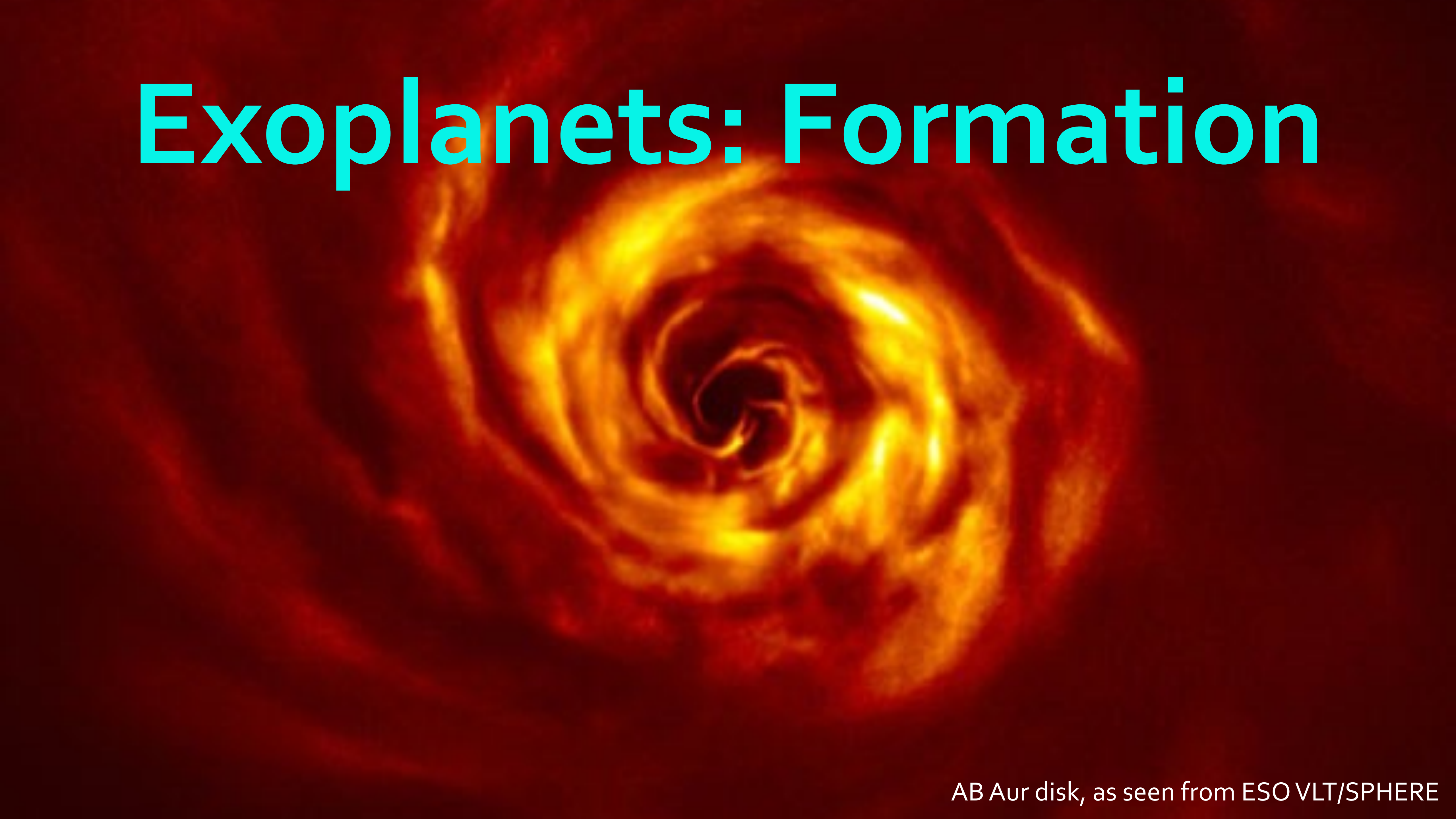
Exoplanets: Formation

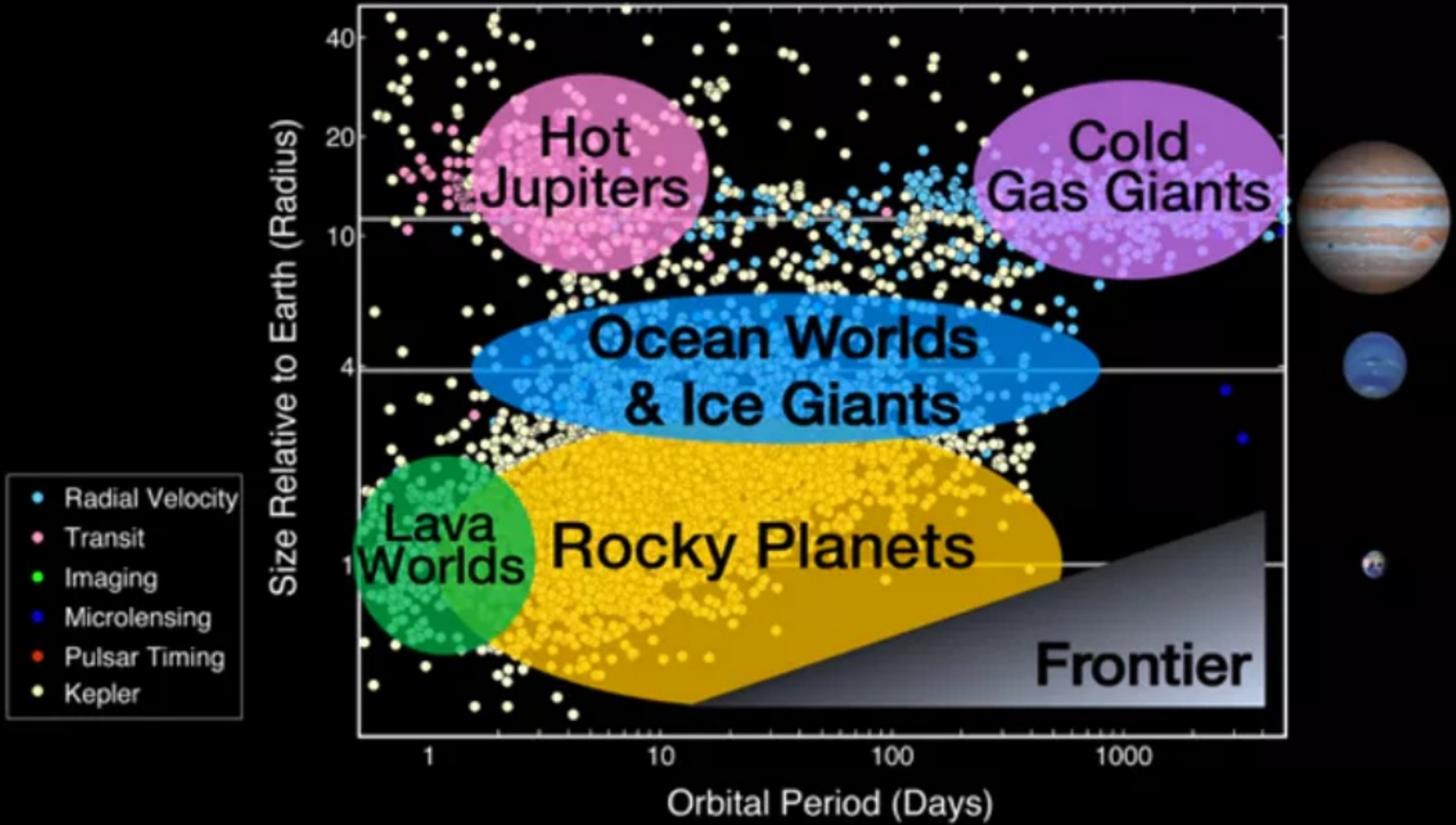


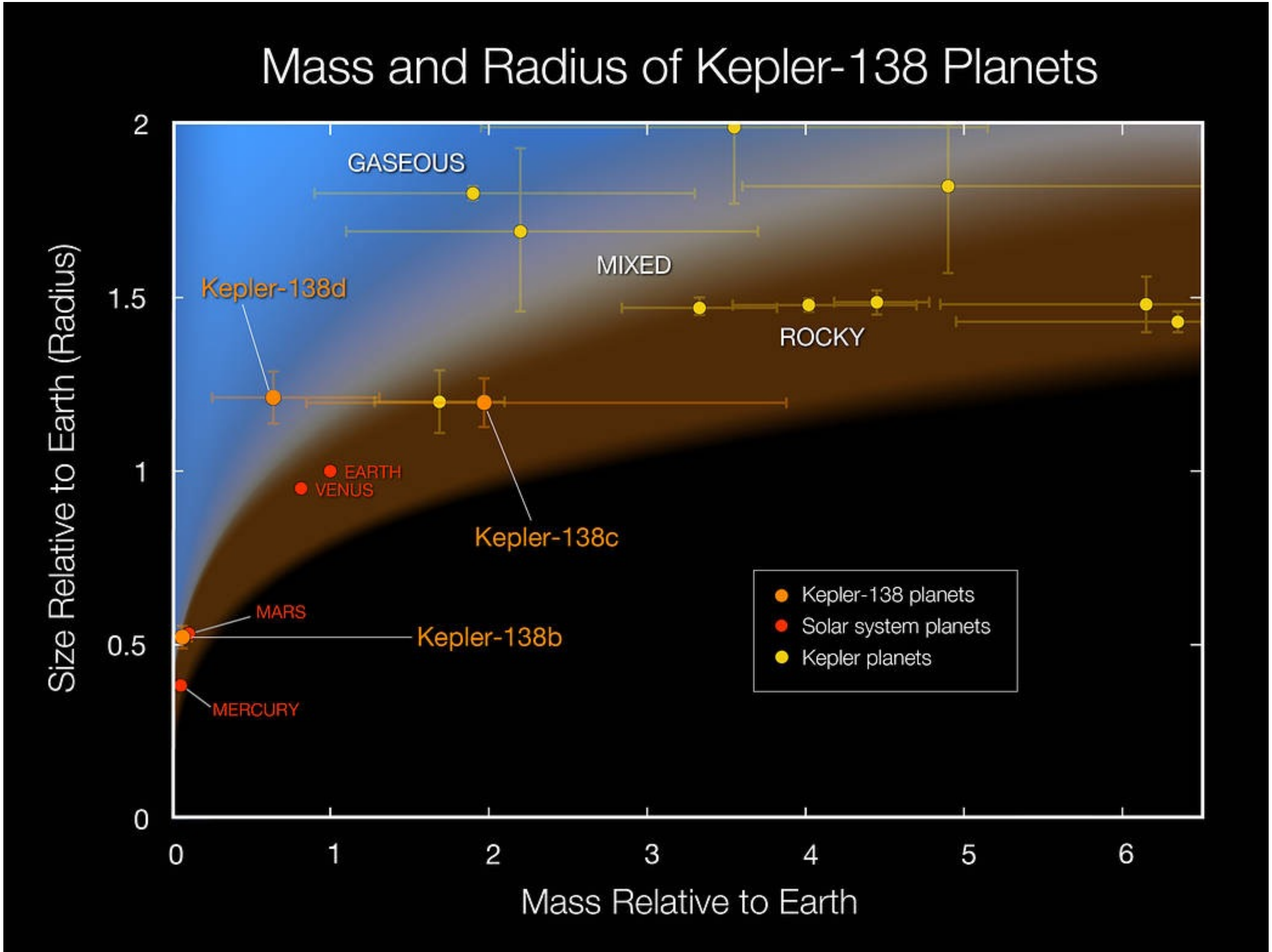
AB Aur disk, as seen from ESO VLT/SPHERE

Review session

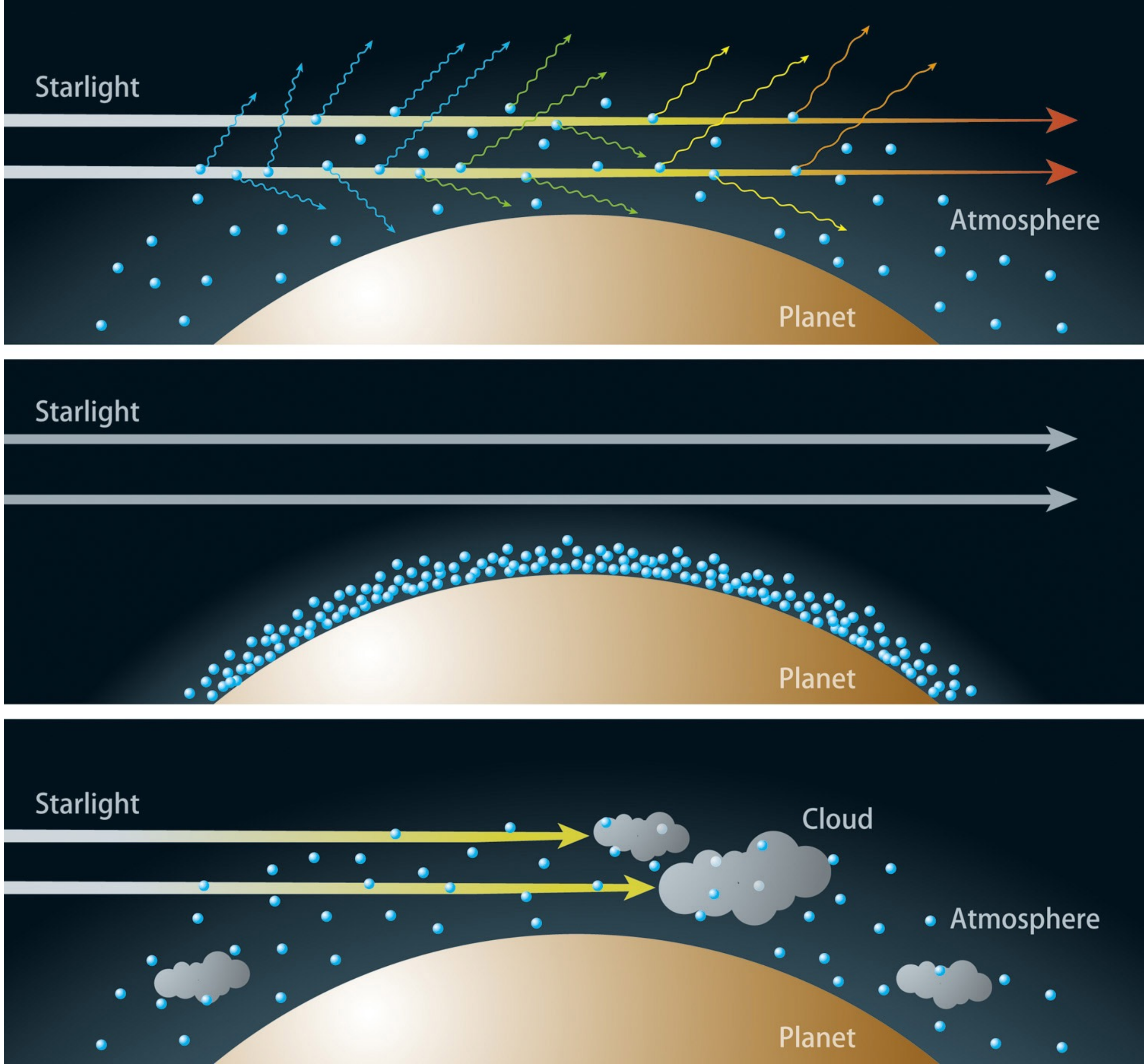
- Tonight, this room, 7pm-8:30pm
- Free Q&A, no slides or presentation planned

Exoplanet Populations




Mass and Radius of Kepler-138 Planets
GASEOUS
MIXED
ROCKY
Kepler-138d
Kepler-138c
Kepler-138b
EARTH
VENUS
MARS
MERCURY
Kepler-138 planets
Solar system planets
Kepler planets
Size Relative to Earth (Radius)
Mass Relative to Earth
0
0.5
1
1.5
2
0
1
2
3
4
5
6

Habitable (liquid water) zone



Transmission studies of atmospheres

- Earth: 6400 km radius, ~10-100 km atmosphere
- (6500/6400)^2=1.03
- Sun's radius: 7e5 km
- Depth=(Rp/R*)^2
  - 8.7e-5 for atmosphere
  - 8.4e-5 for planet
- Tiny signal!

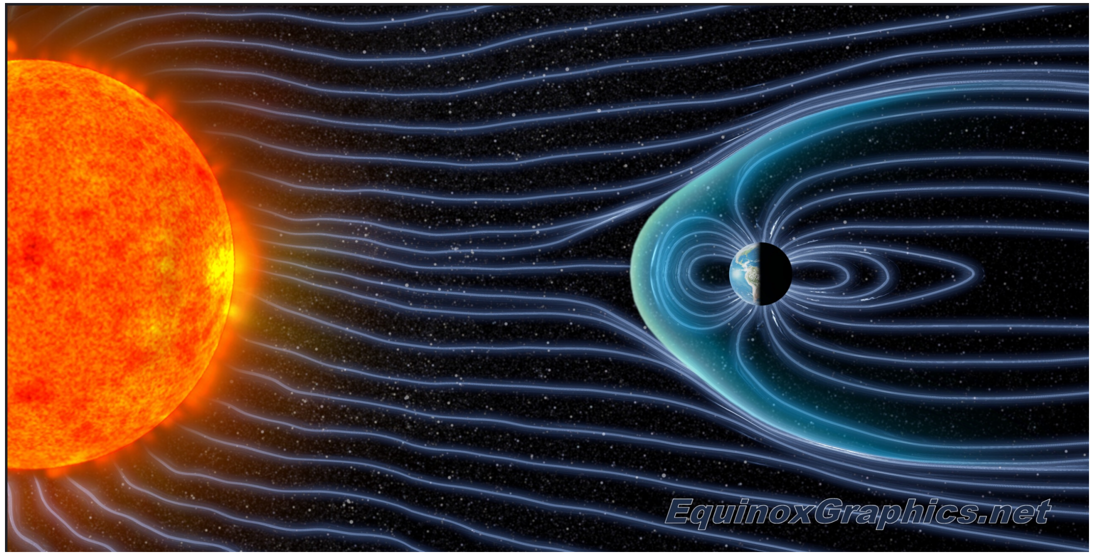
Atmospheric escape:
why did Mars lose its atmosphere?

Properties of Earth, Venus, and Mars

Property	Earth	Venus	Mars
Semimajor axis (AU)	1.00	0.72	1.52
Period (year)	1.00	0.61	1.88
Mass (Earth = 1)	1.00	0.82	0.11
Diameter (km)	12,756	12,102	6,790
Density (g/cm^3)	5.5	5.3	3.9
Surface gravity (Earth = 1)	1.00	0.91	0.38
Escape velocity (km/s)	11.2	10.4	5.0
Rotation period (hours or days)	23.9 h	243 d	24.6 h
Surface area (Earth = 1)	1.00	0.90	0.28
Atmospheric pressure (bar)	1.00	90	0.007

Mars: lower escape velocity, weak magnetic field

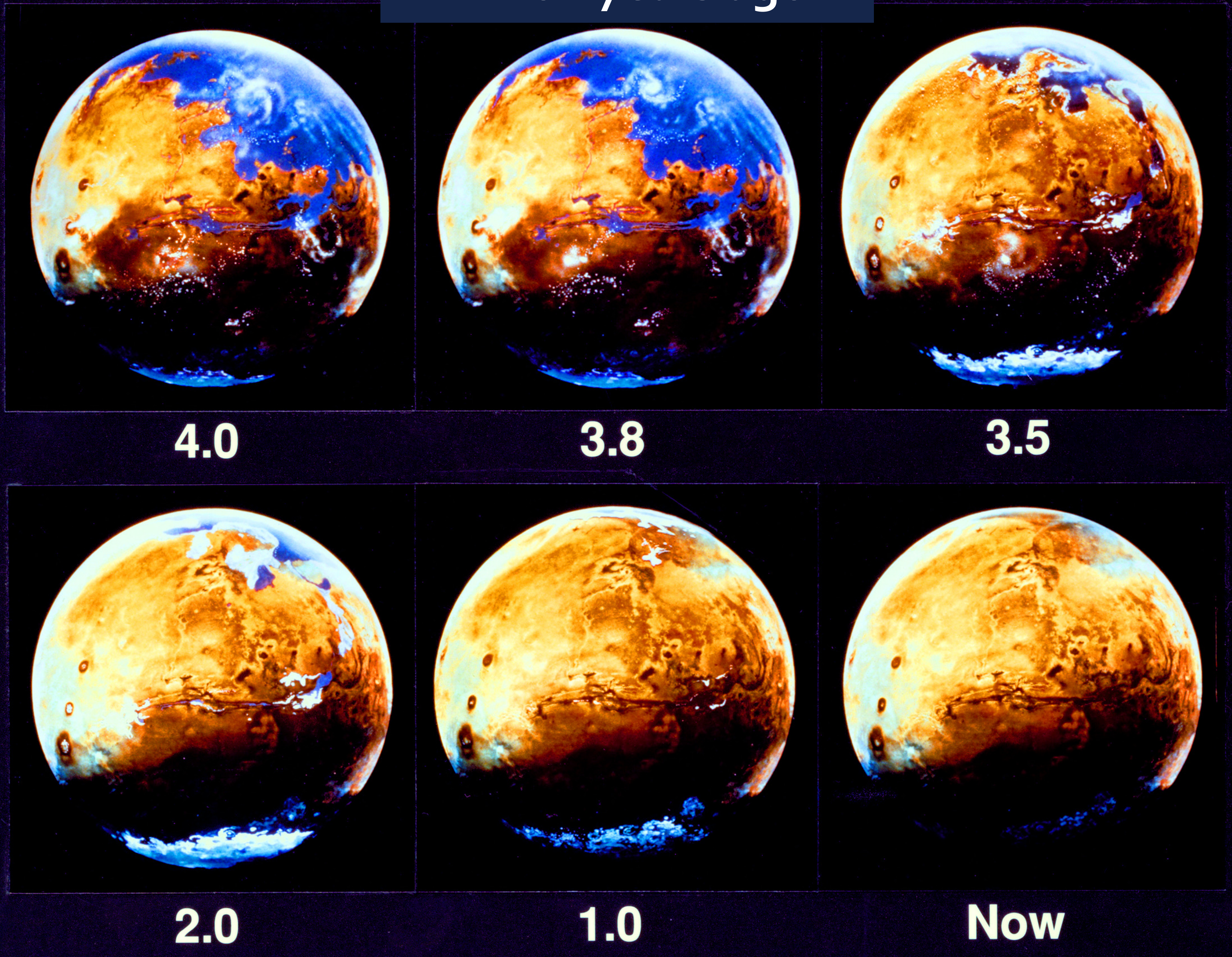
- Mars lost magnetic field!
  - Generated by radioactivity in core
  - Less mass => less radioactivity
  - Volcanos, earthquakes
  - Magnetic field protects atmosphere



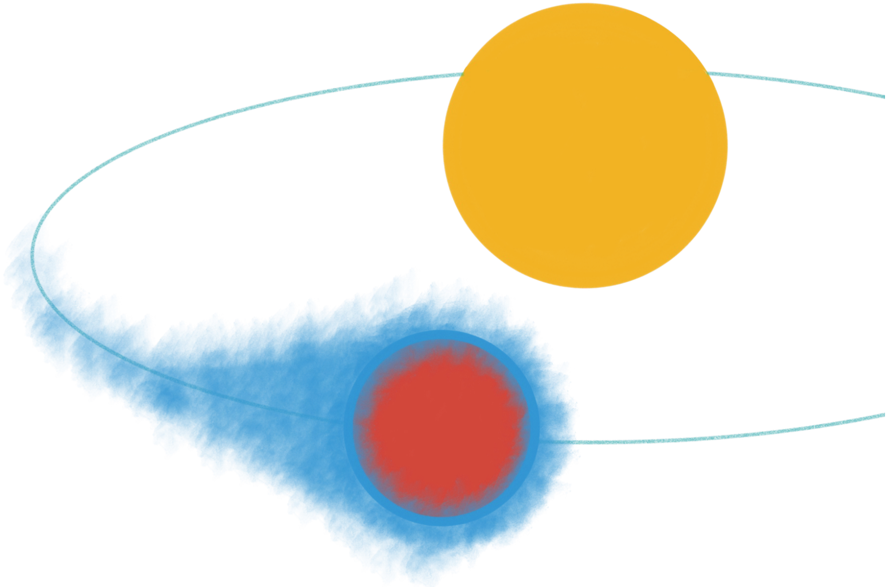
- Escape velocity of Earth: 11 km/s
- Escape velocity of Mars: 5 km/s

HISTORY OF WATER ON MARS

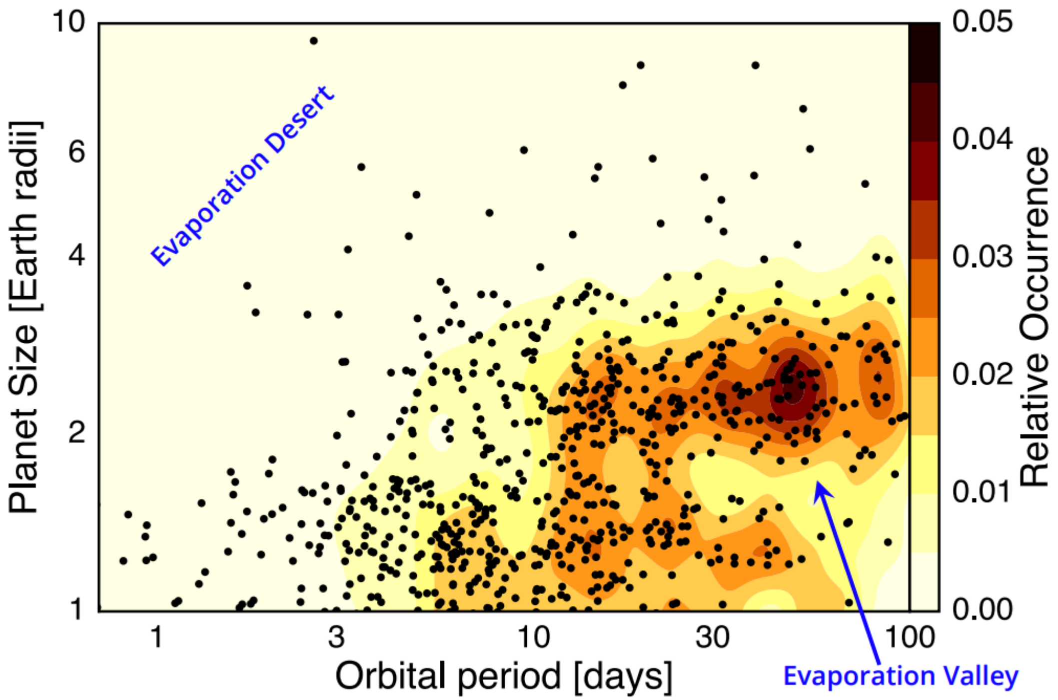
Billion years ago



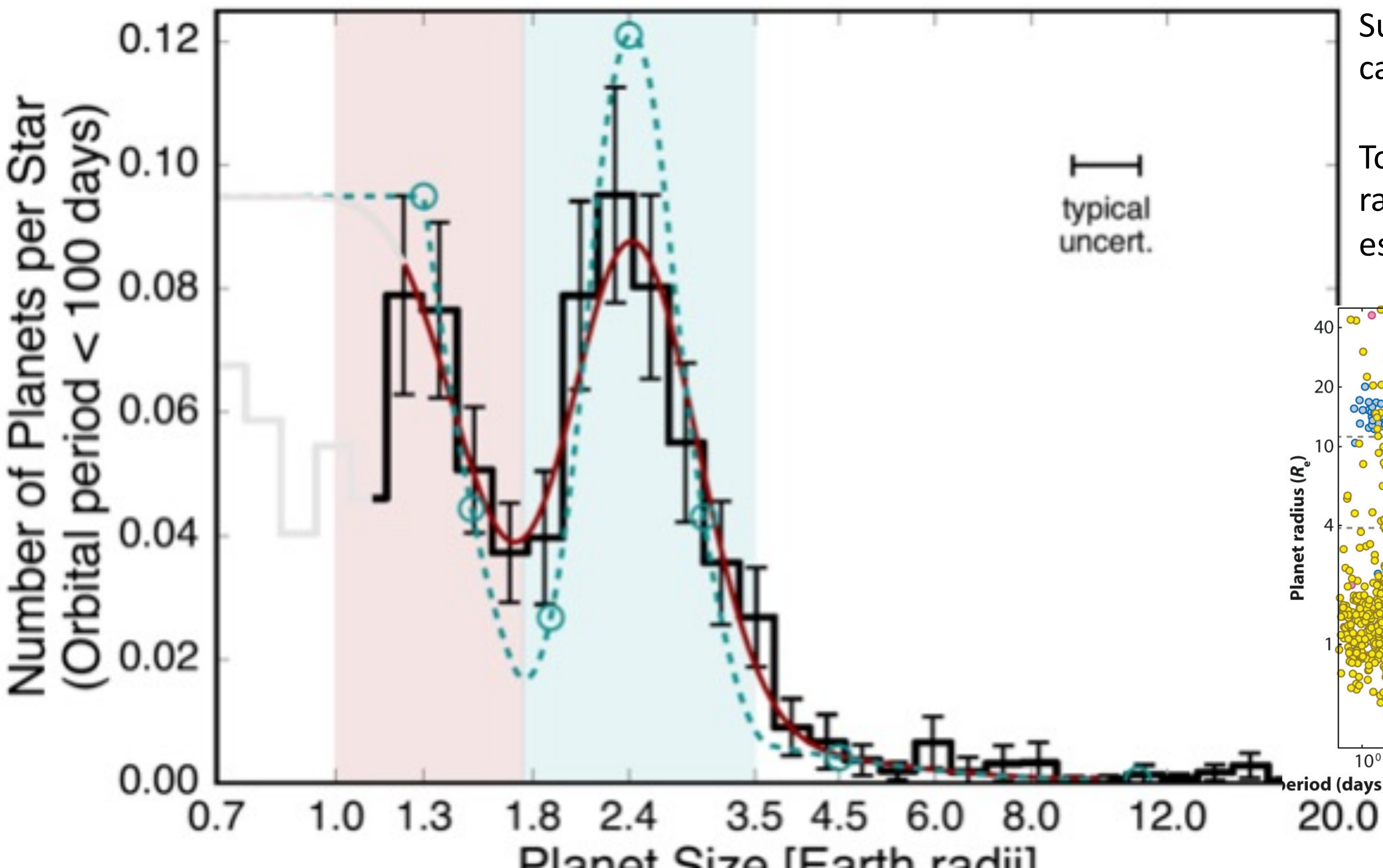
Atmospheric escape detected in planet distributions

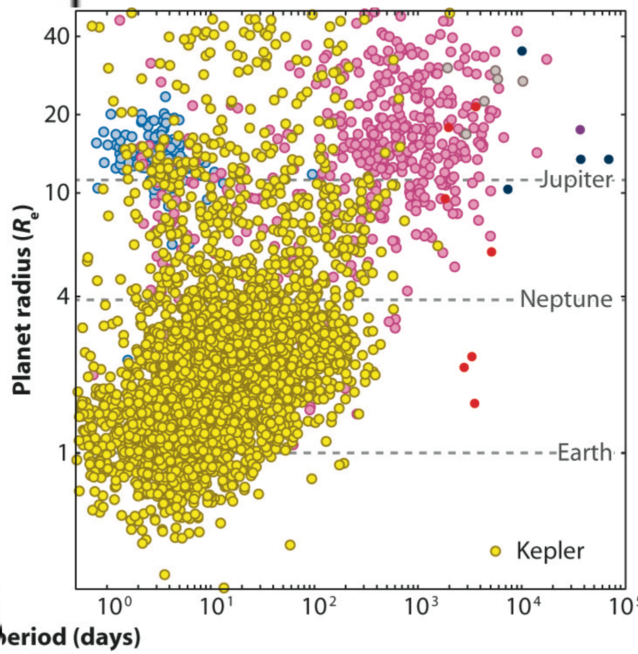


- Measured for hot Jupiters!
  - not enough escape because of high escape velocity
  - provides test for models)



Atmospheric escape detected in planet distributions

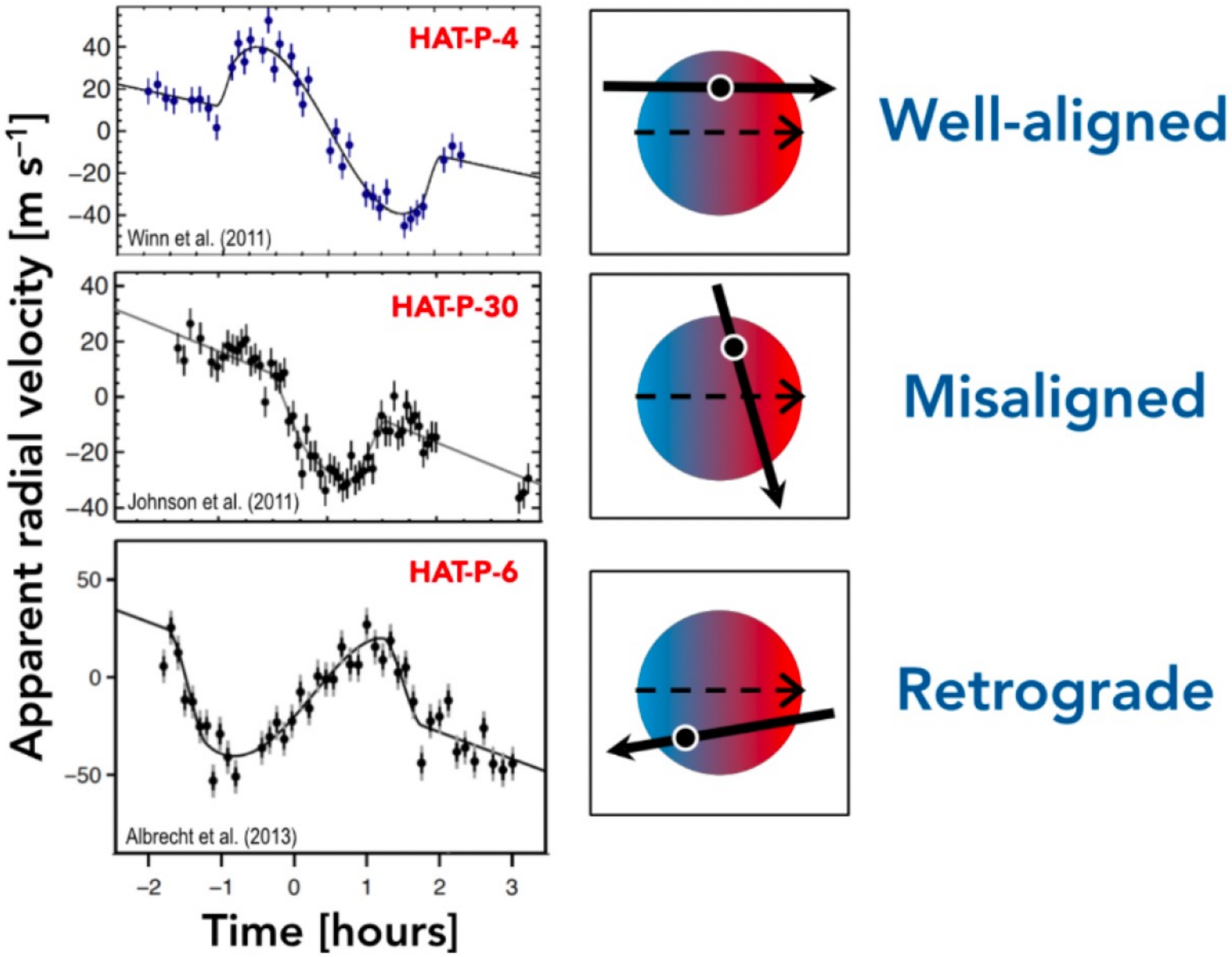




Super-Earths close to star cannot retain atmospheres

Too much energetic radiation, atmosphere escapes

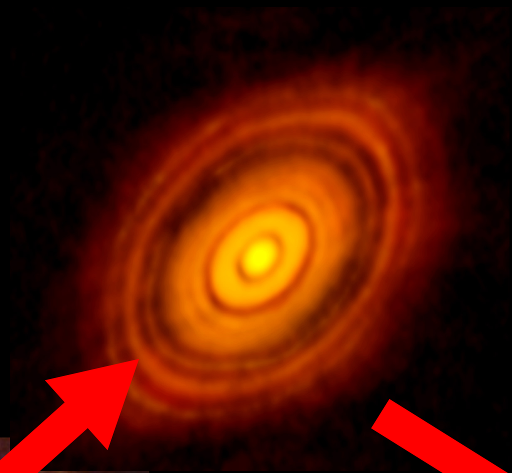
Spin-orbit misalignment



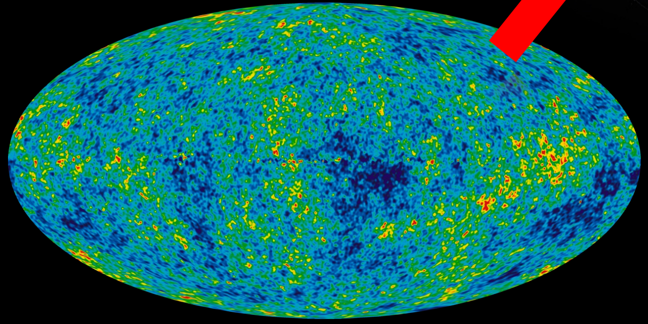
- Most planets seem co-planar, also with stellar rotation
- Some hot Jupiters are misaligned
  - Scattered during unstable interactions with other planets

