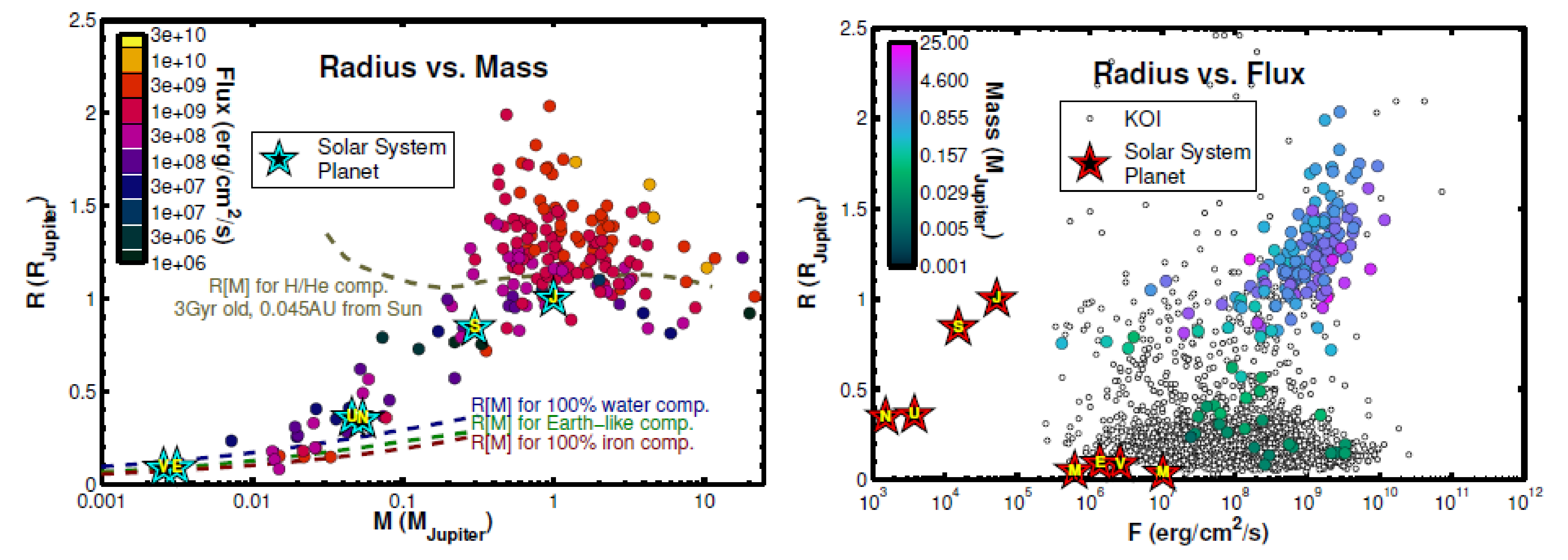
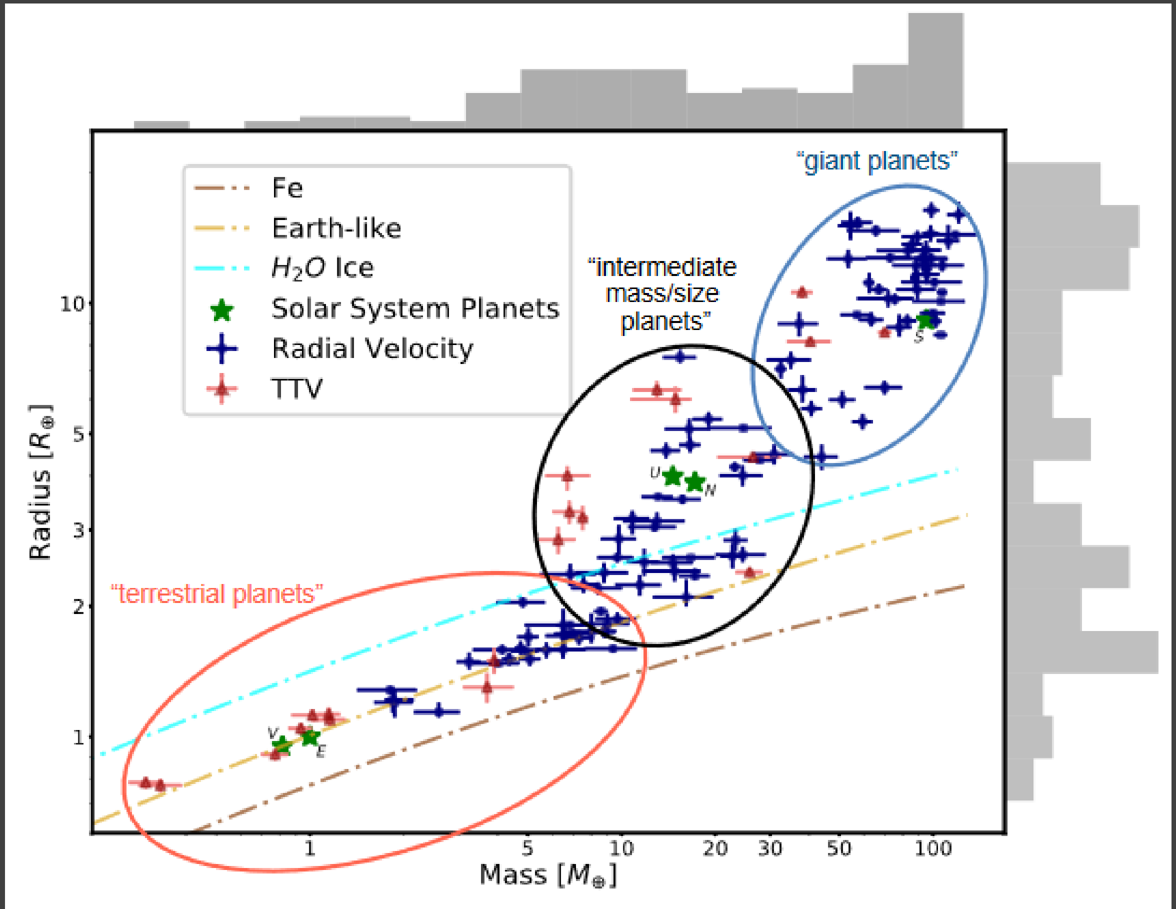
Internal structure and atmospheres of planets

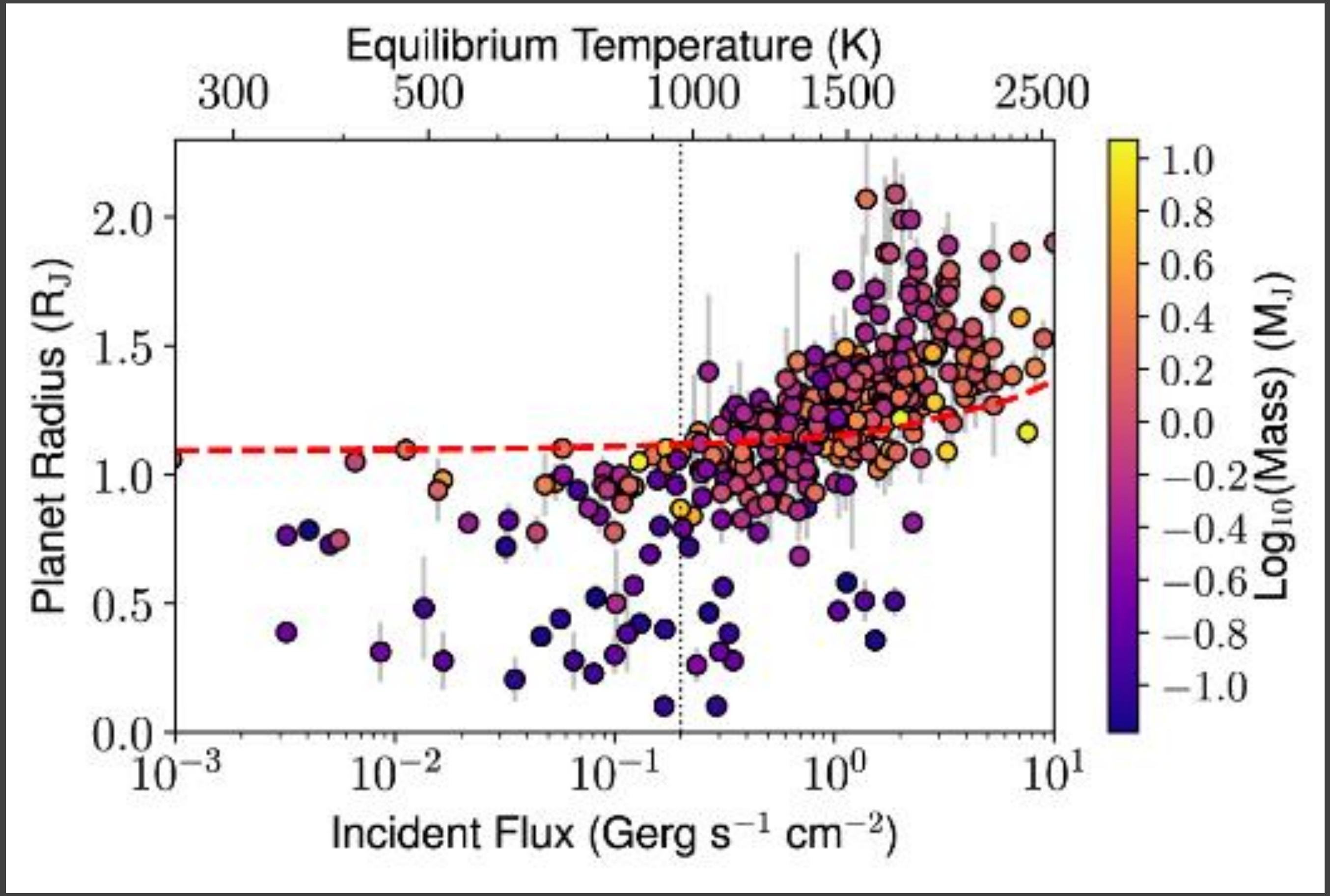
SERGEI POPOV

Sizes and masses



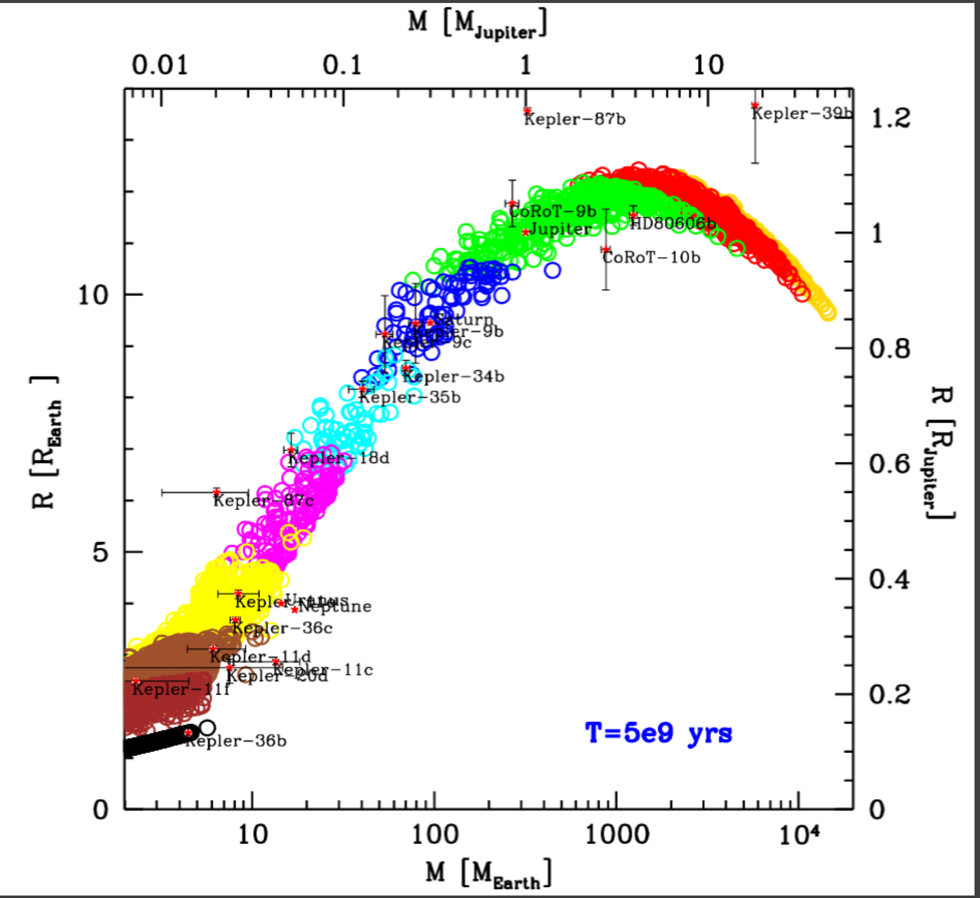
Mass AND radius measurements, heating





2103.08481

Radius vs. mass

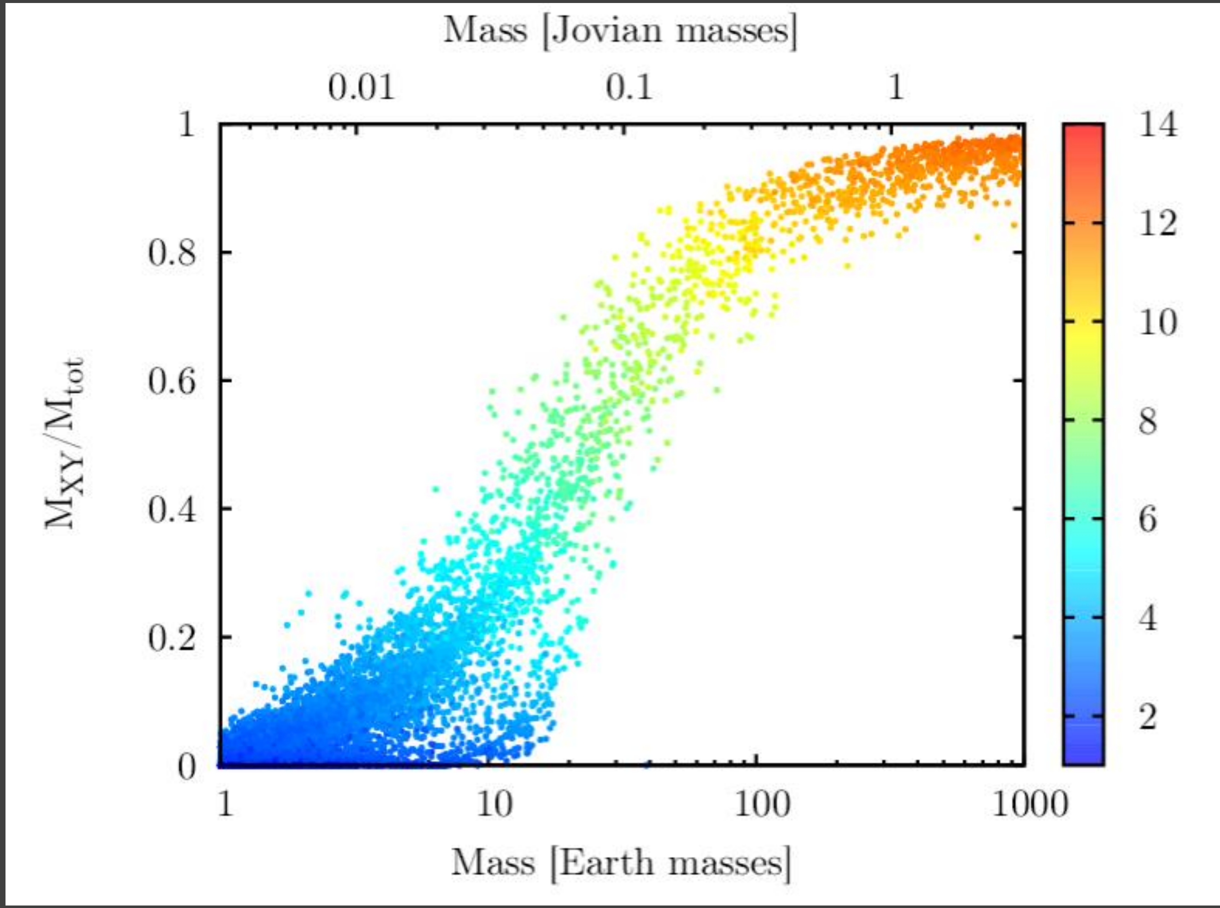


Results of modeling.

Old (relaxed) planets.
Planets ages are usually determined due to stellar ages (1803.03125, 1804.02214).

Colors correspond to different fractions of light elements.

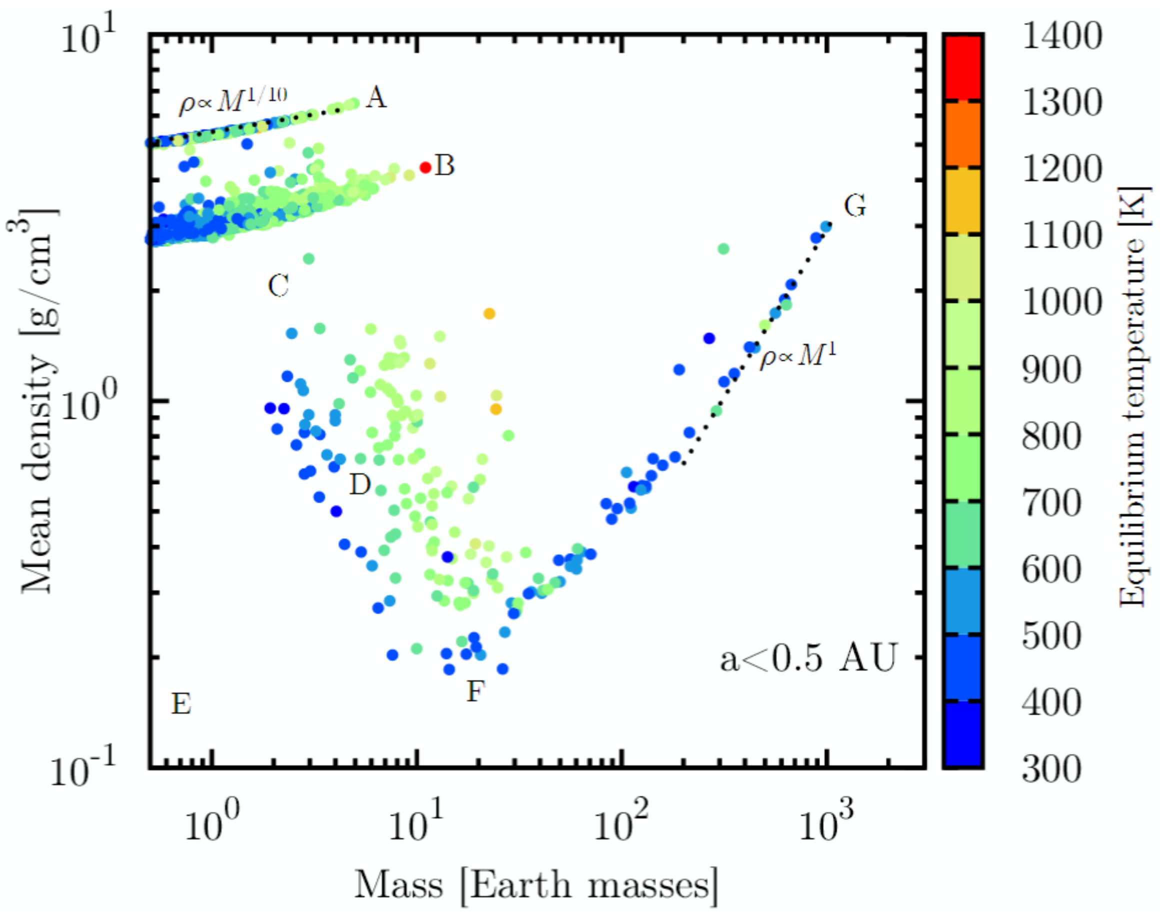
Light elements contribution



Results of modeling.

Different slopes
above and below
~100 Earth masses
are due to different
regimes of gas accretion.

Density and mass

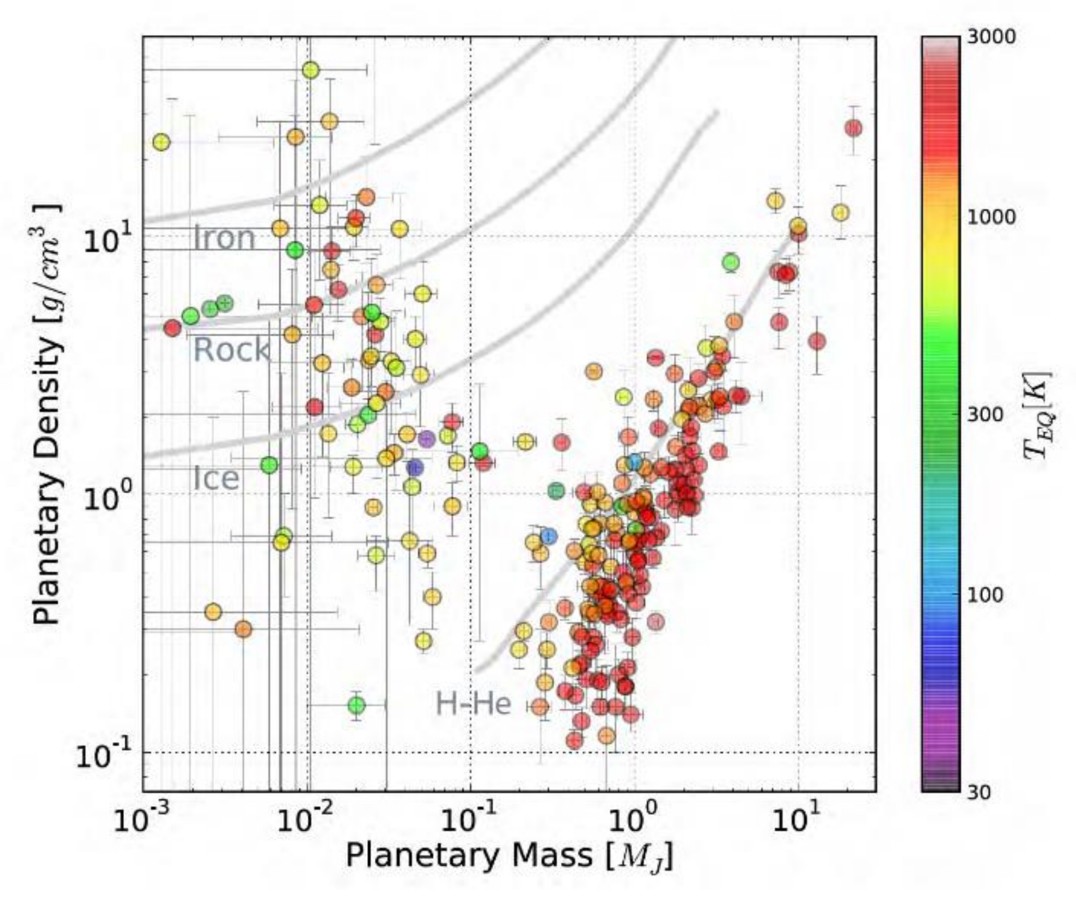


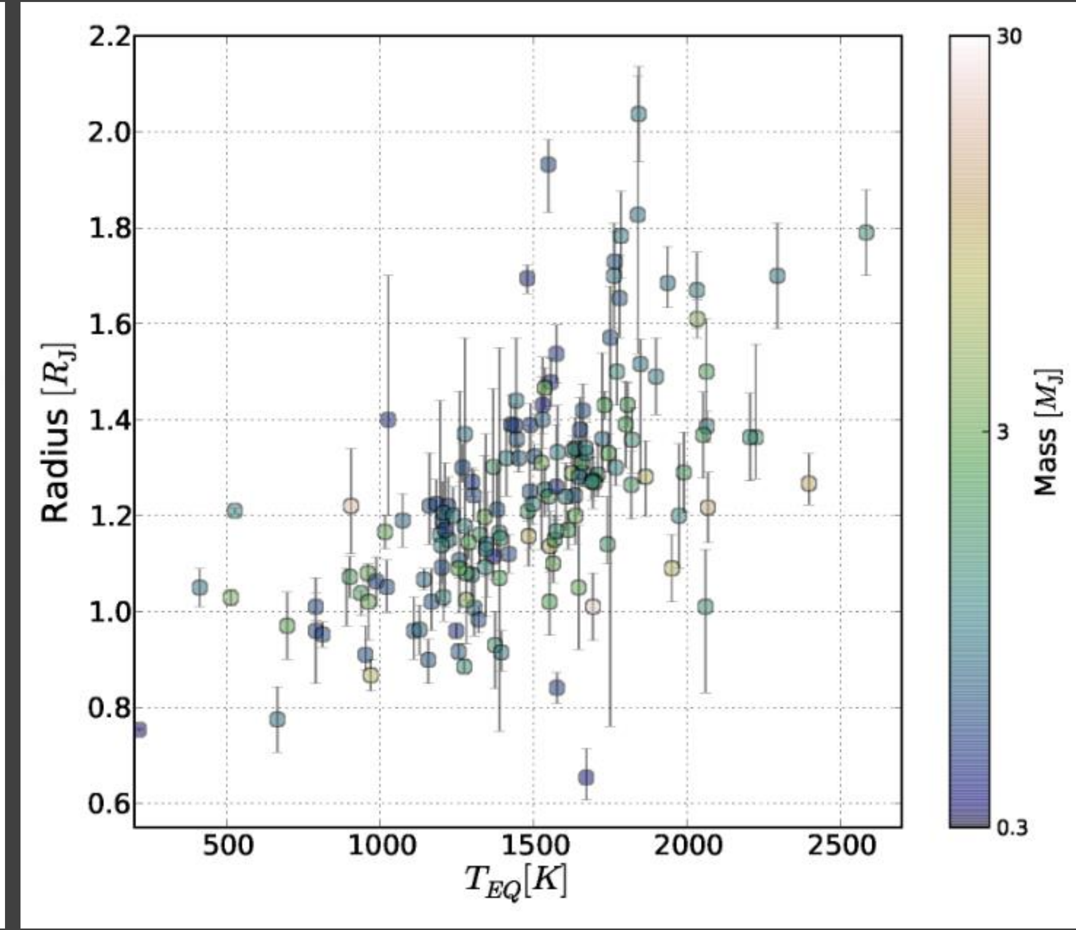
Results of modeling.

Old (5 Gyrs) planets.

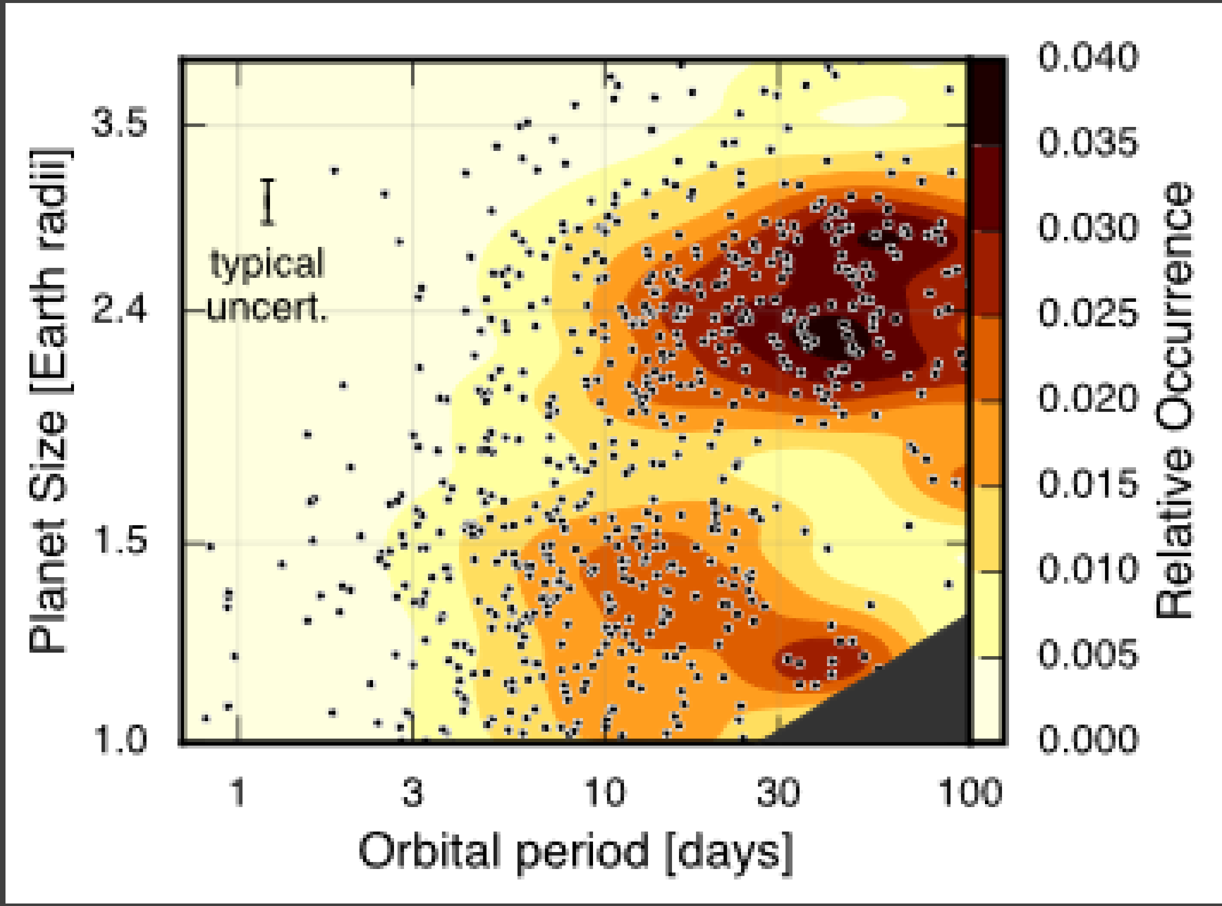
A – solid iron-stone
B – solid ice
C – evaporating
D – low-mass planets with large cores, but with significant fraction of H and He
E – forbidden zone (evaporating)
F – transition to giants
G - giants

Mass-density. Observations. Heating.





