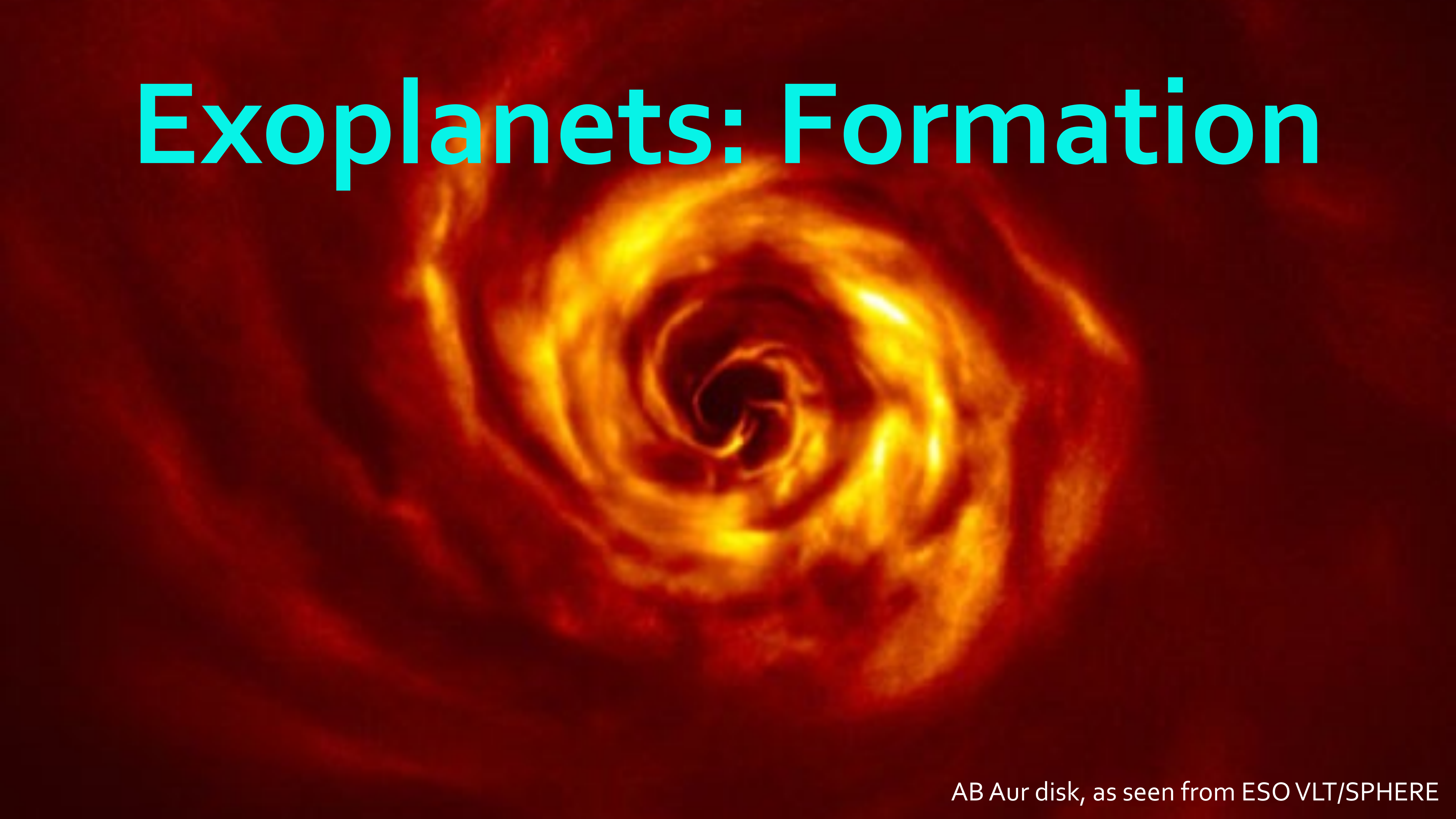
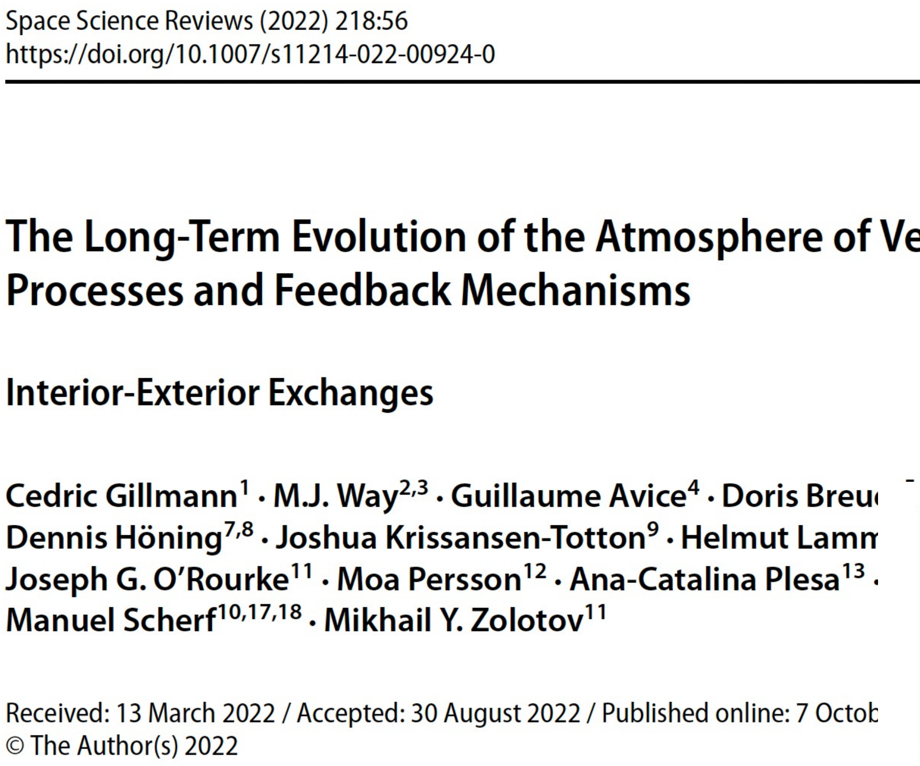
Exoplanets: Formation



AB Aur disk, as seen from ESO VLT/SPHERE

Venus’s atmosphere



Space Science Reviews (2022) 218:56
https://doi.org/10.1007/s11214-022-00924-0

The Long-Term Evolution of the Atmosphere of Venus: Processes and Feedback Mechanisms

Interior-Exterior Exchanges

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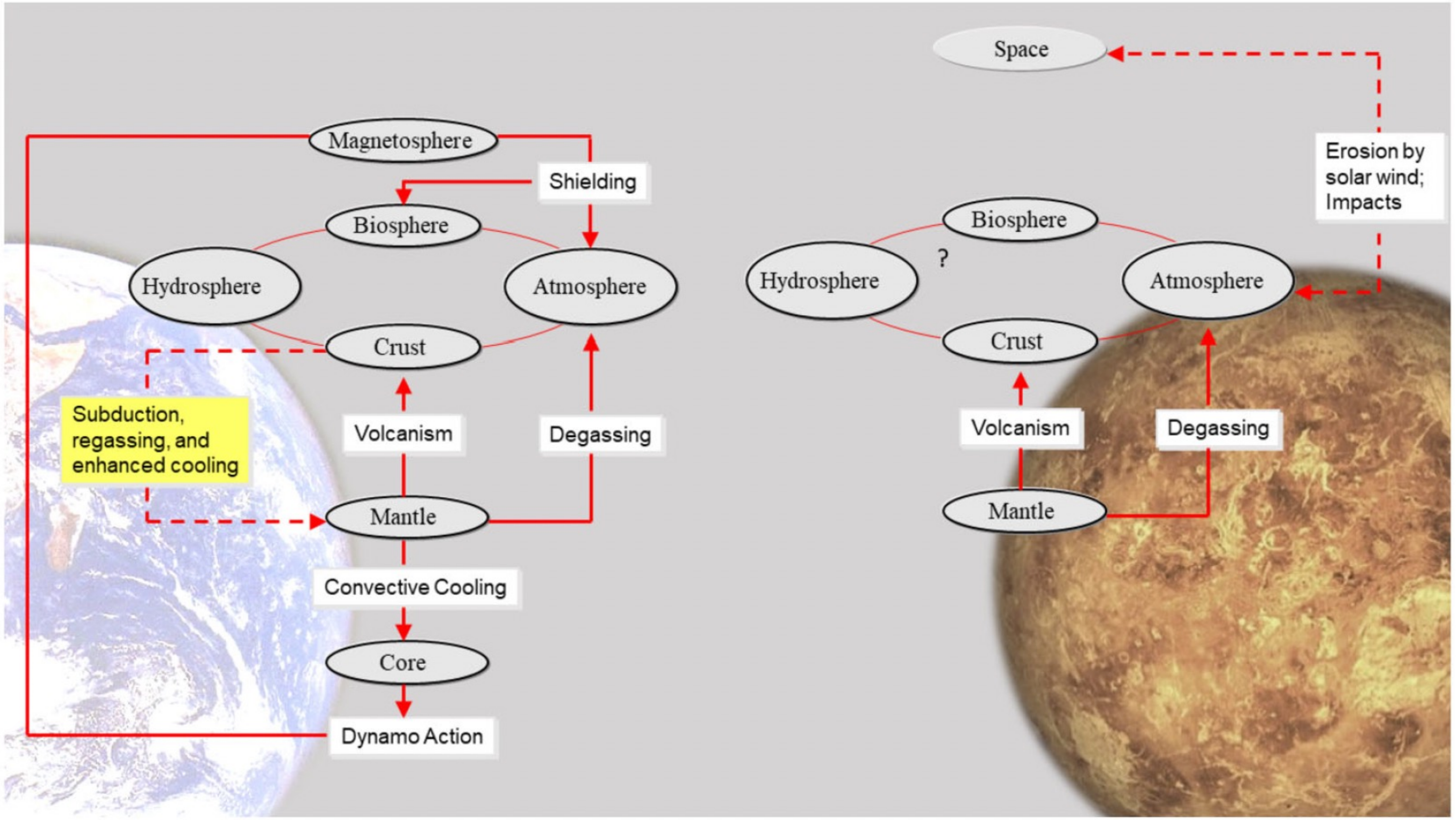
Atmospheres: balance of volcanic outgassing, surface-atmosphere interactions, and atmosphere escape

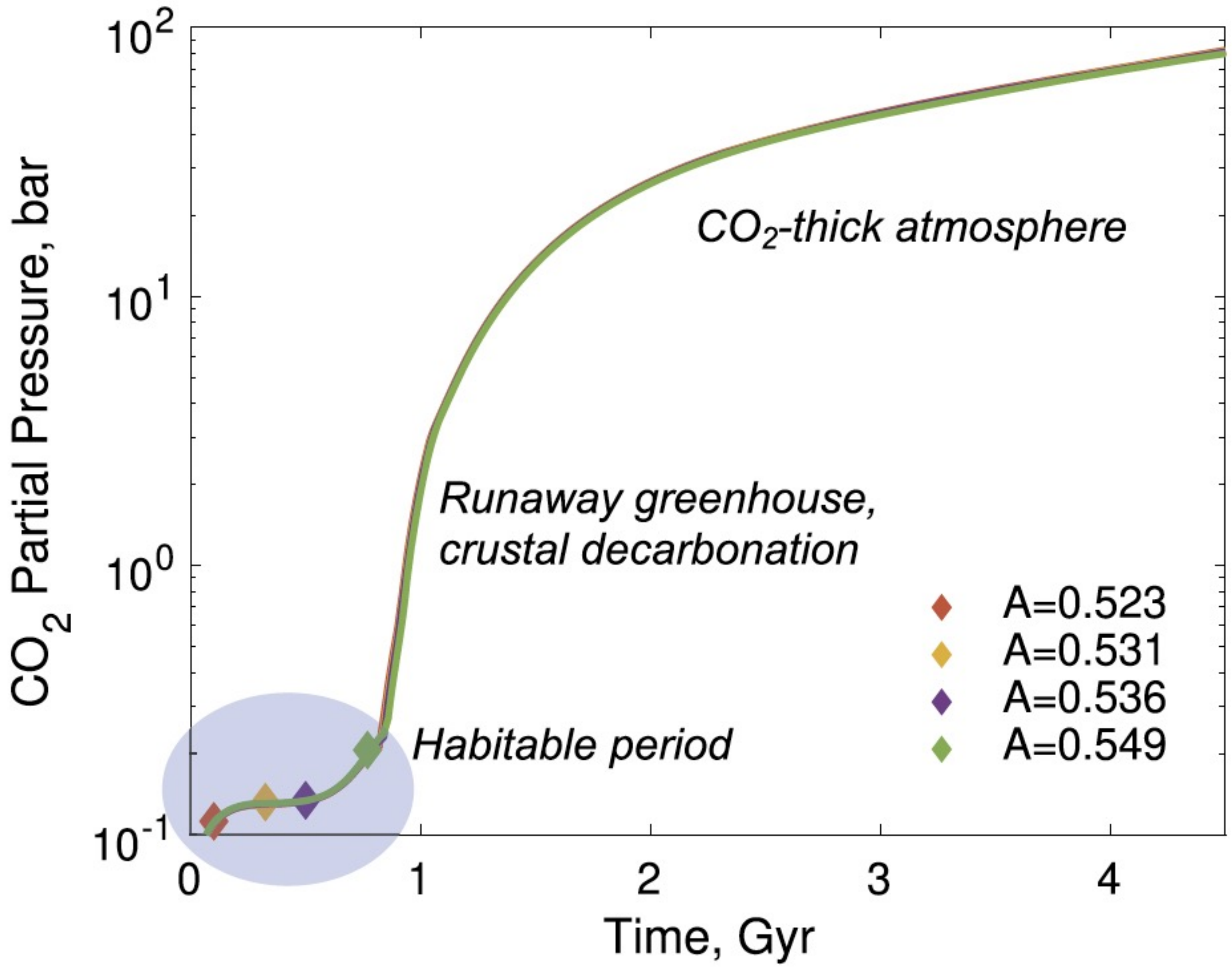


Venus's atmosphere

- the solidification of a magma ocean may have outgassed large amounts of CO2 into the early atmosphere

- The present day atmosphere could be a combination of an early atmosphere resulting from magma ocean solidification, outside contribution from impactors (Gillmann et al. 2020, both early and late) and a later contribution from subsequent long-term magmatic mantle outgassing (Lammer et al. 2018).

- Upcoming missions to Venus: DAVINCI, VERITAS, ENVISION and Shukrayaan-1



Ancient atmosphere of Venus may have been very different

Two main possibilities

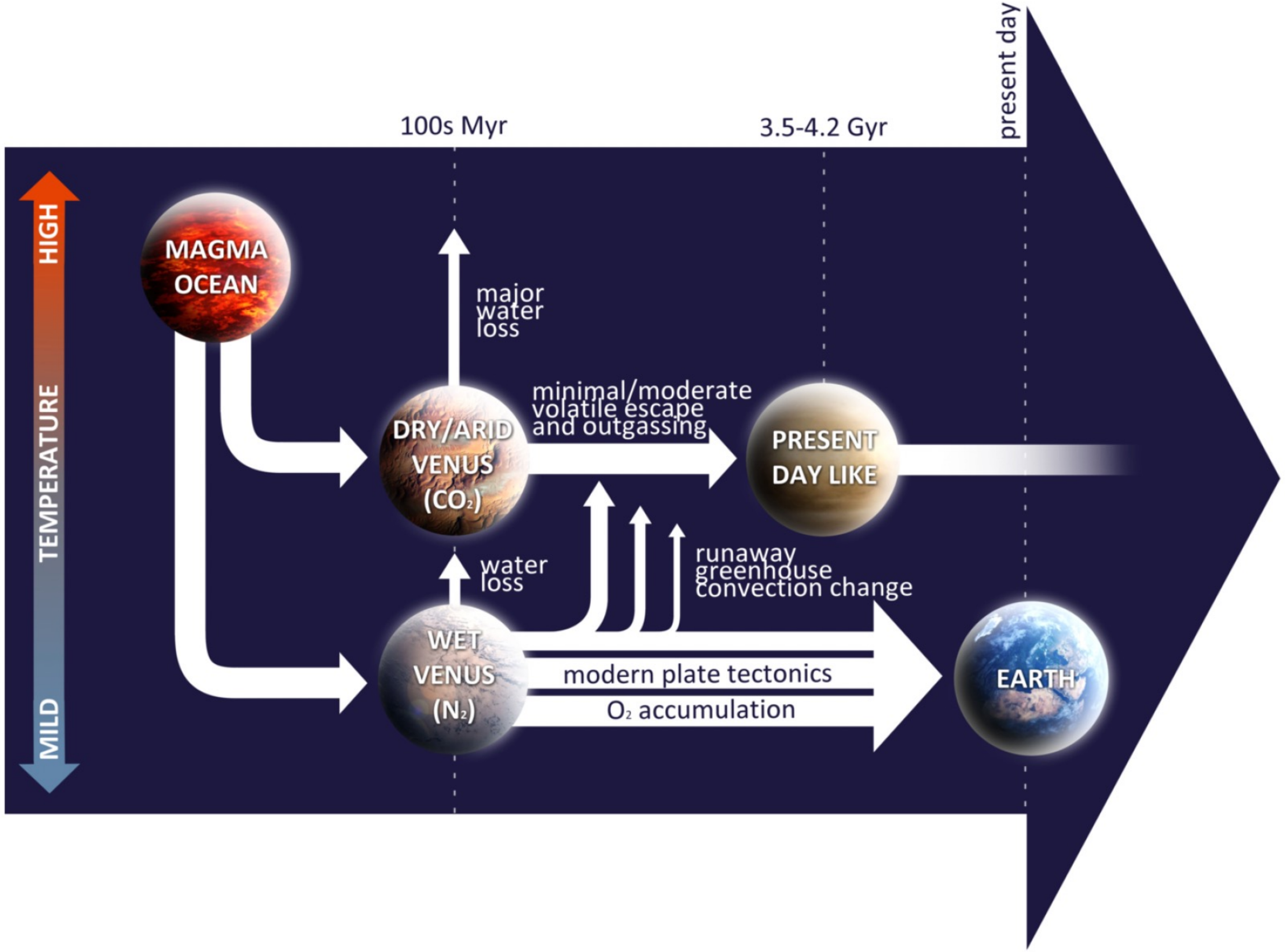
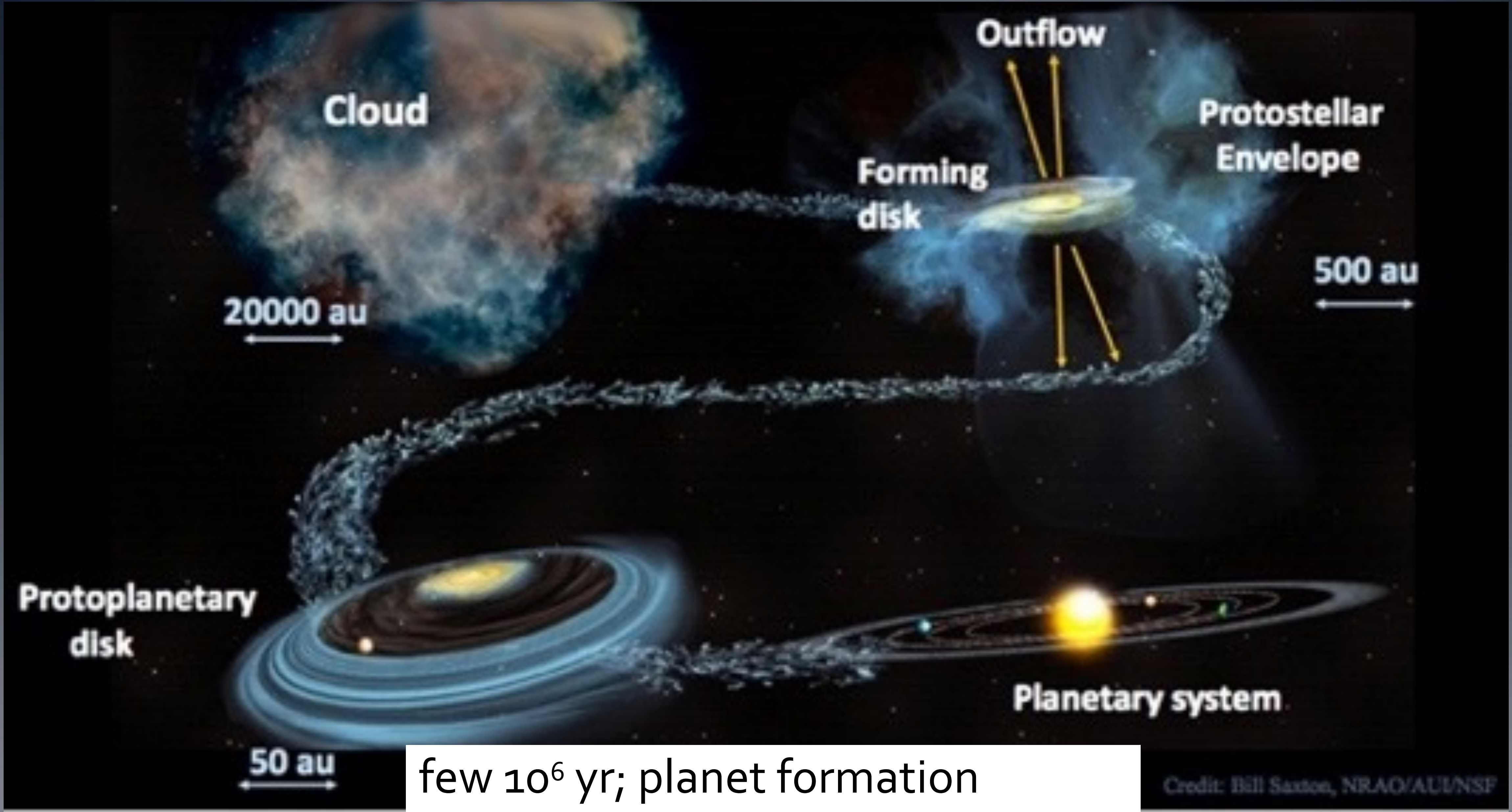


Fig. 10 Current understanding of the extreme tentative scenarios for the evolution of Venus' surface conditions, from its origins to present-day, compared to Earth. On top, Venus lost its surface water early on (desiccated Venus, or stifled outgassing scenarios), while on the bottom evolution, it evolved closer to Earth, retaining a larger portion of its water inventory, until its climate was destabilized. For now, both evolutionary pathways remain consistent with our global knowledge of the planet. Only general evolution trends are represented, Earth-related processes (modern plate tectonics and O_2 accumulation) are not attributed a specific time and only included for comparison with Venus

- The era of a temperate climate could have ended as buried carbonates became unstable at depth and released CO2 into the atmosphere. The rising surface temperature would have moved the decarbonation depth even closer to the surface, leading to a catastrophic outgassing of CO2, thus establishing a strong greenhouse effect (Höning et al. 2021).

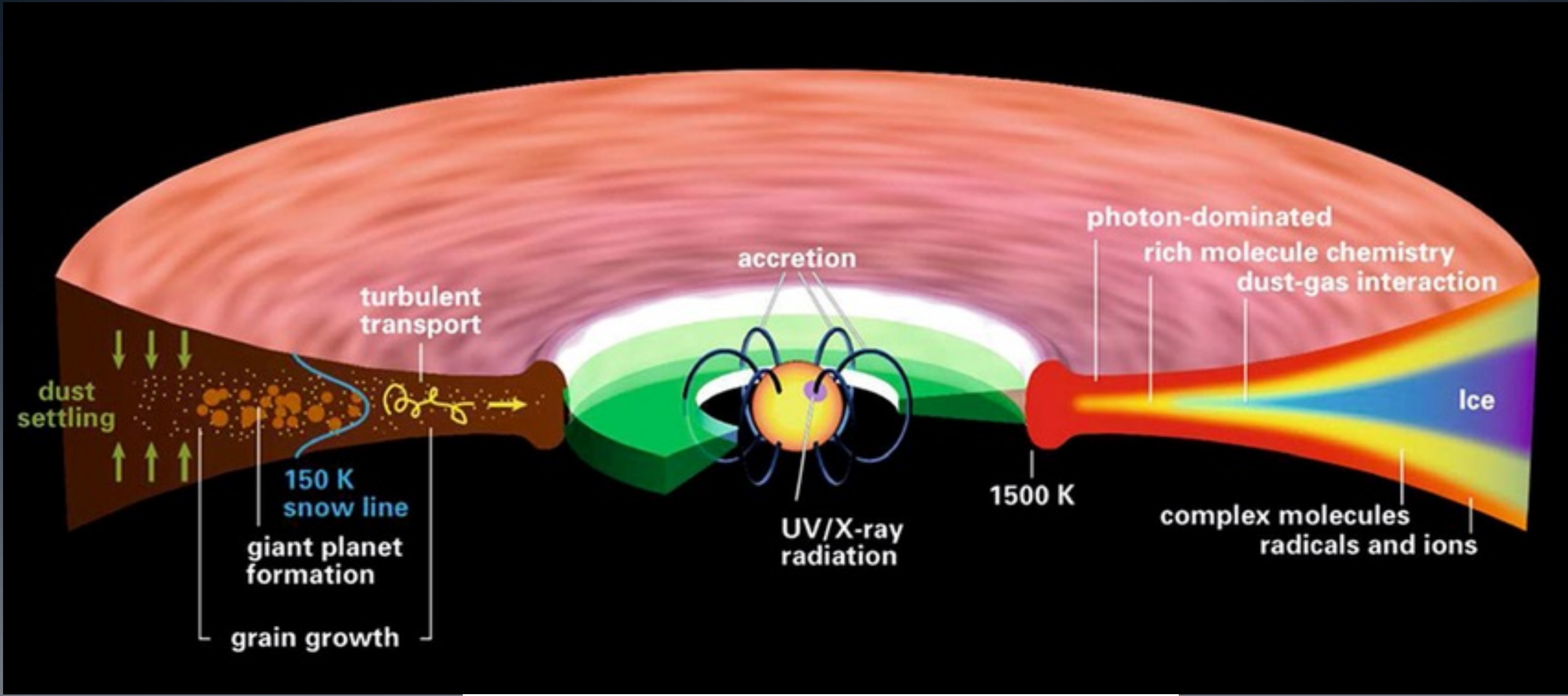
- Early plate tectonics or episodic subduction could also extend the duration of a wet Venus surface via efficient transport of carbonates to the deep mantle, thereby limiting the decarbonation feedback as Venus's surface warms.

Evolution from clouds to planetary systems



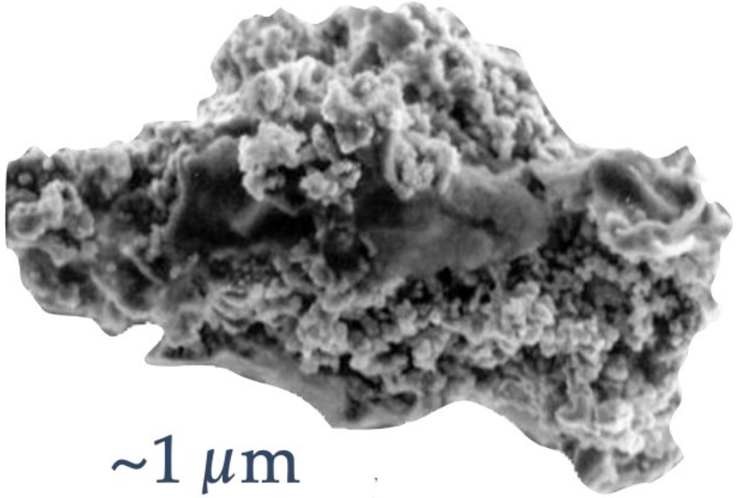
few 10^6 yr; planet formation

Credit: Bill Saxton, NRAO/AUI/NSF



Henning & Semenov (2013)

from



~1 μm

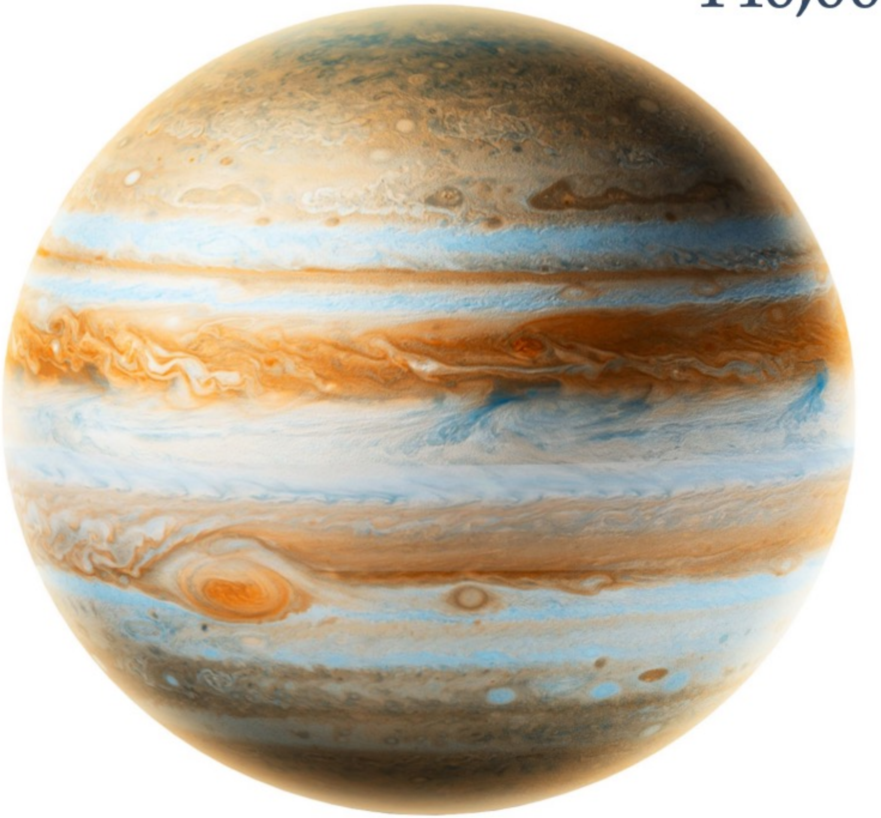
in

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

to

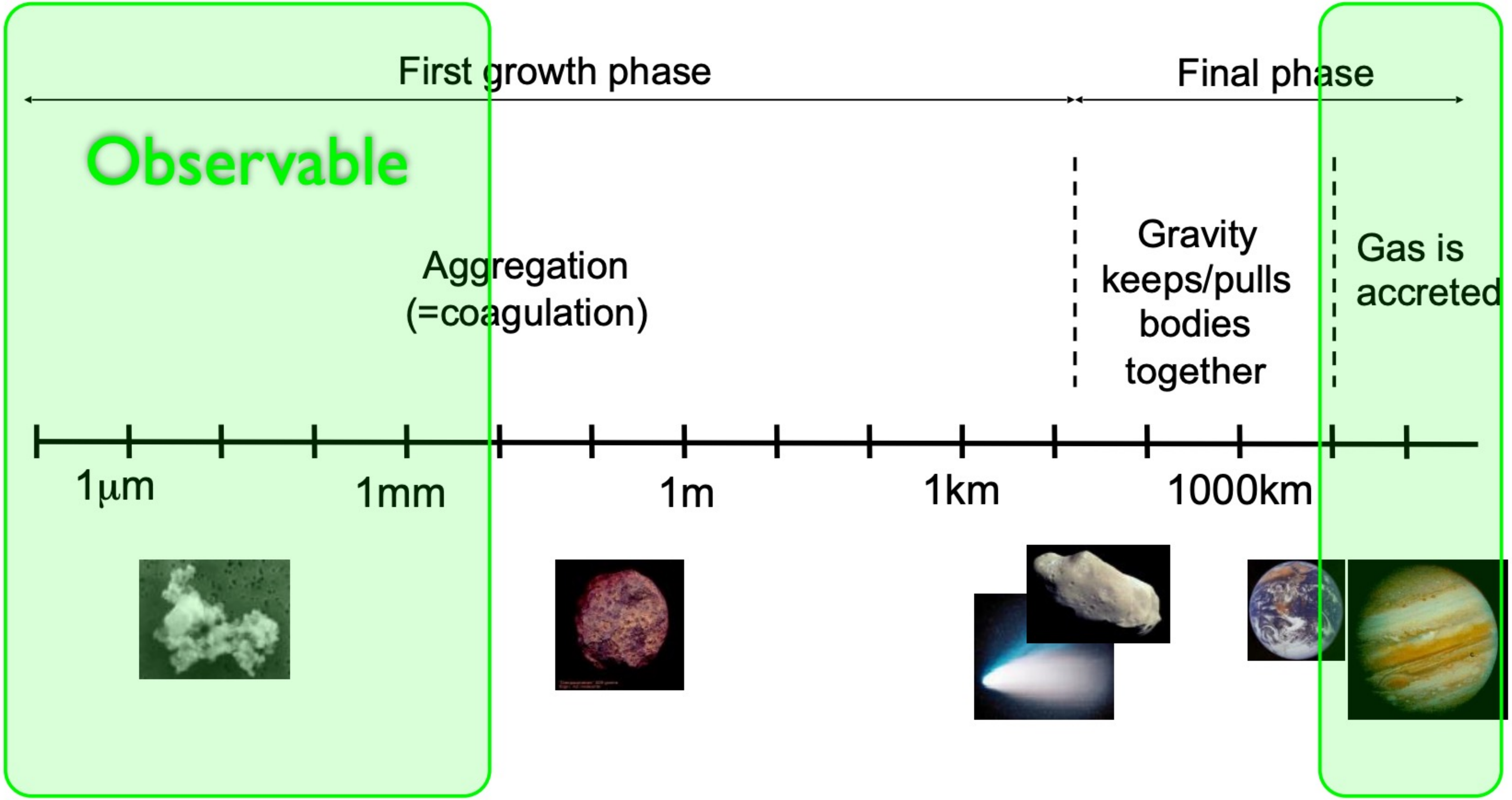
~13,000 km

or



~140,000 km

The long road from dust to planets



First growth phase

Final phase

Observable

Aggregation
(=coagulation)

