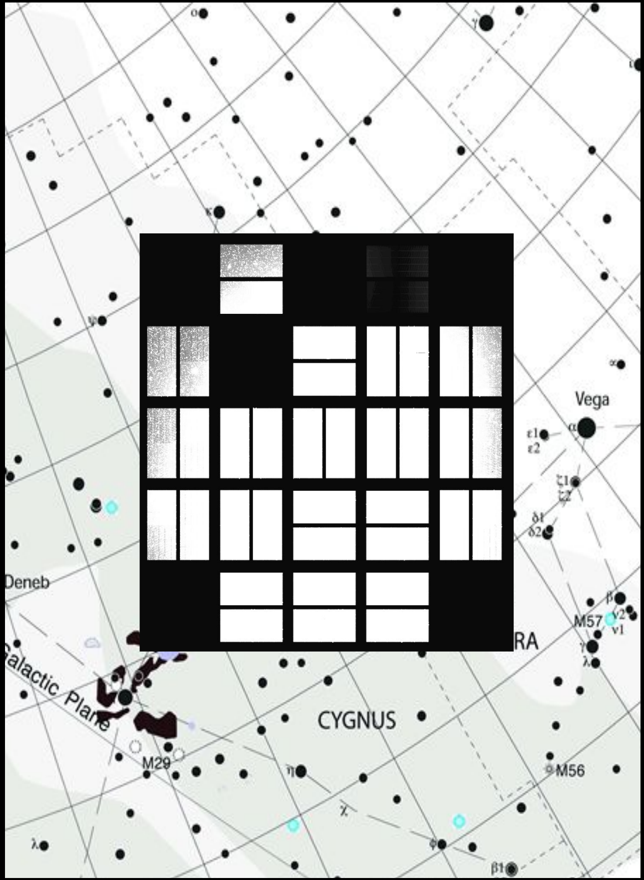
Kepler Orrery

Planetary systems discovered by Kepler observatory

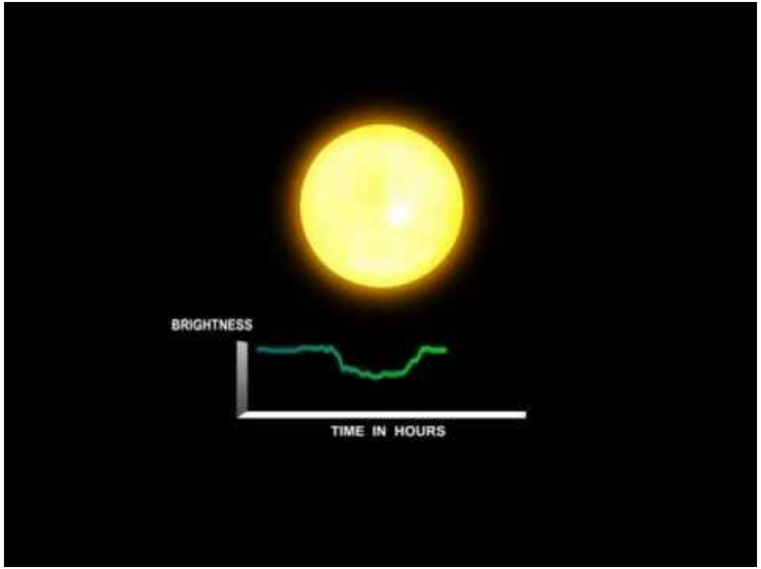


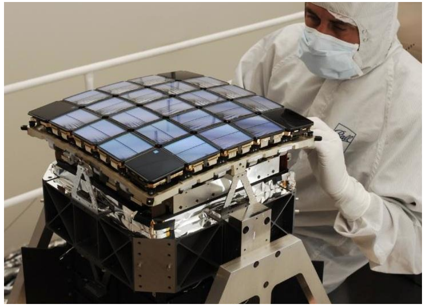
Kepler Observatory

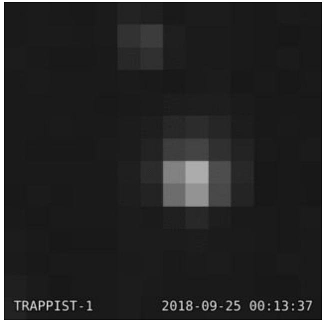
Detector and Field of view



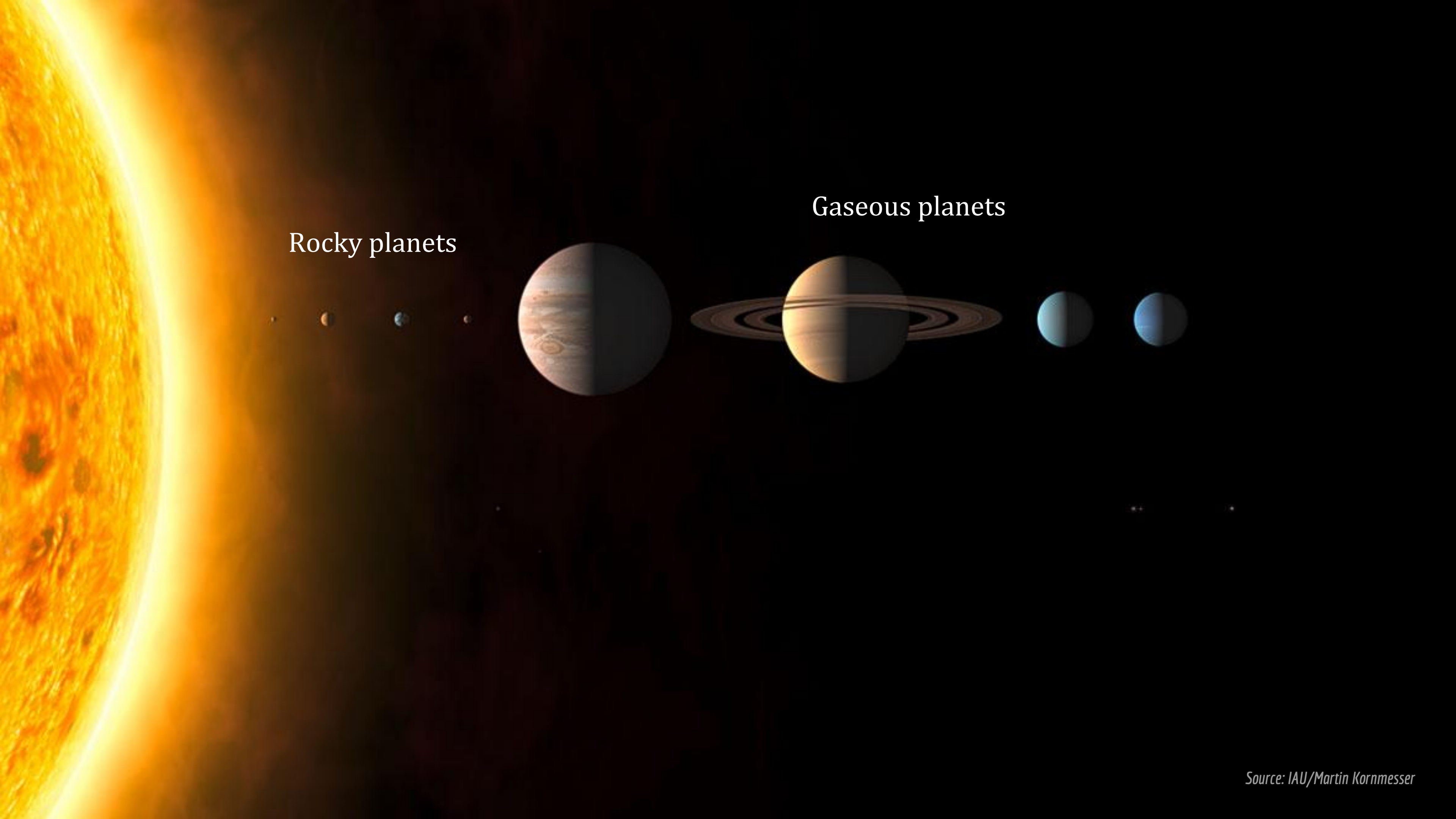
Source: keplerscience.arc.nasa.gov/the-kepler-space-telescope.html







Astrophysical context of planet formation

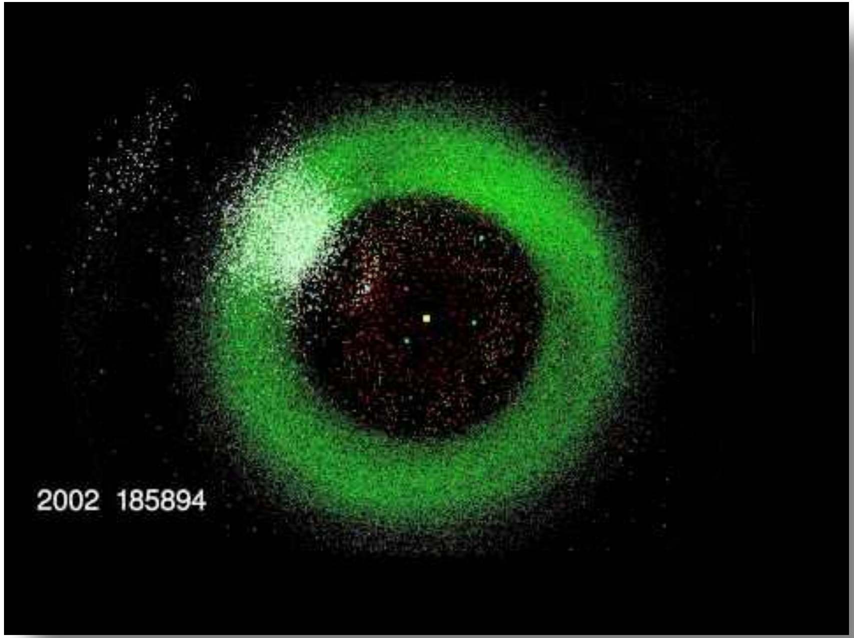

Gaseous planets
Rocky planets
Source: IAU/Martin Kornmesser

Nebular hypothesis

- Bodies rotate in the same direction
- Low inclinations / eccentricities

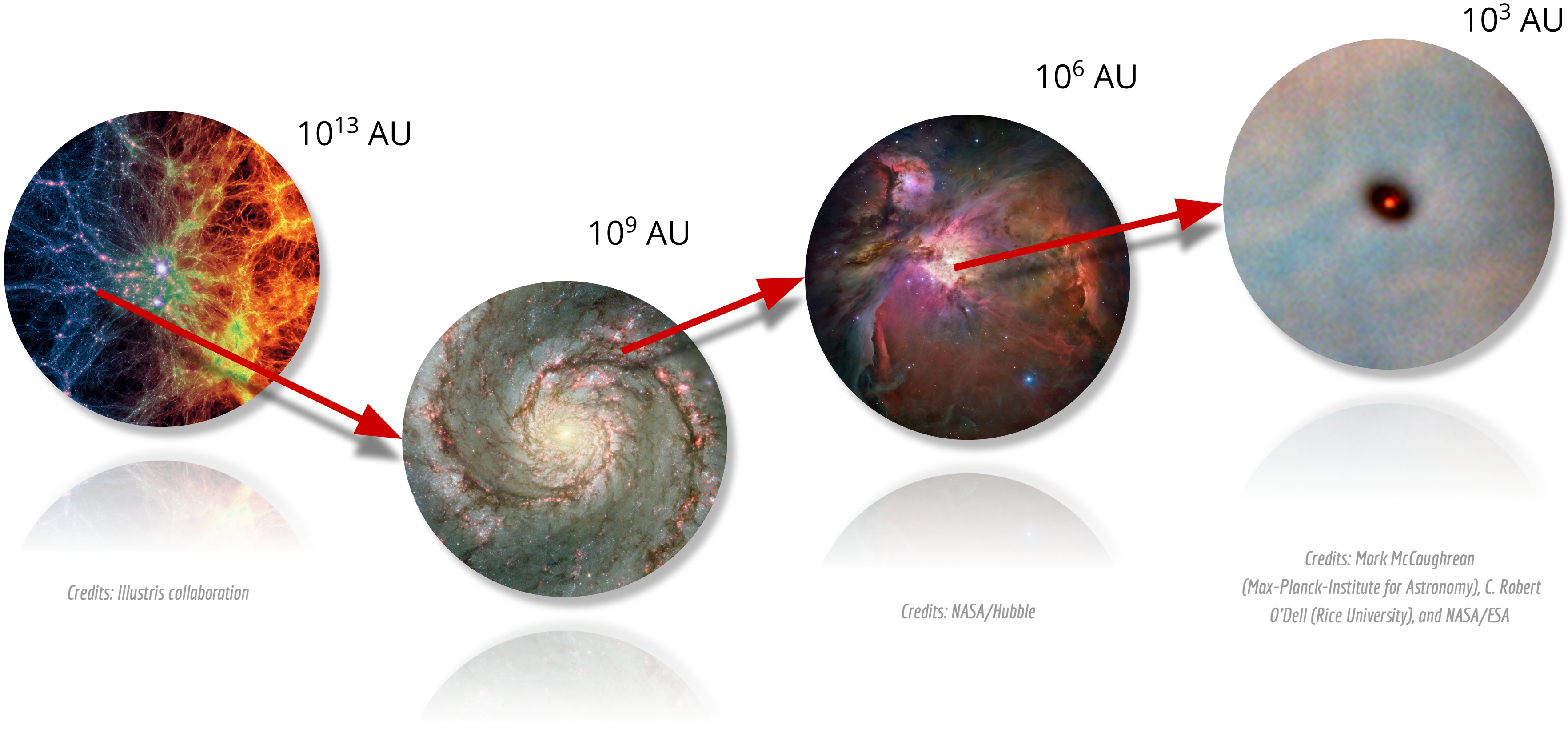
Kant (1755)

Laplace (1796)



Planets condense from a primitive solar atmosphere

From galaxy clusters to planets



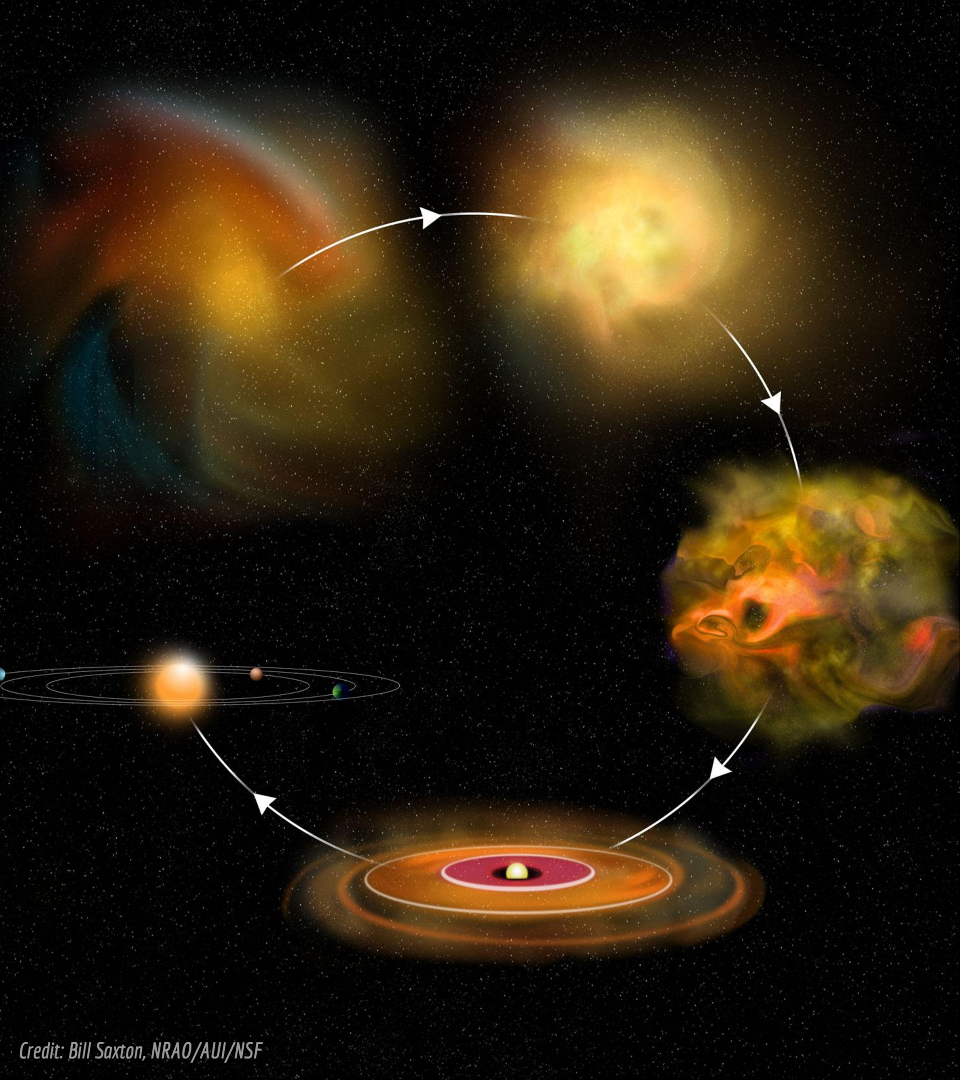
Credits: Illustris collaboration

Credits: NASA/Hubble

Credits: NASA/Hubble

Credits: Mark McCaughrean (Max-Planck-Institute for Astronomy), C. Robert O'Dell (Rice University), and NASA/ESA

