Making Chemically Diverse Planets out of Average Galactic Material

Ruth Murray-Clay
UC Santa Cruz

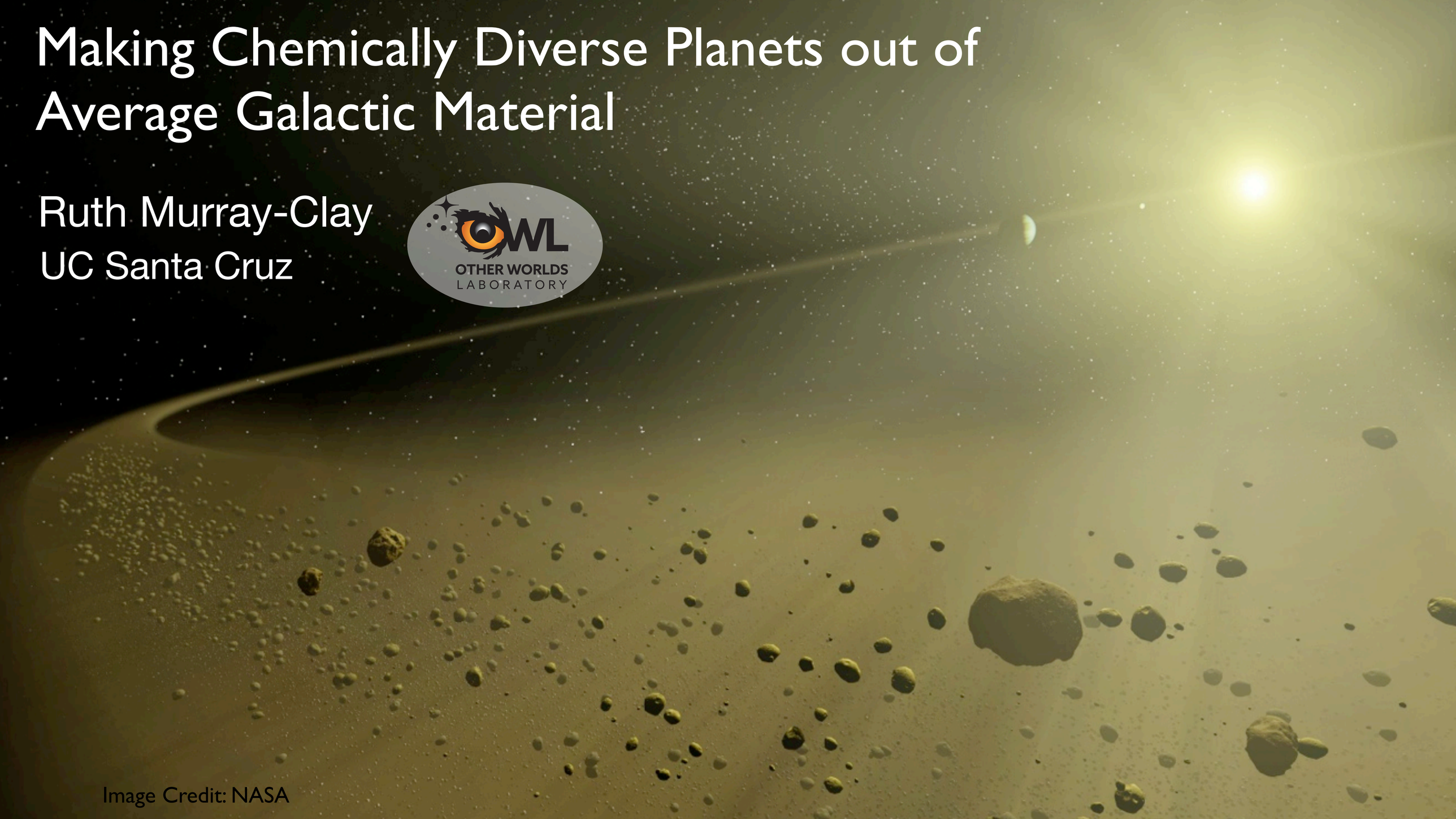
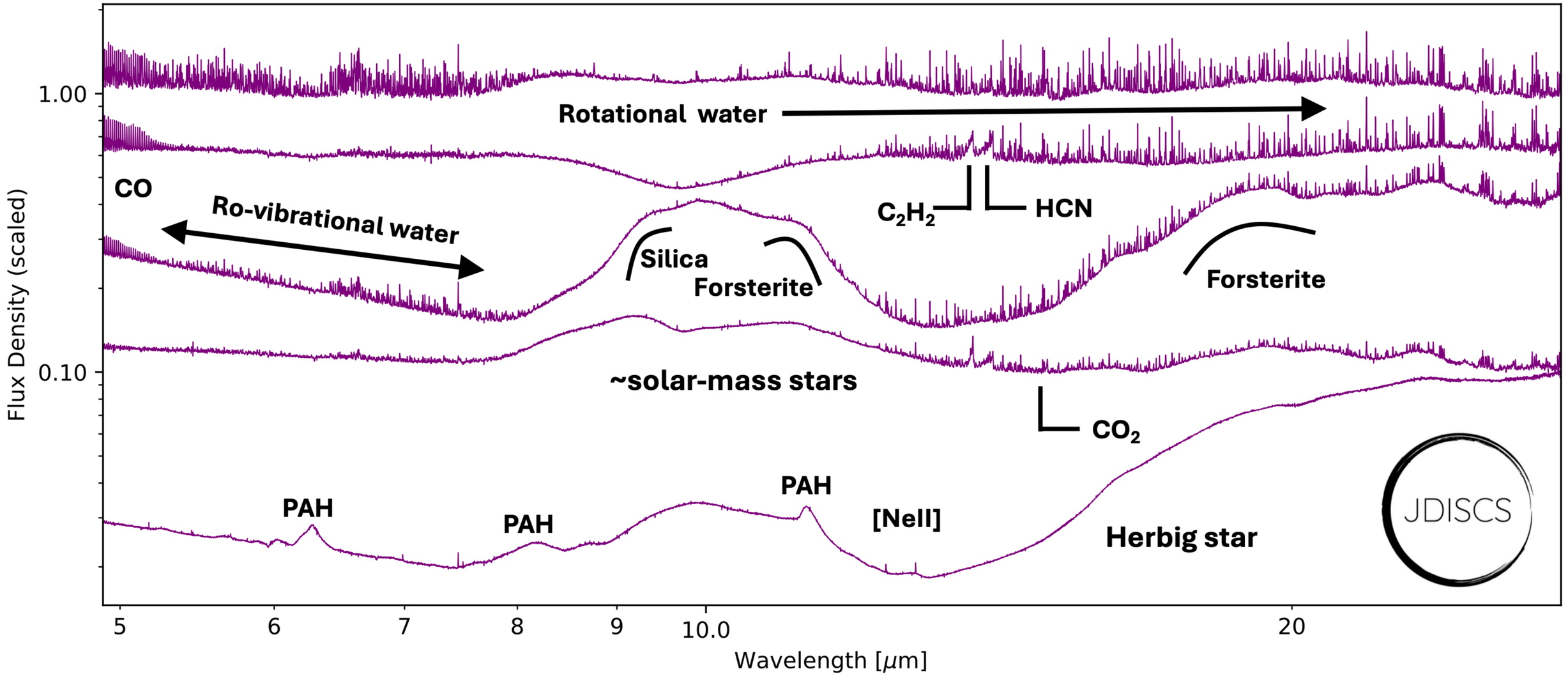


Image Credit: NASA

James Webb Space Telescope (JWST)

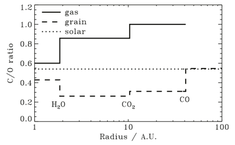
artist's conception

NASA

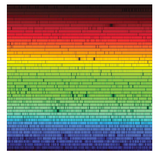

1.00
0.10
Flux Density (scaled)
Rotational water
CO
Ro-vibrational water
Silica
Forsterite
C_2H_2
HCN
Forsterite
~solar-mass stars
CO_2
PAH
PAH
PAH
[NeII]
Herbig star
JDISCS
5
6
7
8
9
10.0
20
Wavelength [μm]

Our best examples: Solar system planets

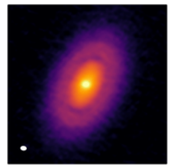
What are the building blocks? Interpreting the periodic table



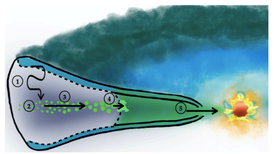
The context of planetary assembly: Planet formation



Spectra put the physics in astrophysics



Probing the building blocks: Protoplanetary disks



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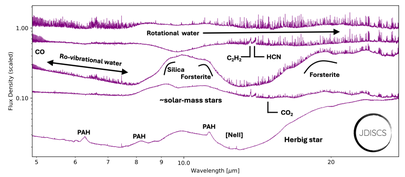

New insights: Mysteries from JWST

Our best examples: Solar system planets

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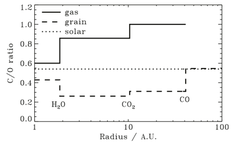

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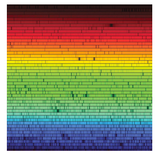

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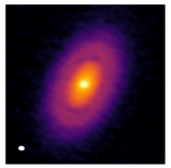

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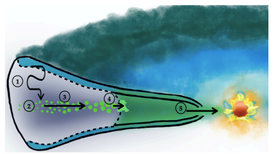

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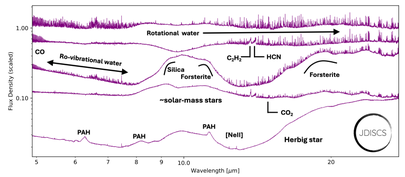

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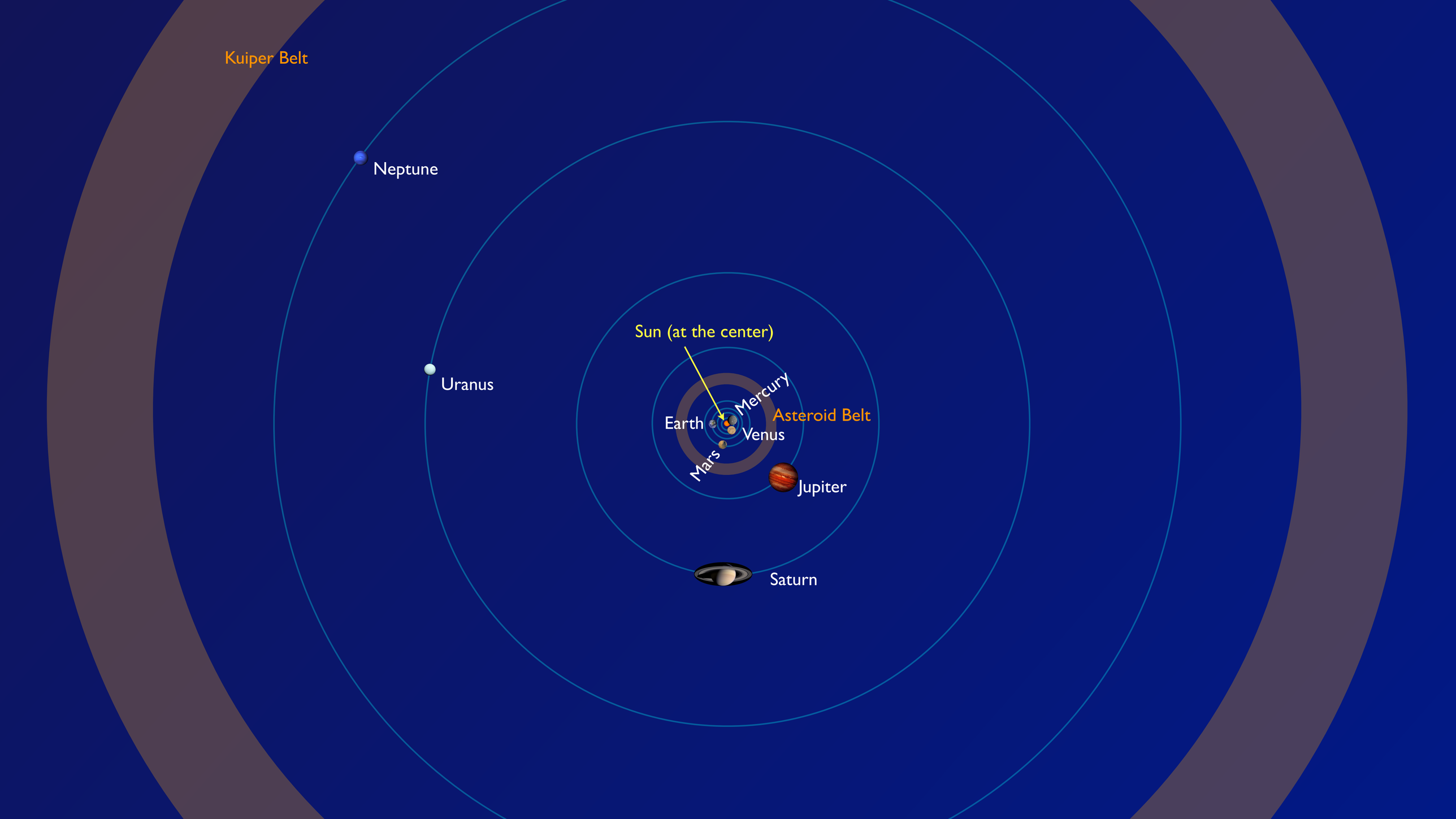
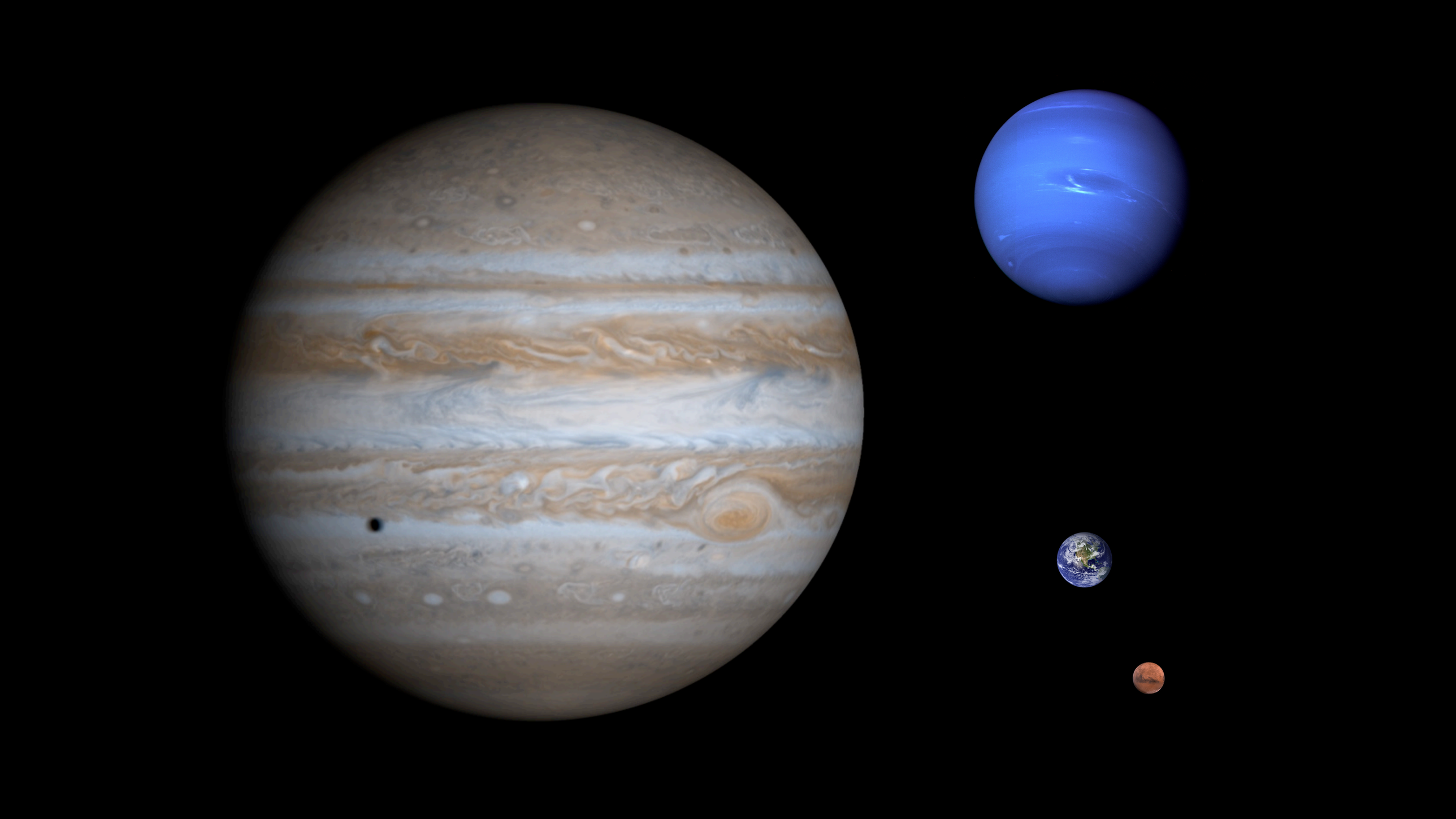
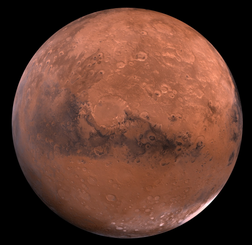
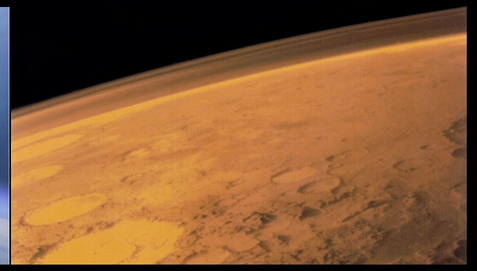

Kuiper Belt
Neptune
Uranus
Sun (at the center)
Mercury
Earth
Asteroid Belt
Venus
Mars
Jupiter
Saturn



terrestrial planets





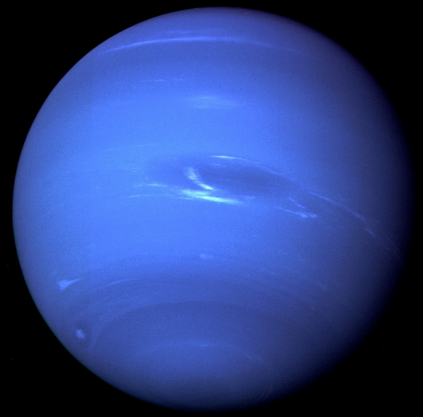
atmosphere

~ 0.0001%

~ 0.000003%

of the planet's mass

ice giants



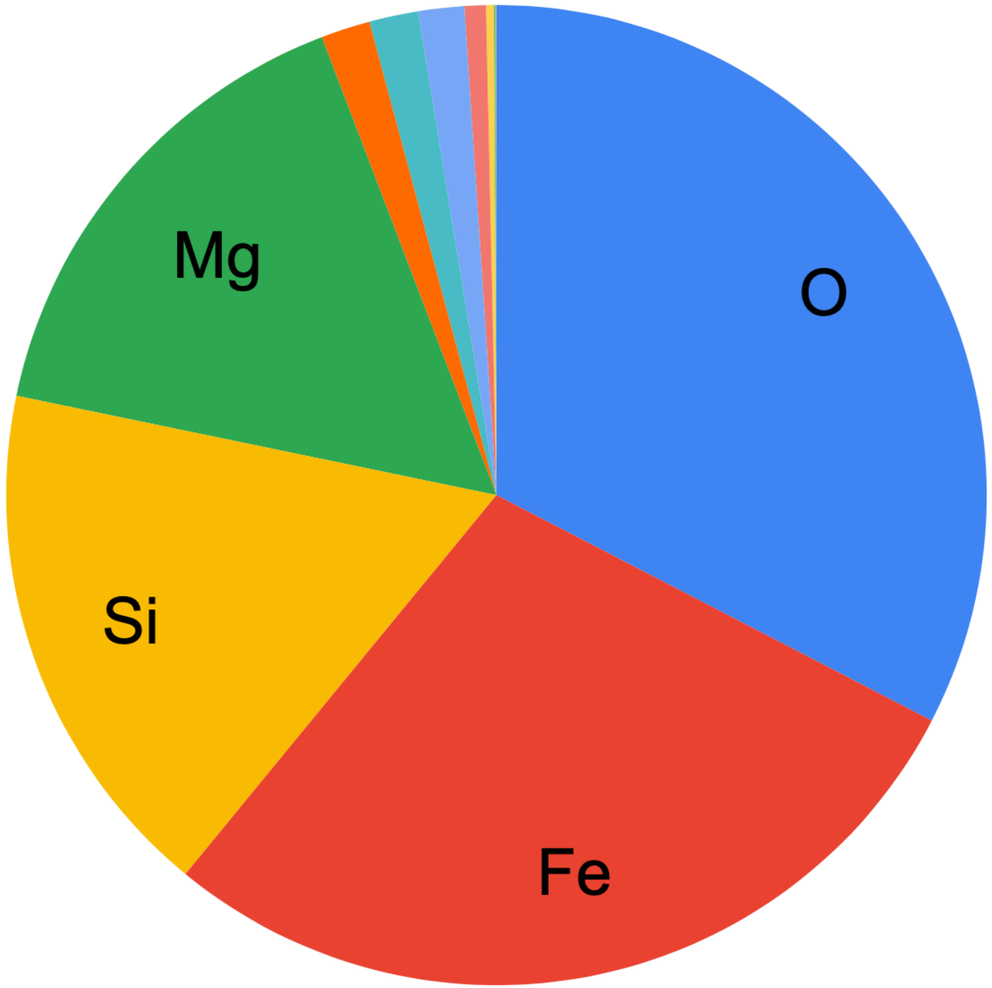
~10% hydrogen & helium atmosphere

gas giants

massive hydrogen & helium atmosphere

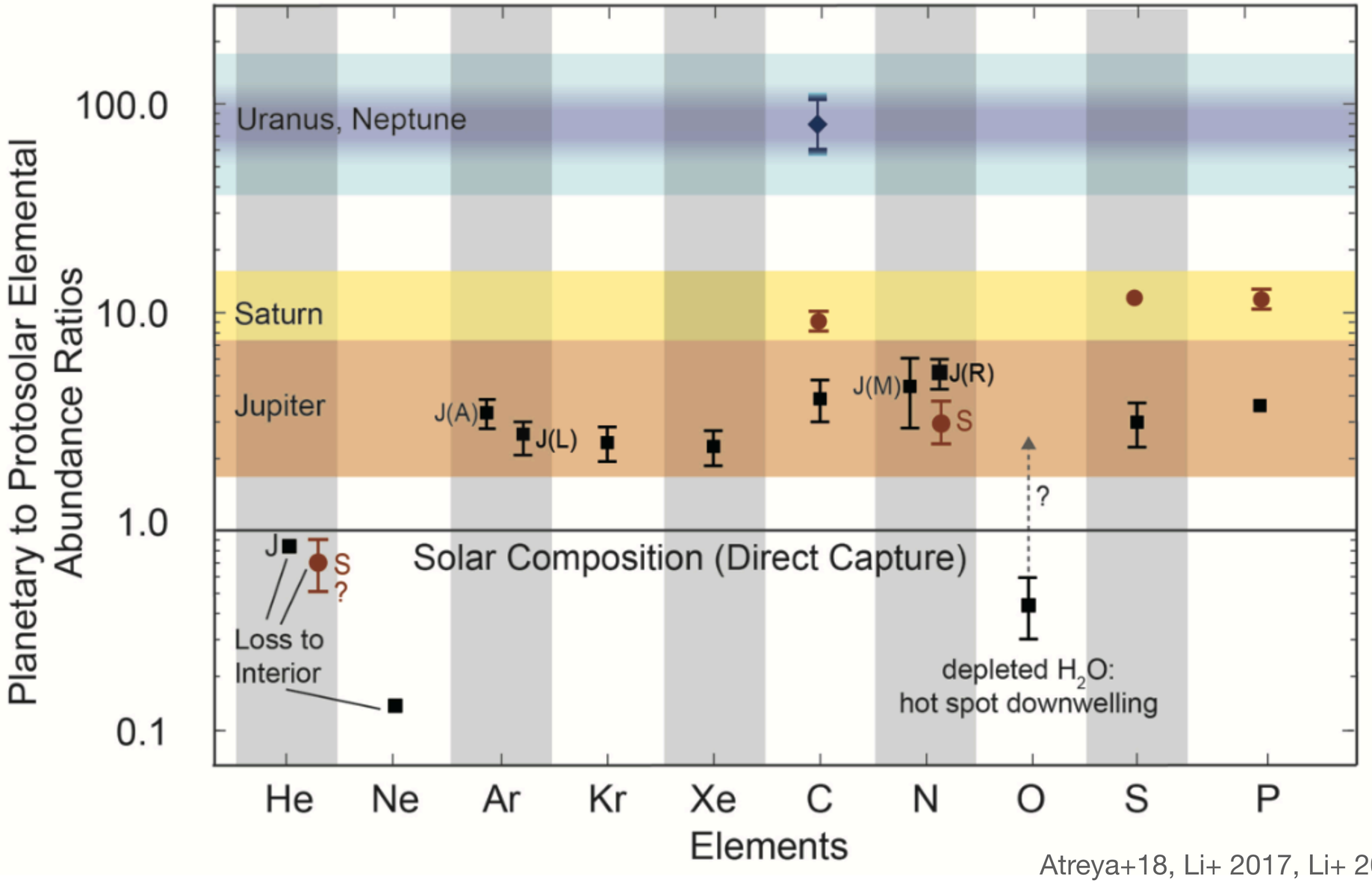
>95% of the planet's mass

Bulk Earth composition (Wt%)



Allègre+ 1995

Jupiter is enriched in heavy (to astronomers) elements



Atreya+18, Li+ 2017, Li+ 2020, Moeckel+ 2023

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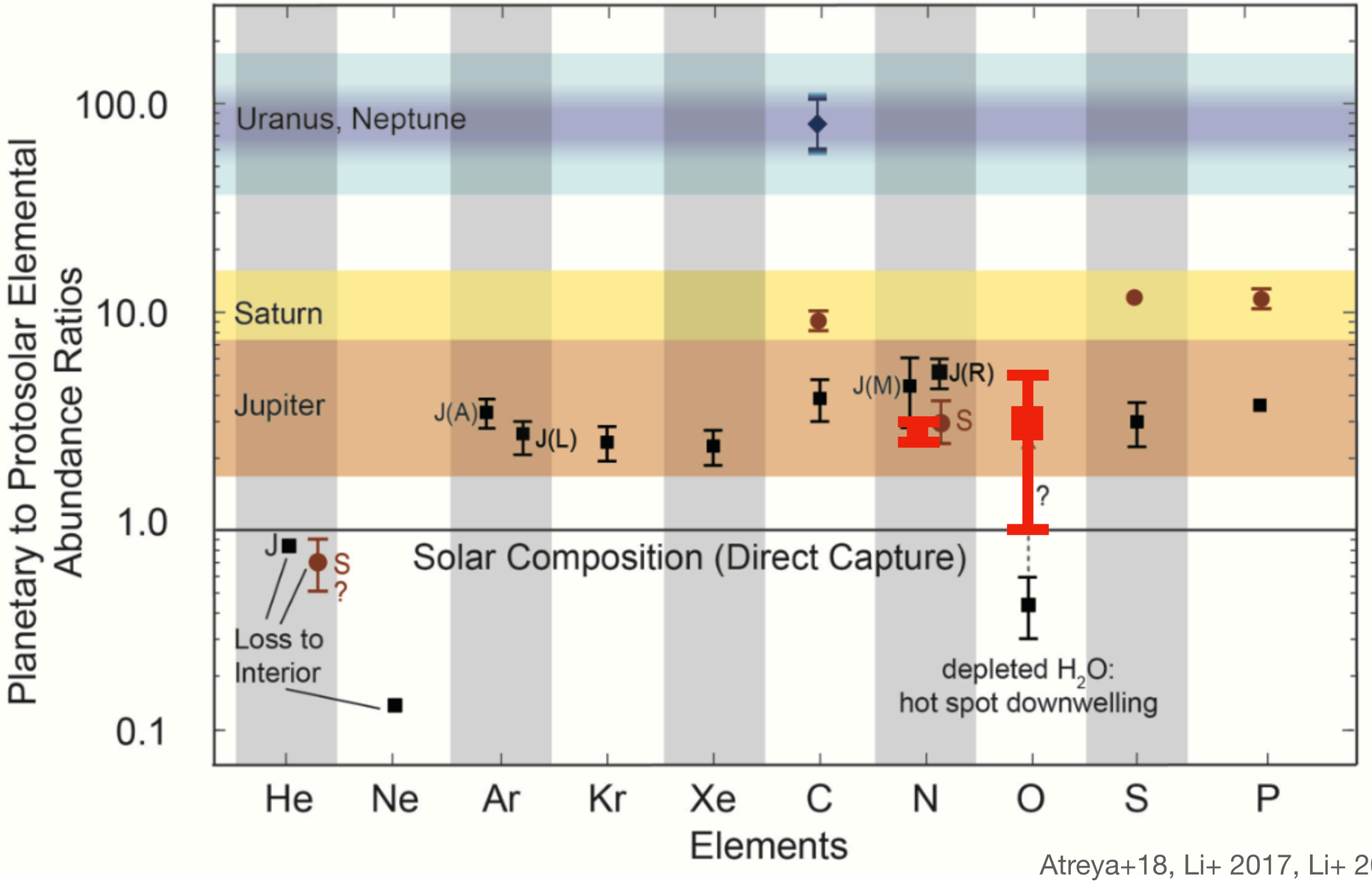