Gravity
keeps/pulls
bodies
together

Gas is
accreted

Basic disk physics: gas and dust

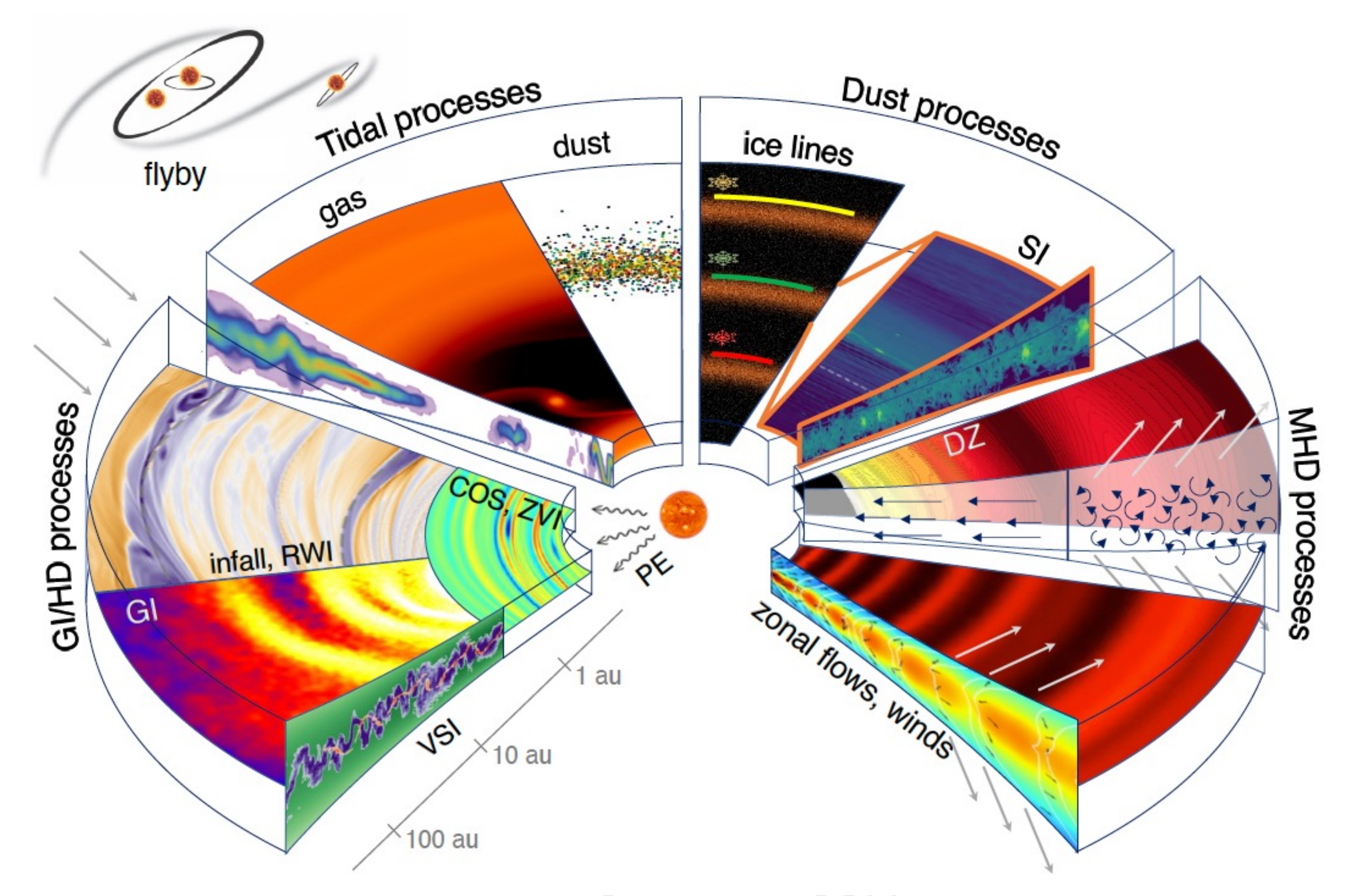
- Gas and dust flow through the disk (radially and vertically)

- 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

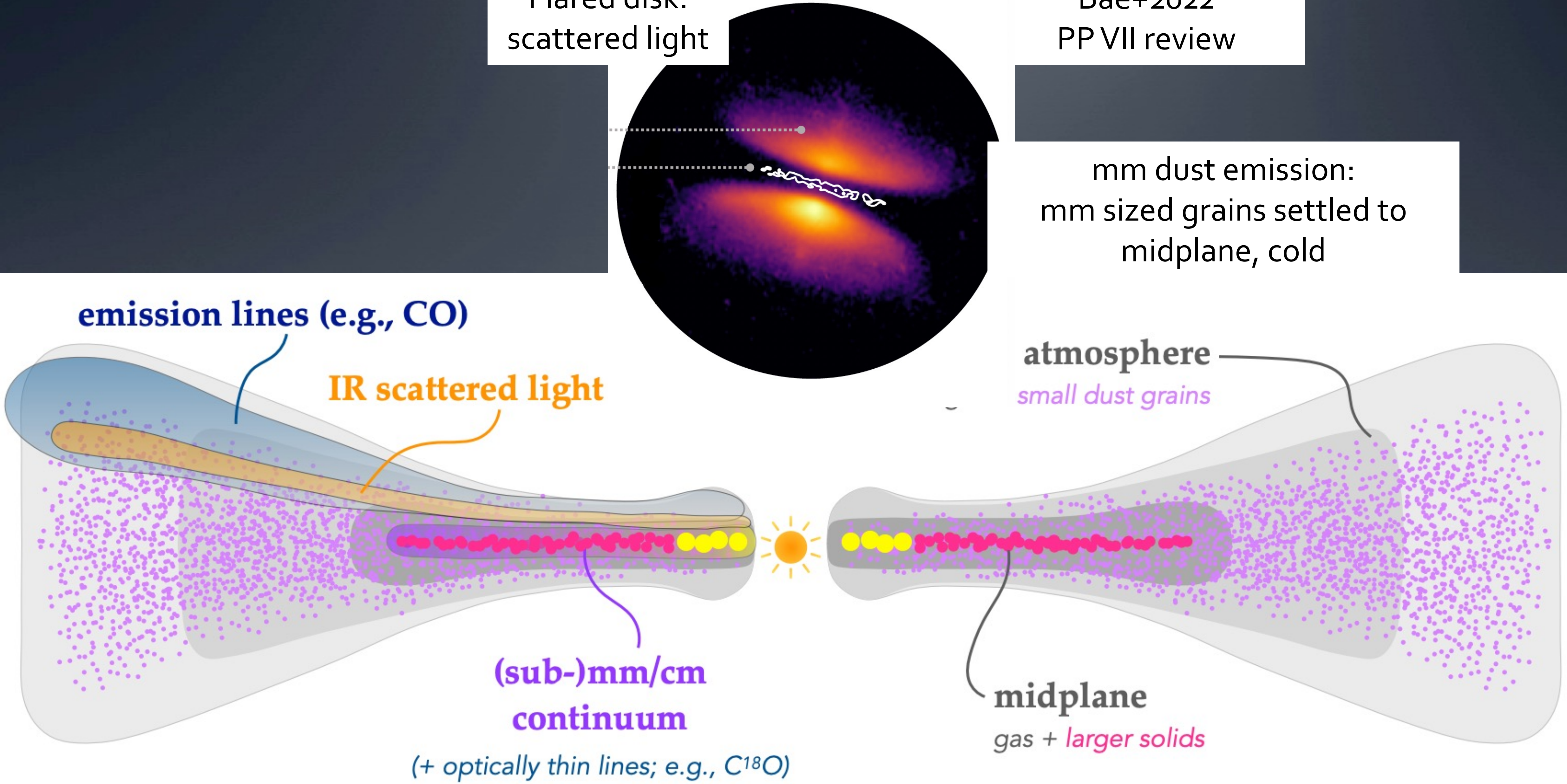
- Complicated combination of microphysics and chemistry

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



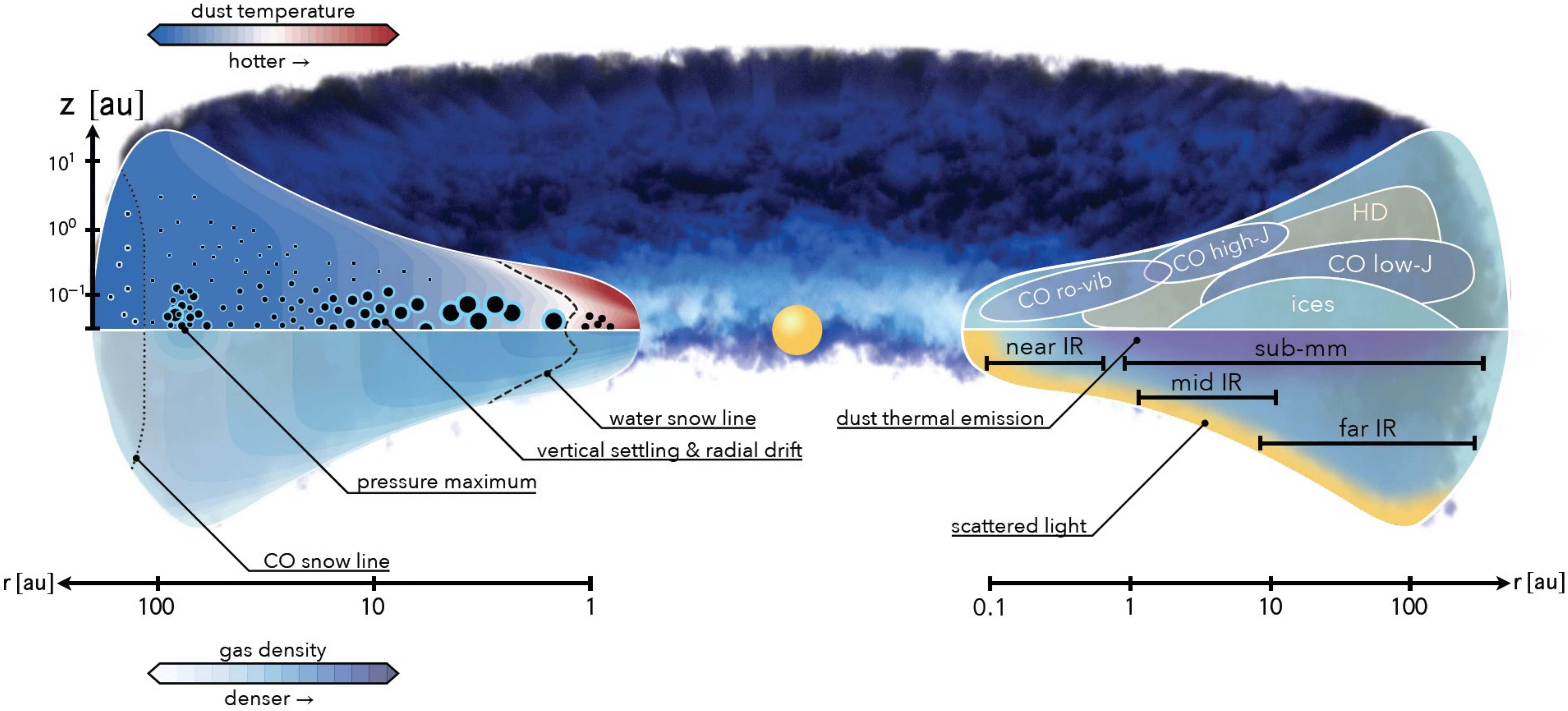
Bae+2022 PPVII



Flared disk:
scattered light

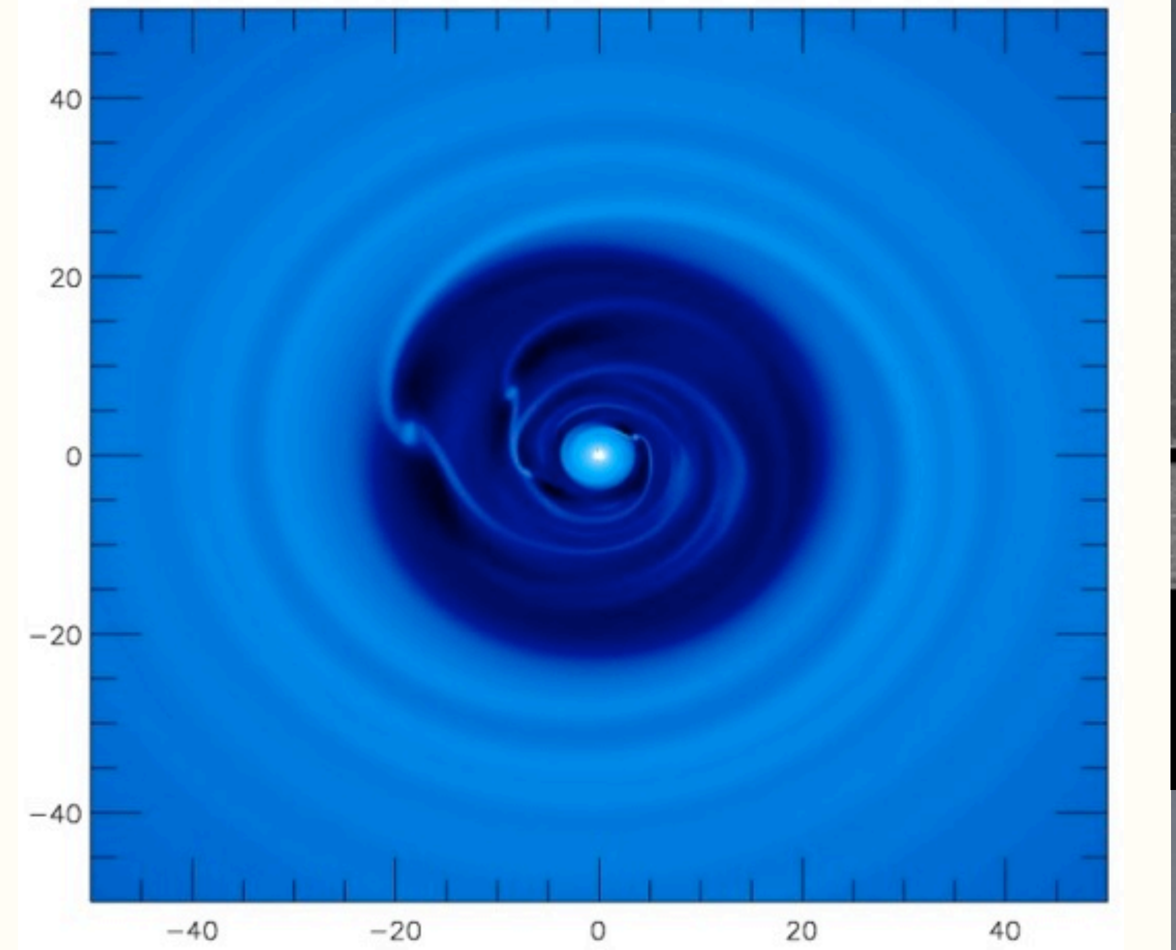
Bae+2022
PP VII review

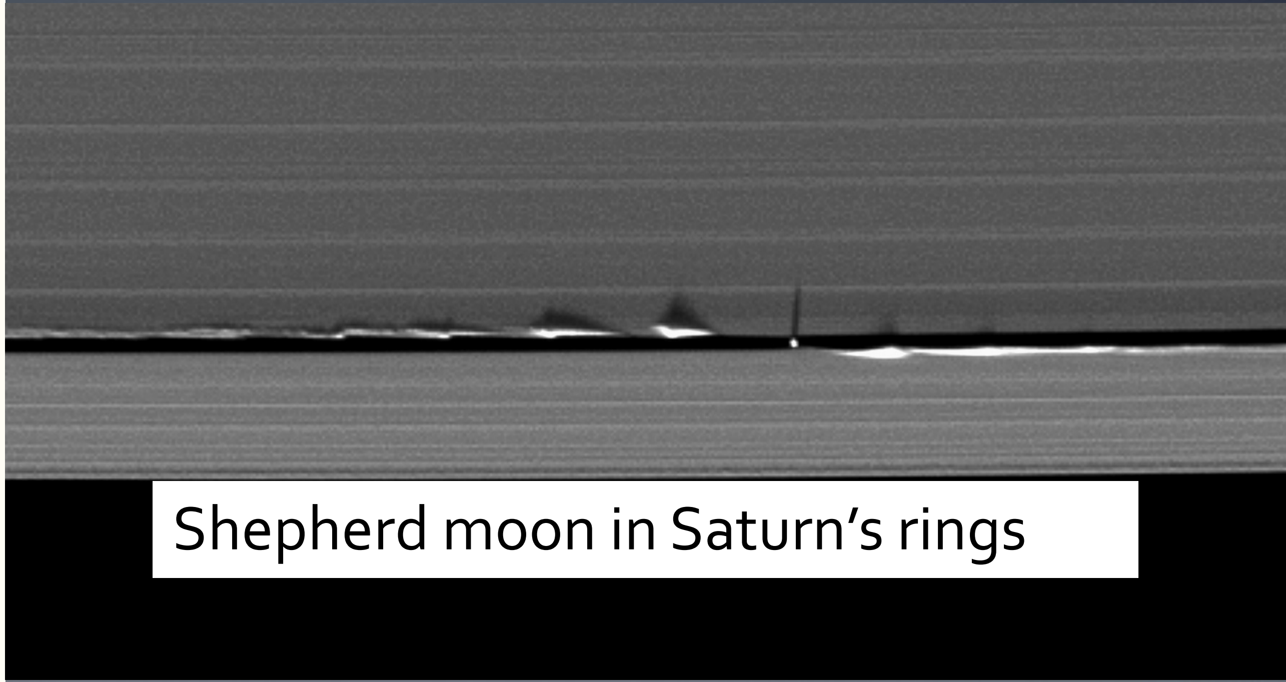
mm dust emission:
mm sized grains settled to midplane, cold


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

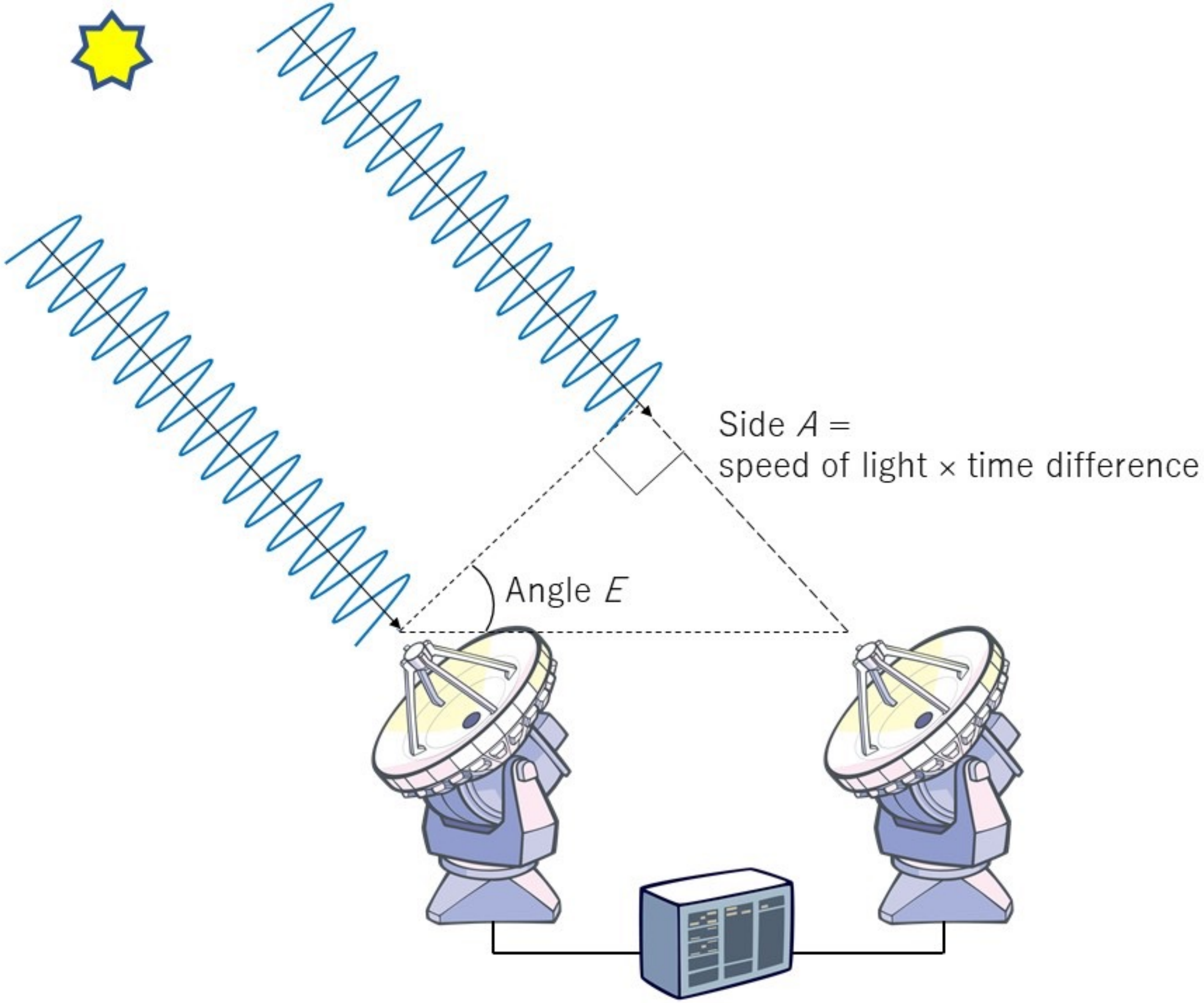
Atacama Large Millimeter Array (ALMA)

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

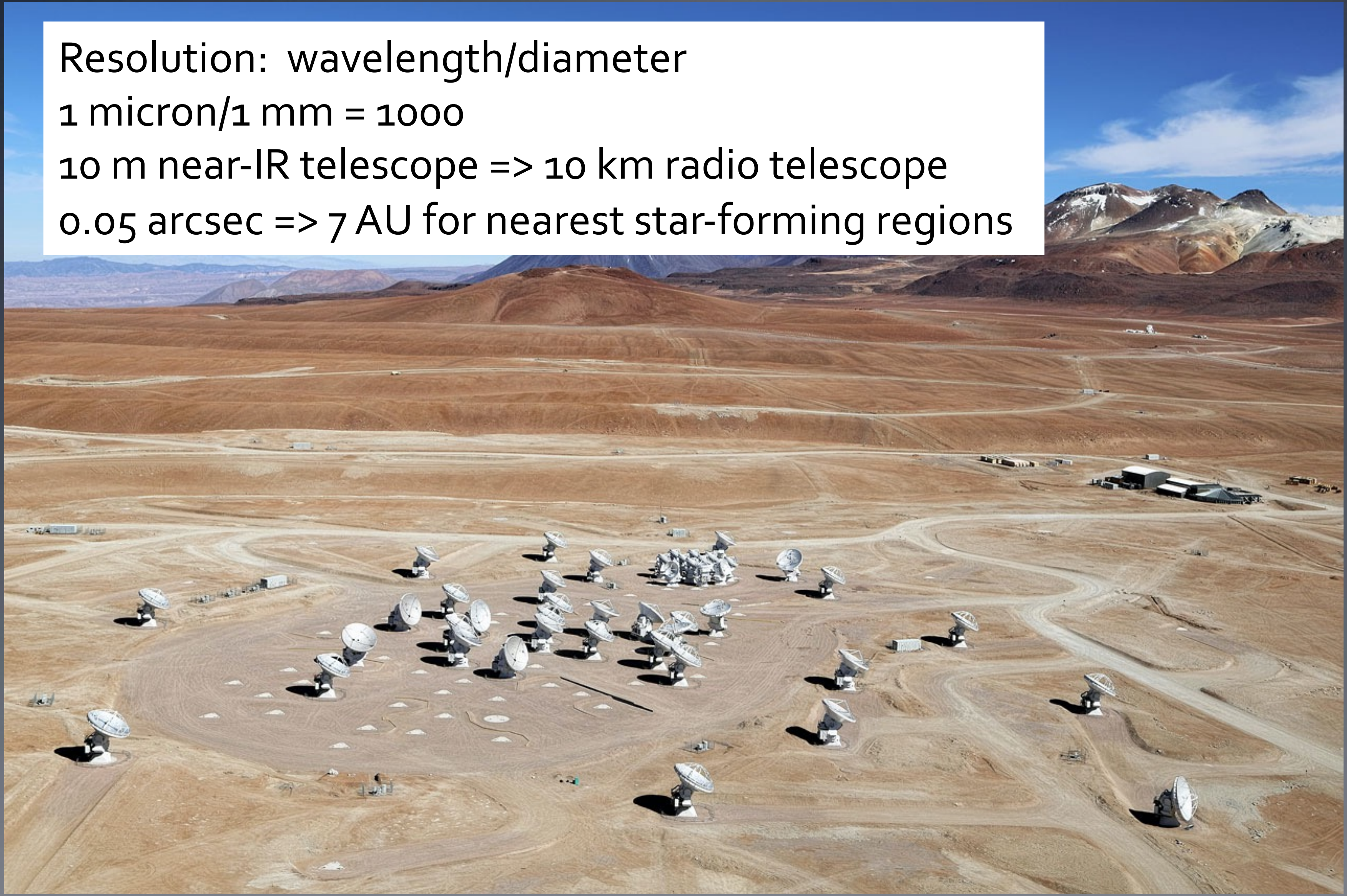
Interferometer

Combine light from different telescopes

Spatial resolution: corresponds to distance between telescopes



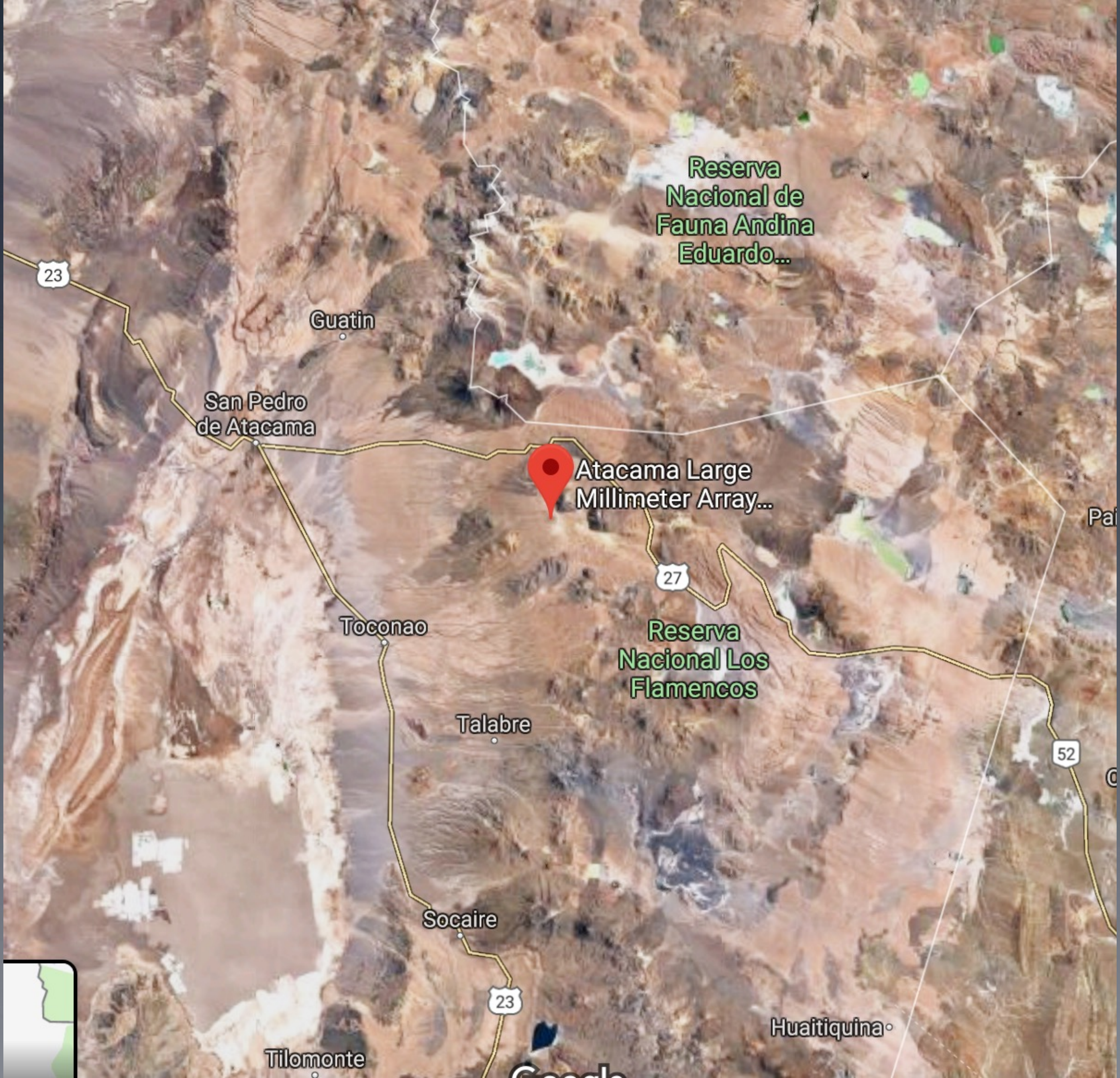
Atacama Large Millimeter Array (ALMA)



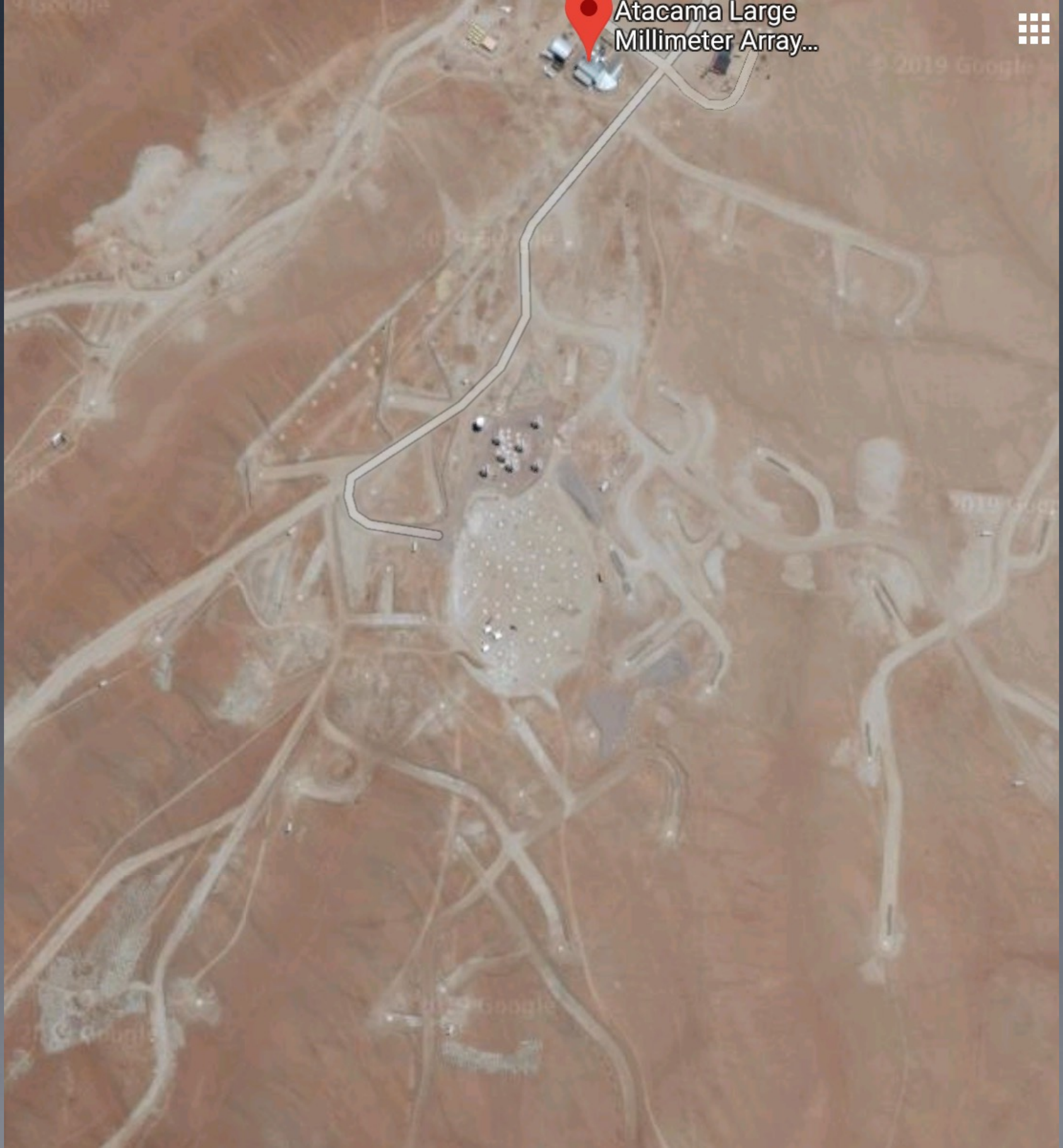
Resolution: wavelength/diameter
1 micron/1 mm = 1000
10 m near-IR telescope => 10 km radio telescope
0.05 arcsec => 7 AU for nearest star-forming regions

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

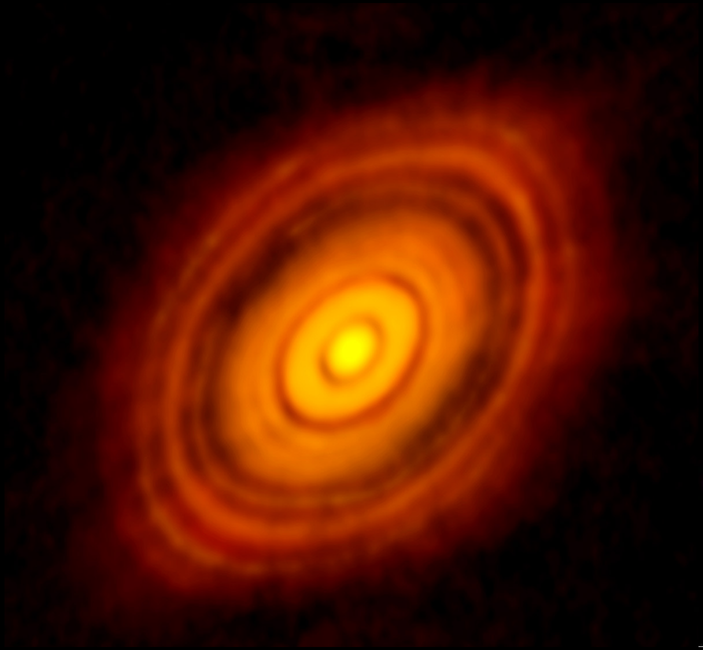

Cali
Colombia
Guyana
French Guiana
Quito
Ecuador
STATE OF RORAIMA
STATE OF AMAPÁ
STATE OF AMAZONAS
STATE OF ACRE
STATE OF PARÁ
Peru
Brazil
STATE OF CEARÁ
Lima District
STATE OF RONDÔNIA
STATE OF MATO GROSSO
STATE OF TOCANTINS
Bolivia
STATE OF BAHIA
STATE OF GOIÁS
Salvador
Atacama Large Millimeter Array...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

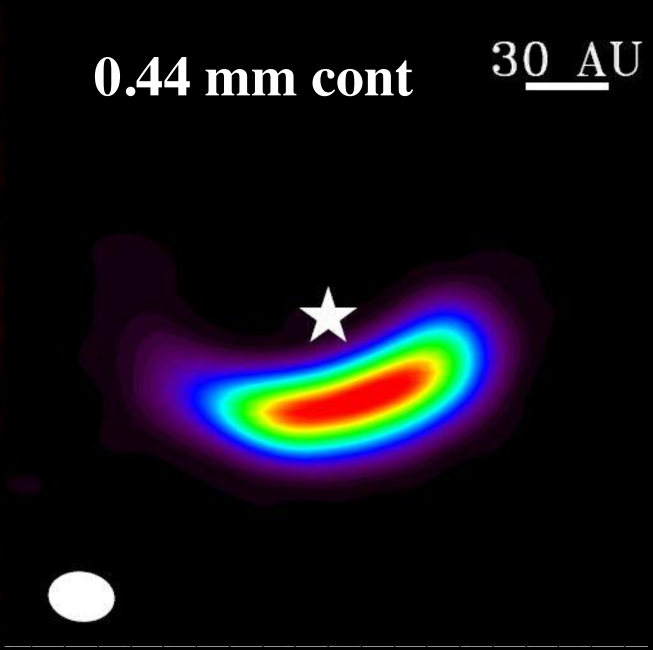

Reserva Nacional de Fauna Andina Eduardo...
23
Guatin
San Pedro de Atacama
Atacama Large Millimeter Array...
Pai
27
Toconao
Reserva Nacional Los Flamencos
Talabre
52
Socaire
23
Huaitiquina
Tilomonte
Google

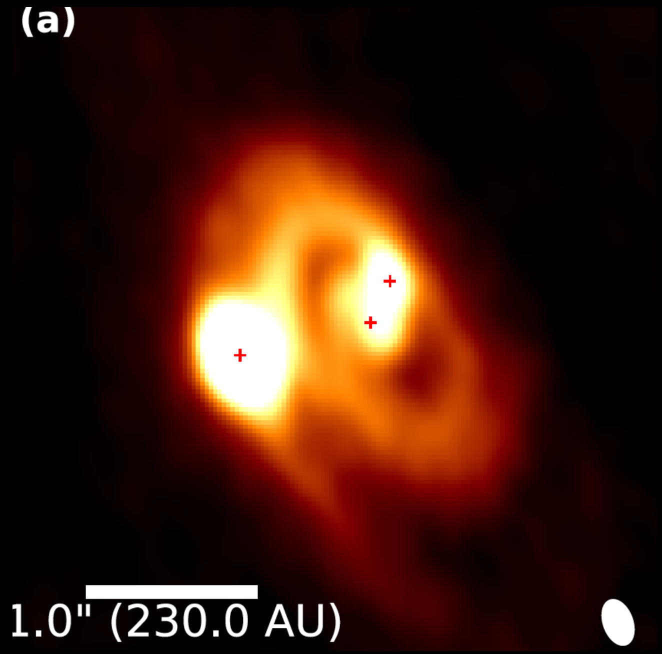

Complejo de Puricó
Atacama Large Millimeter Array...