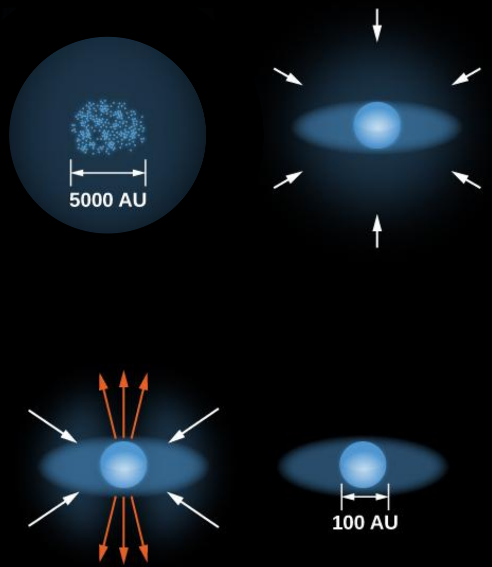
Protoplanetary disks

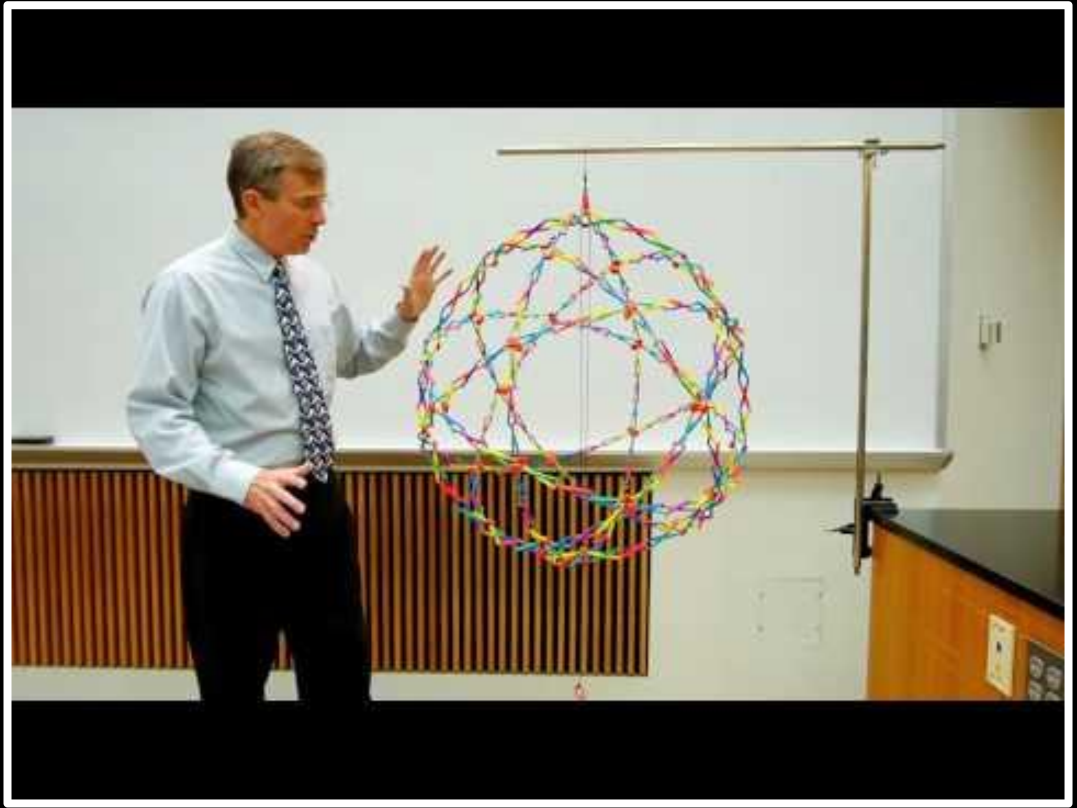


How do planets form?

- Molecular cloud collapses
- Small dust grains merge into larger bodies and form the first planetary cores
- Planet cores accrete gas/dust from the disk
- Rocky planets are believed to form in the final stages
- The system finally relaxes dynamically towards an equilibrium configuration

Disk formation

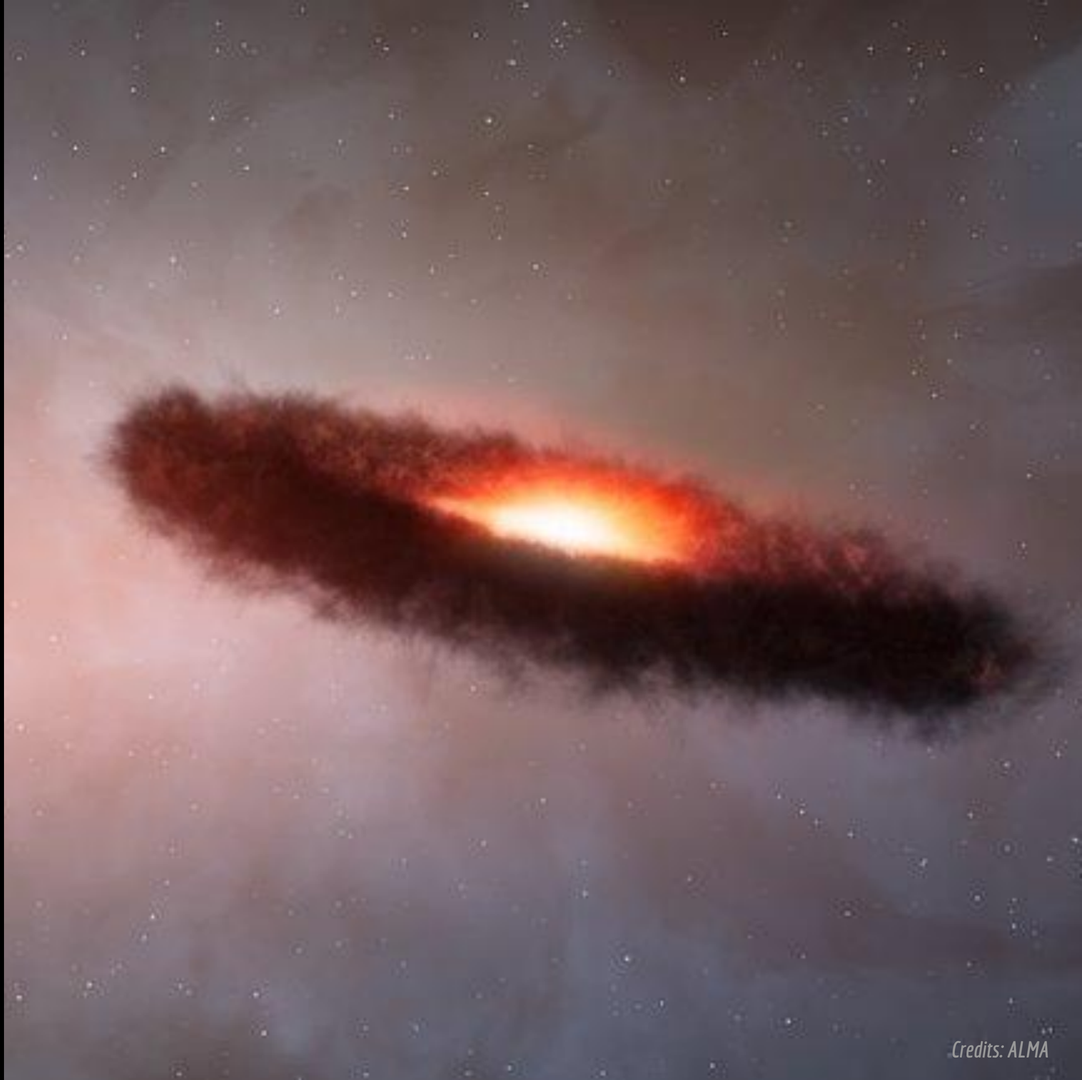




Source: pressbooks.bccampus.ca/astronomy1105/chapter/21-1-star-formation/

Protoplanetary disks

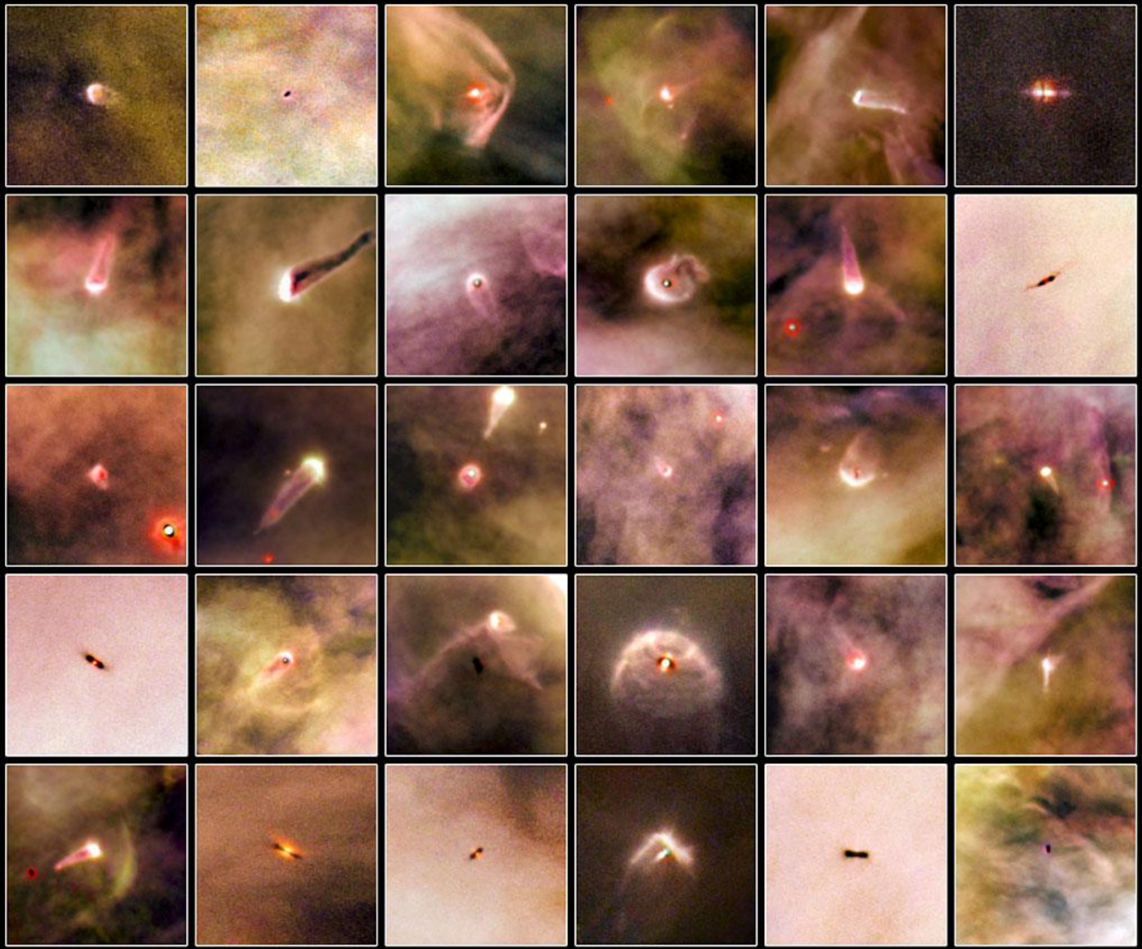
- Gaseous disks rotating orbiting a central object
- Small fraction of dust
- Typical size of 100-1000 AU
- Live for ~1-10 Myr
- Factories of planets



Where do we find disks?

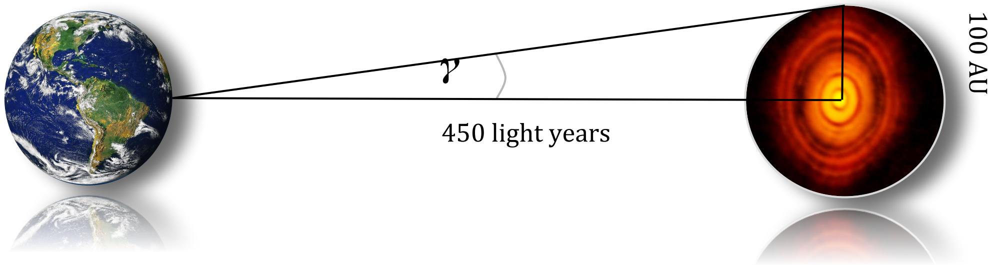
Orion Nebula

Hubble space telescope

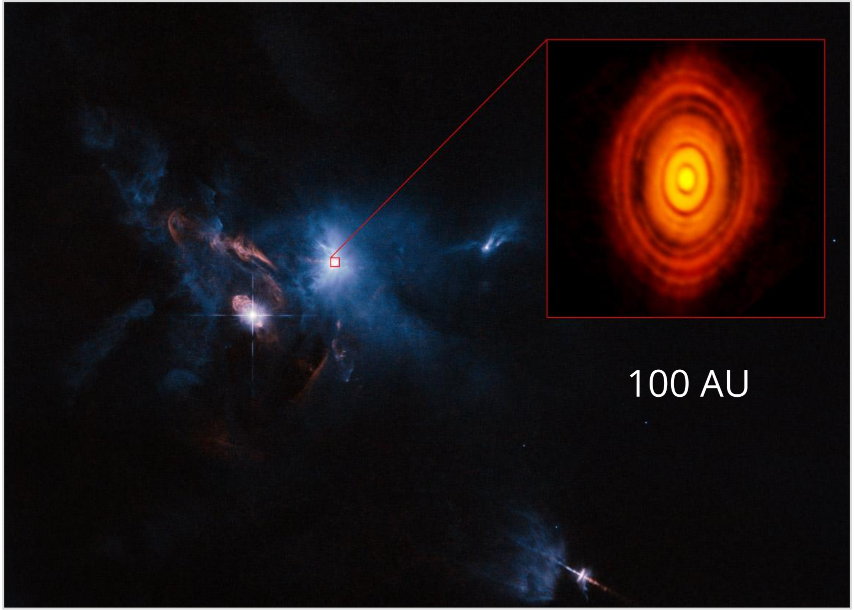


Credit: NASA/ESA an L. Ricci (ESO)

HL TAU & Tw hydra

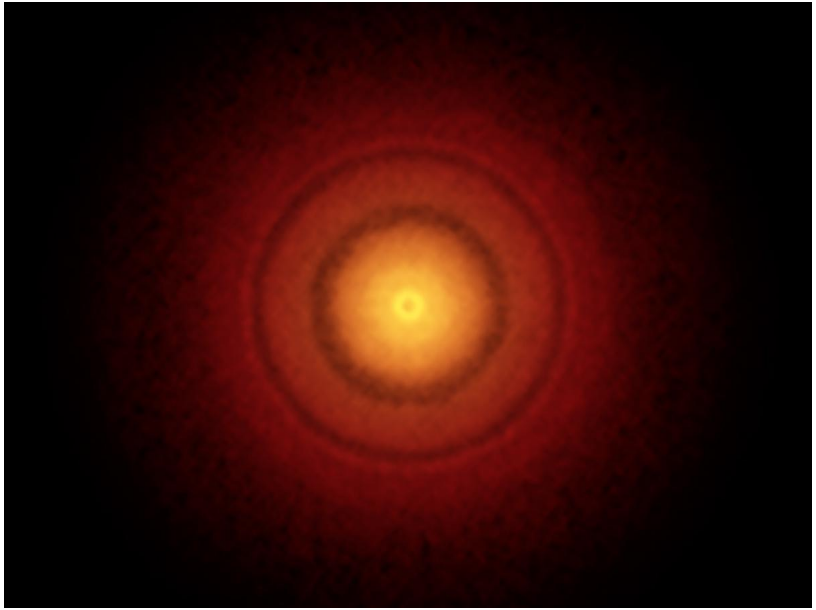


450 light years away from us (1 arcsec)



