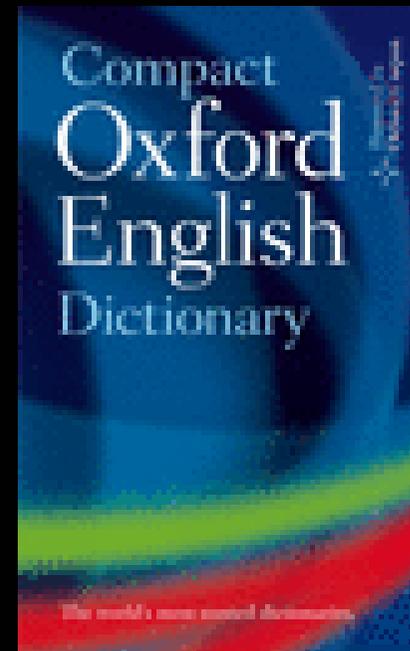


**Über diese  
Vorlesung**

# ~~Sprache~~ Language



**Subject**

# Planetary systems

We will try to understand  
formation, evolution, and properties  
of planetary systems  
around stars

# Subject

- Is formation of planets a typical by-product of star formation?
- How does it depend on the initial conditions?
- What are the main phases of planet formation?
- Which physics governs each phase?
- What are the expected properties of planetary systems?
- Can we explain the properties of the solar system?
- Can we explain diversity of planetary systems?
- Are there planetary systems similar to ours?
- If yes, is the solar system typical or exceptional?
- Are there earth-like planets around other stars?
- Are there habitable planets elsewhere?

...

# Subject

We will address these questions **theoretically**

But we will lean on **observations**

Also, **laboratory** studies can help

# Prerequisites

- “Einführung in die Astronomie” (necessary)
- “Himmelsmechanik” (desirable)

# Related courses

- **“Stellarphysik”** (*every WS, Neuhäuser*)  
Formation and evolution of stars
- **“Exoplaneten”** (*every SS, Neuhäuser*)  
Observations of extrasolar planets
- **“Sonnensystem”** (*last time 2007, Freistetter*)  
Our own planetary system

# Literature

## ➤ Books:

- None, except for Safronov (1969)

## ➤ Review papers:

- Chapters in “Protostars and Planets” II, III, IV, V
- Lissauer (1993) ARAA 31, 129-174
- Papaloizou et al. (1999), ASP Conf. Ser. 160, 186-206

## ➤ Presentations online:

- Lecture courses (can recommend upon request)
- Recent conferences and schools ( can recommend)

## ➤ Contributed papers:

- Available on specific topics (can recommend)

# Web site

[www.astro.uni-jena.de/~krivov/lecturing/formation/formation.html](http://www.astro.uni-jena.de/~krivov/lecturing/formation/formation.html)

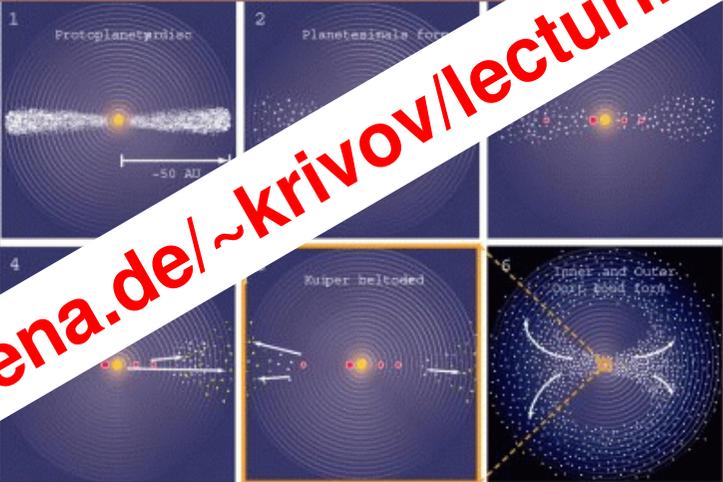
Planetenentstehung - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://www.astro.uni-jena.de/Users/krivov/lecturing/formation/formation.html

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## Planetenentstehung / Planet formation



1 Protoplanetary disk  
2 Planetesimal formation  
4 Kuiper belt/outer disk  
6 Inner and Outer planets

*Image credit: Brett Gladman, Science (2005)*

**Vorlesung / Lecture**  
Alexander Krivov  
Do, 14-16 Uhr

**Übung / Exercises**  
Torsten Löhne  
Do, 16-18 Uhr

Hörsaal/ Lecture room,  
AIU Jena ([Plan](#))

- ..... [Inhalt / Plan](#)
- ..... [Übungen / Exercises](#)
- ..... [Literatur / Literature](#)

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Done

# Abschluß

## ➤ Nichtmodularisiertes Studium:

- Teilnahme an der V → Teilnahmeschein
- Teilnahme an den V und Ü → Leistungsschein

## ➤ Modularisiertes Studium:

- Modulanmeldung
- Zulassung zur Modulprüfung: Teilnahme and den V und Ü
- Modulprüfung: Ü-Ergebnisse
- Wiederholungsprüfung: mündlich
- Modulzeugnis