Atacama Large Millimeter Array...
© 2019 Google

The ALMA revolution:
Dust structures in protoplanetary disks

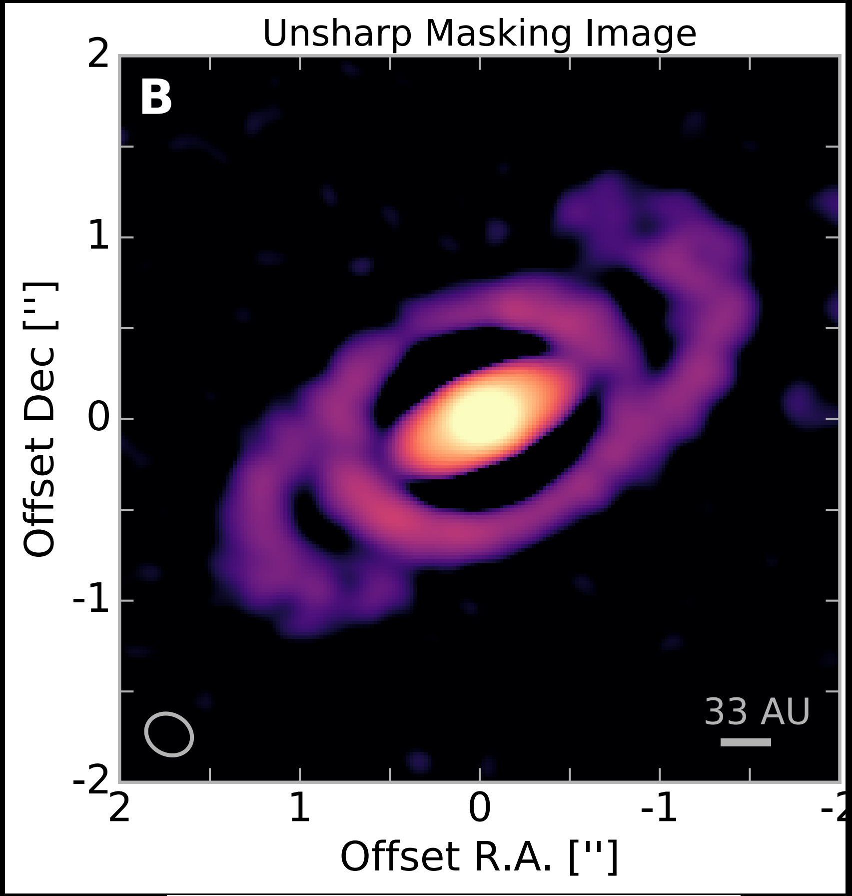




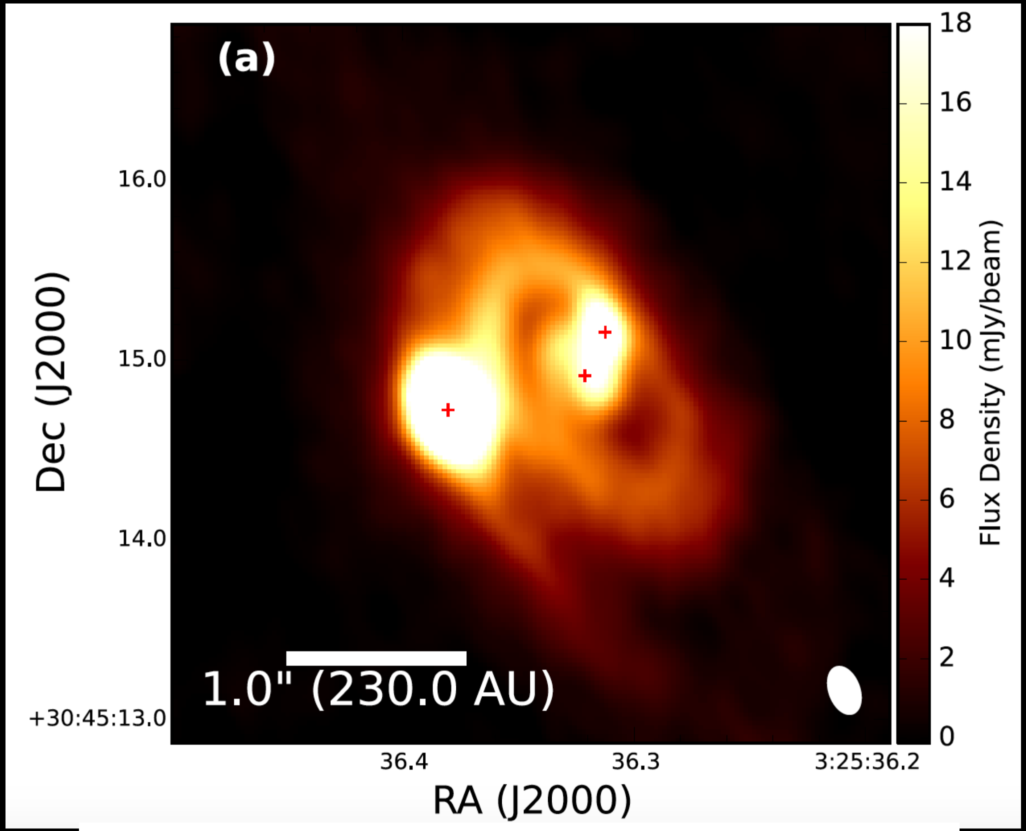


Signs of planets?

Spirals in young protoplanetary disks



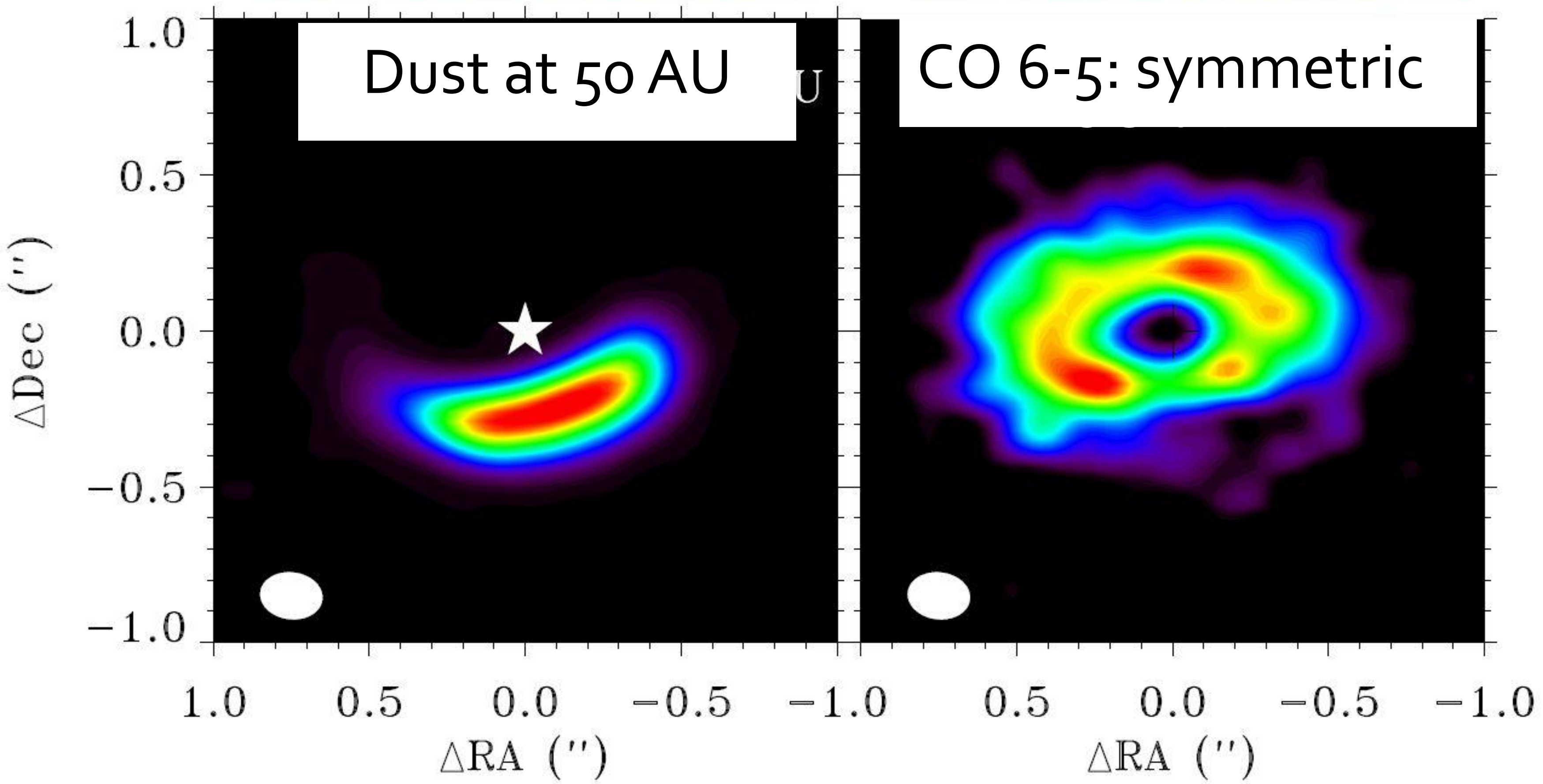
spiral density waves
(Perez+2016)



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

Dust trap in a transition disks

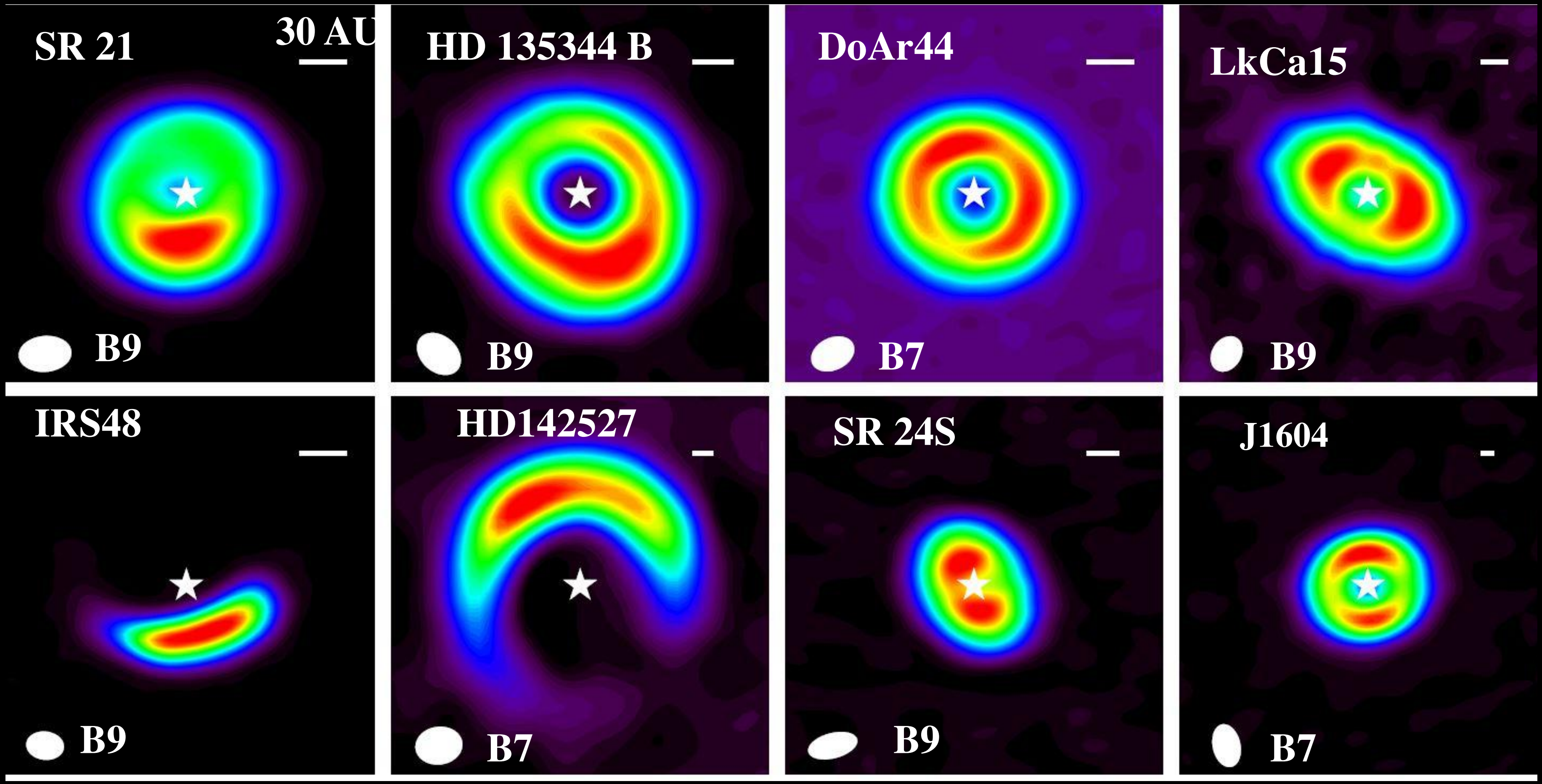
(van der Marel+2013, 2015)

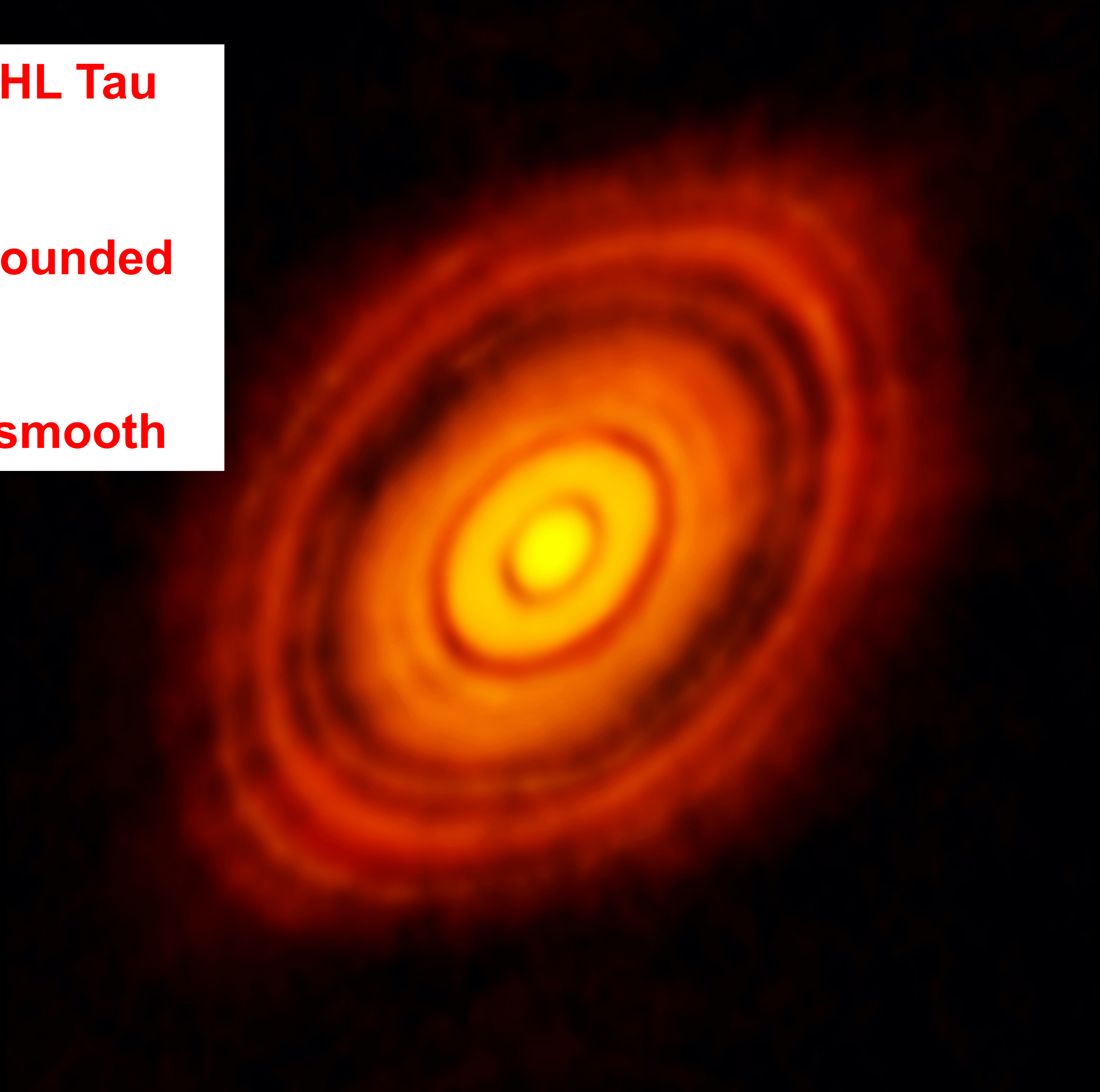


Planet inside hole: Vortex? Comet/KBO factory?

Dust traps with ALMA

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

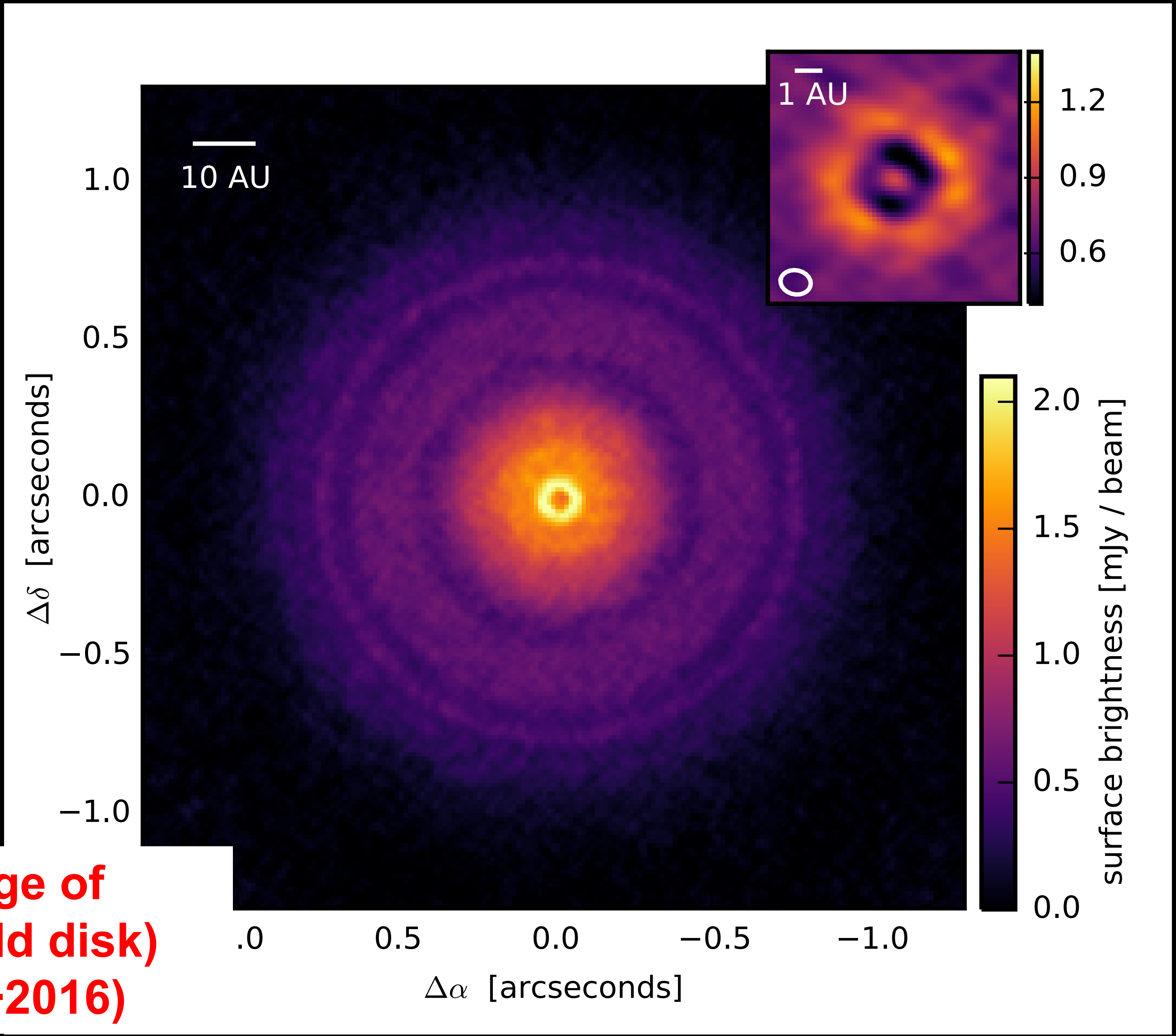




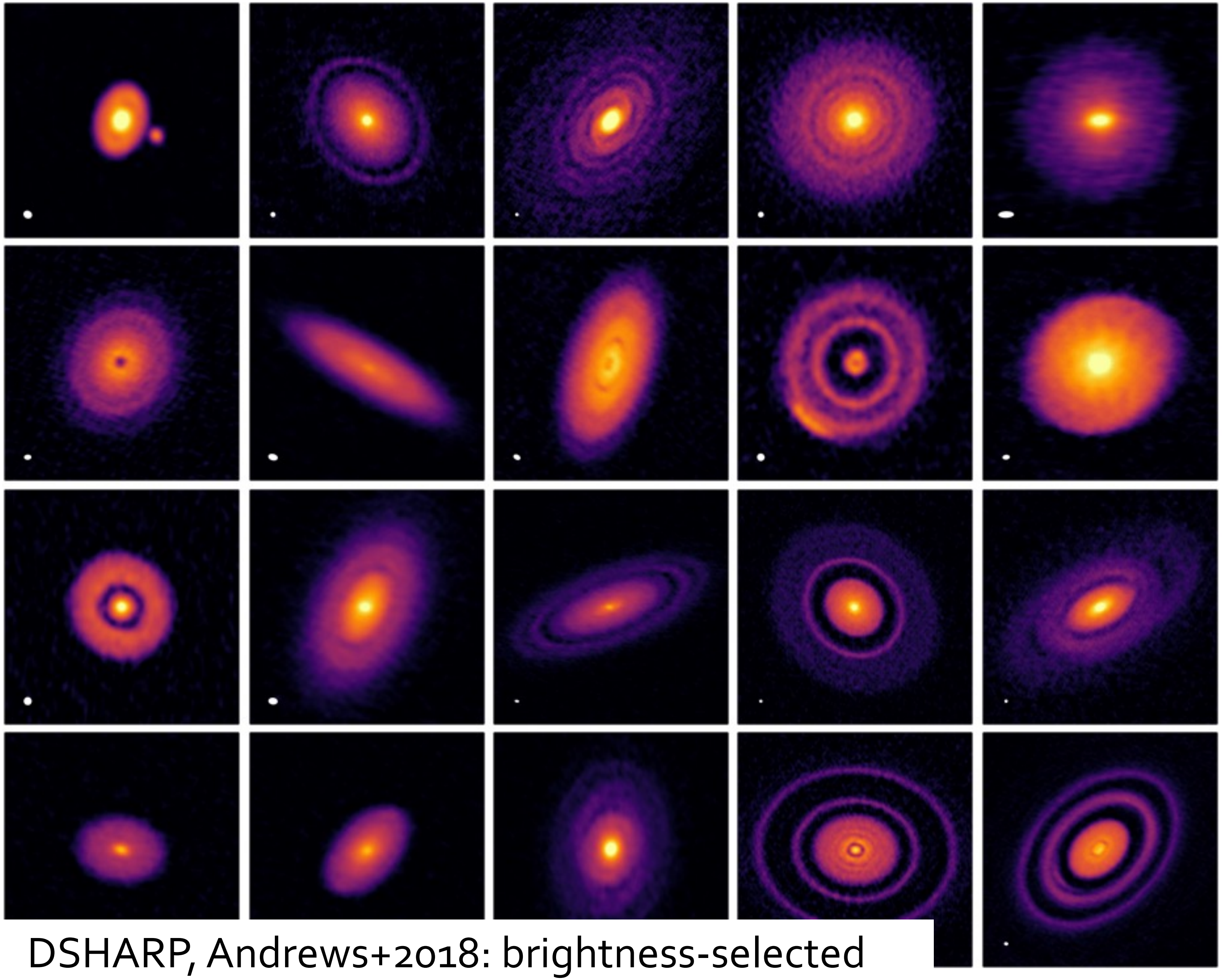
ALMA Image of HL Tau disk

Young disk surrounded by an envelope

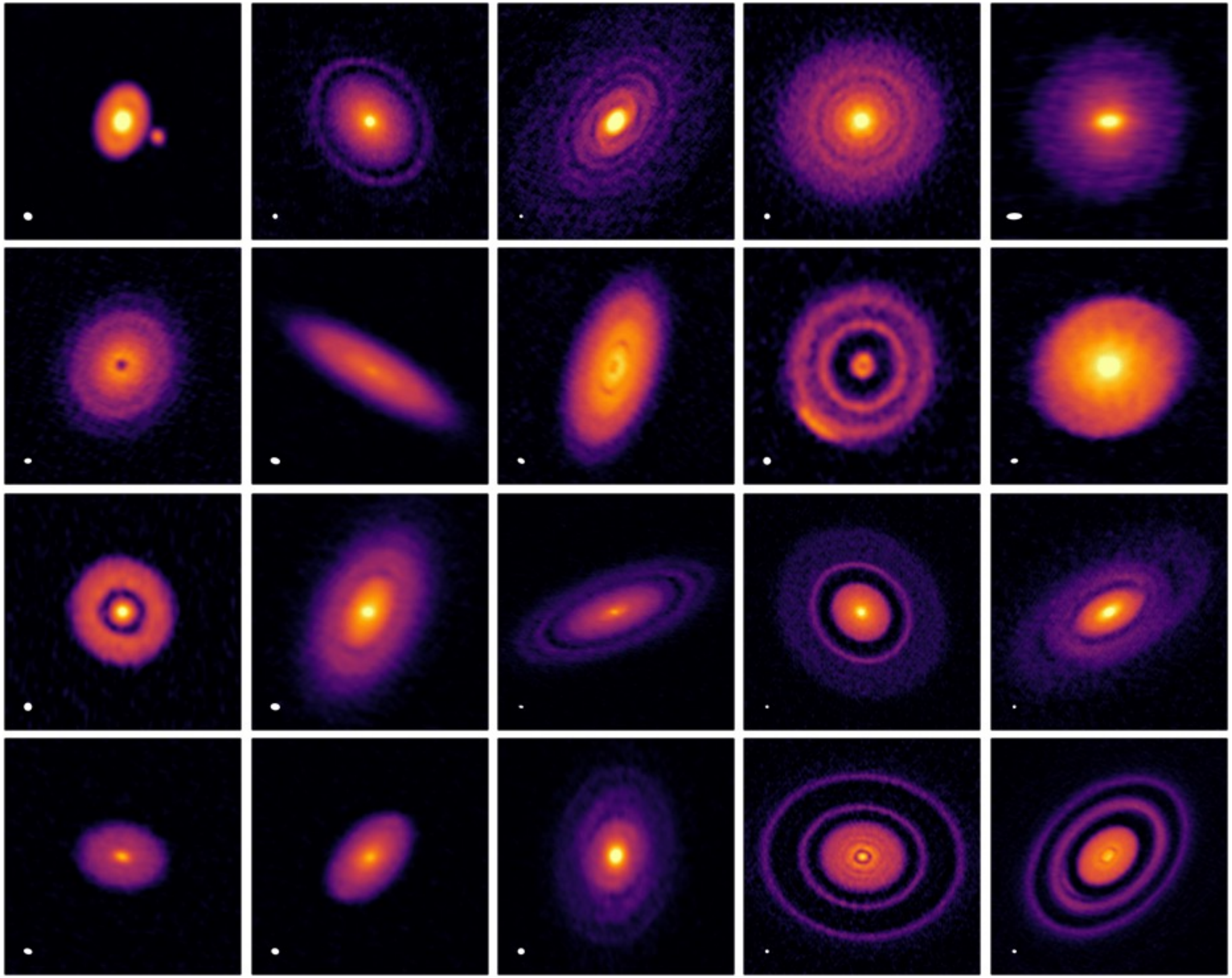
Expected to be smooth



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



DSHARP, Andrews+2018: brightness-selected

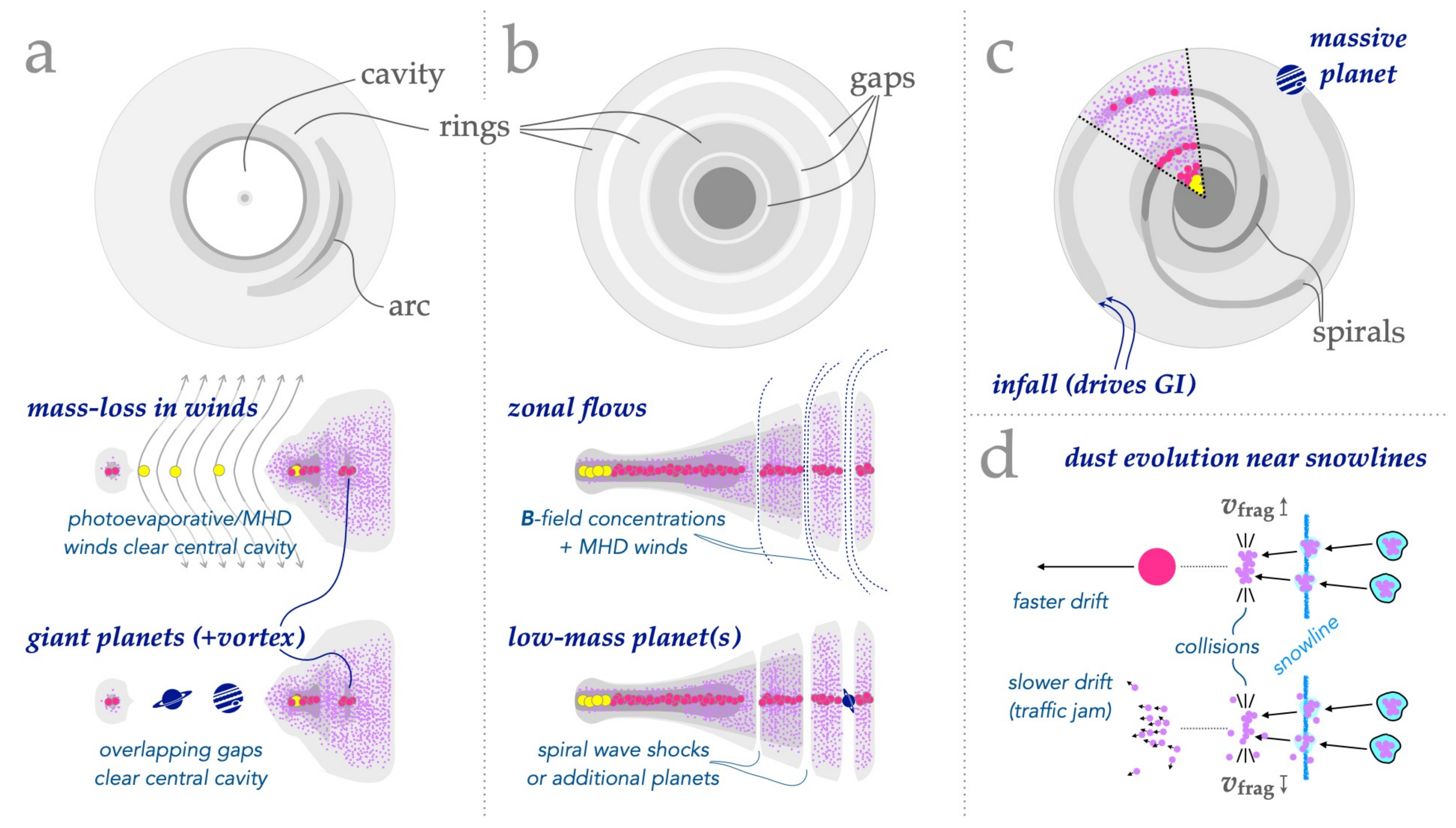


Are rings evidence for planets that already exist?

Or are they created by other physics?

Locations where planet cores may grow?

Chicken/egg problem

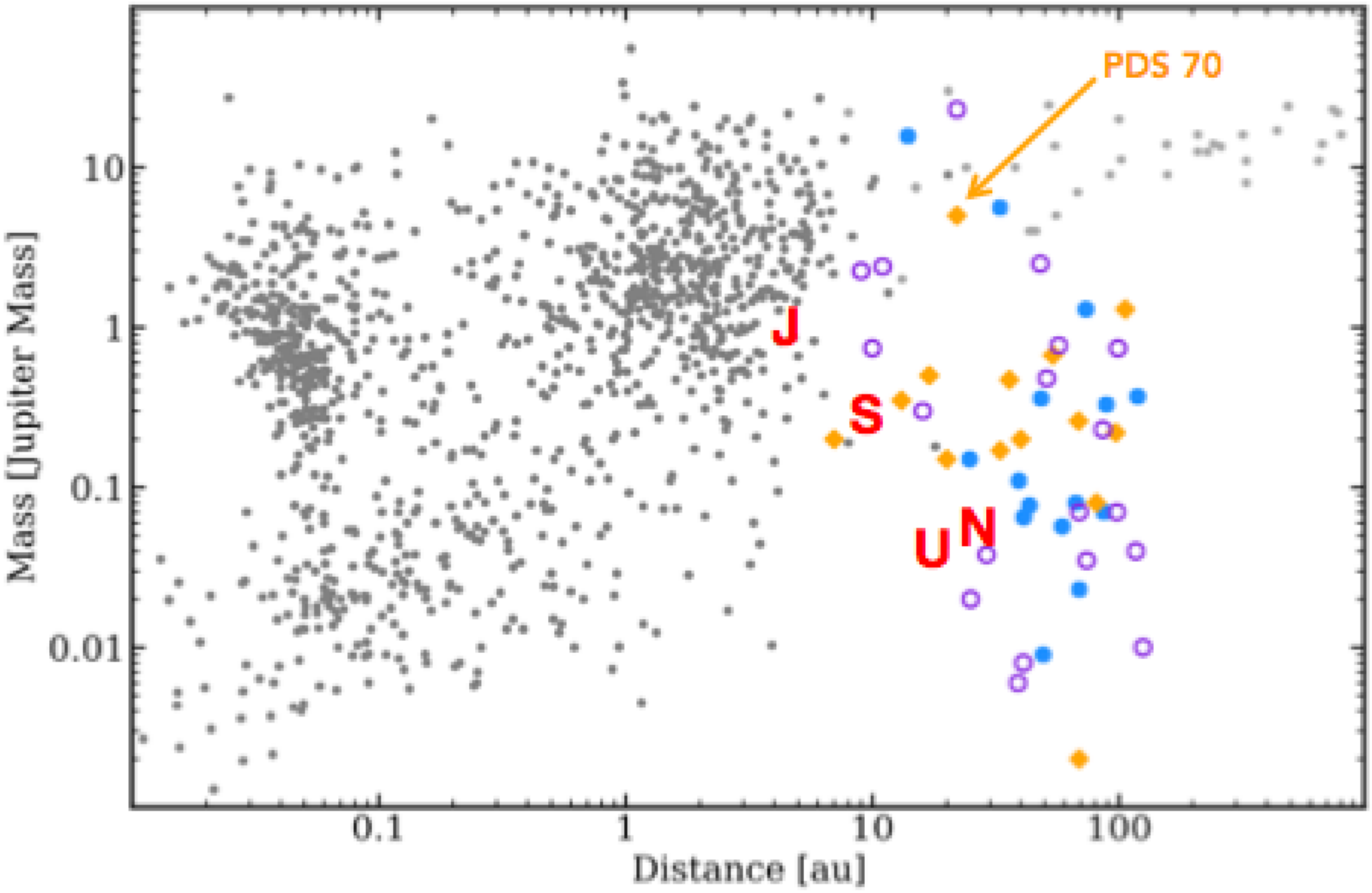


Andrews (2020, ARAA)

What if the gaps are carved by young planets?

