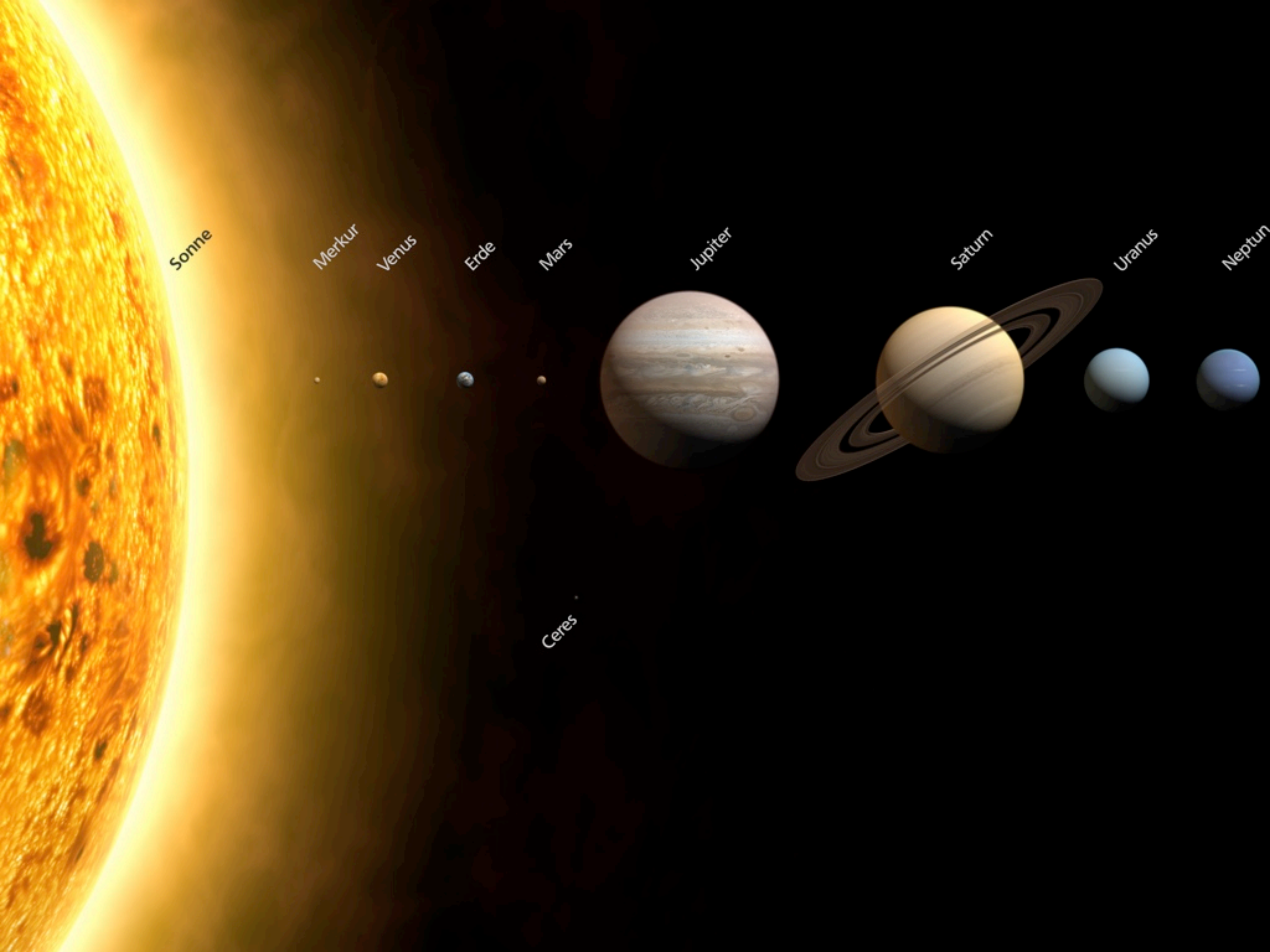
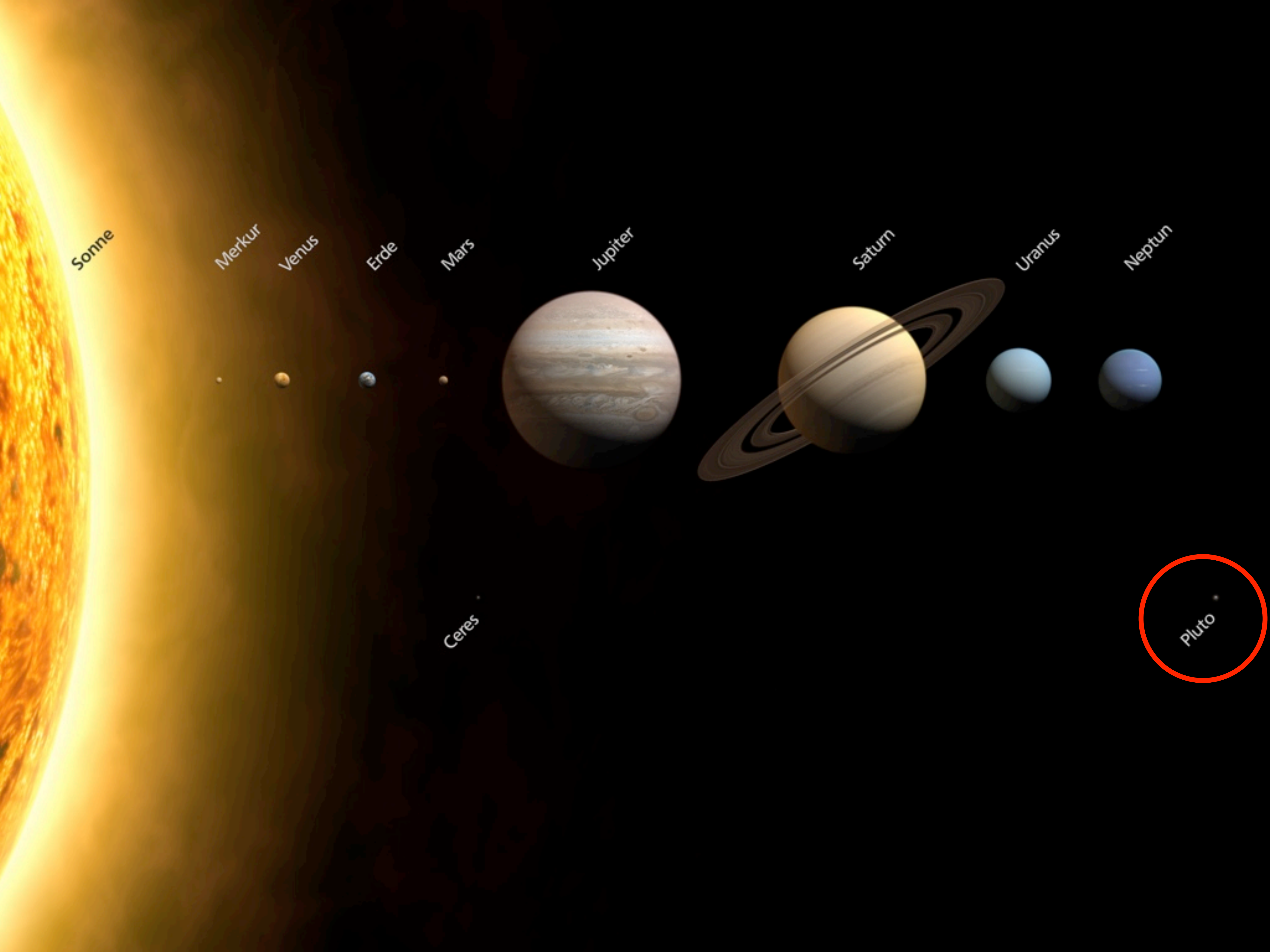
hamburger sternwarte

Ferne Welten: Extrasolare Planeten und die Entstehung von Sonnensystemen

Prof. Dr. Robi Banerjee
Universität Hamburg


Sonne
Merkur
Venus
Erde
Mars
Jupiter
Saturn
Uranus
Neptun
Ceres



Sonne
Merkur
Venus
Erde
Mars
Jupiter
Saturn
Uranus
Neptun
Ceres
Pluto

IAU Resolution: Pluto

RESOLUTION 6A
The IAU further resolves:

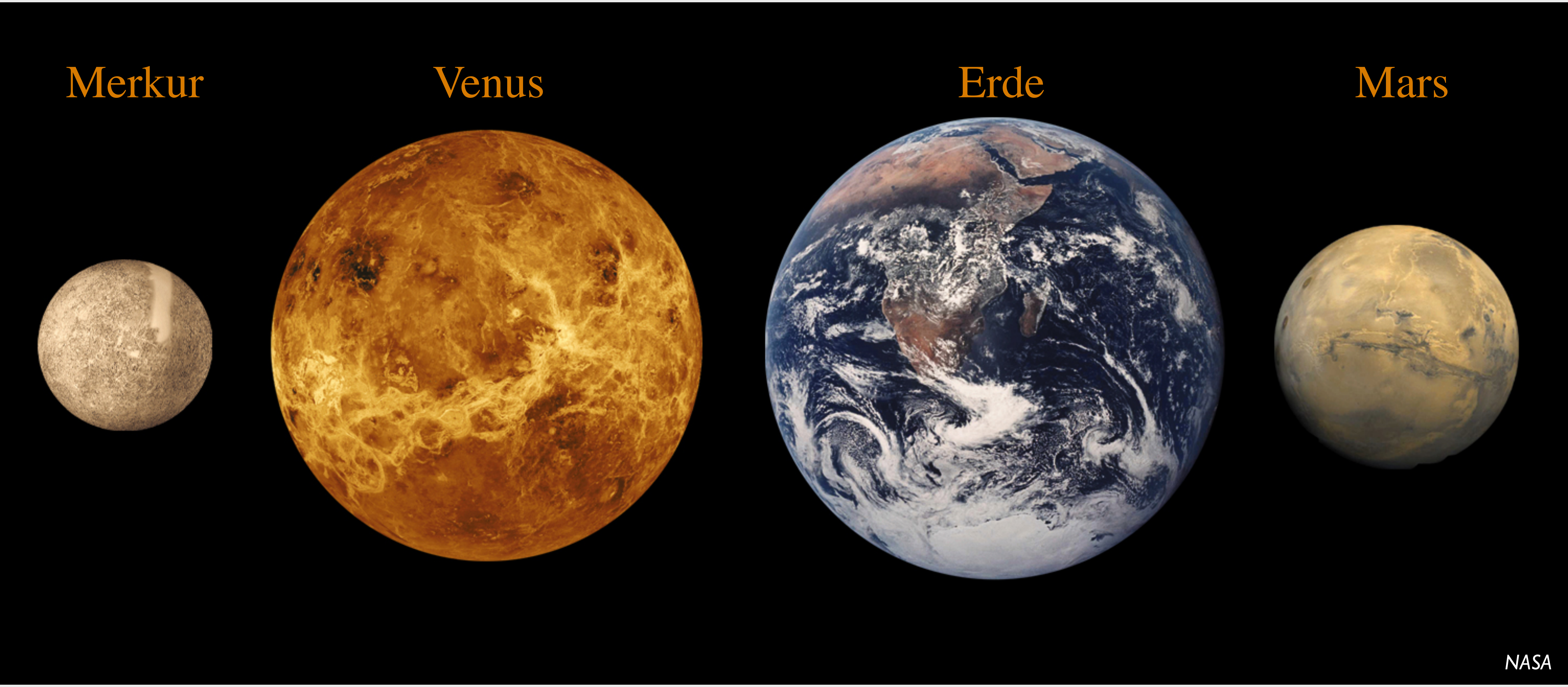
Pluto is a "dwarf planet" by the above definition and is recognized as the prototype of a new category of Trans-Neptunian Objects.

RESOLUTION 6B
The following sentence is added to Resolution 6A:

This category is to be called "plutonian objects."

IAU/Prag: 2006

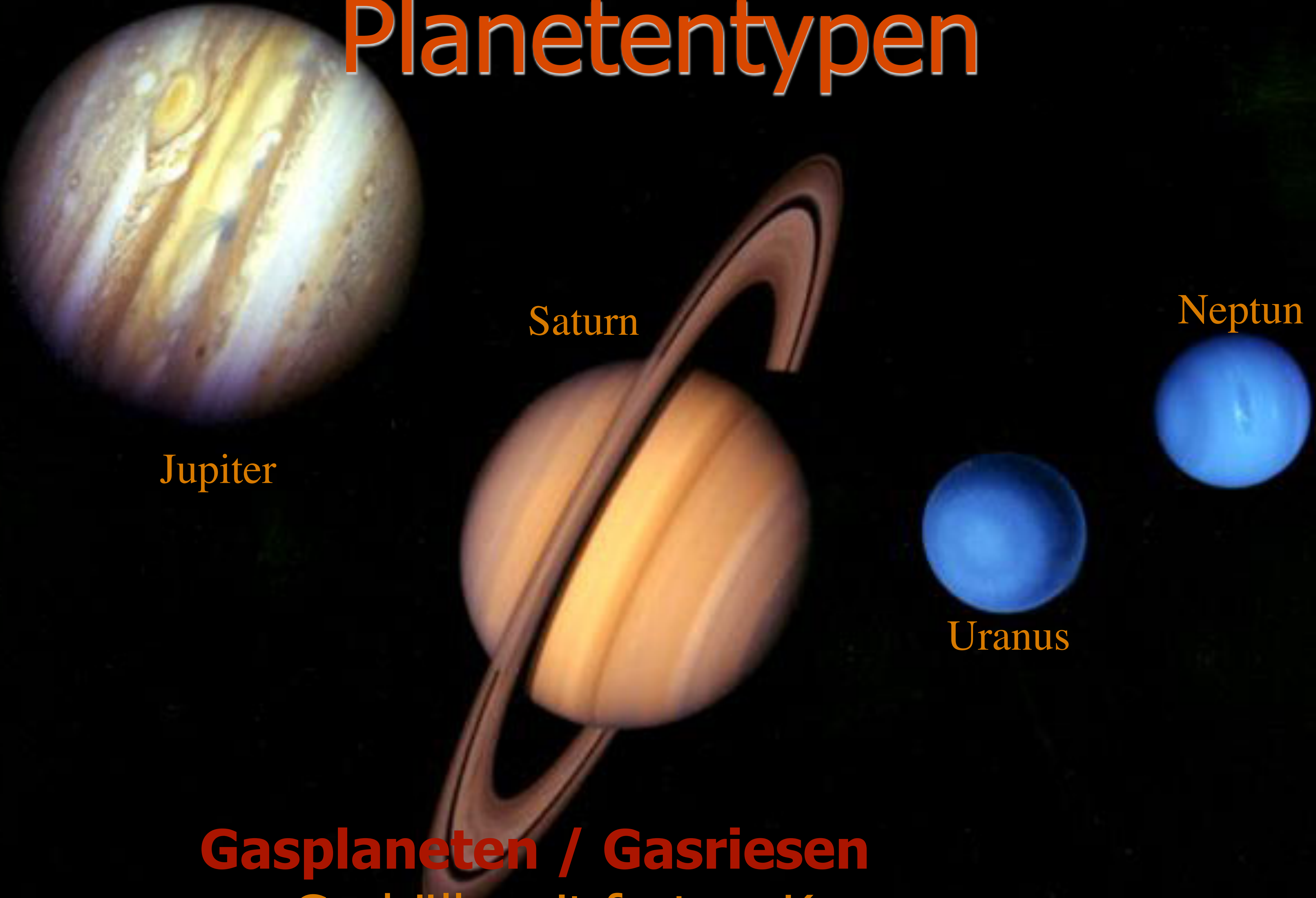
Planetentypen



Terrestrische Planeten

- fester Aufbau: “rocks”
- Entfernung zur Sonne: $a \leq 1.5$ AE

Planetentypen

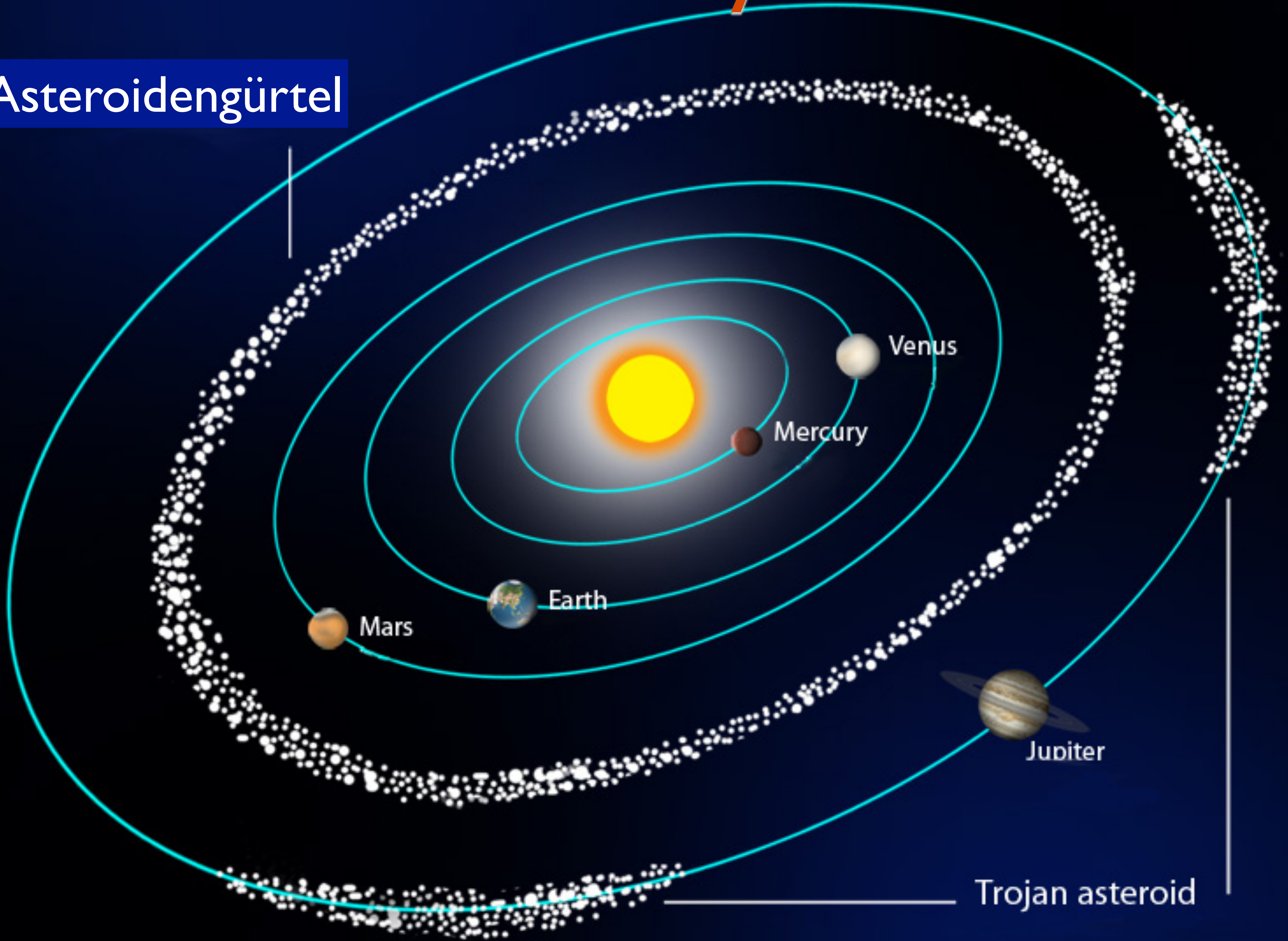


Gasplaneten / Gasriesen

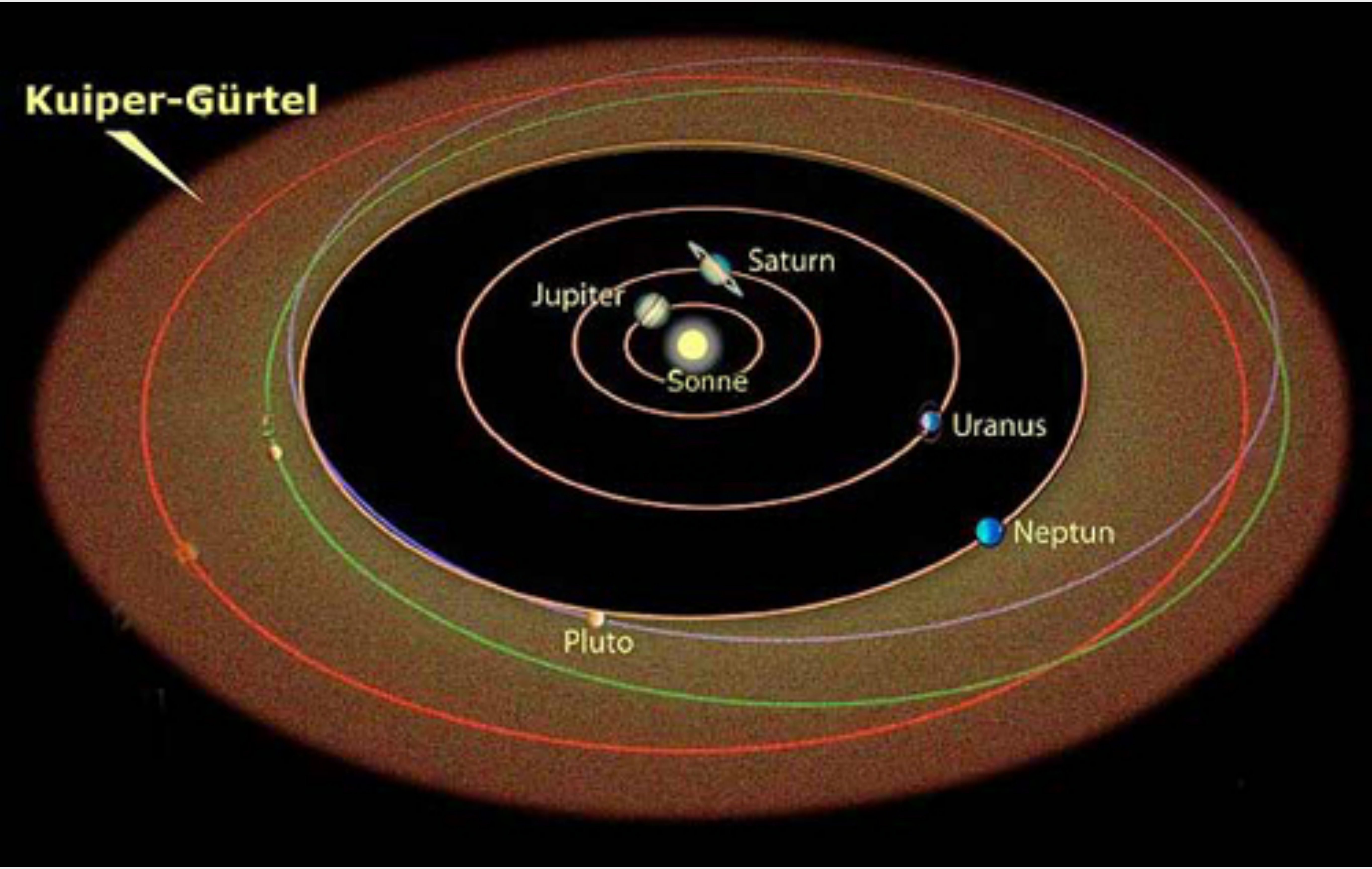
- Gasbälle mit festem Kern
- Entfernung zur Sonne: $a > 5$ AE