Radius valley

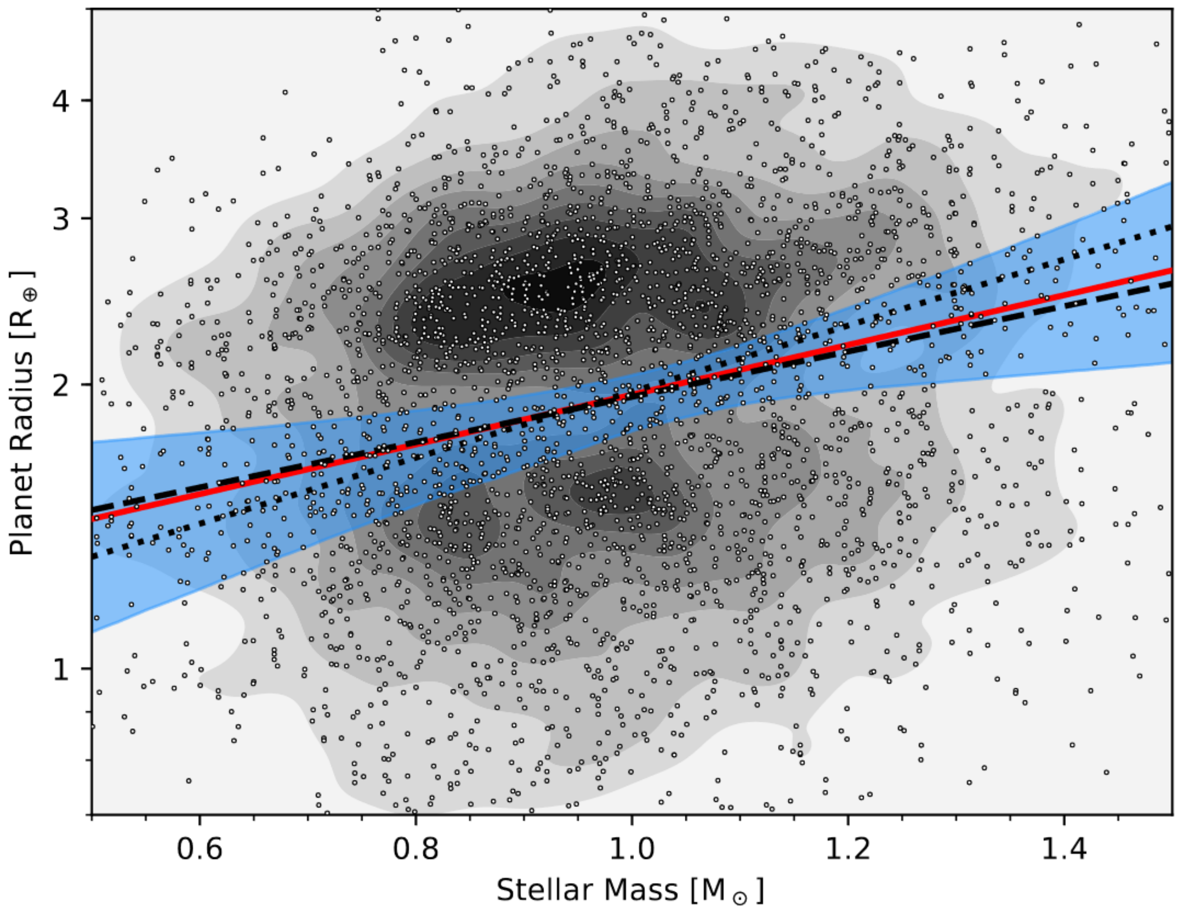


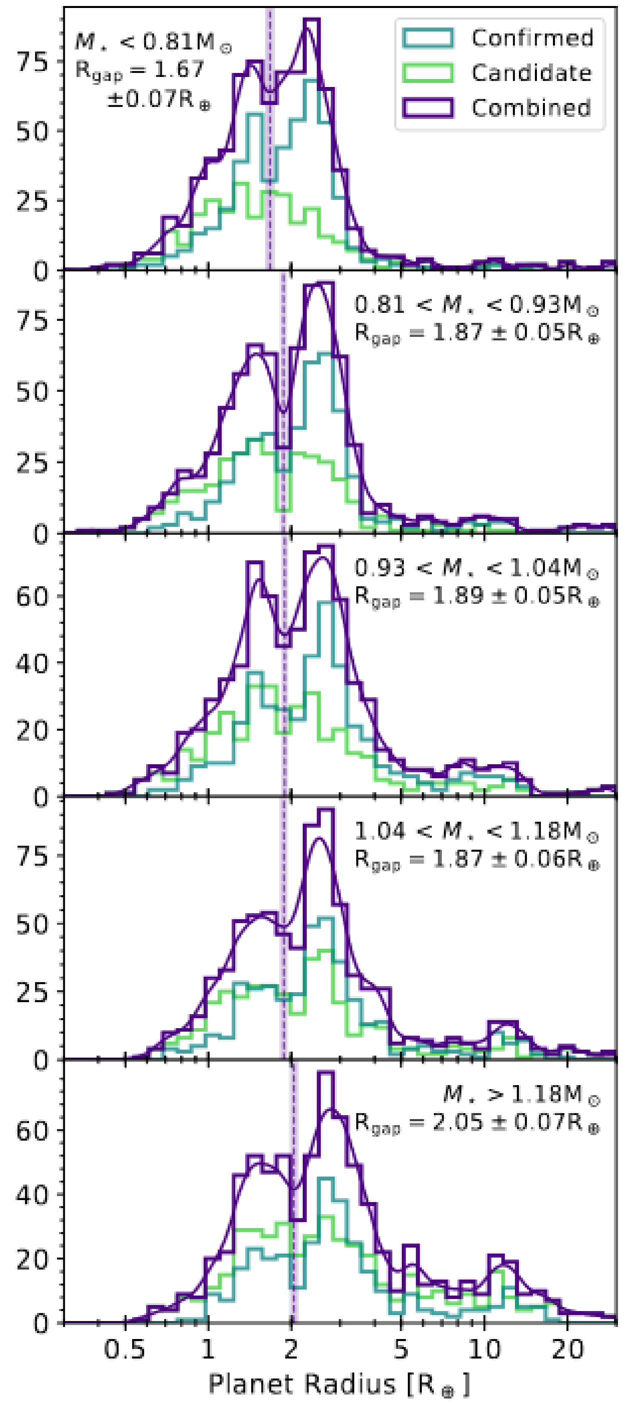
Might be related to formation and internal structure of planets.

Many models exist to explain it.

1811.03202

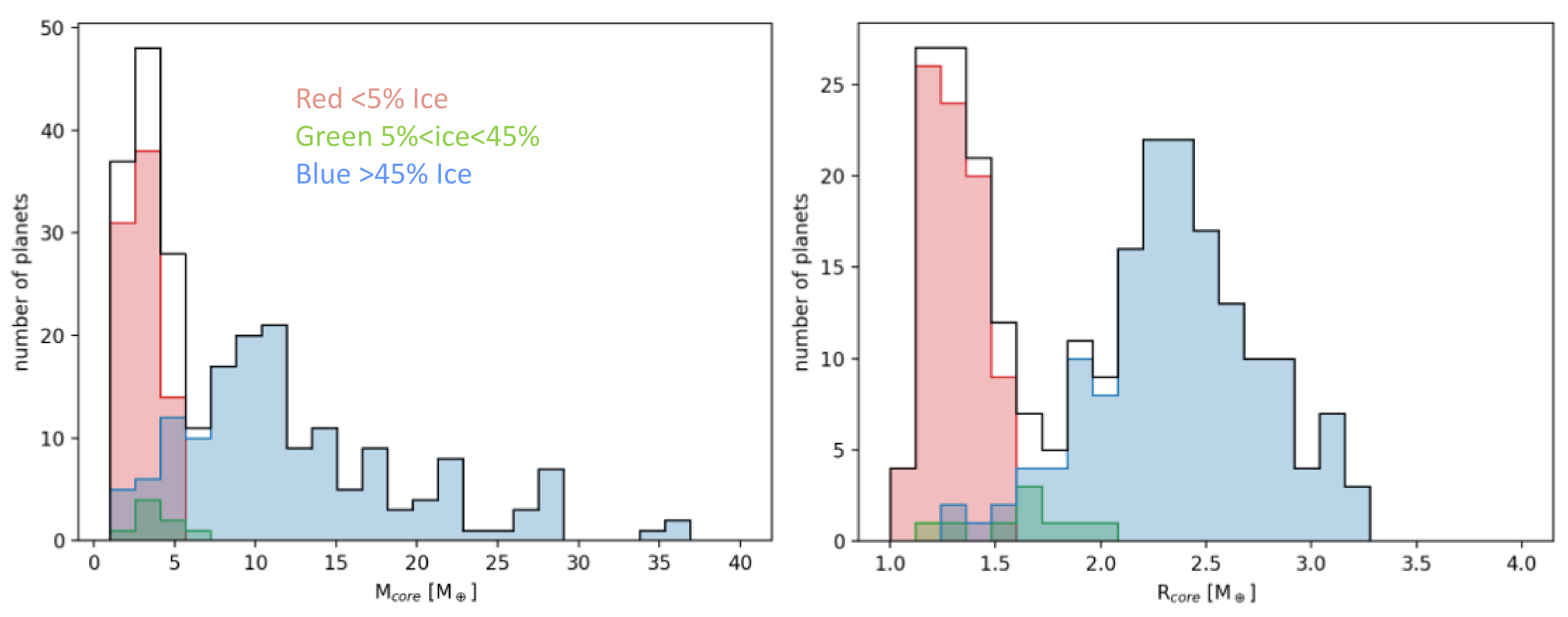
Radius valley vs. host star mass





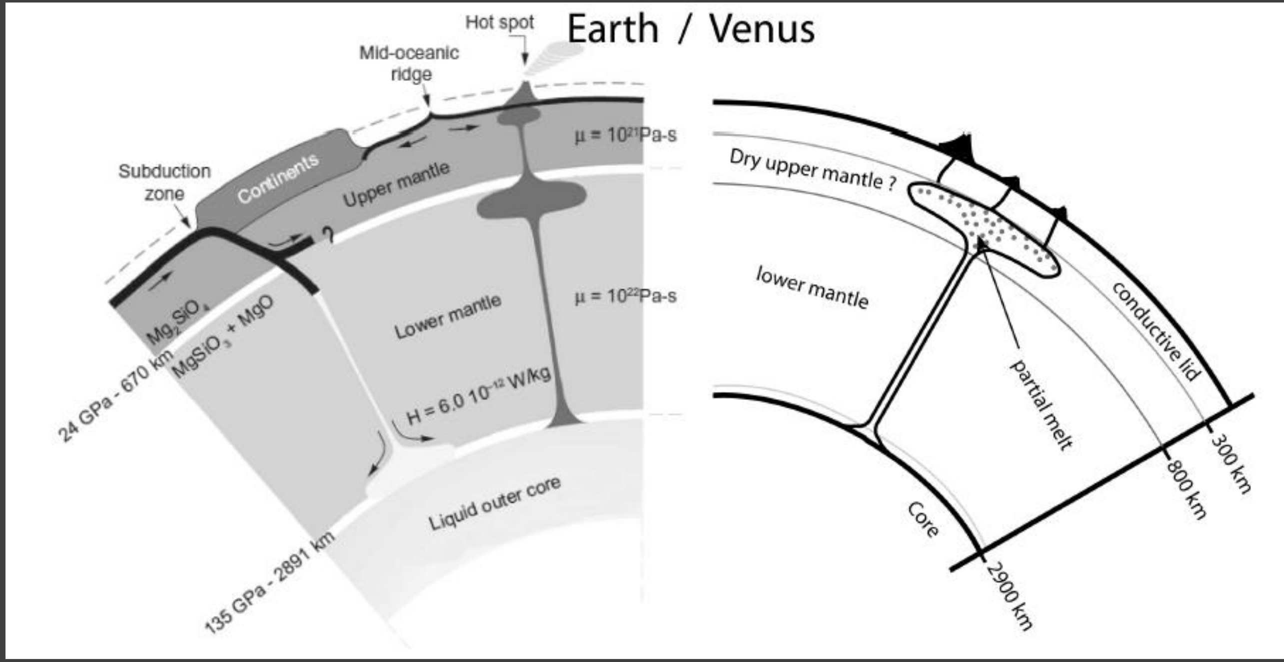
2005.1467

One explanation of the radius valley

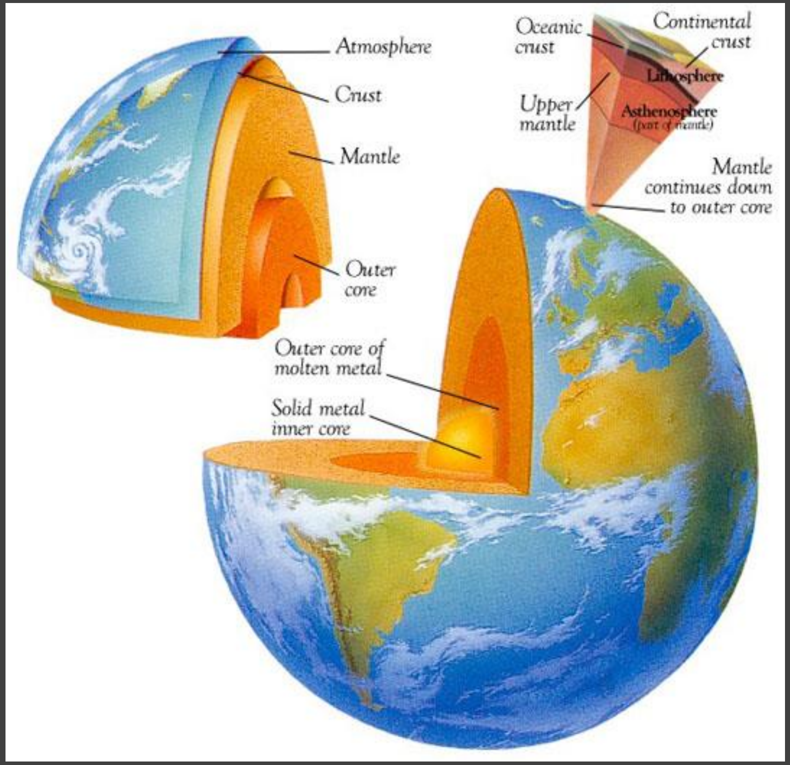


2008.05513

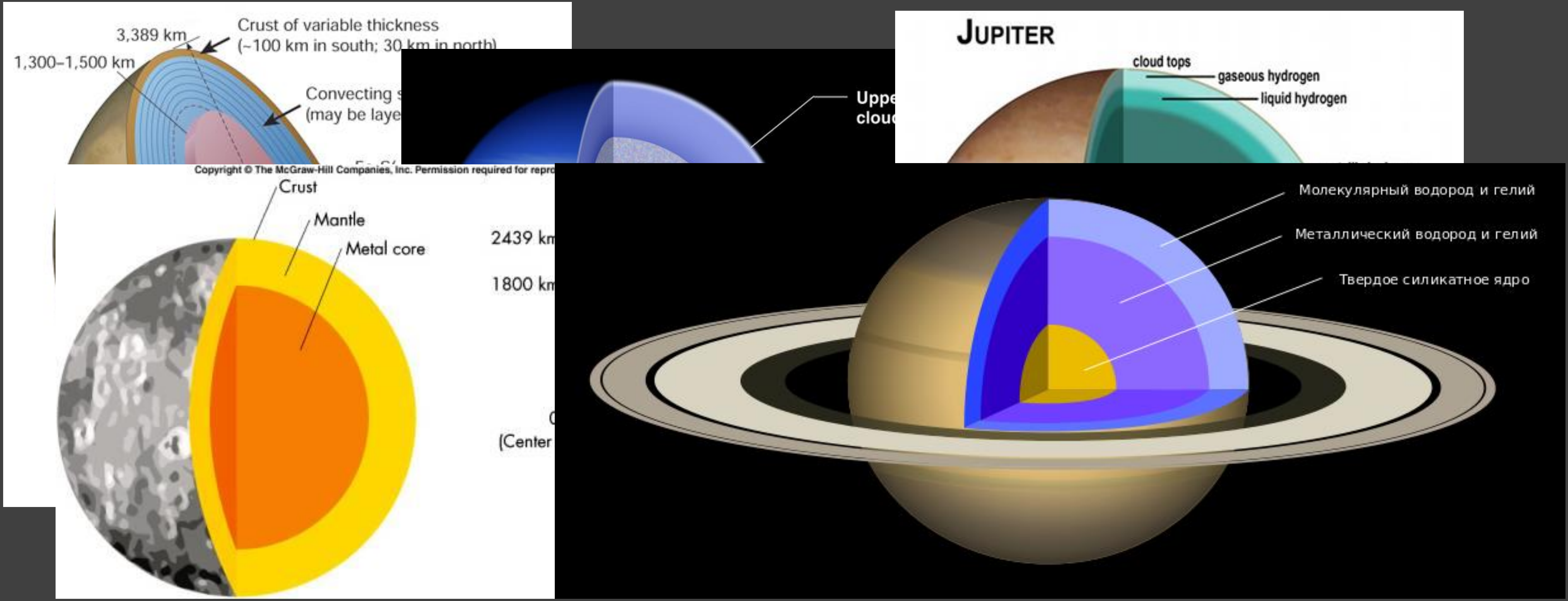
Planet structure

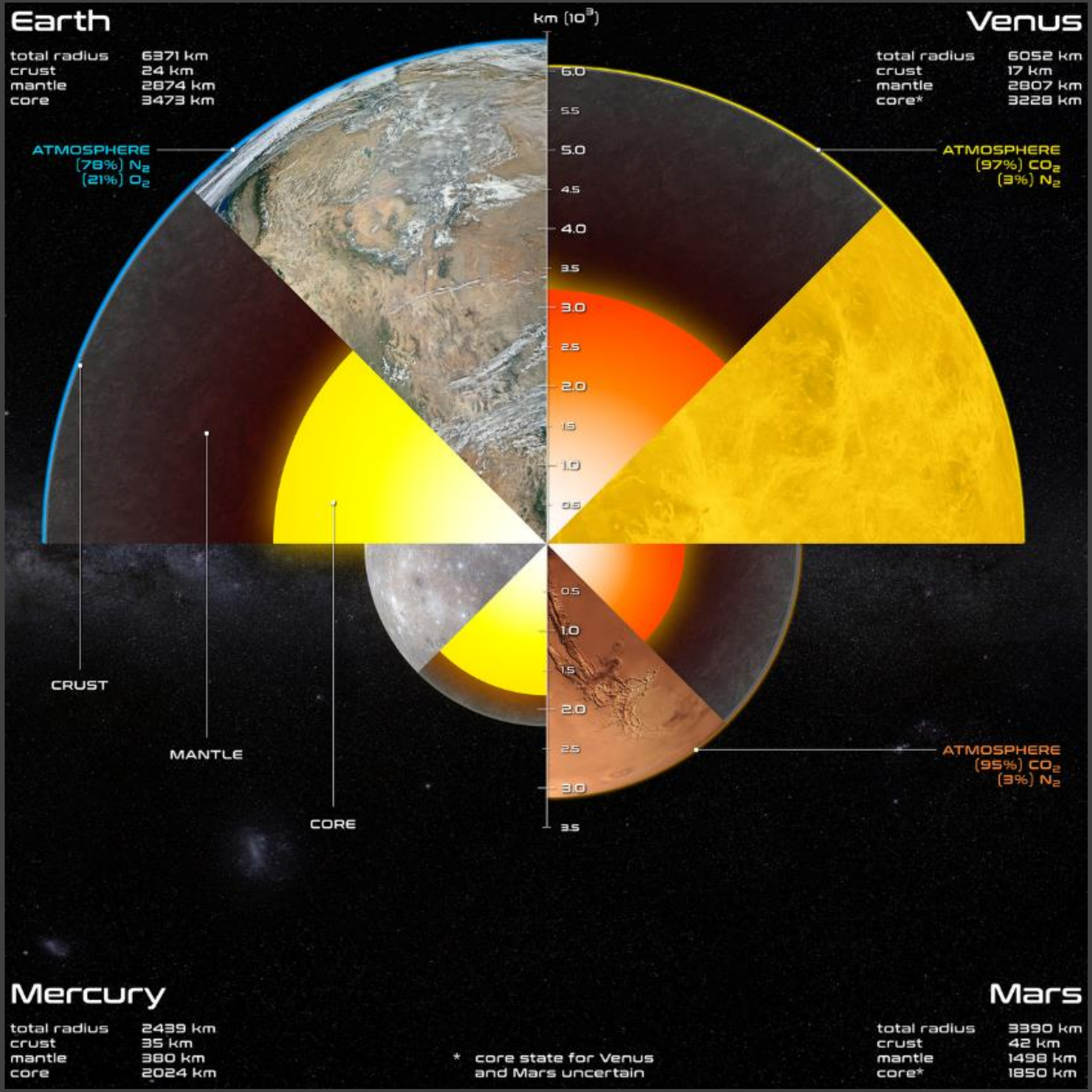


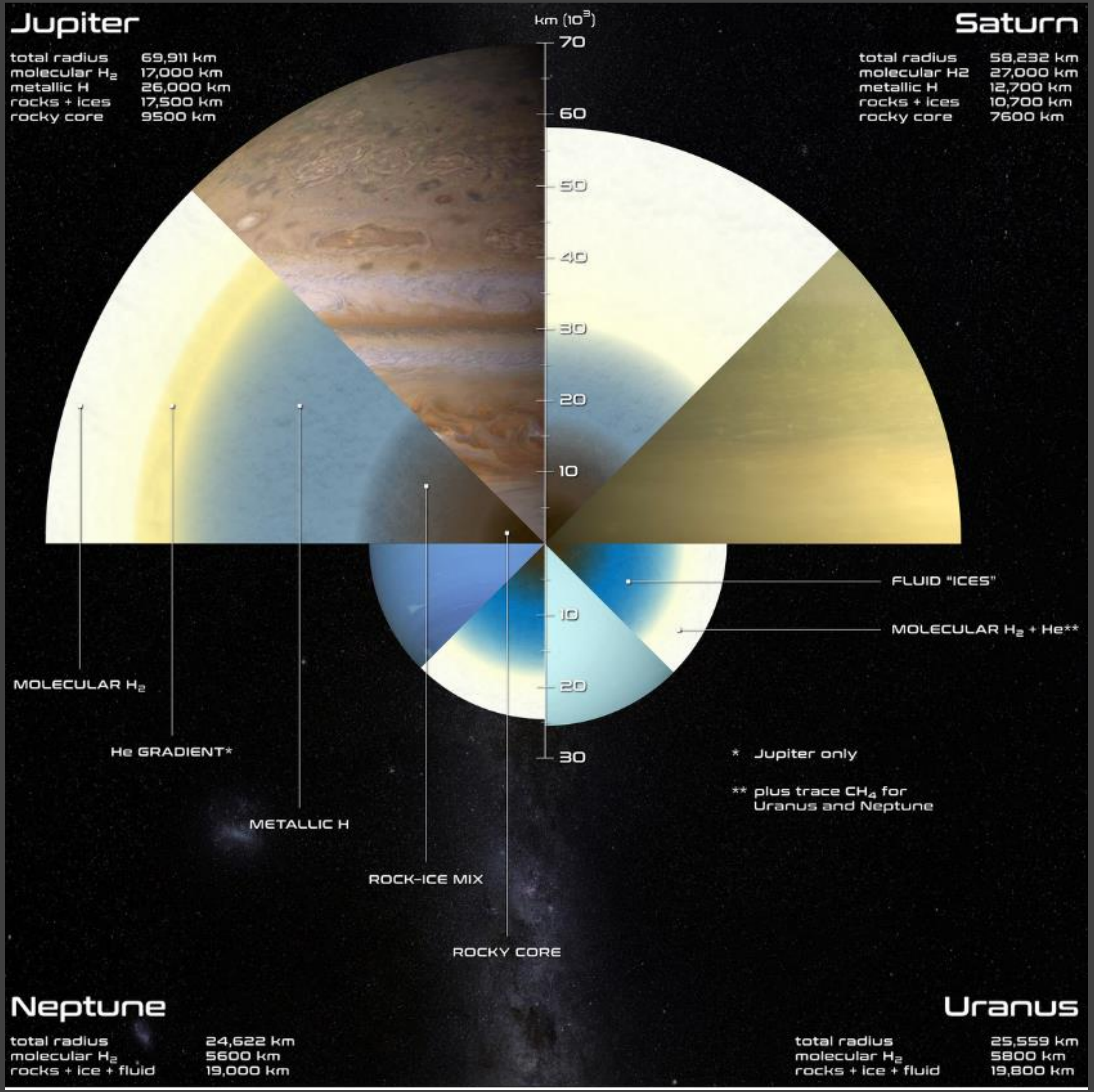
Even about the Earth we do not know many details of the internal structure. Data about other planets is very incomplete and indirect.



Structure of the Solar system planets

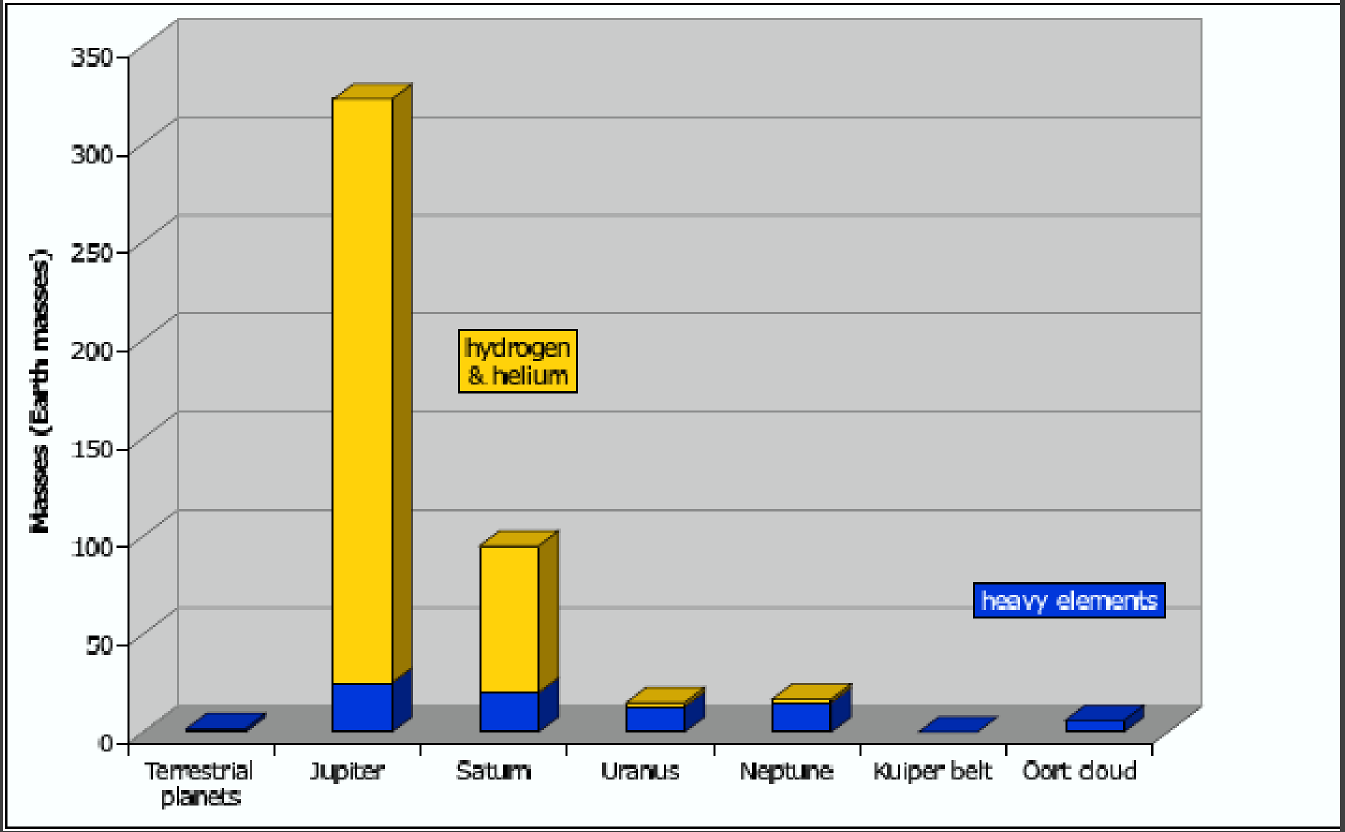



Earth
total radius 6371 km
crust 24 km
mantle 2874 km
core 3473 km
km (10^3)
Venus
total radius 6052 km
crust 17 km
mantle 2807 km
core* 3228 km
ATMOSPHERE
(78%) N2
(21%) O2
ATMOSPHERE
(97%) CO2
(3%) N2
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
CRUST
MANTLE
CORE
ATMOSPHERE
(95%) CO2
(3%) N2
Mercury
total radius 2439 km
crust 35 km
mantle 380 km
core 2024 km
* core state for Venus and Mars uncertain
Mars
total radius 3390 km
crust 42 km
mantle 1498 km
core* 1850 km


Jupiter
total radius 69,911 km
molecular H2 17,000 km
metallic H 26,000 km
rocks + ices 17,500 km
rocky core 9500 km
km (10^3)
70
60
50
40
30
20
10
Saturn
total radius 58,232 km
molecular H2 27,000 km
metallic H 12,700 km
rocks + ices 10,700 km
rocky core 7600 km
FLUID "ICES"
MOLECULAR H2 + He**
MOLECULAR H2
He GRADIENT*
METALLIC H
ROCK-ICE MIX
ROCKY CORE
* Jupiter only
** plus trace CH4 for Uranus and Neptune
Neptune
total radius 24,622 km
molecular H2 5600 km
rocks + ice + fluid 19,000 km
Uranus
total radius 25,559 km
molecular H2 5800 km
rocks + ice + fluid 19,800 km

2012.11628

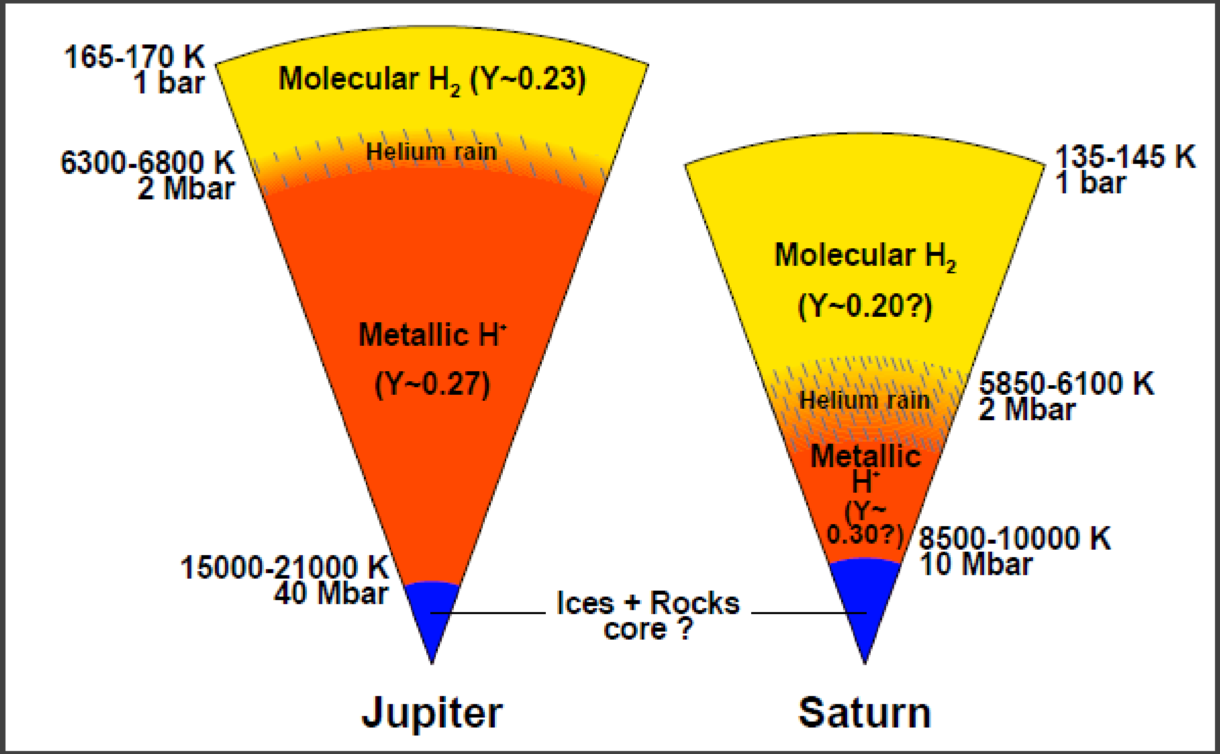
What Solar system planets are made of?