NASA's Juno Mission to Jupiter

Atreya+18, Li+ 2017, Li+ 2020, Moeckel+ 2023

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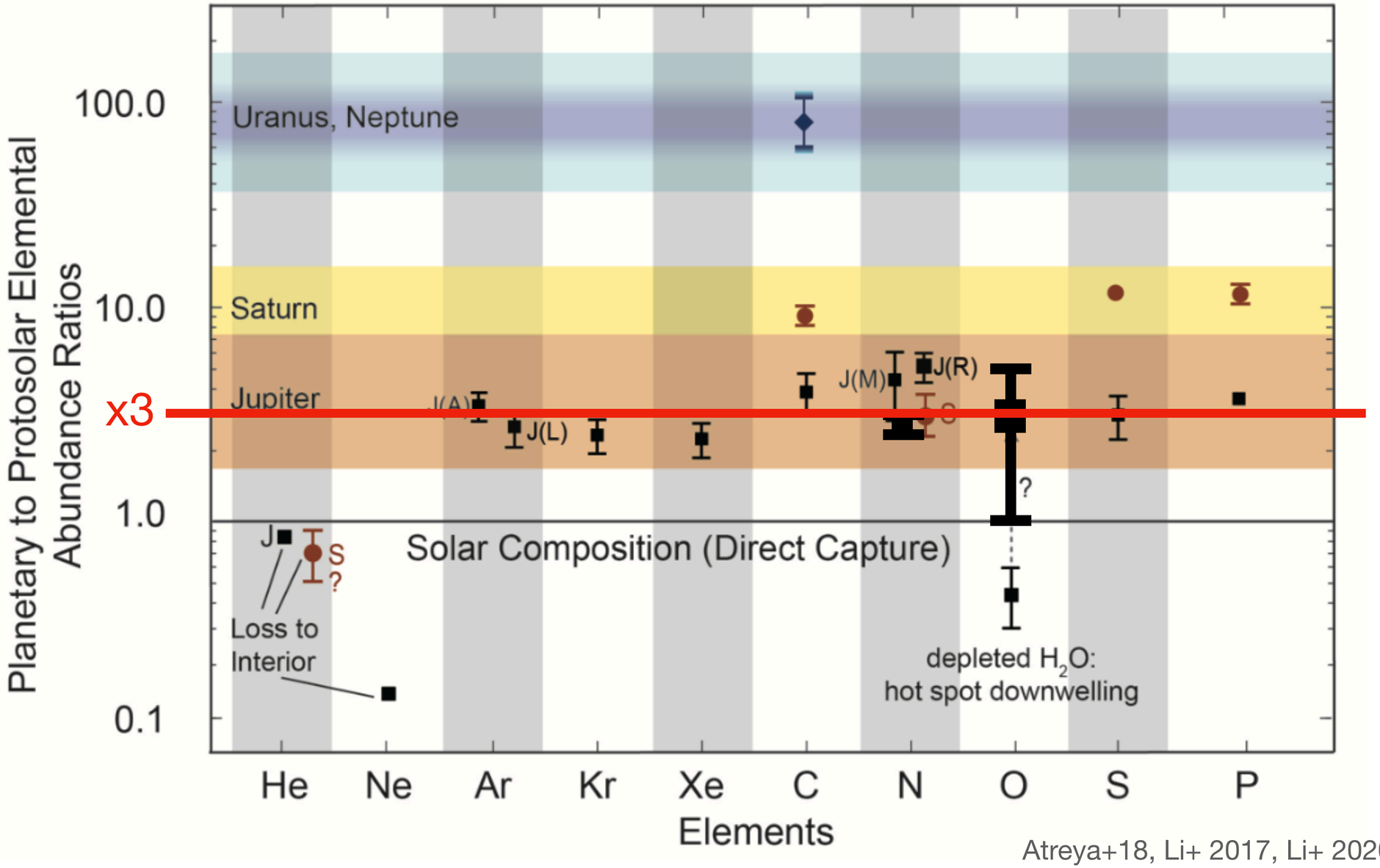

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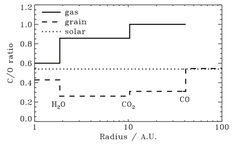

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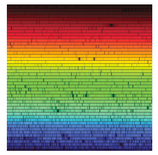

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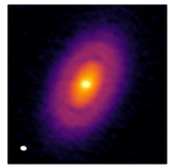

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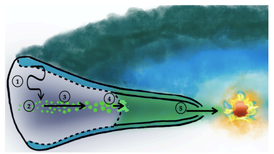

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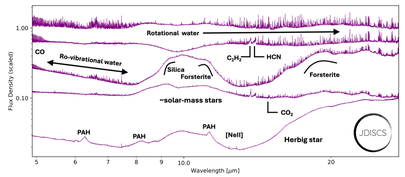
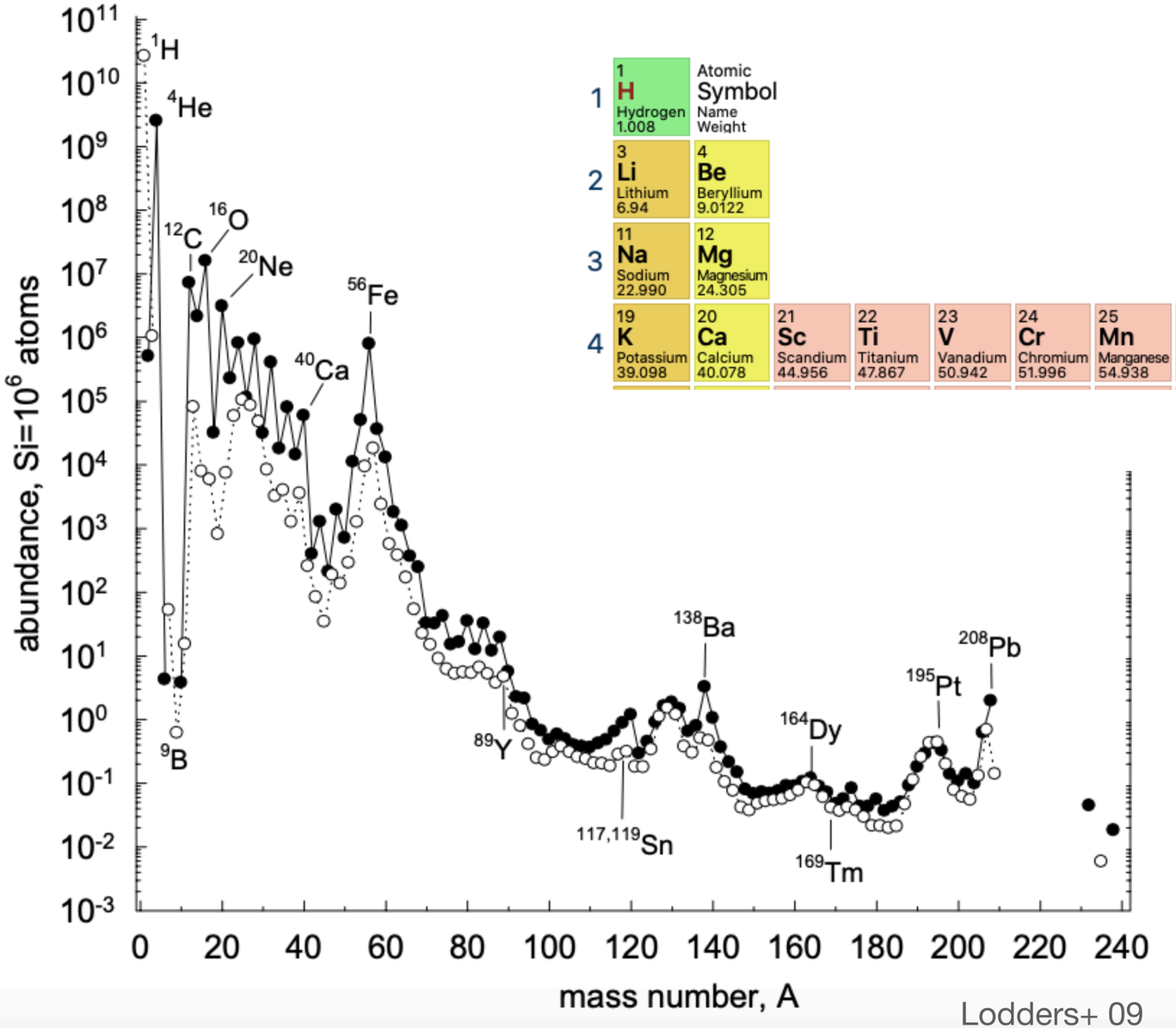


New insights: Mysteries from JWST

Planets are made from abundant atoms



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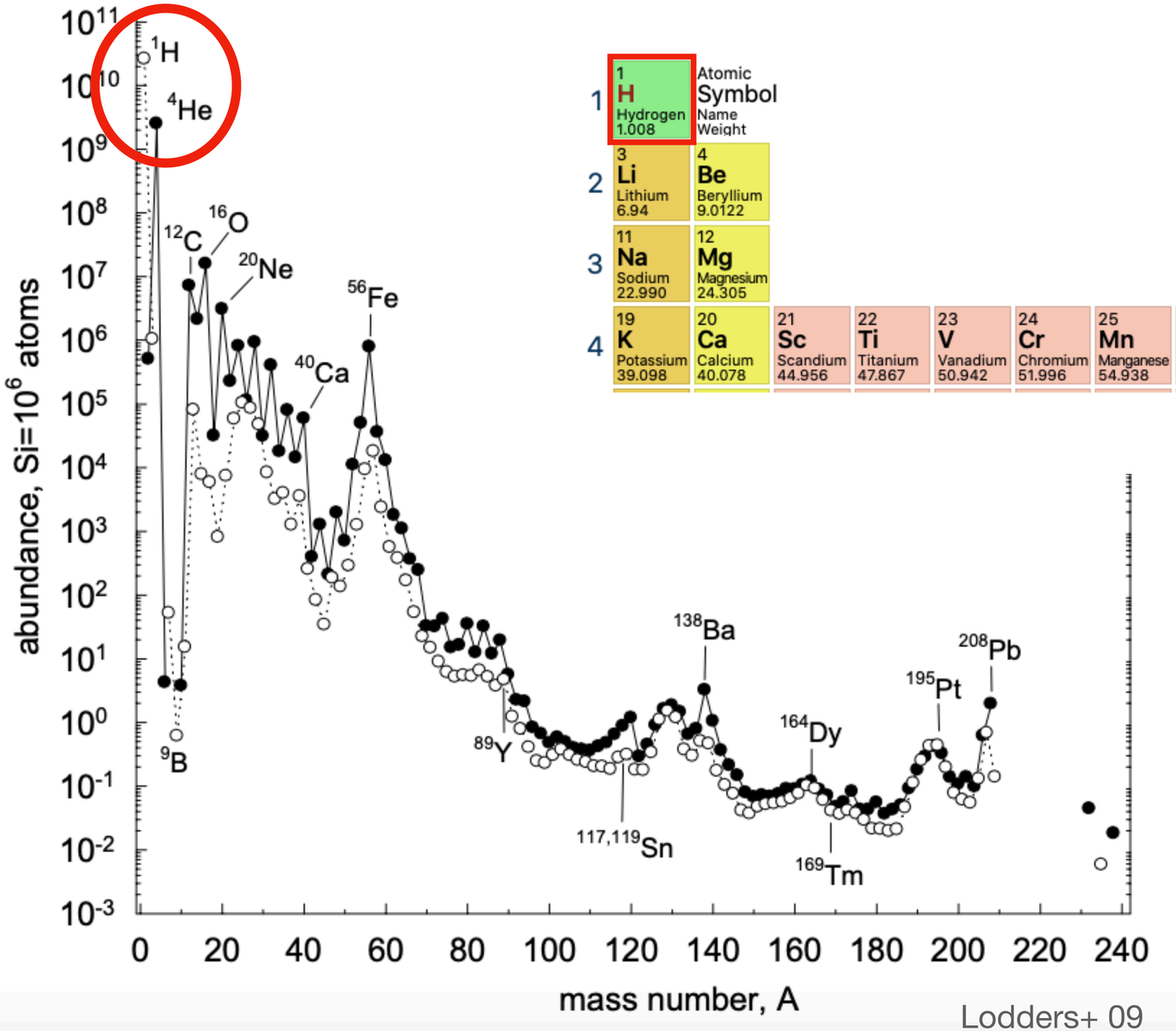
Lodders+ 09

Elemental abundances at time of solar system formation

Planets are made from abundant atoms



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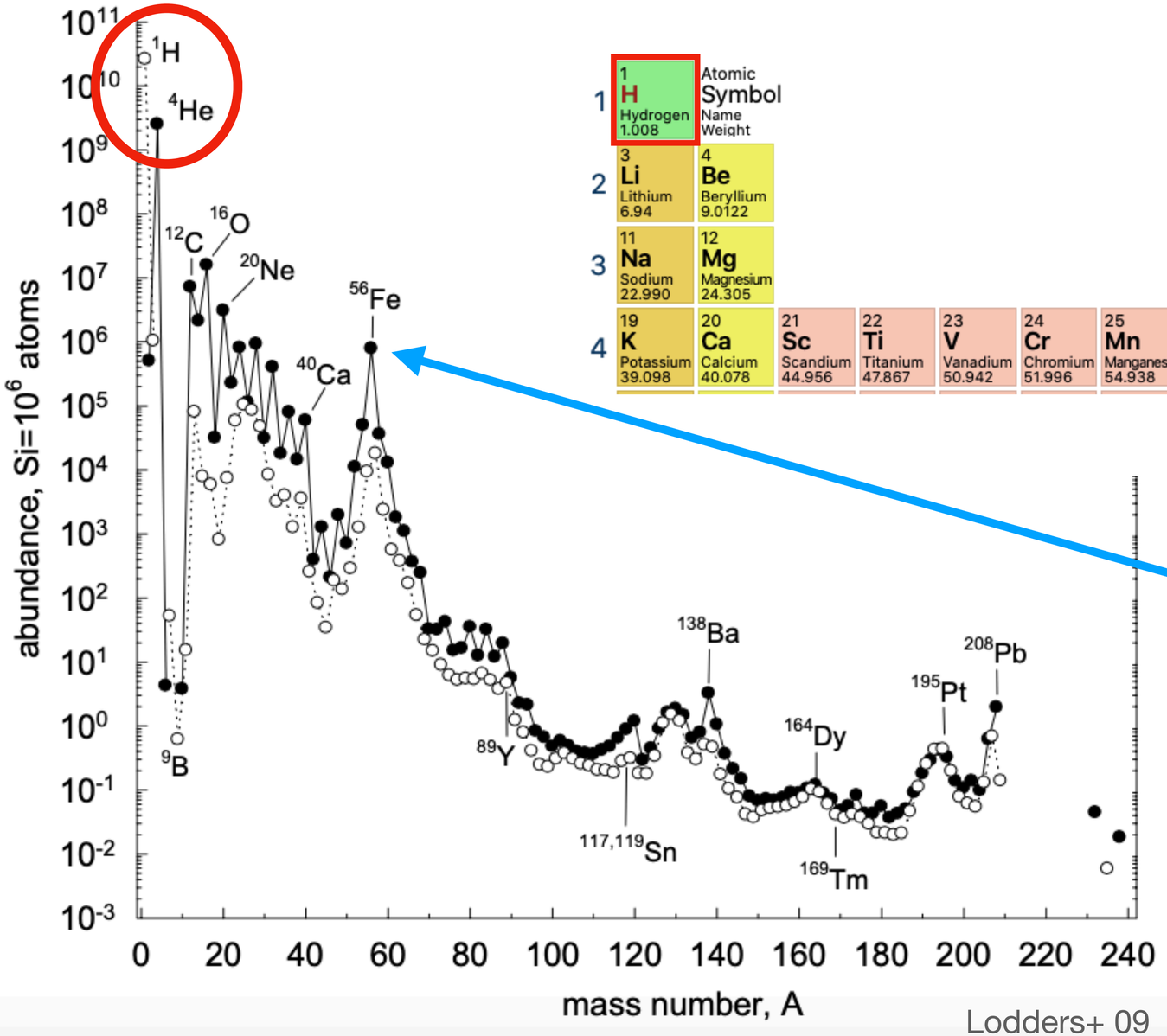

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Highest mass number for which fusion gives you energy

Elemental abundances at time of solar system formation

Lodders+ 09

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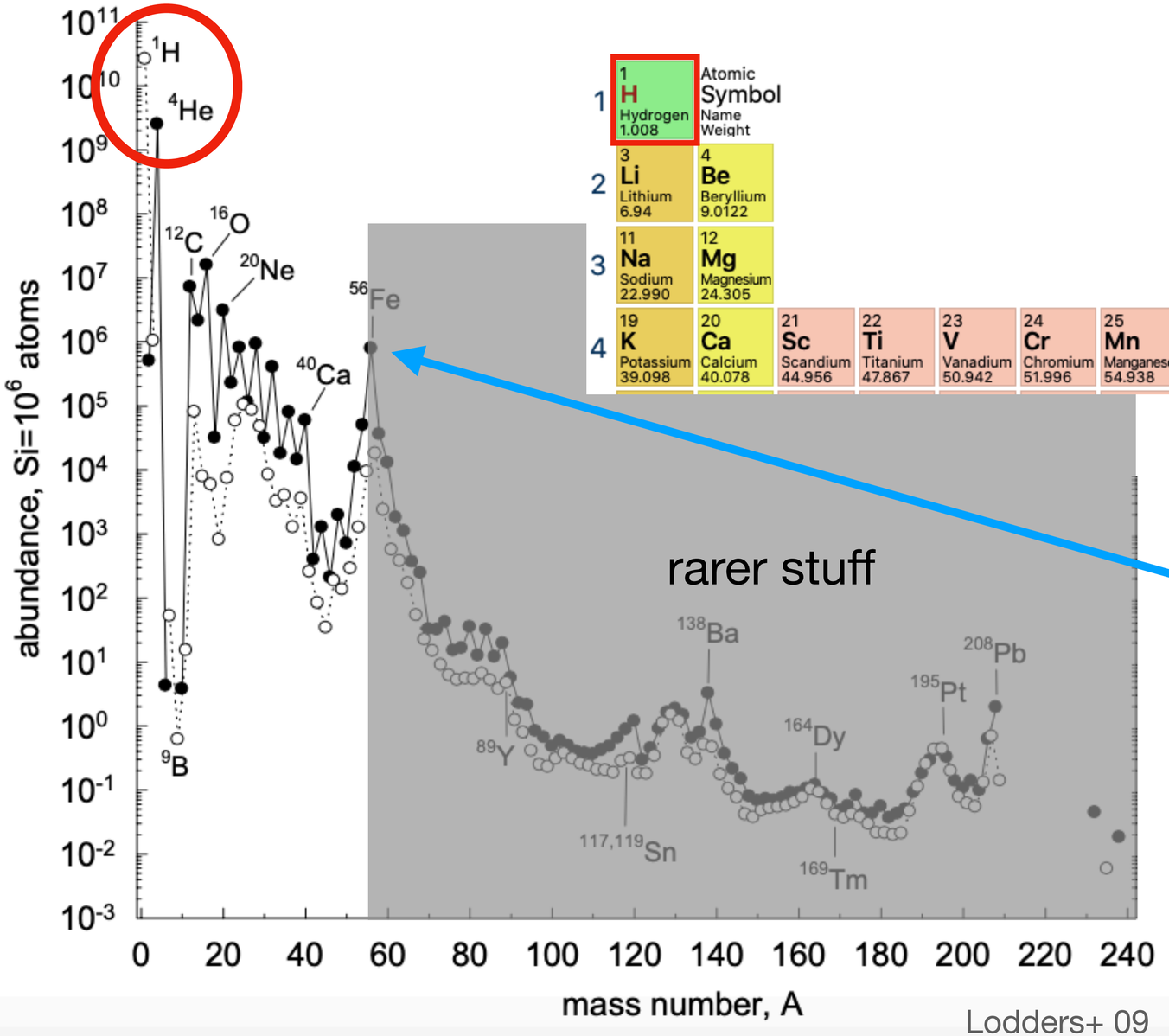

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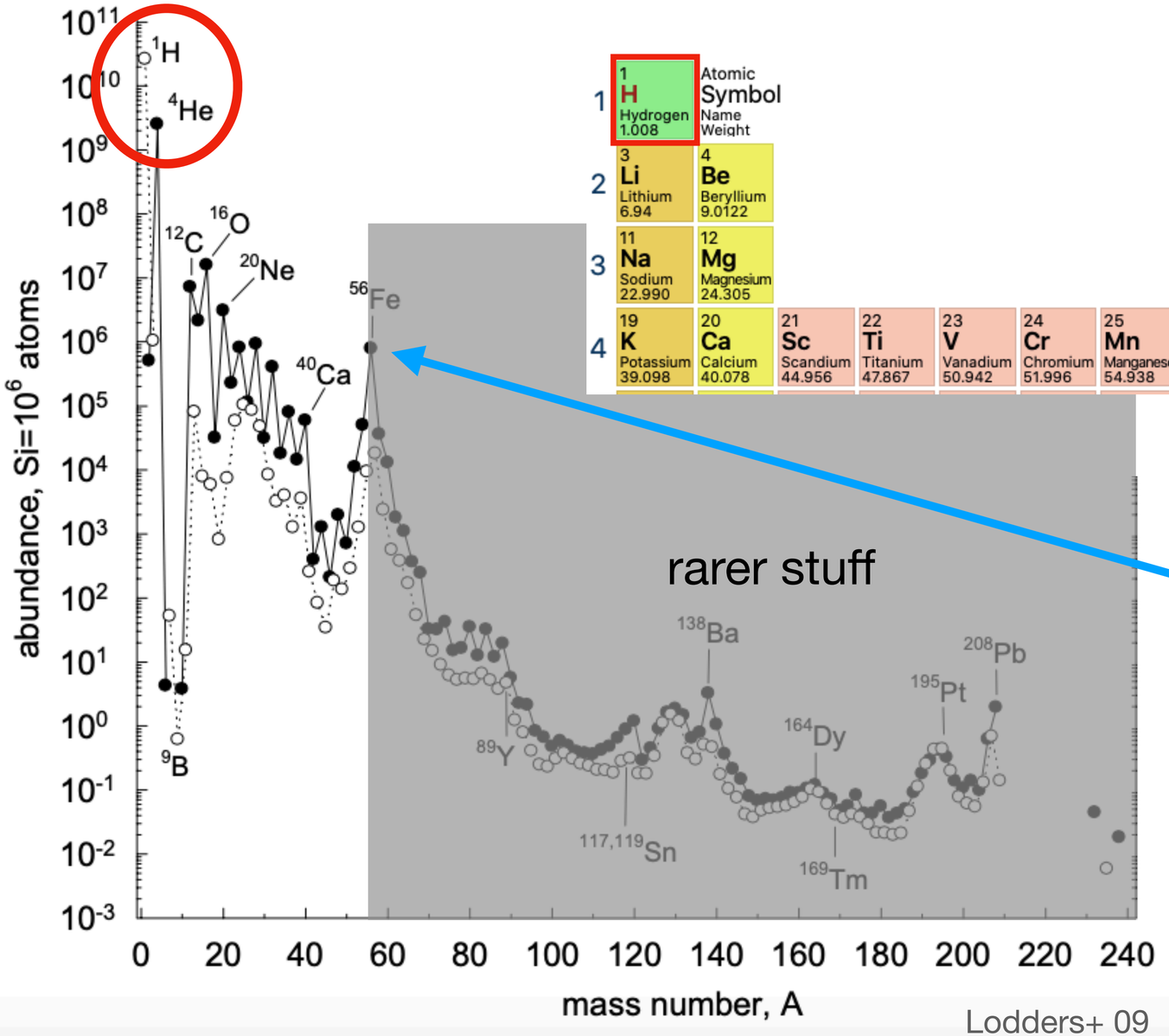

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Iron

Highest mass number for which fusion gives you energy

Elemental abundances at time of solar system formation

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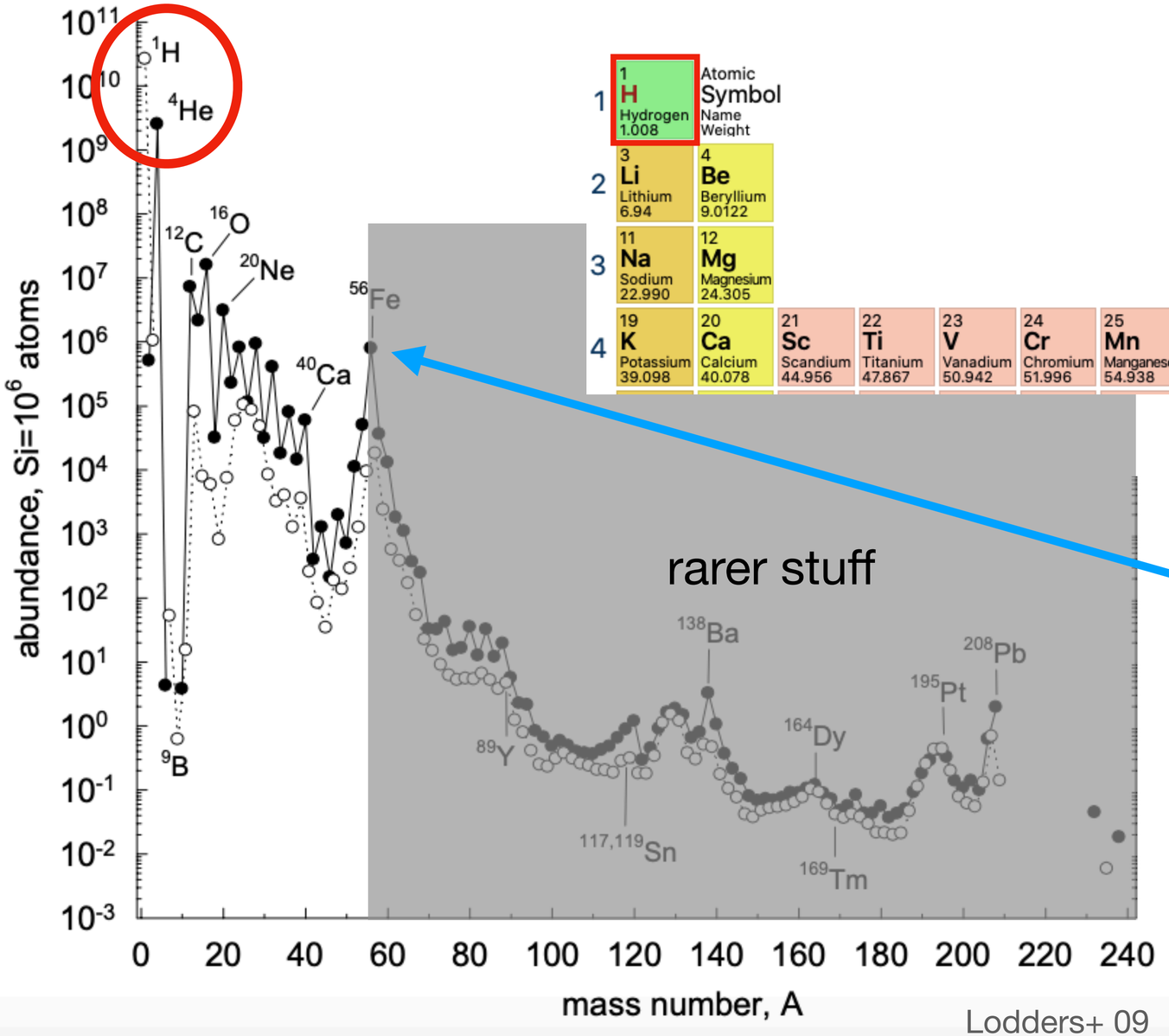

Nickel powers supernova light curves

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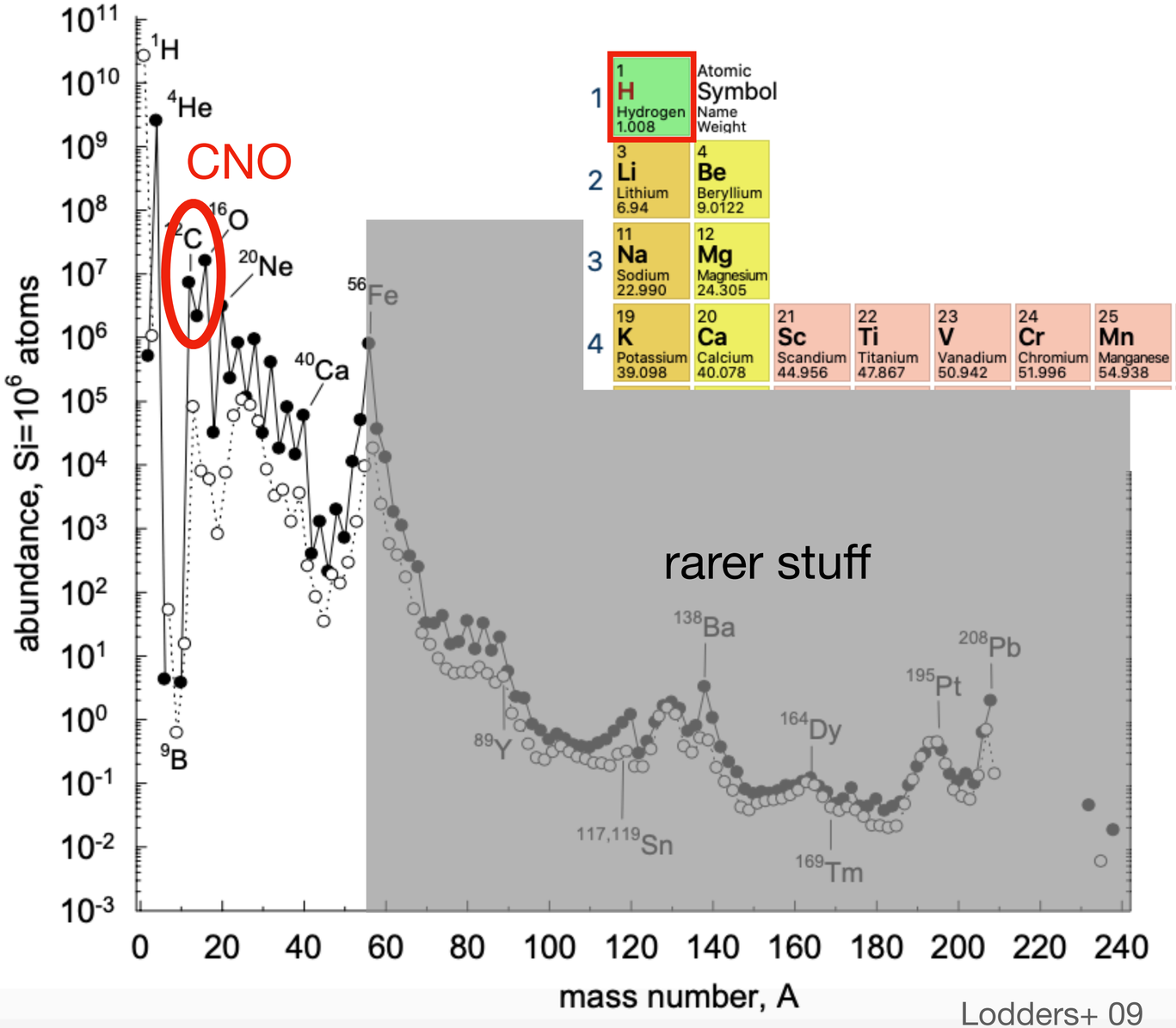