Planetensystem

Asteroidengürtel



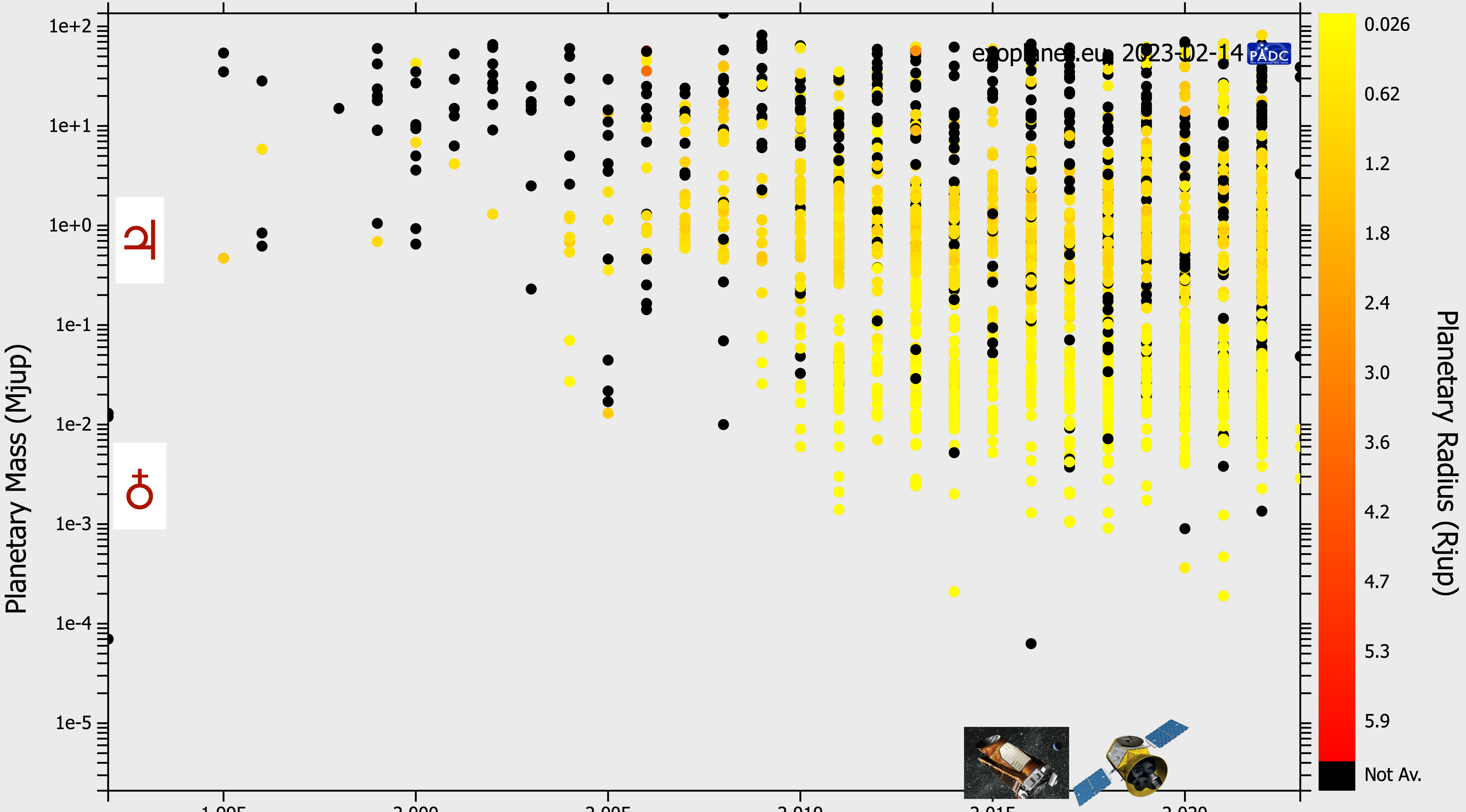
Planetensystem



Extrasolare Planetensysteme

- **The ExtrasolarPlanets Encyclopaedia:** http://exoplanet.eu

⟹ Stand 2023: **ca. 5300 ExoPlaneten**

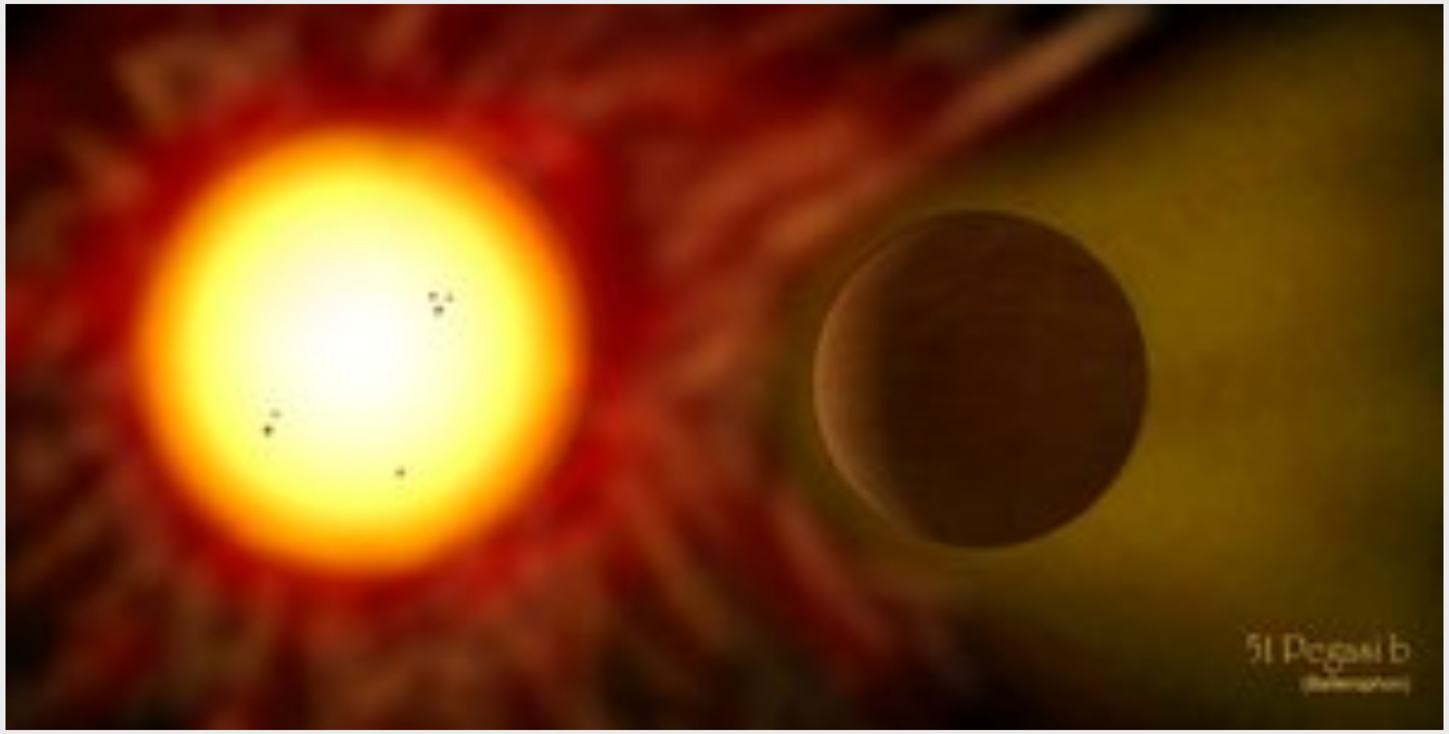


Extrasolare Planeten

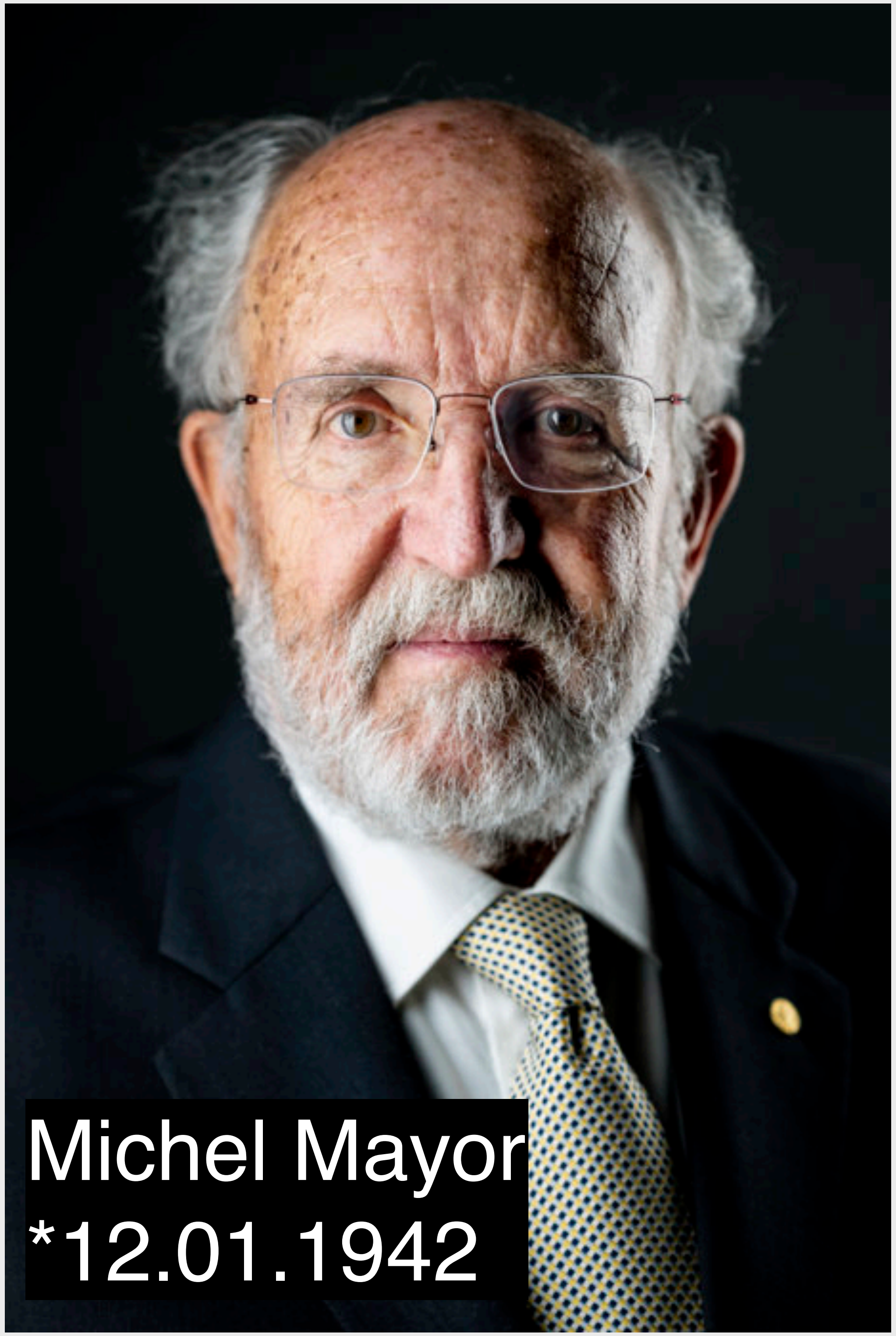
Entdeckung der **ersten** extrasolaren Planeten:

- 1989: HD 114762b, bestätigt 1991 aber evtl. BZ
- 1992: zwei Planeten um **Pulsar** B1257+12
  von A.Wolszcan & D.Frail
- 1995: **51 Pegasi b** : Bellerophon
  von M.Mayor & D.Queloz
  Gasriese um sonnenähnlichen Stern (51 Pegasi)
  $P = 4.23\ \mathrm{d}$
  $a = 0.053\ \mathrm{AE}$

$\Longrightarrow$ erster Planet um
Hauptreihenstern
= sonnenähnlich



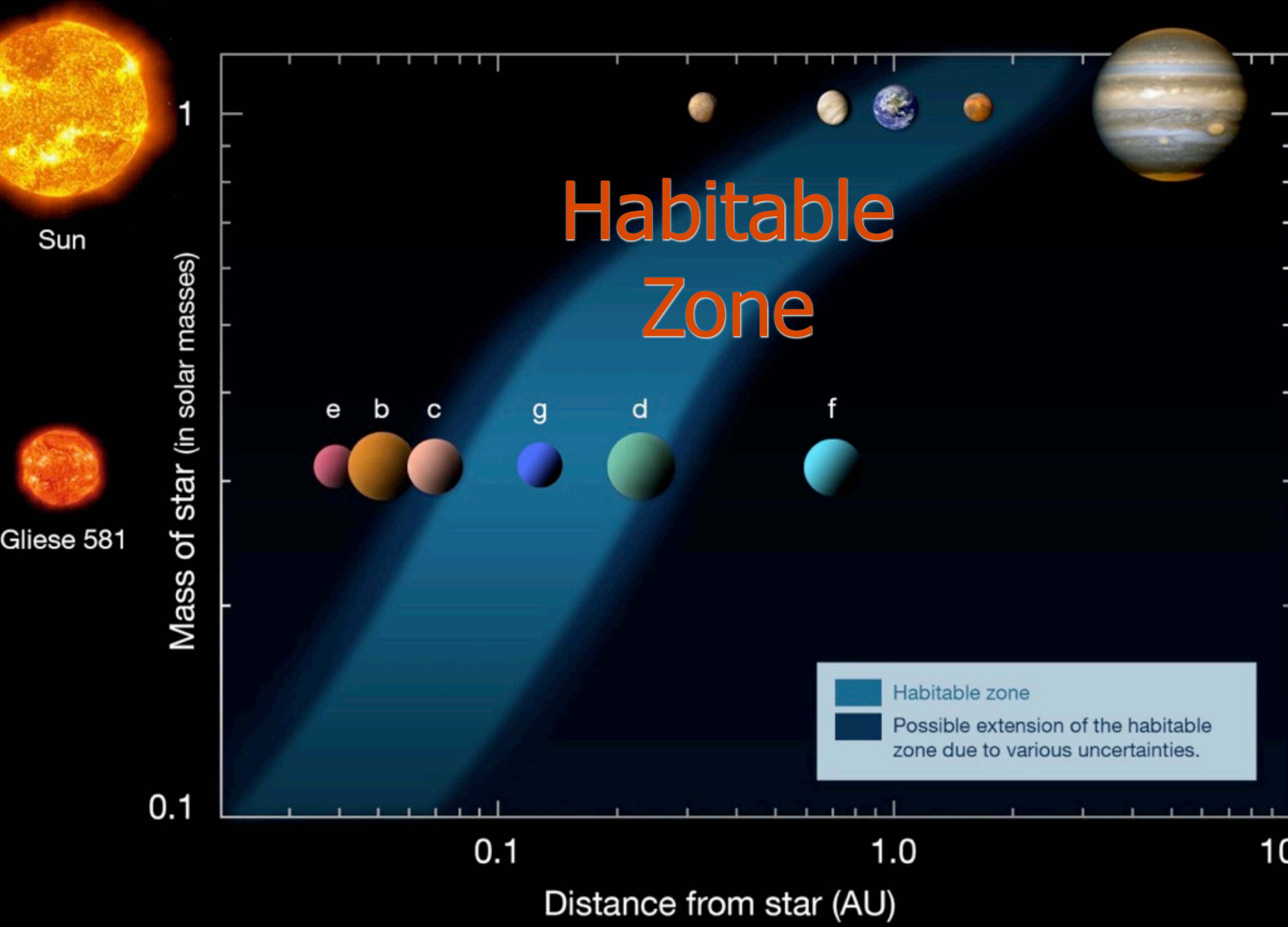
Nobelpreis Physik 2019


Michel Mayor
*12.01.1942


Didier Queloz
*24.02.1966

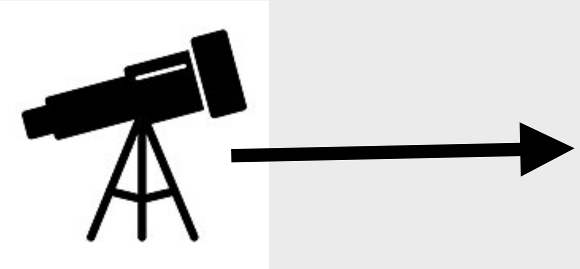
für die Entdeckung des **ersten** extrasolaren Planeten