Except Jupiter and Saturn planets are mostly made of elements heavier than helium.

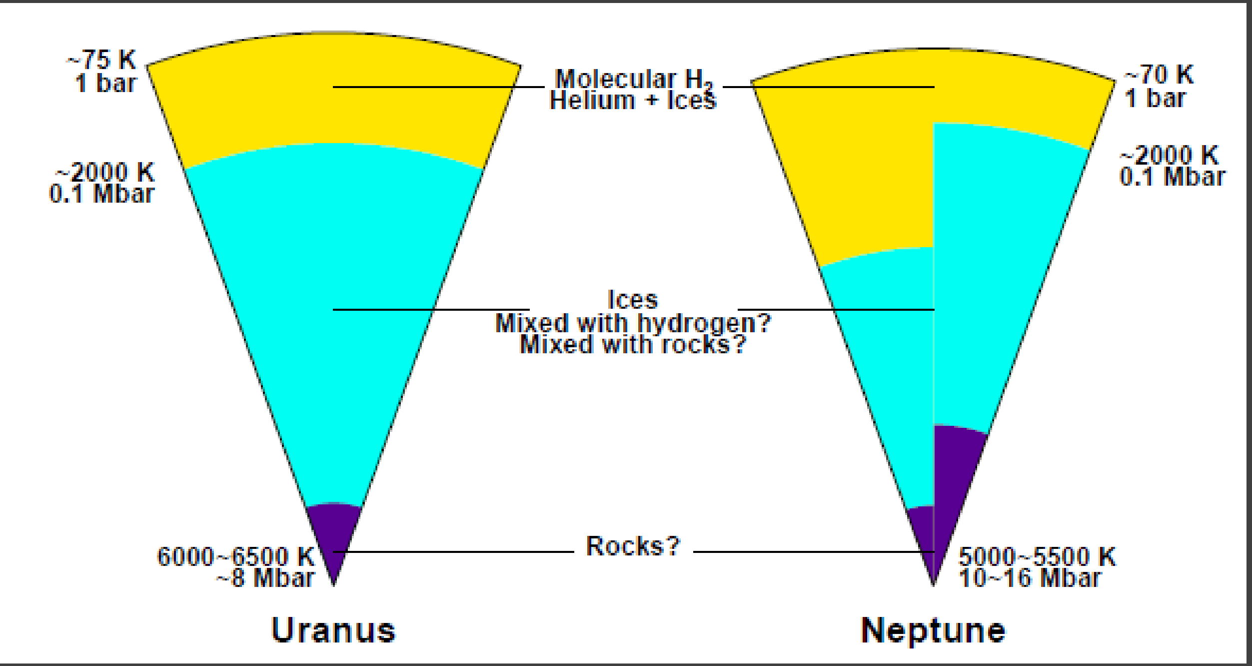
Even icy-giants – Neptune and Uranus, - are mainly made not of H+He.

Structure of giant planets



See 1812.07436 for a recent detailed review.

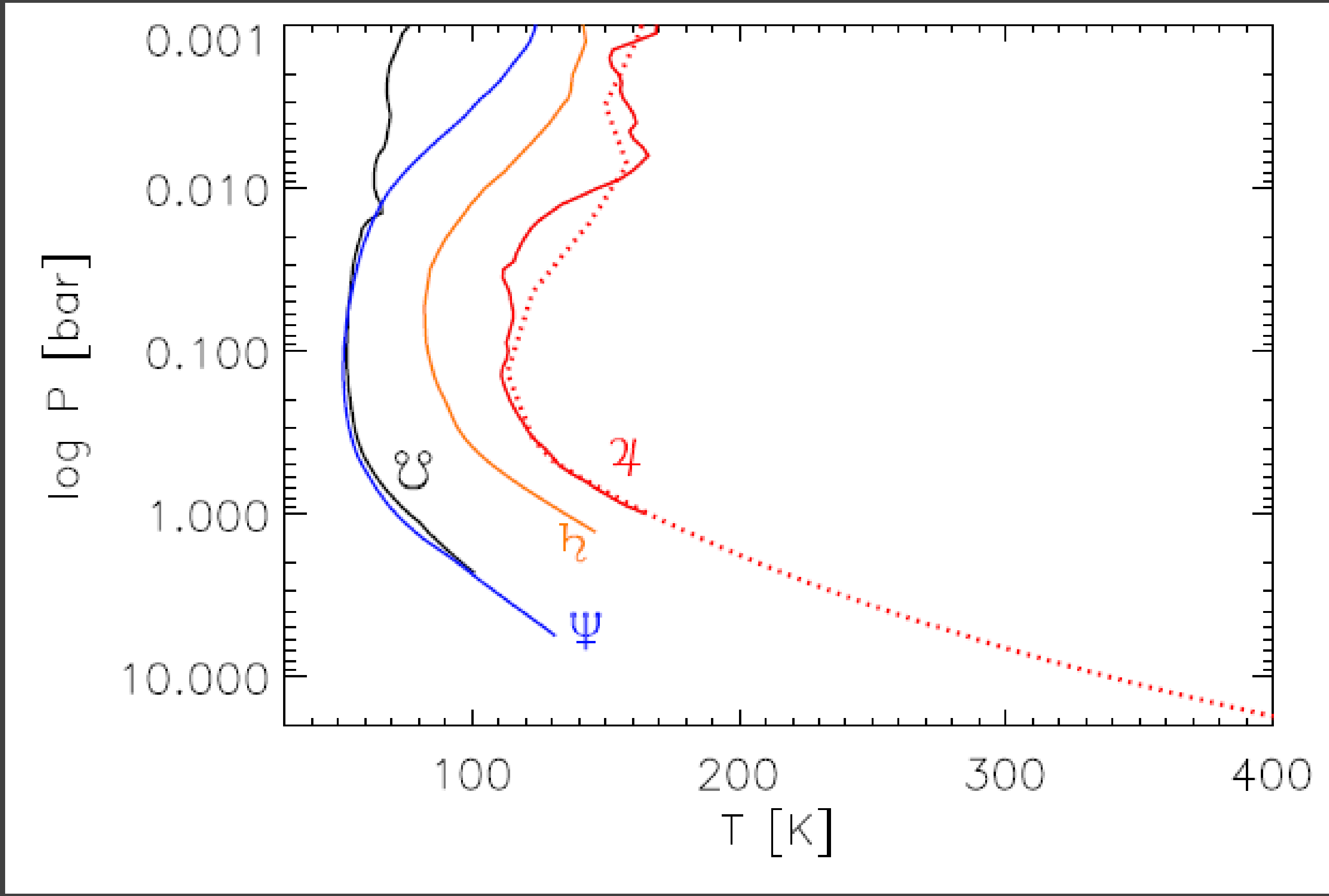
Except Uranus giant planets might not have solid cores.
However, there cores are made of heavy elements.
And so often they are called made of rocks.



1405.3752

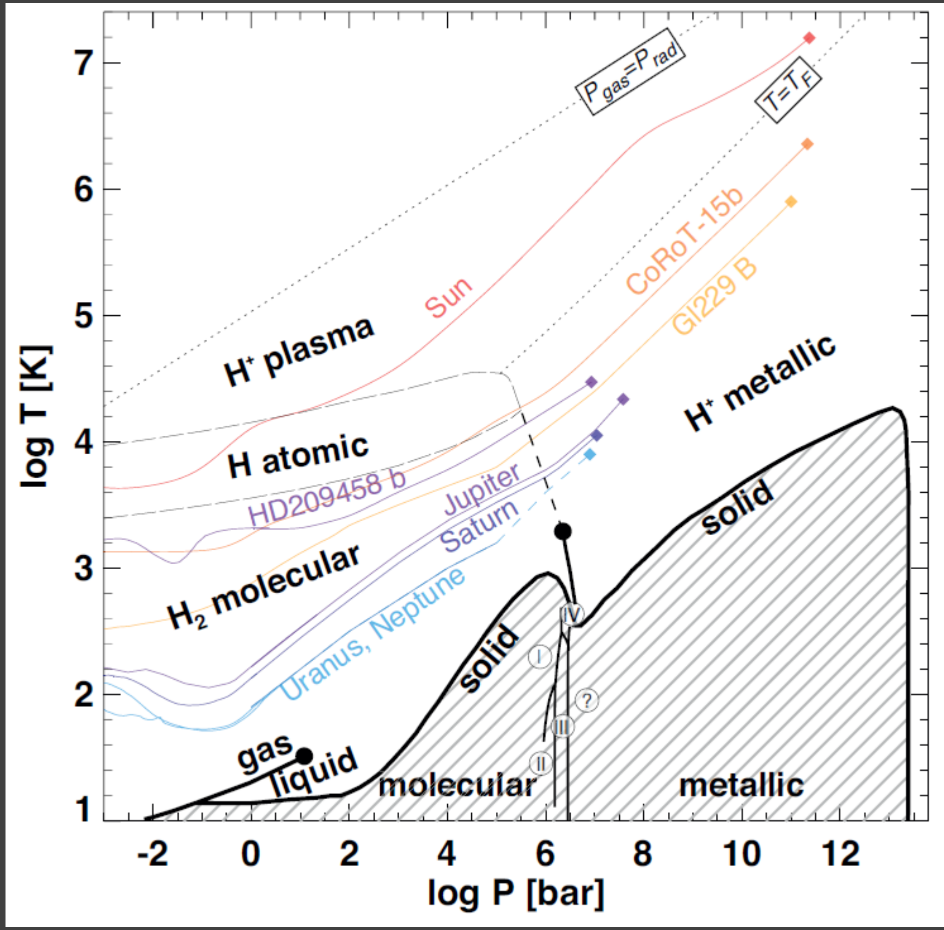
About structure and formation of Uranus and Neptune see 1909.04891, 2007.10783

Temperature and pressure in atmospheres of giants



For Jupiter direct data are available due to Galileo probe measurements.

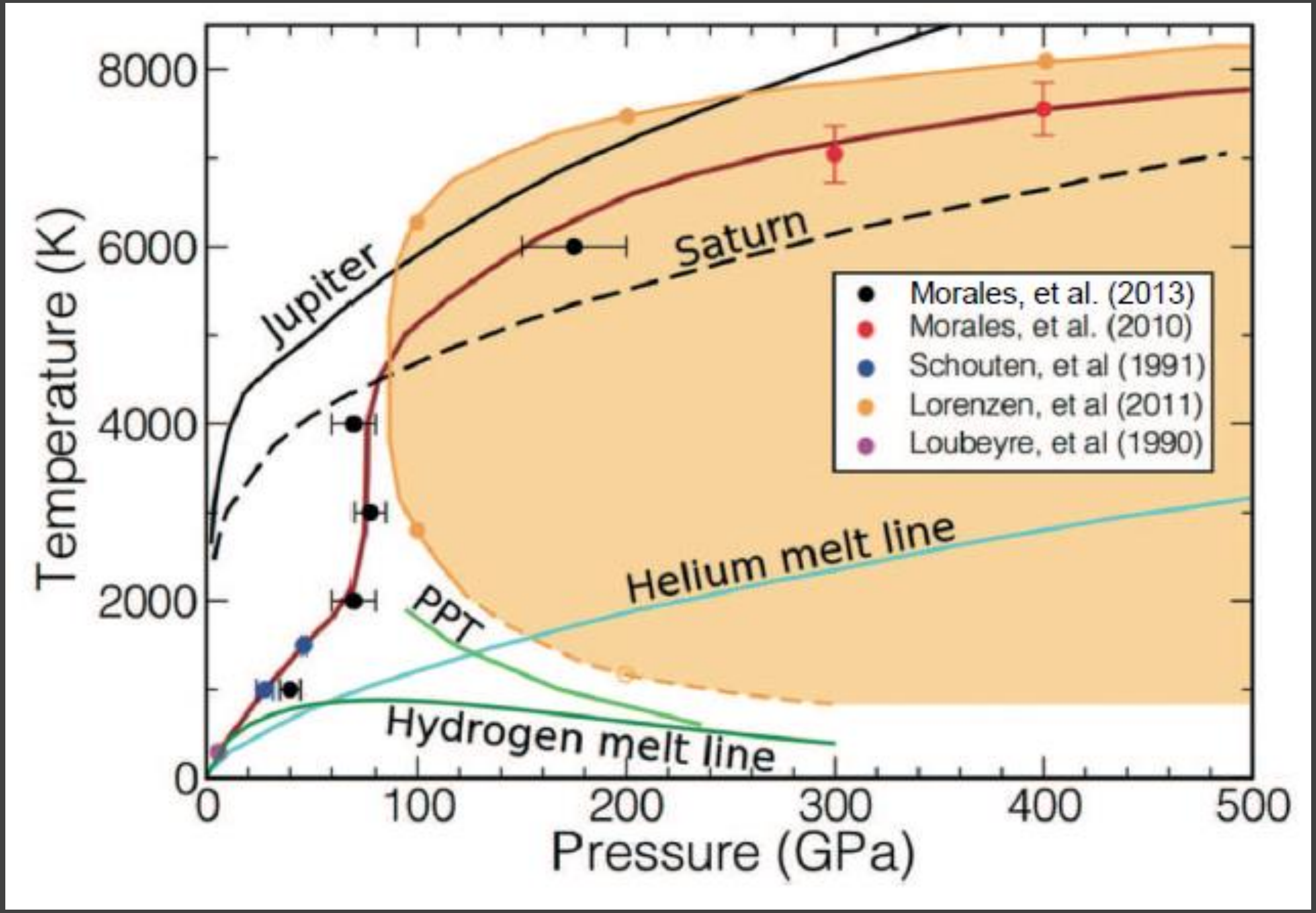
Hydrogene equation of state



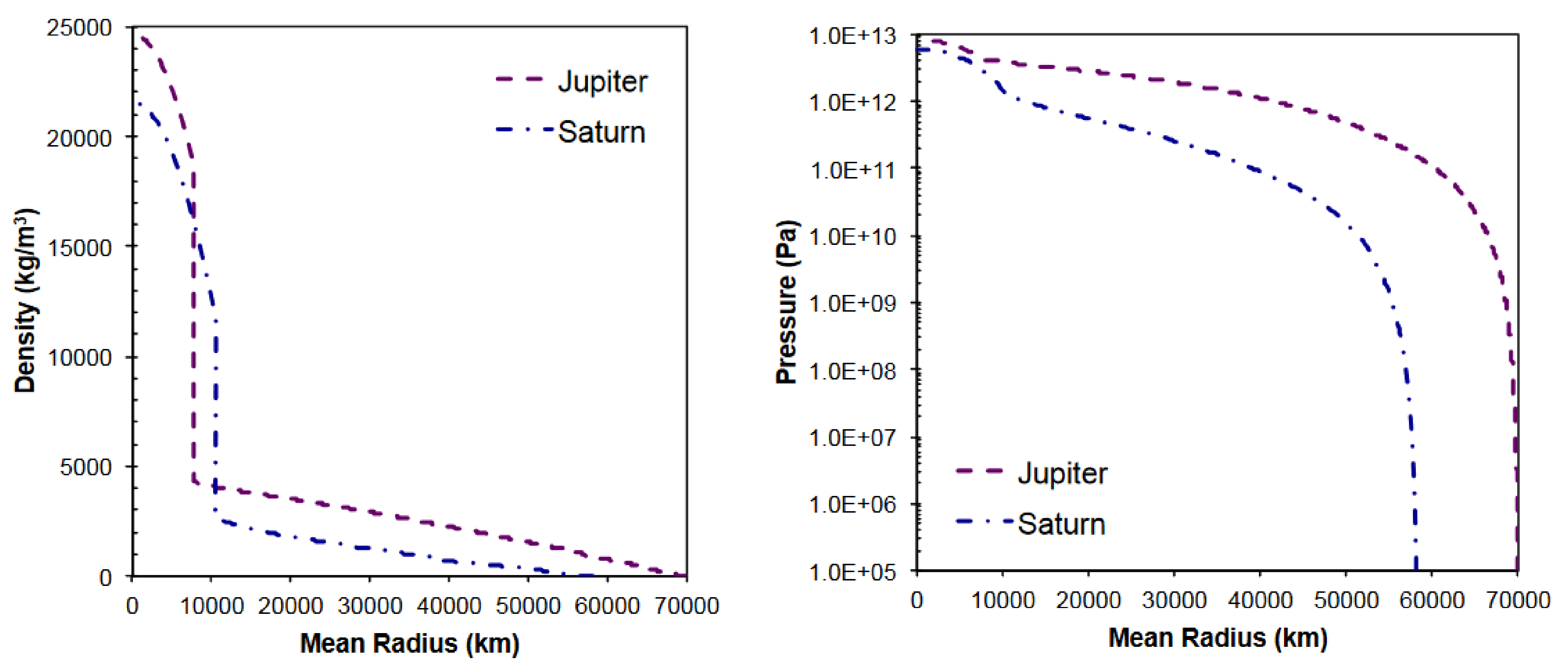
Still, there are important uncertainties even for the hydrogen equation of state.

Some regimes have been never measured in laboratories.

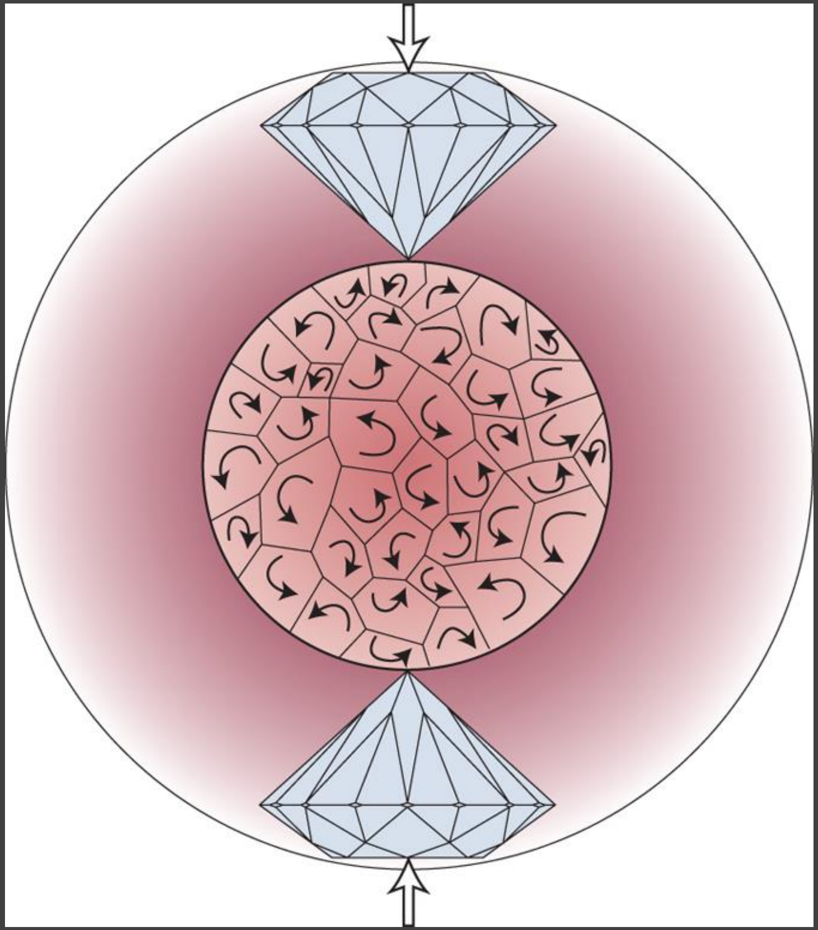
Hydrogen plus helium mixture



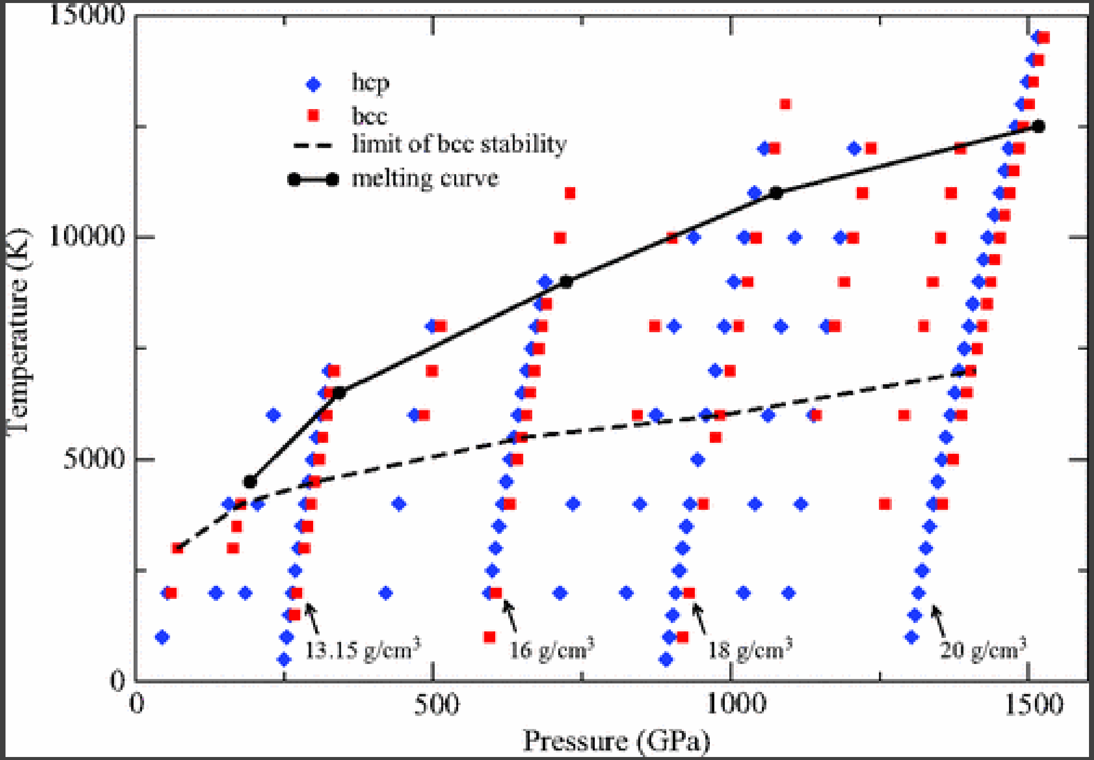
Density and pressure



Diamond anvil cells



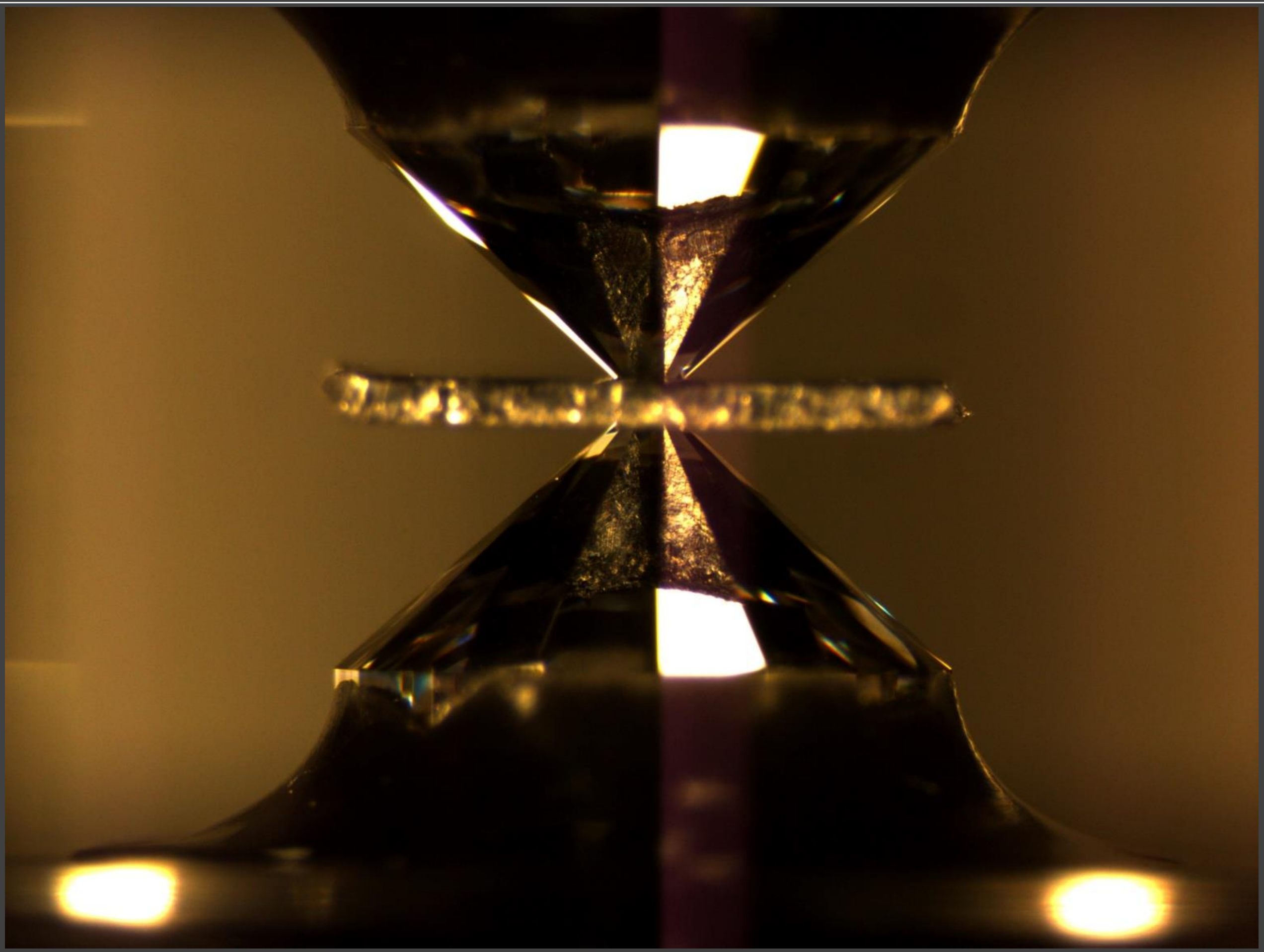
Diamond cells are used to reach high pressures in laboratory experiments. However, it is not enough, and in many cases we have to base only on numerical models.