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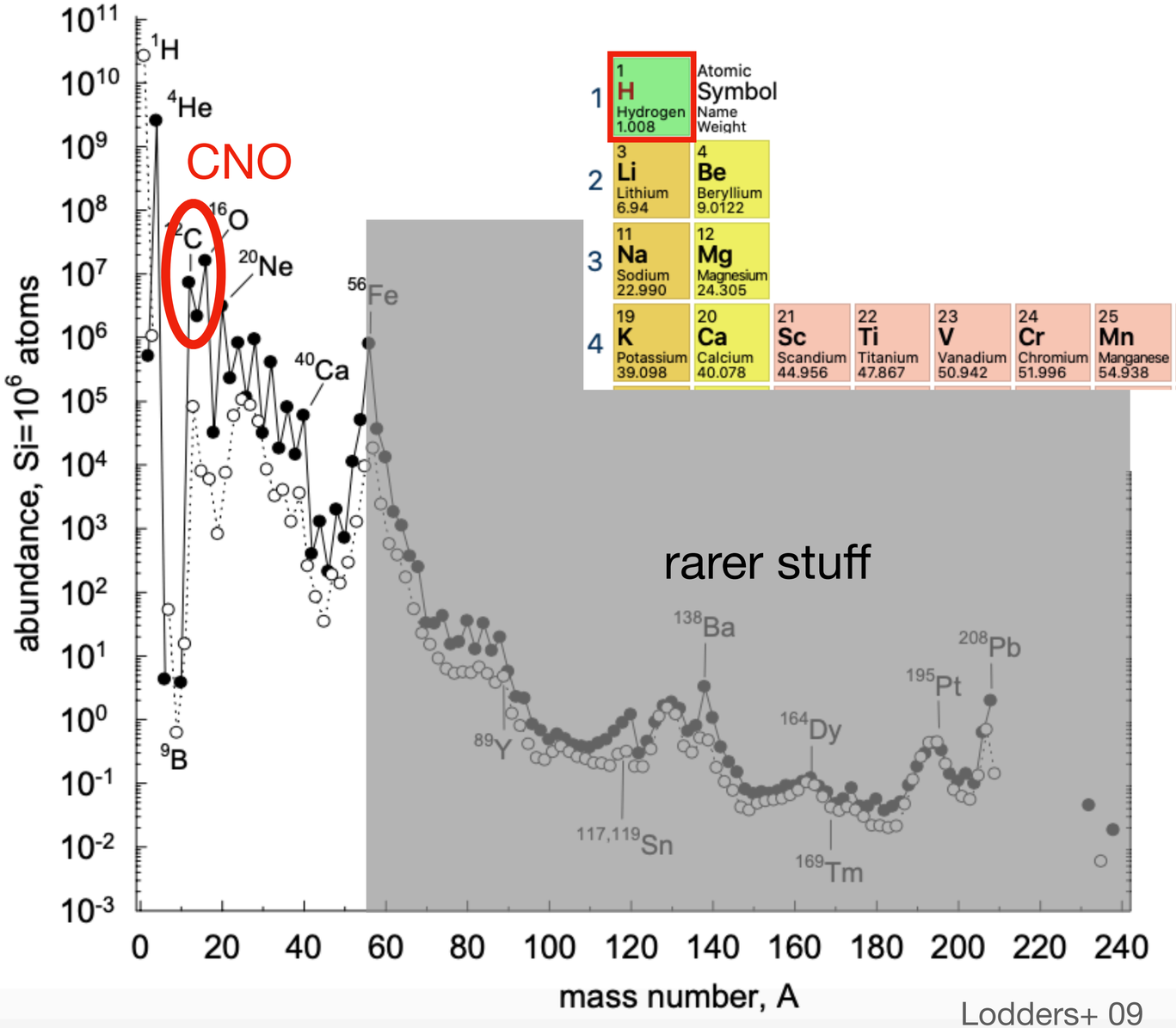
Planets are made from abundant atoms

…arranged in small molecules



H,C,N,O
make common “volatile” molecules

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e.g.:

CH_4, methane, NH_3, ammonia, H_2O water

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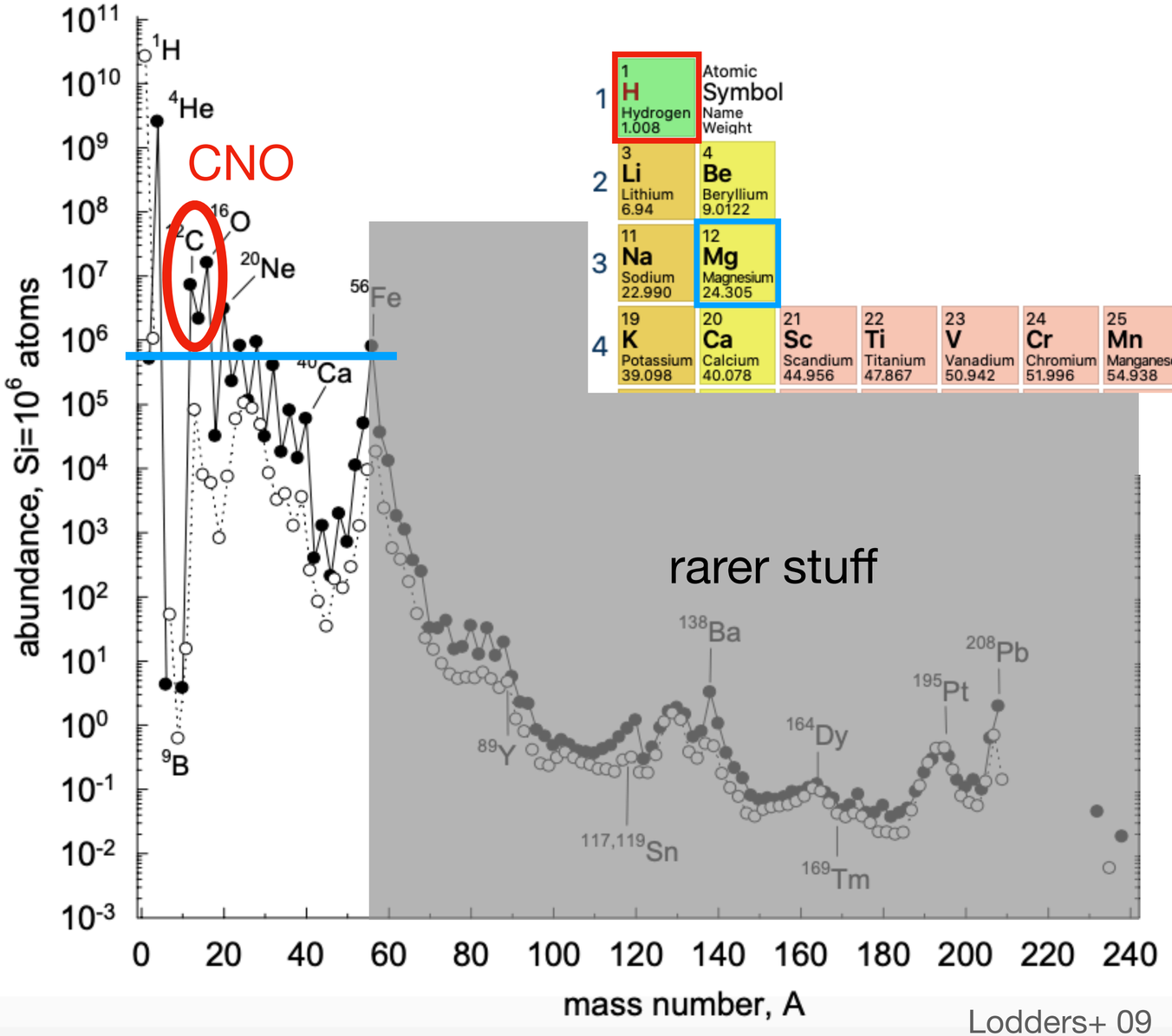
Lodders+ 09

Planets are made from abundant atoms

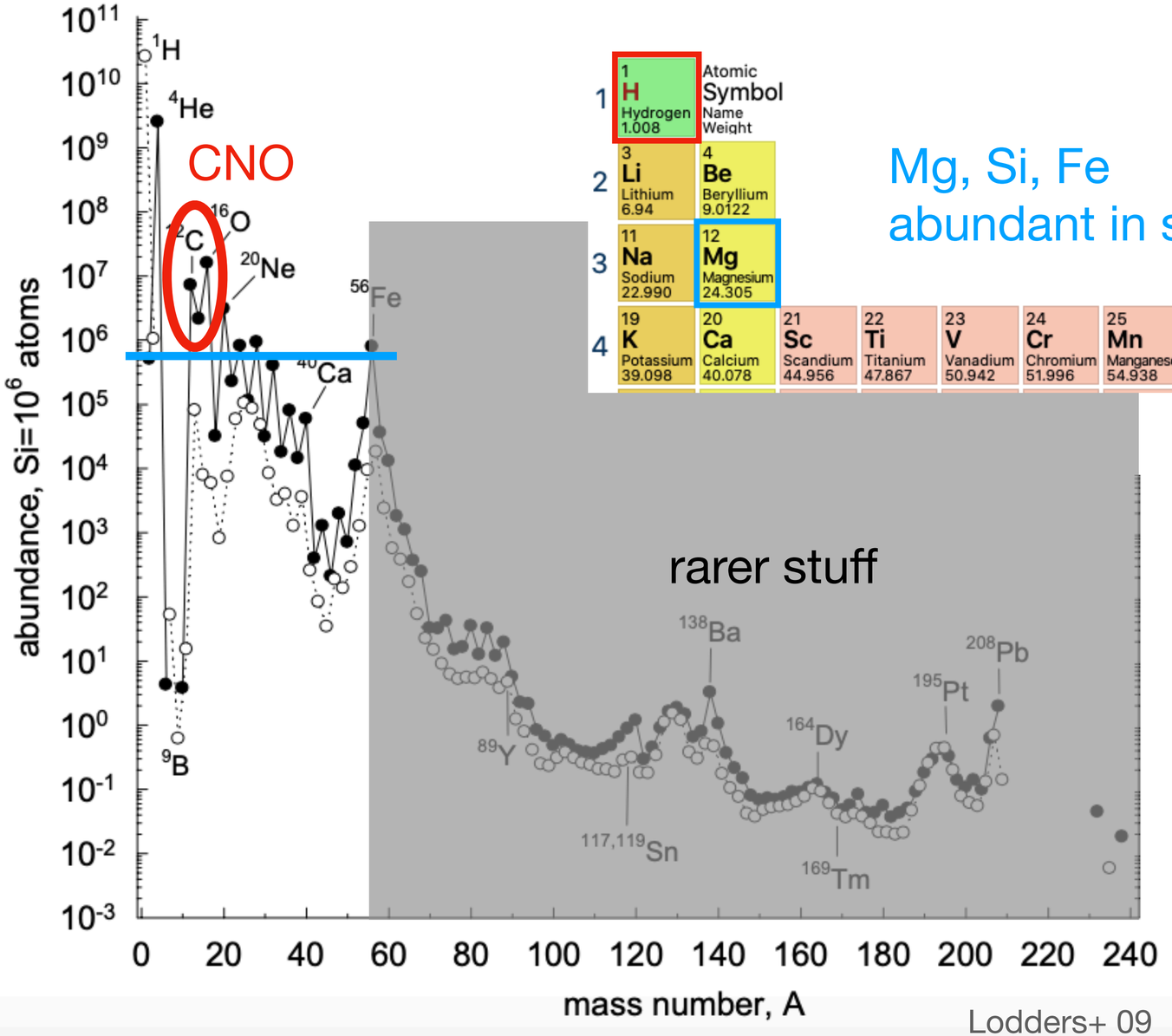


1	1 H Hydrogen 1.008	Atomic Symbol Name Weight															2 He Helium 4.0026
2	3 Li Lithium 6.94	4 Be Beryllium 9.0122											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
3	11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminium 26.982	14 Si Silicon 28.085	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948
4	19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798

Elemental abundances at time of solar system formation

Lodders+ 09

Planets are made from abundant atoms



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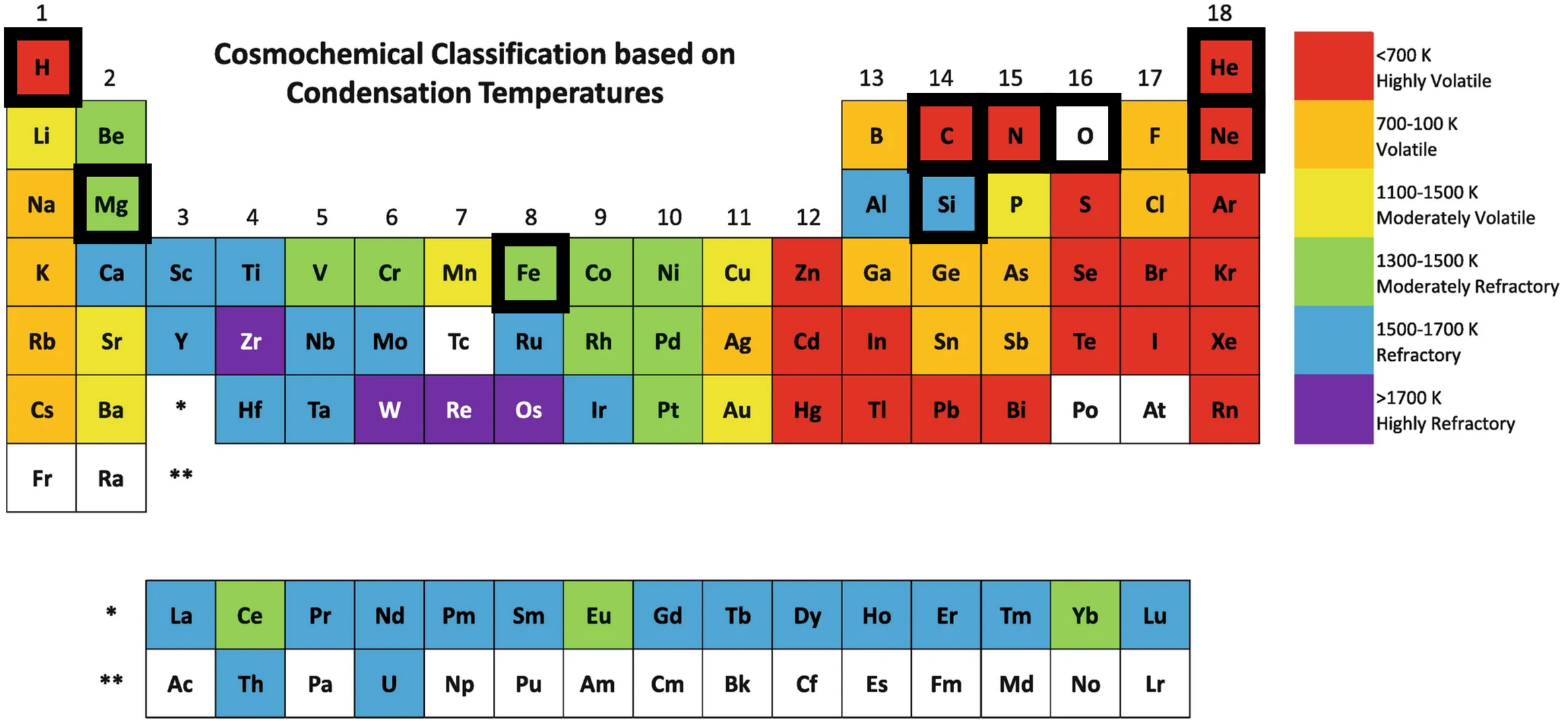
Mg, Si, Fe
abundant in solid Earth

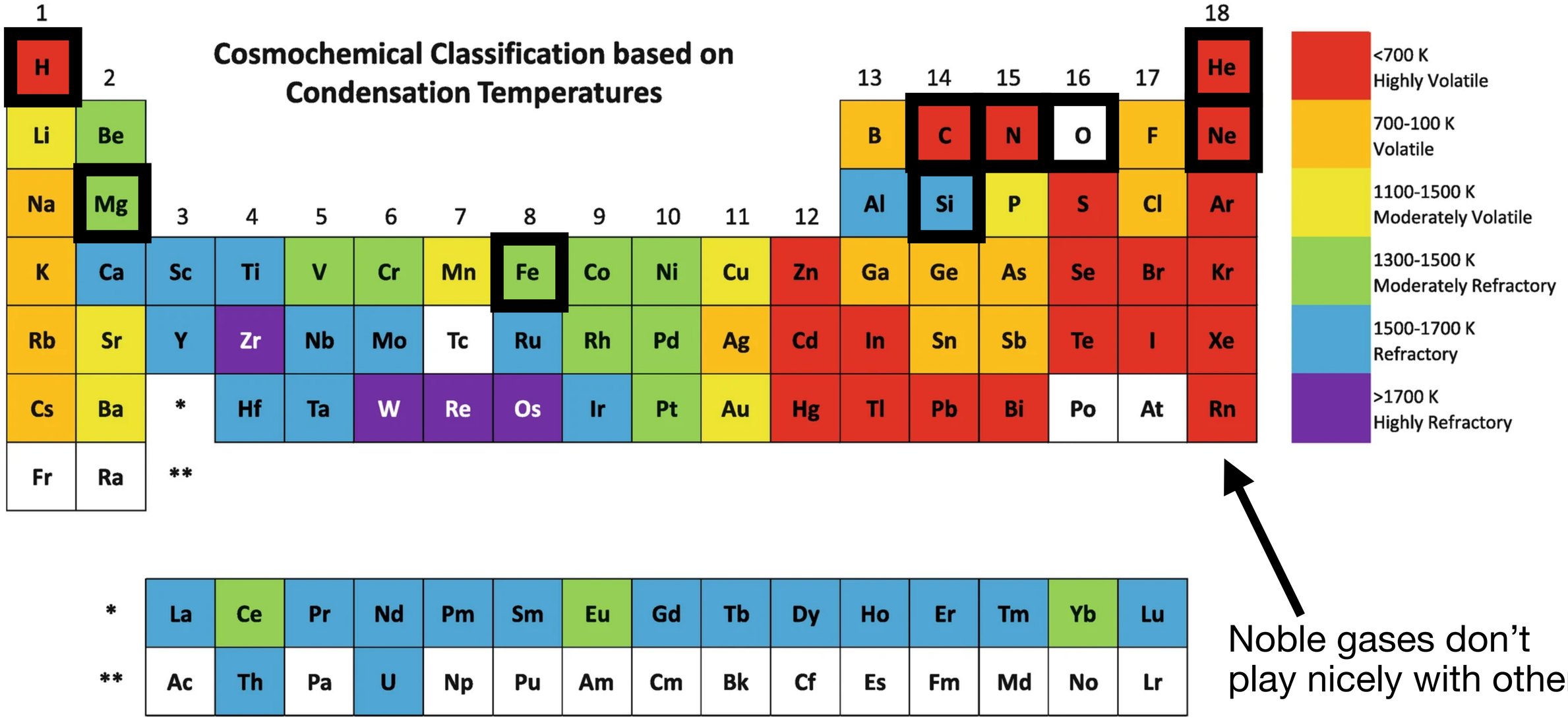
Elemental abundances at time of solar system formation

Lodders+ 09

Cosmochemical Classification based on Condensation Temperatures



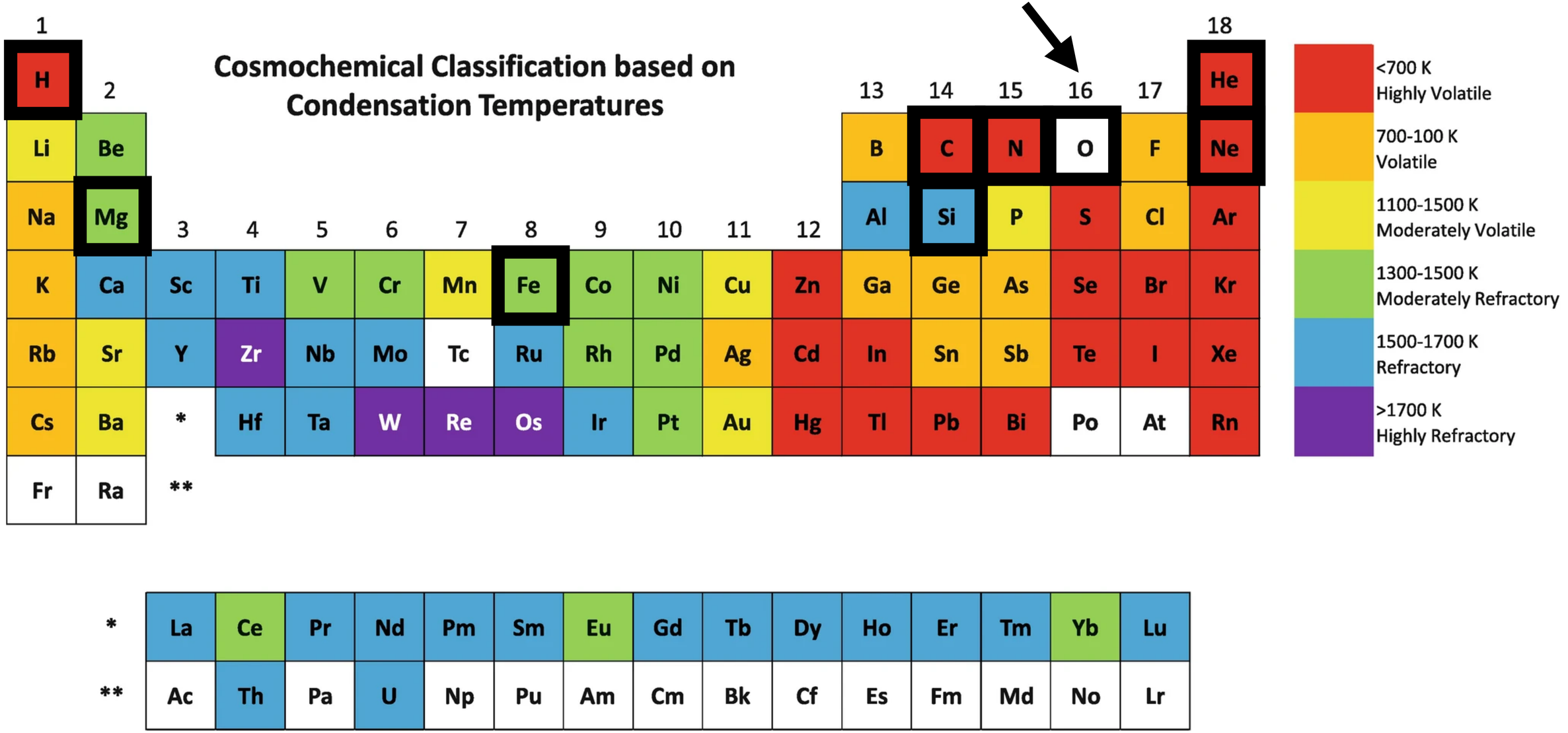
*	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
**	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



Noble gases don't play nicely with others

Encyclopedia of Geochemistry

About half in volatile gases (H_2O, CO, CO_2) and half in silicates (rock)



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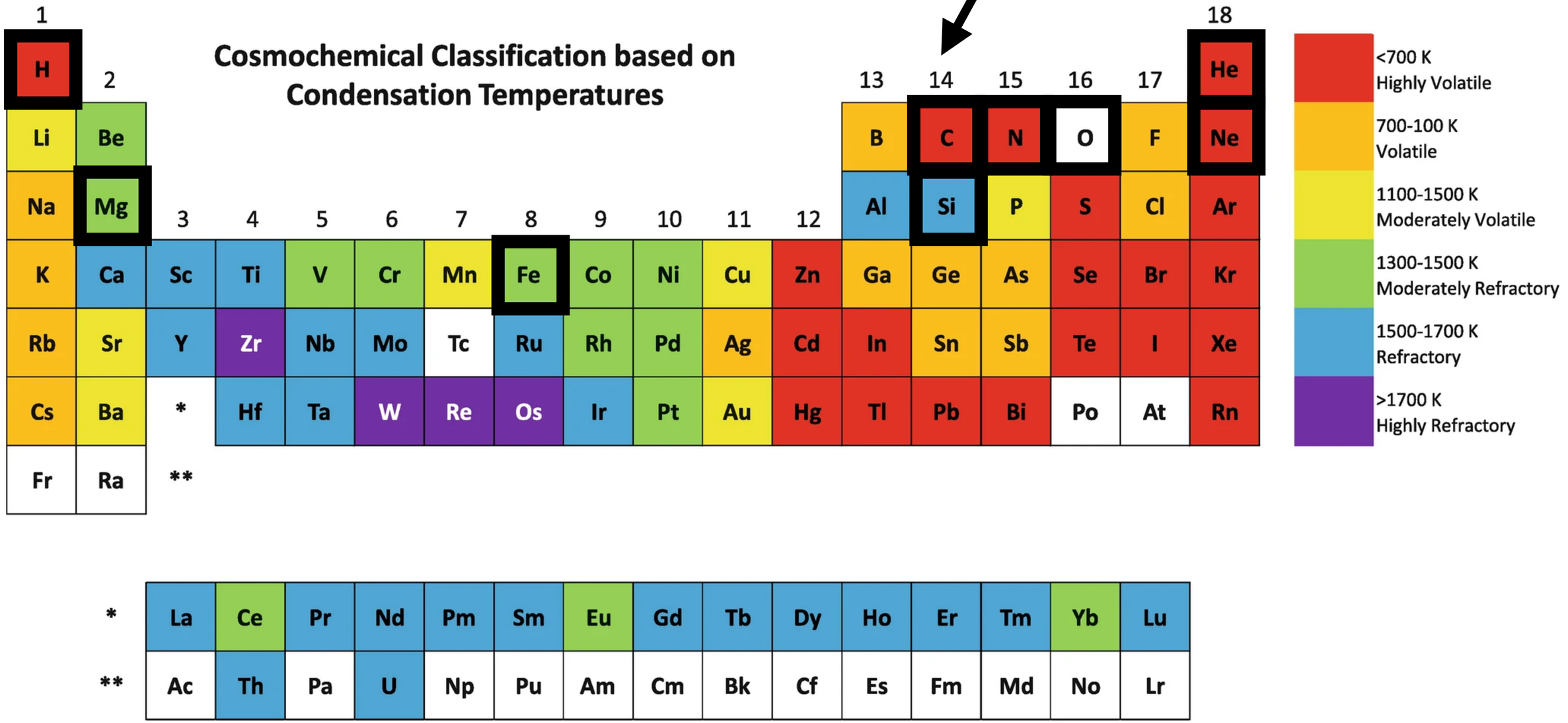
Encyclopedia of Geochemistry

Carbon in hydrocarbons is less volatile than CH_4, CO, CO_2



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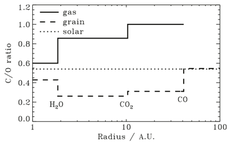
Encyclopedia of Geochemistry

Our best examples: Solar system planets

What are the building blocks? Interpreting the periodic table



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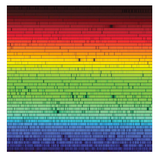

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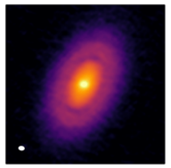
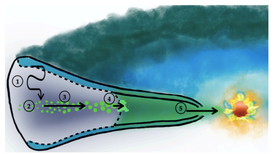
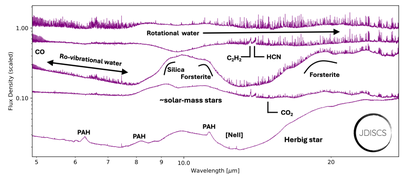


Probing the building blocks: Protoplanetary disks



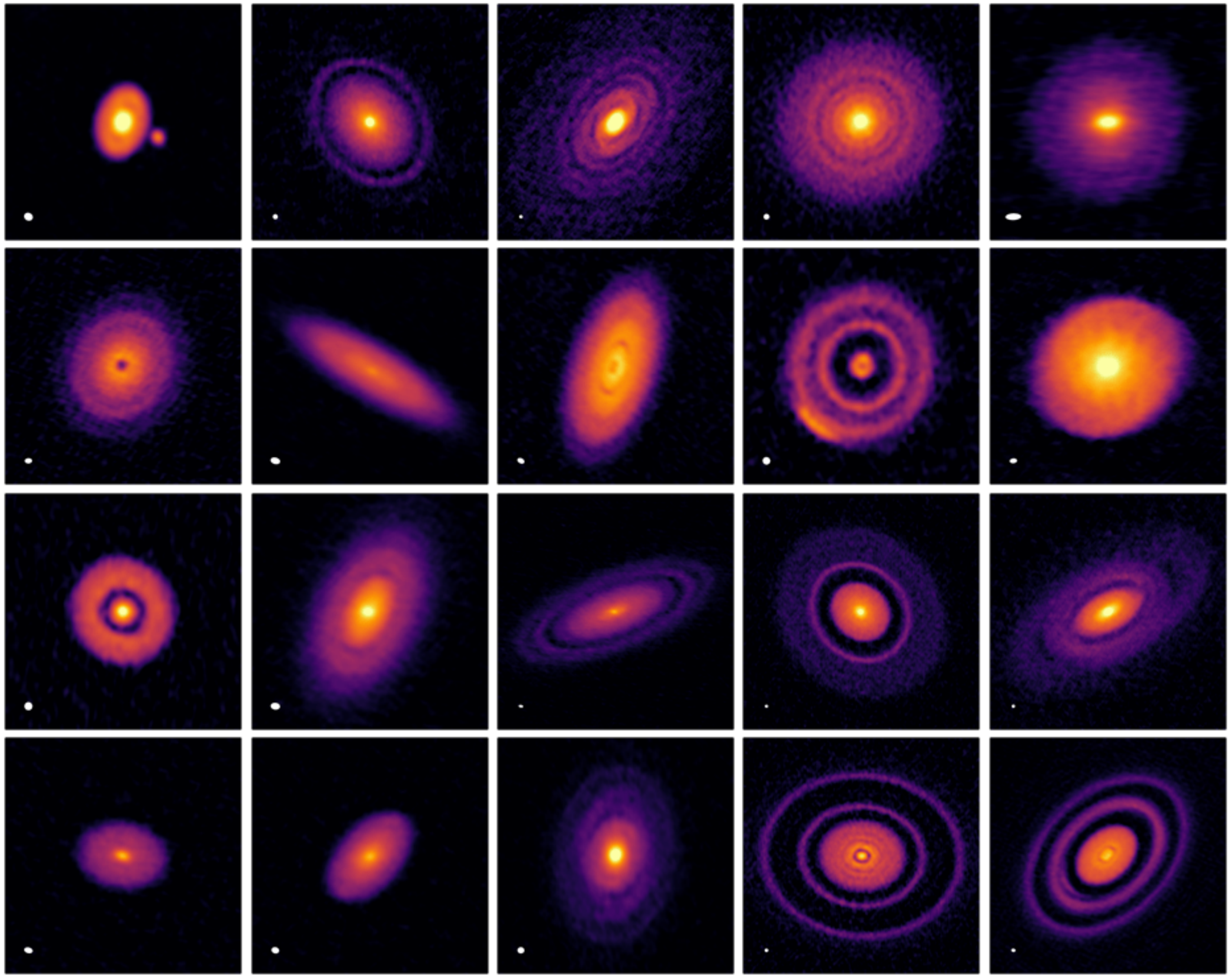
It's more complicated than our original model (isn't it always)