Habitable Zone

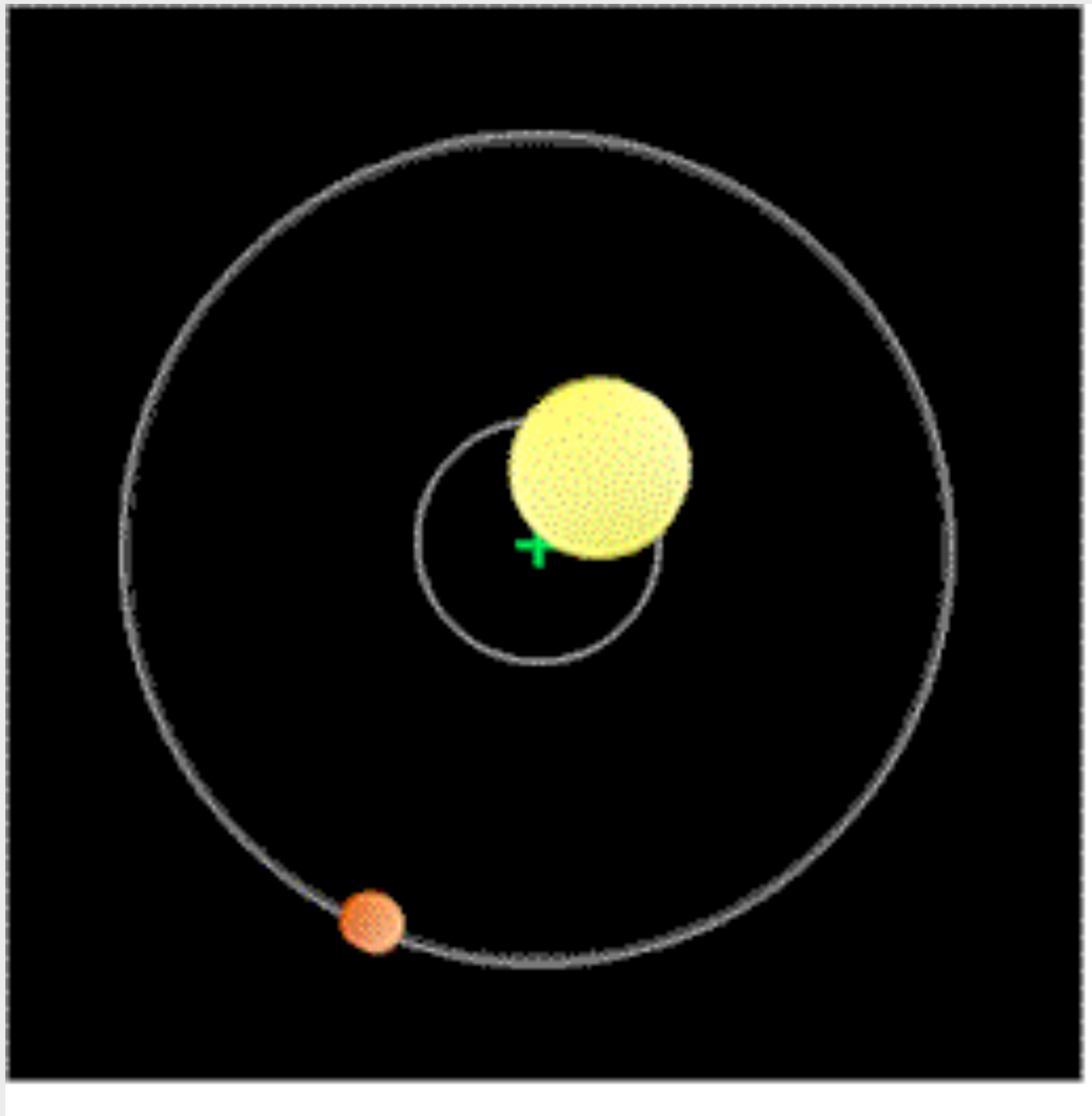


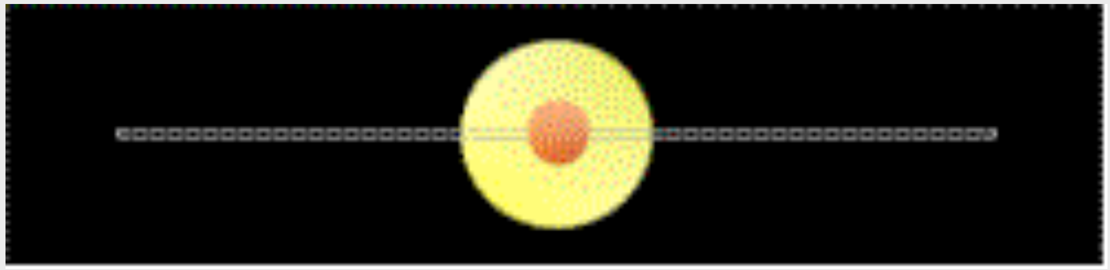
Nachweismethoden

RV-Methode



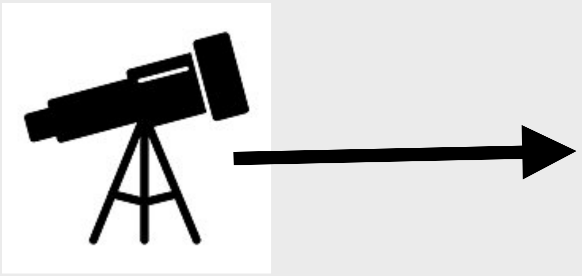
Beobachter



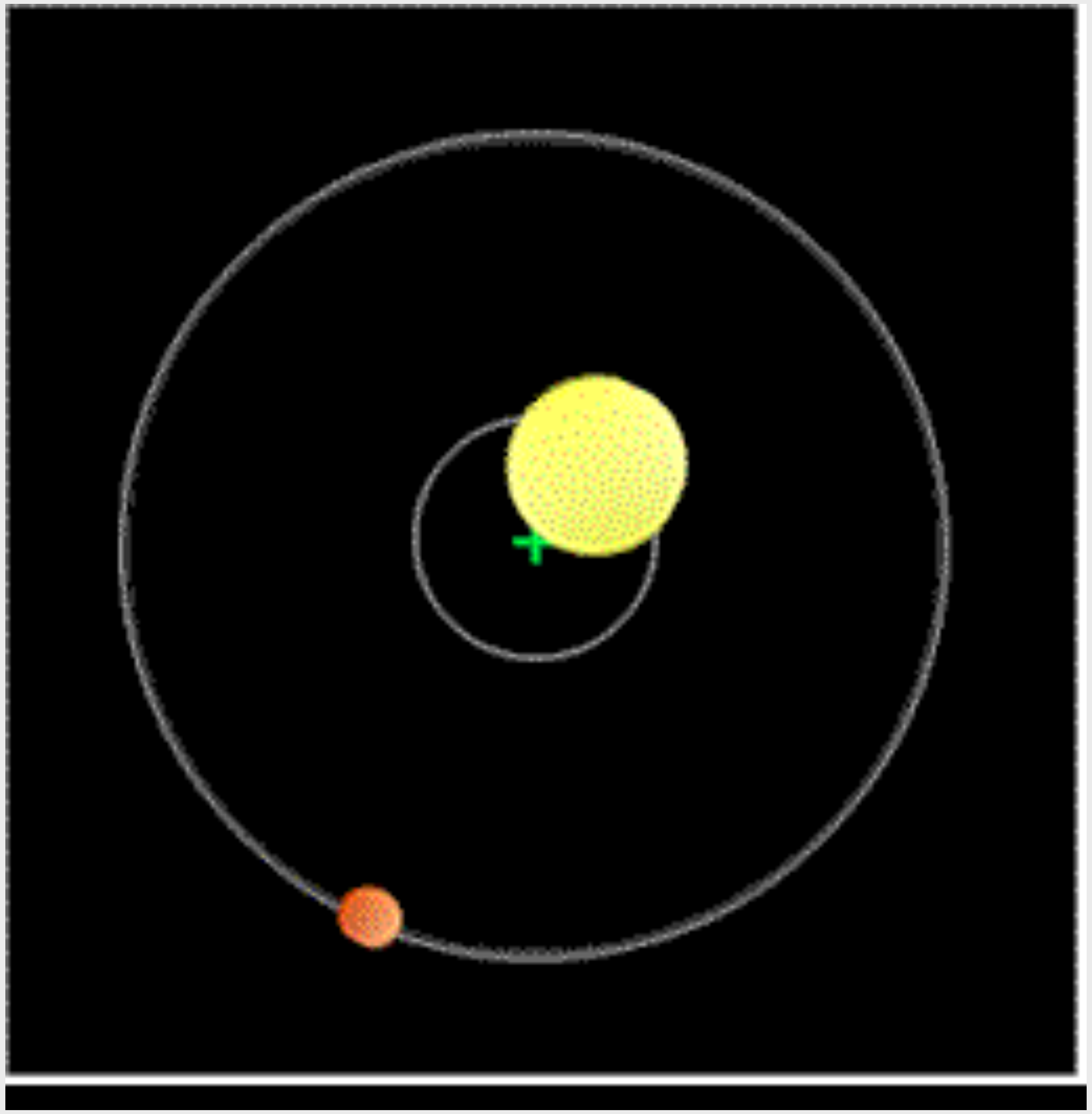


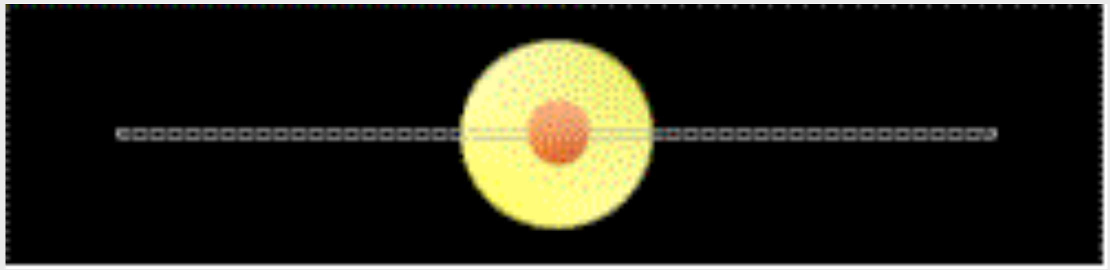
RV: Radialgeschwindigkeitsmethode

RV-Methode



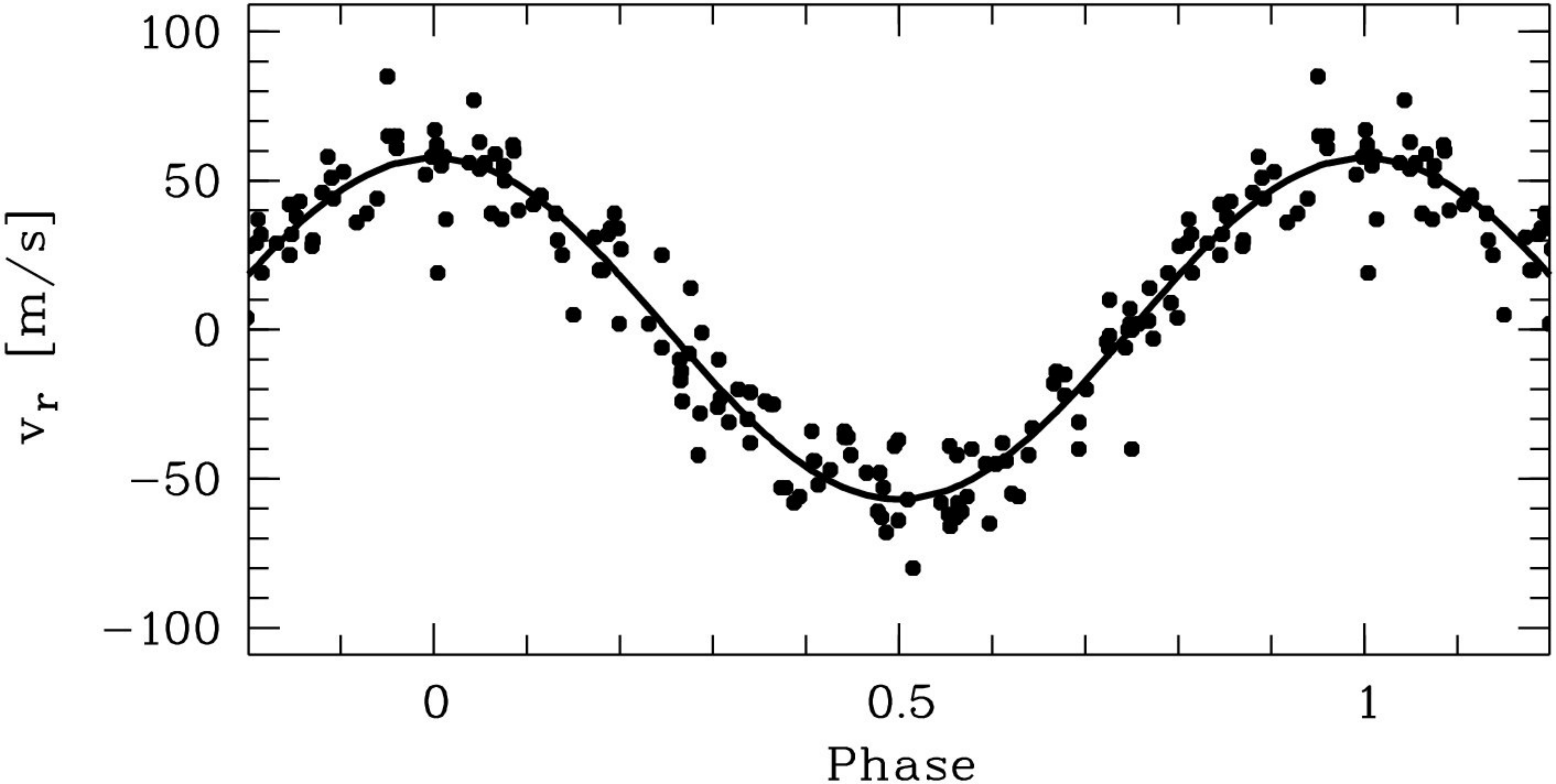
Beobachter





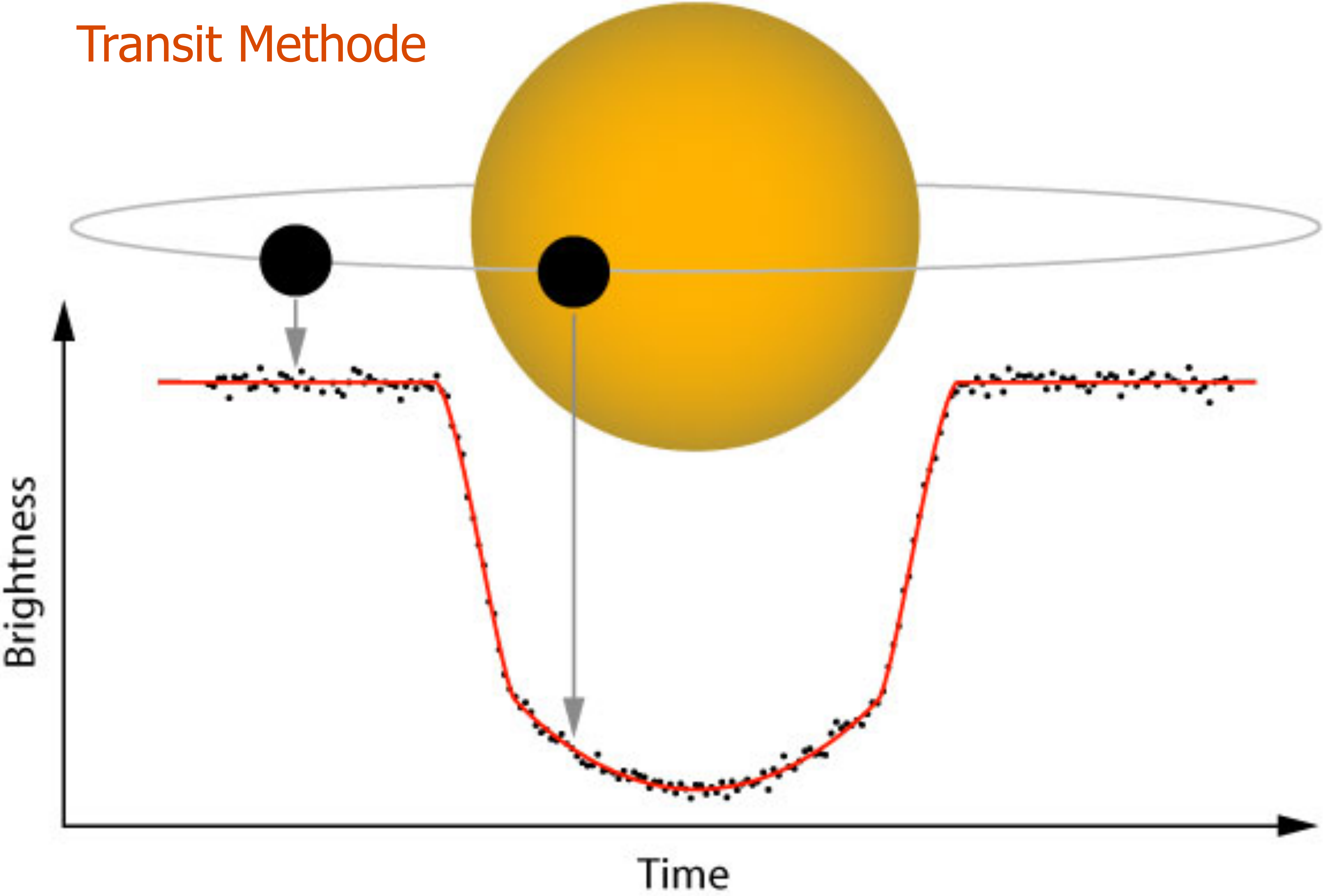
RV: Radialgeschwindigkeitsmethode

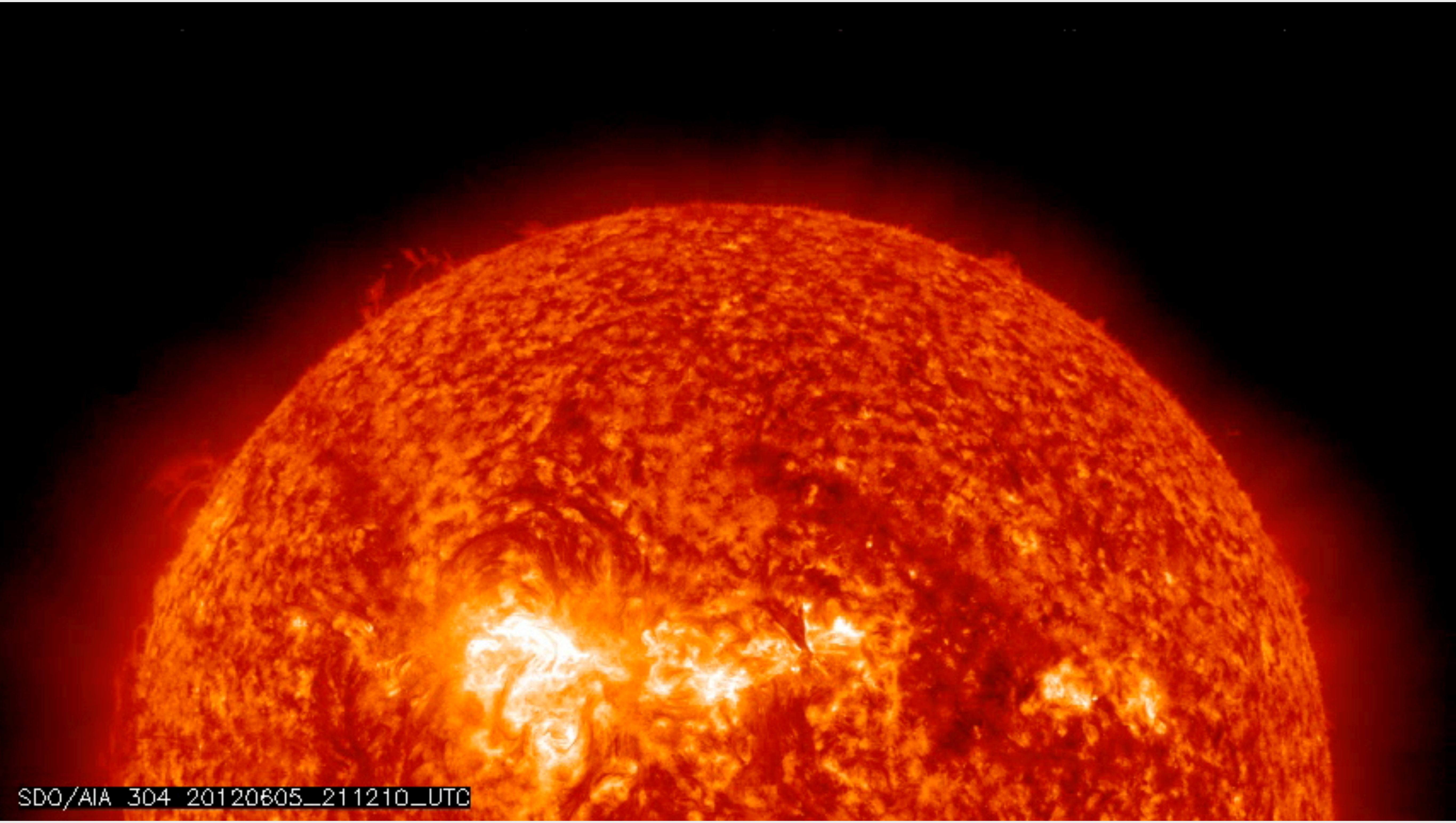
RV-Methode



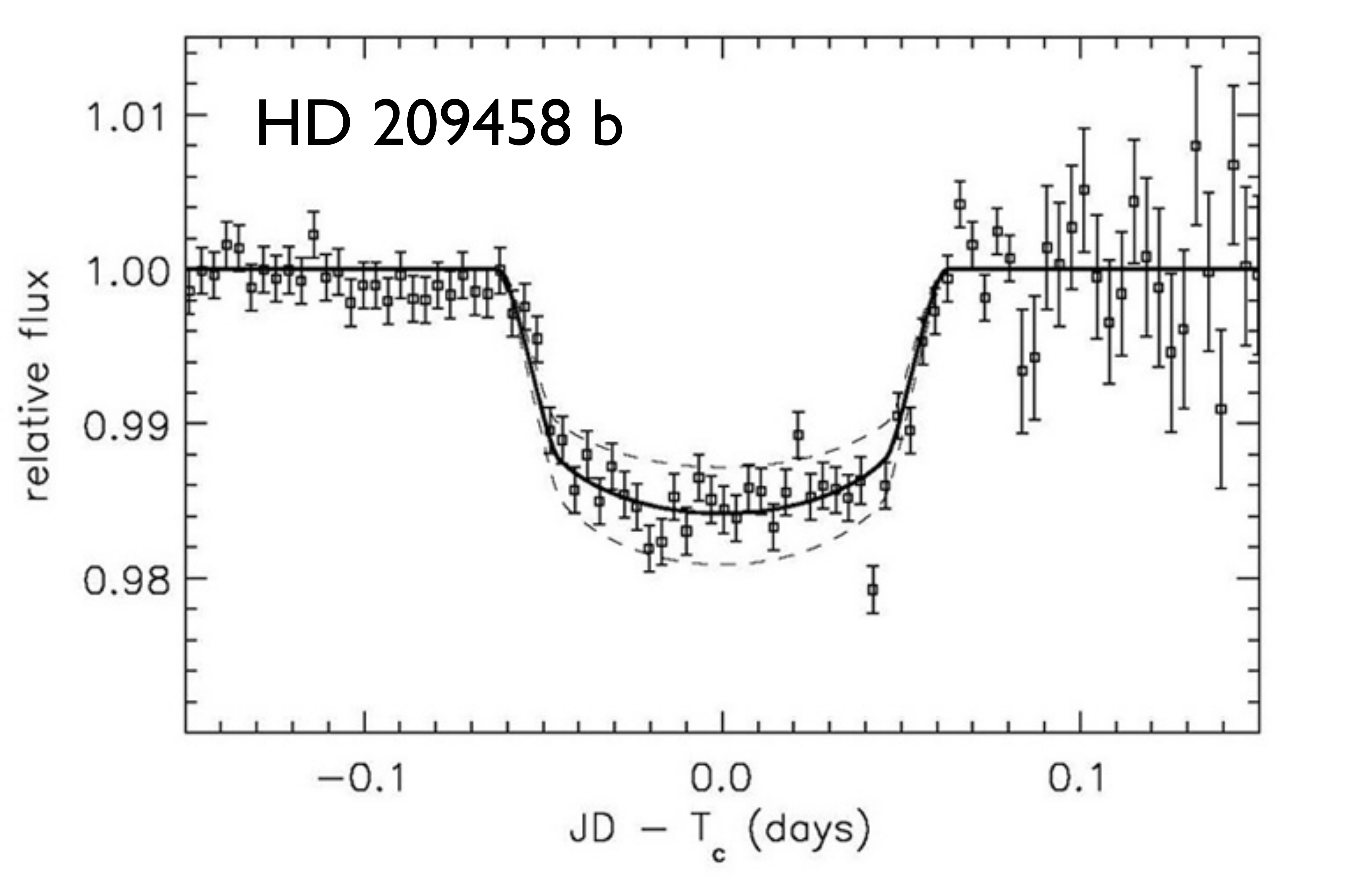
Radialgeschwindigkeitskurve von 51 Peg

Transit Methode

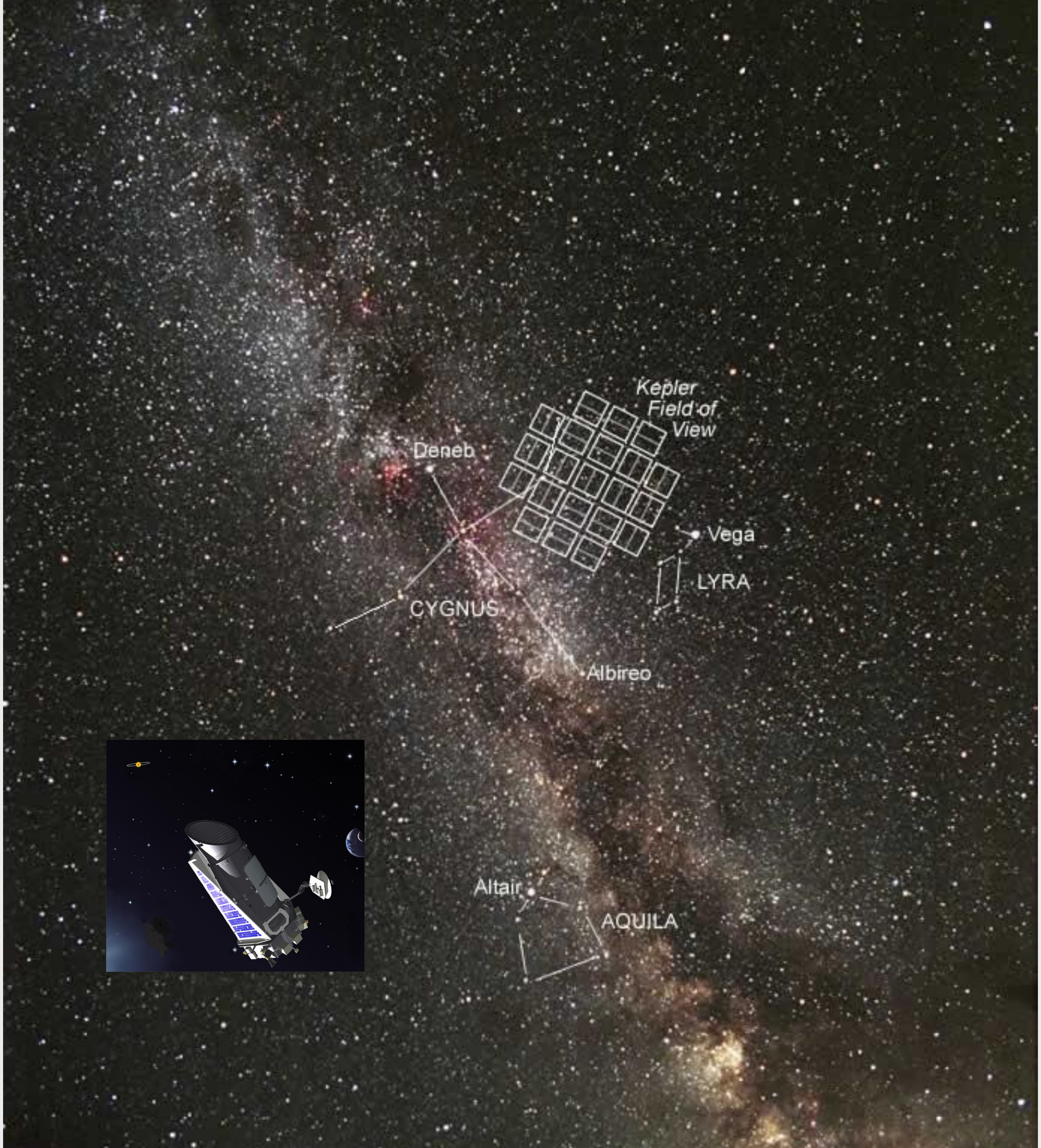



SDO/AIA 304 20120605_211210_UTC

Transit Methode



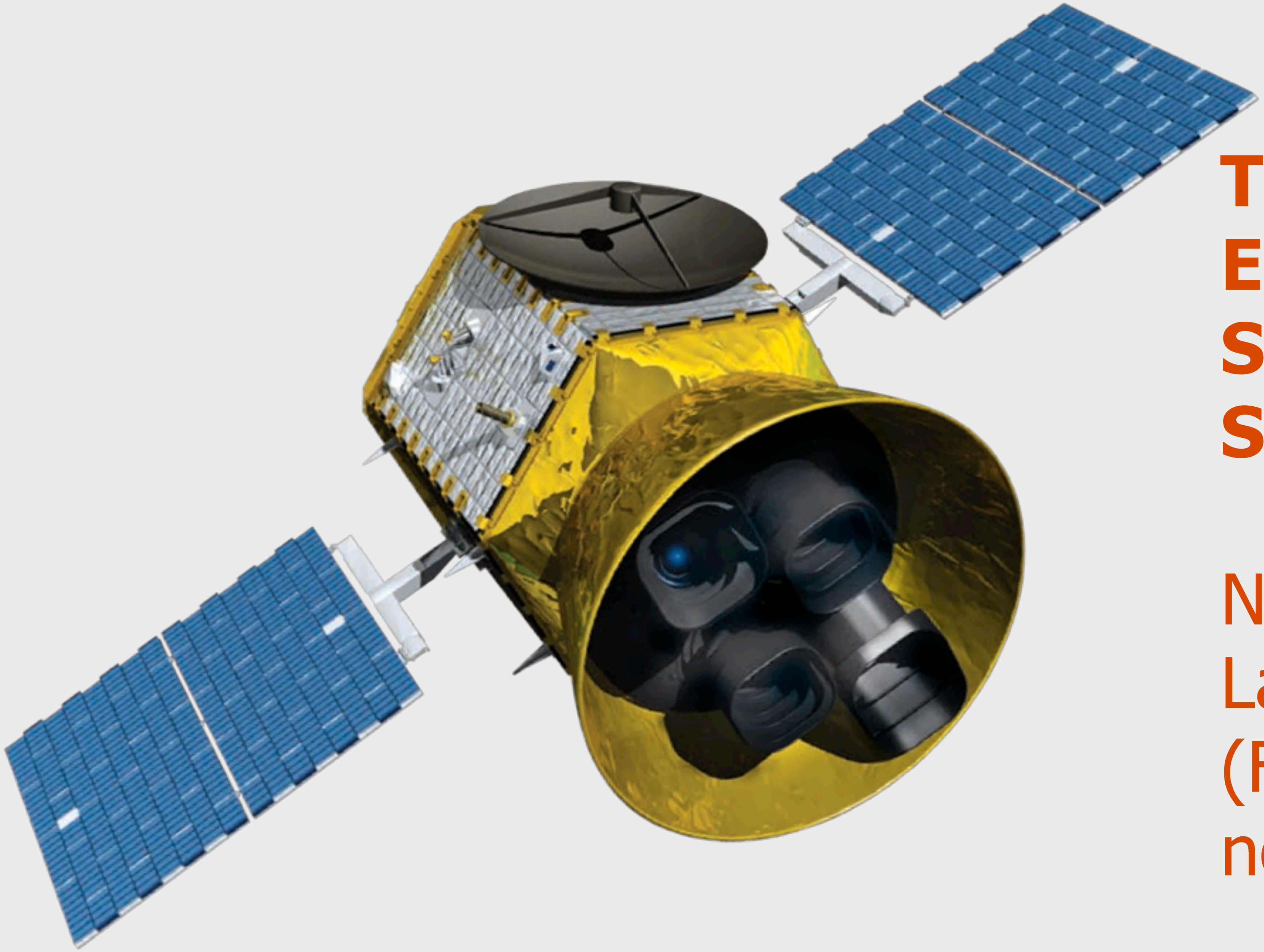
Amateuraufnahme: HD 209458 b um Osiris (in Pegasus)



Kepler Mission: 03/2009 – 08/2013 (Hauptmission)

Weiterbetrieb bis 2018

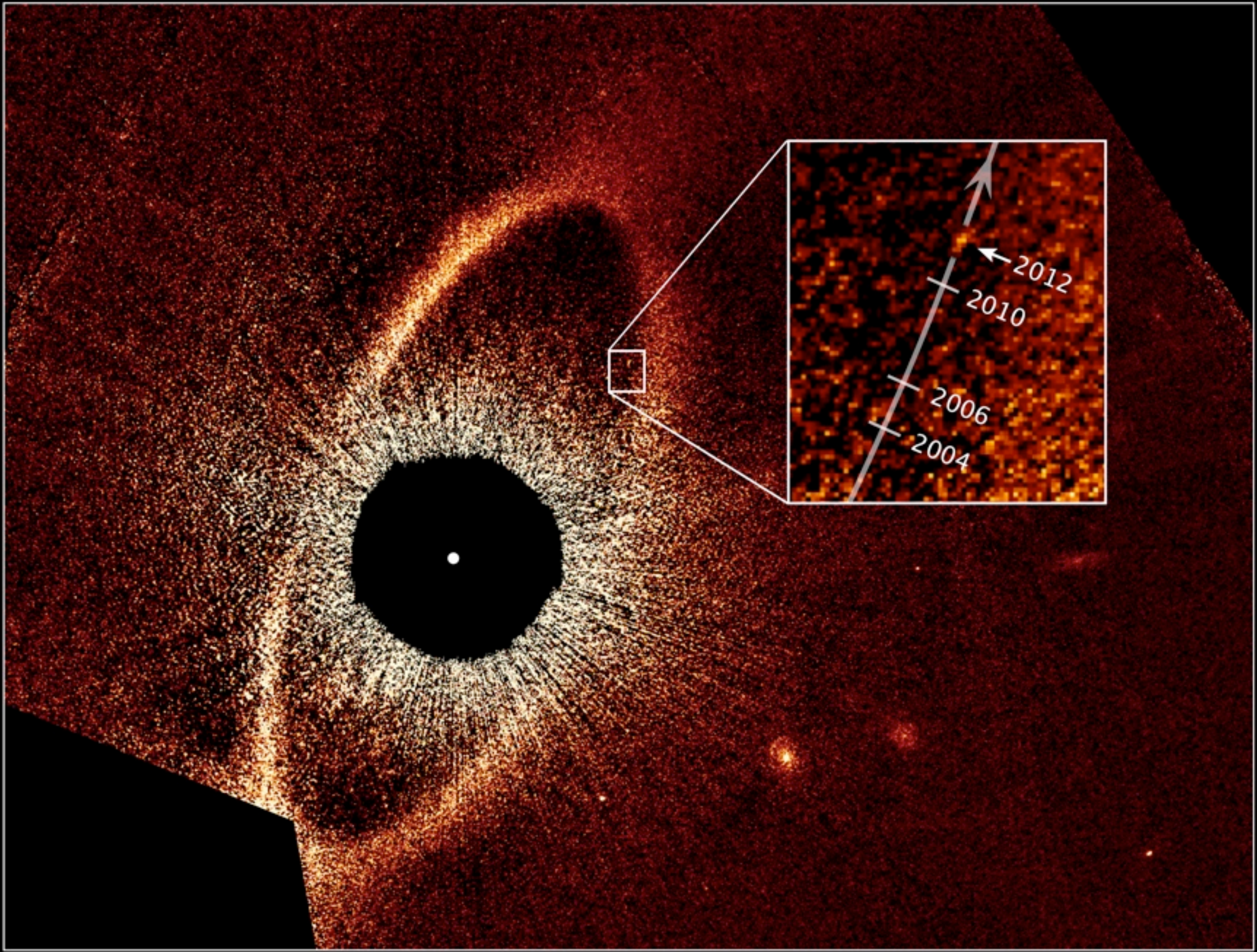
TESS



Transitting
Exoplanet
Survey
Satellite

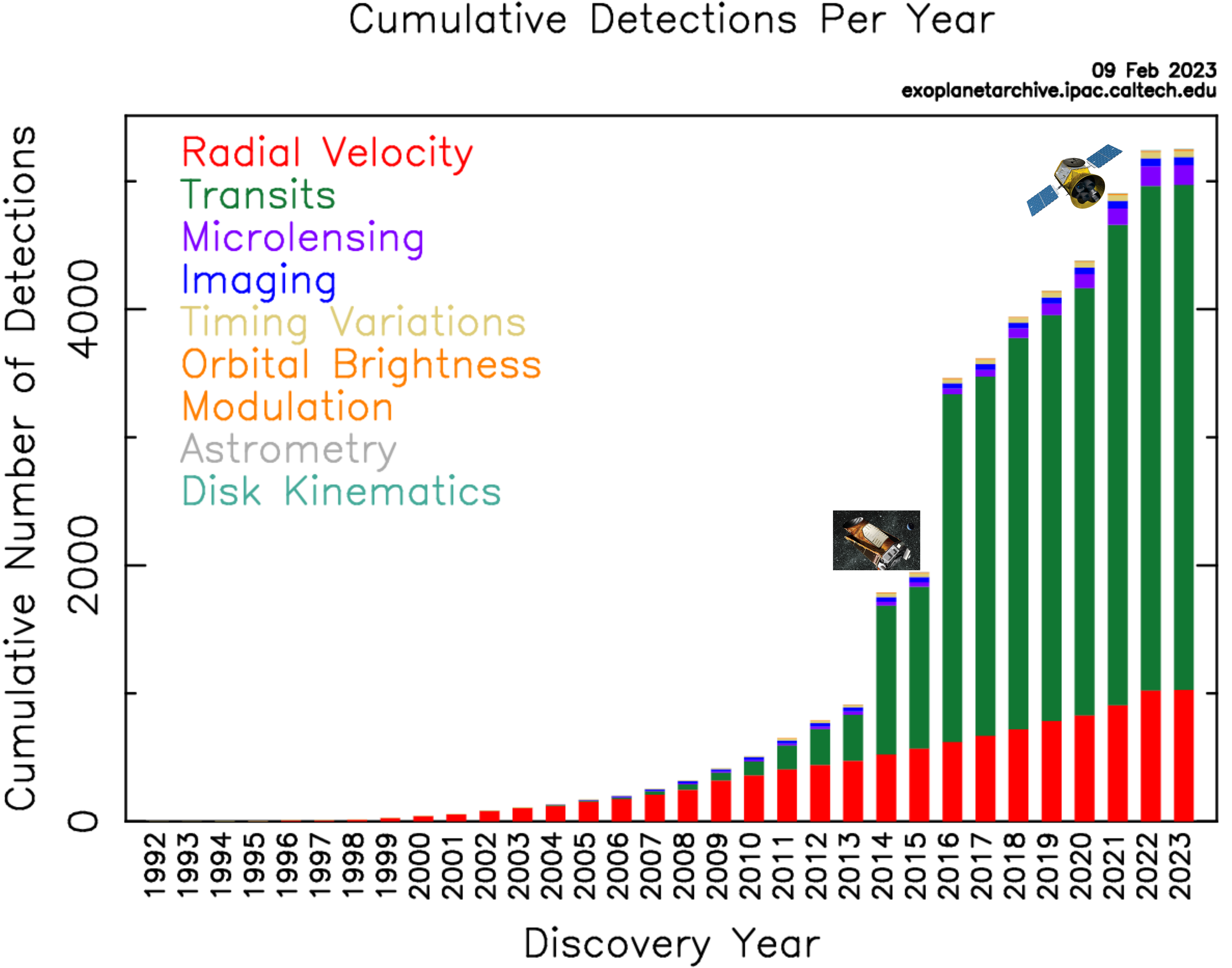
NASA Mission