# **Chapter 1.**

## **Historical overview**

***§1. From antiquity to  
Copernicus***

# Antique theory #1



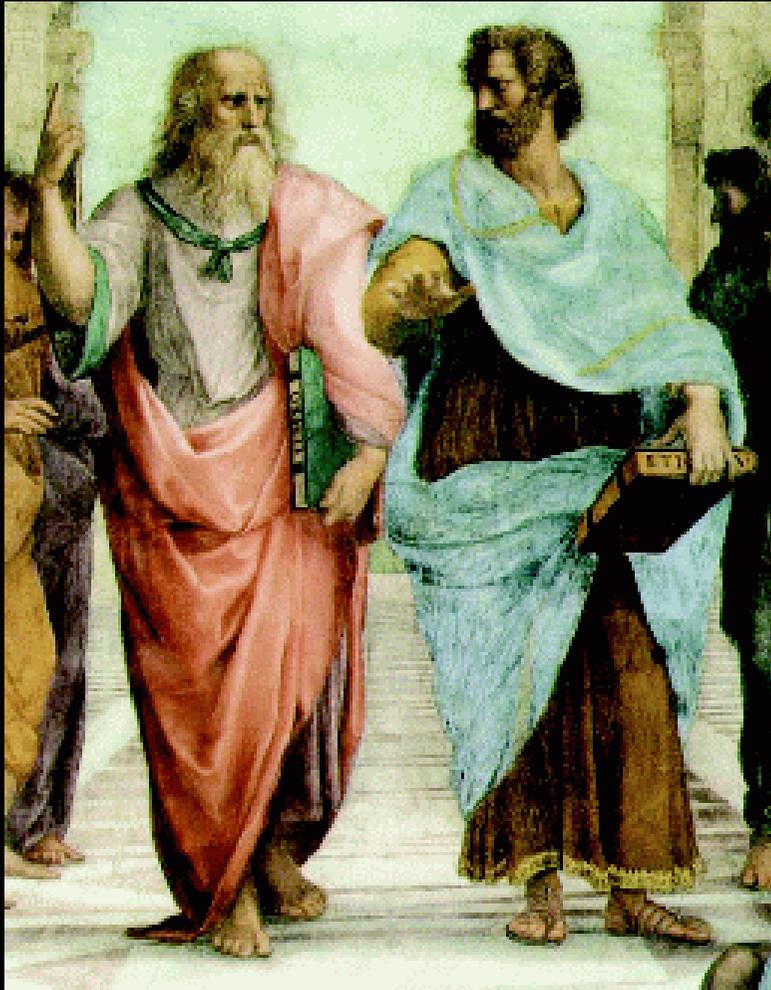
Epicurus (341–270 BC)

Worlds are plural, diverse, changing...  
Leucippus, Democritus,  
Epicurus, Lukretius,...

*In some worlds there is no Sun and Moon,  
in others they are larger than in our world,  
and in others more numerous. In some parts  
there are more worlds, in others fewer...  
in some parts they are rising, in others falling.  
There are some worlds devoid of living  
creatures or plants or any moisture.*

*Democritus (ca. 460-370BC)  
after Hyppolytus (3rd century AD)*

## Antique theory #2



The world is unique,  
geocentric, unchanged

*There cannot be  
more worlds than one.*

*Aristotle (384-322 BC)*

Raphael's „School of Athens“ (fragment)

**Plato**

points to heaven:

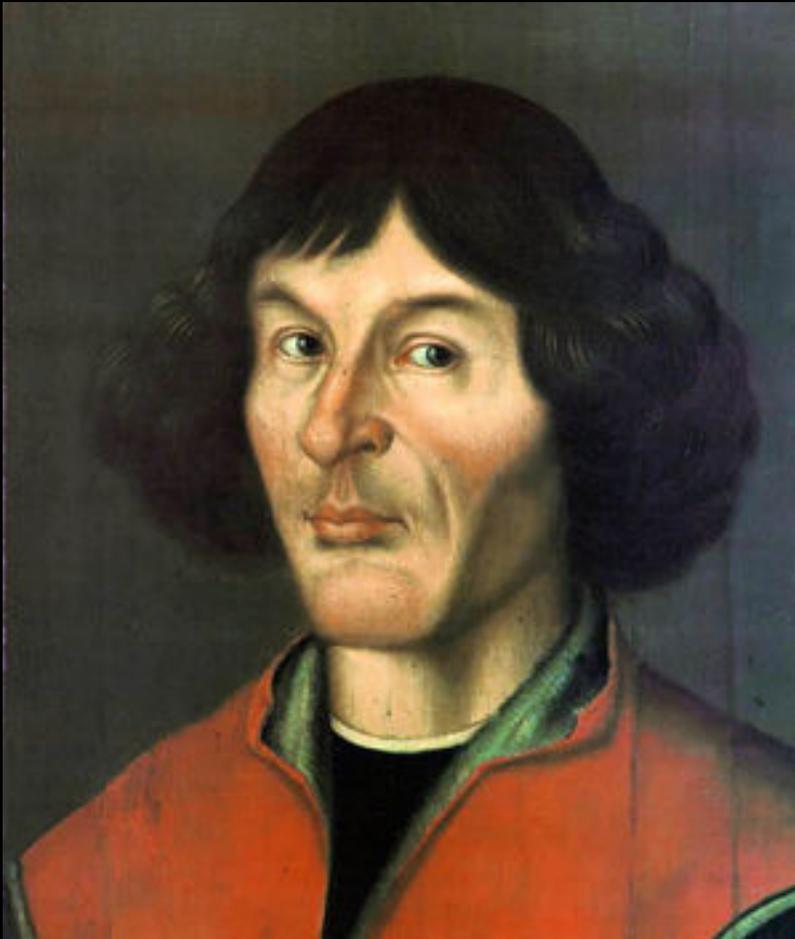
„Planets move around  
Earth on crystal spheres“

**Aristotle**, his student,

points to earth:

„Earth is the center of  
A perfect Universe“

# Medieval theories



Aristotle's work rediscovered in Europe in 13th century His viewpoint prevailed for almost one century. E.g, **Roger Bacon (1214-1297)** at Oxford

But this begins to contradict the Christian doctrine of the time; idea of the plurality of worlds revived, e.g. **William of Ockham (1280-1347)**

Then a long period of hot debates...

**Nicolaus Copernicus (1473-1543)**. His heliocentric system was received as supporting the plurality of planets and their systems in the Universe

**Astronomers got the system to explain,  
namely the Sun and several planets revolving it**

***§2. From Descartes to  
Laplace***

# Descartes



Rene Descartes (1596-1650)

Space is filled with liquid

It builds vortices („disks“)  
around stars

Planets have form in eddies  
of these vortices

# Buffon



A giant comet hit the Sun  
in the past

The impact ejected a cloud  
of material, from which then  
planets formed

George-Louis Leclerc,  
Comte de Buffon (1707-1788)