New insights: Mysteries from JWST

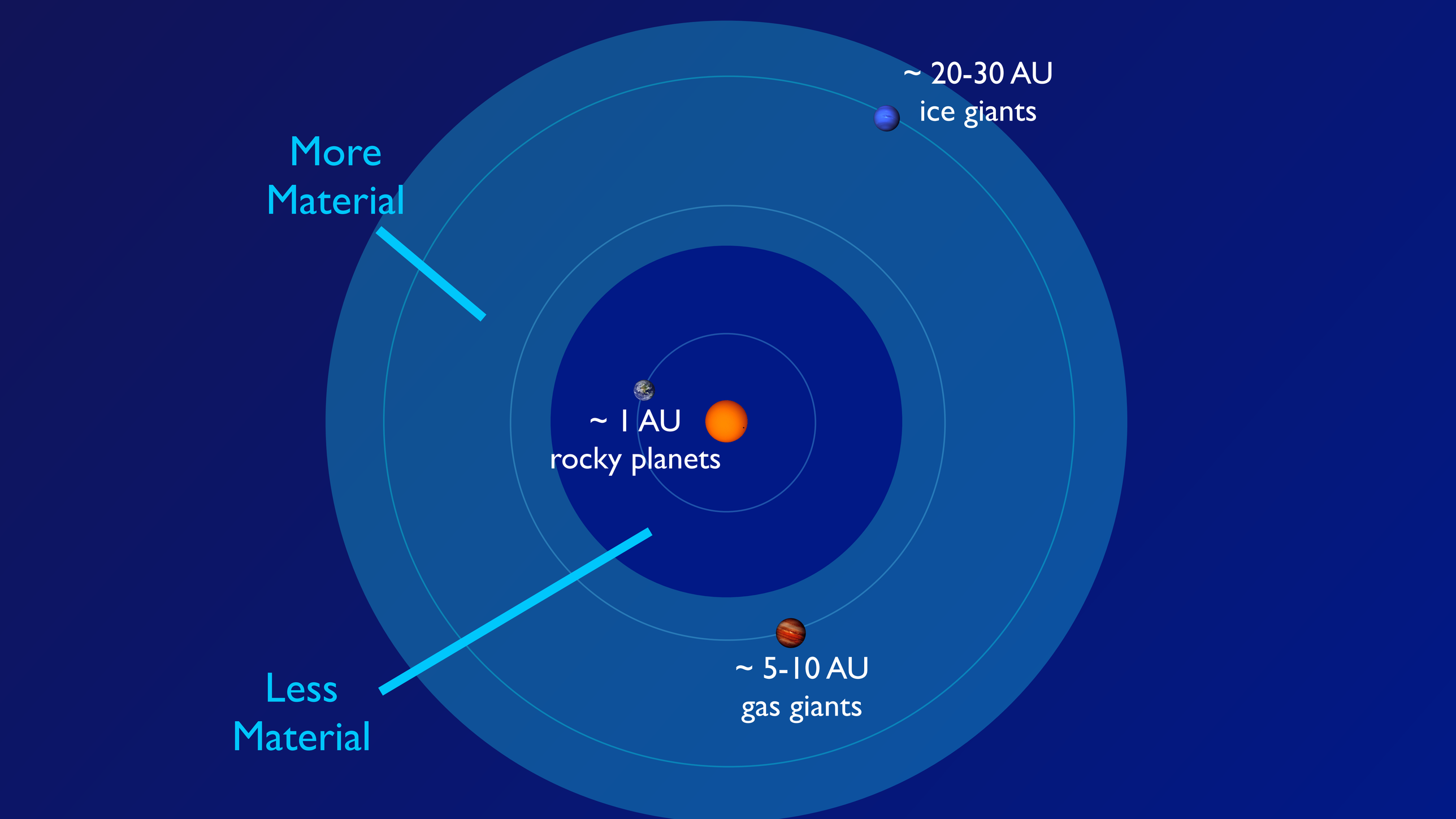

HST Orion Treasury Project

Atacama Large Millimeter Array (ALMA)



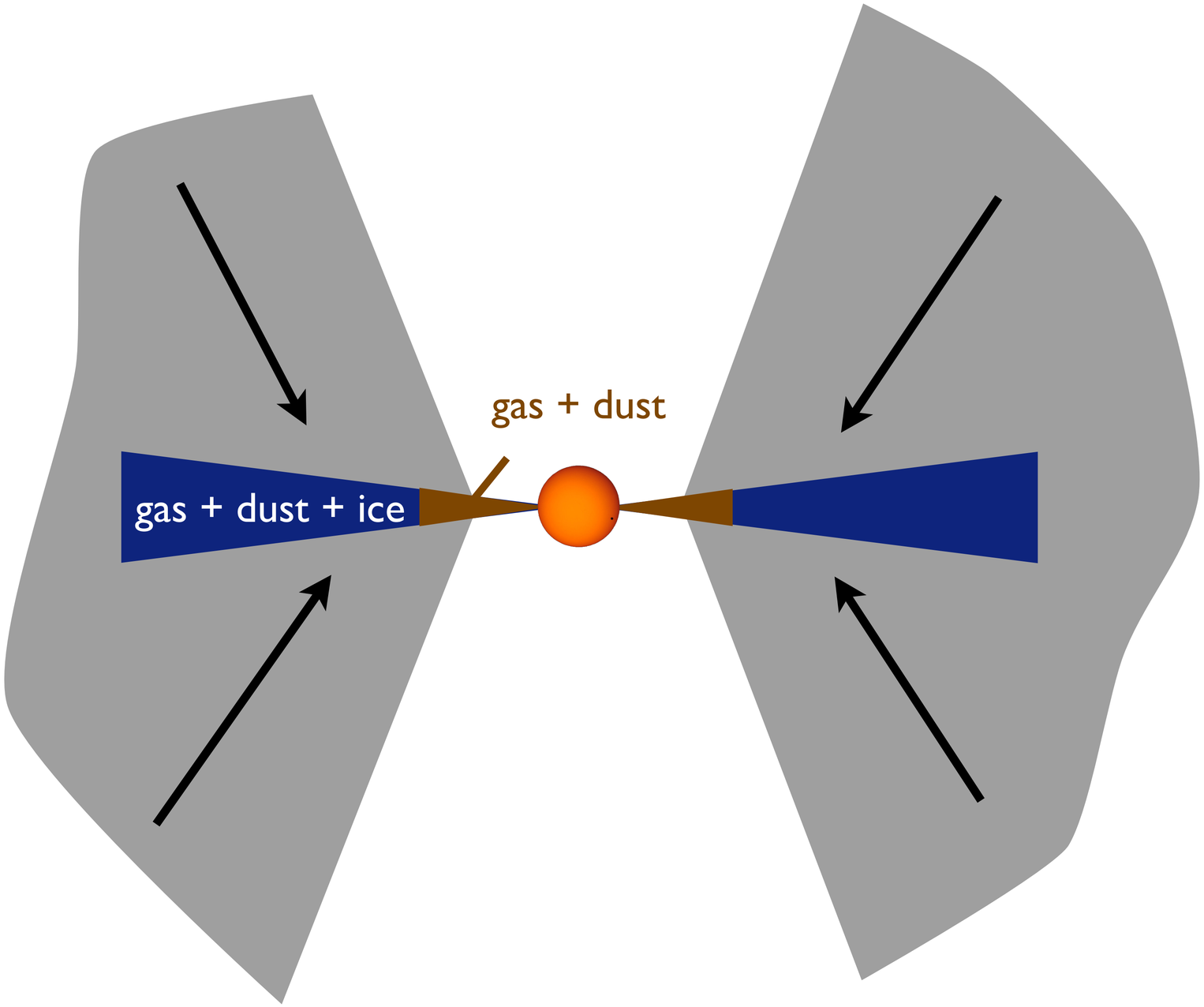
ALMA (DSHARP, Andrews+ 2018)

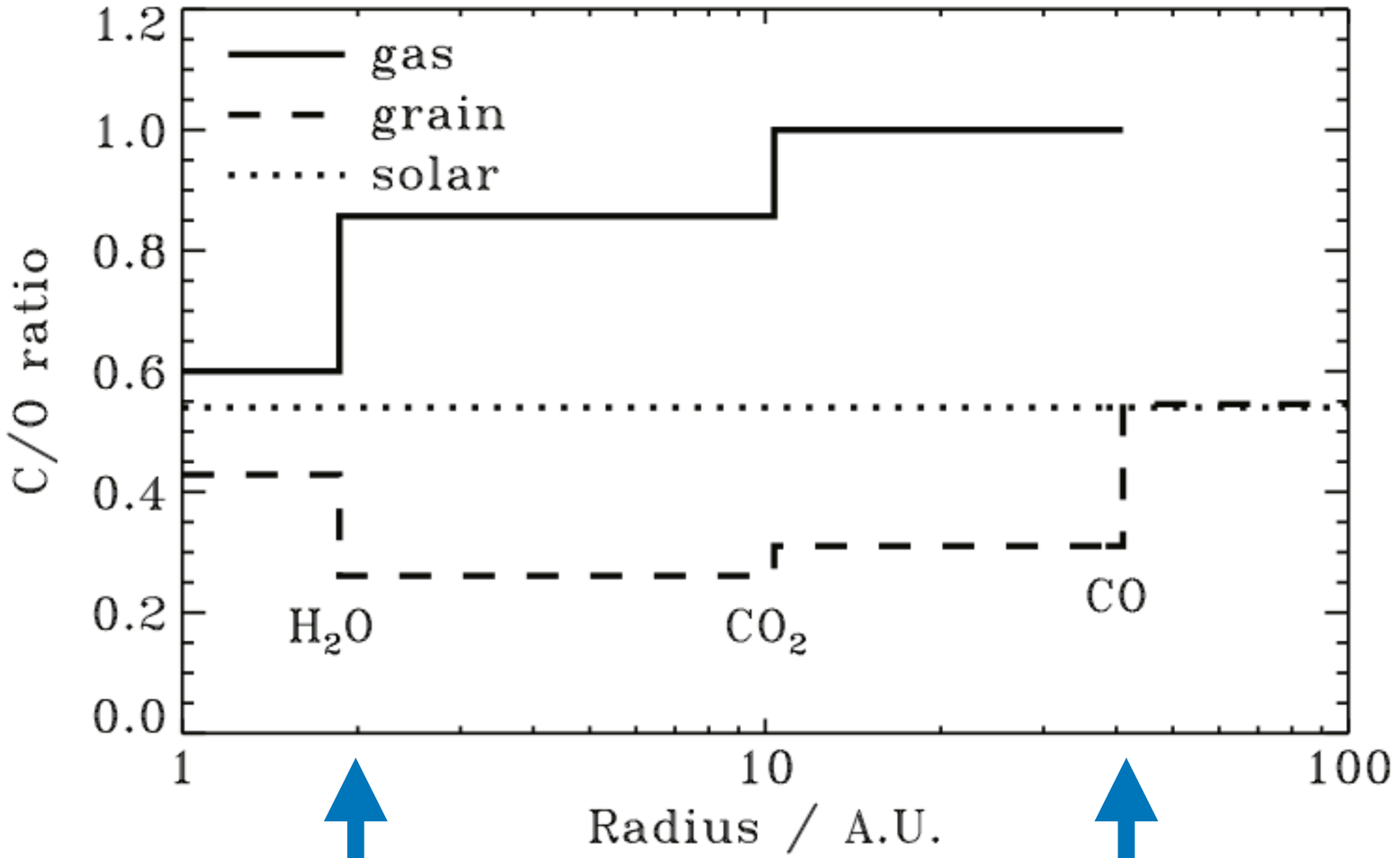
Artist's Conception


~ 20-30 AU
ice giants
More
Material
~ 1 AU
rocky planets
~ 5-10 AU
gas giants
Less
Material

NASA, ESA, M. Robberto, HST Orion Treasury Project, L. Ricci

Until incorporated into planets, most molecules are inherited from the ISM. Which are solid depends on temperature.





extra oxygen in silicates (rock)

extra carbon in hydrocarbons

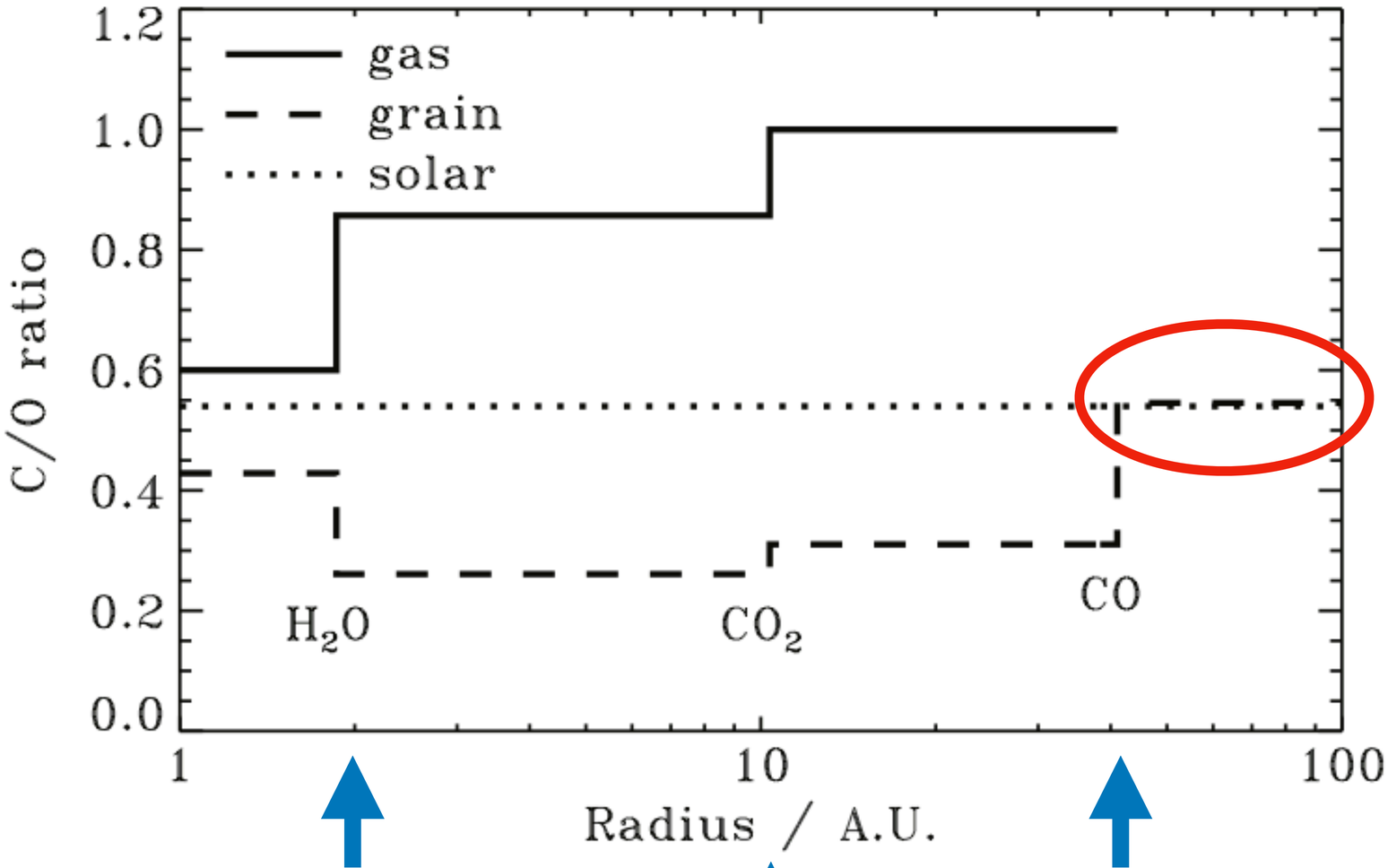
water frozen

carbon dioxide frozen

carbon monoxide frozen

colder

Oberg+ 11



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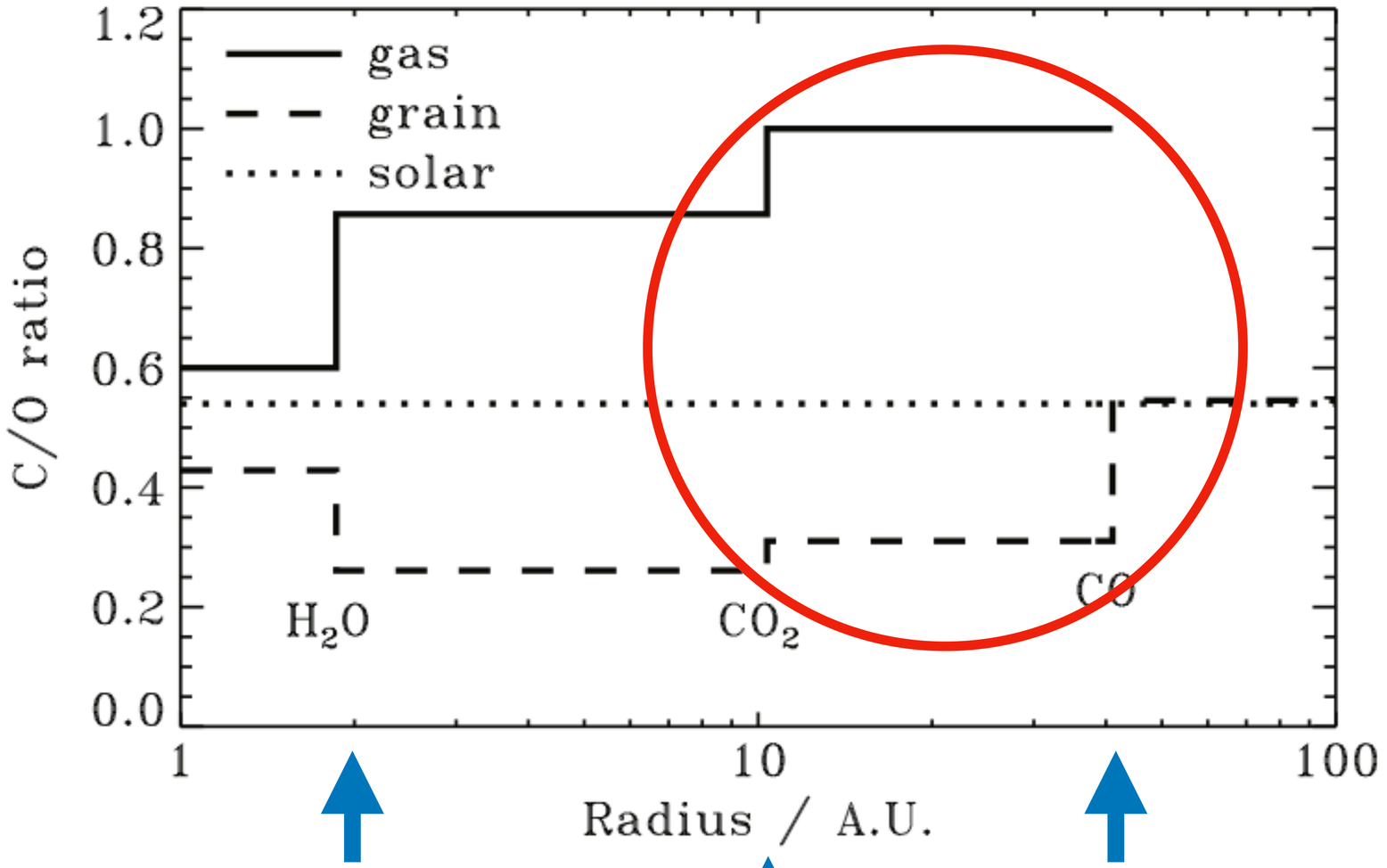

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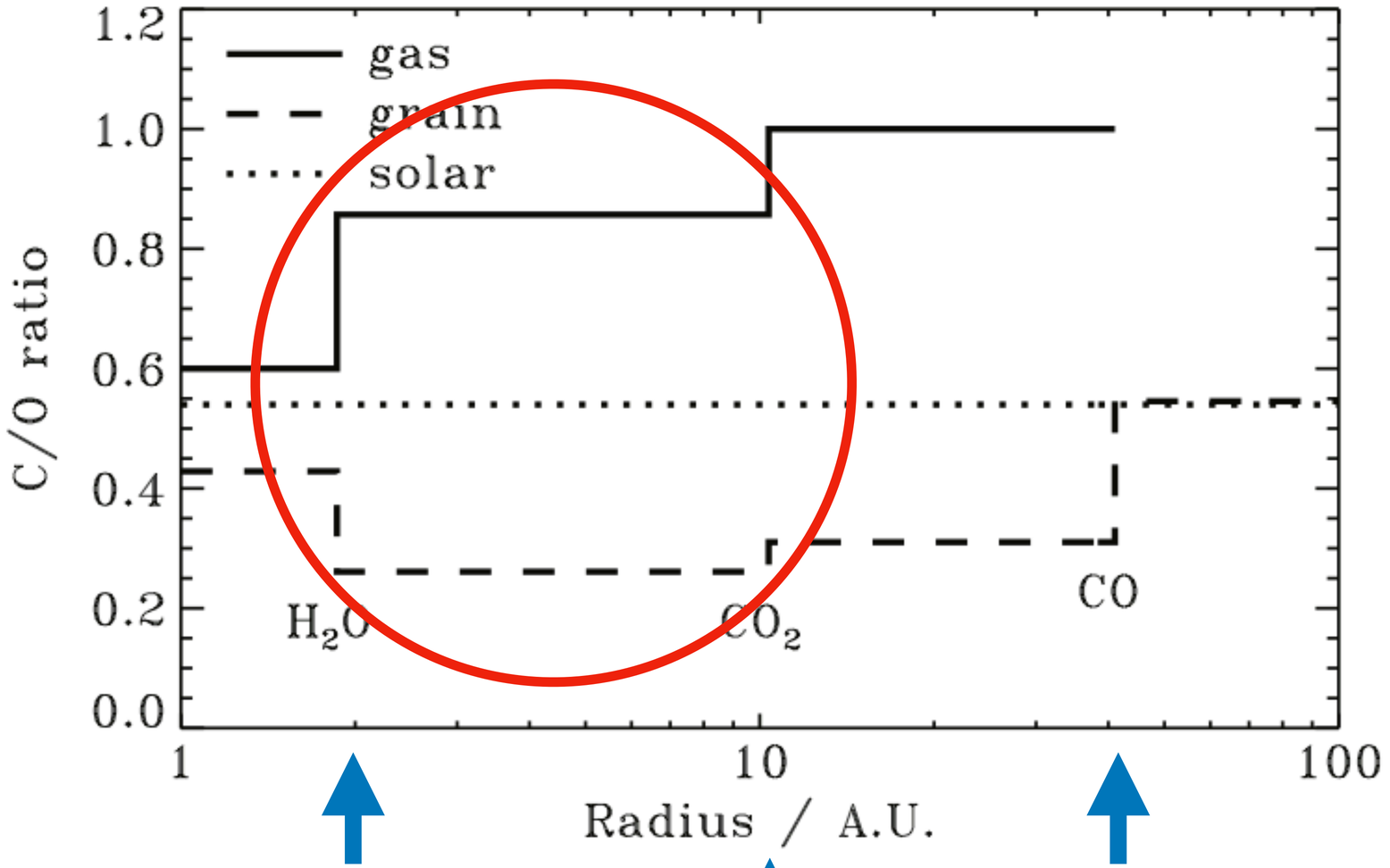

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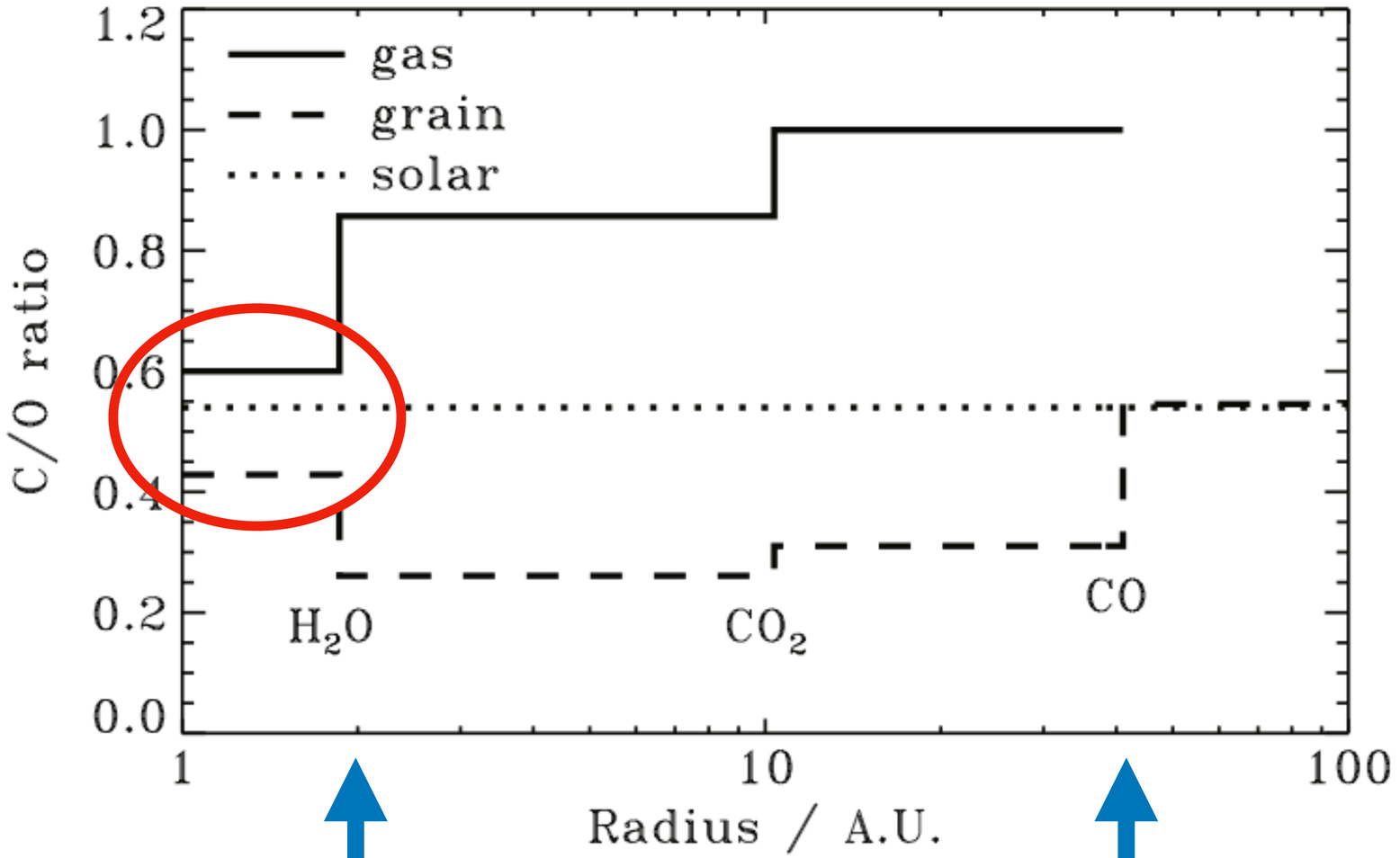

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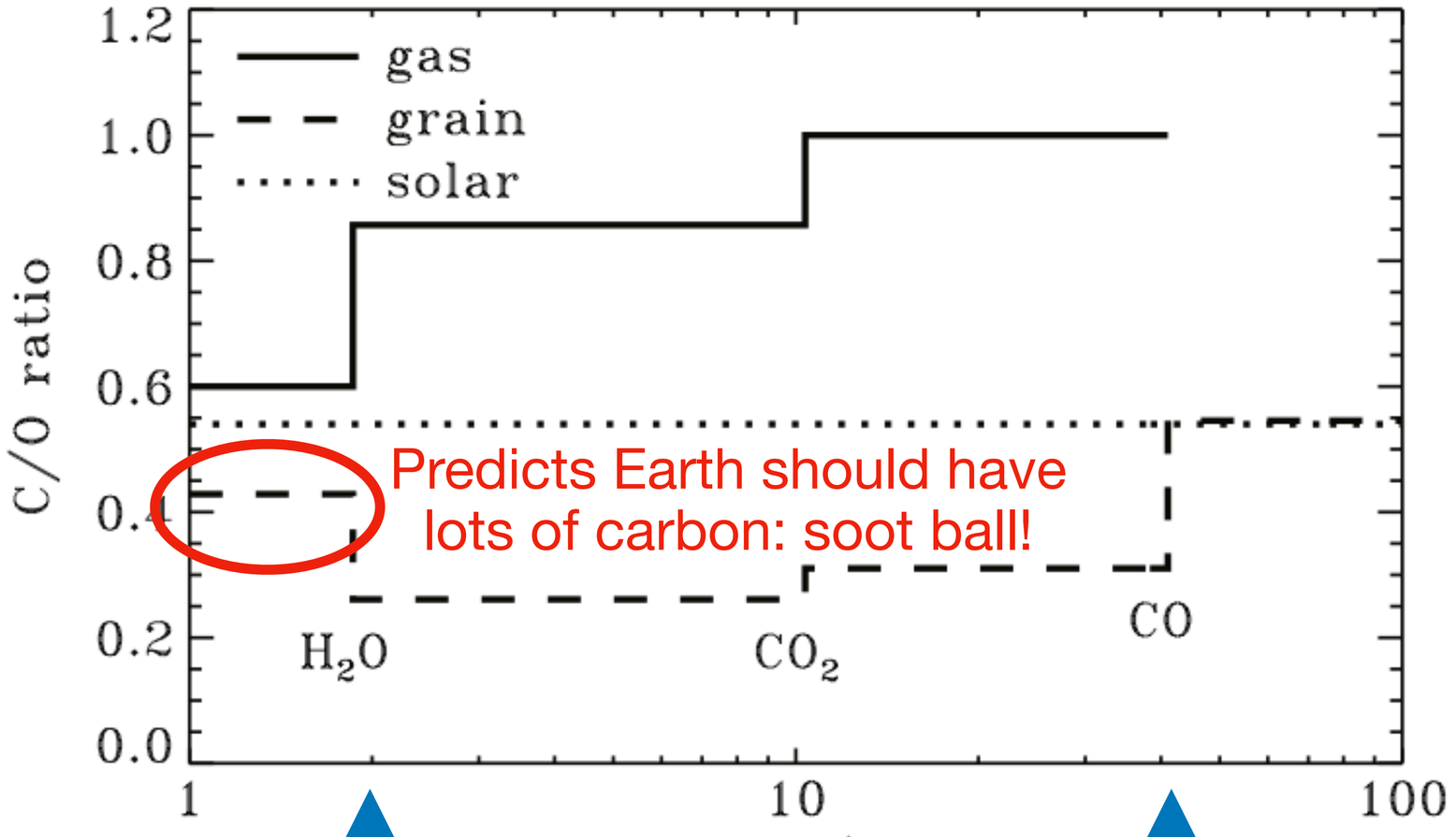


solar 0.54

Predicts Earth should have lots of carbon: soot ball!

extra oxygen in silicates (rock)

extra carbon in hydrocarbons (where does it go???)

