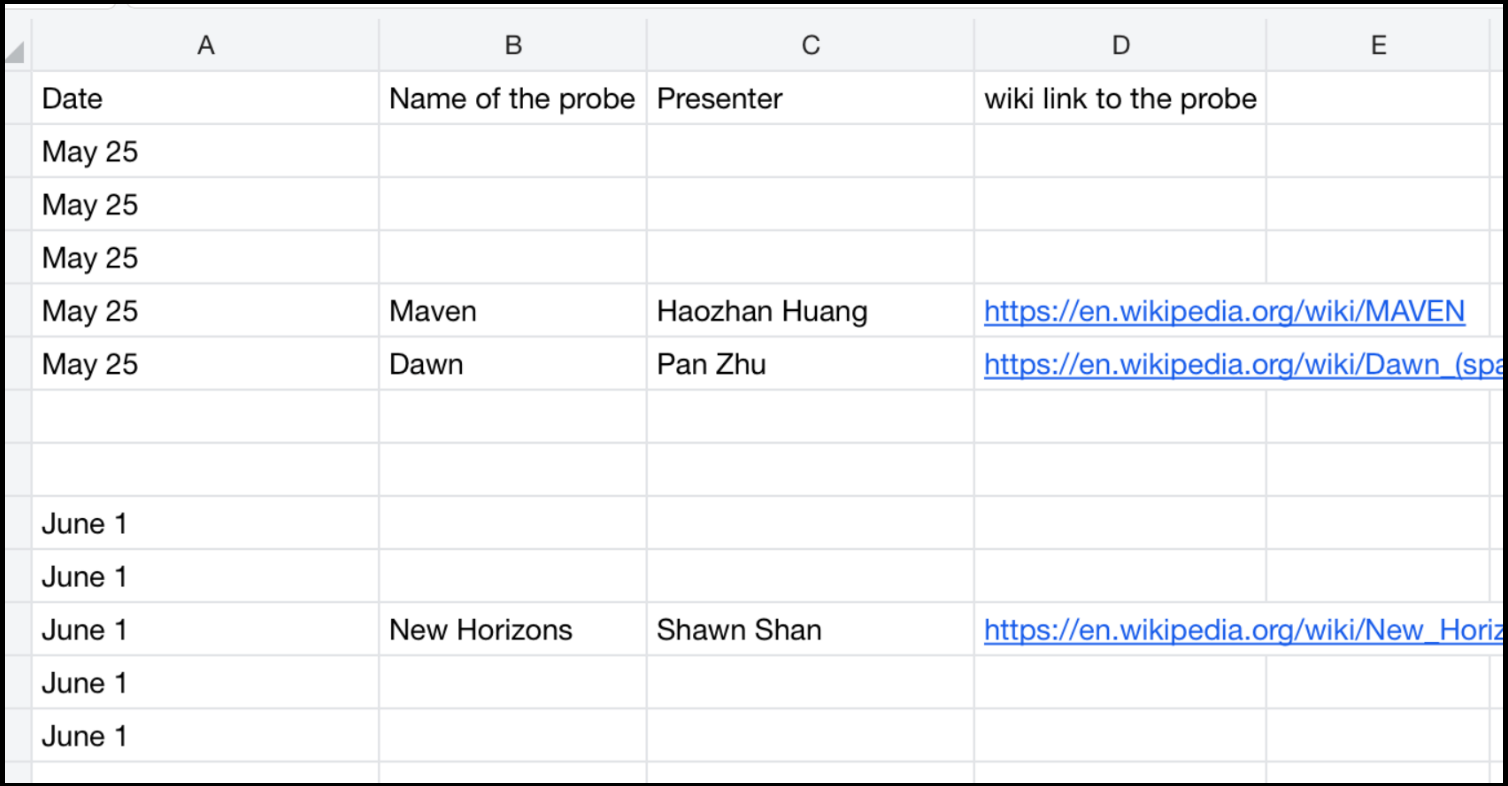
2026.05.09

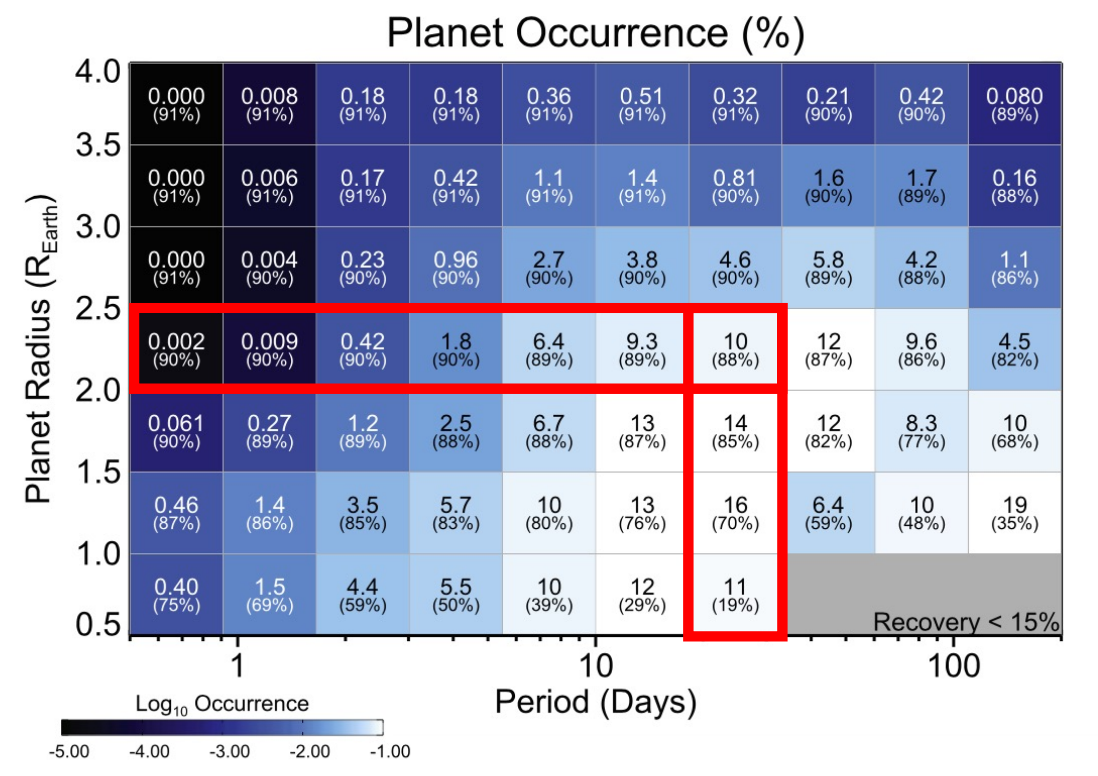


A	B	C	D	E
Date	Name of the probe	Presenter	wiki link to the probe	
May 25				
May 25				
May 25				
May 25	Maven	Haozhan Huang	https://en.wikipedia.org/wiki/MAVEN	
May 25	Dawn	Pan Zhu	https://en.wikipedia.org/wiki/Dawn_(spa	
June 1				
June 1				
June 1	New Horizons	Shawn Shan	https://en.wikipedia.org/wiki/New_Horiz	
June 1				
June 1				

Exoplanet occurrence rate

How can we describe how common a class of planets is?

Planets around M dwarfs from Transit

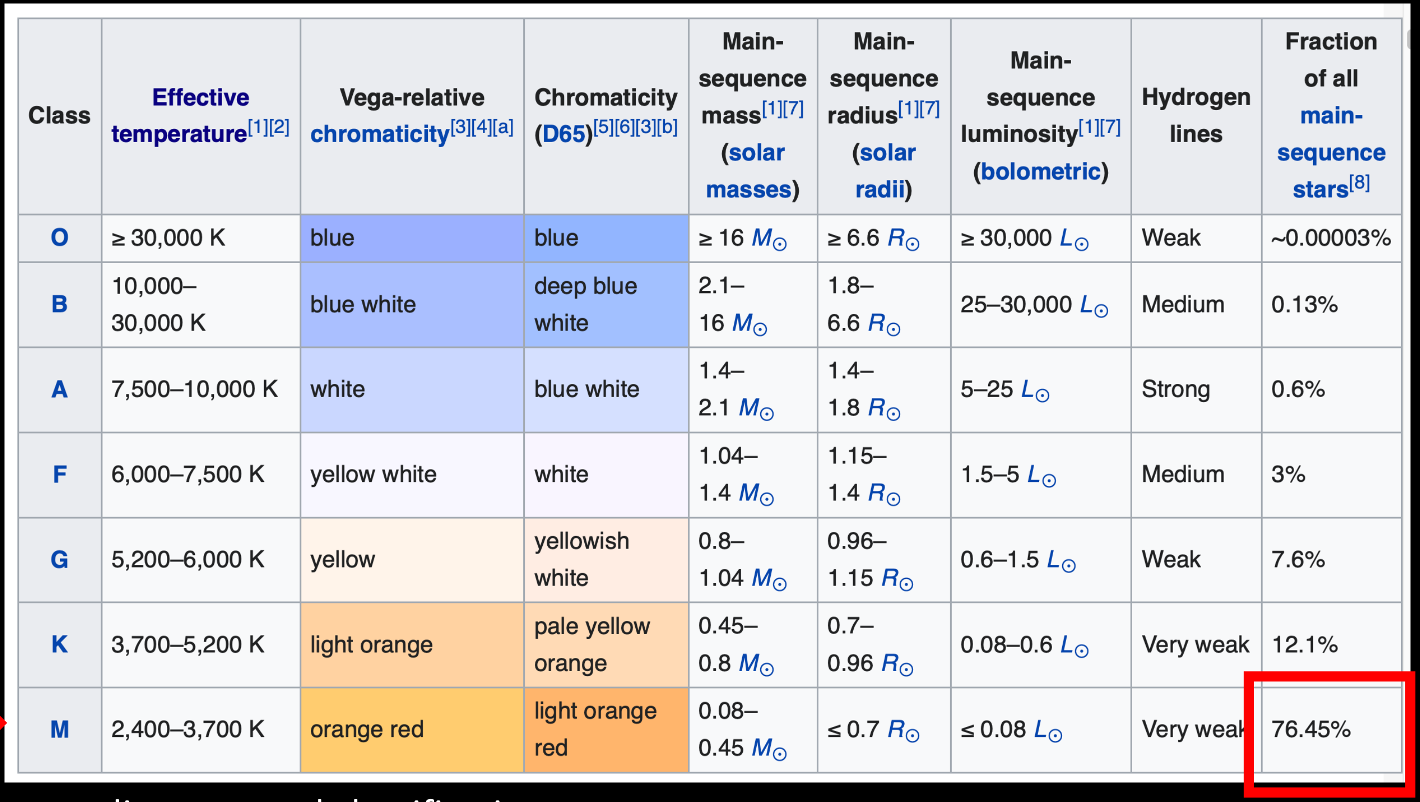


0.000 (91%)	0.008 (91%)	0.18 (91%)	0.18 (91%)	0.36 (91%)	0.51 (91%)	0.32 (91%)	0.21 (90%)	0.42 (90%)	0.080 (89%)
0.000 (91%)	0.006 (91%)	0.17 (91%)	0.42 (91%)	1.1 (91%)	1.4 (91%)	0.81 (90%)	1.6 (90%)	1.7 (89%)	0.16 (88%)
0.000 (91%)	0.004 (90%)	0.23 (90%)	0.96 (90%)	2.7 (90%)	3.8 (90%)	4.6 (90%)	5.8 (89%)	4.2 (88%)	1.1 (86%)
0.002 (90%)	0.009 (90%)	0.42 (90%)	1.8 (90%)	6.4 (89%)	9.3 (89%)	10 (88%)	12 (87%)	9.6 (86%)	4.5 (82%)
0.061 (90%)	0.27 (89%)	1.2 (89%)	2.5 (88%)	6.7 (88%)	13 (87%)	14 (85%)	12 (82%)	8.3 (77%)	10 (68%)
0.46 (87%)	1.4 (86%)	3.5 (85%)	5.7 (83%)	10 (80%)	13 (76%)	16 (70%)	6.4 (59%)	10 (48%)	19 (35%)
0.40 (75%)	1.5 (69%)	4.4 (59%)	5.5 (50%)	10 (39%)	12 (29%)	11 (19%)	Recovery < 15%		

- Binned planet occurrence rate in period-planet radius space.
- The numbers within each grid cell indicate the planet occurrence rate as a percentage (top) and the percentage of injected planet that are recoverable (bottom).
- The gray regions have injected planet recovery rates below 15%.
- ***Add the numbers up, you find on average we have more planets than M stars!***

Dressing & Charbonneau 2015

Example 2: Planets around M dwarfs from Transit



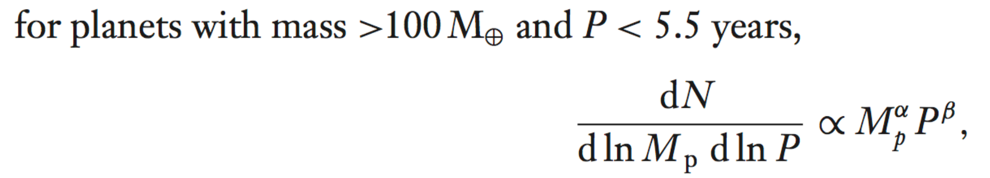
Class	Effective temperature[1][2]	Vega-relative chromaticity[3][4][a]	Chromaticity (D65)[5][6][3][b]	Main-sequence mass[1][7] (solar masses)	Main-sequence radius[1][7] (solar radii)	Main-sequence luminosity[1][7] (bolometric)	Hydrogen lines	Fraction of all main-sequence stars[8]
O	≥ 30,000 K	blue	blue	≥ 16 $M_\odot$	≥ 6.6 $R_\odot$	≥ 30,000 $L_\odot$	Weak	~0.00003%
B	10,000–30,000 K	blue white	deep blue white	2.1–16 $M_\odot$	1.8–6.6 $R_\odot$	25–30,000 $L_\odot$	Medium	0.13%
A	7,500–10,000 K	white	blue white	1.4–2.1 $M_\odot$	1.4–1.8 $R_\odot$	5–25 $L_\odot$	Strong	0.6%
F	6,000–7,500 K	yellow white	white	1.04–1.4 $M_\odot$	1.15–1.4 $R_\odot$	1.5–5 $L_\odot$	Medium	3%
G	5,200–6,000 K	yellow	yellowish white	0.8–1.04 $M_\odot$	0.96–1.15 $R_\odot$	0.6–1.5 $L_\odot$	Weak	7.6%
K	3,700–5,200 K	light orange	pale yellow orange	0.45–0.8 $M_\odot$	0.7–0.96 $R_\odot$	0.08–0.6 $L_\odot$	Very weak	12.1%
M	2,400–3,700 K	orange red	light orange red	0.08–0.45 $M_\odot$	≤ 0.7 $R_\odot$	≤ 0.08 $L_\odot$	Very weak	76.45%

Supplementary reading: spectral classification
en.wikipedia.org/wiki/Stellar_classification

Exoplanet occurrence rate

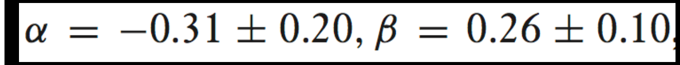
How can we describe how common a class of planets is?