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

gap-inferred planet population

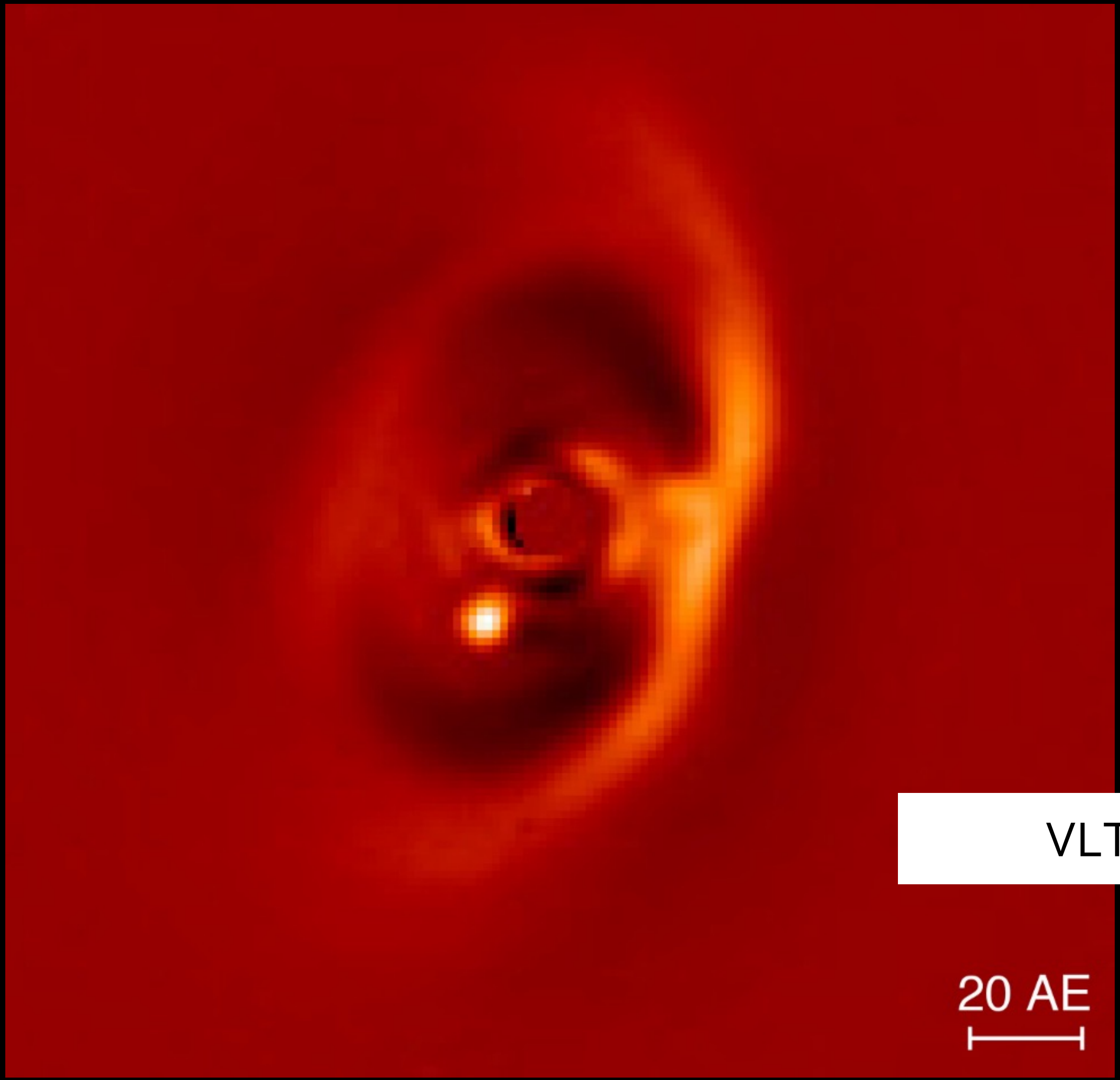


Mass of planet inferred from size and location of the gap

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

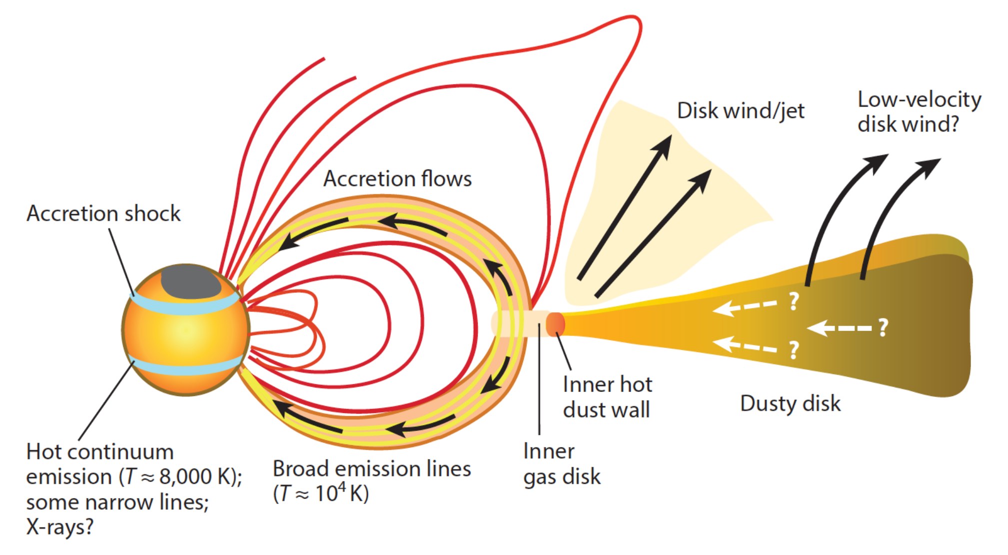
Planet(s) in a disk around the star PDS 70!

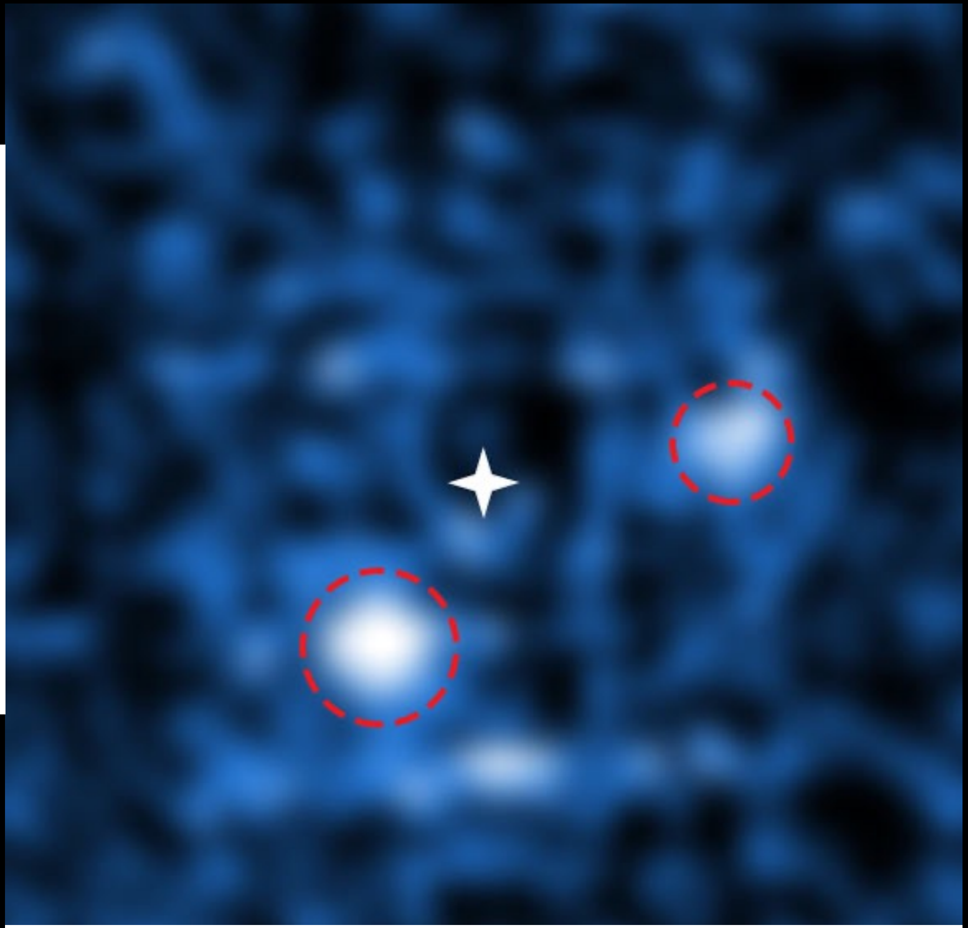
(Keppler et al. 2018)



VLT/Sphere

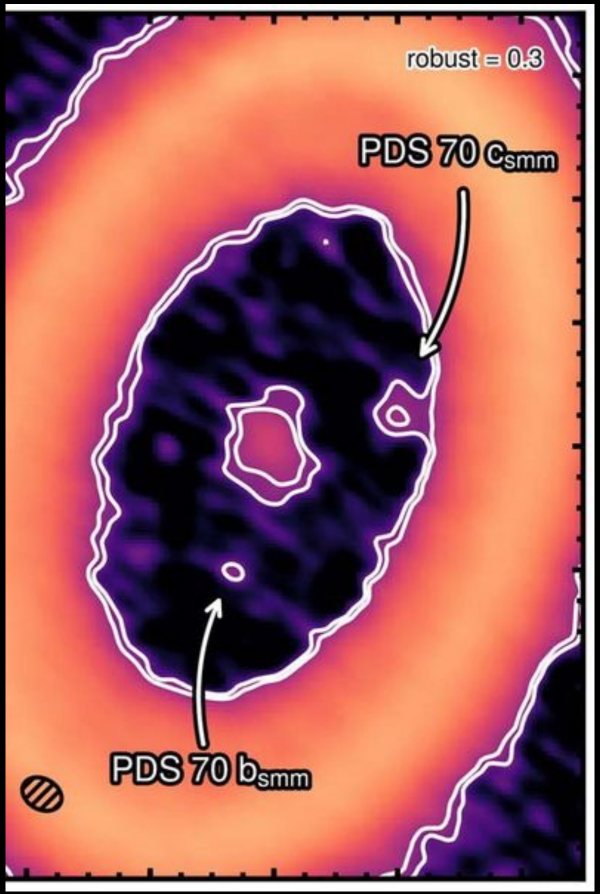
Proto-lunar disks around PDS 70bc?

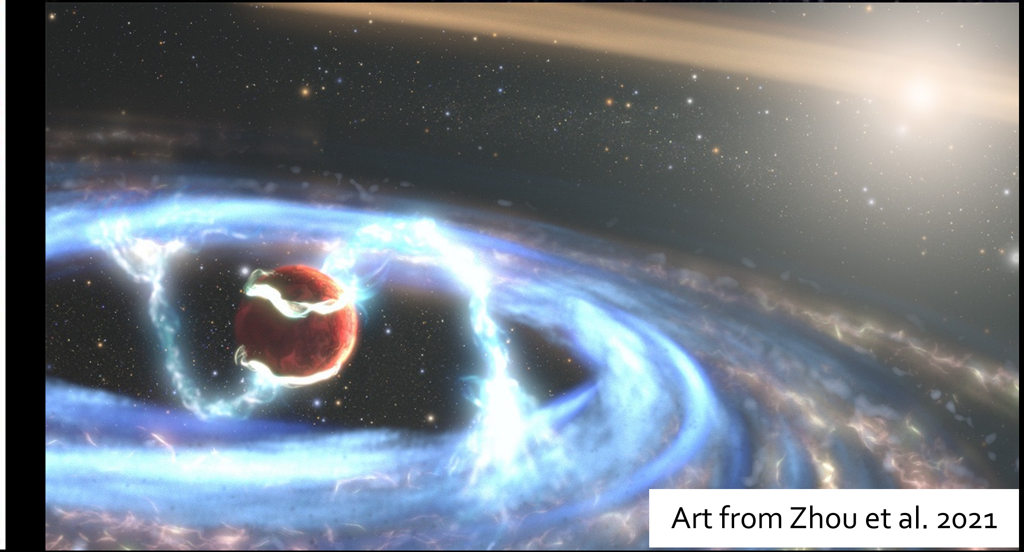


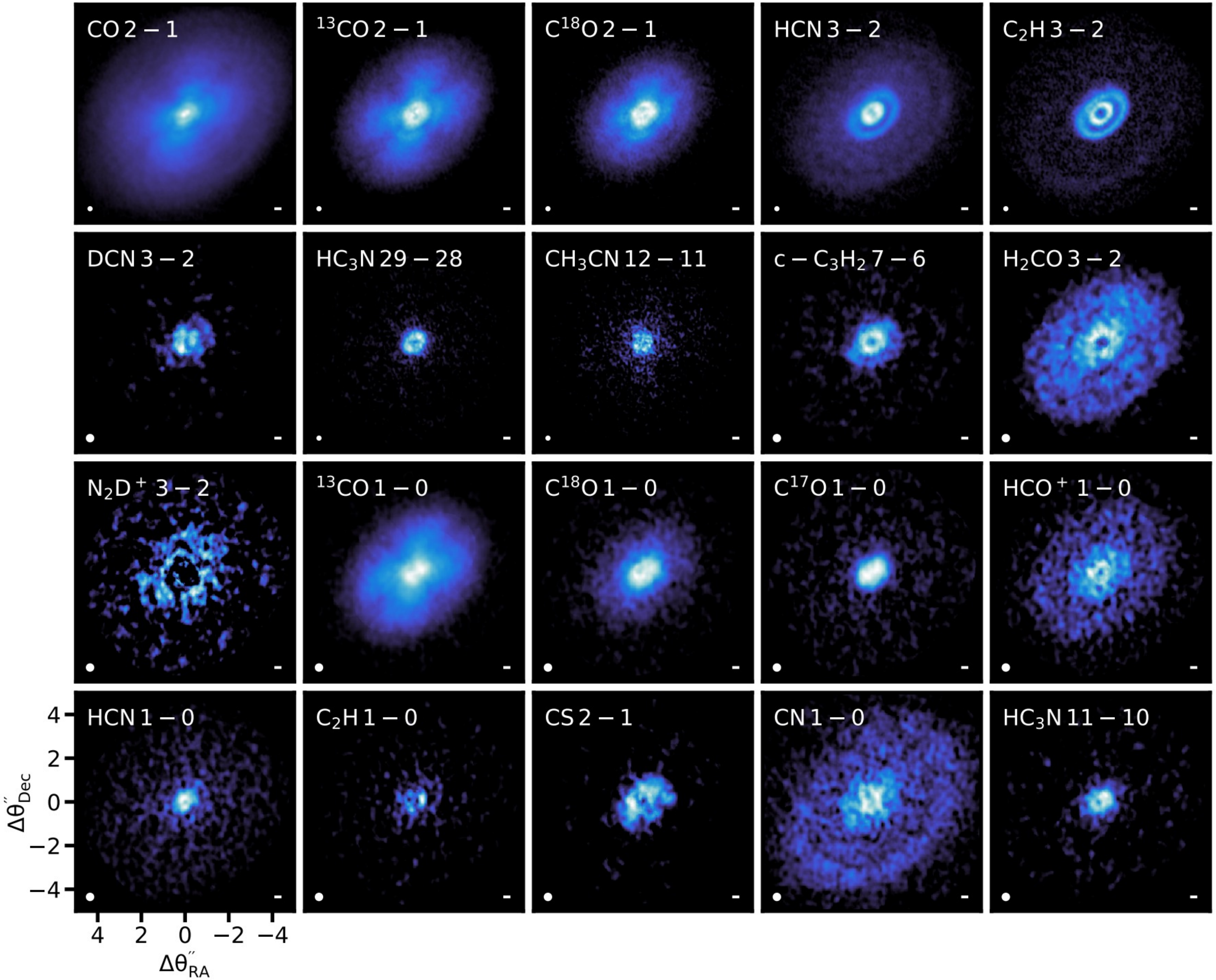


MUSE/H-alpha accretion, Haffert+2019
See also, eg., Bowler+2013; Zhou, Herczeg, et al. 2014; Wagner+2019

Proto-lunar disks around PDS 70bc?



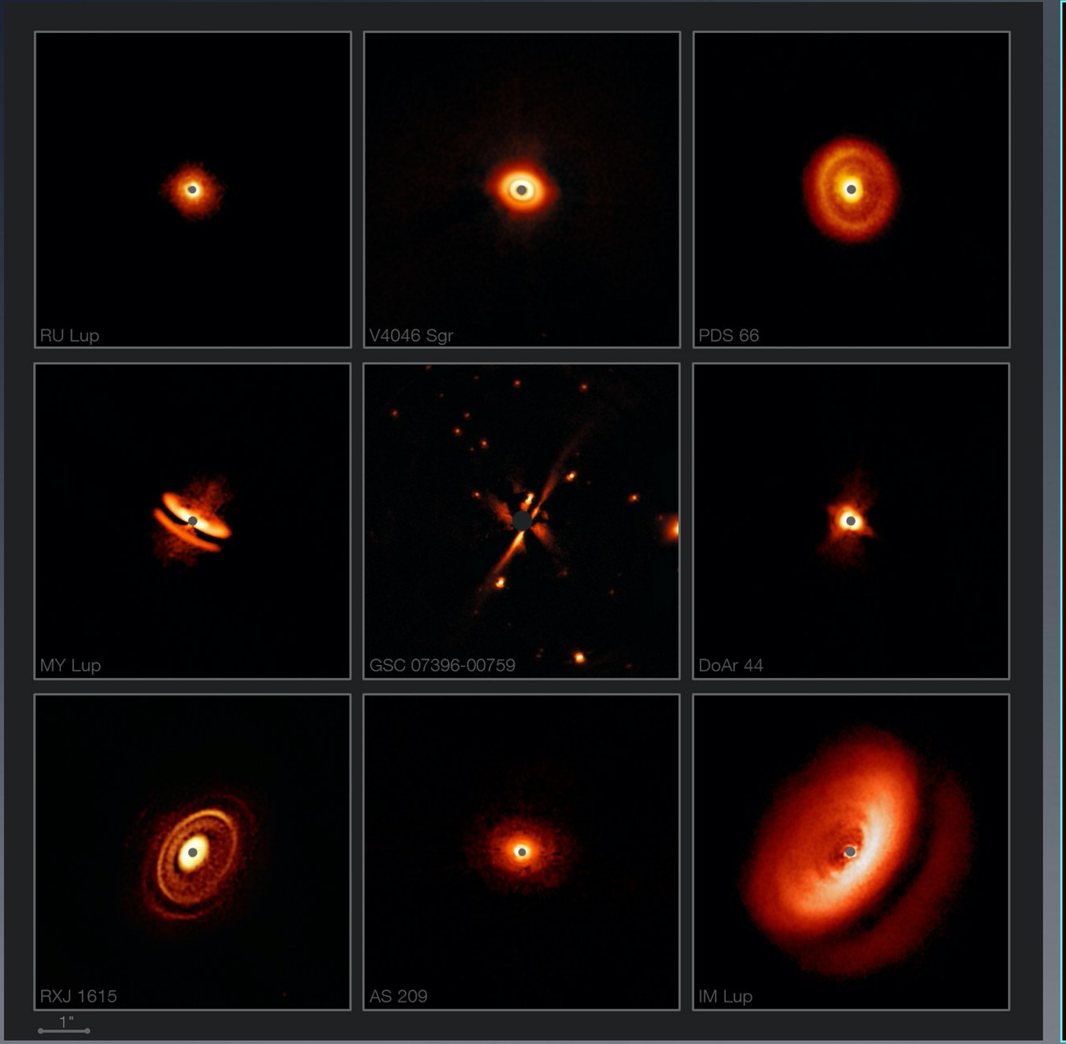

Art from Zhou et al. 2021

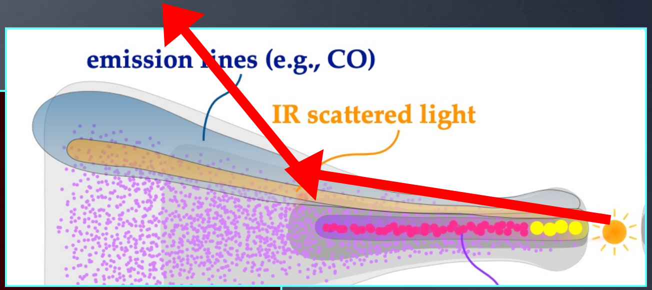


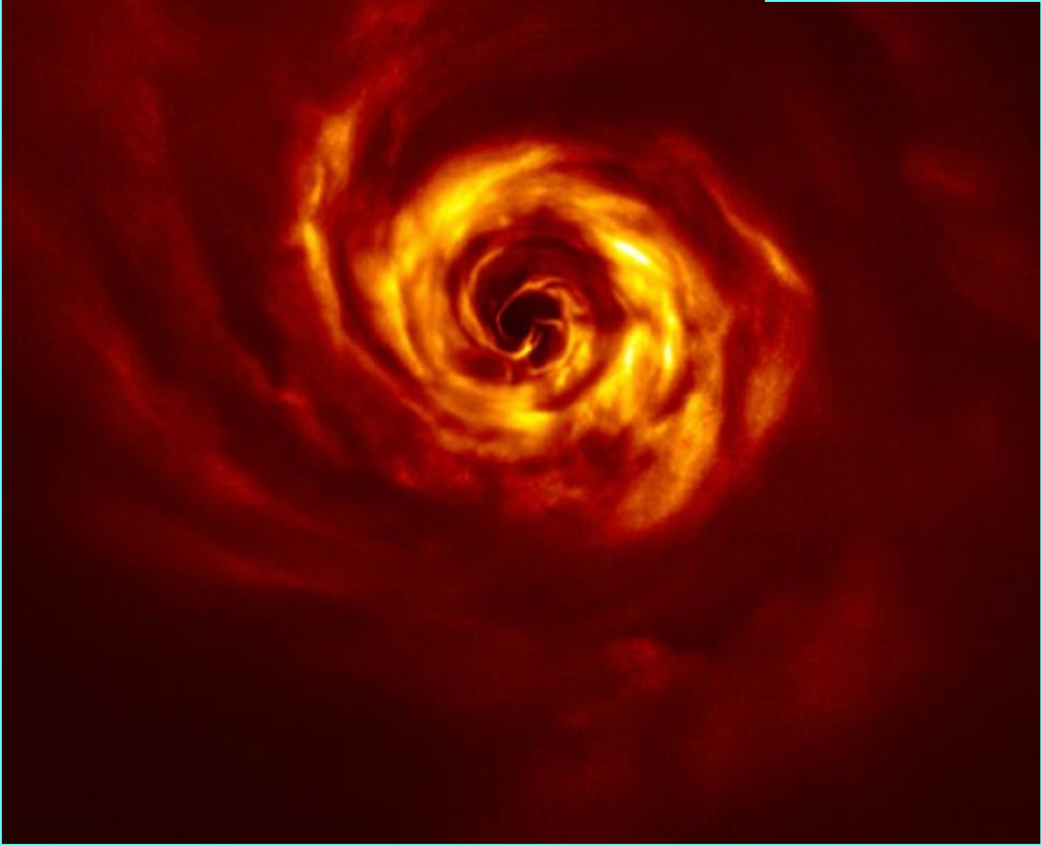
Chemistry of one disk!

(MAPS: Oberg et al. 2021)

Disks in scattered light





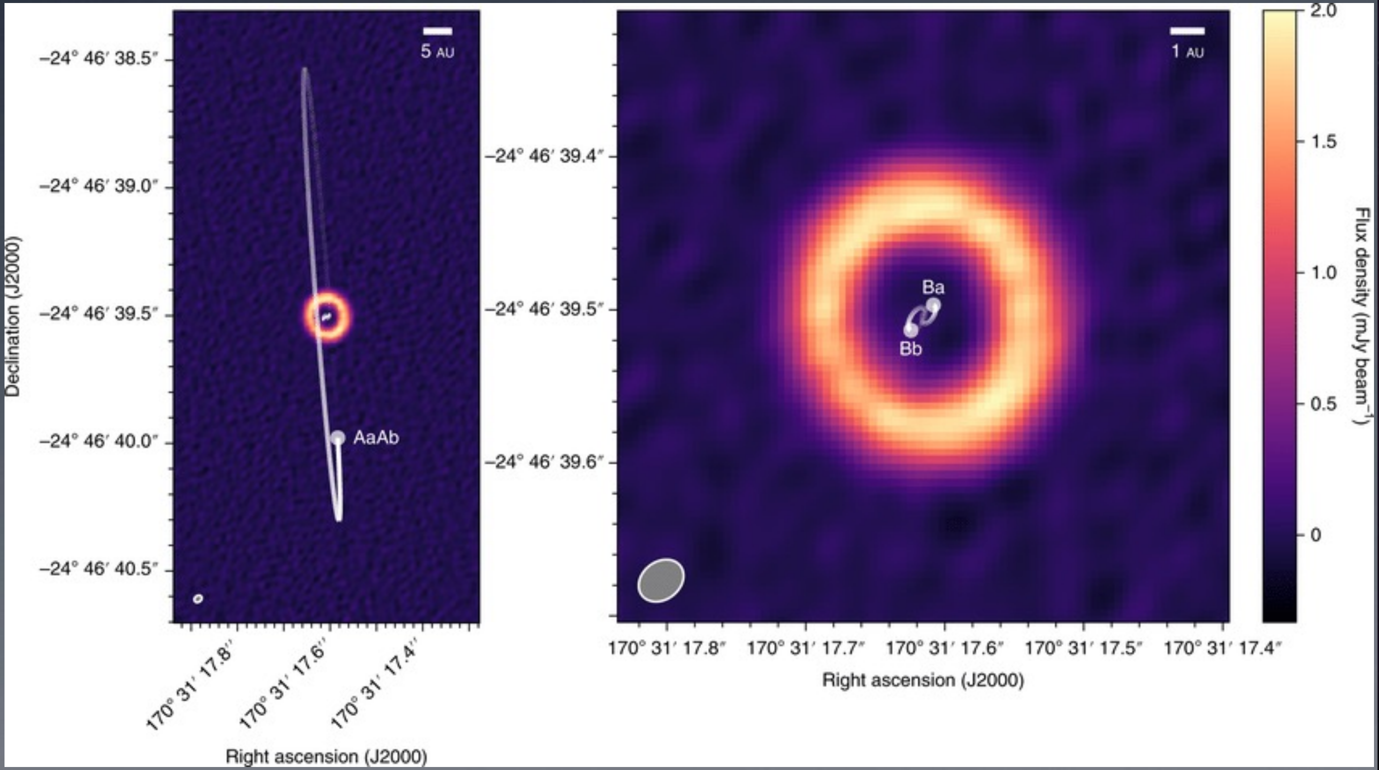


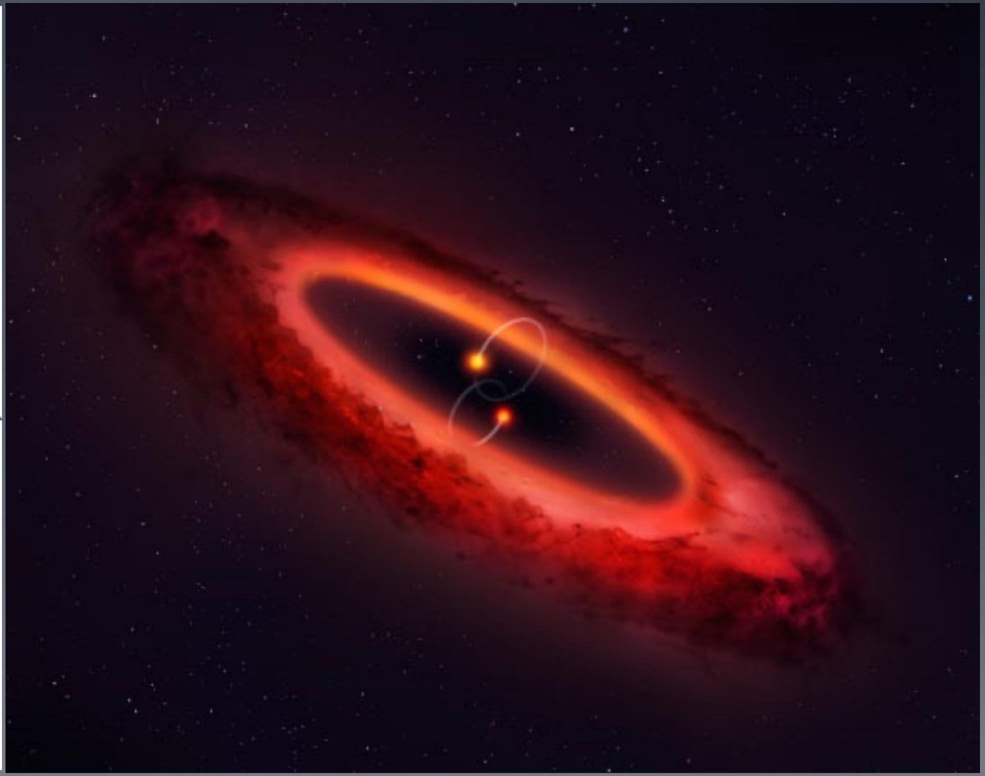
VLT/SPHERE: Garufi+2019; Boccalletti+2019

Weird disk around the binary of HD 98800N

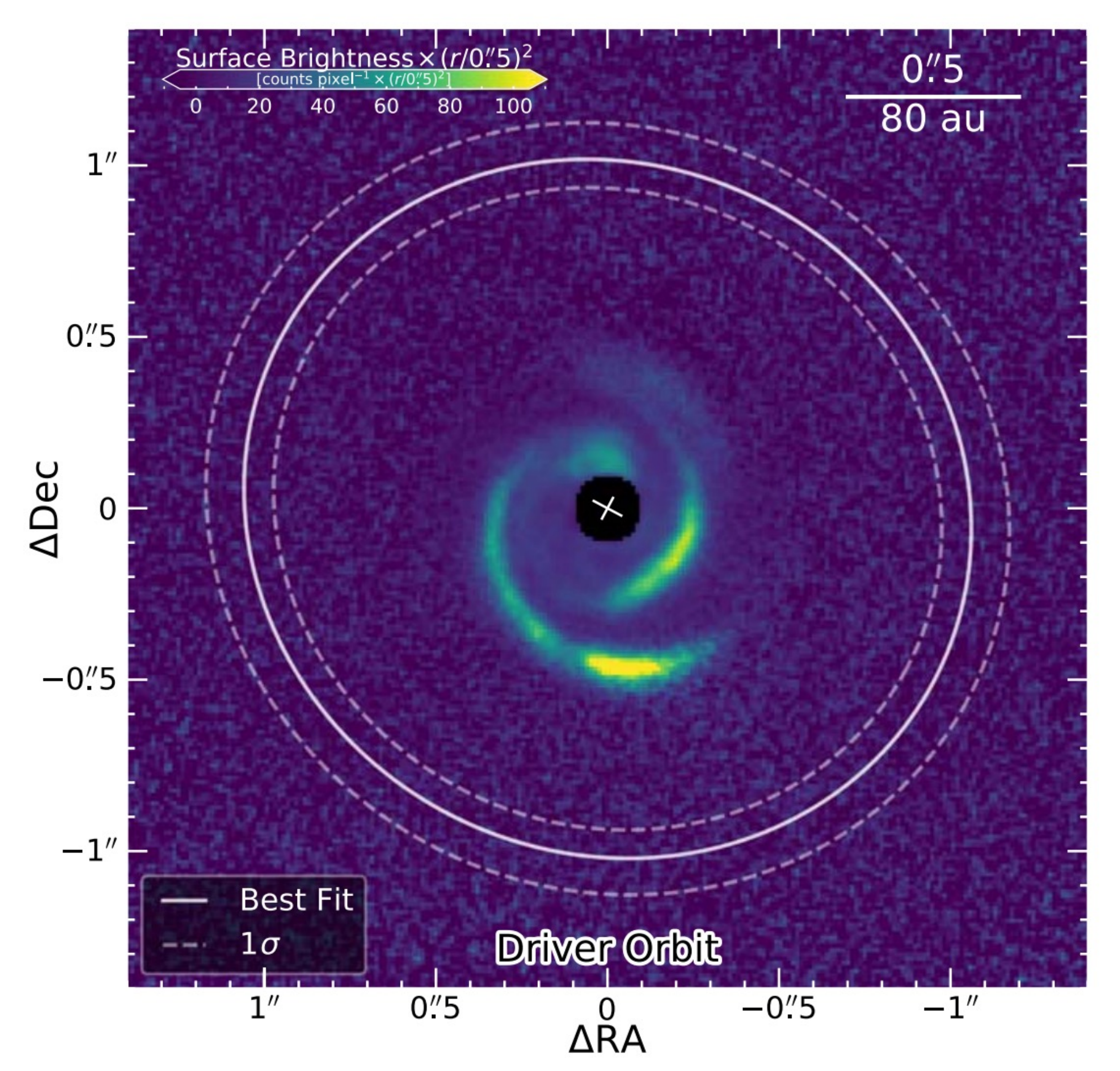
binary in a quadruple system, disk+binary are not coplanar!