water frozen

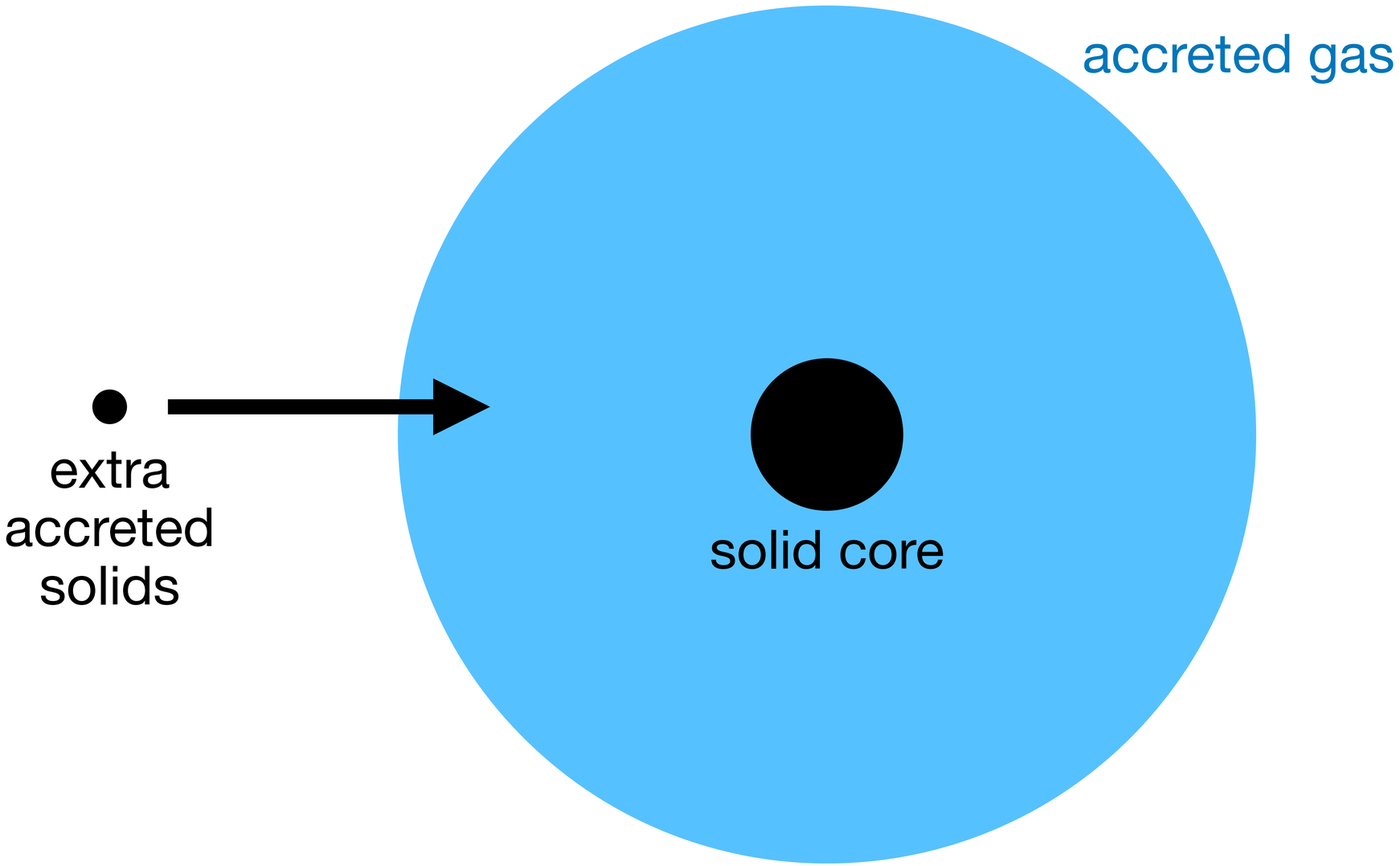
carbon dioxide frozen

carbon monoxide frozen

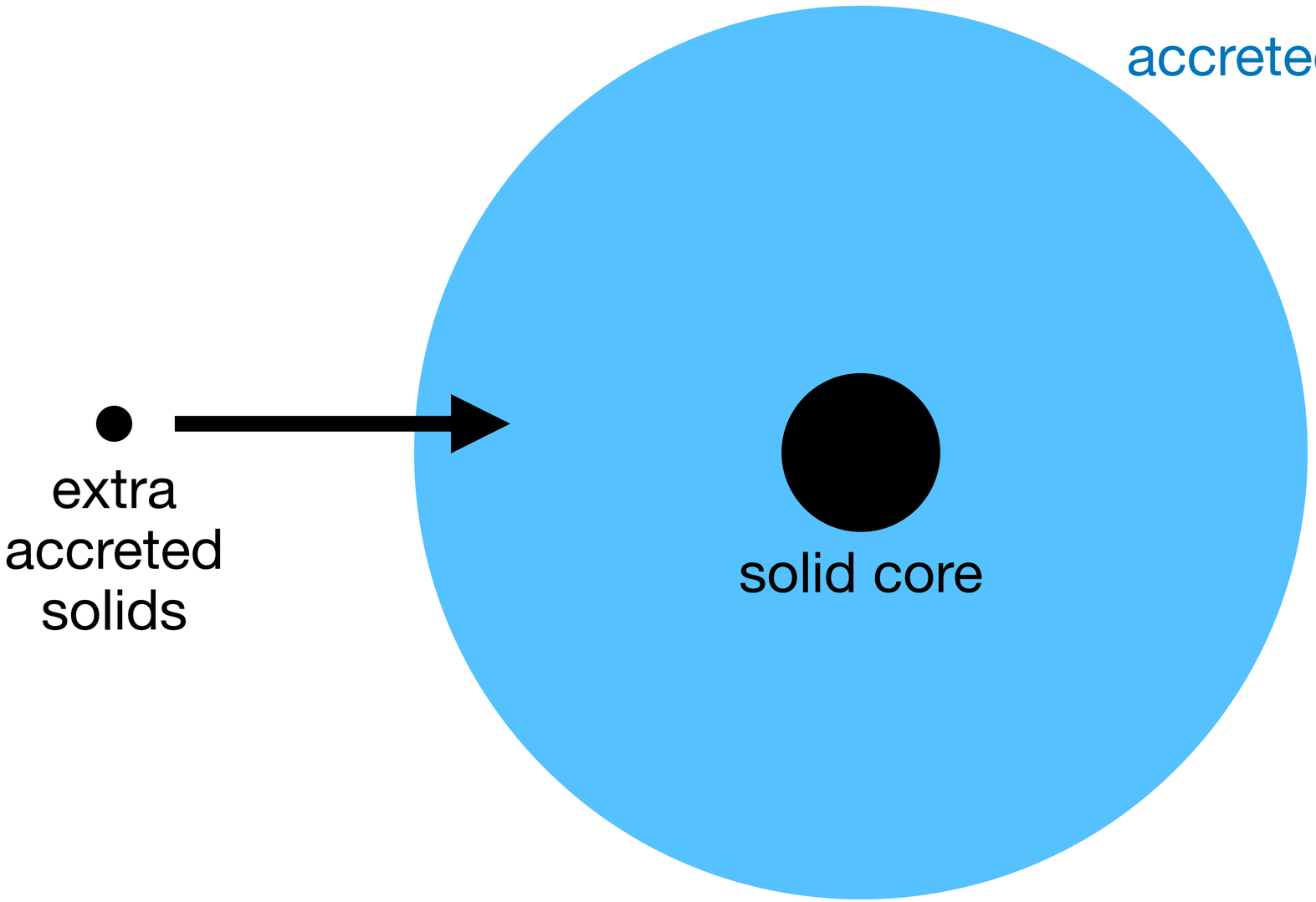
colder

Oberg+ 11

planet

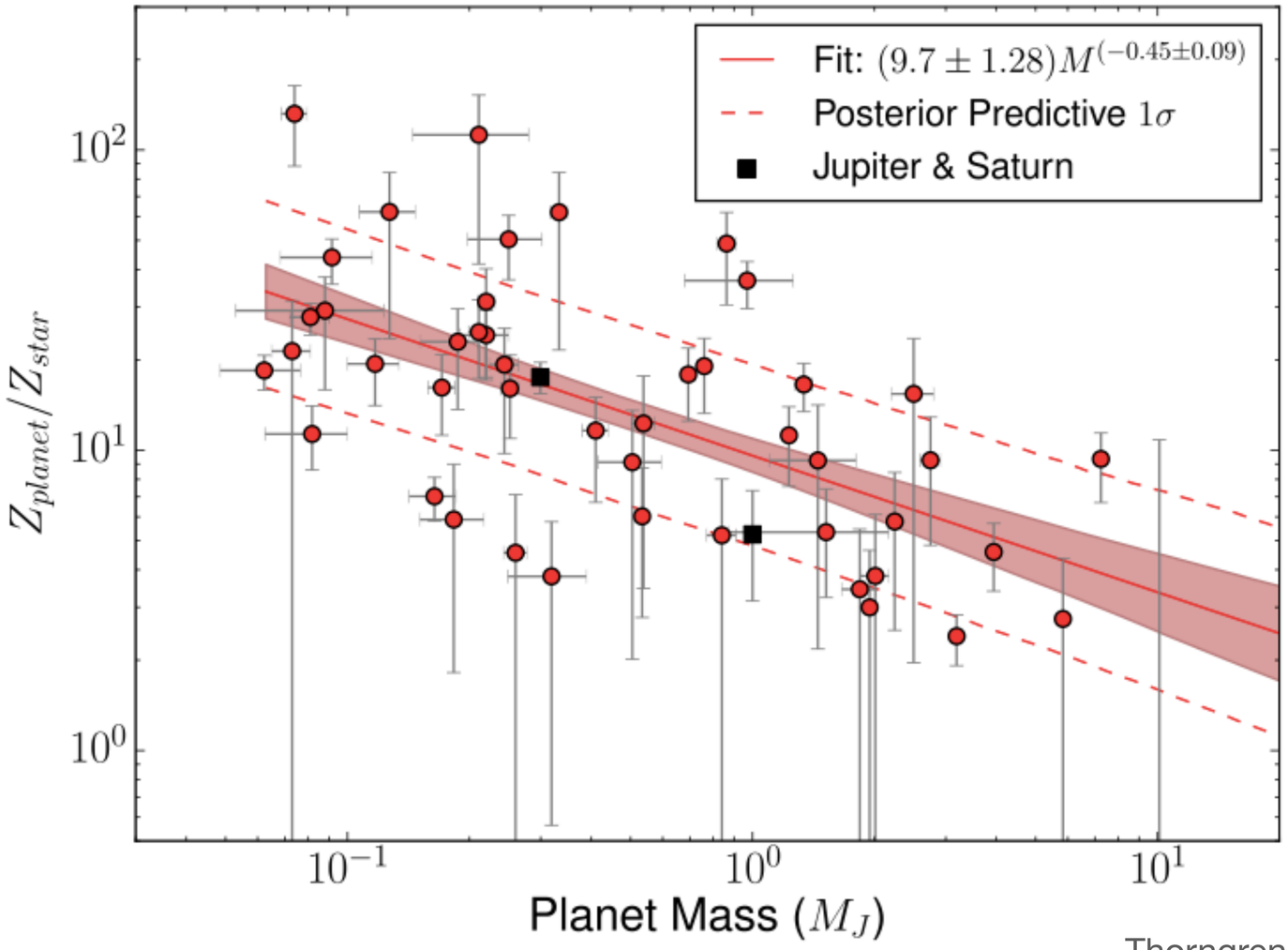


planet



C/O ratio not expected to match that of the star

Extrasolar planets have a broad range of solid/gas ratios



Thorngren+ 16

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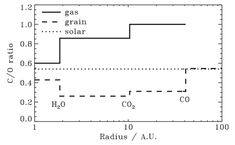

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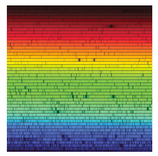

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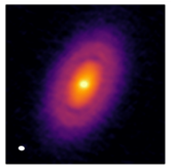

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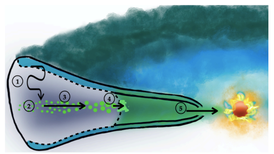

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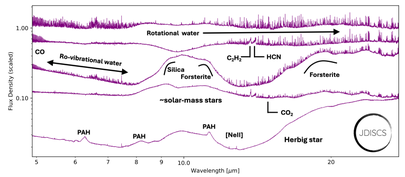

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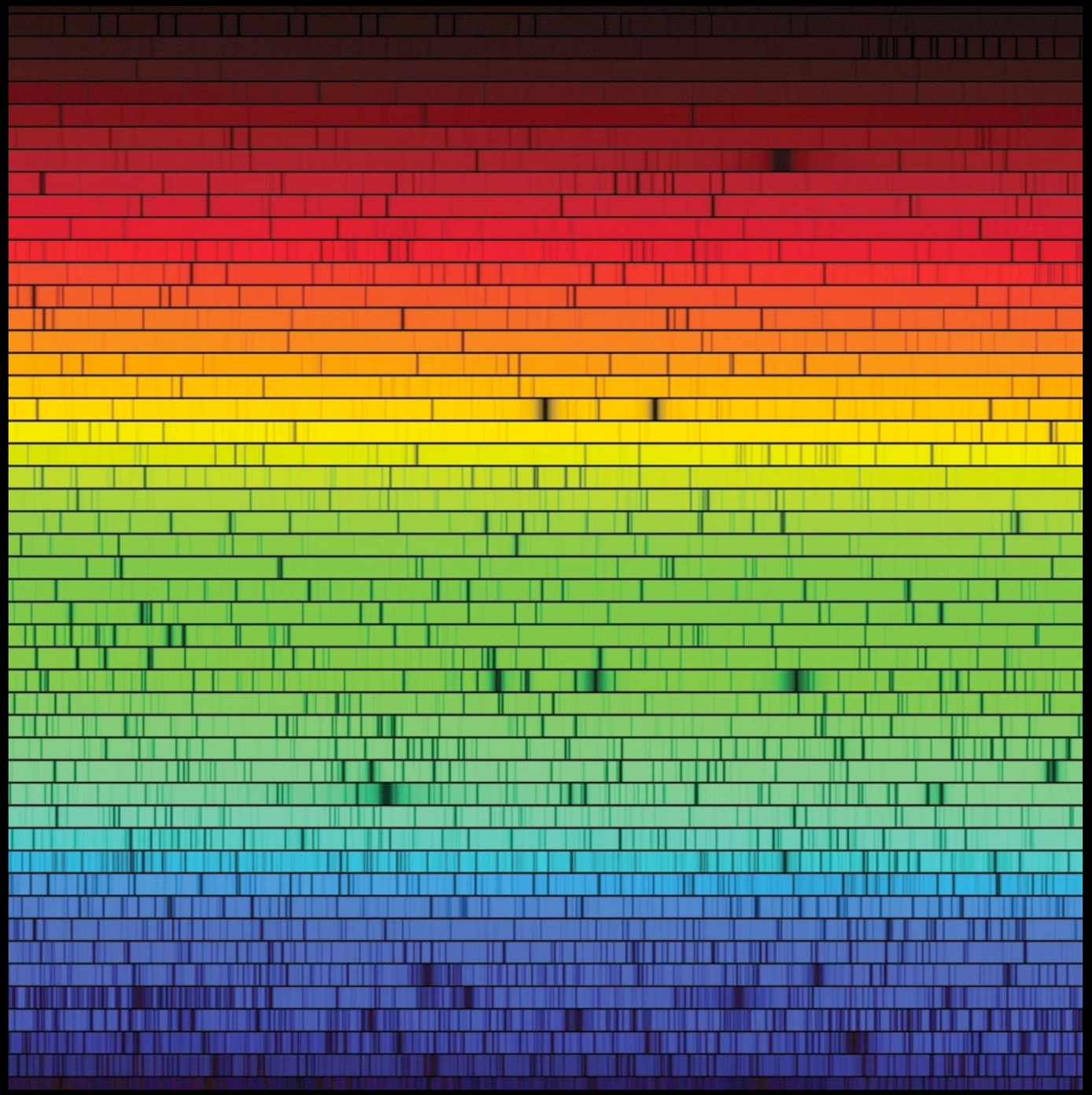
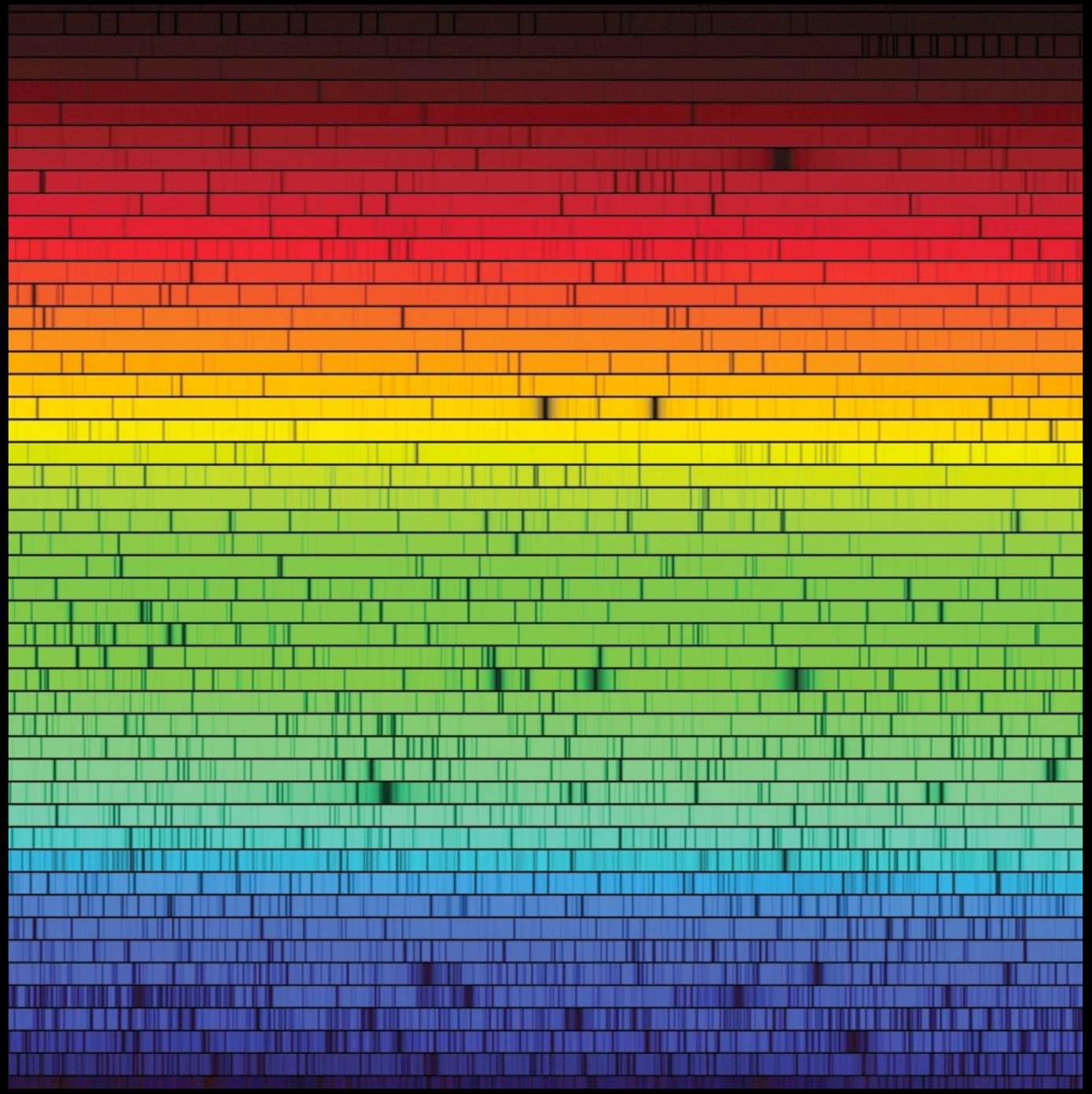
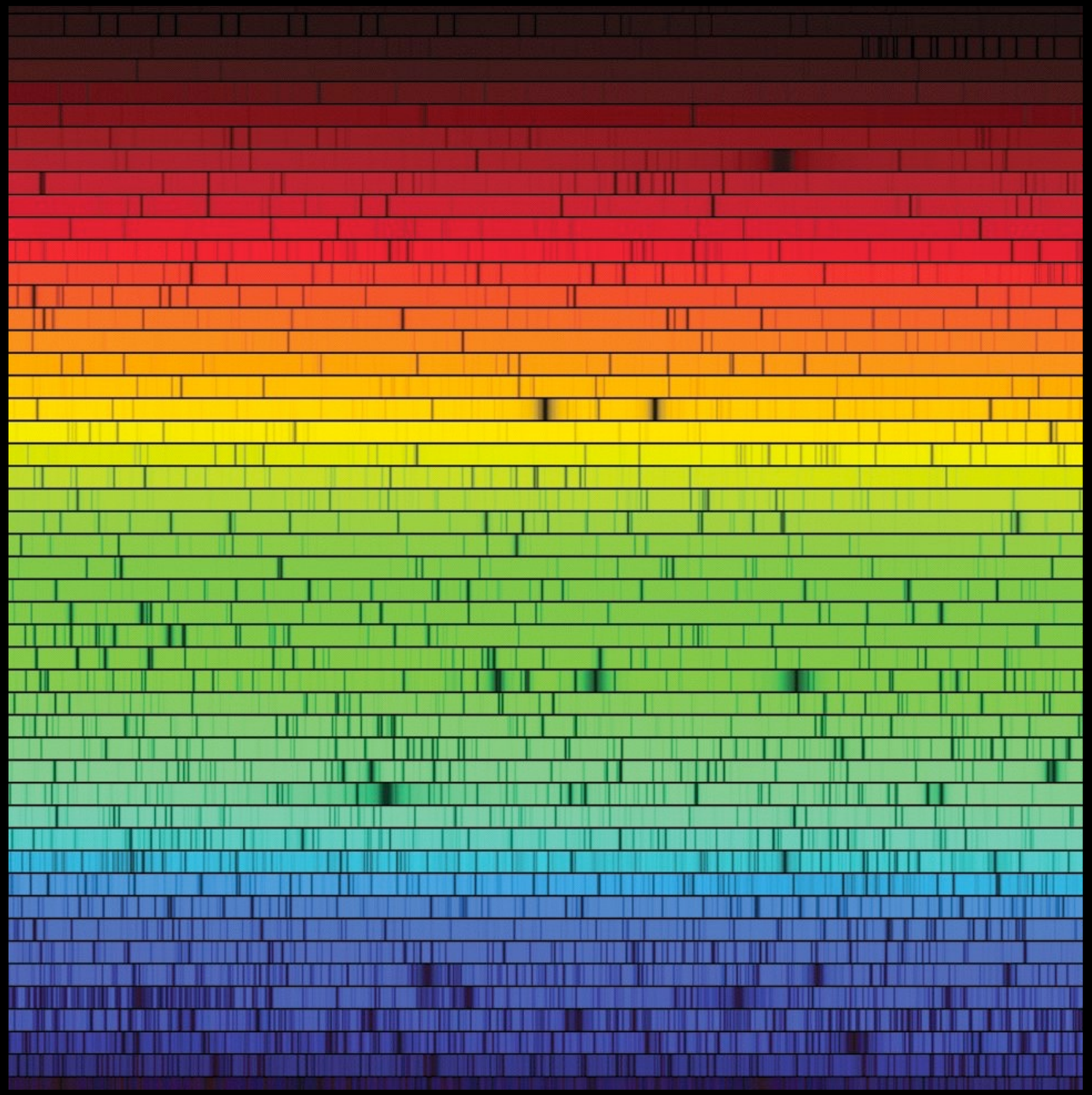