Example 1 : Radial velocity statistics for planets around solar type stars (Cumming et al. 2008)



for planets with mass $>100\,\mathrm{M}_\oplus$ and $P < 5.5$ years,

$$\frac{\mathrm{d}N}{\mathrm{d}\ln M_\mathrm{p}\,\mathrm{d}\ln P} \propto M_p^\alpha P^\beta,$$

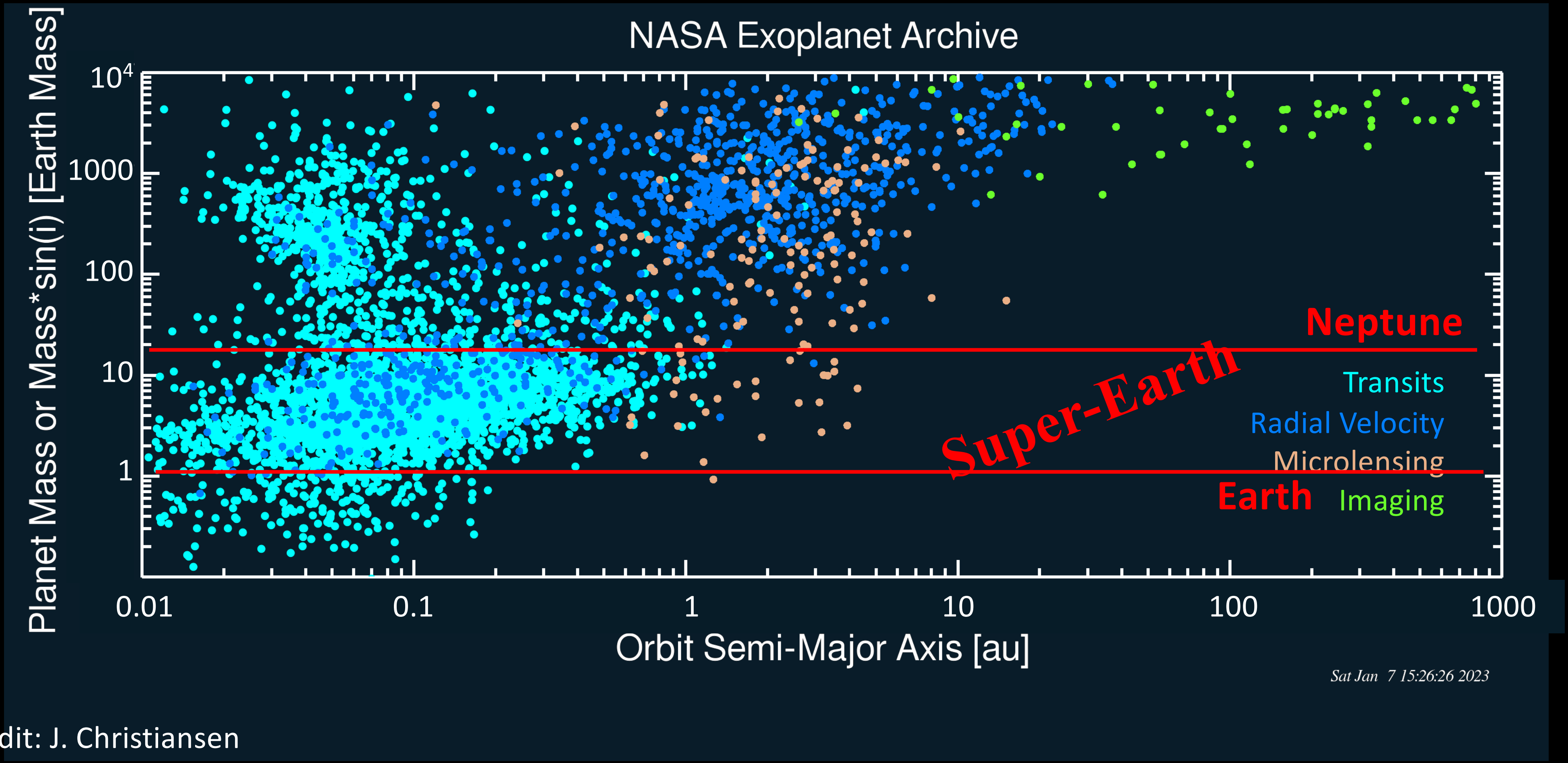


$\alpha = -0.31 \pm 0.20,\ \beta = 0.26 \pm 0.10$

Total number of planets in a bin:

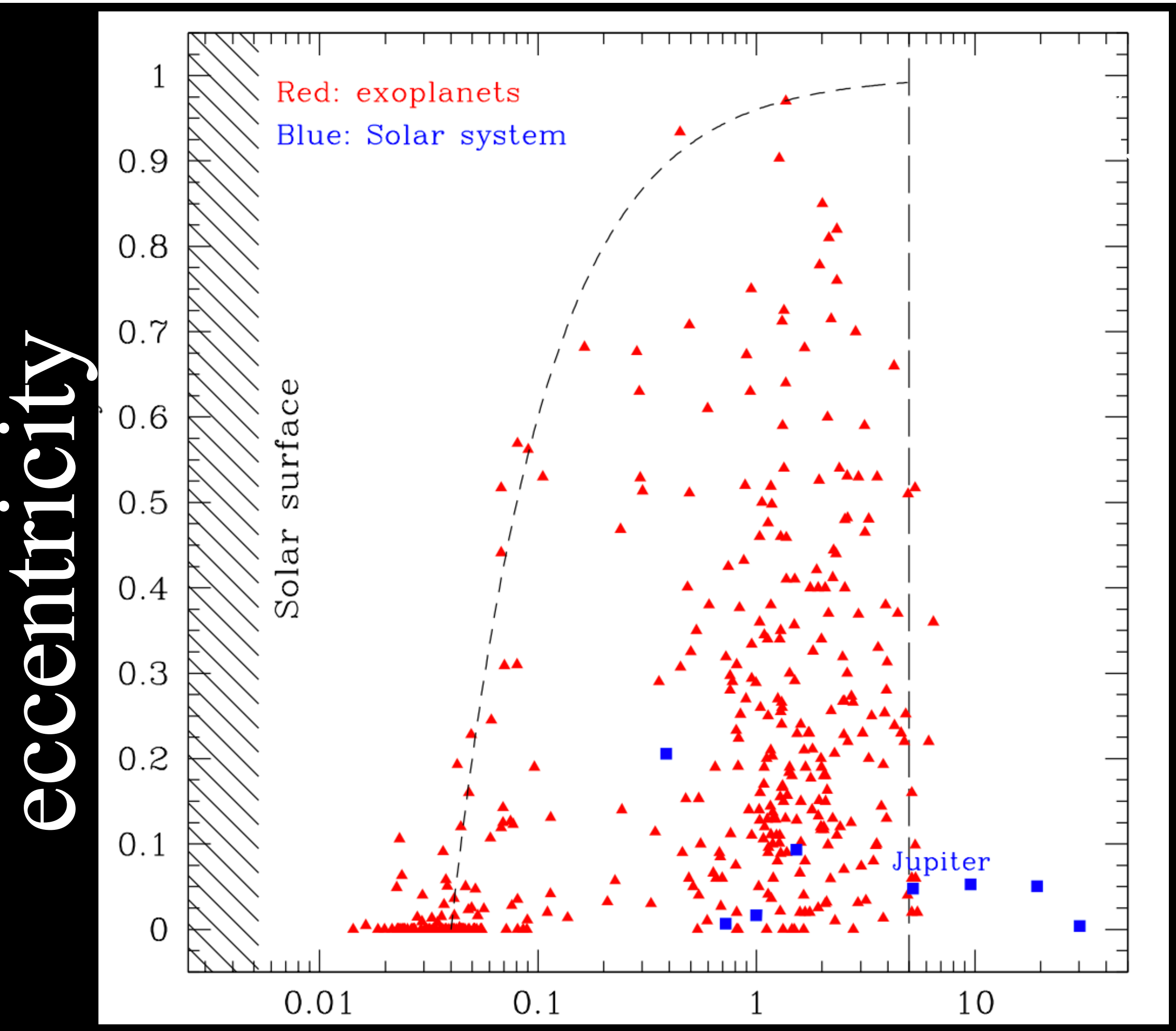
Exoplanet occurrence rate

Fact I: Super-Earths are the most common among detected planets



Credit: J. Christiansen

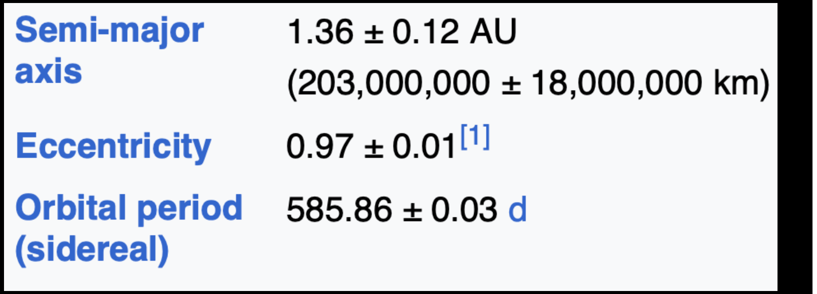
Fact II: Eccentricity



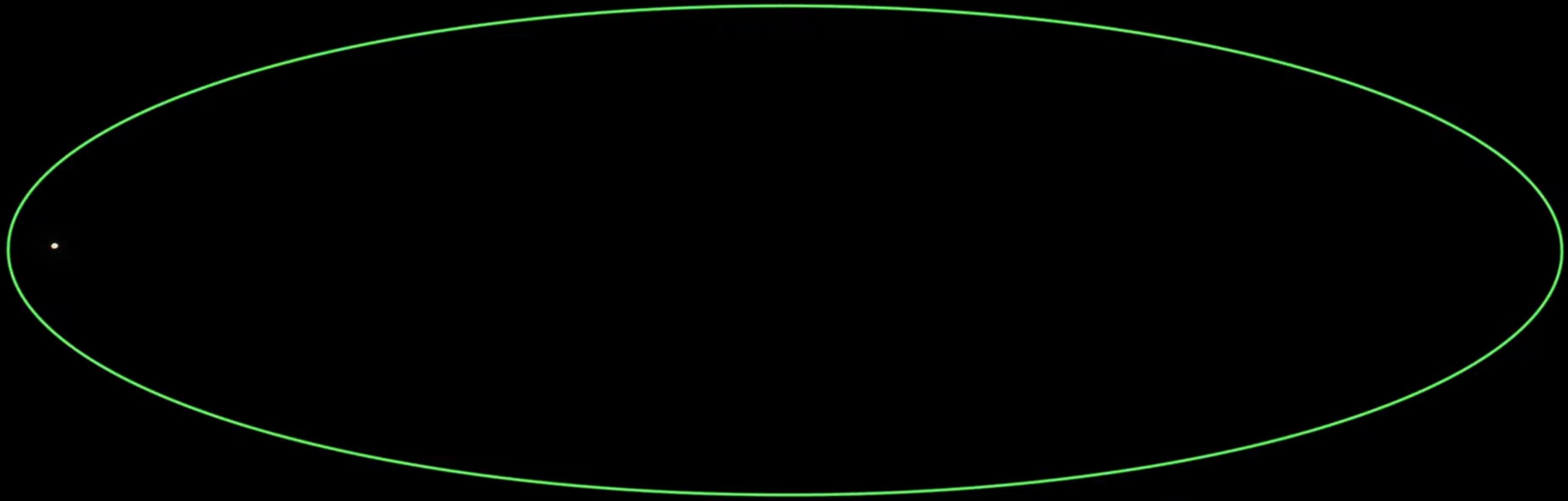
eccentricity

semi-major axis / AU

HD 20782 b



Semi-major axis	1.36 ± 0.12 AU (203,000,000 ± 18,000,000 km)
Eccentricity	0.97 ± 0.01[1]
Orbital period (sidereal)	585.86 ± 0.03 d