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





JWST: Direct imaging searches for exoplanets



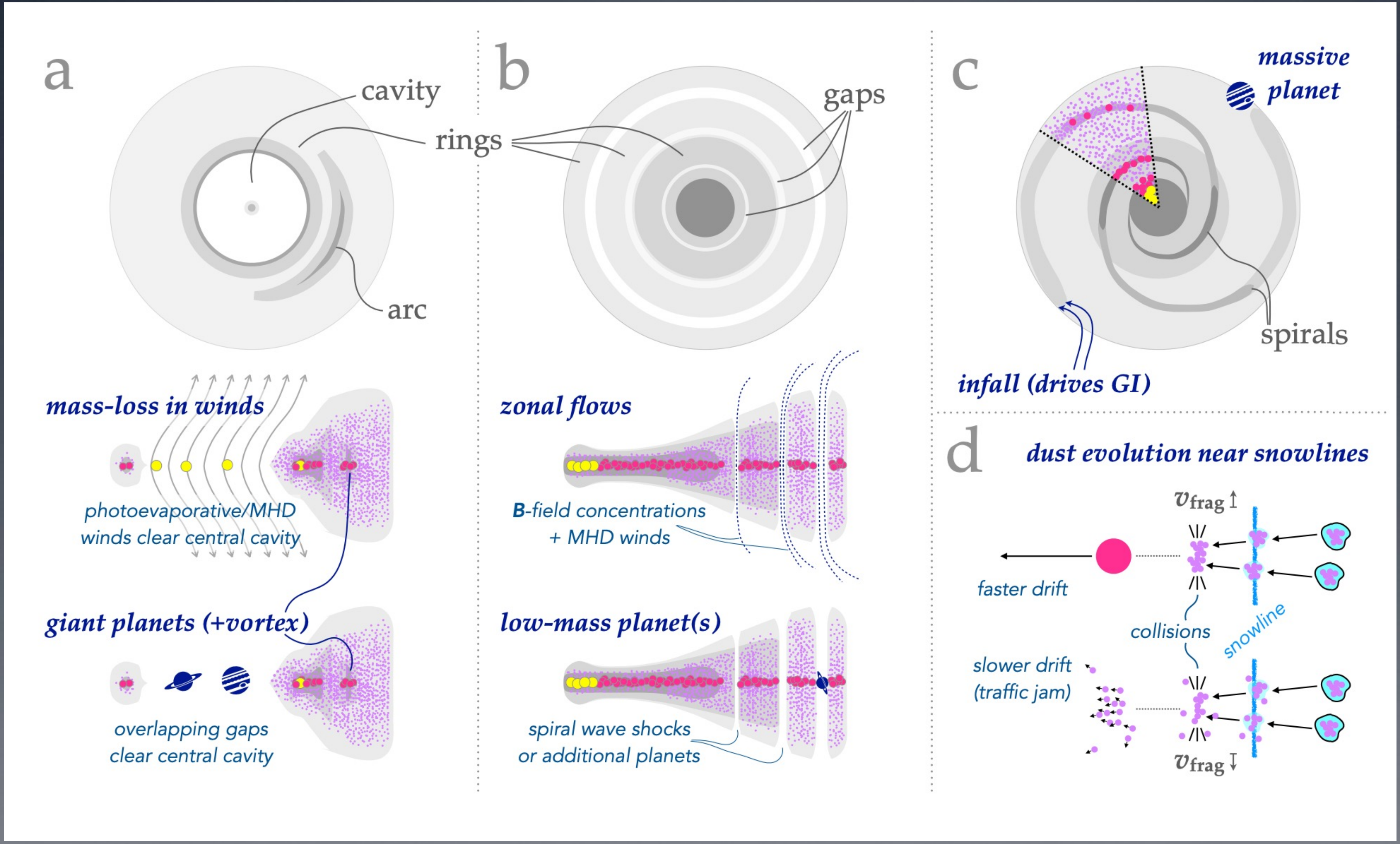
Dong+: MWC 758 spirals excited by a planet?

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

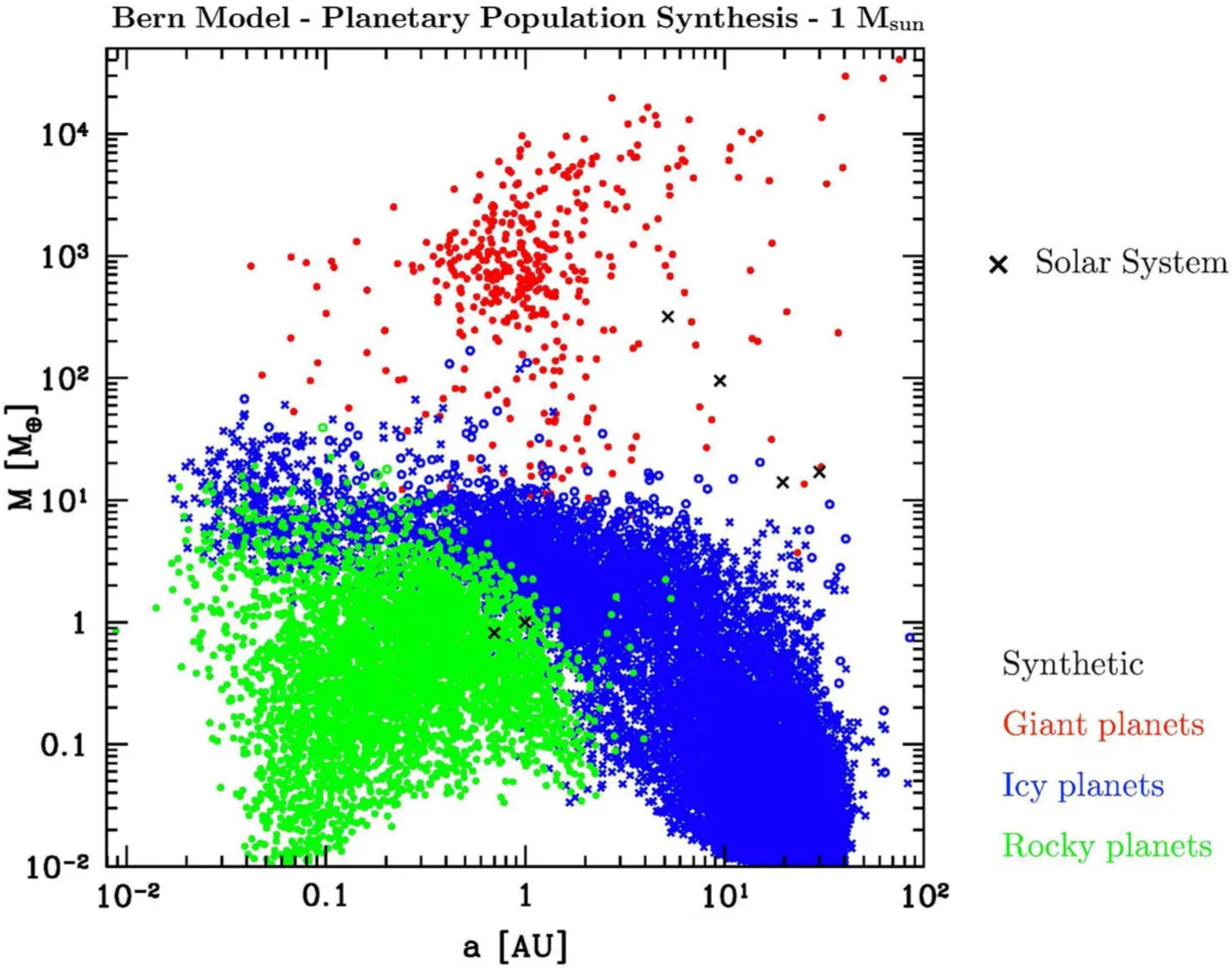
Where is the planet?

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

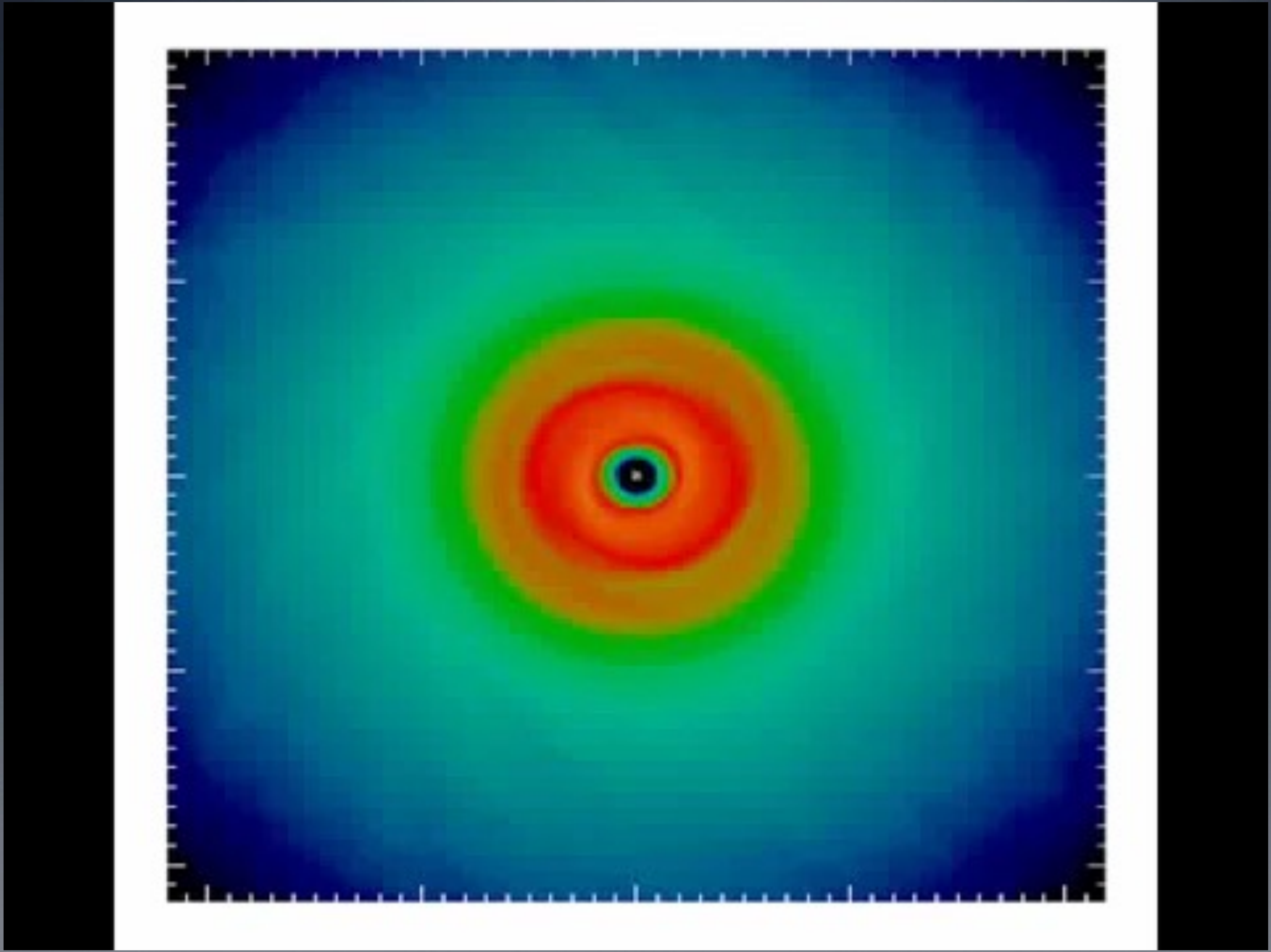
Structures: planets or physics (of planet formation)?



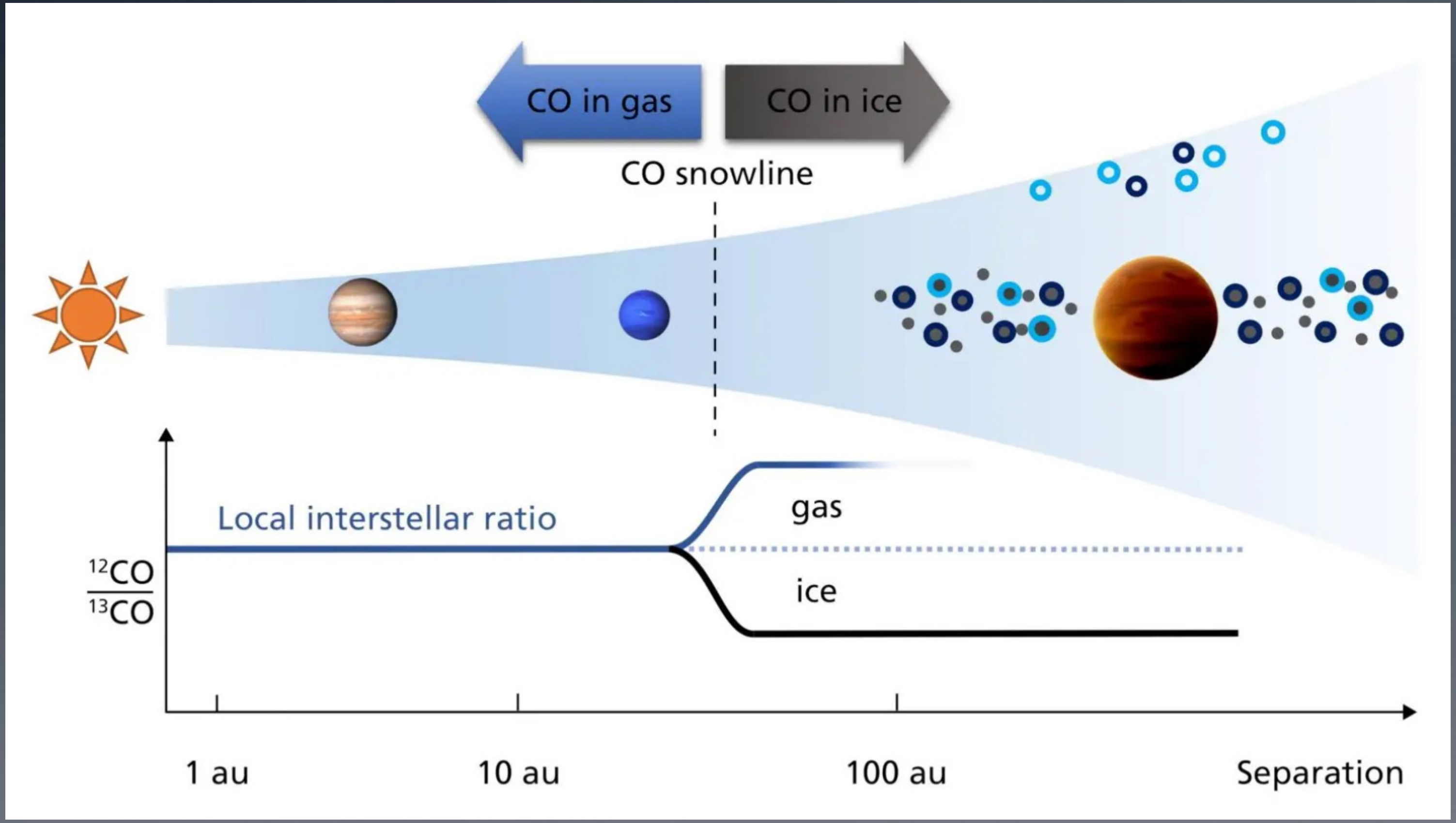
Andrews (2020, ARAA)



Simplify physics, produce synthetic planets

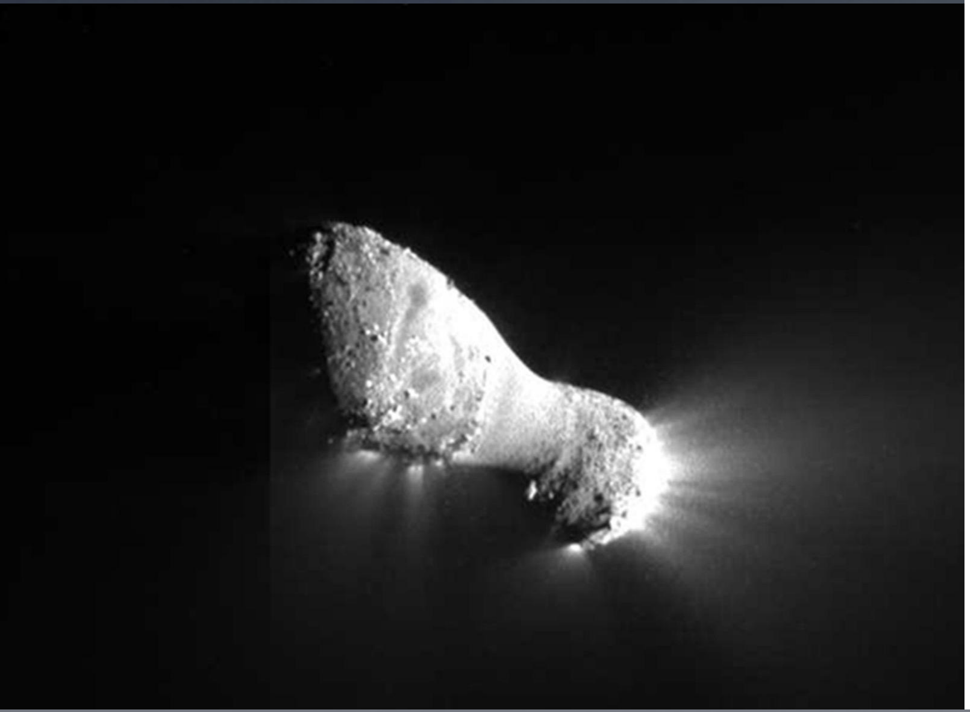


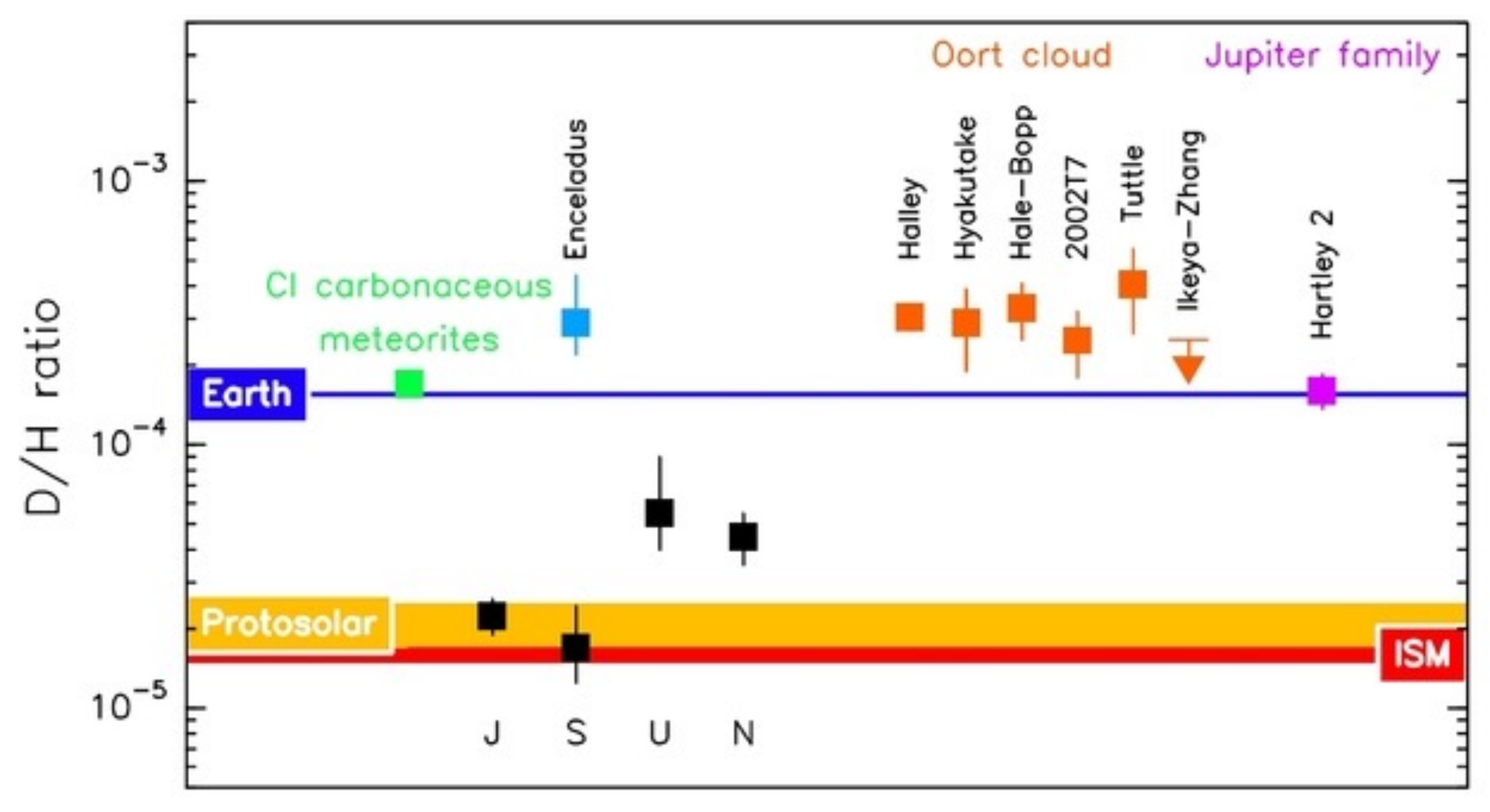
How to affect the abundances of a planet



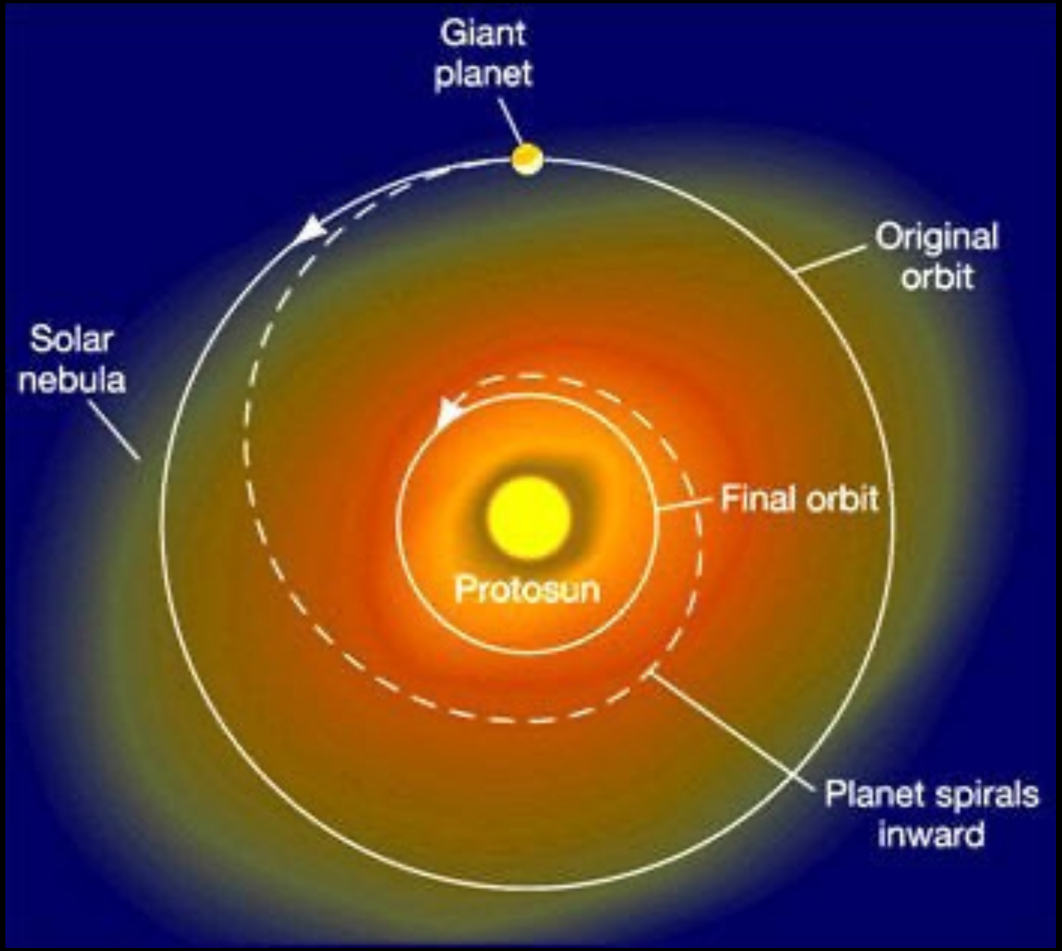
- Some planets will accrete more mass from the gas phase
- Others will have more icy dust grains
- The molecules in gas or ice depends on temperature (snow line)

Comets: possible source for Earth’s water!

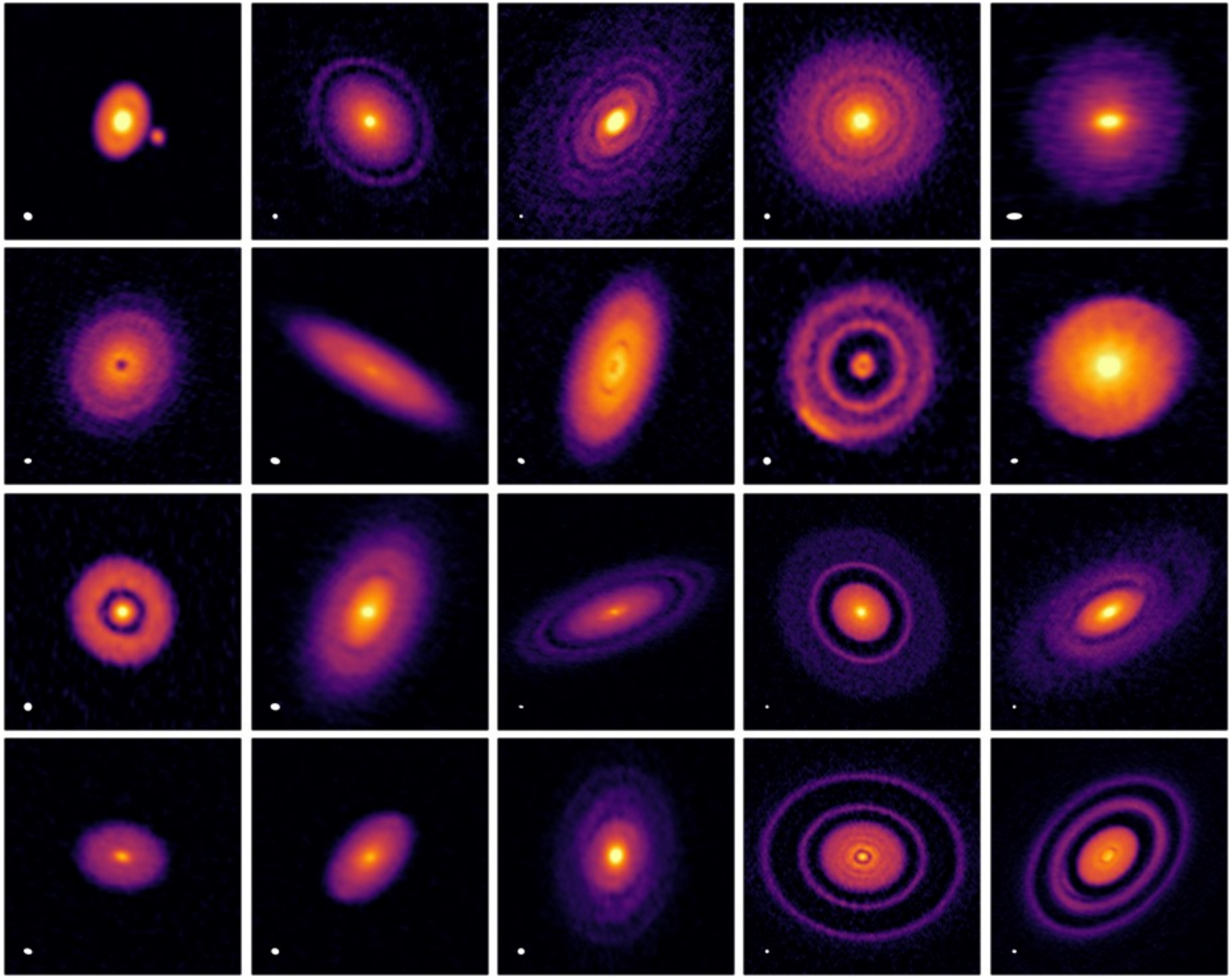




Planet migration



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



Review and search for life: Techniques for discovering exoplanets

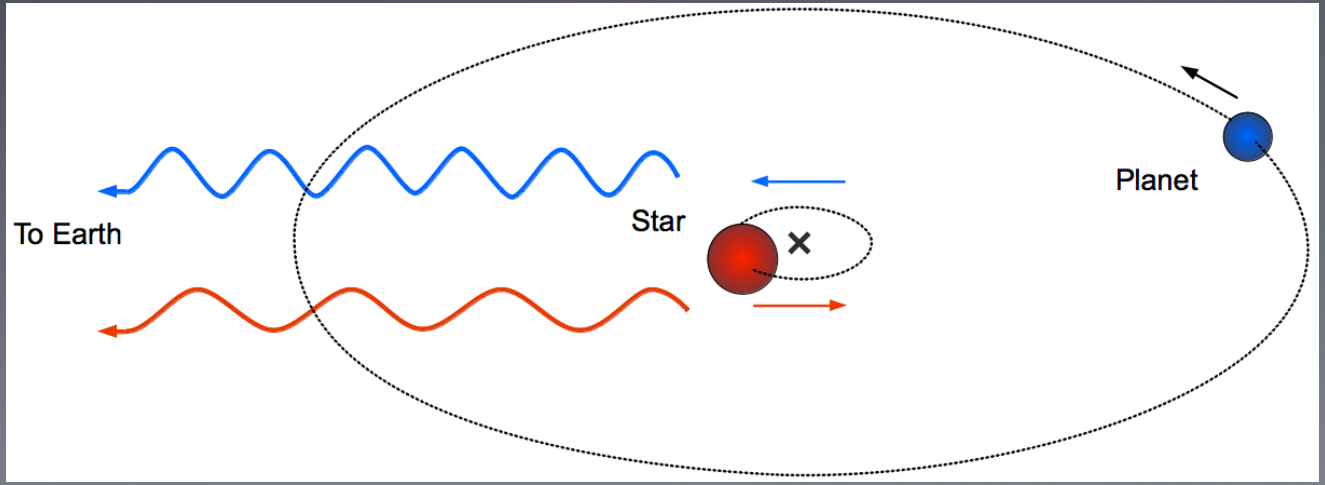
- **Radial velocity:** spectroscopy
- **Transits:** imaging (single-band)
- **Direct imaging:** imaging at high contrast
  - Coronagraph; ground+adaptive optics or space
- **Astrometry:** imaging with high precision
- **Microlensing:** imaging

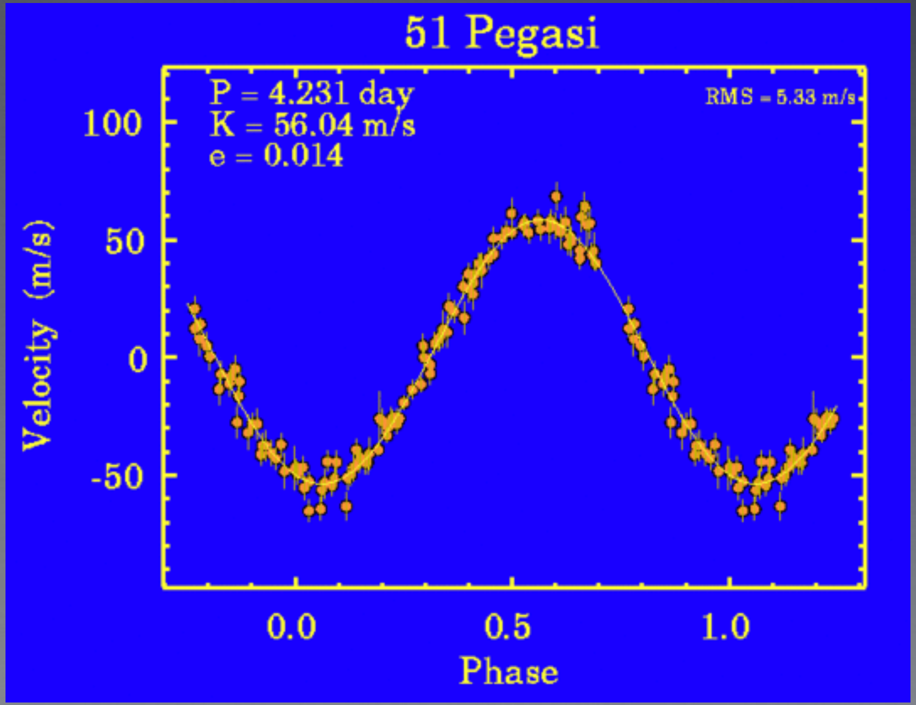
Can combine methods: mass+radius

Characterization: multi-band photometry or spectroscopy

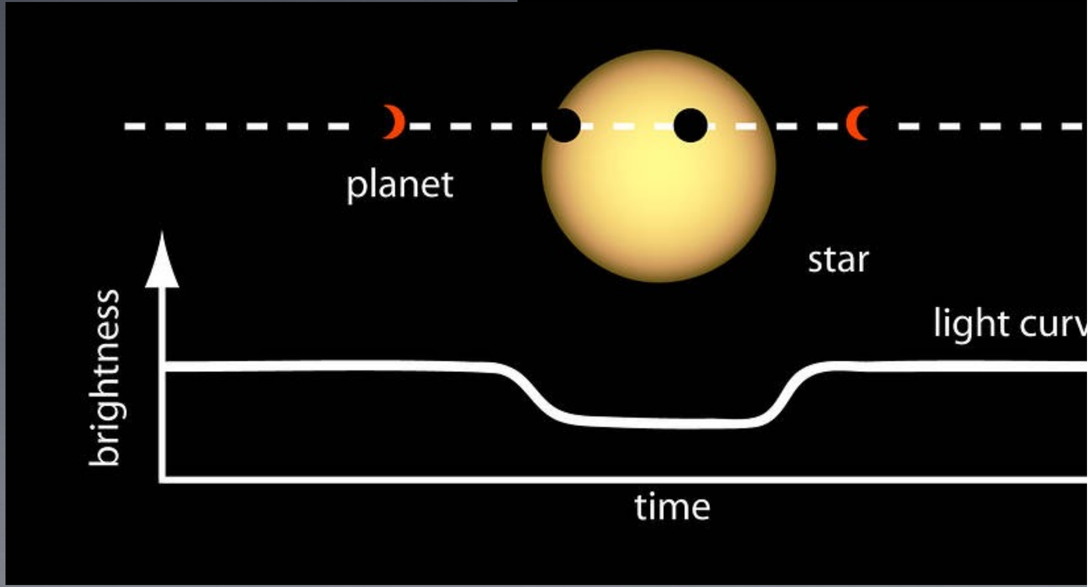
Most common planet-finding techniques

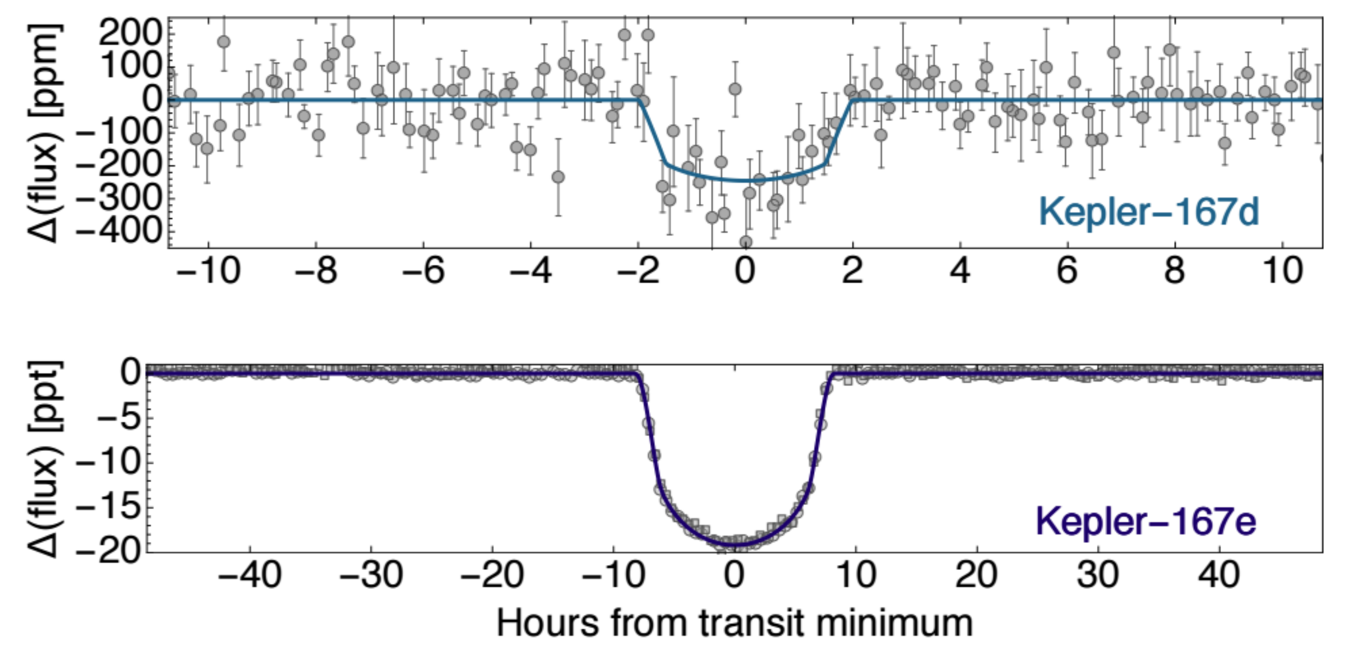
- Radial Velocity: measure the gravitational pull of the planet on the star
- Transit: planet passes in front of a star
- Direct imaging (directly detect the planet; hardest, but possibly most important in search for life)