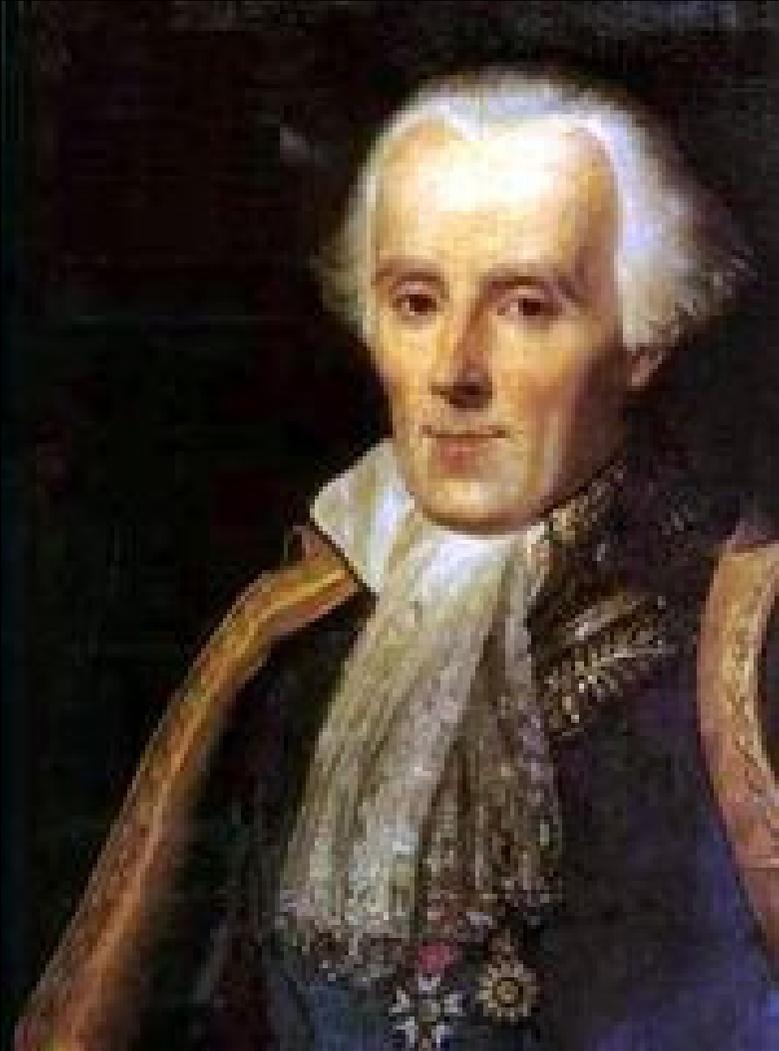
# Kant



Immanuel Kant (1724-1804)

“Give me  
matter and I  
will construct  
world out of  
it”

# Laplace



Formation of planets from a „hydrodynamical continuum“

Solar atmosphere extends in form of a disk over the whole forming system

Rings of material separate from the solar surface

The rings cool down and form planets

Pierre-Simon Laplace (1749-1827)

(1796)

**Astronomers got the first  
qualitatively correct theory:  
the solar nebula**

***§3. Theories of the  
20th century***

# Maxwell



Disproved purely nebular (gas-only-nebula) hypothesis mathematically

Constructed a strict mathematical theory to describe a disk/ring of solid particles orbiting a primary: ring as differentially-rotating, viscous fluid, stability criteria, formation of clumps („drops“)...

By doing so, he not only explained some salient features of **Saturn's rings**, but also **laid down groundwork for future solar system formation theories!**

James Clerk Maxwell (1831-1879)

# Catastrophic and capture theories



Otto Yul'evich Schmidt  
(1891-1956)

Back to **Buffon**?...

Excavation of solar/stellar matter during an encounter with another star

(**Chamberlin, Moulton, 1905;**  
**Jeans, Jeffreys, 1915-1917**)

Capture of interstellar matter with the aid of the center of the Milky Way (**Schmidt, 1944**), magnetic field (**Alfven, 1954-1958**), ...

Difficulties:

- low probability to get „right“ amount of material
- how to explain the same sense of Sun's rotation and revolution of planets?

Prevailing theories in the first half of the 20th cy. Based of wrong ideas about the origin of the protocloud, made progress in understanding of how it develops (esp. Schmidt, Alfven, also Chamberlin: **planet+infinitesimal...**)

# Nebular theory revisited: coming closer!

„Almost“ back to **Kant-Laplace!**

Simultaneous formation of the Sun and planets from a disk of gas and solids

(v. **Weizsäcker, 1943**)

Dynamical, thermal, chemical evolution of a disk of colliding, merging and fragmenting solid bodies

(**Safronov, 1950s-1960s**)

Successfully makes terrestrial planets

Timescale problems with gas planets (too slow)

Further developments of **Safronov's** theory in 1960s, 1970s, 1980s:

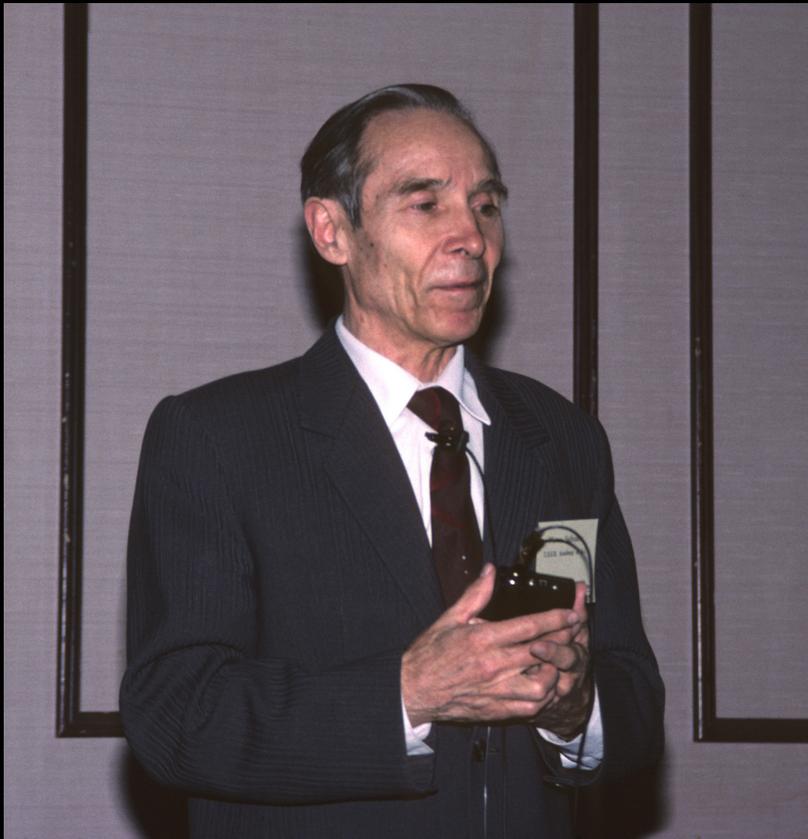
**Hoyle** (magnetic transport of ang. momentum),