Fact III

Small Planets Come in Two Sizes

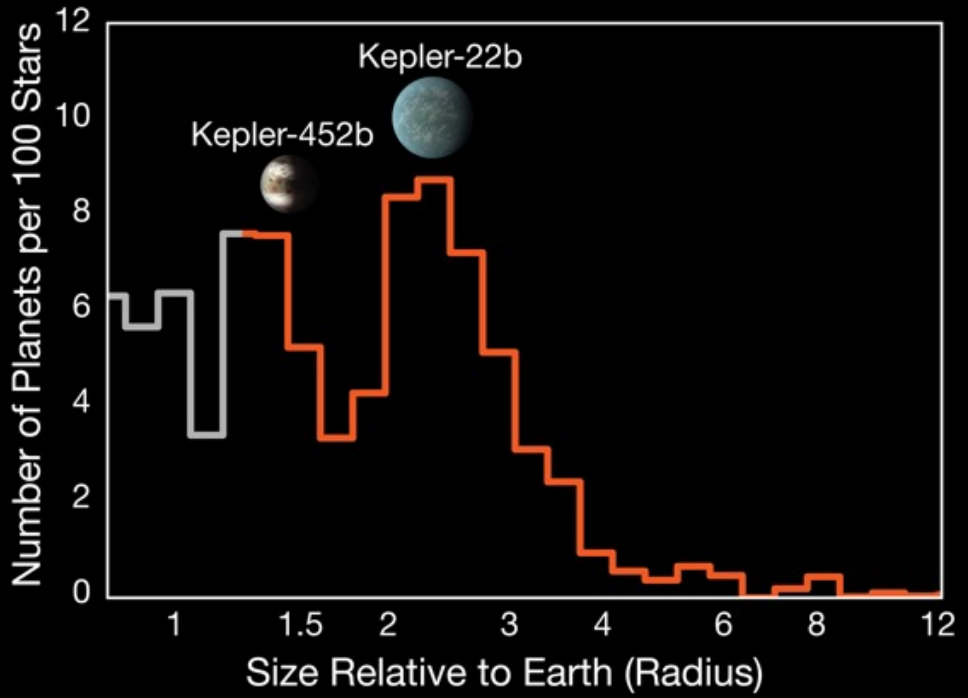
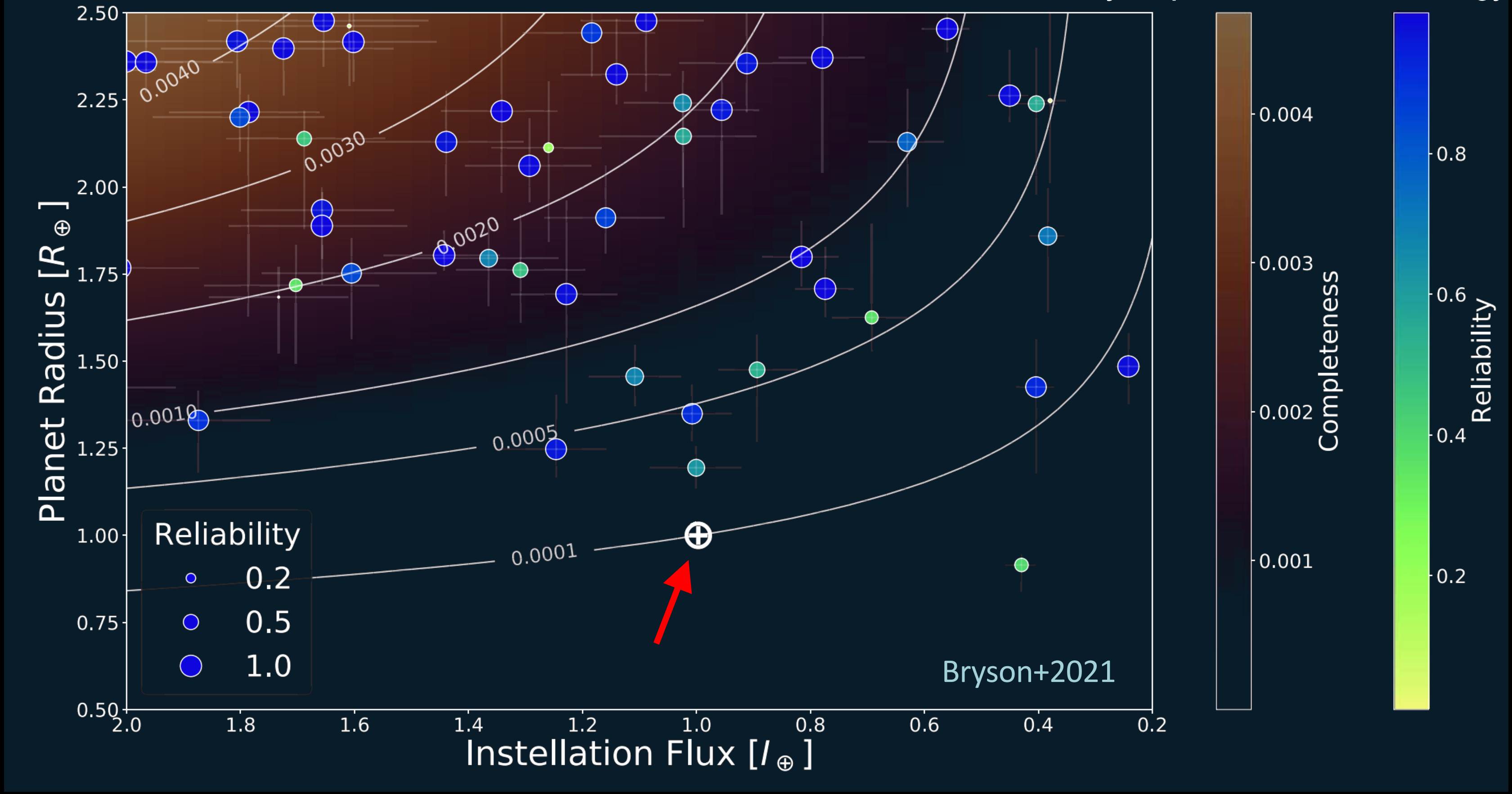


Image credit: NASA/Ames Research Center/CalTech/University of Hawaii/B.J. Fulton

A“second Earth”

The term eta-Earth (also written as ZE) is defined as the mean number per star of rocky planets with between 1 and 1.5-2 Earth-radii that reside in the optimistic habitable zone (HZ) of their host star. -- Source: Encyclopedia of Astrobiology



Credit: J. Christiansen

A“second Earth”

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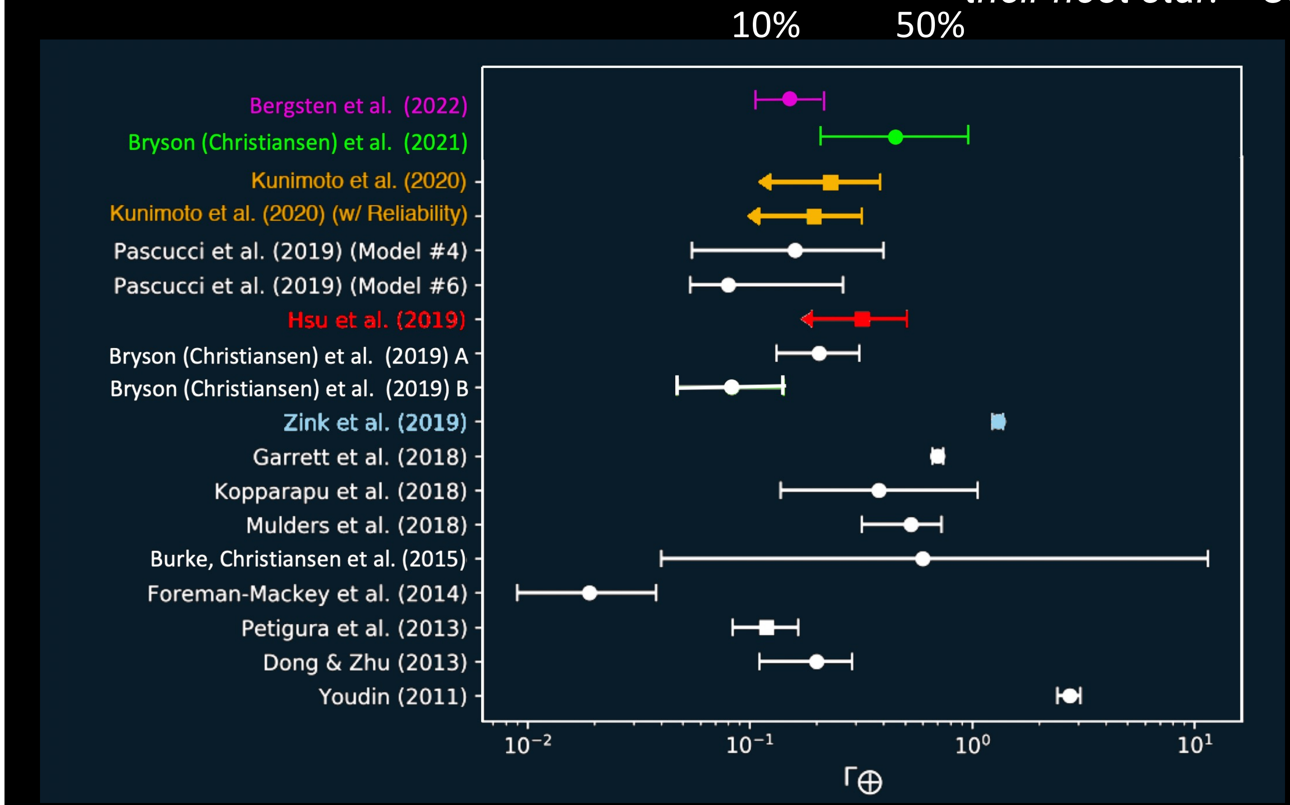


Modified from Hsu+2019

Major recent advances

- Gaia stellar parameters
- Inclusion of reliability
- Exploration of the impact of extrapolating from short-period populations
- Independent pipelines
- Investigation of different methodologies

Credit: J. Christiansen

The very basics from Chapter 14

- Is the solar system the only planetary system in the universe?
  - No
- When did people discover the first planet orbiting a normal star other than the Sun?
  - 1995
- How many planets have people discovered so far
  - A few thousands
- How common are planets in our galaxy
  - Very common; nearly every star has planets
- Is the Solar system common or not?
  - Unclear at the moment. There are many planetary systems quite different from the solar system

