The modern view of planet formation

NMSU ASTRONOMY

Wladimir Lyra

New Mexico State University

Los Alamos NM, May 3rd, 2025

Planet Formation
is an active and evolving field of research

Google

planet formation

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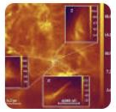
Astrobiology News



New Discovery Changes Views On Star And Planet Formation

The combination of theoretical models and empirical data provides a new perspective for understanding the complex interactions between young...

2 days ago

Rice University

'New era in planet hunting': Rice astronomers help capture striking images of planet formation

International astronomers, including Rice University's Andrea Isella and Charlie Gardner, have unveiled highly detailed images of planets...

4 days ago

SciTechDaily

Vesta Isn't What We Thought – Could It Be a Chunk of a Lost Planet?

Surprising new research reveals Vesta lacks a core, suggesting it may be planetary debris rather than a proto-planet, rewriting its origin...

1 day ago

Earth.com

Each star's neighborhood affects the type of planets that form

Stars have long inspired curiosity among observers, but our understanding of their birth and the creation of planets around them is...

20 hours ago

ExtremeTech

Astronomers Capture Planetary Formation With Unprecedented Clarity

Astronomers have unlocked the sharpest visual yet of planets beginning to form within young solar systems.

21 hours ago

National Radio Astronomy Observatory

exoALMA Gives Astronomers A New Look At How Planets Are Formed

An artist's impression of new data collected by the exoALMA large program, which studied young star systems to map the motions of gas to...

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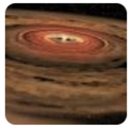
Space

These are the sharpest images yet of planets being born around distant stars

ALMA observations of carbon monoxide emission from 15 protoplanetary disks reveal a stunning variety of gas structures, including gaps,...

2 days ago

Universe Today

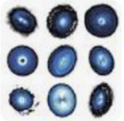


Scientists Gain a New Understanding of How Stars and Planets Form

As young stars form, they exert a powerful influence on their surroundings and create complex interactions between them and their...

1 day ago

Center for Astrophysics | Harvard & Smithsonian



exoALMA and CfA Provide a New Look at How Planets Are Formed

Beyond planet hunting, this survey with significant CfA contributions will reveal the mechanics behind planet forming discs.

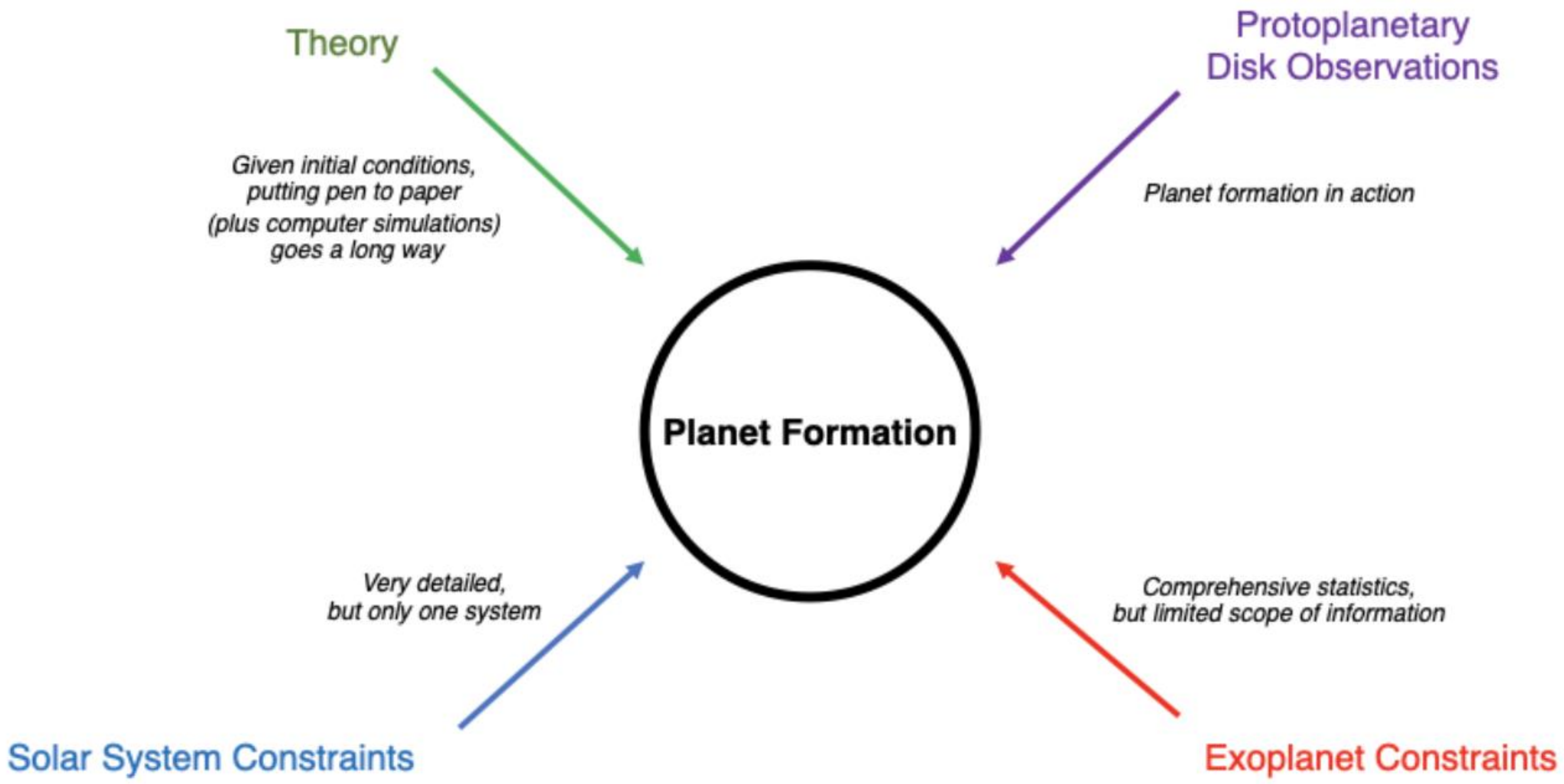
4 days ago

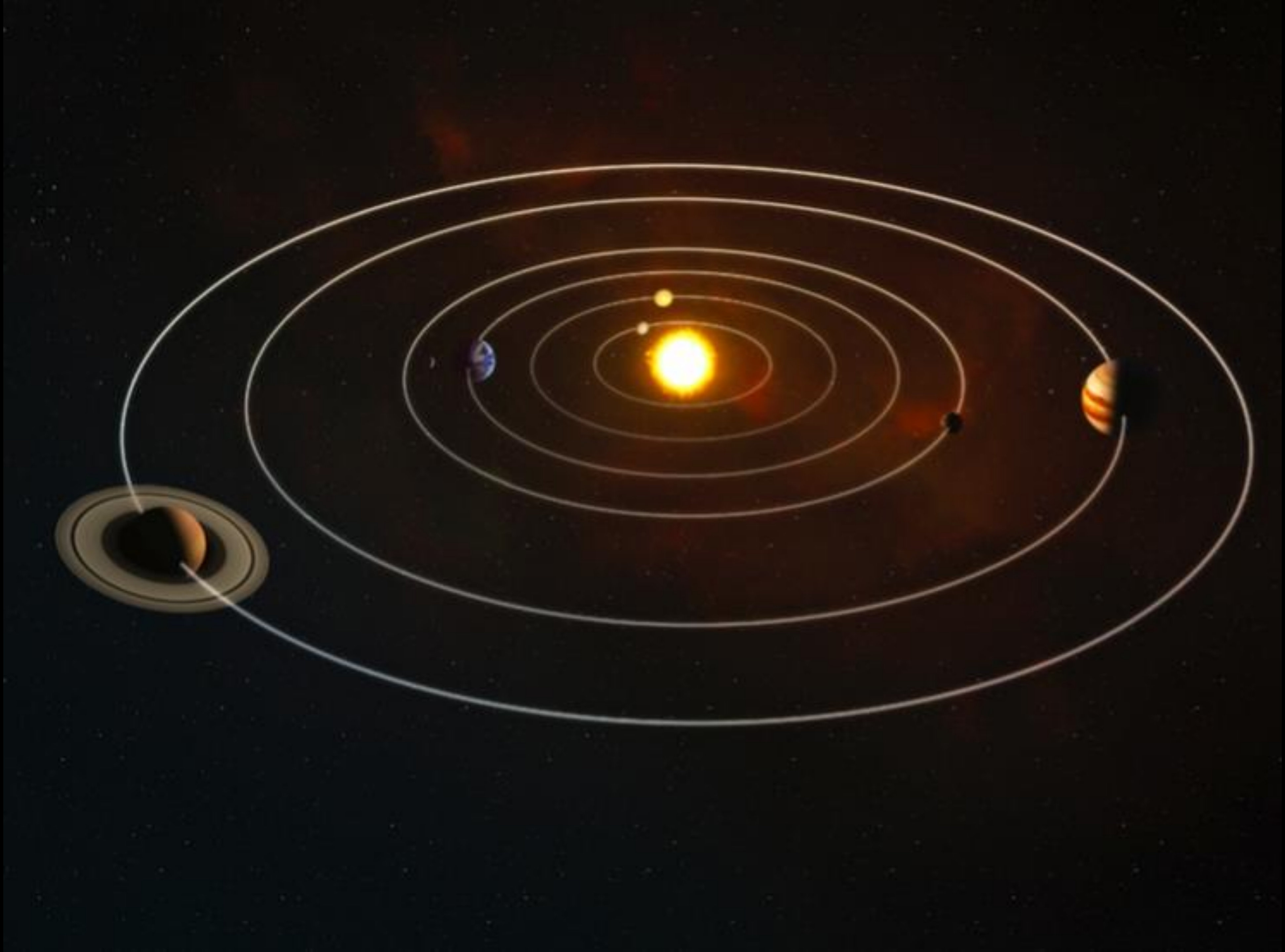
MSUToday

New research shatters long-held beliefs about asteroid Vesta

Why this matters: · New findings change how Vesta is defined as not quite an asteroid or a planet. · This research challenges previous...

4 days ago

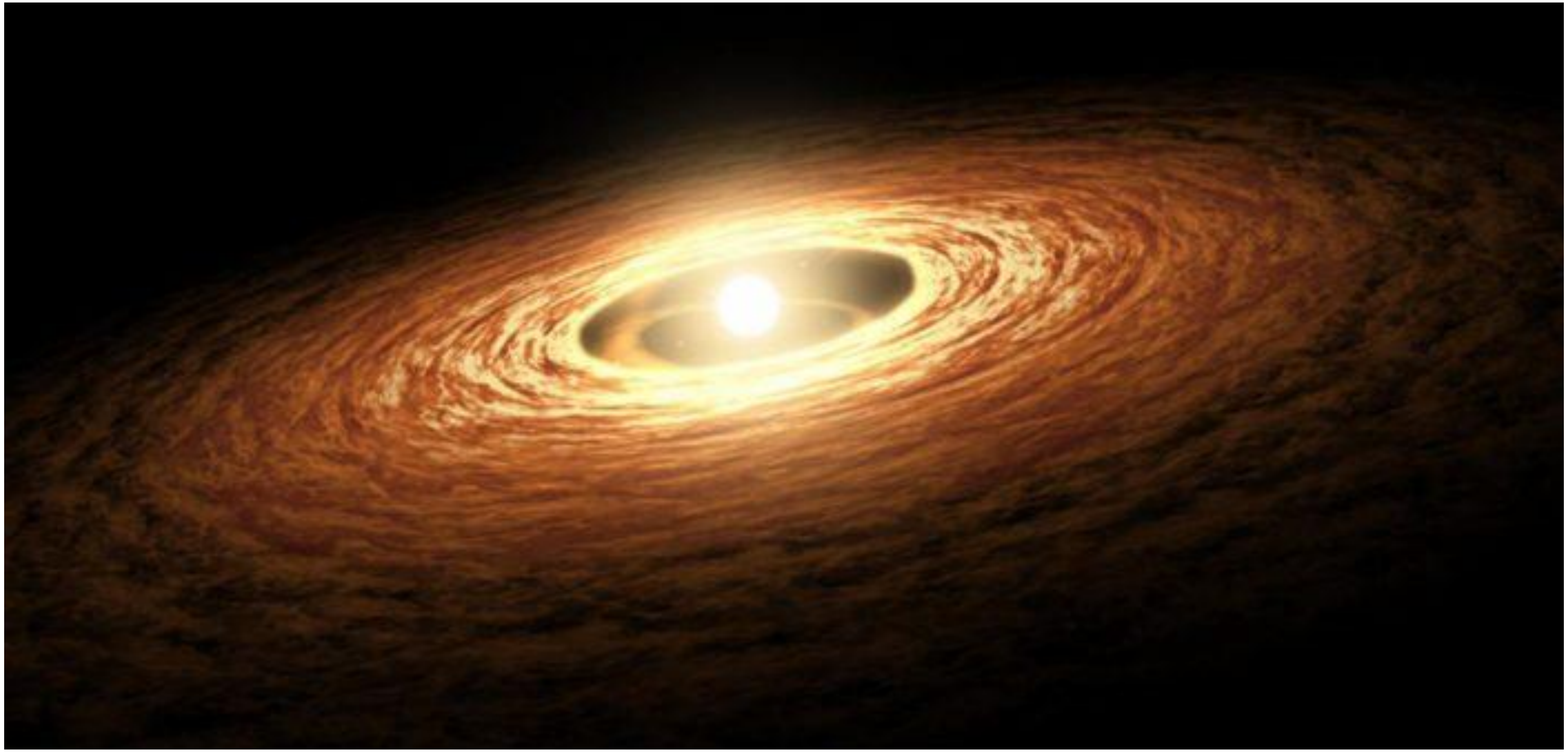

Theory
Given initial conditions, putting pen to paper (plus computer simulations) goes a long way
Protoplanetary Disk Observations
Planet formation in action
Planet Formation
Very detailed, but only one system
Solar System Constraints
Comprehensive statistics, but limited scope of information
Exoplanet Constraints

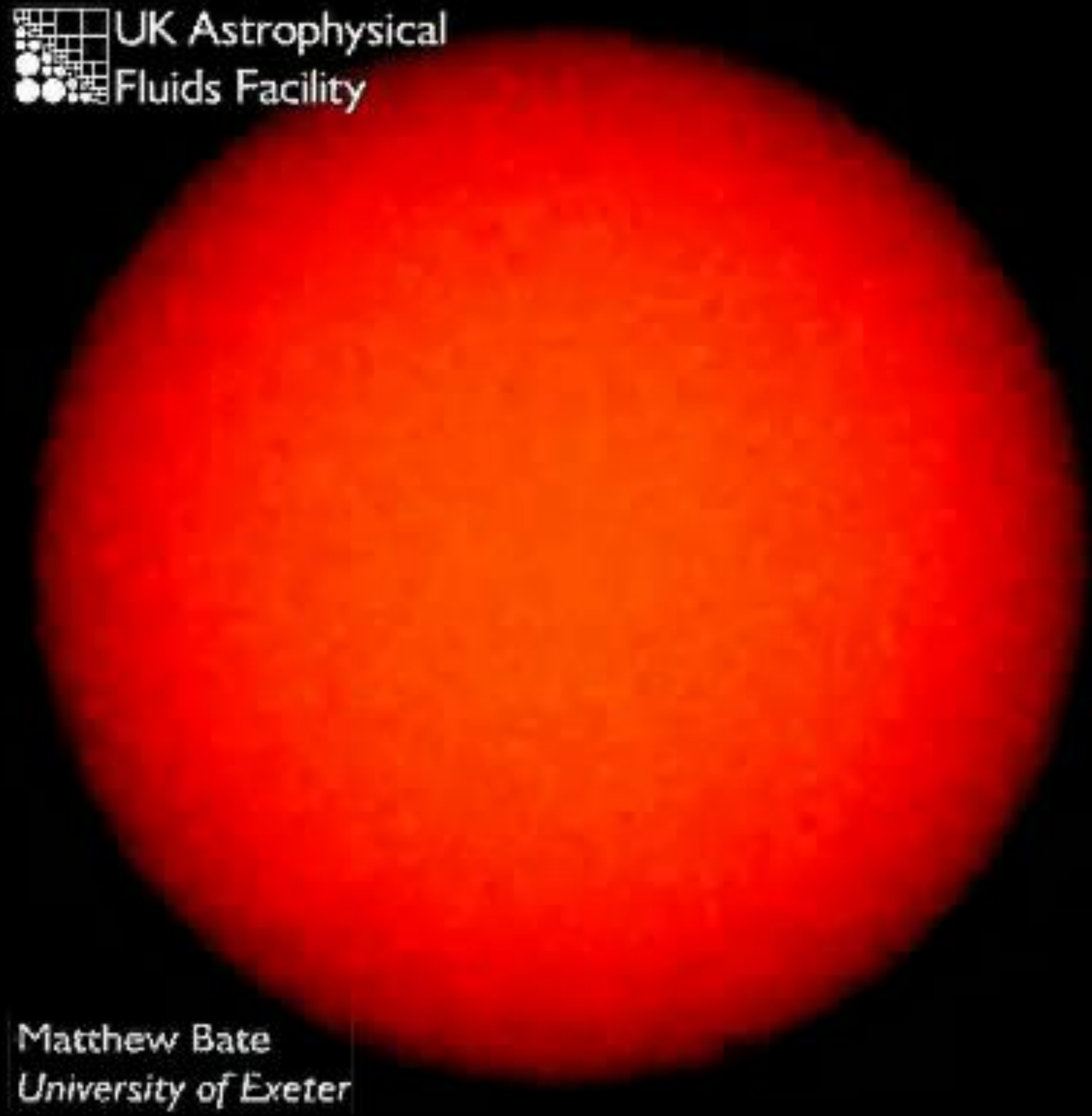


Voyager 10 approach sequence

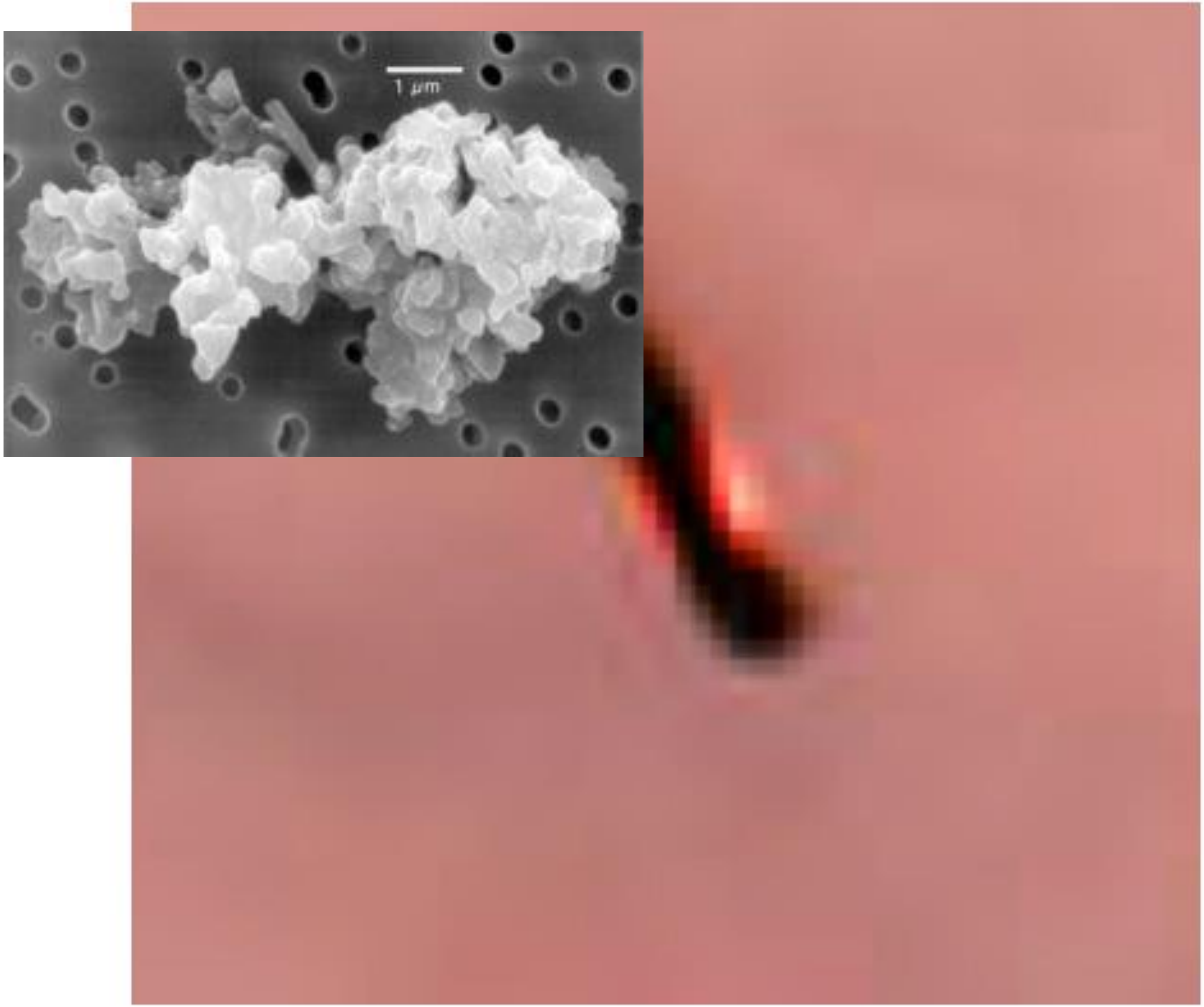
The Solar Nebula

Nebular hypothesis – planets form in disks of gas and dust (Kant 1755, Laplace 1794)



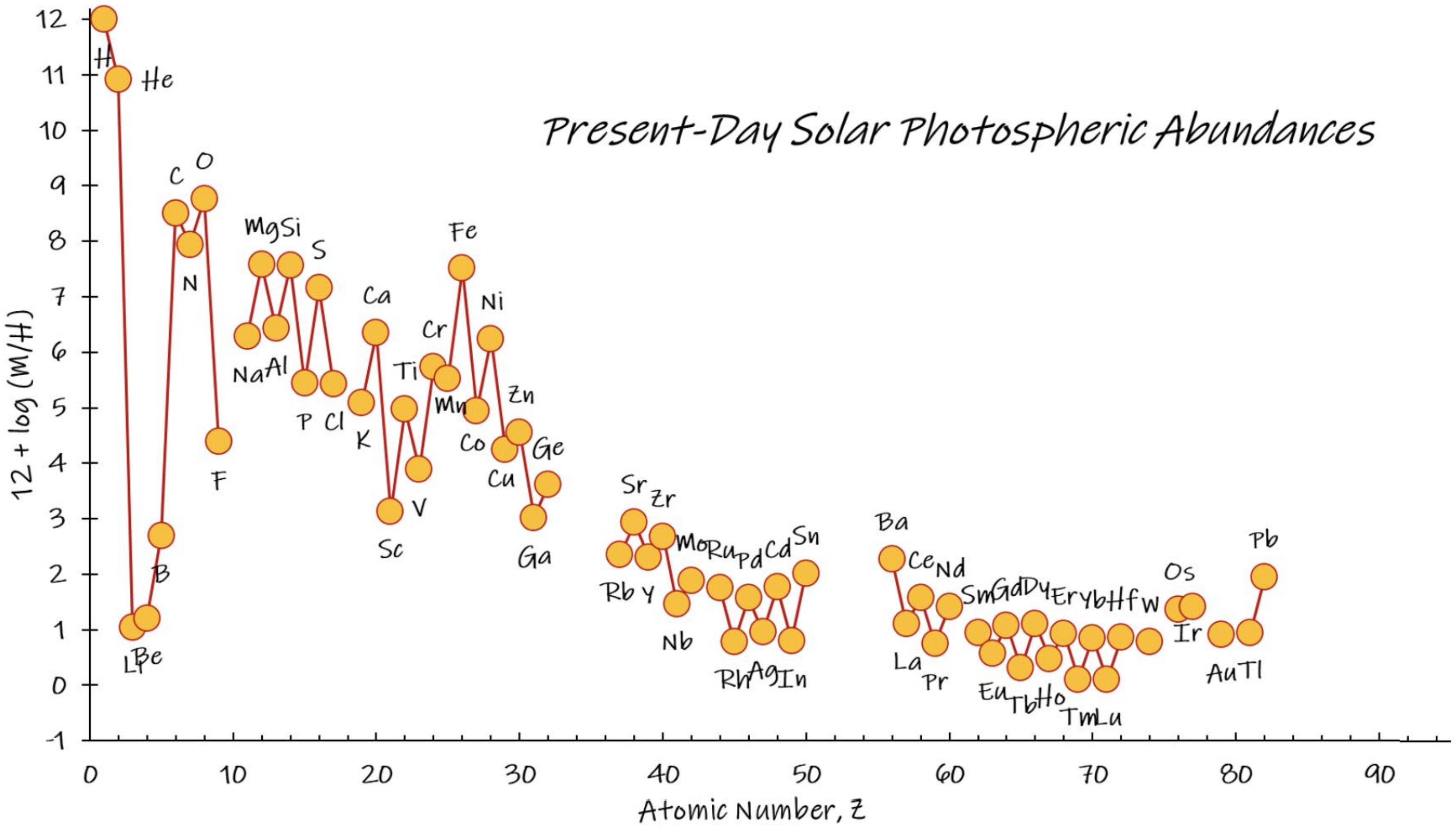

UK Astrophysical
Fluids Facility
Matthew Bate
University of Exeter


Betelgeuse
Bellatrix
Orion's Belt
Orion Nebula
Rigel
Saiph


1 µm


100 *Earth masses*
10 *Earth masses*
1 *Earth mass*

Chemical Composition of the Sun



<u>Most abundant elements, in order:</u>

H (71%) He (27%)

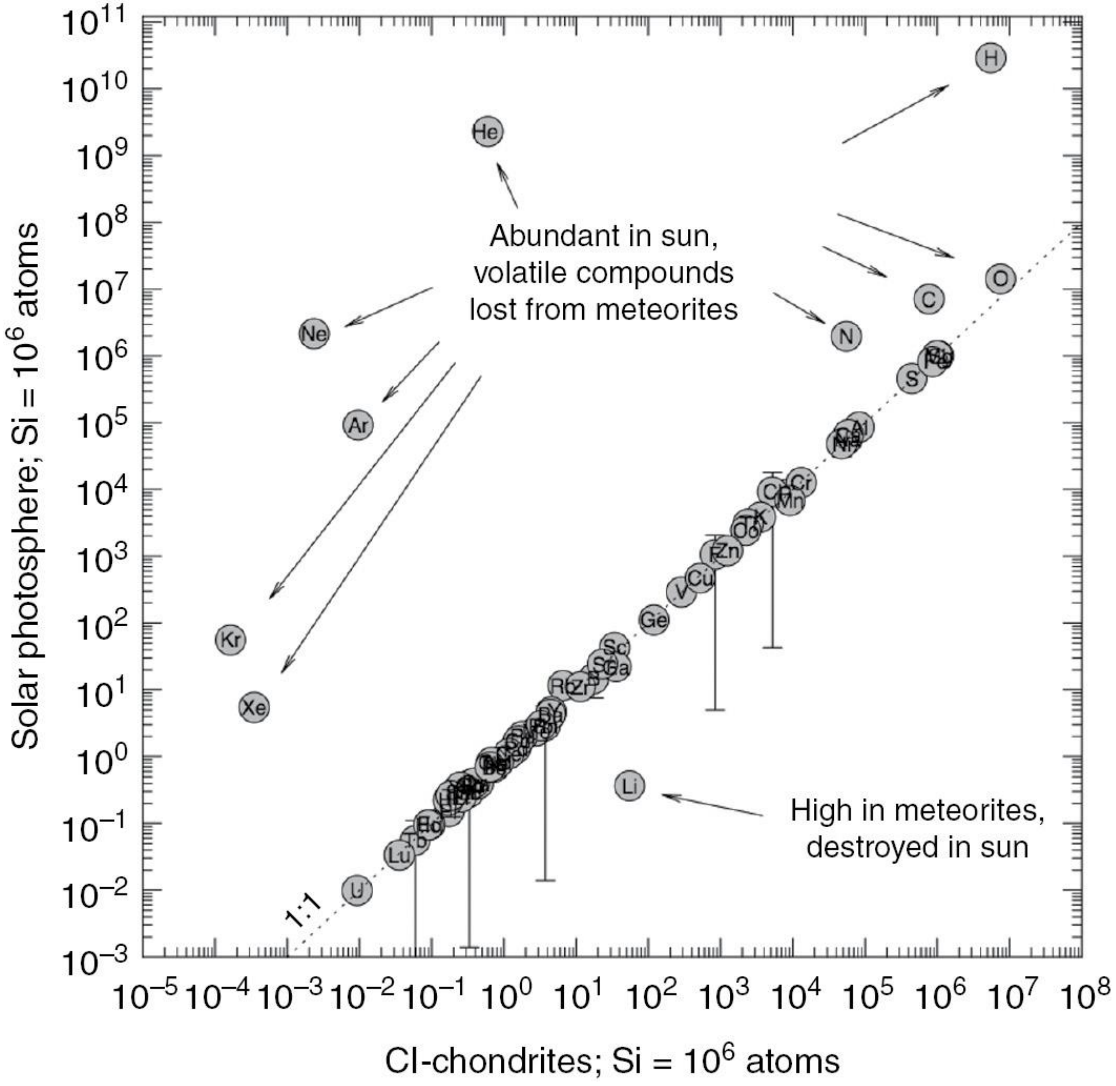
O (1.04%) C (0.46%)