**Cameron** (instabilities),

**Wetherill, Greenberg, Weidenschilling**

(numerical simulations),

,... and many, many others



DPS Charlottesville, Oct. 1990  
Victor Safronov (Kuiper Prize recipient)

**Victor Sergeevich Safronov**  
(1917-1999)

# A more or less present-day theory

An interstellar cloud collapses and flattens to form a protosun and a gas disk around it

Solids in the disk collide and grow from mm (dust) to km (planetesimals) and sediment to the plane. Gas-driven dynamics

Planetesimals grow to Mm (planetary embryos). Gravity-dominated dynamics

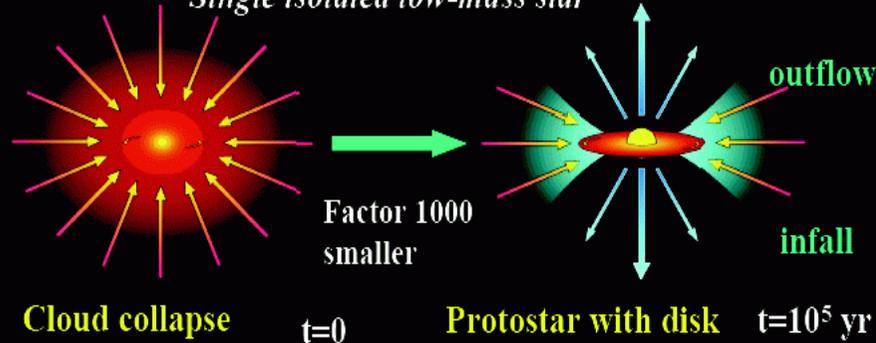
Embryos accrete gas and form gas giants

Remaining gas and planetesimals swept out from the disk. Oort cloud formation

Formation of terrestrial planets

## Scenario for star and planet formation

*Single isolated low-mass star*

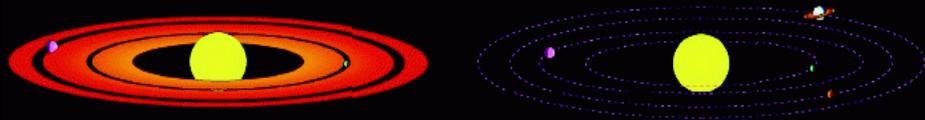


Cloud collapse

$t=0$

Protostar with disk

$t=10^5$  yr



Formation of planets

?

$t=10^6-10^7$  yr

Solar system

$t>10^8$  yr

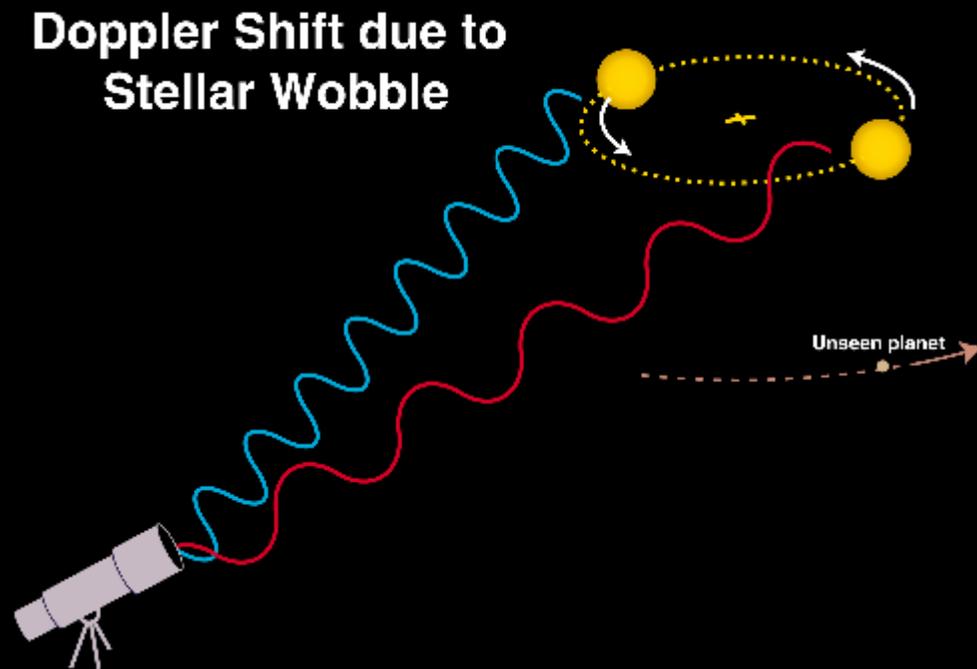
**Astronomers got theories  
that fully involved known physical laws**

**These theories successfully explained  
salient features of the solar system**

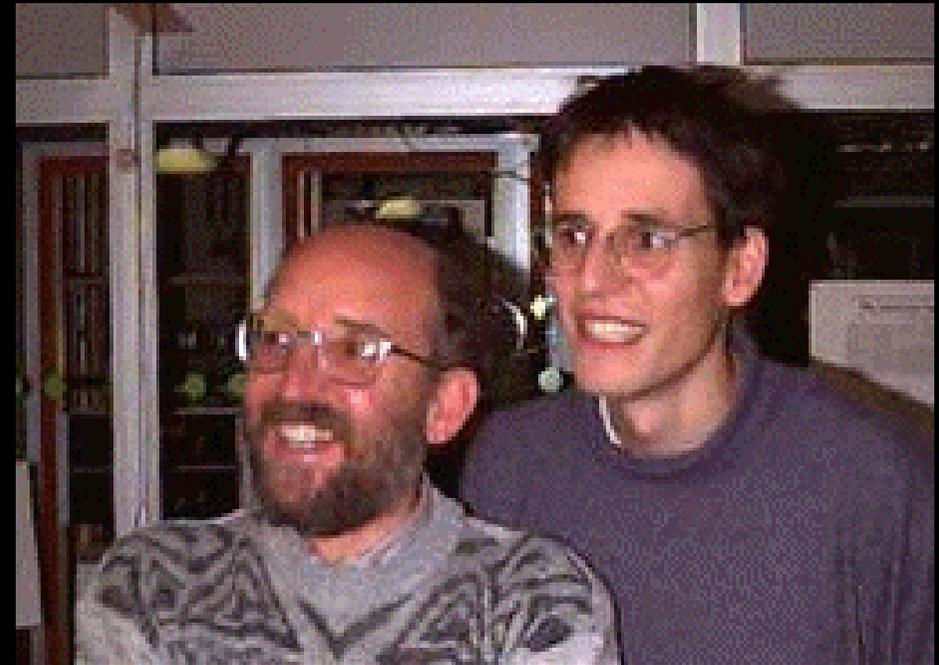
***§4. Observational  
revolution of 1990s***