Merkel (2013)

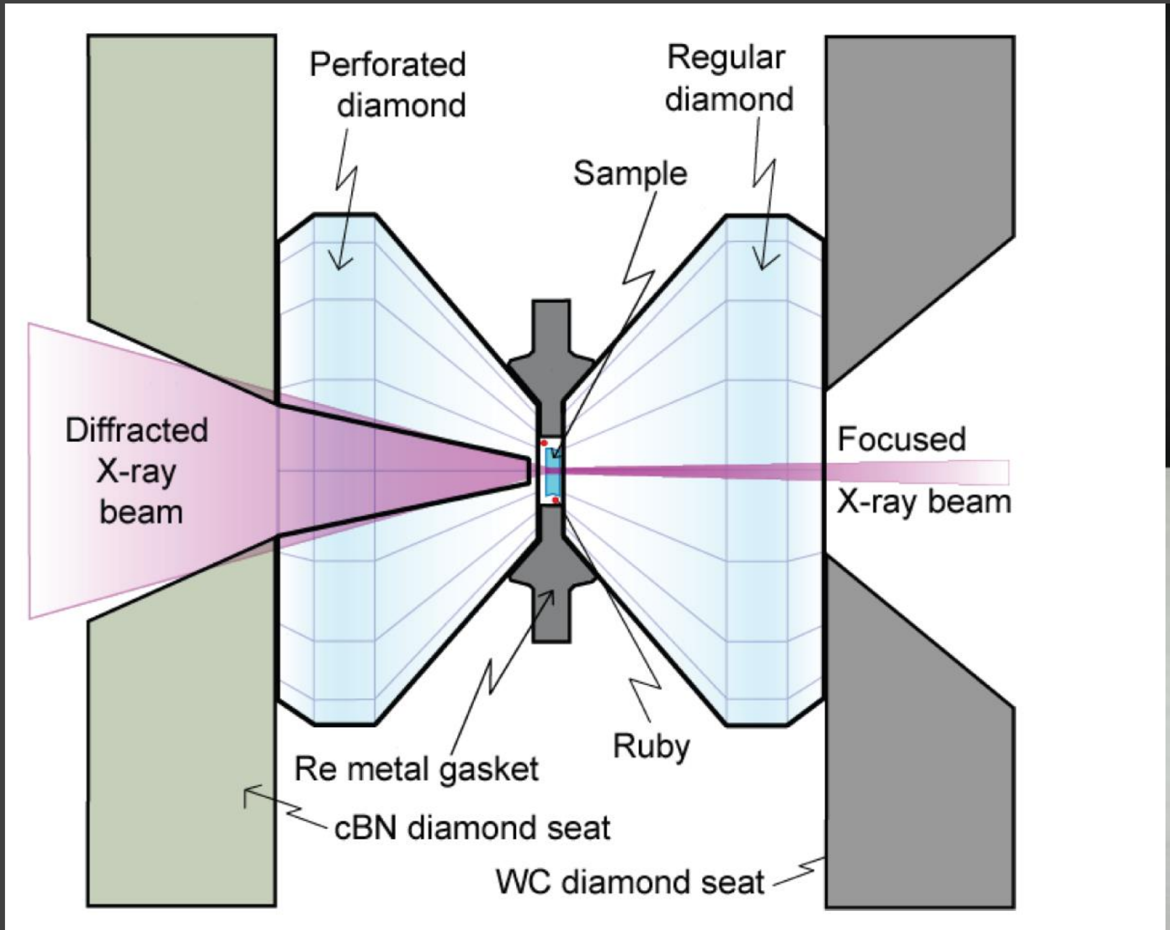
Bouchet et al. (2013)

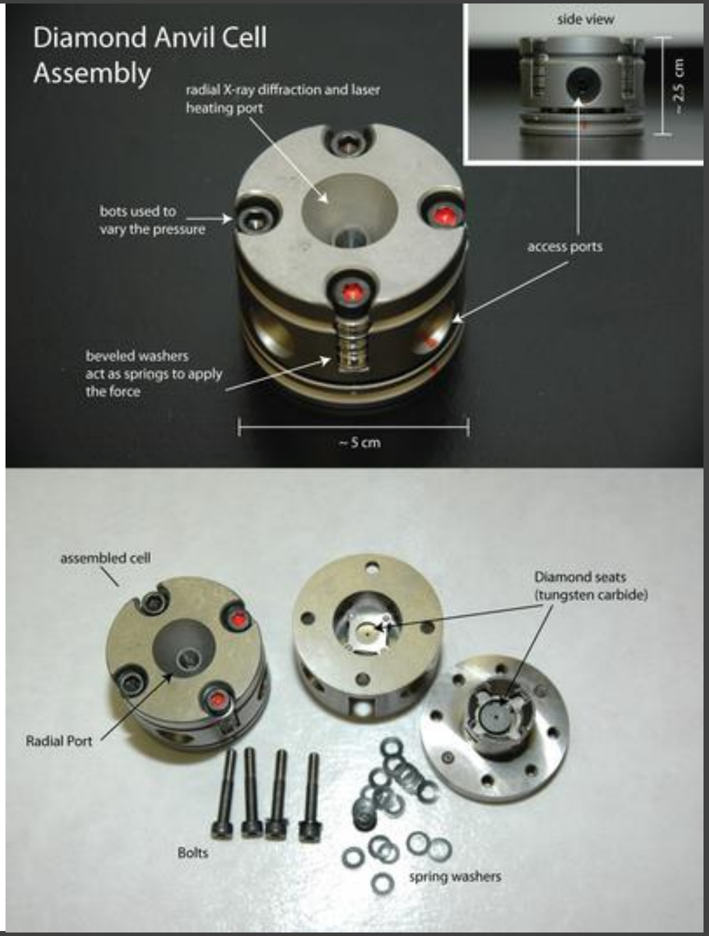
Diamond cell



http://serc.carleton.edu/NAGTWorkshops/mineralogy/mineral_physics/diamond_anvil.html

Scheme of the experiment

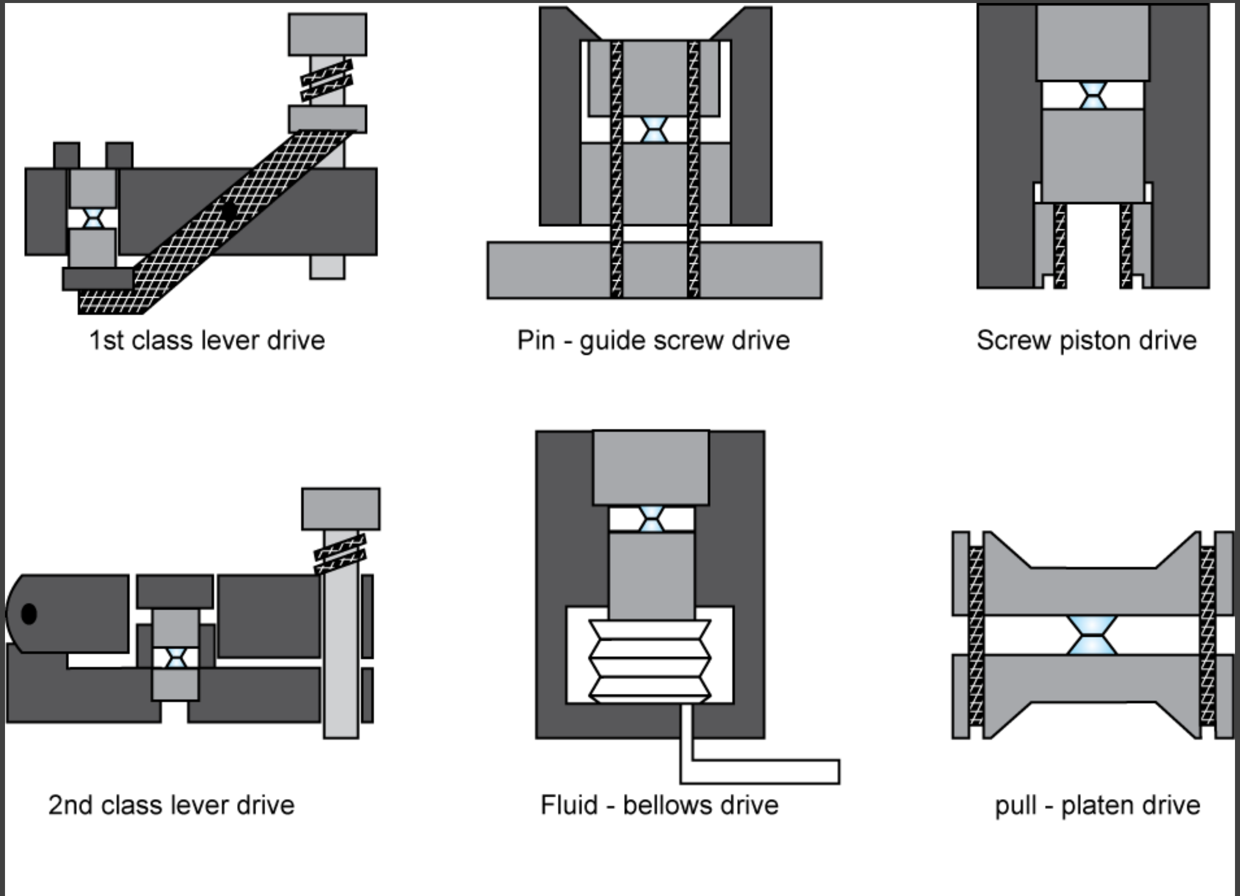




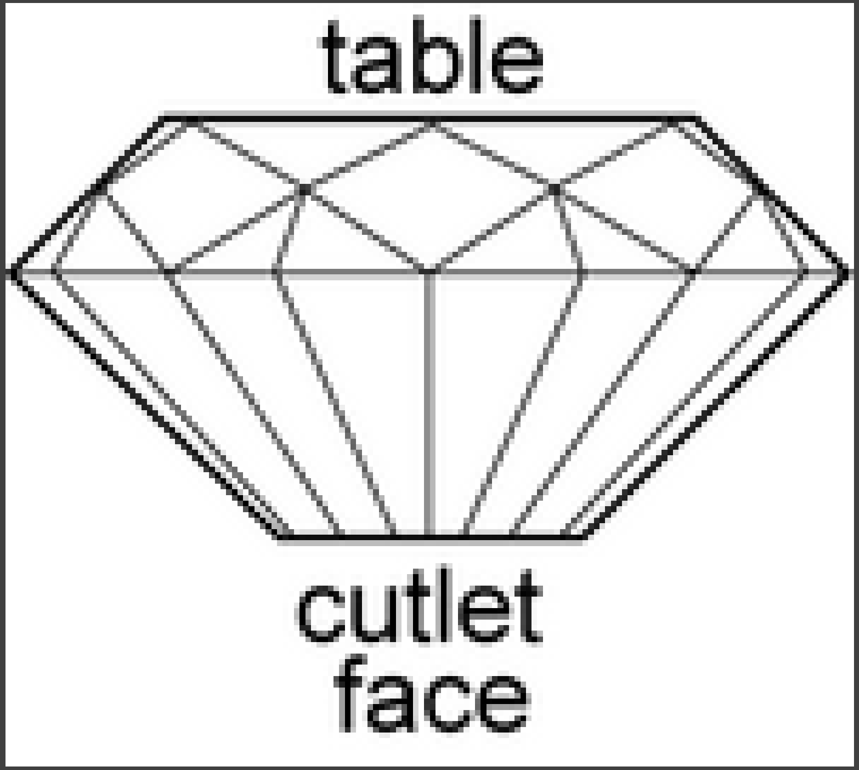
http://serc.carleton.edu/NAGTWorkshops/mineralogy/mineral_physics/diamond_anvil.html

How to press?

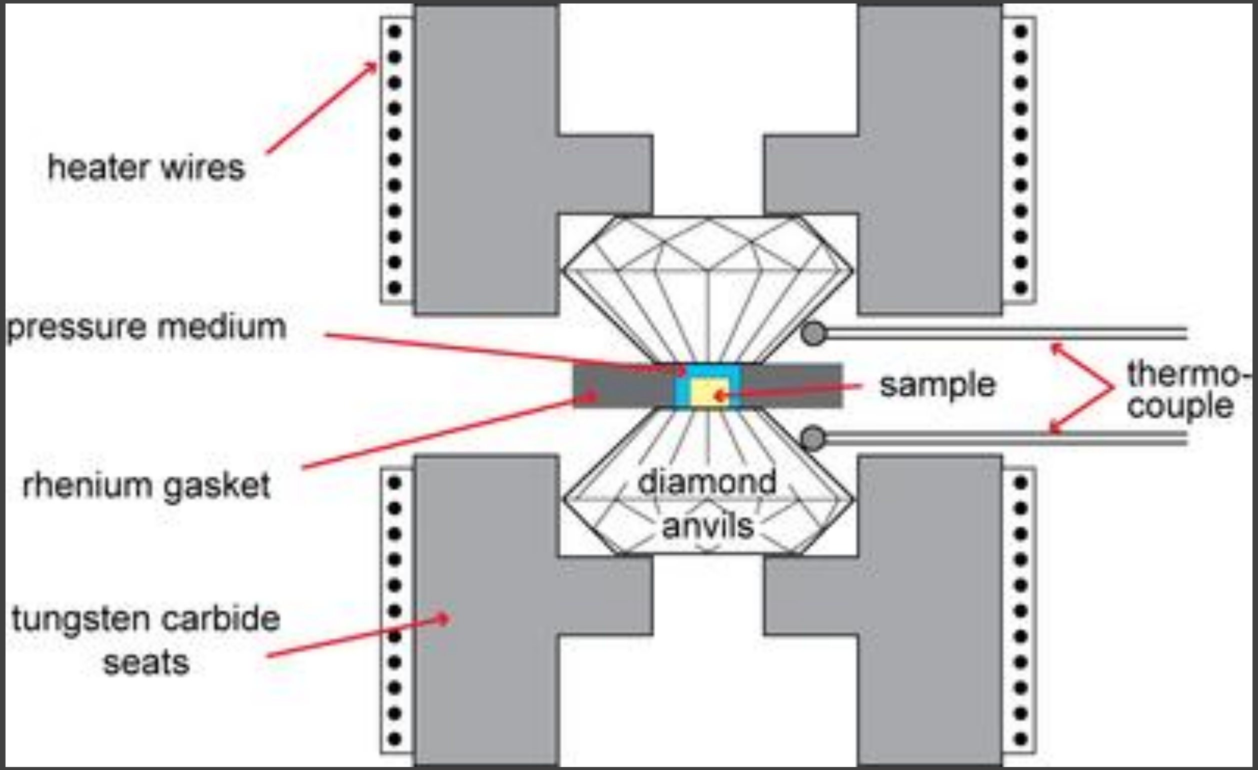
http://serc.carleton.edu/NAGTWorkshops/mineralogy/mineral_physics/diamond_anvil.html



six basis ways of providing force in the DAC (Bassett, 1979)

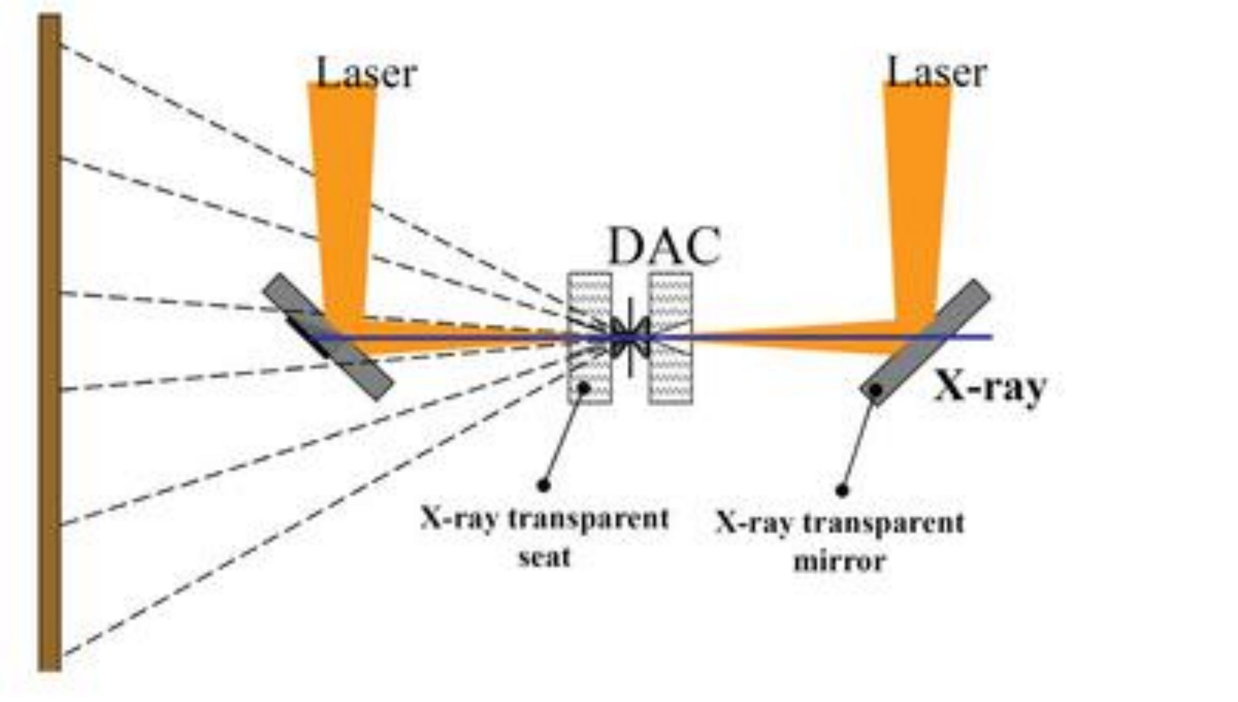


How to heat the matter



Up to 1300K

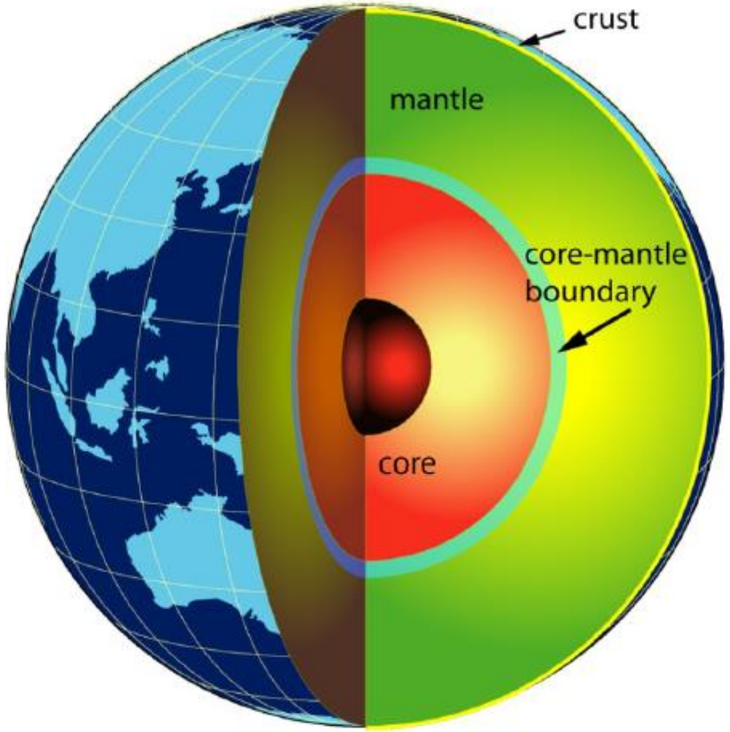
Electric current (for lower temperatures)
or laser (for higher temperature).

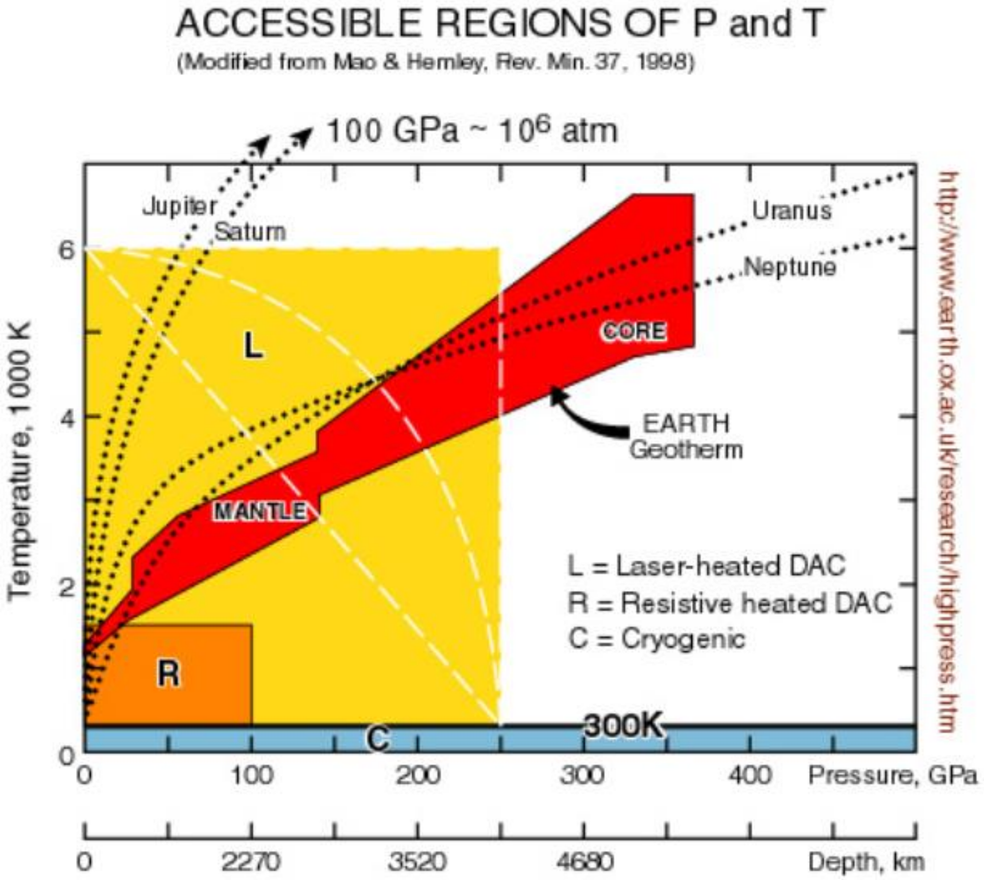


Above 1300K

http://serc.carleton.edu/NAGTWorkshops/mineralogy/mineral_physics/diamond_anvil.html

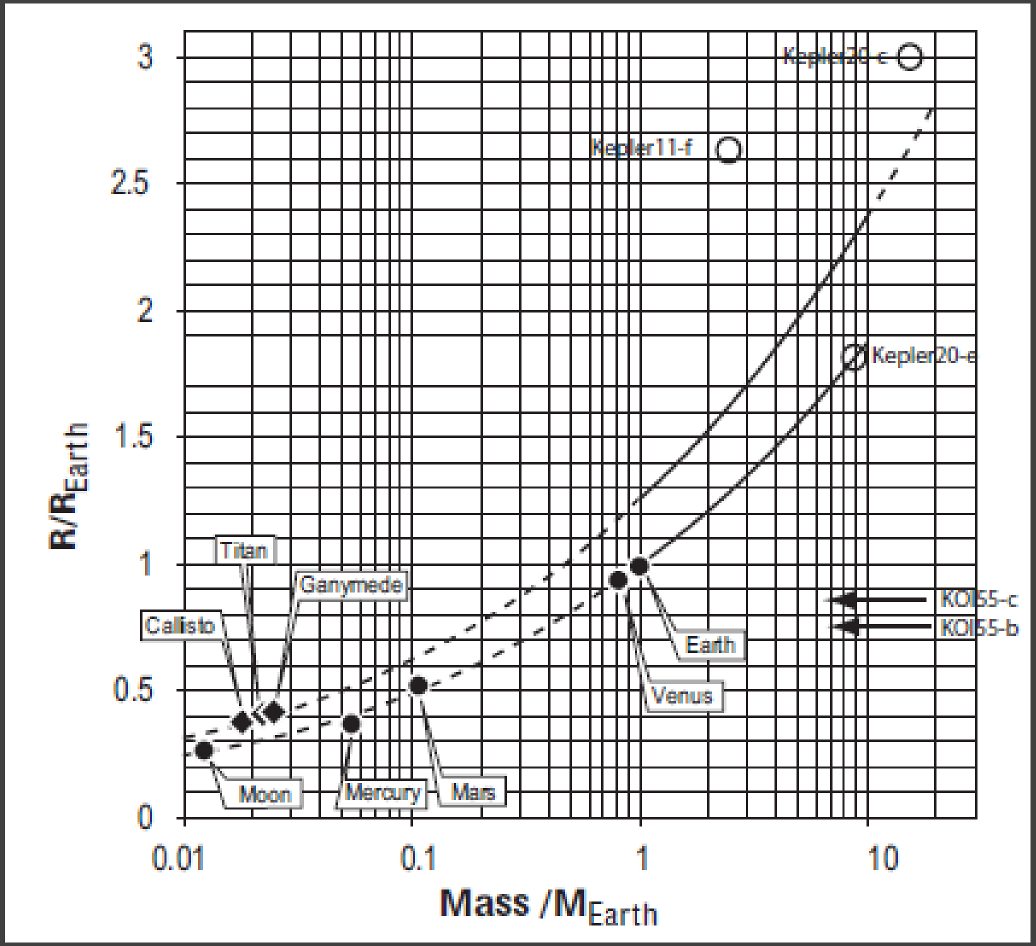
Comparison with conditions in the Earth





http://mini.physics.sunysb.edu/~pstephens/downloadable/ehm_dac.pdf

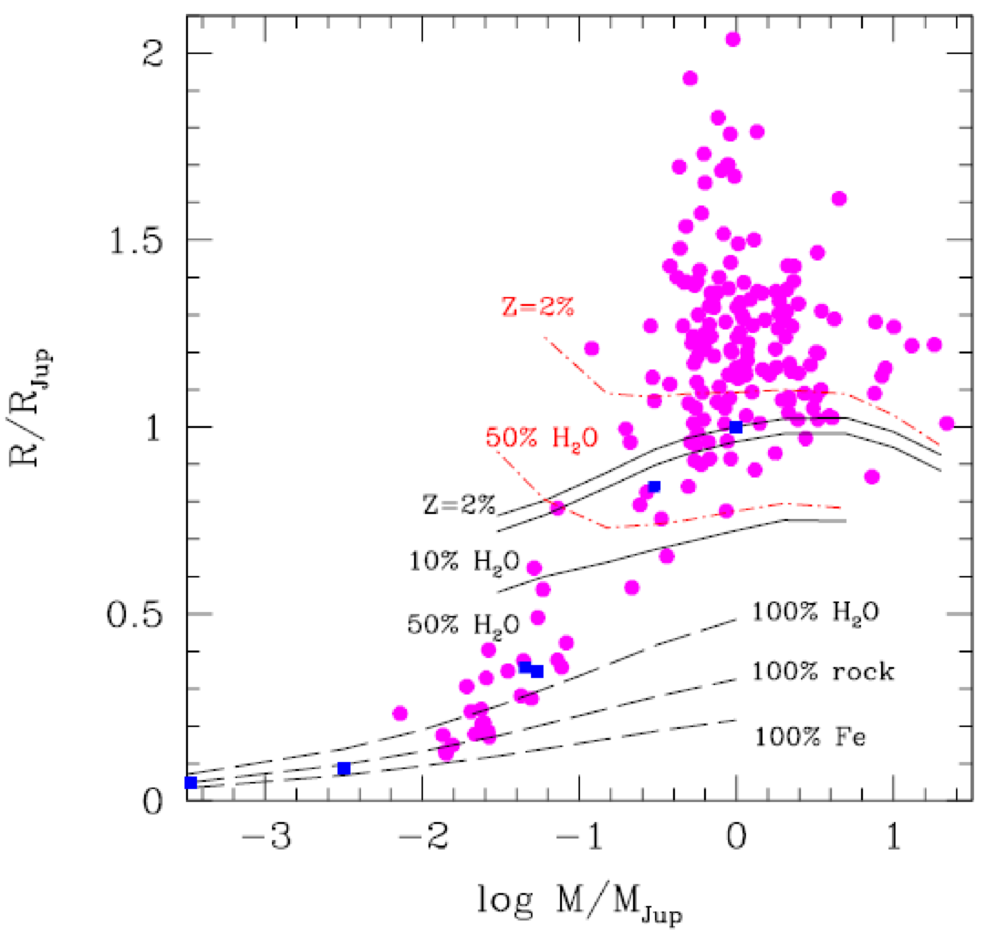
Mass-radius models for planets



Relatively simple model
based on just 8 key elements.

Good results for Solar system planets.

Mass-radius diagram for exoplanets



Planet radius, of course, depends on its composition.