Our astrophysical origins

Milky Way Galaxy
(if we could see it from "above")

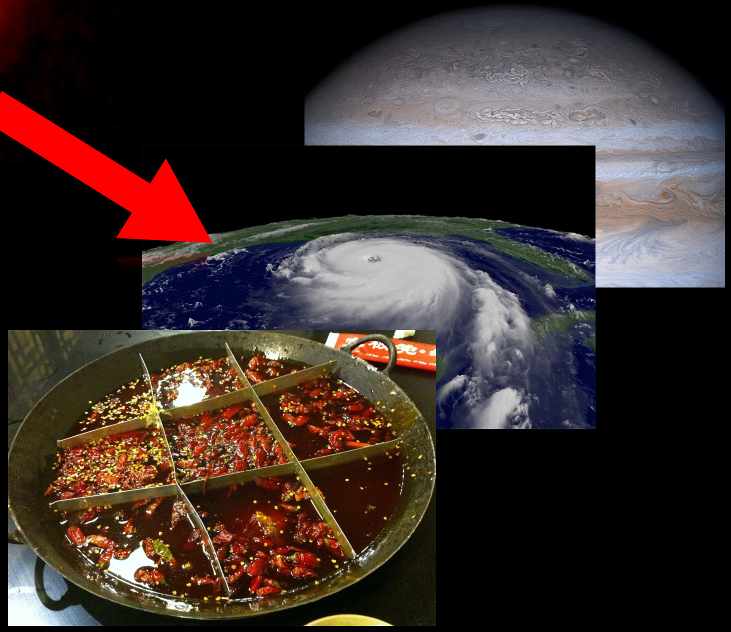


Protoplanetary disks



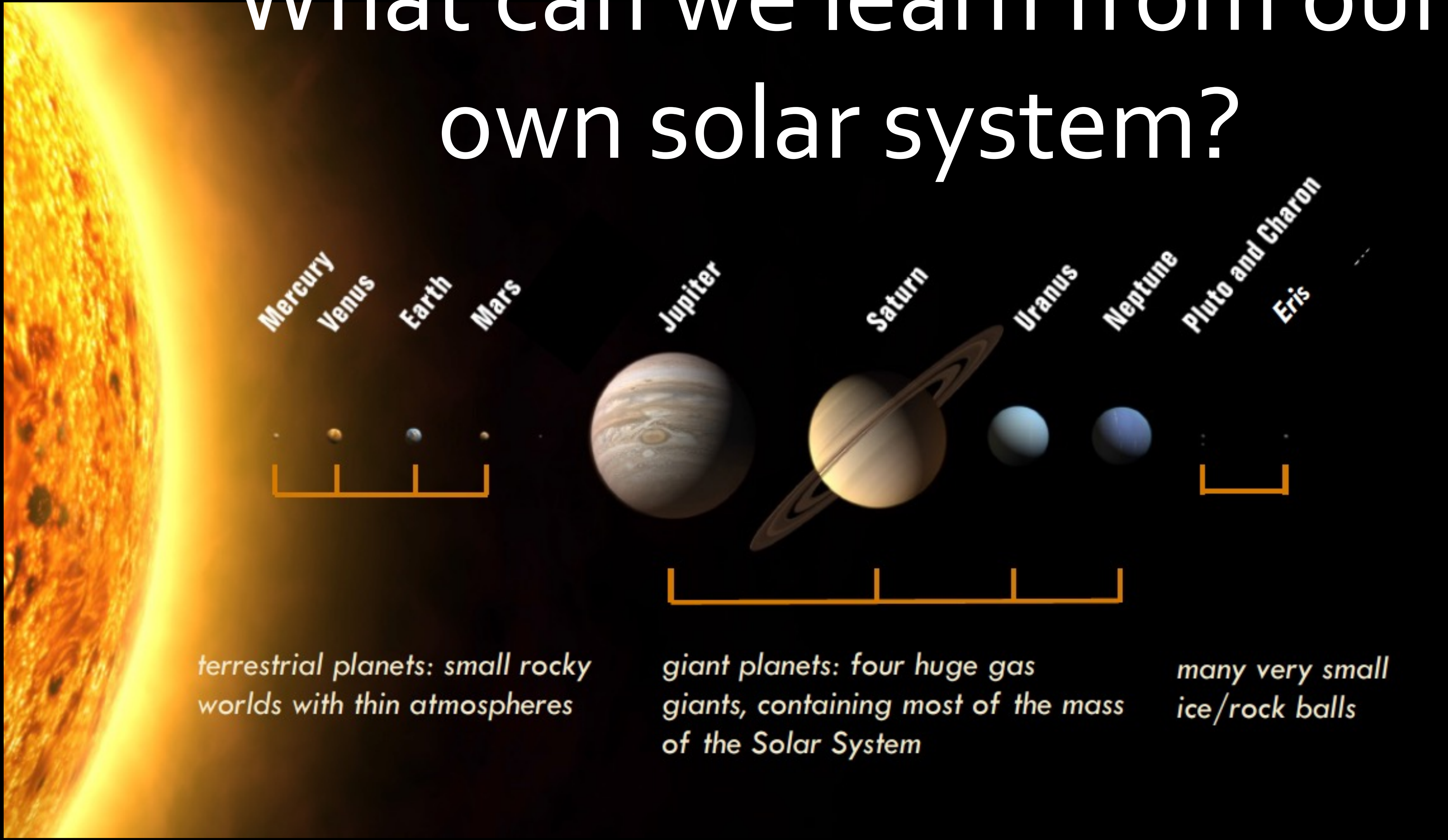
Cosmic Microwave Background (early universe)

Molecular Clouds

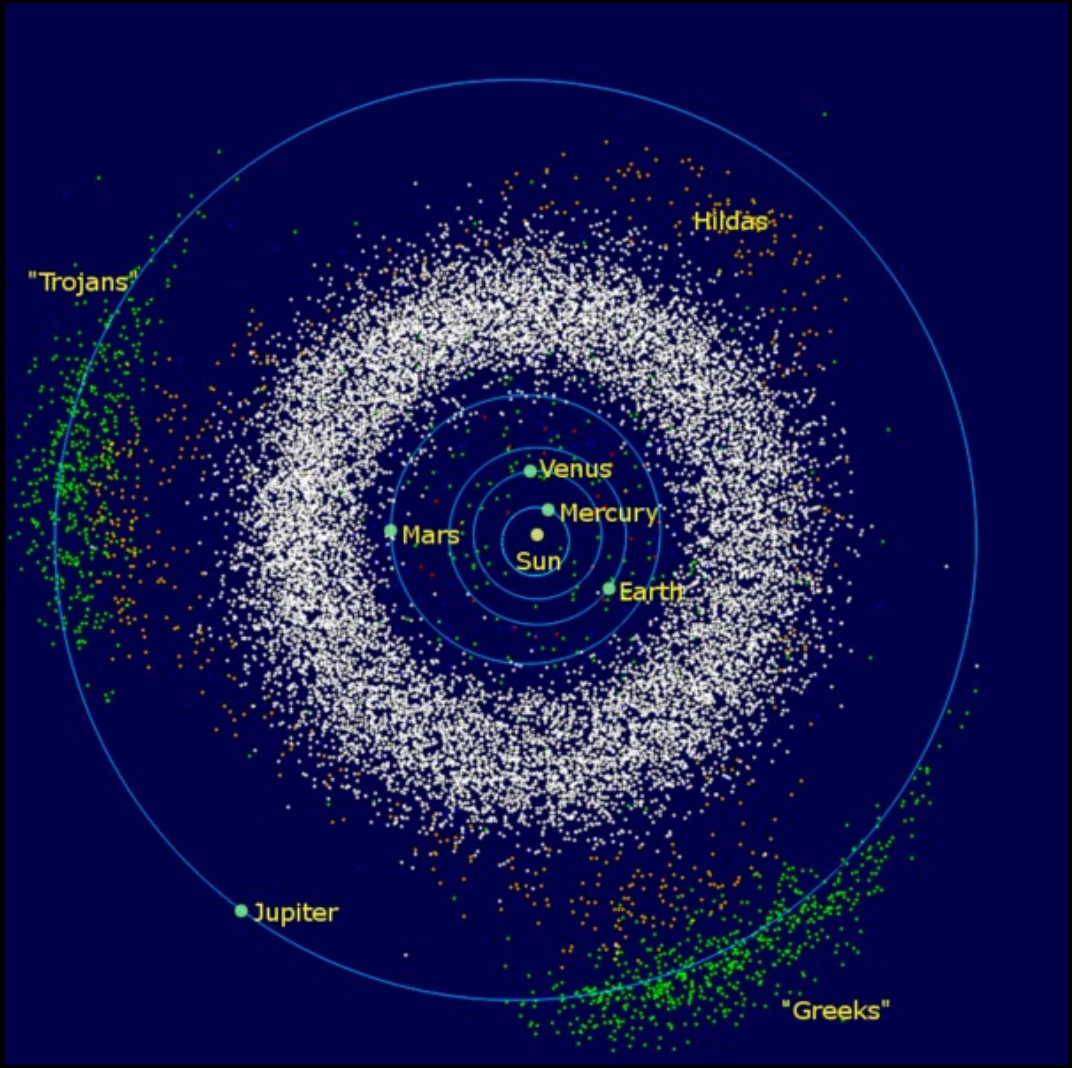


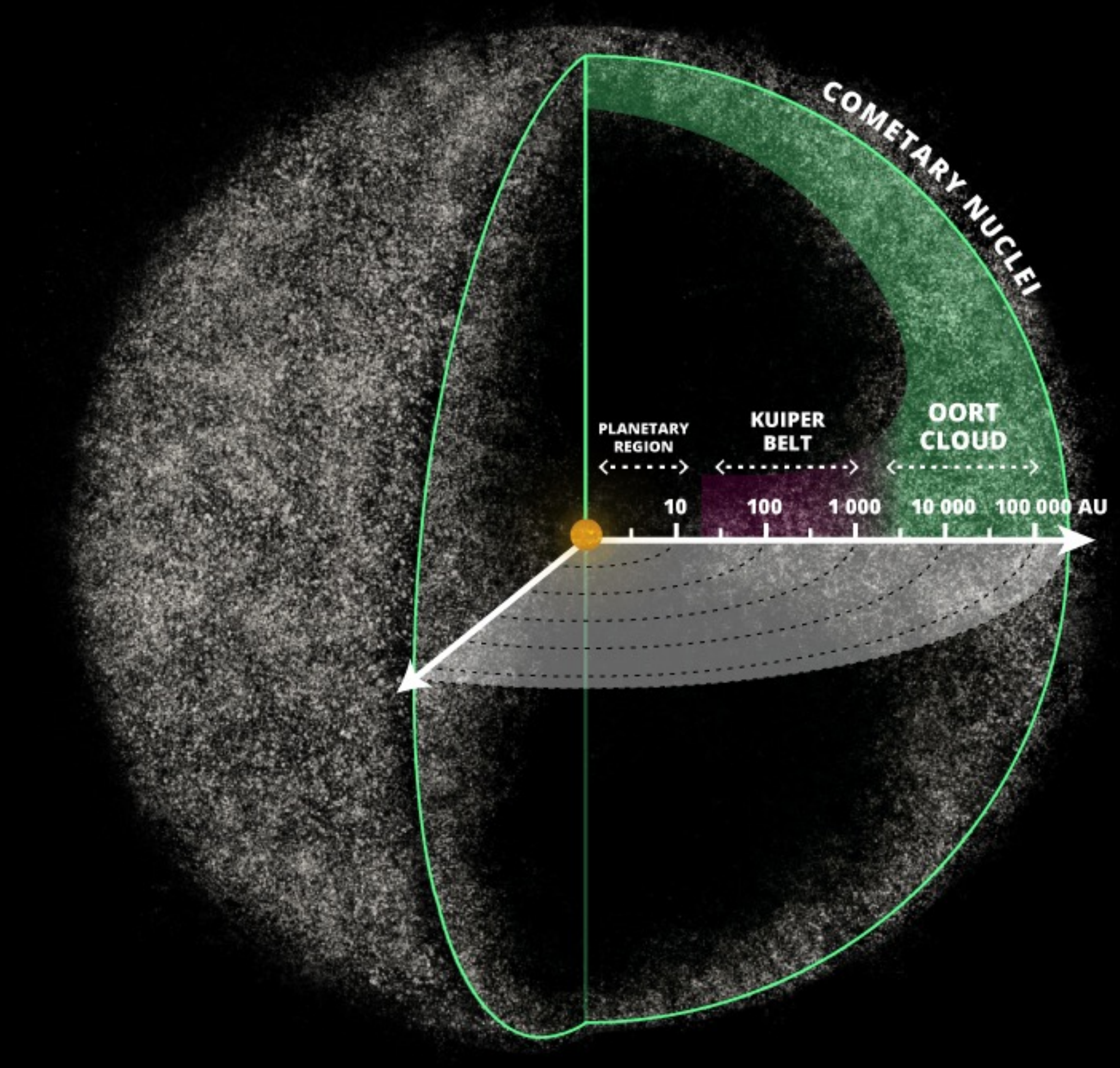
Planets, atmospheres, and life!

What can we learn from our own solar system?



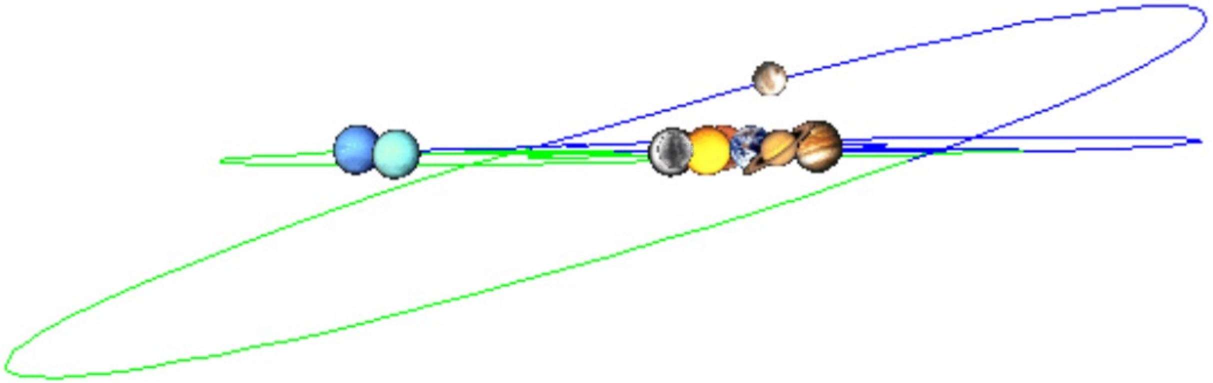
Debris from the solar system:
asteroids, comets, Kuiper Belt Objects

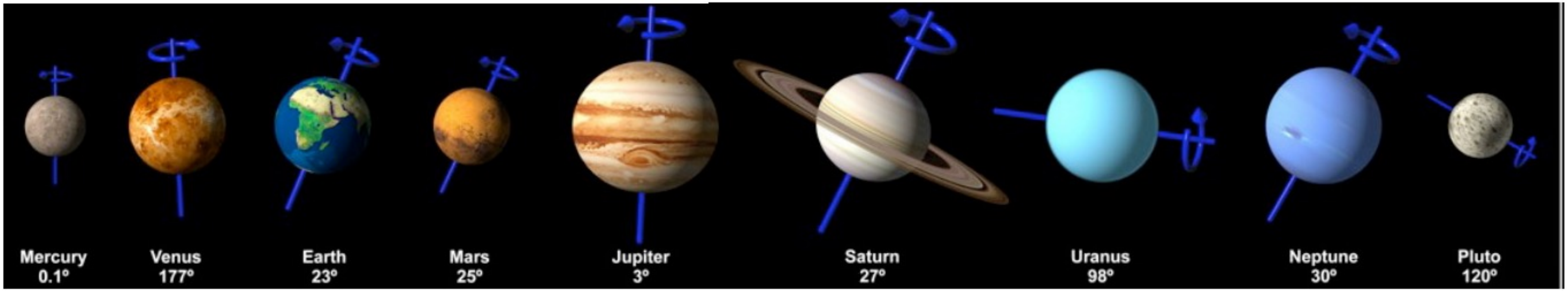




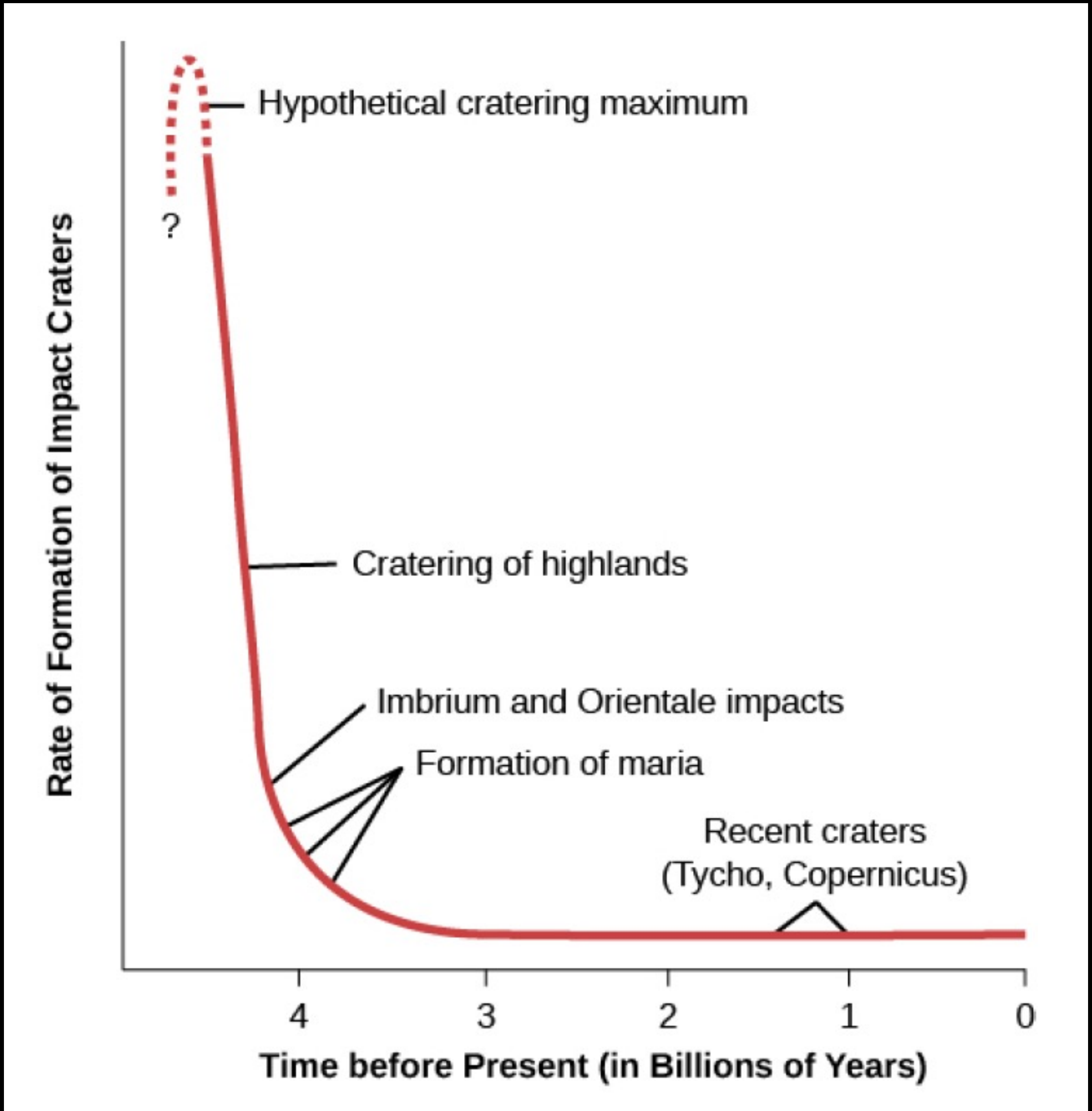
Space Facts / Laurine Moreau

All the planets (but not Pluto) orbit in the same direction and in the same plane: the *ecliptic* (to within 6o).





Collisions were common!



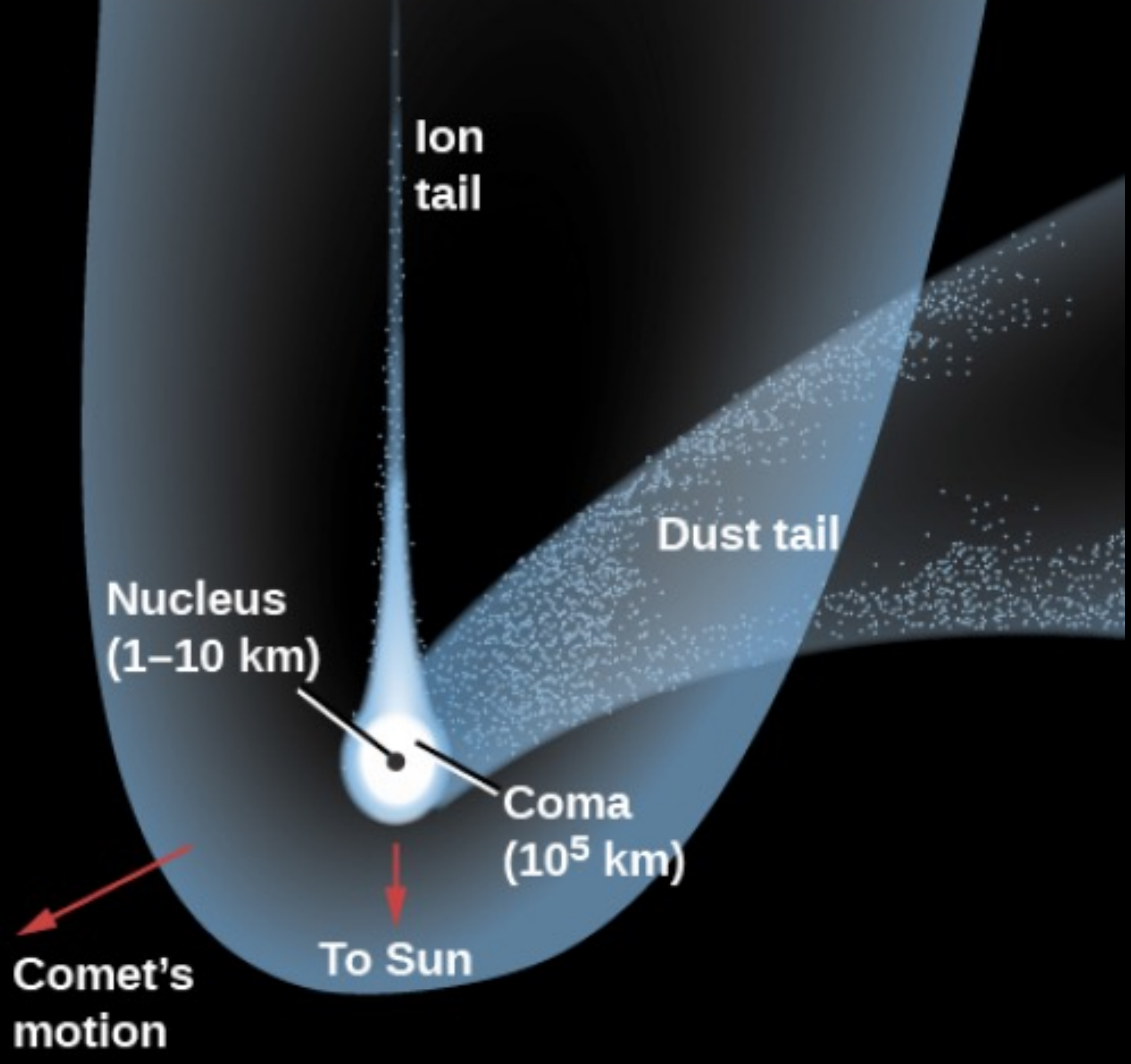
Moon formation!

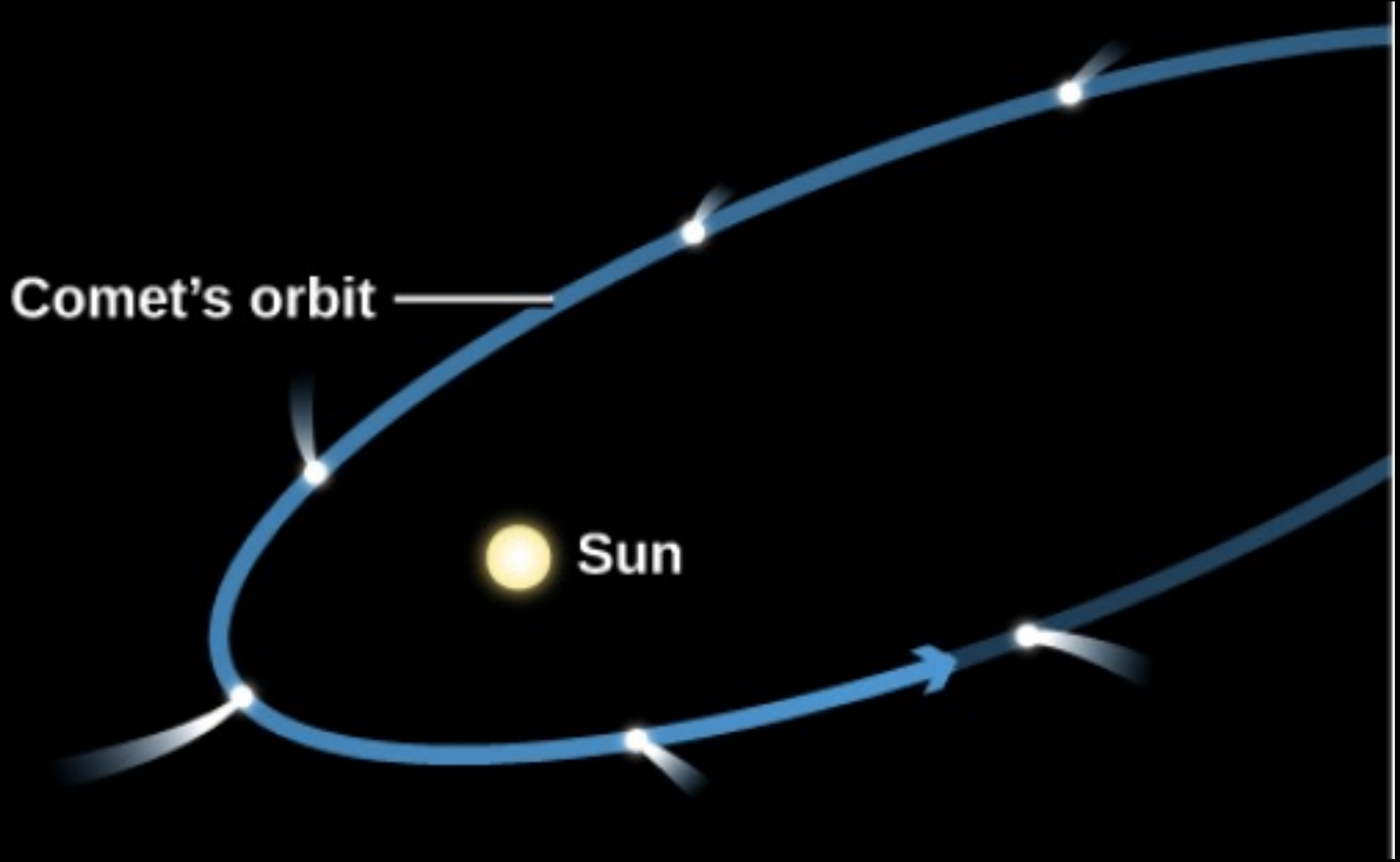
Abundances: comets, asteroids

- Asteroids: leftover planetessimals, mostly between Mars & Jupiter
  - Carbon-rich
  - Metallic
  - Silicaceous (rocky)
  - No ice, formed inside snow line

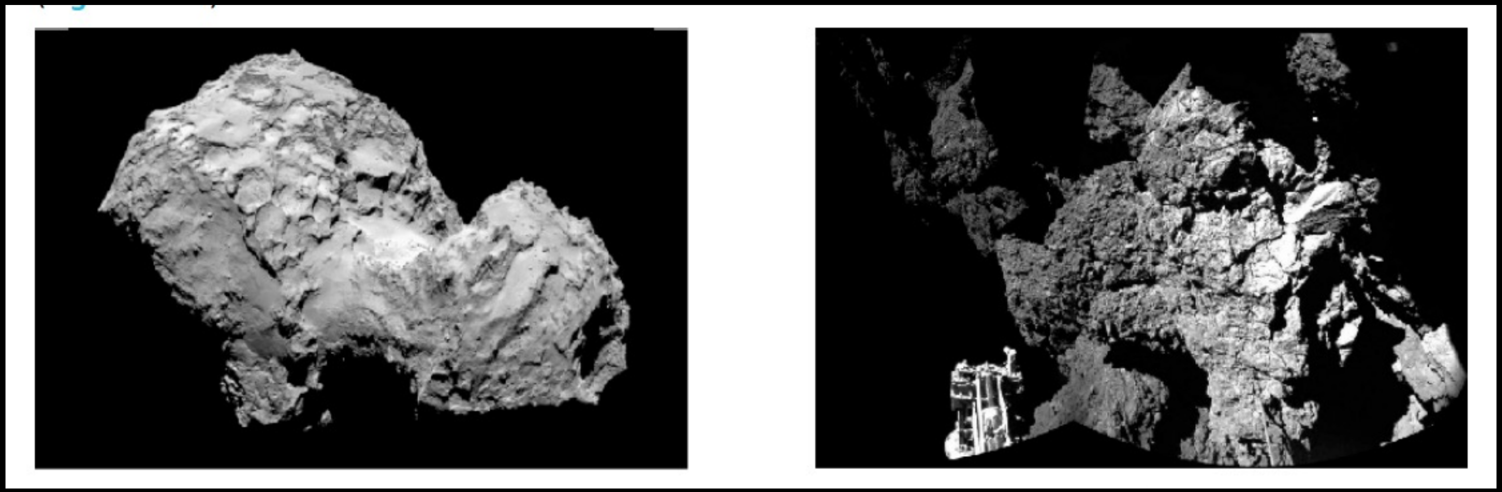
- Comets: ices, formed beyond the snow line
  - Comets may have delivered water to earth!

- Kuiper Belt Objects: ices beyond snow line

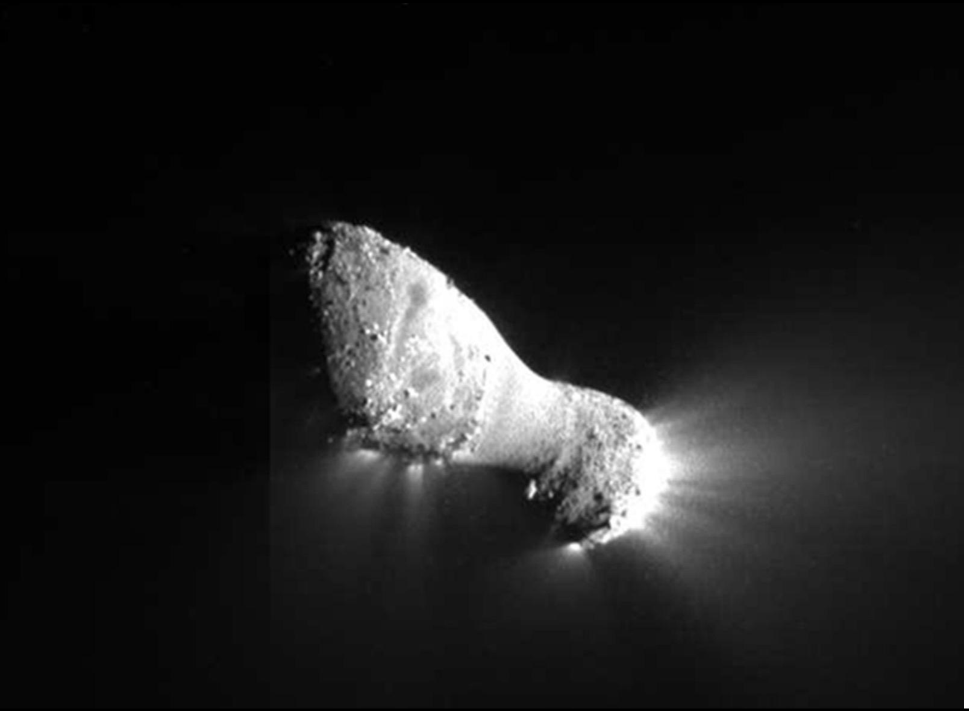

Ion
tail
Dust tail
Nucleus
(1–10 km)
Coma
(10^5 km)
To Sun
Comet's
motion

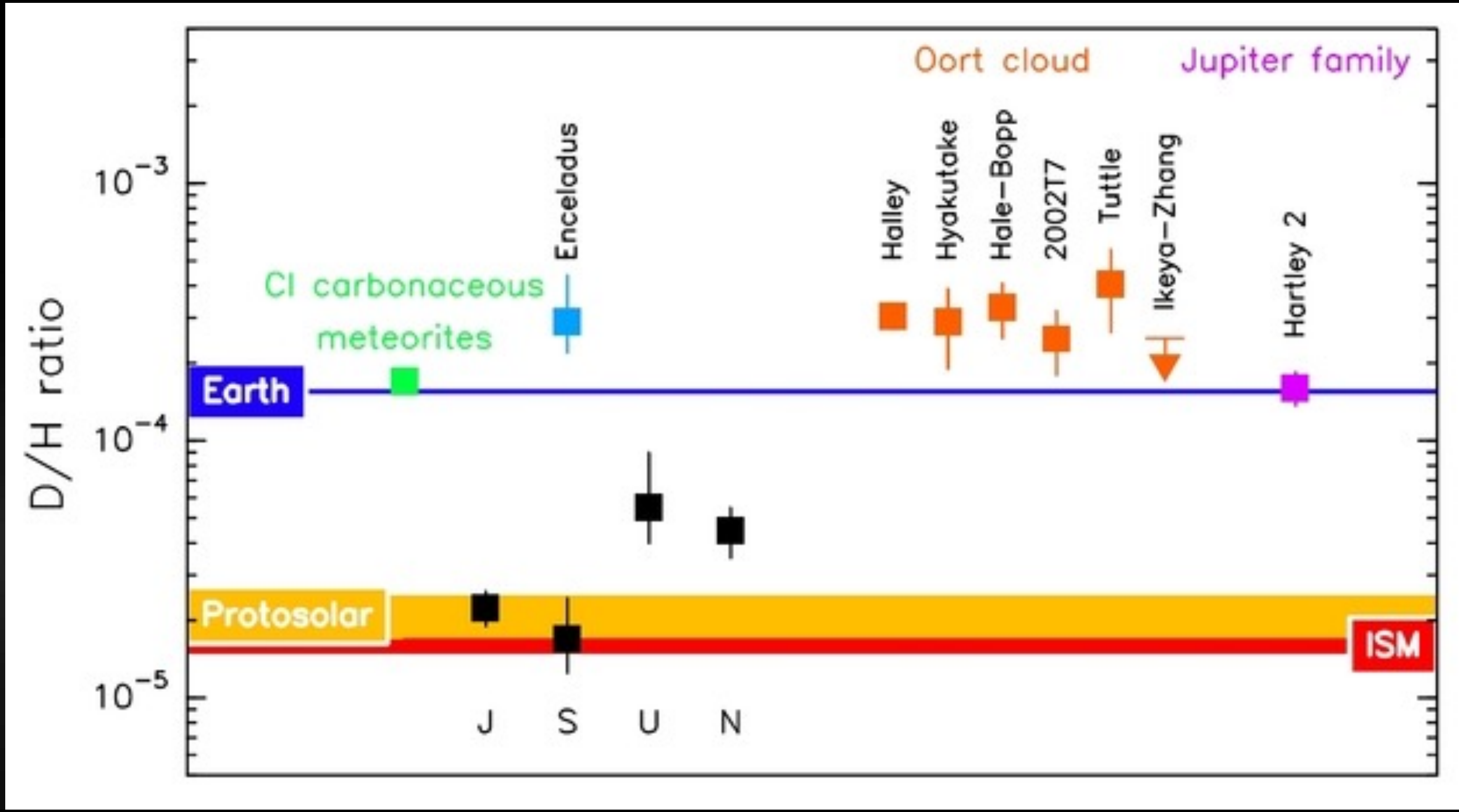

Comet's orbit
Sun

Rosetta Mission: landed on Comet 67P (!!!)