Solar spectrum



lower energy photons

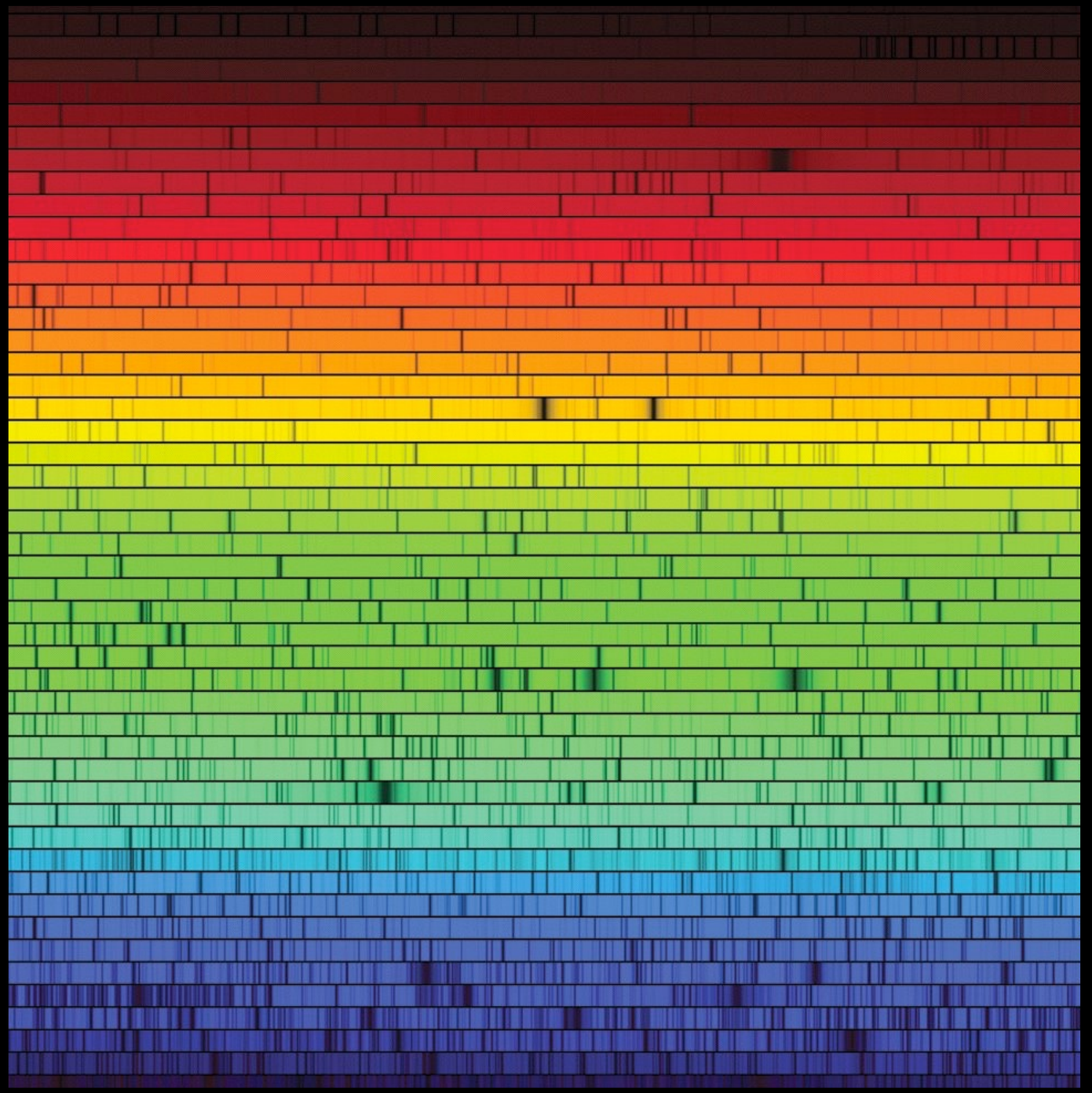
higher energy photons



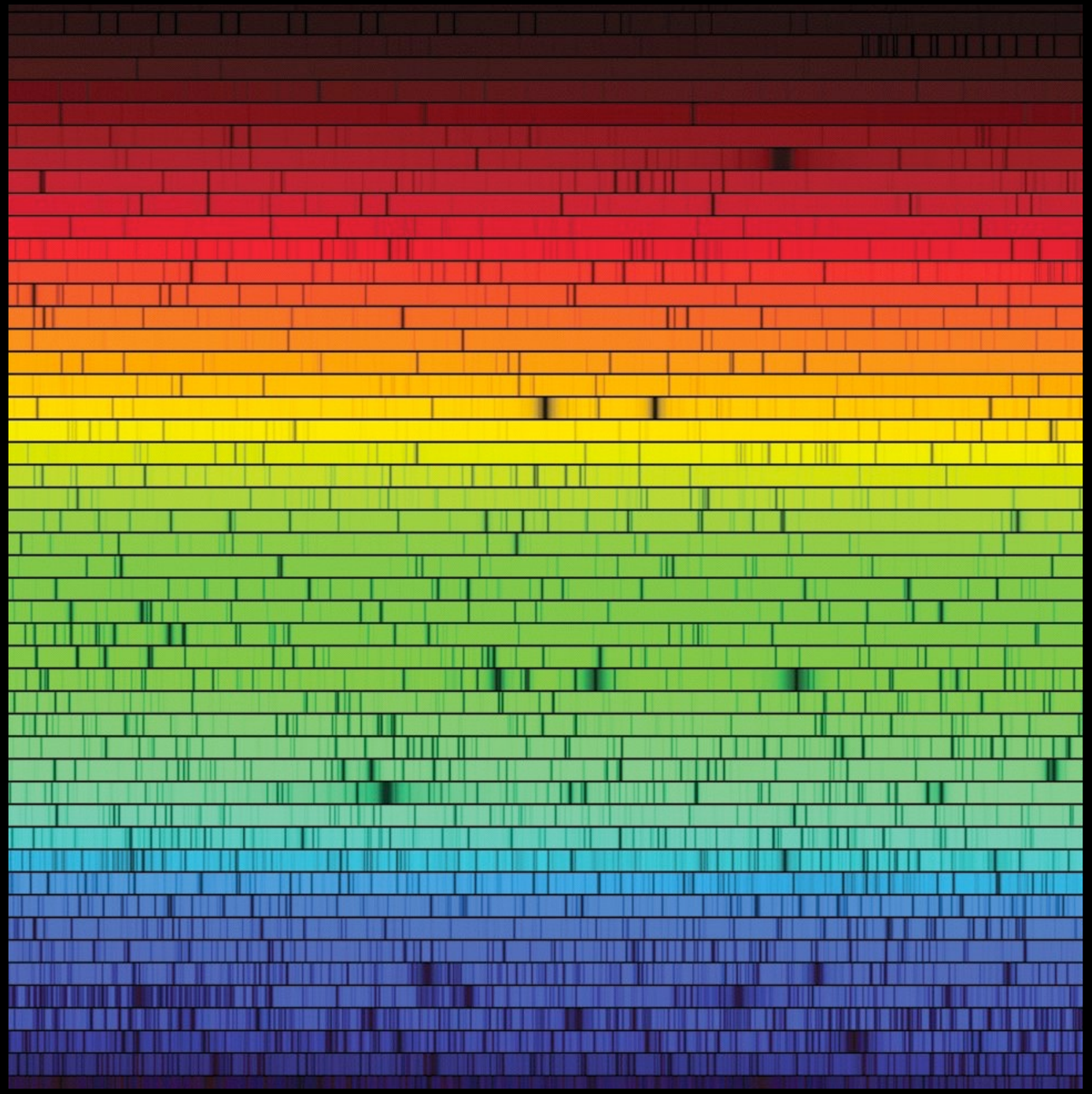
dimmer

brighter

dimmer

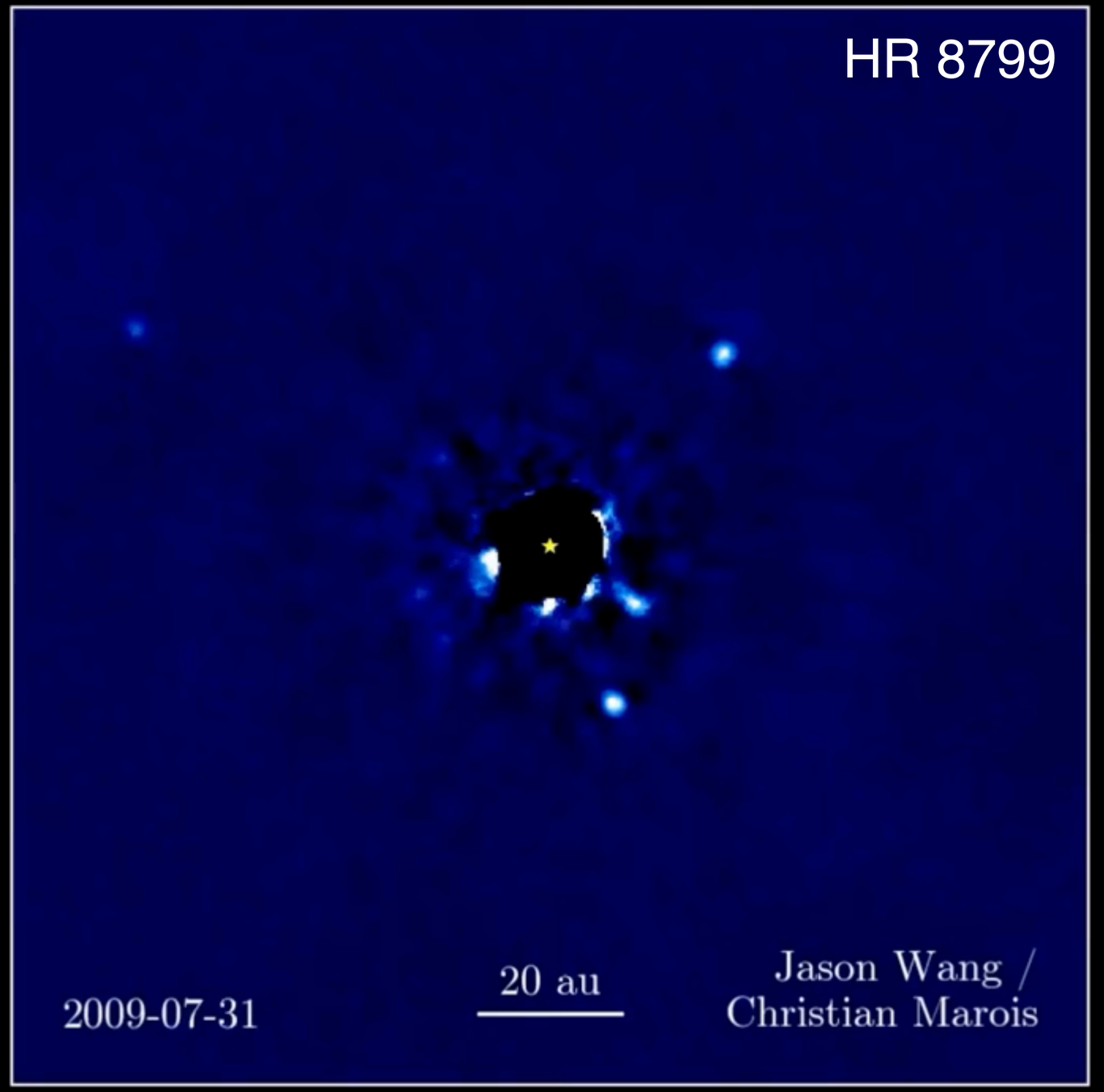


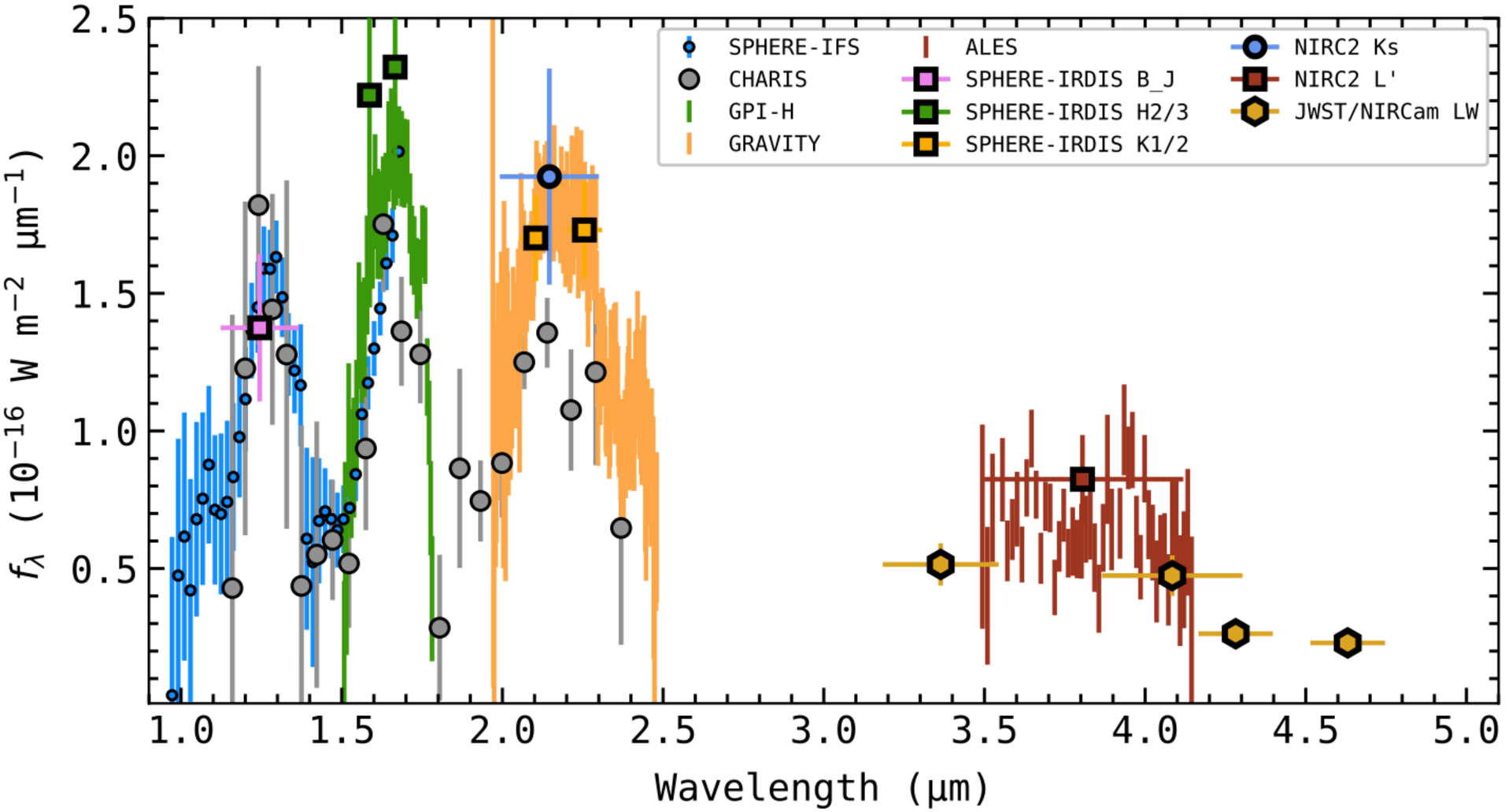
dark
“spectral lines”



JWST looks in the infrared, where quantum mechanics places many molecular lines

wide-separation giant planets





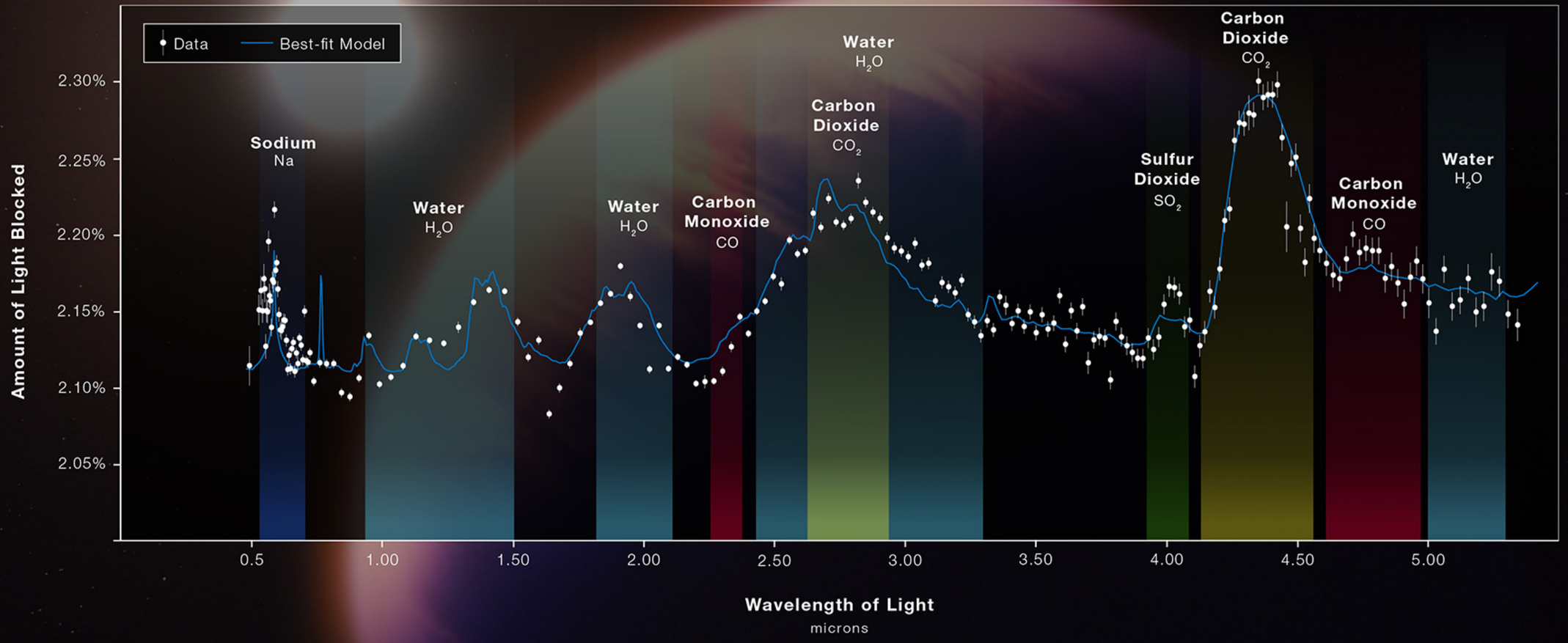
HR 8799 e

Balmer+ 2025

HOT GAS GIANT EXOPLANET WASP-39 b

ATMOSPHERE COMPOSITION

NIRSpec PRISM



WEBB
SPACE TELESCOPE

Our best examples: Solar system planets

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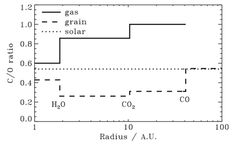

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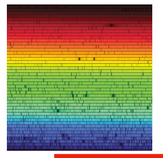

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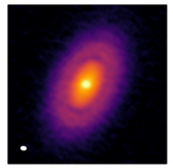

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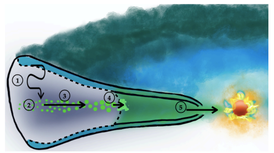

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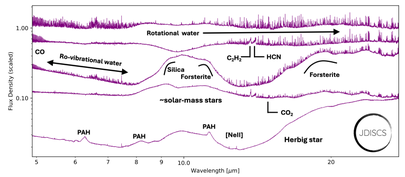
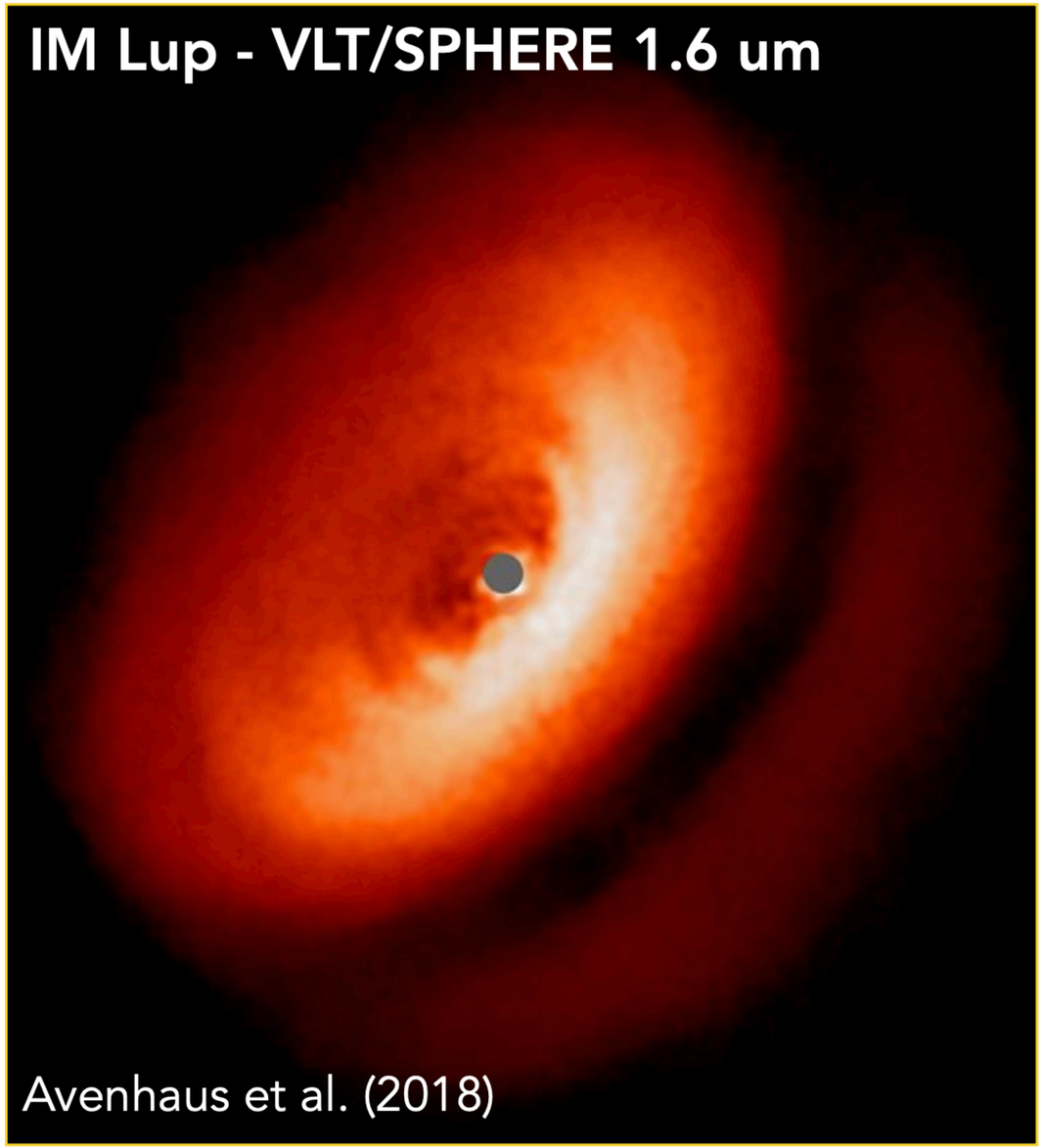
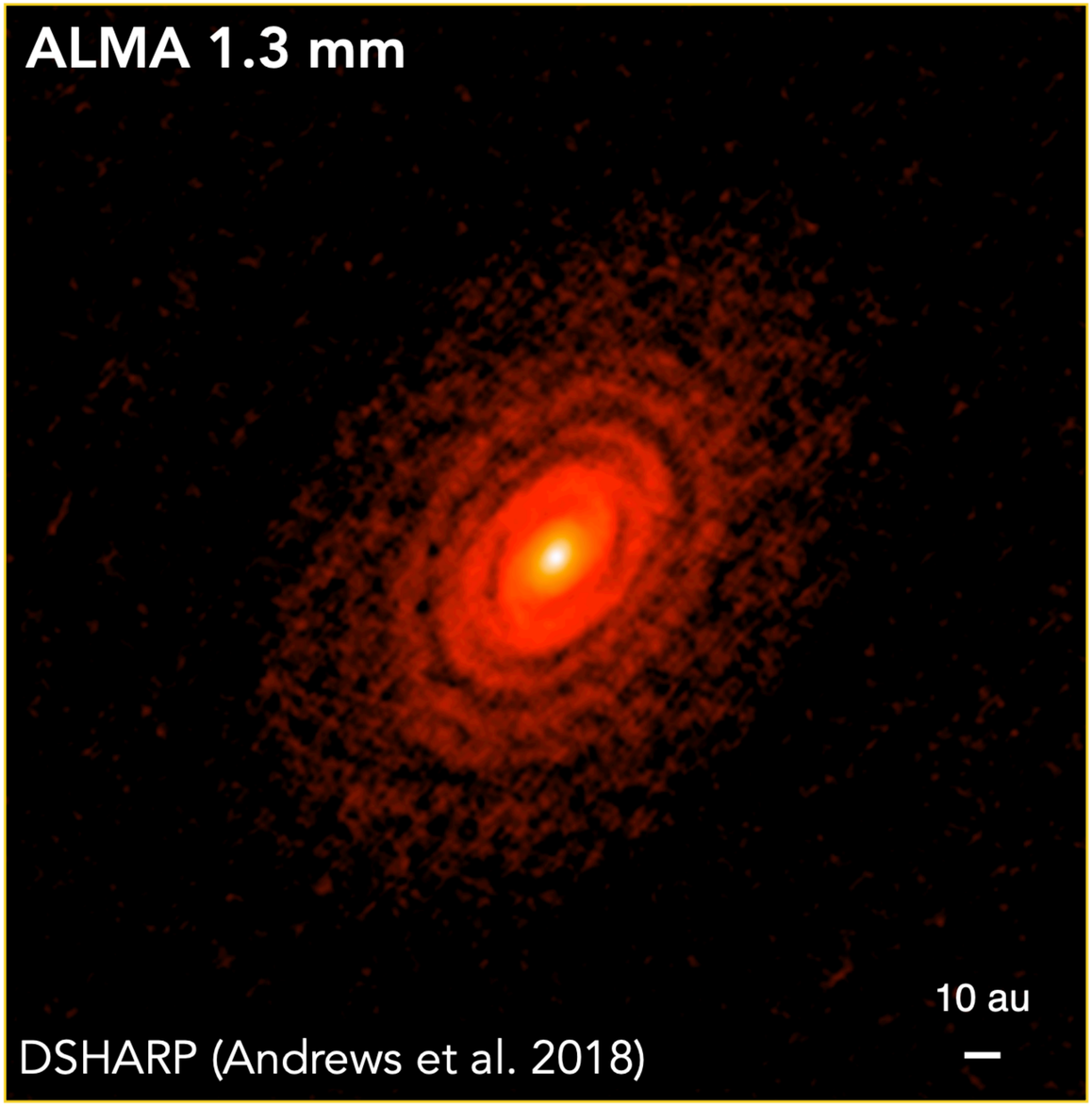


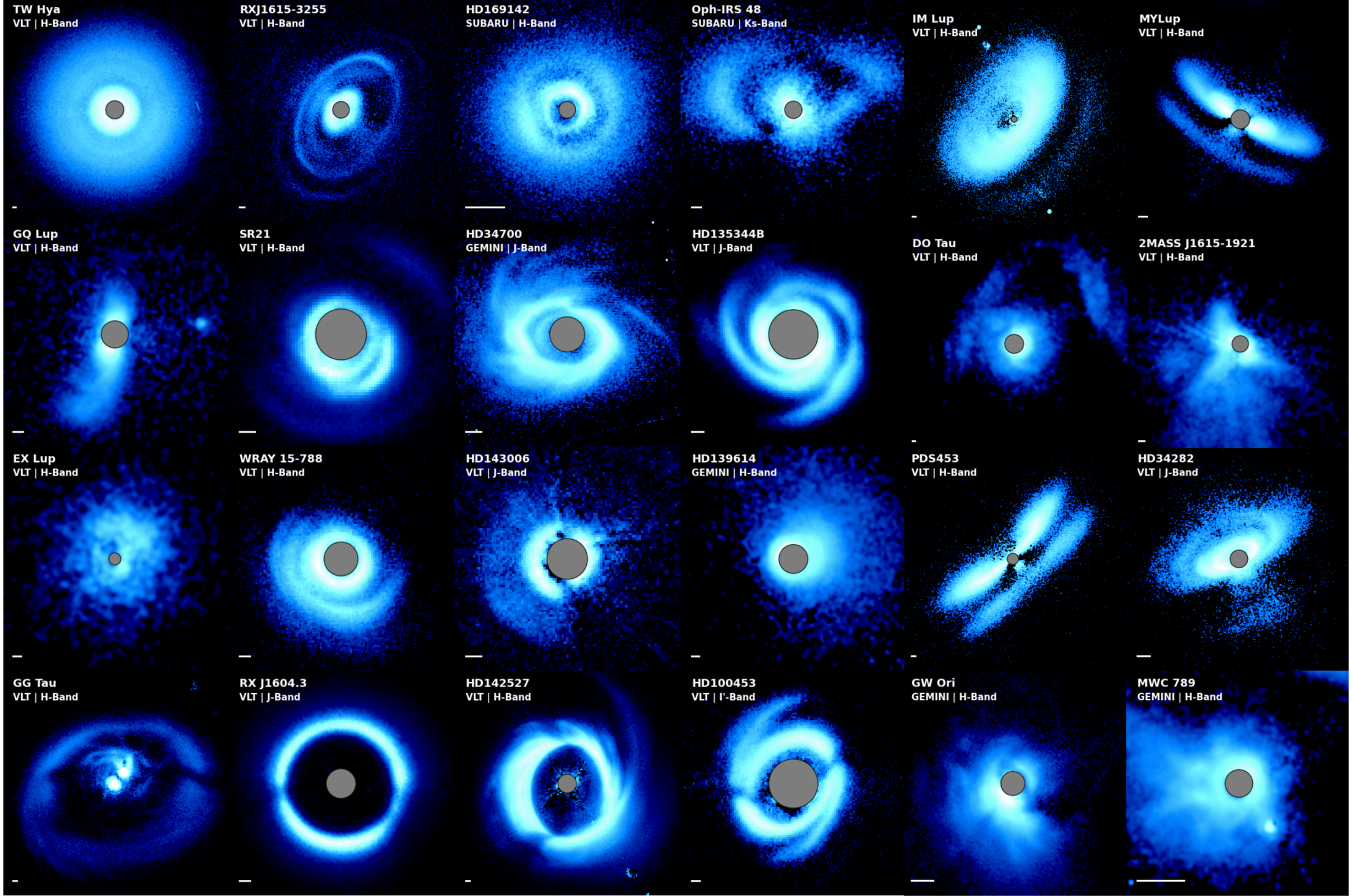
New insights: Mysteries from JWST

Disks probed by dust

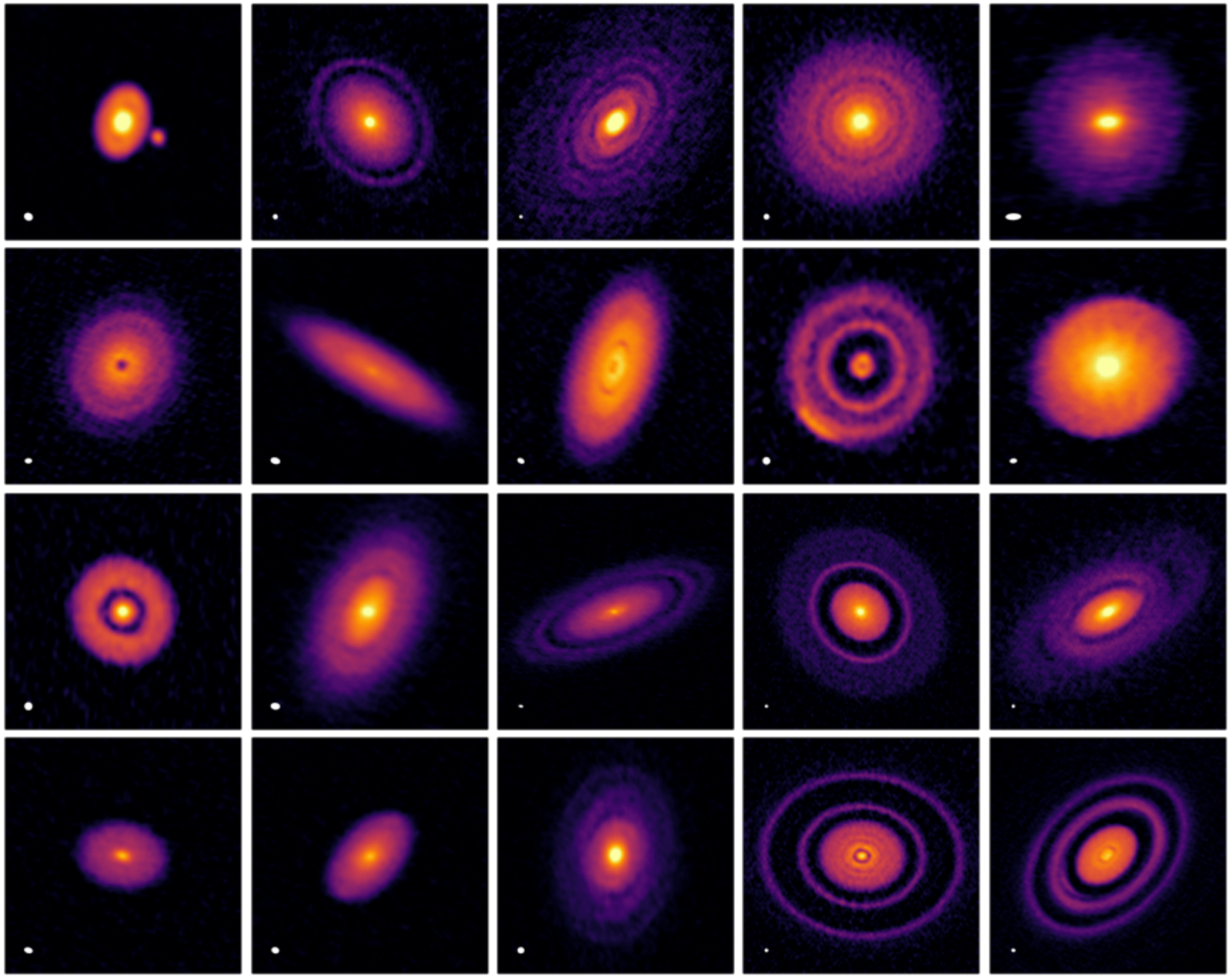




Slide credit: Zawadzki

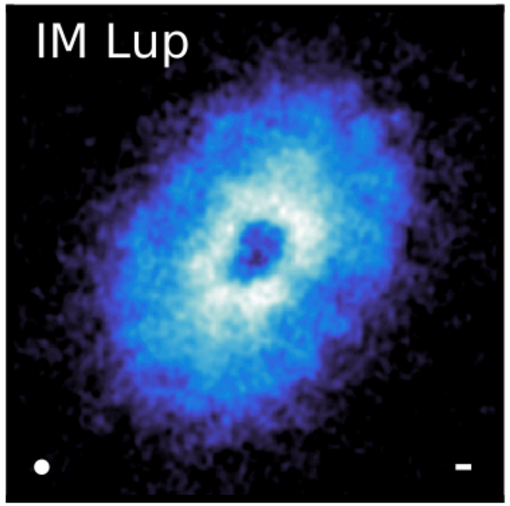


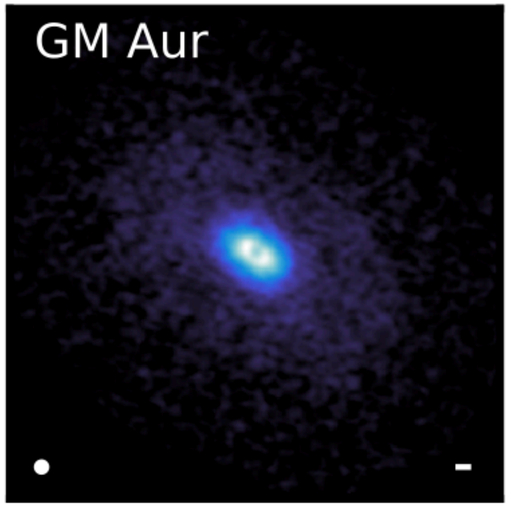
Benisty + 2023, PPVII review

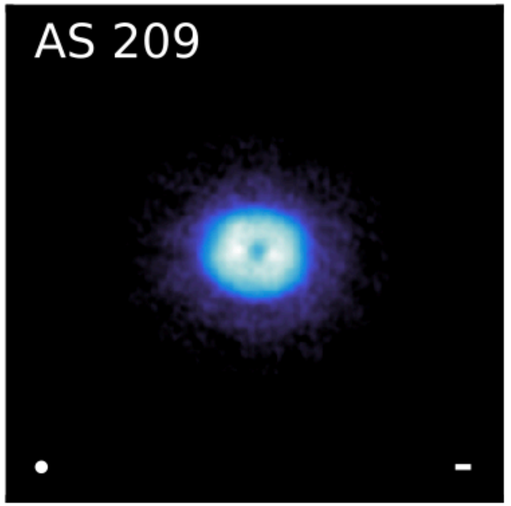


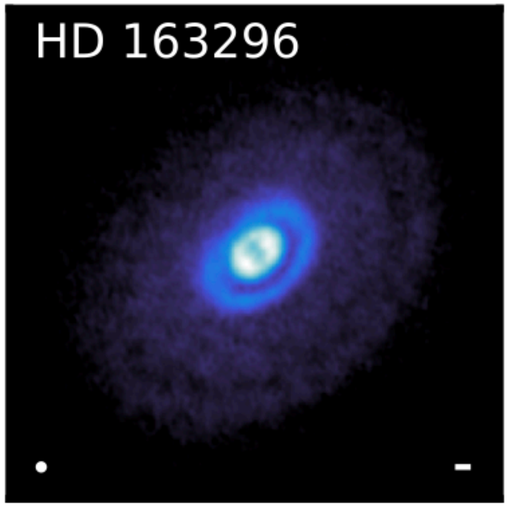
ALMA (DSHARP, Andrews+ 2018)