# I. Discovery of extrasolar planets (1995-)

## Doppler (radial velocity) measurements



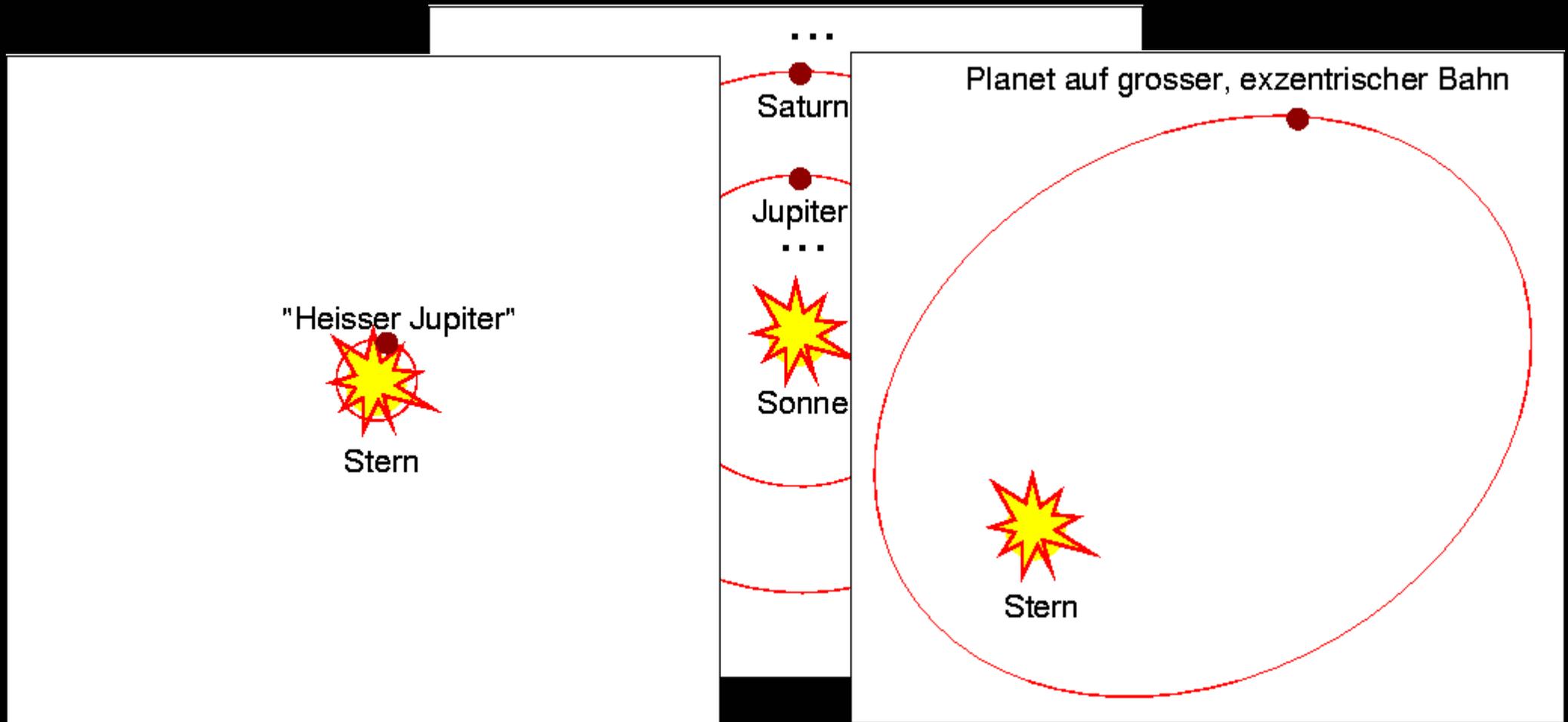
After: G. Marcy



Michel Mayor and Didier Queloz

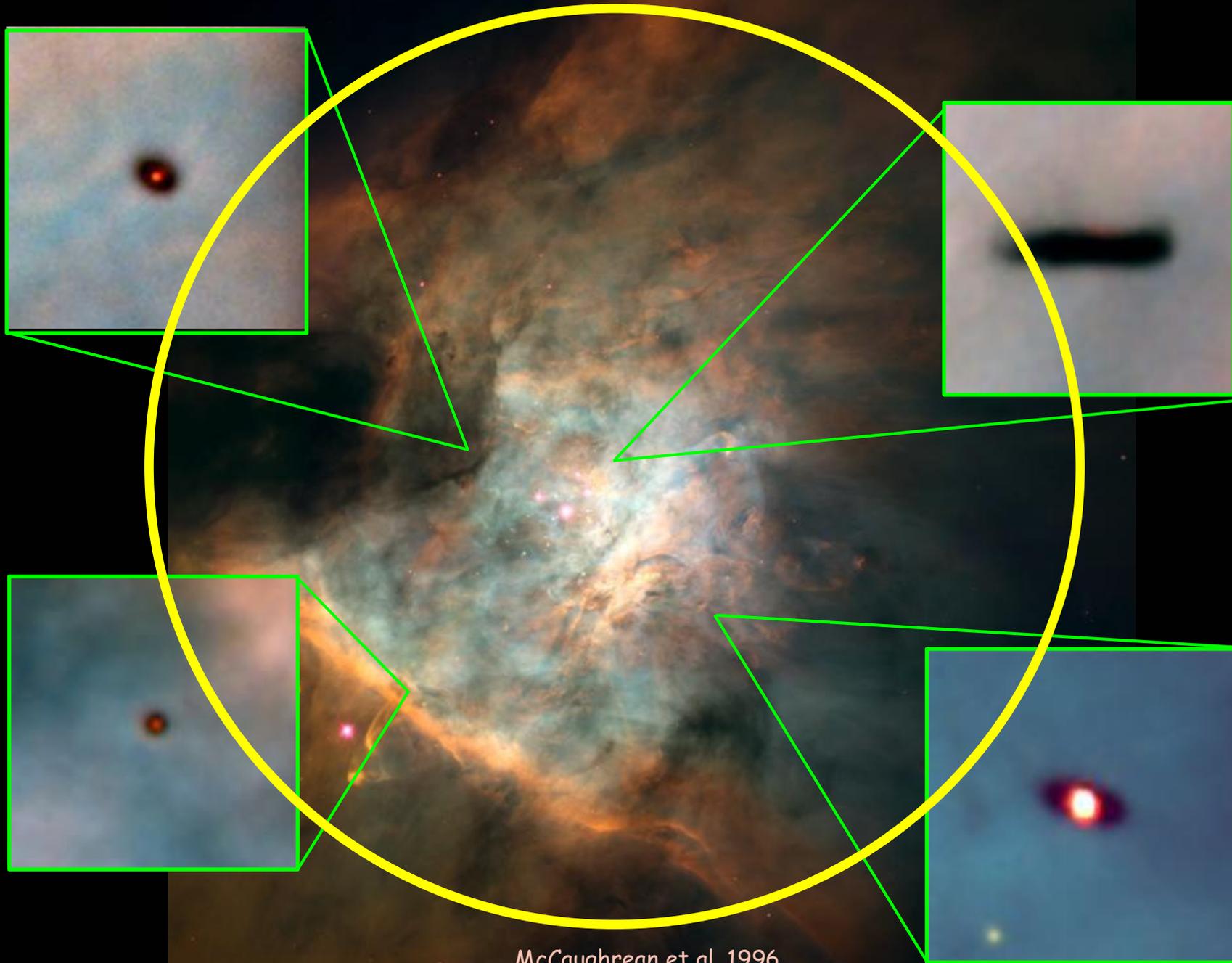
# I. Discovery of extrasolar planets (1995-)

## Bizarre results



**Solar system vs extrasolar planetary systems  
(287 planets discovered to date)**

## II. Direct images of proplyds (1992-)



McCaughrean et al. 1996

### III. Discovery of the Kuiper belt (1992-)



Kenneth Edgeworth  
(1880-1972)

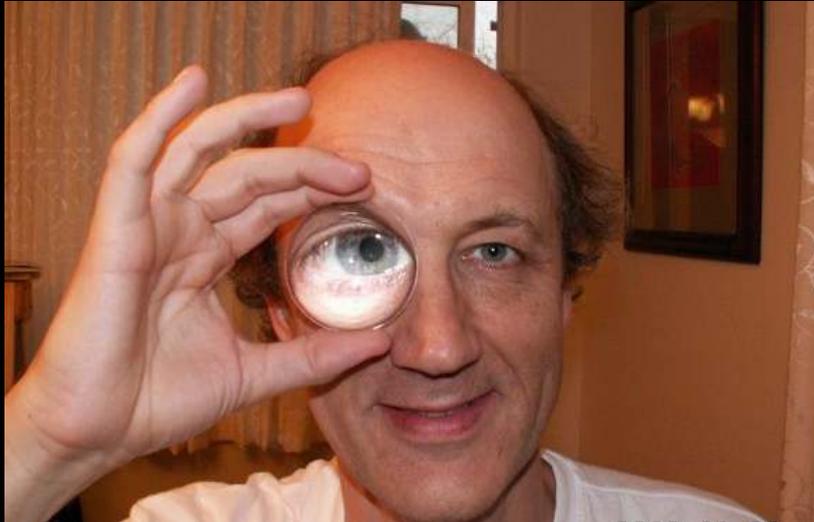


Gerard Kuiper  
(1905-1973)

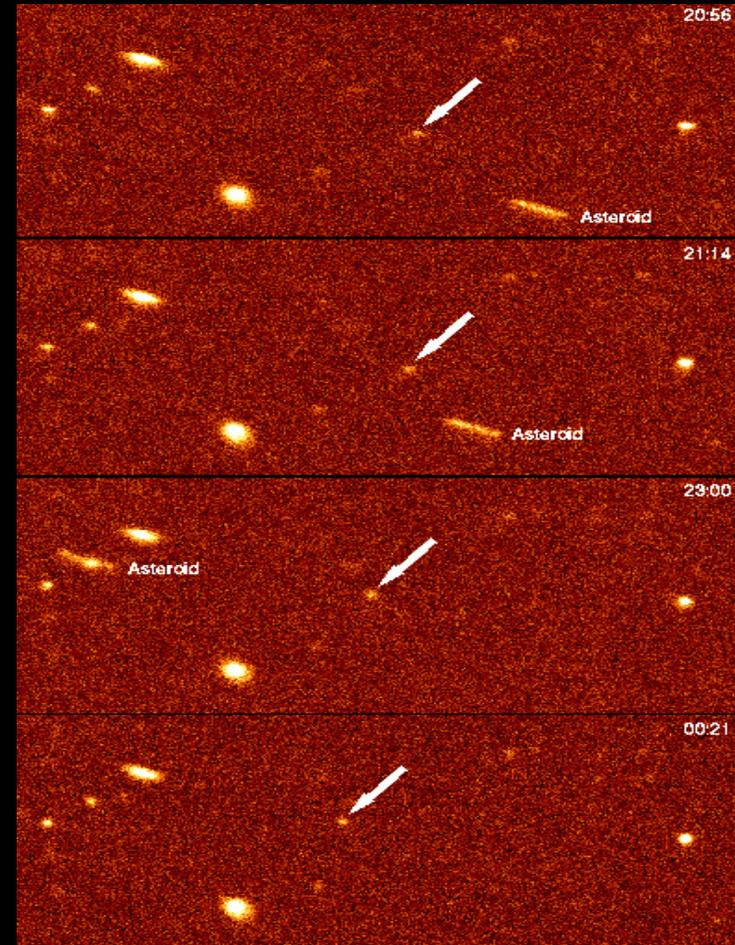
The prediction made in 1949-1951 had to wait a bit... till 1992

# III. Discovery of the Kuiper belt (1992-)

Dave Jewitt



Jane Luu



Discovery images (1992)

# III. Discovery of the Kuiper belt (1992-)

- The solar system is much larger than thought before
- Some KBOs (e.g. 2003 UB313, Eris) are larger than Pluto
- KBOs are „fossils“ from early stages

## *THE OUTER SOLAR SYSTEM*

This animation shows the motion of the outer part of the solar system over a 100-year time period. The sun is at the center and the orbits of the planets Jupiter, Saturn, Uranus and Neptune are shown in light blue (the locations of each planet are shown as large crossed circles).