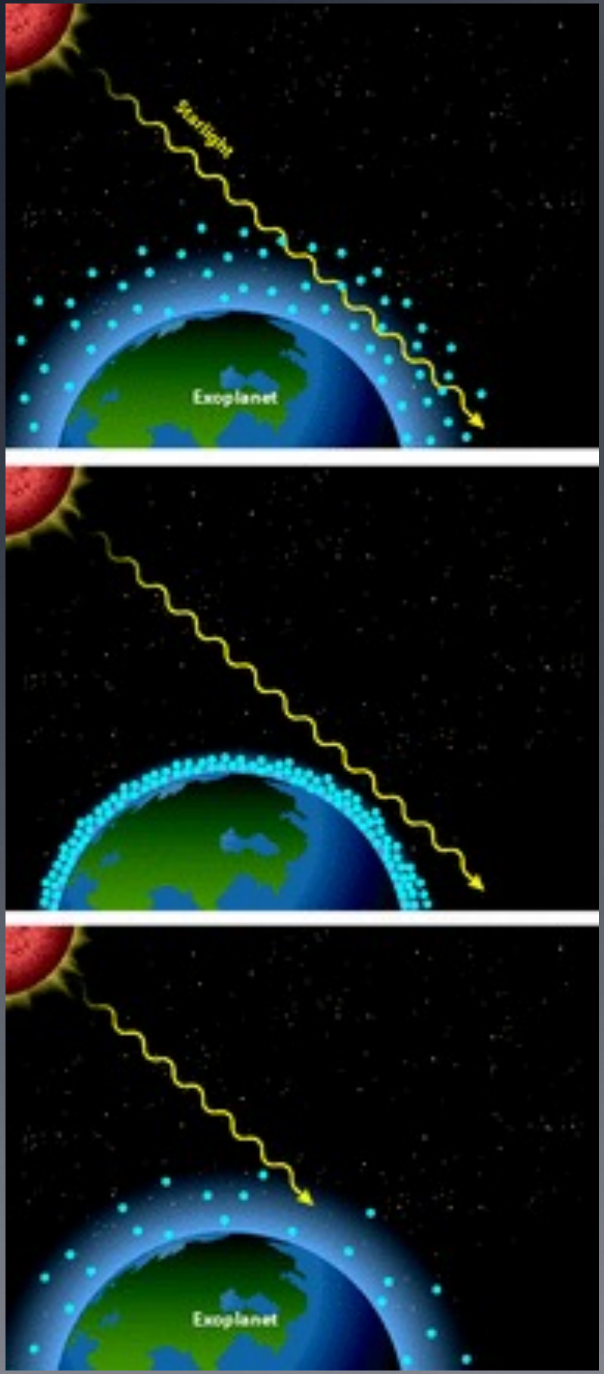


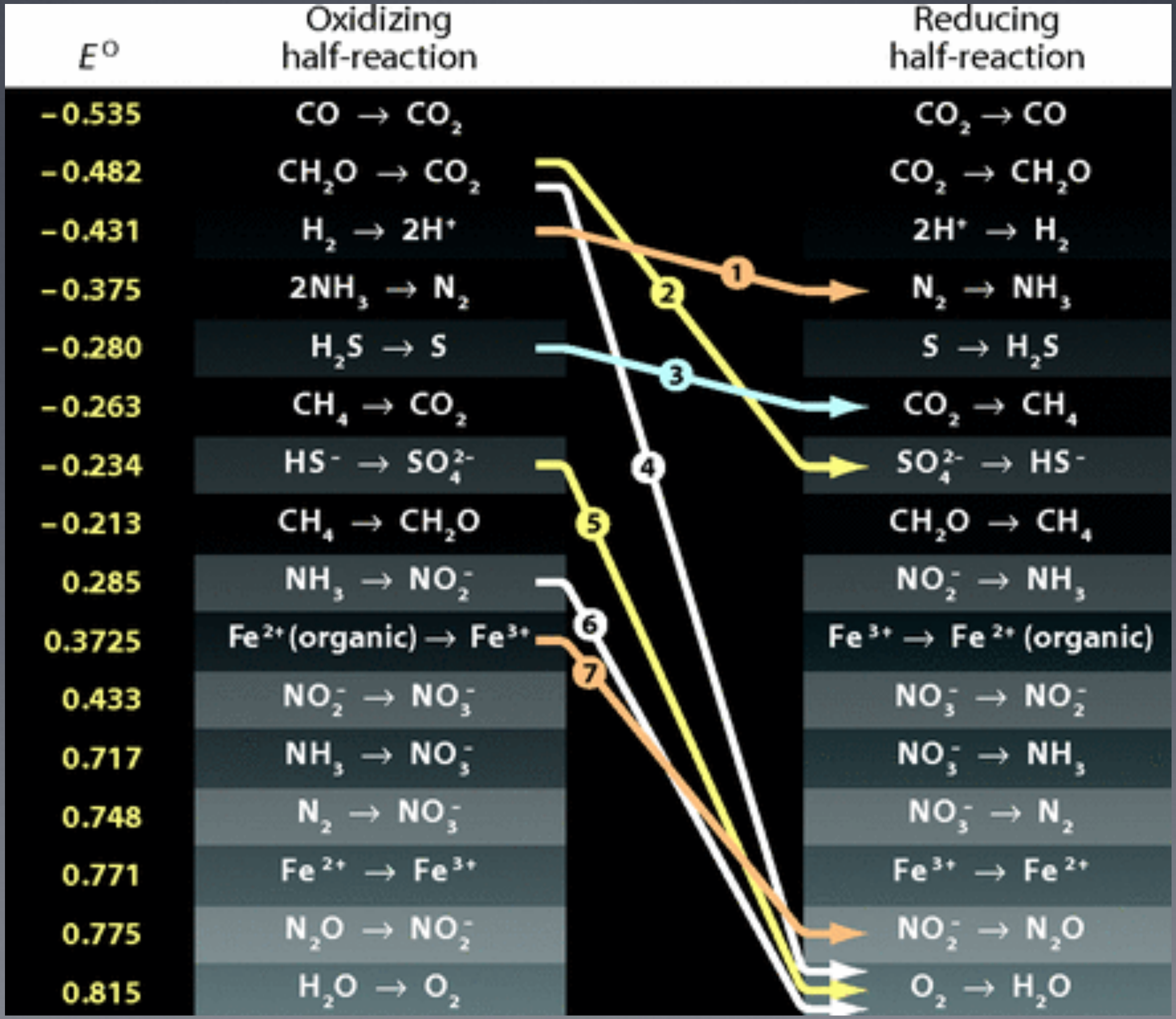
Transit method to detect exoplanets





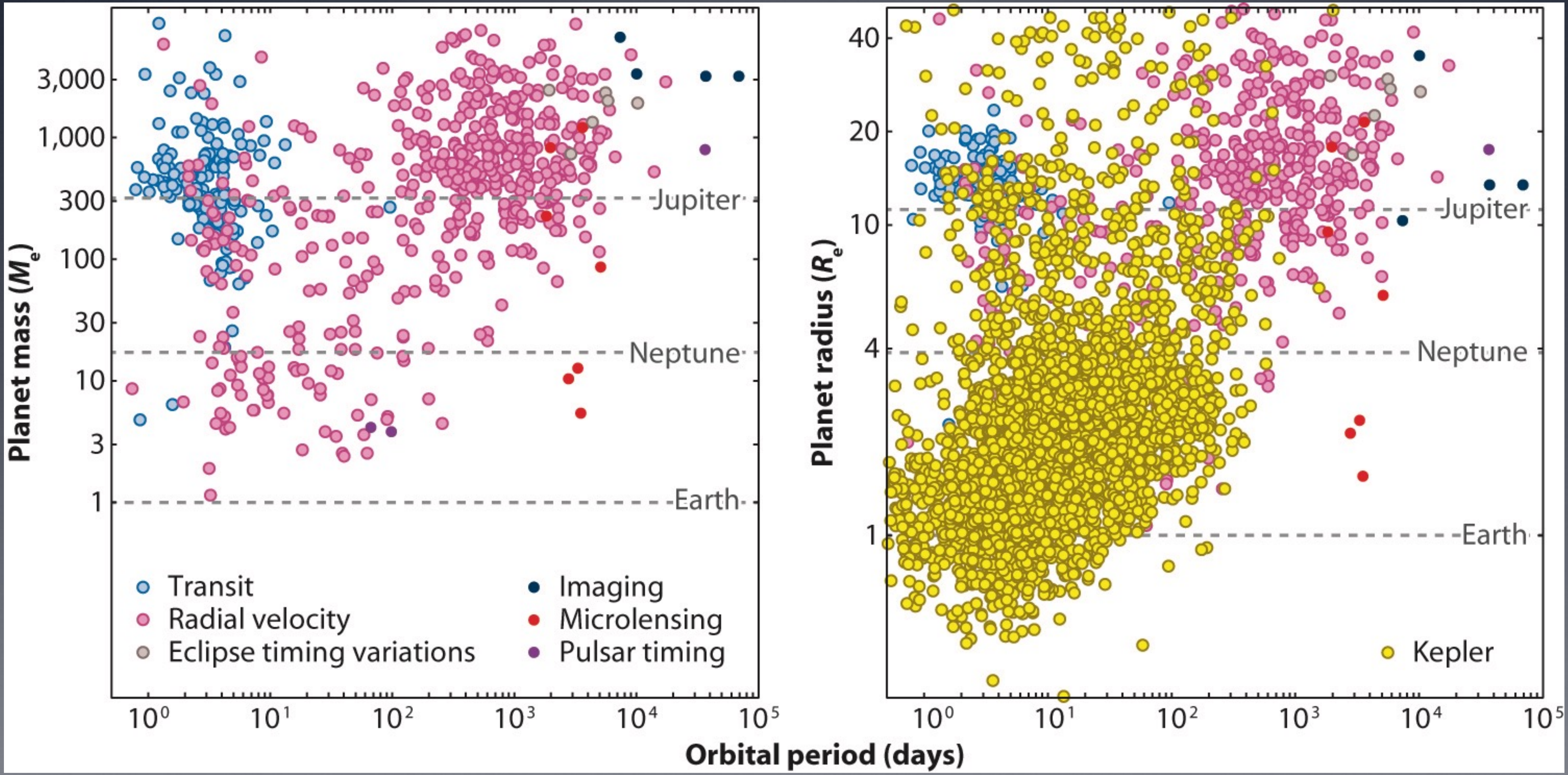
Exoplanet atmospheres!

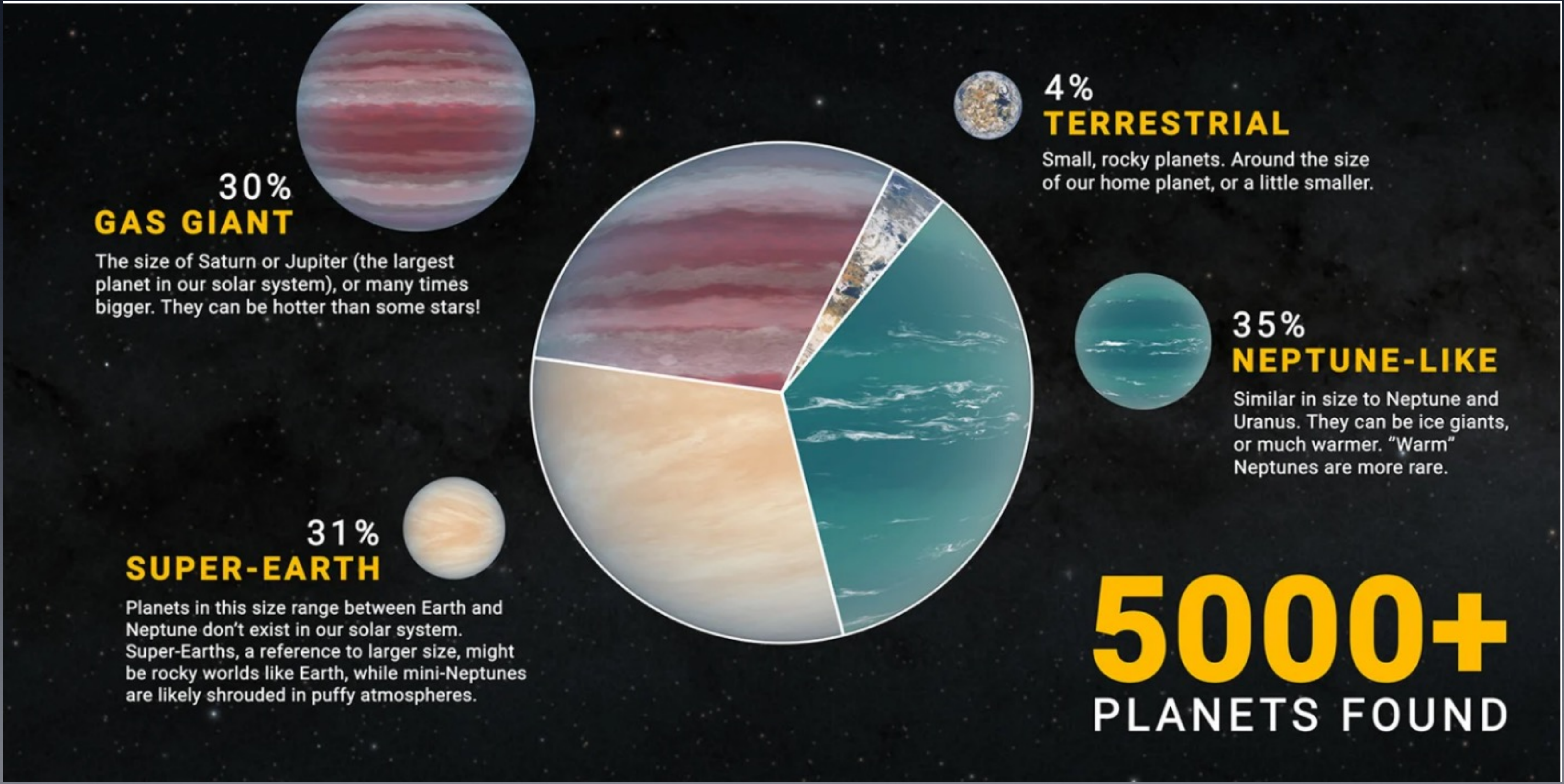




E^0	Oxidizing half-reaction	Reducing half-reaction
−0.535	$CO \rightarrow CO_2$	$CO_2 \rightarrow CO$
−0.482	$CH_2O \rightarrow CO_2$	$CO_2 \rightarrow CH_2O$
−0.431	$H_2 \rightarrow 2H^+$	$2H^+ \rightarrow H_2$
−0.375	$2NH_3 \rightarrow N_2$	$N_2 \rightarrow NH_3$
−0.280	$H_2S \rightarrow S$	$S \rightarrow H_2S$
−0.263	$CH_4 \rightarrow CO_2$	$CO_2 \rightarrow CH_4$
−0.234	$HS^- \rightarrow SO_4^{2-}$	$SO_4^{2-} \rightarrow HS^-$
−0.213	$CH_4 \rightarrow CH_2O$	$CH_2O \rightarrow CH_4$
0.285	$NH_3 \rightarrow NO_2^-$	$NO_2^- \rightarrow NH_3$
0.3725	Fe^{2+}(organic) $\rightarrow Fe^{3+}$	$Fe^{3+} \rightarrow Fe^{2+}$(organic)
0.433	$NO_2^- \rightarrow NO_3^-$	$NO_3^- \rightarrow NO_2^-$
0.717	$NH_3 \rightarrow NO_3^-$	$NO_3^- \rightarrow NH_3$
0.748	$N_2 \rightarrow NO_3^-$	$NO_3^- \rightarrow N_2$
0.771	$Fe^{2+} \rightarrow Fe^{3+}$	$Fe^{3+} \rightarrow Fe^{2+}$
0.775	$N_2O \rightarrow NO_2^-$	$NO_2^- \rightarrow N_2O$
0.815	$H_2O \rightarrow O_2$	$O_2 \rightarrow H_2O$

Exoplanets are common!





30%

GAS GIANT

The size of Saturn or Jupiter (the largest planet in our solar system), or many times bigger. They can be hotter than some stars!

4%

TERRESTRIAL

Small, rocky planets. Around the size of our home planet, or a little smaller.

35%

NEPTUNE-LIKE

Similar in size to Neptune and Uranus. They can be ice giants, or much warmer. "Warm" Neptunes are more rare.

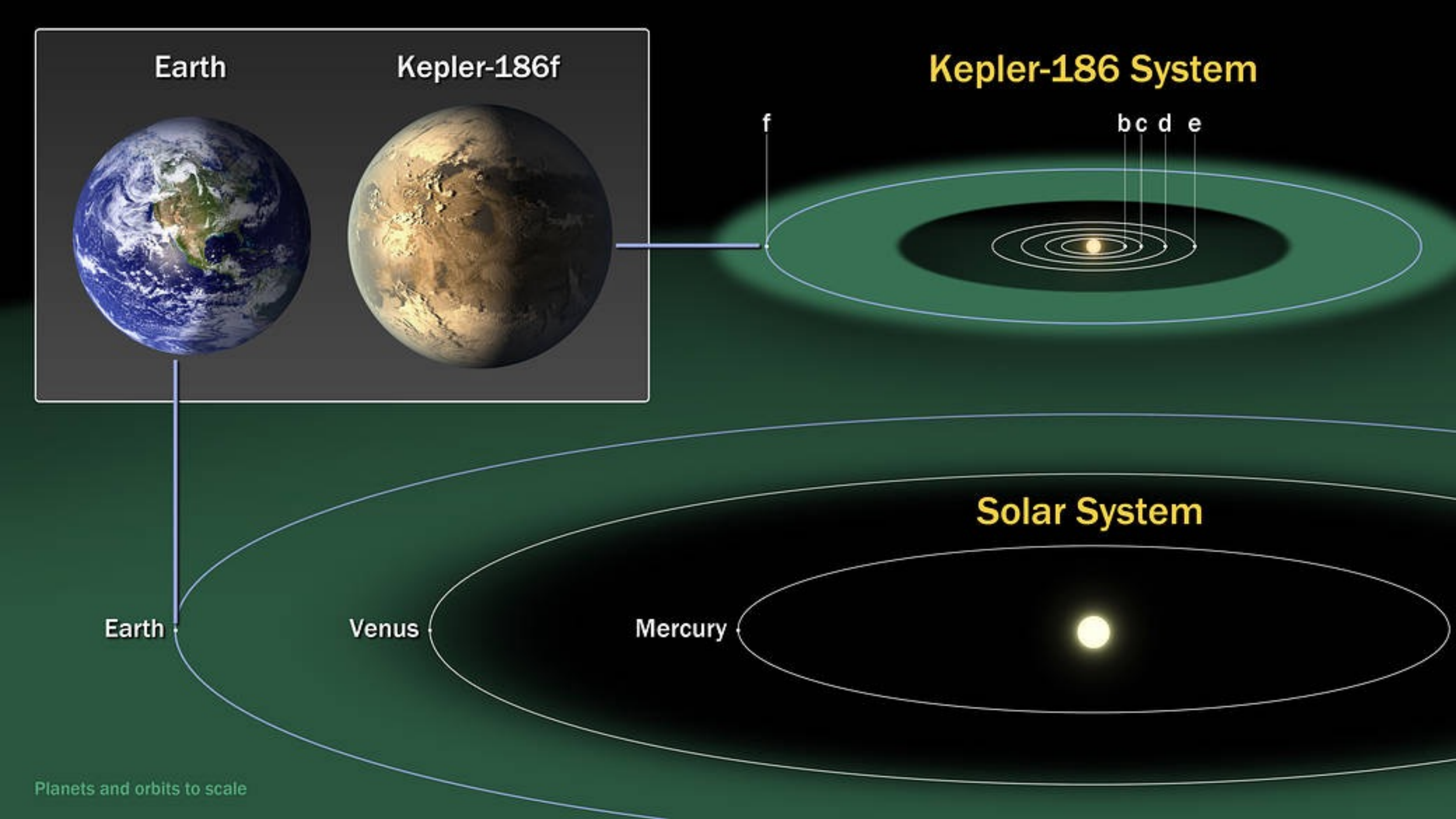
31%

SUPER-EARTH

Planets in this size range between Earth and Neptune don't exist in our solar system. Super-Earths, a reference to larger size, might be rocky worlds like Earth, while mini-Neptunes are likely shrouded in puffy atmospheres.

5000+

PLANETS FOUND



Planets and orbits to scale

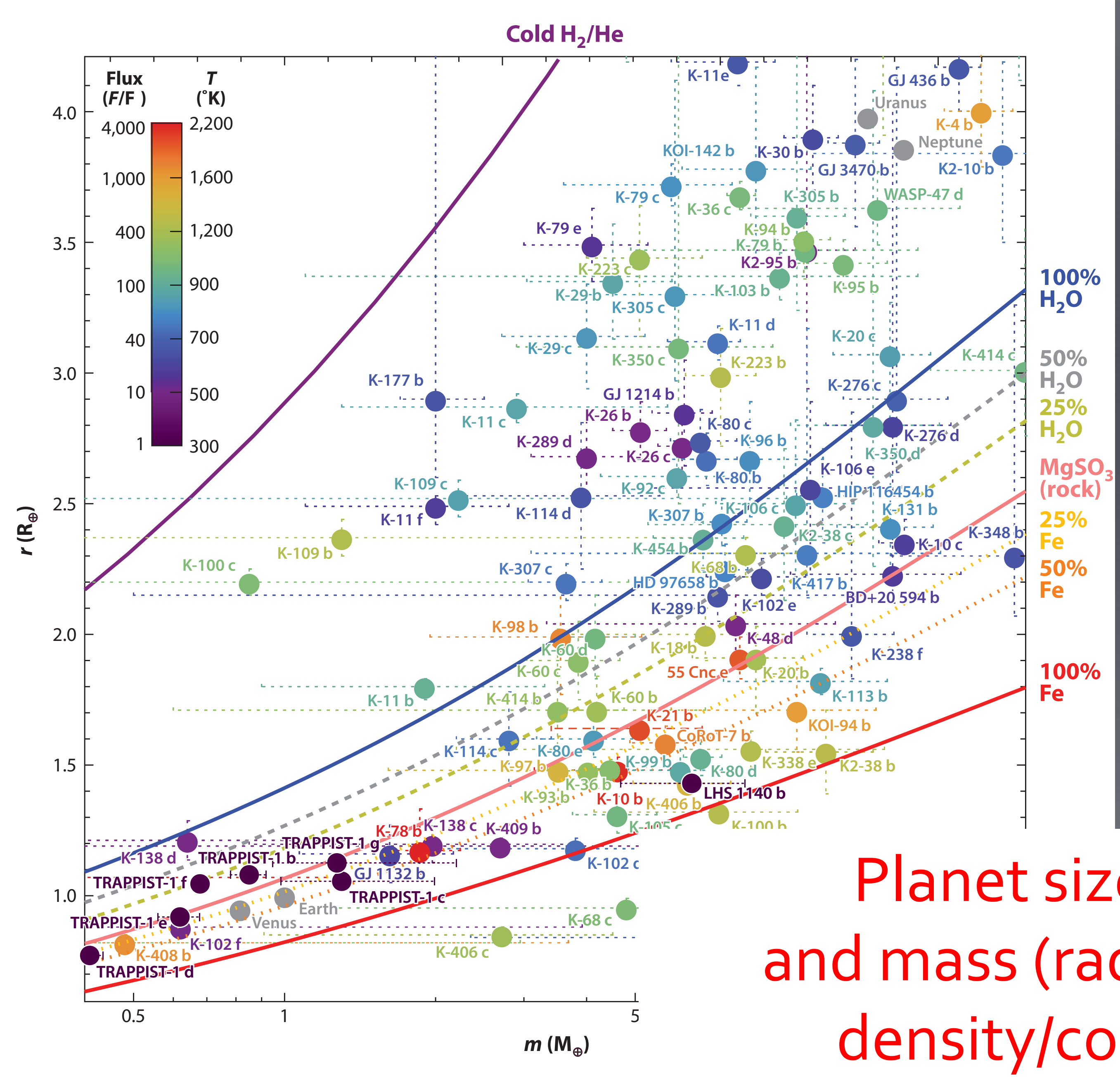
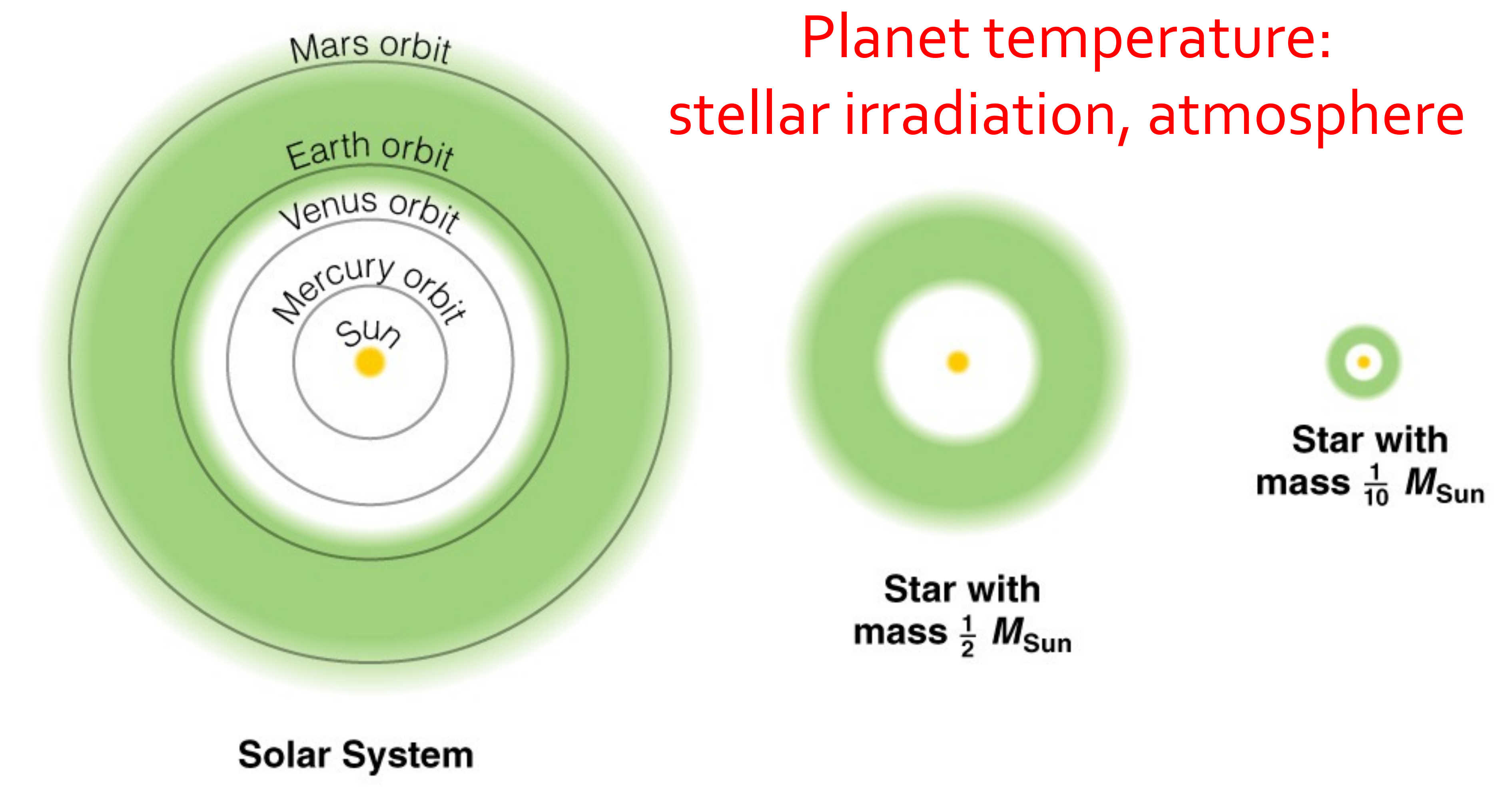


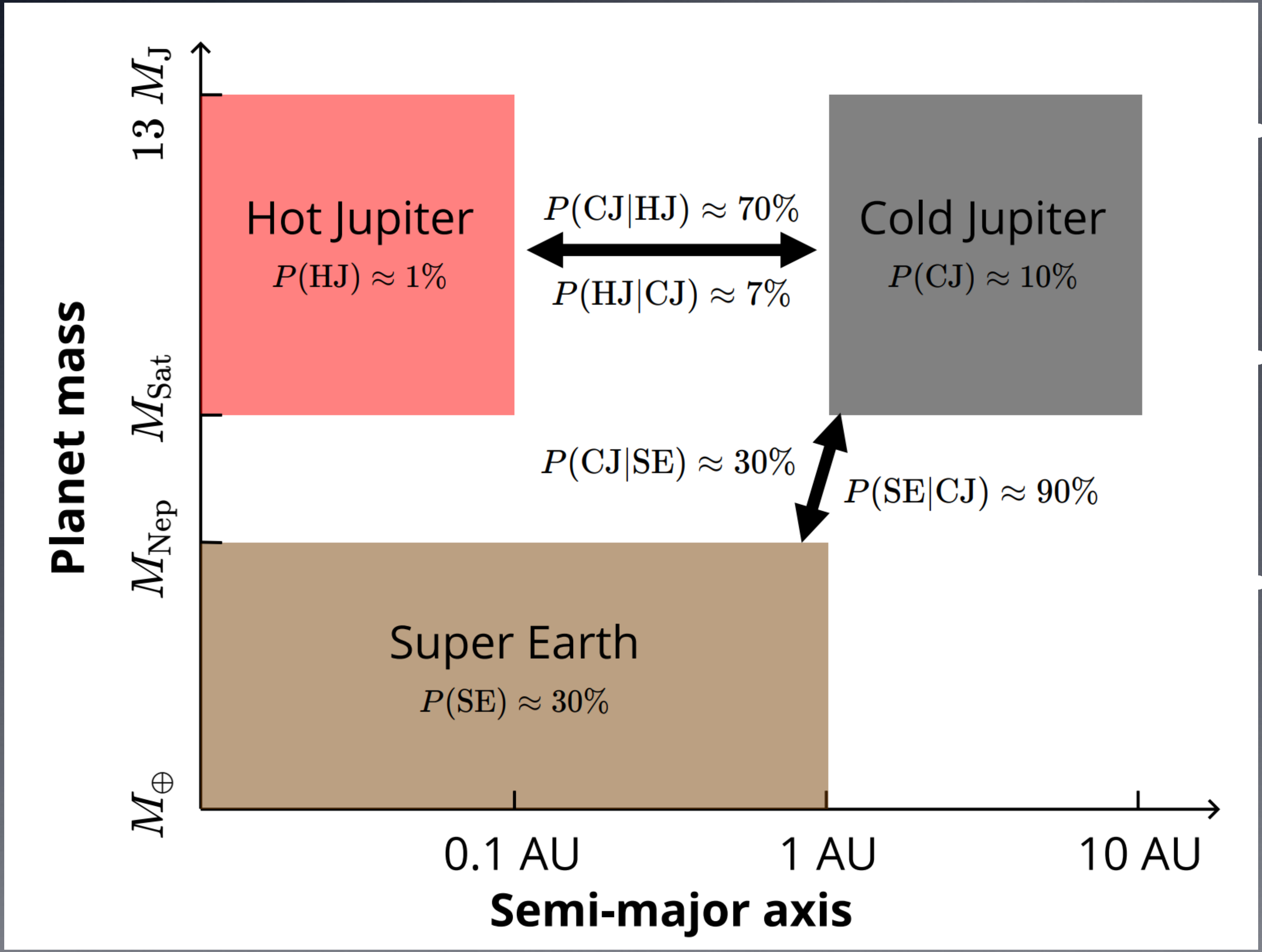
Figure 1

Planet size (transit)
and mass (radial velocity):
density/composition

Are habitable planets likely?