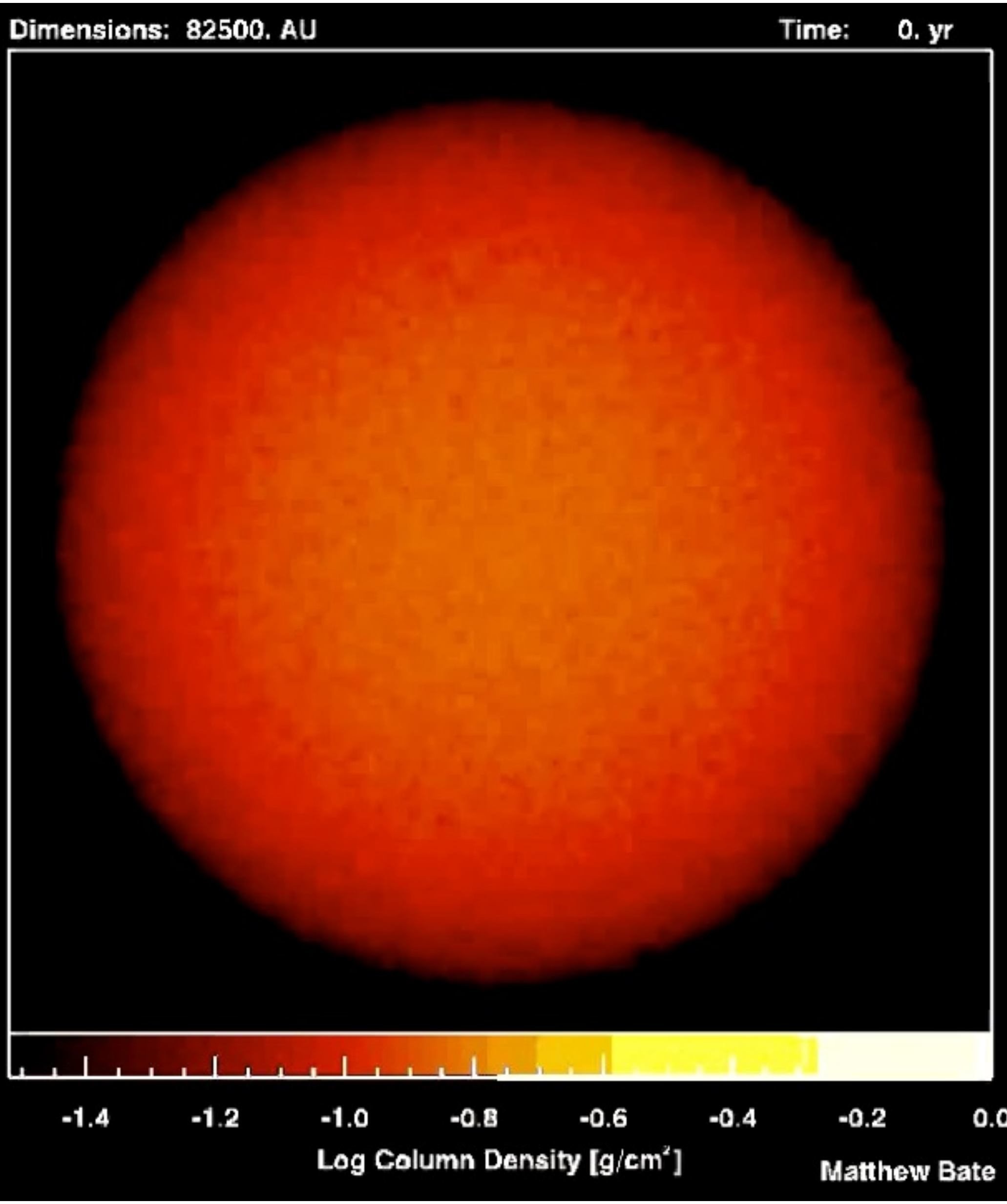
Planet Formation

Chapter 15

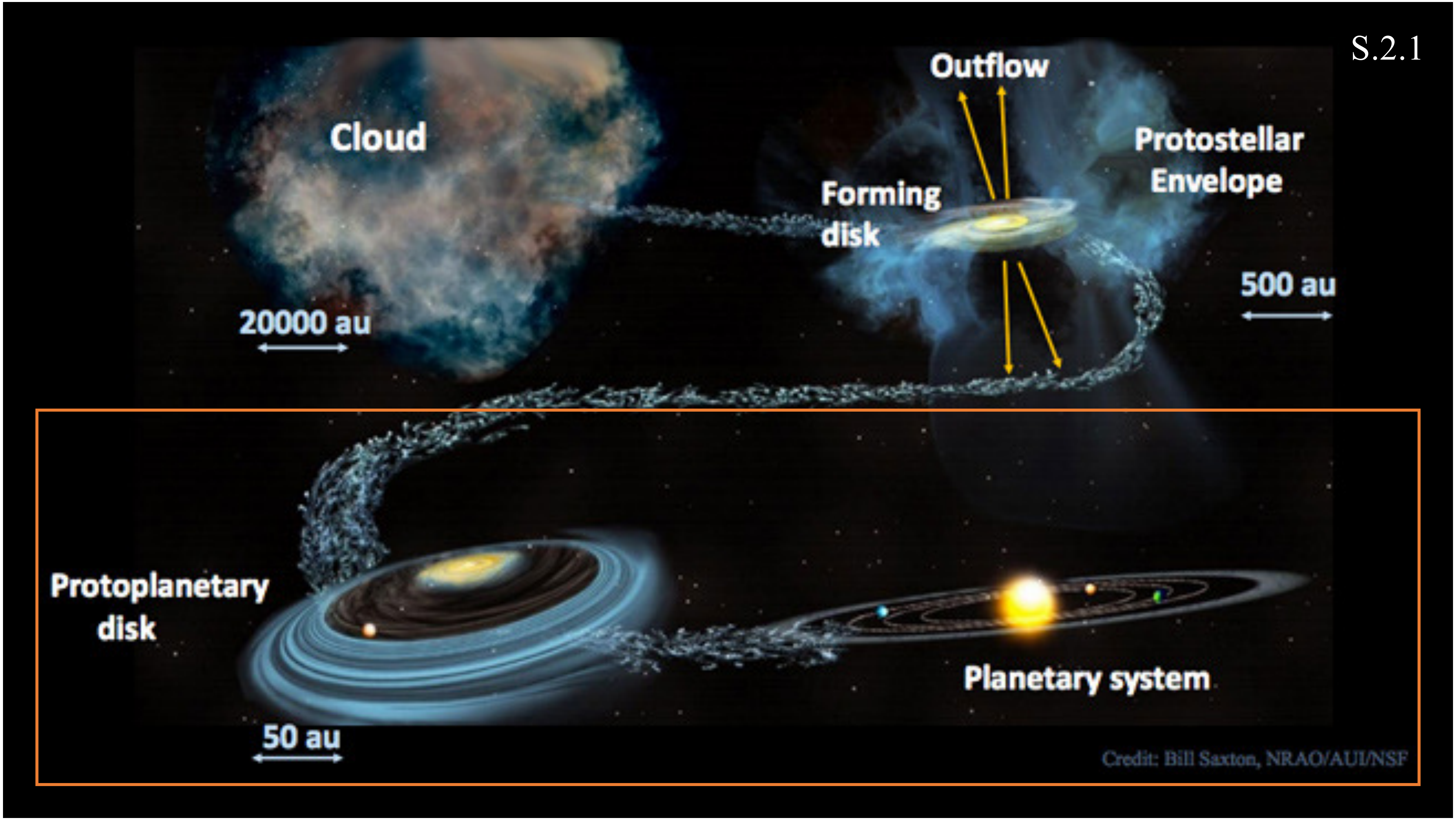
Protoplanetary Disk

Credit: CfA / Harvard

Giant Molecular Cloud Collapse: Simulation



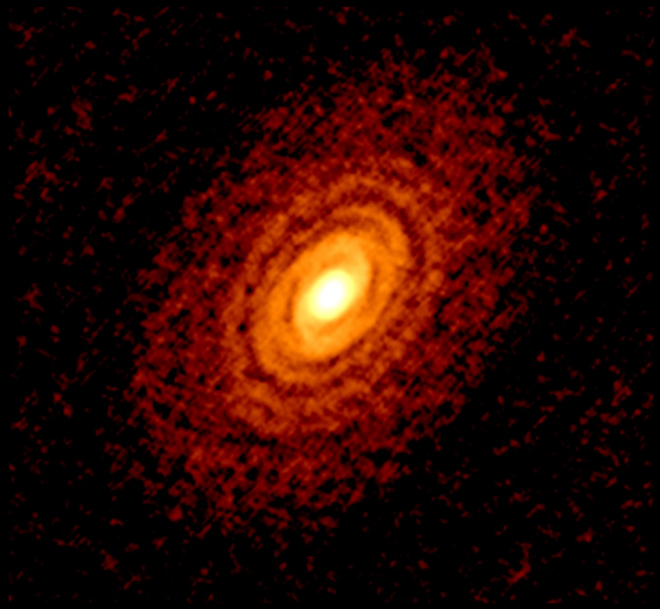
https://www.youtube.com/watch?v=YbdwTwB8jtc

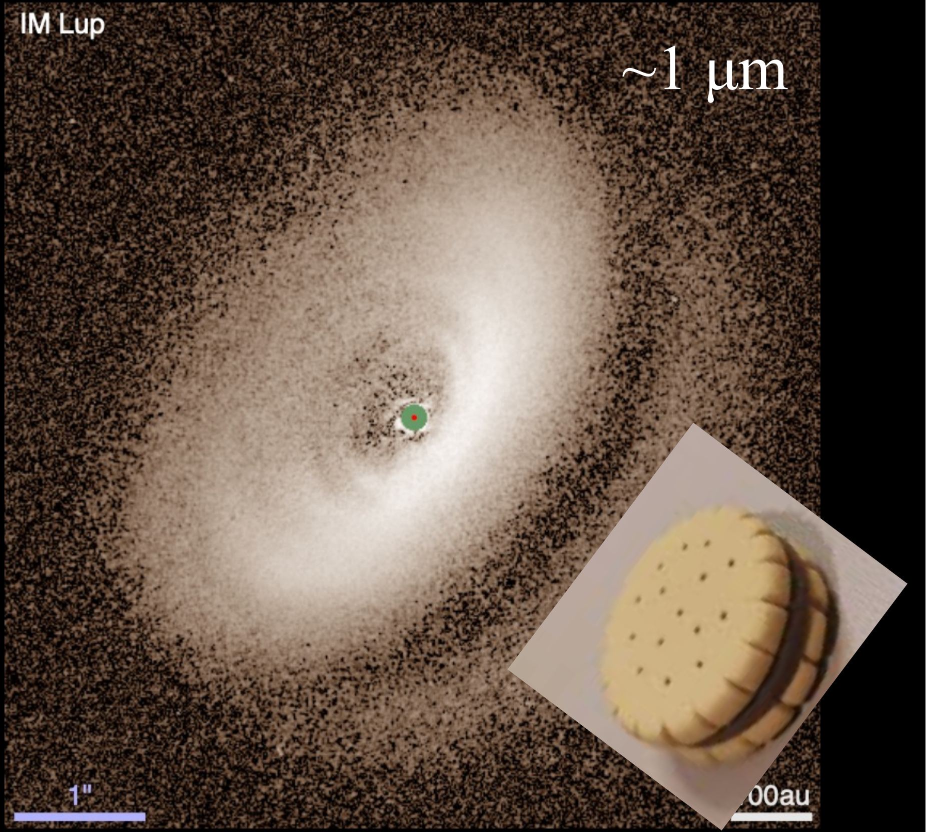


Credit: Bill Saxton, NRAO/AUI/NSF

Real Images of Protoplanetary Disks: IM Lup

~1 mm





~1 μm

Inclination: 48 degree

Millimeter Dust Emission / ALMA (Andrews+18)

Near-Infrared Scattered light / SPHERE (Avenhaus+18)