Comets: possible source for Earth's water!

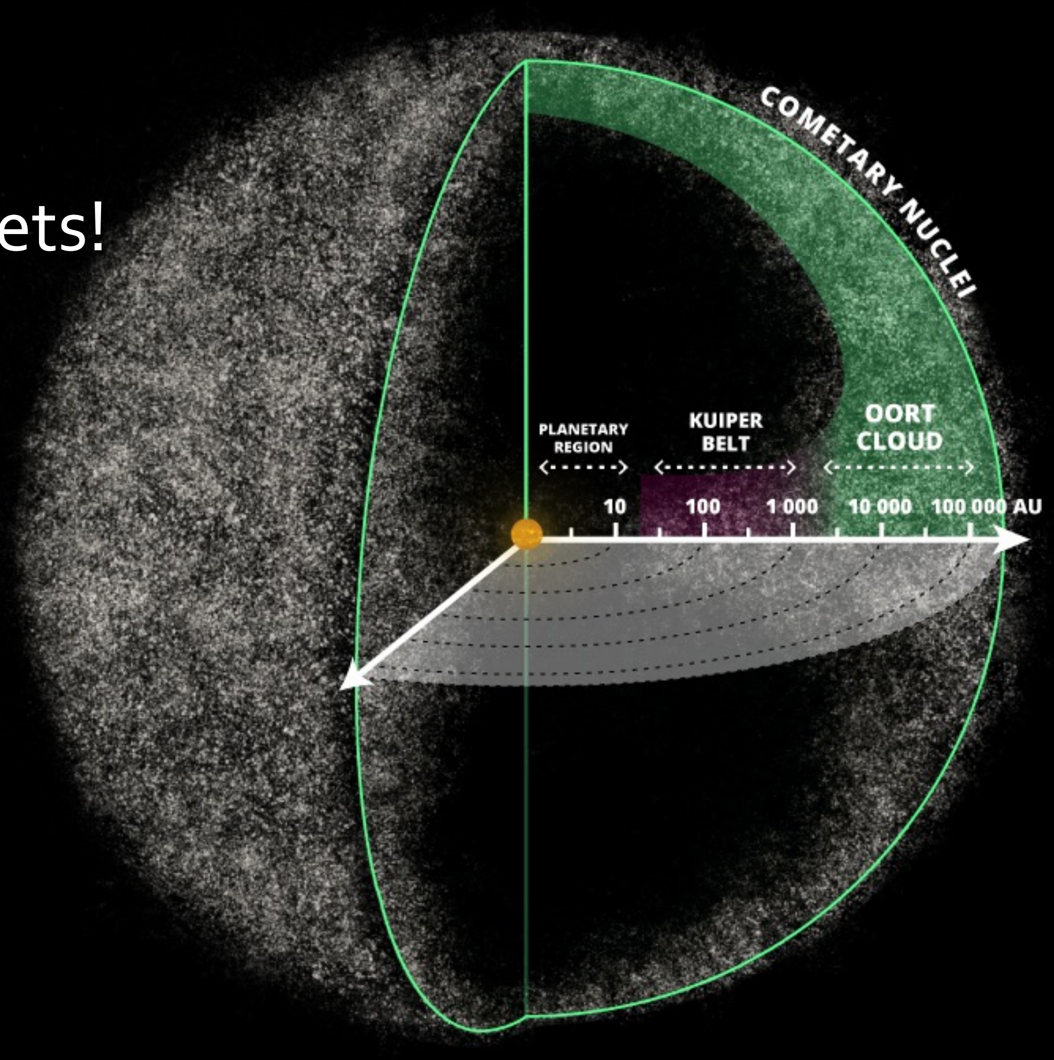




How did they get there?

Planetessimals that never formed into planets

Scattered by giant planets!

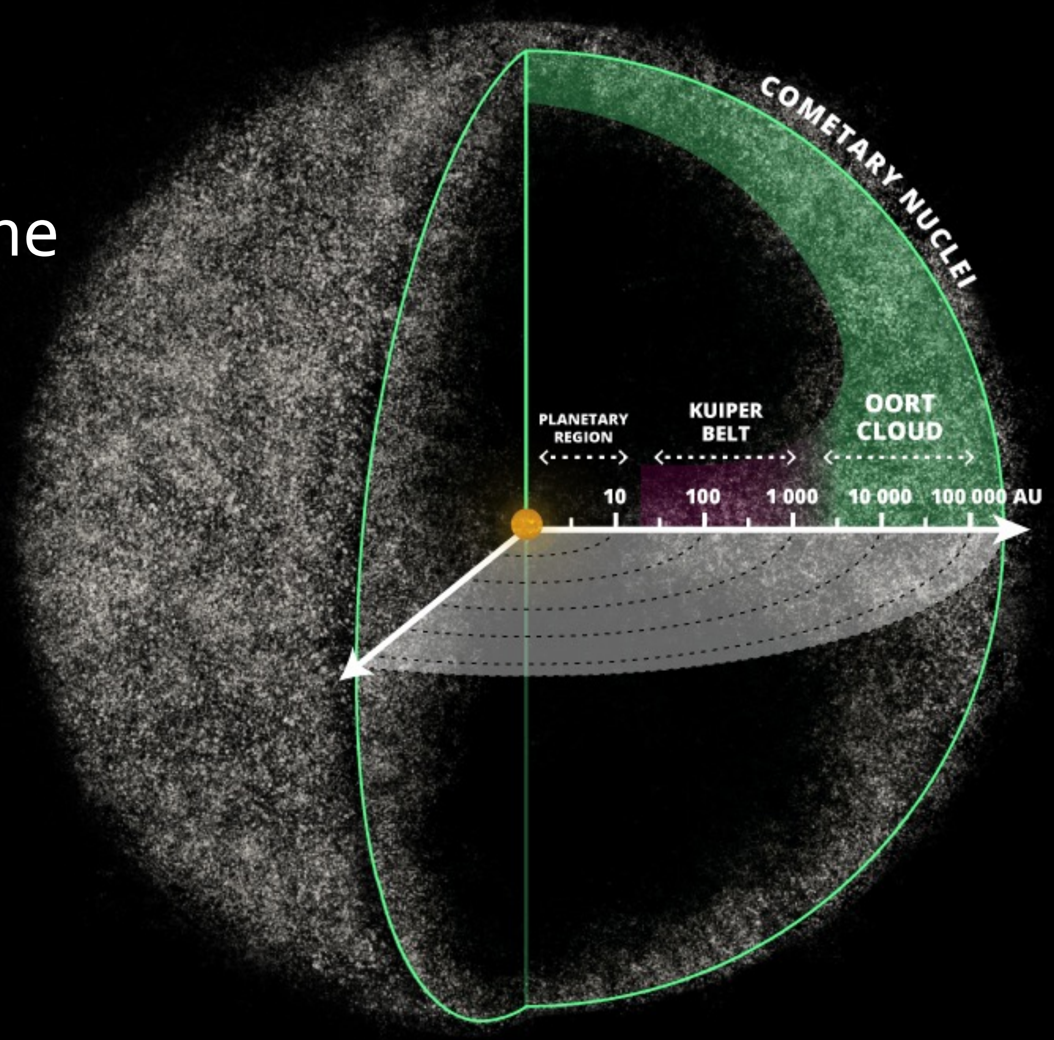


Space Facts / Laurine Moreau

How did they get here?

Dynamical interactions in Oort cloud:

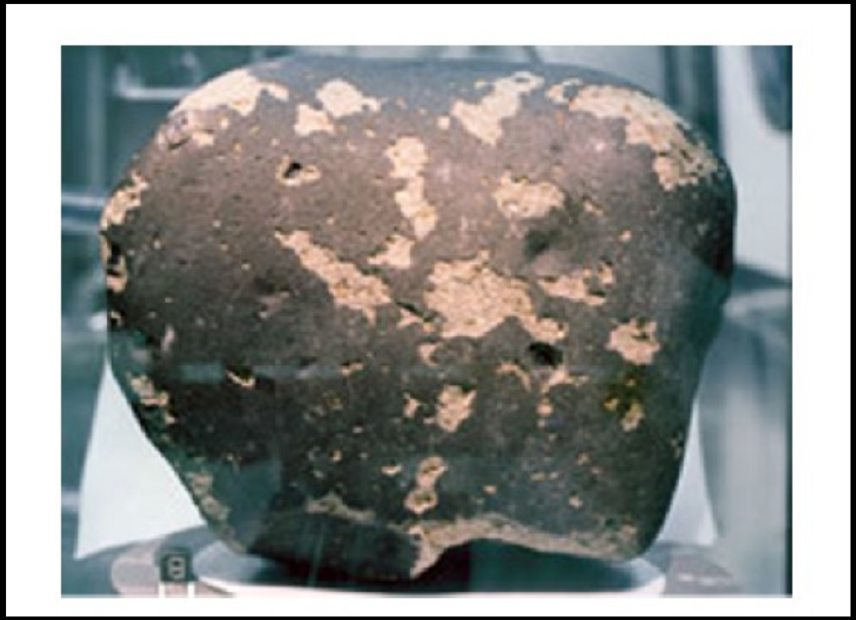
Unstable, sometimes one heads to inner solar system



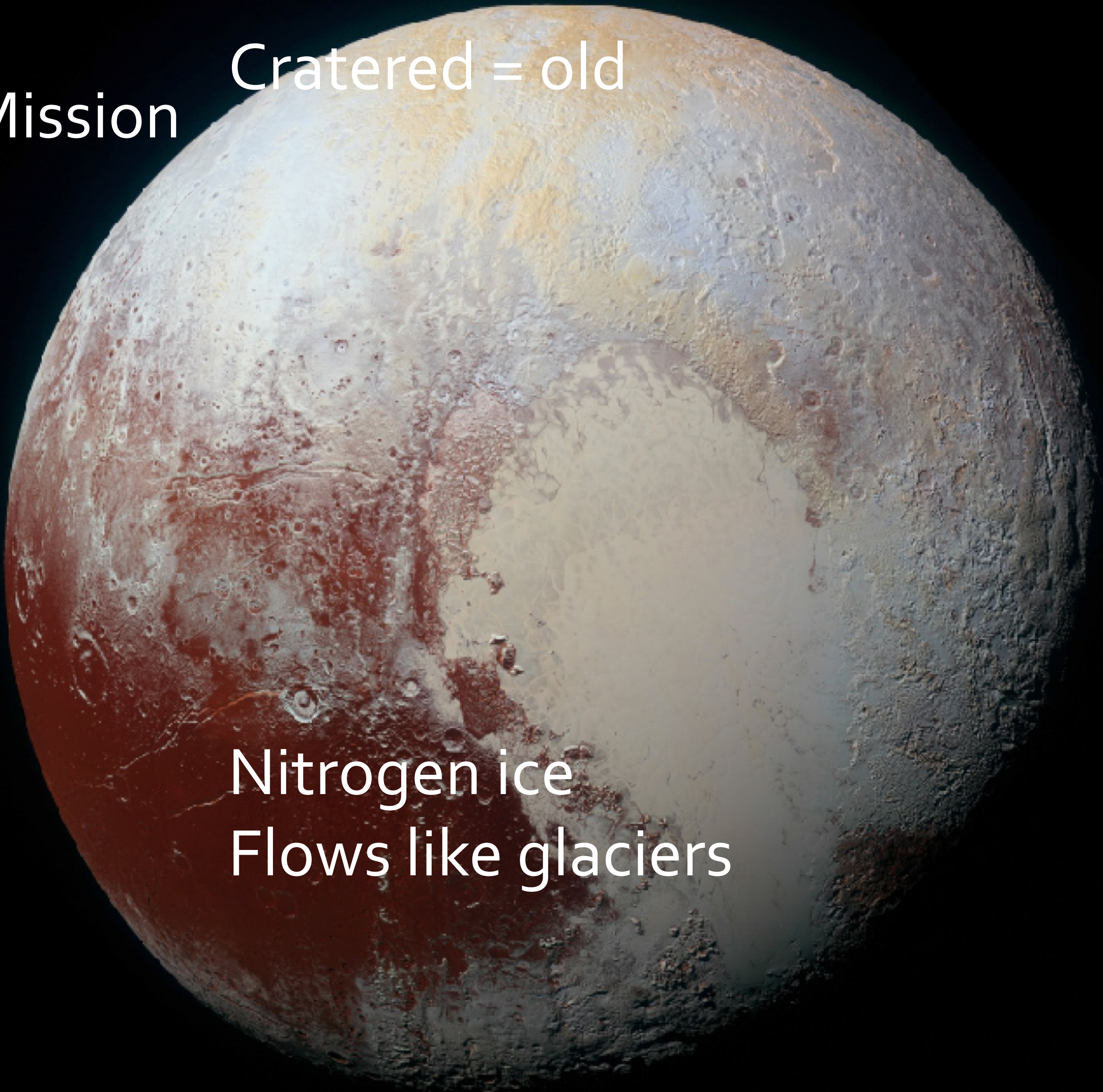
Space Facts / Laurine Moreau

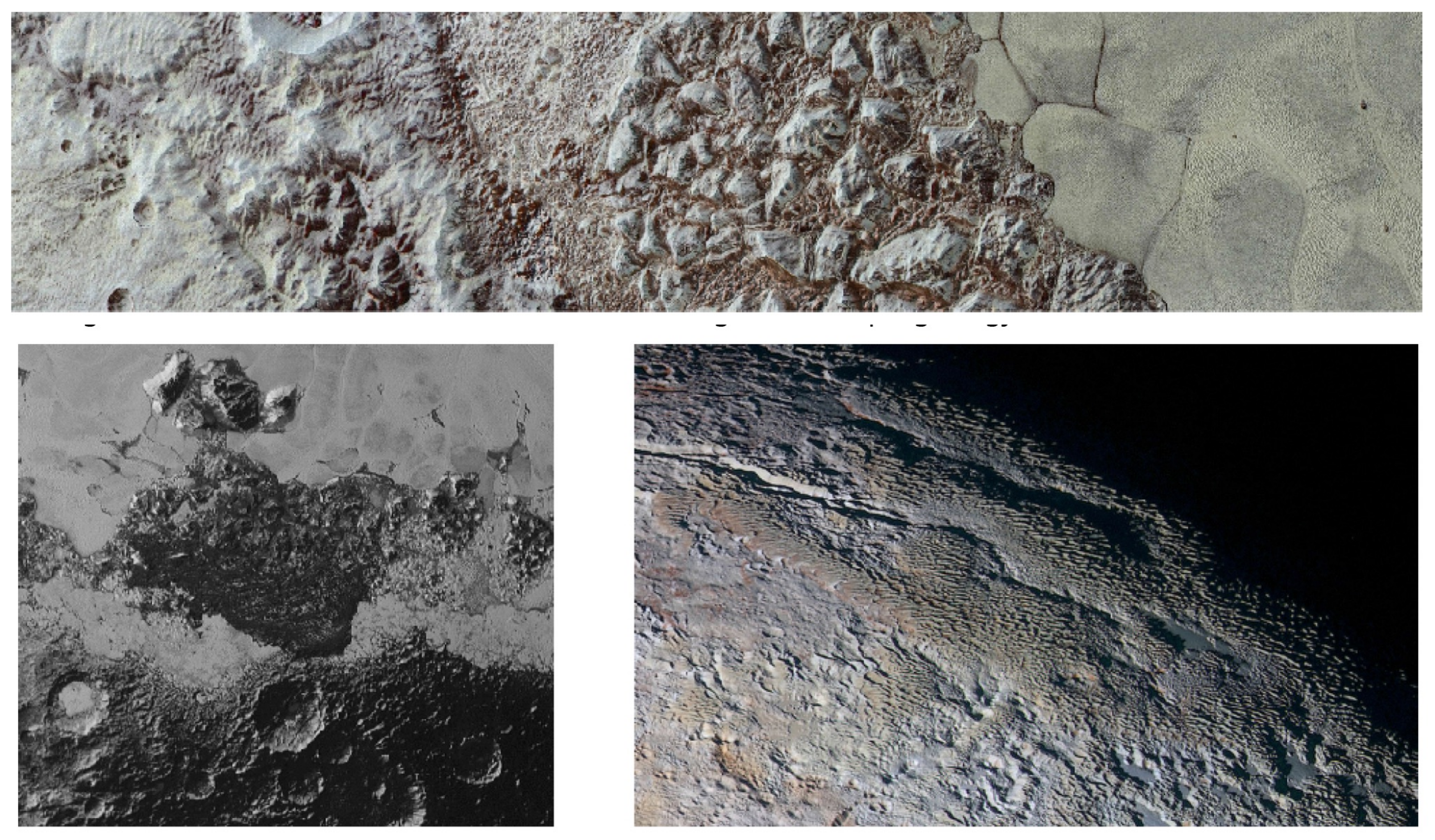
Asteroid composition

- Sample return!
- Antarctica meteors
  - also some Mars rocks!
- Spectroscopy from ground/space



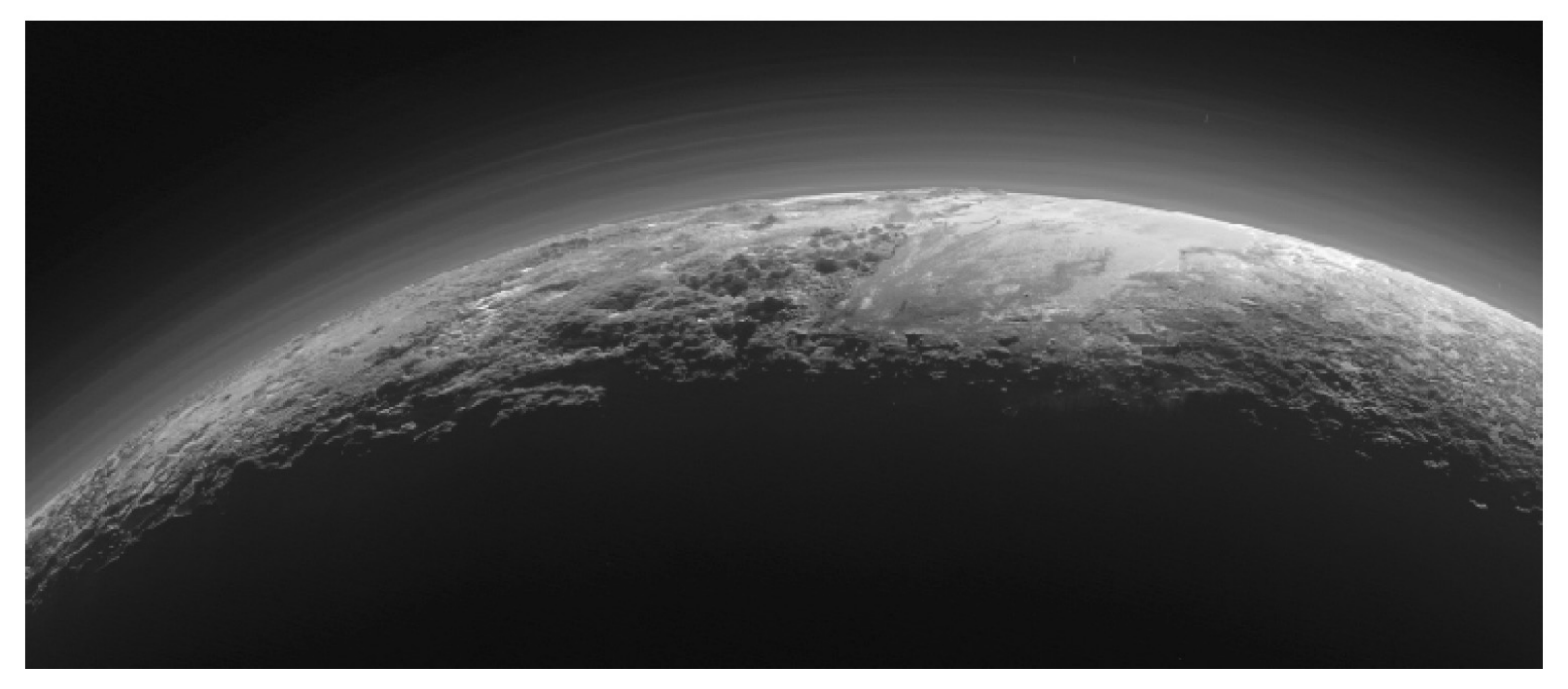
Pluto from
New Horizons Mission

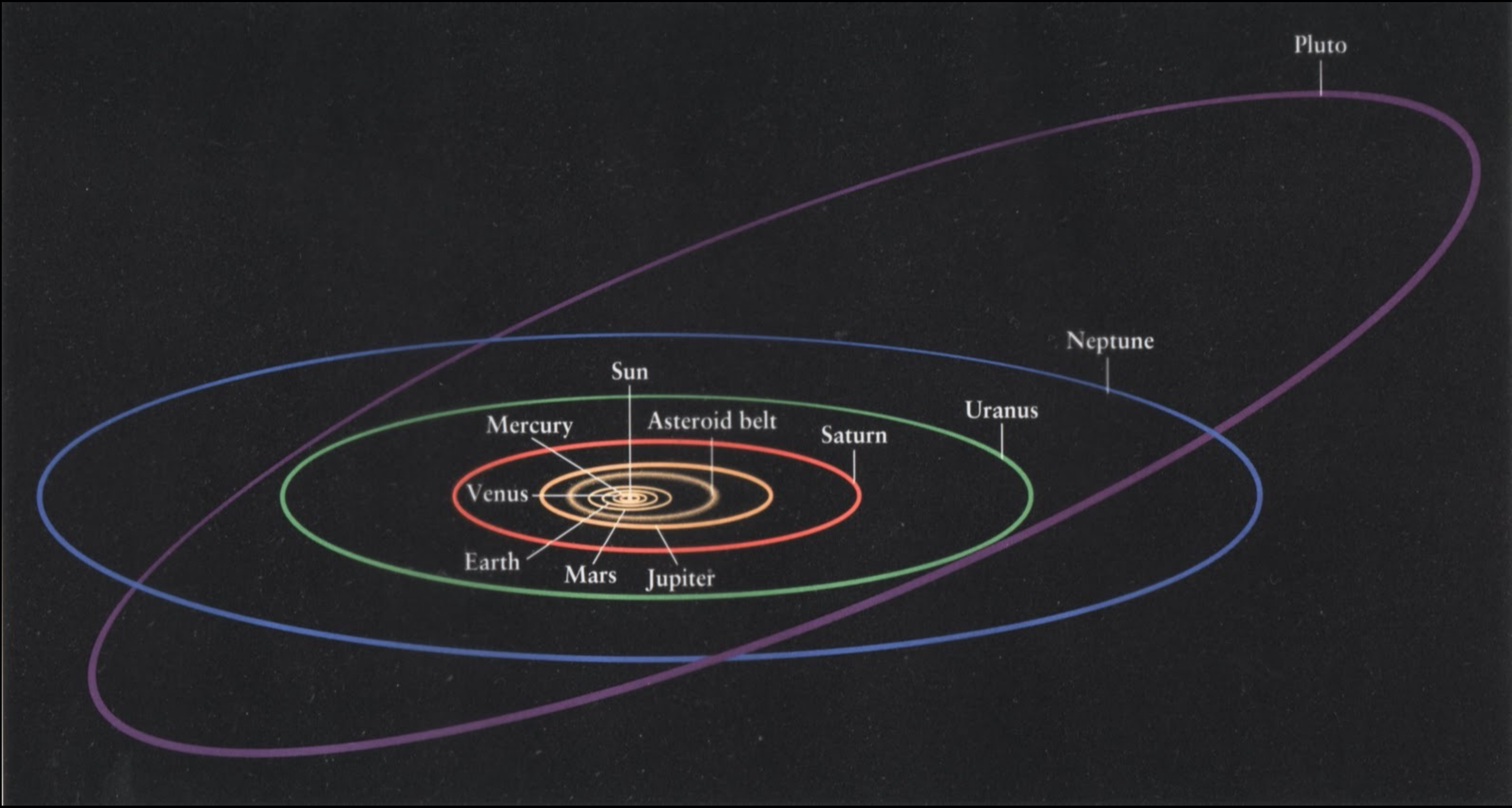




Ice mountains, 3 km high

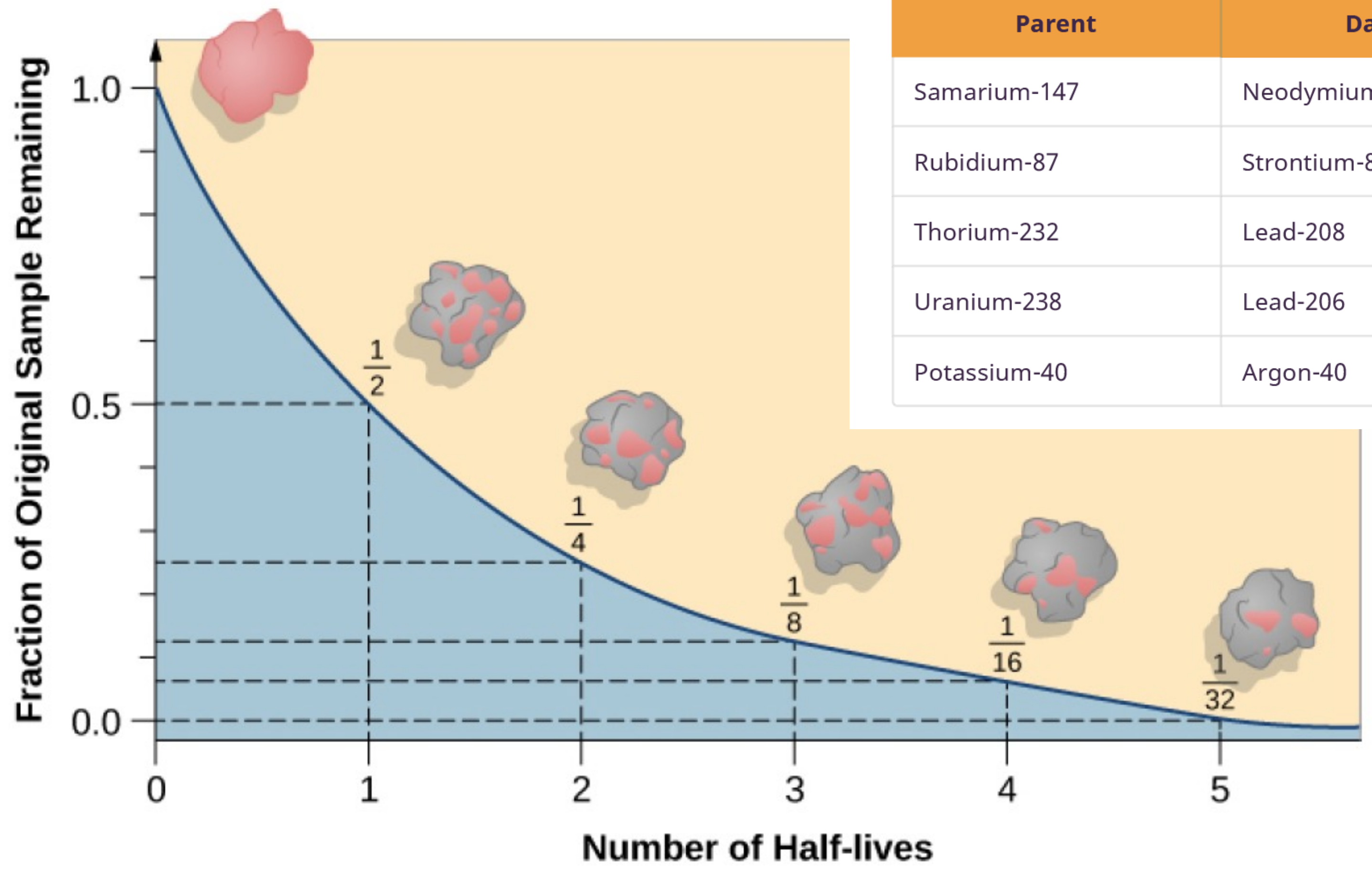
Haze! Pluto has an atmosphere
Likely from solar radiation, will disappear when Pluto is farther from the Sun




Pluto
Neptune
Sun
Uranus
Mercury
Asteroid belt
Saturn
Venus
Earth
Mars
Jupiter

New Horizons flyby of Kuiper Belt Object MU-69 (36 km across)

Age of solar system: 4.567 billion years



Parent	Daughter	Half-Life (billions of years)
Samarium-147	Neodymium-143	106
Rubidium-87	Strontium-87	48.8
Thorium-232	Lead-208	14.0
Uranium-238	Lead-206	4.47
Potassium-40	Argon-40	1.31

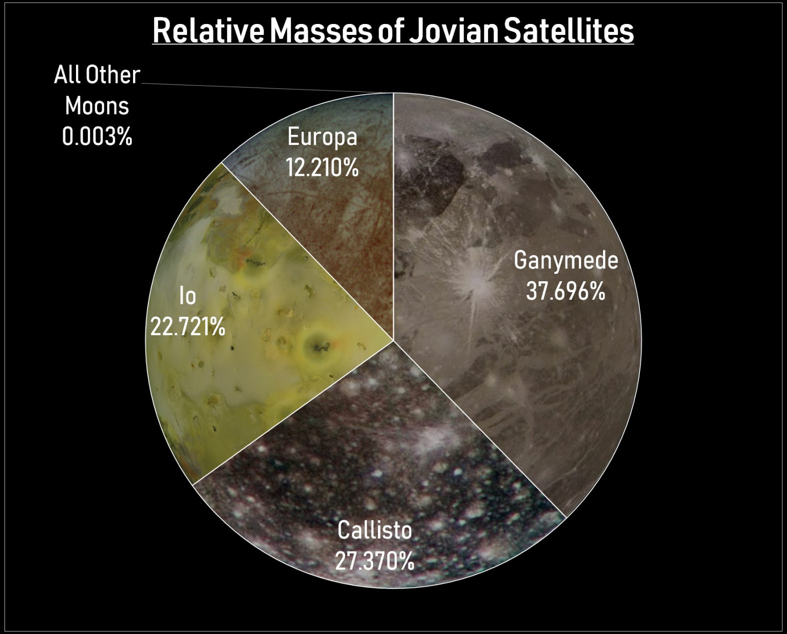
Formation near supernova?

- Meteoritic abundance: elevated Mg-26, a decay product of Al-26
- Core-collapse supernova produce Al-26
- Solar system: likely formed in high-mass star-forming region, affected by supernova!

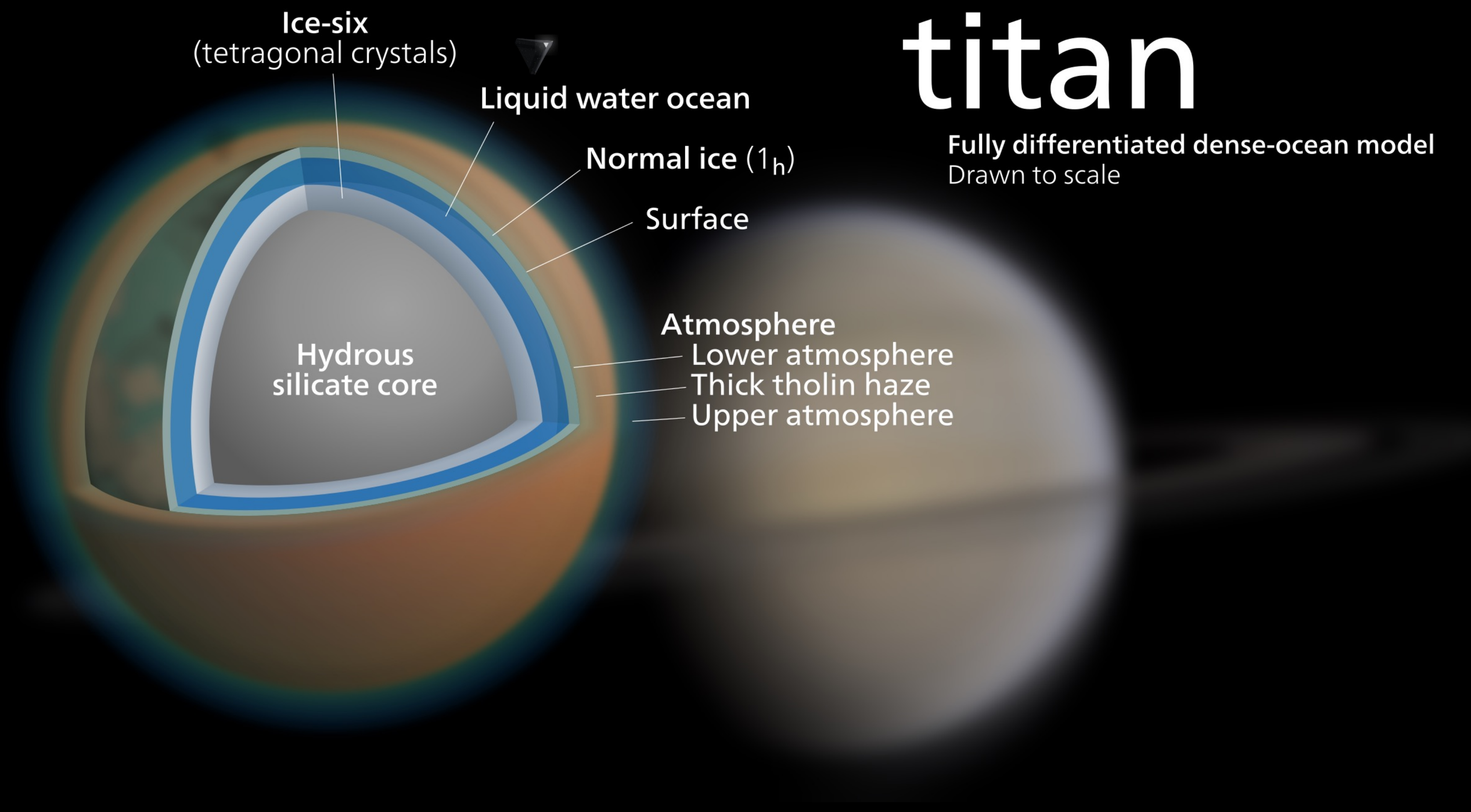
Chondrites

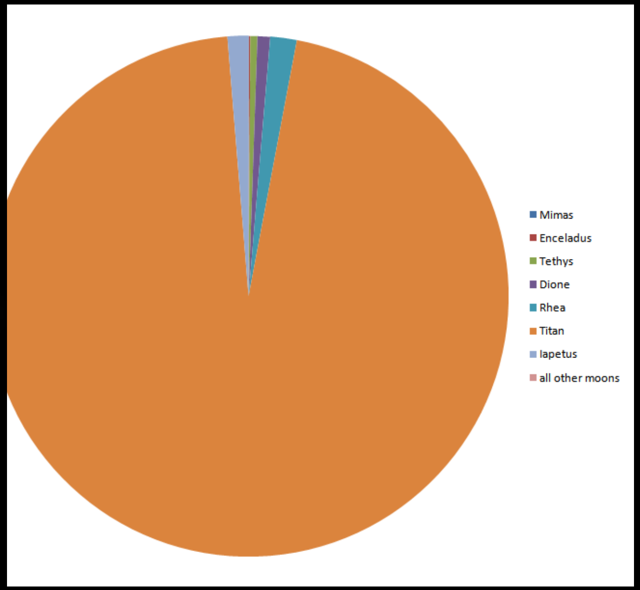
- Spherical silicate+metal grains, microns-mm in size
- 85% of all meteorites
- Requires temperatures of ~1000-1500 K
- Heating event over very short (10,000 year) timescale

Galilean satellites of Jupiter
Jupiter had its own disk!