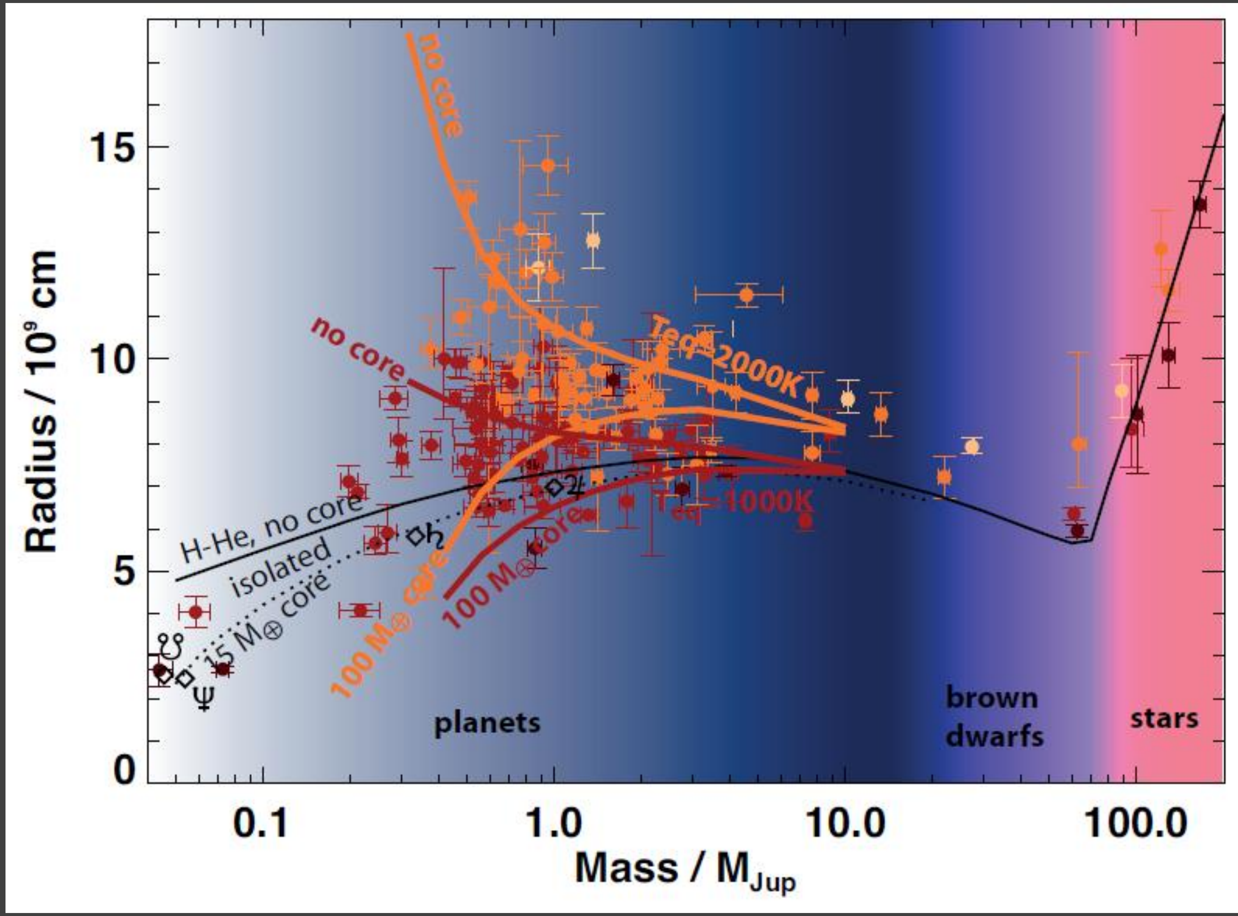
Light planets typically do not have extended gas envelopes.

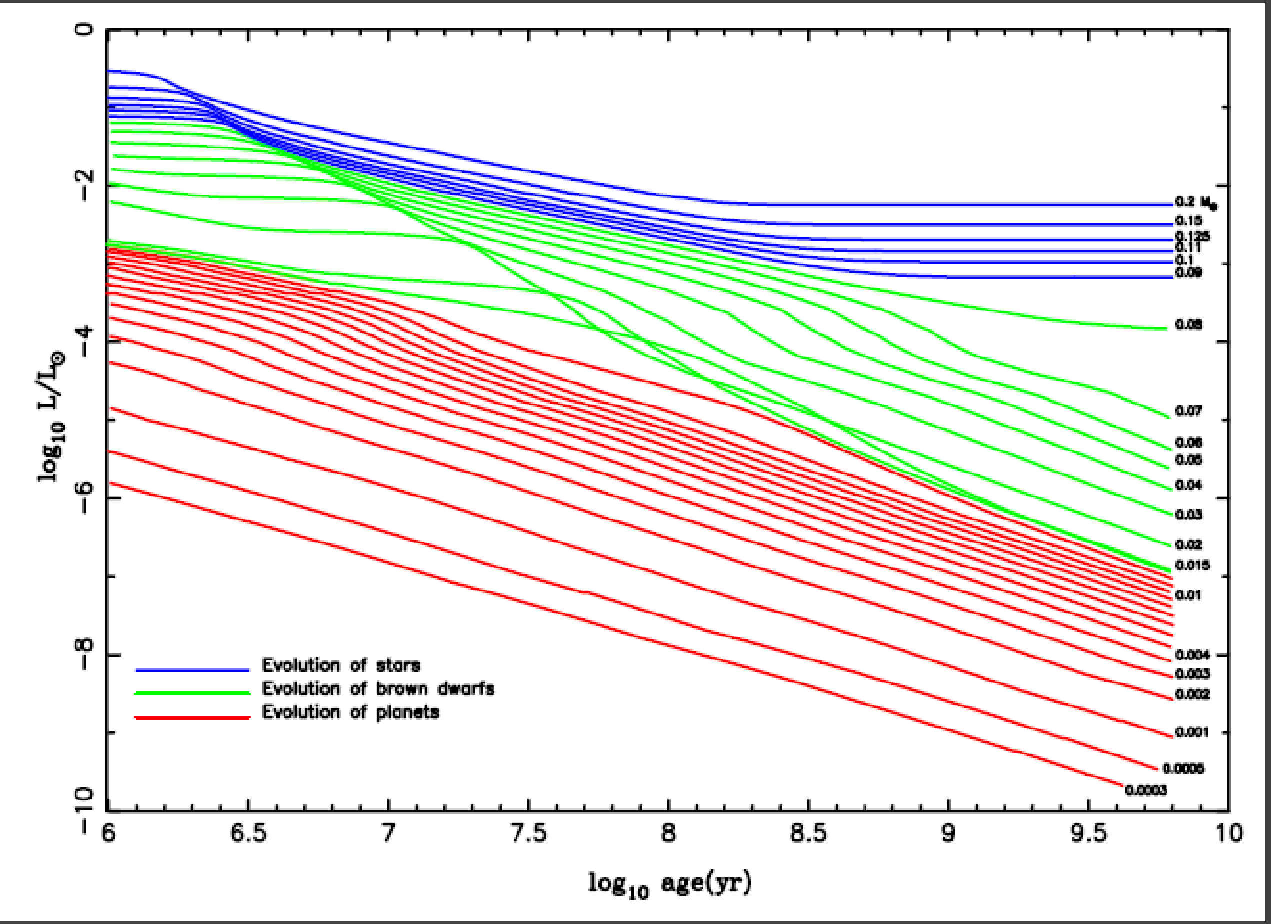
Oppositely, giant planets might hath very thick gas envelopes.

Very often data on mass and radius
can be explained by different combinations of ingredients.

Solid and long-dashed lines (in black) are
for non-irradiated models.
Dash-dotted (red) curves correspond to
irradiated models at 0.045 AU from a Sun.

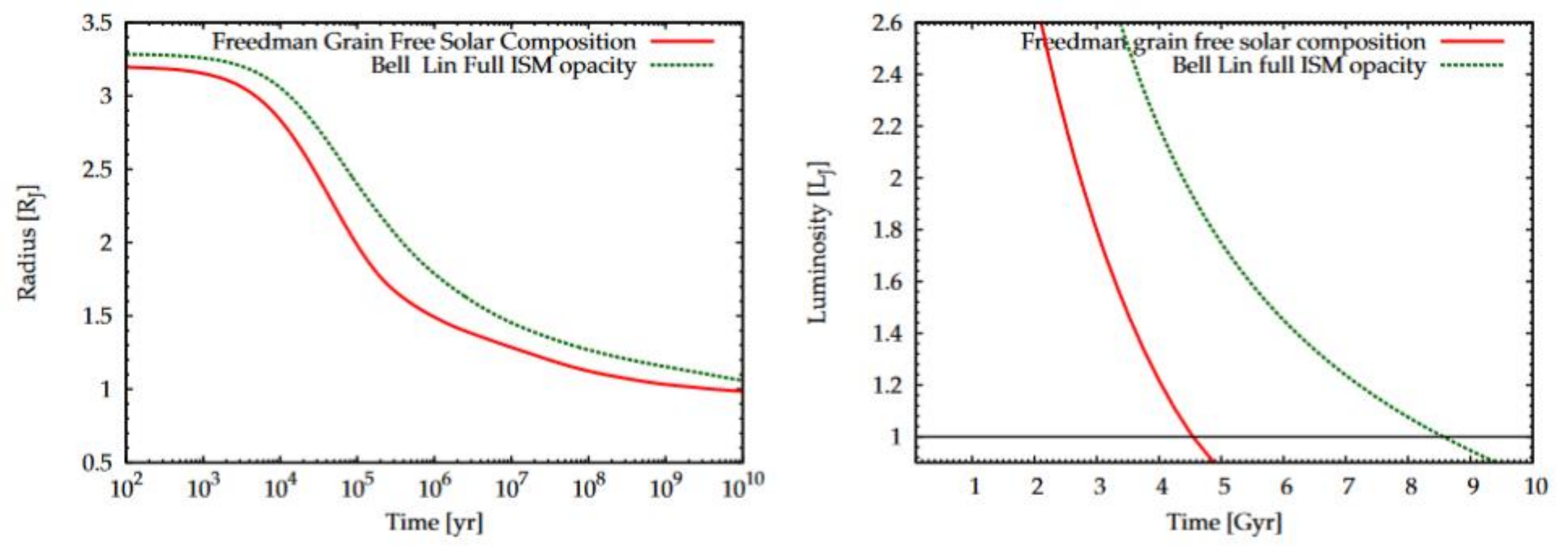
Theory vs. observations





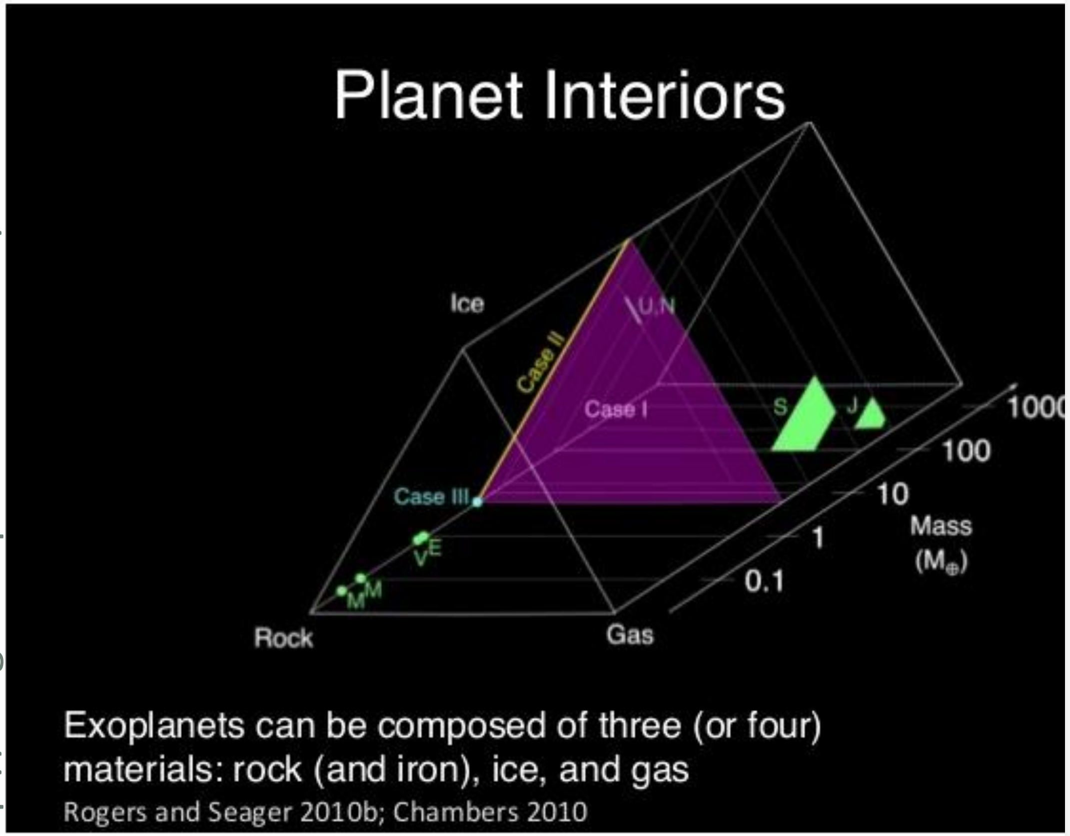
1405.3752

Evolution of giant planets

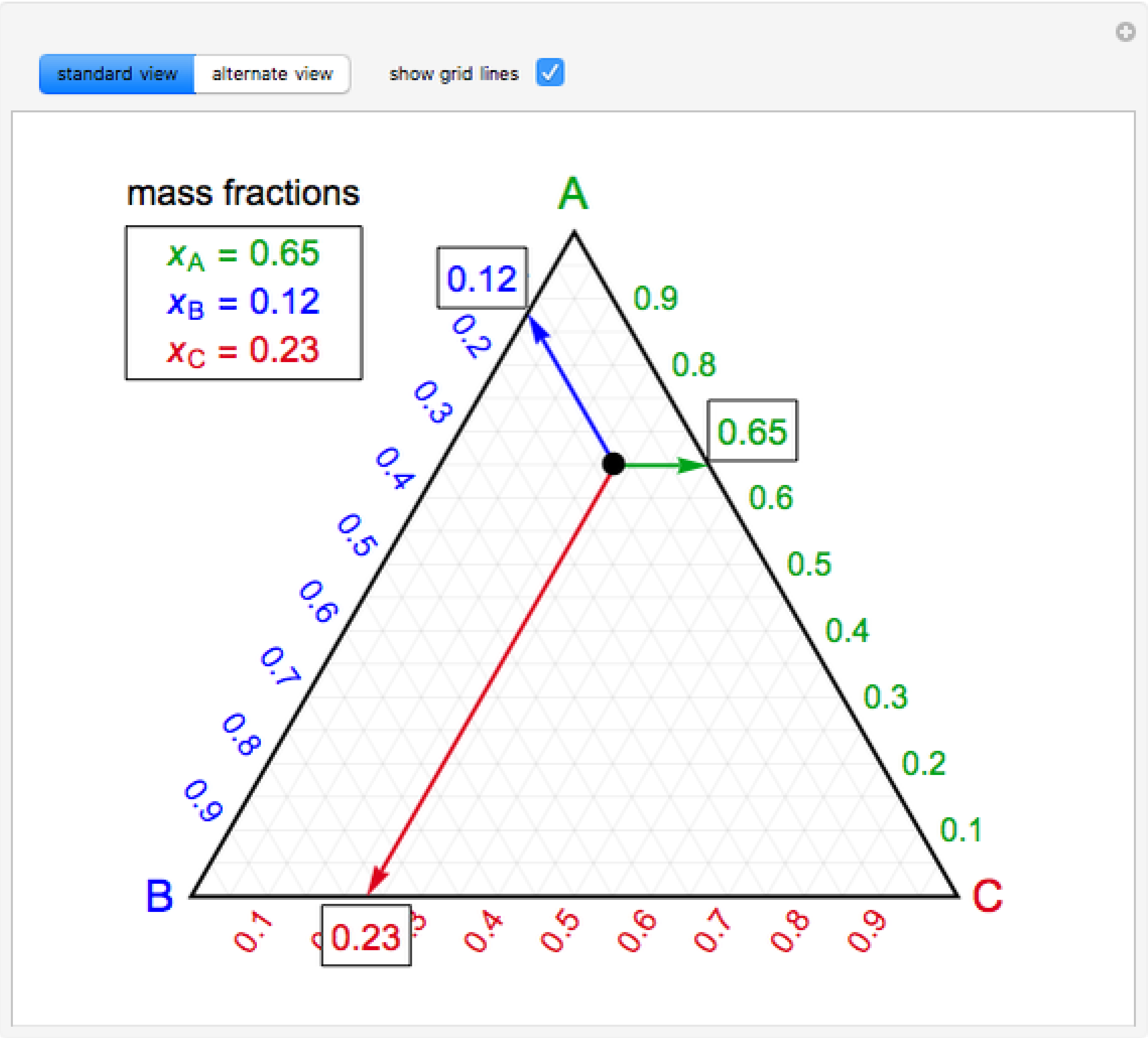


1604.07558

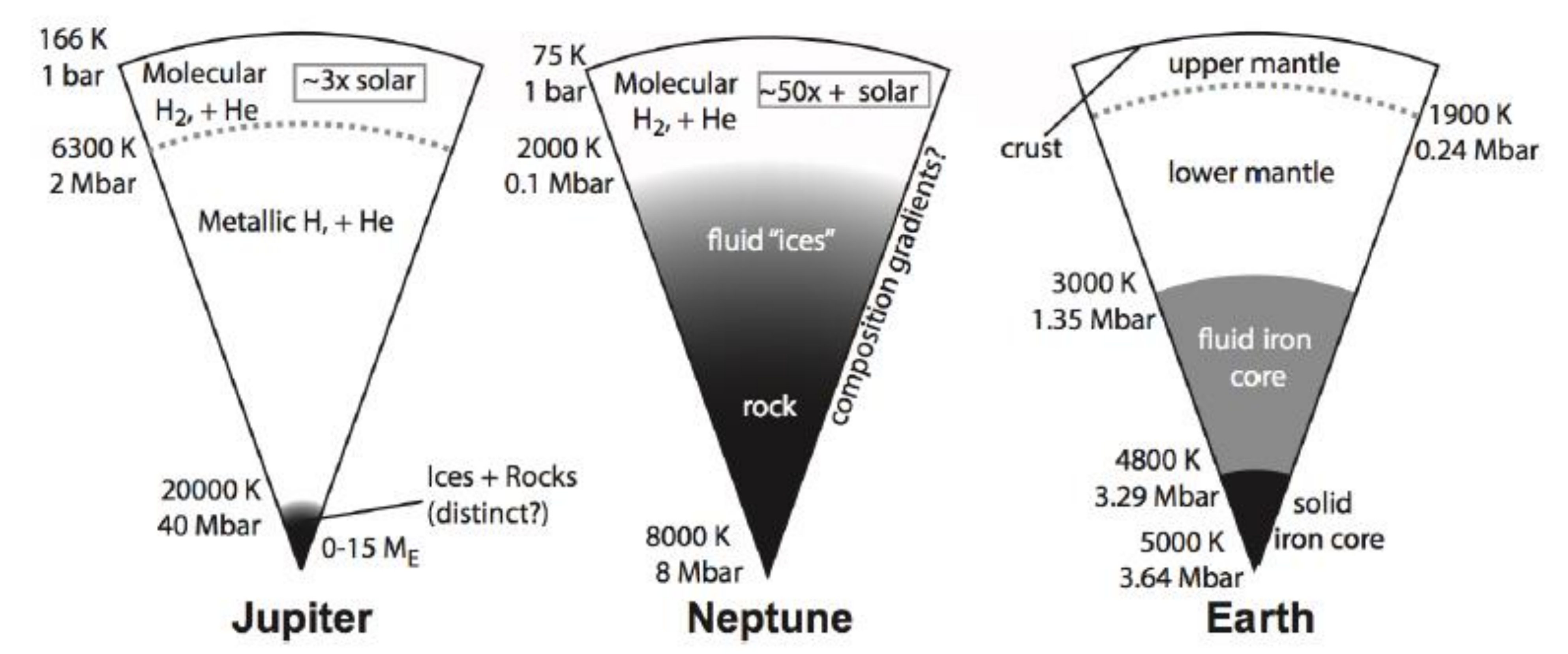
Three main ingred



http://seagerexoplanets.mit.edu/research.htm

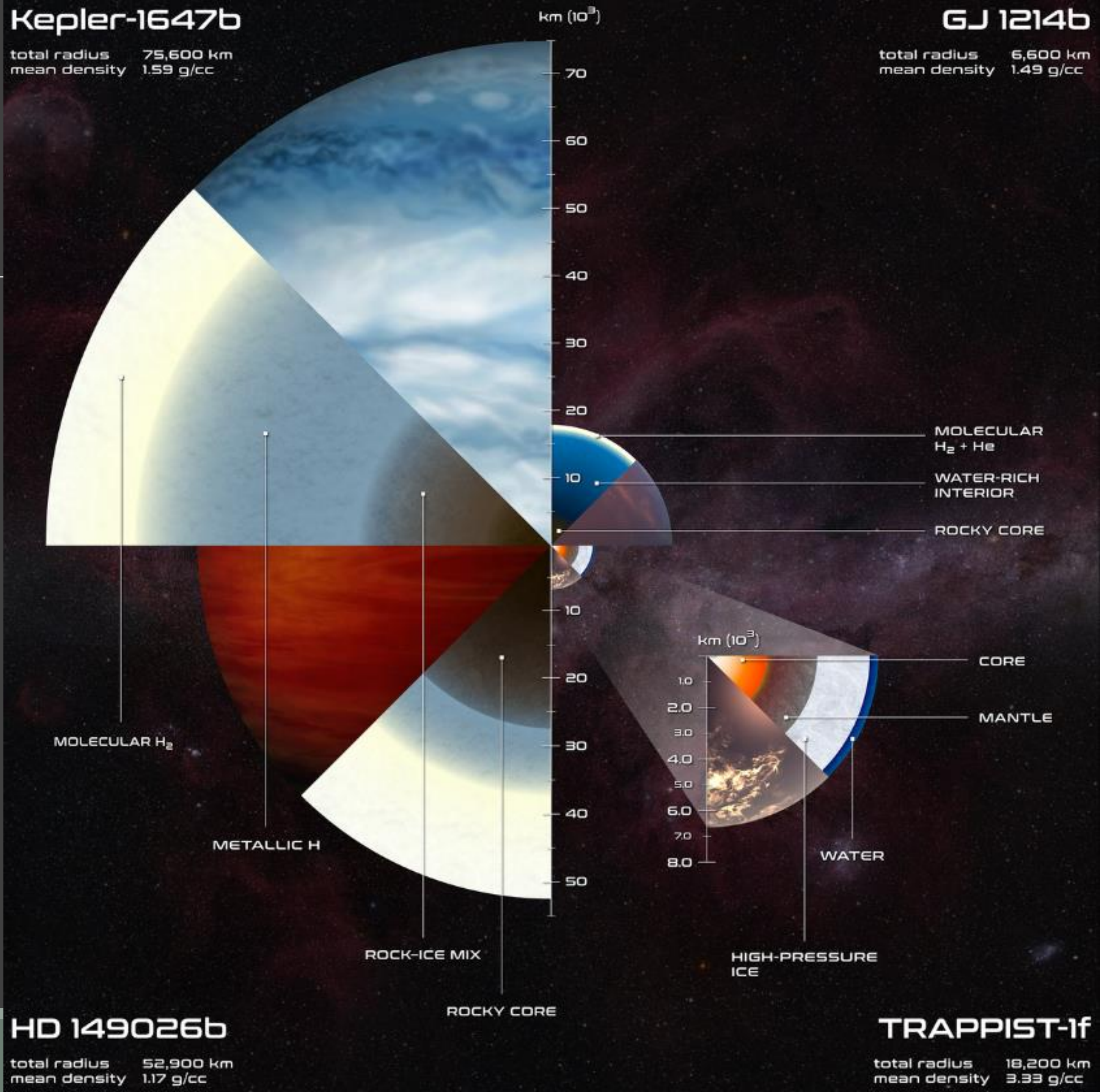


Three main types of planets



Gas giants	Icy giants	Solid planets
H/He	H/He+ice+core	Si, Mg, Fe, O, C

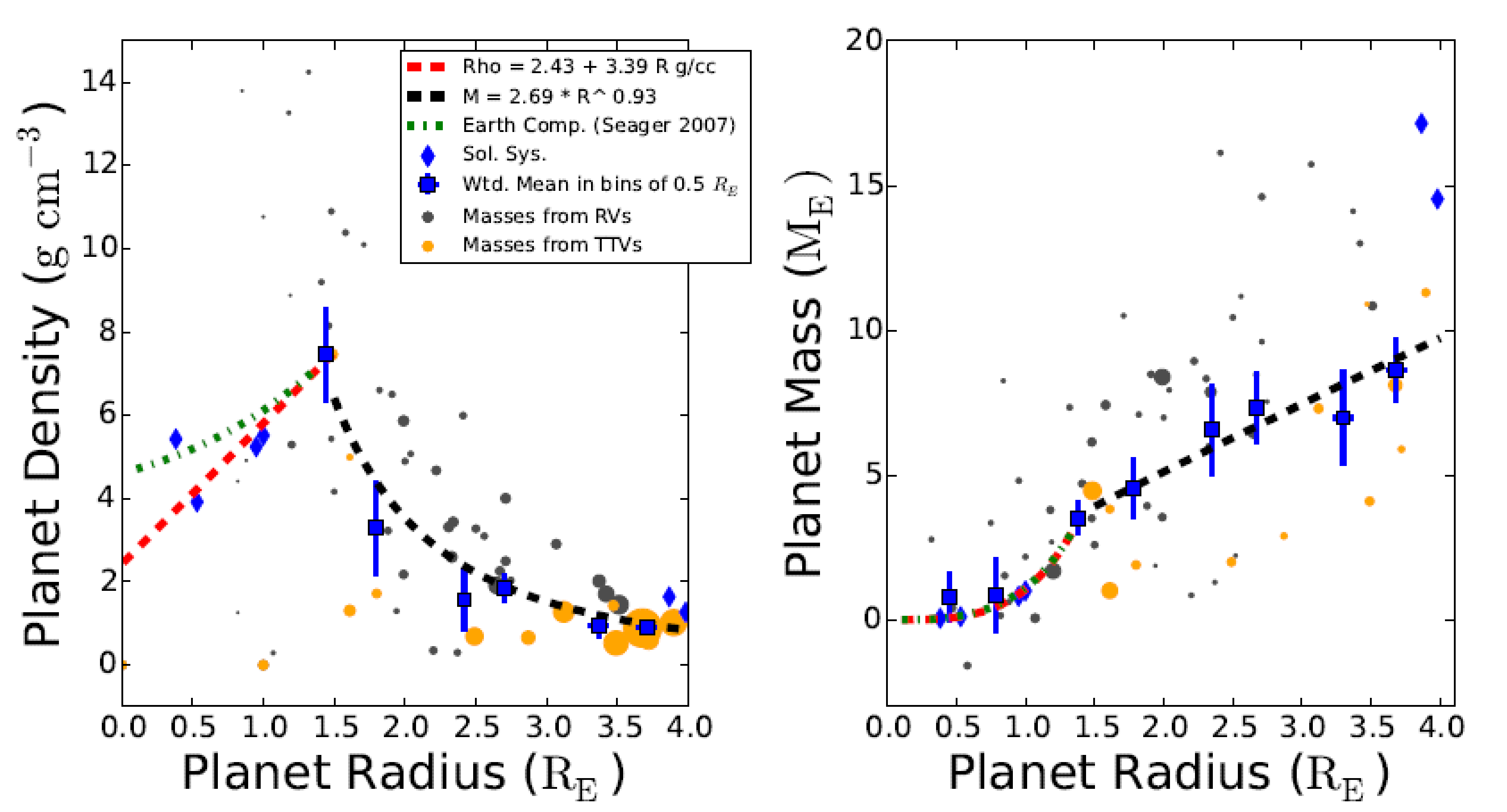
1312.3323



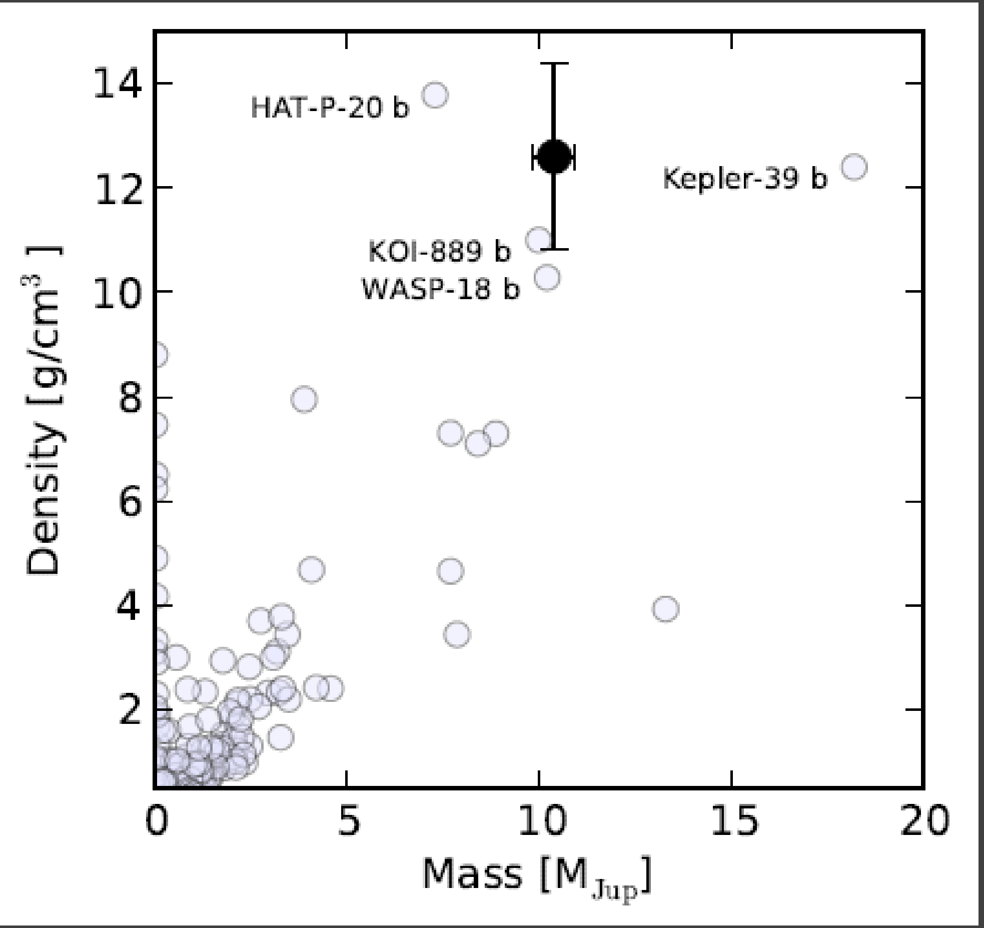
Kepler-1647b
total radius 75,600 km
mean density 1.59 g/cc
GJ 1214b
total radius 6,600 km
mean density 1.49 g/cc
km (10^3)
MOLECULAR H_2 + He
WATER-RICH INTERIOR
ROCKY CORE
MOLECULAR H_2
METALLIC H
ROCK-ICE MIX
ROCKY CORE
CORE
MANTLE
WATER
HIGH-PRESSURE ICE
HD 149026b
total radius 52,900 km
mean density 1.17 g/cc
TRAPPIST-1f
total radius 18,200 km
mean density 3.33 g/cc