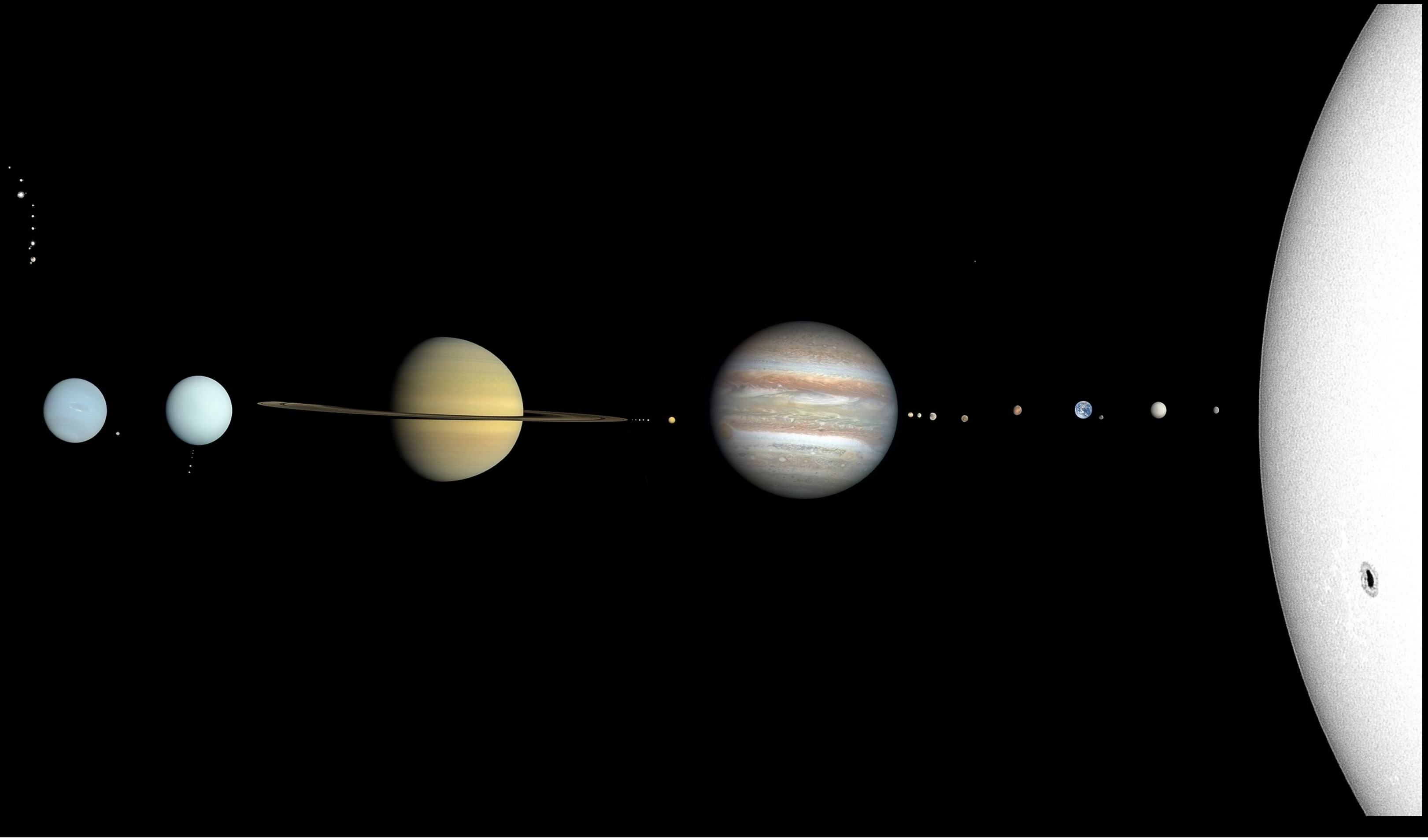
Planet Formation

Initial Conditions

Final Products

Credit: Bill Saxton, NRAO

Planets form in protoplanetary disks – *why?*
Solar system evidence



Planets form in protoplanetary disks – *why?*
Imaged planets forming in disks

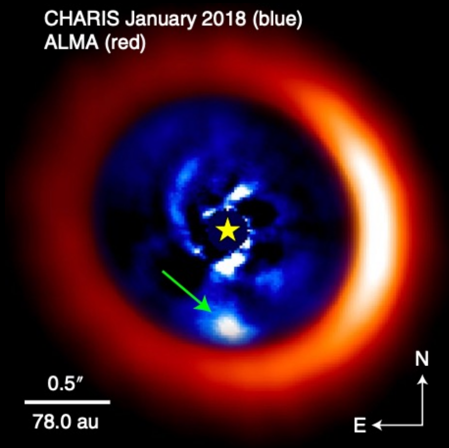
PDS 70

VLT / SPHERE

Keppler + 18
Muller + 18

AB Aur

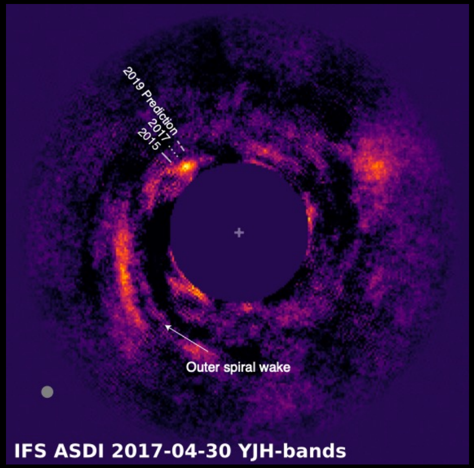
Subaru / SCExAO



Currie + 22

HD 169142

VLT / SPHERE



Hammond + 23

Planet Formation

Initial Conditions

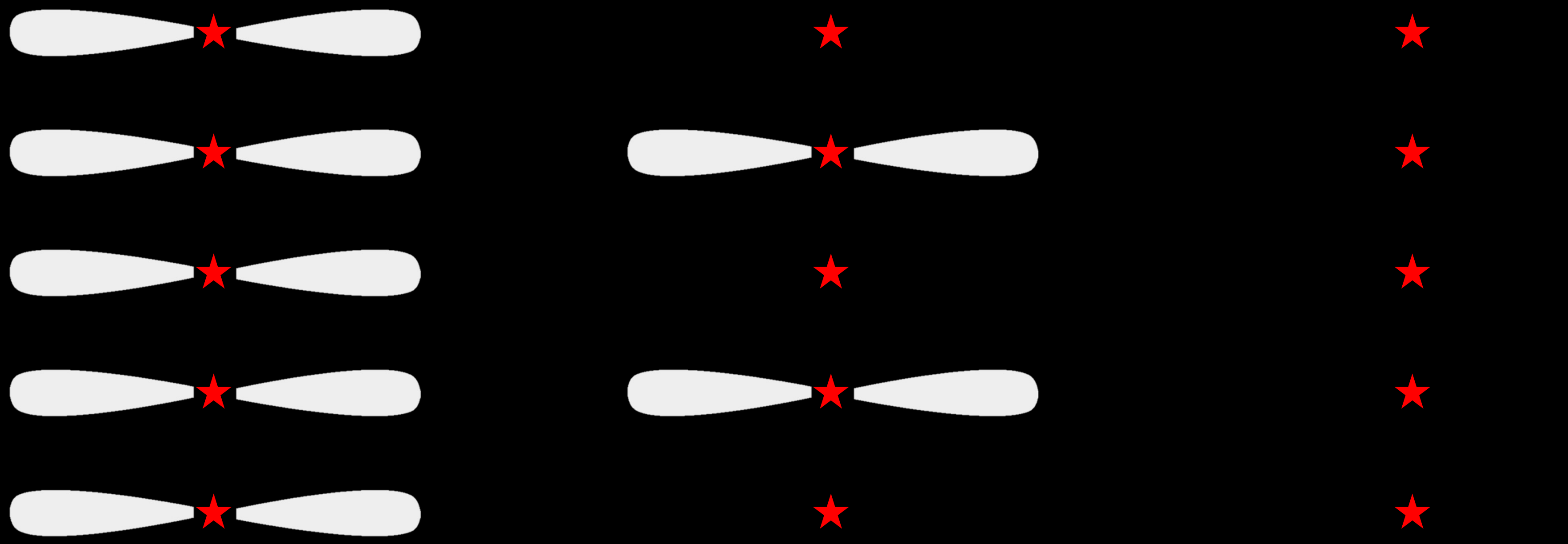
FAST !

In a few million years

Final Products

Credit: Bill Saxton, NRAC

Protoplanetary Disks Dissipate in a few Million Years



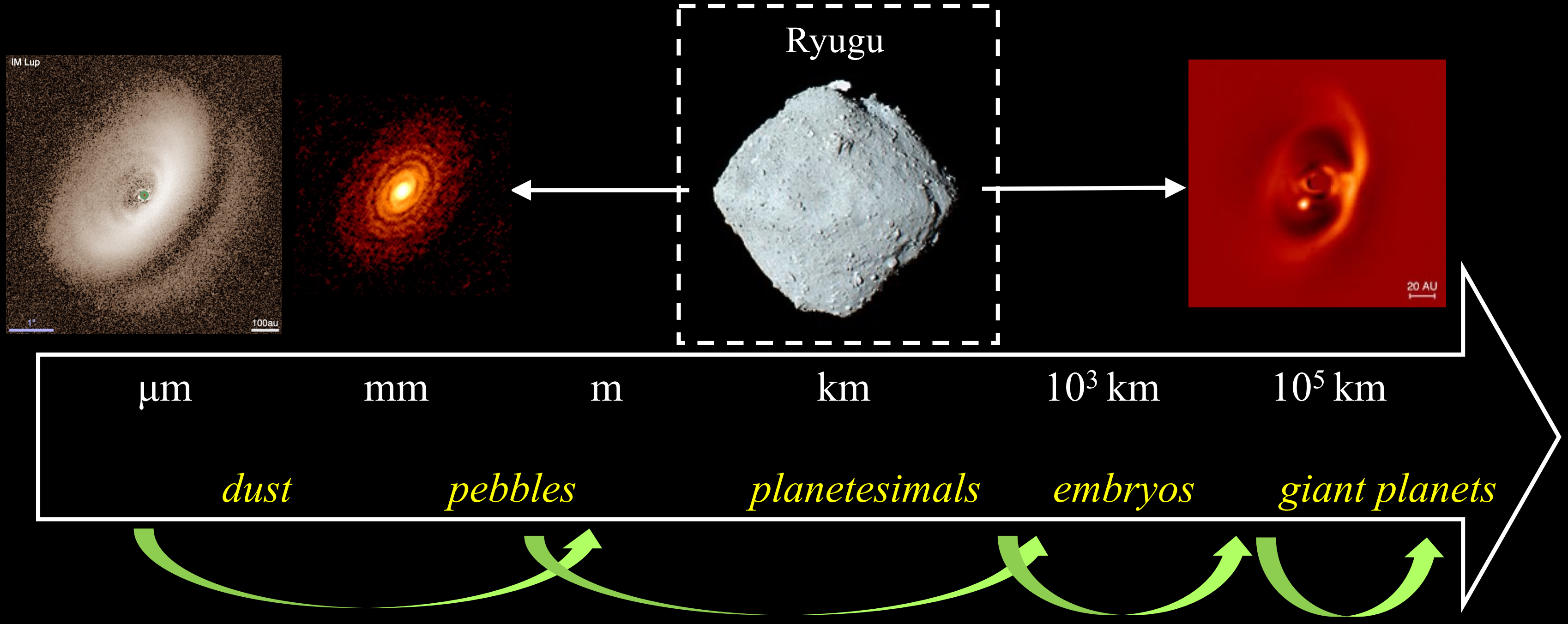
1 Million Years

3 Million Years

10 Million Years

Two Main Avenues of Planet Formation

I: Core Accretion (Bottom-Up)



Disk Observations

Ryugu

Size µm mm m km 10^3 km 10^5 km

Name *dust* *pebbles* *planetesimals* *embryos* *giant planets*

Physical Processes

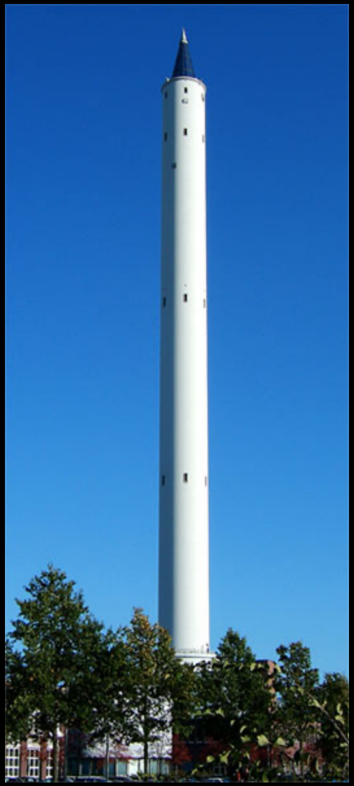
Grain growth and coagulation

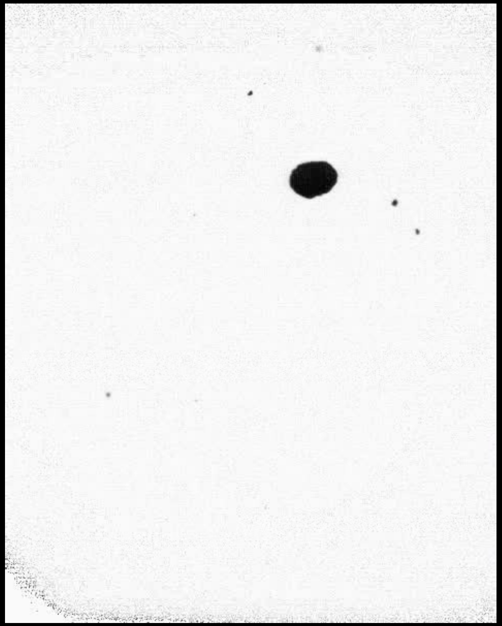
Streaming instability?

Pebble accretion?

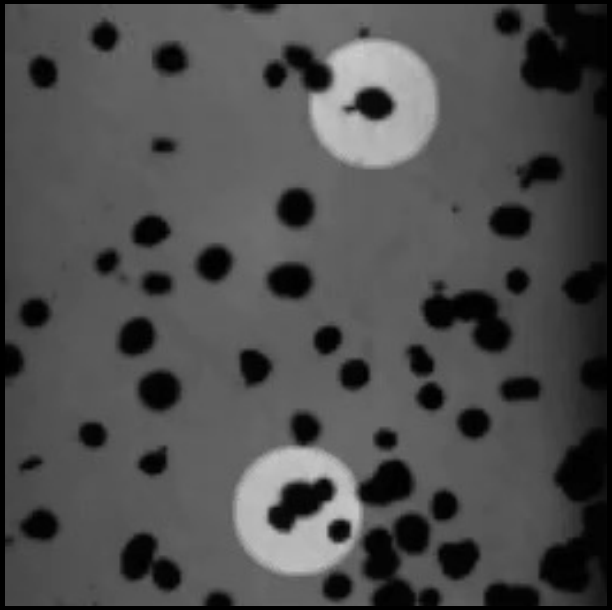
Gas accretion

Grain growth and coagulation



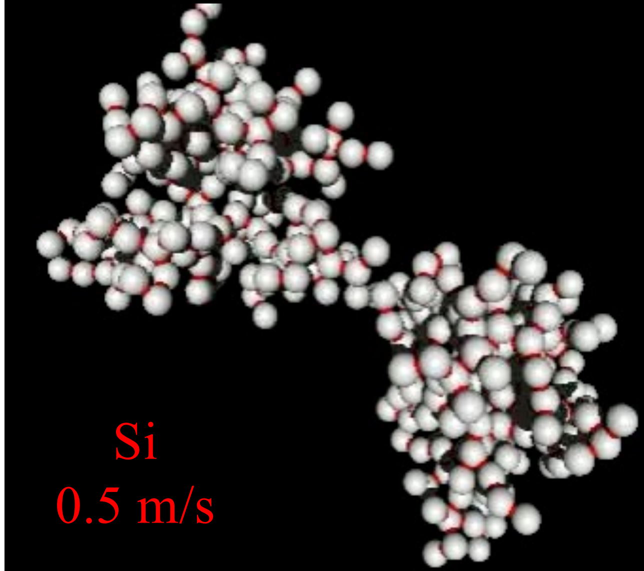


Fragmentation



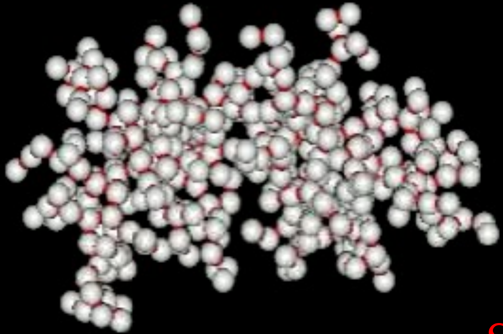
Sticking

Suggested reading: Blum & Wurm (2008), Guttler et al. (2010)



Si
0.5 m/s

Paszun et al.

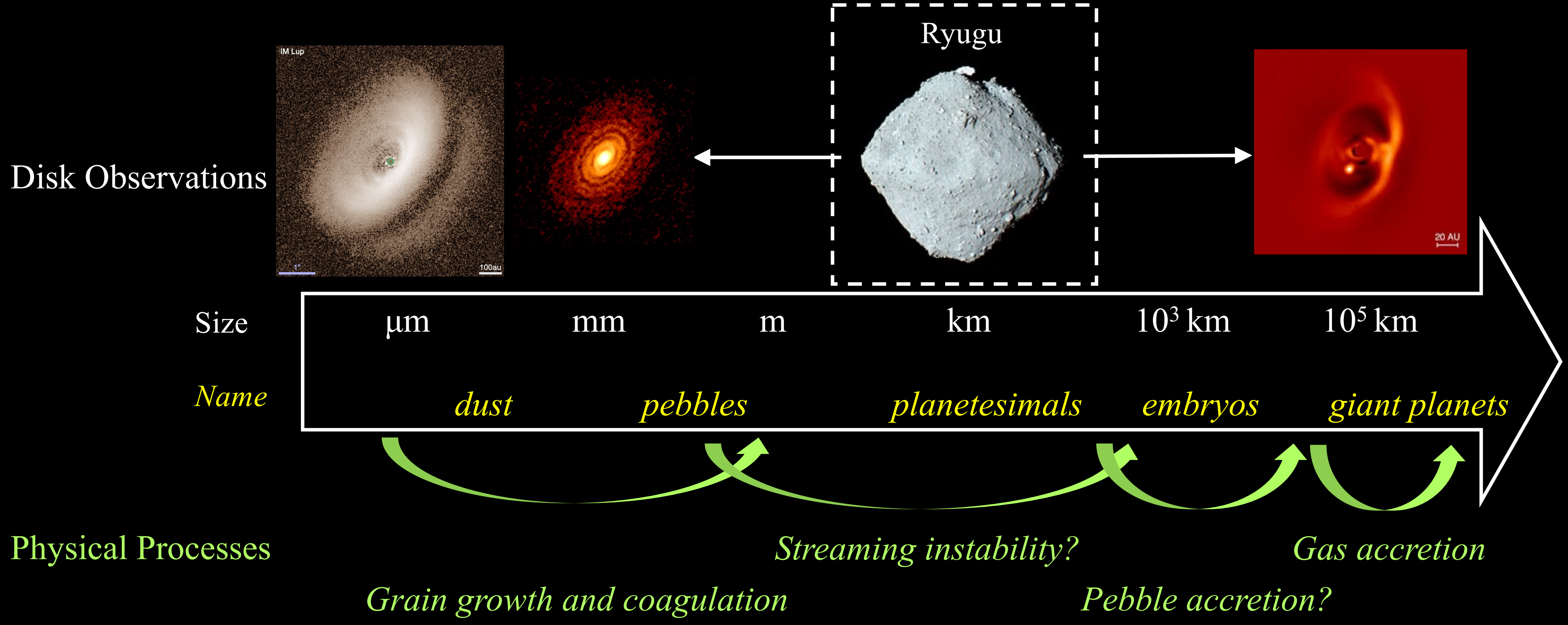


Si
2 m/s

H_2O
8 m/s

Two Main Avenues of Planet Formation

I: Core Accretion (Bottom-Up)