Launch: 18. April 2018
(Falcon 9/Space X)
noch aktiv

ca. 300 bestätigte
Exoplaneten
6000 Kandidaten



Fomalhaut System

Hubble Space Telescope • STIS


Cumulative Detections Per Year
09 Feb 2023
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Disk Kinematics
Cumulative Number of Detections
0
2000
4000
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Discovery Year

Entstehung von Planetensystemen

Sternentstehung

- Typische Galaxie: ~ 100 Milliarden Sterne
- Insterstellare Medium (ISM): atomares Gas, ionisiert, neutral, T ~ tausend - Million Grad
- Dunkelwolken: H, H_2 (99% der Masse), CO, Staub (1%)
- Sternentstehungsrate heute: 3-5 Sterne/Jahr

Edward Barnard: Entdeckung von Dunkelwolken

Taurus Nebel

ESA/Hubble & NASA: Judy Schmidt

Orion Nebel: Deep field, by Robert Gendler

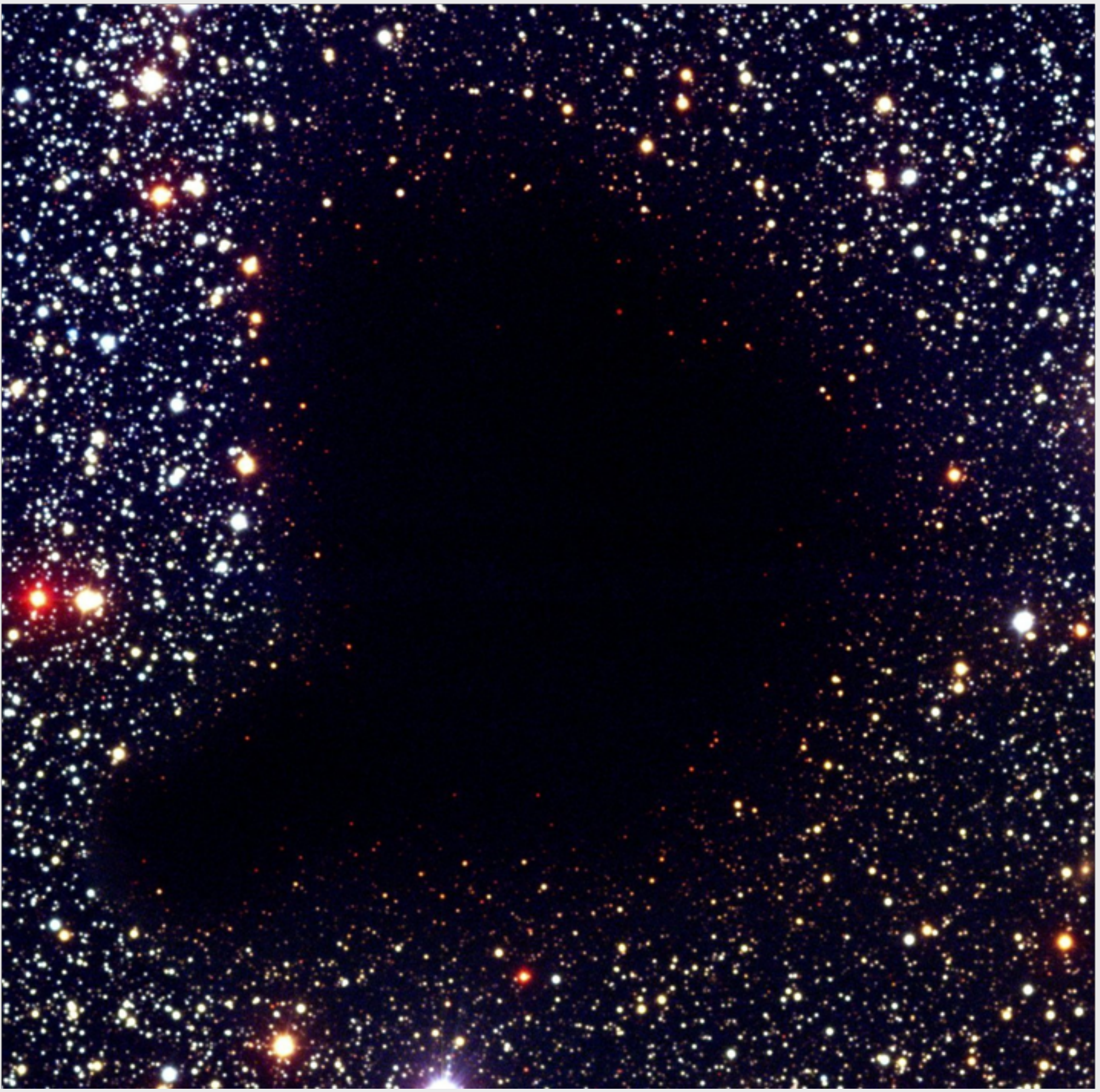
Elephantenrüssel Nebel - IC1396A


“Mystic Mountain” in Carina Nebula, *HST, NASA, ESA*

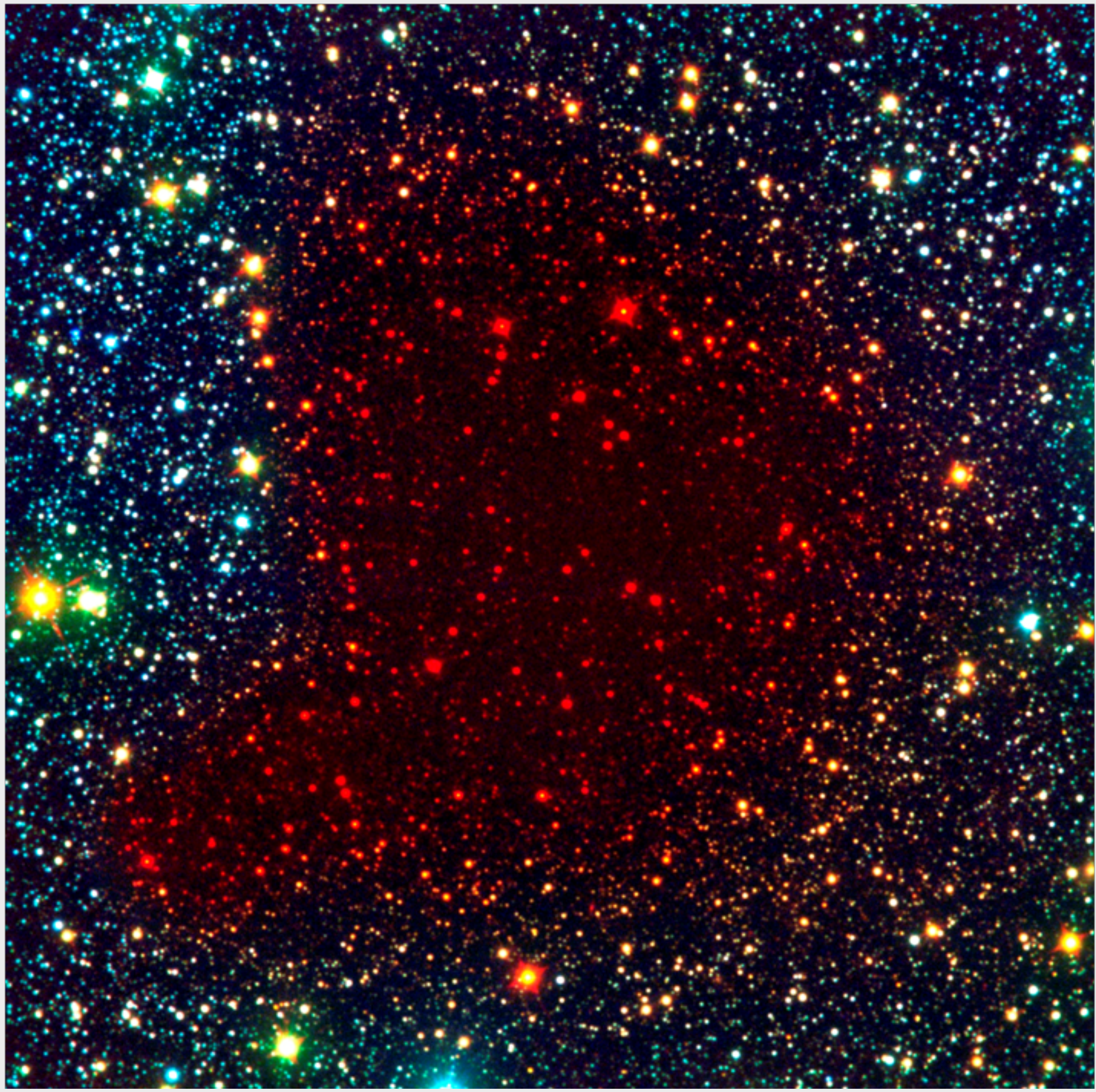
Hubble Teleskop: “Säulen der Schöpfung” im Adlernebel