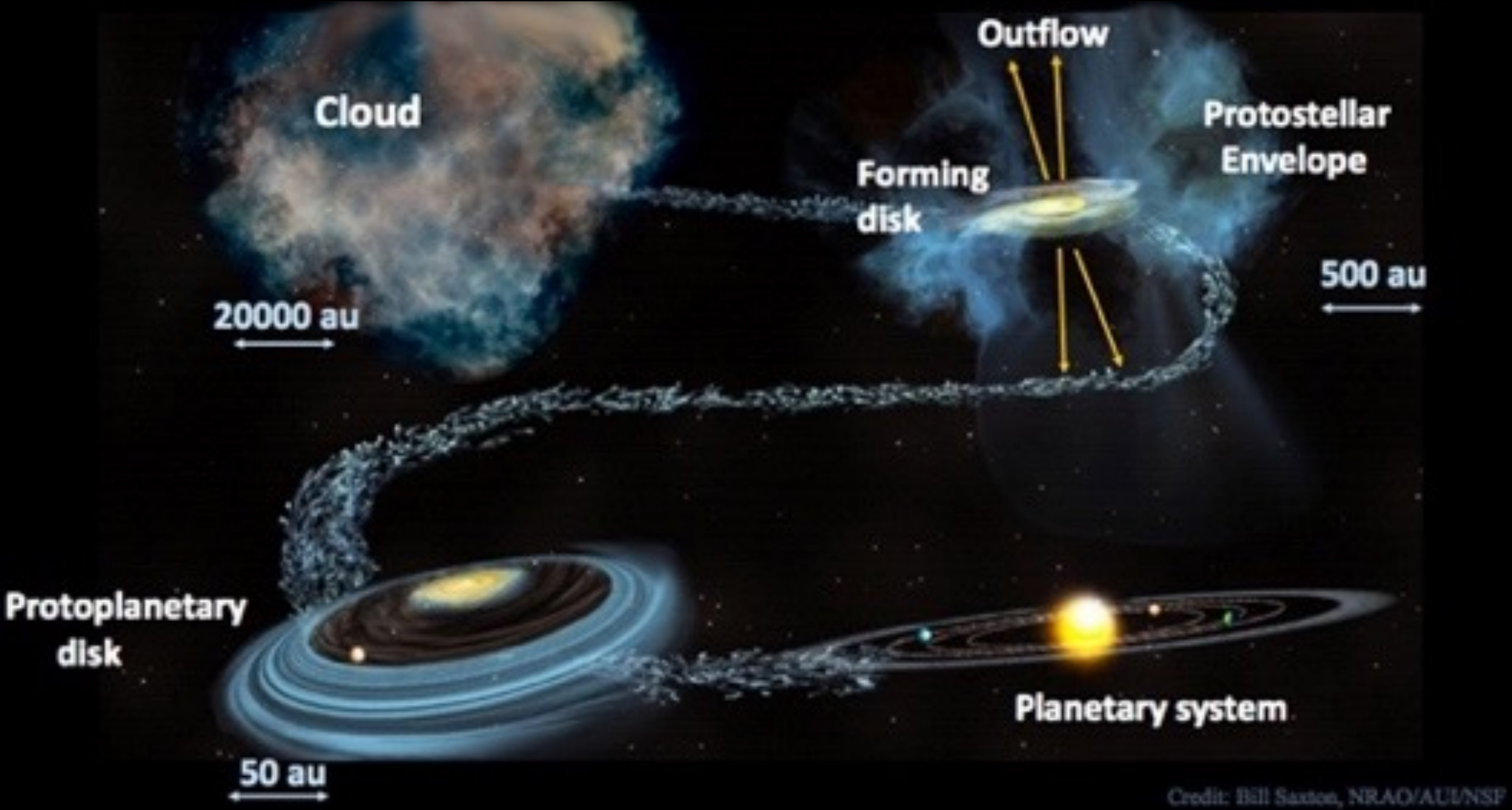


Moons of Saturn: Saturn had a disk

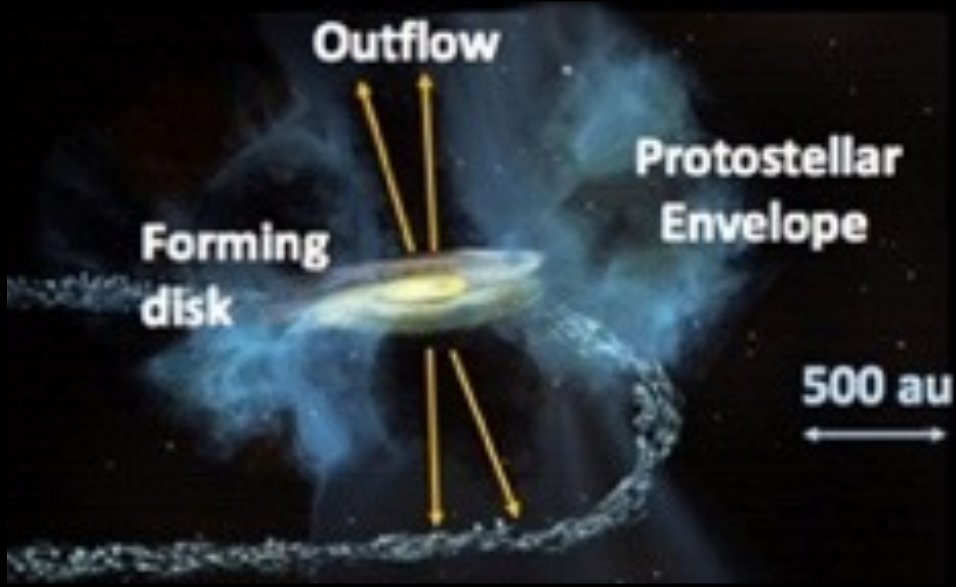




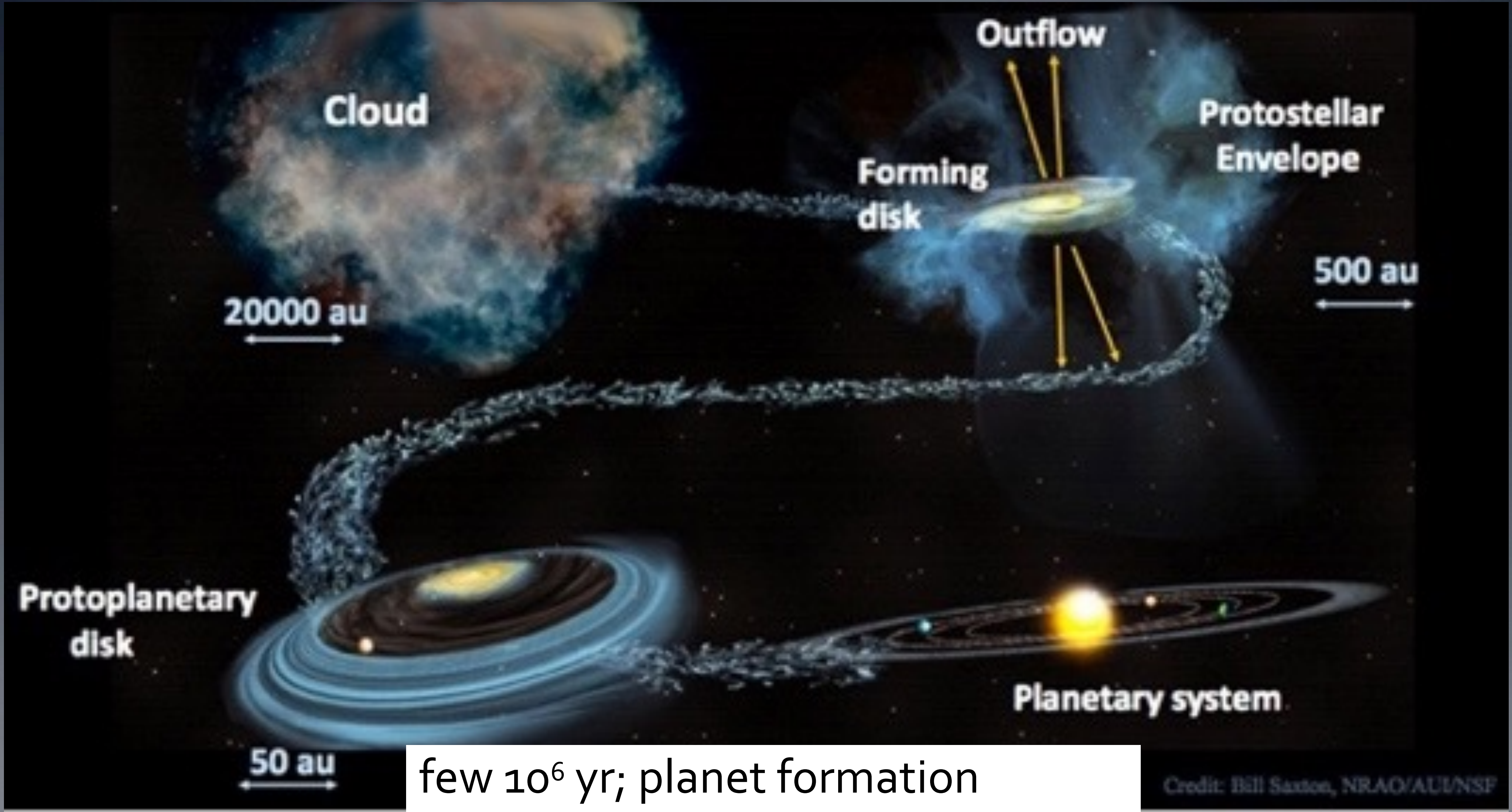
Evolution from clouds to planetary systems



JWST image of protostar L1527

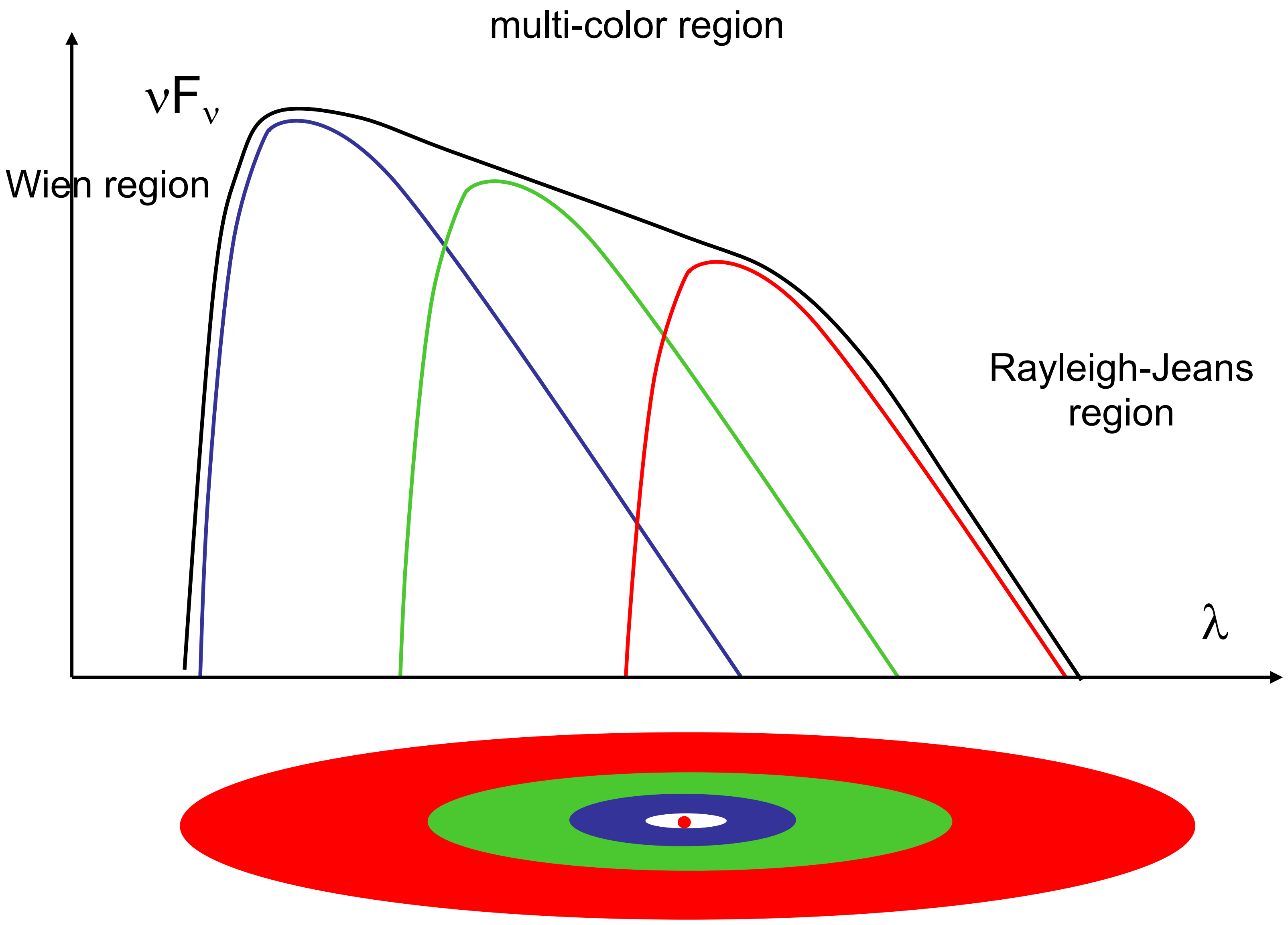


Evolution from clouds to planetary systems



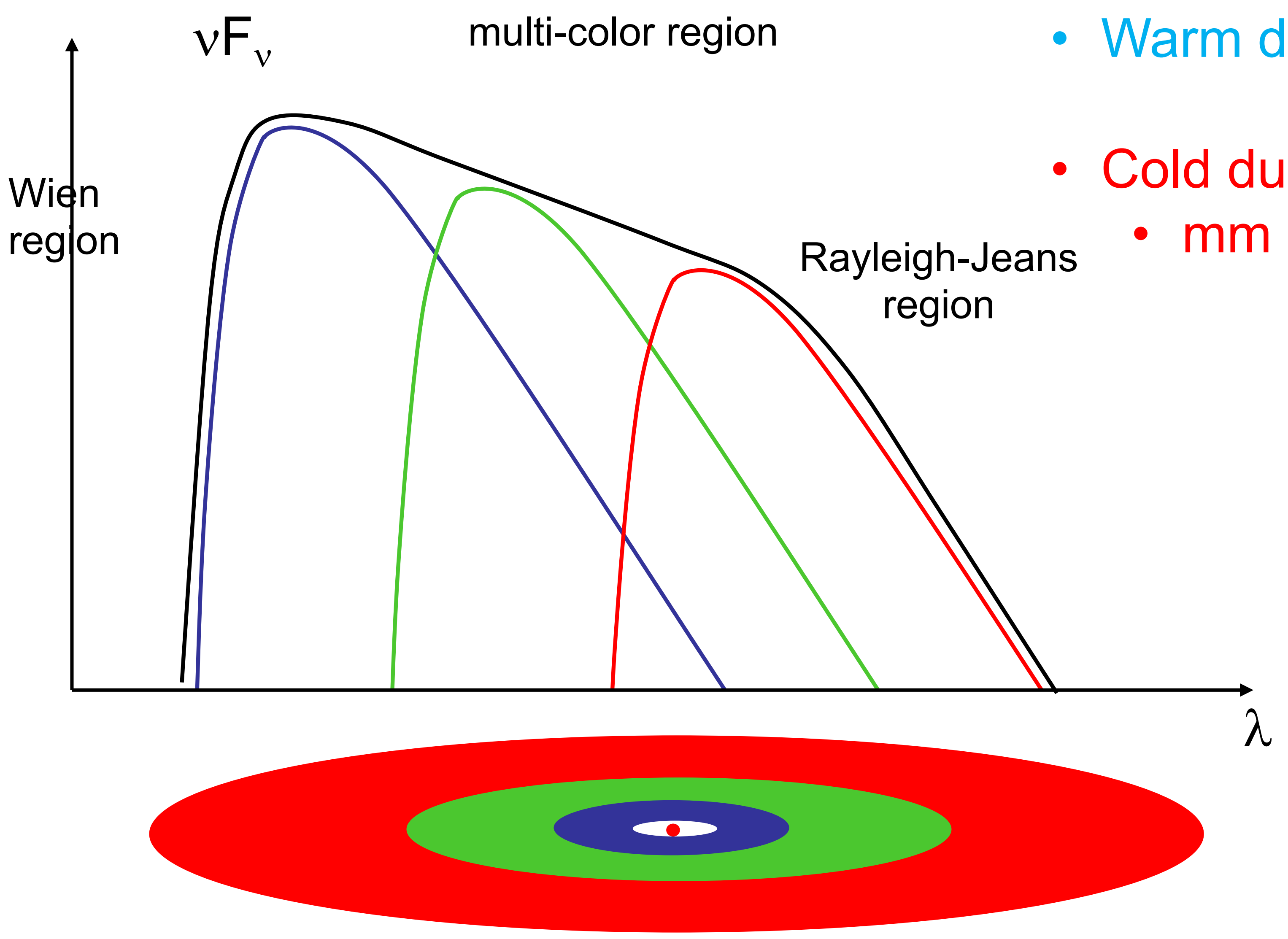
few 10^6 yr; planet formation

Multi-color blackbody disk emission



Slide from C. Dullemond

Multi-color blackbody disk emission

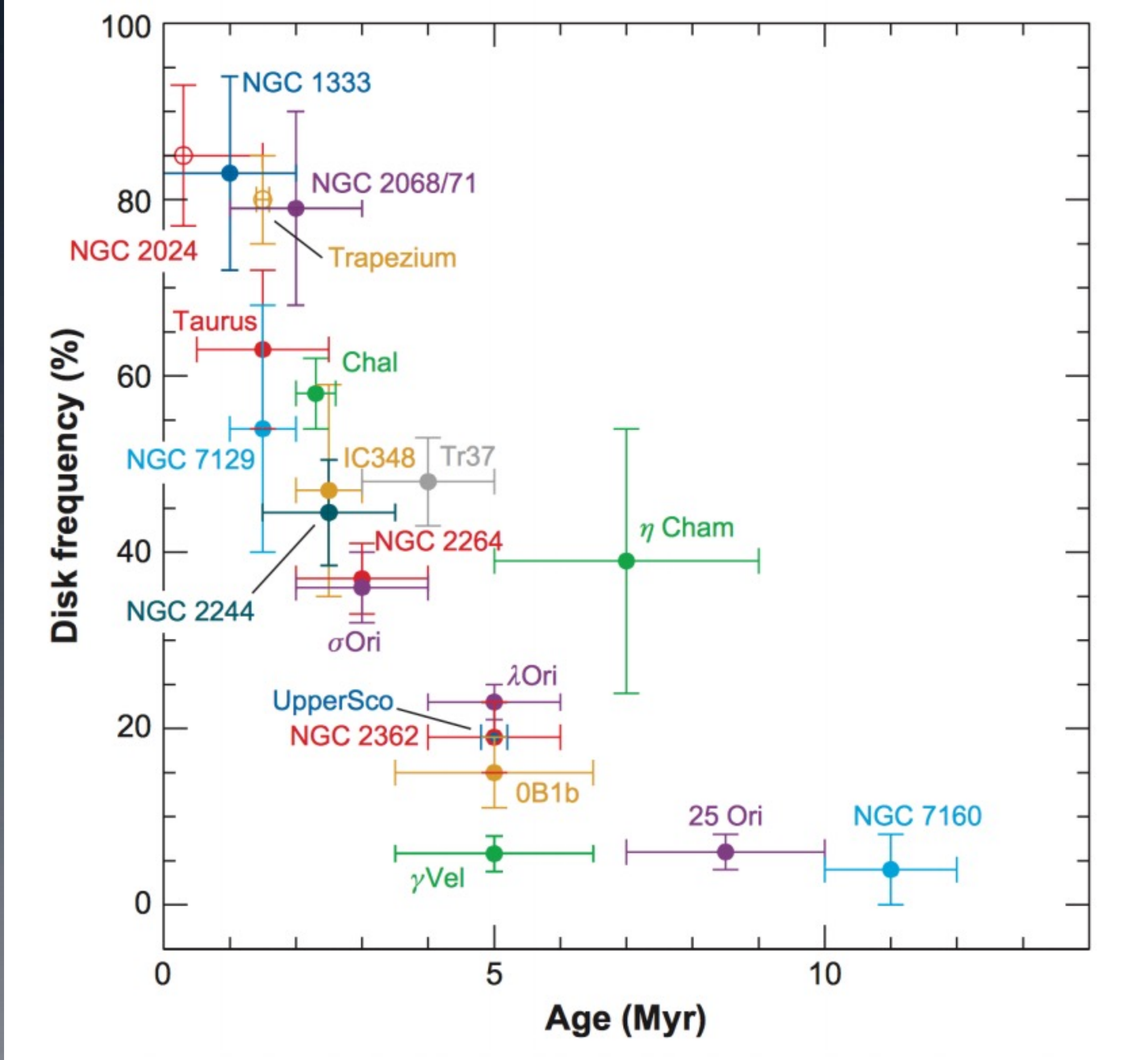


- Warm dust: emits at short wavelength
- Cold dust: emits at long wavelengths
  - mm observations

Disk lifetime:

Find members of a region of forming stars

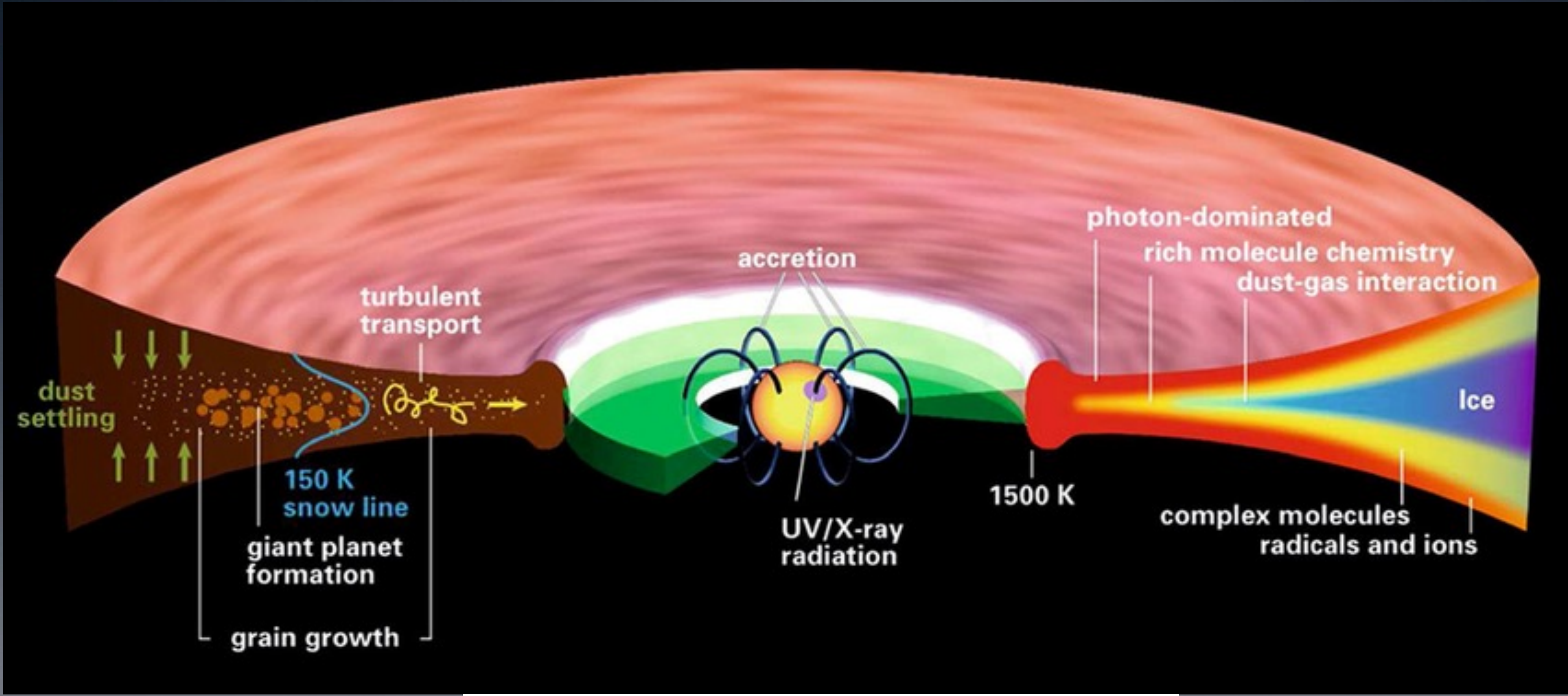
Measure how many have disks



Disk lifetime:

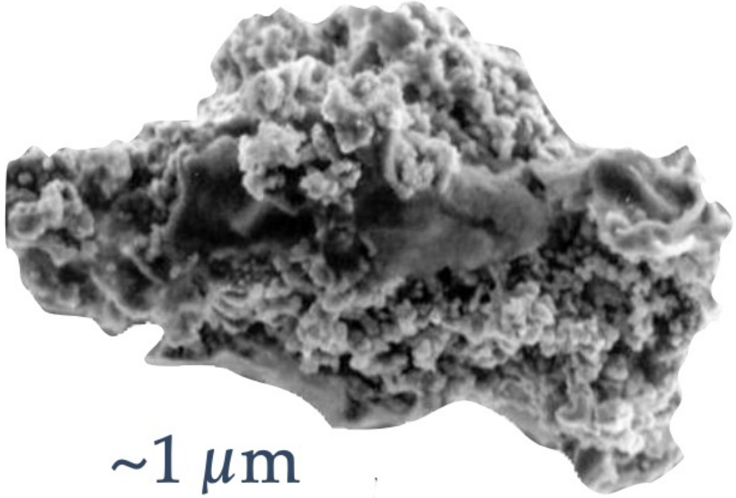
fraction of members of a cluster with disks versus cluster age

Typical disk lifetime: 3 Myr with a lot of scatter



Henning & Semenov (2013)

from



~1 μm

in

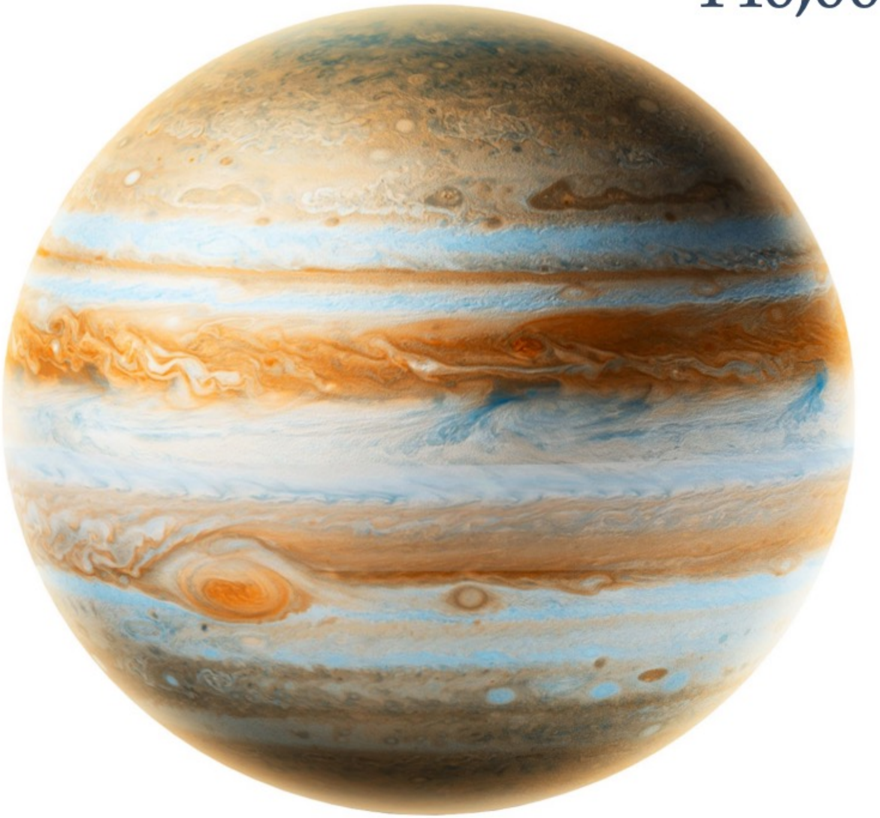
~30,000,000,000 km (~100 AU)

to

~13,000 km

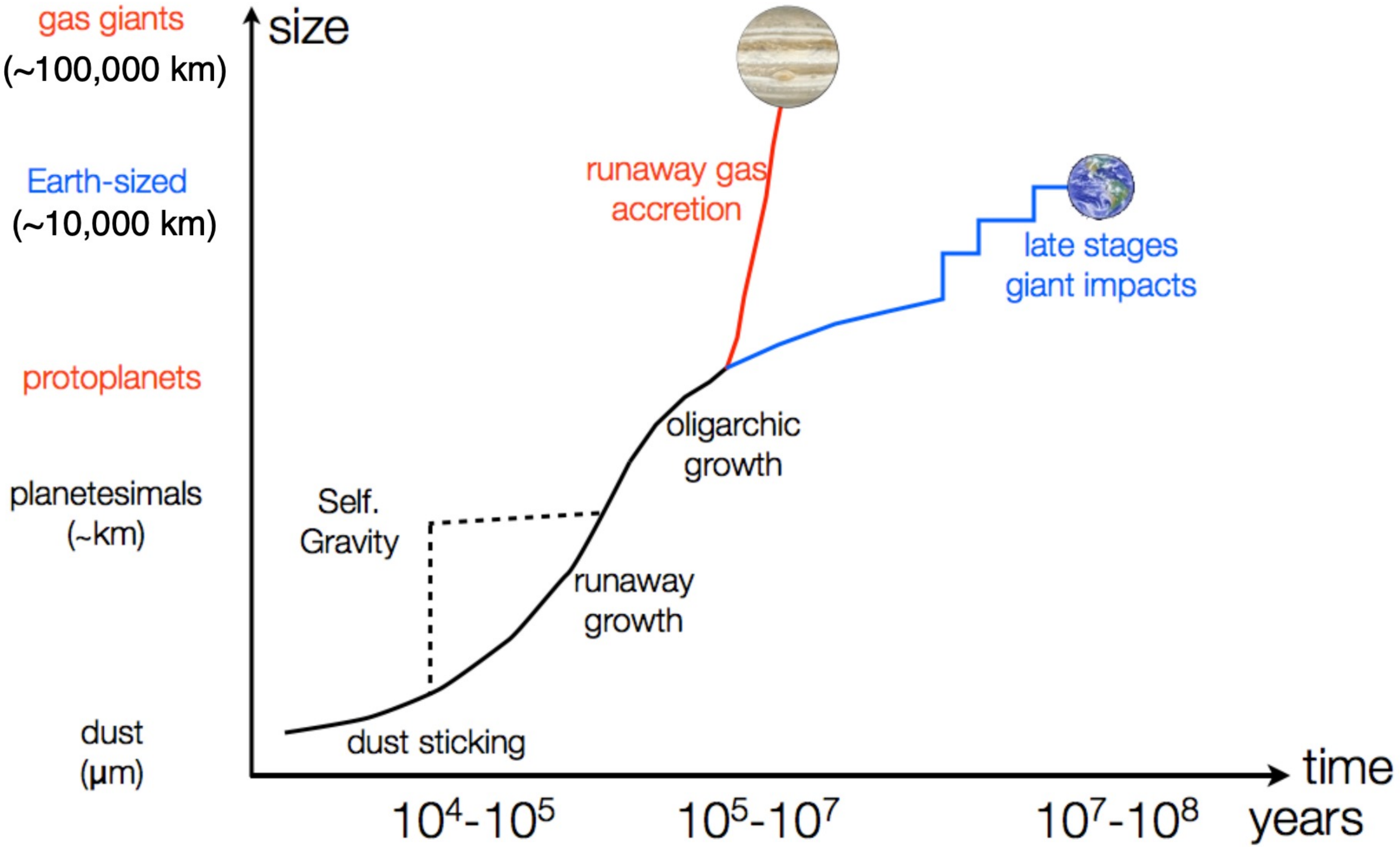
or

~140,000 km

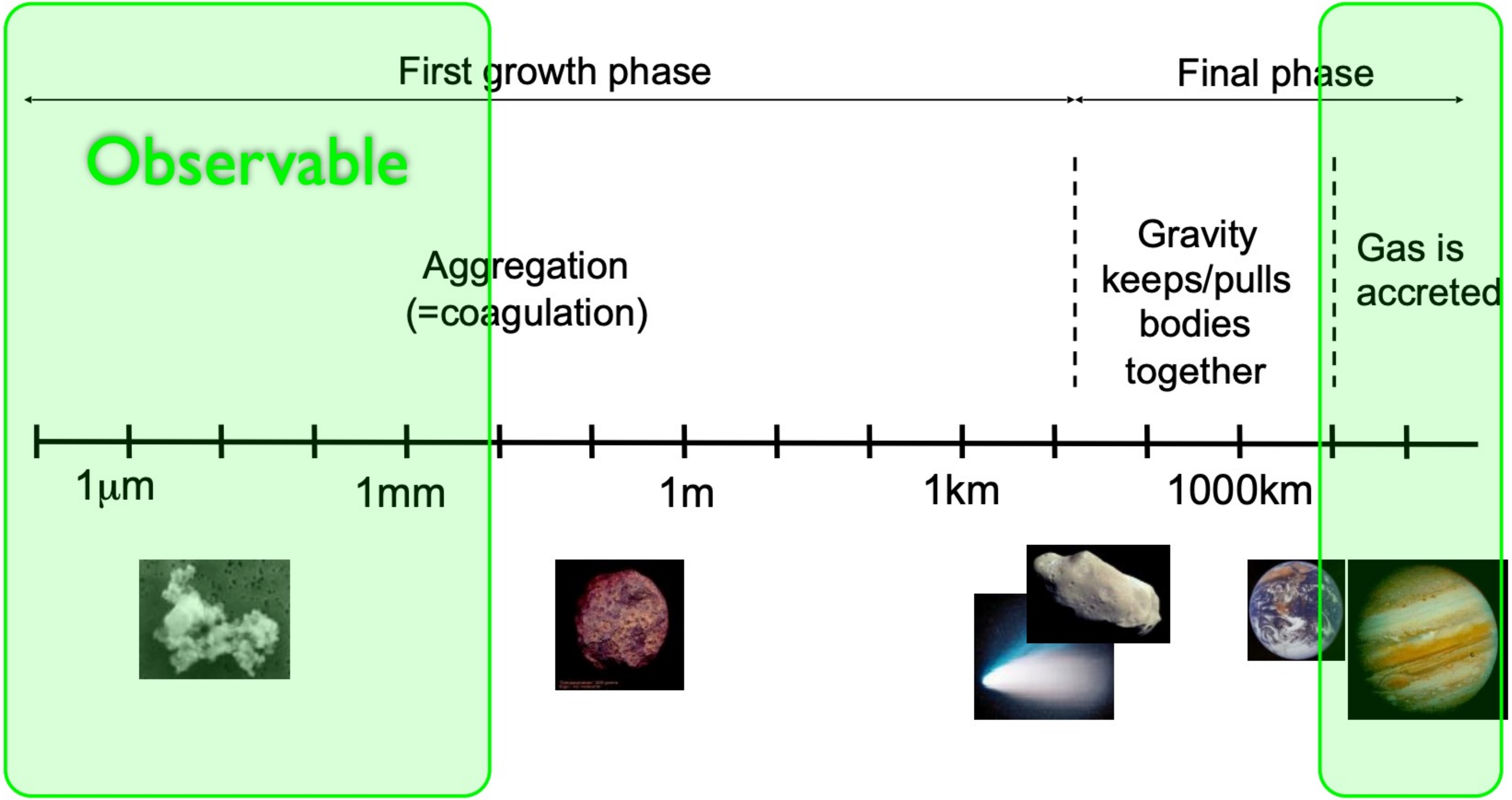


Formation of gas giants

(if sufficient gas is present)



The long road from dust to planets



Basic disk physics: gas and dust

- Gas and dust flow through the disk (radially and vertically)
- Physics of instabilities
  - Positive feedback: a small change (epsilon) continues to grow => instability!
  - Negative feedback: a small change is balanced out and does not grow => stable
- Complicated combination of microphysics and chemistry