Ryugu

Disk Observations

Size: µm, mm, m, km, 10^3 km, 10^5 km

Name: *dust*, *pebbles*, *planetesimals*, *embryos*, *giant planets*

Physical Processes

Grain growth and coagulation

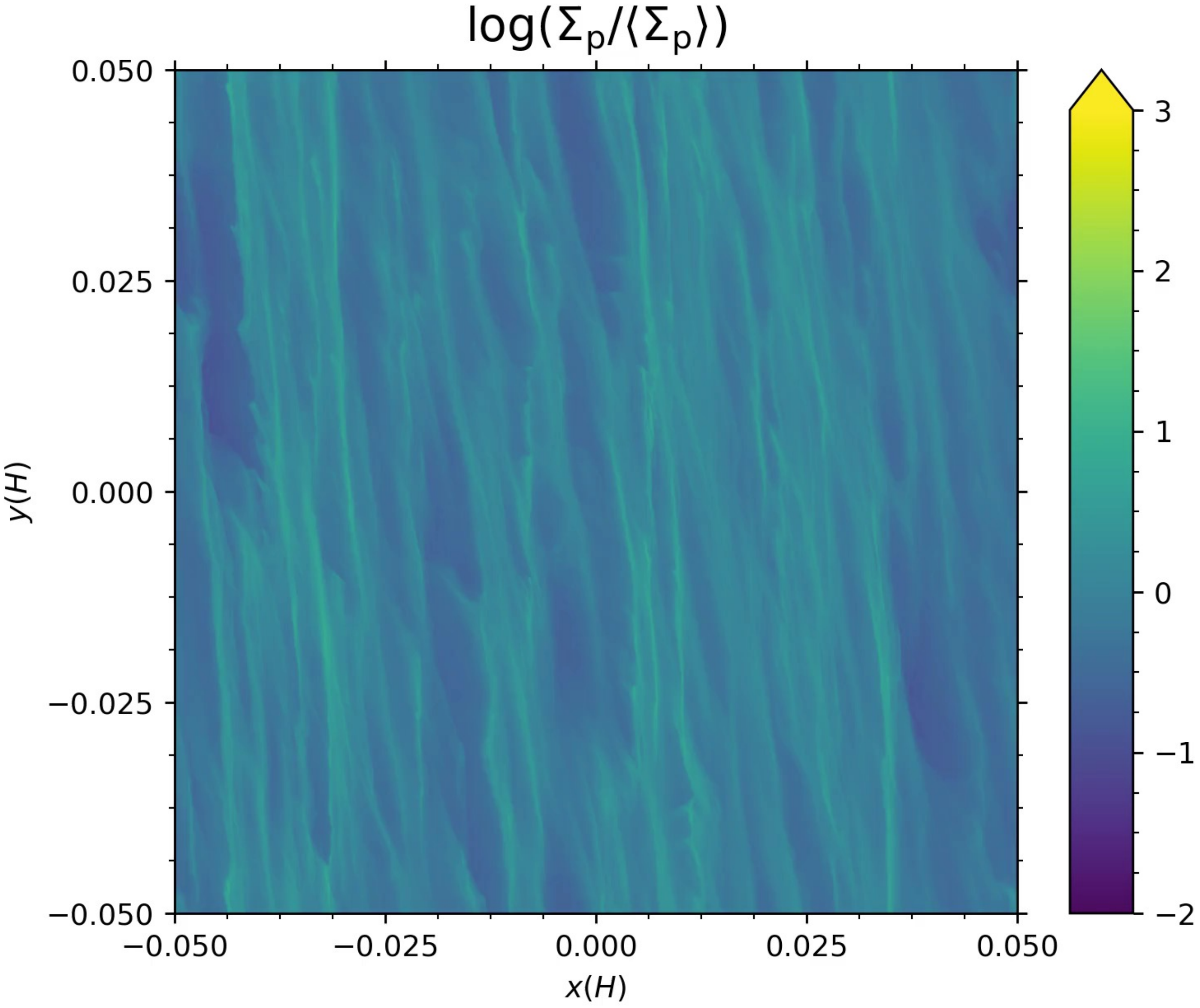
Streaming instability?

Pebble accretion?

Gas accretion

Streaming instability

Rixin Li



Two Main Avenues of Planet Formation

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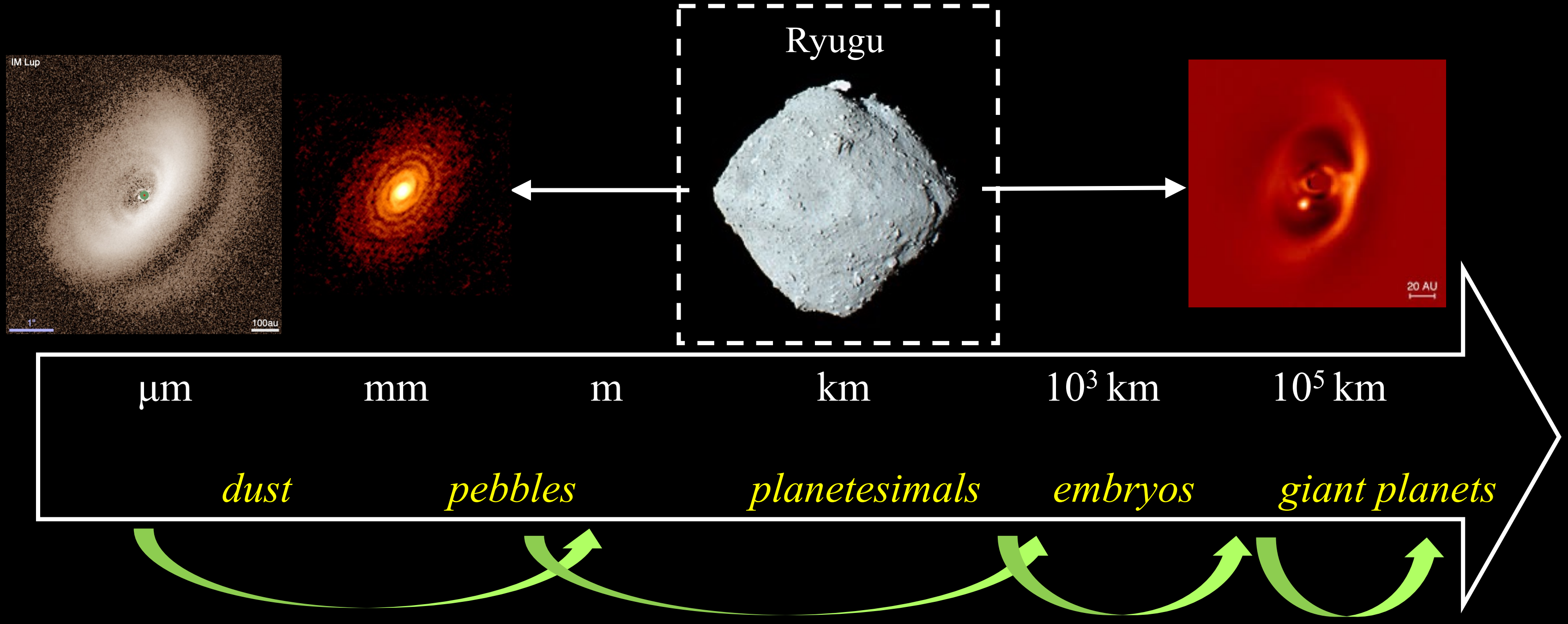


Disk Observations

Size: μm, mm, m, km, 10^3 km, 10^5 km

Name: *dust*, *pebbles*, *planetesimals*, *embryos*, *giant planets*

Physical Processes

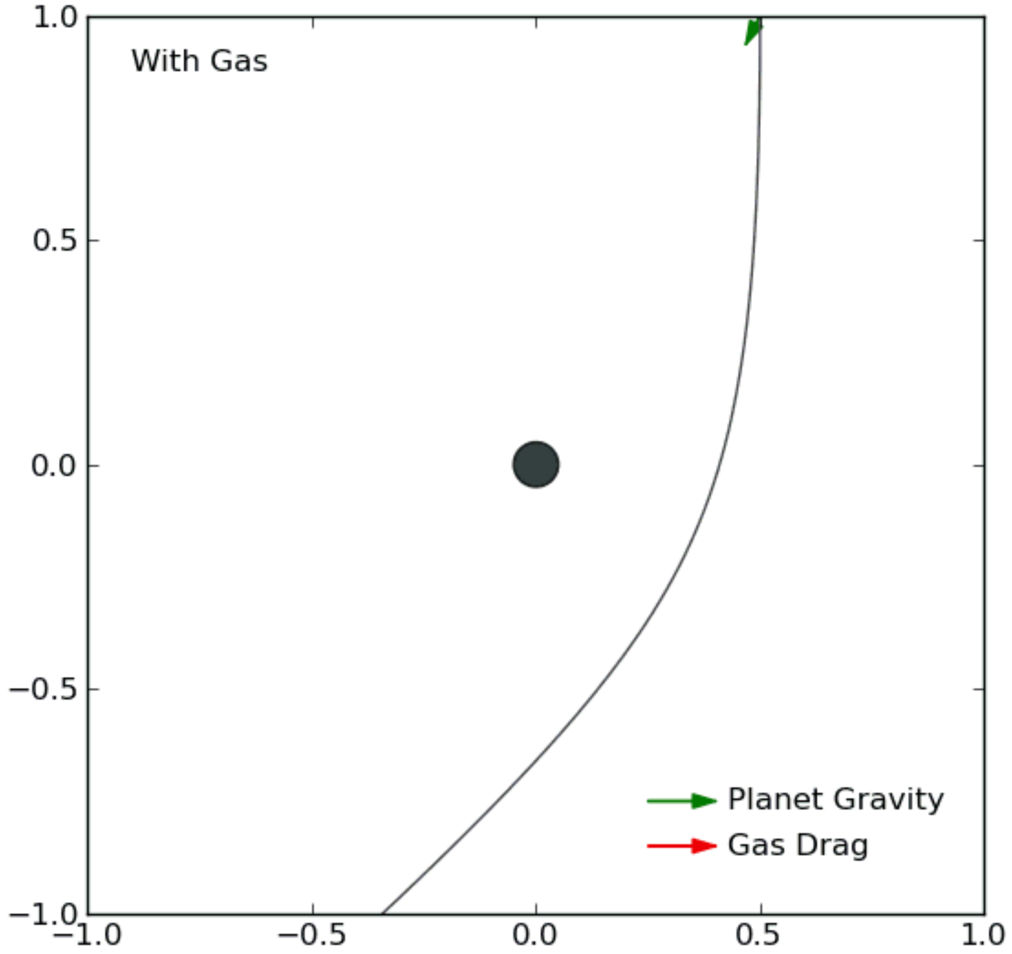
Grain growth and coagulation

Streaming instability?

Pebble accretion?

Gas accretion

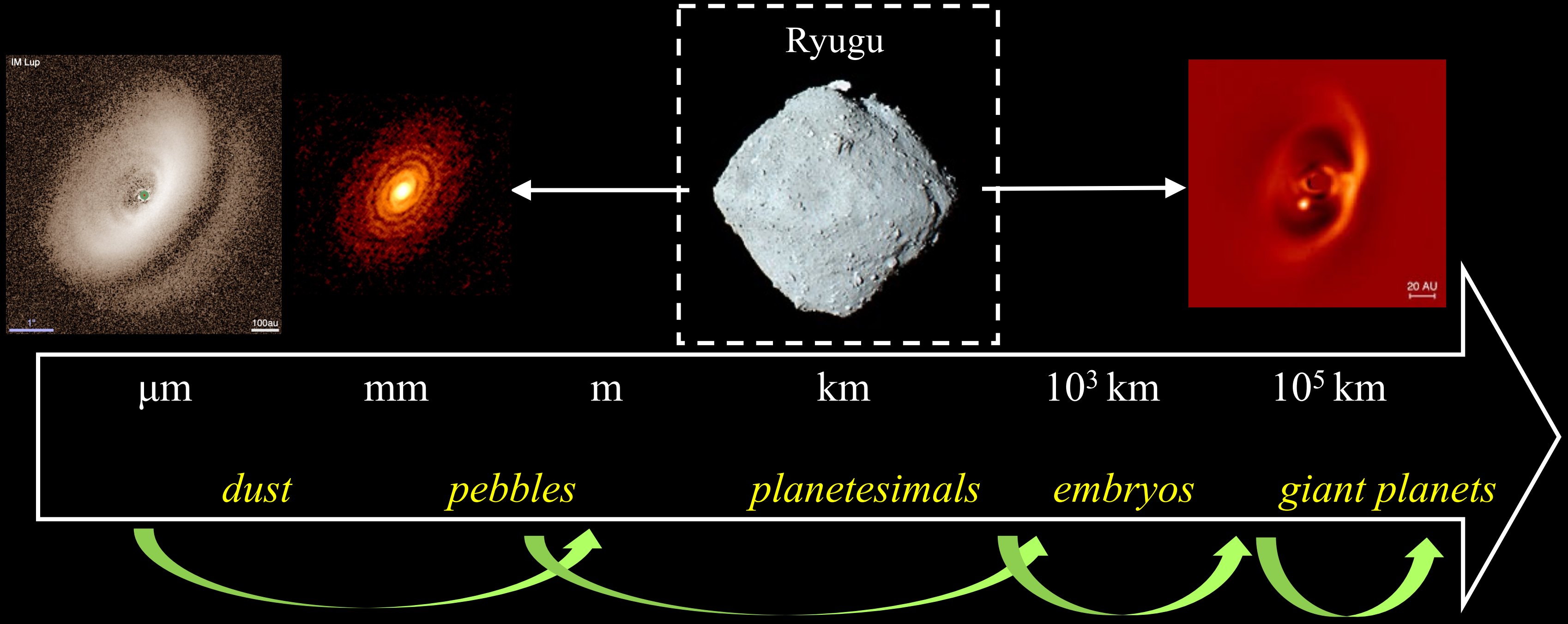
Pebble accretion



M. Lambrechts

Two Main Avenues of Planet Formation

I: Core Accretion (Bottom-Up)