kosmischer Staub

kosmischer Staub

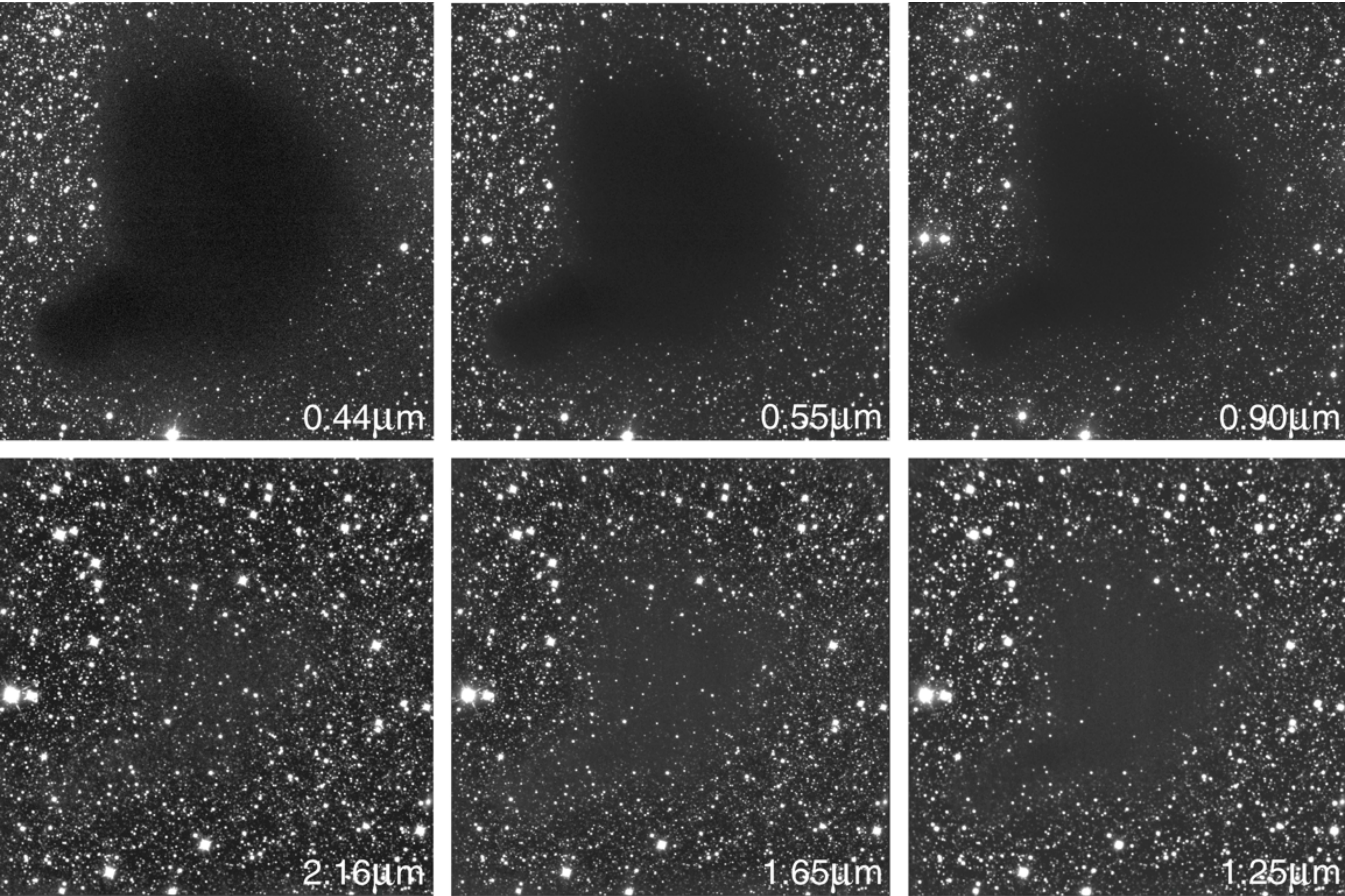


optisch

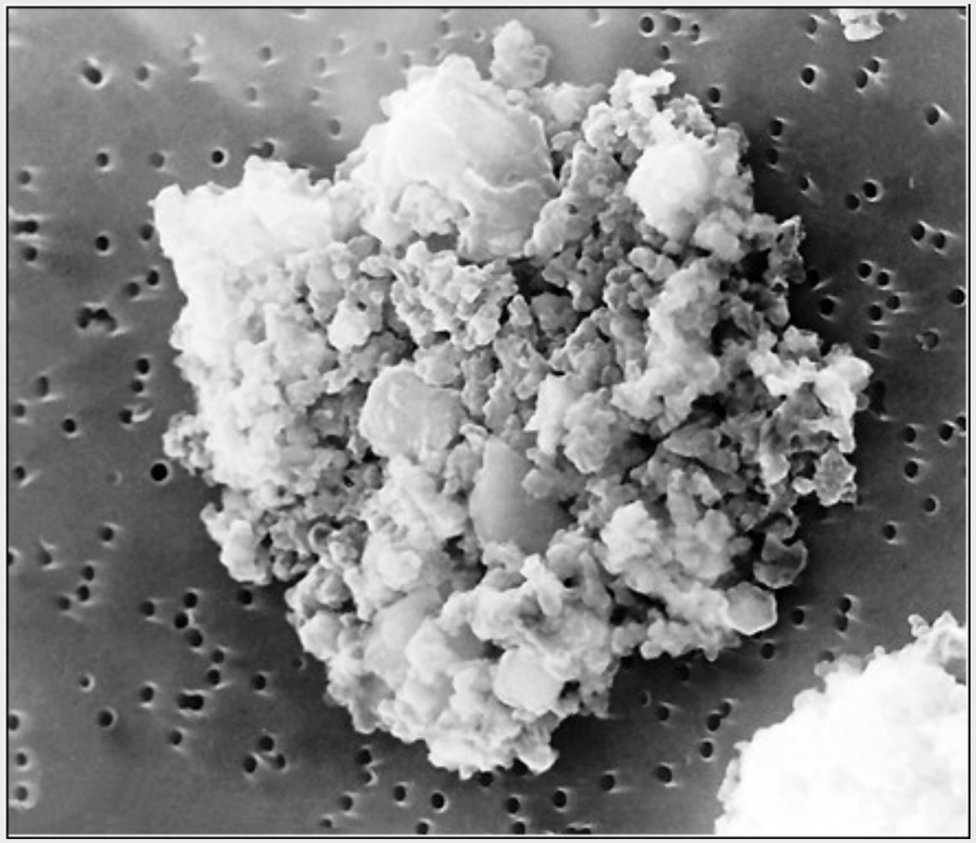


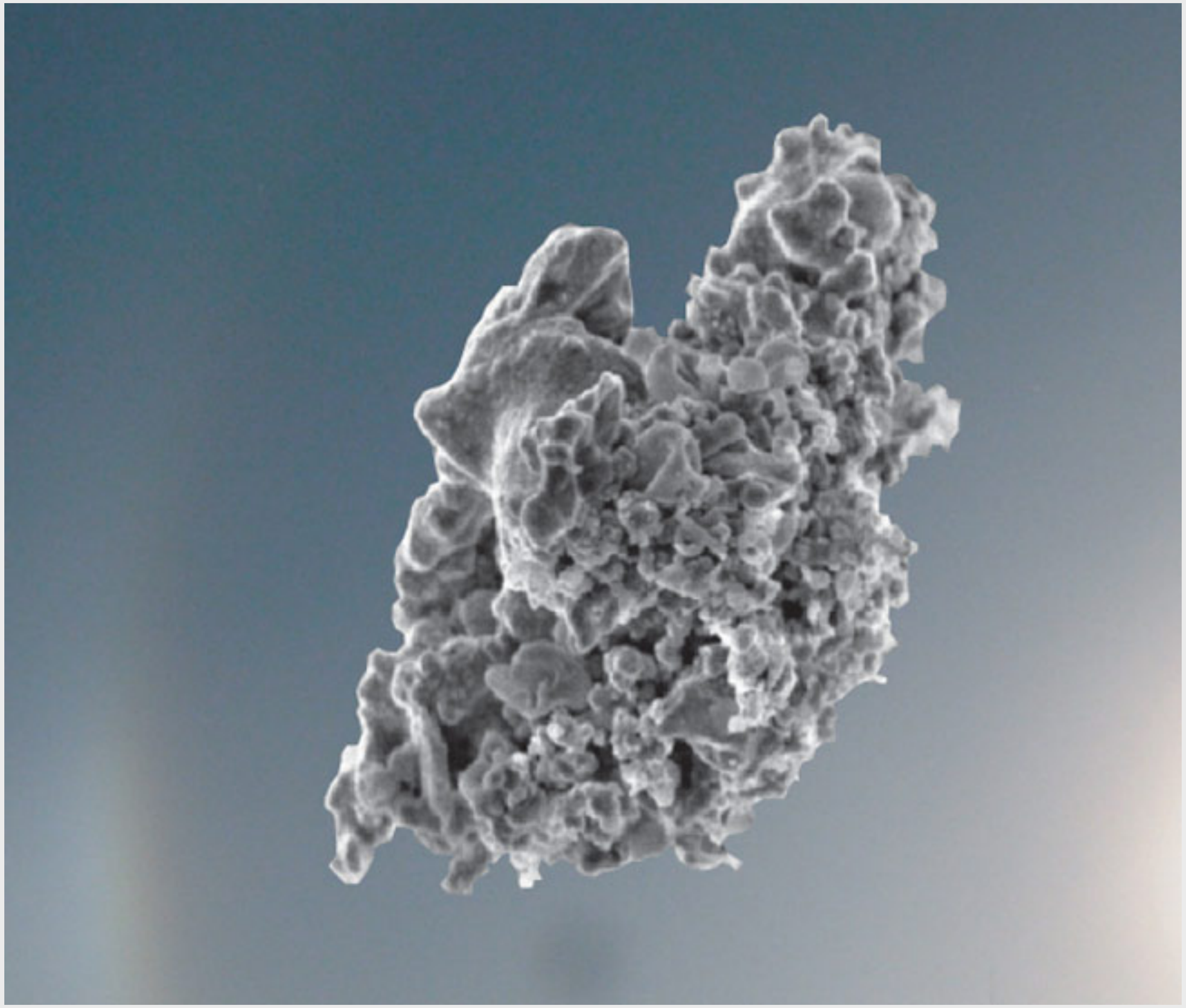
infrarot

kosmischer Staub



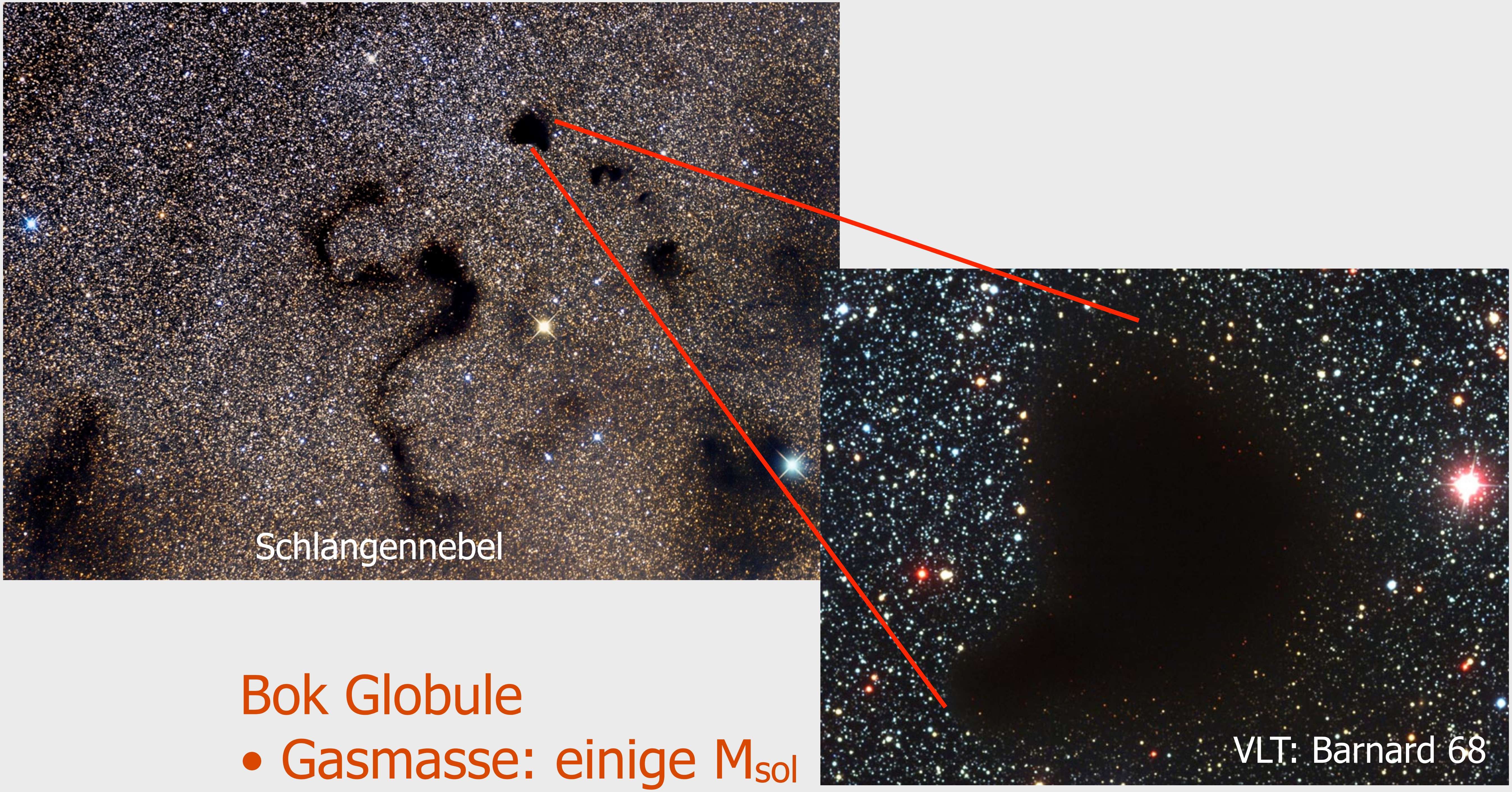
kosmischer Staub





- Zusammensetzung:
  Silikate, Graphit, Eis, ...
- Größe: 0.1 – 10 µm

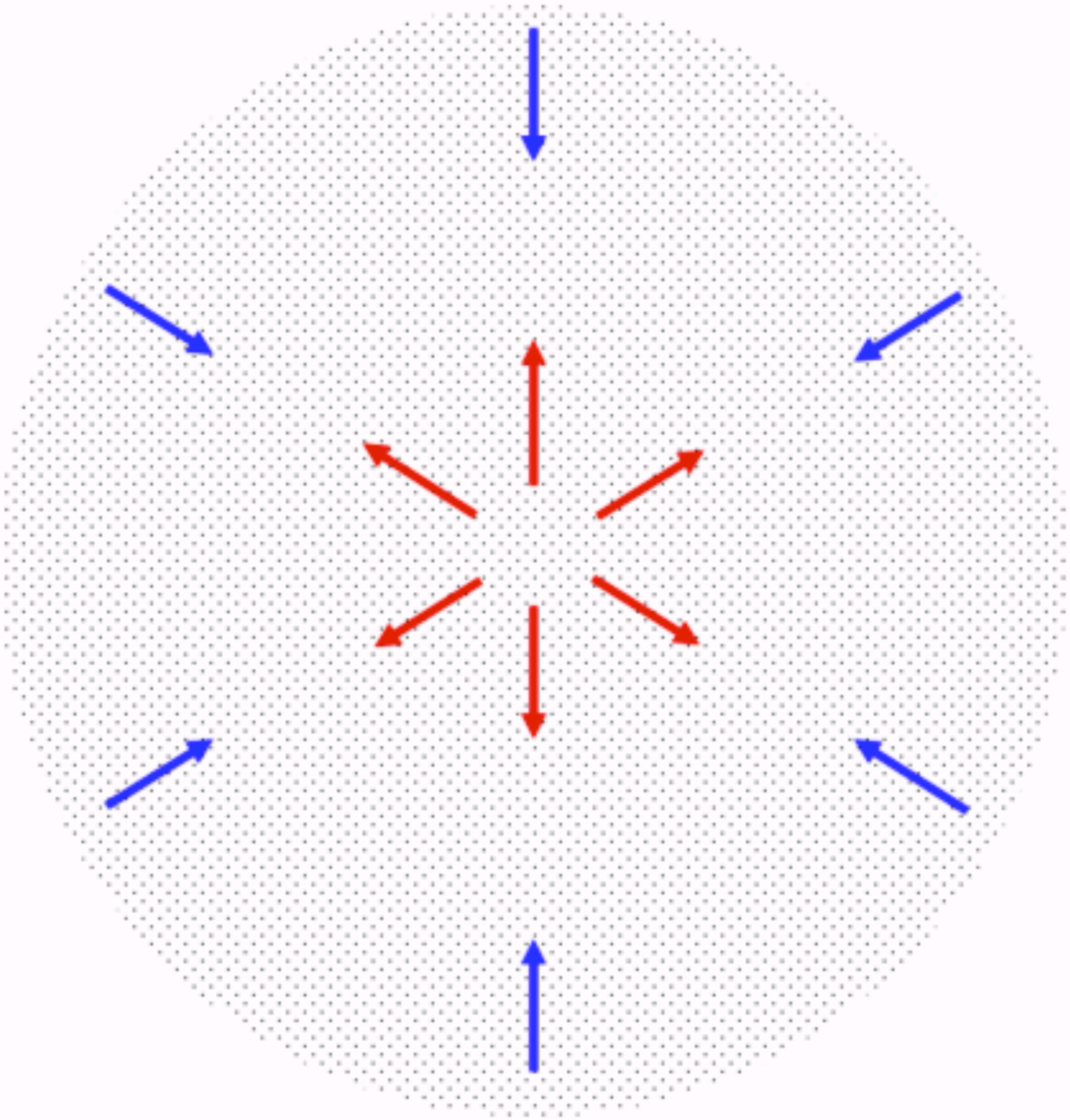
Sternentstehung


Schlangennebel

VLT: Barnard 68

Bok Globule
- Gasmasse: einige M_{sol}
- sehr **kalt**: T = 10 K
- D ~ 10.000 AE

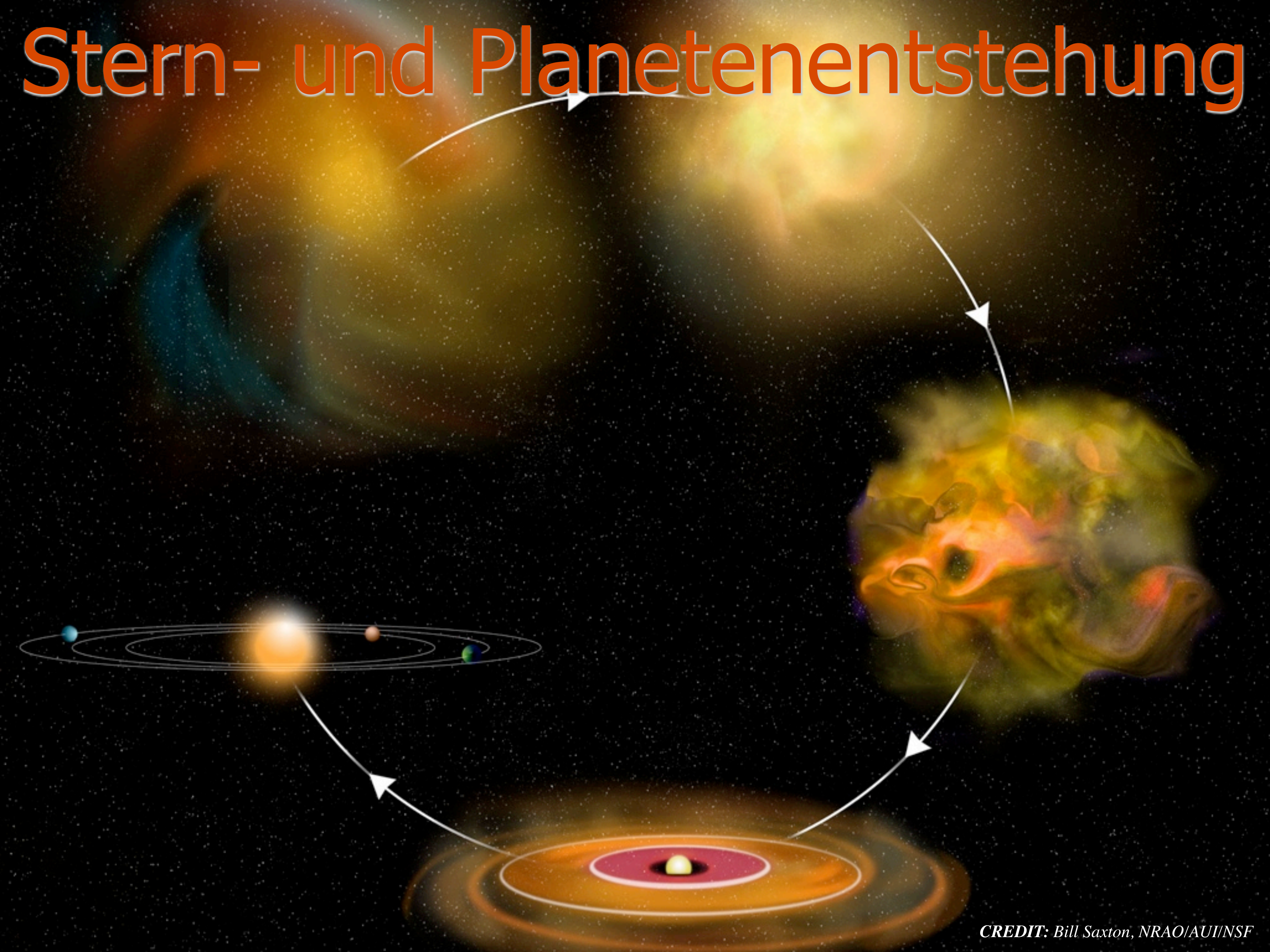
Gravitations-Instabilität



↓ Gravitationsdruck

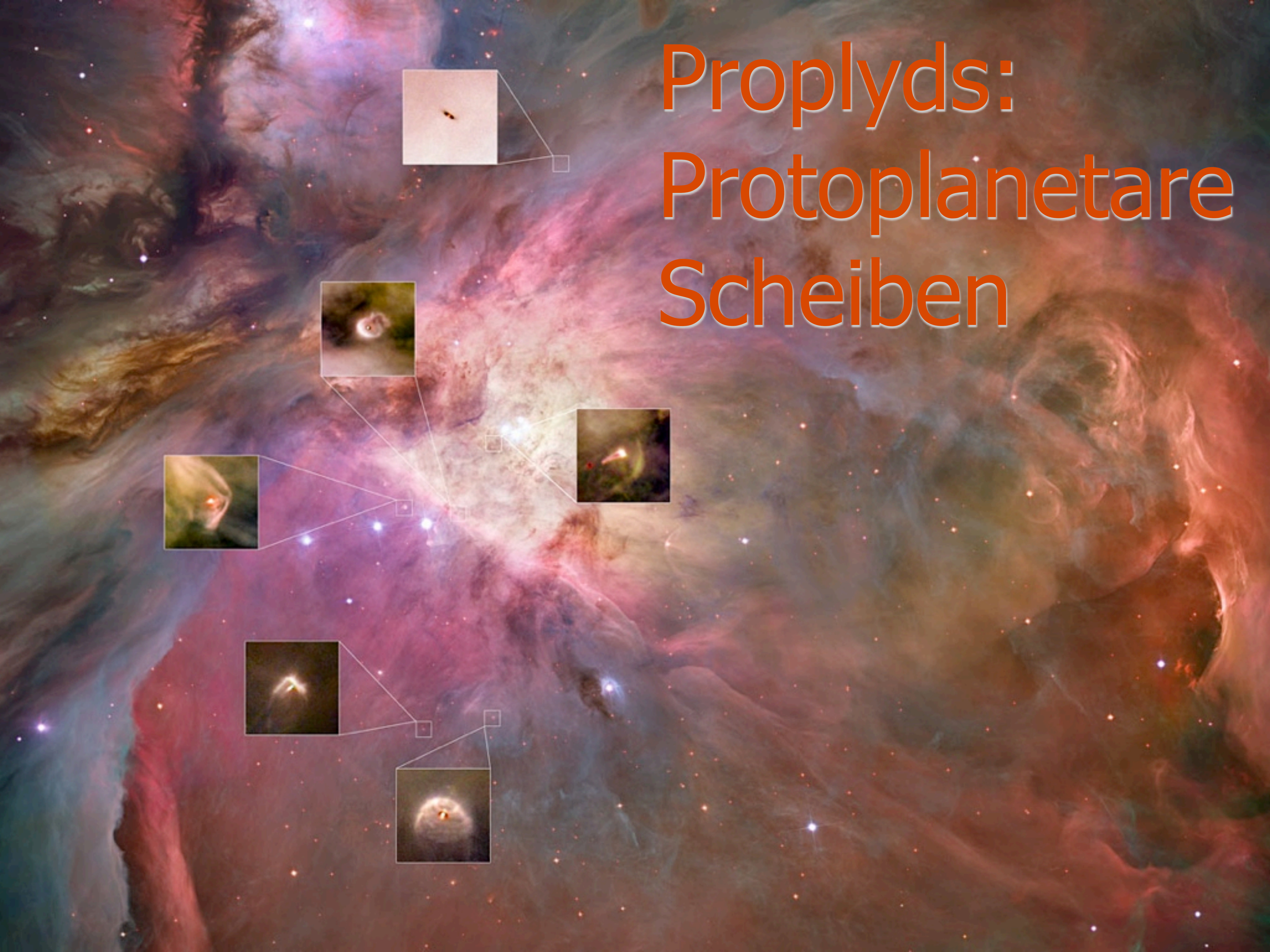
↑ Druck durch Teilchenbewegung
(Thermischer Druck)