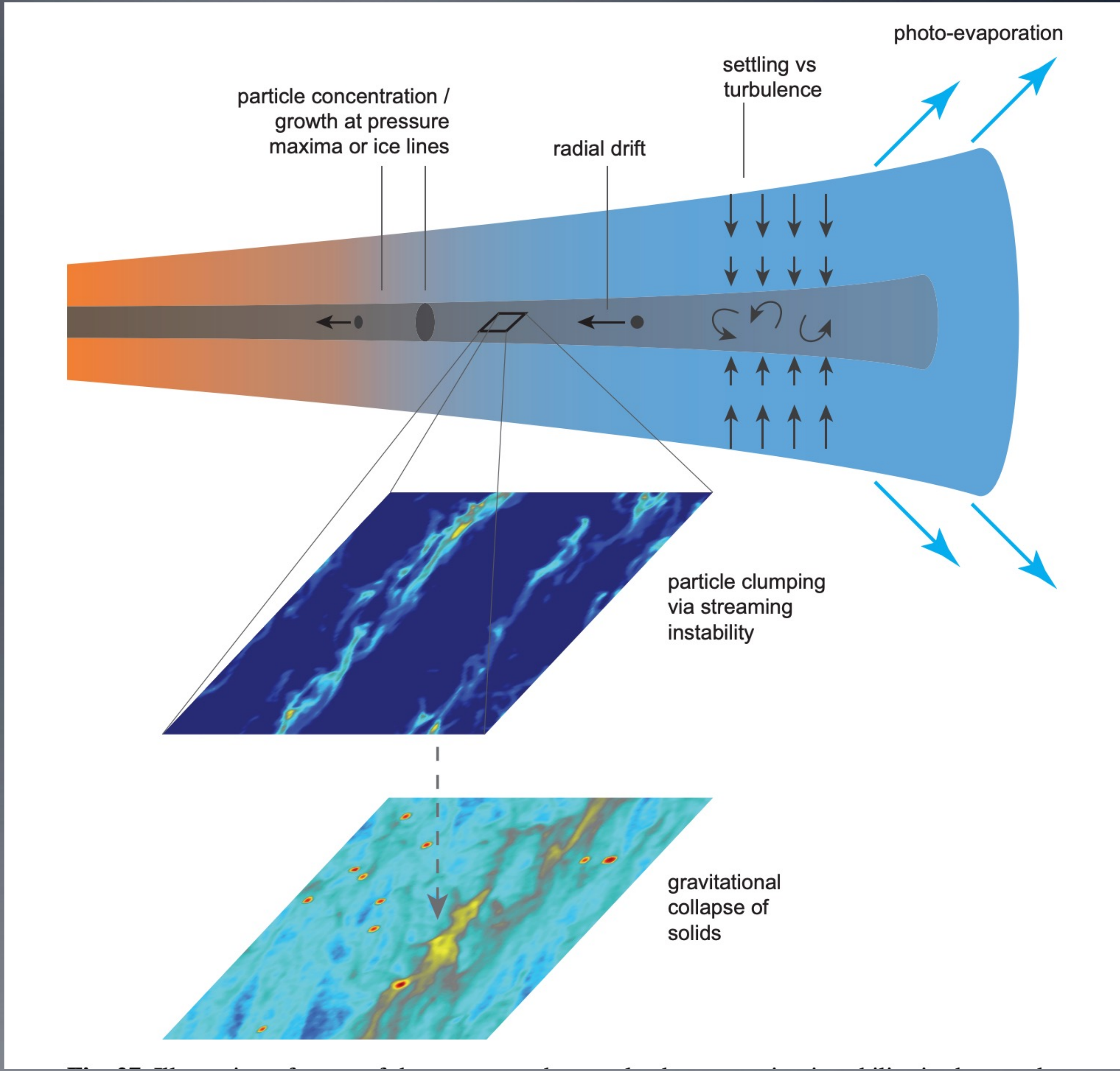
Dust drift

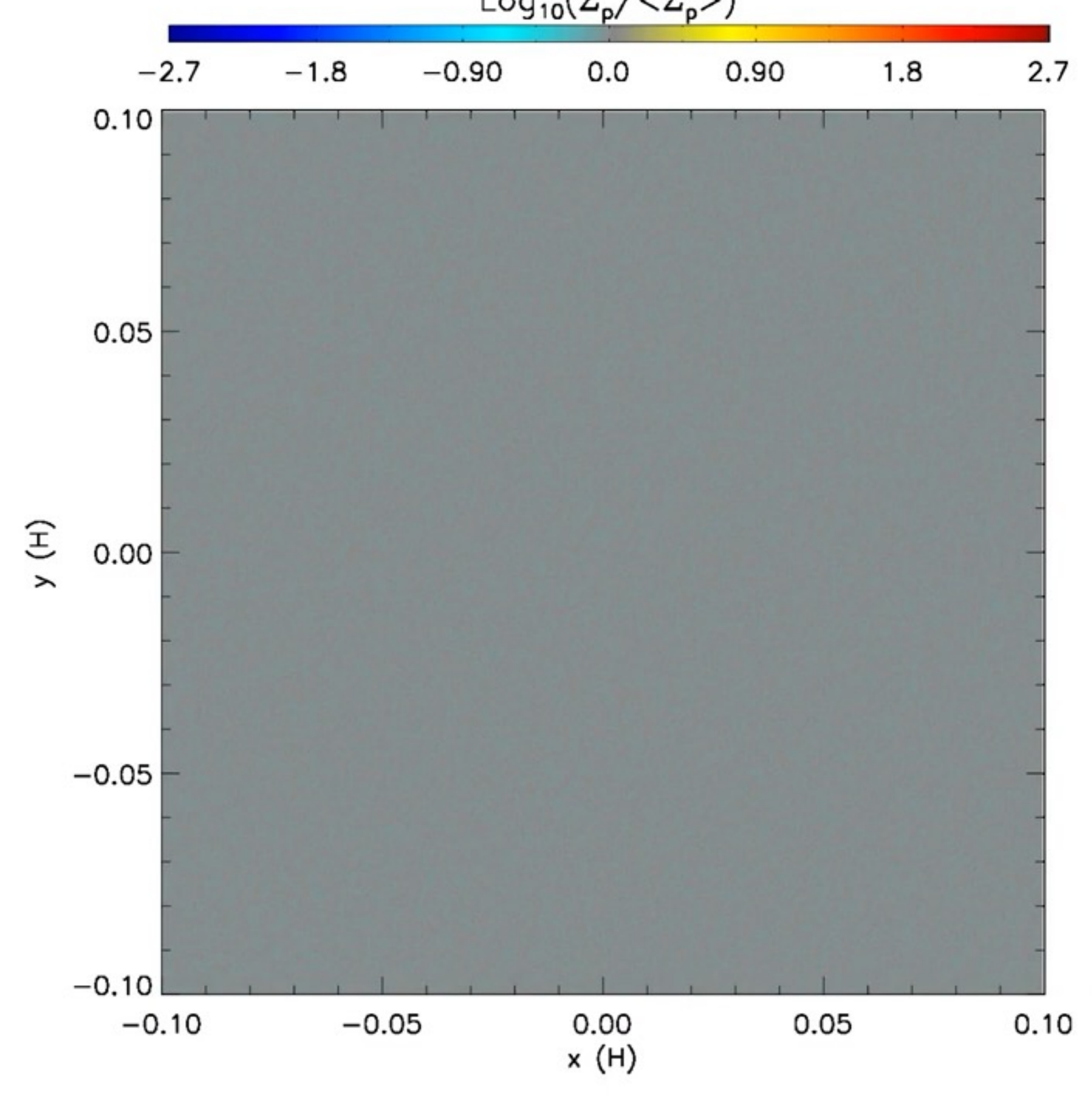
- Disks are Keplerian rotators
- Gas pressure: gas is sub-Keplerian
- Dust feels headwind, drifts inward (to pressure maxima)
  - Loses velocity => lower angular momentum => moves inward
- Timescales short: how do disks survive?

Disk simulations and planet formation

- Planet cores initially form by the **streaming instability**
  - Interaction between dust and gas leads to increase in density, gravitational collapse to form a core

- Planets continue to gain mass by pebble accretion
  - Dust grains slow and drift to planet core when they pass nearby

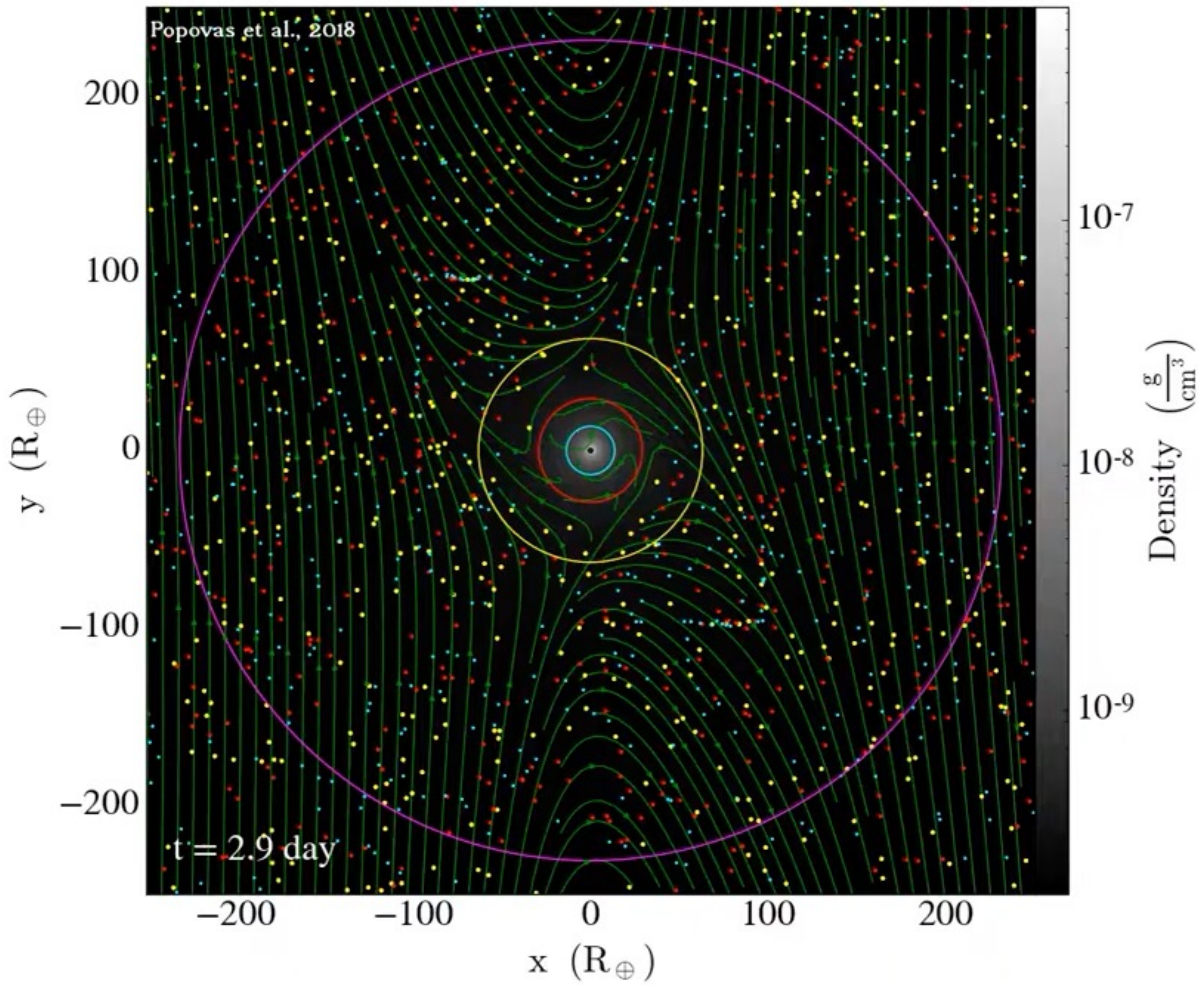




Streaming Instability

Instability that leads to growth of large rocky/metallic cores

Collects dust to increase density enough to gravitationally collapse

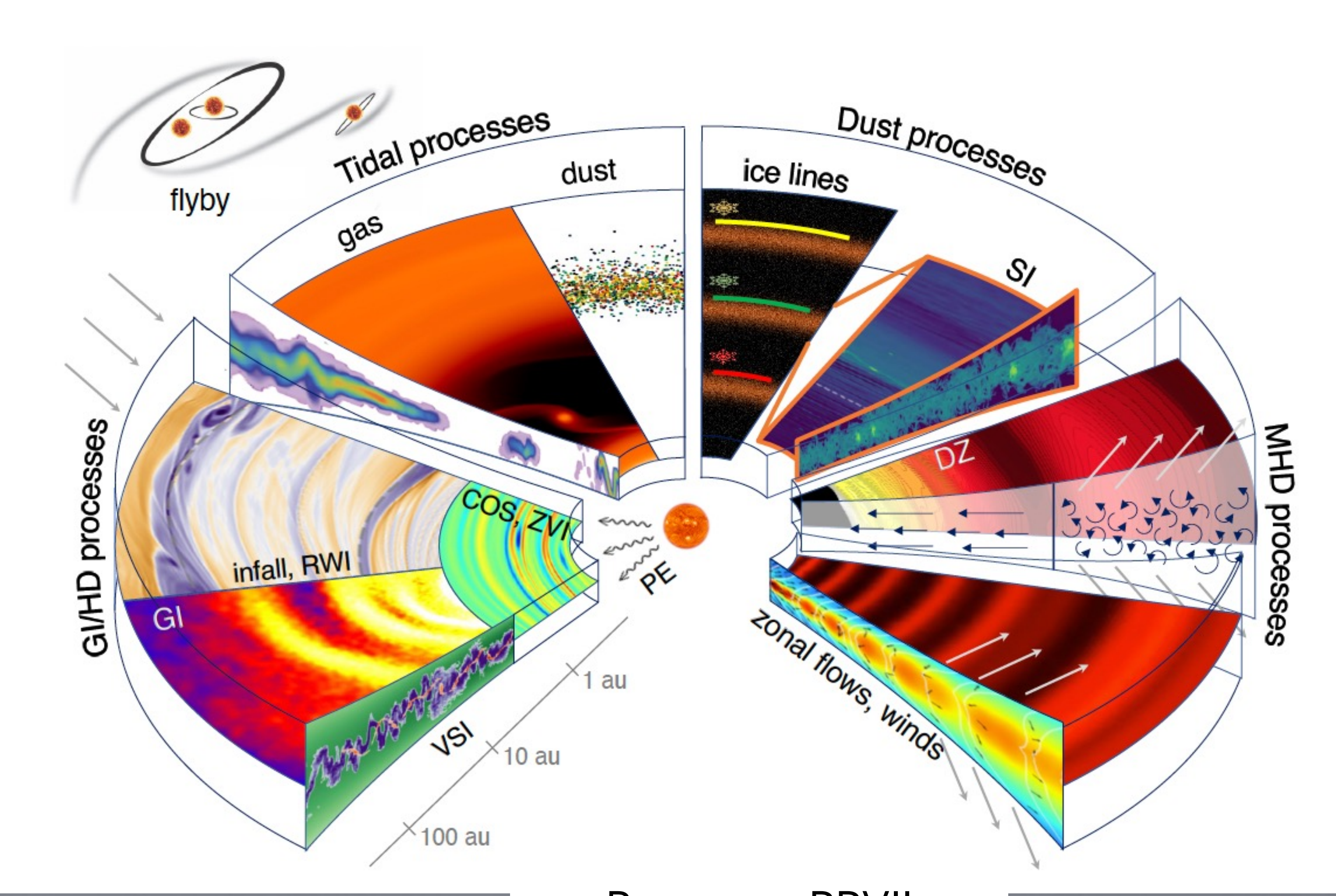


Pebble Accretion

- Secondary growth
- Core attracts over a gravitational radius
- Friction increases the radius

Problem: most microphysics not observable

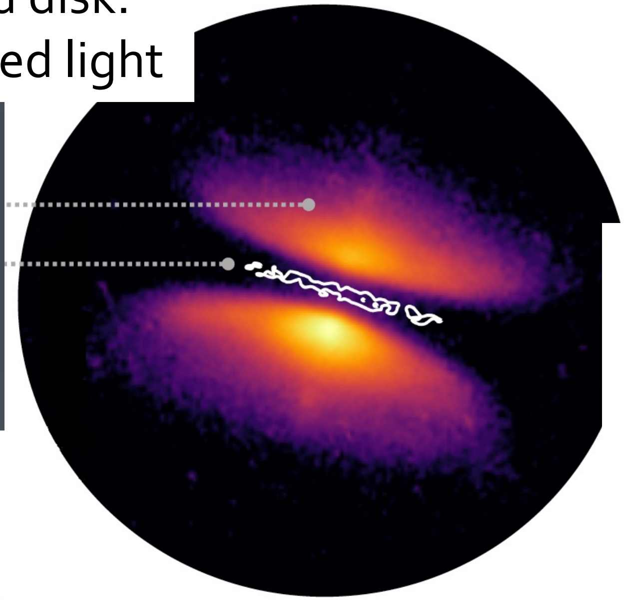
- Non-ideal MHD physics occurs on small scales
  - Magnetic fields, turbulence: usually not detectable
- Grain growth is for labs/computers
  - Observationally parameterized with a single number
- Optical depth: often see surfaces and not inside
- Chemistry: always uncertain



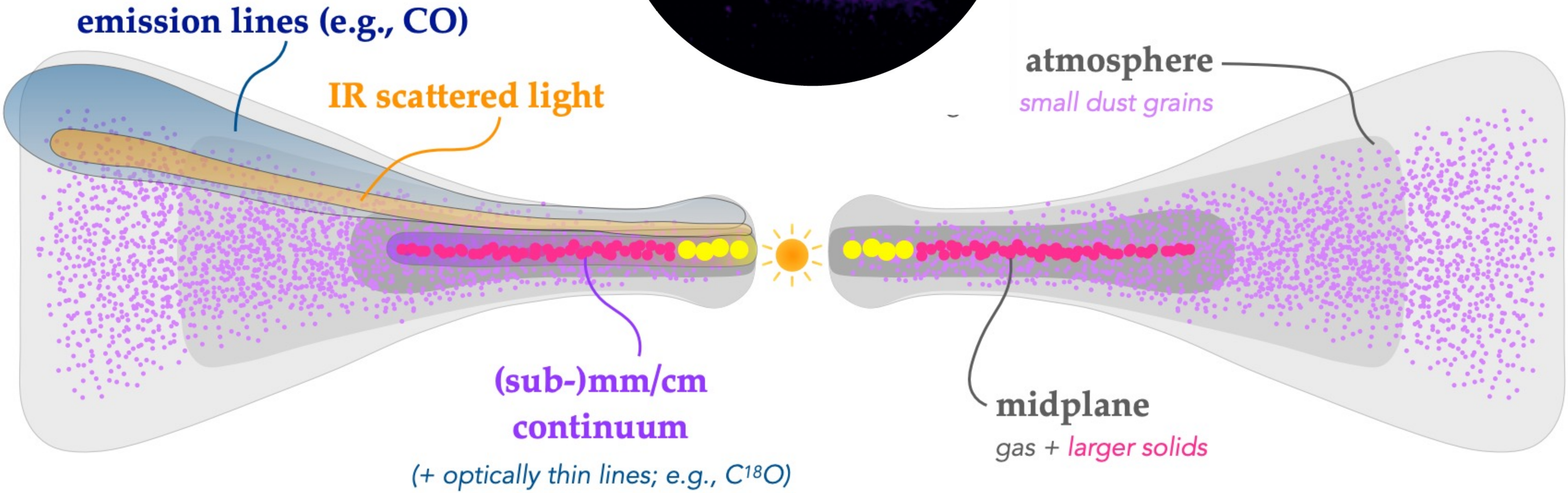
Bae+2022 PPVII

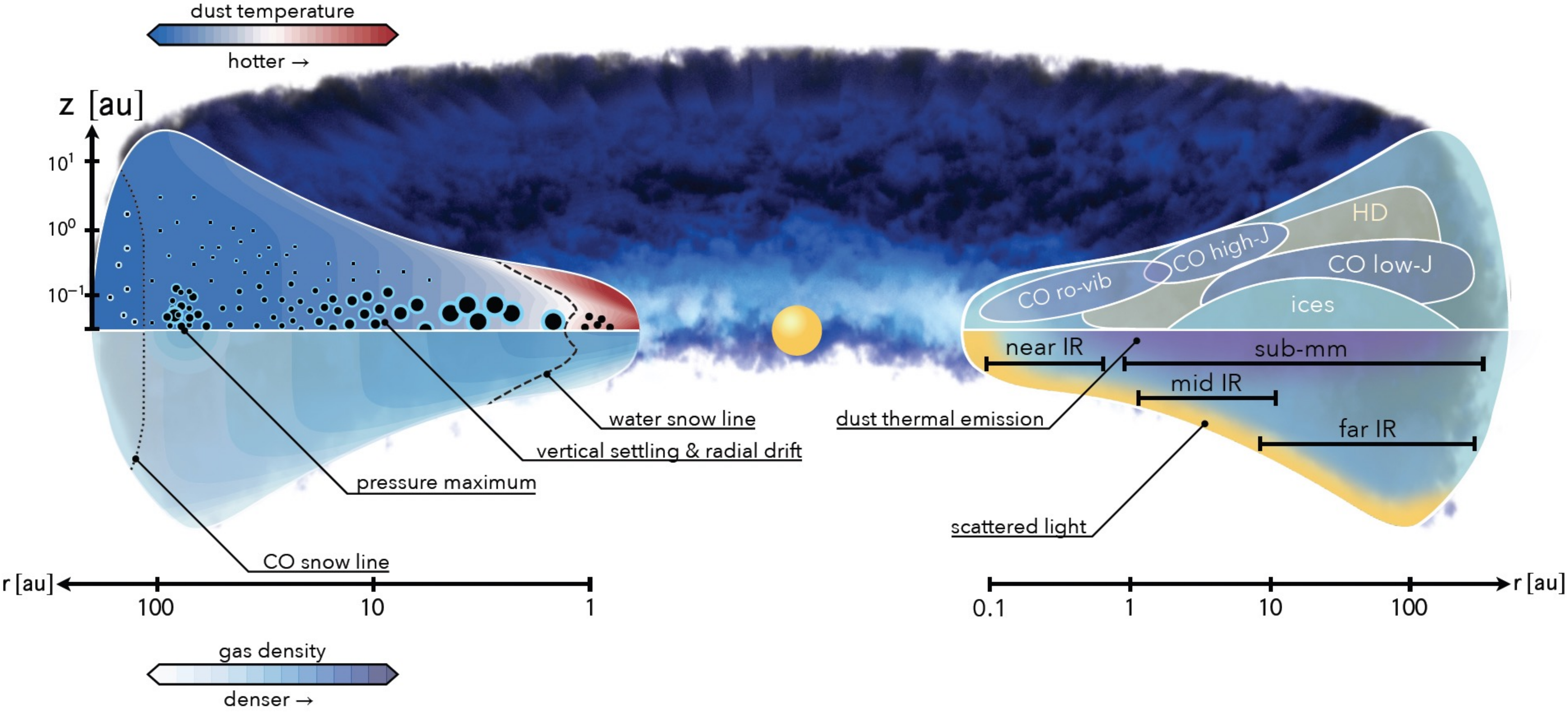
Flared disk:
scattered light

Bae+2022
PP VII review



mm dust emission:
mm sized grains settled to midplane, cold

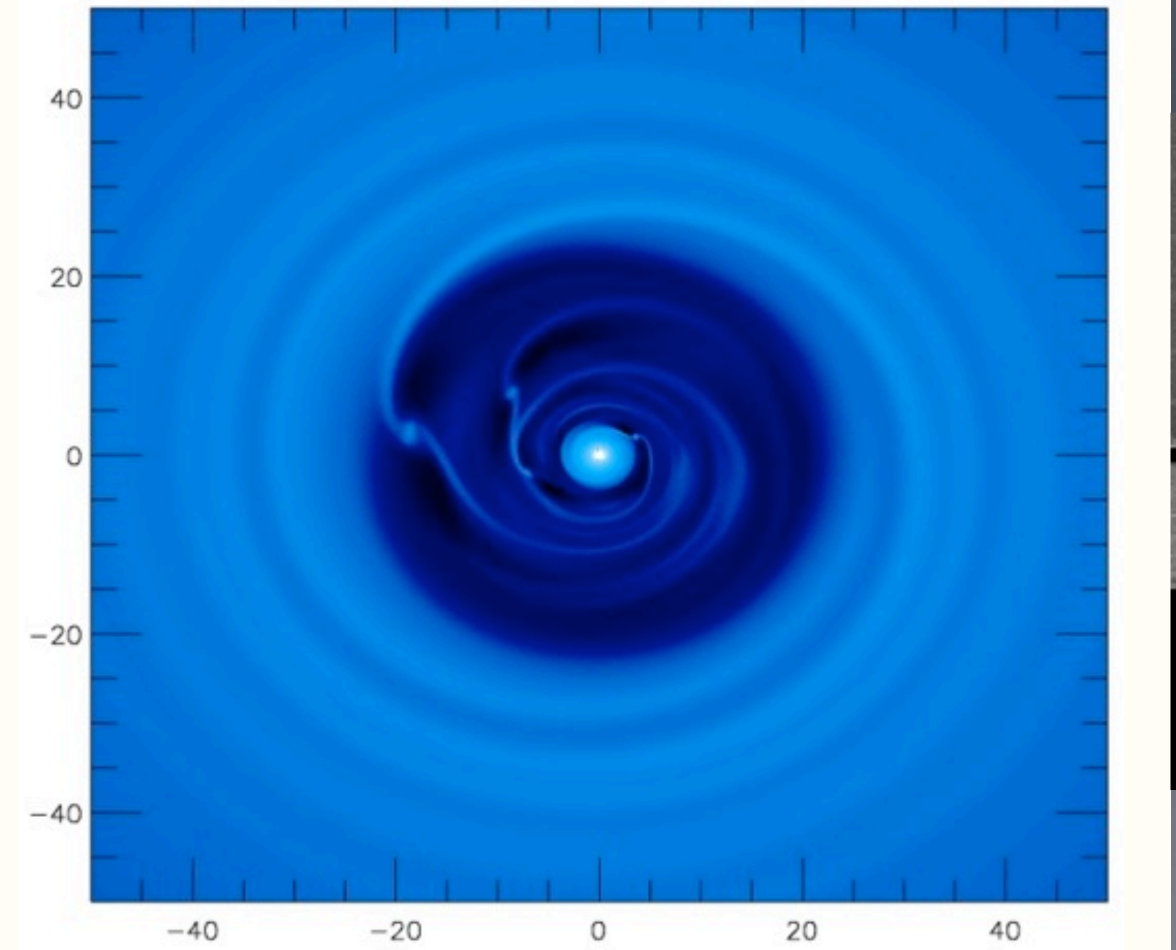


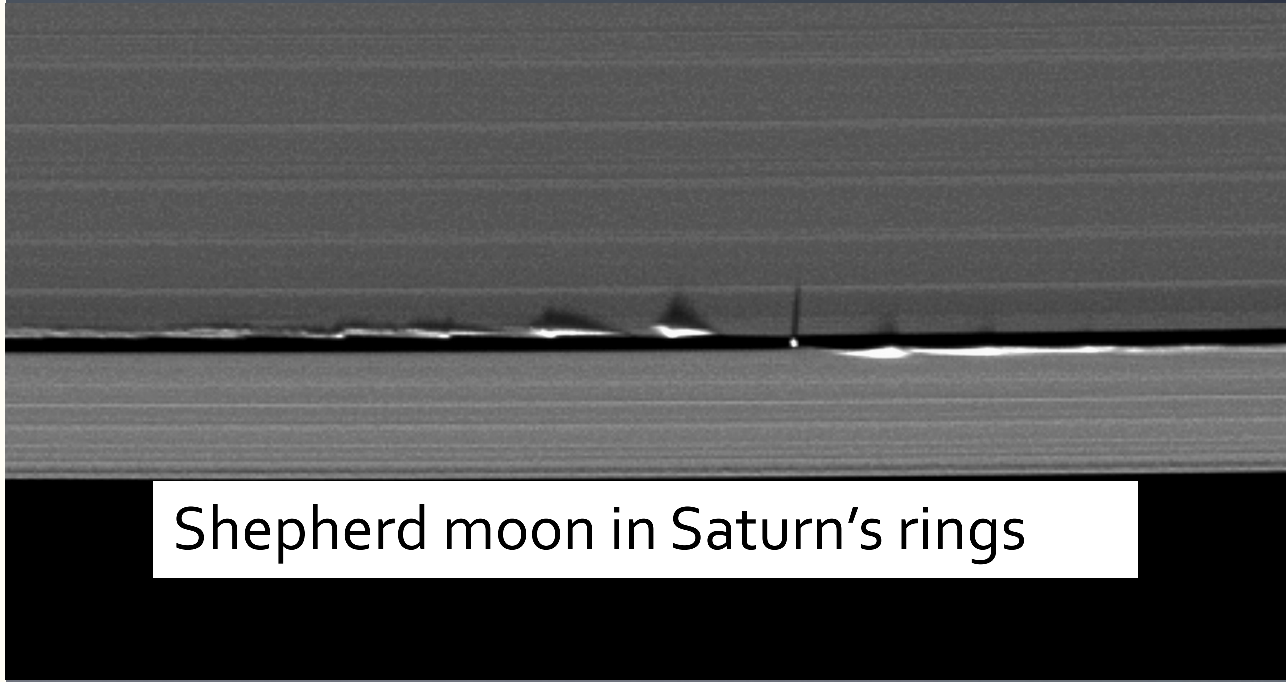


dust temperature
hotter →
z [au]
10^1
10^0
10^-1
HD
CO high-J
CO low-J
CO ro-vib
ices
near IR
sub-mm
mid IR
far IR
water snow line
dust thermal emission
vertical settling & radial drift
pressure maximum
scattered light
CO snow line
r [au]
100
10
1
0.1
1
10
100
r [au]
gas density
denser →

How would a forming planet affect a disk?

(e.g., Zhu+2011)





Shepherd moon in Saturn's rings

Gaps in disks: first proposed by Lin & Papaloizou 1986

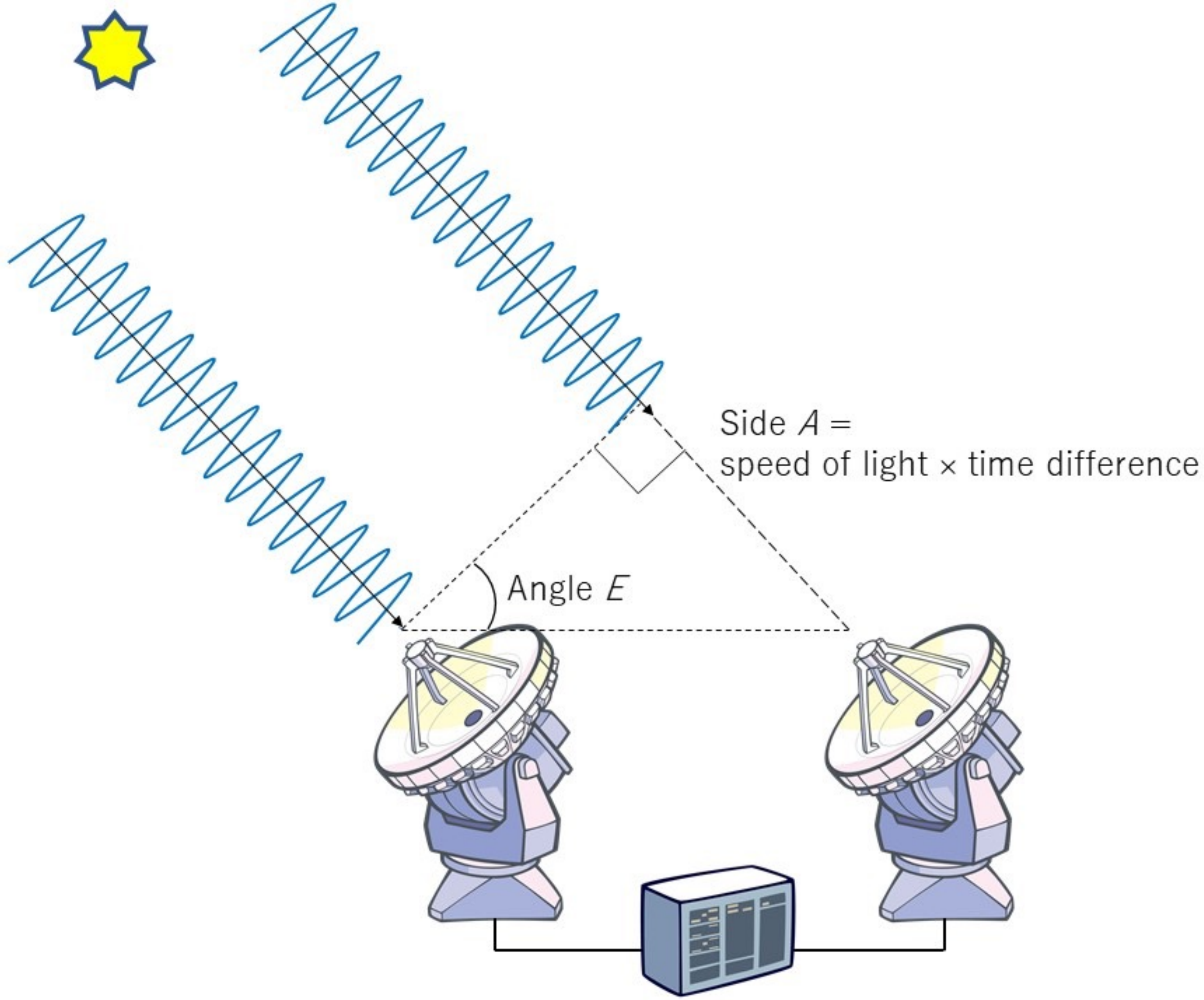
Atacama Large Millimeter Array (ALMA)