Ne (0.13%) Fe (0.11%) N (0.1%)

Si (0.06%), Mg (0.05%), S (0.04%)

Bergemann et al. 2025

Refractories in meteorites: Solar Composition



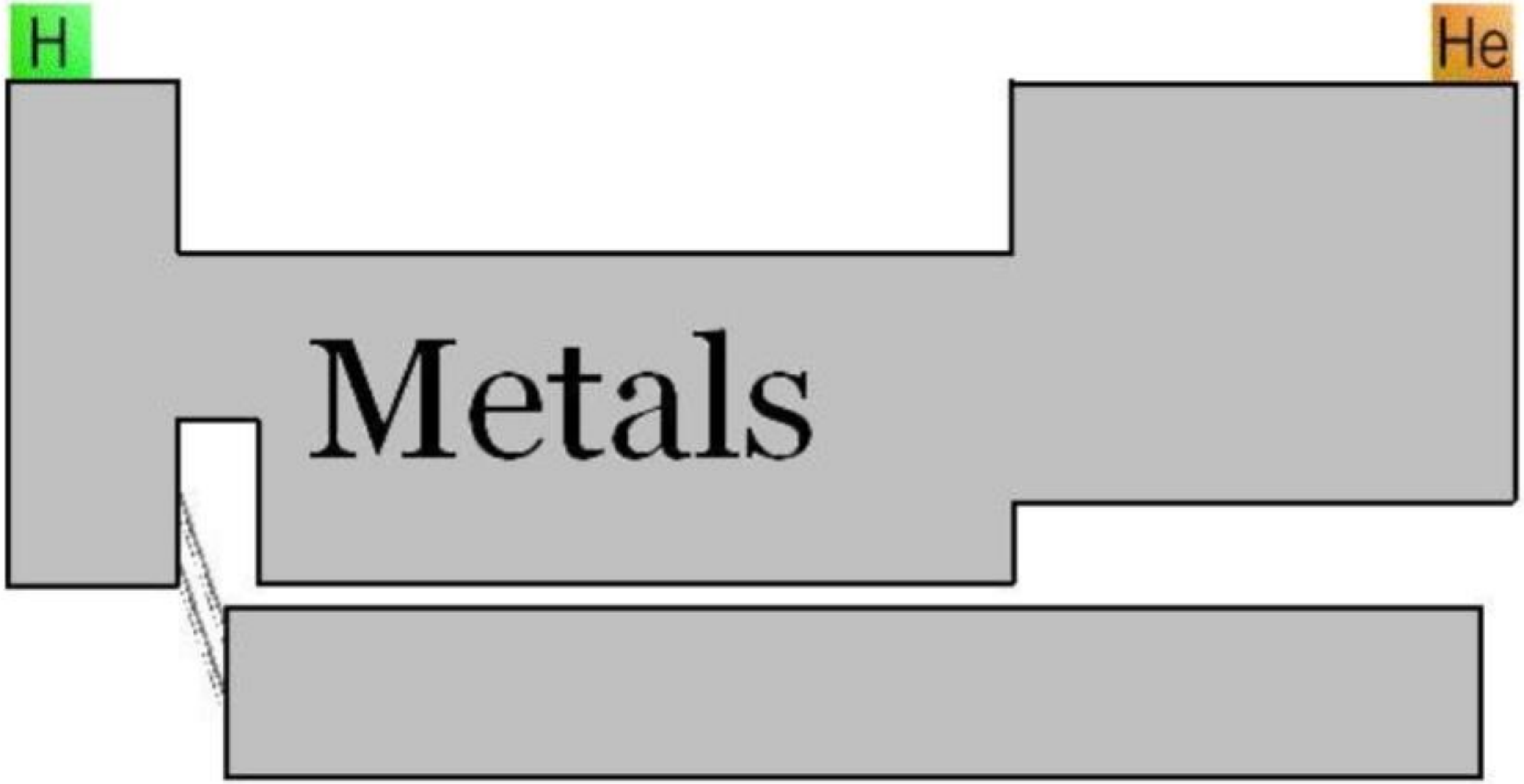
Lodders 2020

Periodic Table

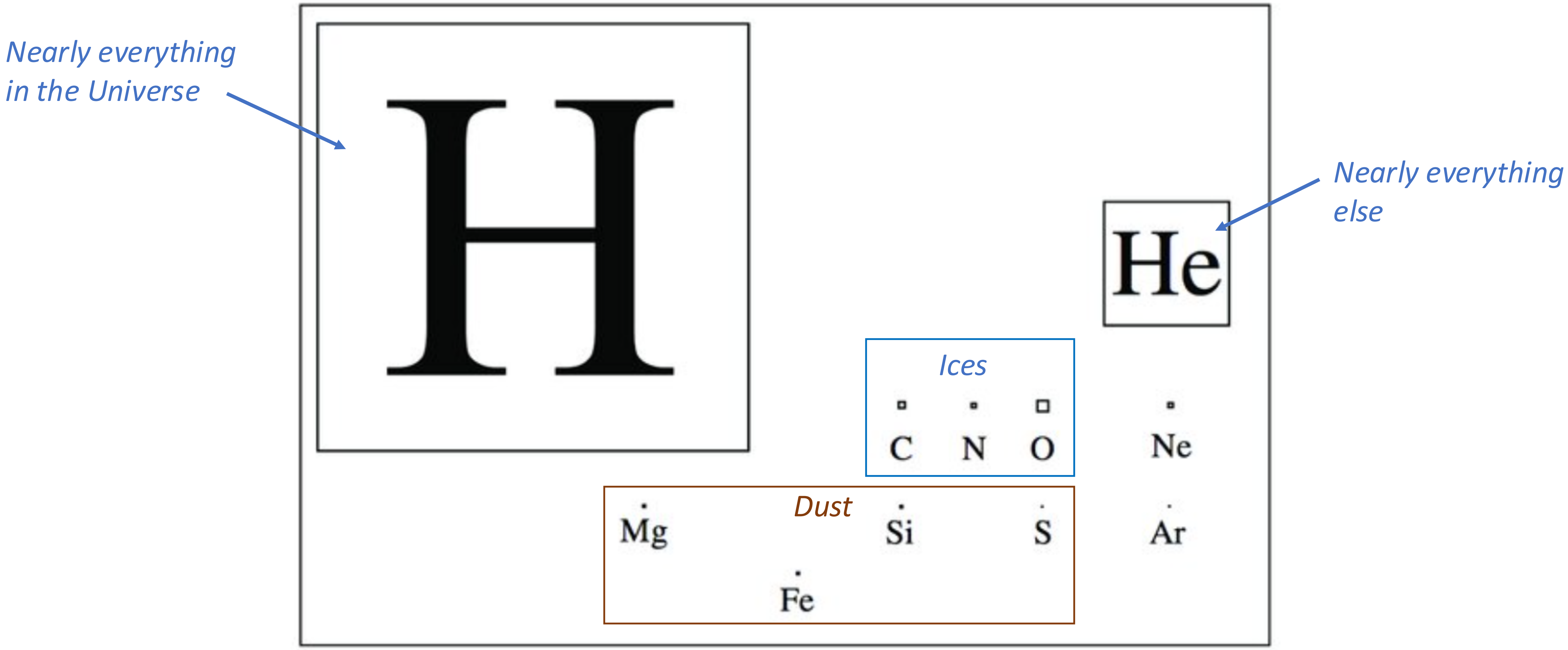
1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesi...											13 Al Aluminium	14 Si Silicon	15 P Phosph...	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Mangan...	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germani...	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybde...	43 Tc Techneti...	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Caesium	56 Ba Barium	57 La Lanthan...	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89 Ac Actinium	104 Rf Rutherfo...	105 Db Dubnium	106 Sg Seaborg...	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitneri...	110 Ds Darmsta...	111 Rg Roentge...	112 Cn Coperni...	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovi...	116 Lv Livermor...	117 Ts Tenness...	118 Og Oganes...
			58 Ce Cerium	59 Pr Praseod...	60 Nd Neodym...	61 Pm Prometh...	62 Sm Samarium	63 Eu Europium	64 Gd Gadolini...	65 Tb Terbium	66 Dy Dysprosi...	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium	
			90 Th Thorium	91 Pa Protacti...	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californi...	99 Es Einsteini...	100 Fm Fermium	101 Md Mendele...	102 No Nobelium	103 Lr Lawrenc...	

- Alkali metals
- Alkaline earth metals
- Transition metals
- Post-transition metals
- Metalloids
- Reactive nonmetals
- Noble gases
- Lanthanides
- Actinides
- Unknown properties

The Astronomer's Periodic Table

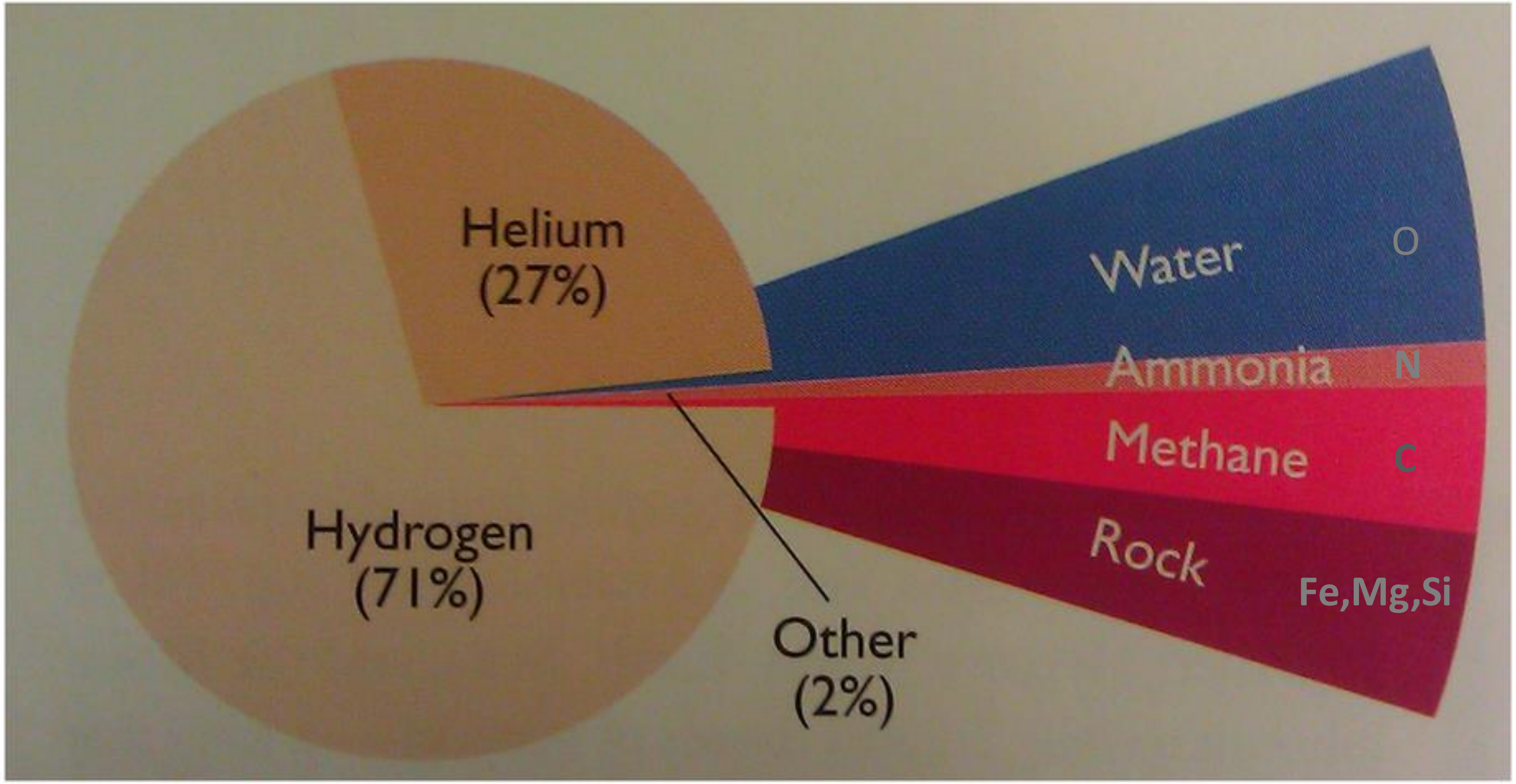


The Planetary Astronomer's Periodic Table



Solar composition:

H ~ 0.71
He ~ 0.27
Metals ~ 0.02



Beatty et al. (1999): *The New Solar System*

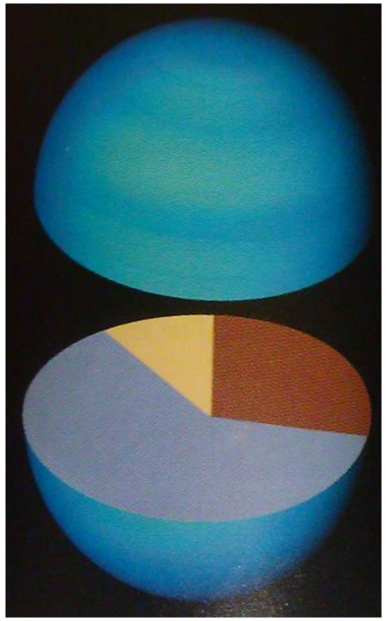
Classes of planets

Rocky Planets

Earth

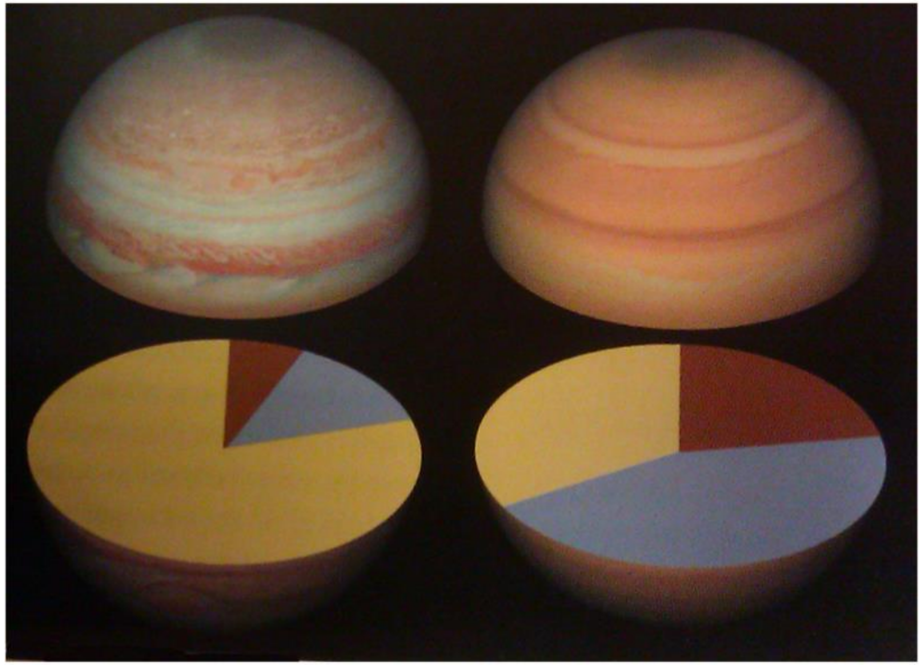
Ice Giants

Uranus/Neptune



Gas Giants

Jupiter Saturn



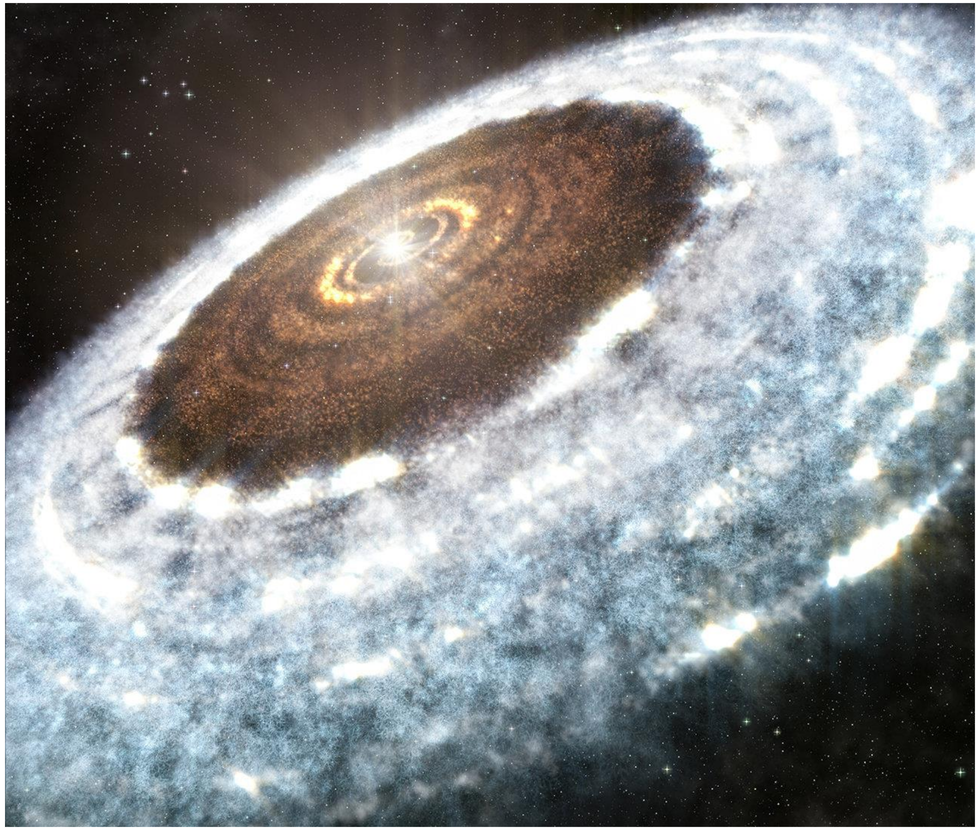
Rock

Ice

Gas

Beatty et al. (1999): *The New Solar System*

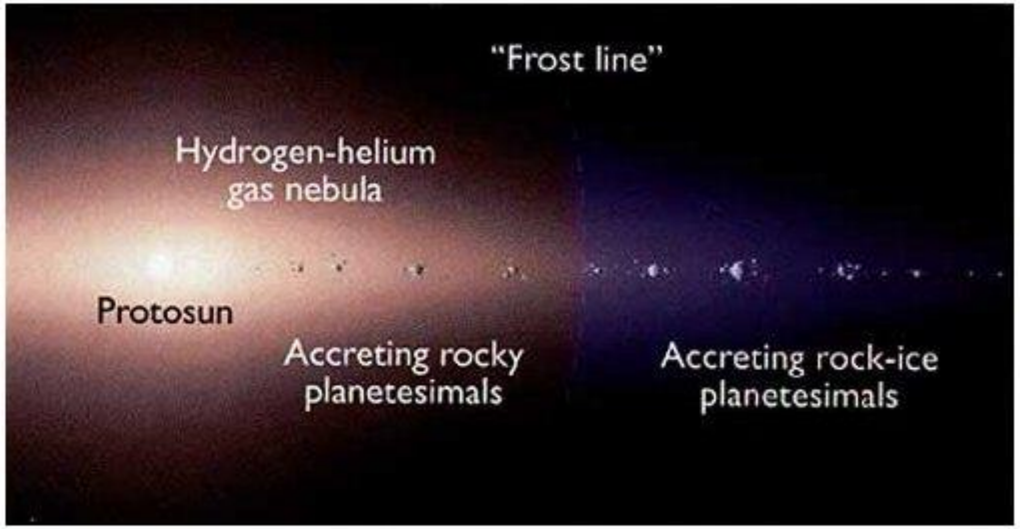
Snowline



The idea, *roughly*

<u>**Inward of snowline**</u>

Rocks only
(small)

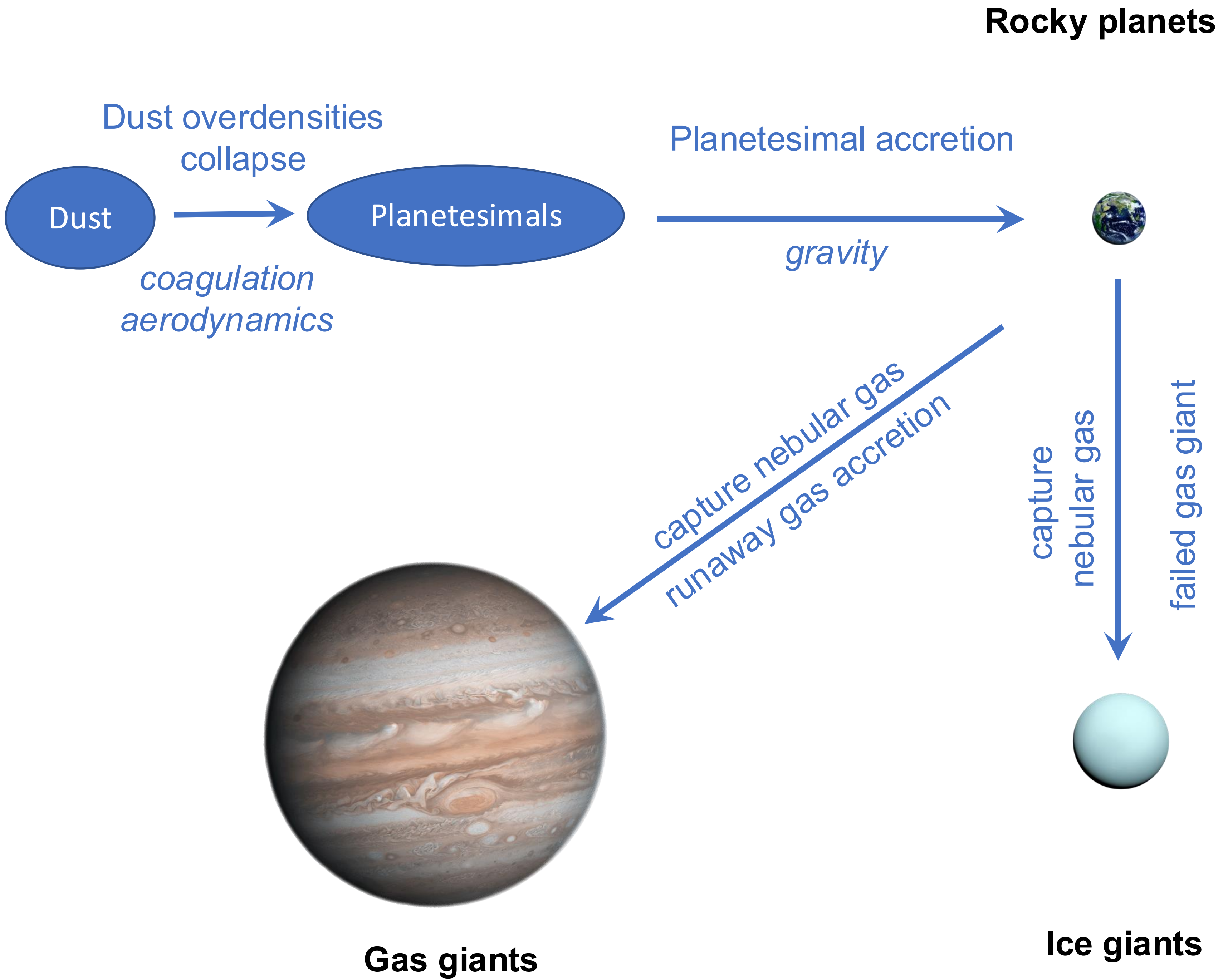


<u>Outward of snowline</u>

Ice comes to aid!
Growing big
icy/rocky cores.