Disk Observations

Size μm mm m km 10^3 km 10^5 km

Name *dust* *pebbles* *planetesimals* *embryos* *giant planets*

Physical Processes

Grain growth and coagulation

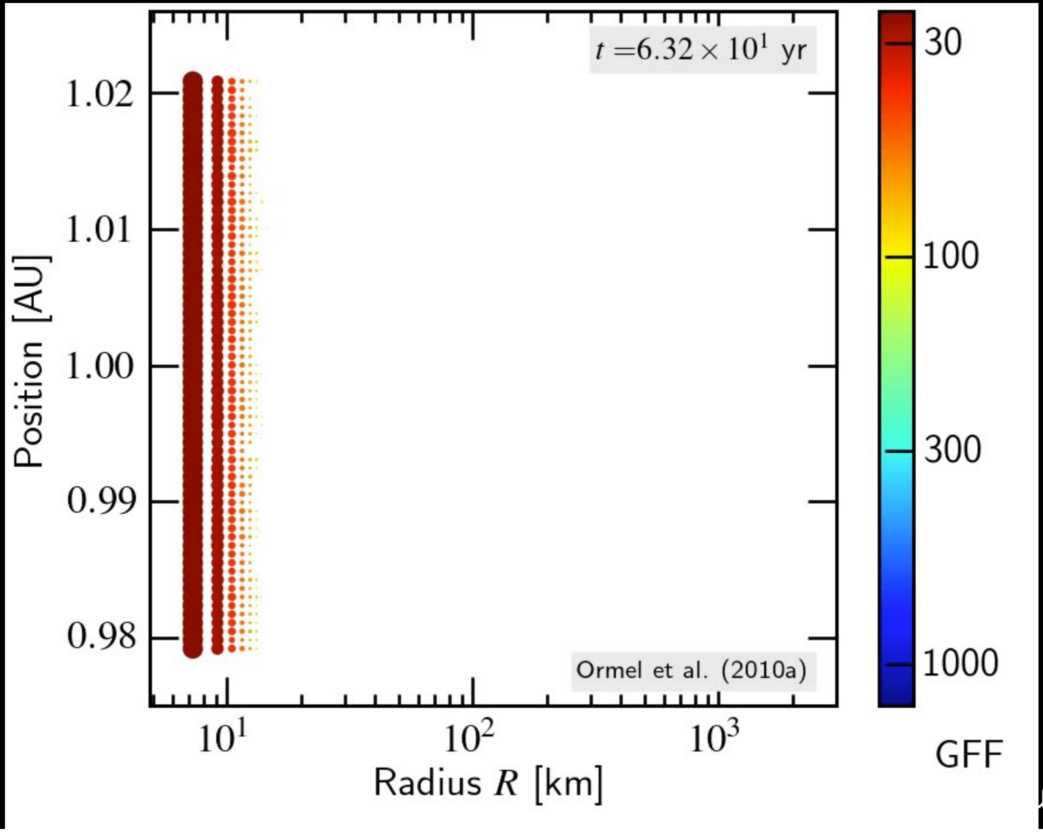
Streaming instability?

Pebble accretion?

Gas accretion

Runaway growth and the emergence of Oligarchies

- The end stage of runaway and oligarchic growth: massive embryos well separated
- Mutual gravitational scattering pump up the relative velocity of embryos, bringing them into orbit-crossing orbits.
- The color shows the amount of dynamical excitation with respect to the largest body in the simulation: blue colors indicate a dynamical cold system, whereas red colors indicate a dynamical hot system.



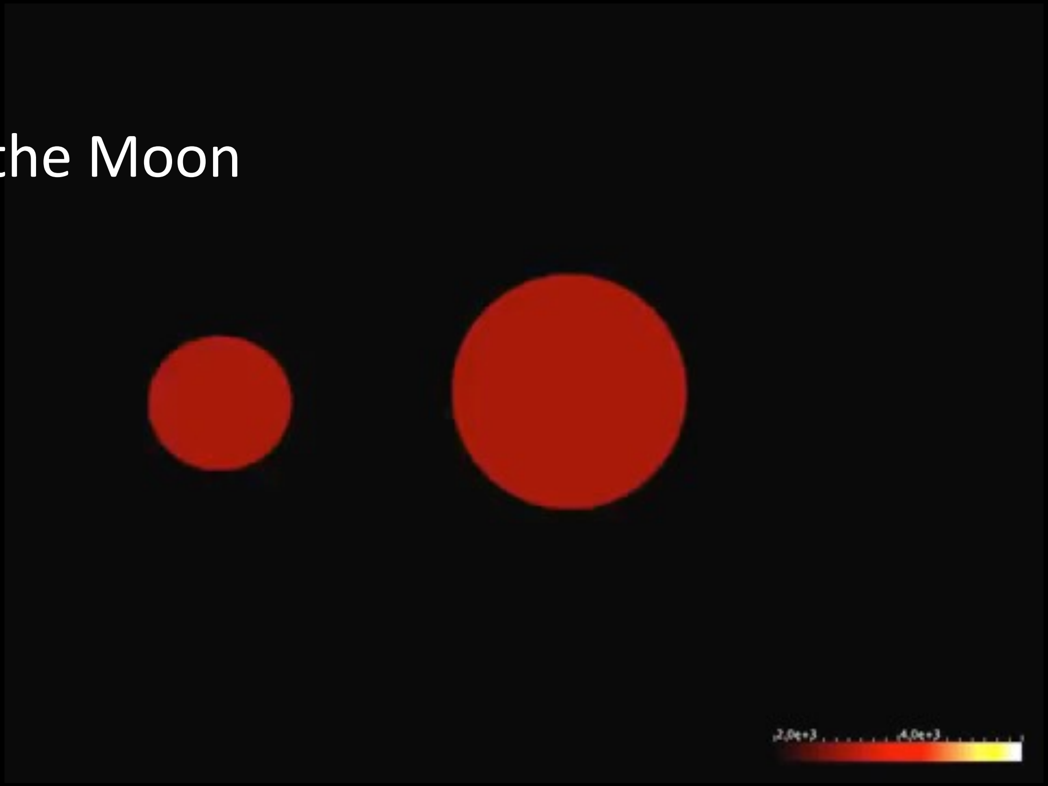
sing factor

https://staff.fnwi.uva.nl/c.w.ormel/science.html

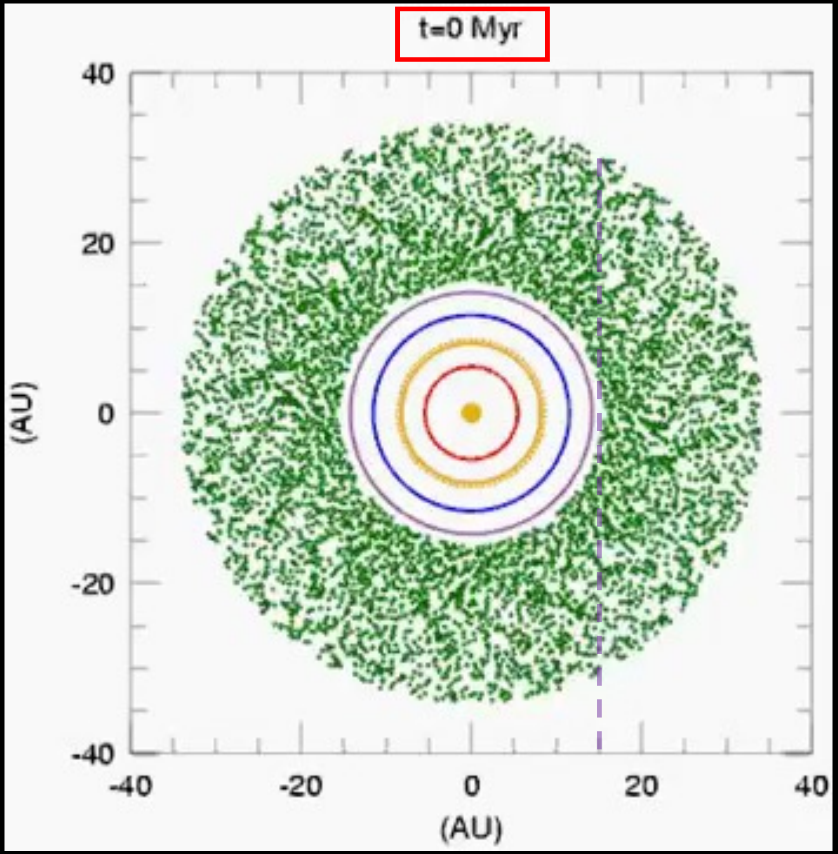
Final Assembly

Once gas is gone, *e* and *i* of oligarchies can grow; leading to orbit crossing, and giant impacts

Simulation of the Moon forming event



Long Term Evolution – Nice Model

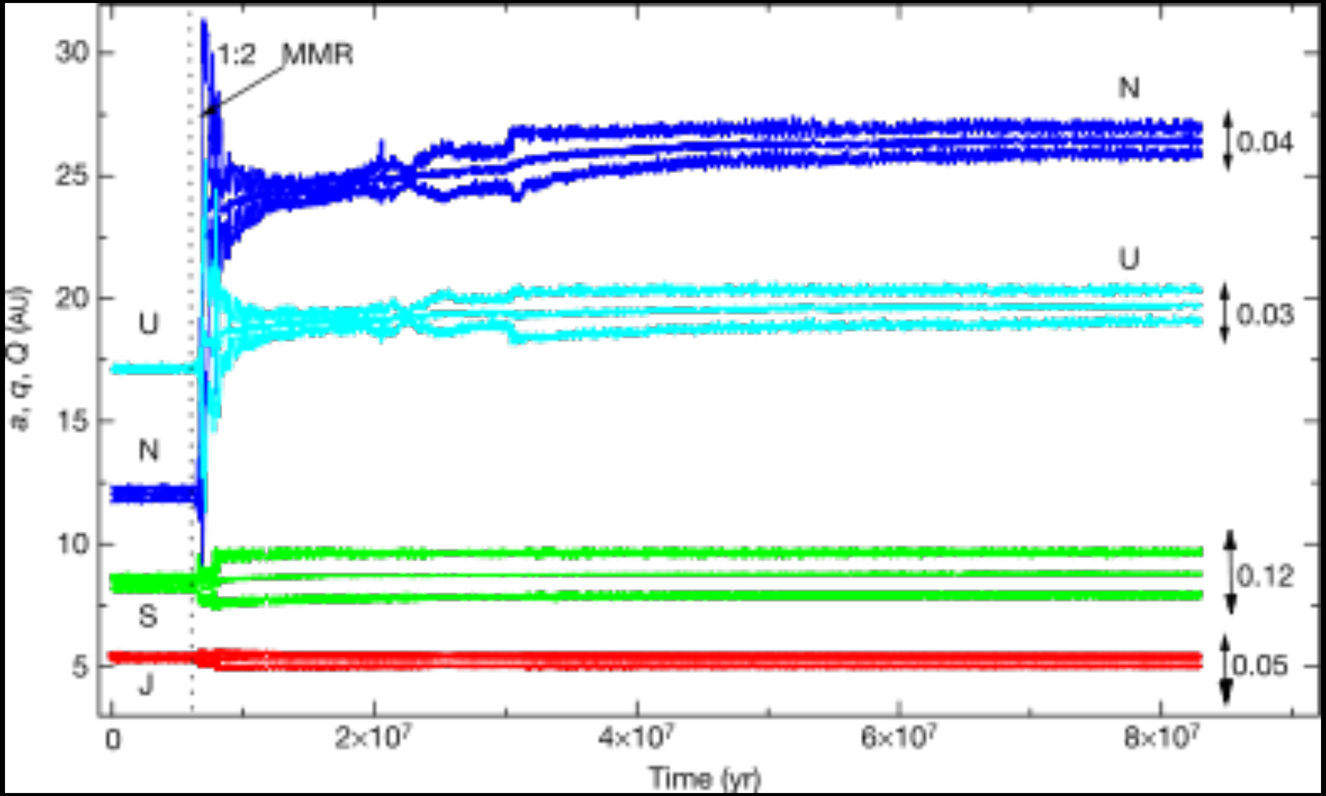


What happened?