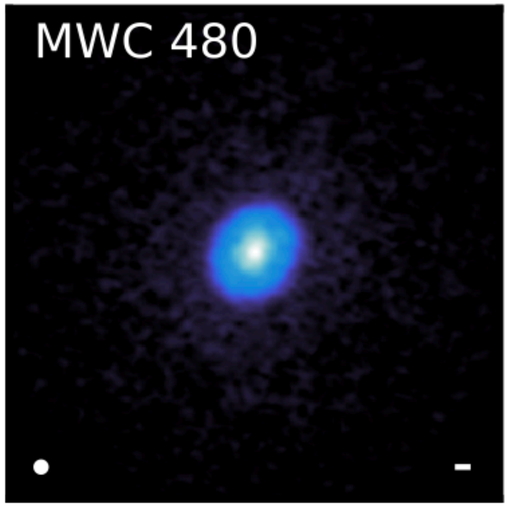
HCN towards the five MAPS disks



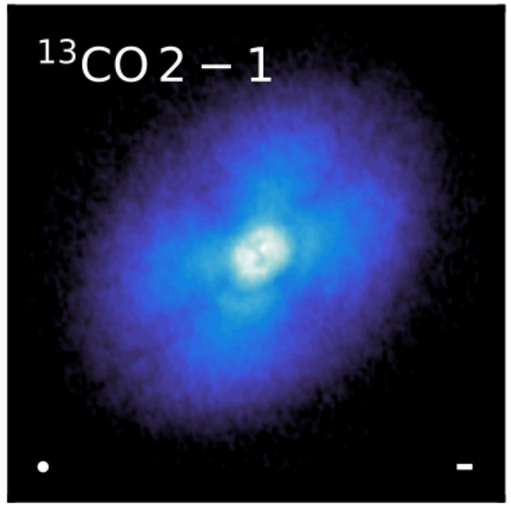


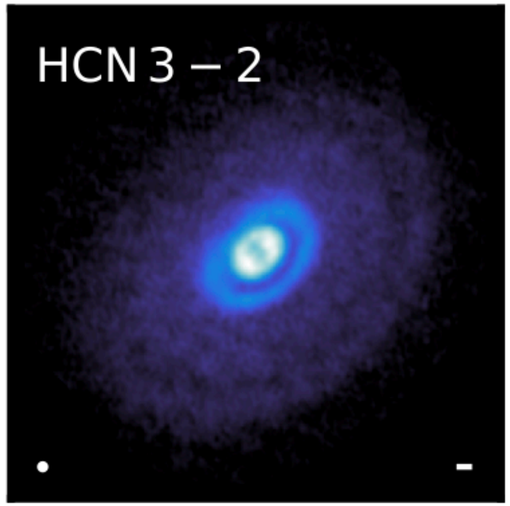


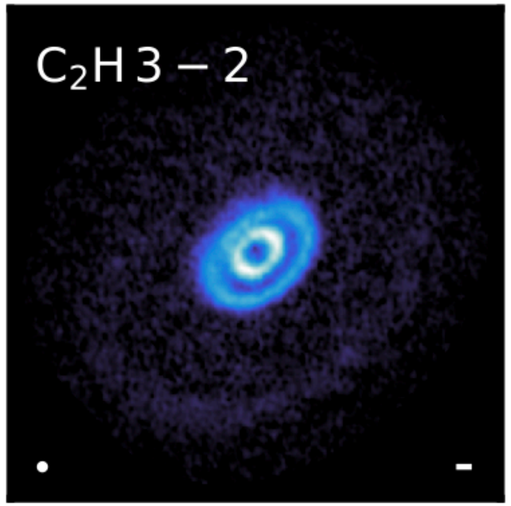


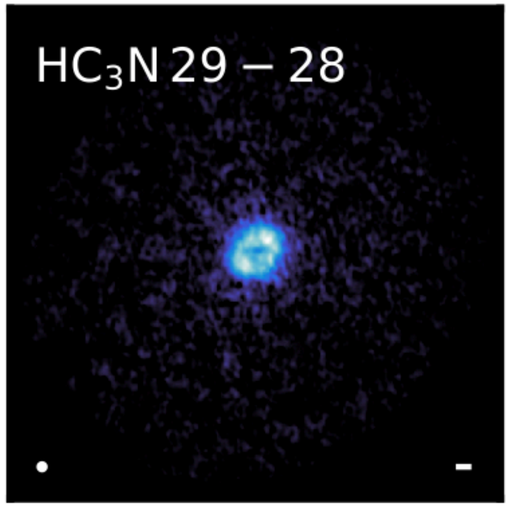


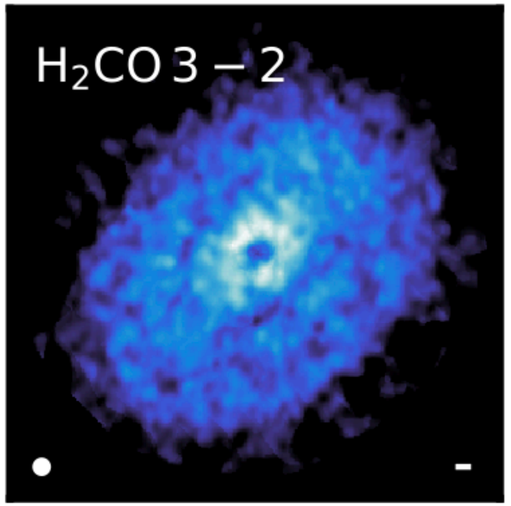
Five molecular faces of one disk (HD 163296)



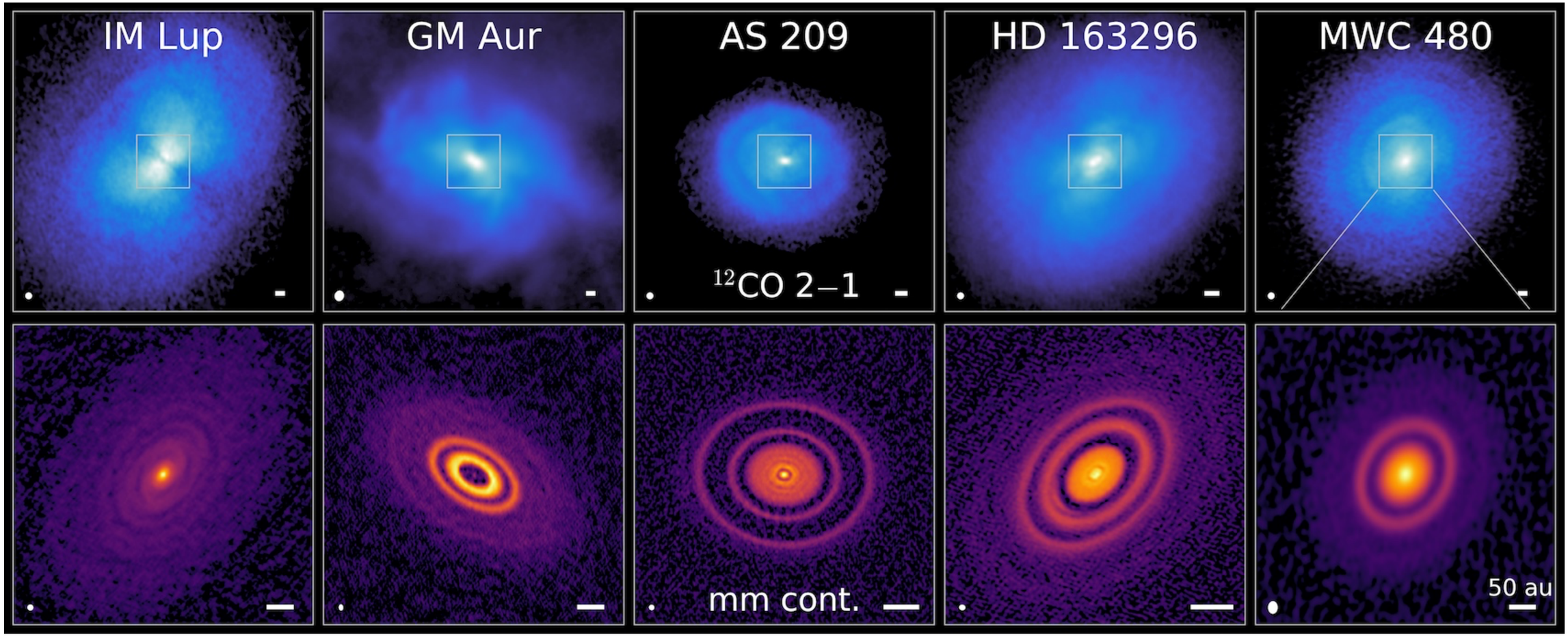








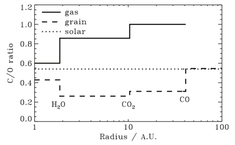
Öberg+ 2021



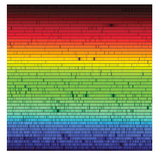
MAPS, DSHARP surveys with ALMA

Our best examples: Solar system planets

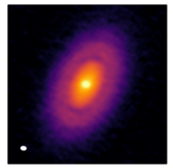
What are the building blocks? Interpreting the periodic table



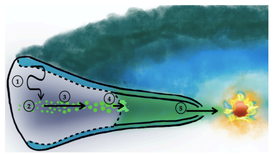
The context of planetary assembly: Planet formation



Spectra put the physics in astrophysics



Probing the building blocks: Protoplanetary disks



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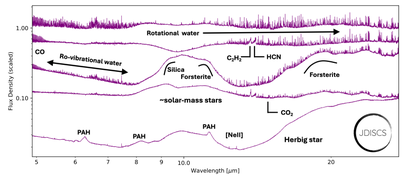
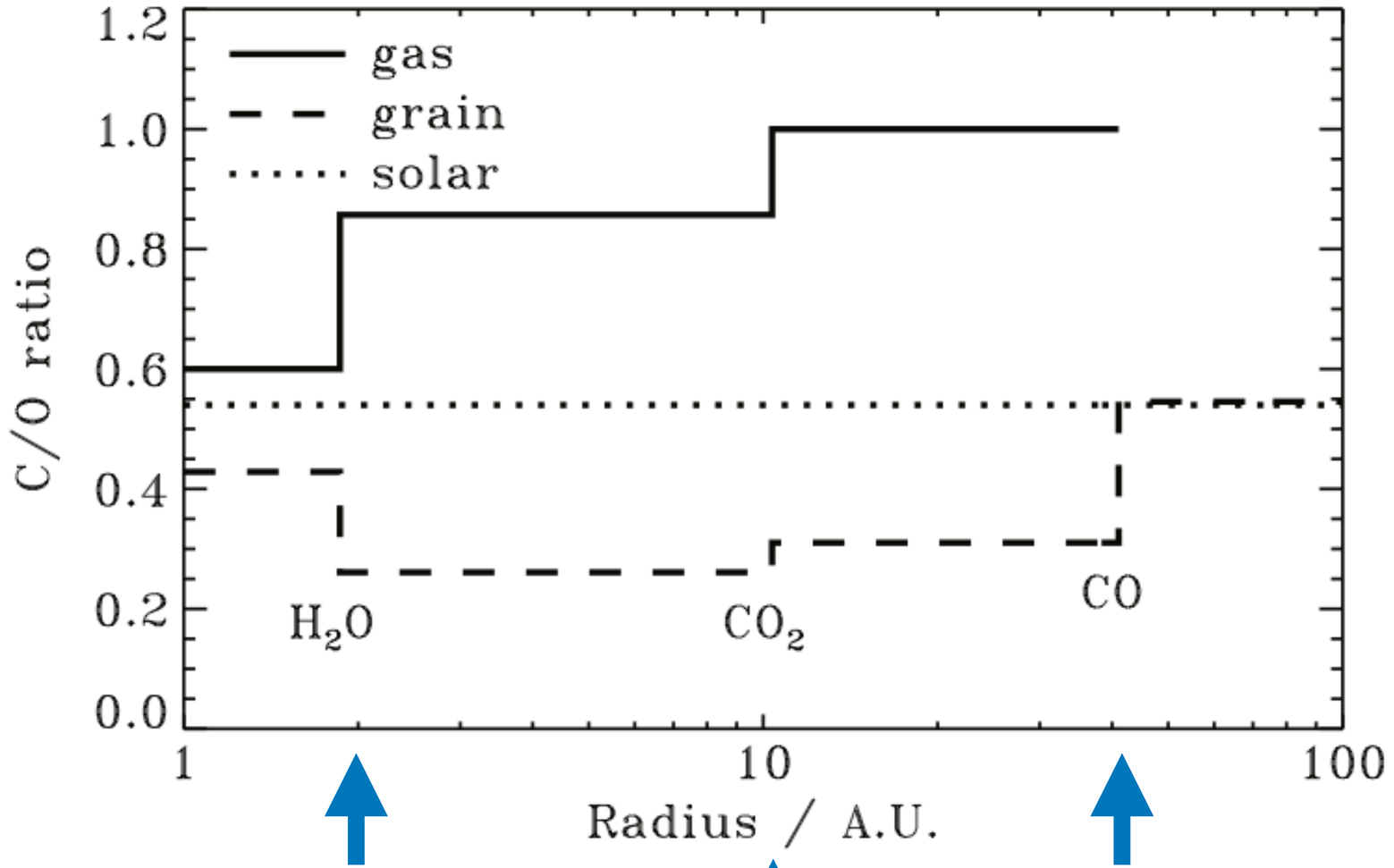


New insights: Mysteries from JWST



extra oxygen in silicates (rock)

extra carbon in hydrocarbons (where does it go???)

water freezes

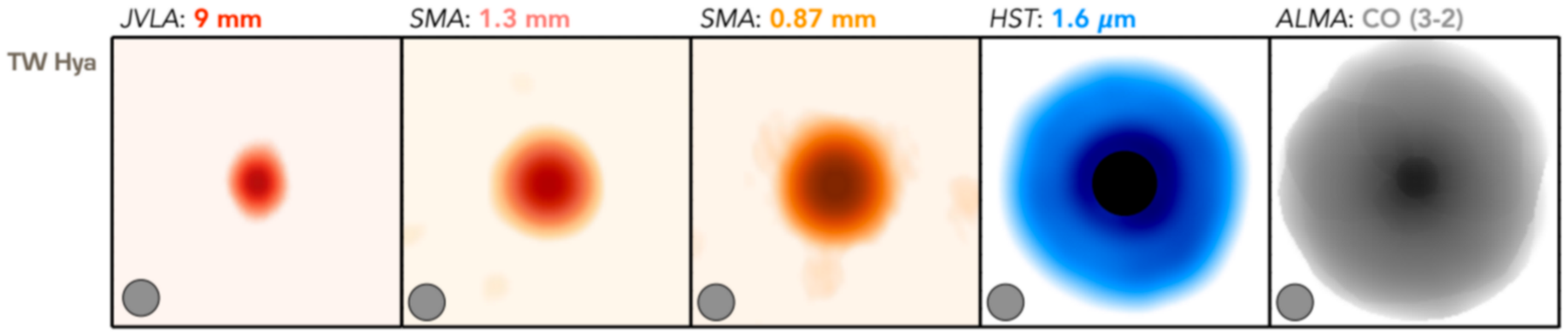
carbon dioxide freezes

carbon monoxide freezes

colder

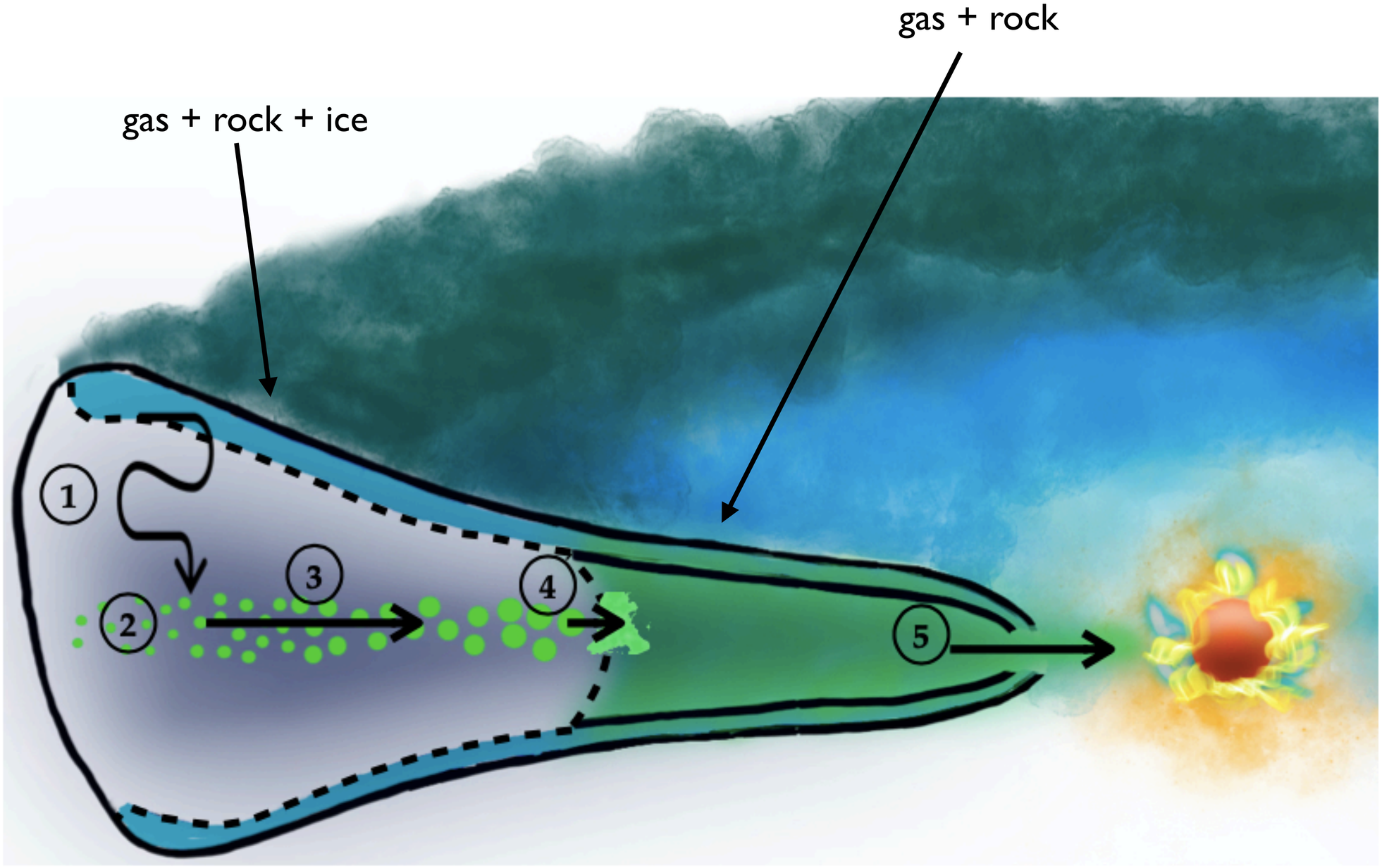
Oberg+ 11

Larger particles are concentrated closer to the star in observed protoplanetary disks.



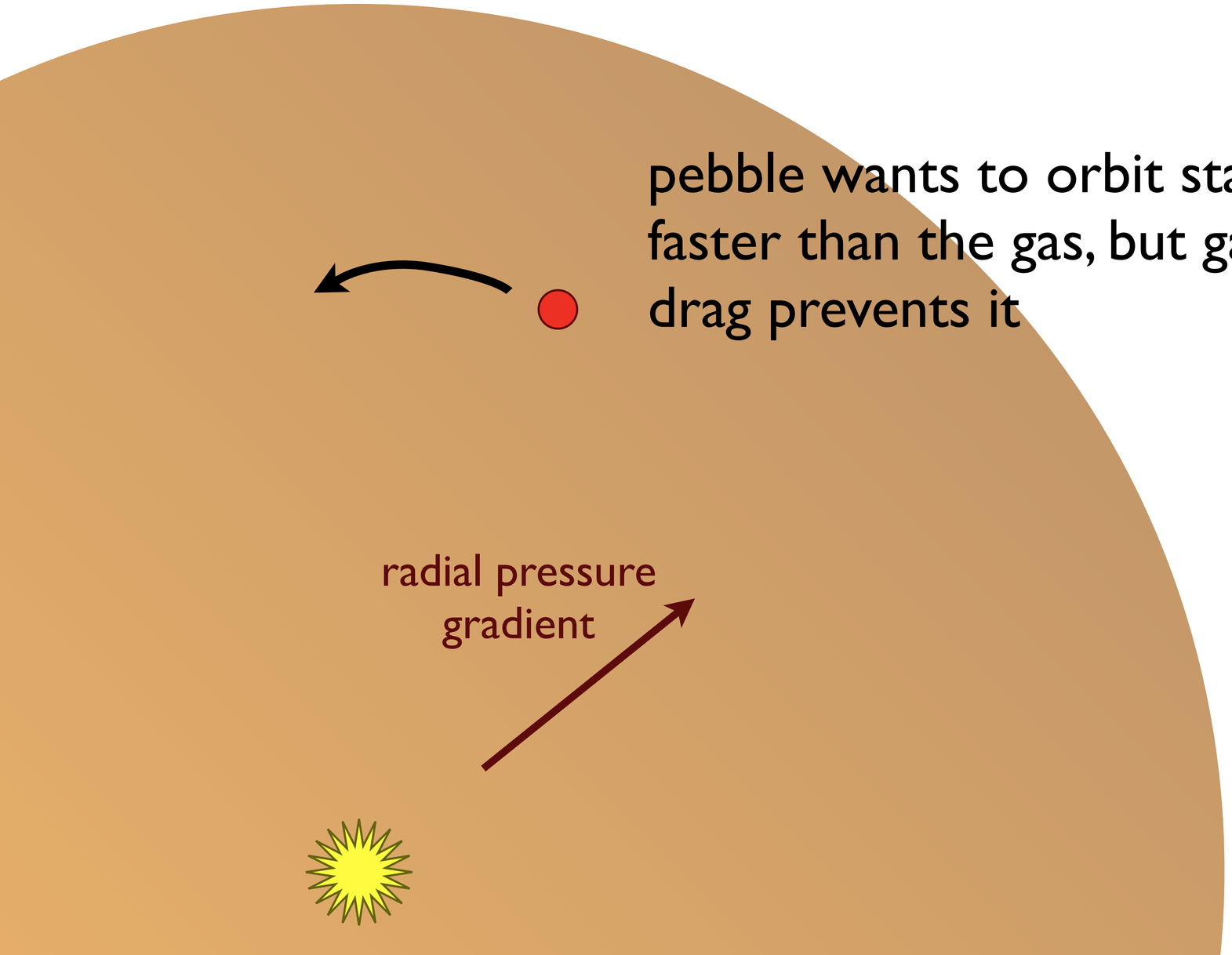
Andrews 2016

Particle Size

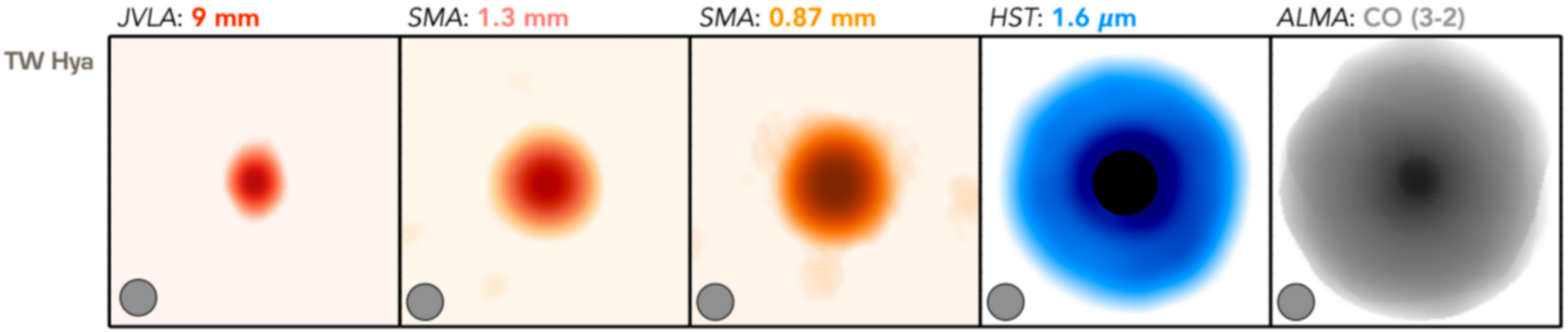


Powell et al. 2022

Gas drag causes drift



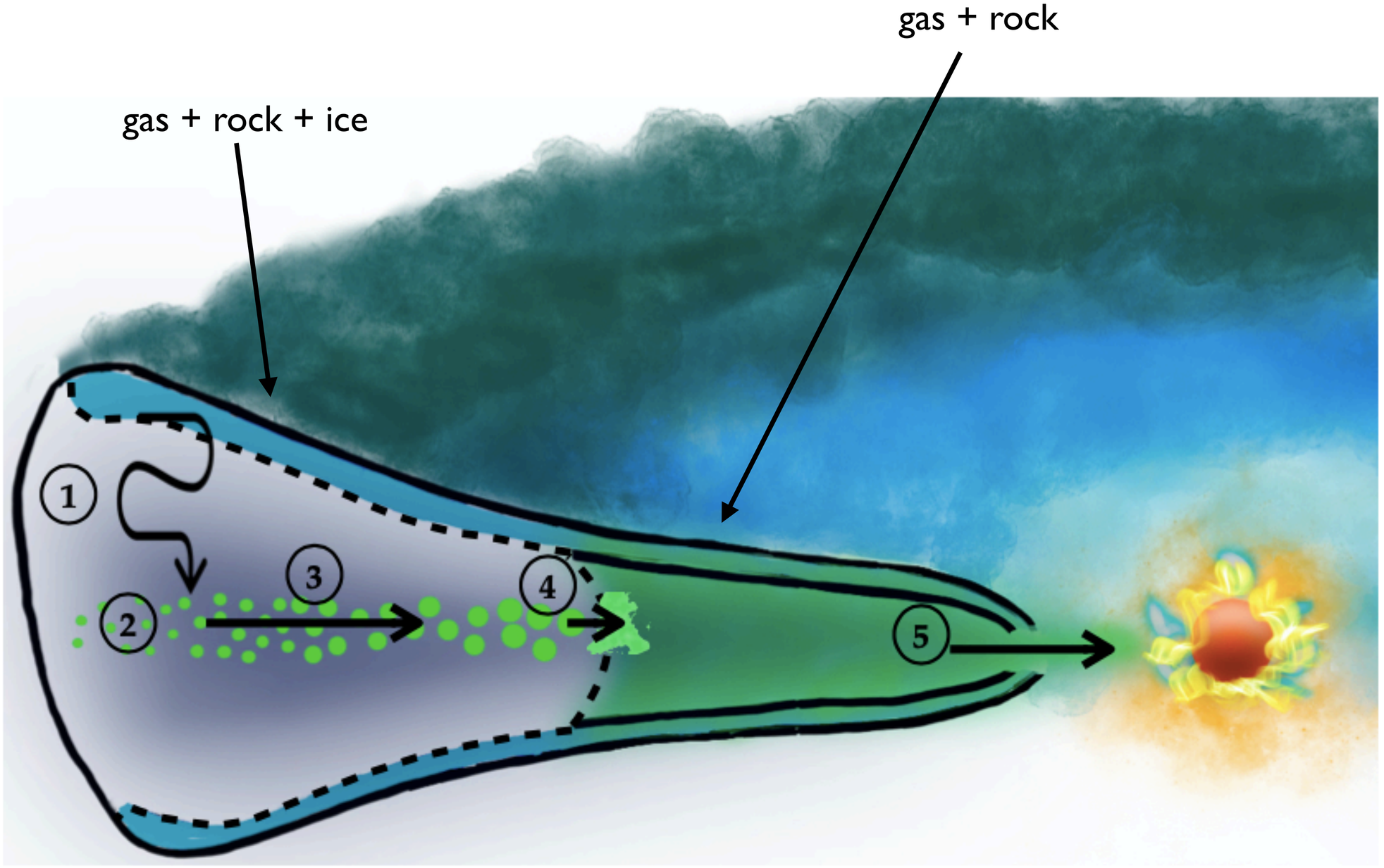
pebbles fall toward the star at their terminal velocity



Particle Size

larger particles drift inward
more quickly

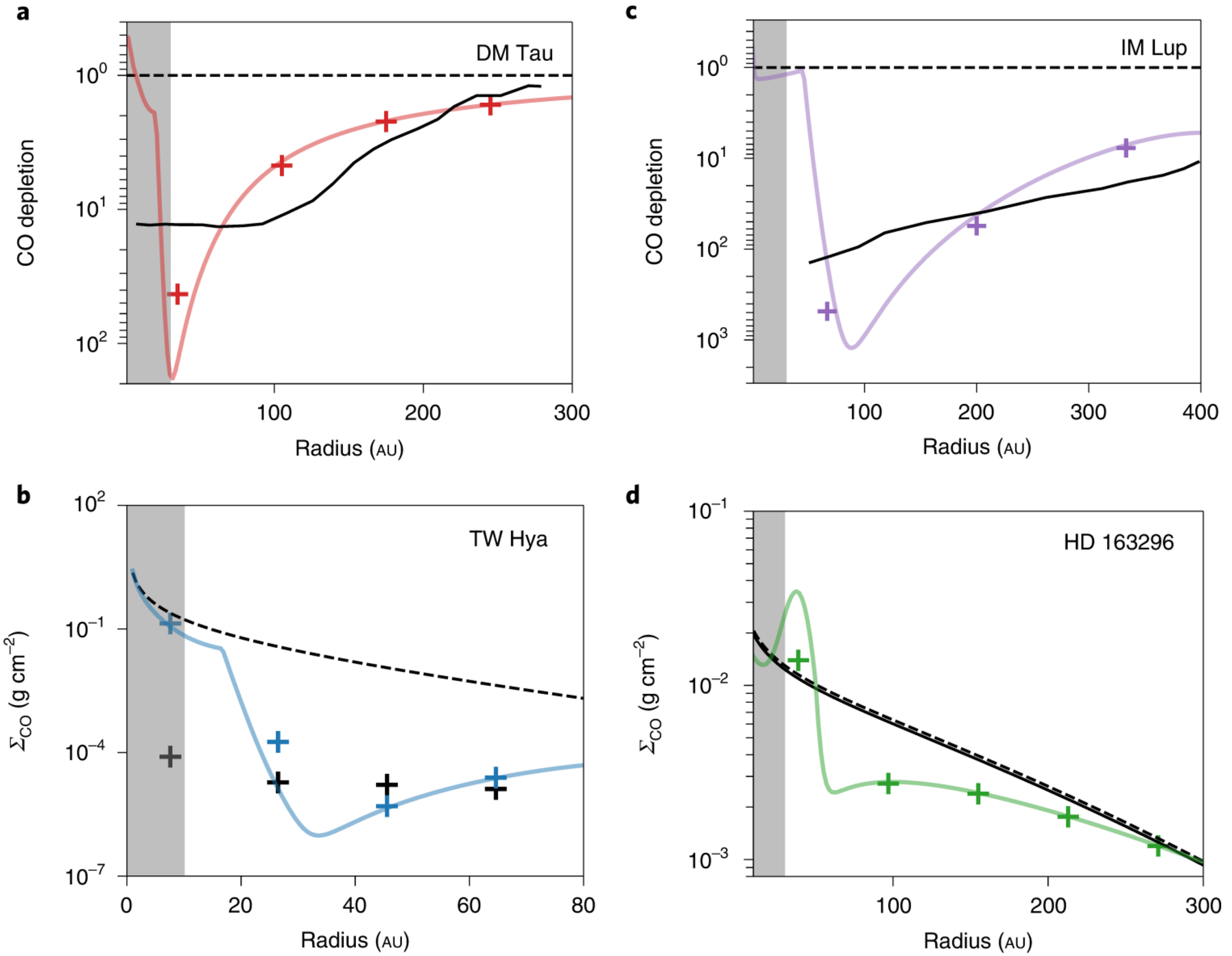
Menu et al. 2014, L.I. Cleeves, Andrews et al. 2012, Debes et al. 2013,
images from presentation by Sean Andrews May 2016



“reverse” cloud physics!