“Core Accretion”

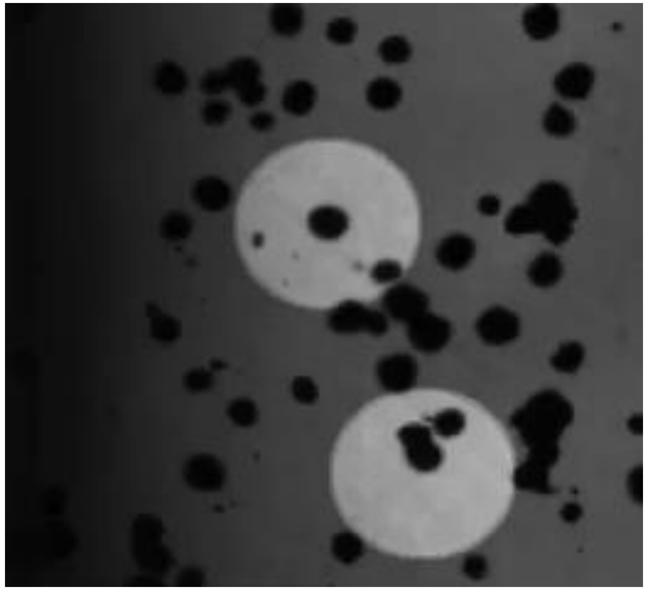
Core Accretion



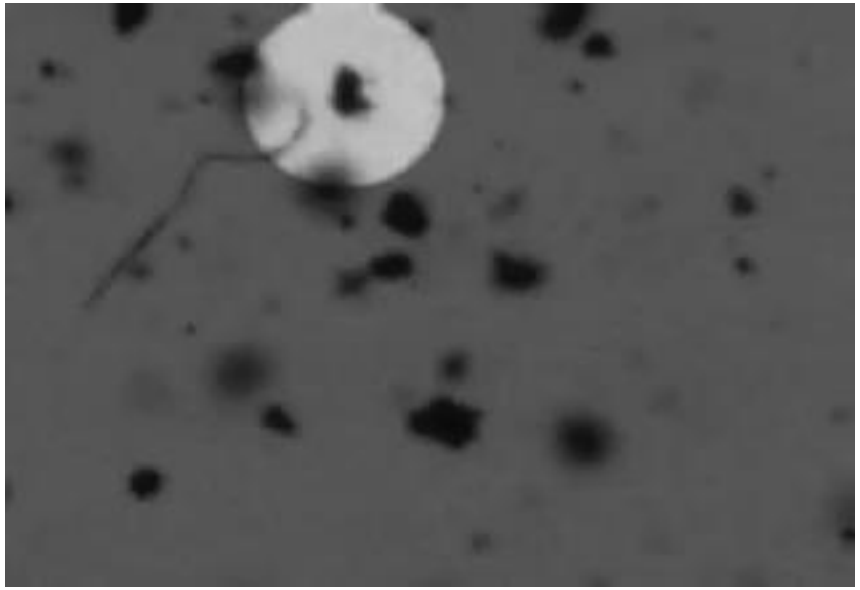
“Bottom-Up”: Dust Growth and Core Accretion

Grain collision outcomes

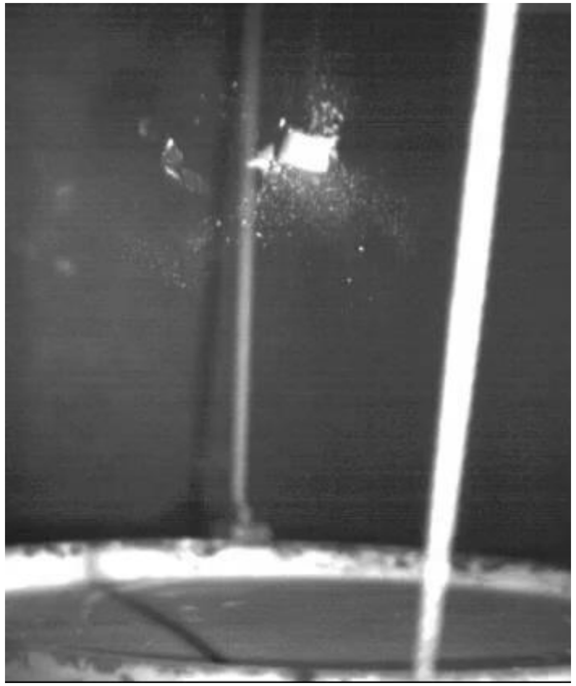
Bouncing



Sticking

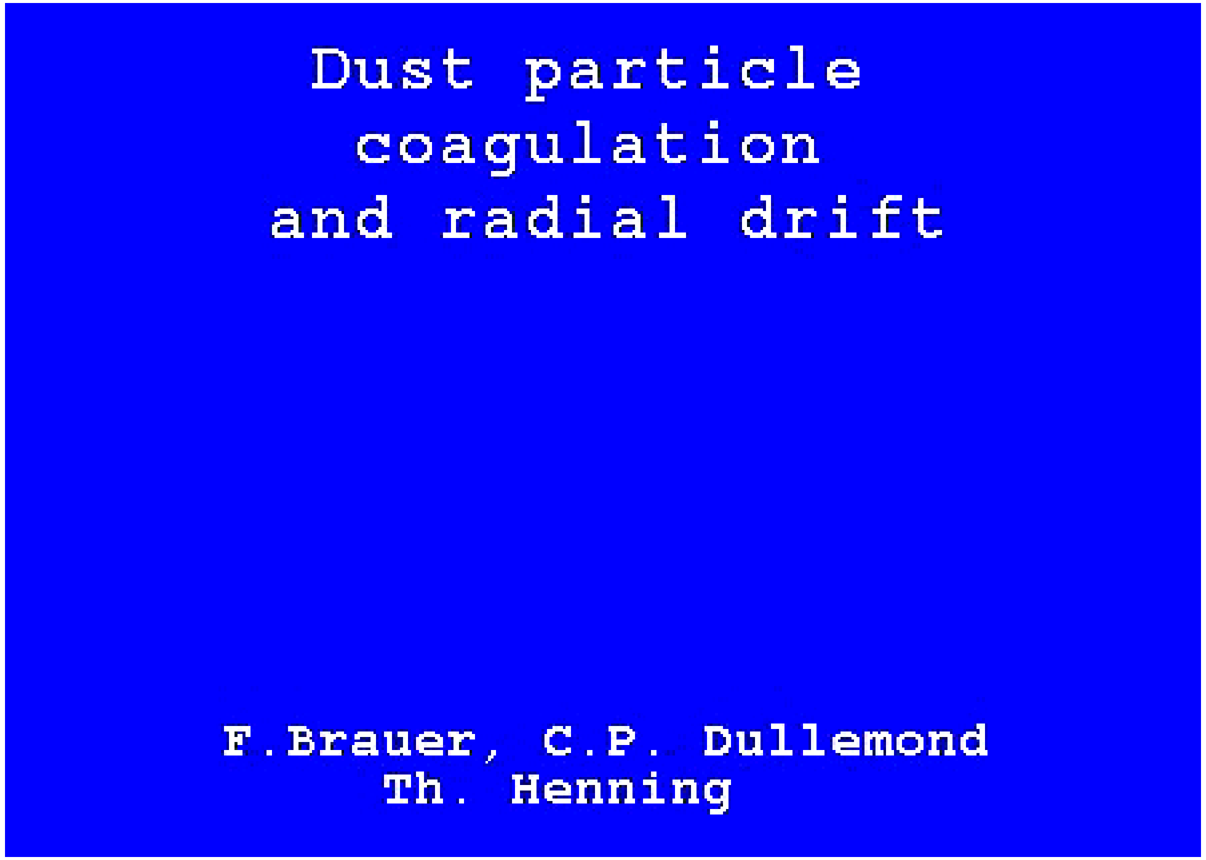


Destruction



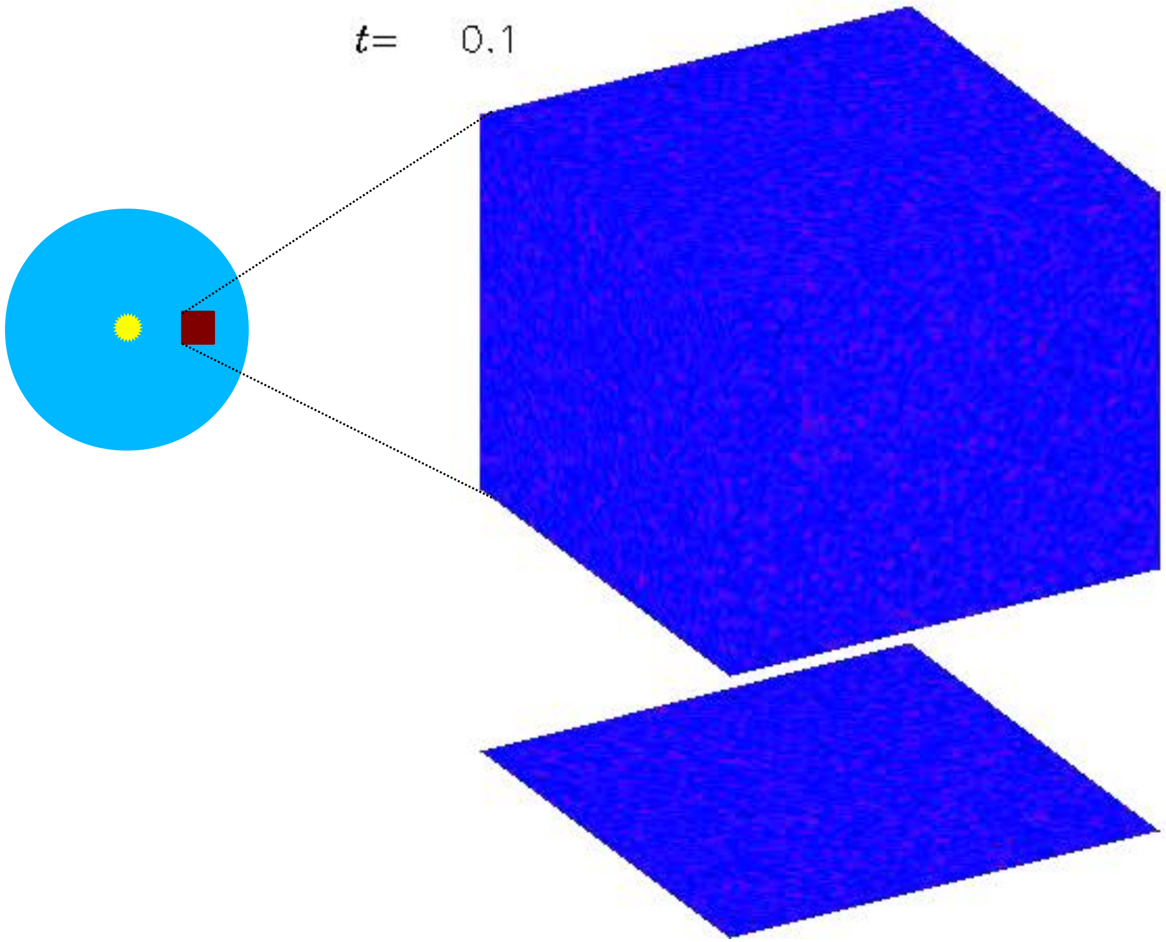
Guttler et al. (2010); Zsom et al. (2010)

Dust Growth and Drift



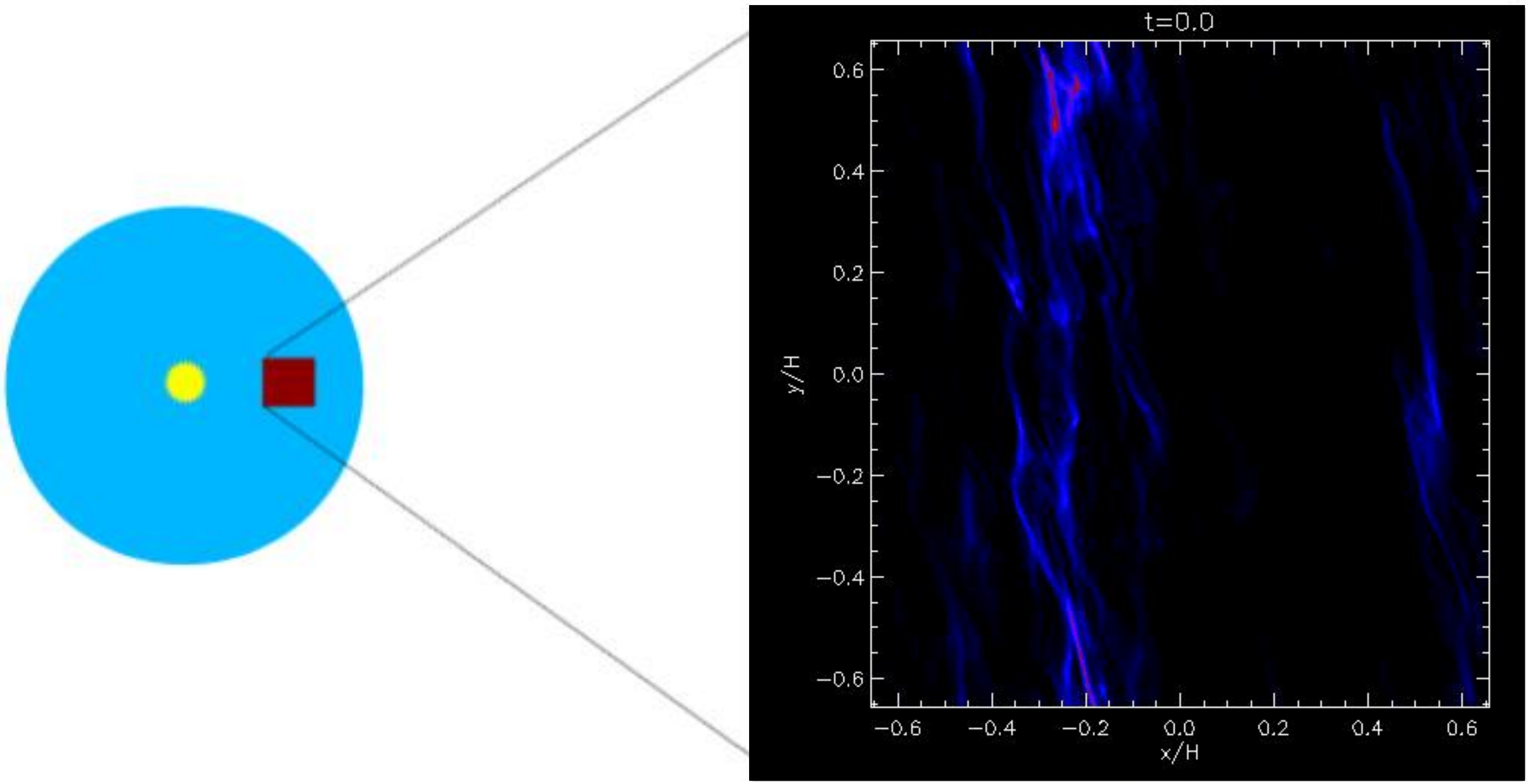
"Streaming" Instability

The dust drift is not orderly, but turbulent



Johansen & Youdin (2007); Video credit: Anders Johansen

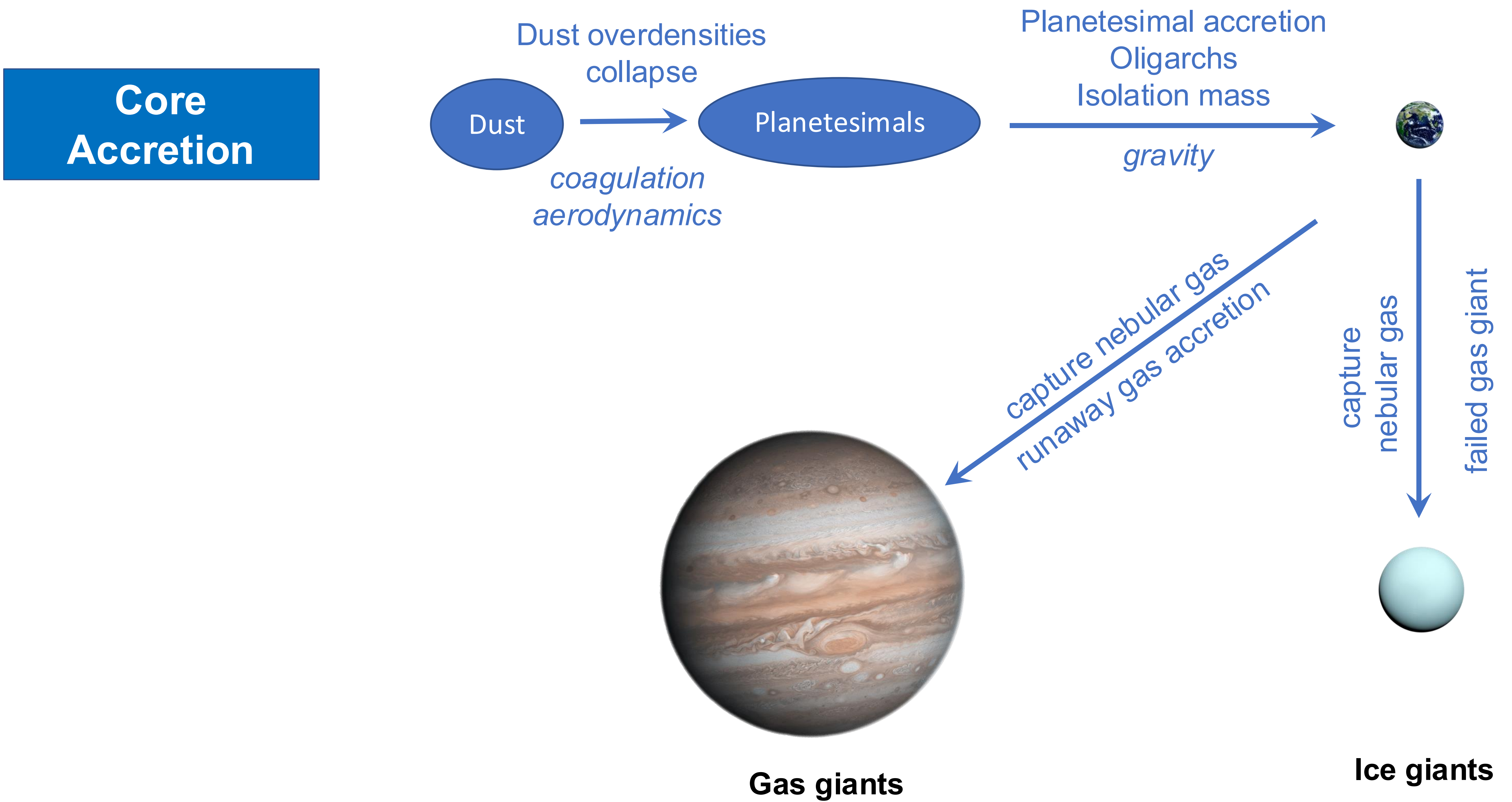
Gravitational collapse into km-sized objects ("planetesimals")



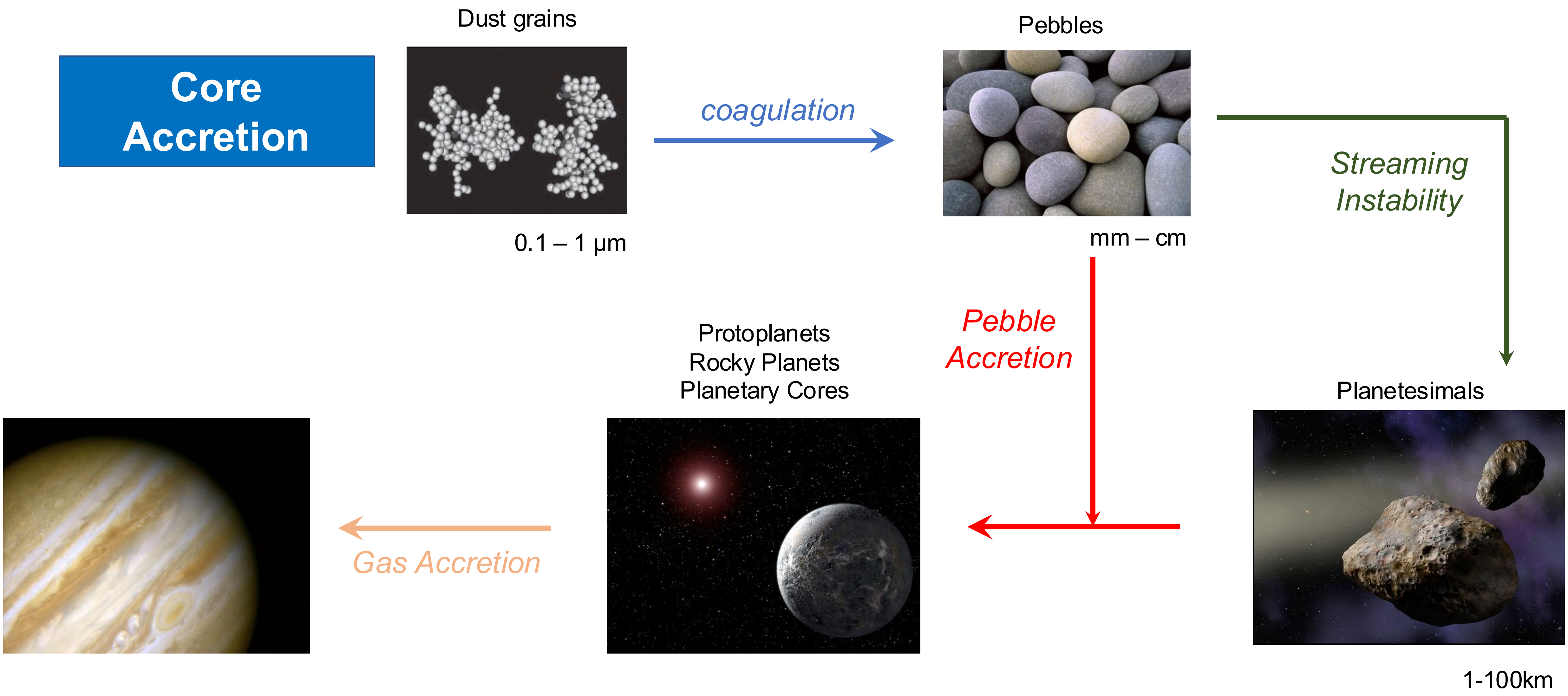
Johansen et al. (2007)

Video credit: Anders Johansen

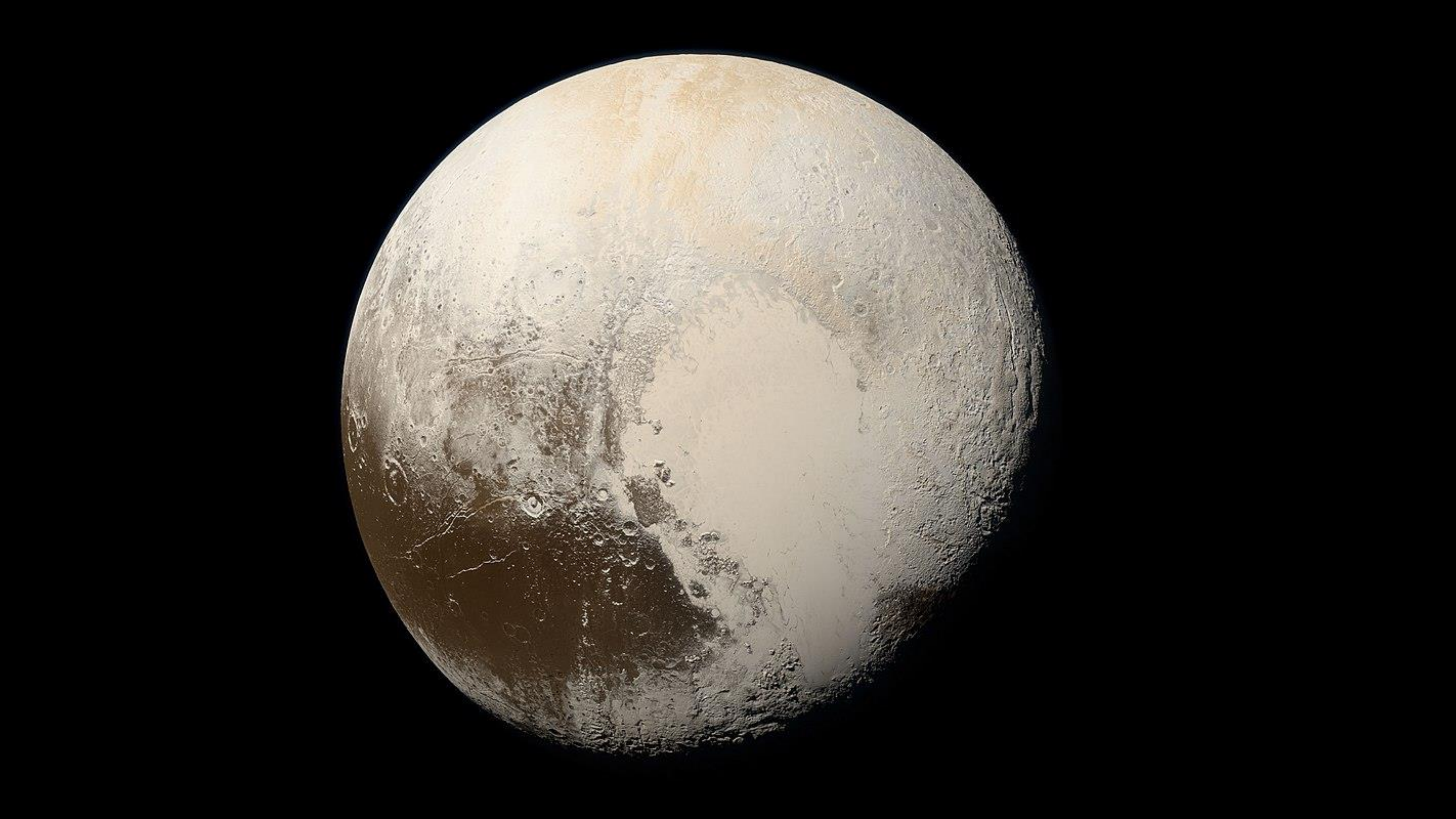
Core Accretion *(…30 yrs ago)*



Core Accretion



How can we verify the streaming instability hypothesis?



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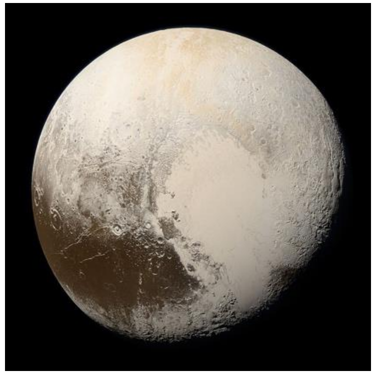
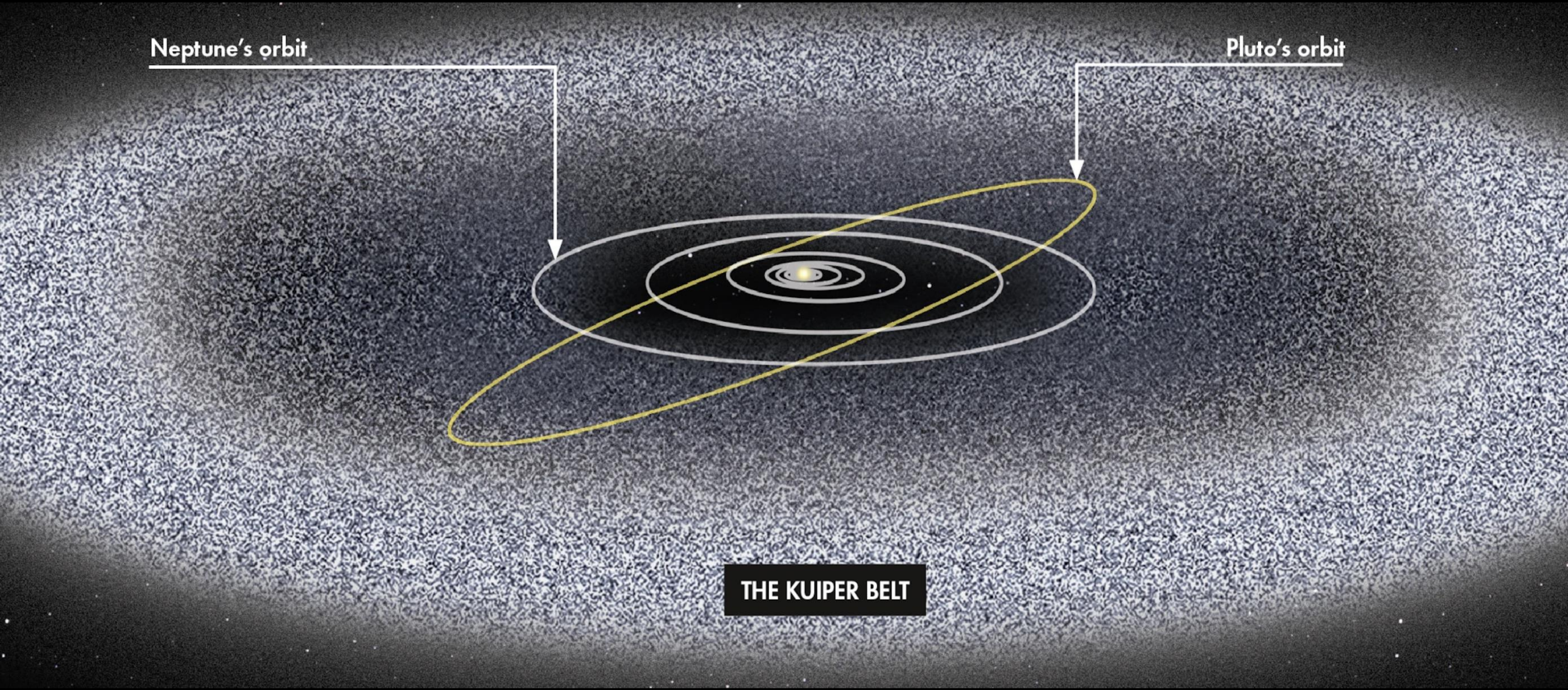
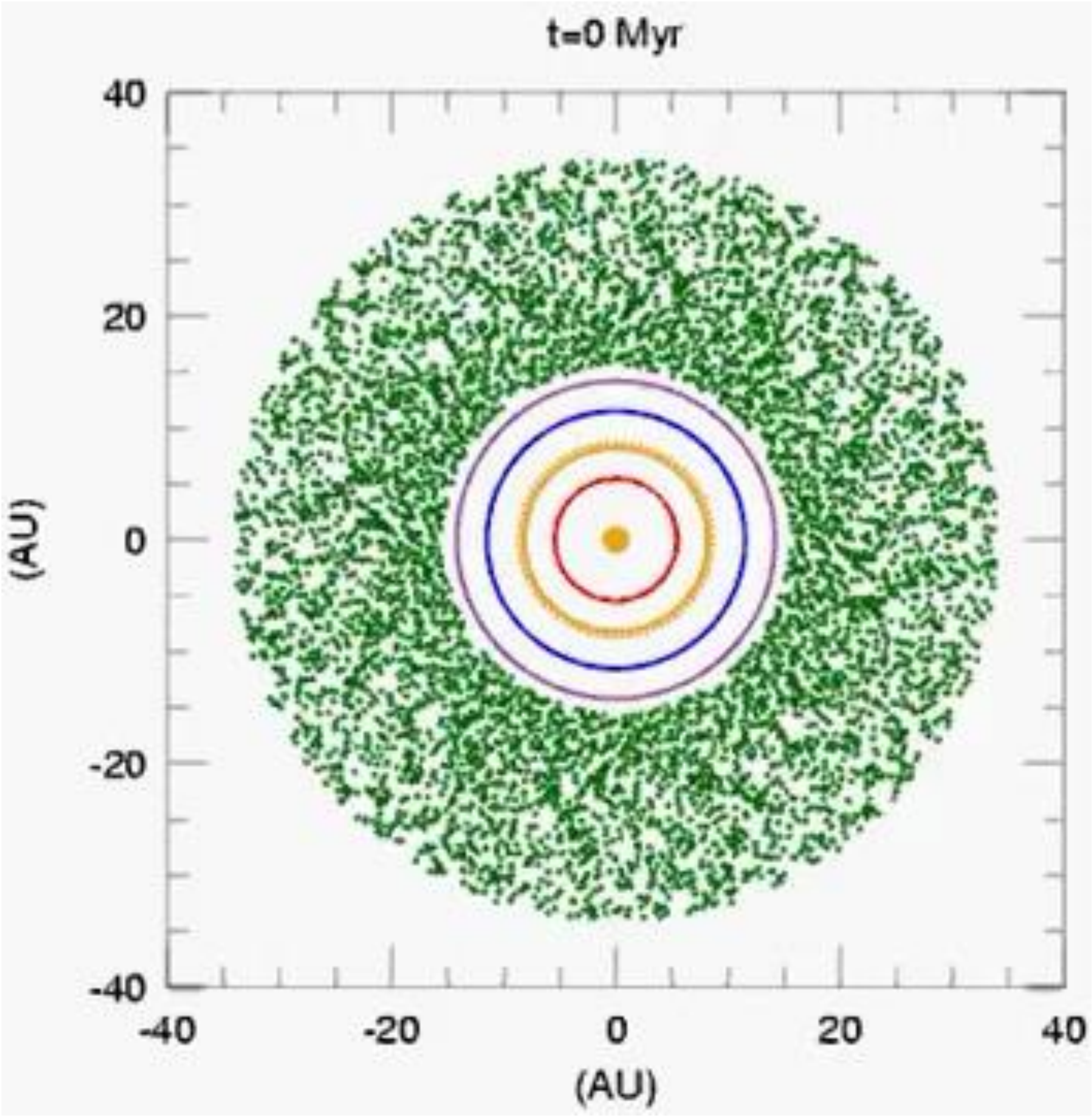


Pluto sponsor?