2012.11628

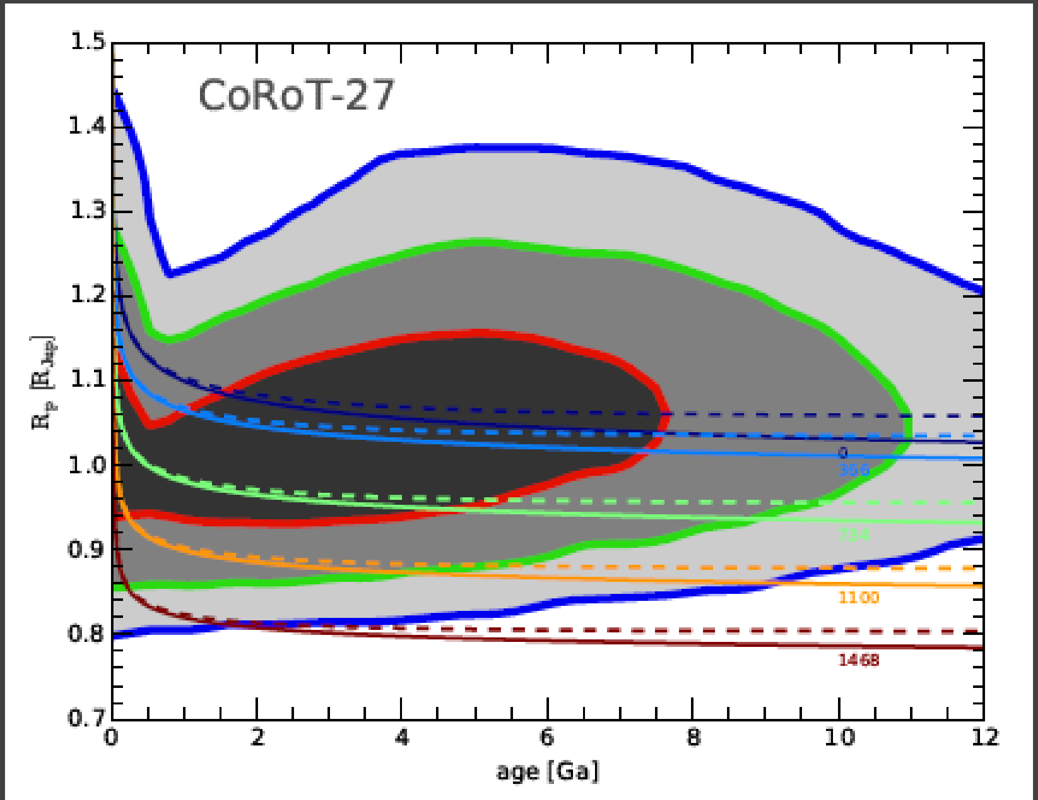
Thick atmospheres for $M>4M_{Earth}$



Corot-27b. Dense planet



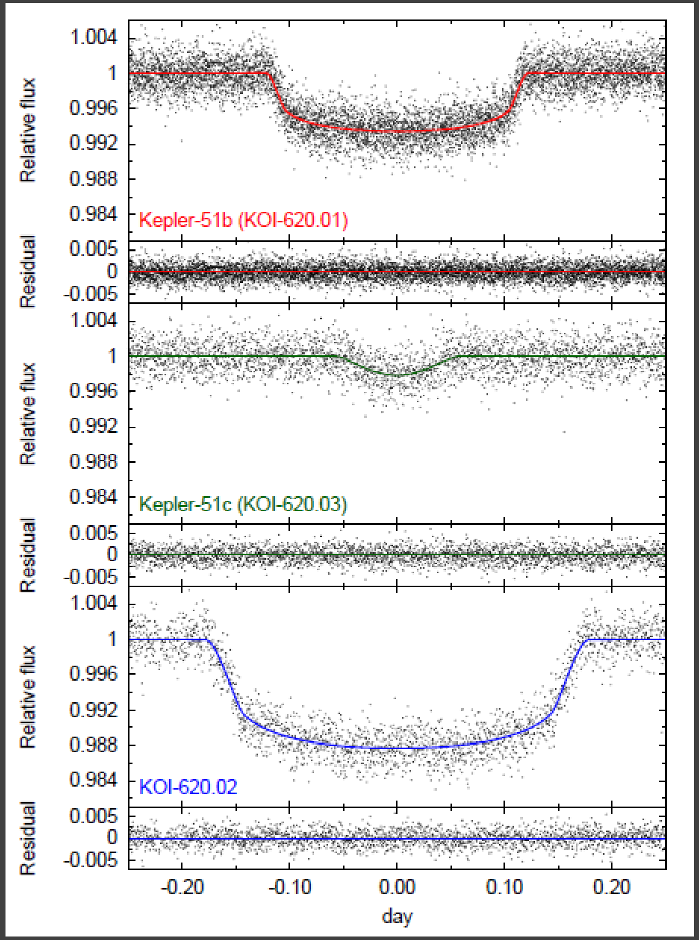
Orbital period 3.6 days.
Solar-like star



Now the densest is KELT-1b: 23.7+/- 4 gcm^{-3}. 1808.04533

1401.1122

Kepler-51. Crumbly planets.

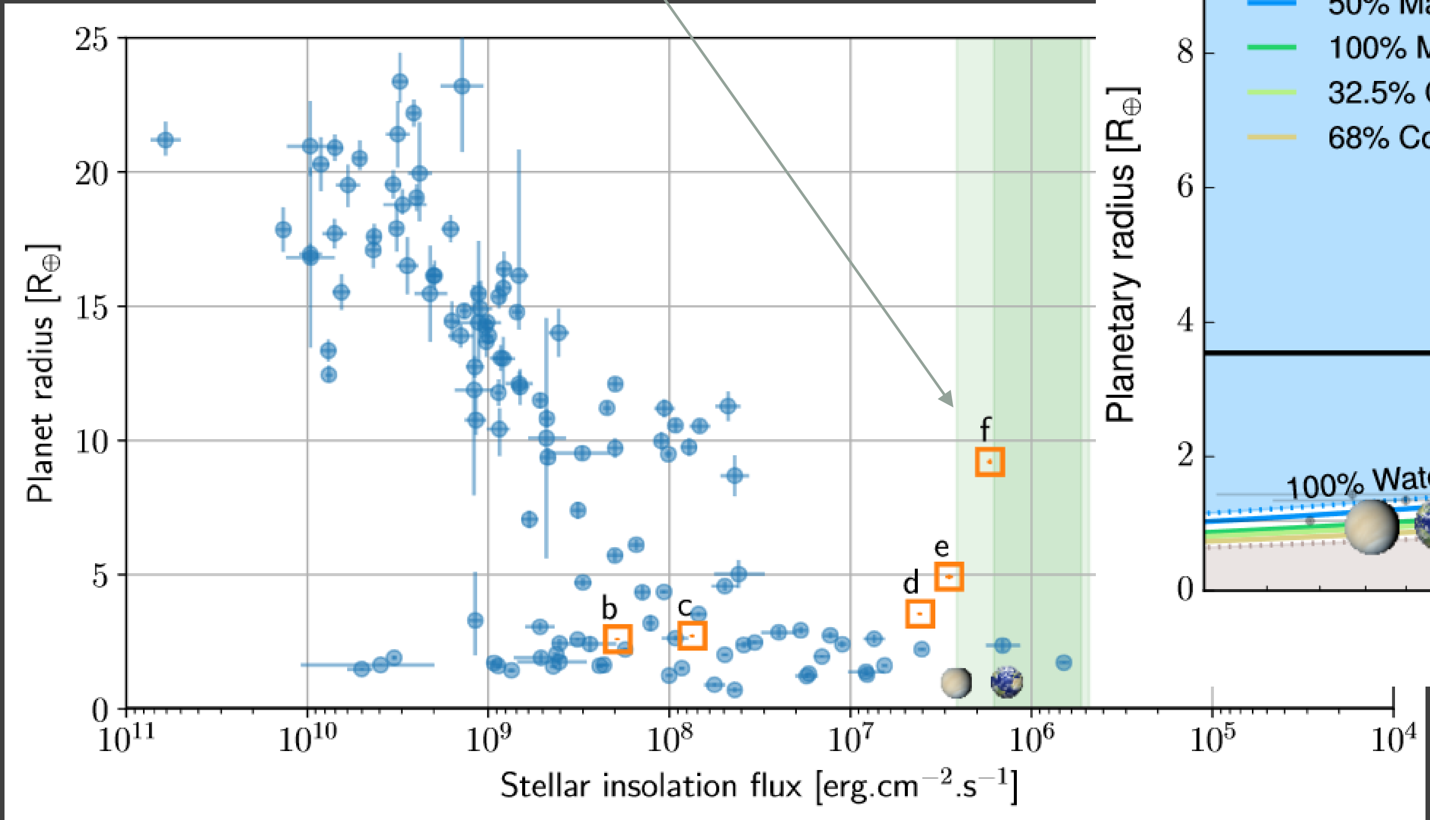


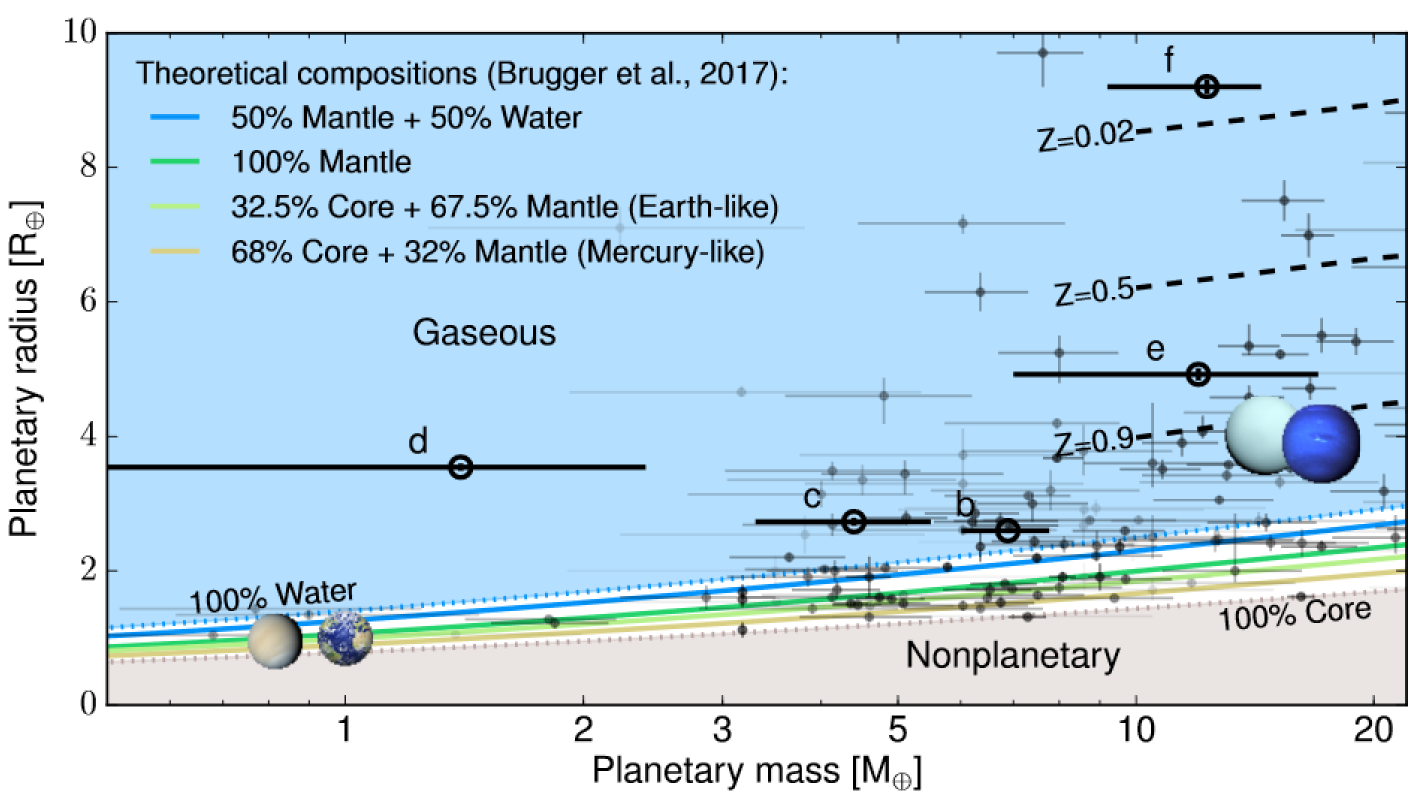
Solar type star.
Three planets with masses 2-8 M_{earth} and low densities: <0.05 g/cm^3

Orbital periods 45-130 days.

An extremely low-density and temperate giant planet

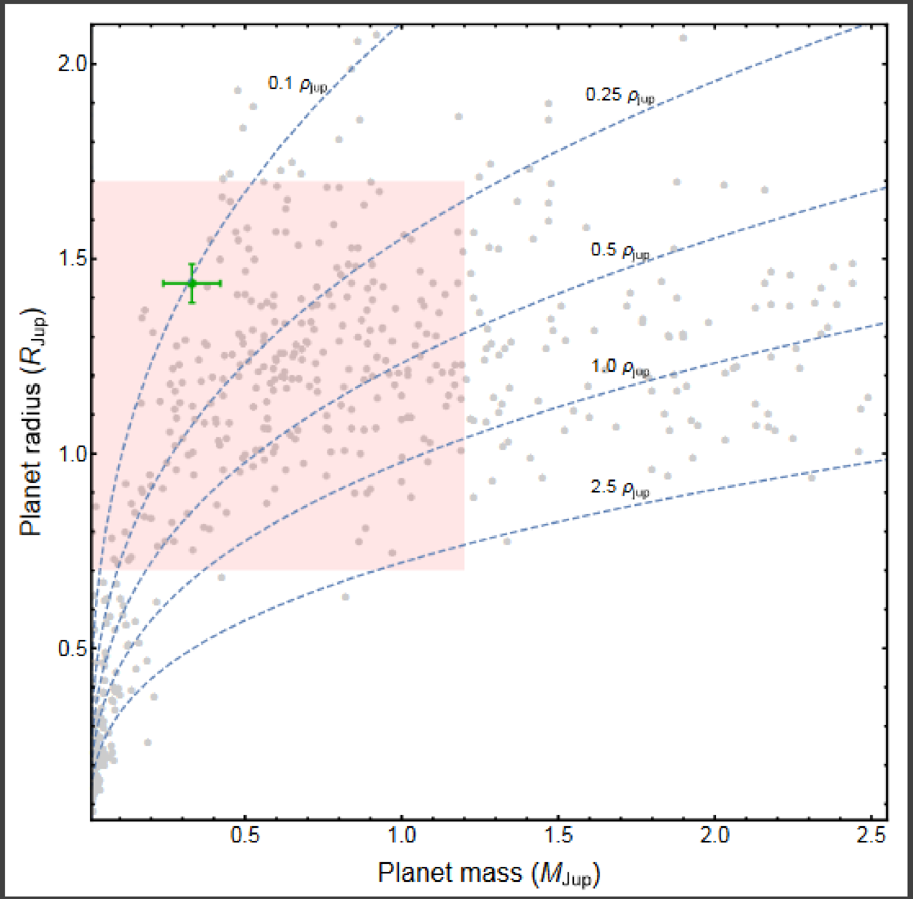
Density <0.1 g/cm3





Normal insolation

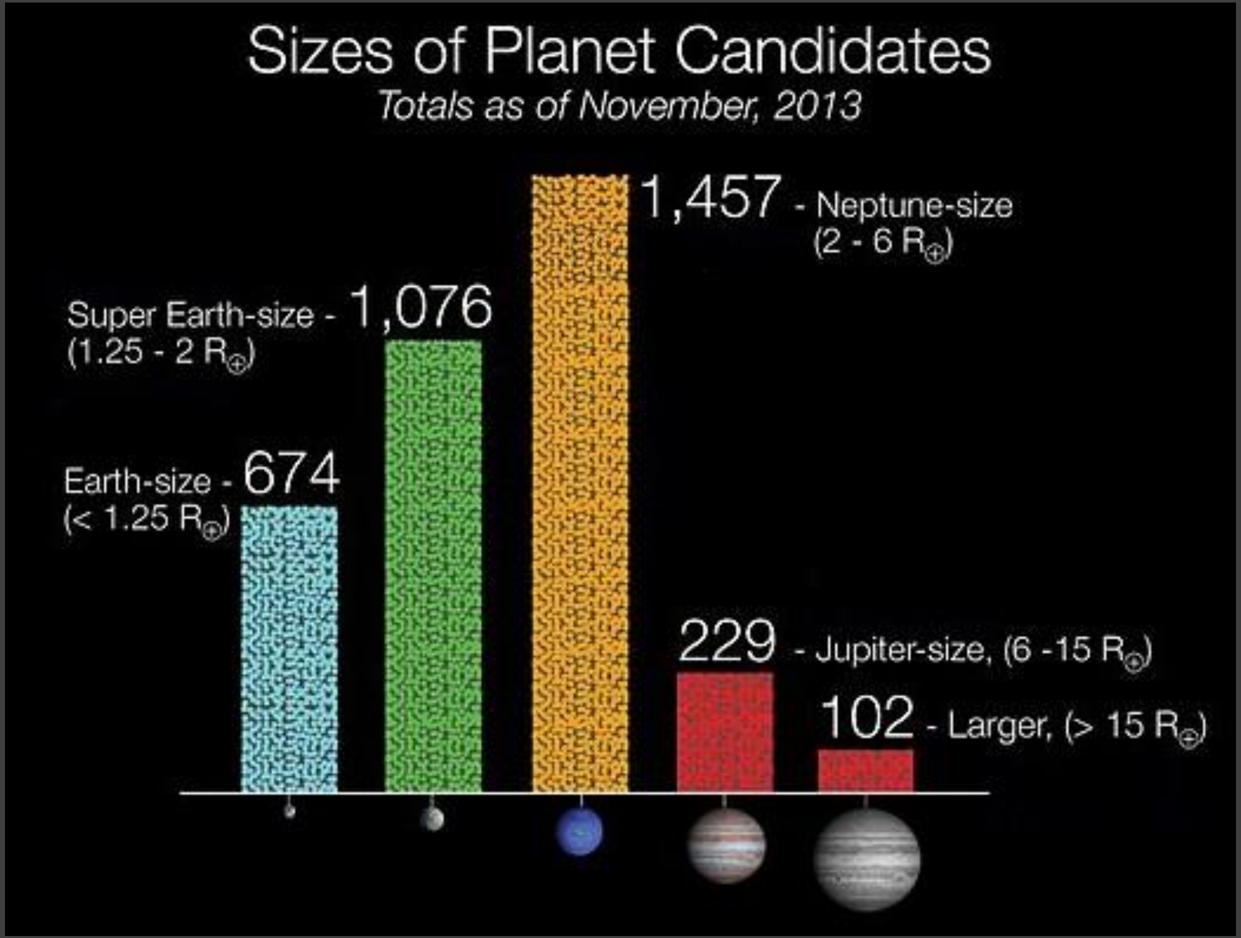
Inflated hot jupiter

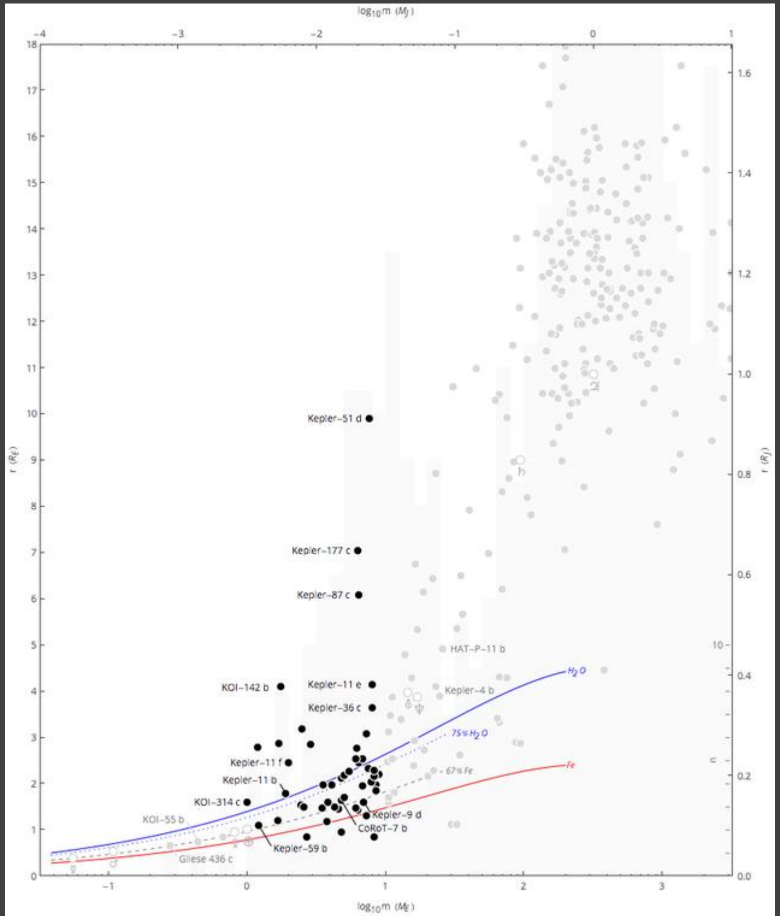


Mass and radius measured together.
Grazing transit.
Density 0.1-0.17 g/cm3

Superearths. Diversity of properties.

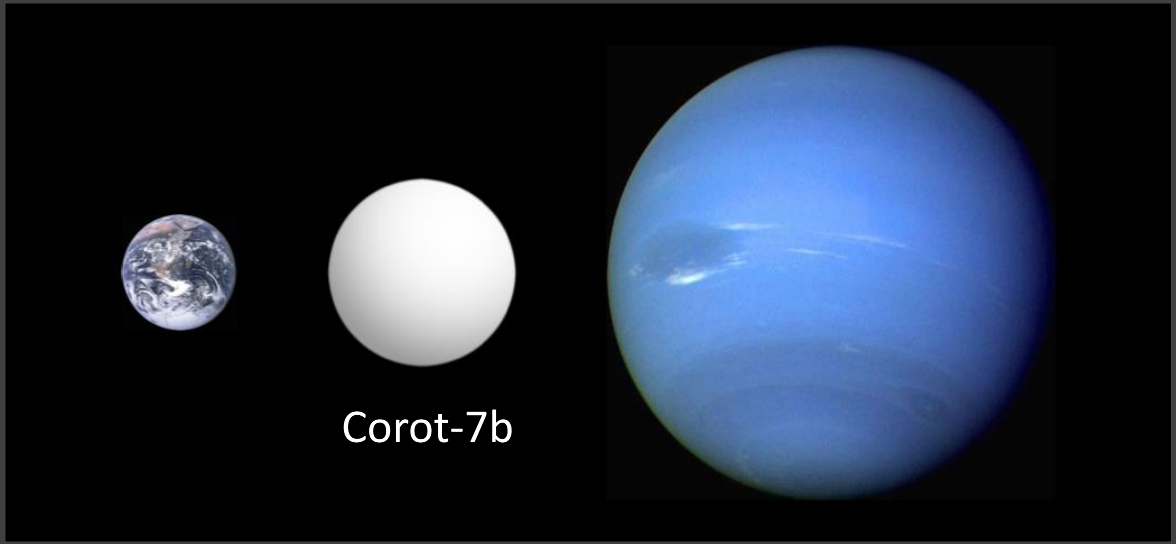
Wikipedia

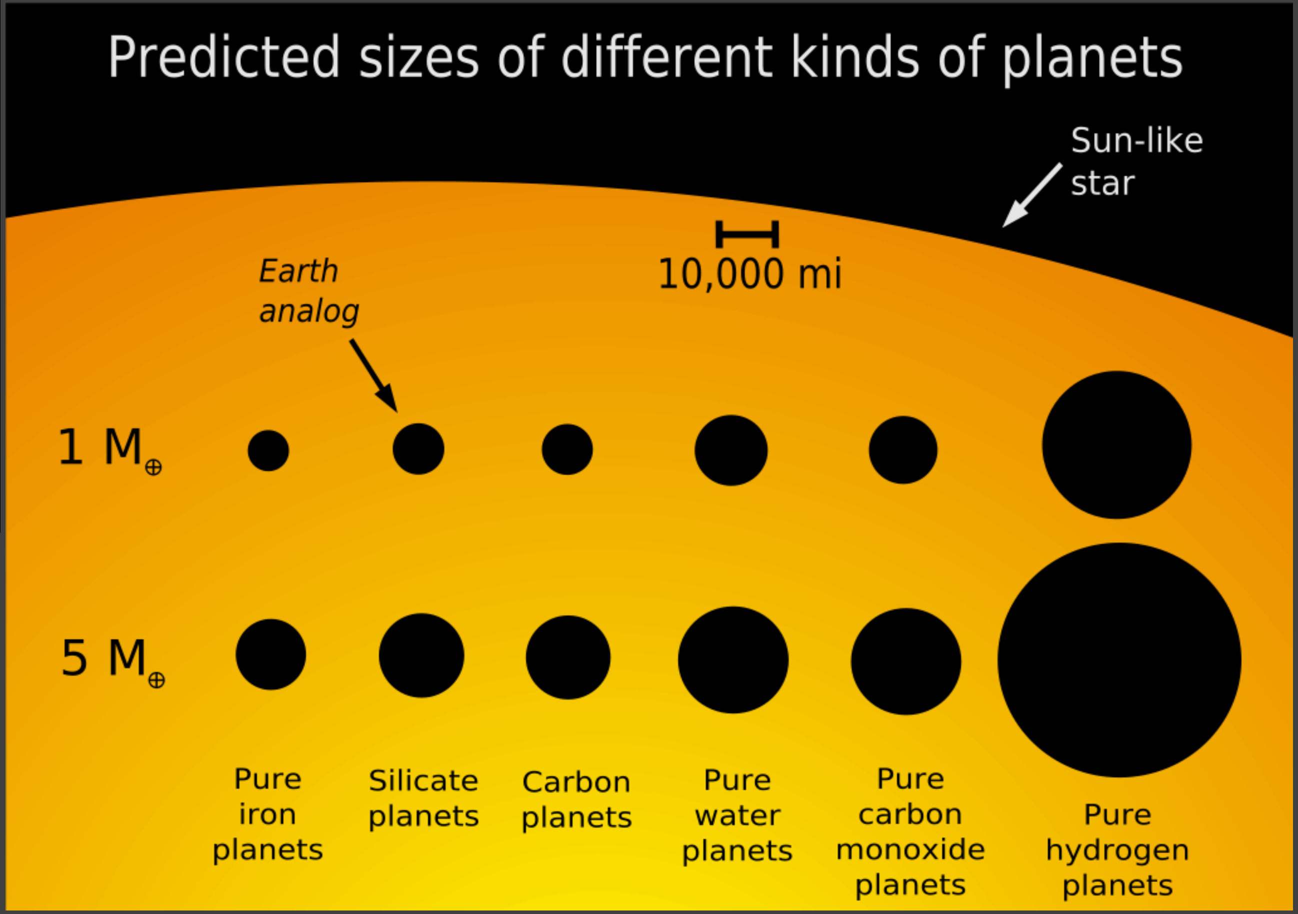




Sizes of superearths

Wikipedia

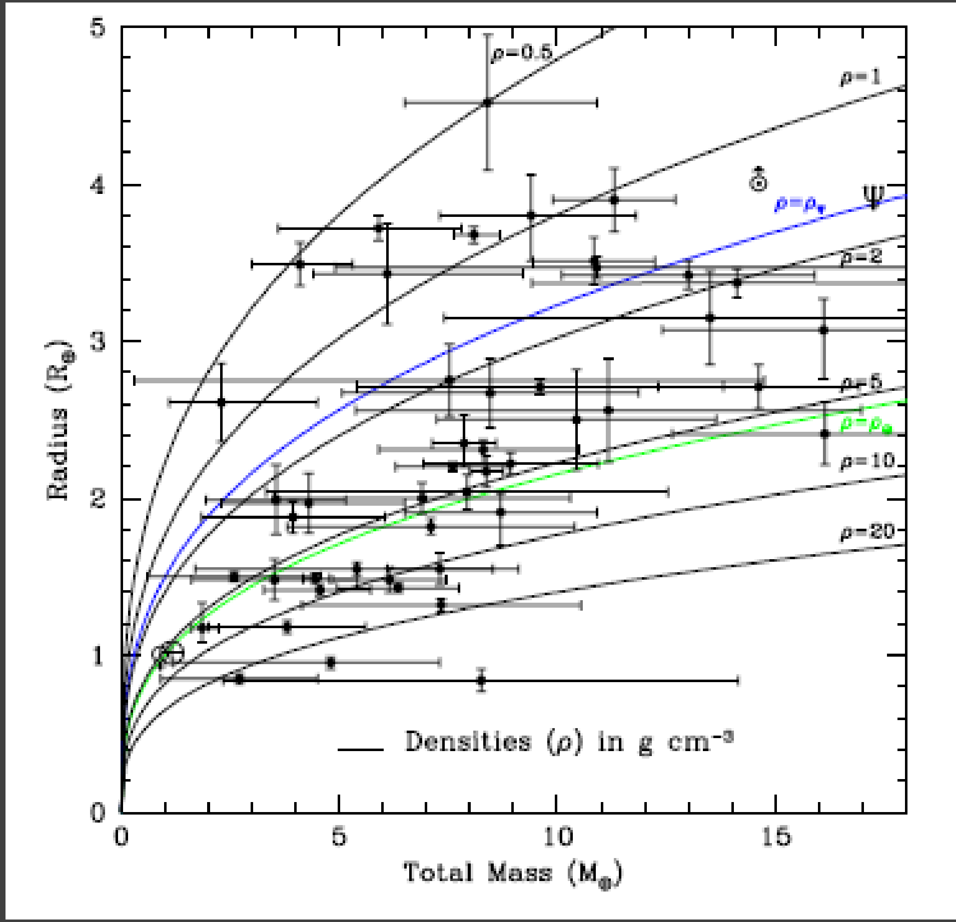




Typical radii 1-4 of the Earth
I.e., between the Earth and Neptune).