Planet temperature:
stellar irradiation, atmosphere

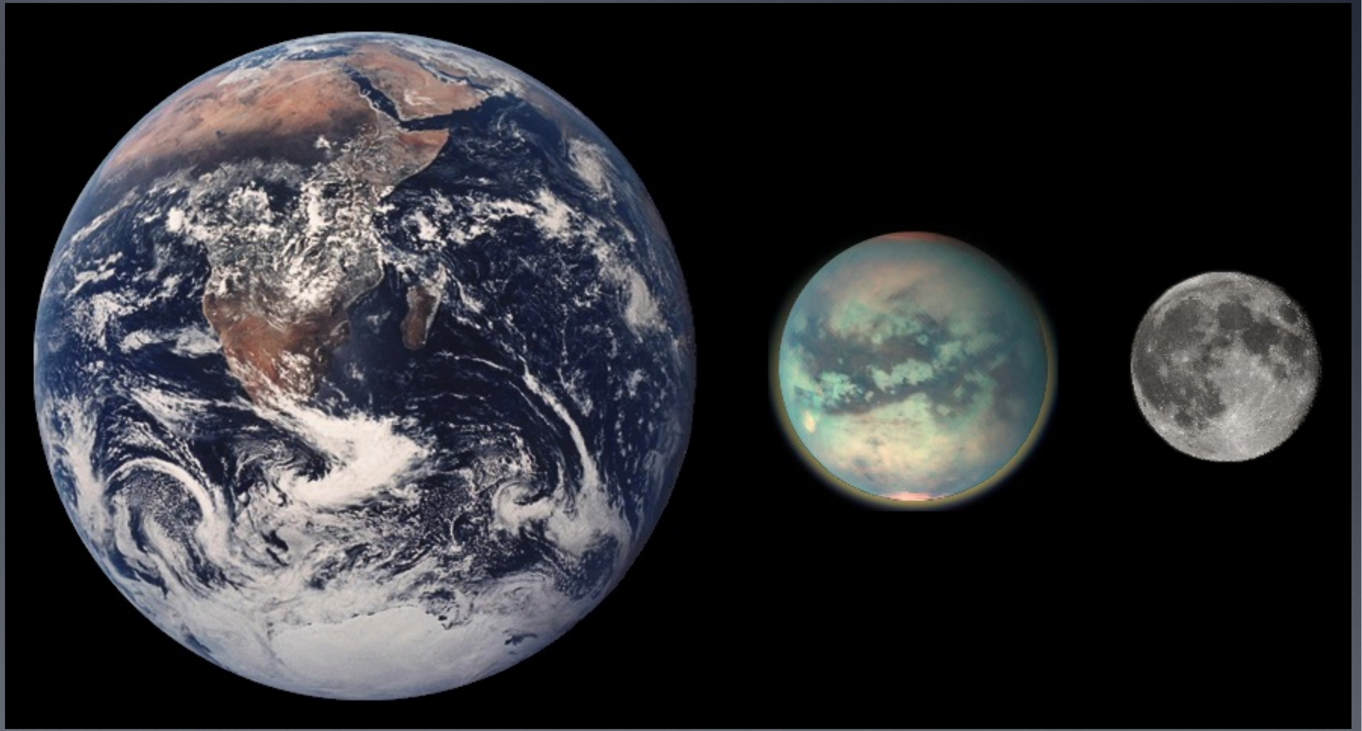




- Most common systems have Super-Earths
- Cold Jupiters (like solar system): not too unusual
- Hot Jupiters: rare but easy to detect

Is life common? Search in solar system

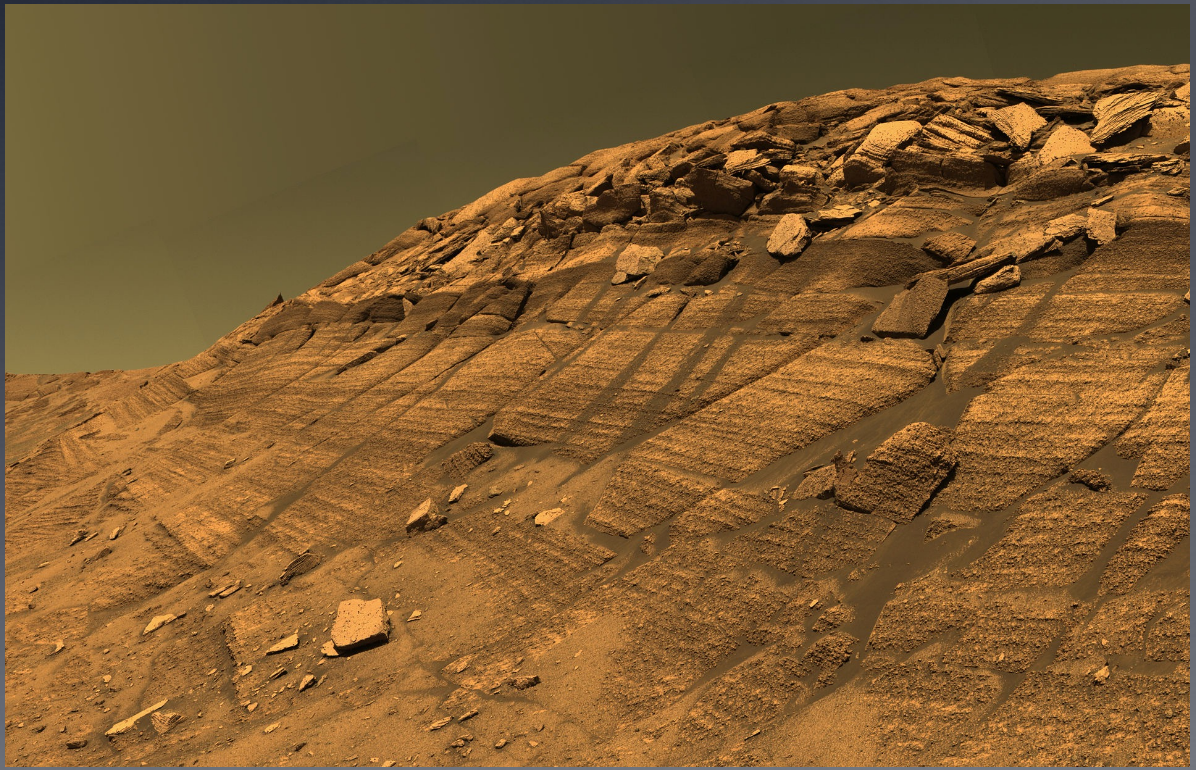
- Europa and Enceladus: water worlds
  - Europa, moon of Jupiter
  - Enceladus, moon of Saturn
- Titan: moon of Saturn, thick methane atmosphere+ground

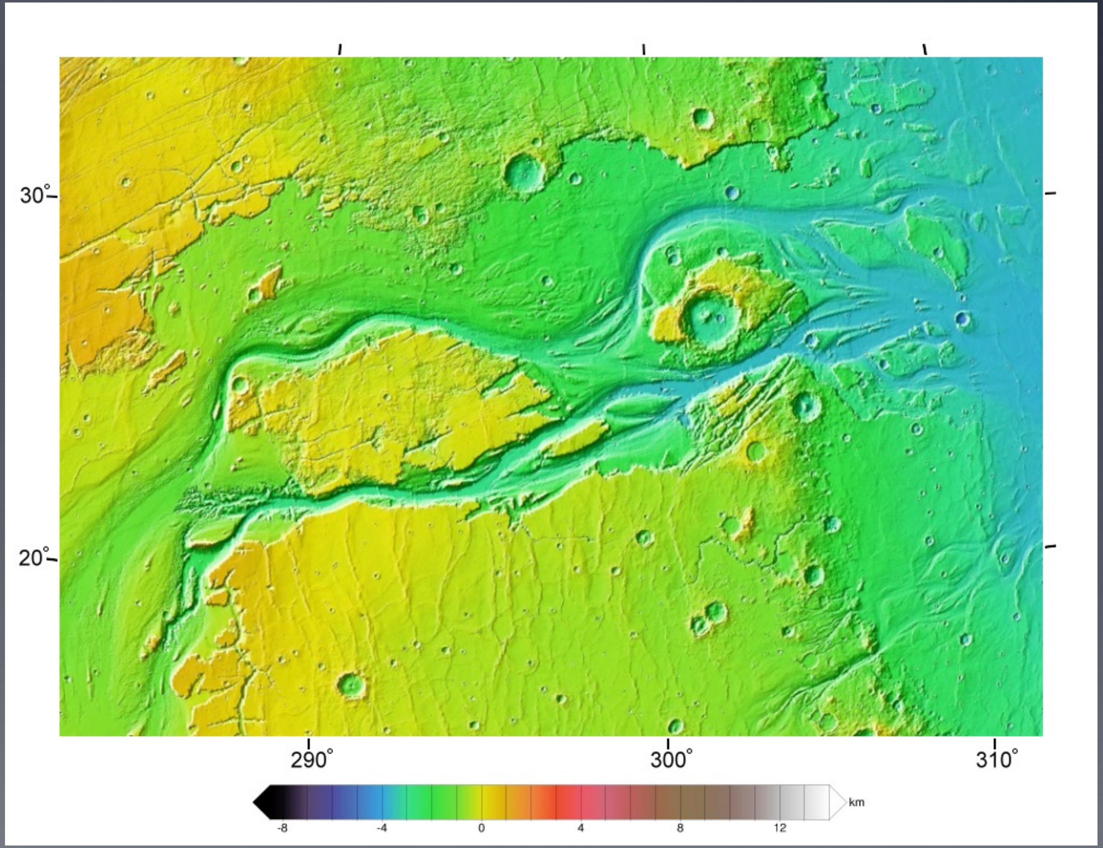


Possible life paths

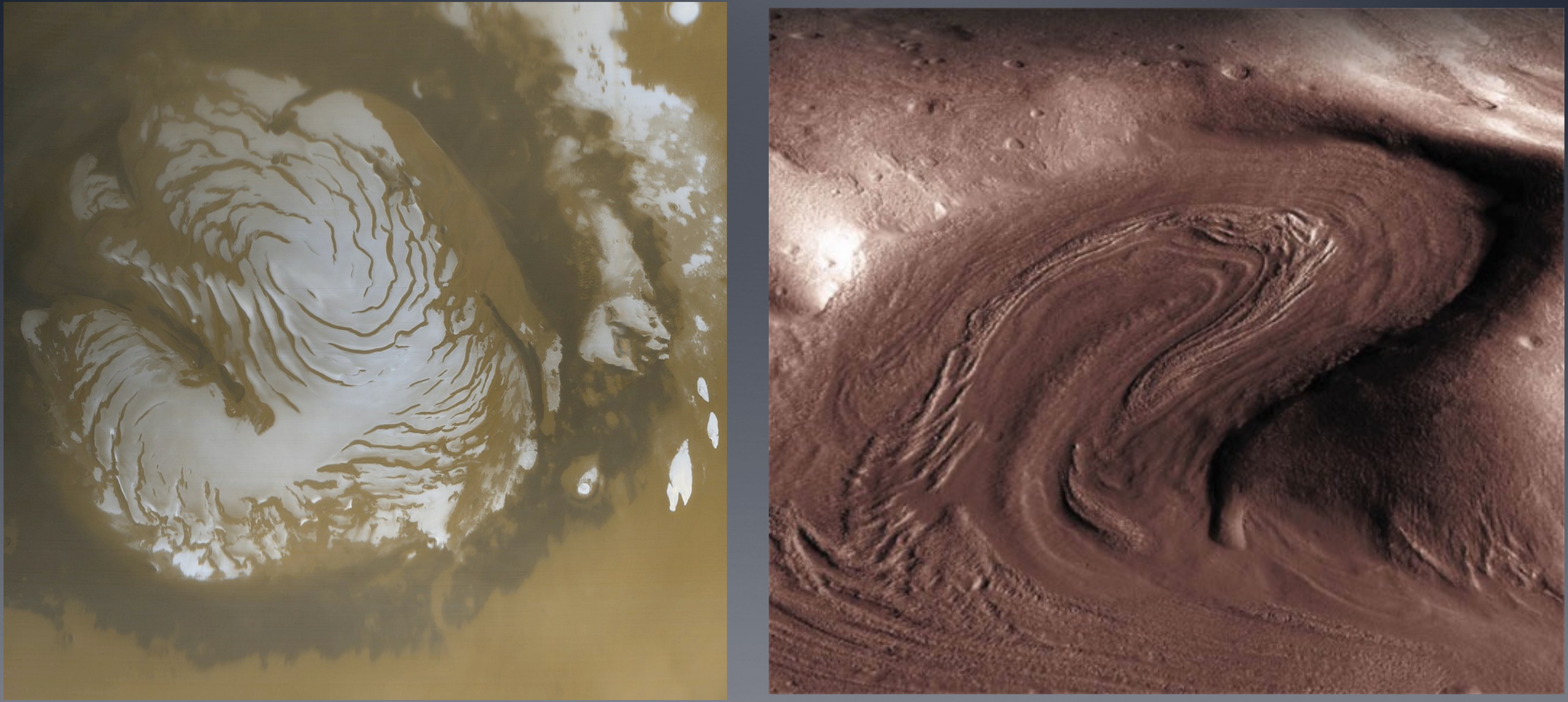
- Develop independently
- Delivered from elsewhere: panspermia
  - 10,000s kg of rubble from asteroid impact could have landed on Titan and on the Galilean moons of Jupiter (eg, Europa)

Water on Mars

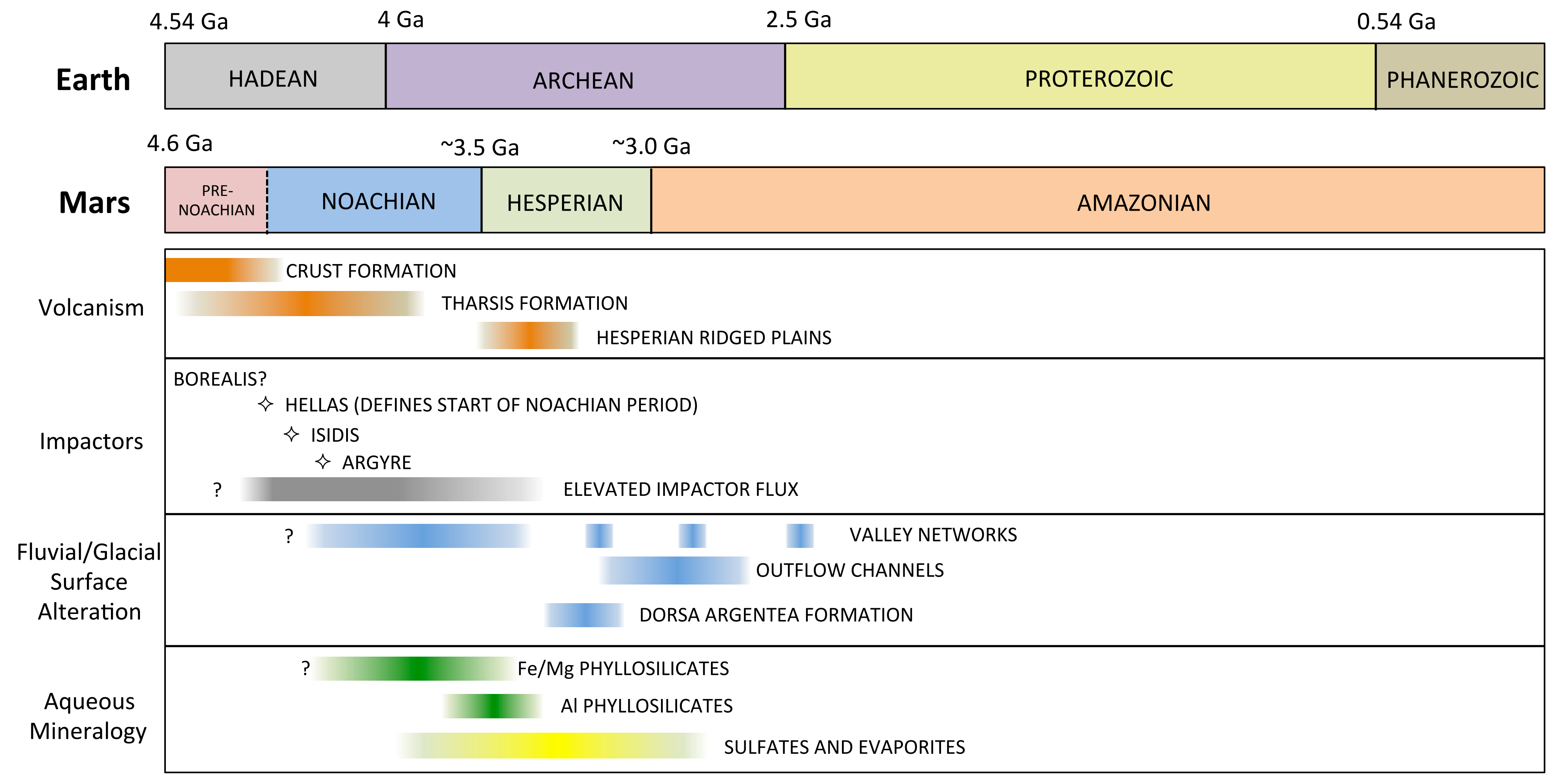




Water on Mars



Mars lost most of atmosphere: life long ago?



4.54 Ga
4 Ga
2.5 Ga
0.54 Ga

Earth
HADEAN
ARCHEAN
PROTEROZOIC
PHANEROZOIC

4.6 Ga
~3.5 Ga
~3.0 Ga

Mars
PRE-NOACHIAN
NOACHIAN
HESPERIAN
AMAZONIAN

Volcanism
CRUST FORMATION
THARSIS FORMATION
HESPERIAN RIDGED PLAINS

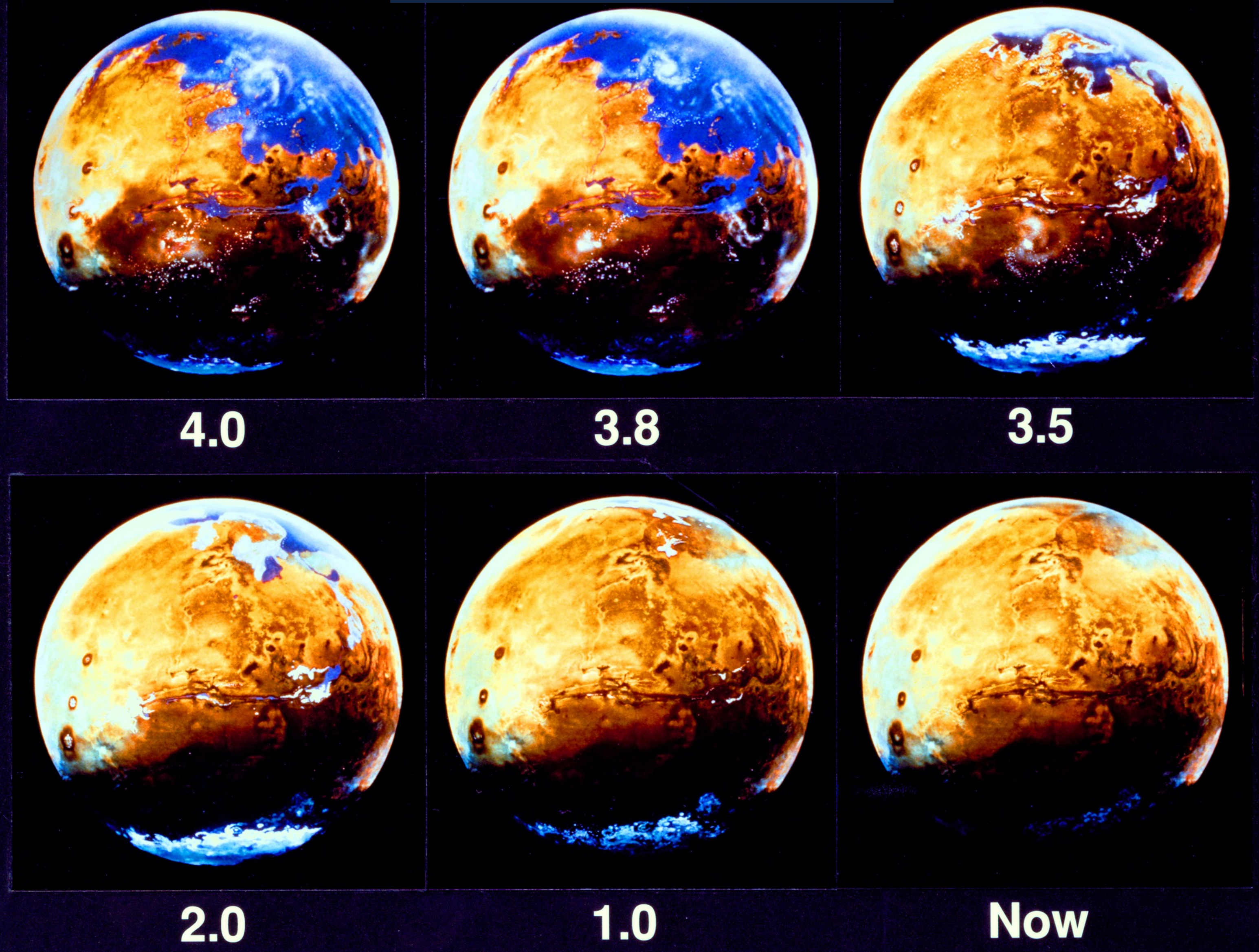
Impactors
BOREALIS?
✧ HELLAS (DEFINES START OF NOACHIAN PERIOD)
✧ ISIDIS
✧ ARGYRE
? ELEVATED IMPACTOR FLUX

Fluvial/Glacial Surface Alteration
? VALLEY NETWORKS
OUTFLOW CHANNELS
DORSA ARGENTEA FORMATION

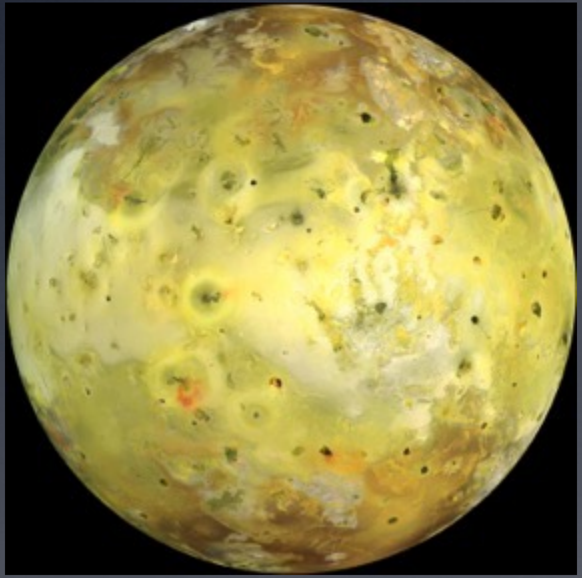
Aqueous Mineralogy
? Fe/Mg PHYLLOSILICATES
Al PHYLLOSILICATES
SULFATES AND EVAPORITES

HISTORY OF WATER ON MARS

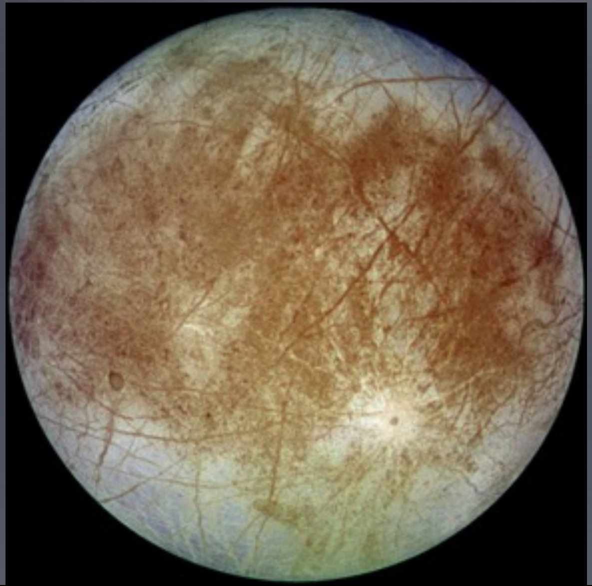
Billion years ago



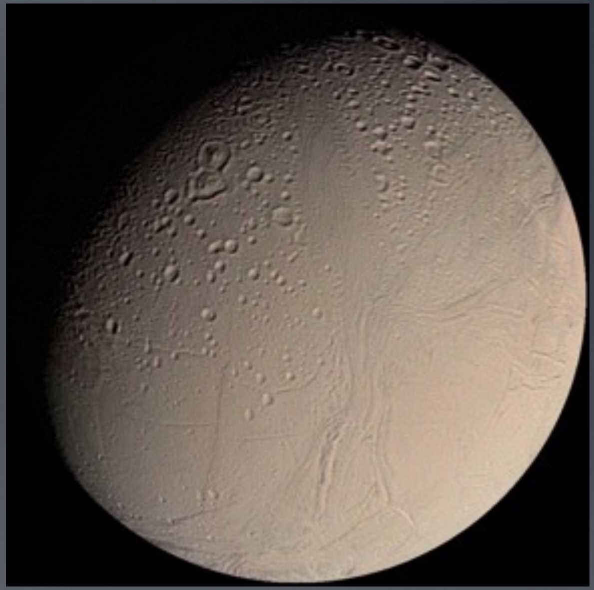
Io (not Titan)

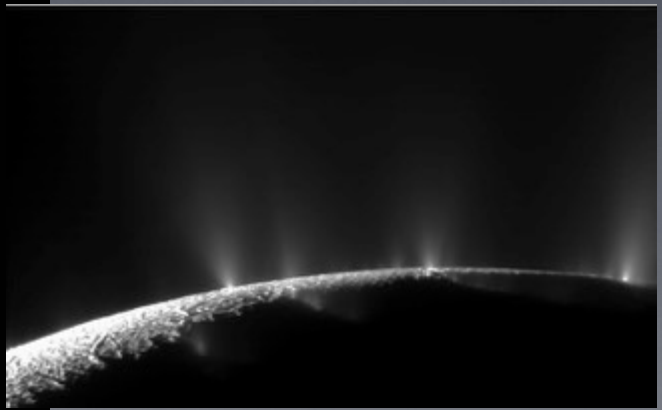


Europa



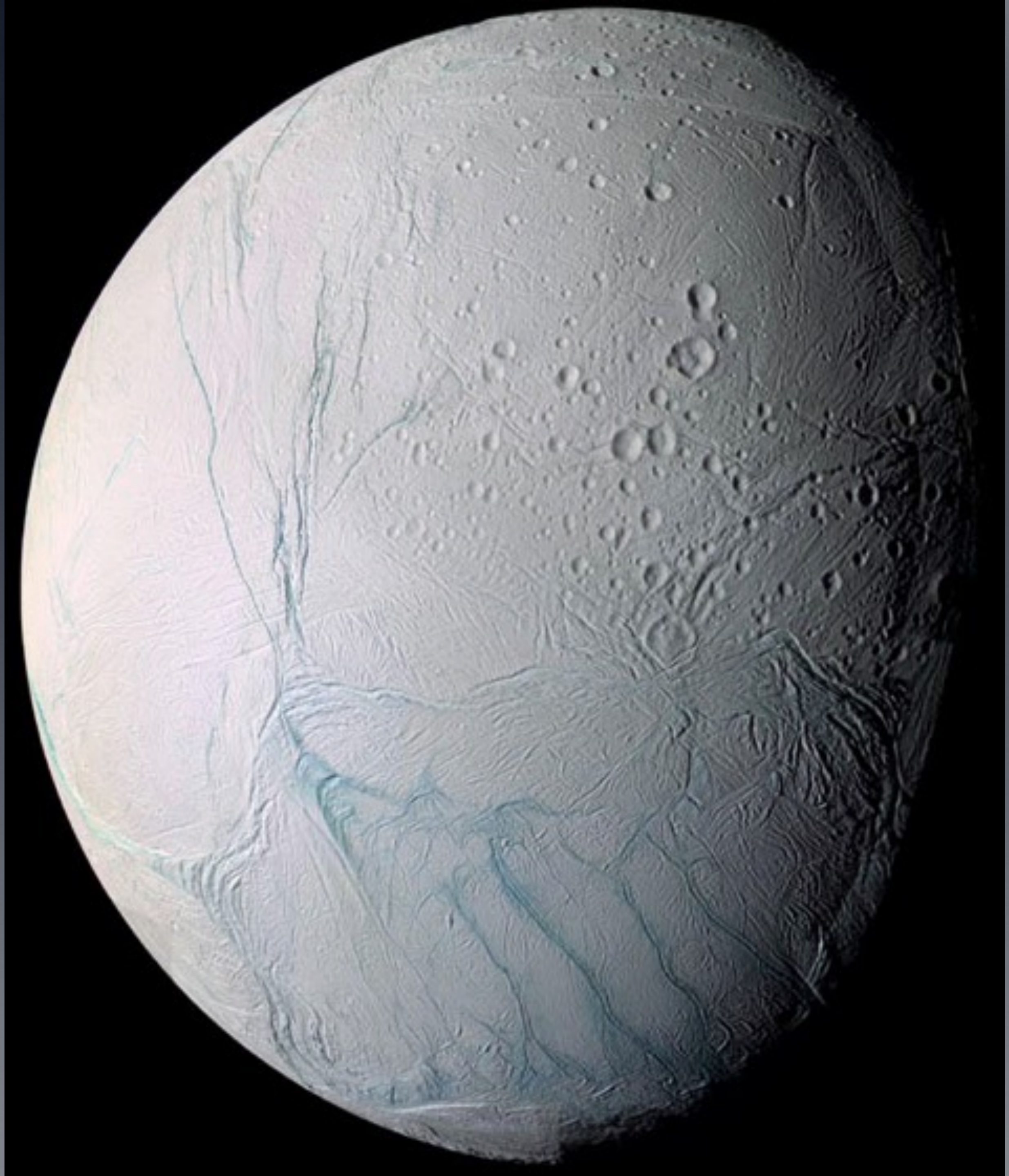
Enceladus



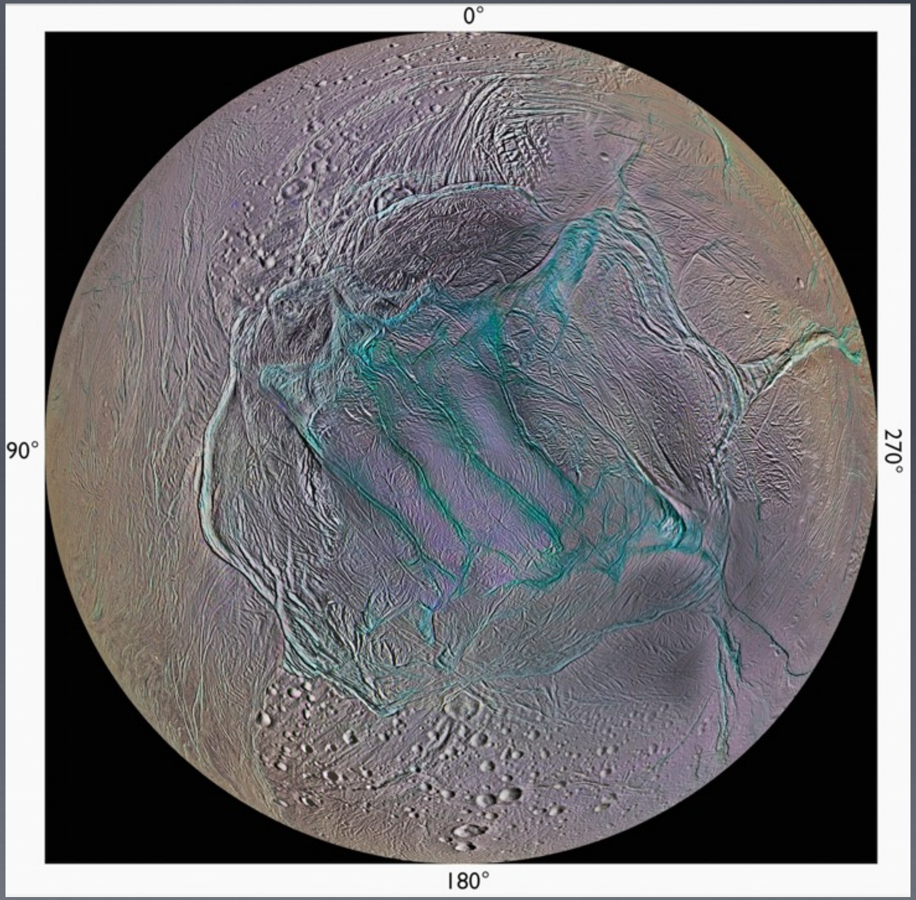


All these moons are heated by tides

Enceladus: moon of Saturn

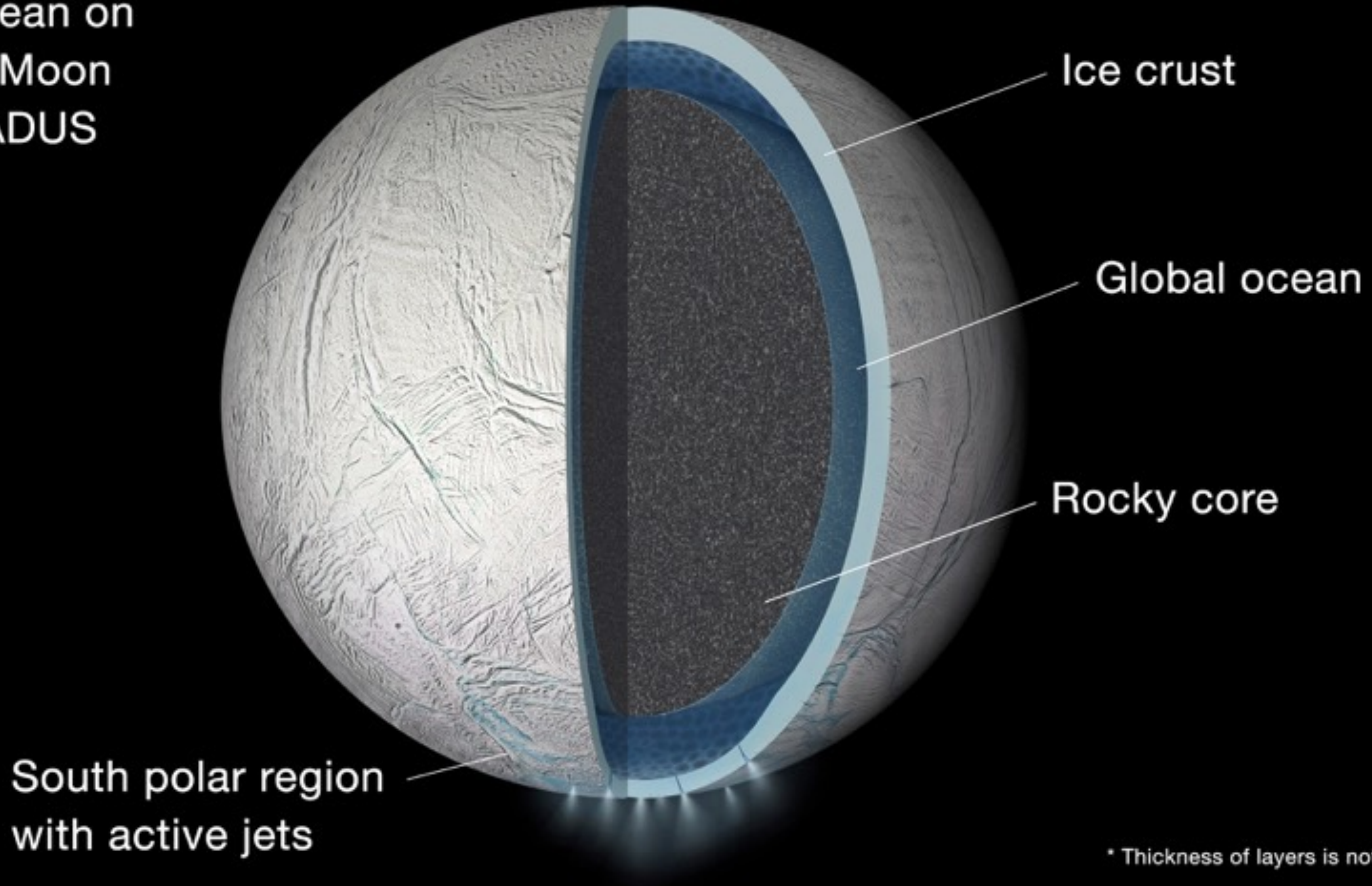


Cassini-ISS images of Enceladus



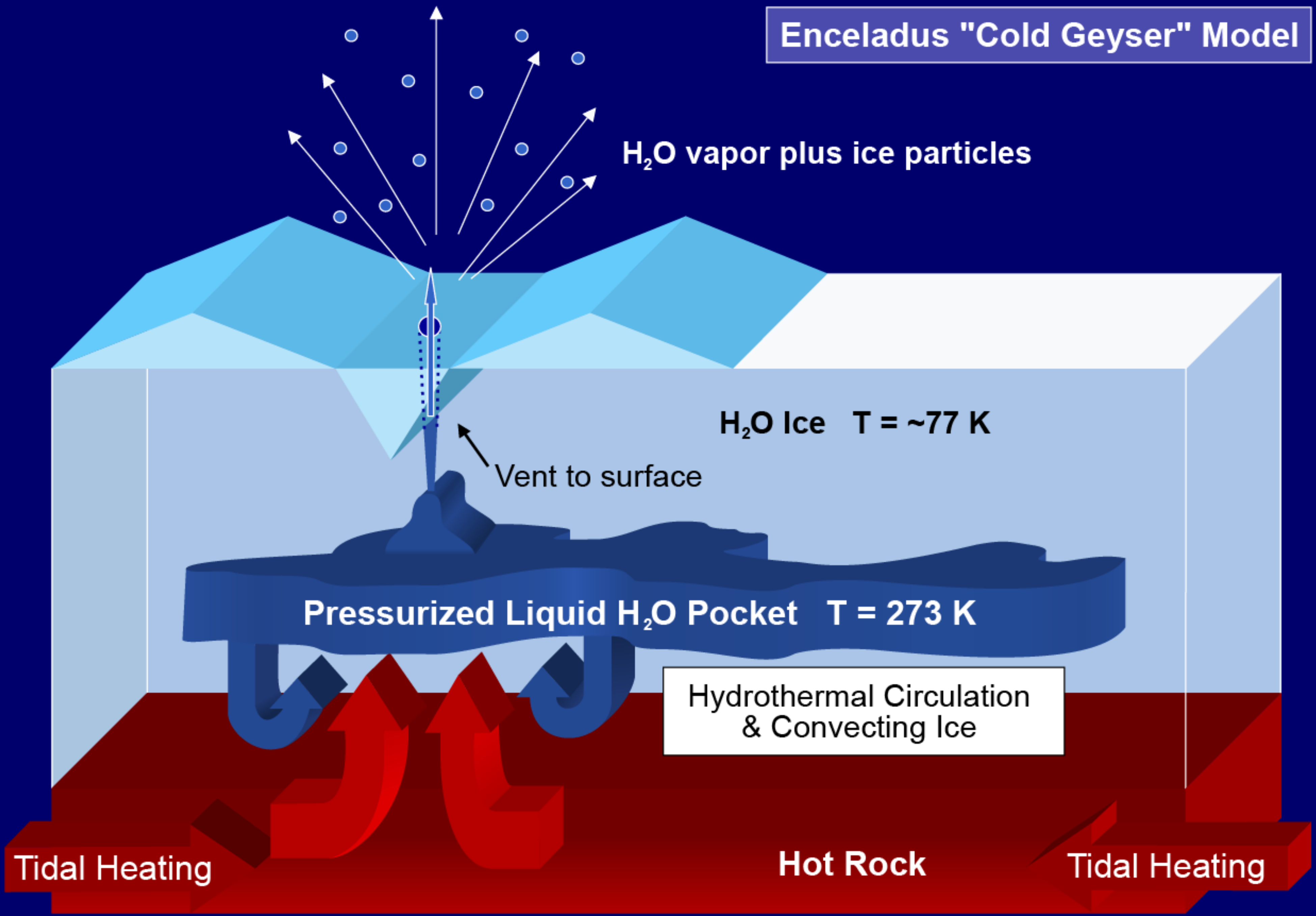
- Plumes of salt water, sand, nitrogen (in ammonia), nutrients and organic molecules
- Hydrothermal activity, an energy source, in Enceladus's subsurface ocean.
- Underground warm water: provides a possible location for life!