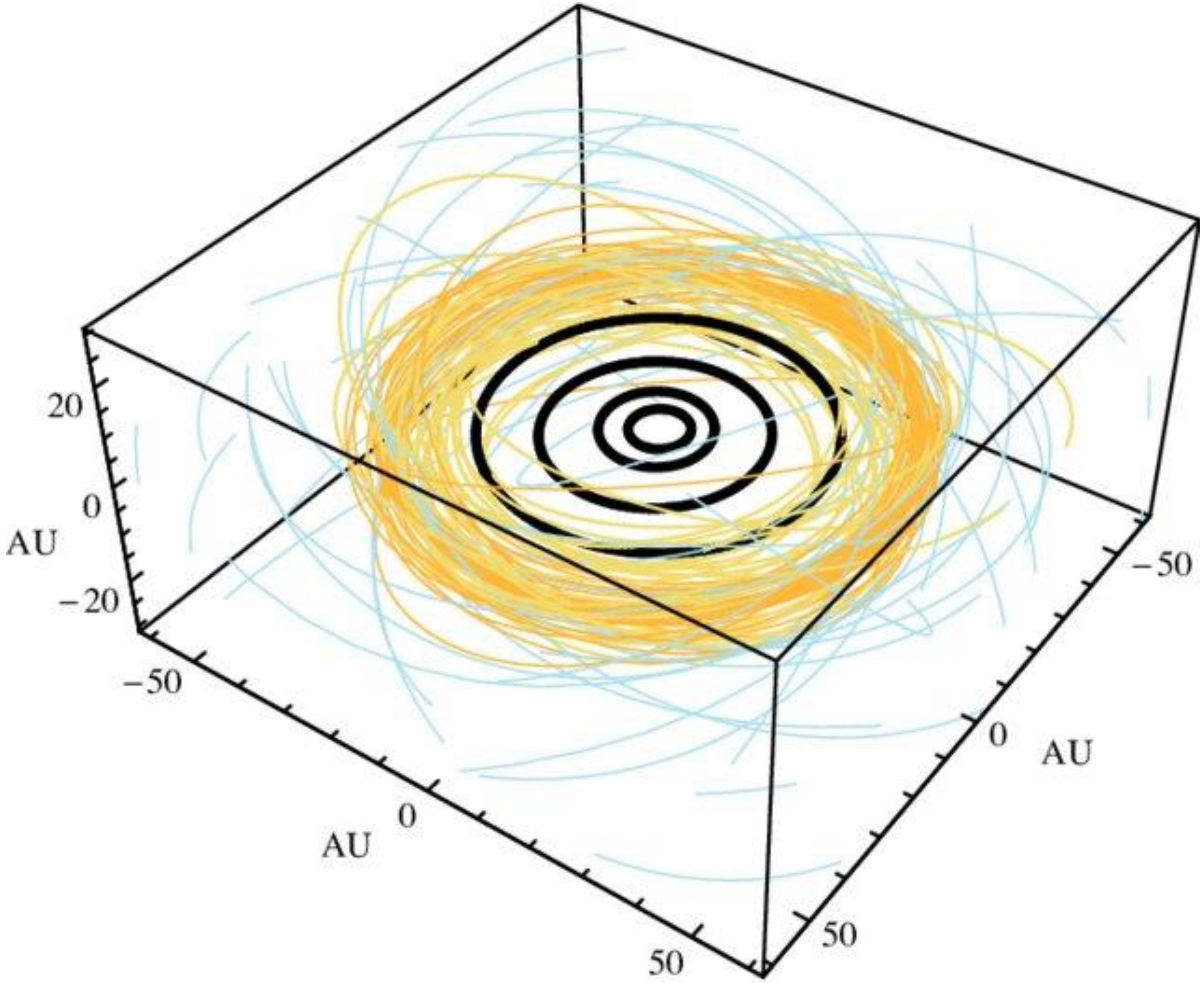

Neptune's orbit
Pluto's orbit
THE KUIPER BELT

Evolution of the orbits of the giant planets



Tsiganis et al. (2005); Gomes et al. (2005); Morbidelli et al. (2005); Video credit: Alessandro Morbidelli

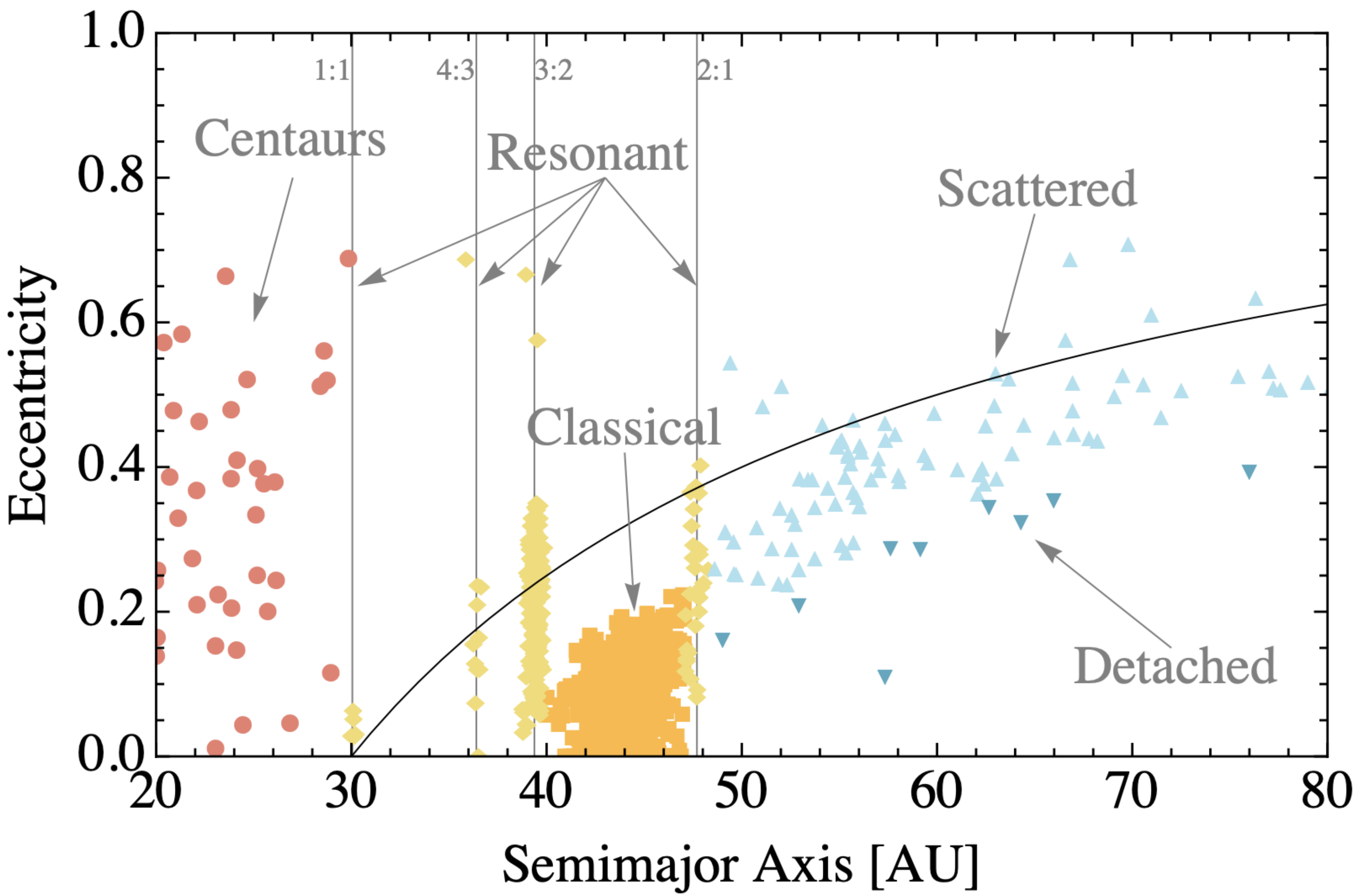
Structure of the Kuiper Belt



Lacerda (2009)

Classicals
Scattered
Resonants

Structure of the Kuiper Belt

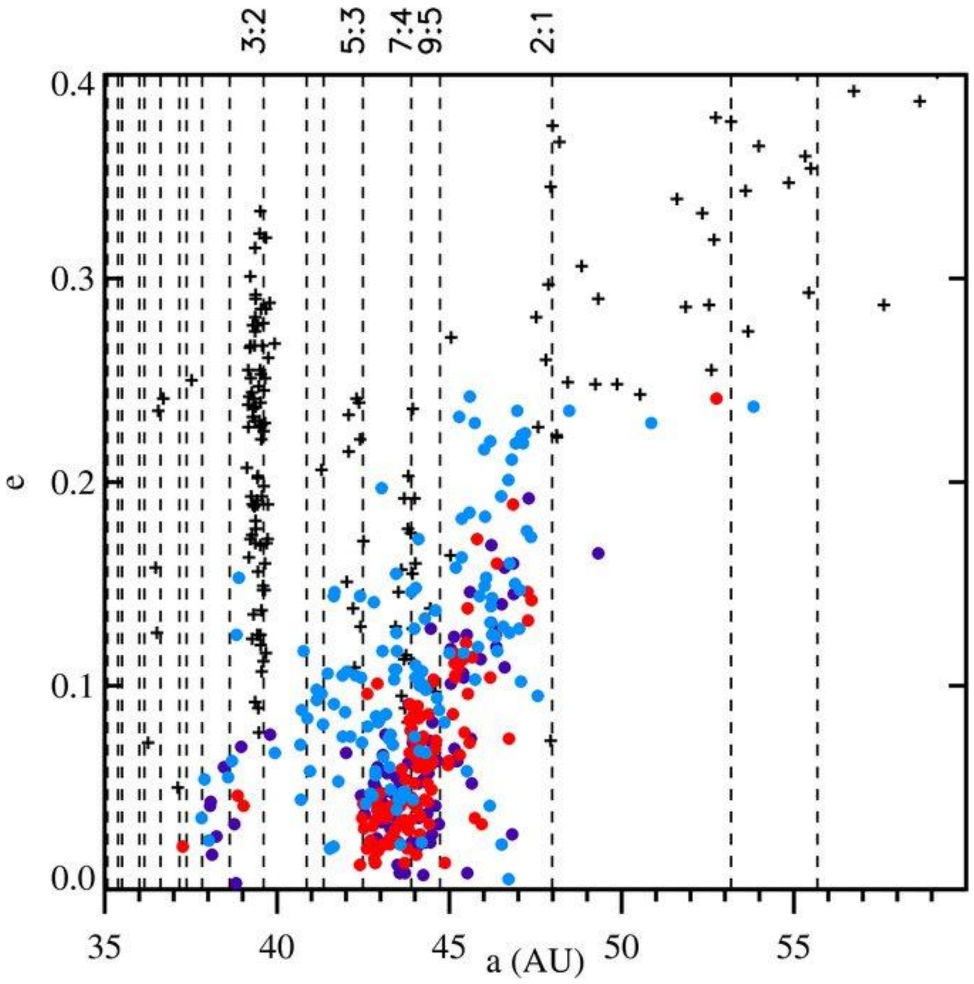


Classicals:

Objects between 40 and 50 au

Lacerda (2009)

“Cold” Classical Kuiper Belt Object



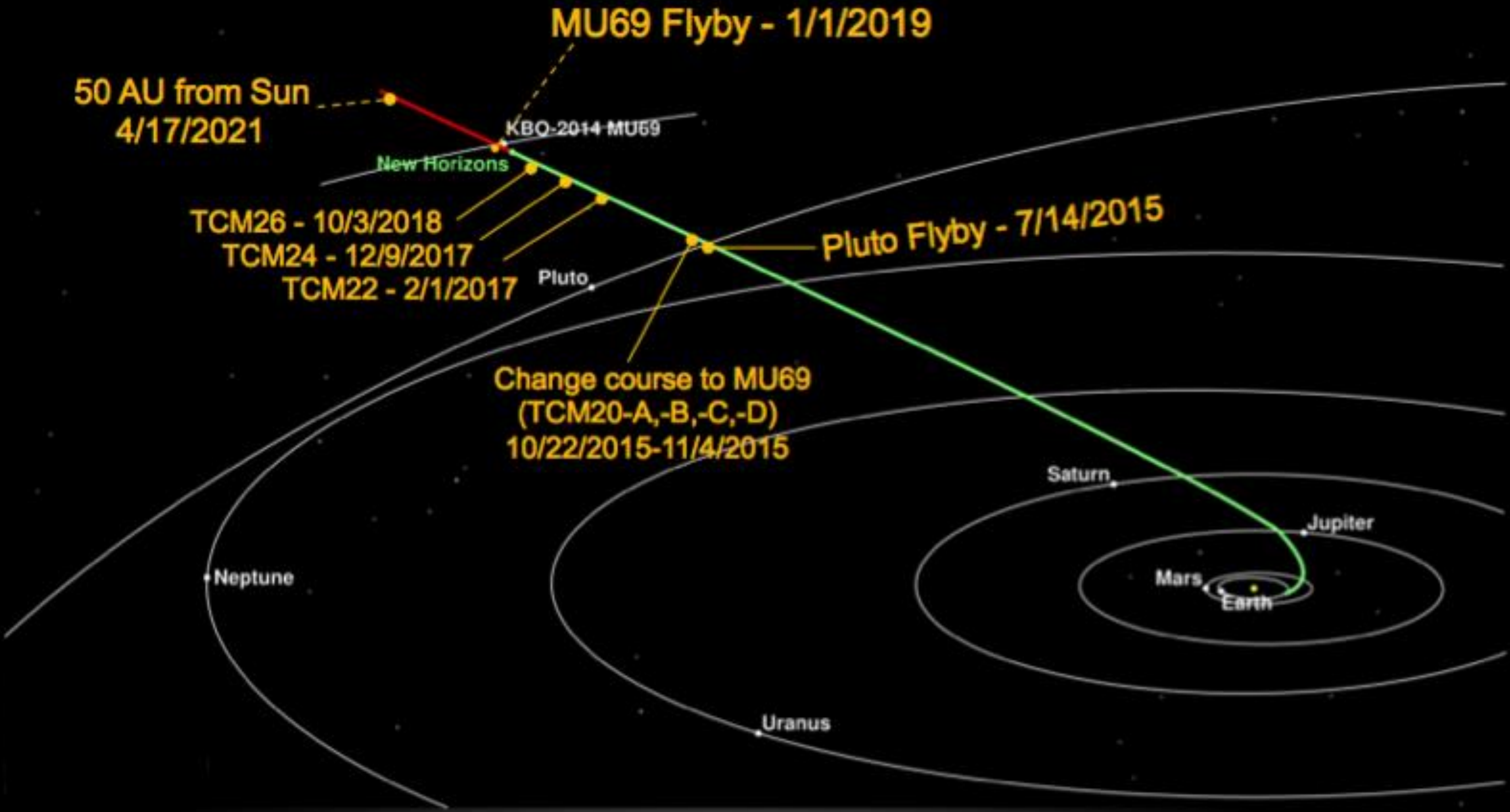
+ Resonant and Scattered
Cold Classical $i<2^o$
“Ambiguous” $2^o<i<6^o$
Hot Classicals $i>6^o$

A dynamically cold population: low inclination and low eccentricity orbits, like the planets.

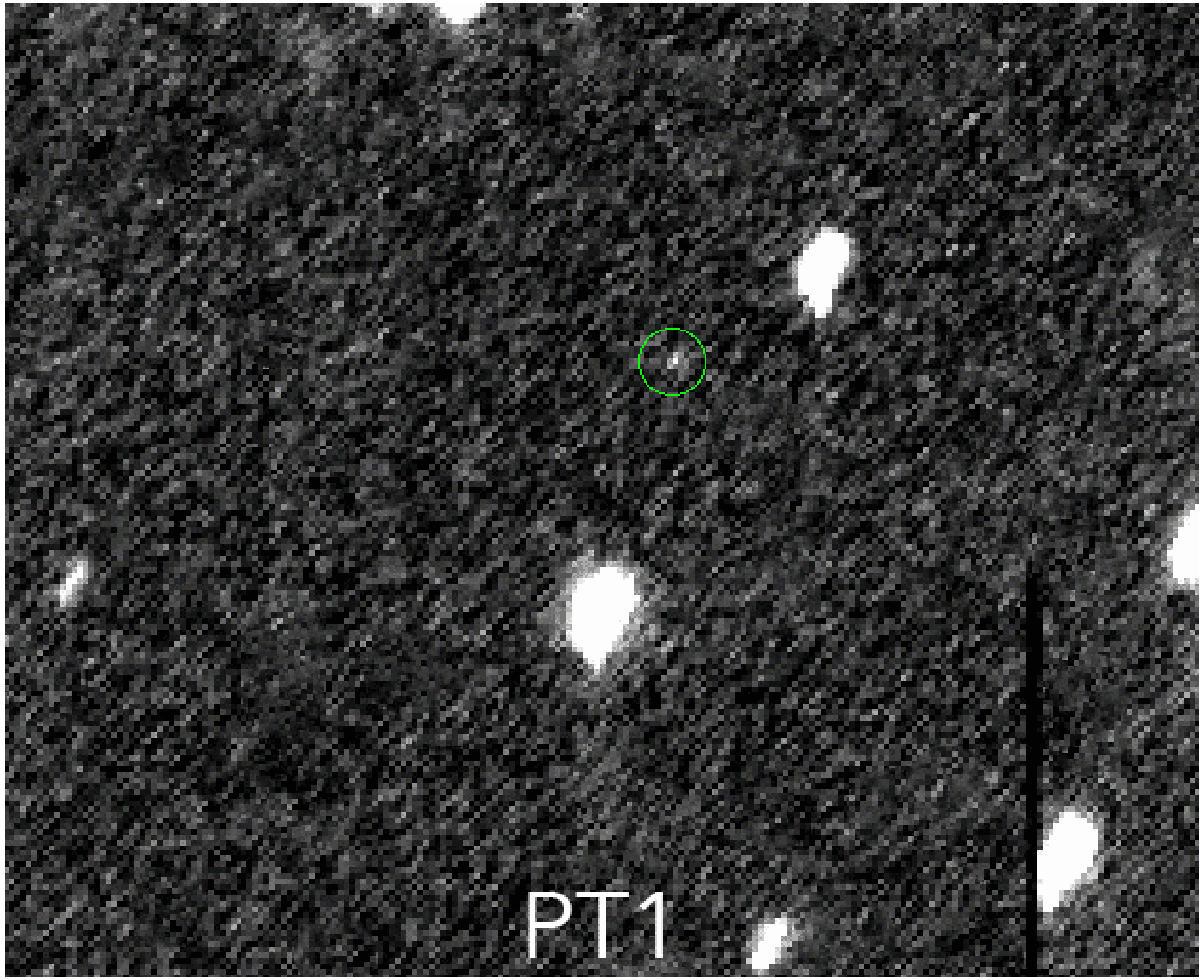
Presumably pristine planetesimals

Dawson & Murray-Clay (2012)