Credits: ALMA

200 light years

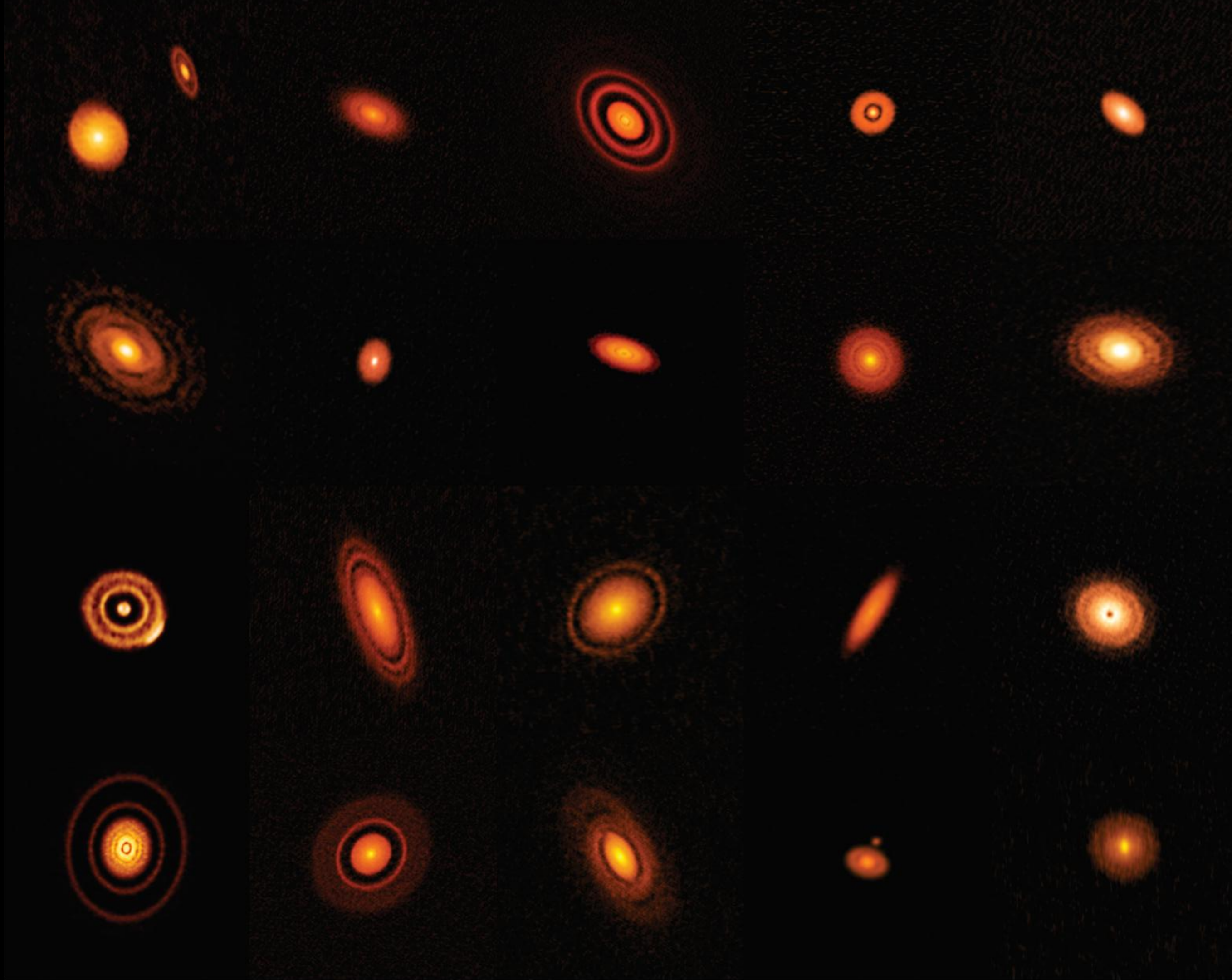


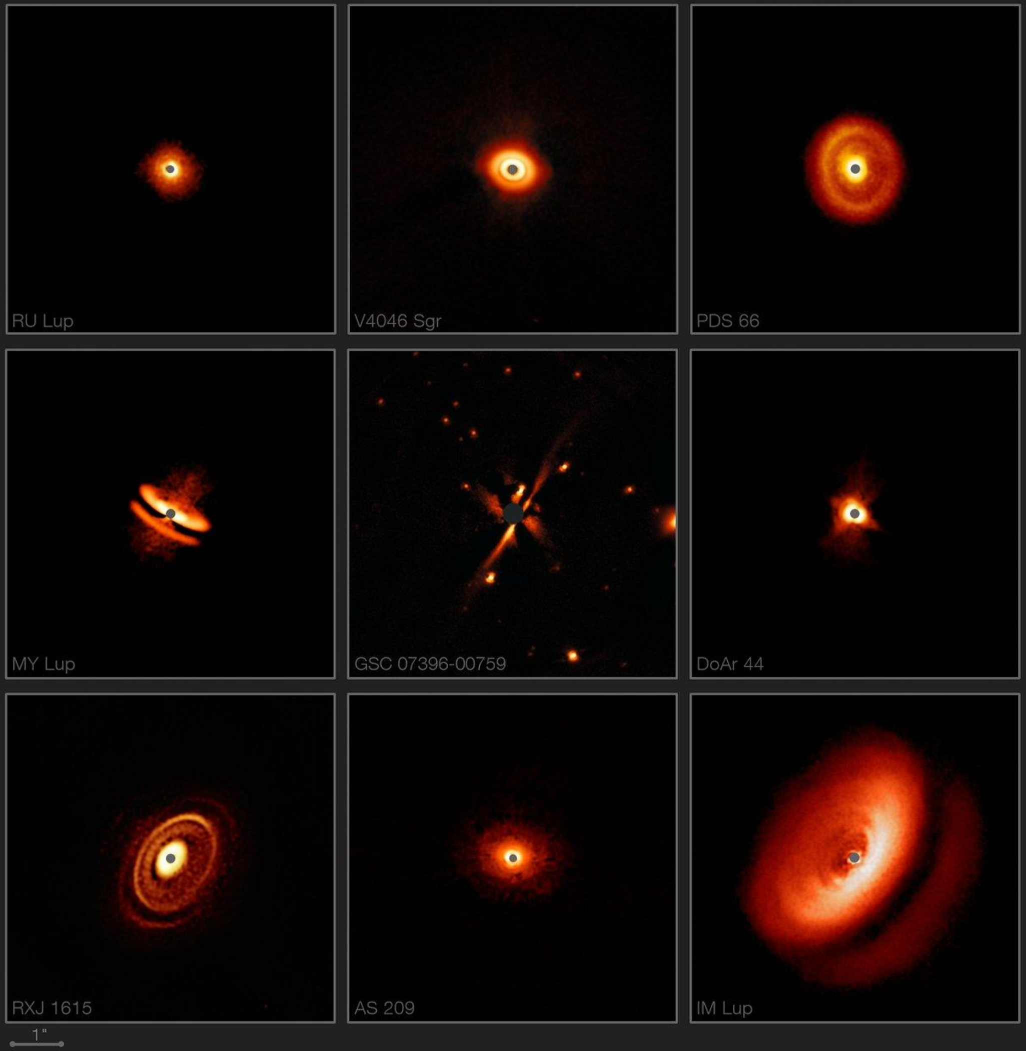
Credits: S. Andrews (Harvard-Smithsonian CfA); B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)

DSHARP

"Disk substructures at high Angular resolution Project"

Credits: ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; NRAO/AUI/NSF, S. Dagnello





Dusty disks

SPHERE at VLT

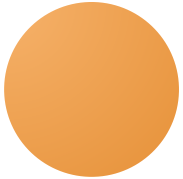
Credits: ESO/H. Avenhaus et al./E. Sissa et al./DARTT-S and SHINE collaborations

STAR + GAS + SOLIDS = PLANETS

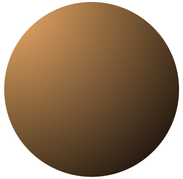
Building blocks of planets

Solids dynamics

$$S = 4\pi R^2$$



vs



$$V = \frac{4}{3}\pi R^3$$

$$\frac{S}{V} \propto \frac{1}{R}$$

Cross section of the body
Friction forces

Mass of the body
Inertia

The smaller the object, the larger the surface to volume ratio

Solids dynamics

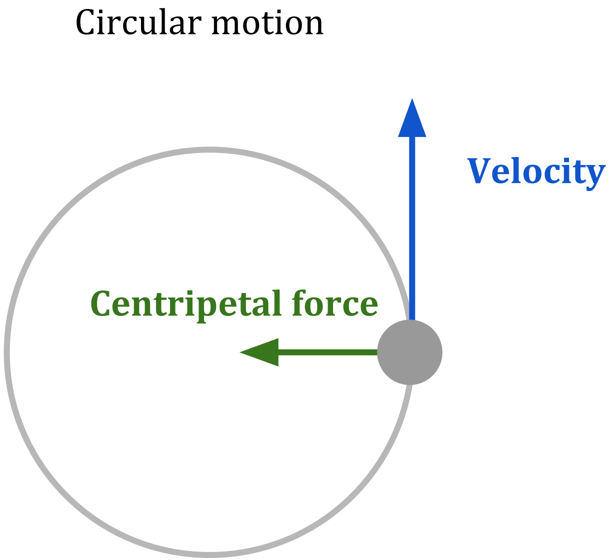
Solids behave differently depending on their size and mass

Small solids trace air flow

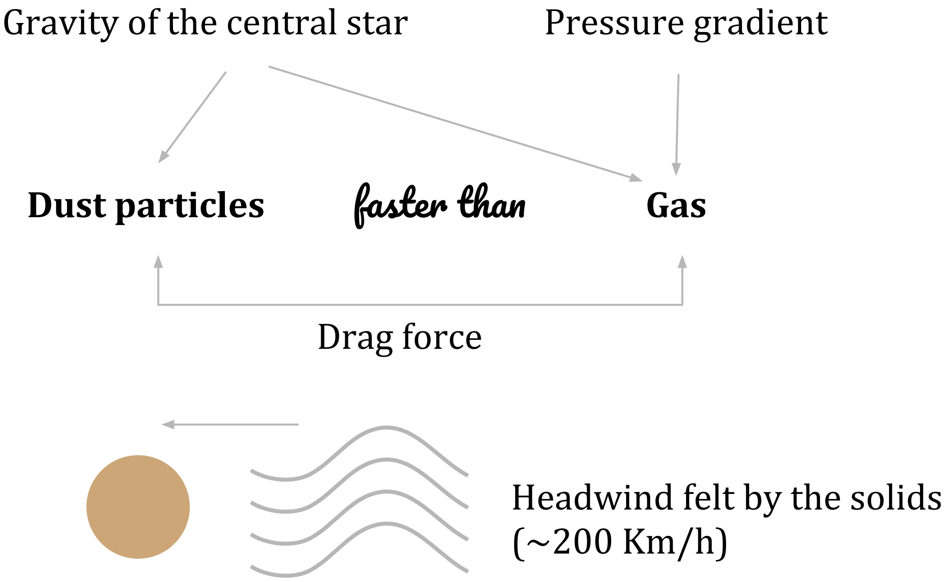
Larger solids partially trace air flow

Even larger solids decouple almost completely from air flow

Solids dynamics in protoplanetary disks



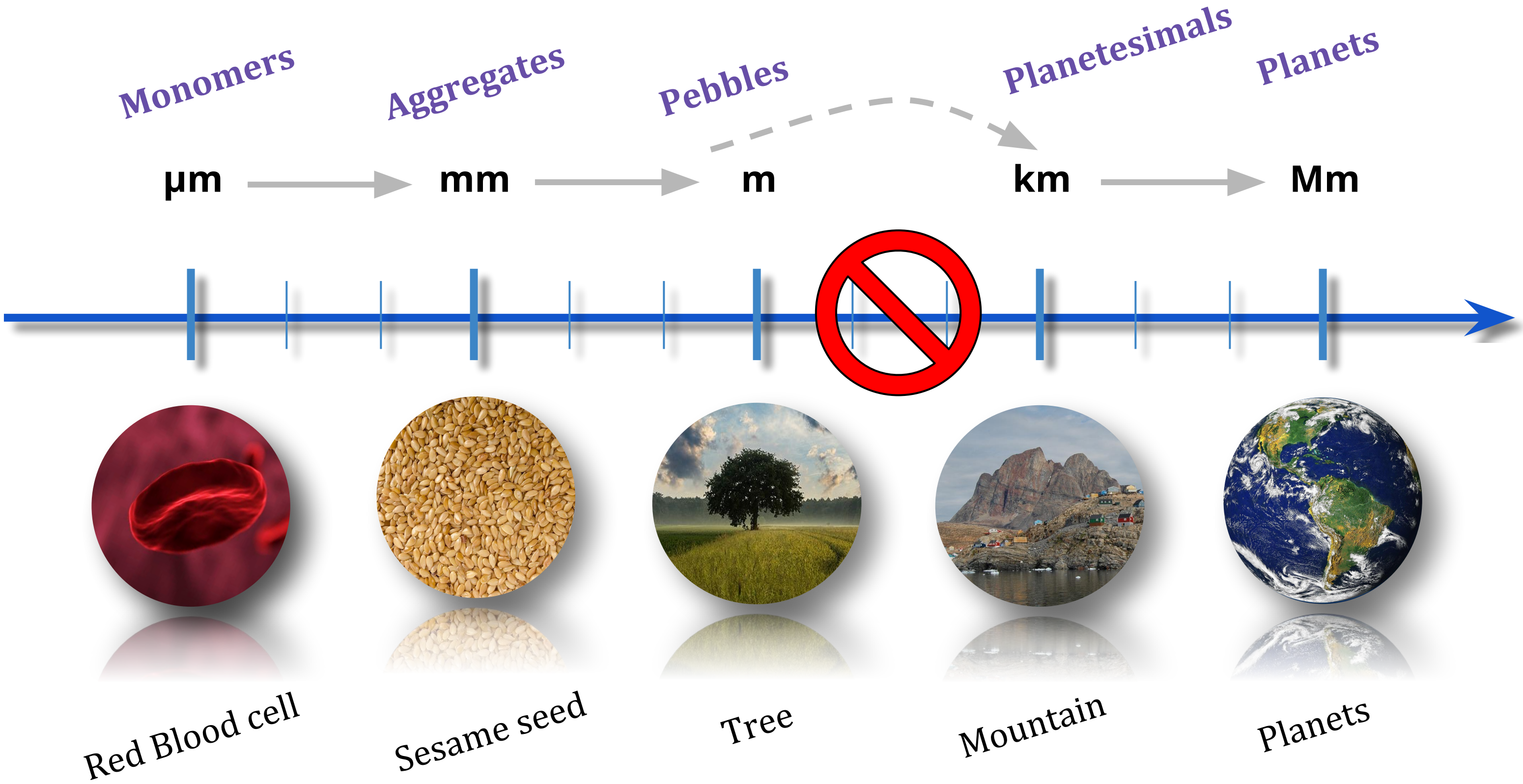
Centripetal forces (idealized picture)



Solids dynamics in protoplanetary disks

- Drag force depends on:
    - Particle size
    - Ambient density
        - Denser medium is able to remove momentum more efficiently
- Small particles are well coupled to the gas
    - Dynamics governed by drag forces
- Large particles are decoupled from the gas
    - Dynamics governed by inertia / external forces