Sub-mm **interferometer**, 5000m high plateau in Chile

Interferometer

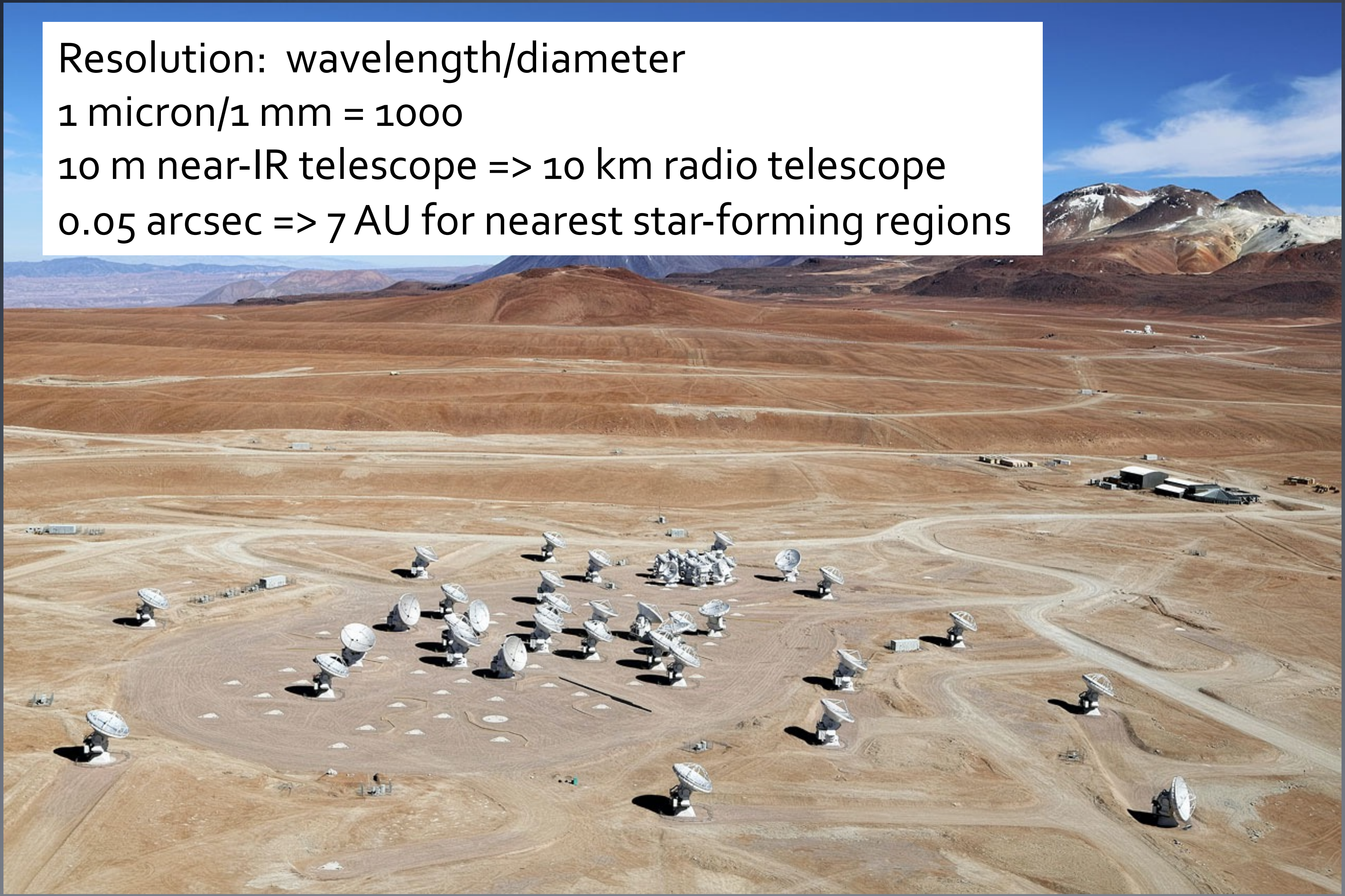
Combine light from different telescopes

Spatial resolution: corresponds to distance between telescopes



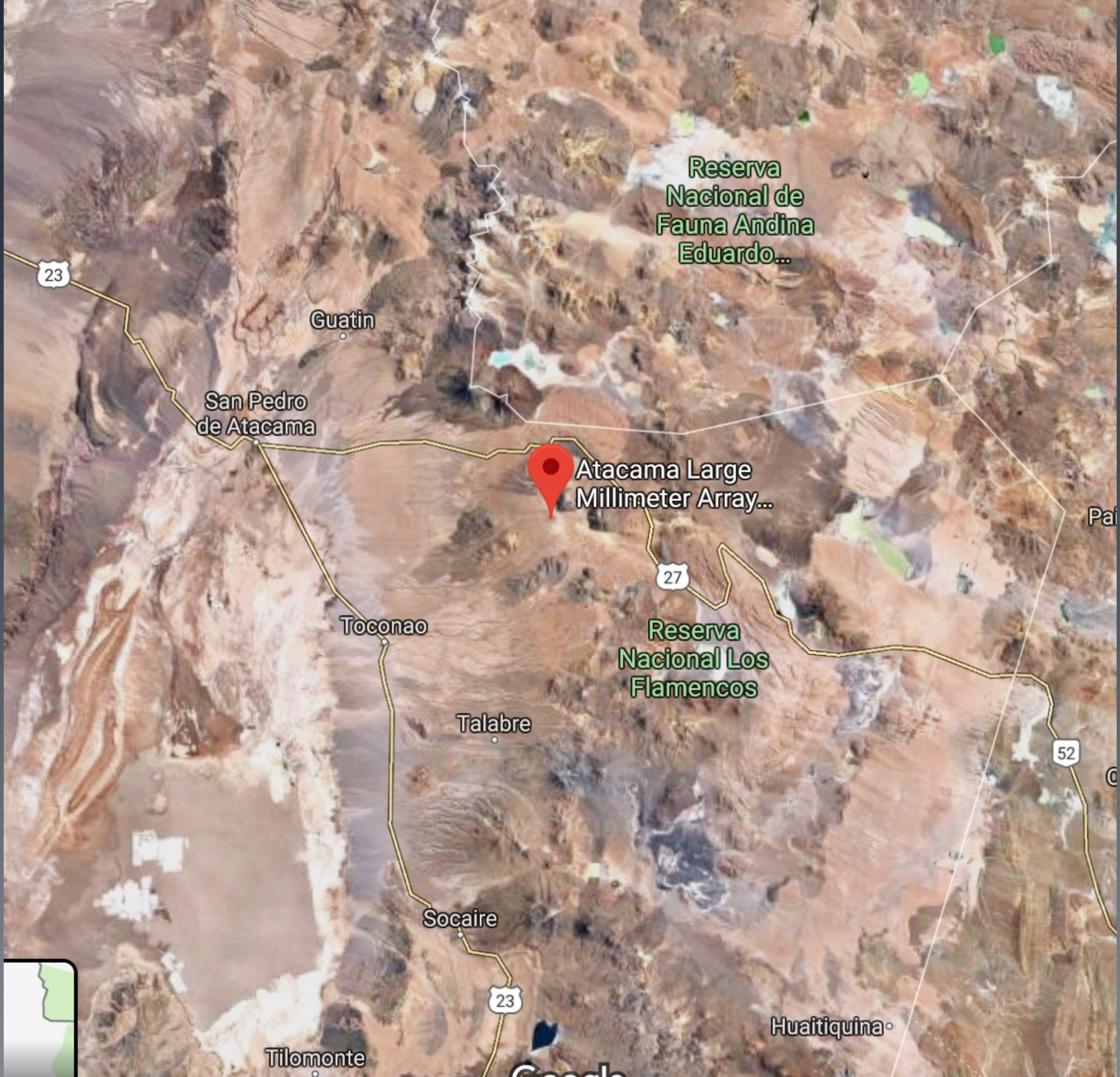
Atacama Large Millimeter Array (ALMA)

Resolution: wavelength/diameter
1 micron/1 mm = 1000
10 m near-IR telescope => 10 km radio telescope
0.05 arcsec => 7 AU for nearest star-forming regions

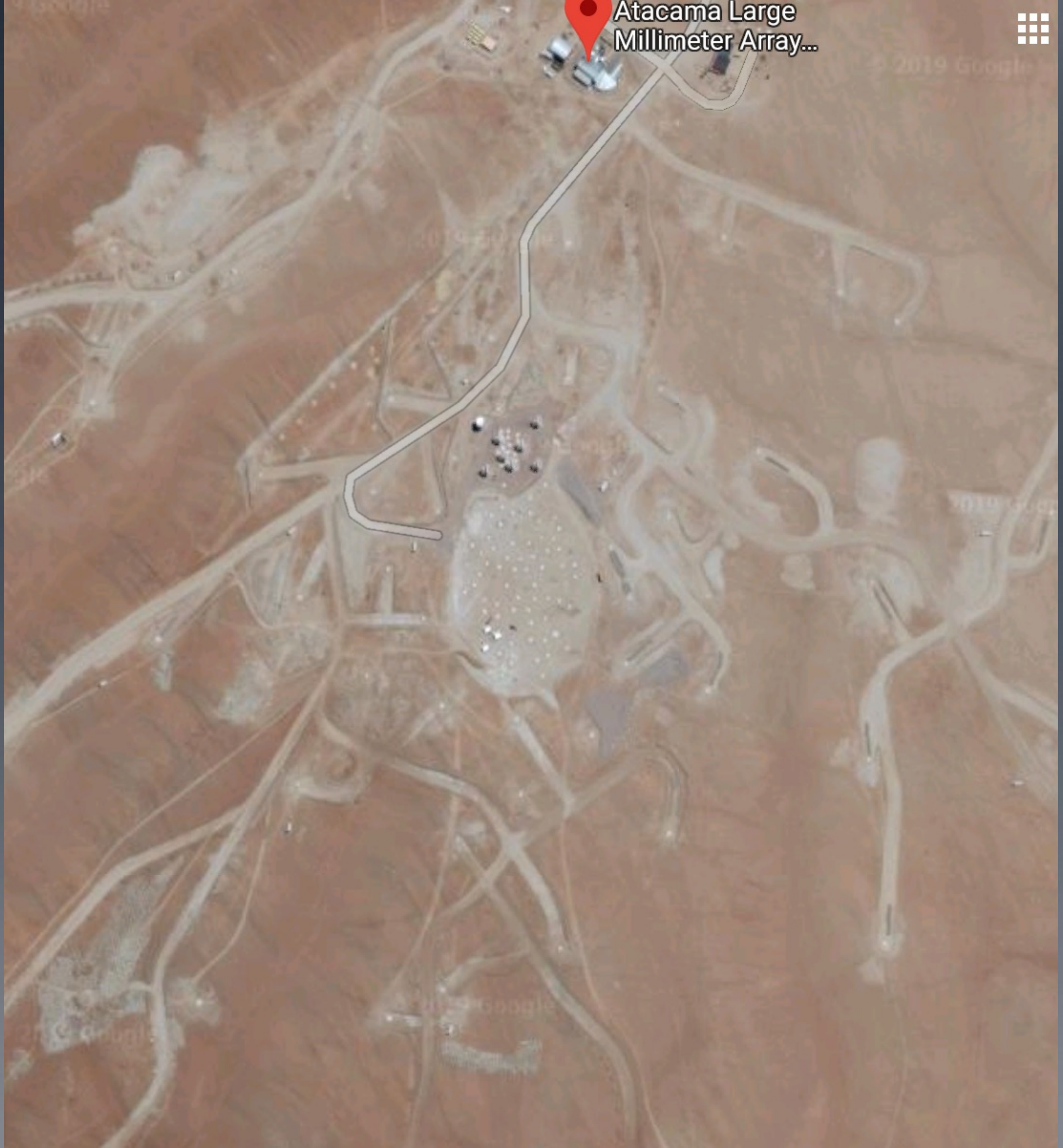


Sub-mm **interferometer**, 5000m high plateau in Chile

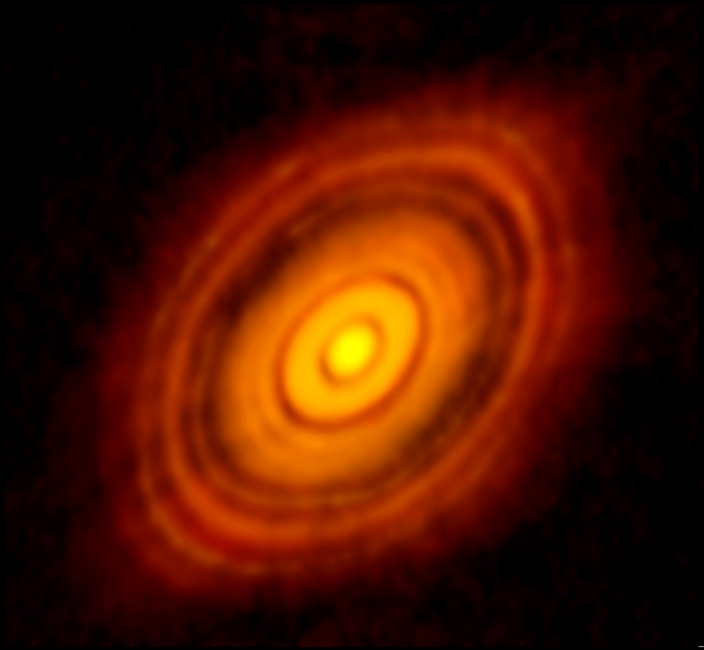

Cali
Colombia
Quito
Ecuador
Guyana
French
Guiana
STATE OF
RORAIMA
STATE OF
AMAPÁ
STATE OF
AMAZONAS
STATE OF ACRE
STATE OF PARÁ
Peru
Lima District
Brazil
STATE OF
CEARÁ
STATE OF
RONDÔNIA
STATE OF
MATO
GROSSO
STATE OF
TOCANTINS
Bolivia
STATE OF
BAHIA
STATE OF
GOIÁS
Salvador
Atacama Large
Millimeter Array...
STATE OF
MINAS
GERAIS
Paraguay
Asunción
STATE OF
SÃO PAULO
Chile
STATE OF
SANTA
CATARINA
Córdoba
Santiago
Uruguay
Argentina
Montevideo

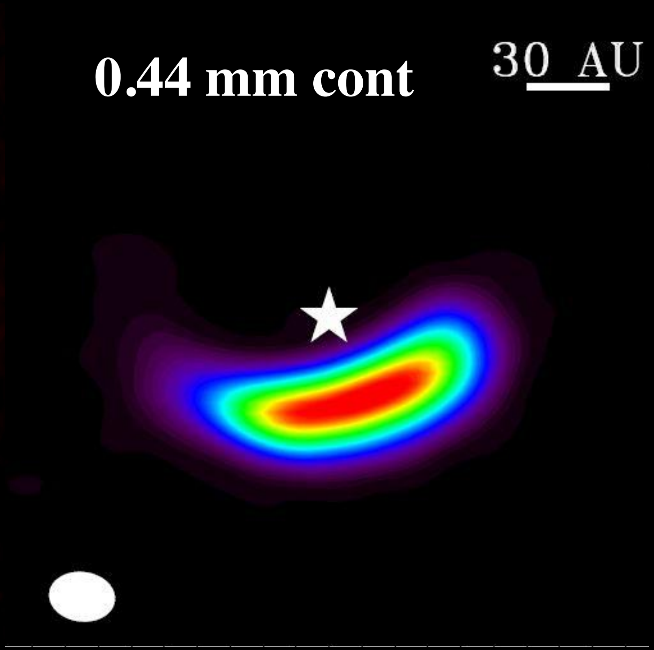

Reserva Nacional de Fauna Andina Eduardo...
23
Guatin
San Pedro de Atacama
Atacama Large Millimeter Array...
27
Toconao
Reserva Nacional Los Flamencos
Talabre
52
Socaire
23
Huaitiquina
Tilomonte

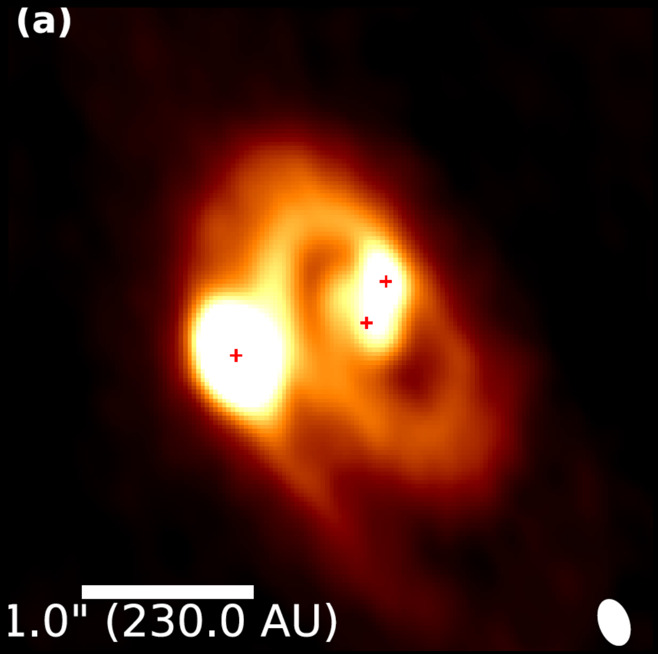

Complejo
de Puricó
Atacama Large
Millimeter Array...


Atacama Large
Millimeter Array...
© 2019 Google

The ALMA revolution:
Dust structures in protoplanetary disks

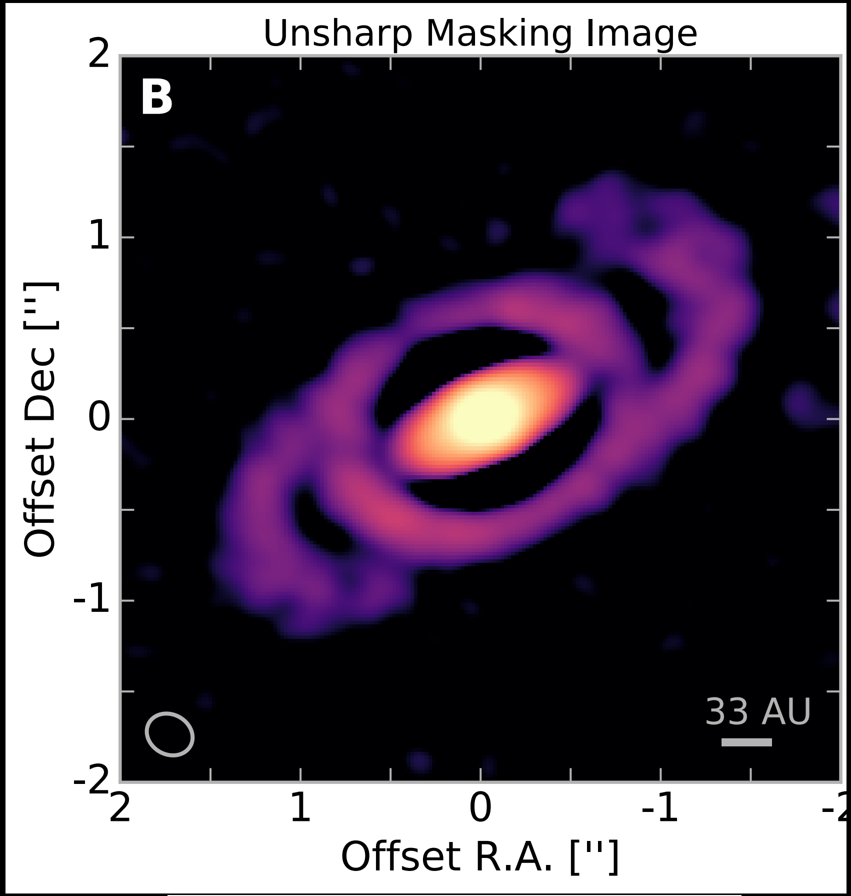




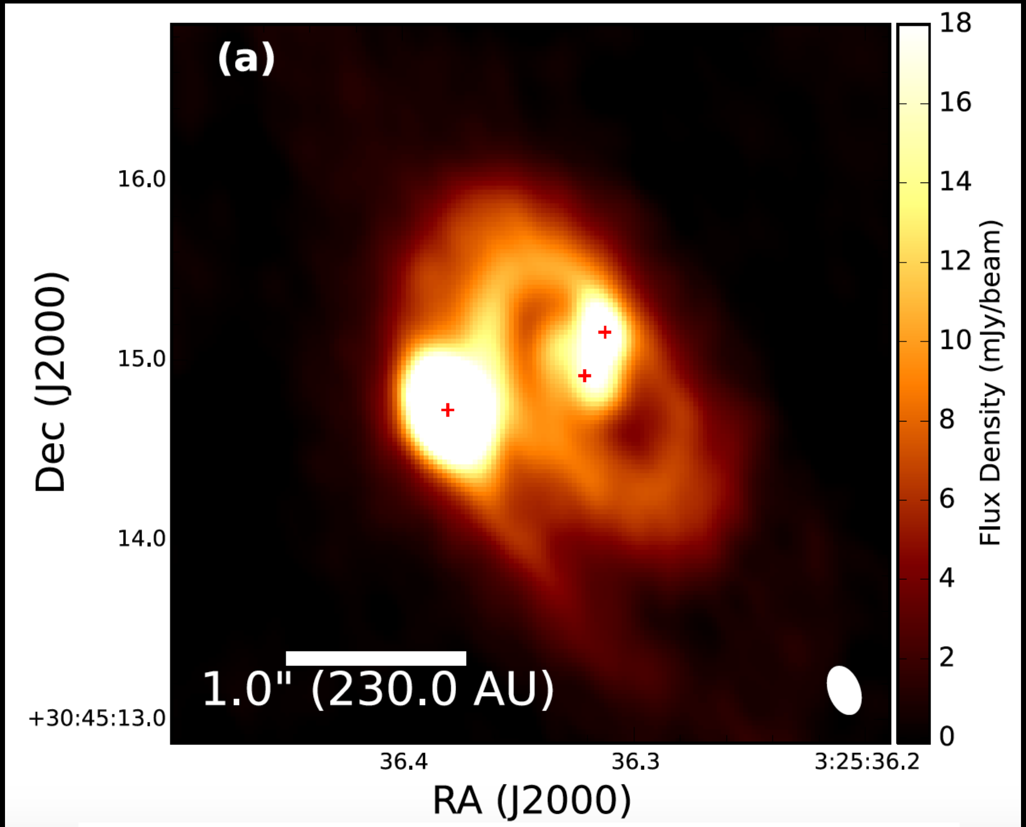


Signs of planets?

Spirals in young protoplanetary disks



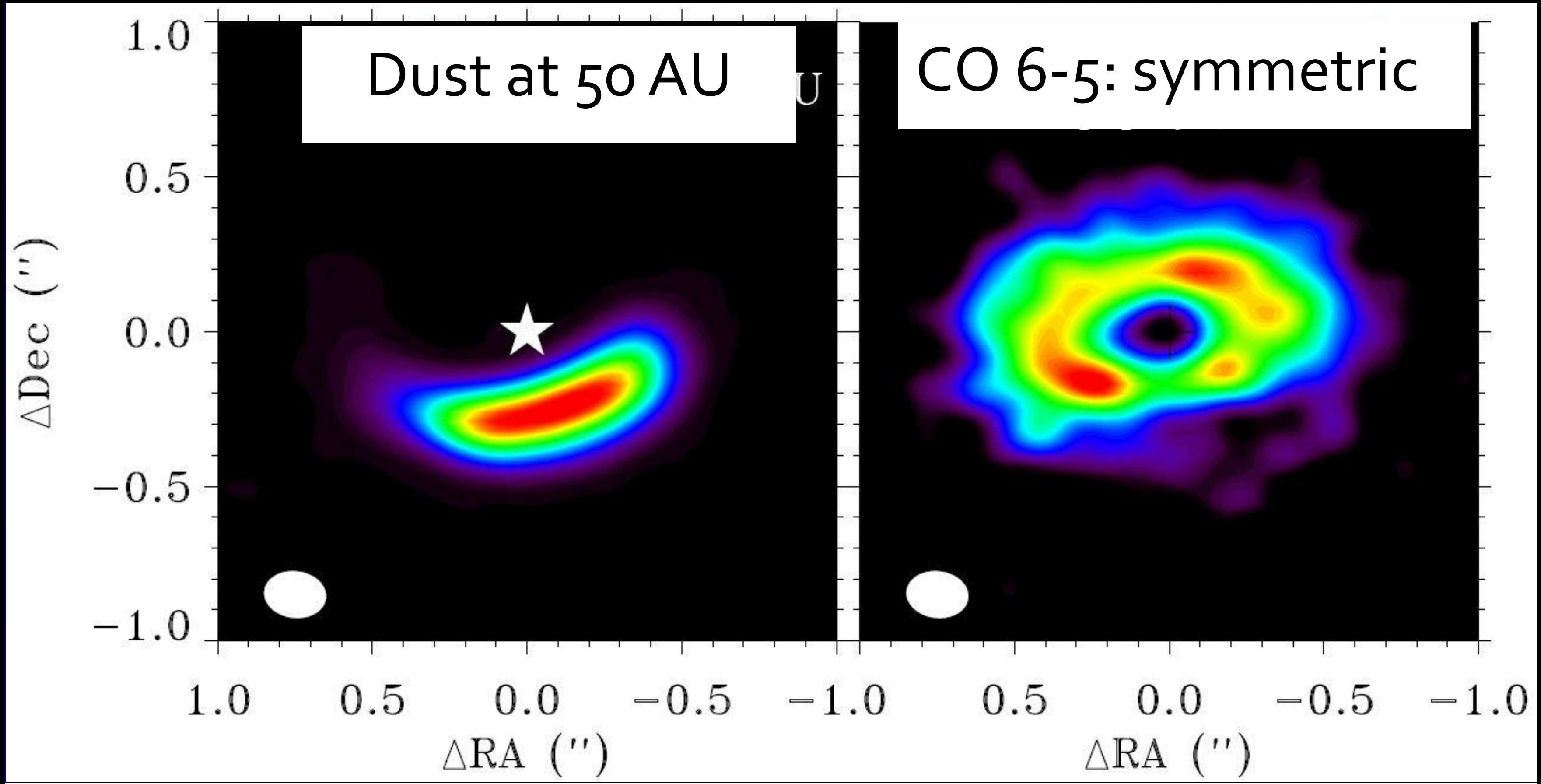
spiral density waves (Perez+2016)



Binary formation in young, gravitationally unstable disk (Tobin+2016)

Dust trap in a transition disks

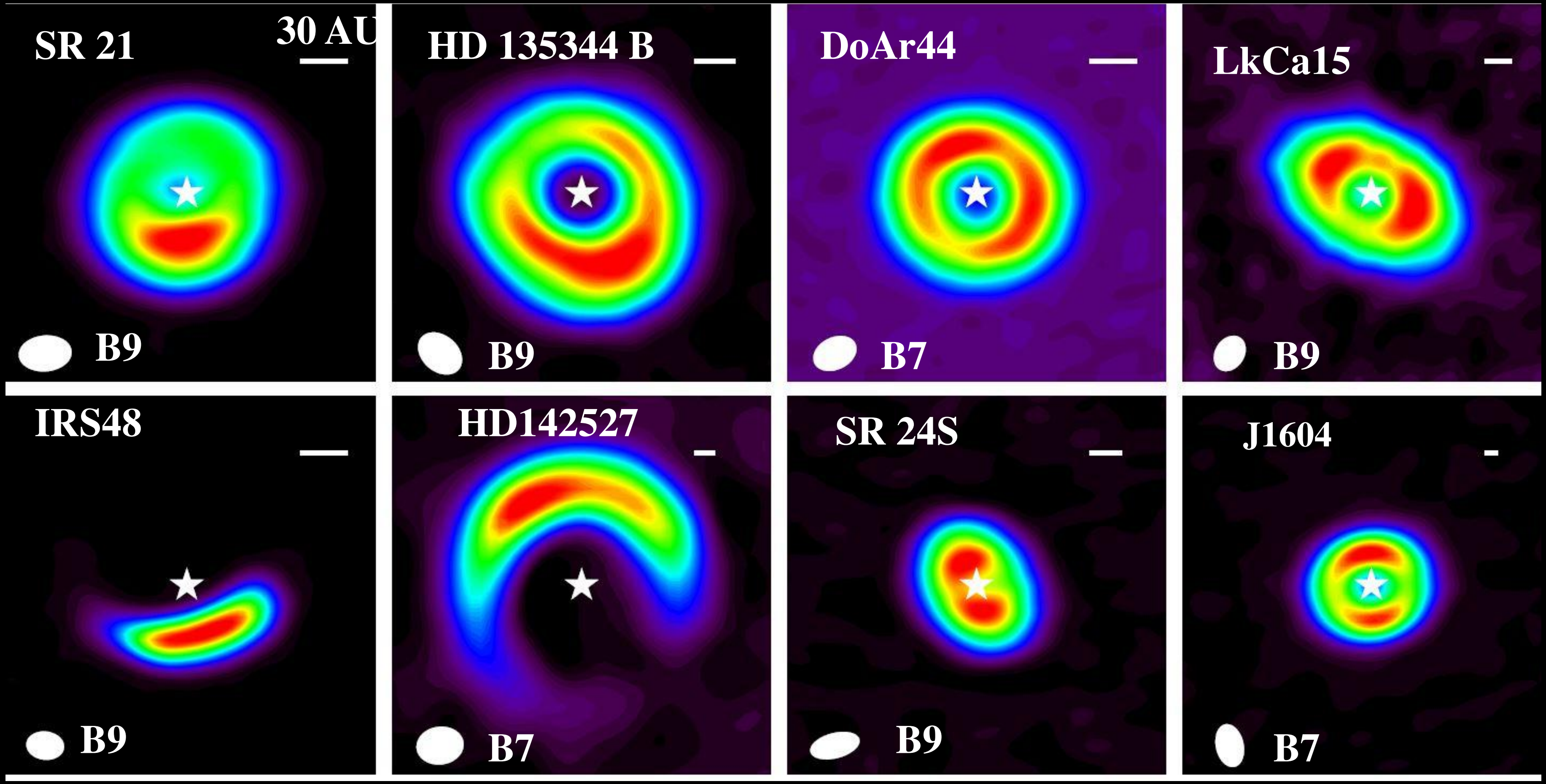
(van der Marel+2013, 2015)



Planet inside hole: Vortex? Comet/KBO factory?

Dust traps with ALMA

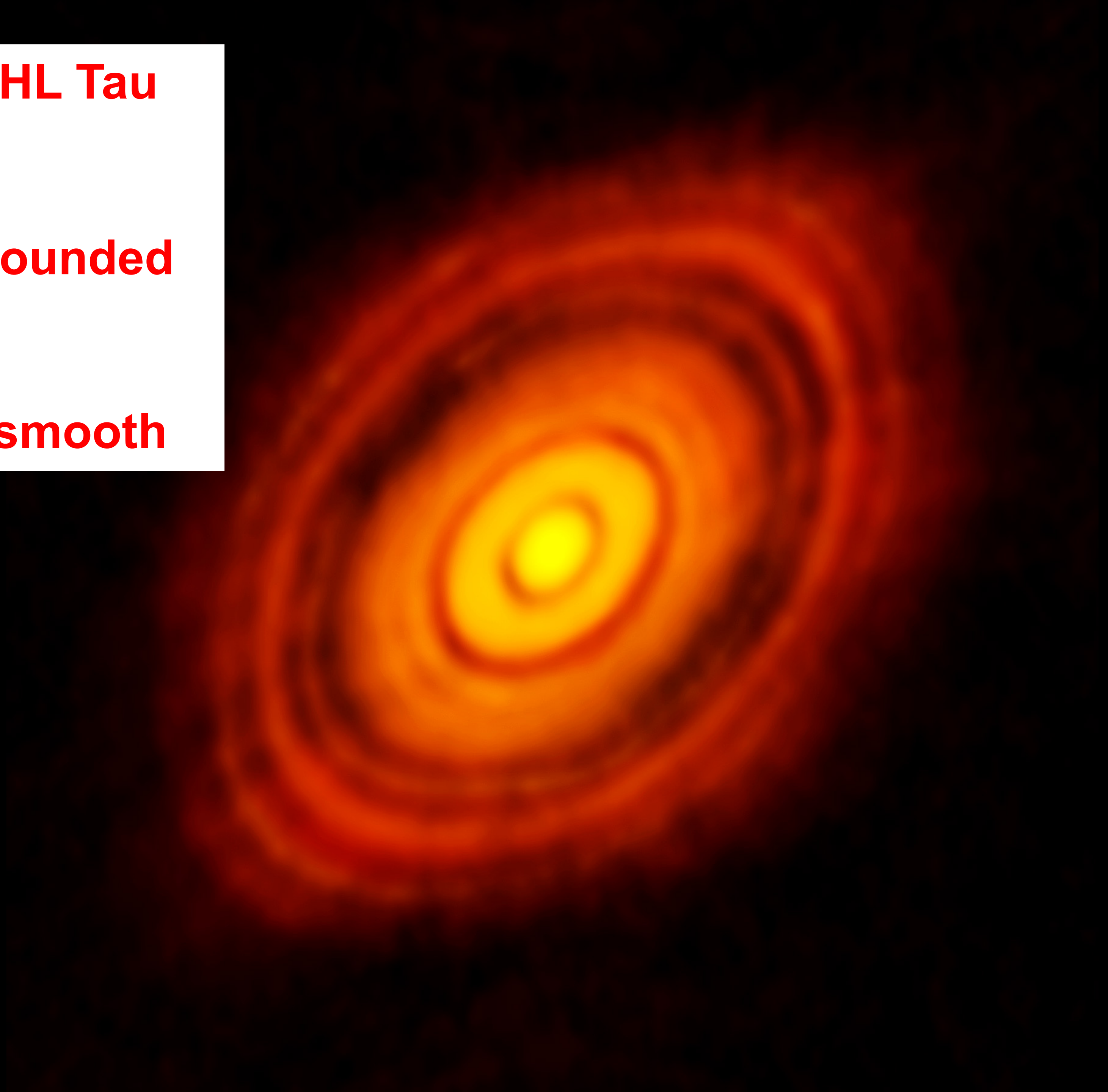
(e.g., van der Marel+2015; Pinilla+2015)