New Horizons Trajectory

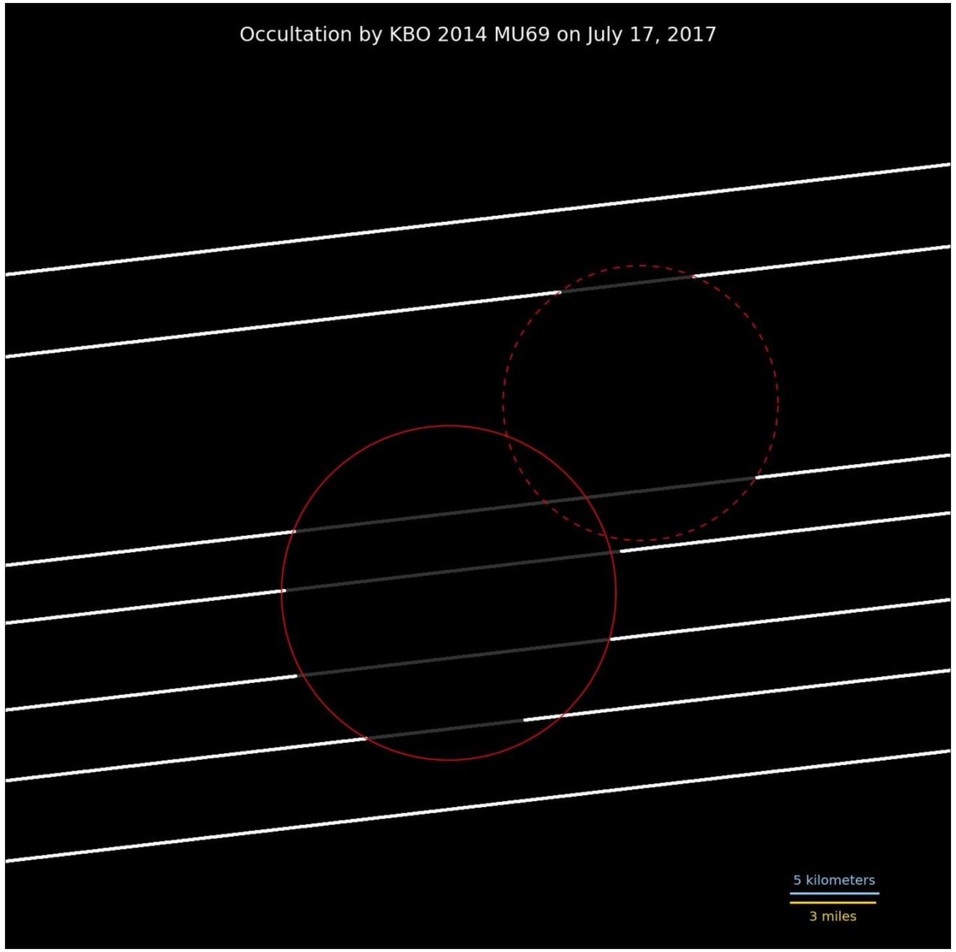


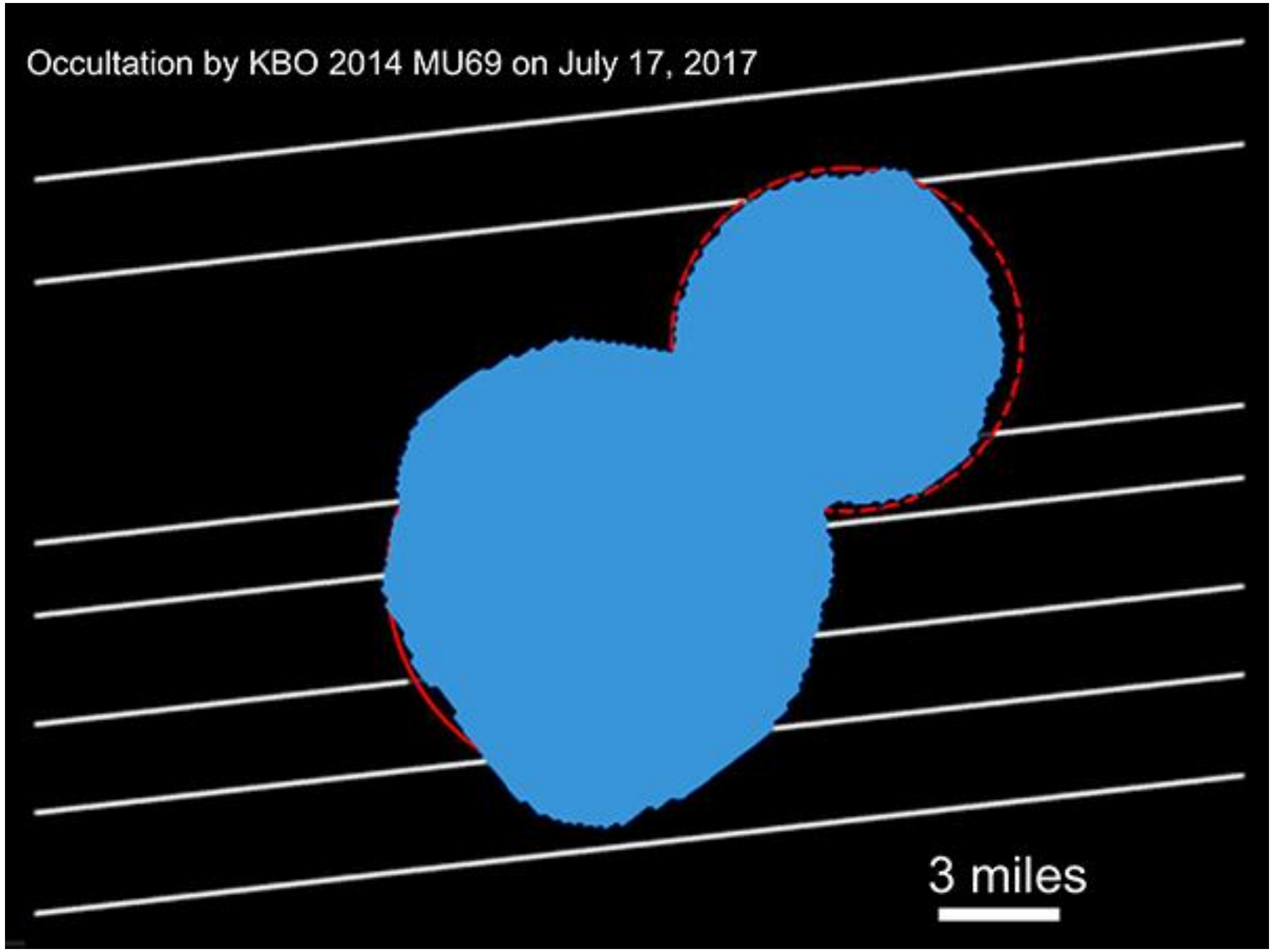
Arrokoth: Discovery



Discovery: Marc Buie. Video credit: Bruce Murray

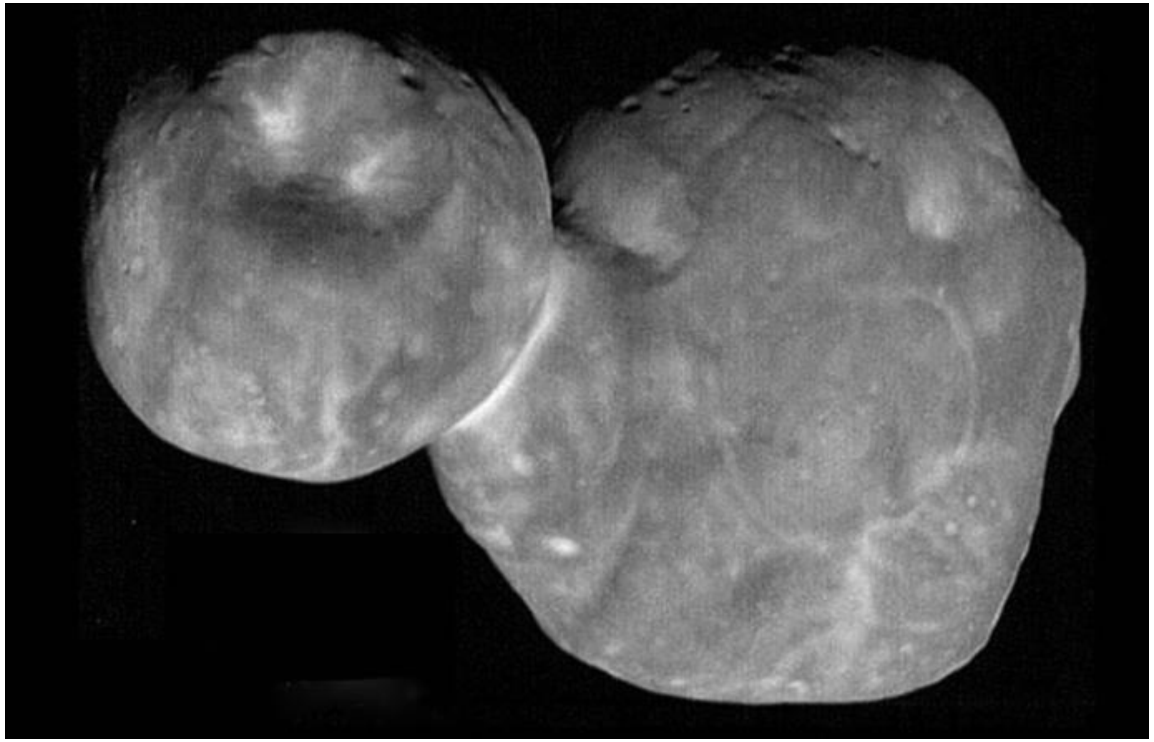
Occultation data suggests binary





Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

Approach sequence: Contact Binary

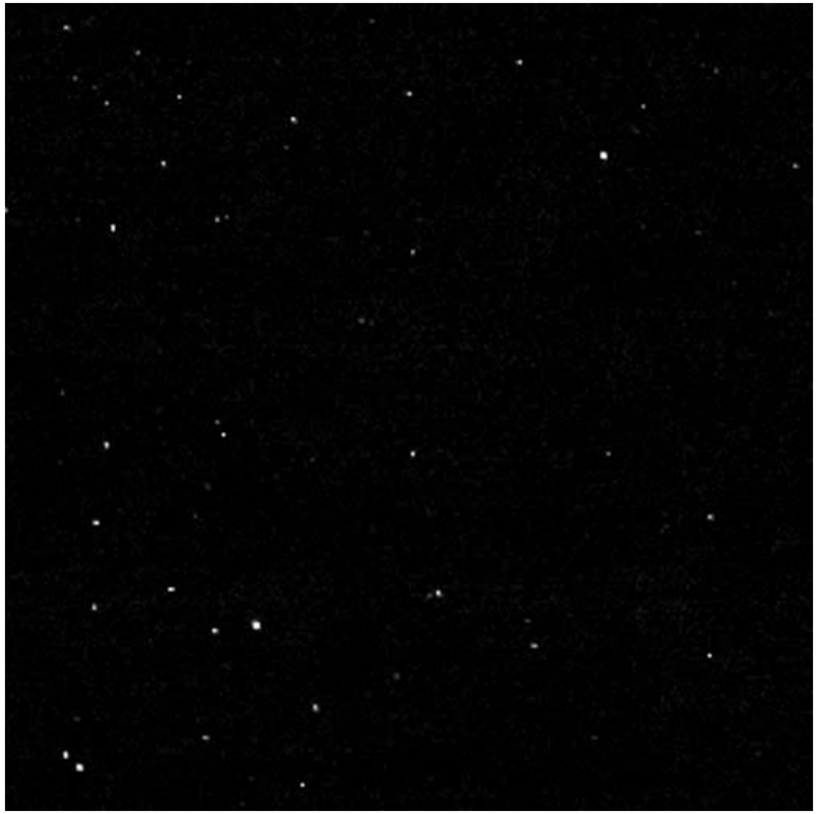


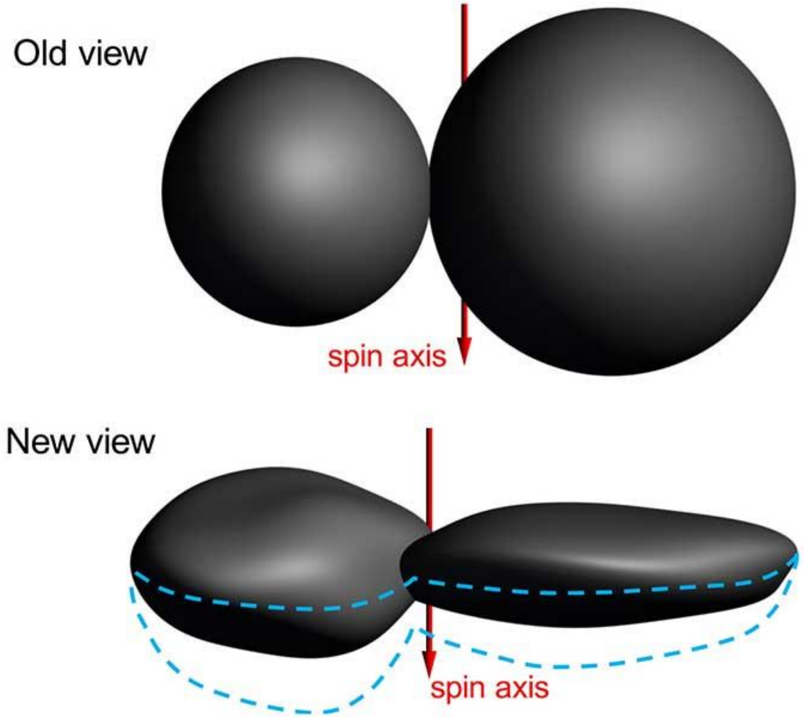
Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

“The Snowman”

Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

Departure sequence: Shape

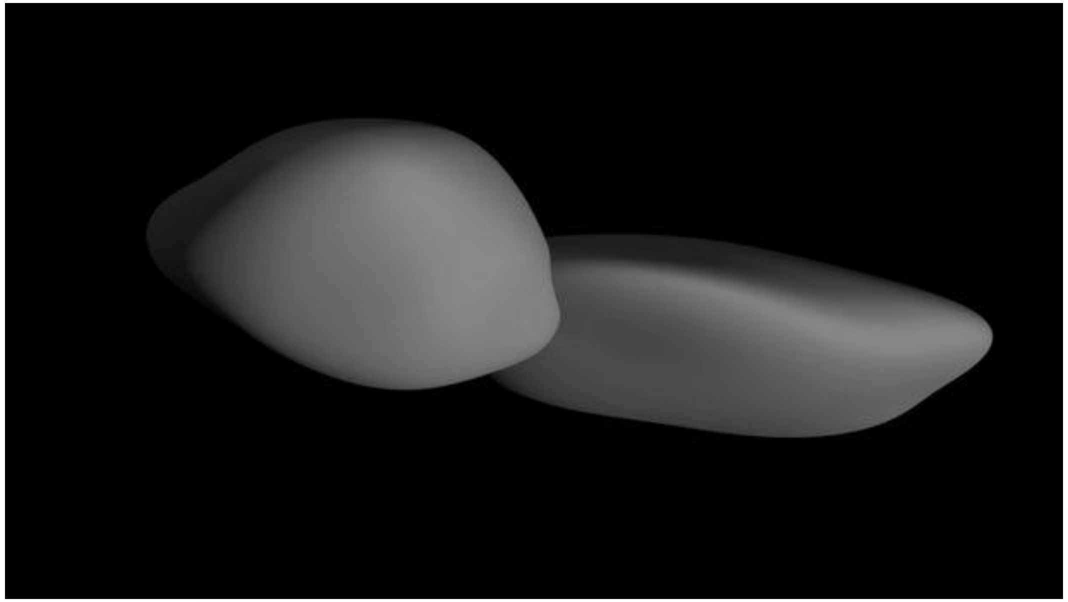




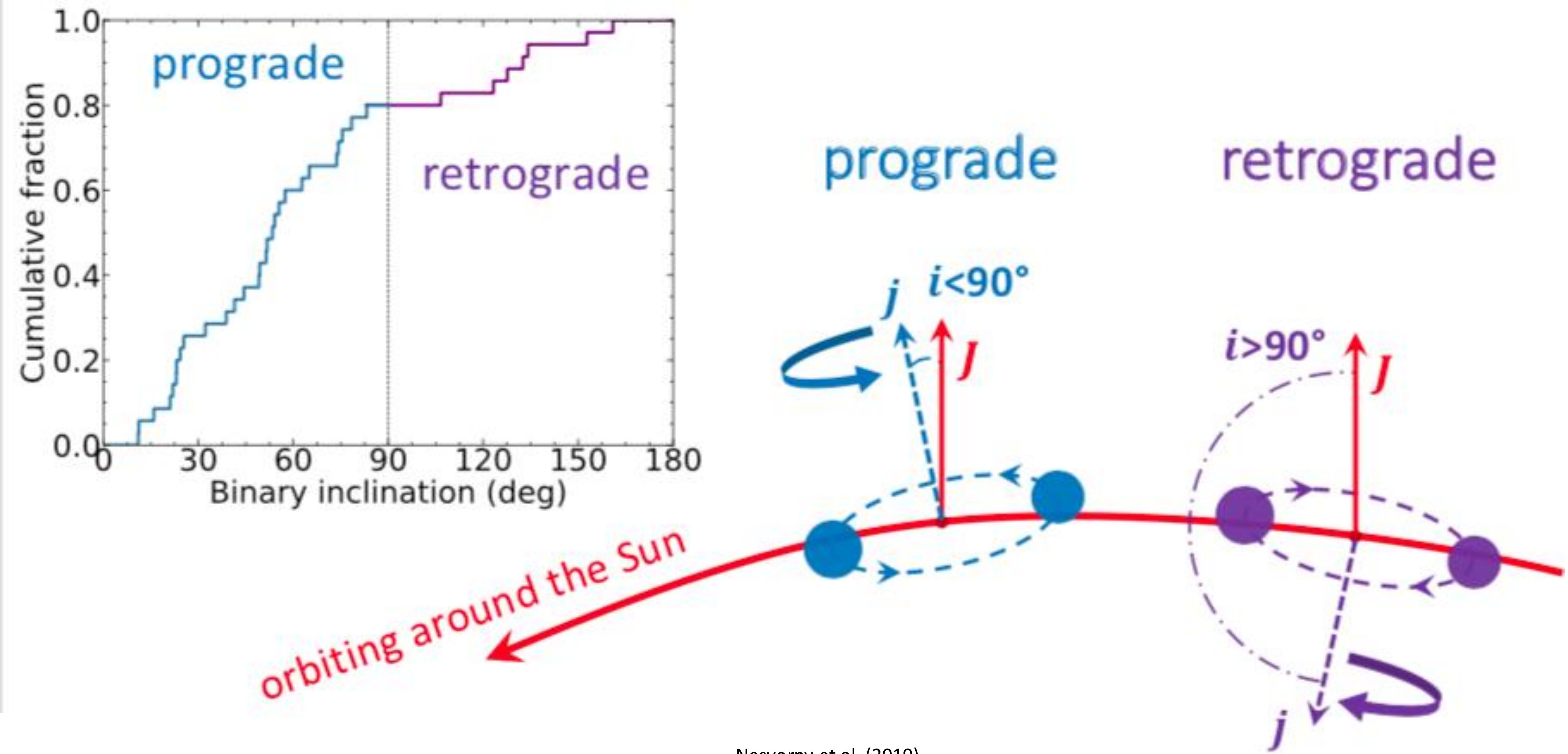
Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

“The Snowman”

Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute



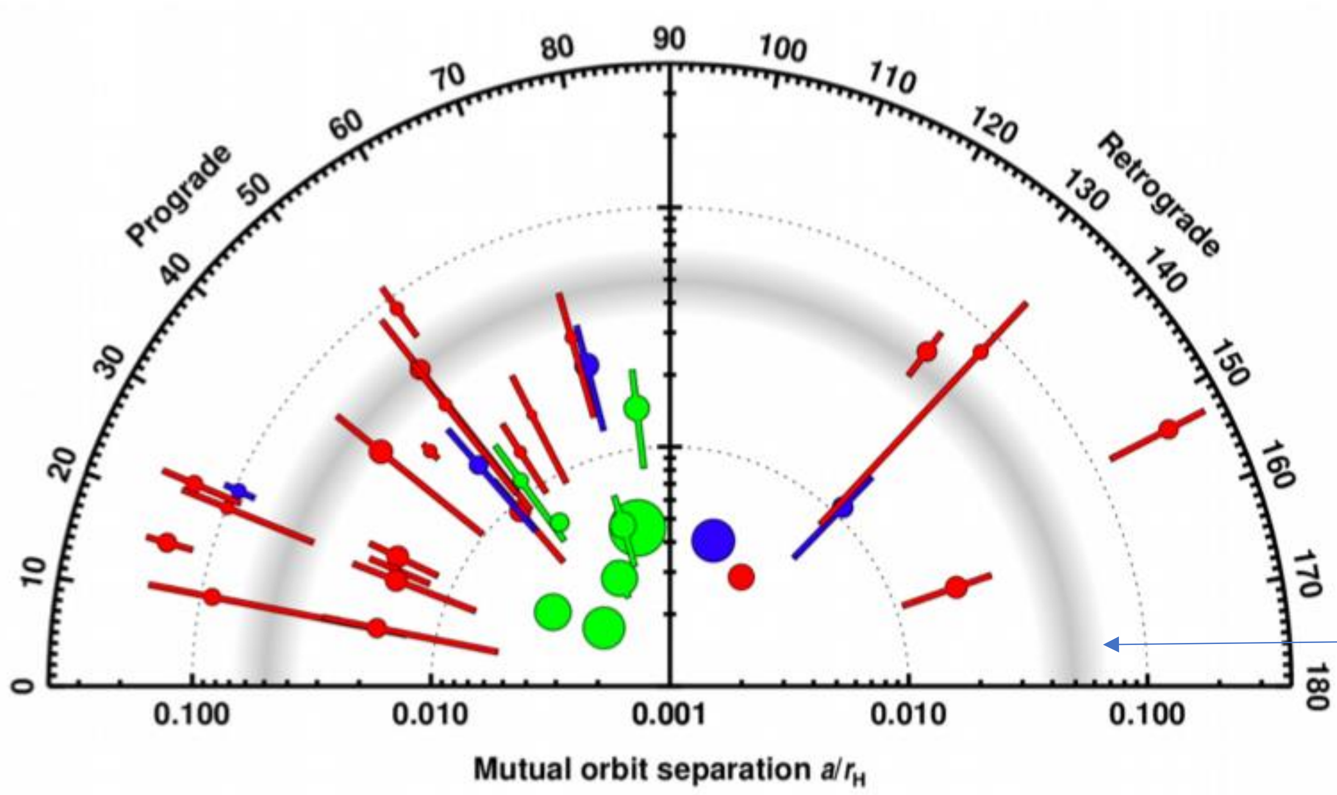
Preference for Prograde



Nesvorny et al. (2019)

Prograde vs Retrograde

Protractor Plot



Cold Classicals

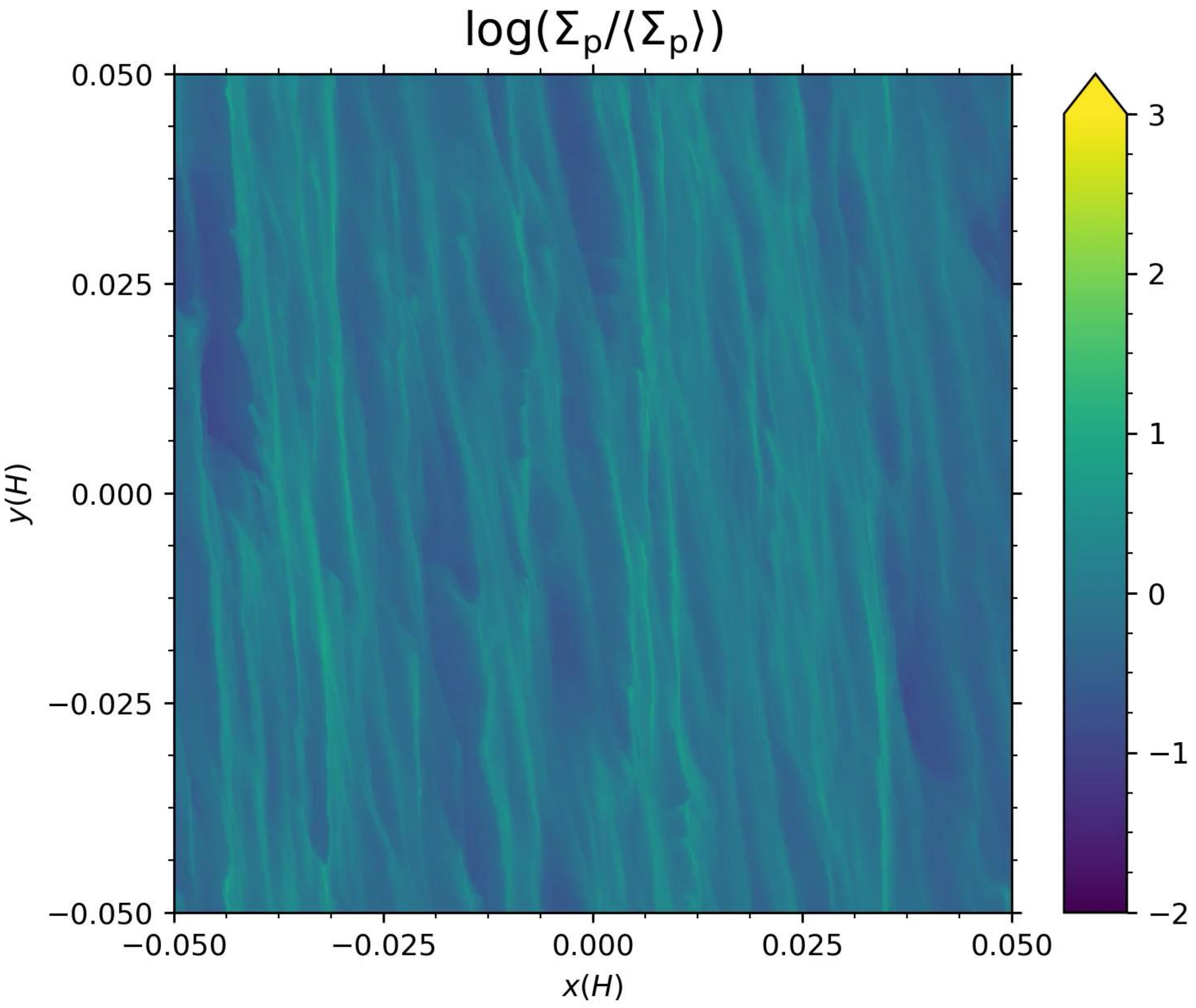
Resonant

Scattered Disk

Transition
tight-wide binaries

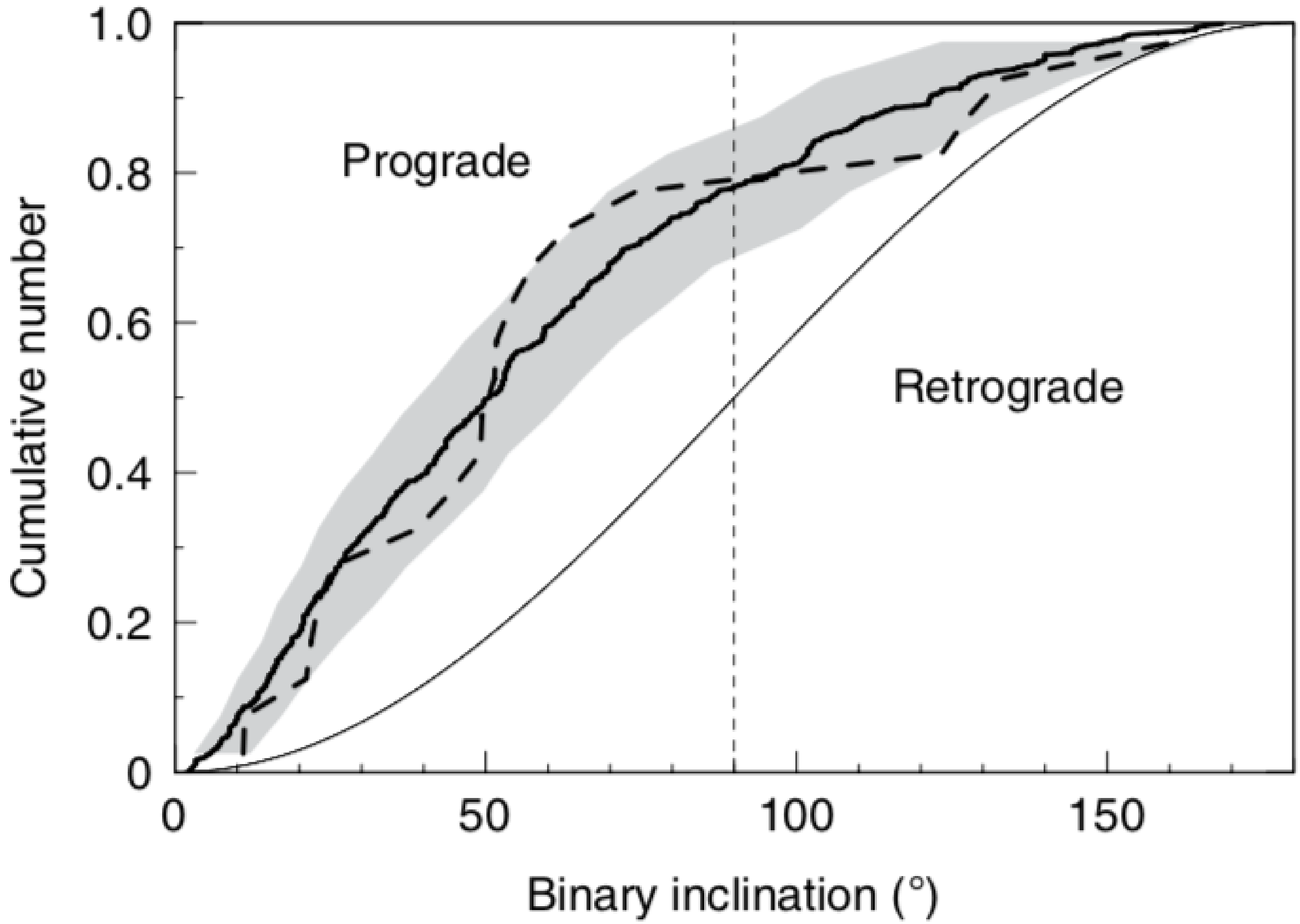
Grundy et al. (2019)

Finding binaries



Video credit: Rixin Li

Preference for Prograde (~80%)

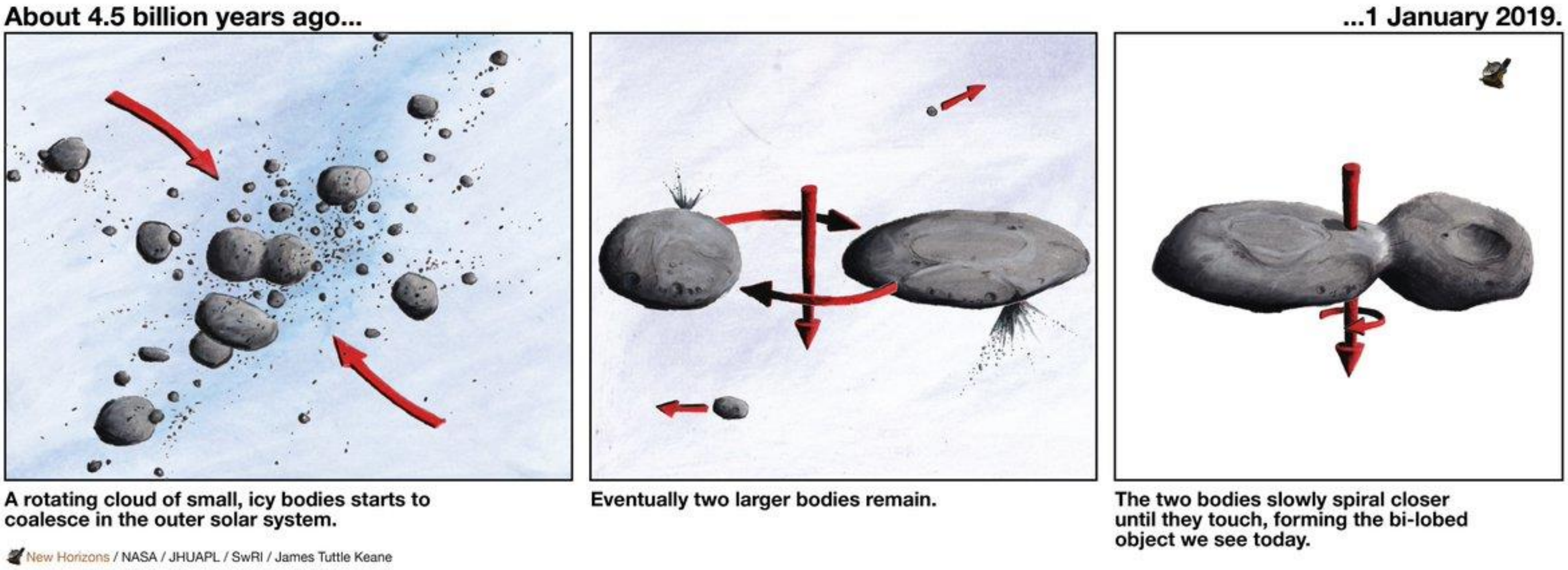


Streaming Instability Model (solid)

Kuiper Belt objects (dashed)

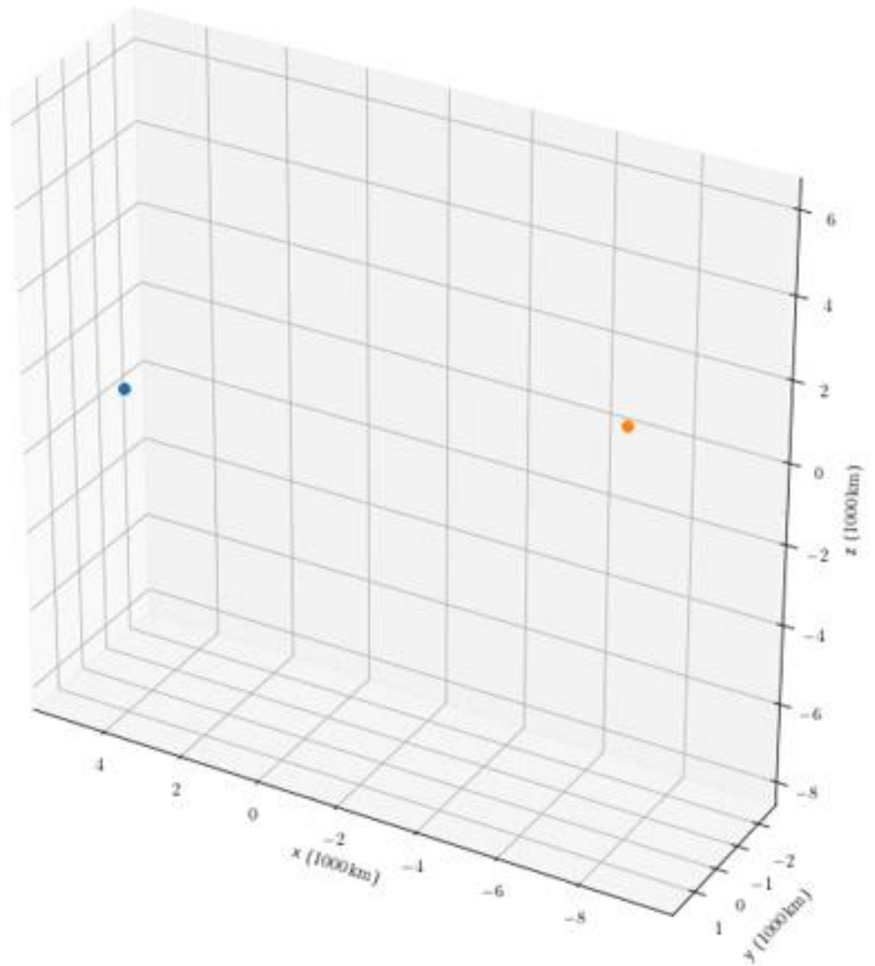
Nesvorny et al. (2019)