From stardust to planets

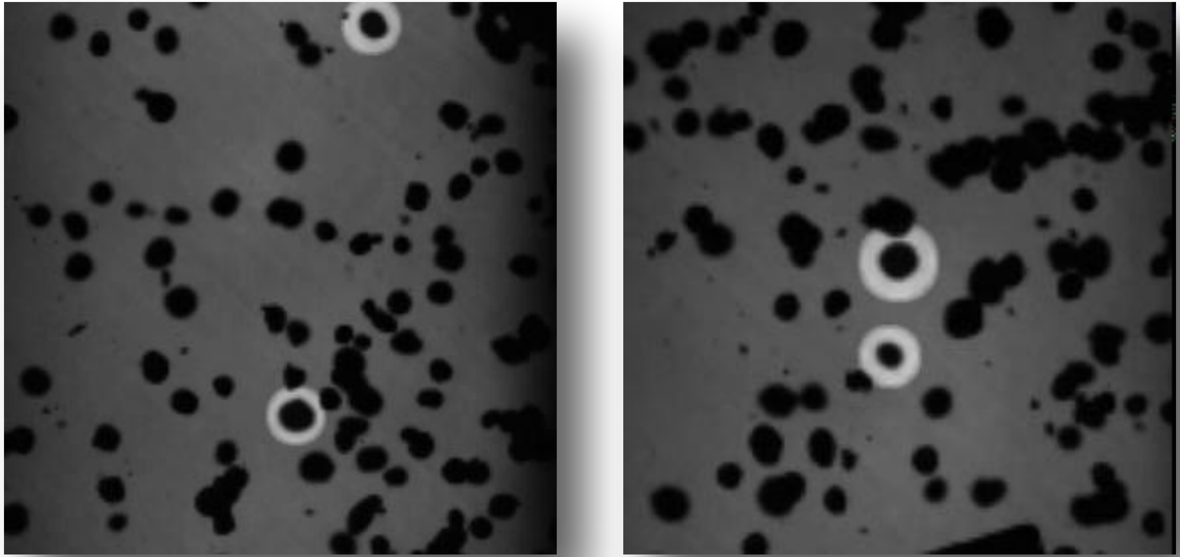


Microgravity experiments
Bremen University

Weidlin et al. (2011)

WFB/Jonas Ginter

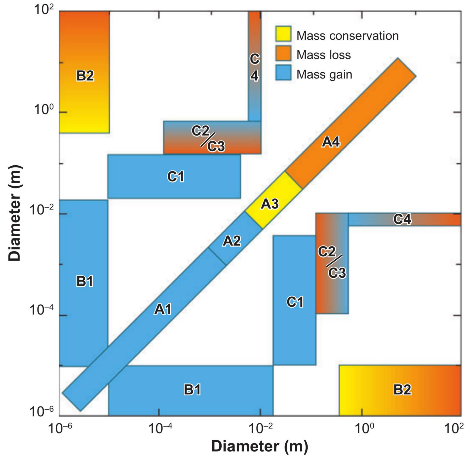
Growth barriers



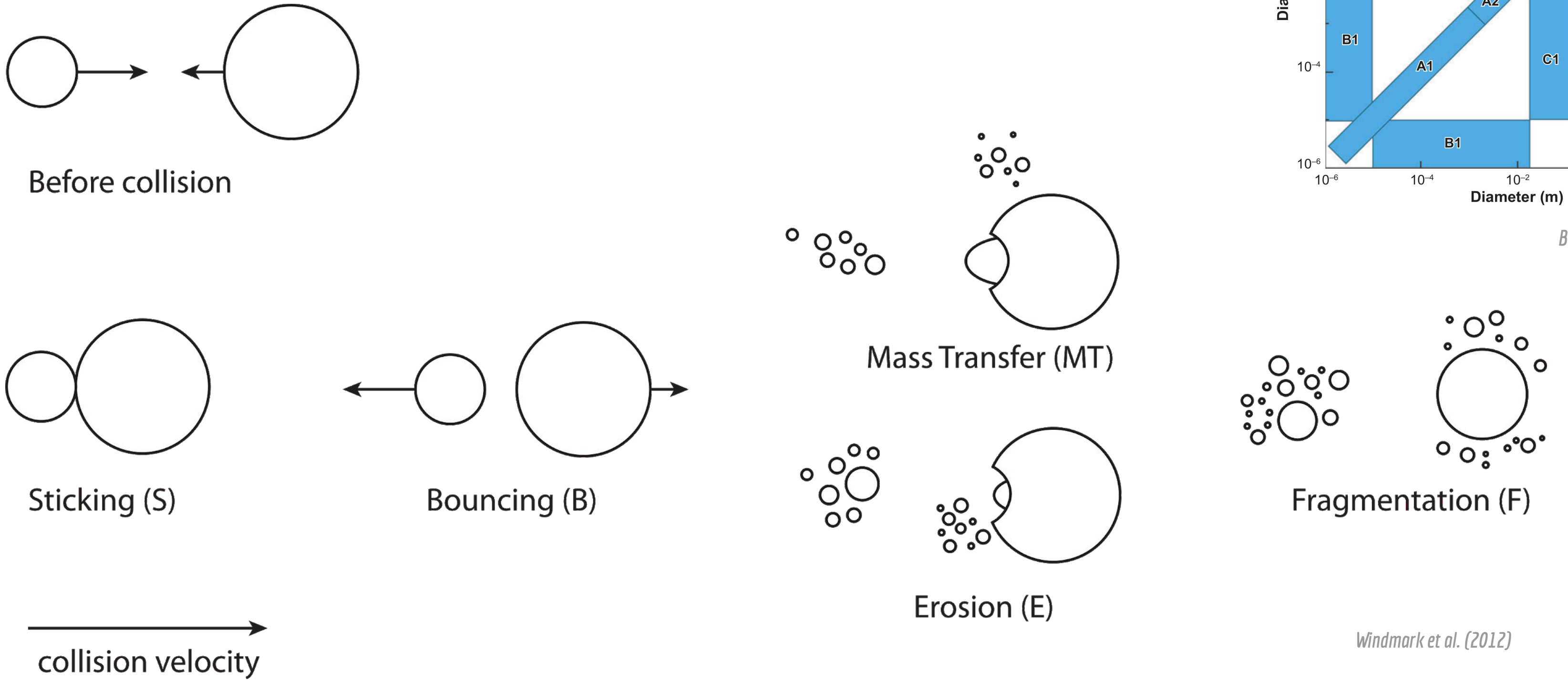
Weidlin et al. (2011)

Beitz et al. (2011)

Dust growth



Blum & Wurm (2008)



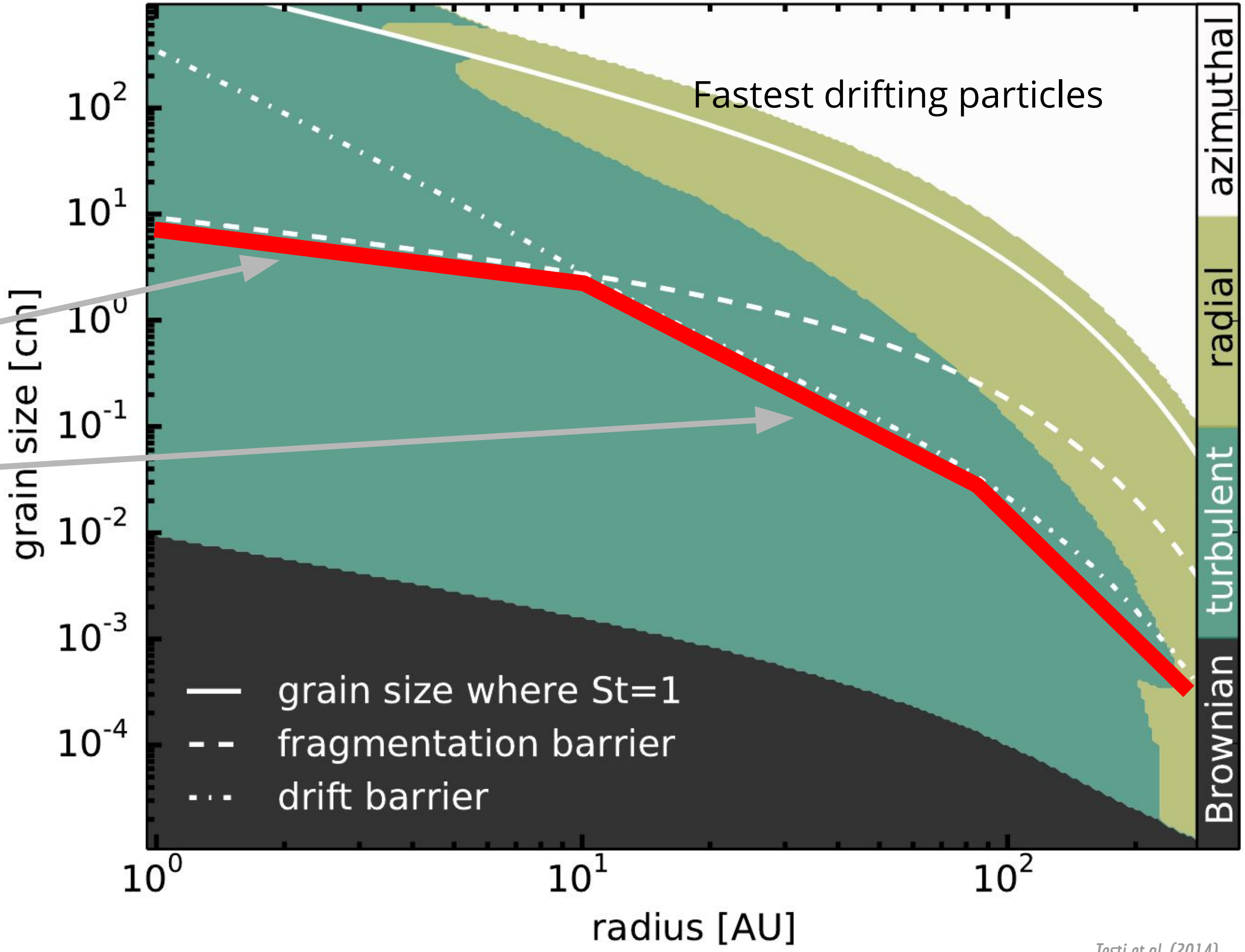
Windmark et al. (2012)

Growth barriers

Fragmentation

Drift

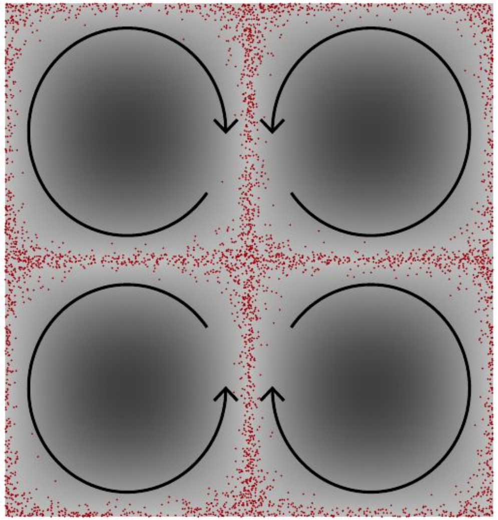
Big particles get destroyed by collisions or by falling into the star



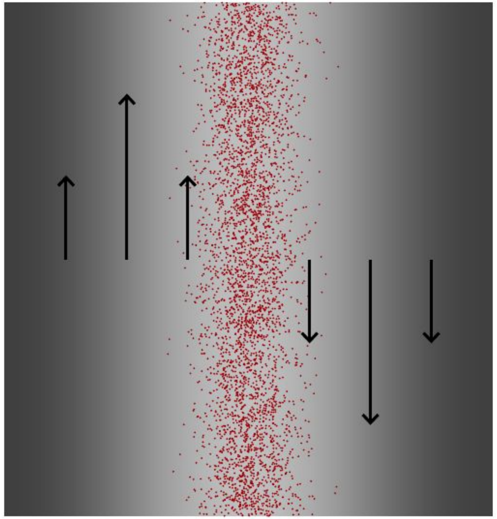
Testi et al. (2014)

How do we concentrate dust?