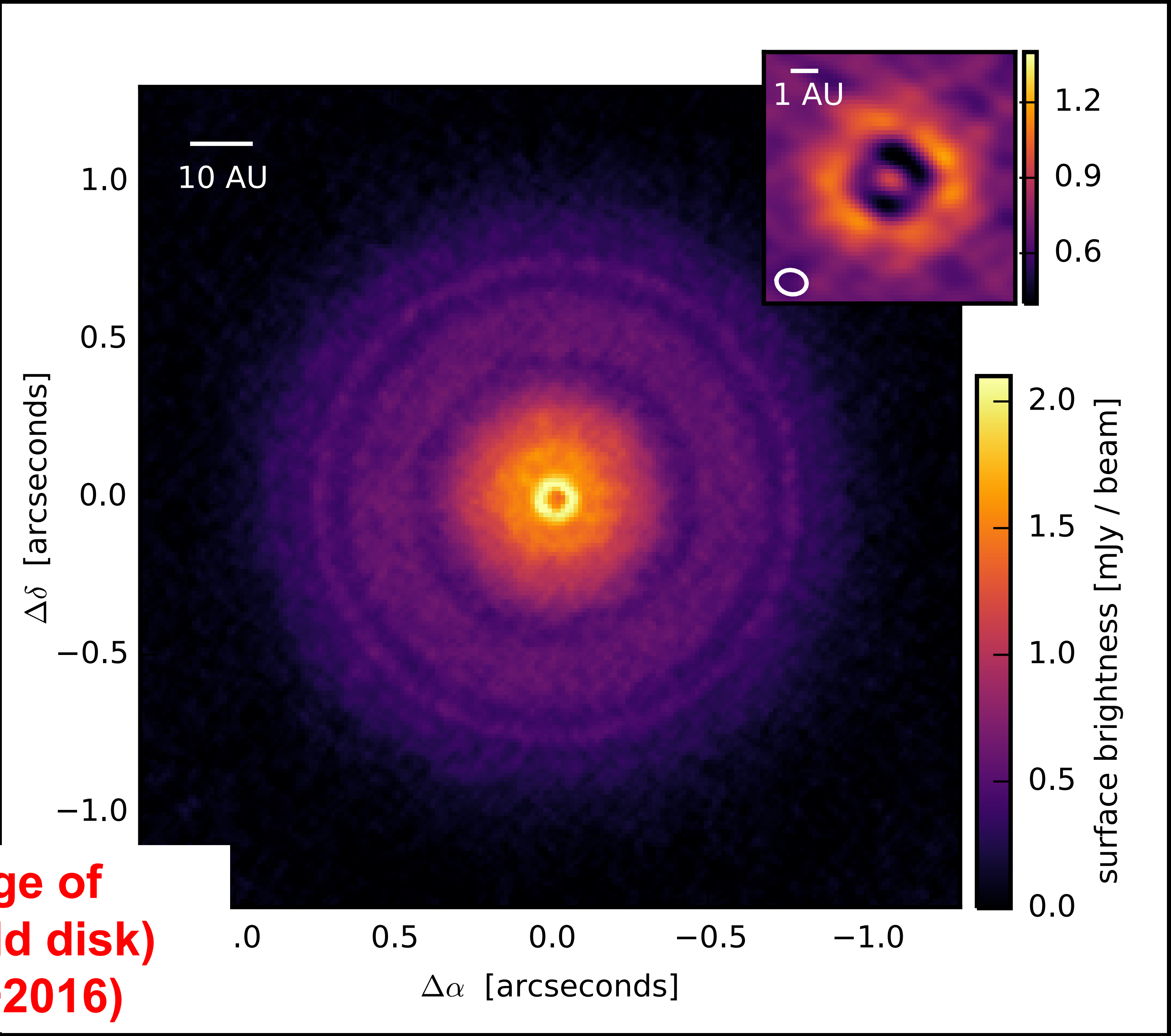


ALMA Image of HL Tau disk

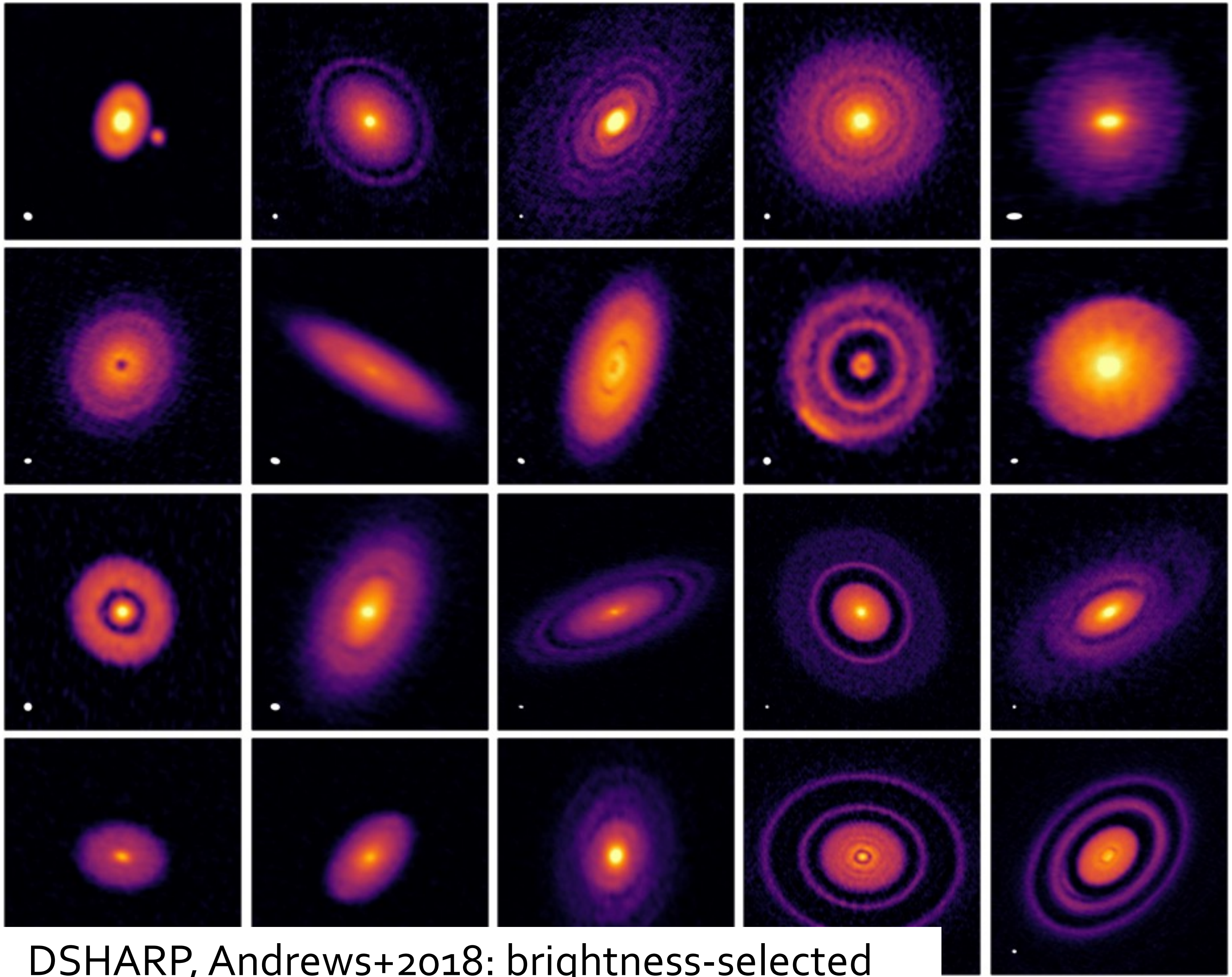
Young disk surrounded by an envelope

Expected to be smooth

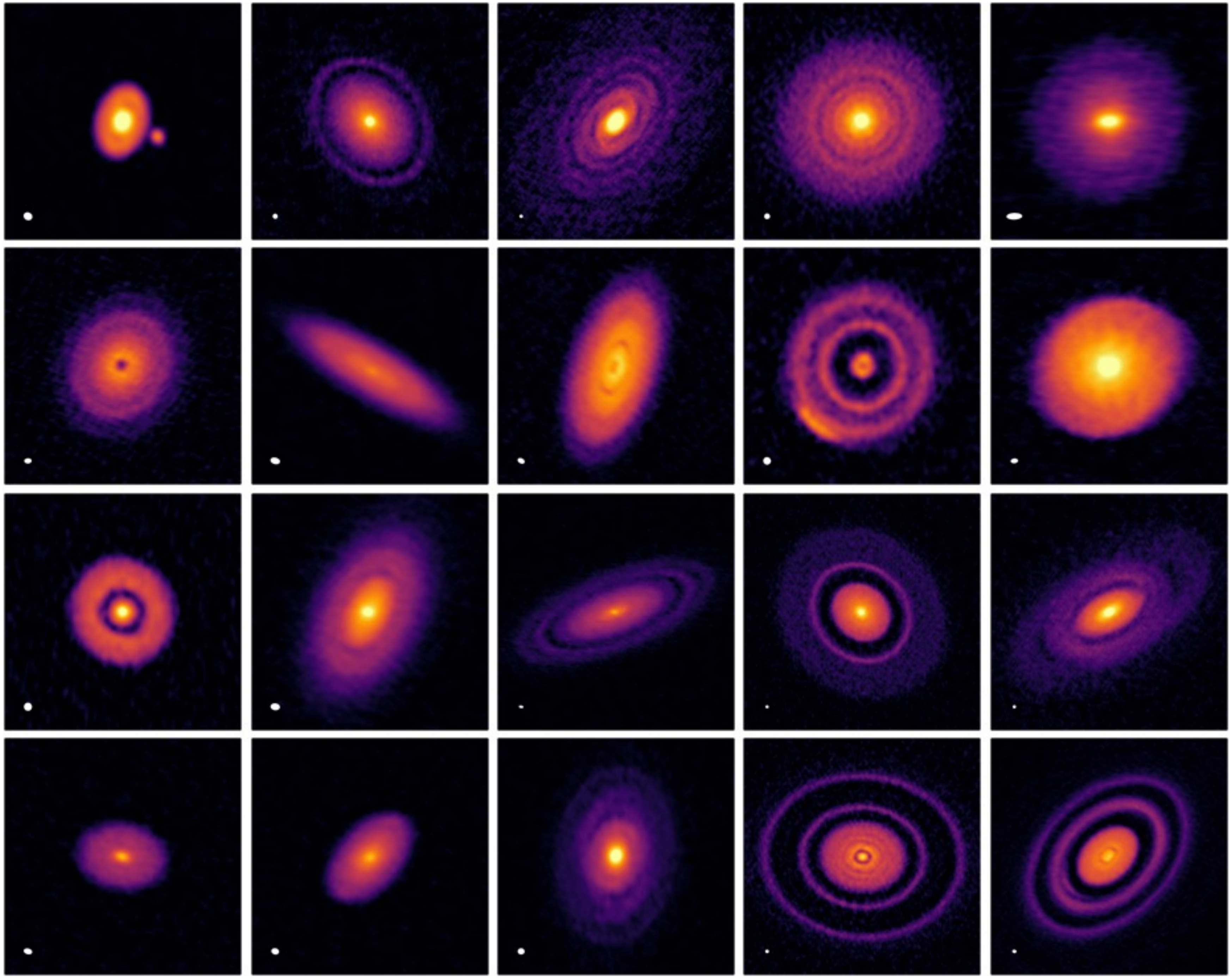




ALMA Image of TW Hya (old disk) (Andrews+2016)



DSHARP, Andrews+2018: brightness-selected

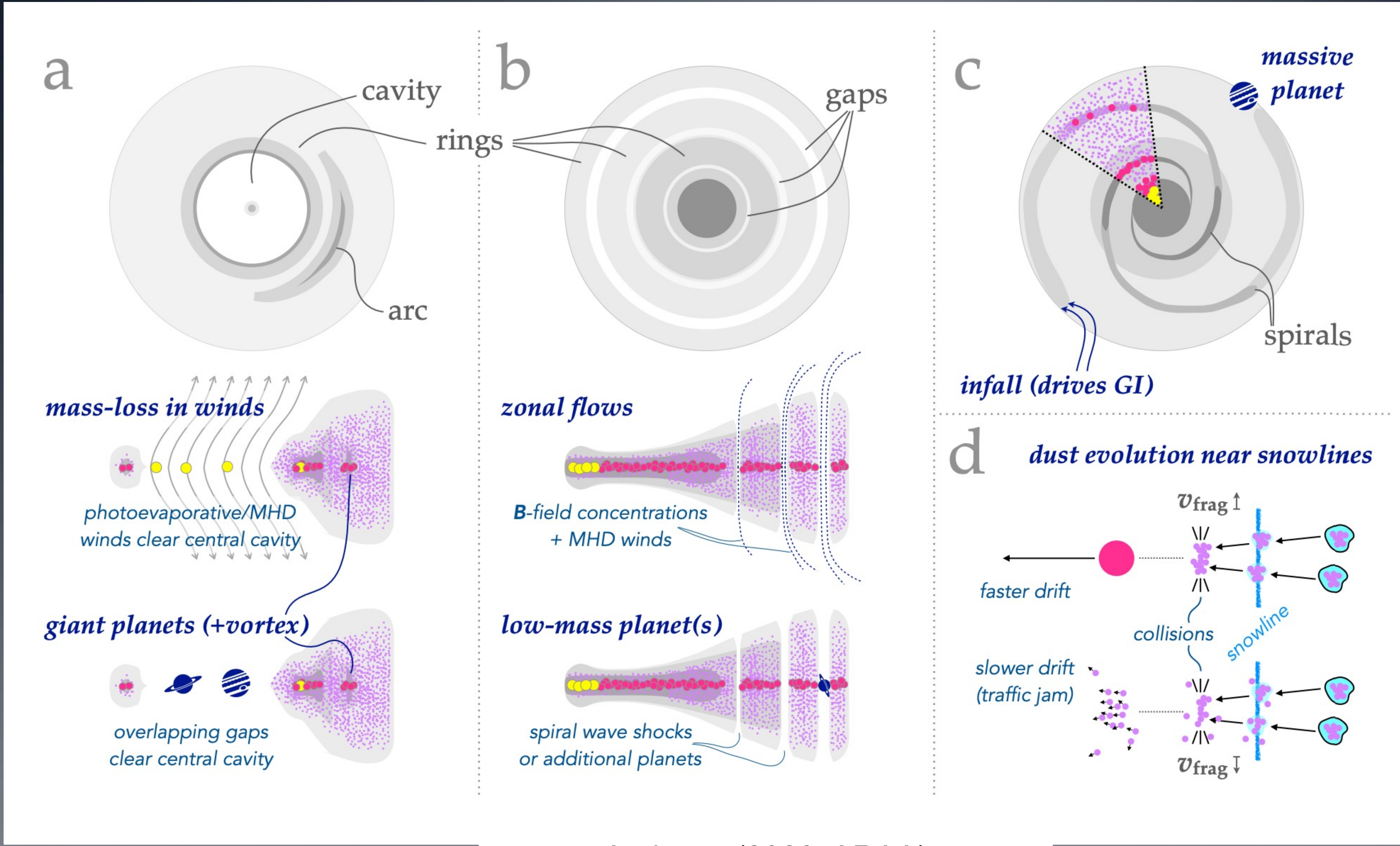


Are rings evidence for planets that already exist?

Or are they created by other physics?

Locations where planet cores may grow?

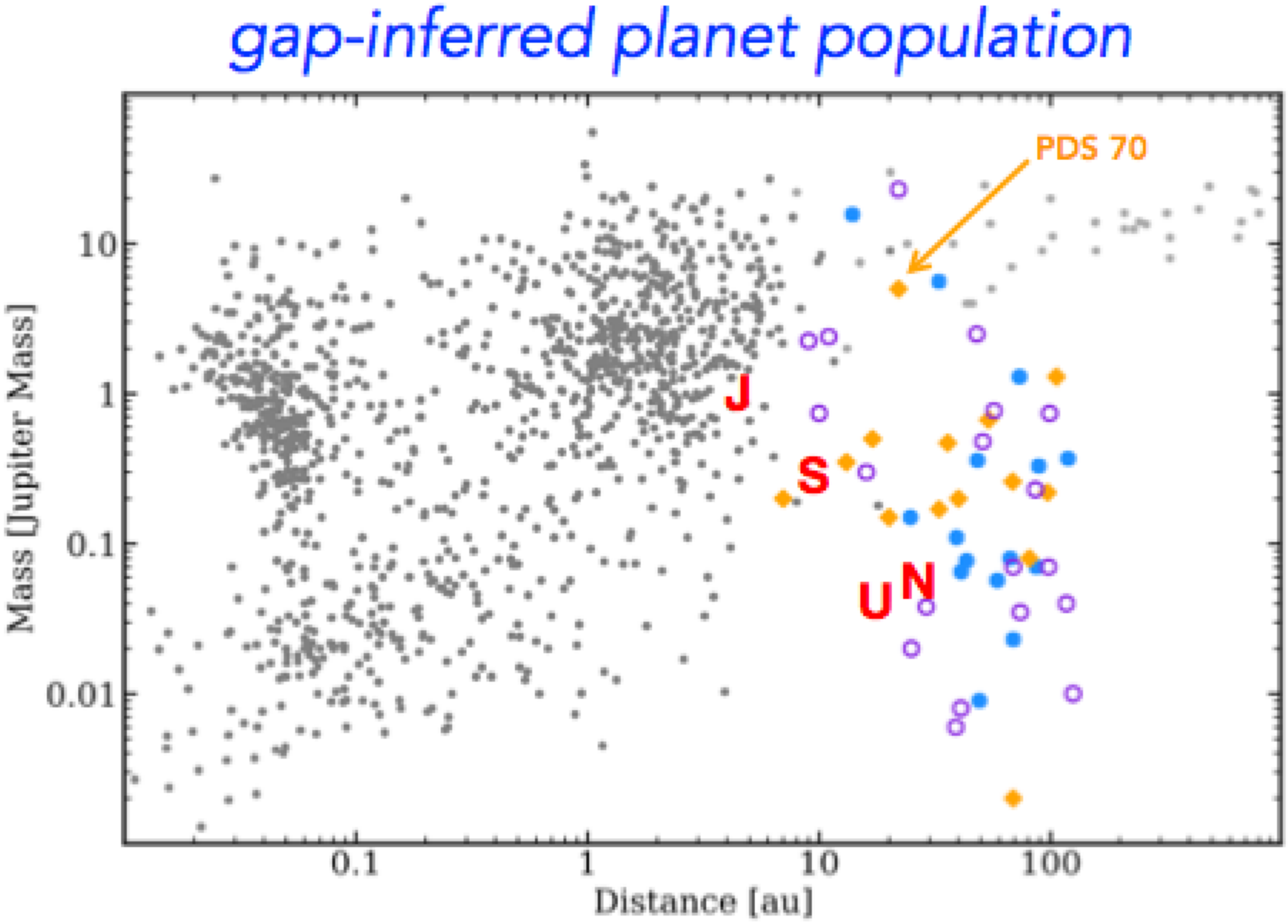
Chicken/egg problem



Andrews (2020, ARAA)

What if the gaps are carved by young planets?

(Lodato et al. 2019, from Long et al. 2018)

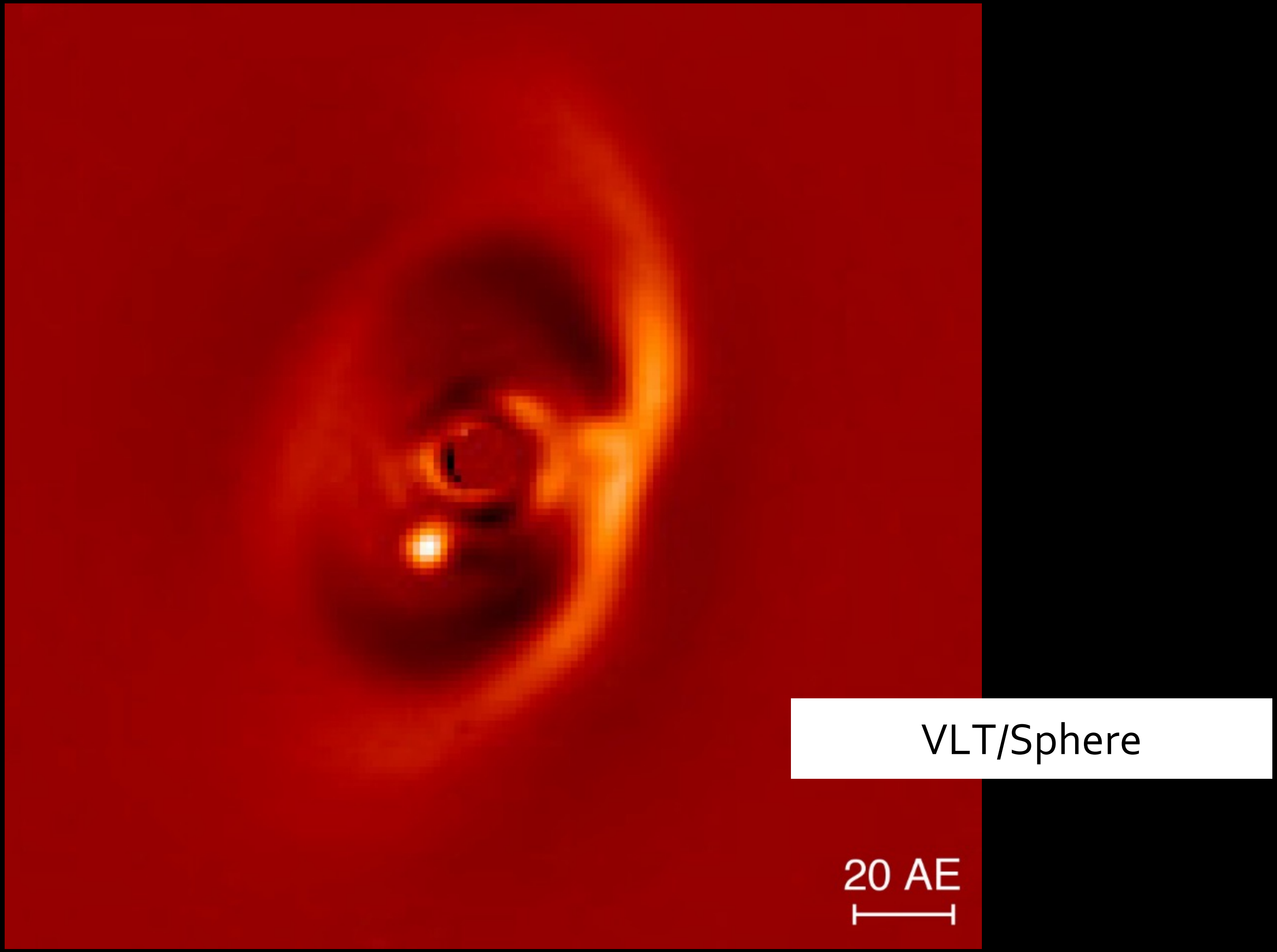


Mass of planet inferred from size and location of the gap

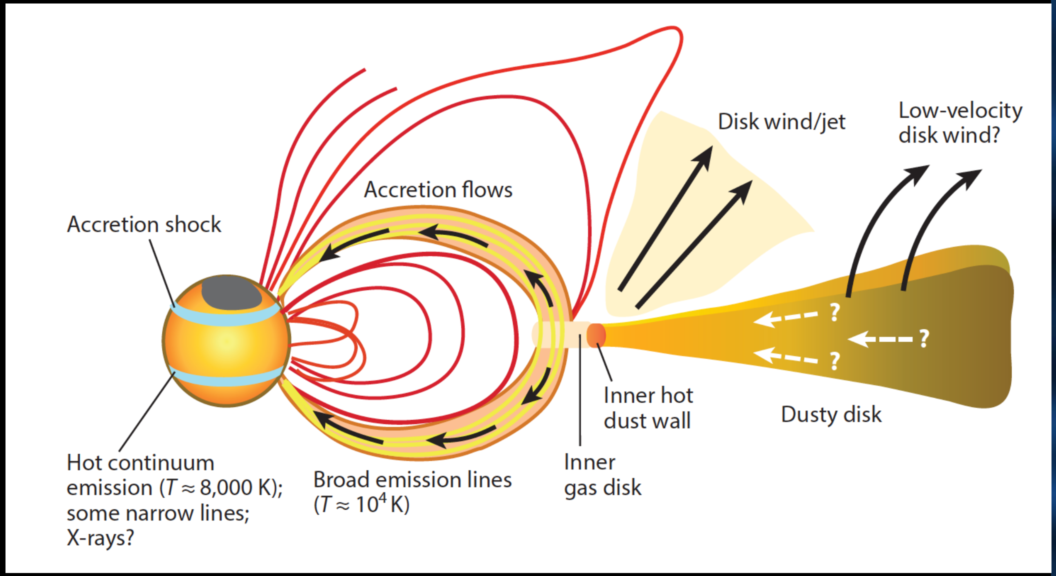
Zhang+2018 (DSHARP); Bae+2018 (archival)

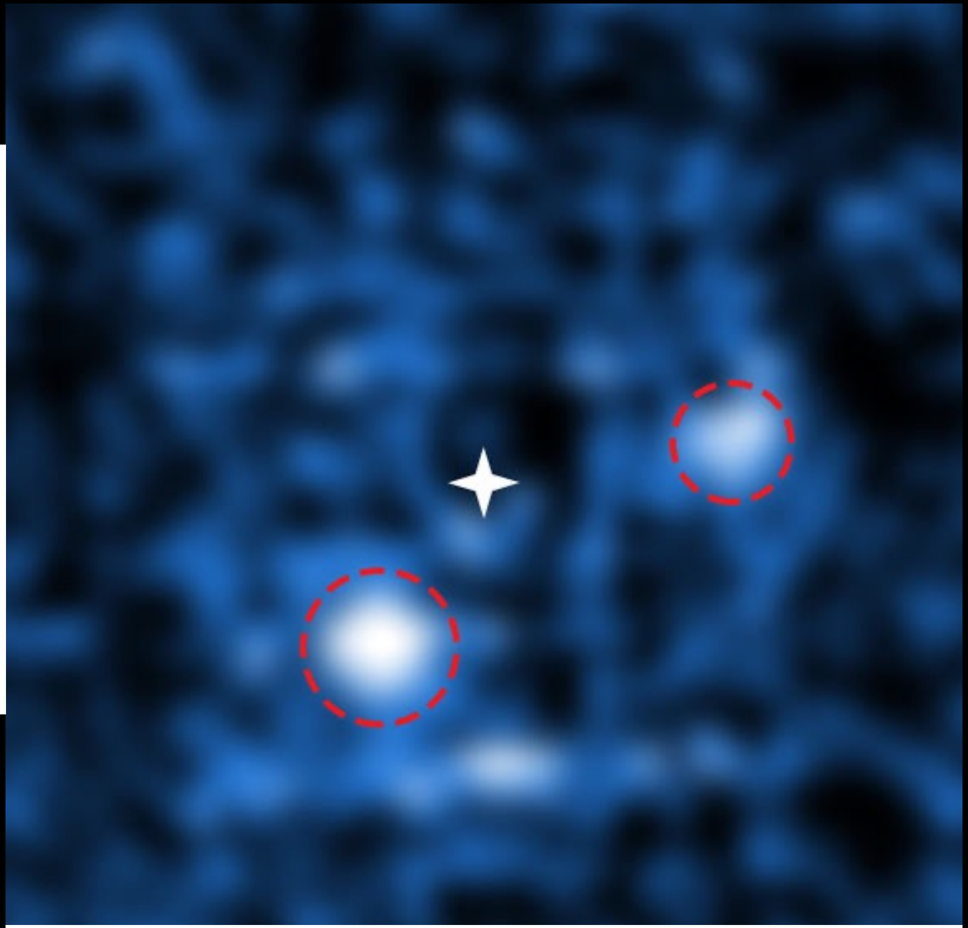
Planet(s) in a disk around the star PDS 70!

(Keppler et al. 2018)



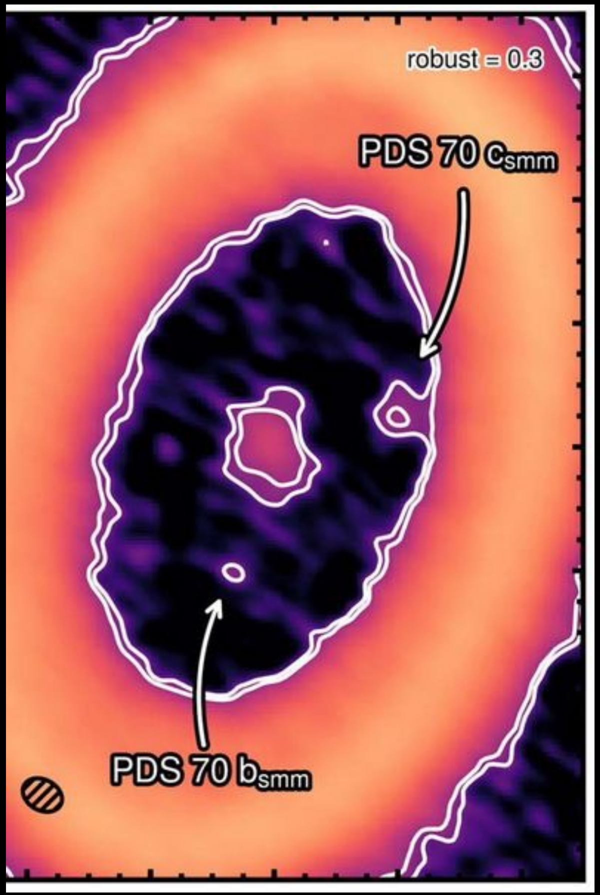
Proto-lunar disks around PDS 70bc?

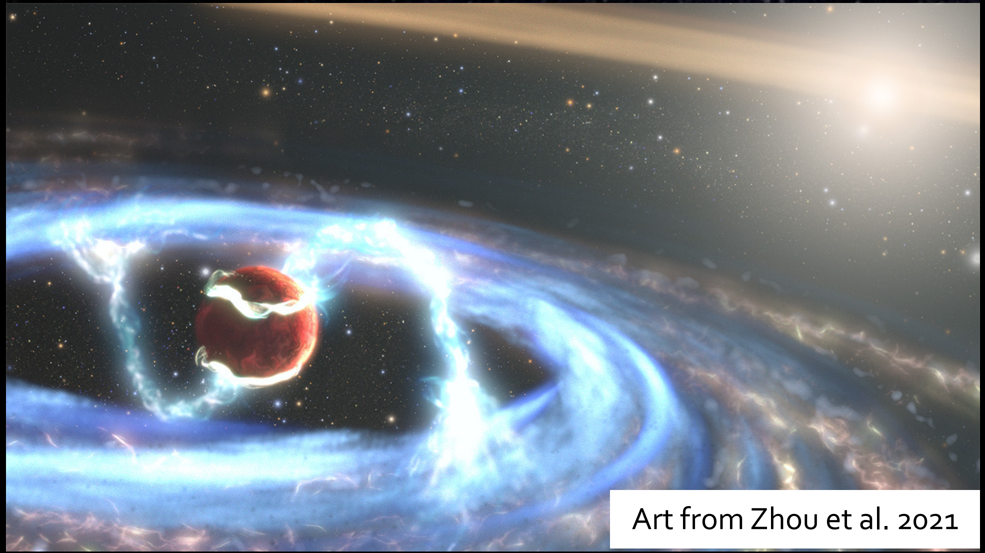




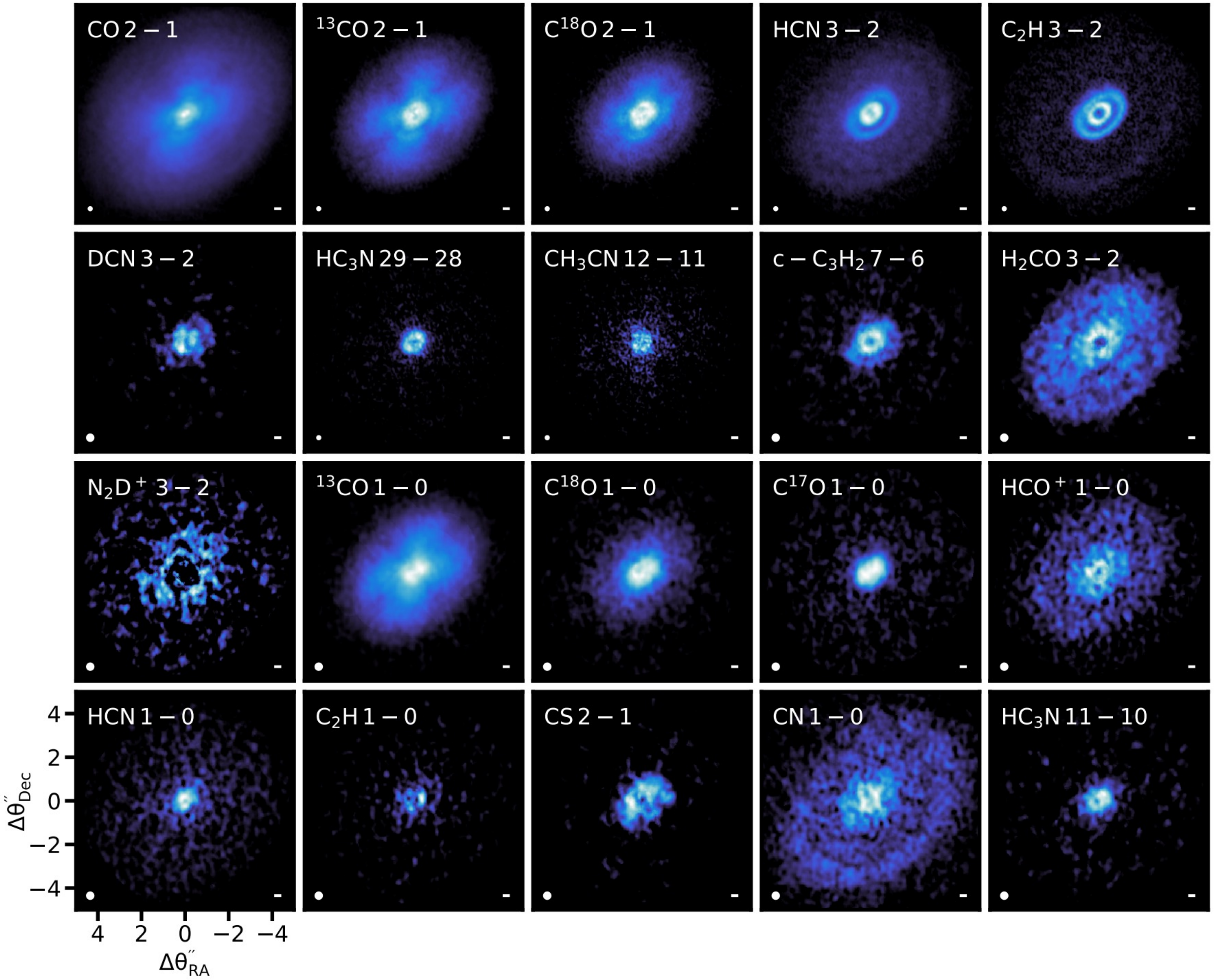
MUSE/H-alpha accretion, Haffert+2019
See also, eg., Bowler+2013; Zhou, Herczeg, et al. 2014; Wagner+2019

Proto-lunar disks around PDS 70bc?





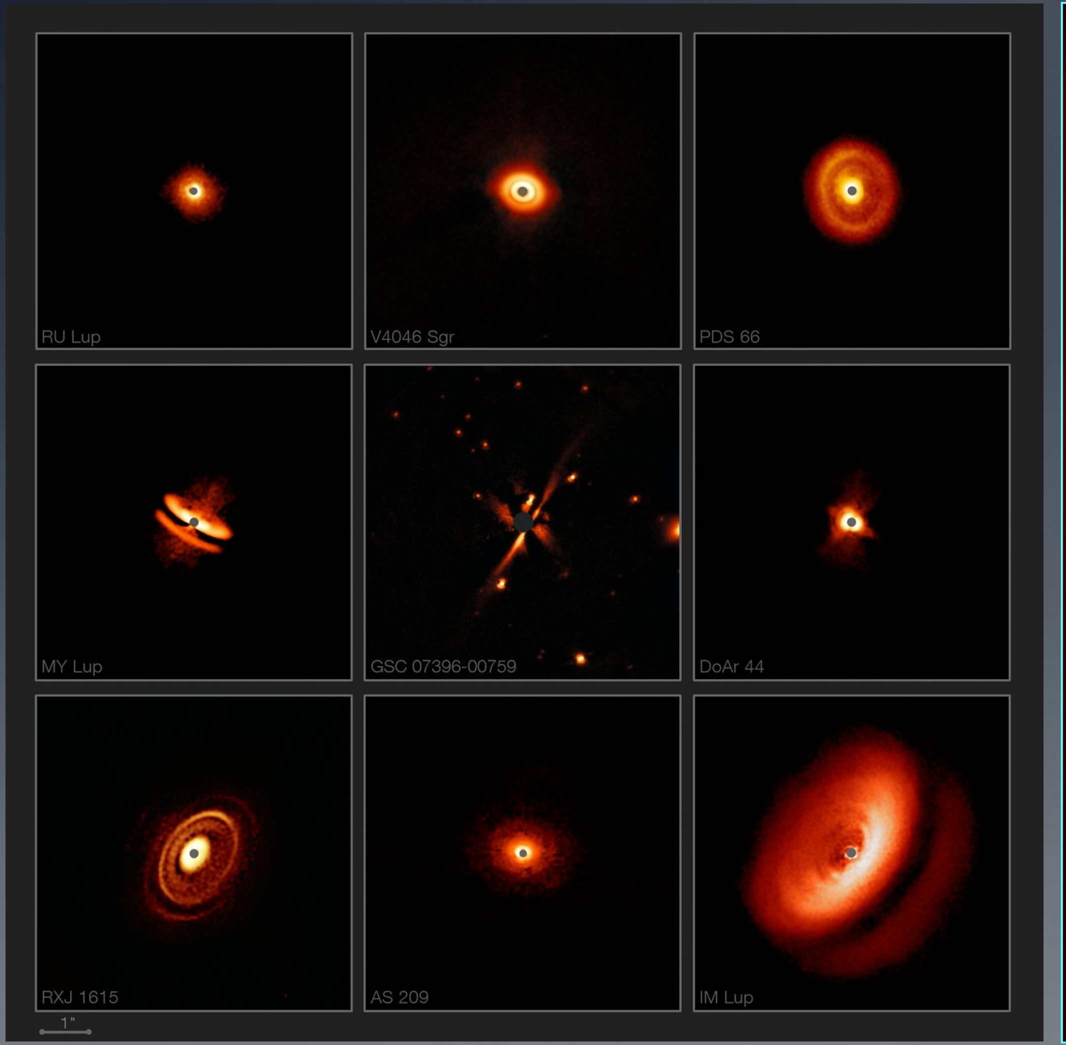
Art from Zhou et al. 2021

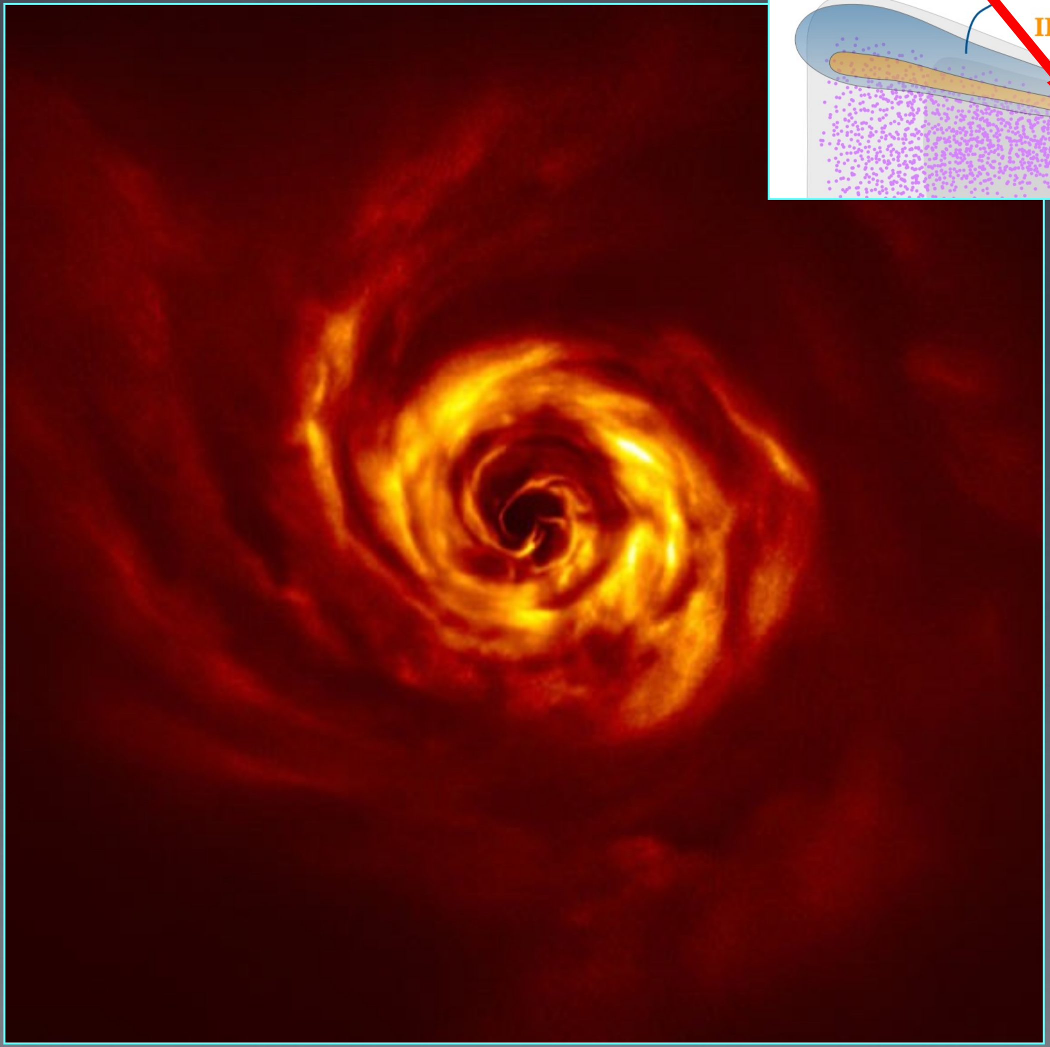


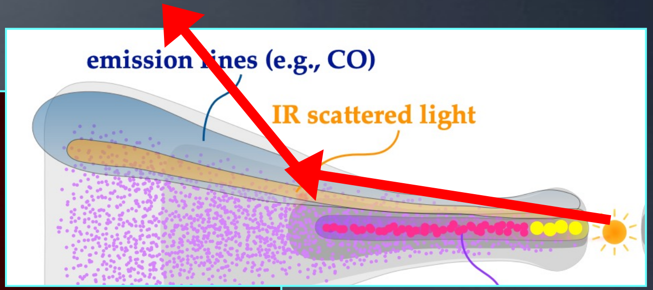
Chemistry of one disk!