The Formation of Arrokoth



time = -1.3 kyr

Wenu - Weeyo

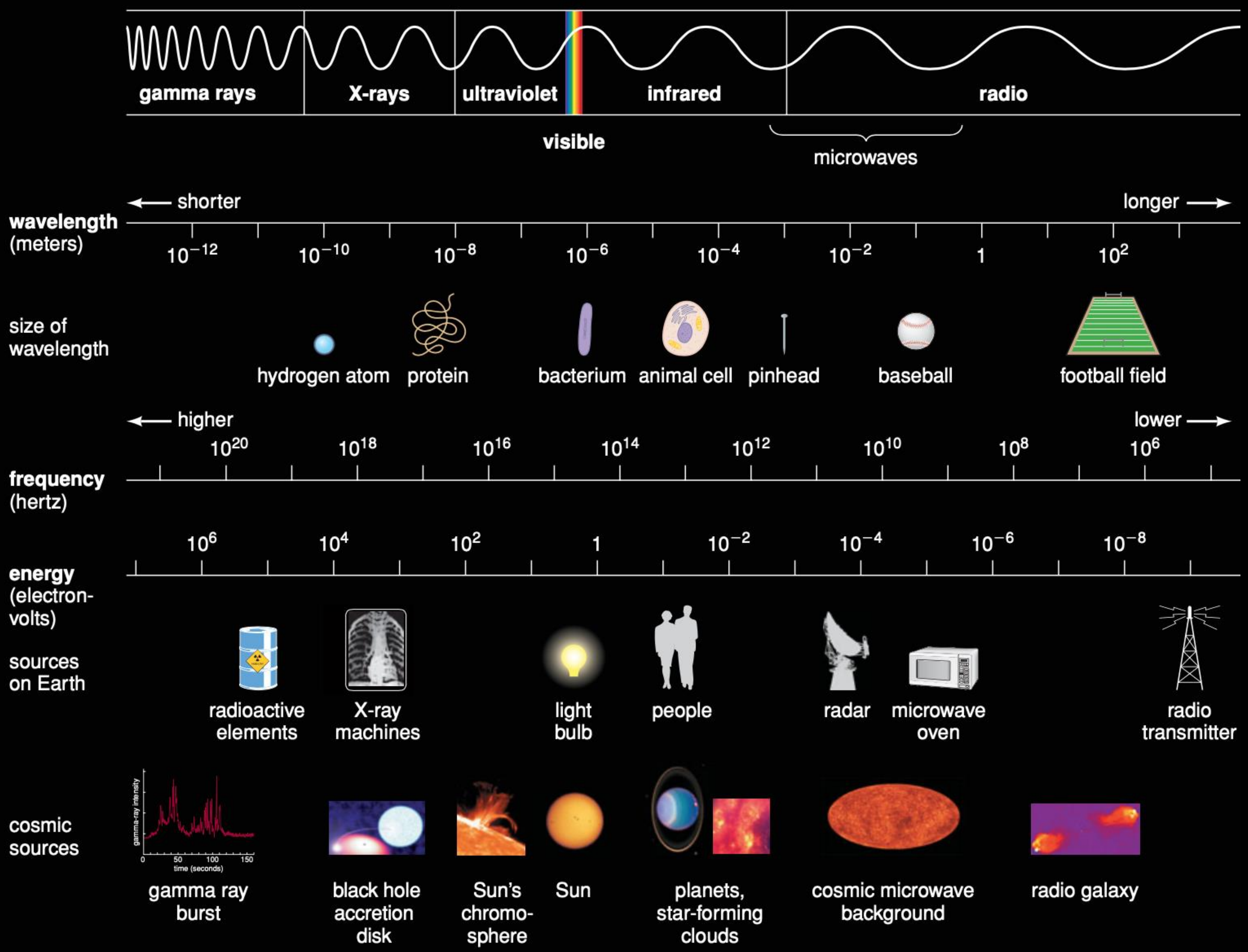


MONASH University

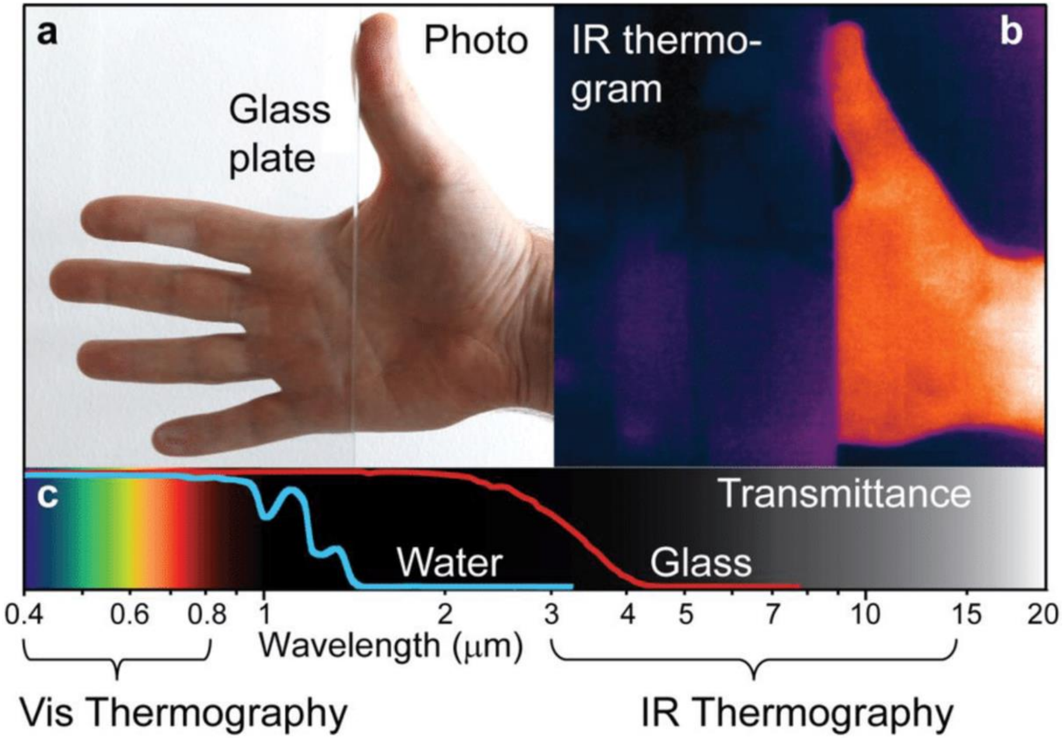
MoCA Monash Centre for Astrophysics

The *Hubble Space Telescope* view of disks in Orion

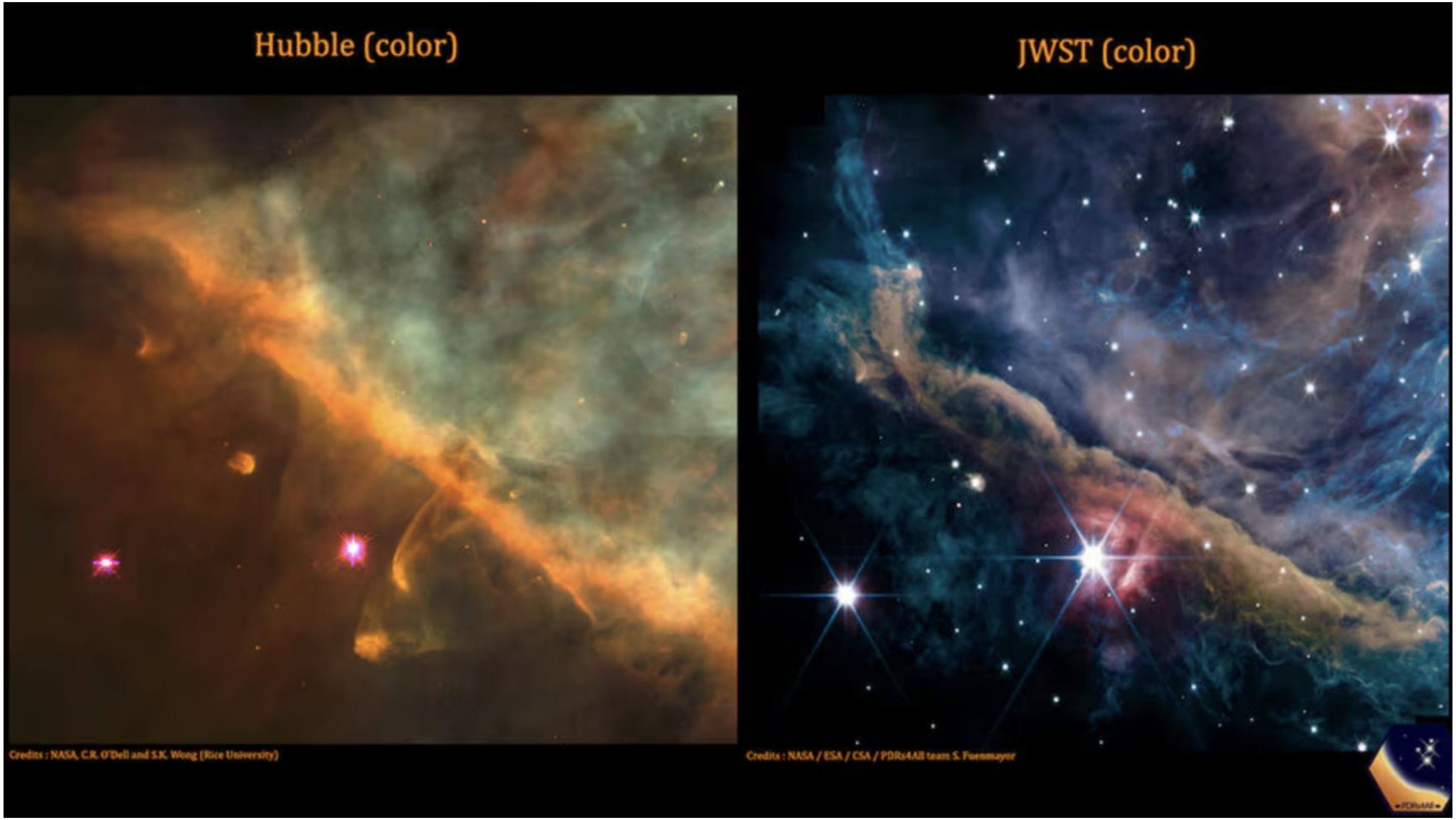
The Electromagnetic Spectrum



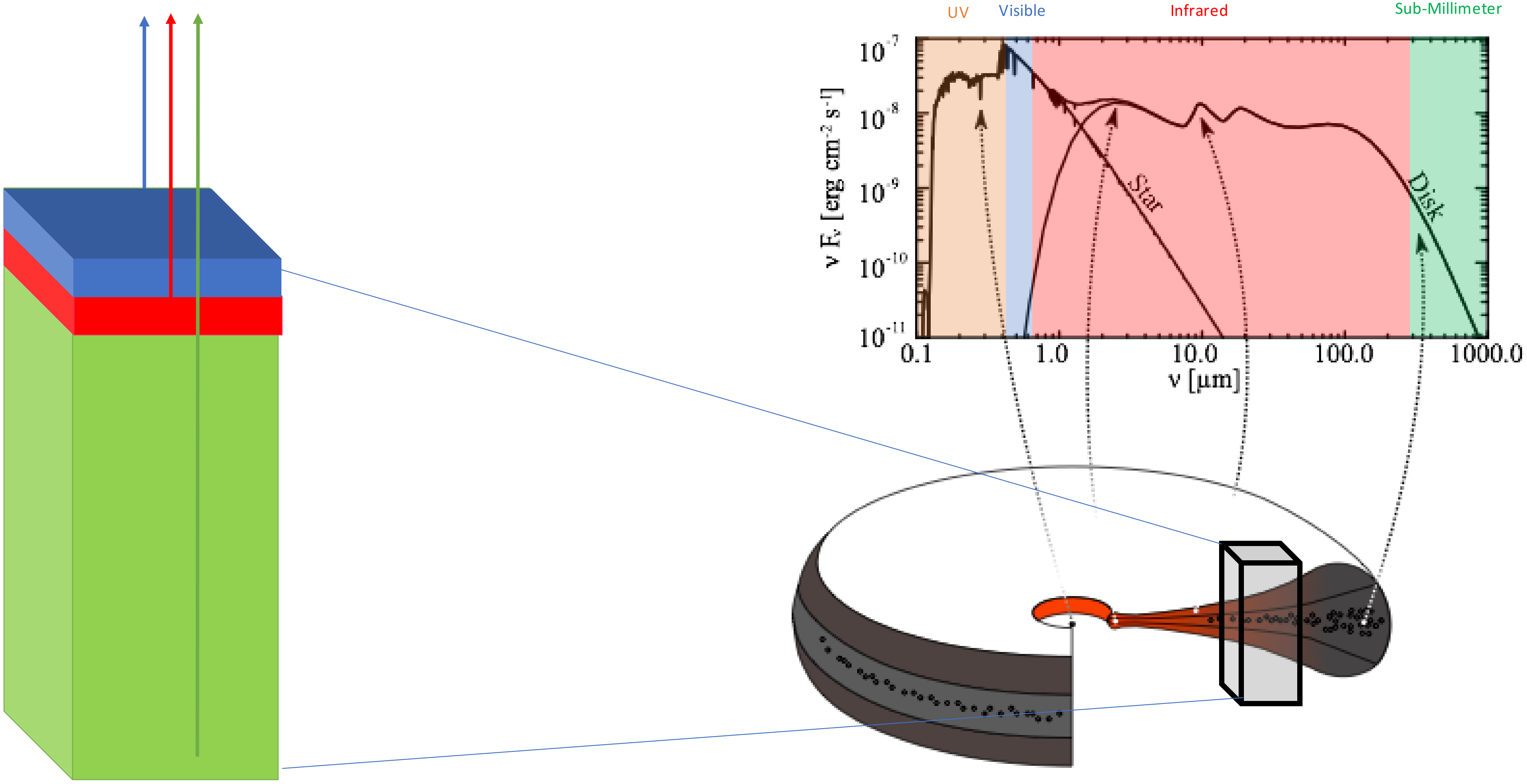
Optical vs Infrared



Optical vs Infrared

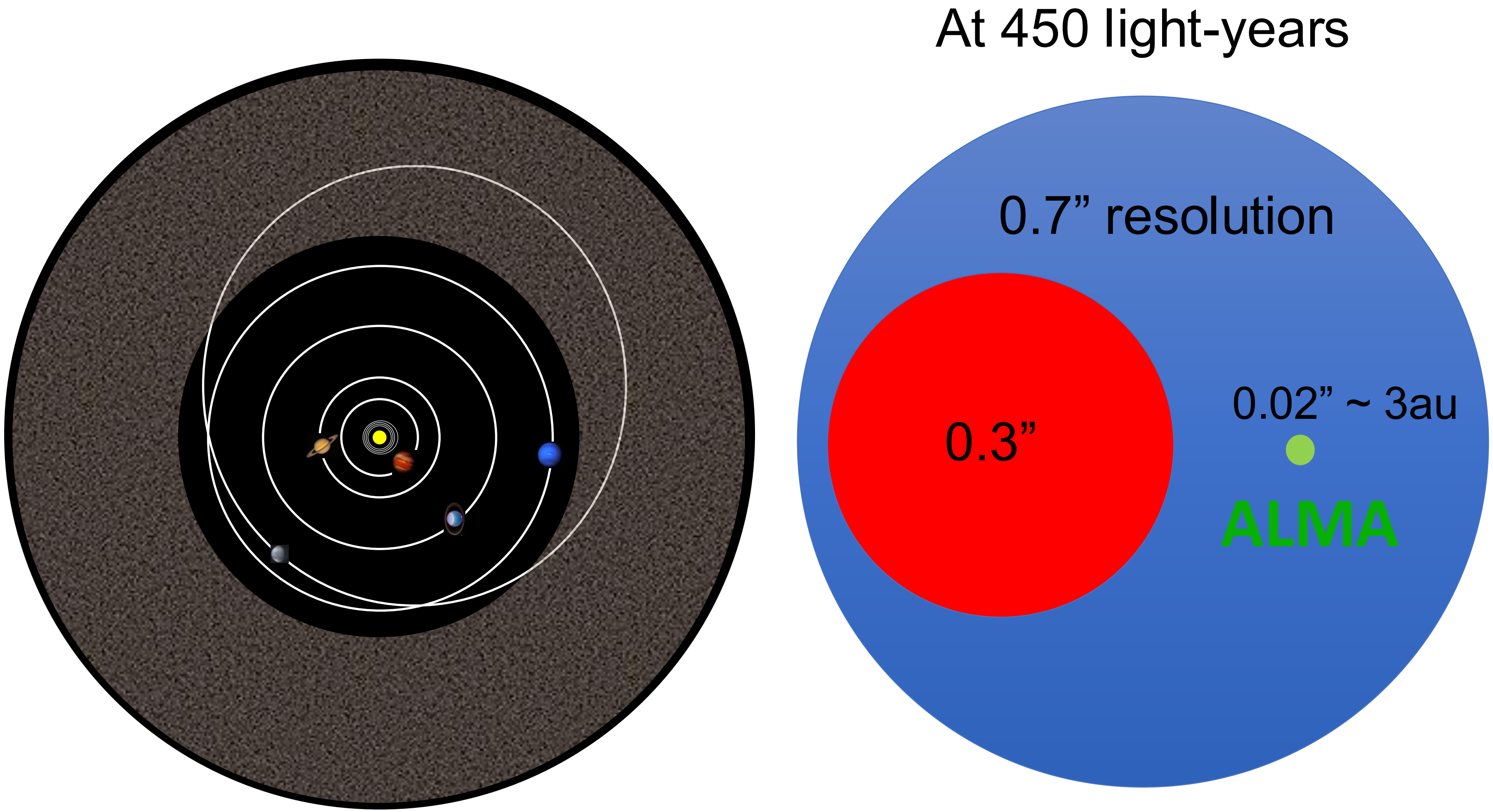


Disk spectra



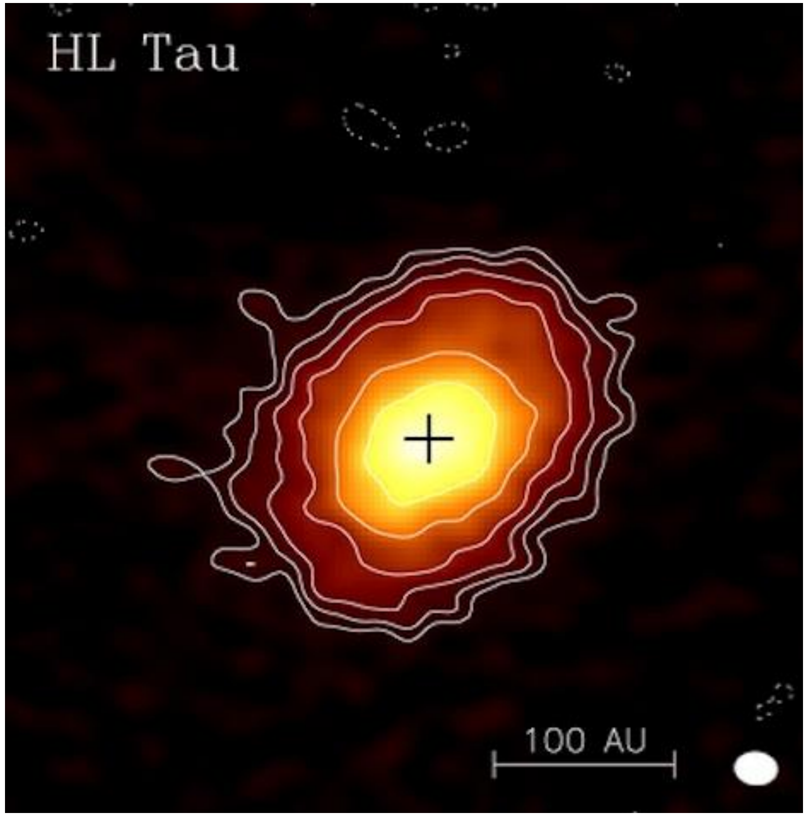
The Atacama Large (sub-)Millimeter Array (ALMA)

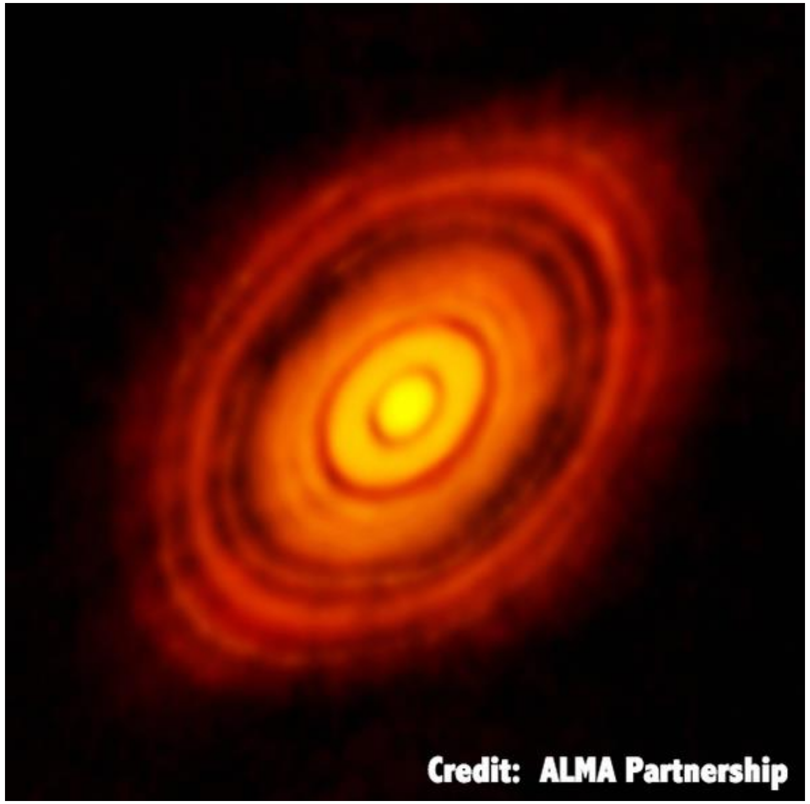
The Very Large Array (VLA)


At 450 light-years
0.7” resolution
0.3”
0.02” ~ 3au
ALMA

Before ALMA

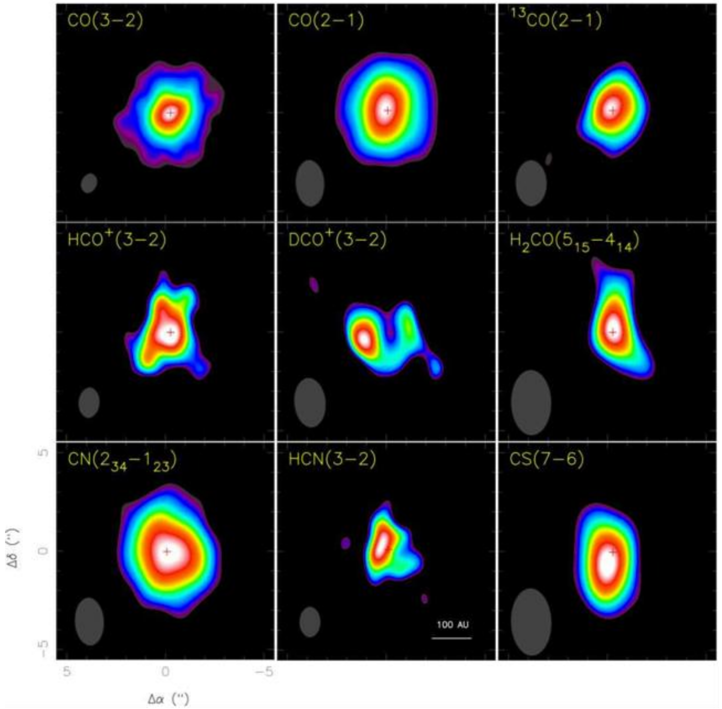
ALMA



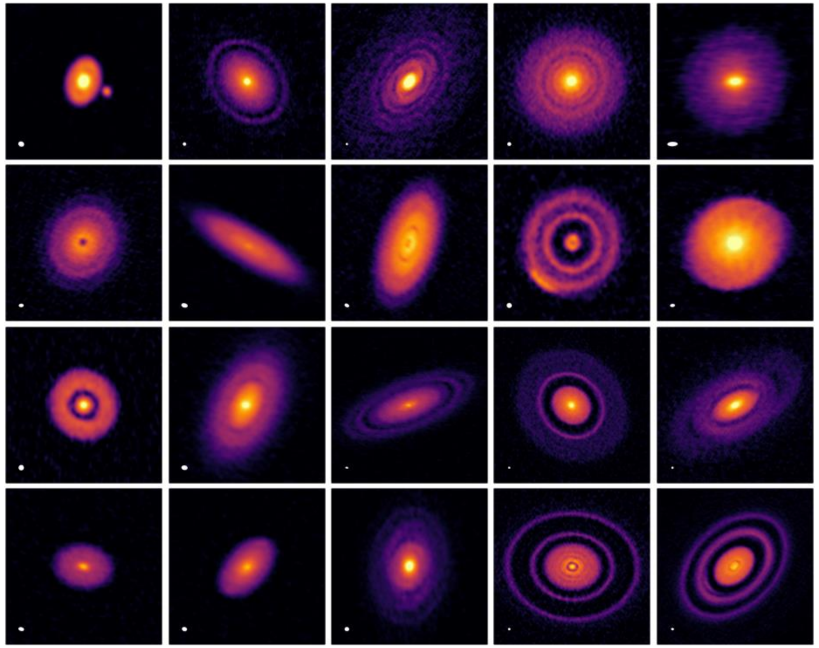


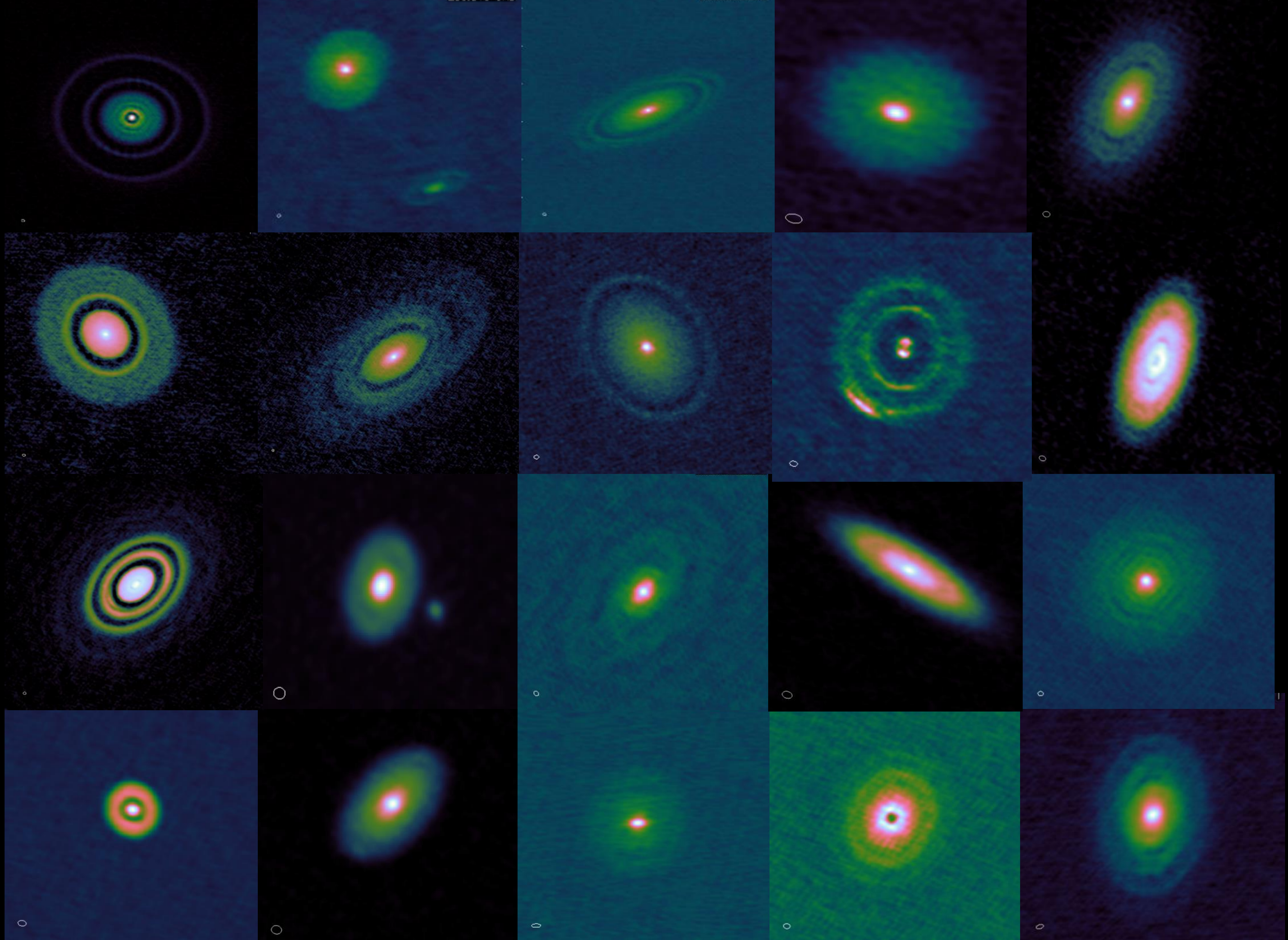
Hubble Space Telescope (HST)