Global Ocean on Saturn's Moon ENCELADUS

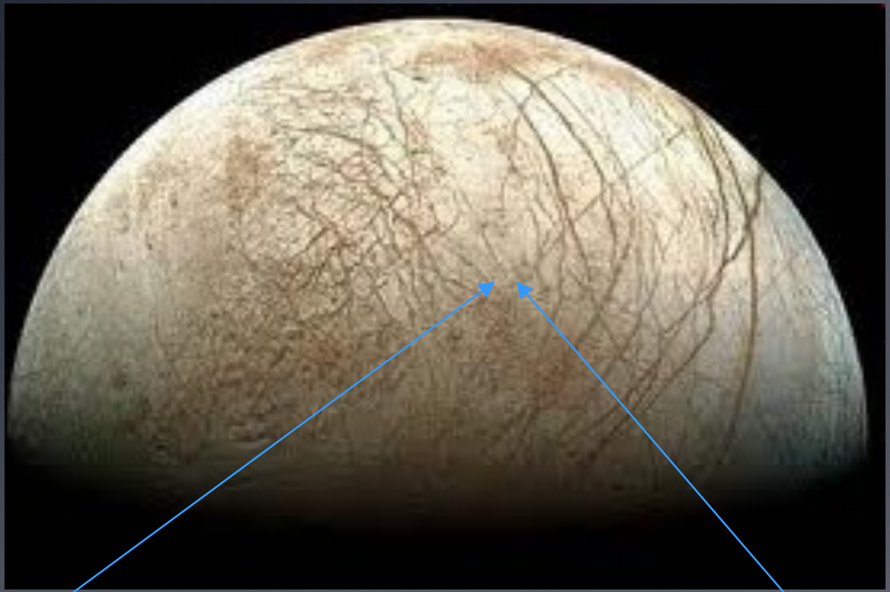


* Thickness of layers is not to scale

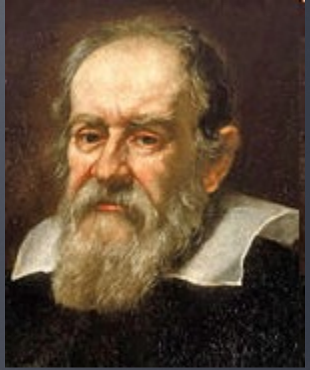
Enceladus "Cold Geyser" Model



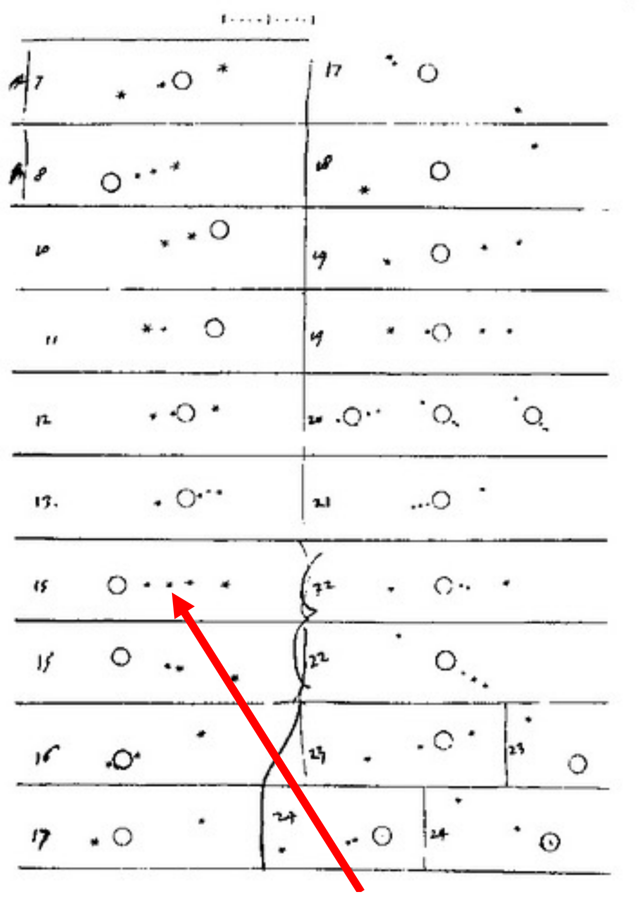
Europa: ice moon of Juputer



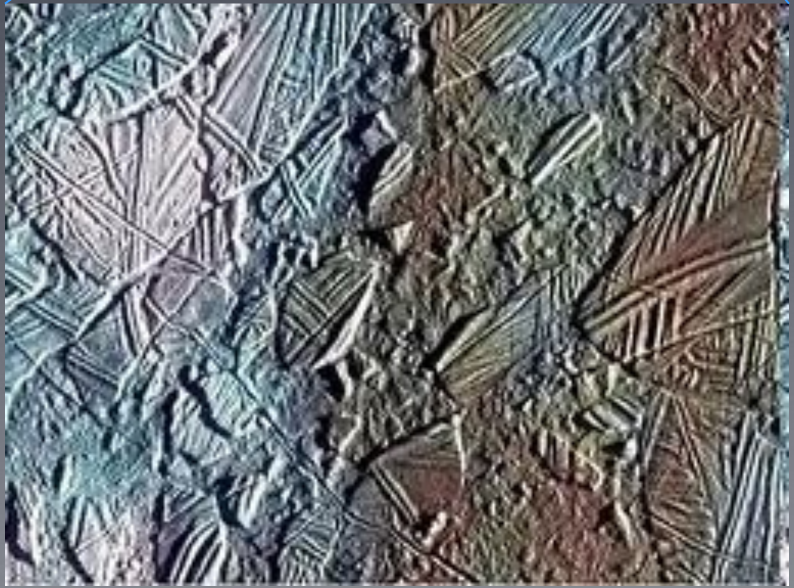
Very young surface
(no craters)



Galileo Galilei

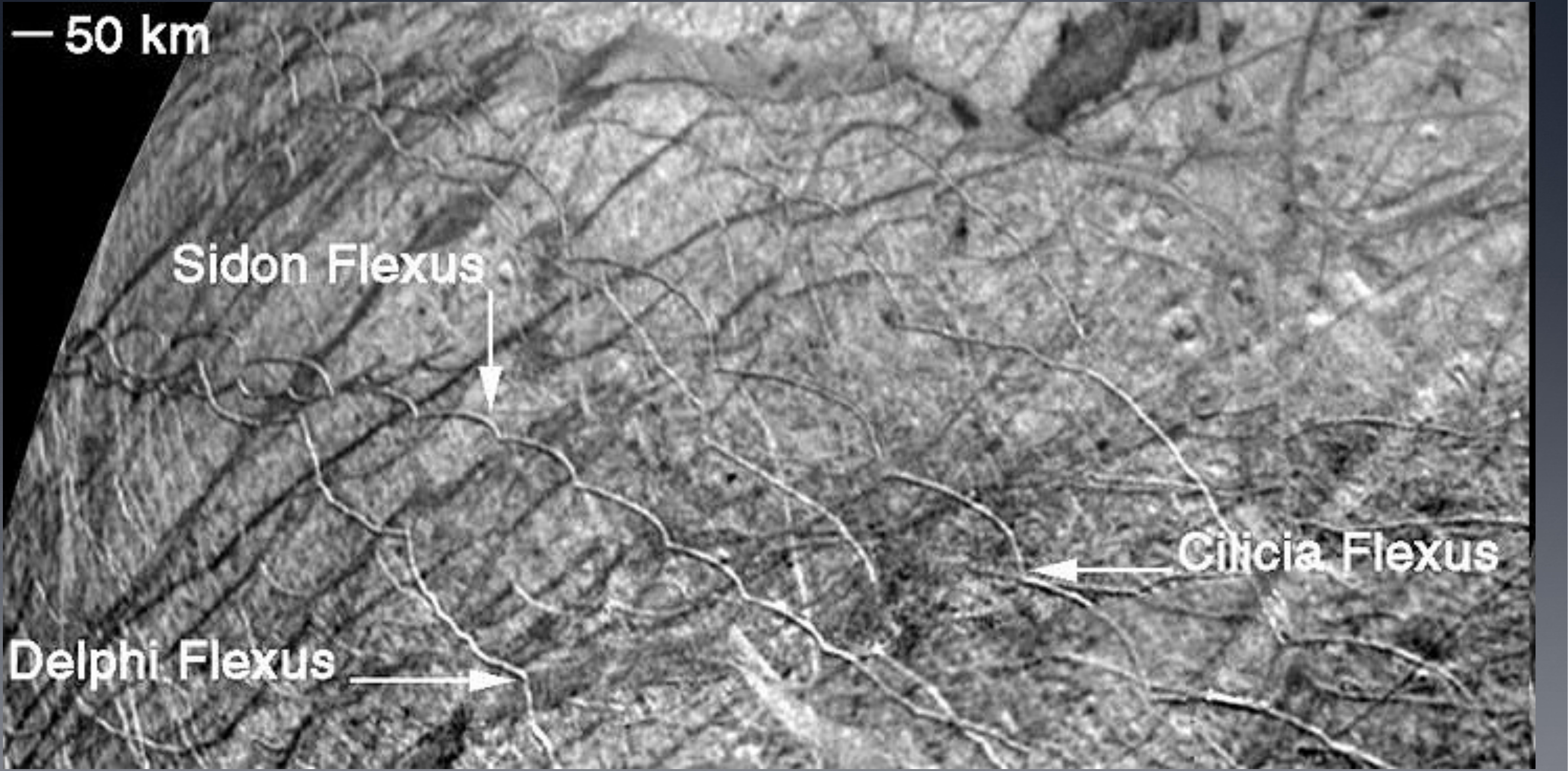


Europa!

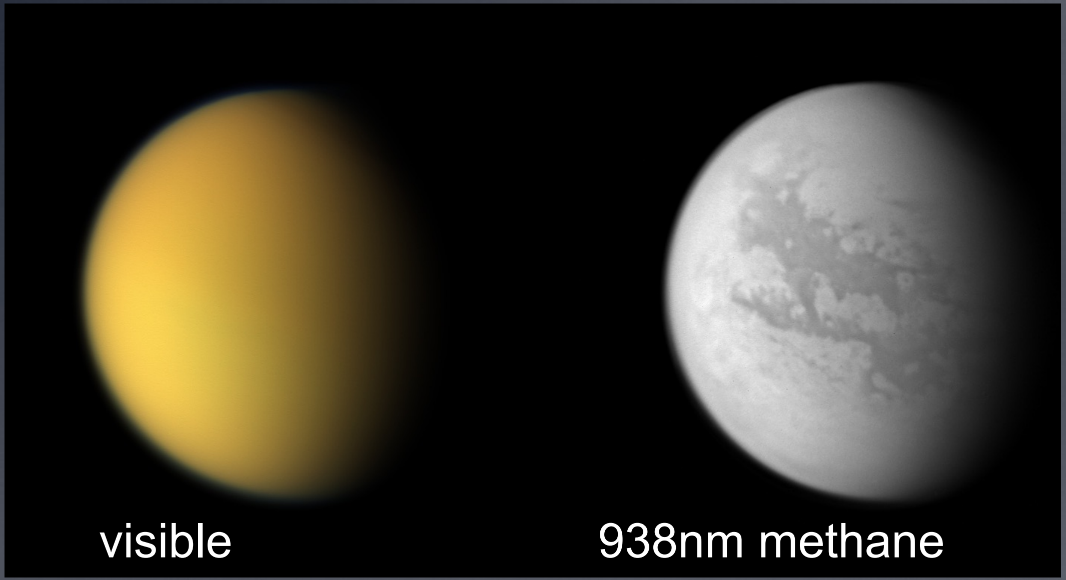


Icebergs on
the surface!

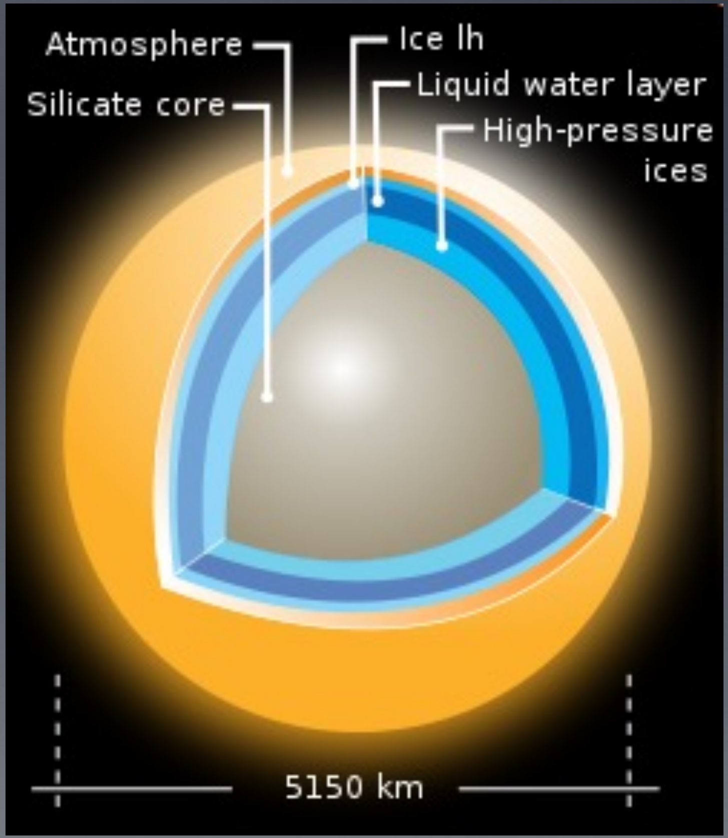
Europa



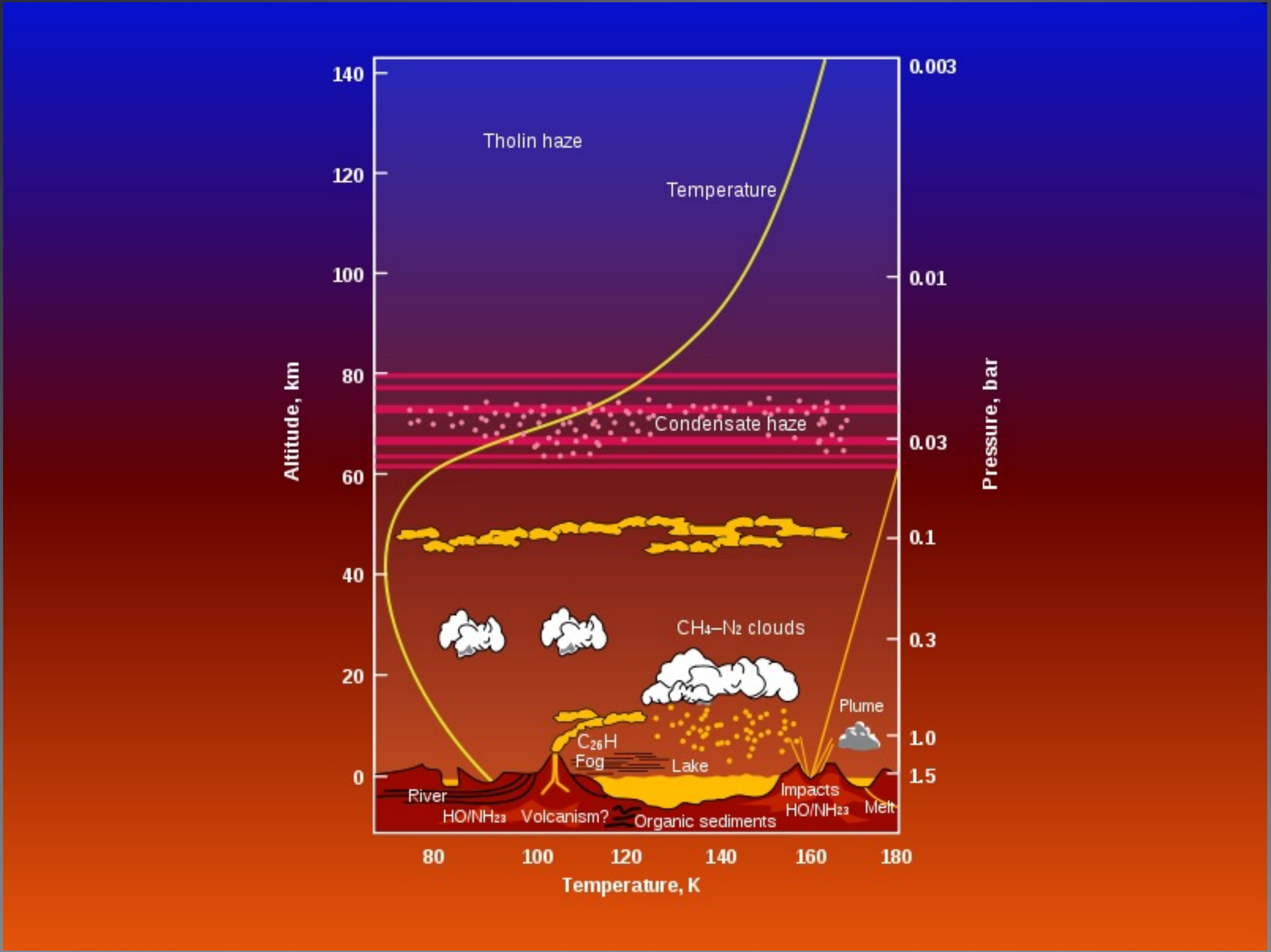
Titan: 2nd largest moon in solar system


visible

938nm methane

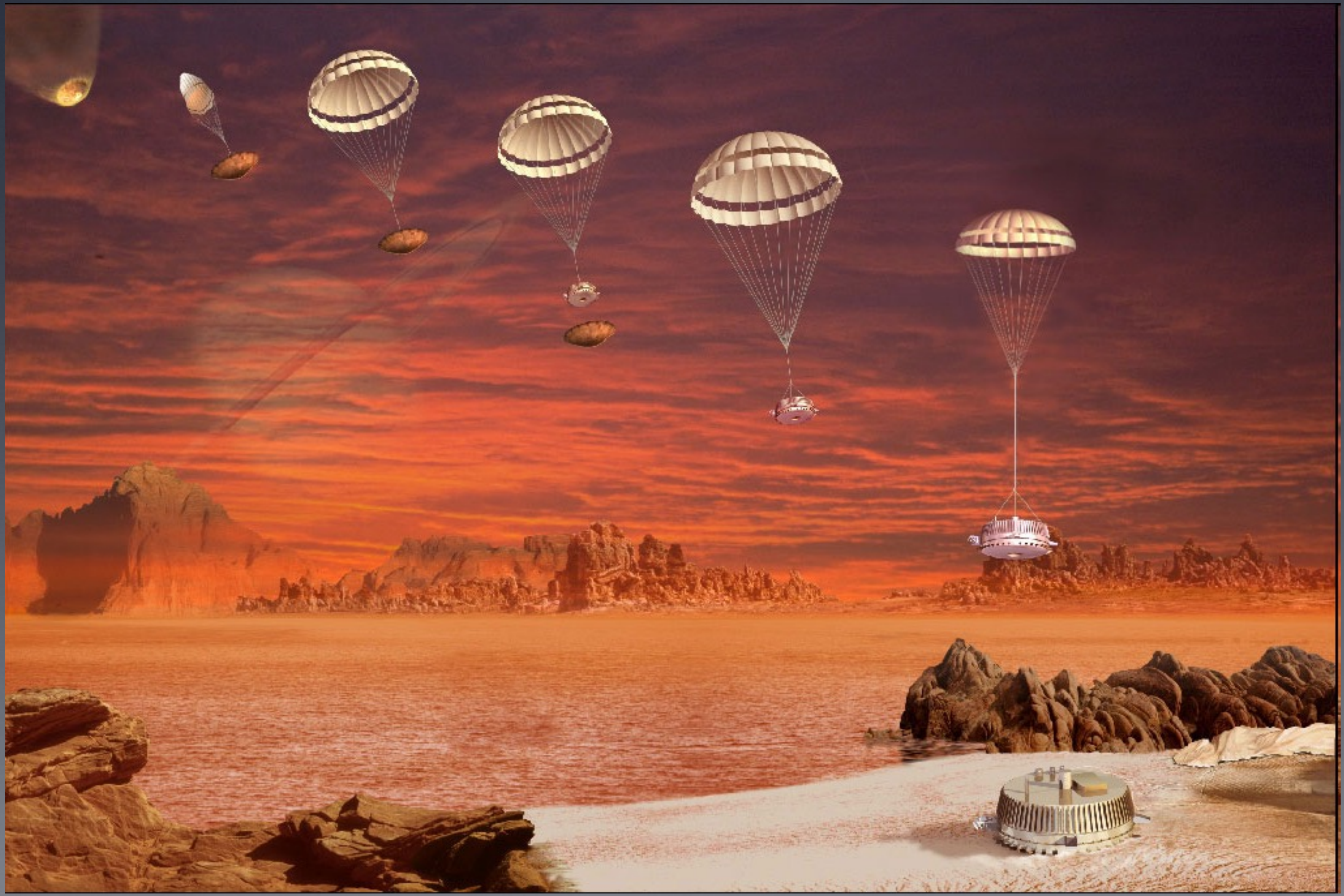


Titan’s atmosphere structure



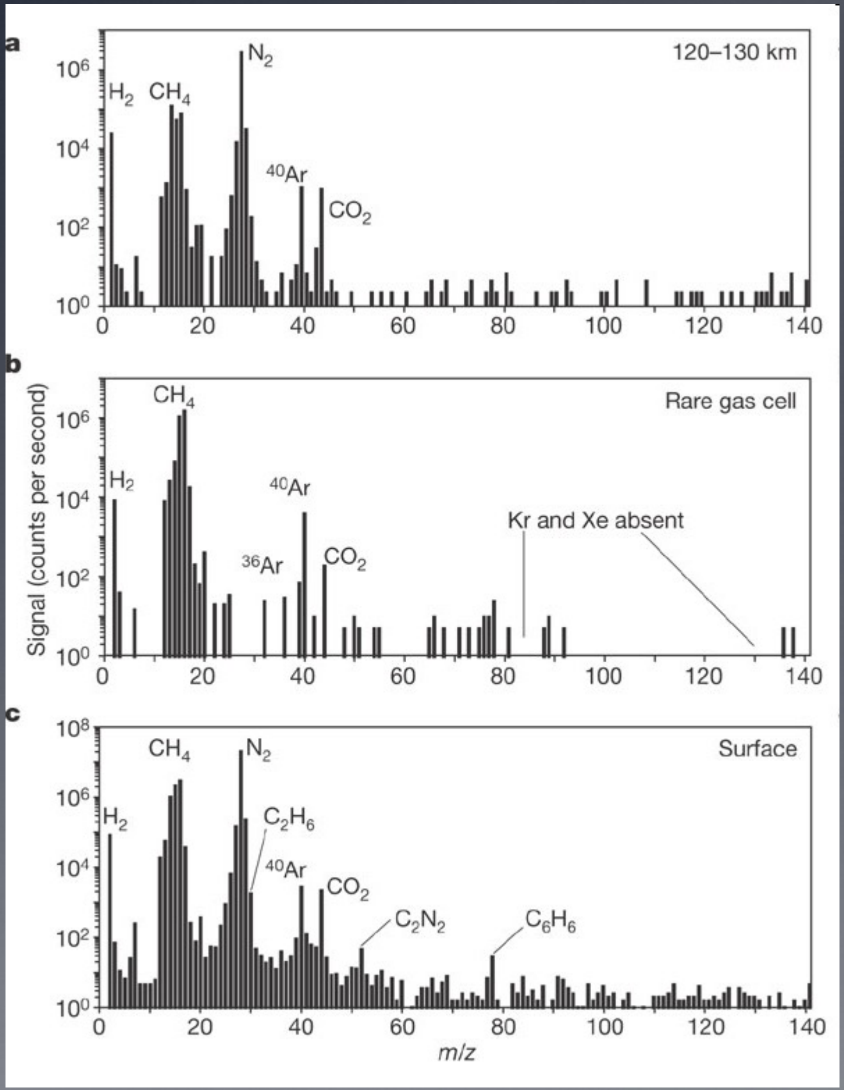
The Huygens probe landing on Titan

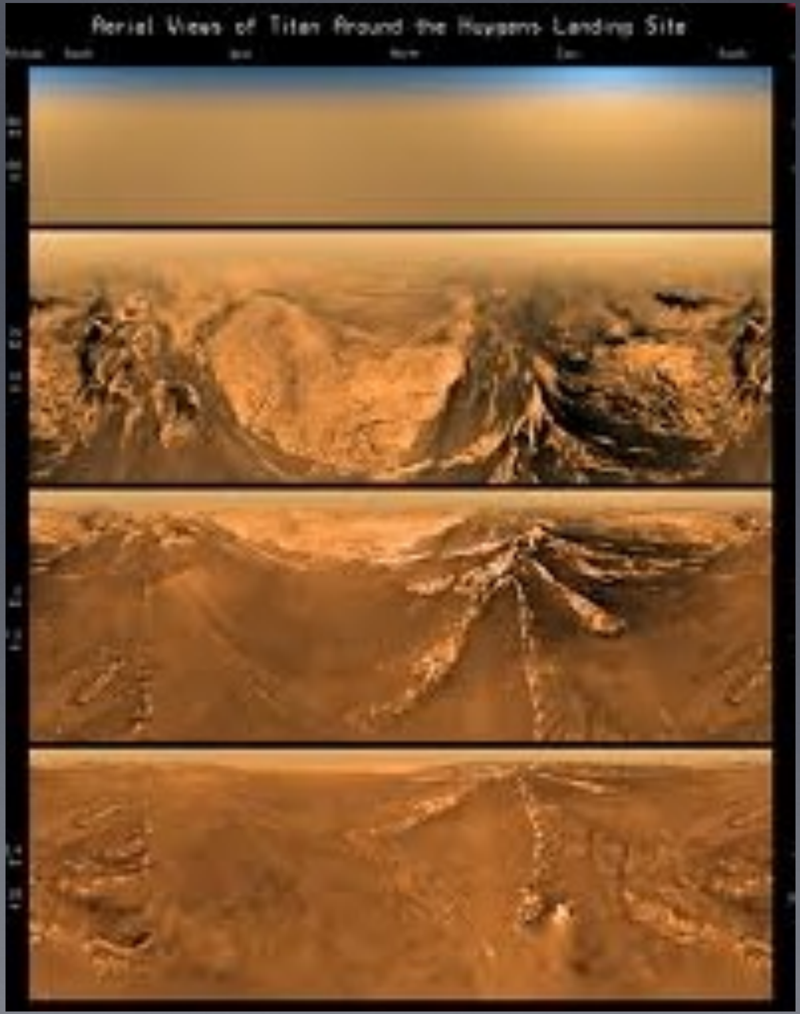
The Huygens lander:



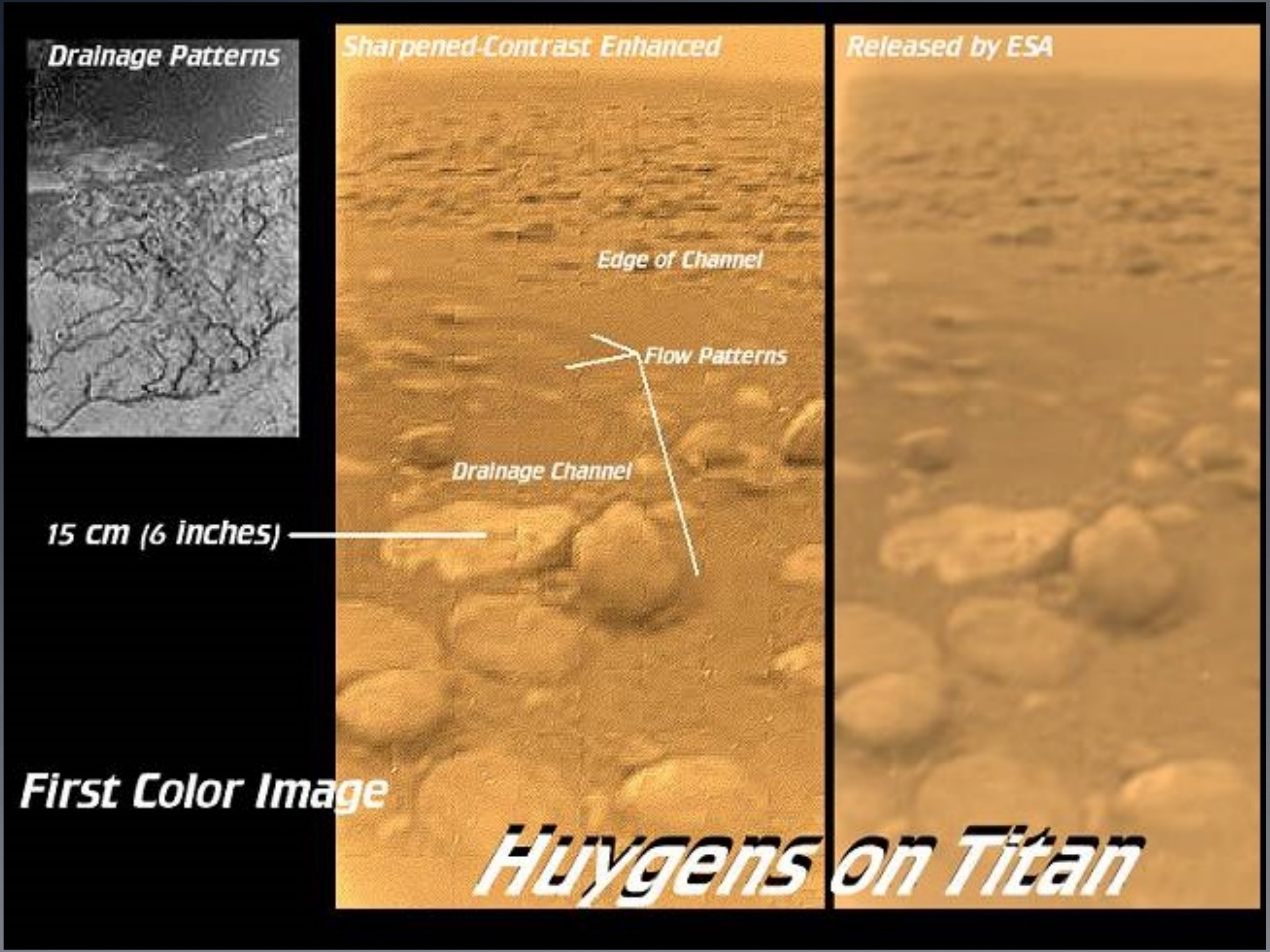
Titan: 2nd largest moon in solar system

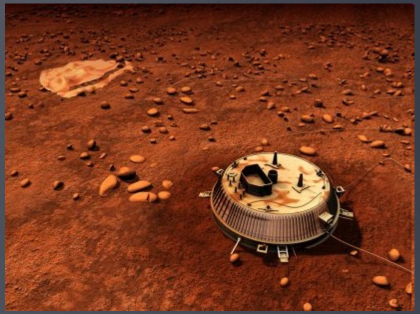
Atmosphere composition from descent





Images from Titan's surface!





Evidence for liquid methane on the surface

Heating of the surface by the probe caused methane outgassing

A possible Enceladus (or Europa) mission

- First: Where is the water?
  - At South Pole tiger stripes
  - 1-50km deep
- How to reach water
  - Fly through plumes
  - Land safely near the plume (not easy because the surface is rough) and then drill (hot brick?)
- Staged approach
  - Saturn orbiter with multiple flybys provides detailed maps; then an Enceladus orbiter and lander; finally, mobility to explore with a rover
- Tests for life
  - Microscopy, culture a sample, labeled nutrients, identify life molecules: amino acids, polypeptides, polysaccharides, lipids, nucleic acids and DNA

Europa Missions

Europa Clipper:
NASA, launch: 2023
Confirm ice shell+ocean
Study geology, composition of ice/ocean (incl. biosignatures)
$2B USD

JUICE:
ESA, launch in 2022
Focus on Ganymede, but two flybys of Europa in 2029

Europa Lander:
NASA, under study. Need to first evaluate whether can land (jagged ice)

Other upcoming planetary missions

- Venus: NASA (2021) selected two missions for ~2030
- Dragonfly: drone to Titan!
- ESA: Comet Interceptor (2029)

Change missions (嫦娥)

- Chang’e 1, 2 (2007, 2010): Lunar orbiter
- Chang’e 3 (2013): Lunar lander and Yutu rover
- Chang’e 4 (2018): first landing on far side of moon
- Chang’e 5 (2020): Lunar lander and sample return
- Chang’e 6 (2024): Lunar lander and sample return
- Chang’e 7 (2024): Drone! (without atmosphere)

Building to robotic lunar base and manned mission

Planetary missions from China

- Tianwen-1 (天问2021): Mars lander, Zhurong rover
- ZhengHe: sample return mission from comet
- Mars sample return missions
- Gan De (2030): Jupiter orbiter (and Callisto lander?)
- Mission to Uranus (2030s)?
- Other missions may include leaving the solar system

Crewed space missions

- Space Station
  - International Space Station
  - Tiangong Space Station
- Moon
  - Apollo program: Six US missions (last in 1972)
  - Chinese Lunar Exploration Program: 2030s
    - Chinese-Russian base on moon?
- Mars – 160 times further than moon at closest approach
  - US plans in mid-2030s, but unfunded
  - China plans in 2033