(MAPS: Oberg et al. 2021)

Disks in scattered light





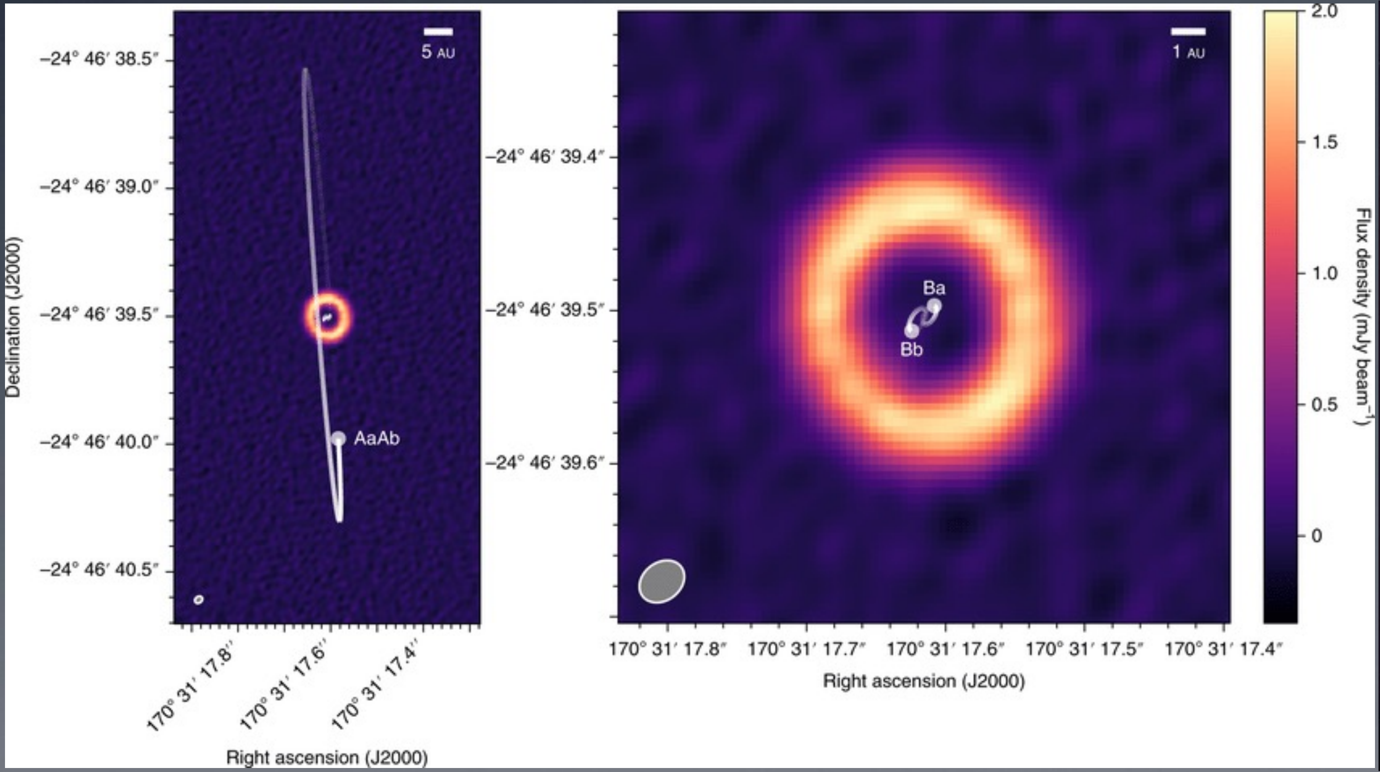


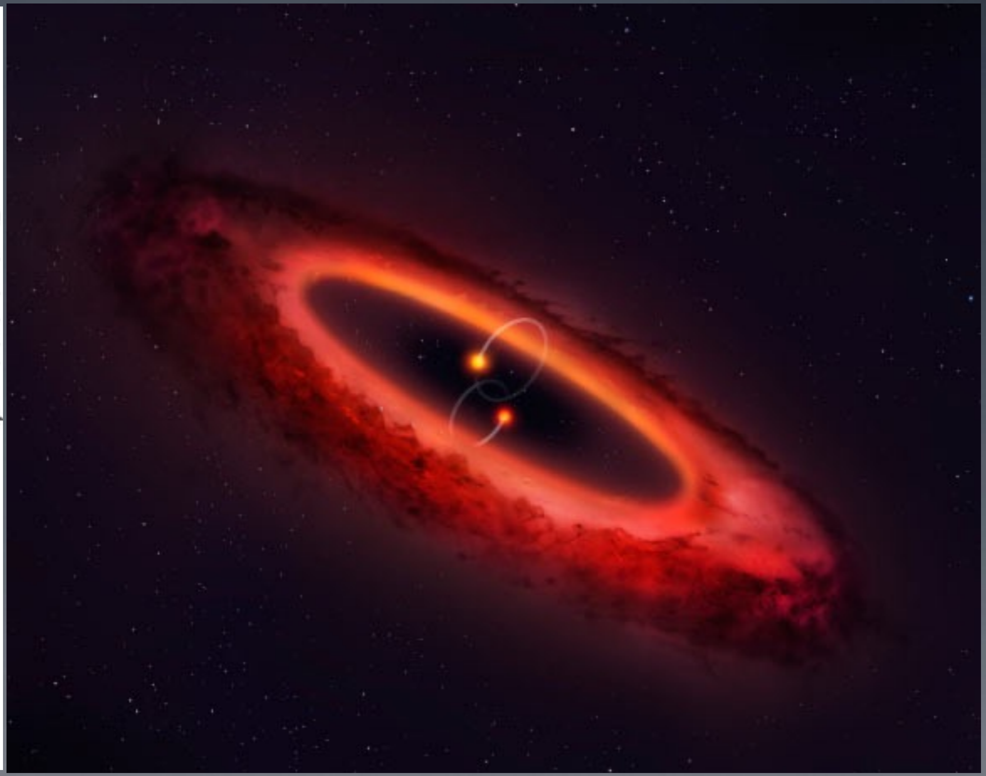
VLT/SPHERE: Garufi+2019; Boccalletti+2019

Weird disk around the binary of HD 98800N

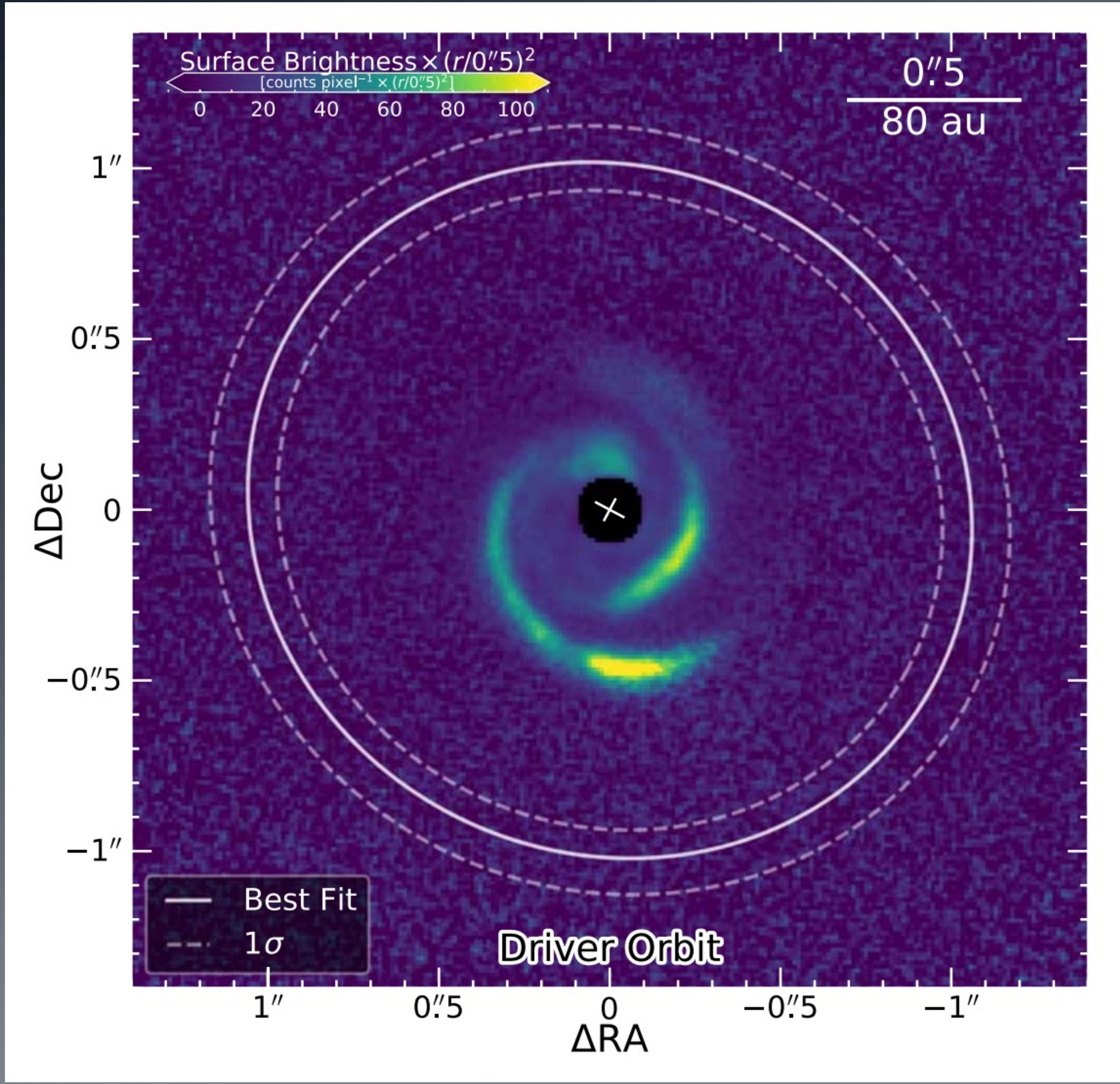
binary in a quadruple system, disk+binary are not coplanar!

(could some planetary systems in binary star systems be very, very weird?)





JWST: Direct imaging searches for exoplanets



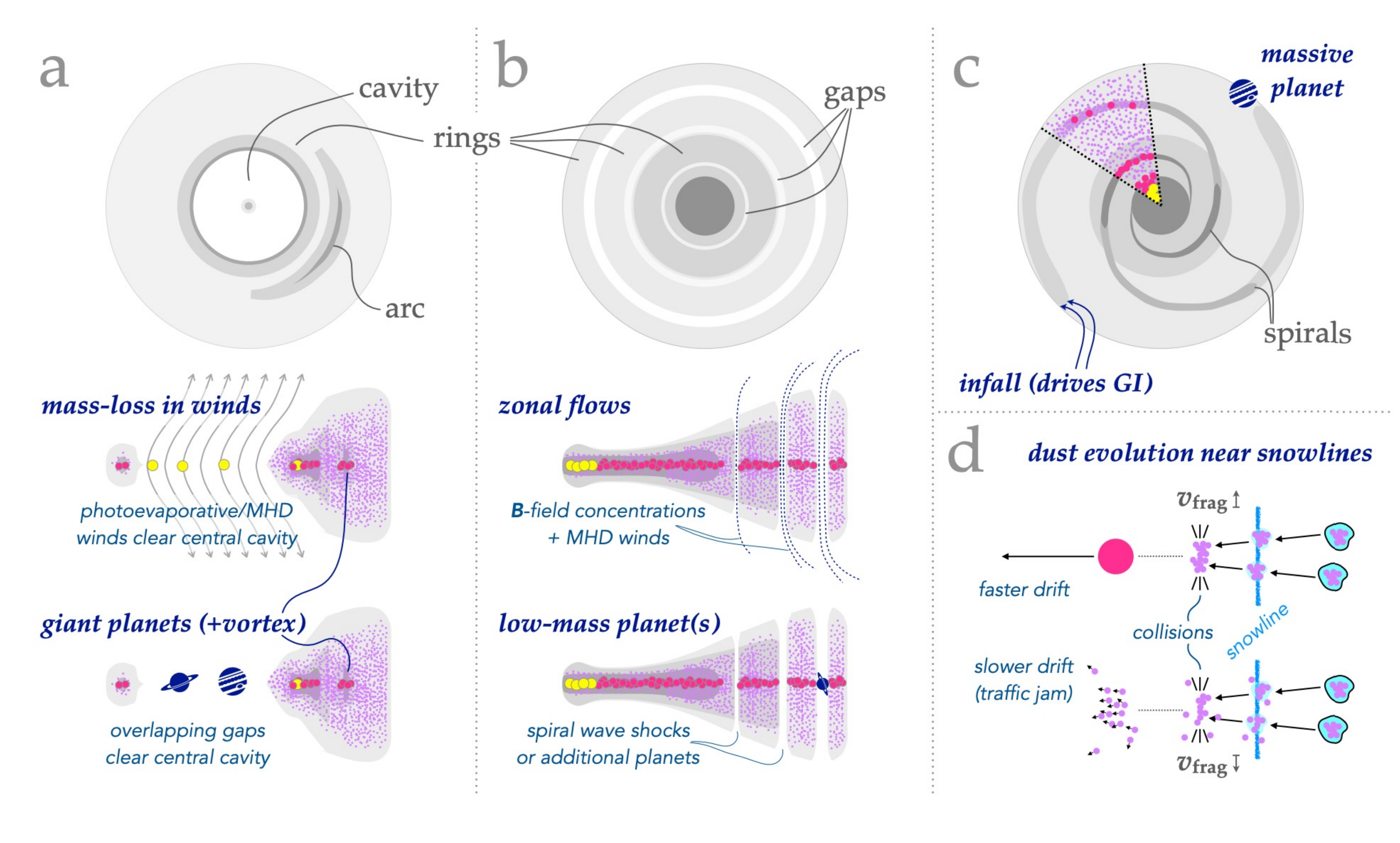
Dong+: MWC 758 spirals excited by a planet?

Ren, Dong, et al. 2020: orbital motion of spirals consistent with a planet

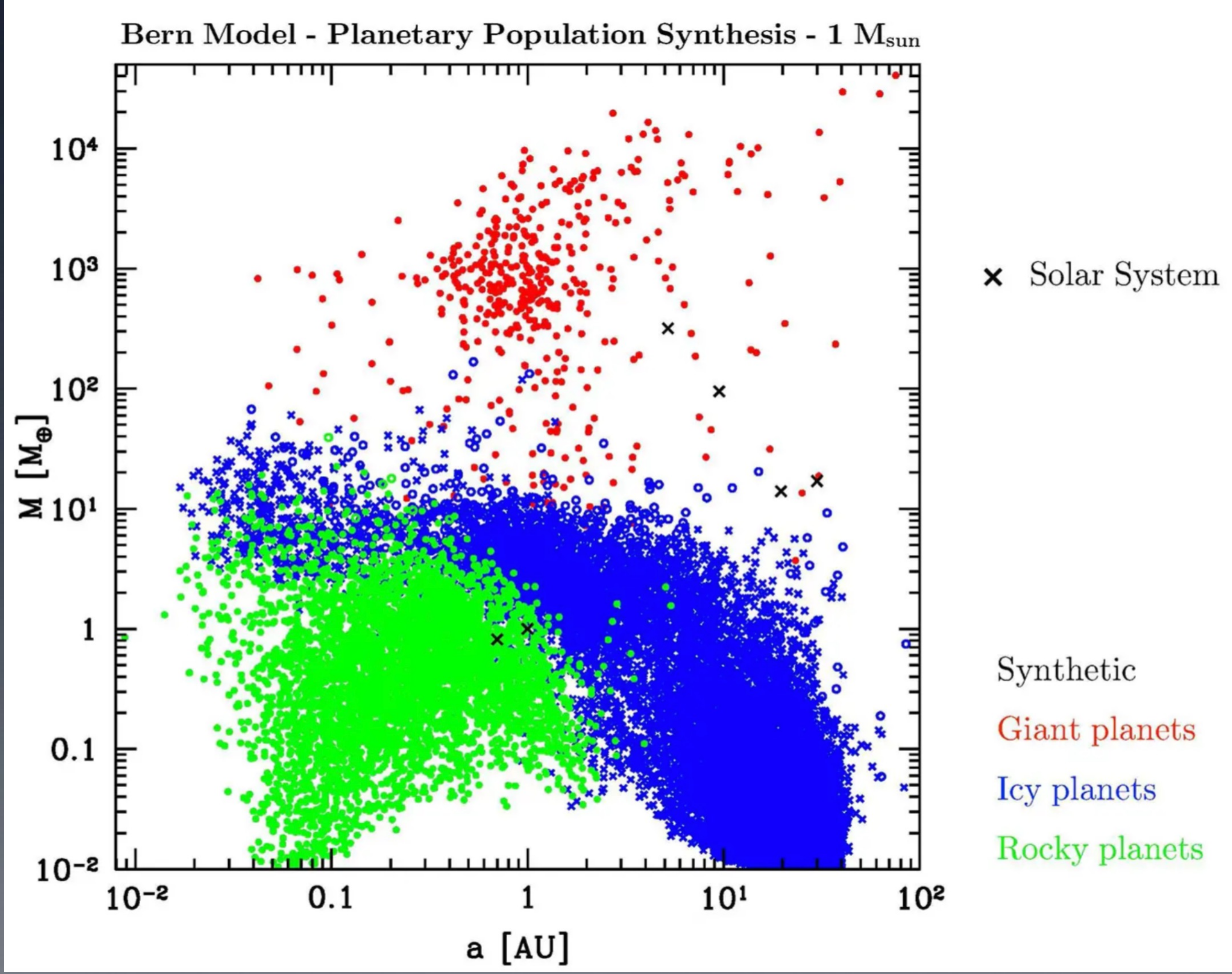
Where is the planet?

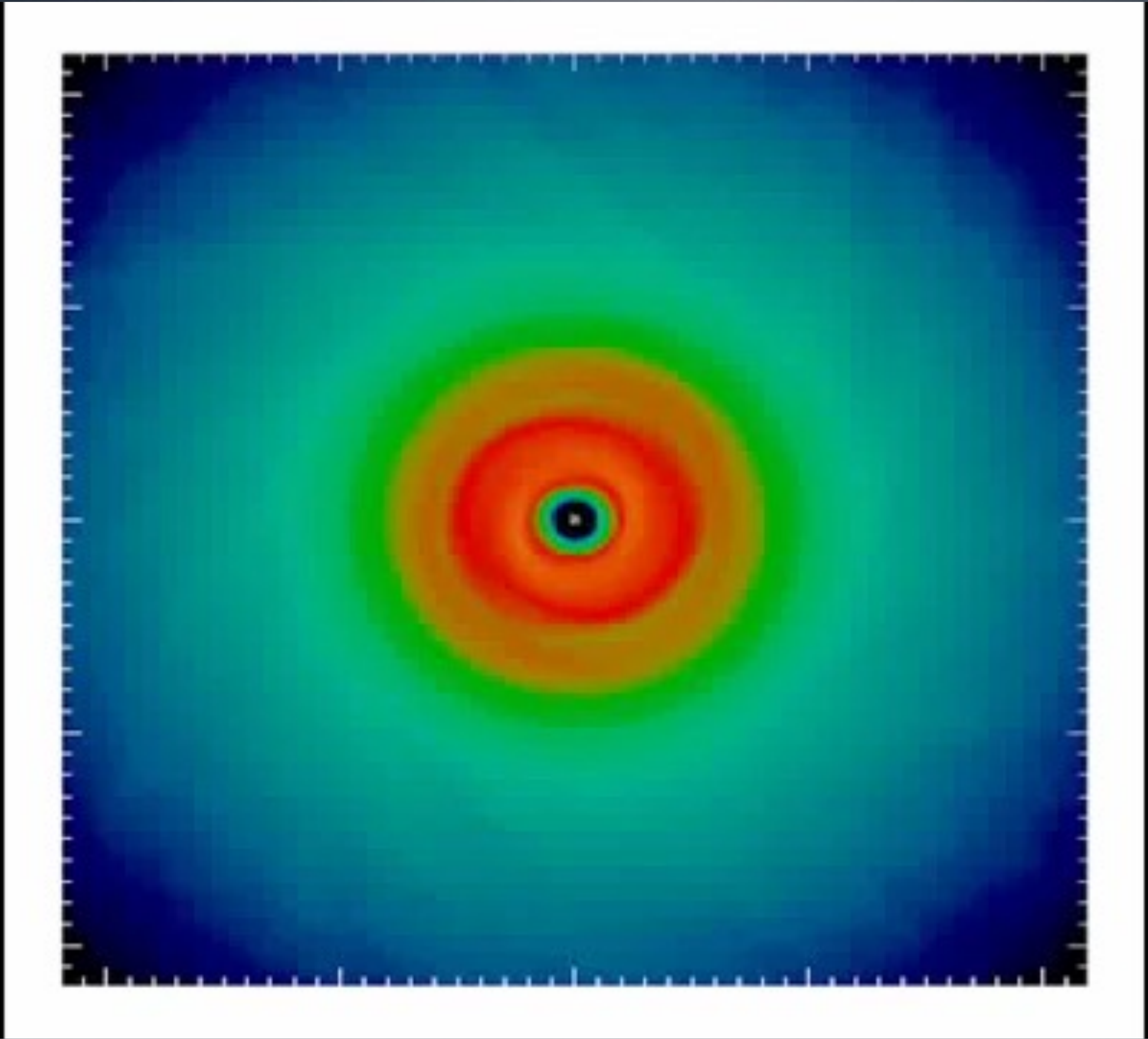
JWST will find it (or not): 100 x more sensitive than ground-based observations

Structures: planets or physics (of planet formation)?

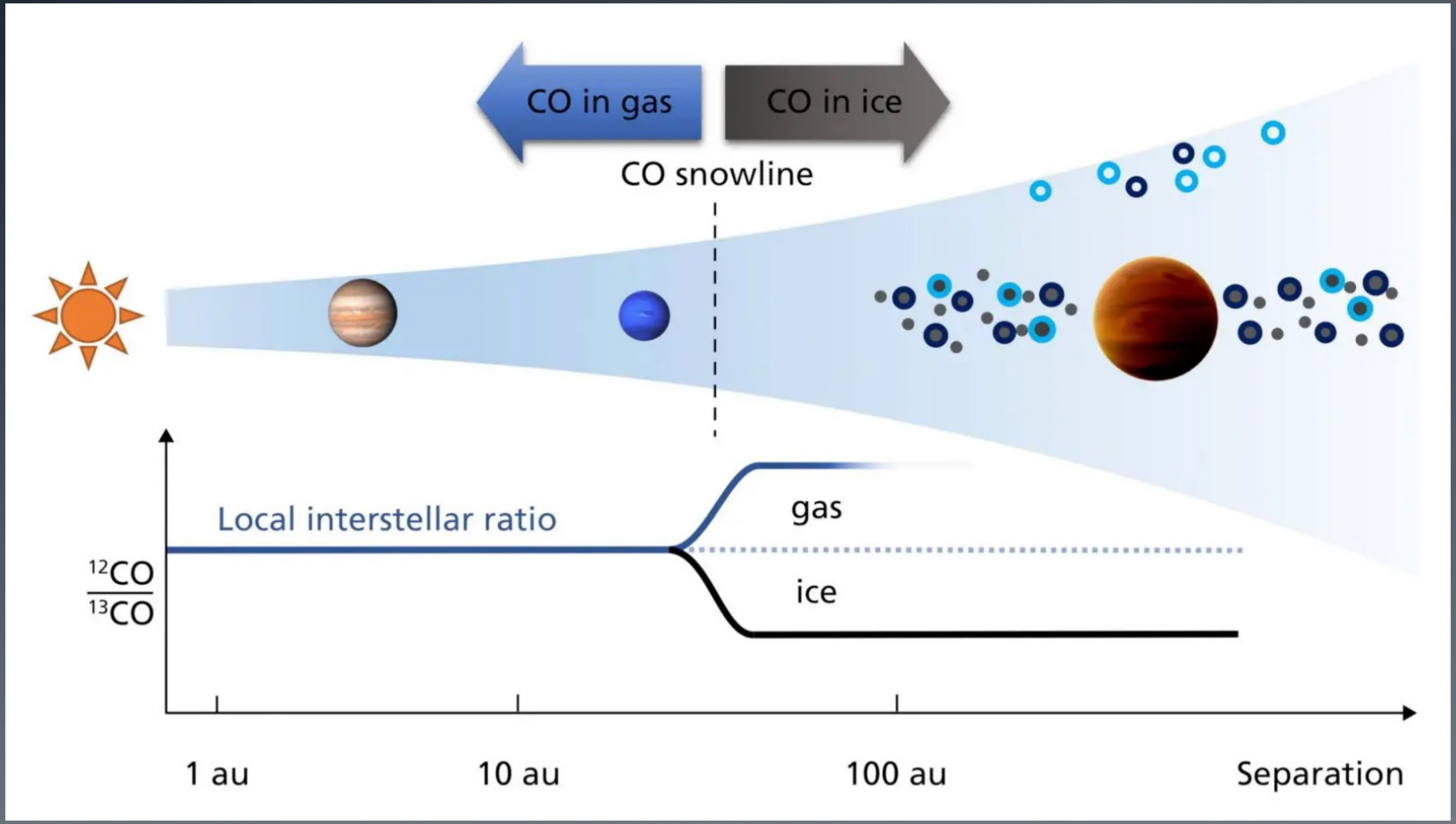


Andrews (2020, ARAA)


Bern Model - Planetary Population Synthesis - 1 M_{sun}
M [$M_\oplus$]
10^4
10^3
10^2
10^1
1
0.1
10^{-2}
10^{-2}
0.1
1
10^1
10^2
a [AU]
× Solar System
Synthetic
Giant planets
Icy planets
Rocky planets

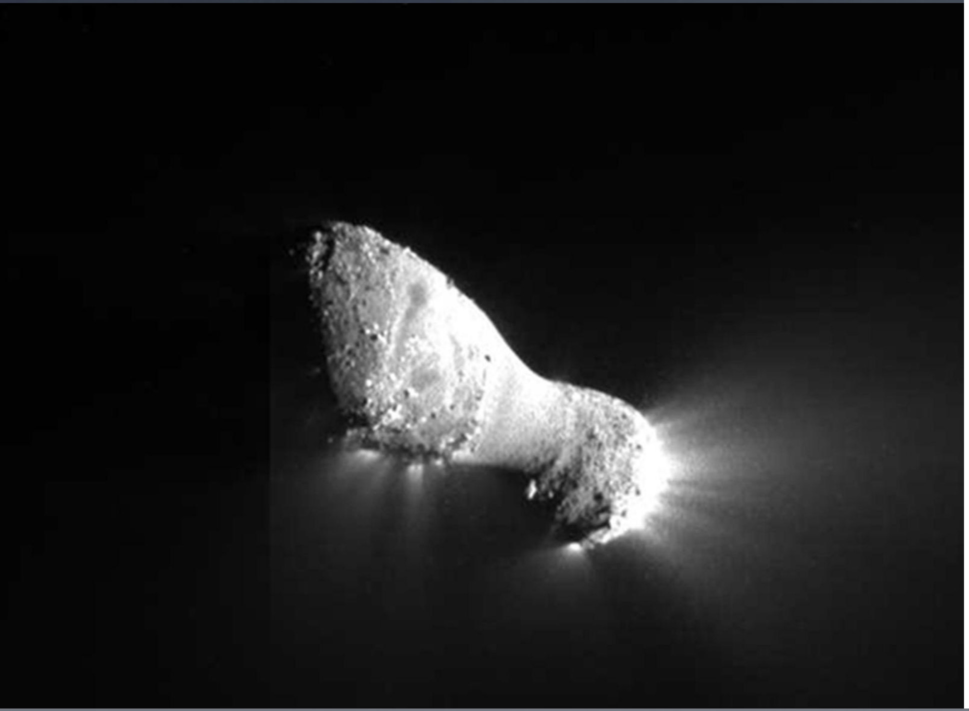


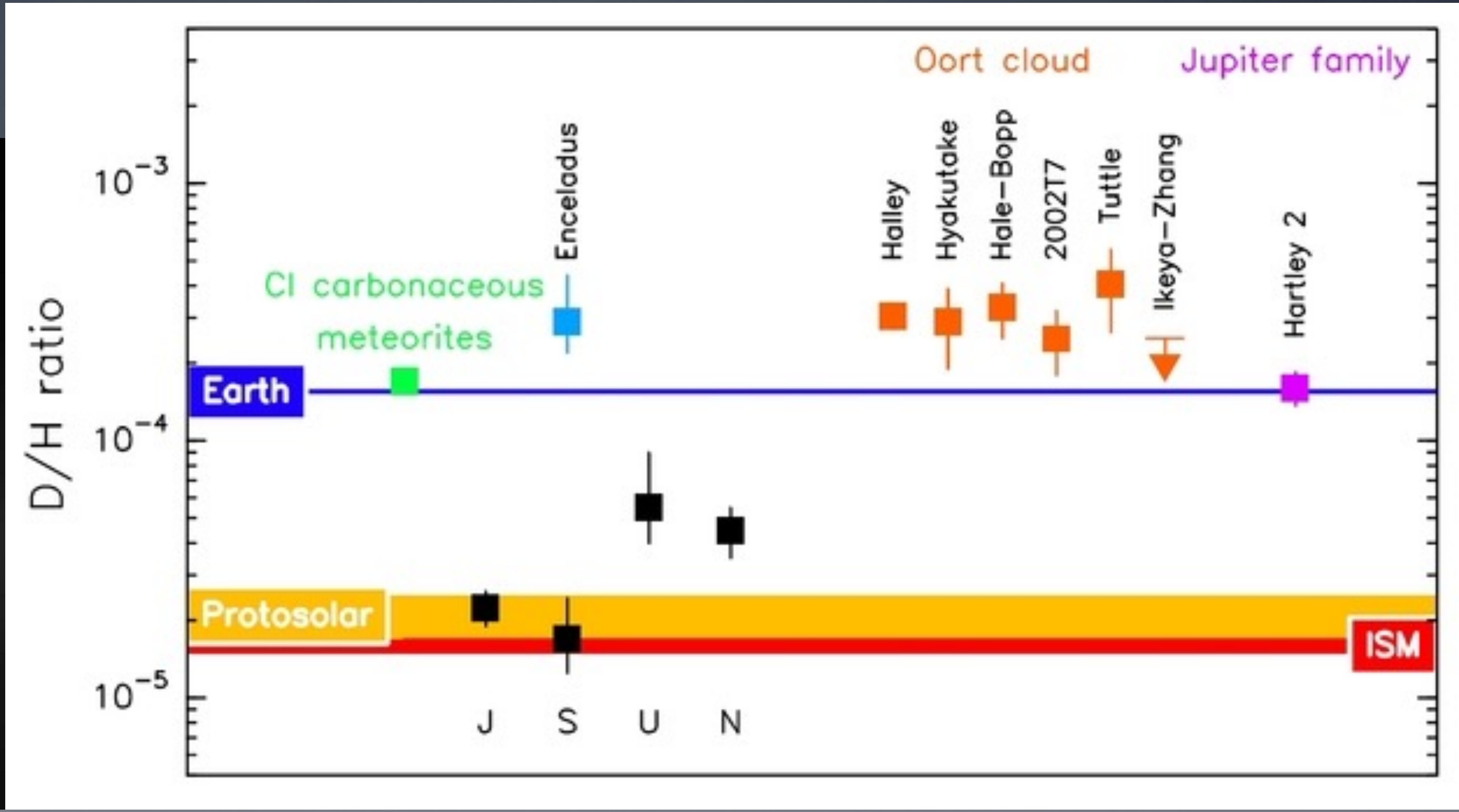
How to affect the abundances of a planet



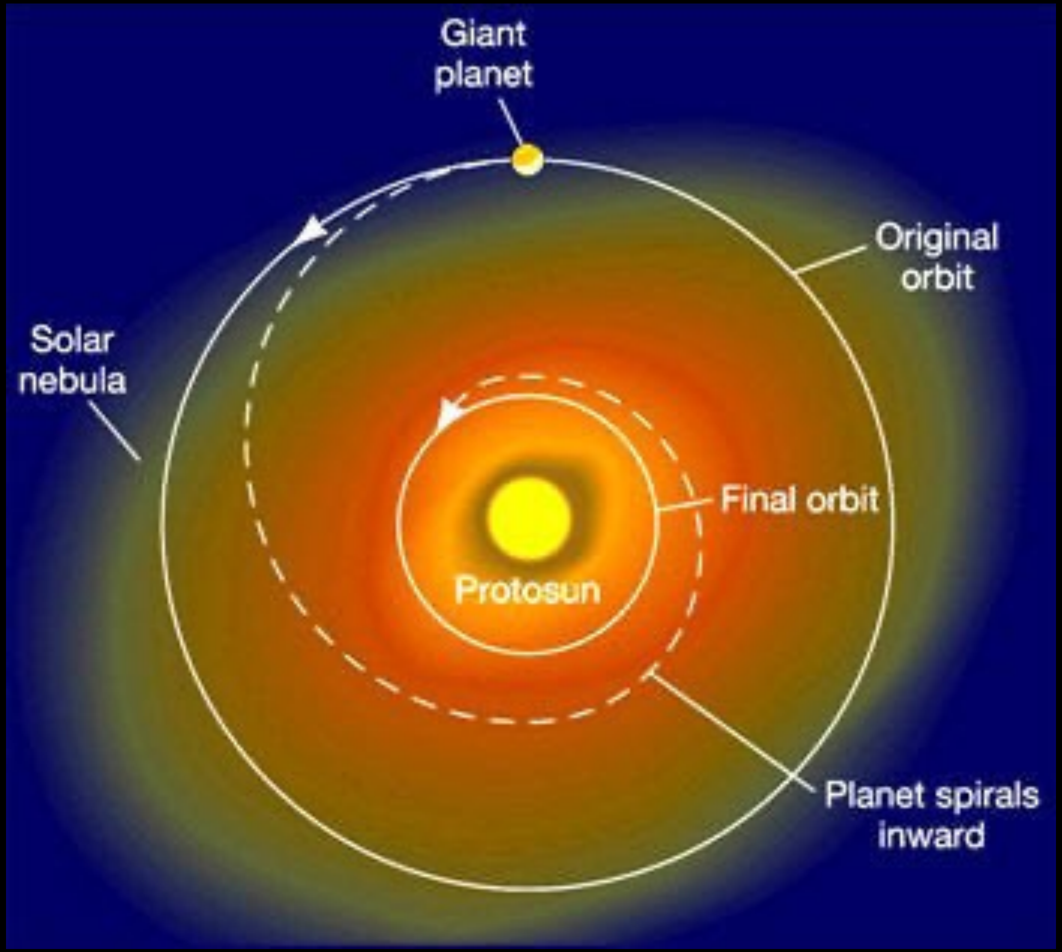
- Some planets will accrete more mass from the gas phase
- Others will have more icy dust grains
- The molecules in gas or ice depends on temperature (snow line)

Comets: possible source for Earth's water!





Planet migration



- Planets formation location may differ from final location
- Interactions with disk: can move inward or outward