Sub-Millimeter Array (SMA)

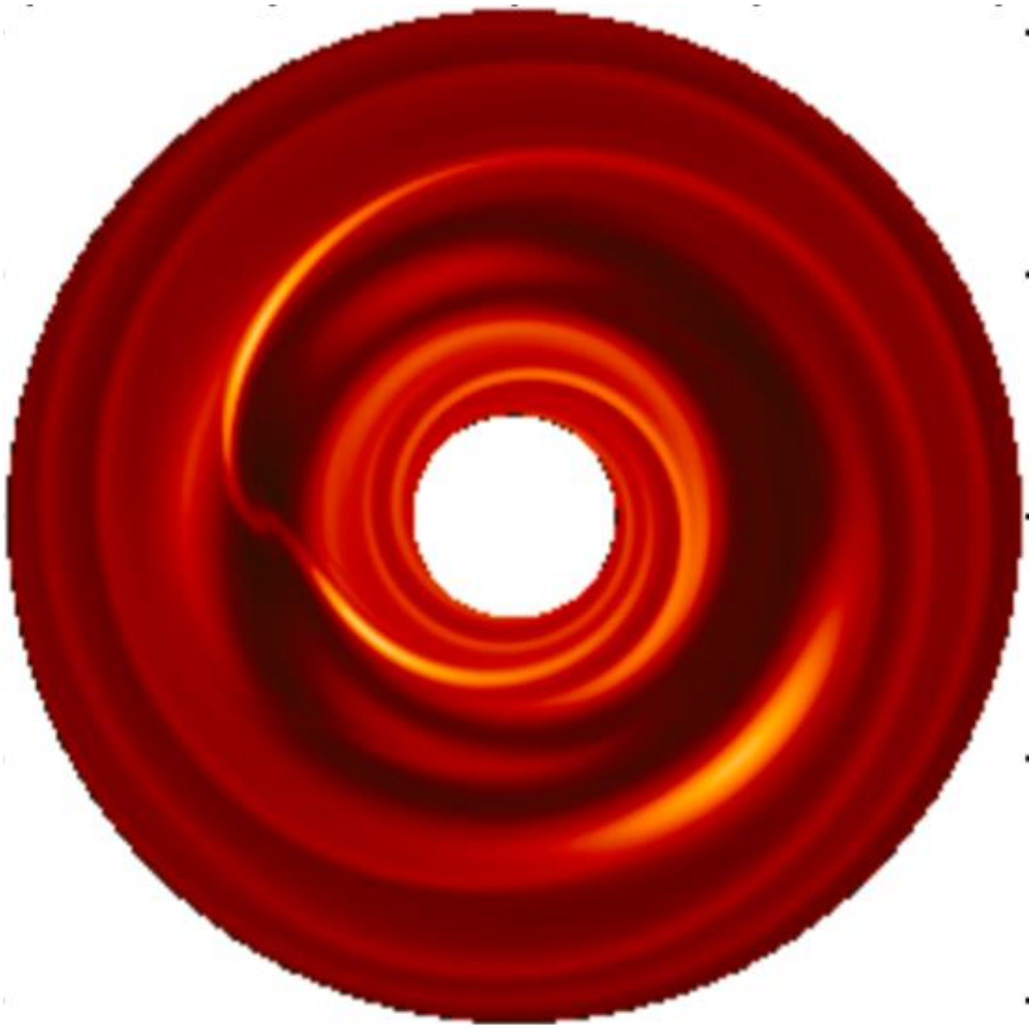


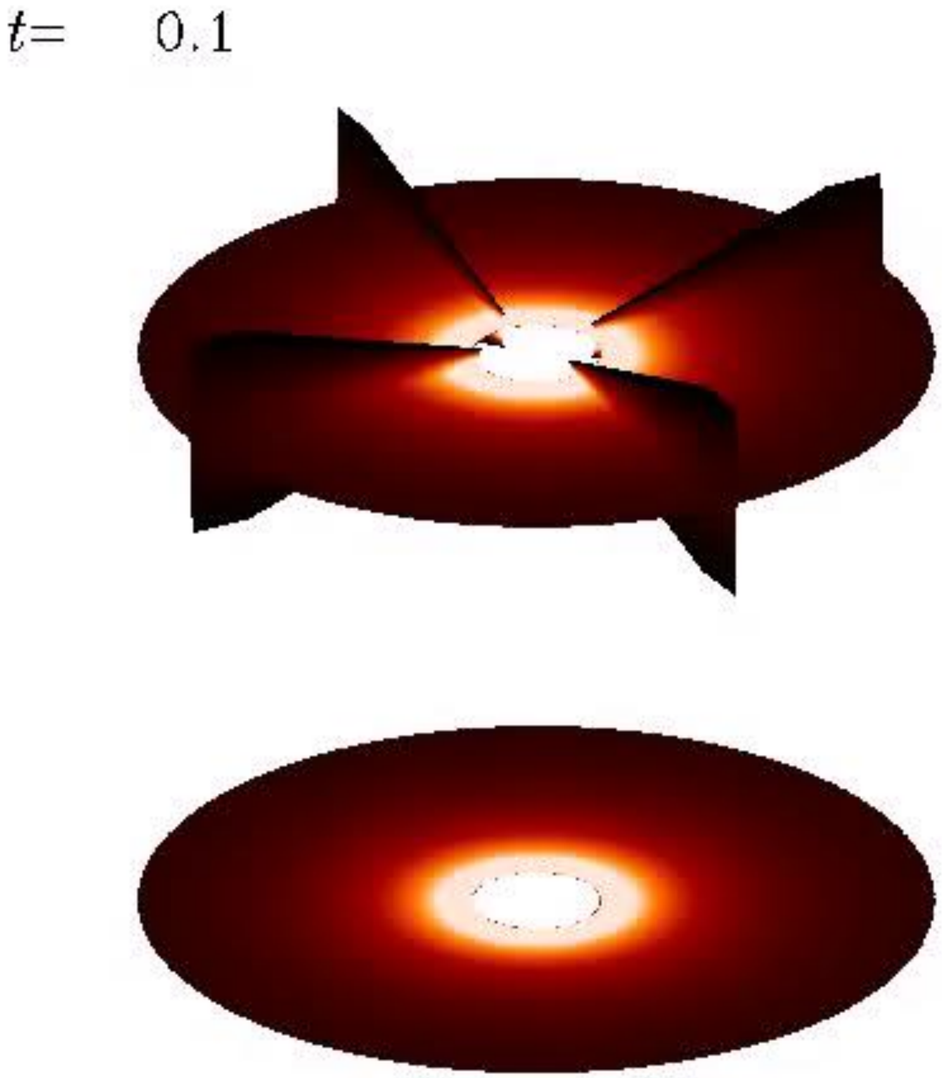
Atacama Large (sub-)Millimeter Array (ALMA)





Planets carve gaps in disks

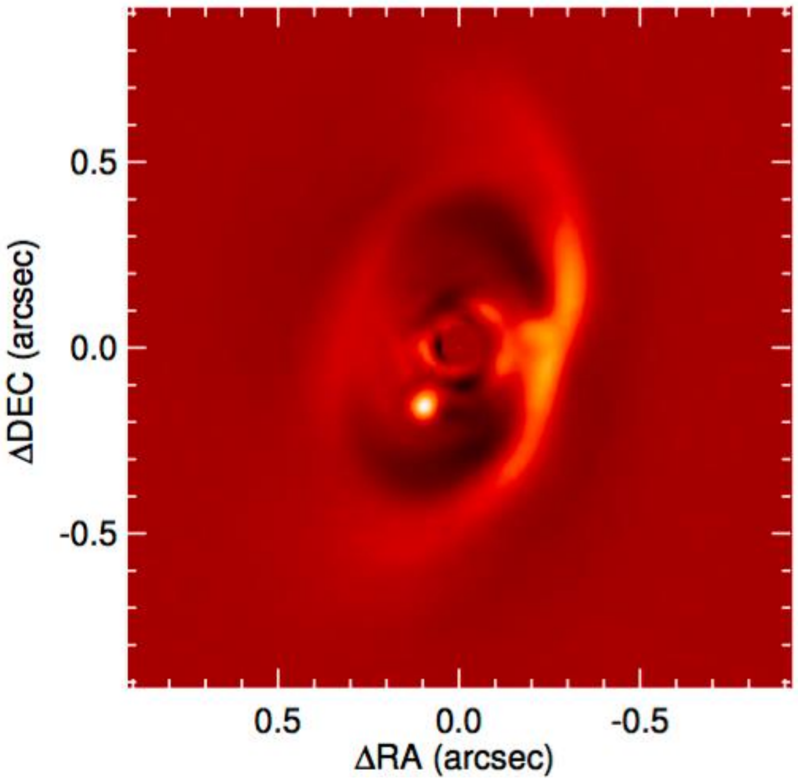




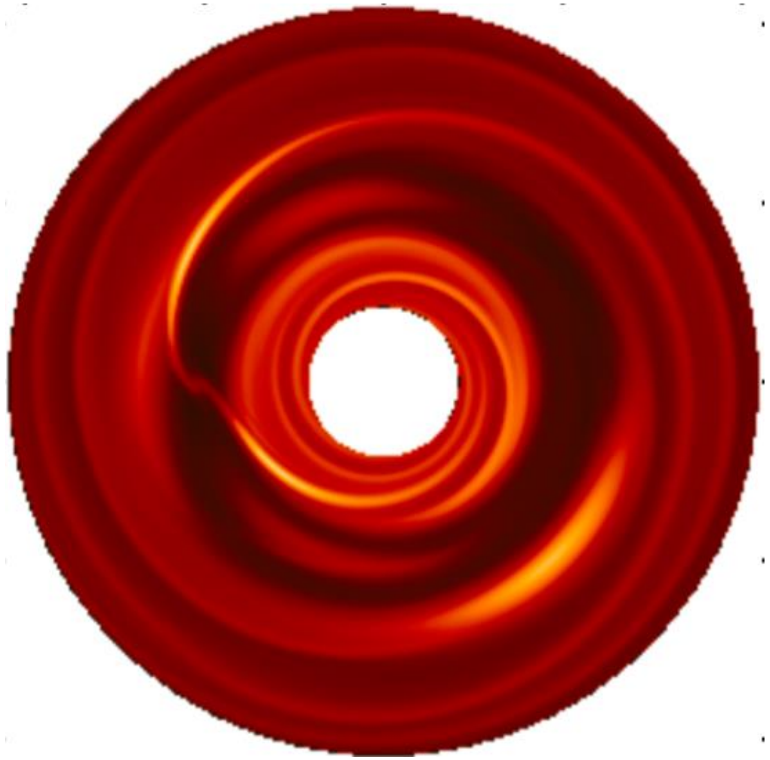
Lyra et al (2009); Video Credit: Wladimir Lyra

PDS 70b: A young planet spotted inside a gap

PDS 70 and PDS 70b

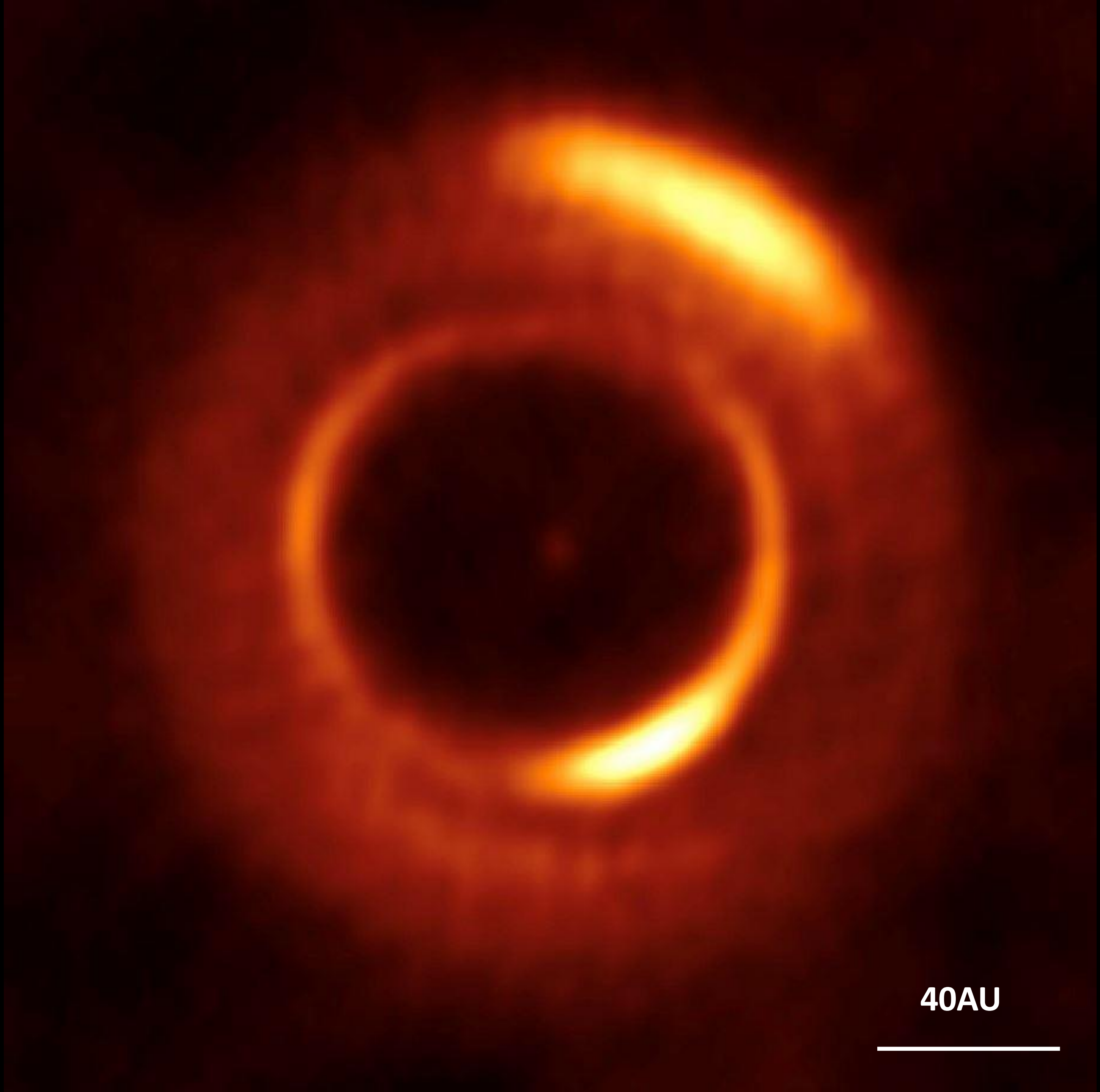


Keppler et al. (2018)



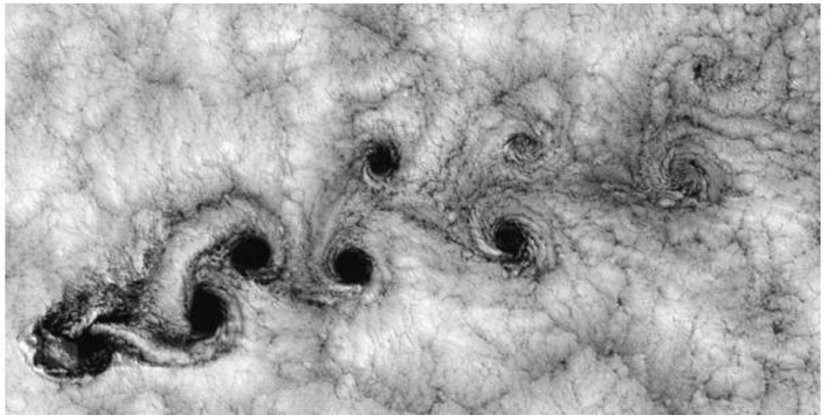
Lyra et al (2009)

MWC 758

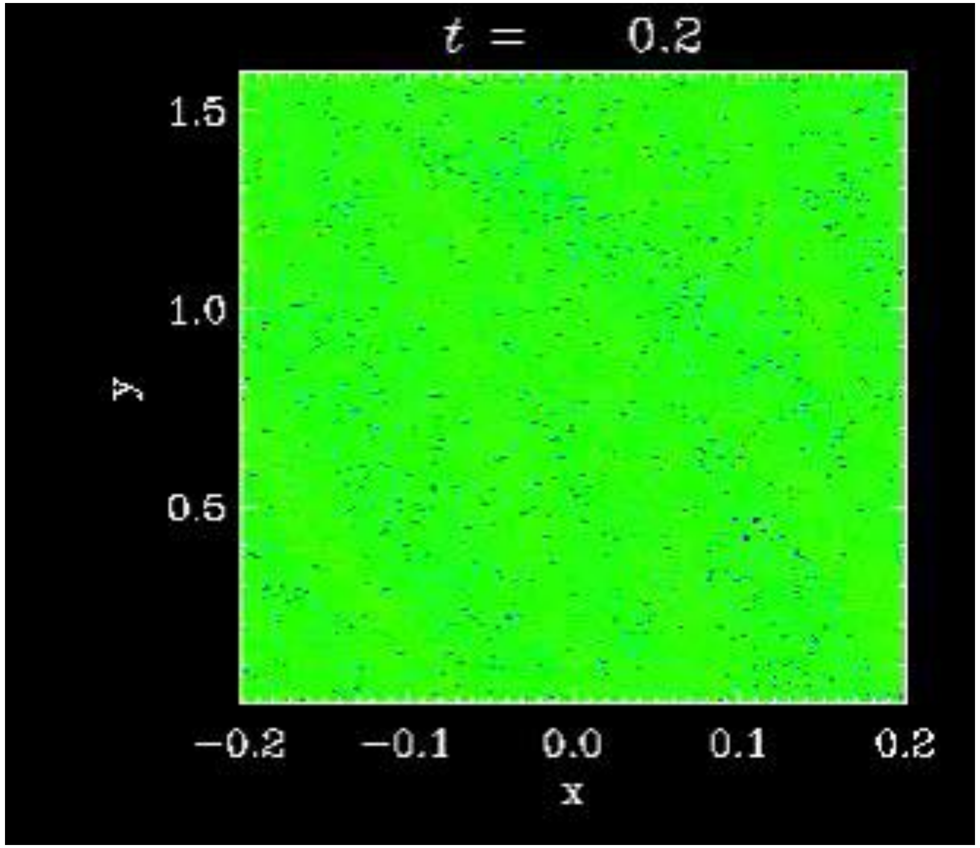


Dong et al. (2018)

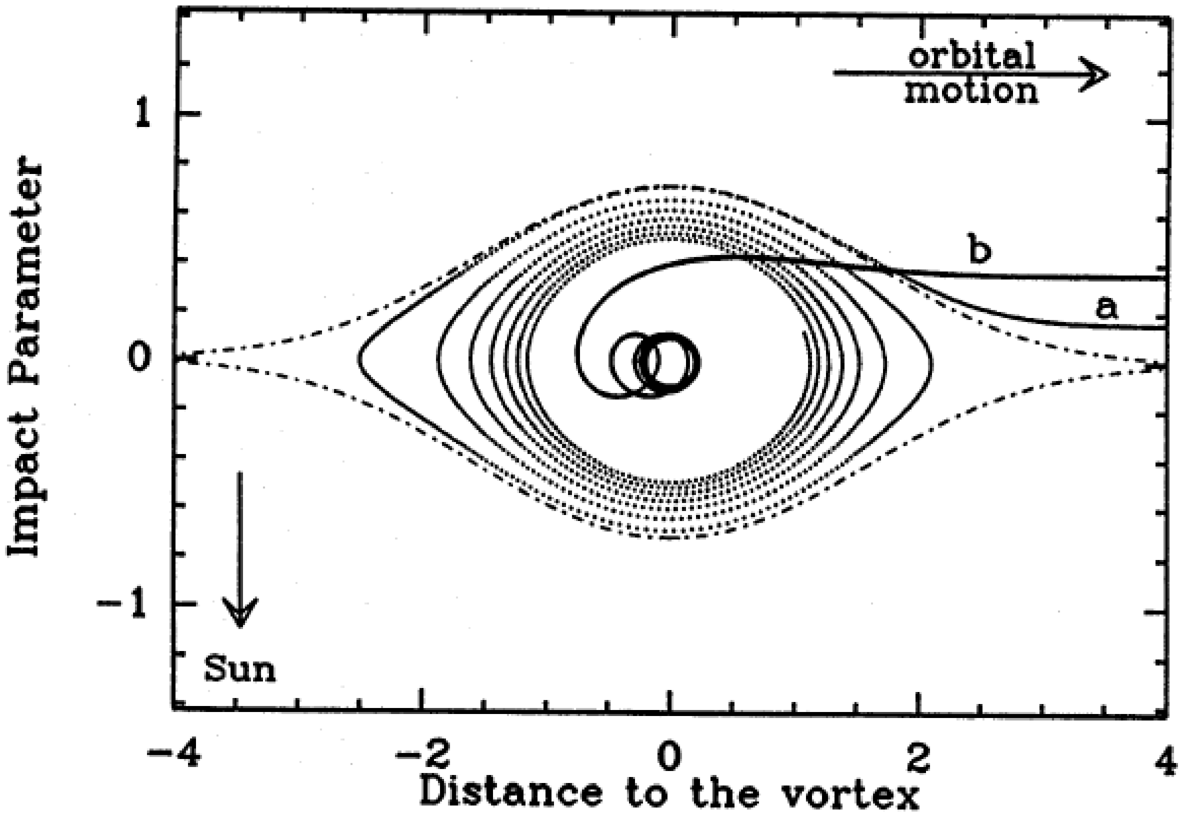
Vortices – an ubiquitous fluid mechanics phenomenon



Vortex Trapping



Video credit: Natalie Raettig



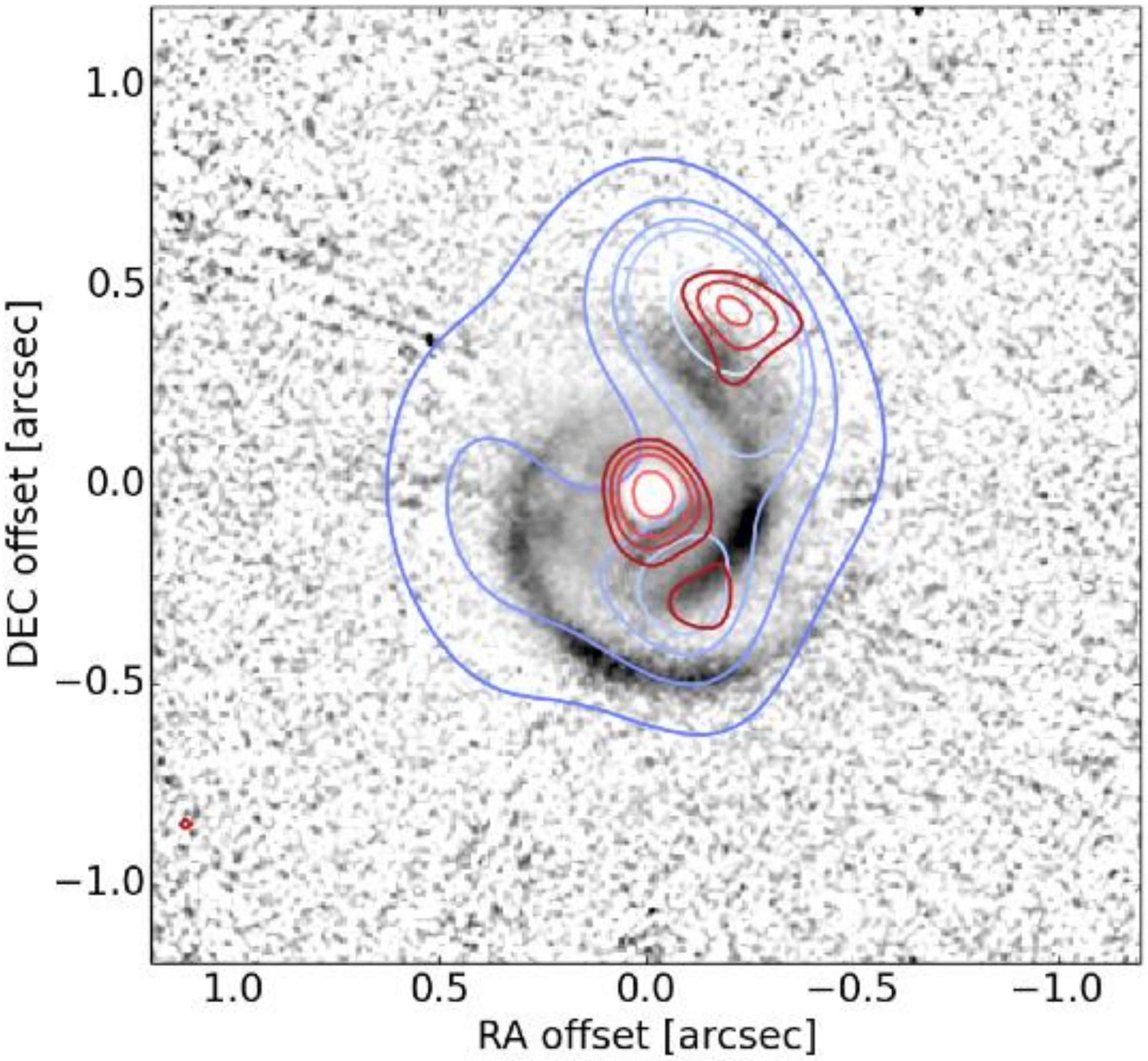
Barge & Sommeria (1995)