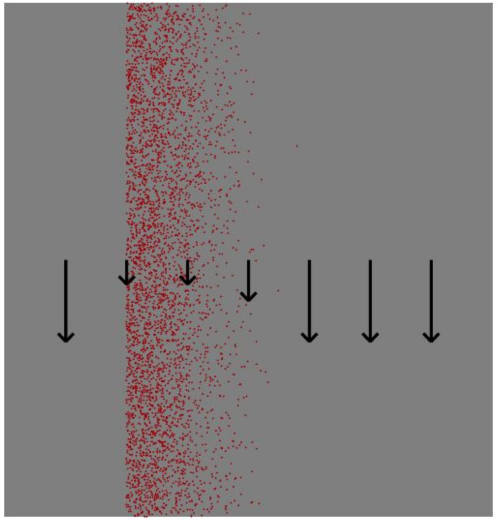
Eddies



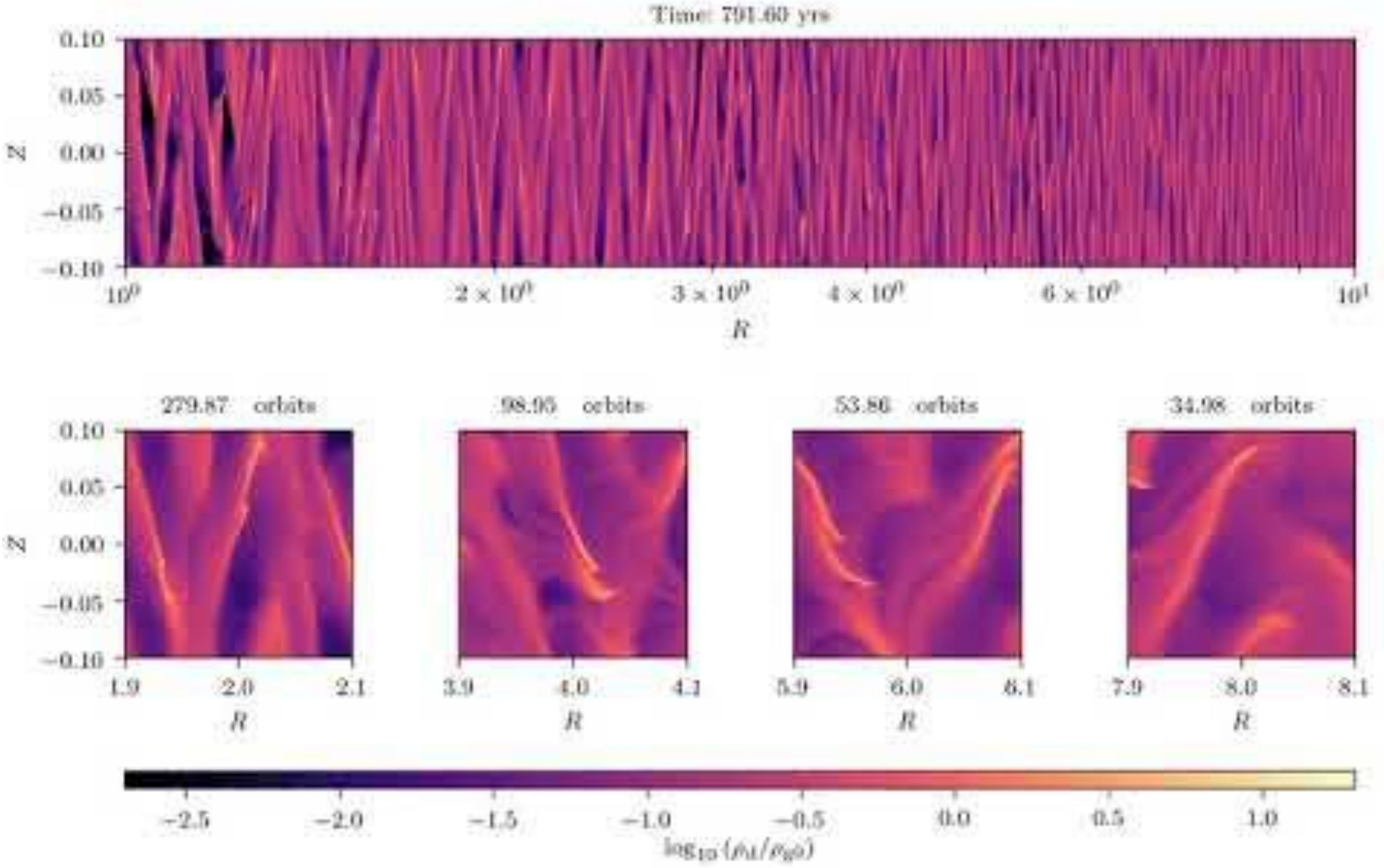
Pressure bumps



Streaming instability

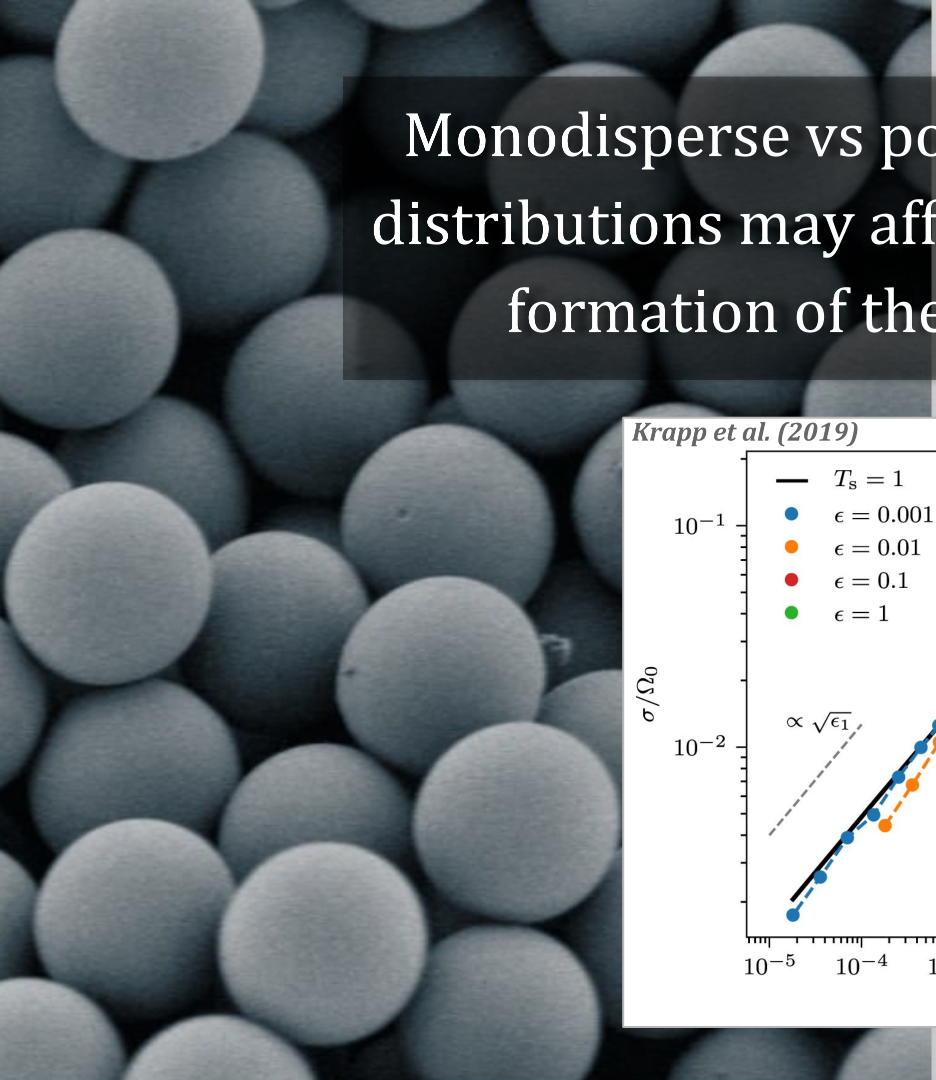


Johansen et al. (2014)

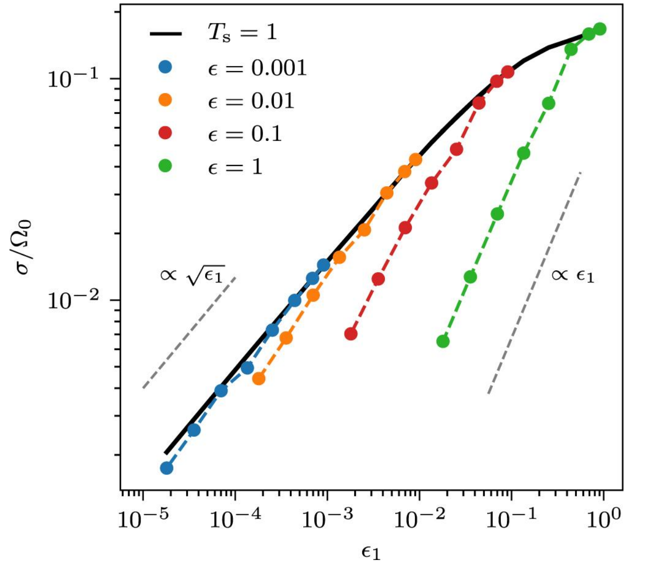


Time: 791.60 yrs
Z
R
279.87 orbits
98.95 orbits
53.86 orbits
34.98 orbits
$\log_{10}(\rho_d/\rho_g)$

Monodisperse vs polydisperse particles distributions may affect the dynamics and formation of the building blocks

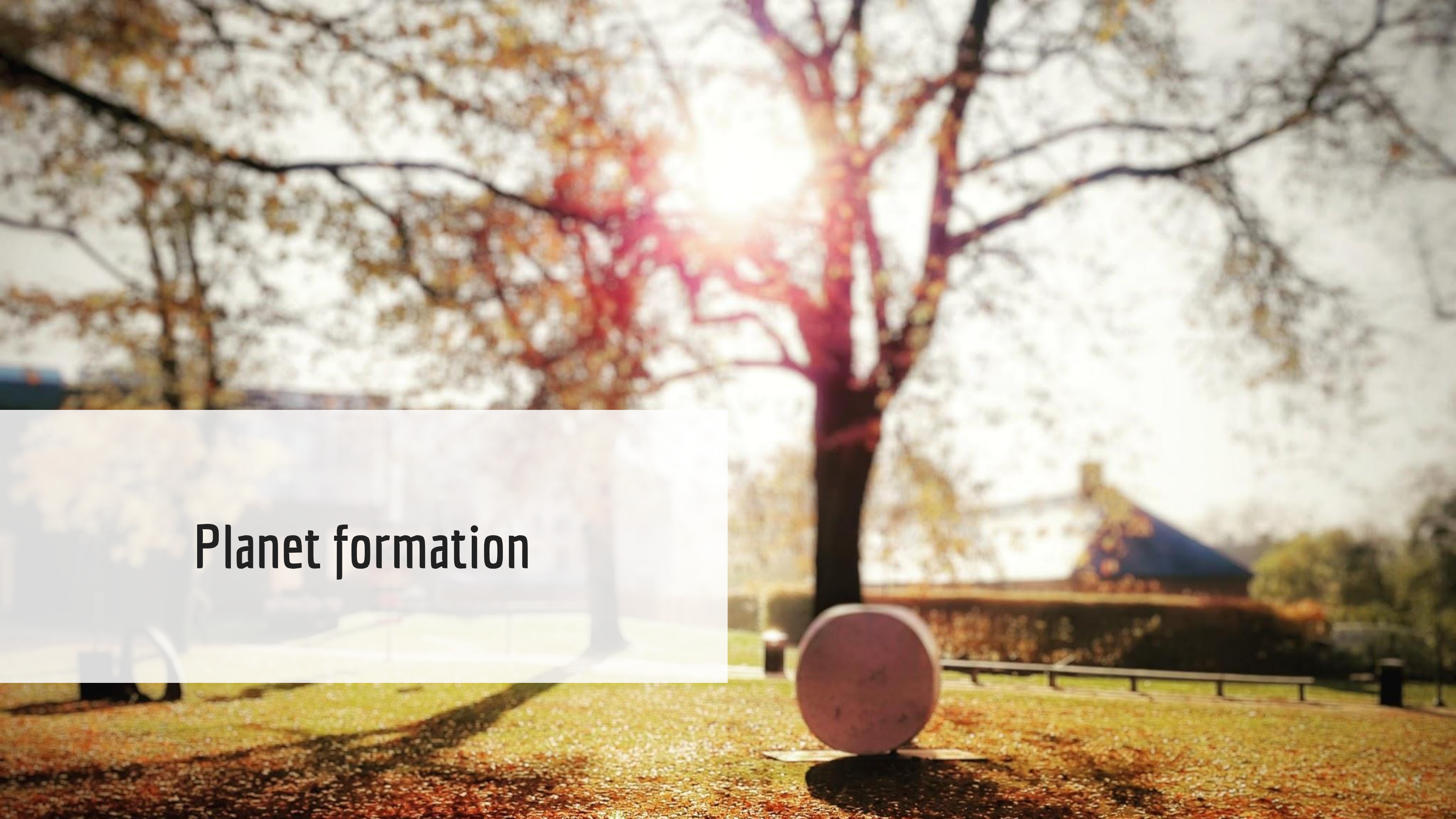


Krapp et al. (2019)



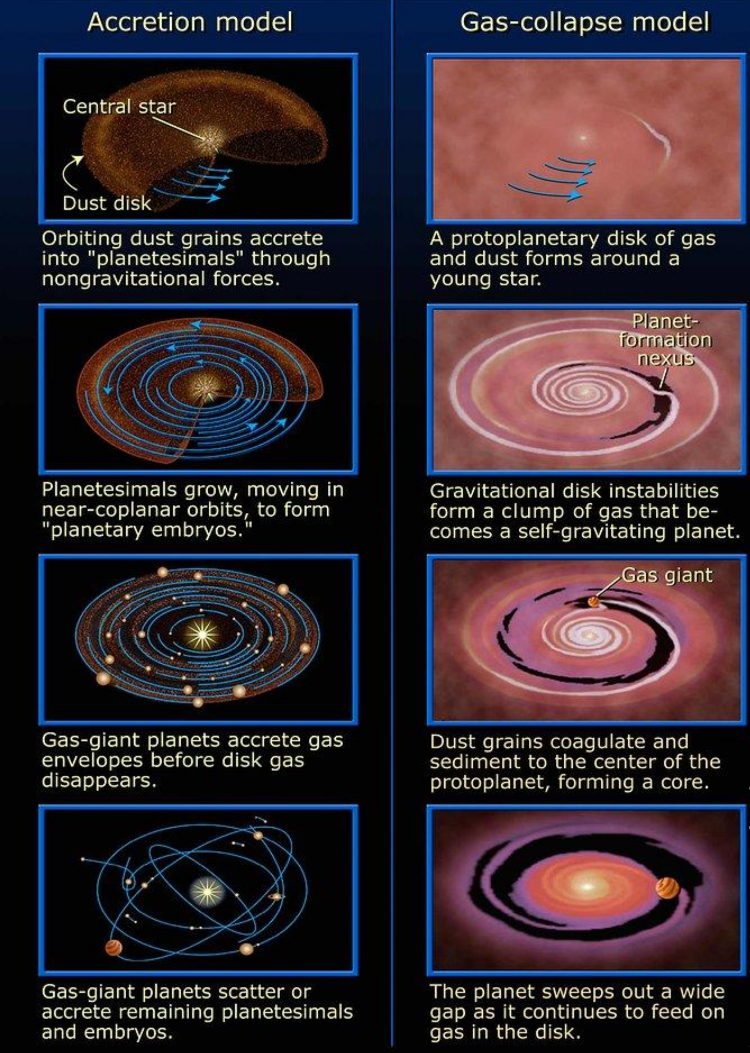
Blum, J., Beitz, E., et al. (2014)

END OF THE FIRST PART

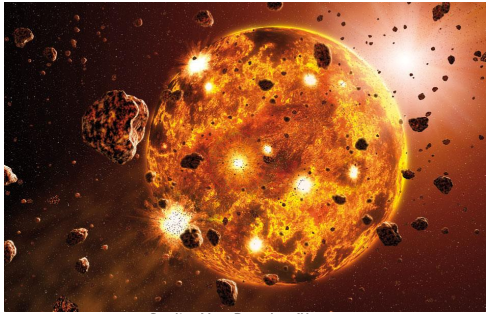


Planet formation

Two planet formation scenarios



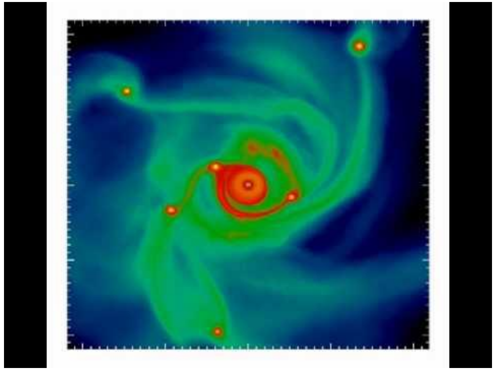
Credits: NASA/ESA and A. Feild (STScI)



Credit: Alan Brandon/Nature

Core accretion model

Bottom-up

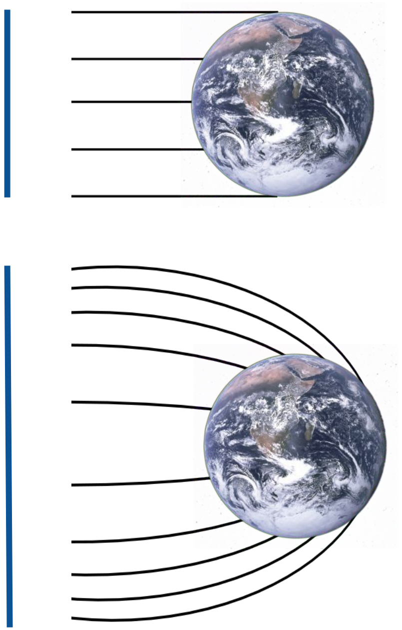


Gravitational instability

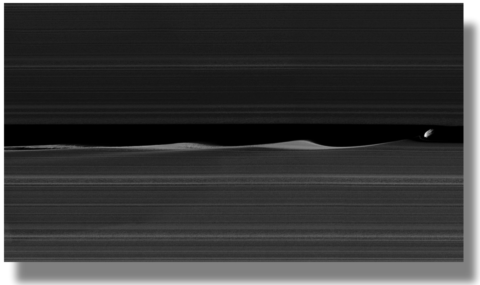
Top-down

Core accretion: Planetesimal accretion

Assisted by gravitational focusing



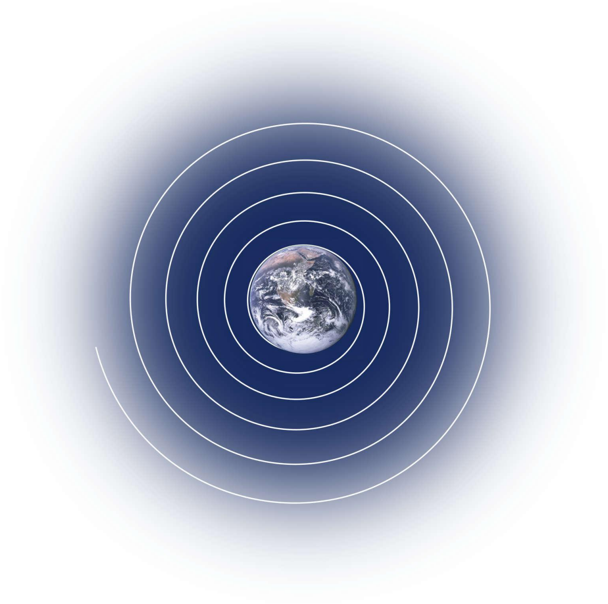
- Big gravitational bodies
- Depends on the radius of the accreting body (cross section)
- It takes long time



Credit: NASA/JPL/SSI

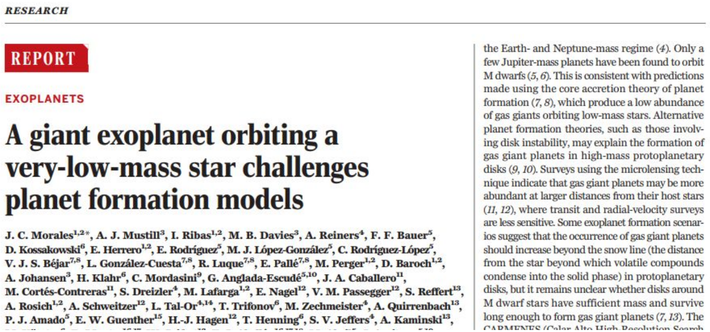
Core accretion: Pebble accretion

- Small negligible gravitational mass particles accrete onto large gravitating bodies in gas-rich environments
- It basically depends on the mass of the gravitating body and the surrounding density, not its size
- It is fast and very efficient



Pebble accretion is a also a planetesimal formation mechanism

Core accretion or Gravitational instability?