Comets: blue squares (filled for numbered periodic comets, outline for other comets)

High-e objects: cyan triangles

Centaurs: orange triangles

Plutinos: white circles (Pluto itself is the large white crossed circle)

"Classical" TNOs: red circles

Scattered Disk Objects: magenta circles

The individual frames were generated on an OpenVMS system, using the PGLOT graphics library. The animation was put together on a RISC OS 4.03 system using !InterGif.

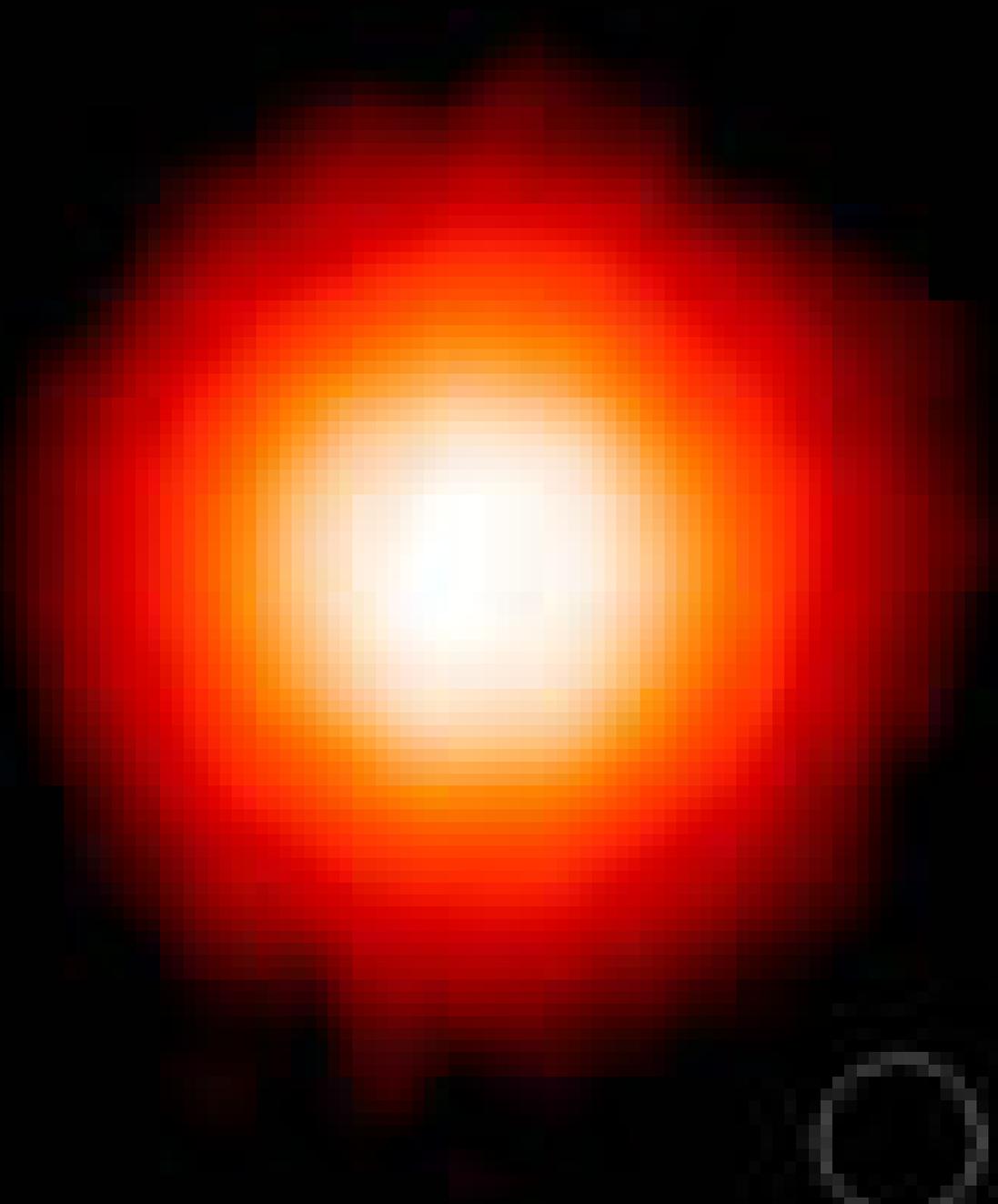
# IV. Discovery of debris disks (1984-)

*~10 Myr age*

Infrared excesses  
(the Vega  
phenomenon)