Stern- und Planetenentstehung

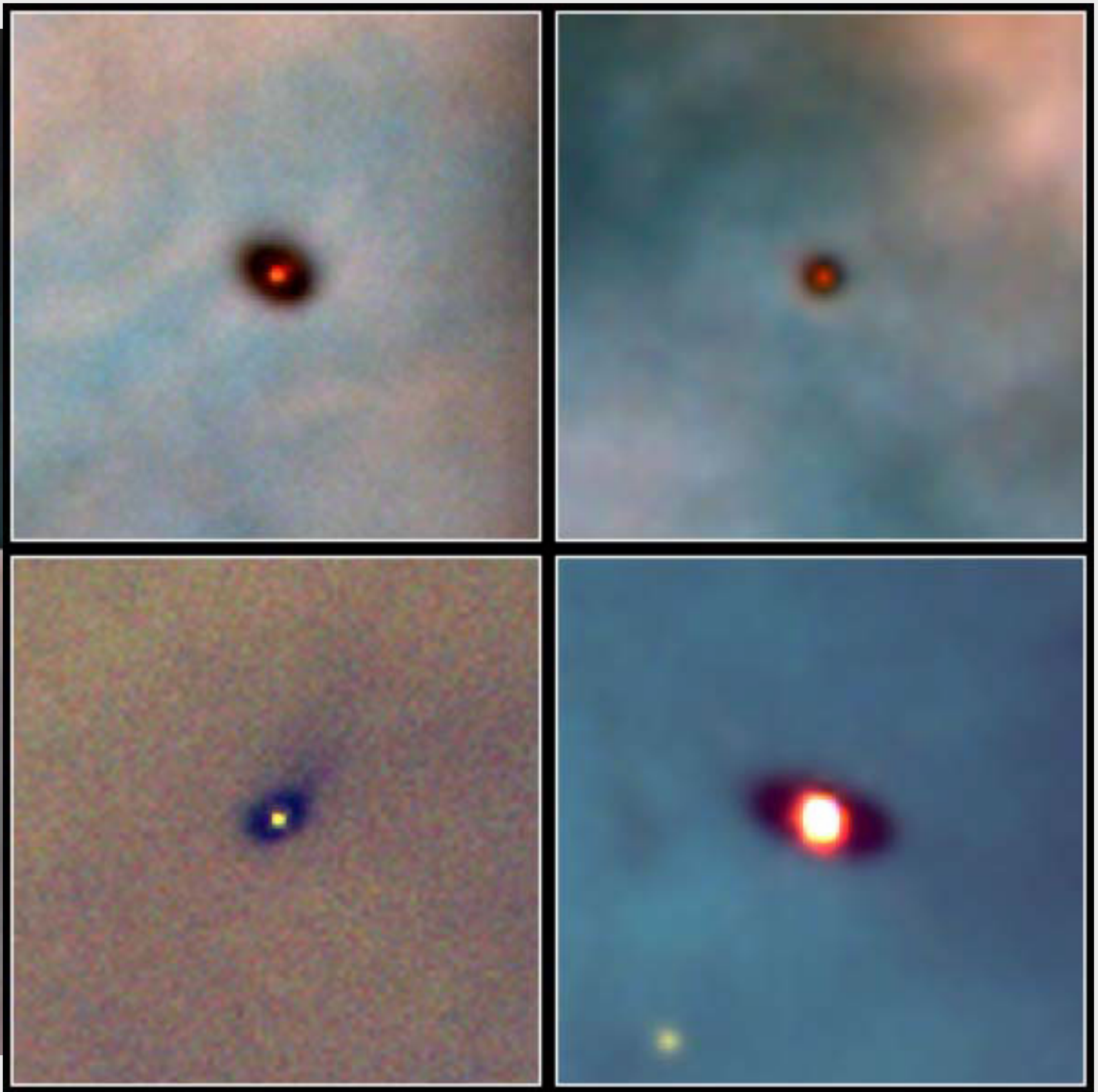


CREDIT: *Bill Saxton, NRAO/AUI/NSF*

Proplyds: Protoplanetare Scheiben



Protoplanetare Scheiben



Protoplanetary Disks
Orion Nebula

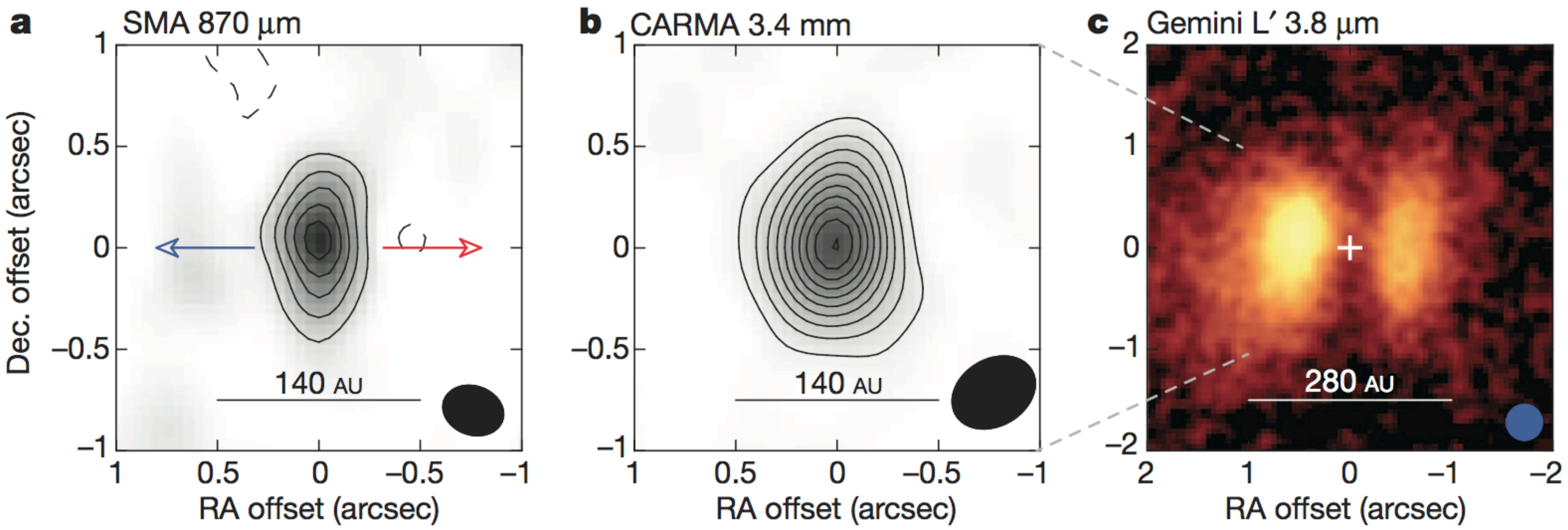
HST · WFPC2

PRC95-45b · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

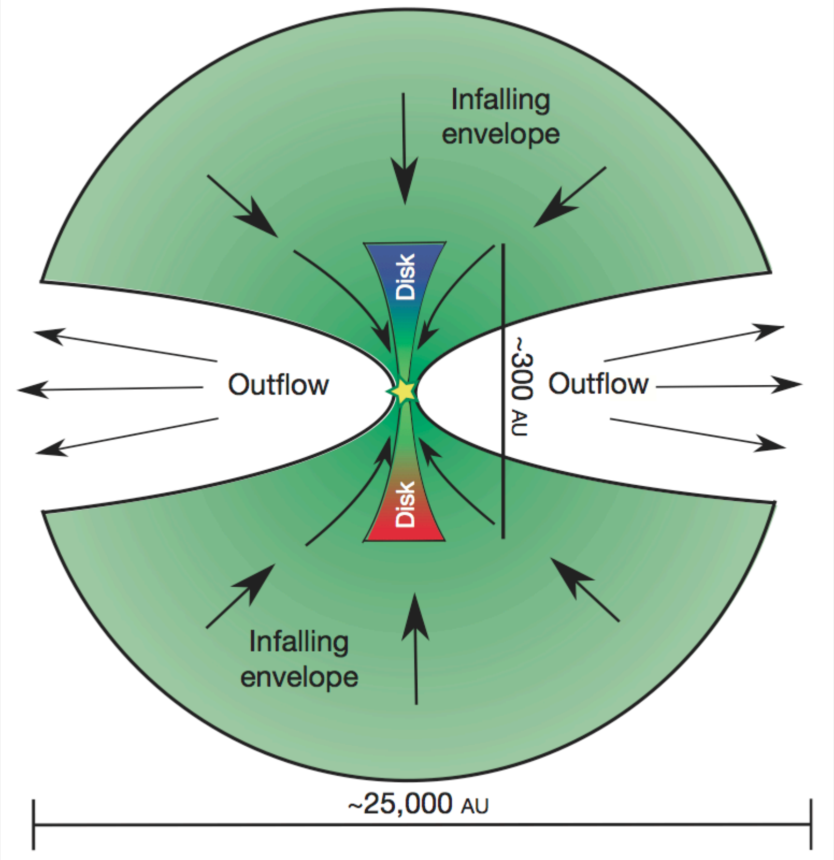
Simulation: Paul Clark (Uni Heidelberg)

HL Tau: ALMA (ESO/NRAO/NAOJ)

Protoplanetare Scheiben



Tobin et al., Nature 2012

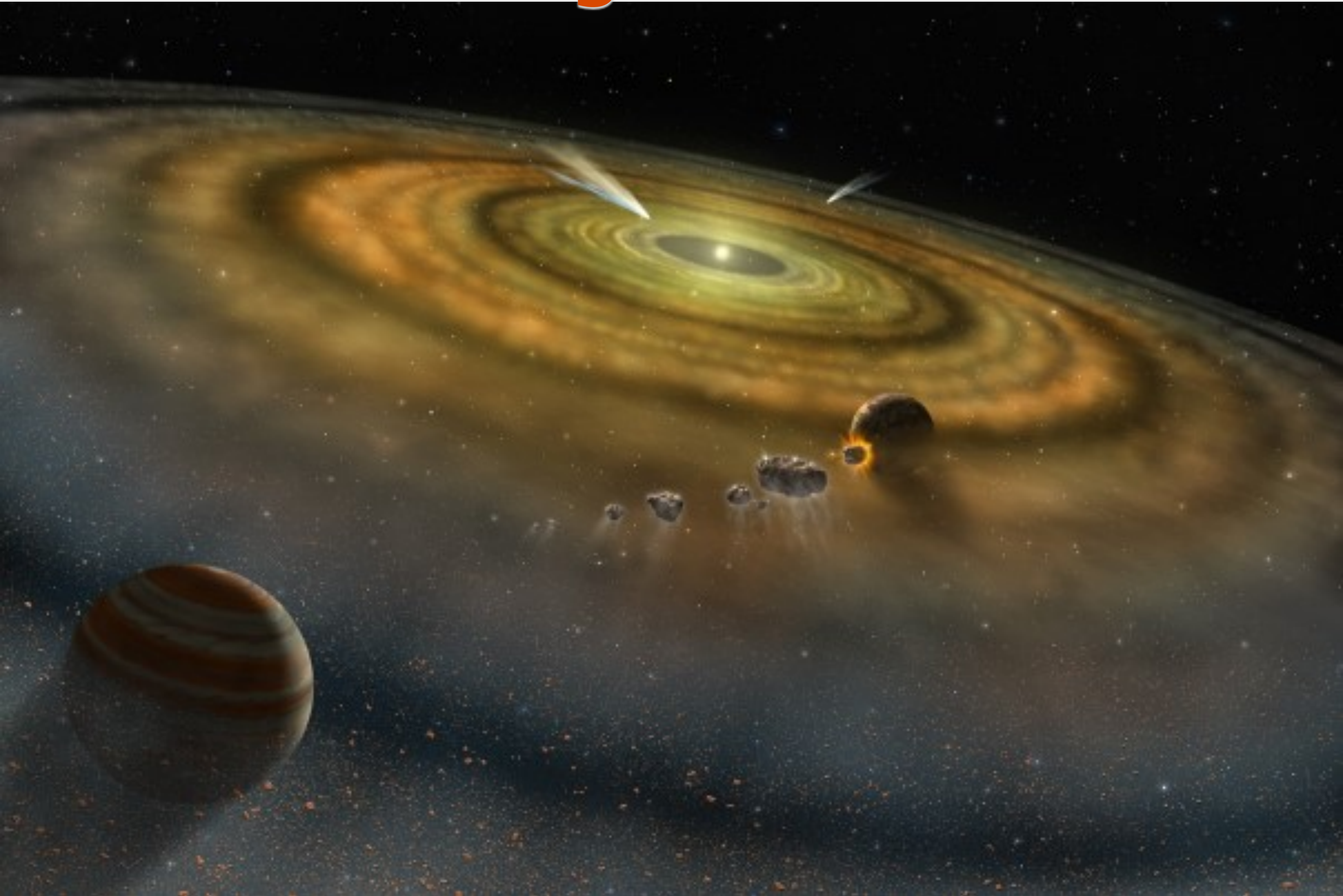


L1527 IRS:

Alter < 300.000 Jahre

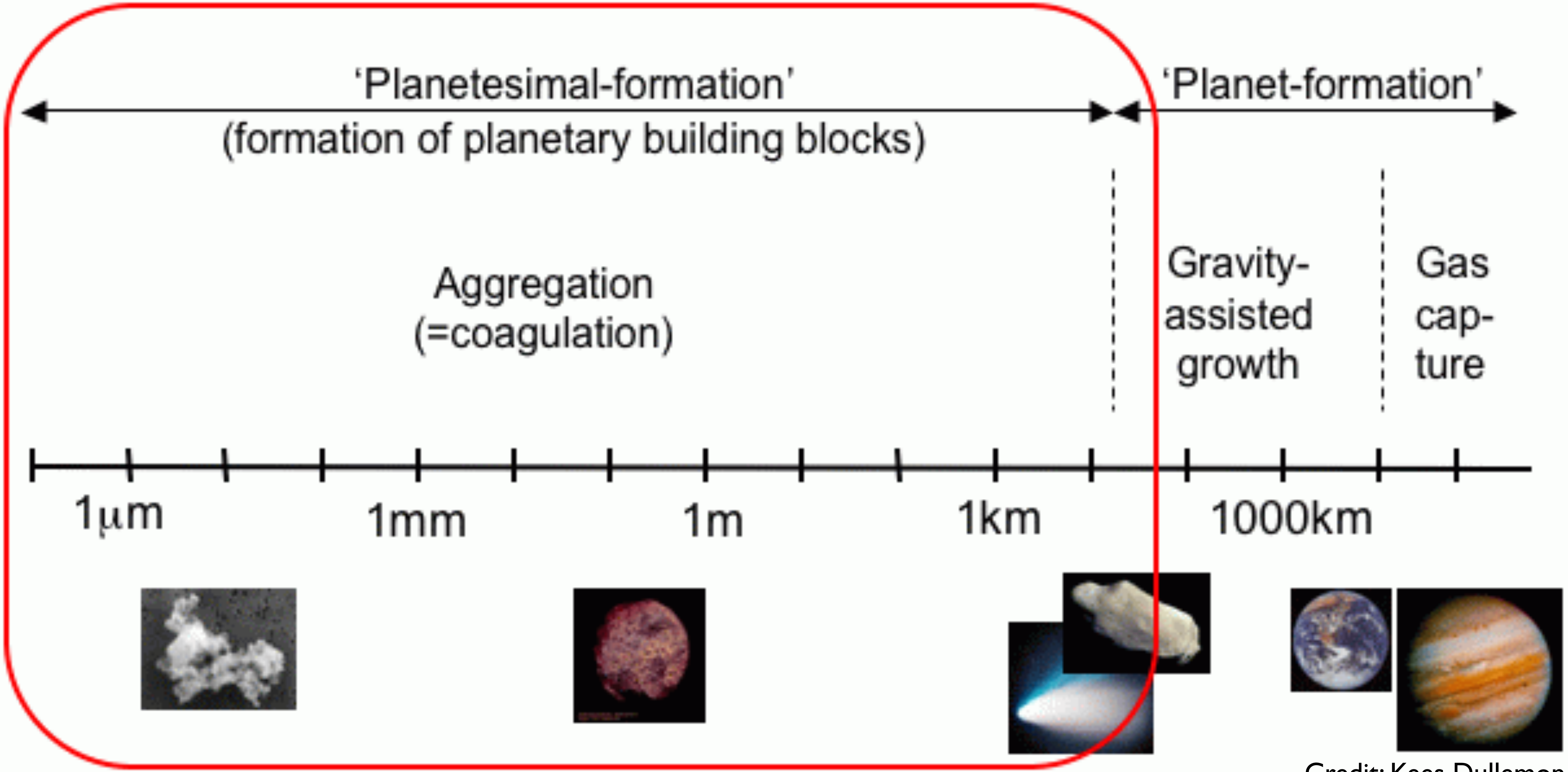
Masse $\sim 0.2\ M_\odot$

Entstehung von Planeten



Entstehung von Planeten

Vom Staub zu Planeten

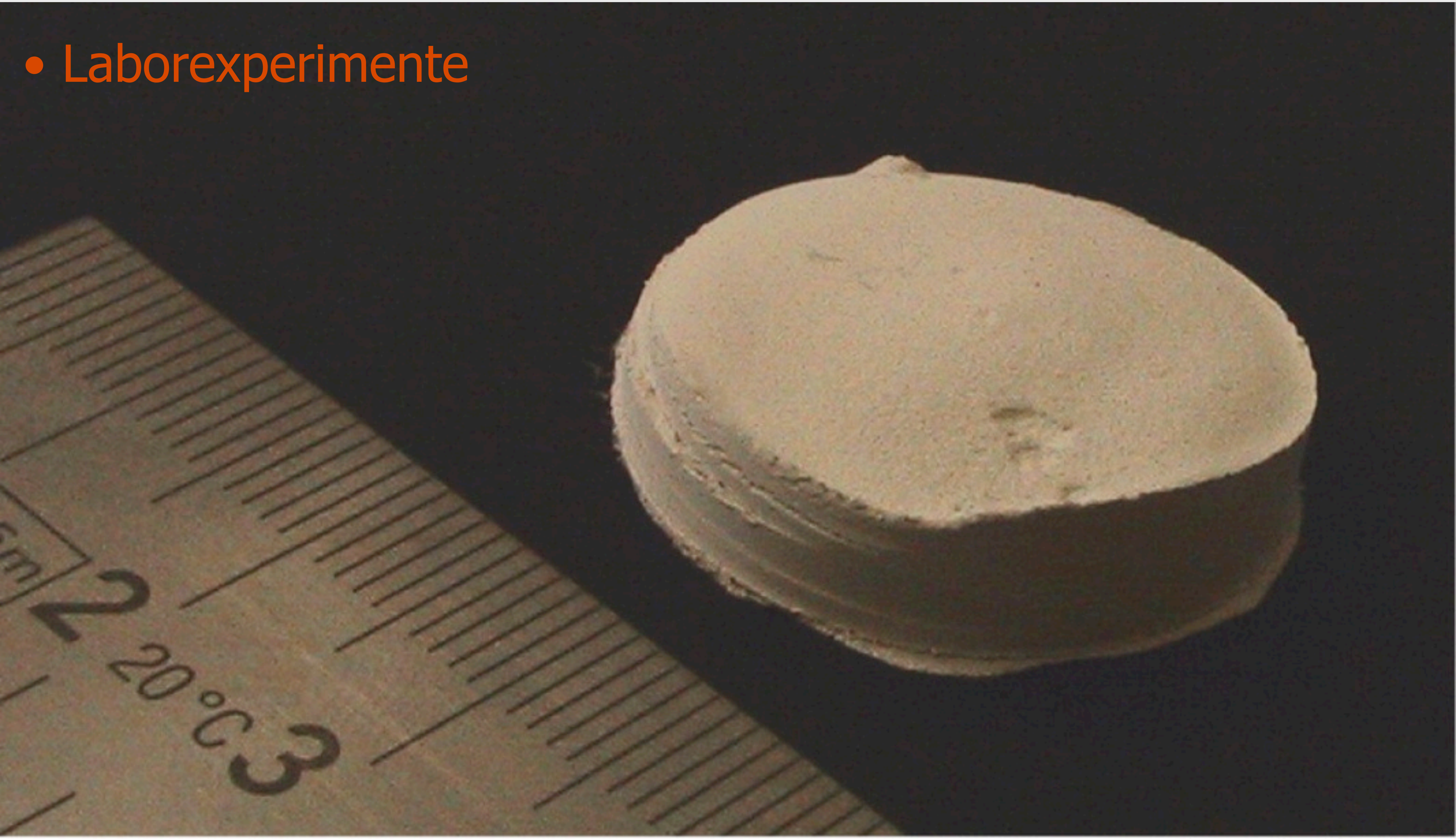


Credit: Kees Dullemon

⇒ “Wachstum”: vom Staub zum Planeten: 12 Größenordnungen

Staubwachstum

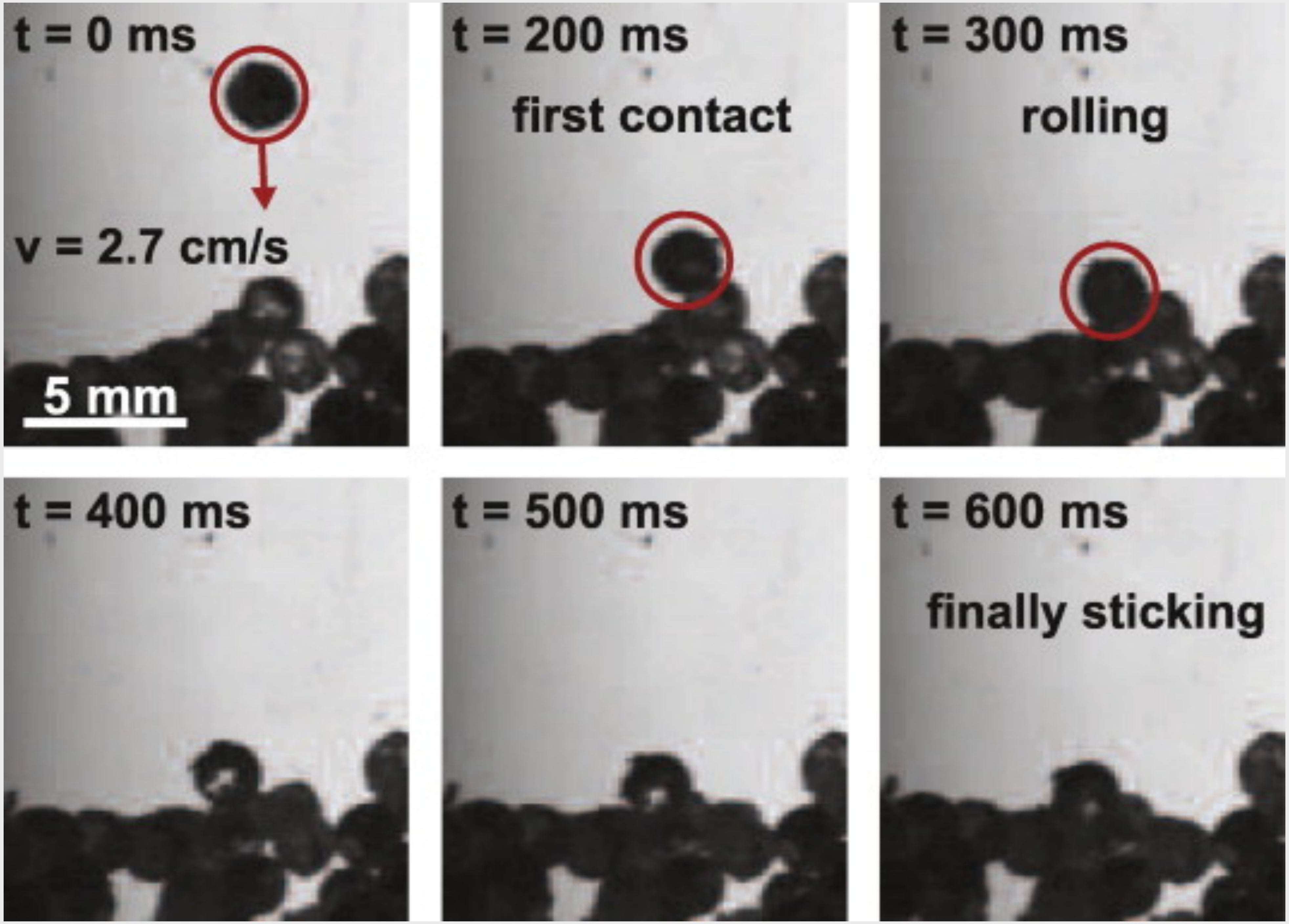
- Laborexperimente



Blum J, Wurm G. 2008.