RESEARCH

REPORT

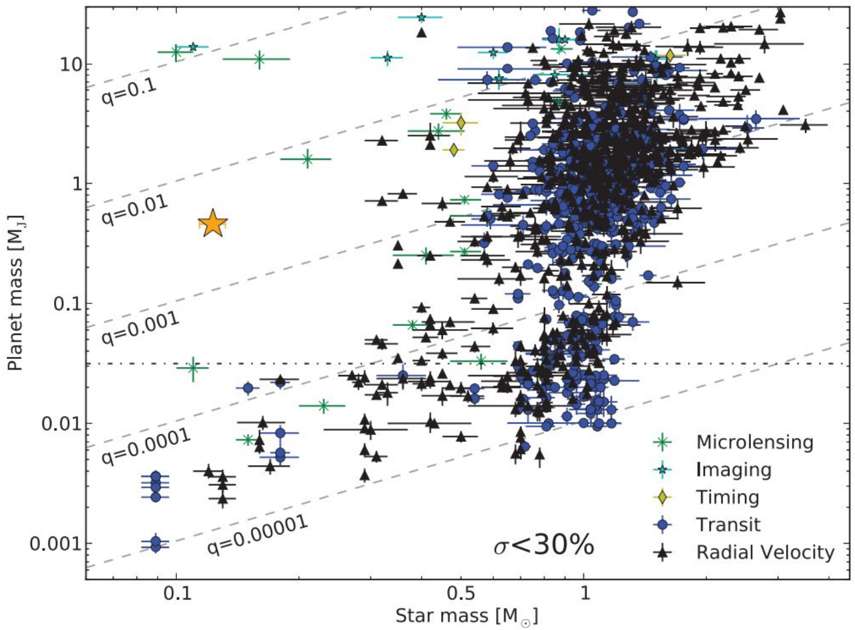
EXOPLANETS

A giant exoplanet orbiting a very-low-mass star challenges planet formation models

J. C. Morales[1,2]*, A. J. Mustill[3], I. Ribas[1,2], M. B. Davies[3], A. Reiners[4], F. F. Bauer[5], D. Kossakowski[6], E. Herrero[1,2], E. Rodríguez[5], M. J. López-González[5], C. Rodríguez-López[5], V. J. S. Béjar[7,8], L. González-Cuesta[7,8], R. Luque[7,8], E. Pallé[7,8], M. Perger[1,2], D. Baroch[1,2], A. Johansen[3], H. Klahr[6], C. Mordasini[9], G. Anglada-Escudé[5,10], J. A. Caballero[11], M. Cortés-Contreras[11], S. Dreizler[4], M. Lafarga[1,2], E. Nagel[12], V. M. Passegger[12], S. Reffert[13], A. Rosich[1,2], A. Schweitzer[12], L. Tal-Or[4,14], T. Trifonov[6], M. Zechmeister[4], A. Quirrenbach[13], P. J. Amado[5], E. W. Guenther[15], H.-J. Hagen[12], T. Henning[6], S. V. Jeffers[4], A. Kaminski[13],

the Earth- and Neptune-mass regime (4). Only a few Jupiter-mass planets have been found to orbit M dwarfs (5, 6). This is consistent with predictions made using the core accretion theory of planet formation (7, 8), which produce a low abundance of gas giants orbiting low-mass stars. Alternative planet formation theories, such as those involving disk instability, may explain the formation of gas giant planets in high-mass protoplanetary disks (9, 10). Surveys using the microlensing technique indicate that gas giant planets may be more abundant at larger distances from their host stars (11, 12), where transit and radial-velocity surveys are less sensitive. Some exoplanet formation scenarios suggest that the occurrence of gas giant planets should increase beyond the snow line (the distance from the star beyond which volatile compounds condense into the solid phase) in protoplanetary disks, but it remains unclear whether disks around M dwarf stars have sufficient mass and survive long enough to form gas giant planets (7, 13). The CARMENES (Calar Alto High-Resolution Search

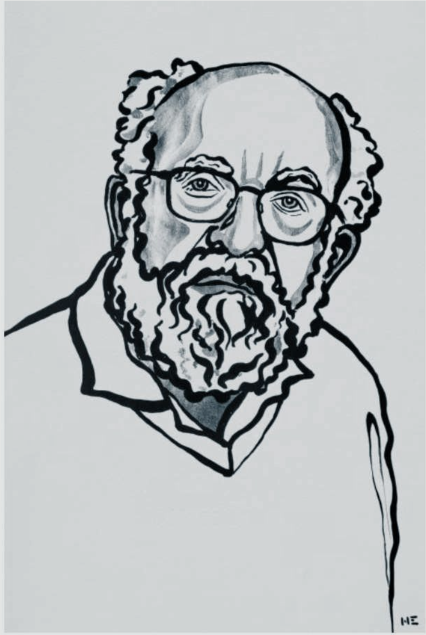
Morales et al. (2019)



Morales et al. (2019)

- Star GJ 3512
  - Mass $\sim 0.1\ M_{sun}$
- Planet GJ 3512 b
  - Mass $> 0.46\ M_{jup}$
  - Period: 204 days
  - Eccentricity: 0.44

Planet migration



Ill. Niklas Elmehed. © Nobel Media.

Michel Mayor

Prize share: 1/4

Ill. Niklas Elmehed. © Nobel Media.

Didier Queloz

Prize share: 1/4

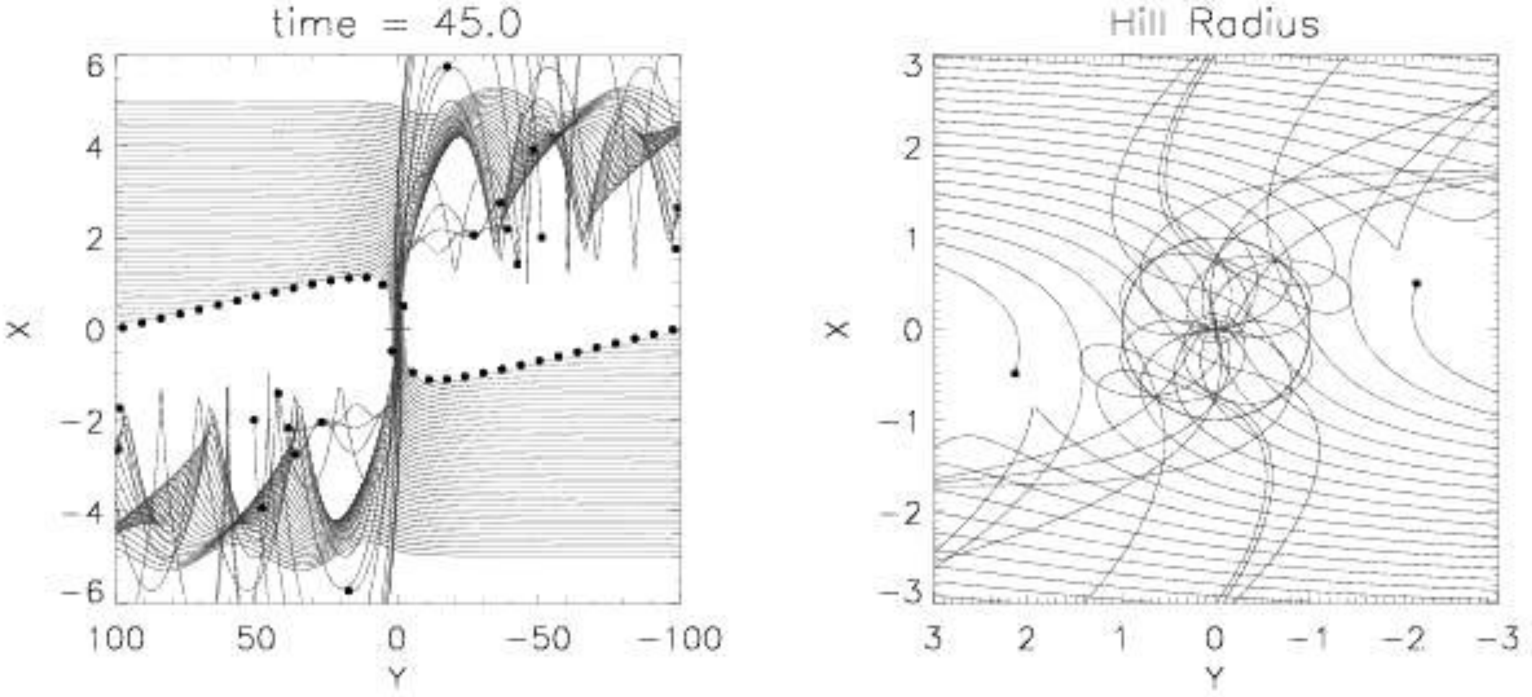
Orbital migration of the planetary companion of 51 Pegasi to its present location

D. N. C. Lin*, P. Bodenheimer* & D. C. Richardson†

* UCO/Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064, USA
† Canadian Institute for Theoretical Astrophysics, McLennan Laboratories, University of Toronto, 60 St George Street, Toronto, Ontario, Canada M5S 1A7

The recent discovery[1] and confirmation[2] of a possible planetary companion orbiting the solar-type star 51 Pegasi represent a breakthrough in the search for extrasolar planetary systems. Analysis of systematic variations in the velocity of the star indicate that the mass of the companion is approximately that of Jupiter, and that it is travelling in a nearly circular orbit at a distance from the star of 0.05 AU (about seven stellar radii). Here we show that, if the companion is indeed a gas-giant planet, it is extremely unlikely to have formed at its present location. We suggest instead that the planet probably formed by gradual accretion of solids and capture of gas at a much larger distance from the star (~5 AU), and that it subsequently migrated inwards through interactions with the remnants of the circumstellar disk. The planet's migration may have stopped in its present orbit as a result of tidal interactions with the star, or through truncation of the inner circumstellar disk by the stellar magnetosphere.

Gravitational perturbations



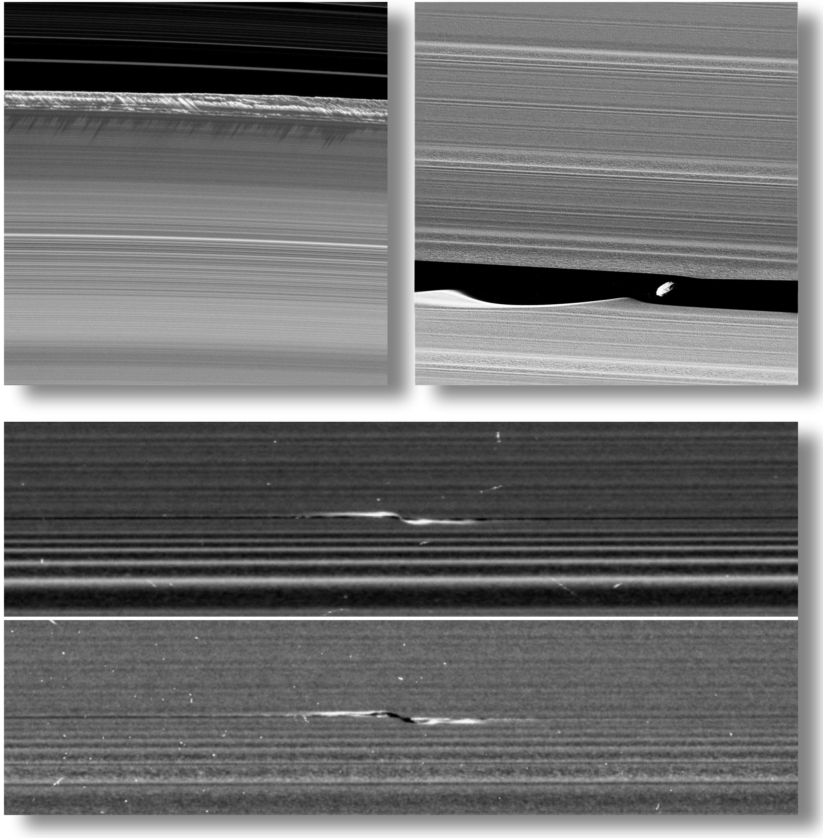
Credit: Joseph Hahn

Planet-disk interaction

- Gravitational interaction between the embryos and the surrounding material
    - Disk feels gravity of the of the planet (accelerated by the planet), which, by action-reaction law, accelerates also the planet
- Embedded planetary cores evolve dynamically because of this force