- Planet orbits gradually expand
- Planetesimal disk is pushed out
- Instability occurs when J and S cross 2:1 resonance
  - N and U flip orbits
  - Outer planetesimal disk is largely disrupted

Gomes, Levison, Tsiganis and Morbidelli
https://www.youtube.com/watch?v=VXeOh3xmrQM

Nice Model



https://en.wikipedia.org/wiki/Nice_model

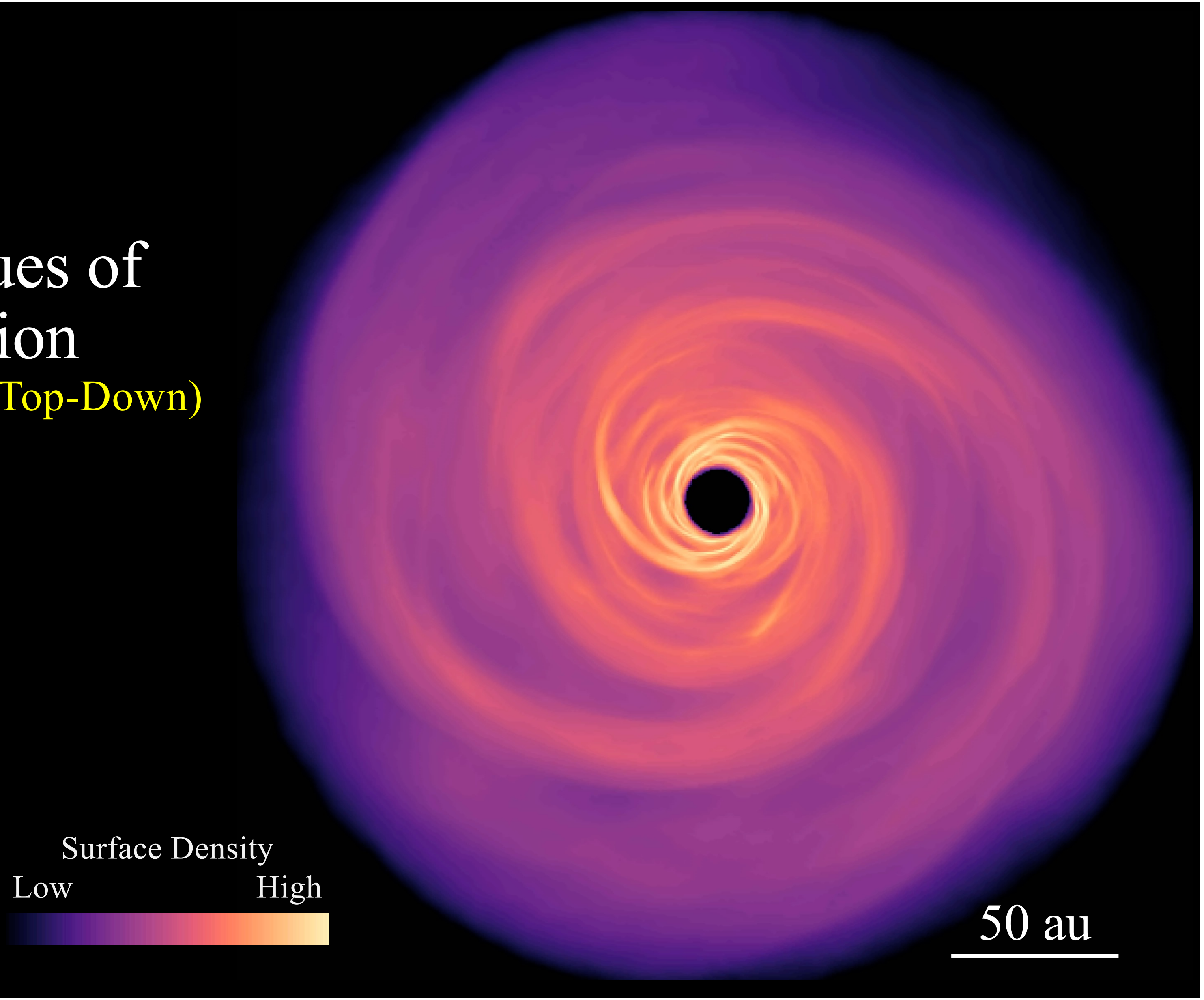
Two Main Avenues of Planet Formation

I: Core Accretion (Bottom-Up)

S.6.3

Two Main Avenues of Planet Formation

II: Gravitational Instability (Top-Down)



Hongping Deng

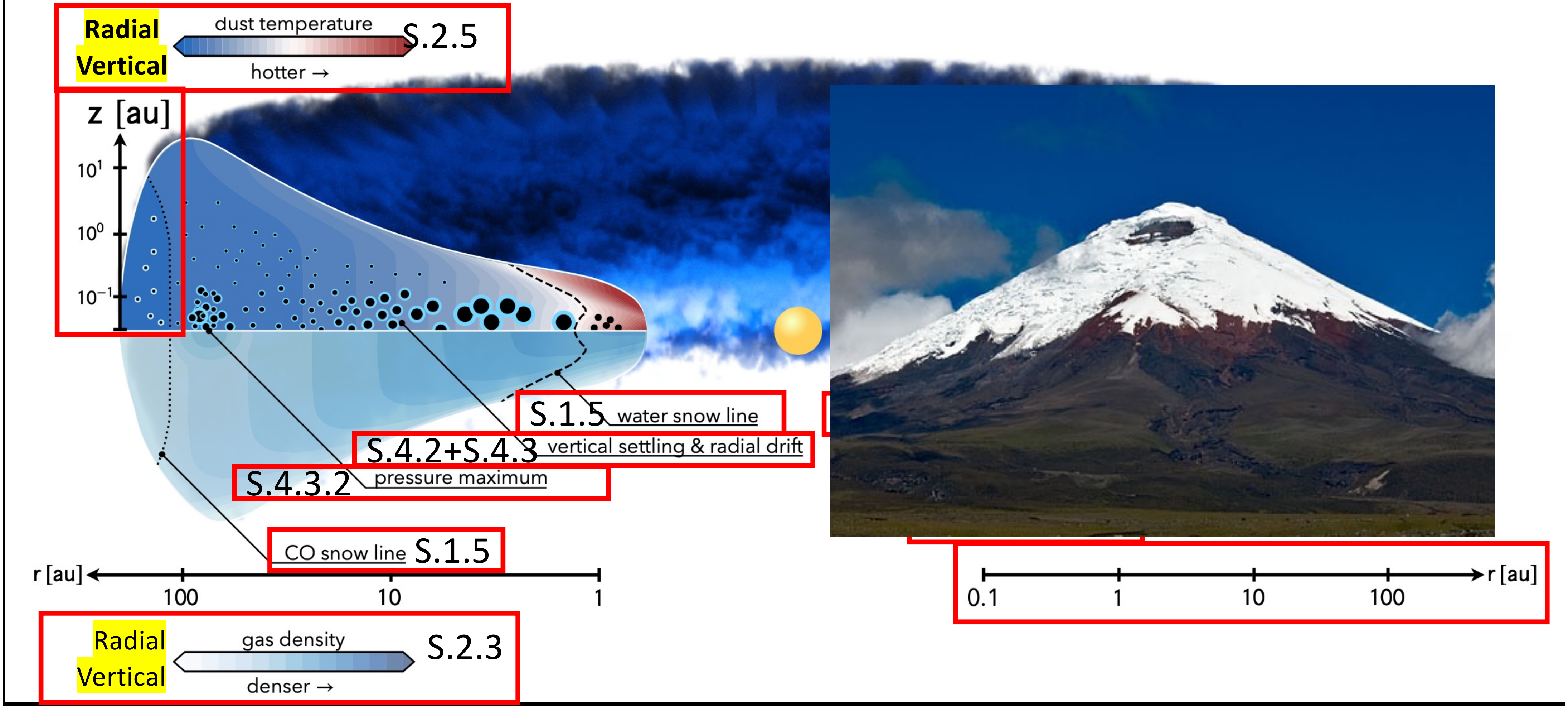
Planet Formation

Initial Conditions

Final Products

In a few million years

Credit: Bill Saxton, NRAC



Miotello+22 , Fig. 1

The initial condition of planet formation: what are disks made of?

- Gas: ~99% of the mass; almost transparent
  - H_2 + He: 98% of the gas
  - CO, H_2O, etc
- Dust / pebbles: ~1% of the mass; main source of opacity
  - Different size, composition, porosity, etc
- Magnetic field
- If large bodies have formed: planetesimals / planets

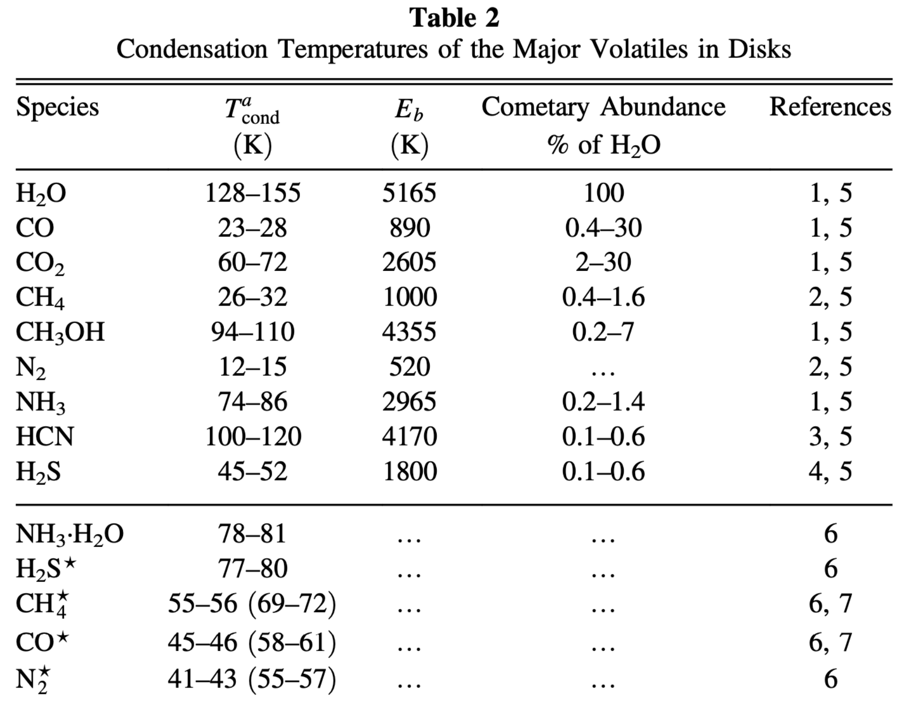


Table 2
Condensation Temperatures of the Major Volatiles in Disks

Species	T^a_{cond} (K)	E_b (K)	Cometary Abundance % of H_2O	References
H_2O	128–155	5165	100	1, 5
CO	23–28	890	0.4–30	1, 5
CO_2	60–72	2605	2–30	1, 5
CH_4	26–32	1000	0.4–1.6	2, 5
CH_3OH	94–110	4355	0.2–7	1, 5
N_2	12–15	520	…	2, 5
NH_3	74–86	2965	0.2–1.4	1, 5
HCN	100–120	4170	0.1–0.6	3, 5
H_2S	45–52	1800	0.1–0.6	4, 5
$NH_3{\cdot}H_2O$	78–81	…	…	6
$H_2S^{\star}$	77–80	…	…	6
$CH_4^{\star}$	55–56 (69–72)	…	…	6, 7
$CO^{\star}$	45–46 (58–61)	…	…	6, 7
$N_2^{\star}$	41–43 (55–57)	…	…	6

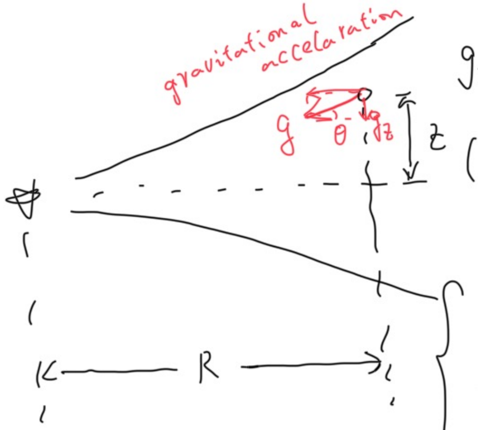
Zhang et al. 2015

Vertical structure in disks

- Very similar to deriving the vertical structure in an atmosphere

Assignment 4

Vertical structure in disks



$g_z = g\sin\theta = \frac{GM_\odot}{R^2+z^2}\frac{z}{\sqrt{R^2+z^2}} \xrightarrow[\quad]{z \ll R} \frac{GM_\odot z}{R^3}$

$(z \ll R)$

Hydrostatic: $\frac{dP}{dz} = -\rho\frac{GM_\odot}{R^3}z$ (15.7, note the extra ρ)

Ideal gas: $P = \frac{\rho kT}{\mu_a m_H}$ (3.14)

Isotheal vertical structure: $T = $ Const.

$$\frac{kT}{\mu_a m_H}\frac{d\rho}{dz} = -\rho\frac{GM_\odot}{R^3}z \Rightarrow \int_{\rho(z=0)}^{\rho(z)}\frac{d\rho}{\rho} = \int_0^z -\frac{\mu_a m_H}{kT}\frac{GM_\odot}{R^3}z\,dz$$

$$\Rightarrow \rho(z) = \rho(z=0)\,e^{-z^2/\frac{2kTR^3}{\mu_a m_H GM_\odot}}, \quad \underline{H \equiv \sqrt{\frac{kTR^3}{\mu_a m_H GM_\odot}}}$$ definition

$\rho(R,z) = \rho(R,z=0)\,e^{-z^2/2H^2}$ (H depends on R, H(R)

Total column densiy $\Sigma(R) = \int \rho(R,z)\cdot dz = \overline{\int \rho(R,z=0)\,e^{-\frac{z^2}{2H^2}}dz}$

$\int e^{-x^2}dx$, Gaussian integral (A4 P8)

- Hydrostatic equilibrium https://en.wikipedia.org/wiki/Hydrostatic_equilibrium

Key Concepts

- A wide variety of observations within and beyond our Solar System are combined with theoretical models to draw a picture of planetary formation.
- Stars form from the collapse of molecular cloud cores. Almost all stars form together with circumstellar disks. Much of the material in these disks is accreted by the growing star, and in most cases, some accumulates into planets.
- Most of the material in our Sun's protoplanetary disk was well mixed on the molecular level, but this mixing was not complete.
- Terrestrial planets as well as other solid rocky and icy bodies form by accretion of solid bodies, primarily via pairwise physical collisions.
- Silicates and metal-rich condensates existed throughout almost all of the Sun's protoplanetary disk, but ices existed only in the outer parts. Well inside Mercury's orbit, the temperature was too high for solids to exist.
- Gas giant planets probably formed by the growth of a solid core followed by gravitational accumulation of hydrogen and helium.
- Earth's Moon formed by the collision of a roughly Mars-sized body with Earth 4.5 billion years ago; both bodies had differentiated prior to the impact.
- The high eccentricities of most known extrasolar giant planets, as well as the close-in orbits of many gas giant exoplanets, imply that considerable planetary migration has occurred. Planet–disk interactions as well as planet–planet scattering can lead to migration.