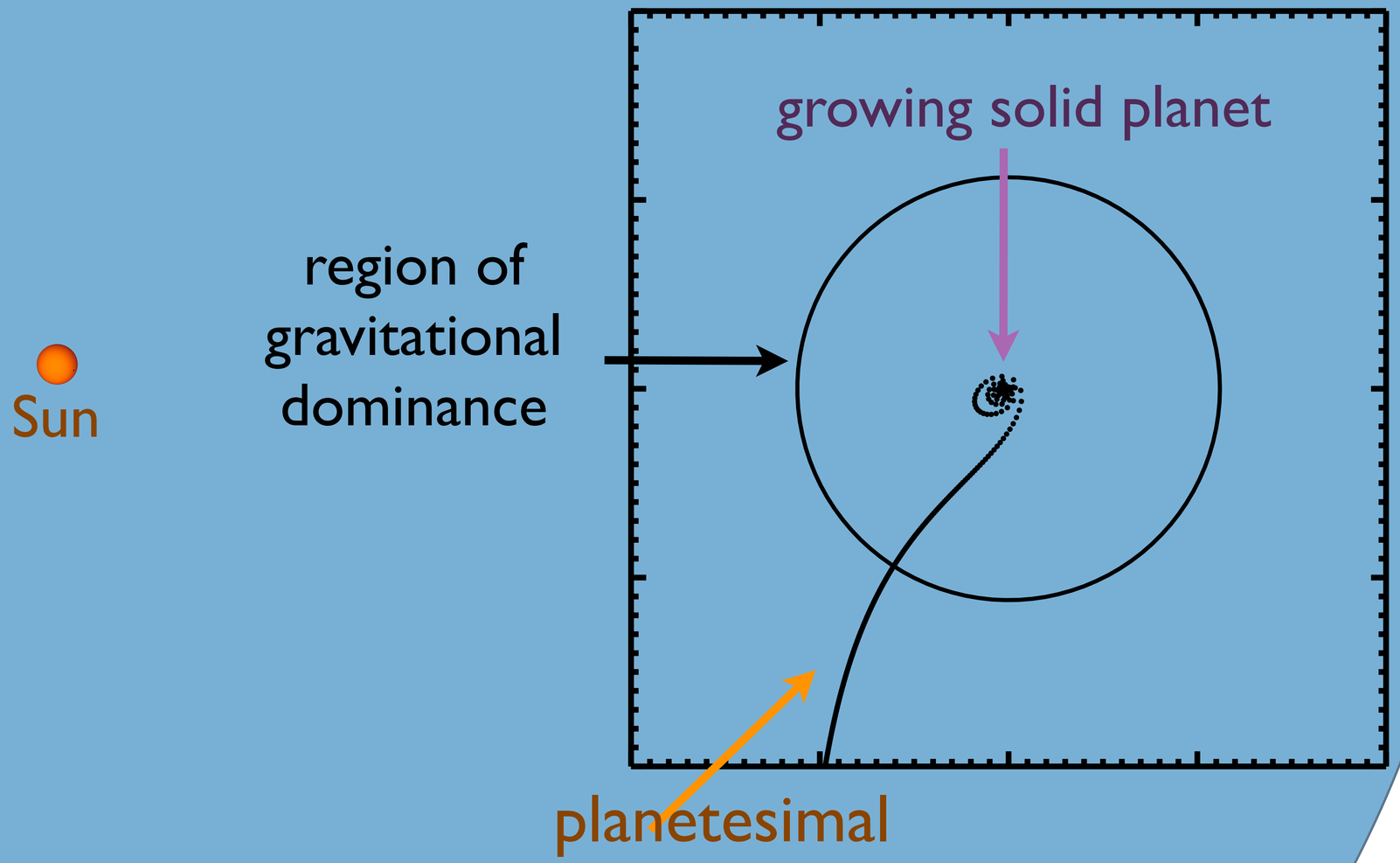
Powell et al. 2022

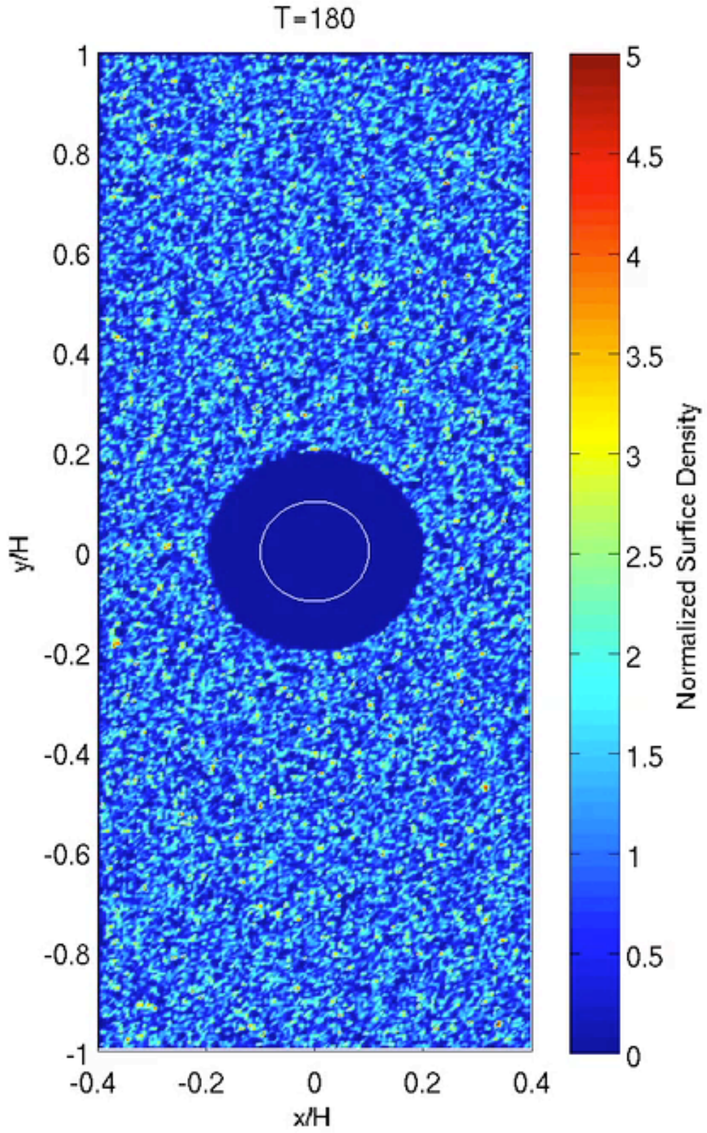
CO gas depletion depends on age and turbulence level in the disk



Powell et al. 2022

Pebble accretion:
Capture by gas drag allows fast growth of planets





Ormel & Klahr 2010, Lambrechts & Johansen 2012, Rosenthal et al. 2018, Xu et al. 2017

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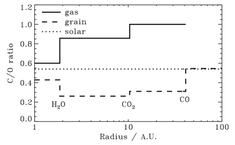

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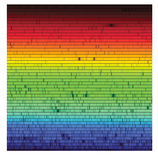

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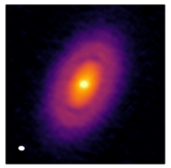

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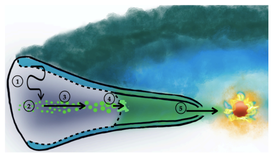

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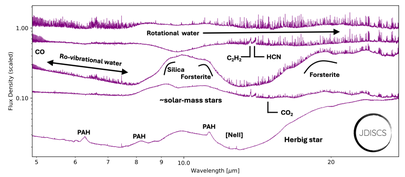

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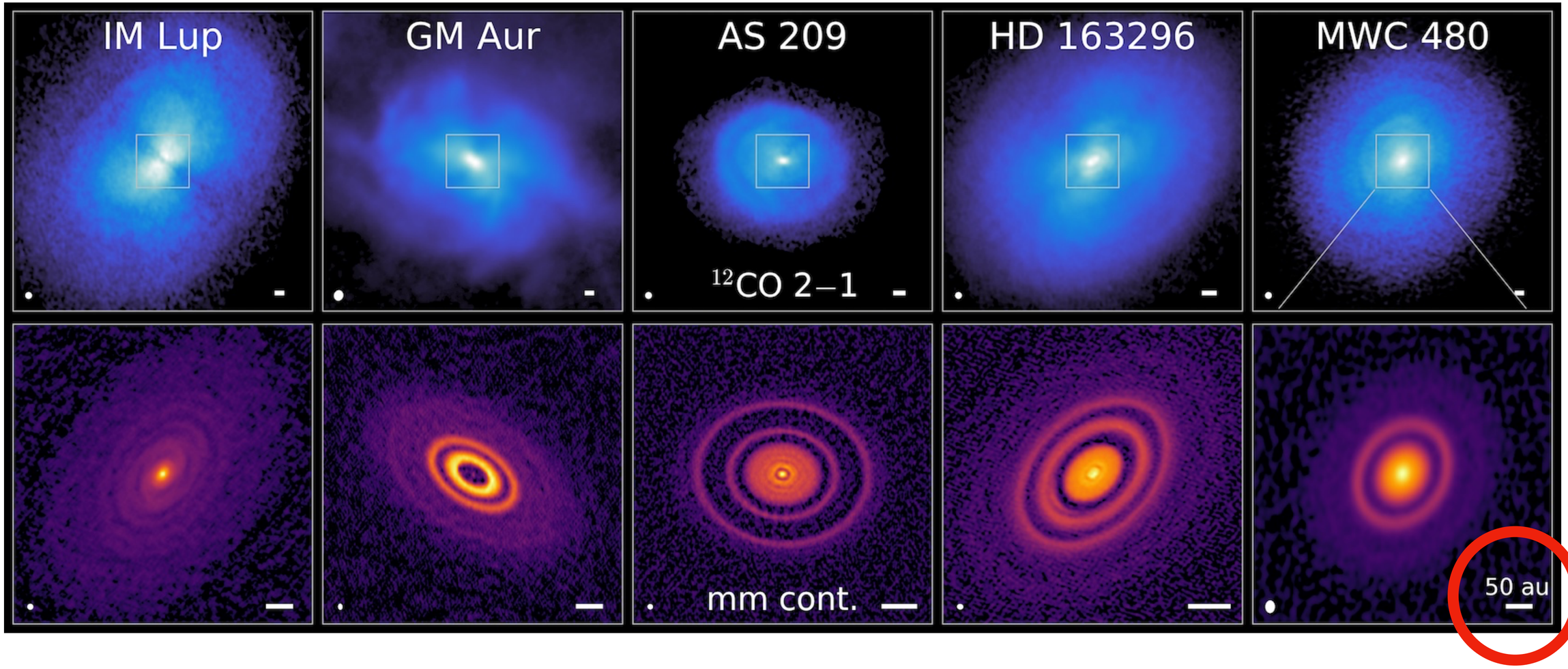
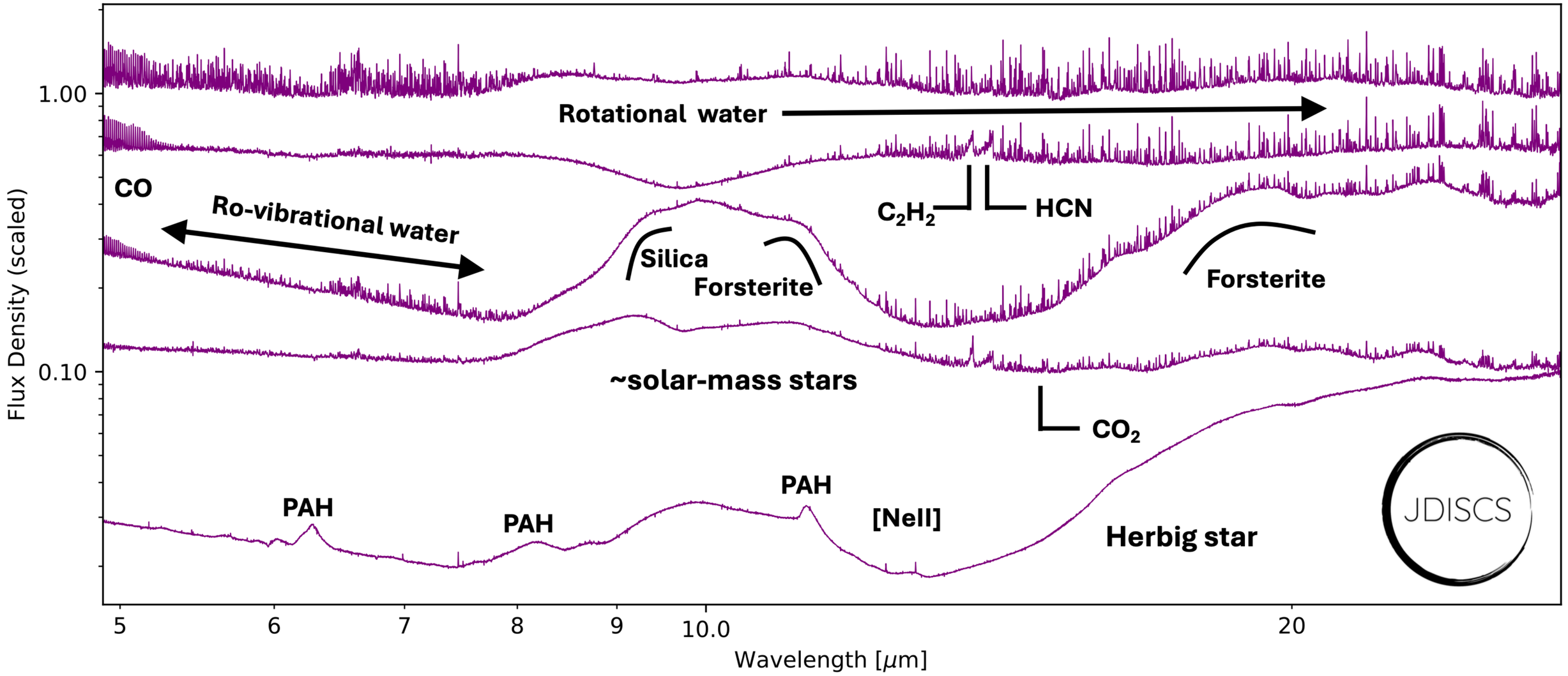
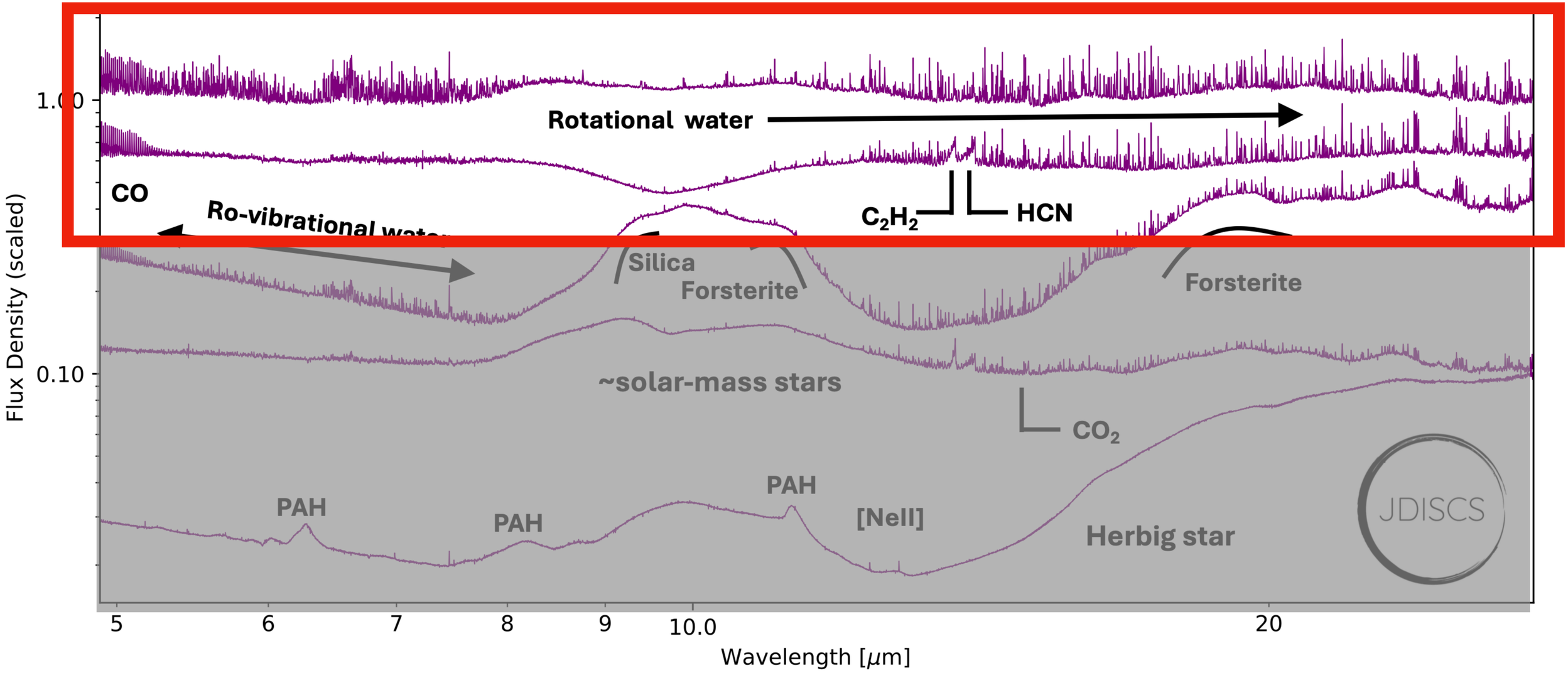


!

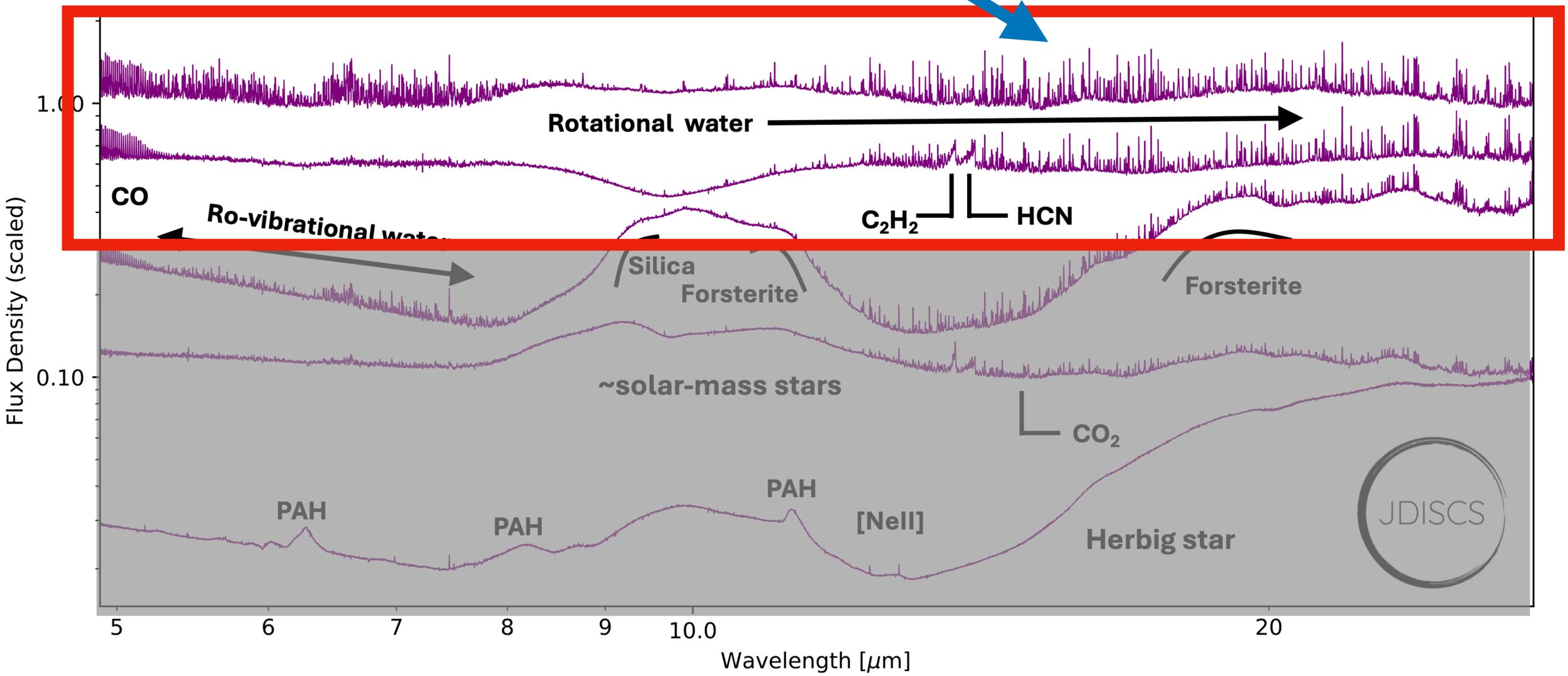
MAPS, DSHARP surveys with ALMA

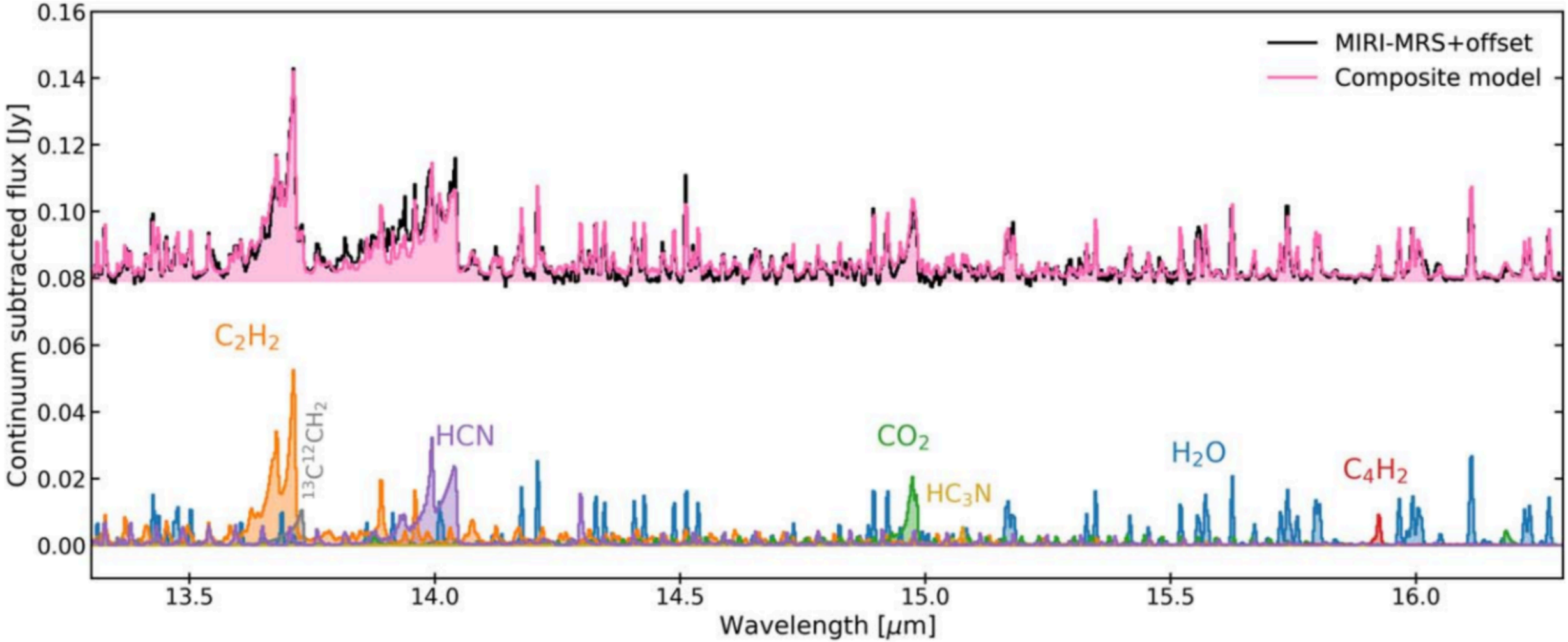
These spectra probe the inner disk, near where Earth formed!



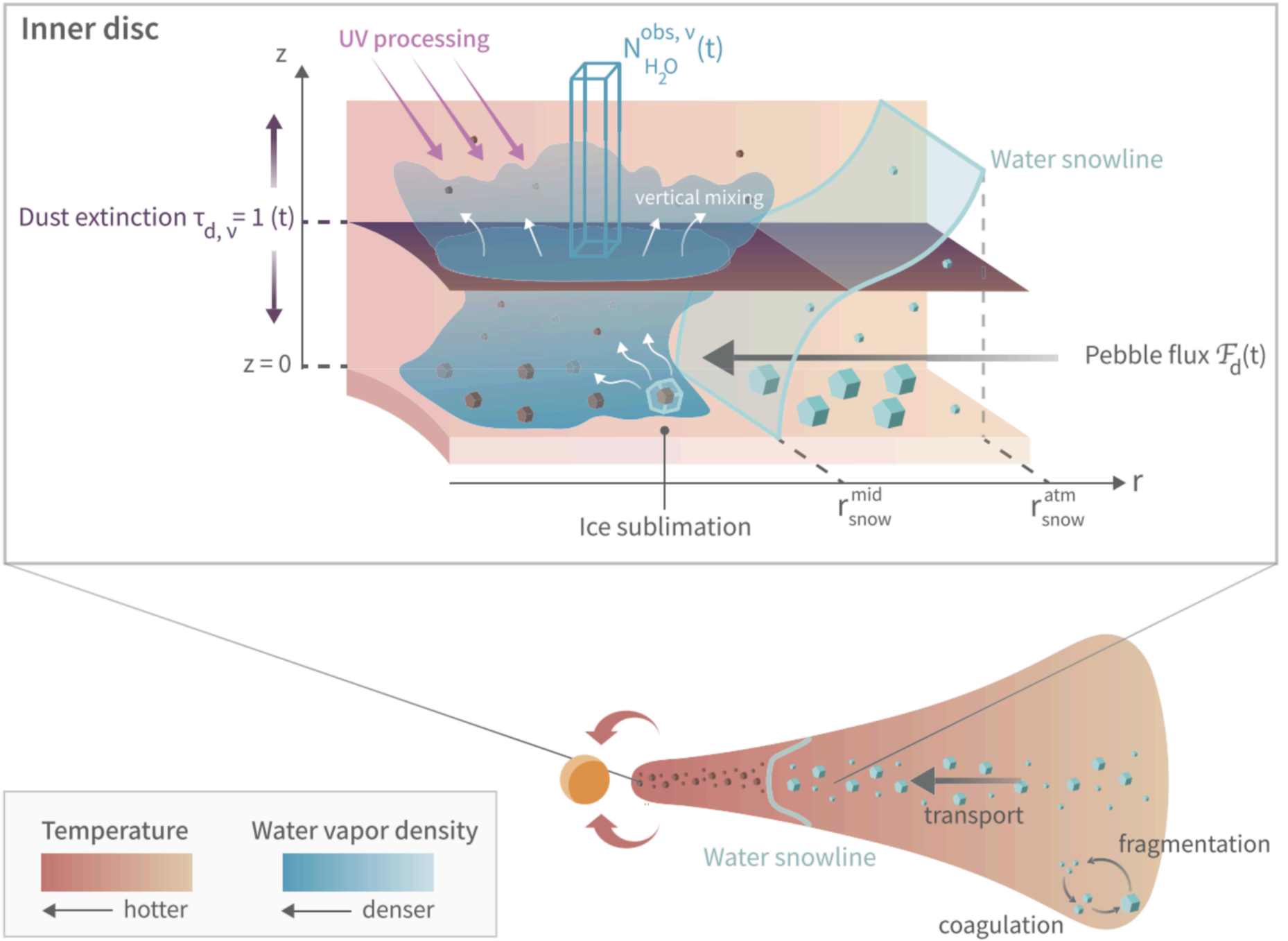

1.00
0.10
Flux Density (scaled)
Rotational water
CO
Ro-vibrational wate
C_2H_2
HCN
Silica
Forsterite
Forsterite
~solar-mass stars
CO_2
PAH
PAH
PAH
[NeII]
Herbig star
JDISCS
5
6
7
8
9
10.0
20
Wavelength [μm]

Each of these is a water line

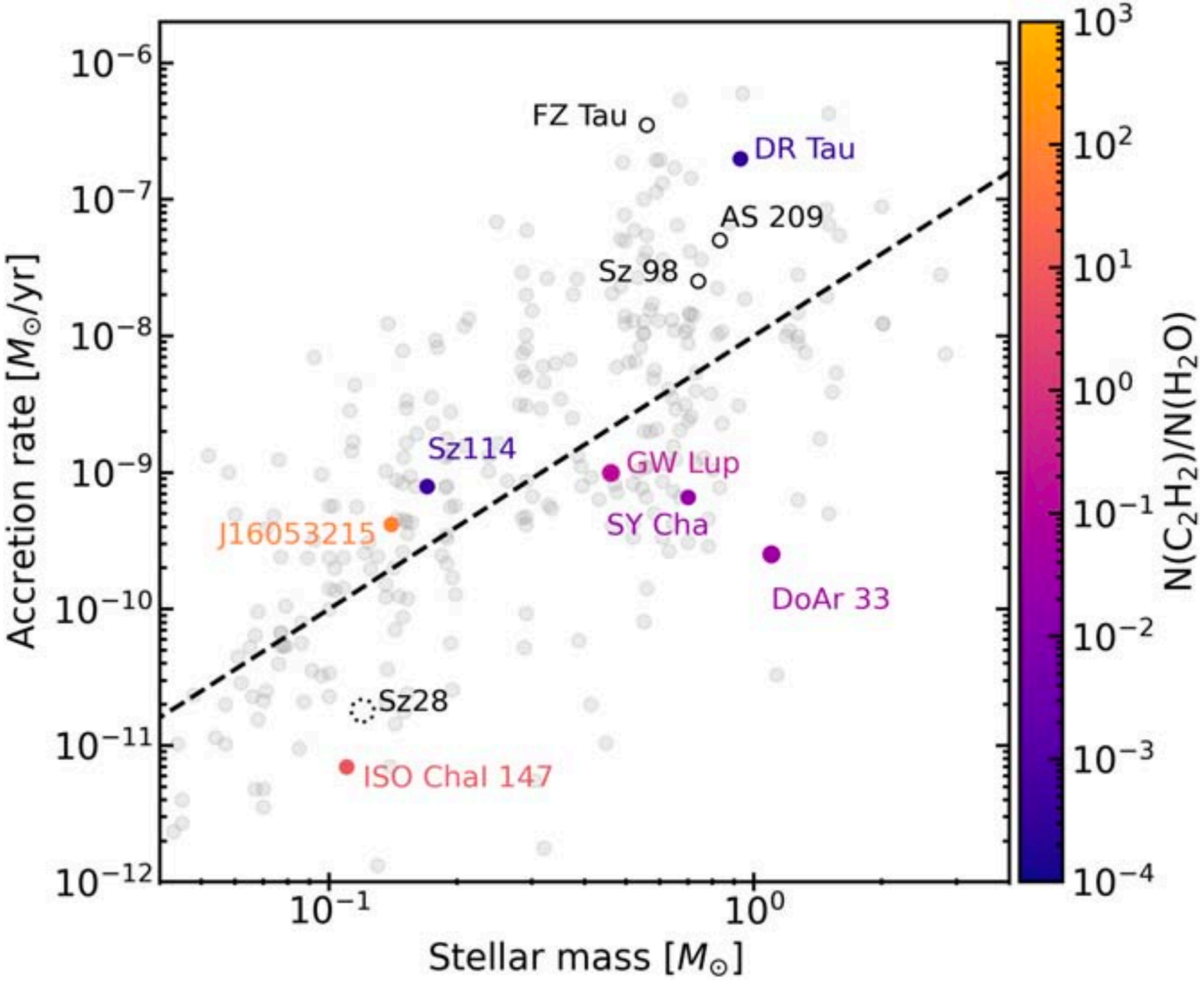




Colmenares+ 2024


Inner disc
UV processing
$N^{obs,\nu}_{H_2O}(t)$
z
Dust extinction $\tau_{d,\nu} = 1$ (t)
z = 0
vertical mixing
Water snowline
Pebble flux $\mathcal{F}_d$(t)
r
Ice sublimation
r^{mid}_{snow}
r^{atm}_{snow}
Temperature
hotter
Water vapor density
denser
transport
fragmentation
coagulation
Water snowline

Houge+ 2025



Colmenares+ 2024

How chemically diverse can planets made out of average galactic material be?