↓

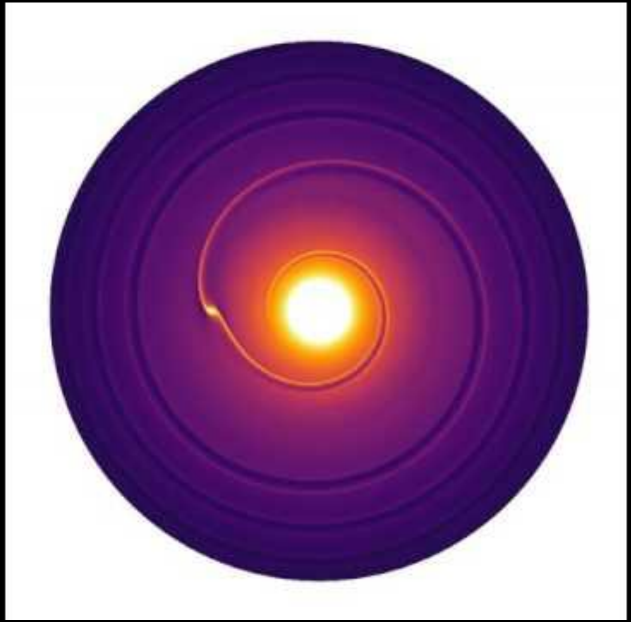
Planet migration



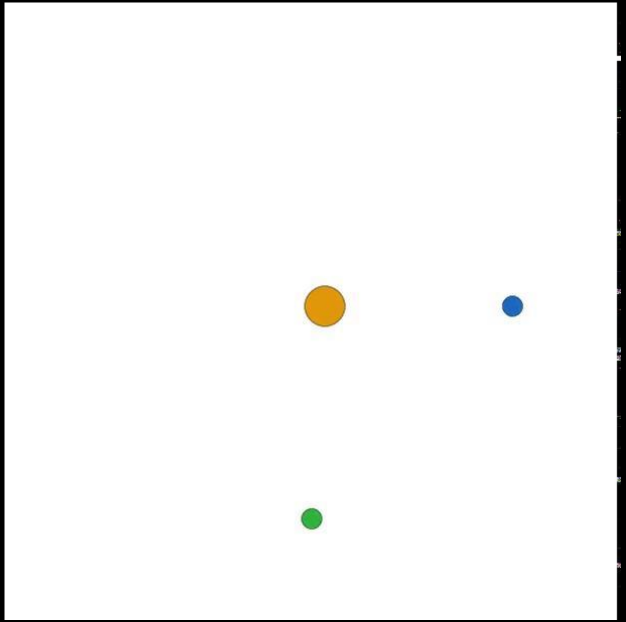
Credit: NASA/JPL/SSI

Types of interaction

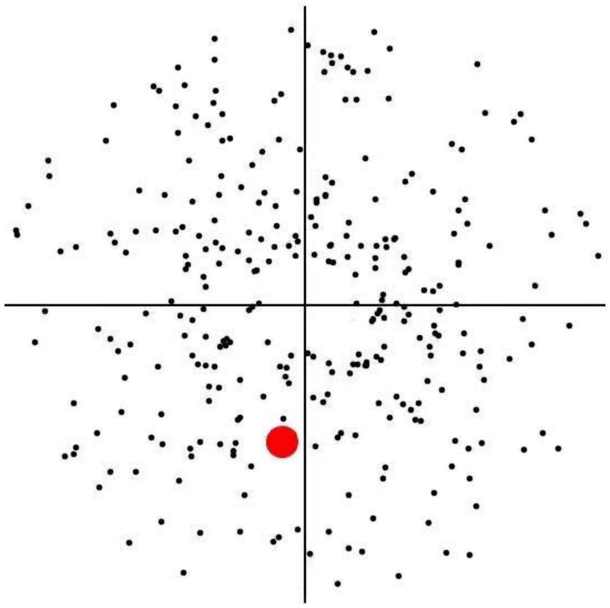
Large-scale perturbations



Localized perturbations

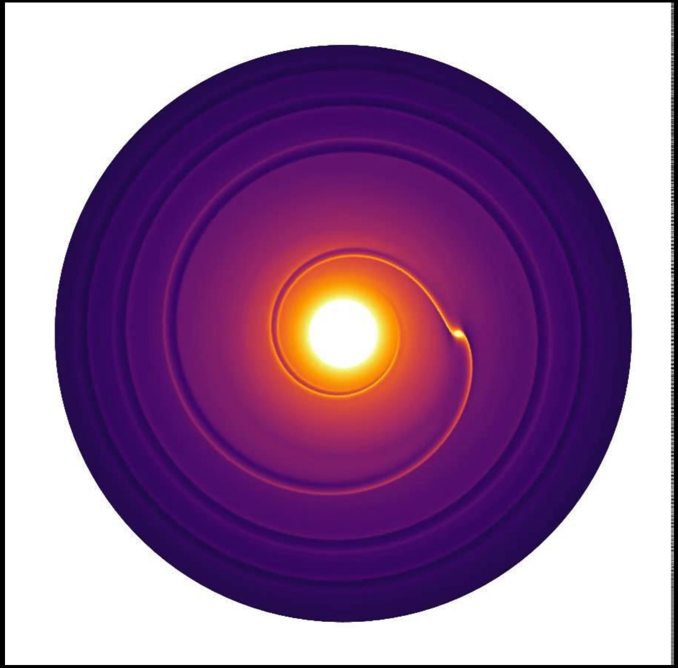


Alternative frame of reference

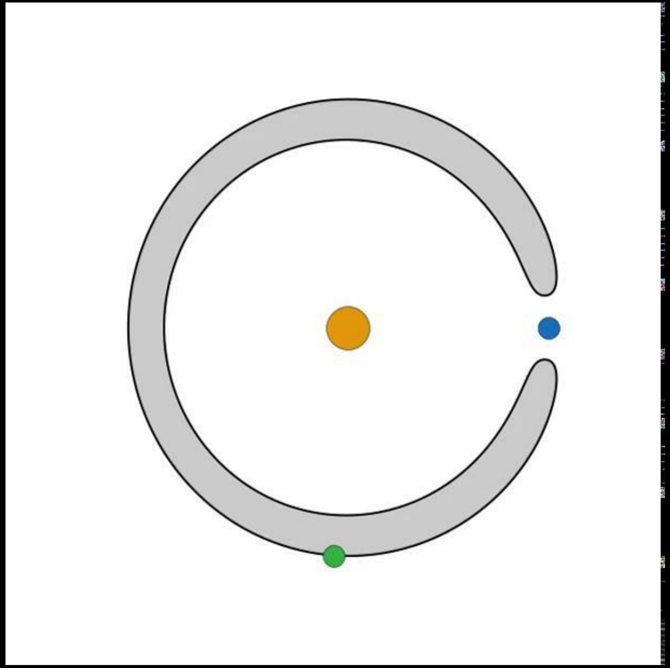


Types of interaction

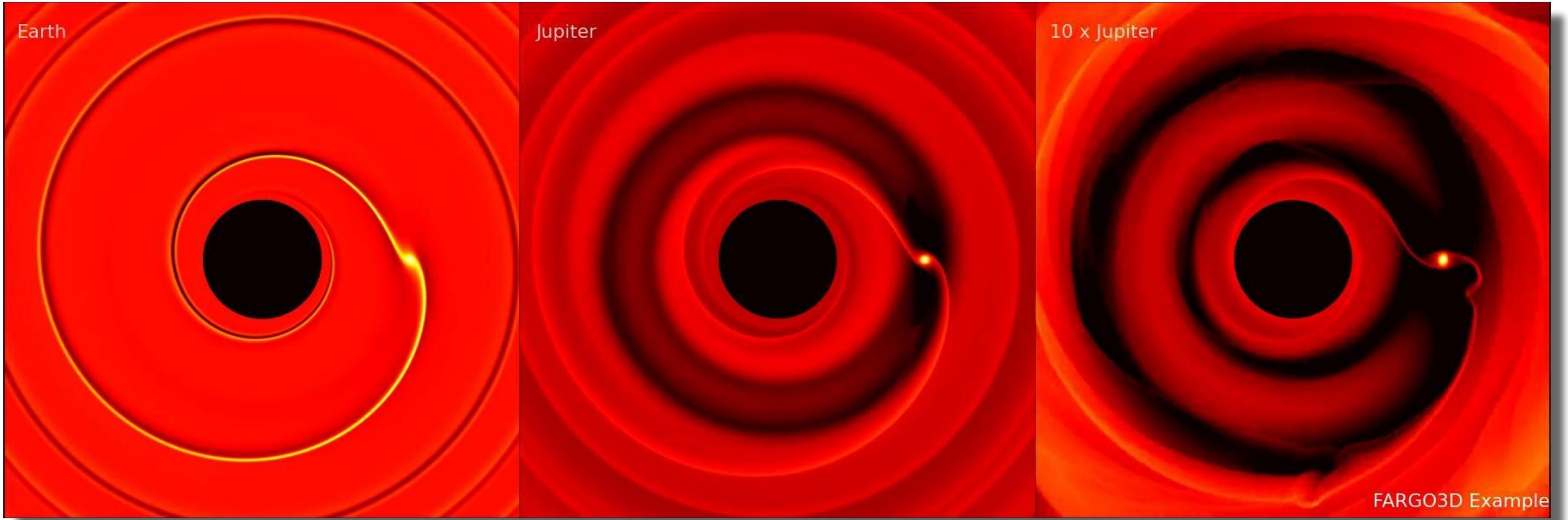
Large-scale perturbations



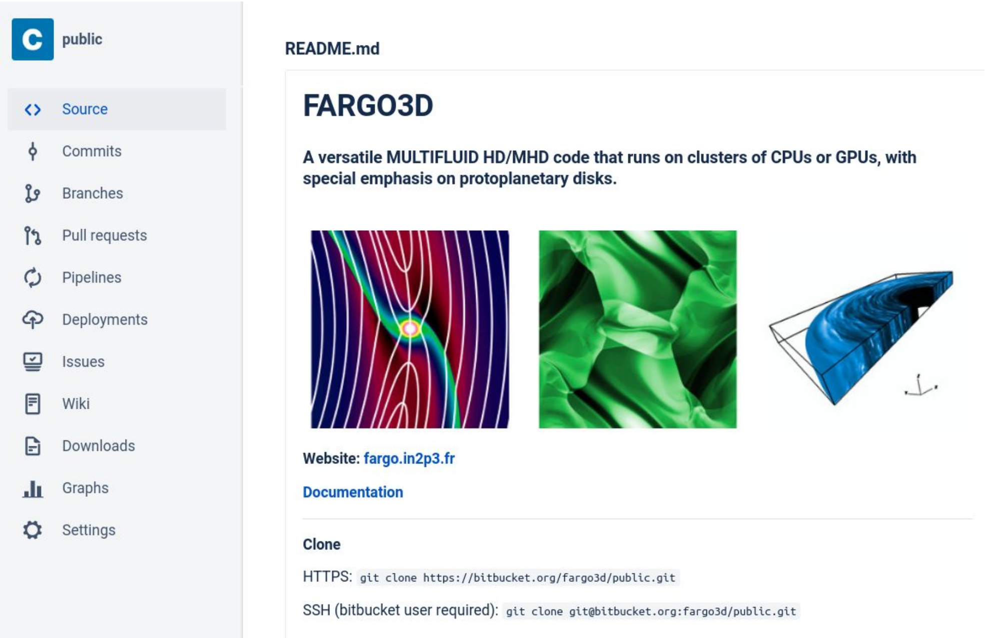
Localized perturbations



The outcome depends on the planet mass



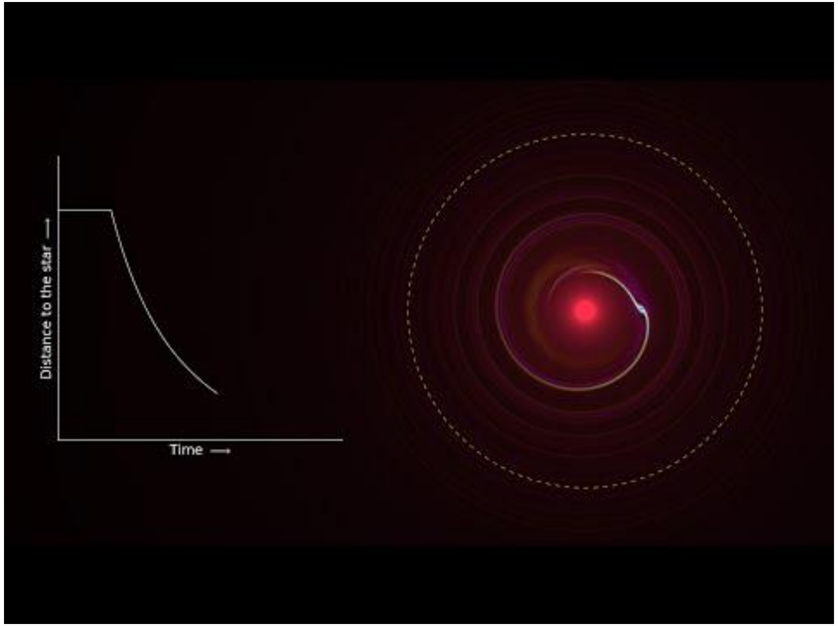
How do we simulate planet migration?



http://fargo.in2p3.fr - https://bitbucket.org/fargo3d/public

Some outcomes of this interaction

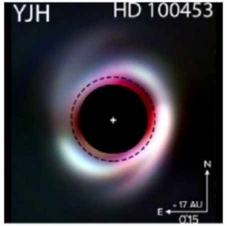
- Planets migrates mostly inwards
  - Fast inward migration problem
- Orbits are circularized
  - How do we explain eccentricity of exoplanets?
- The inclinations are also damped
  - How do we explain retrograde planets?
- Several planets can end-up in mean-motion resonances



Circular and coplanar orbits are an outcome of these models, which is in good agreement with the Solar System

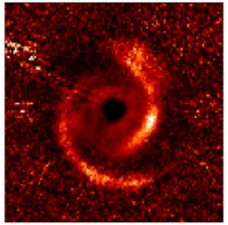
Do we have observational evidence of this interaction?

HD 100453
Wagner et al. (2015)

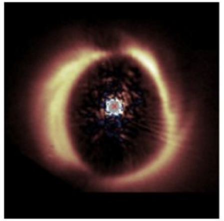


SAO 206462
Stolker et al. (2016)

MWC 758
Benisty et al. (2015)

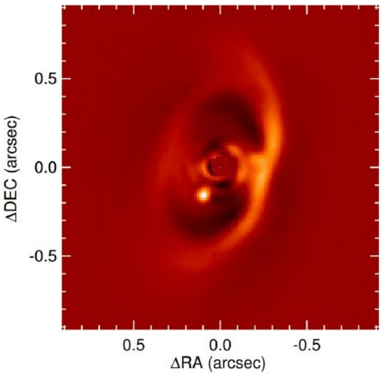


HD 14257
Avenhaus et al. (2014)

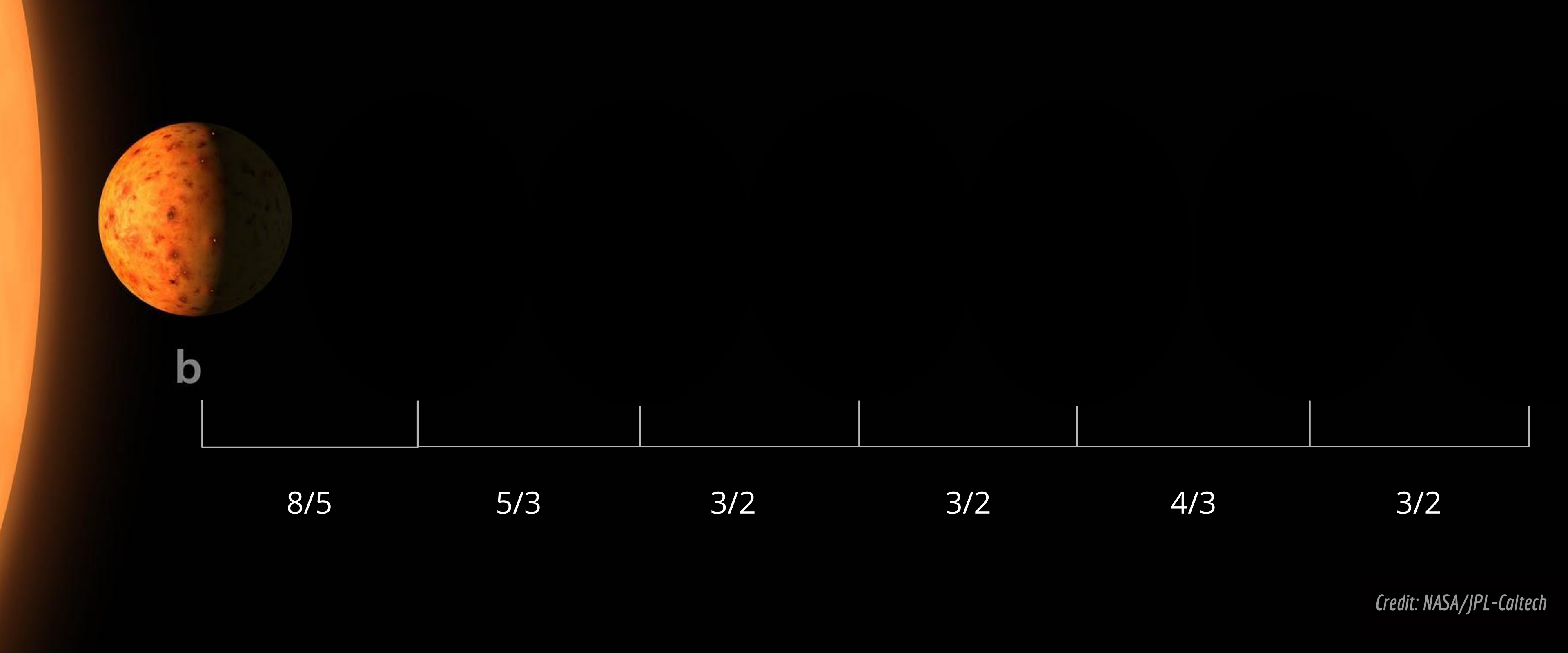


Elias 2-27
Credit: B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)

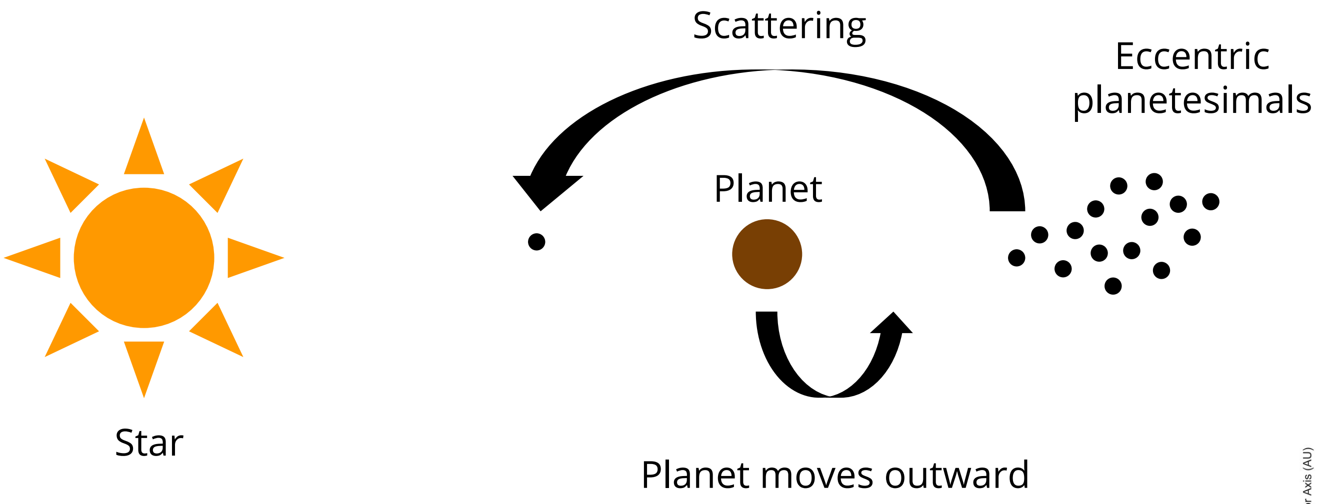
PDS70 - Müller et al. (2018)