Sometimes low density planets in the range are called mini-Neptunes.

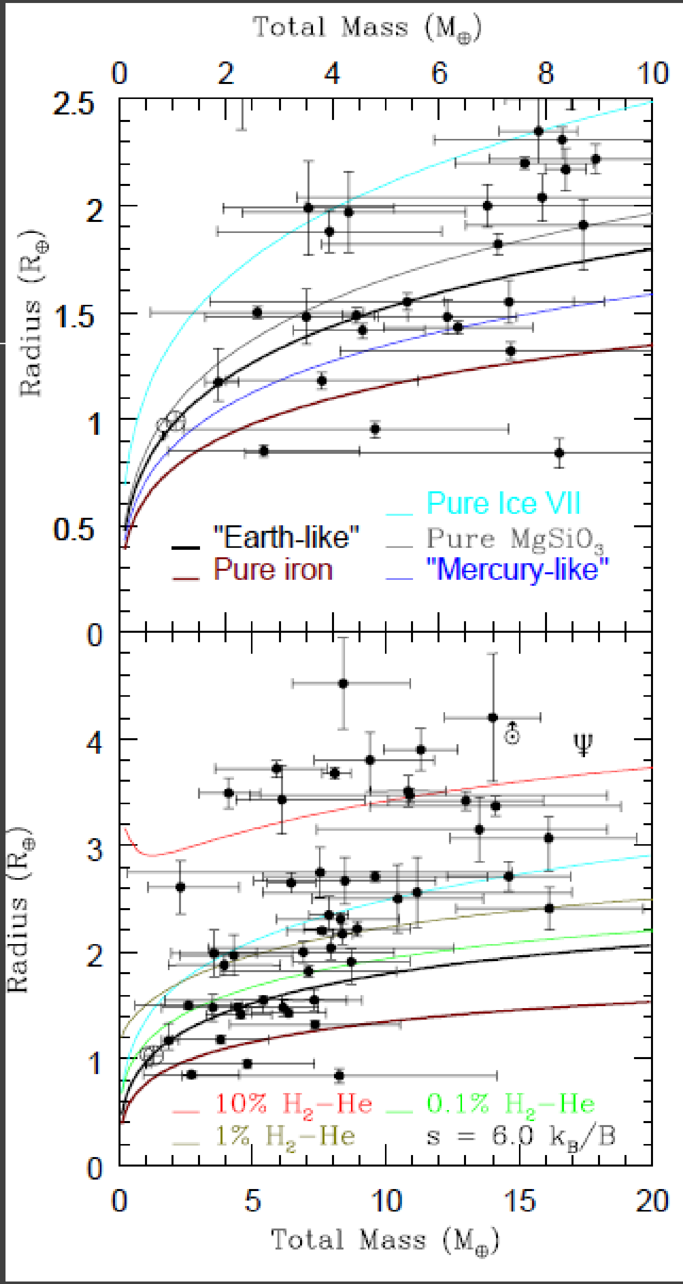
Superearths: mass-radius



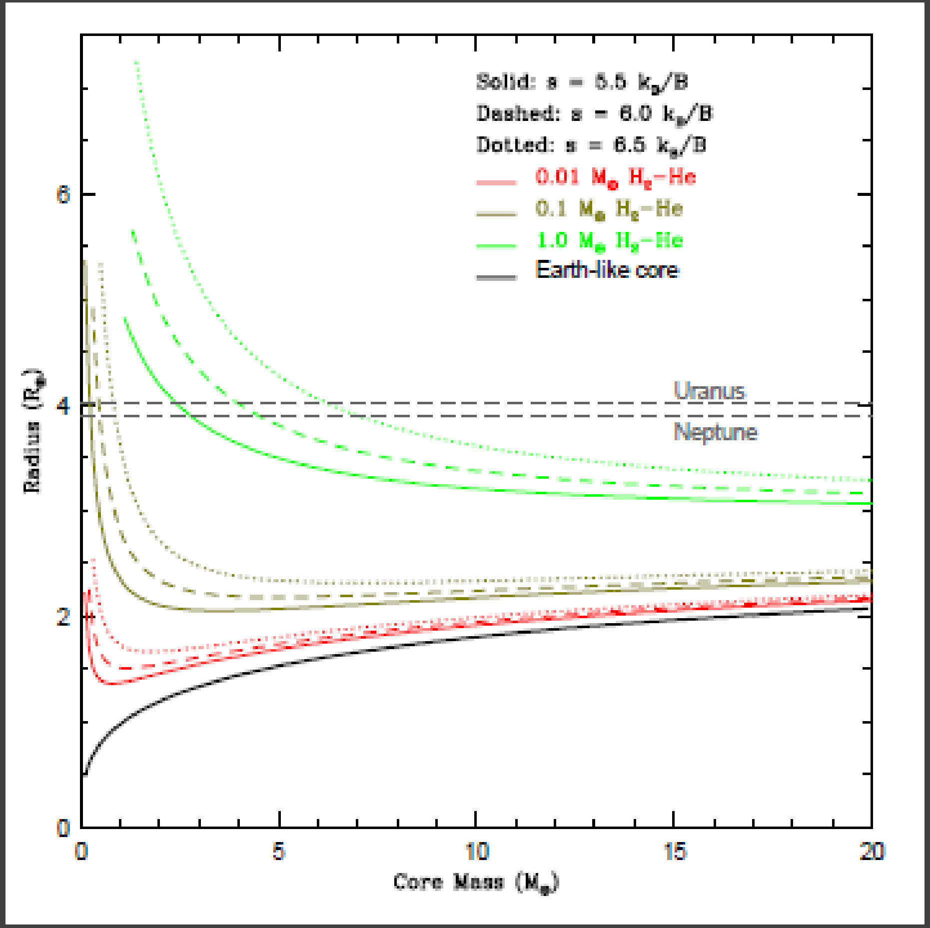
Superearths are very numerous planets.
Only those with well-determined
mass and radius are shown.

Inner cores can consist either of rocks
(and iron) or of ices.

Some of superearths obviously
have thick gas envelopes.
This is a challenge to formation models.



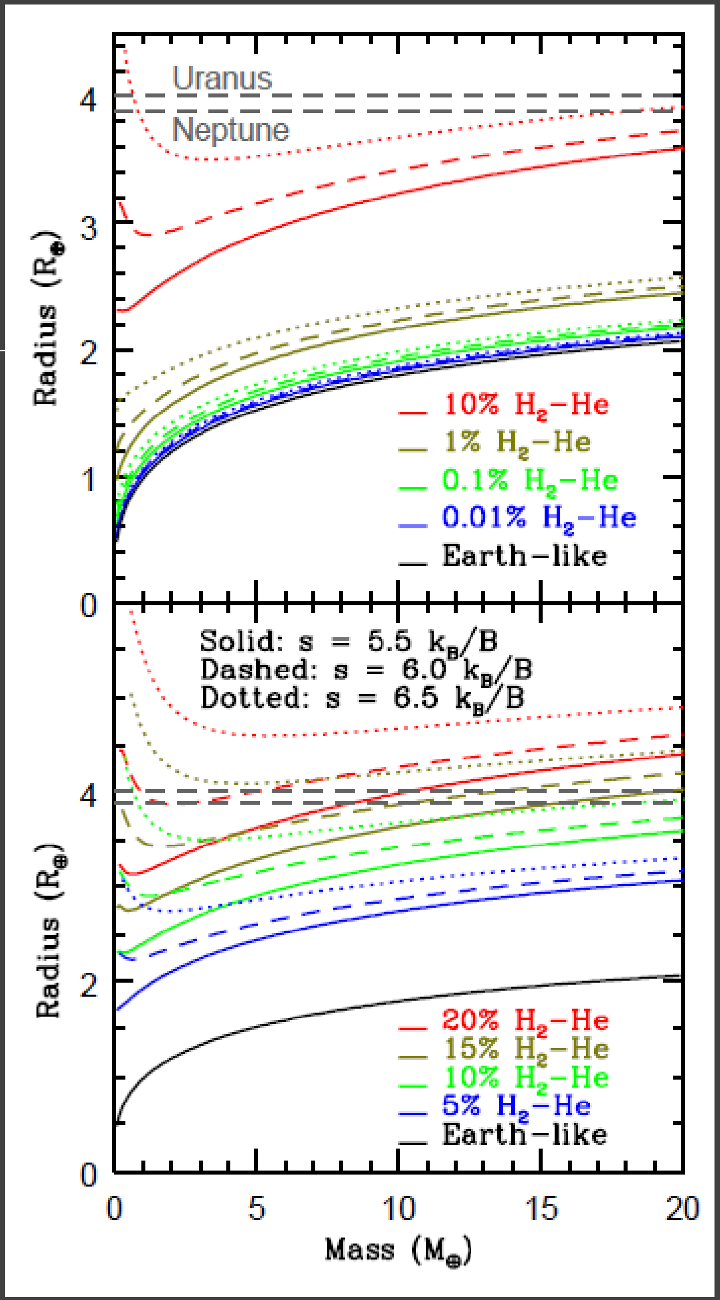
Superearths models



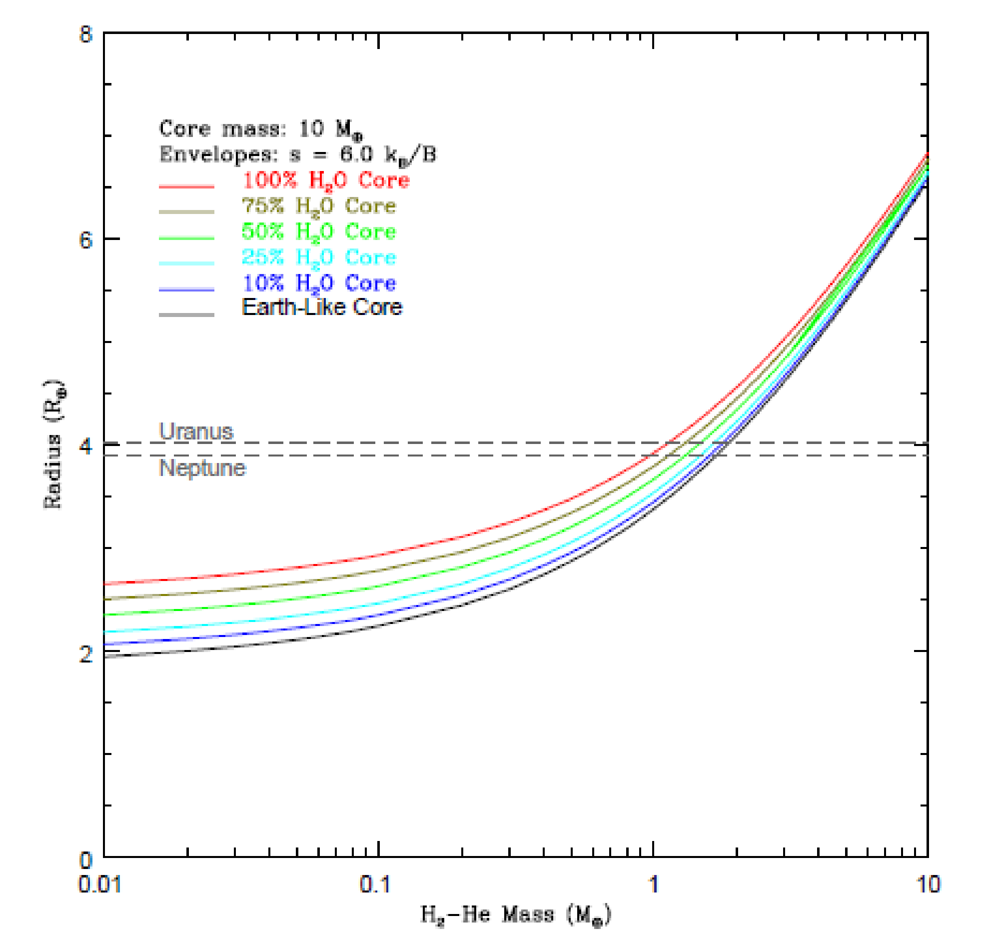
For less massive planets parameters are mainly determined by the core.
For more massive – by the outer envelope.

Heating can be also important.

Results are shown for planets with solid earth-type cores.



Just add some water



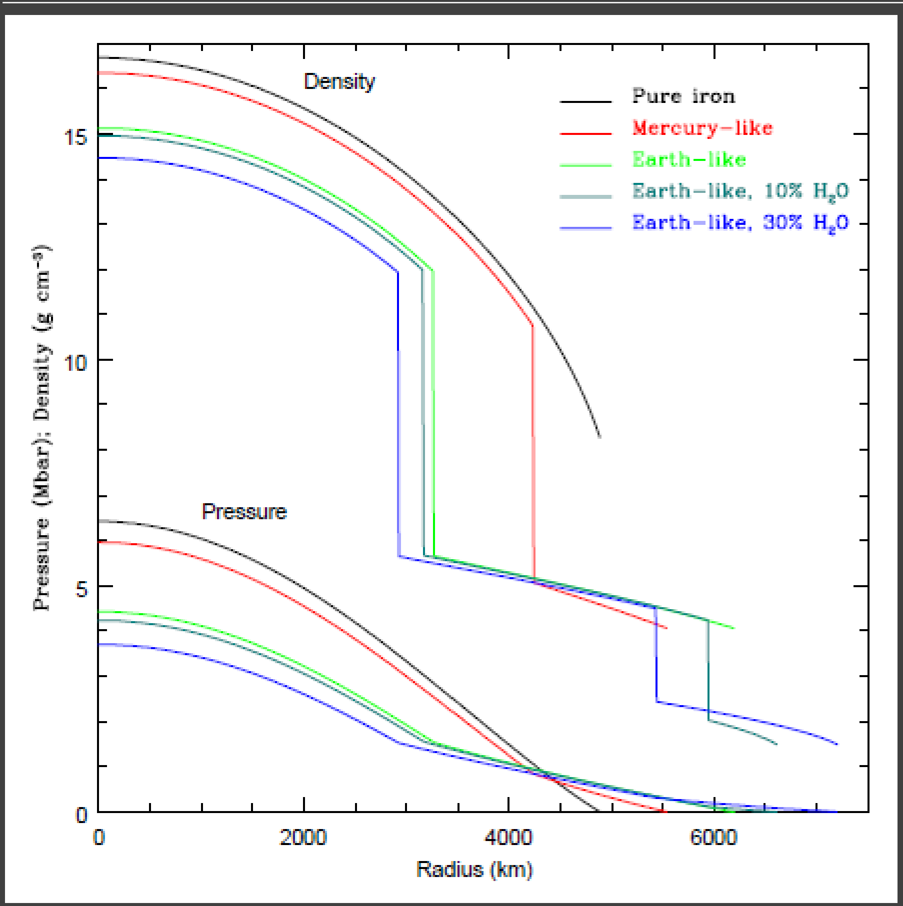
Let us fix the planet mass and change the fraction of ice.

Here water is added as an ice layer above a solid (rocky) core.

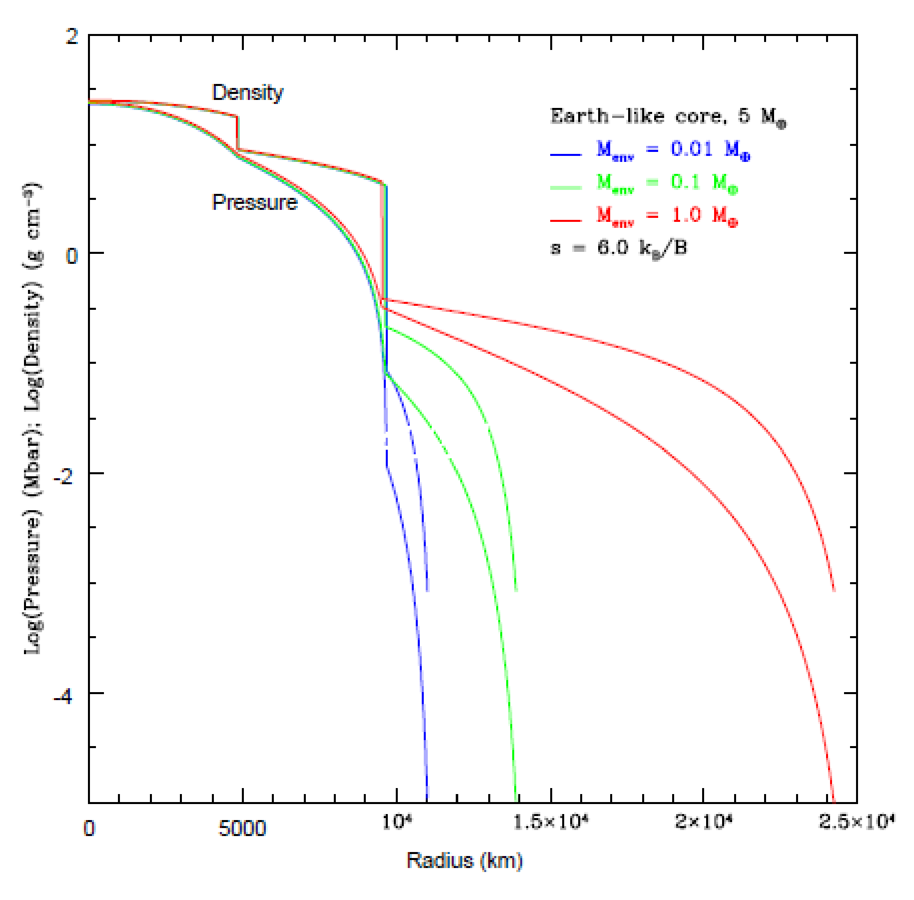
Only for lower masses it is possible to distinguish (by radius measurements) between pure-ice cores and pure-rock cores.

1402.4818

Internal structure

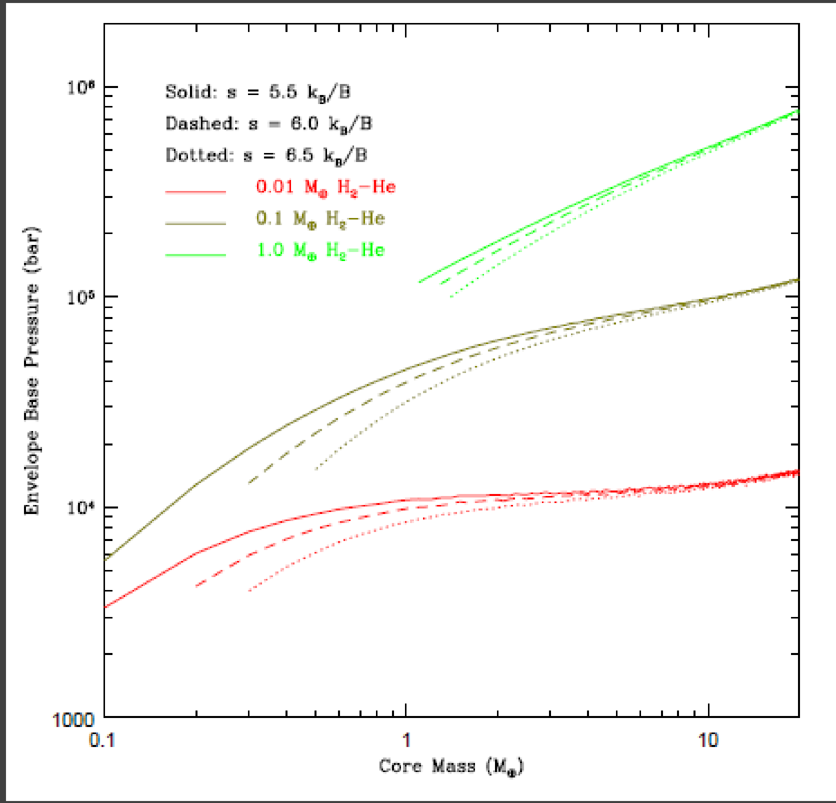


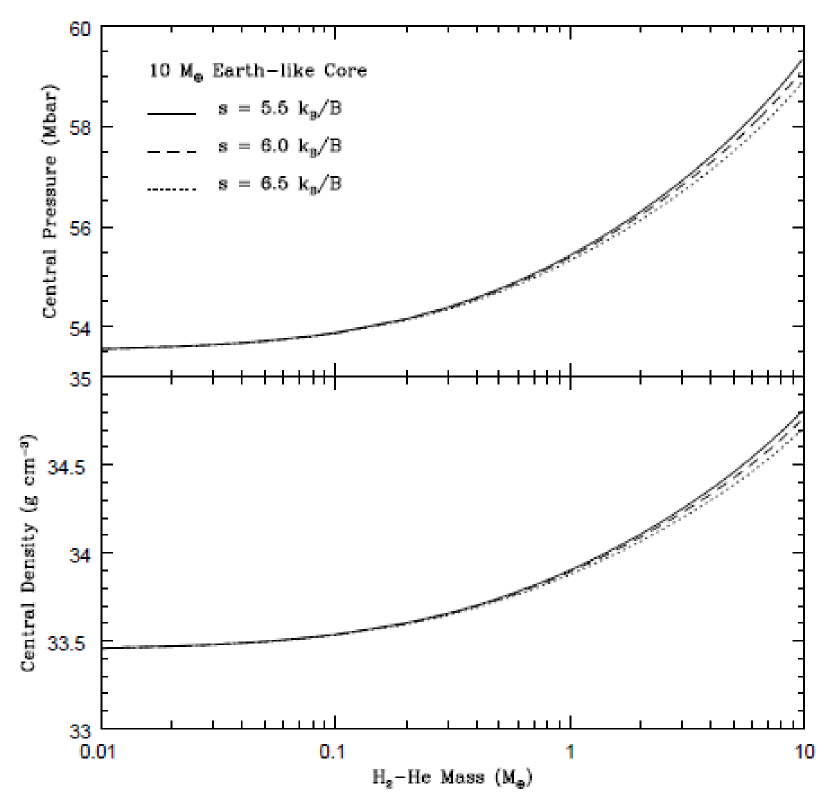
Without an envelope

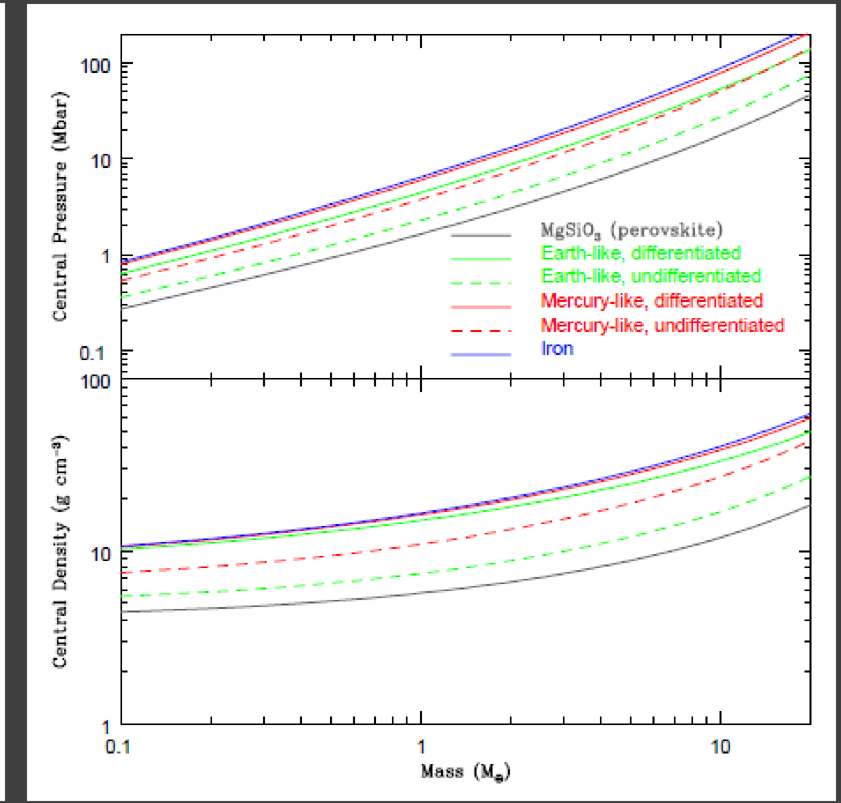


With an envelope

Under pressure





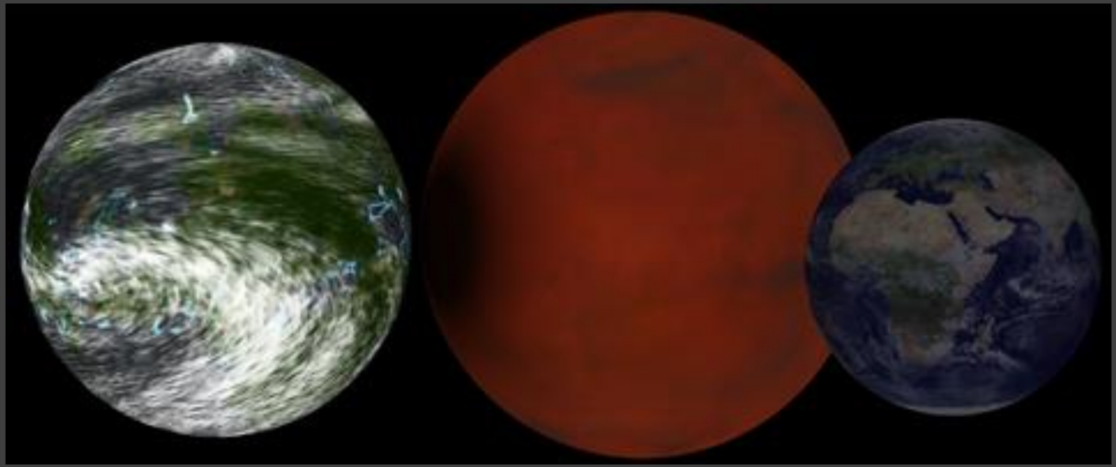


Interiors might have high pressure and density

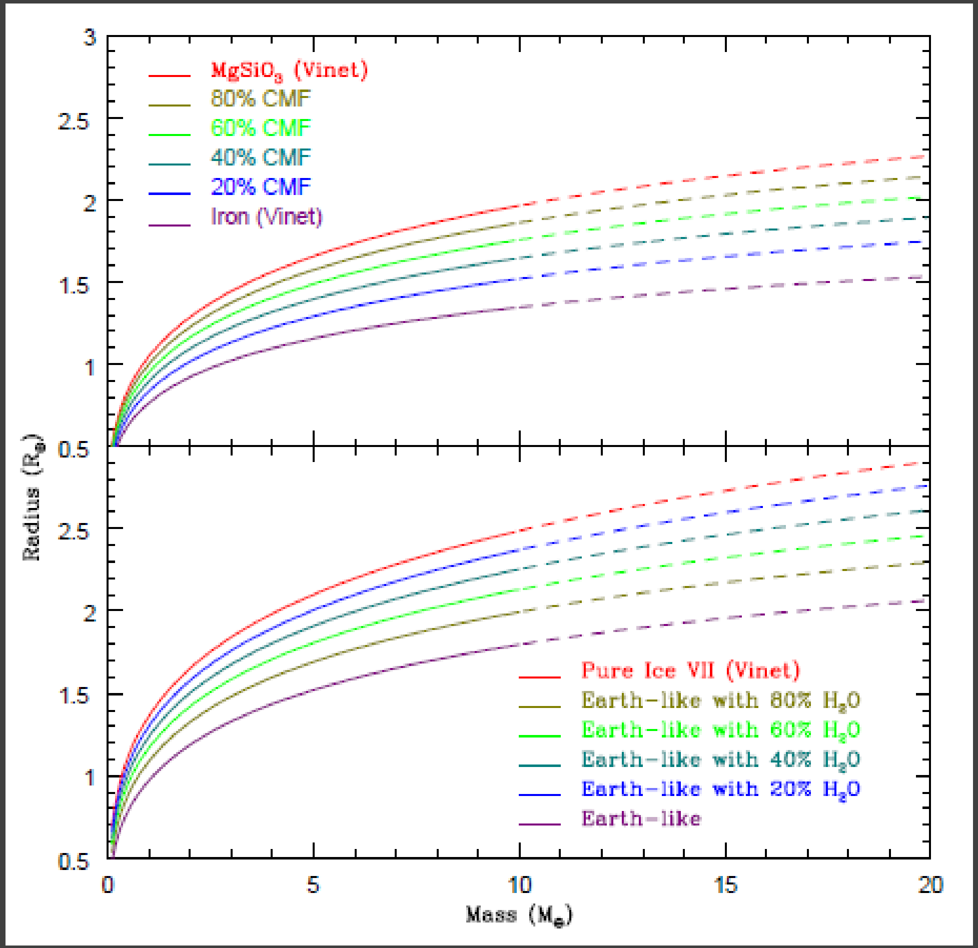
1402.4818

Soil and water

Wikipedia

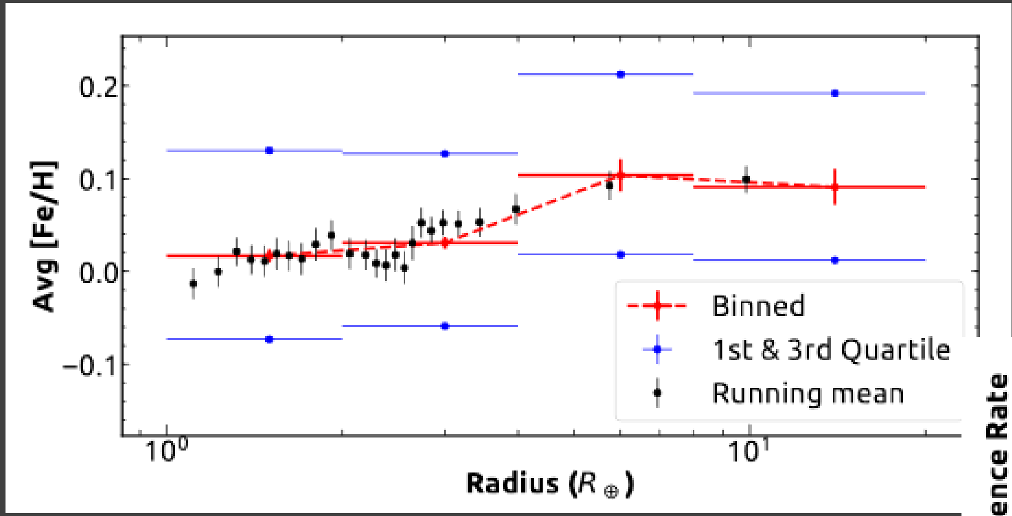


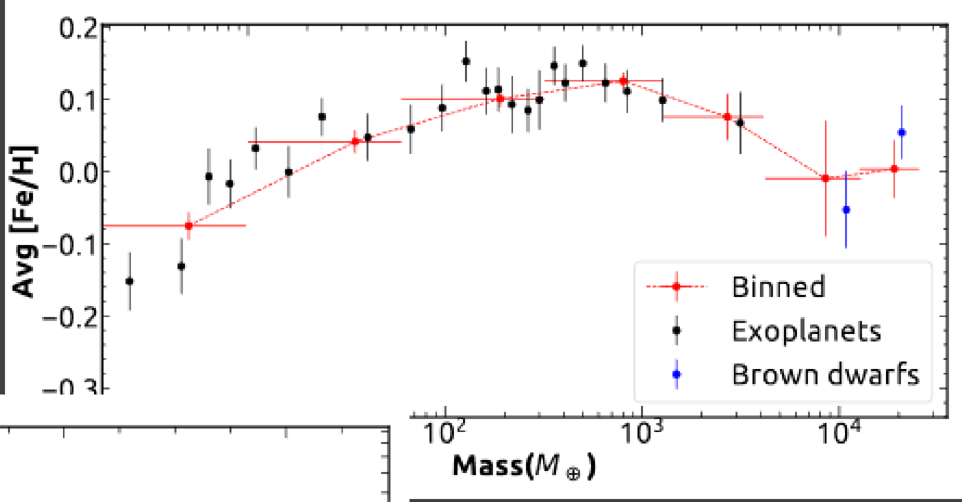
Radius vs. mass for different water content