Direct images  
of debris disks

*~1 Gyr age*



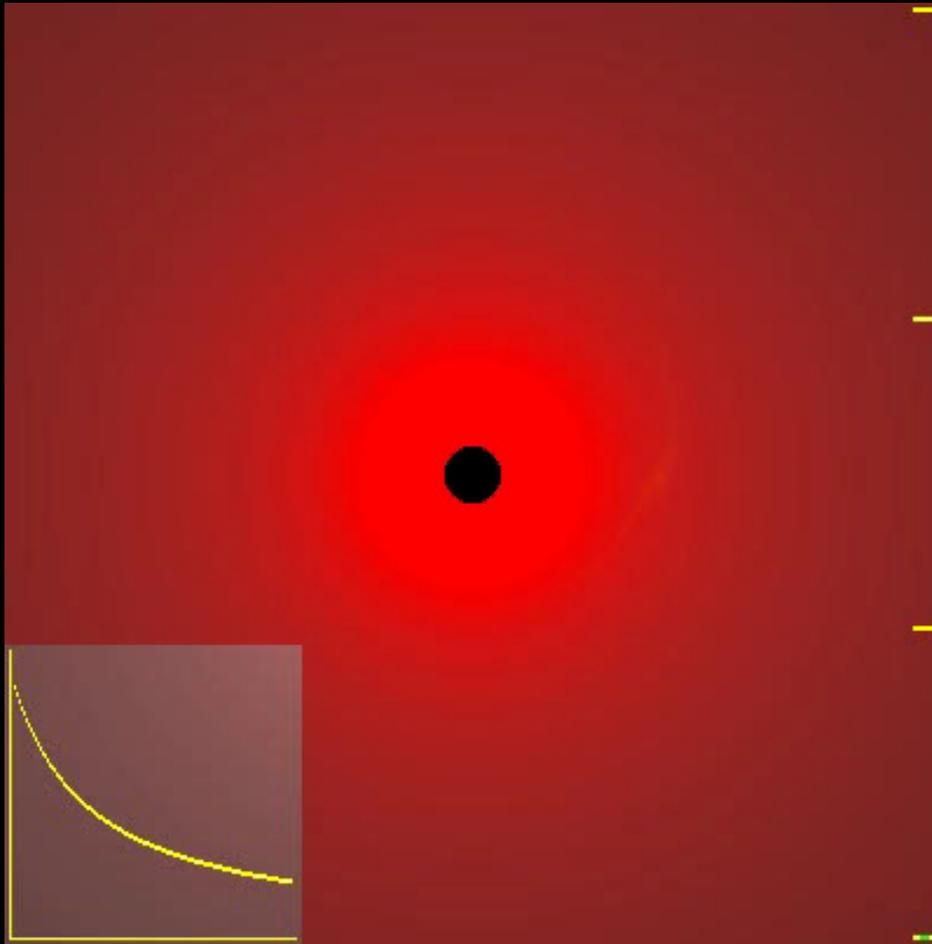
**From observations,  
astronomers got strong support  
to their theory of the solar system formation,  
but at the same time got  
new challenges to confront!**

***§5. Present state  
of the theory***

**How did the theory respond to  
these discoveries?**

**The answer will be provided  
by 12 lectures to come,  
now just a couple of examples!**

# Attempts to extend the theory: migration



Predicted already in 1980s  
(Goldreich, Tremaine, Ward, Lin,...),  
and not received enough attention,  
but is now reinforced!

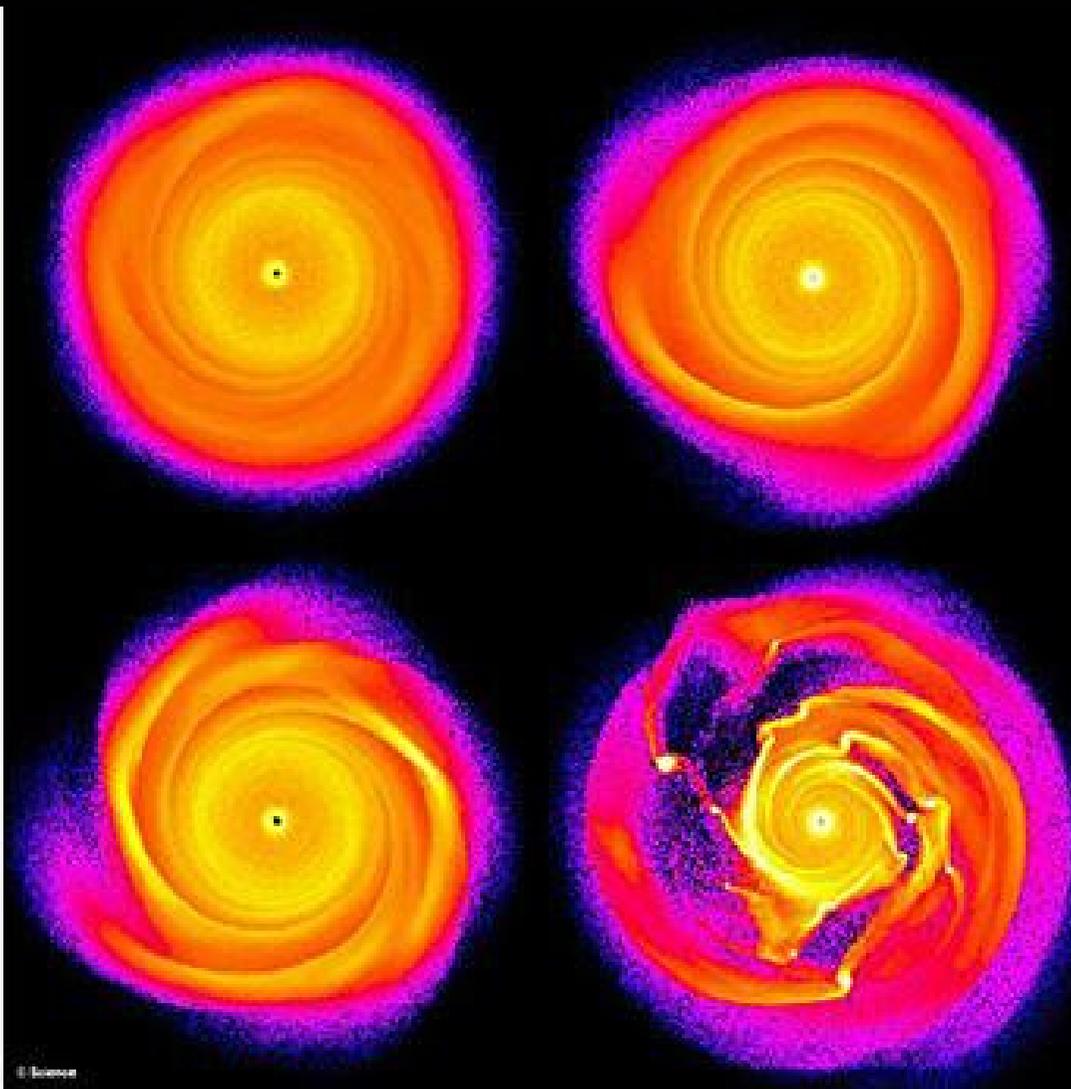
Protoplanet interacts with the gaseous  
portion of the disk, which results in  
its (usually, inward) migration

Successfully explains „hot jupiters“,  
but fails to explain „normal“ planets  
in the solar system!

Animation:  
P. Armitage (U. Colorado)

# Alternative scenarios

Gravitational instability of the disk and direct formation of giant planets



After: Alan Boss