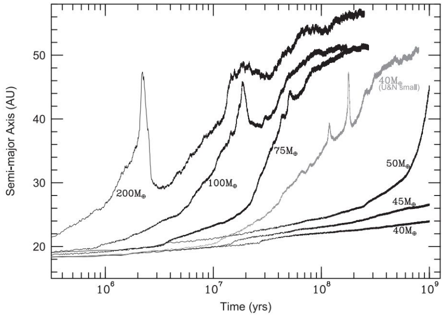


TRAPPIST-1



Planetesimal-driven migration

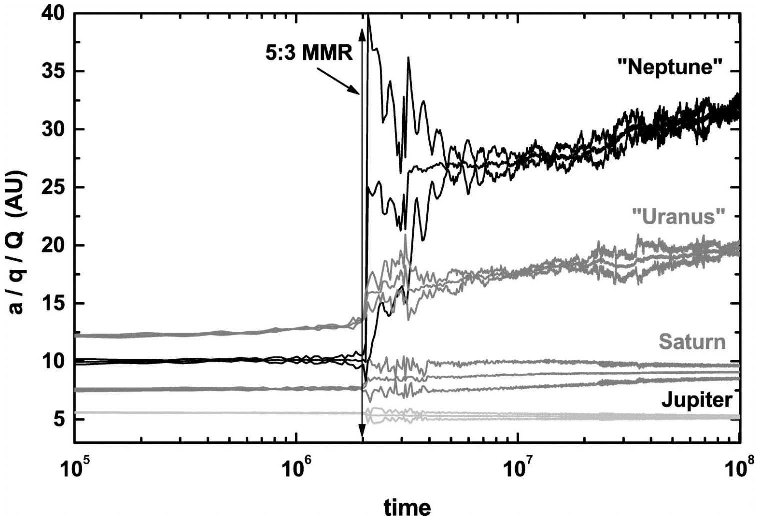




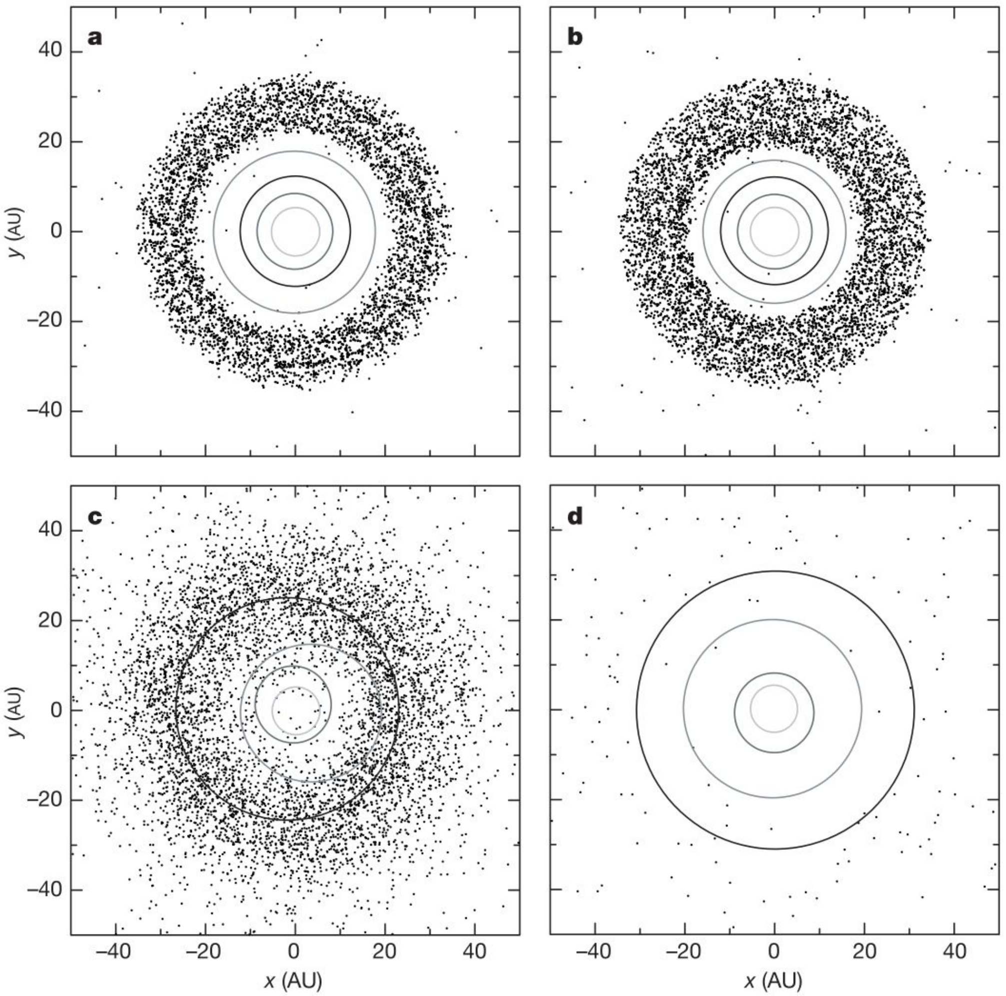
Levison et al. (2007)


What can we learn from the
Solar System?

Nice model



Morbidelli et al. (2007)

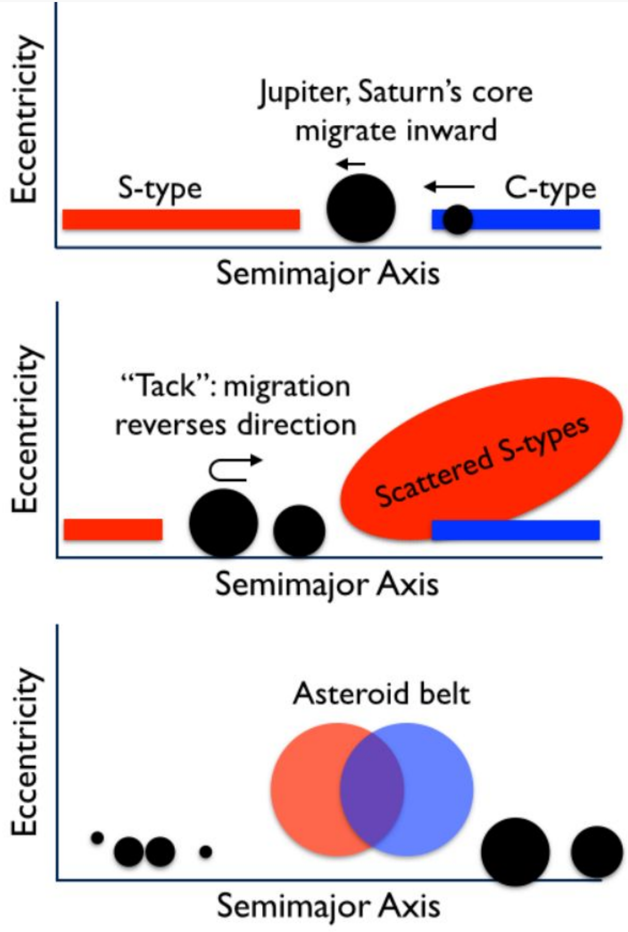


Gomes et al. (2005)

Grand tack hypothesis

Recipe to form a Solar System

- Bimodal initial distribution of S-type and C-type asteroid
- Inward migration of Jupiter and Saturn scatter away S-type asteroids
- When Jupiter and Saturn are locked in Mean motion resonance, they migrate outwards
- The inner Solar System is formed from the residuals



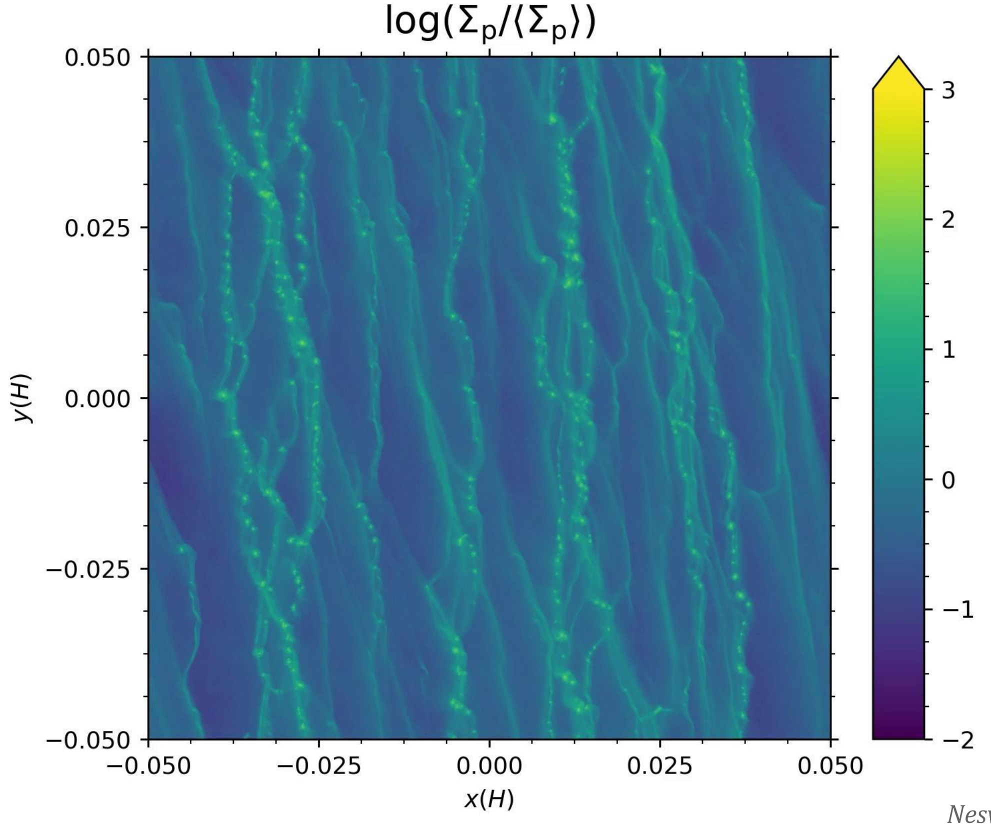
Morbidelli & Raymond (2016)

Ultima Thule

- Located at the Kuiper belt
- Farthest, and perhaps the oldest, object explored by a spacecraft
- Can it tell us how the building blocks of planets form?

Credits: NASA/Johns Hopkins Applied Physics Laboratory/Southwest Research Institute, National Optical Astronomy Observatory

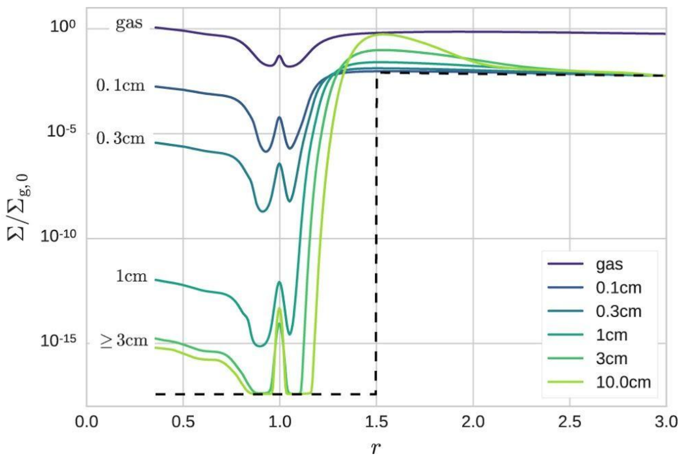
Streaming instability can explain this?



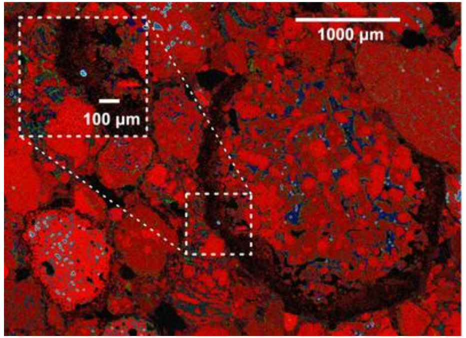
Nesvorny et al. (2019)

Constraining models

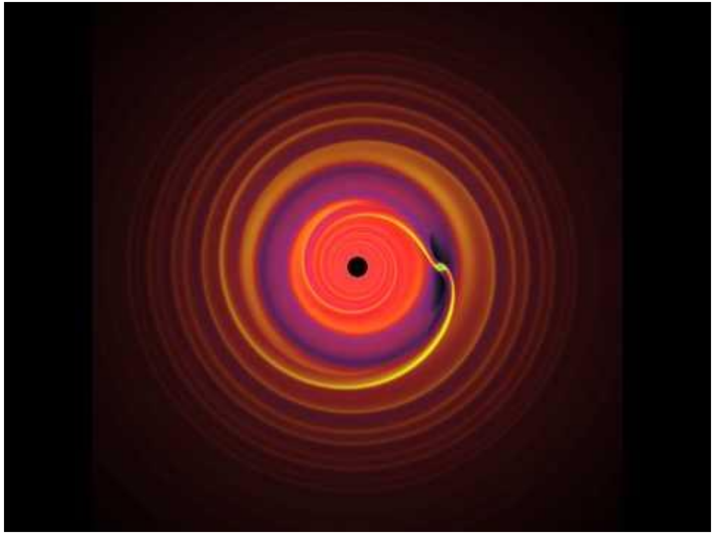
Jupiter blocks drifting particles
from the outer Solar System



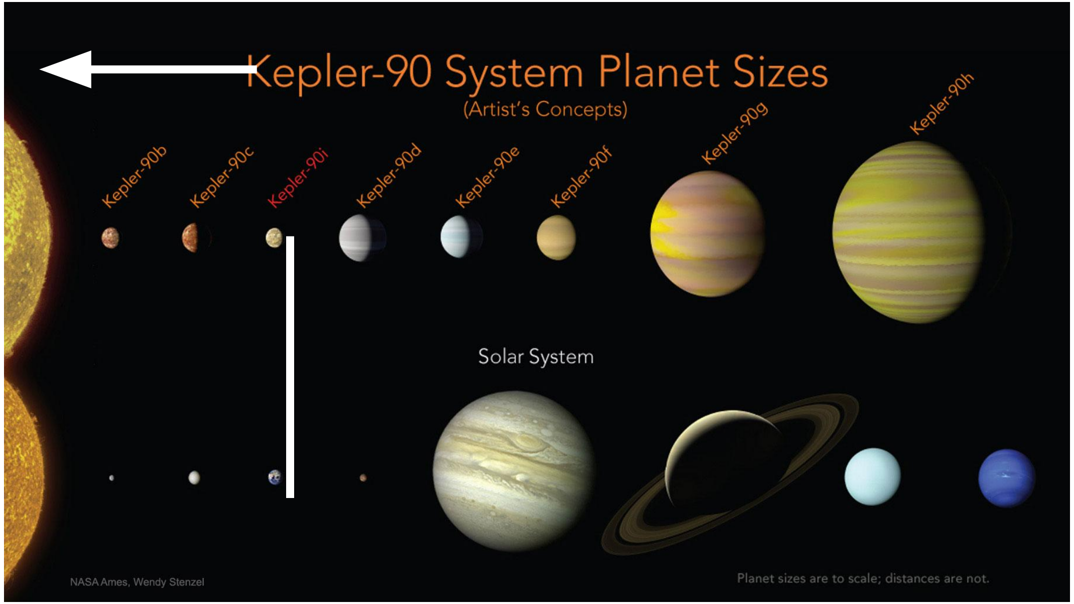
Weber et al. (2018)

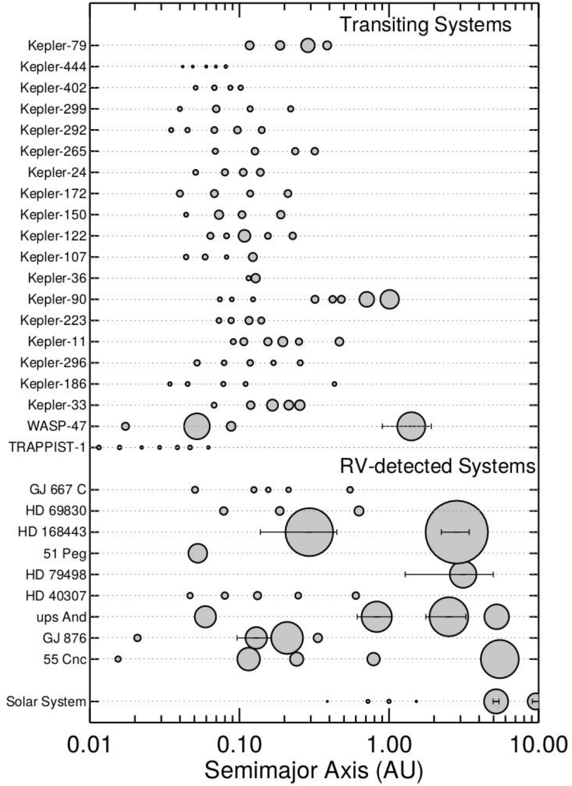


Haugbølle et al. (2019)



All planetary systems are different





Raymond et al. (2018)

Summary

Summary

- Stars are formed in molecular clouds
  - Disks are formed together with the star
    - Disks are dusty disks

- Planetary bodies form from dust
  - Dust needs to growth before forming the planets
    - Barriers

- If we overcome the barriers, a planetary core is formed
  - Planets interact with the disk (and other planets) gravitationally
    - Planets move while they form

- When the disk dissipates, the system relaxes dynamically
  - Instabilities and ejections may occur

- If the planets are at the right distance from the star → liquid water

... "Given our lack of understanding of these issues, even most successful formation models remain on shaky grounds."

from "Challenges in Planet Formation",
Morbidelli & Raymond, 2016.