Staubwachstum

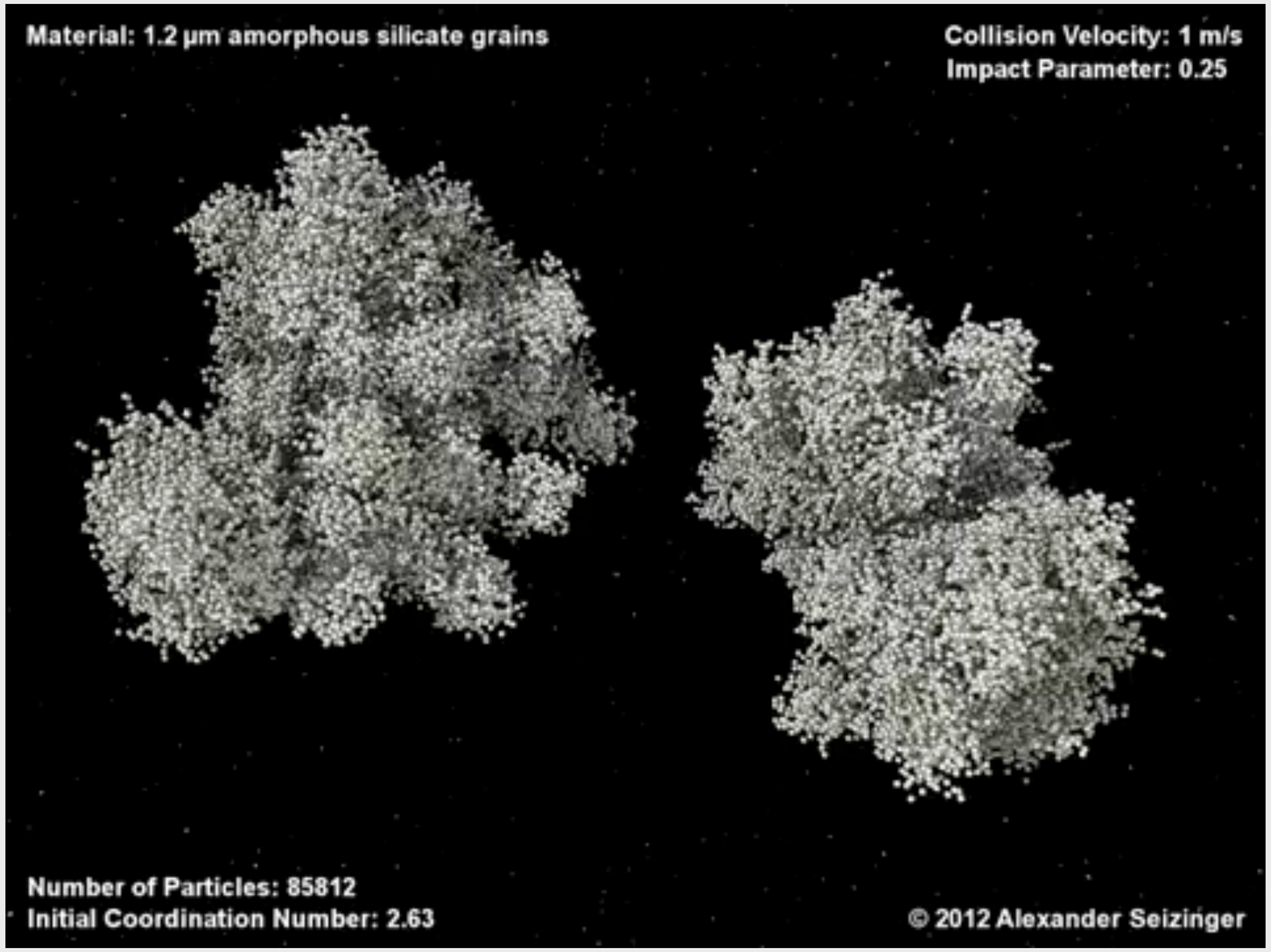
- Laborexperimente



Beitz et al. 2012, Braunschweig

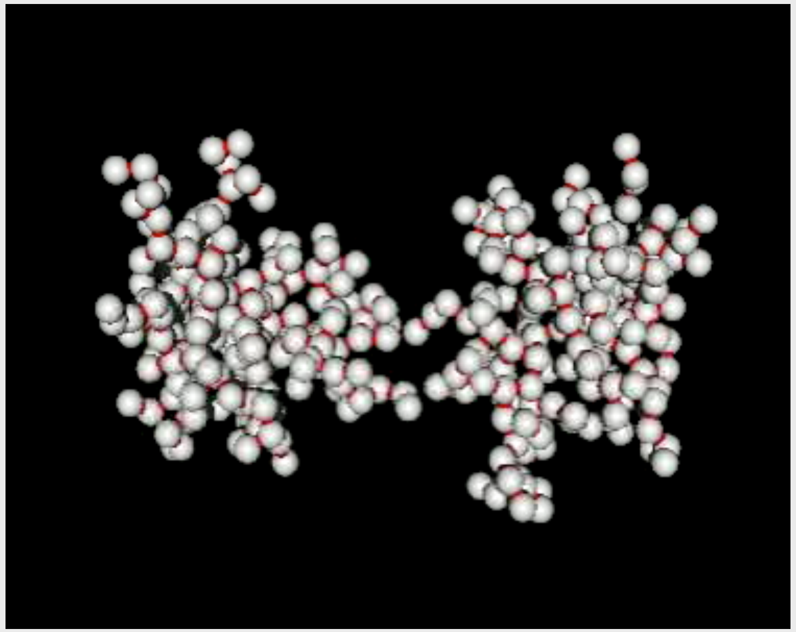
Staubwachstum

- Computersimulationen

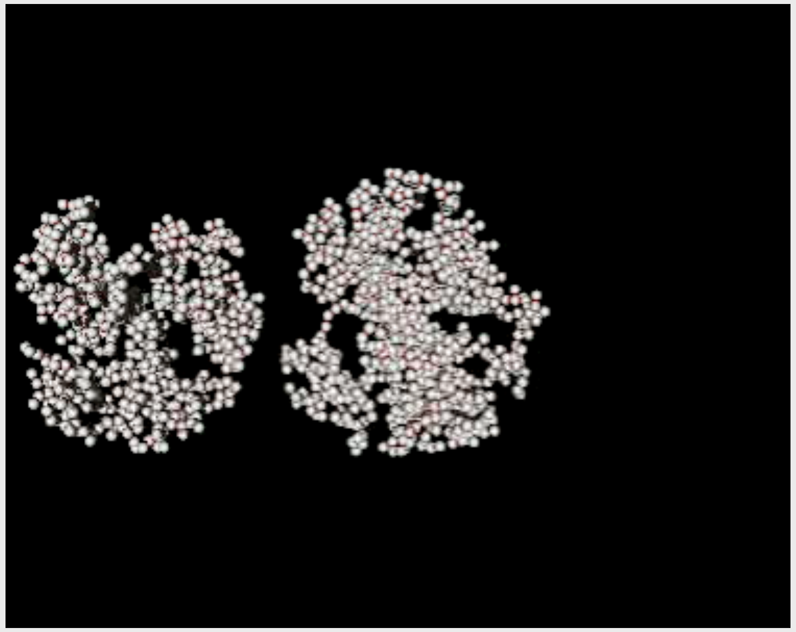


Staubwachstum

- Computersimulationen: *Paszun & Dominik* 2009

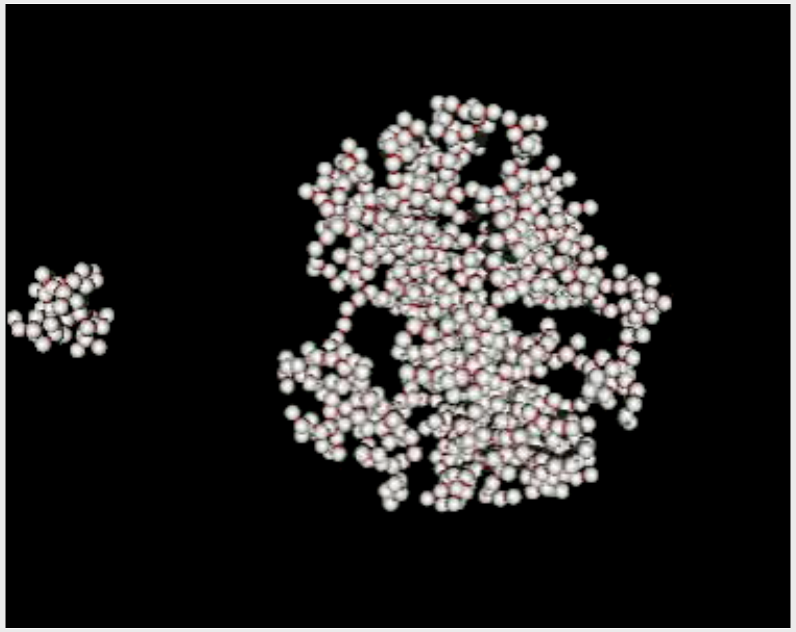


$v_{imp} = 0.75$ m/sec

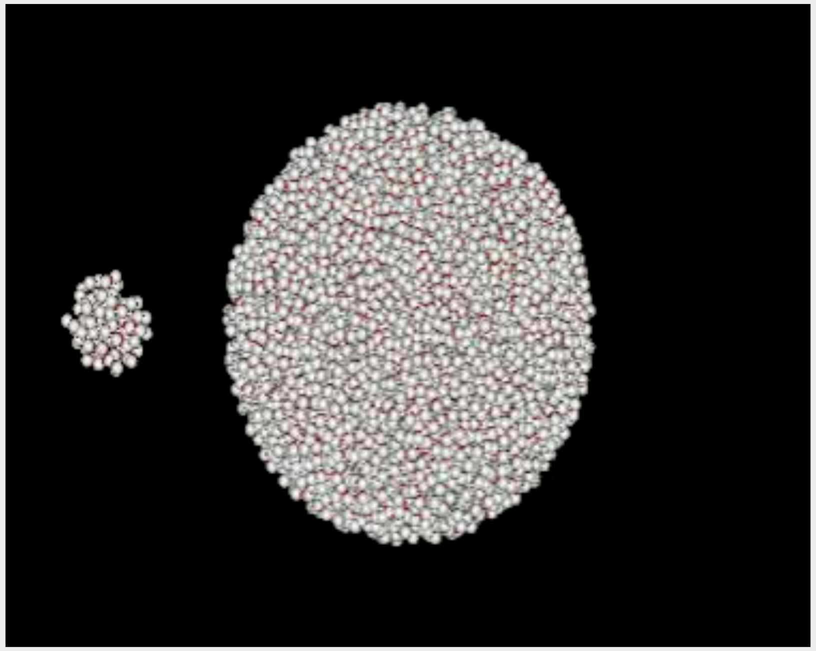


$v_{imp} = 2$ m/sec

Teilchen: SiO_2
Monomers
$D = 1.2\ \mu m$

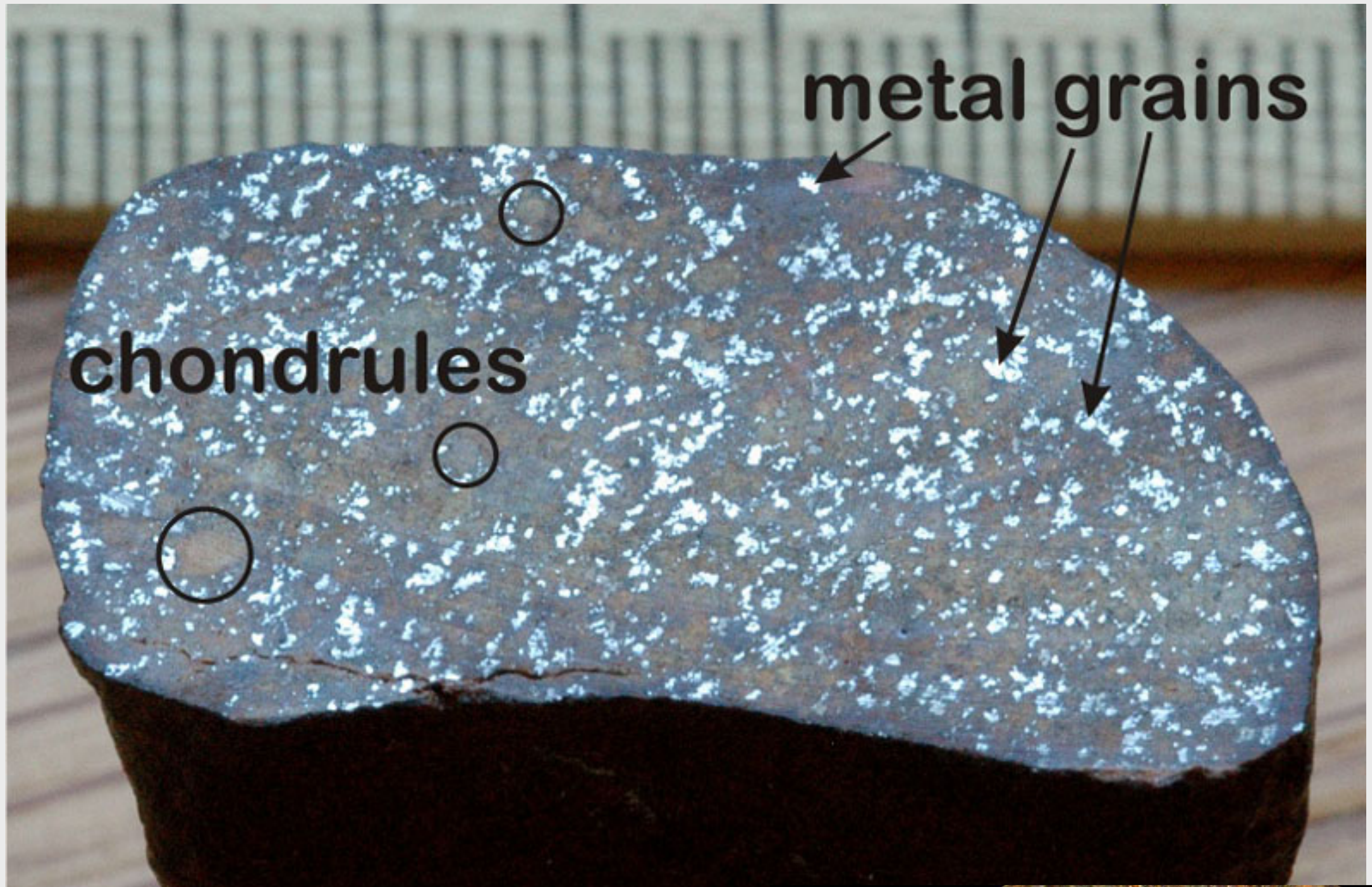


$v_{imp} = 2$ m/sec

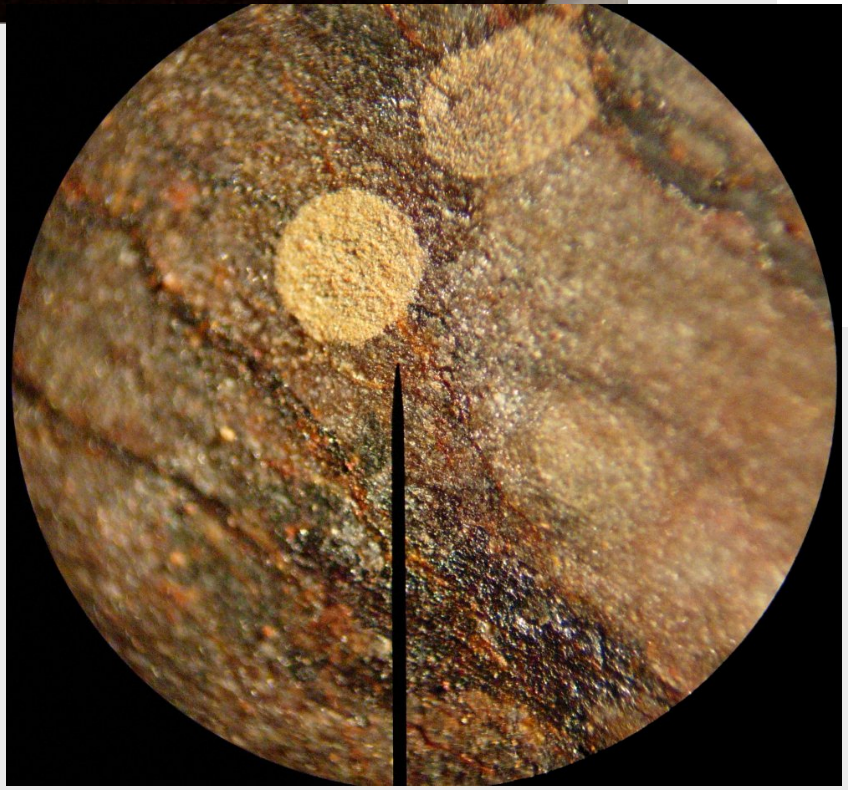


$v_{imp} = 25$ m/sec

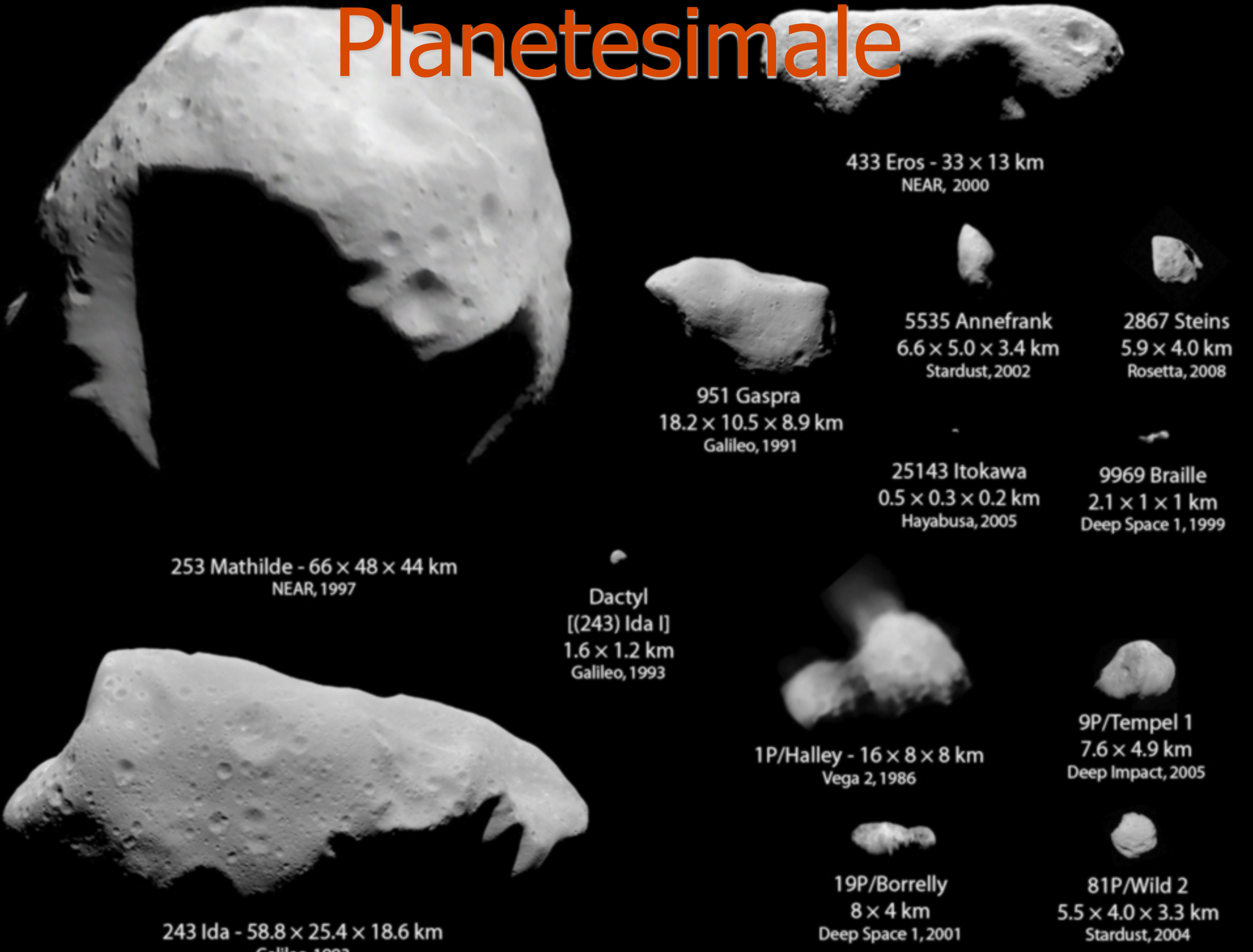
Staubwachstum



Chondren in Meteoriten



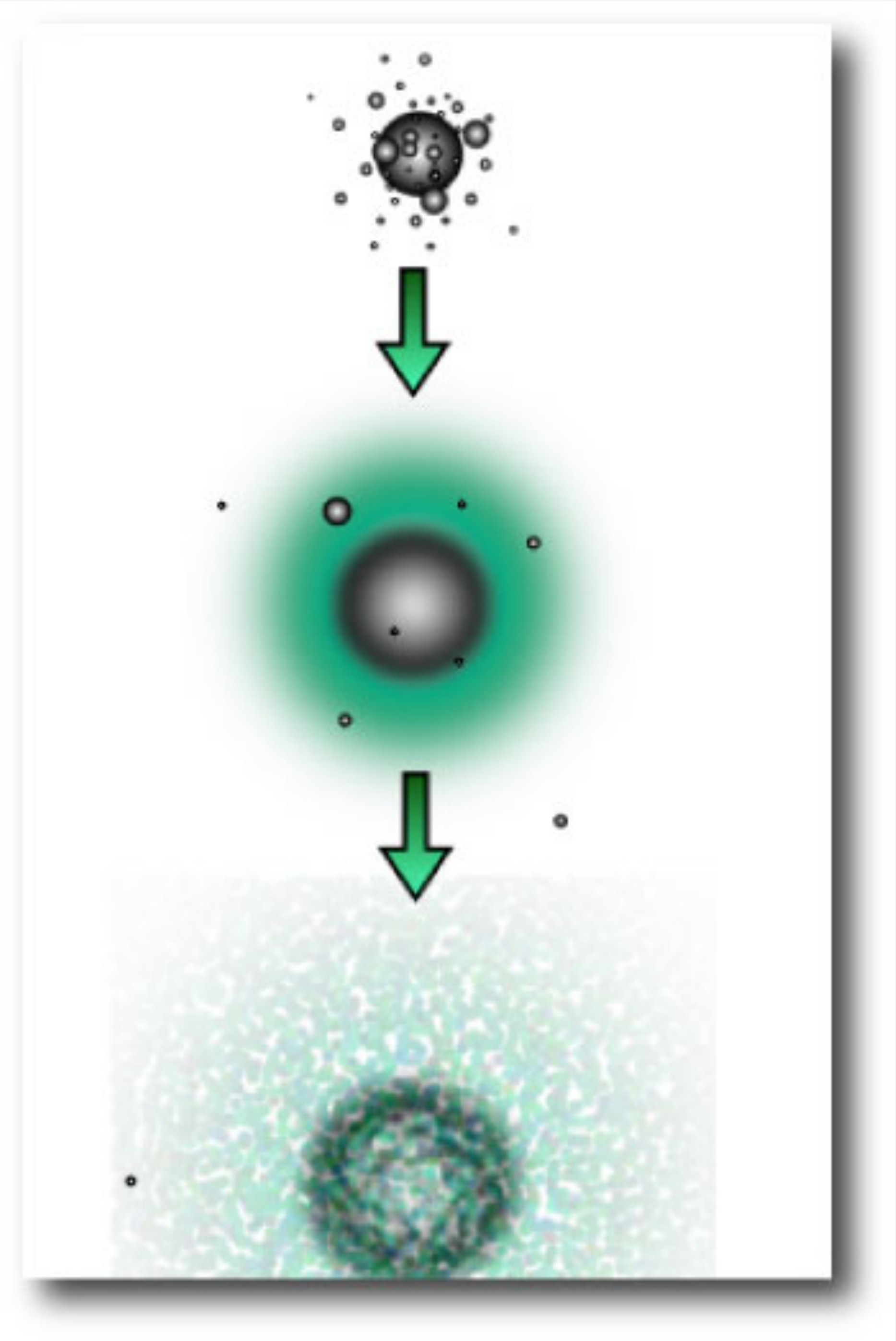
Planetesimale



Credits: E. Lakdawalla von der Planetary Society

Entstehung von Planeten

Zwei Hauptmechanismen



- **"core accretion" model**:

  ⟹ **langsames** Anwachsen durch Koagulation:
  t ~ 1000 Jahre für cm-Objekte
  \+ Anziehung durch Gravitation

  ⟹ effizient in Sternnähe ($a < 5$ AE) in der Scheibenmitte

  ⟹ terrestrische Planeten?

Entstehung von Planeten

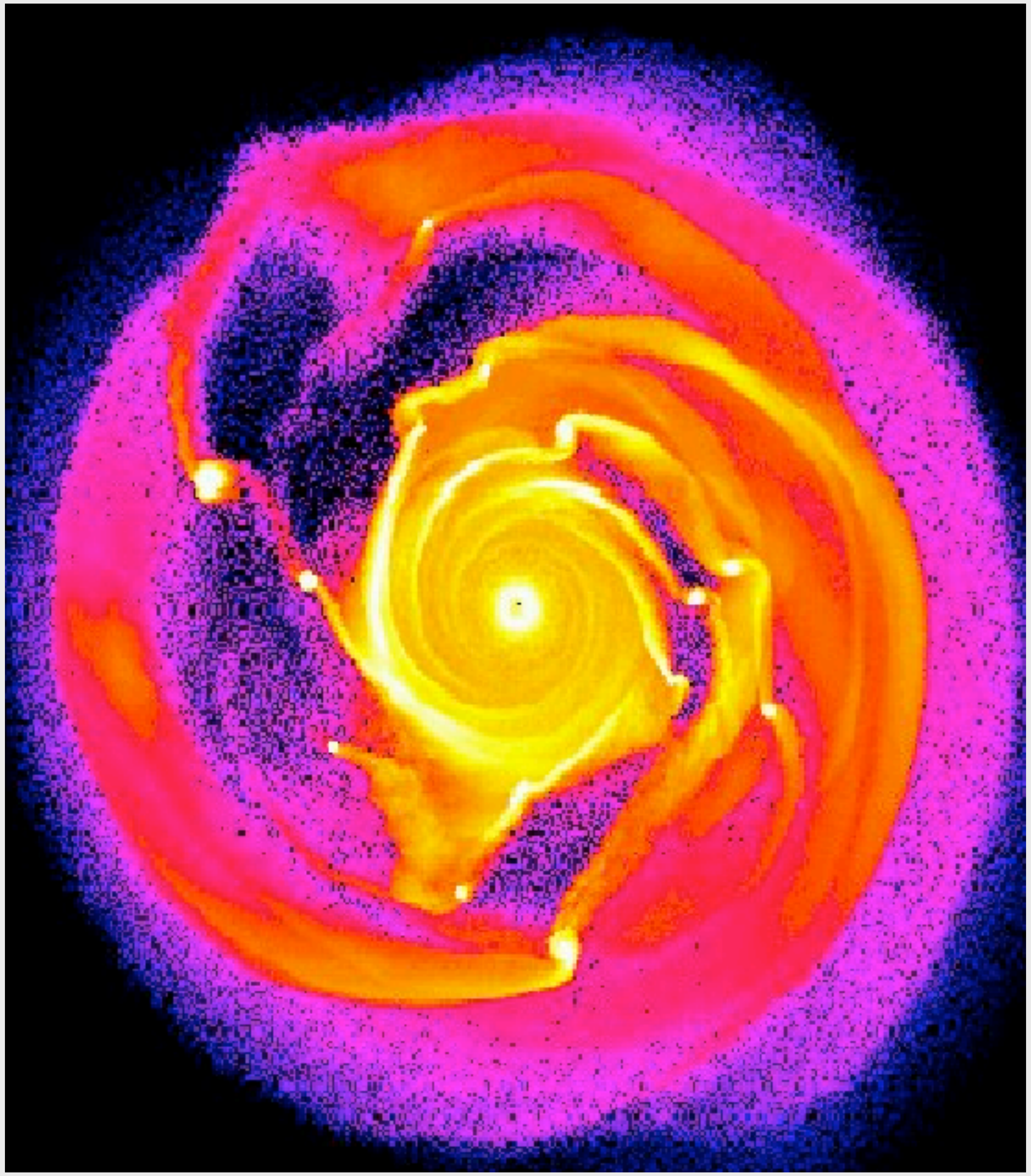
Zwei Hauptmechanismen

- **"core accretion" model**
- **Gravitationsinstabilität in der Scheibe**:

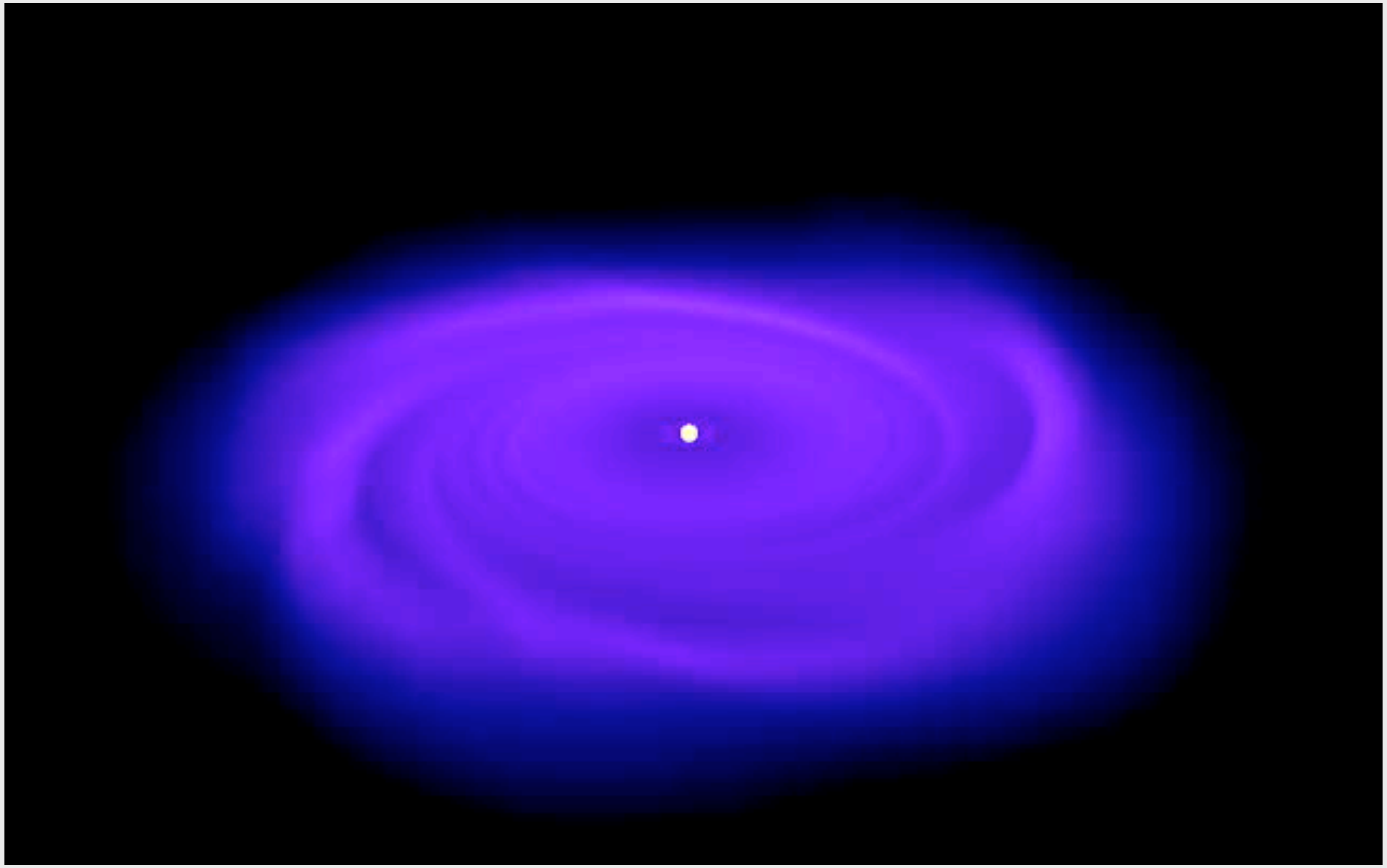
⟹ schneller Kollaps von dichten, kalten Regionen:
$t \sim 10$ Jahre für Gasriesen!

⟹ effizient in kühlen Außenbereichen der Scheibe

⟹ Gasriesen?



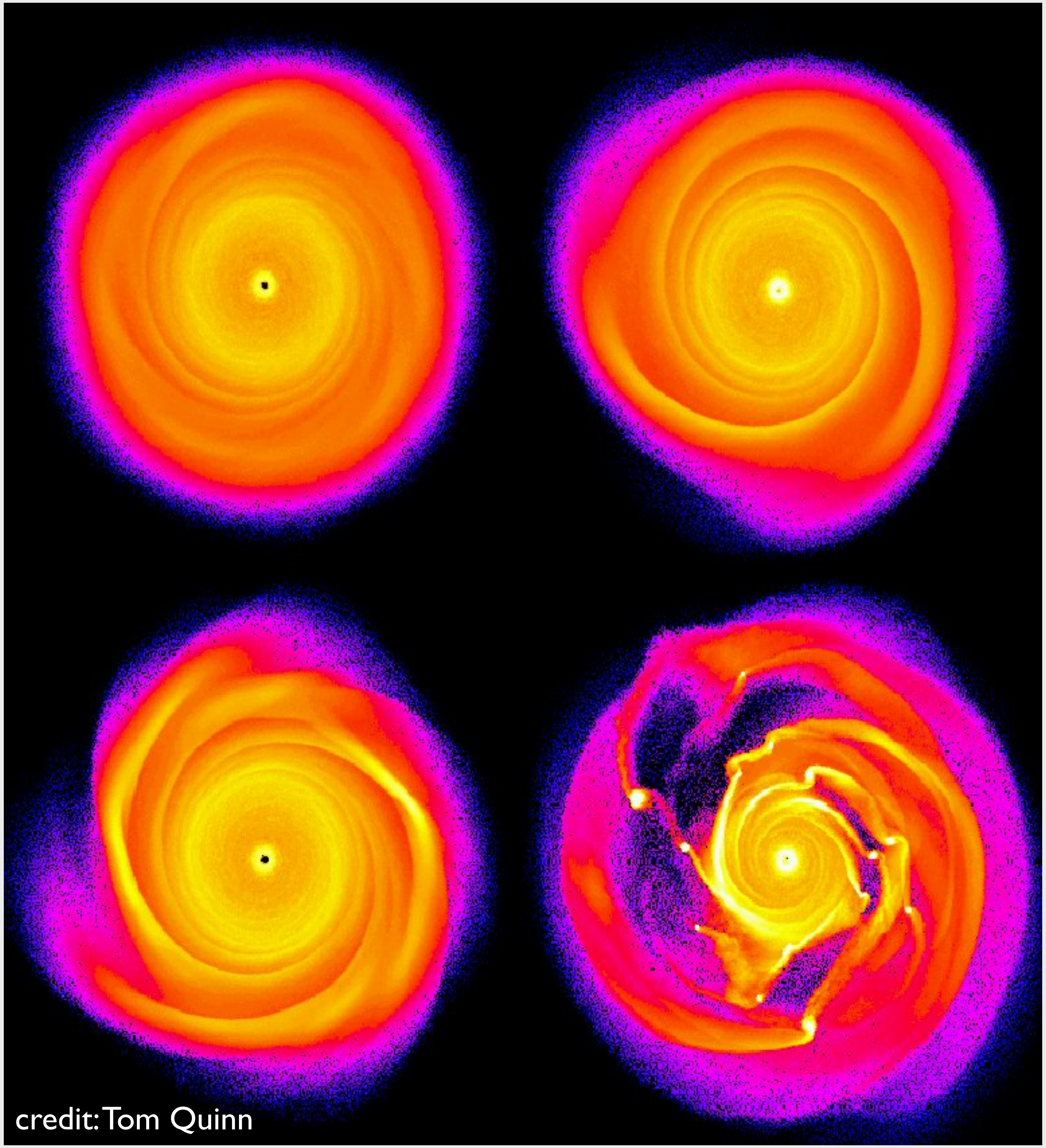
Entstehung von Planeten



credit: James Wadsley

- Gravitationsinstabilität / Fragmentation der protoplanetaren Scheibe

Entstehung von Planeten


credit: Tom Quinn

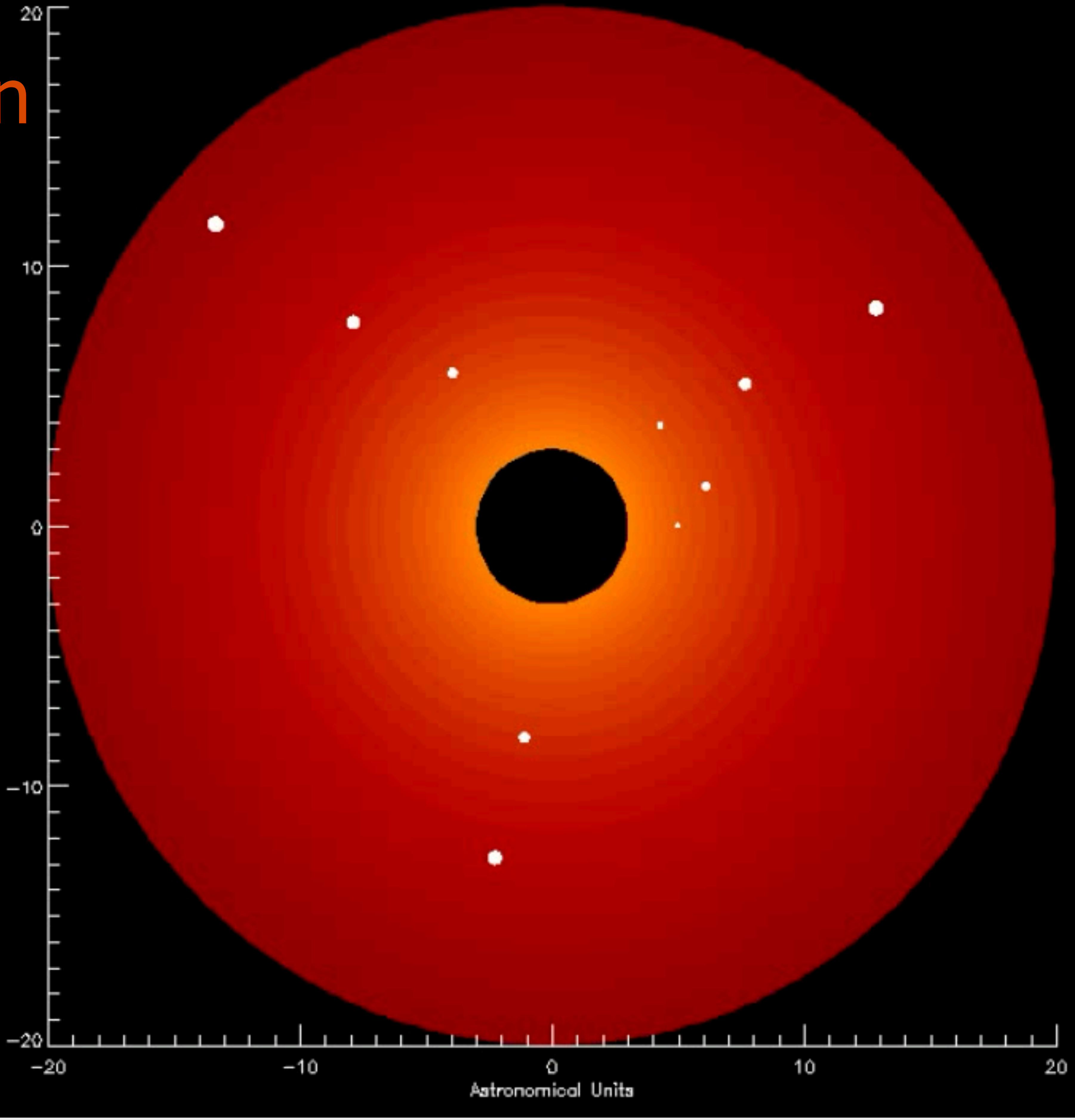
Fragmentation der Scheibe durch Gravitationsinstabilität

$\Longrightarrow$ "schwere" Scheibe notwendig (~ 1 $M_\odot$)

$\Longrightarrow$ fester Kern der Gasplaneten?

$\Longrightarrow$ "core accretion" + Fragmentation?

Migration



Willy Kley & Richard Nelson 2012

Entstehung von Planeten

Offene Fragen

- **Drehimpulsverteilung:**
  - Masse der Sonne im Sonnensystem: 99.9 %
  - Drehimpuls der Sonne nur 0.5%

  ⇒ wie wird der Drehimpuls umverteilt?

- **Entstehung Asteroidengürtel / Kuiper belt:**
  - Kollision mit Protoplaneten?

- **Statistik:**
  - erdähnliche Planeten / Gasriesen
  - Habitable Zone

hamburger sternwarte

Leben im Weltraum?

Drake-Gleichung (von Frank Drake 1961 vorgestellt):

$$N = R_* \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L$$

- N : Anzahl intelligenter Zivilisationen

- R_* : Sternentstehungsrate
- f_p : Sterne mit Planetensystemen
- n_e : Planeten in bewohnbarer (habitabler) Zone
- $f_l * f_i$: Anteil mit intelligentem Leben
- f_c : Willig zur Kommunikation
- L : Lebensdauer einer solchen Zivilisation