Disk Tomography
SPHERE-ALMA-VLA overlay of MWC 758

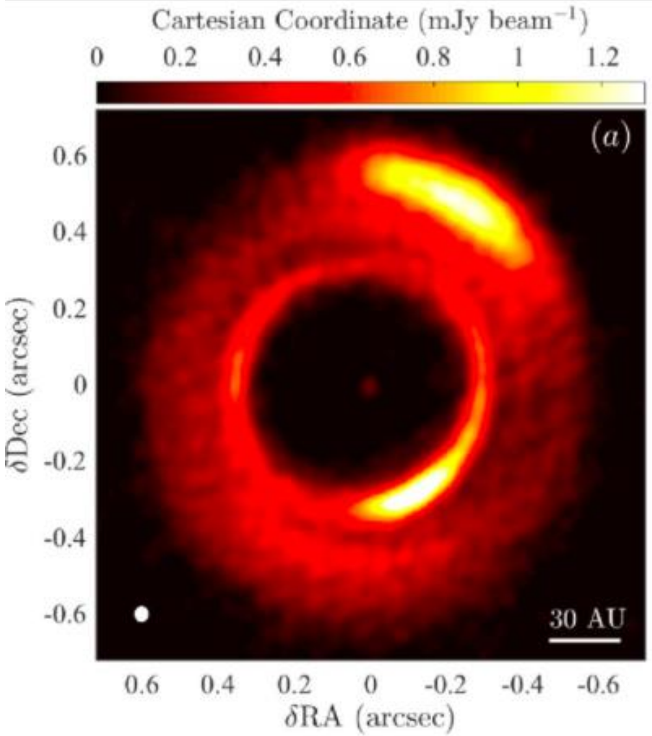
SPHERE (μm)

ALMA (~ mm)

VLA (cm-m)



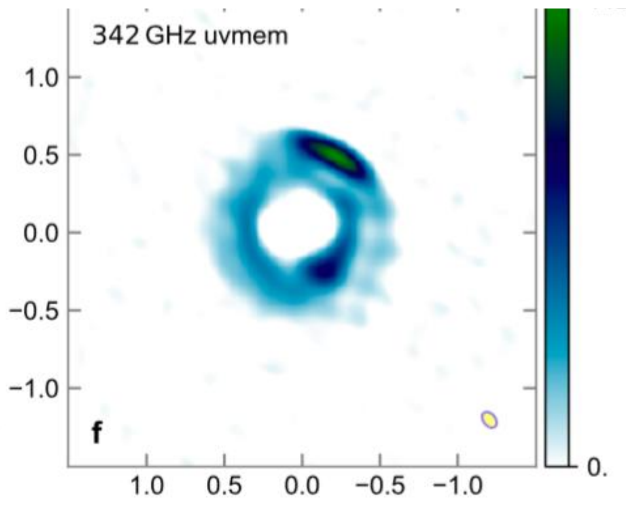
ALMA



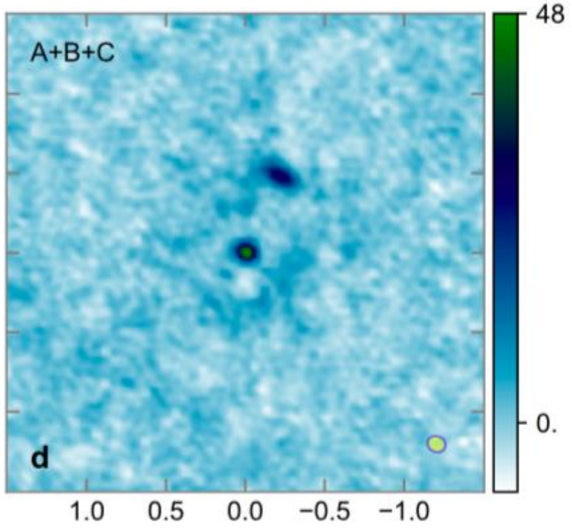
Marino et al. (2015); Dong et al. (2018)

Vortex trapping

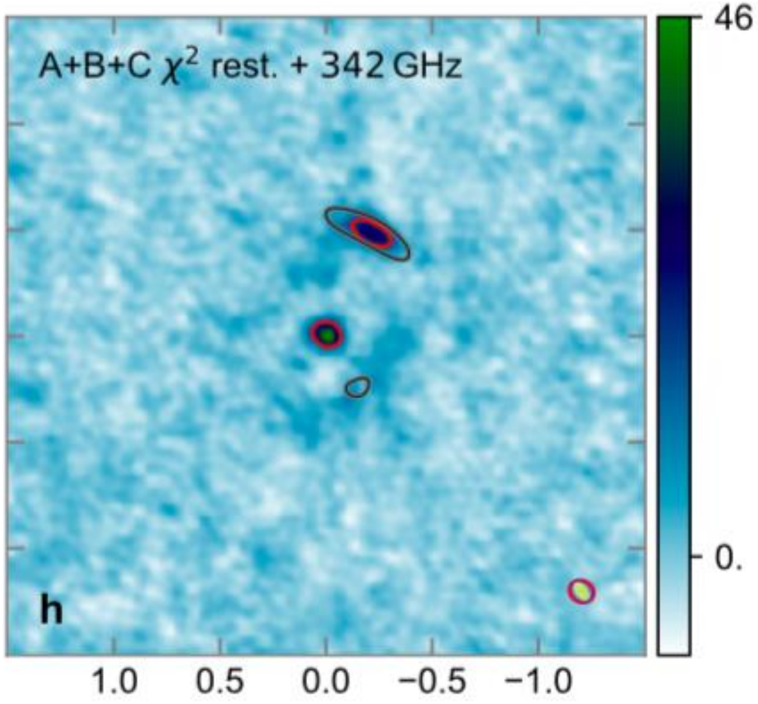
ALMA (mm)



VLA (cm-m)

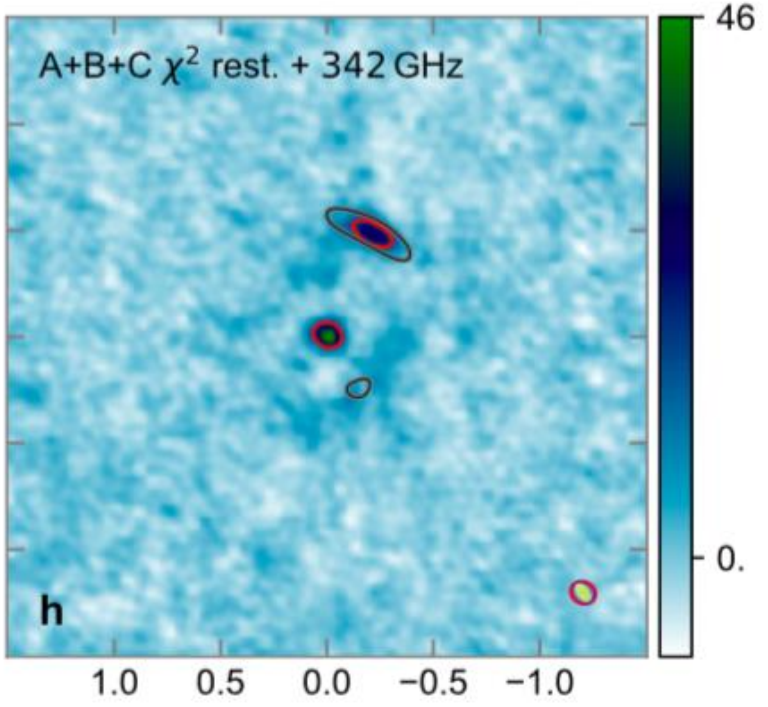


Overlay

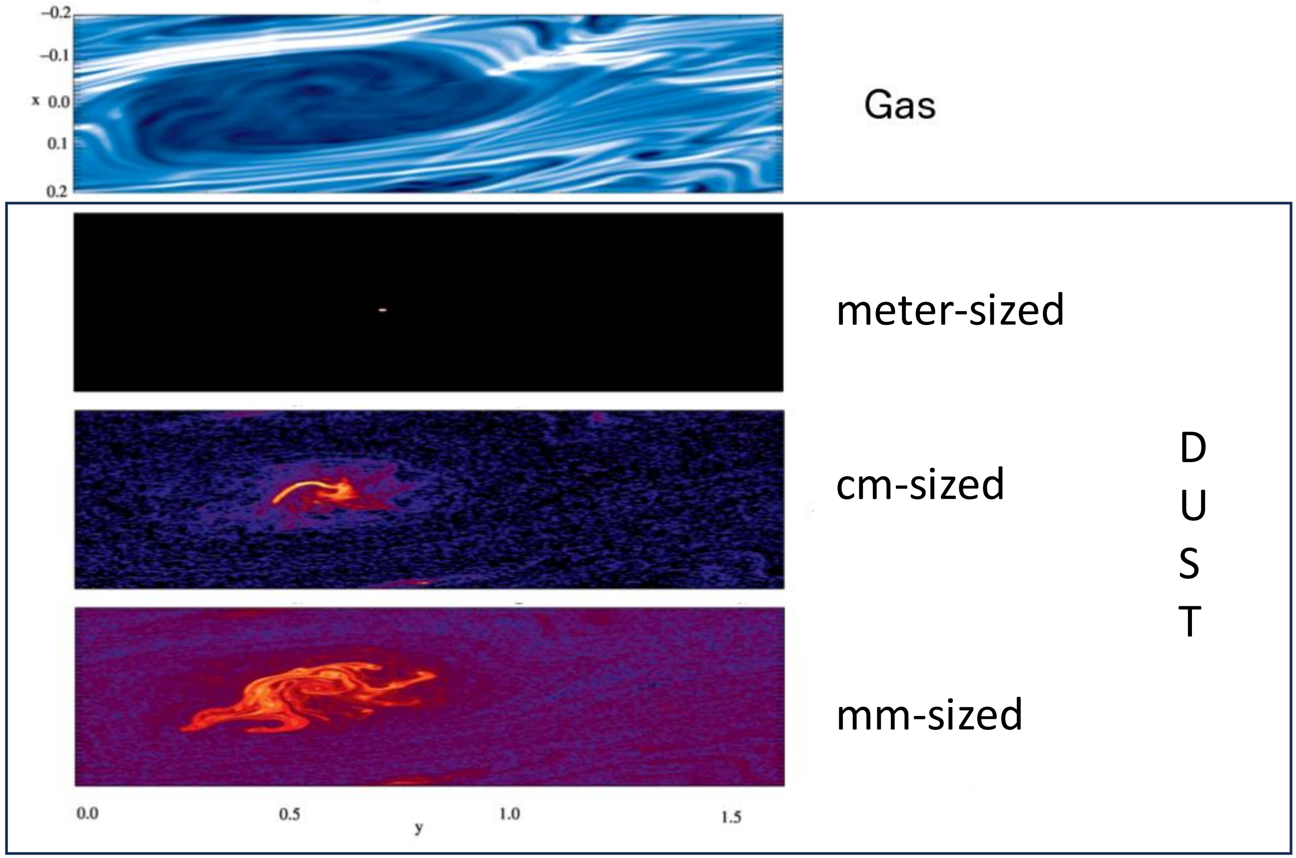


Casassus et al. (2019)

Model vs Observation



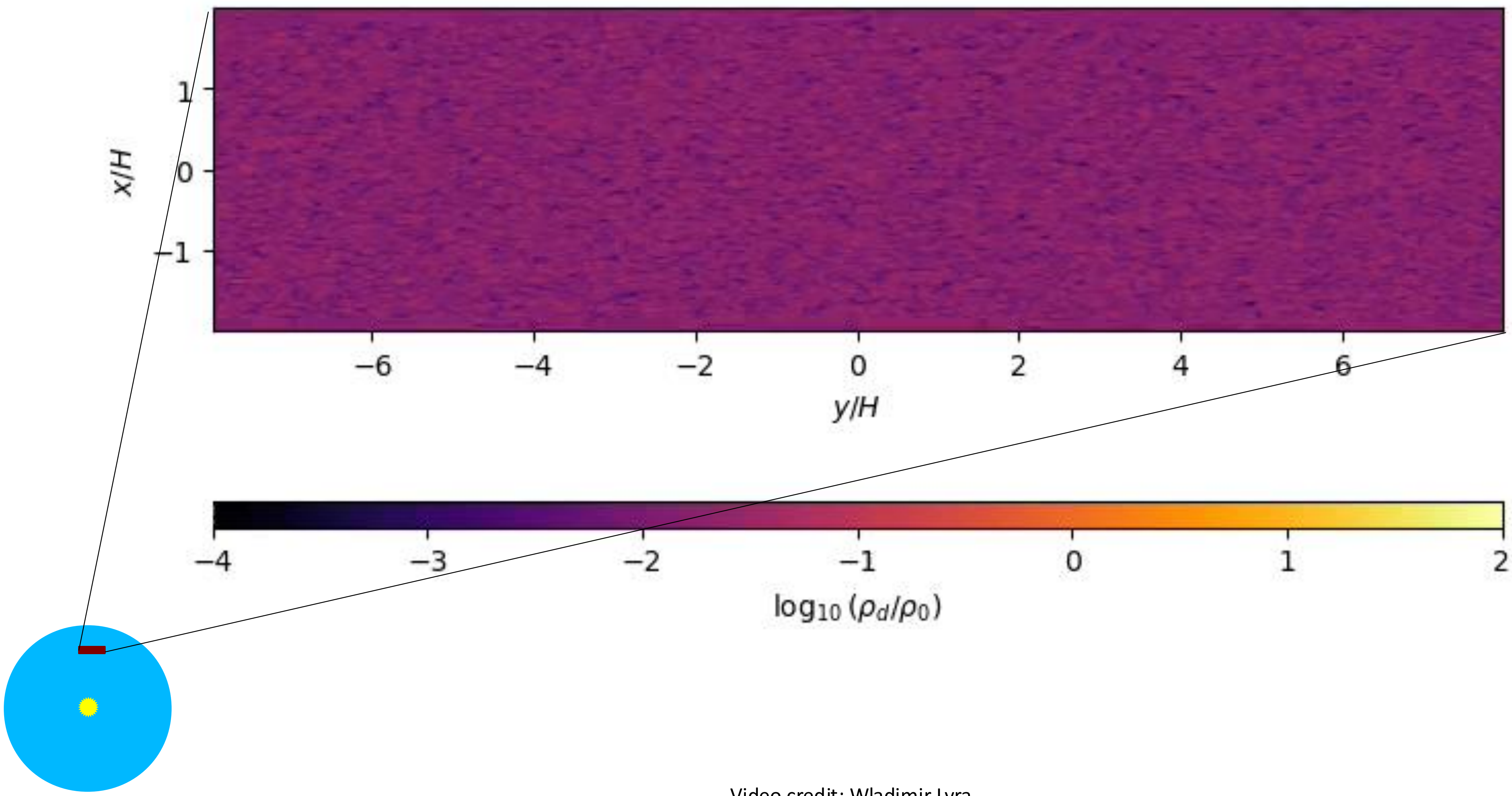
Observation



Model

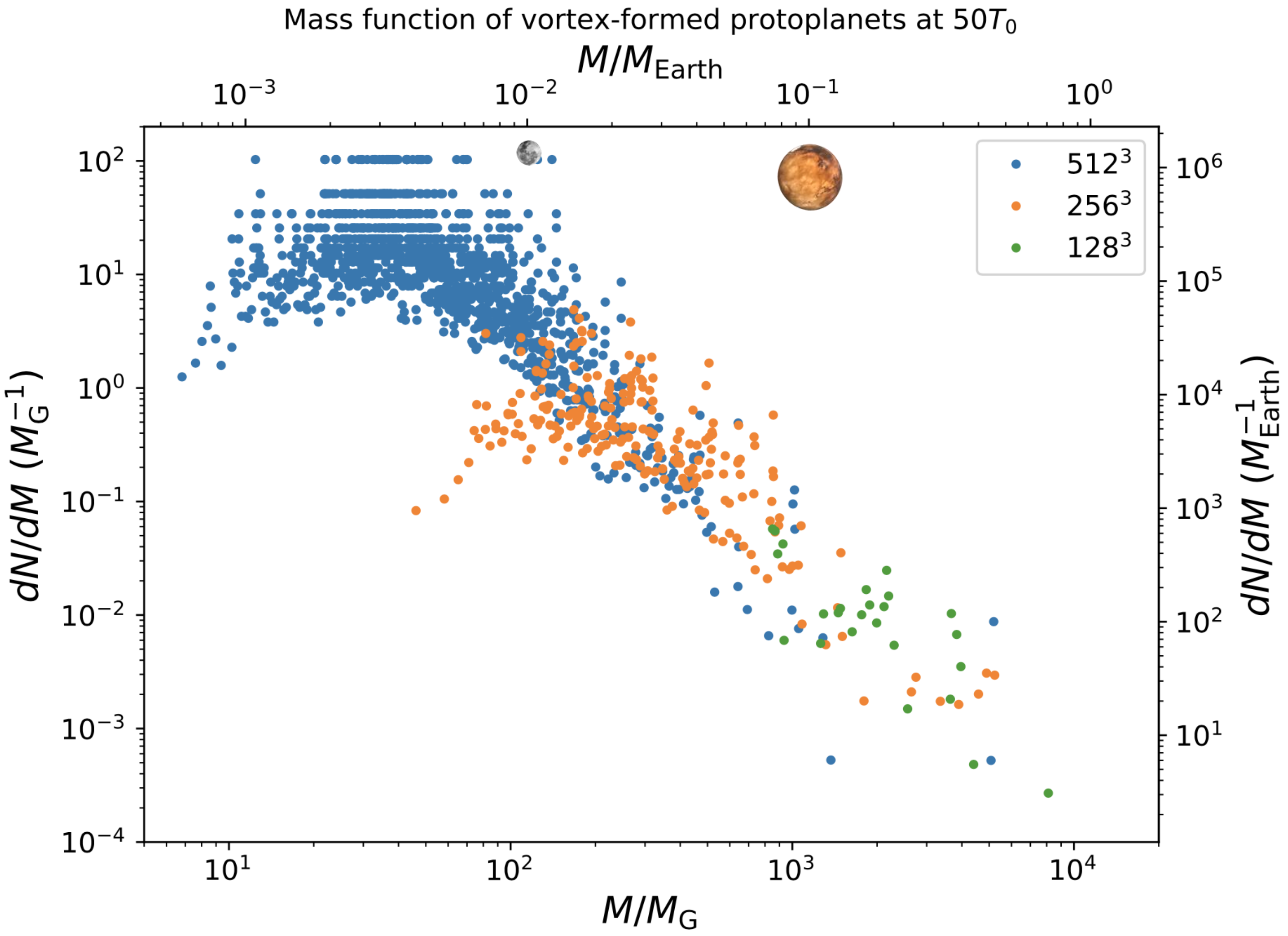
Casassus et al. (2019); Raettig et al. (2015)

Vortex Trapping



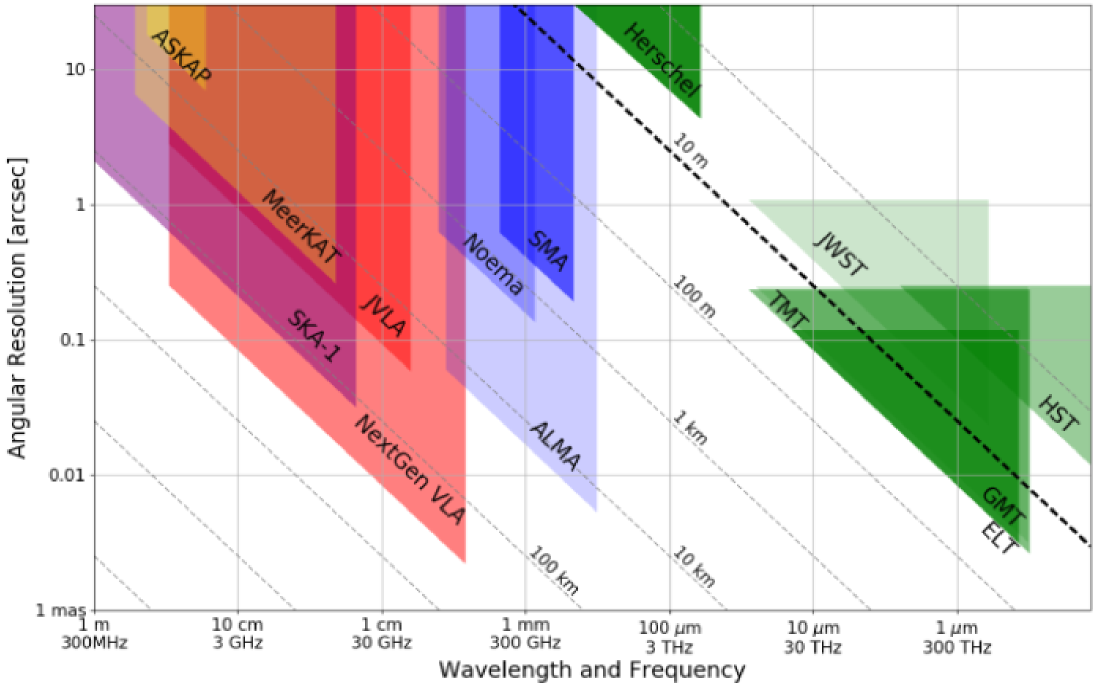
Video credit: Wladimir Lyra

Mass Function



Lyra et al. (2024)

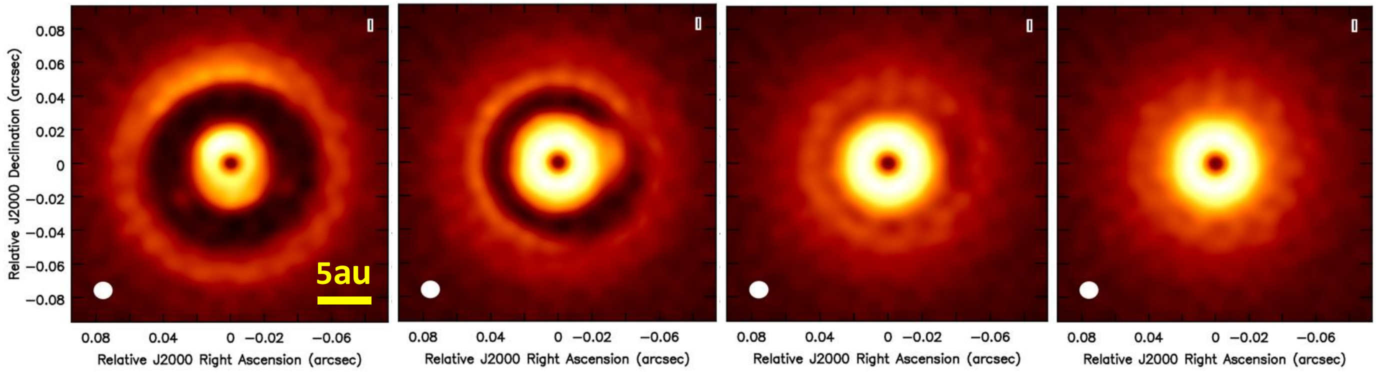
Next Generation Very Large Array (ngVLA)



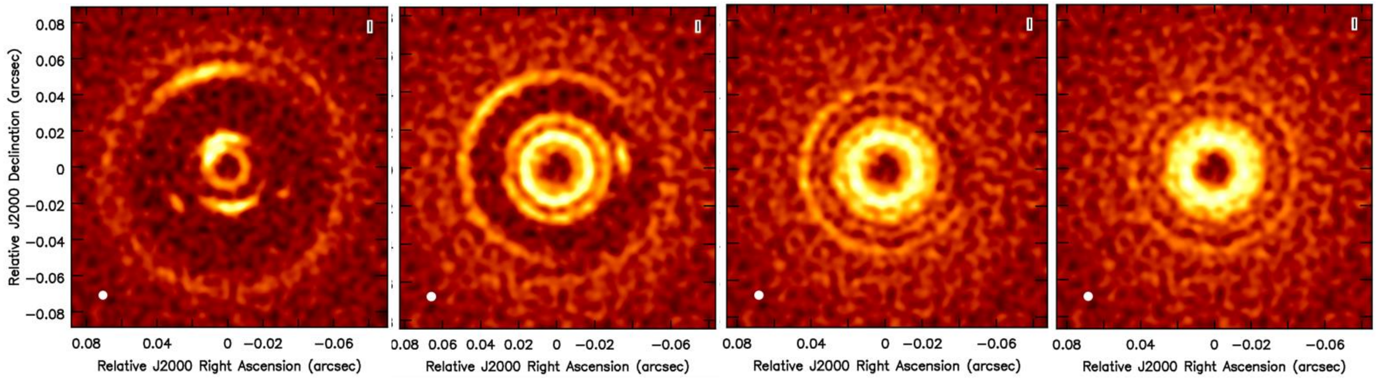
Planets at 5AU

Jupiter | Saturn | Neptune | 10 M_{Earth}

ALMA at 0.87mm



ngVLA at 3mm

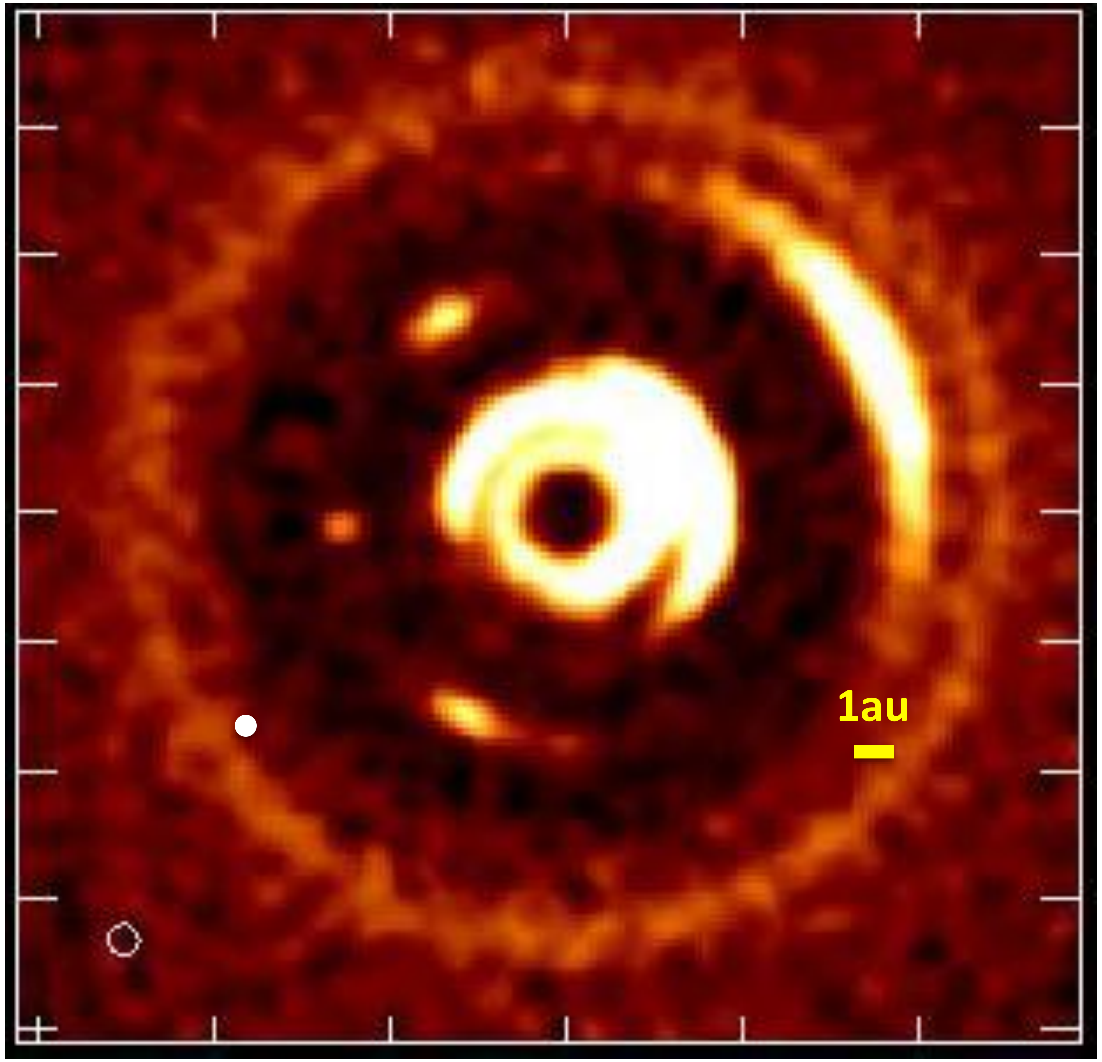


ngVLA will identify gaps/substructures down to ~5-10 M_{Earth}

Credit: Luca Ricci

ngVLA

Jupiter at 5 AU – 500 light years away



Credit: Luca Ricci