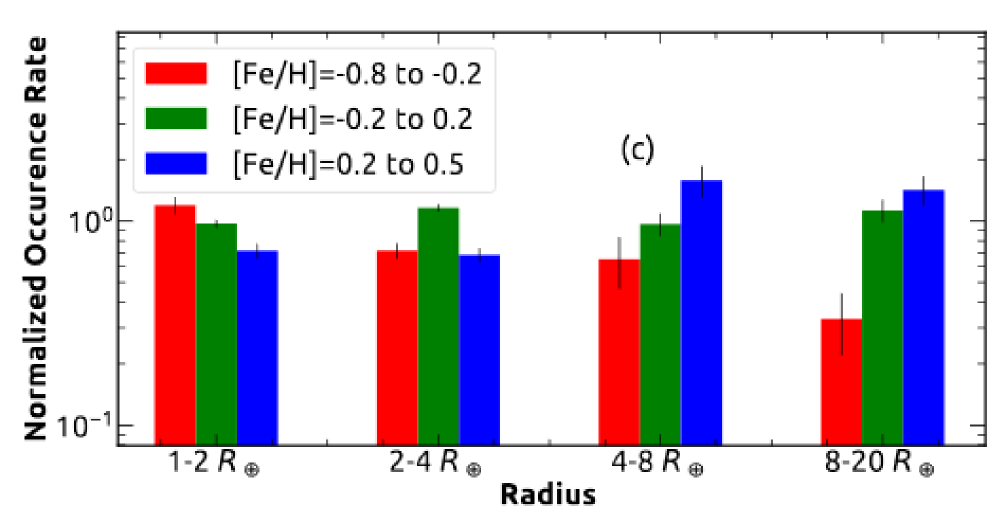


Stellar metallicity and planets

Parameters of planets strongly correlates with stellar metallicity

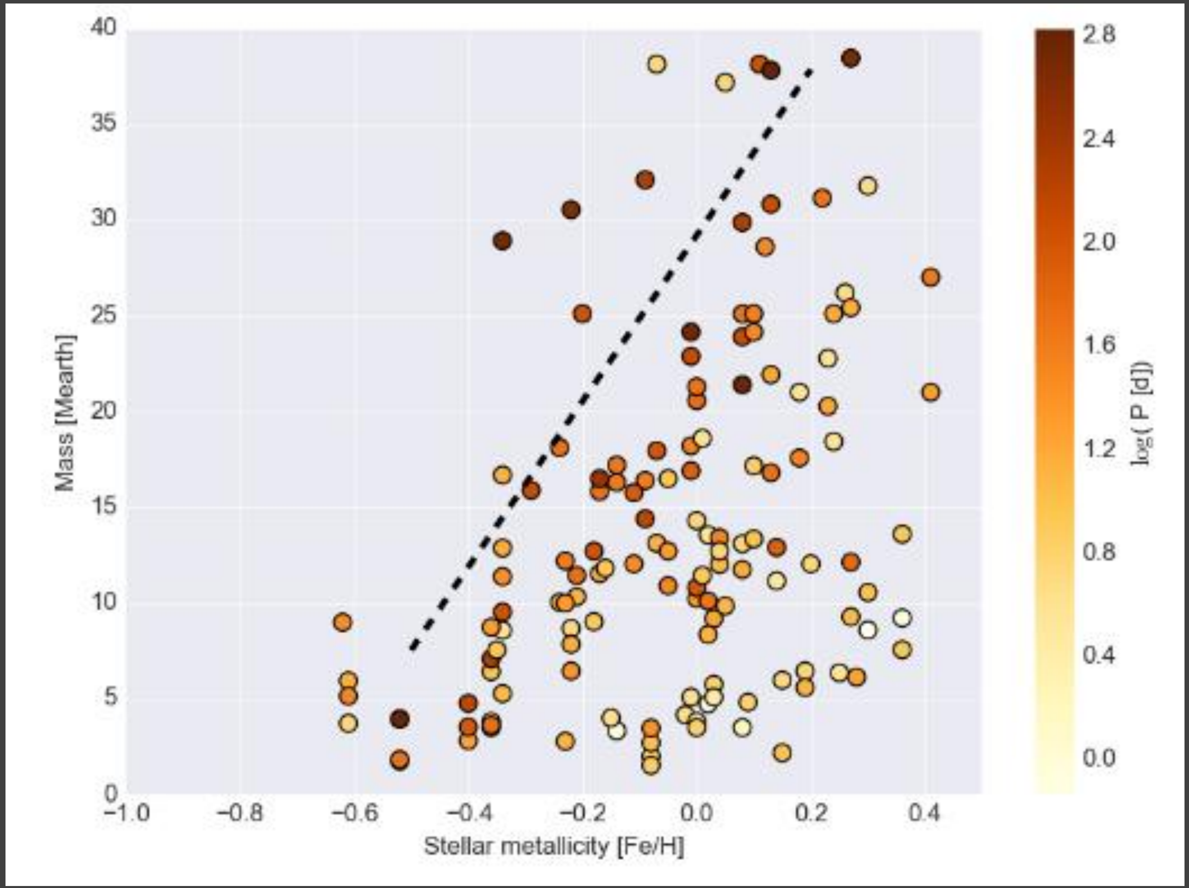


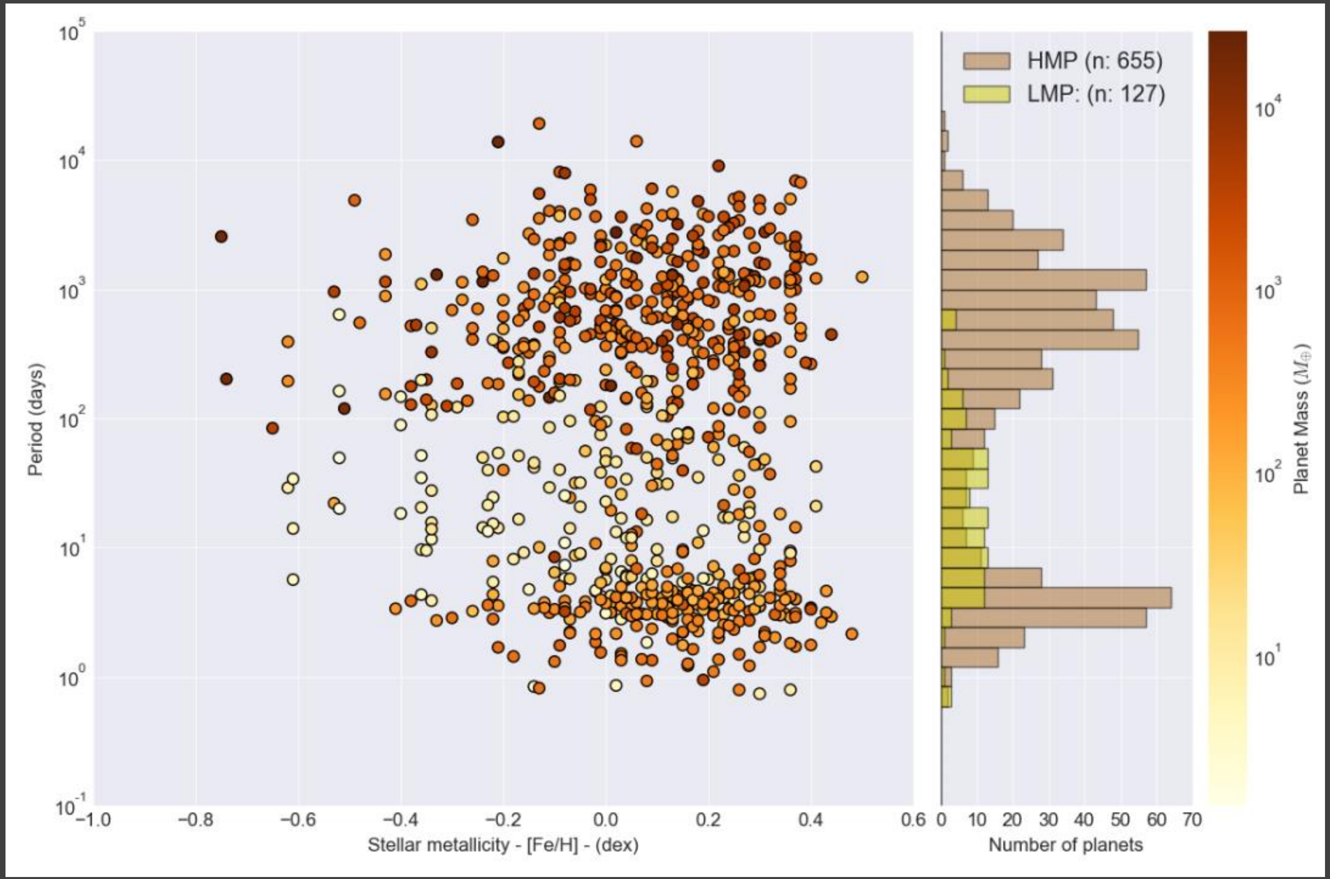




1809.08385

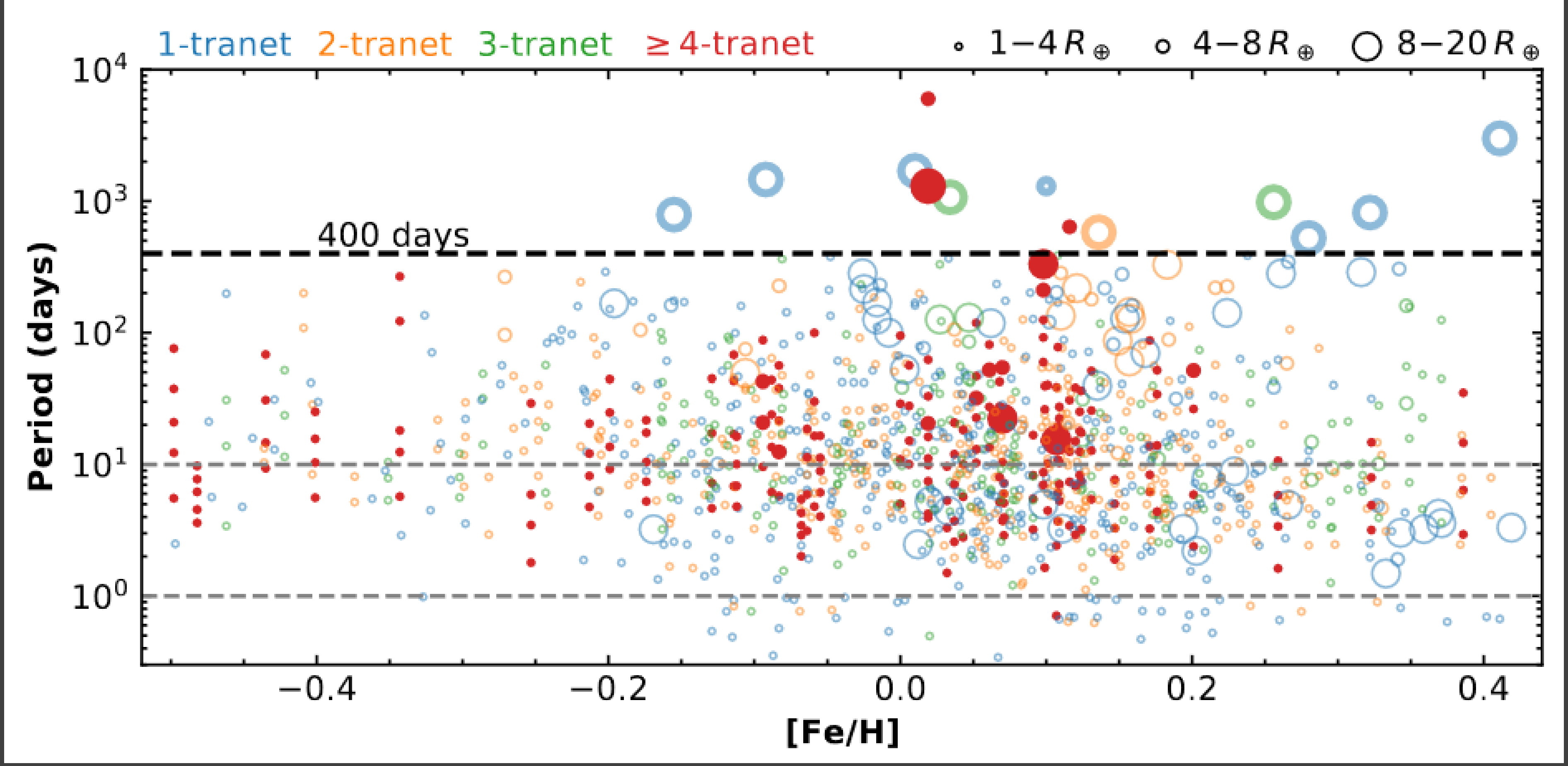
No massive planets around low-metallicity stars





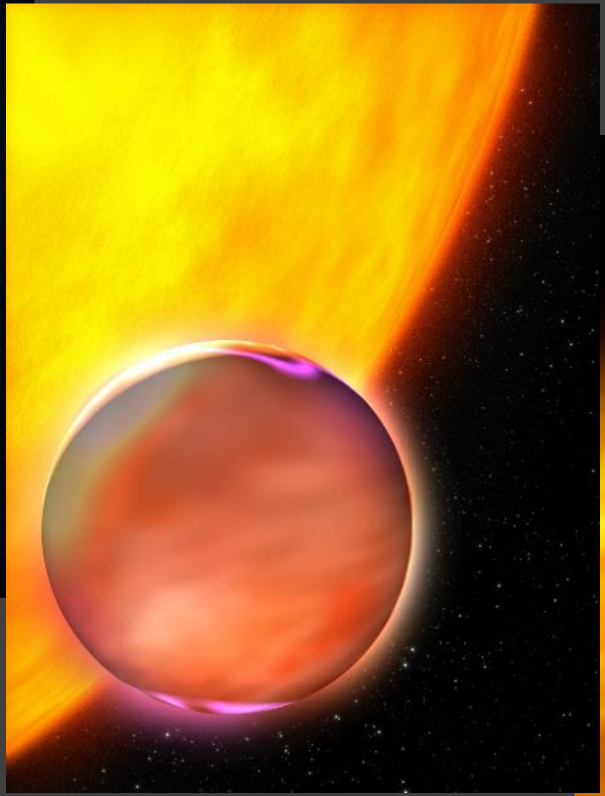
1903.04937

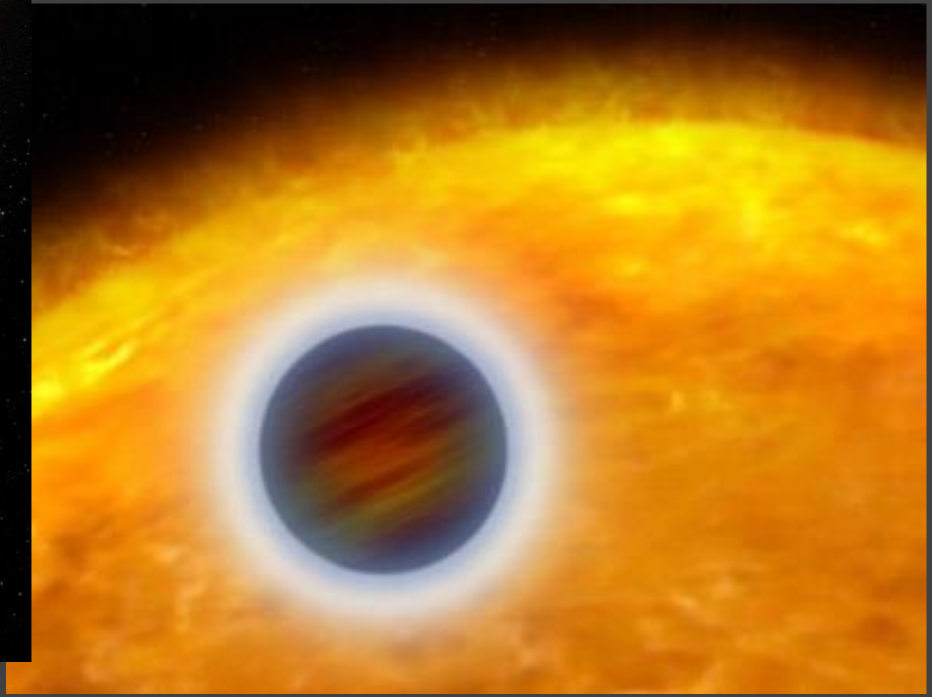
Metallicity effect



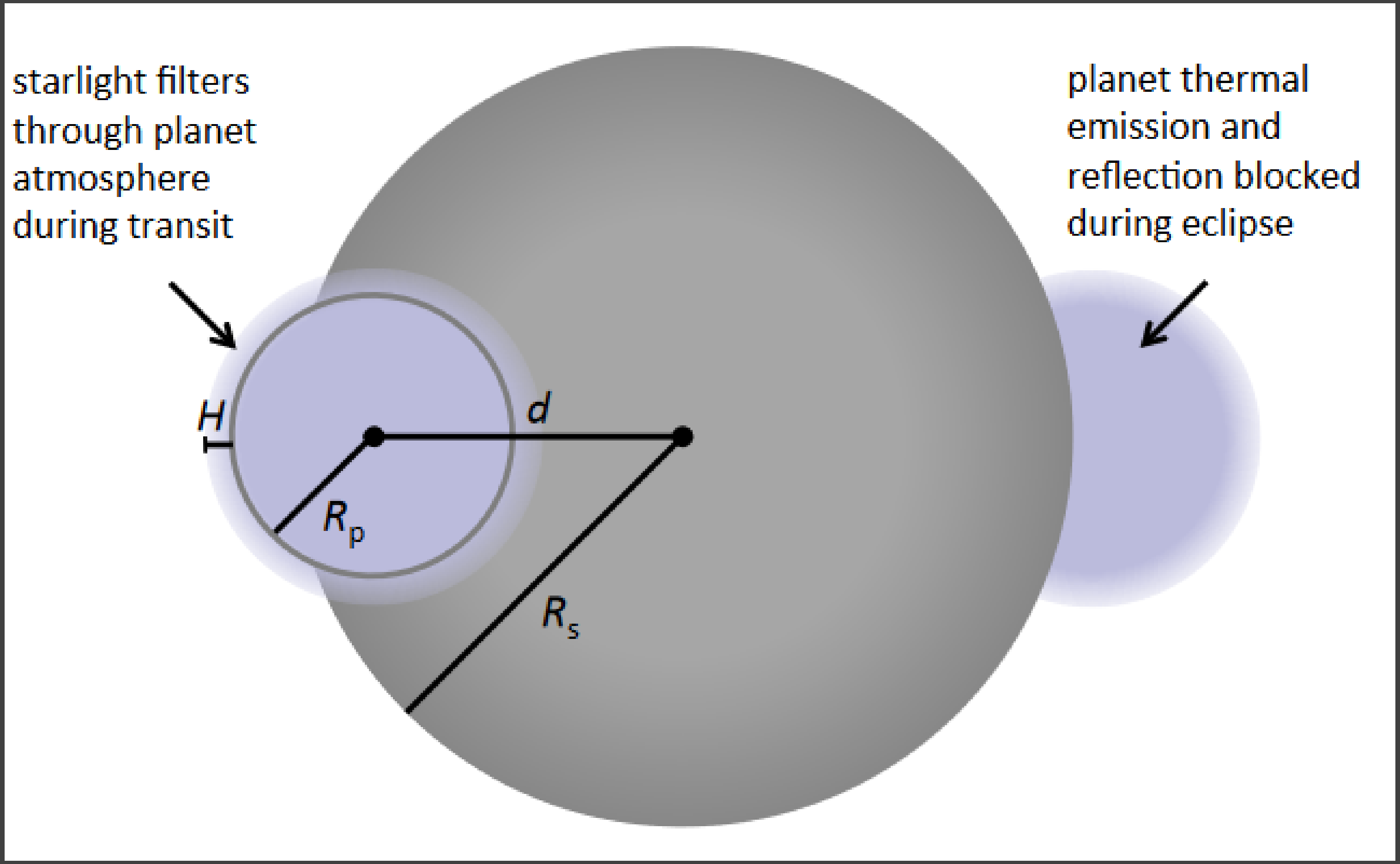
2103.02127

Atmospheres

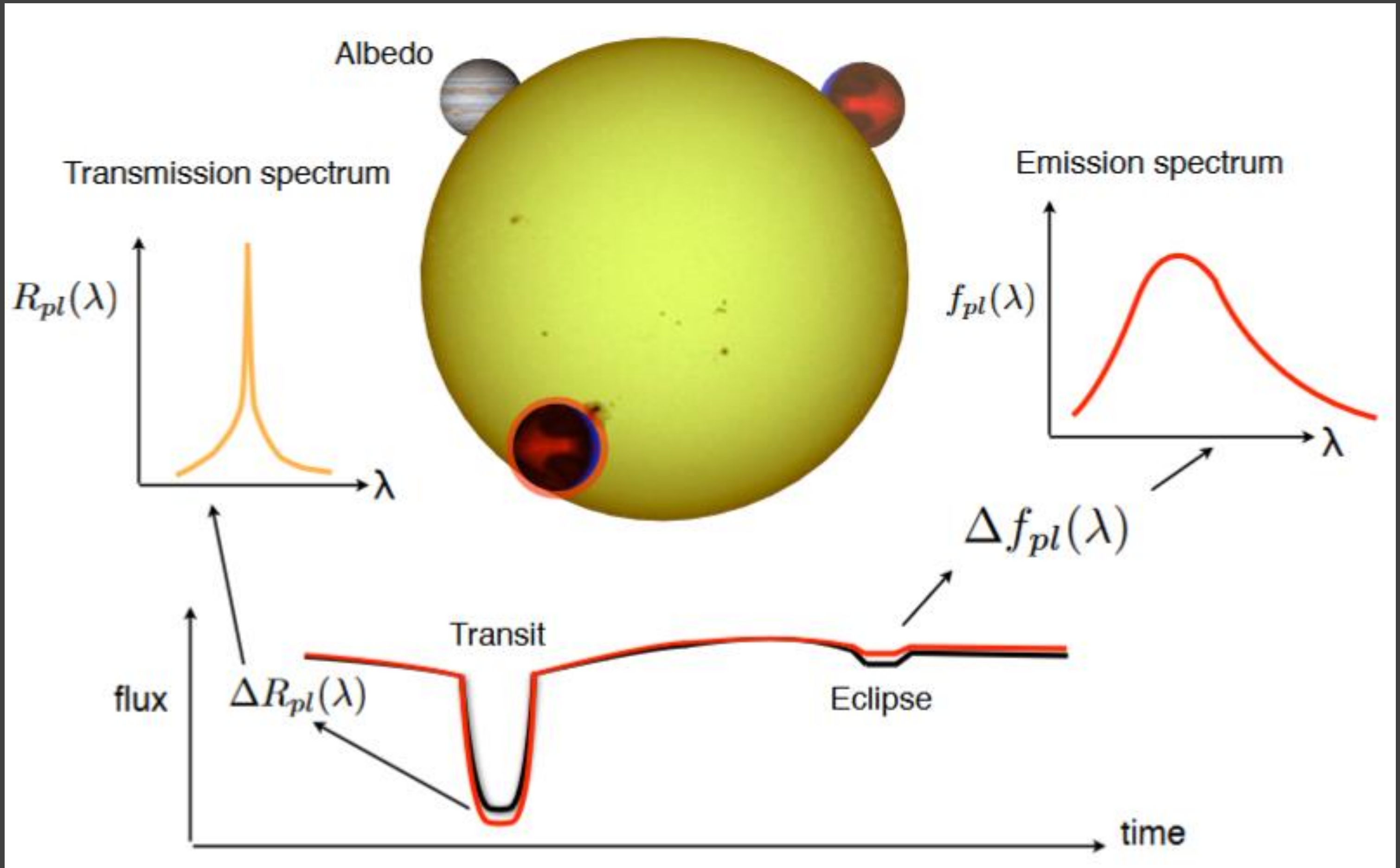




Transits and atmosphere studies



Planet studies during transits

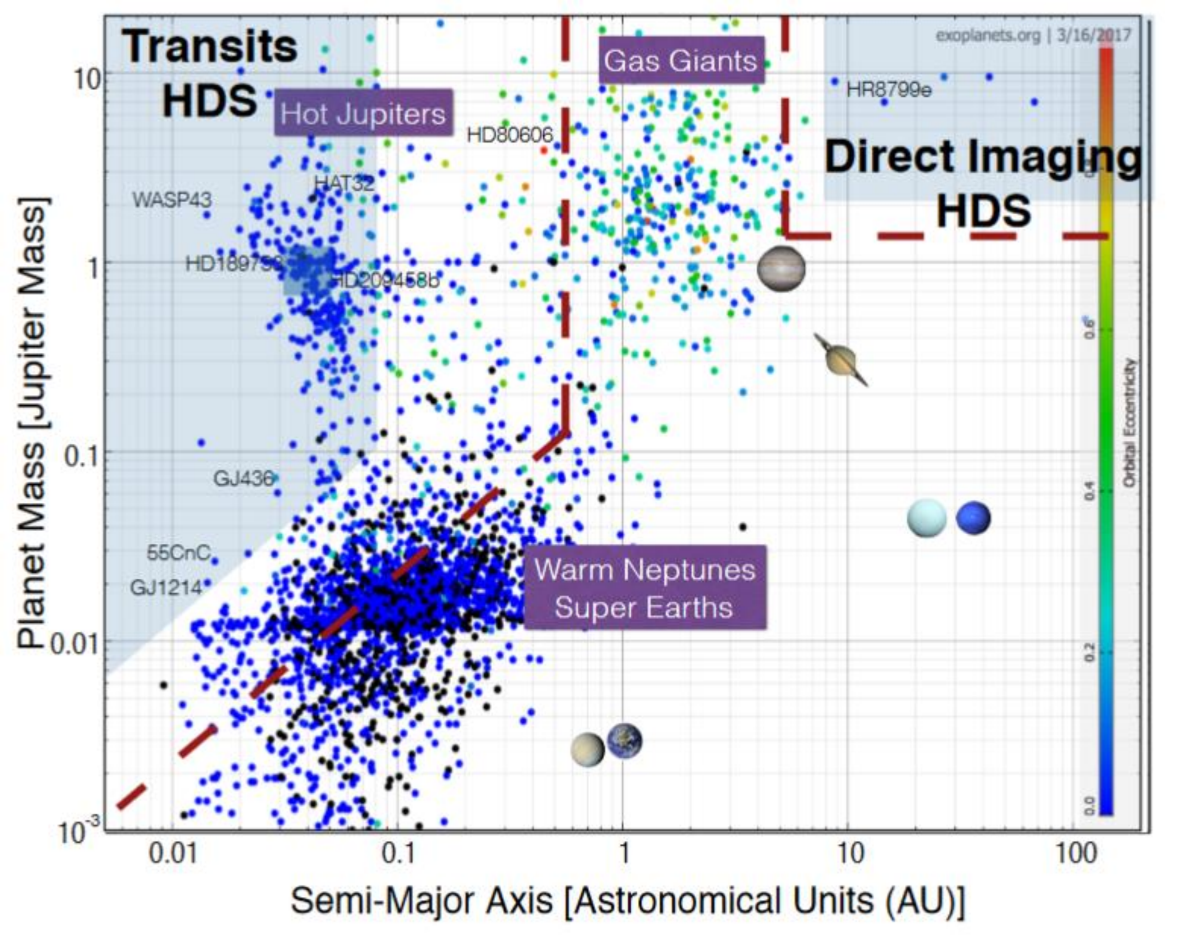


- Integrated properties of the surface (albedo)
- Transmission spectrum
- Emission spectrum
- Mapping

See a review in 1810.04175

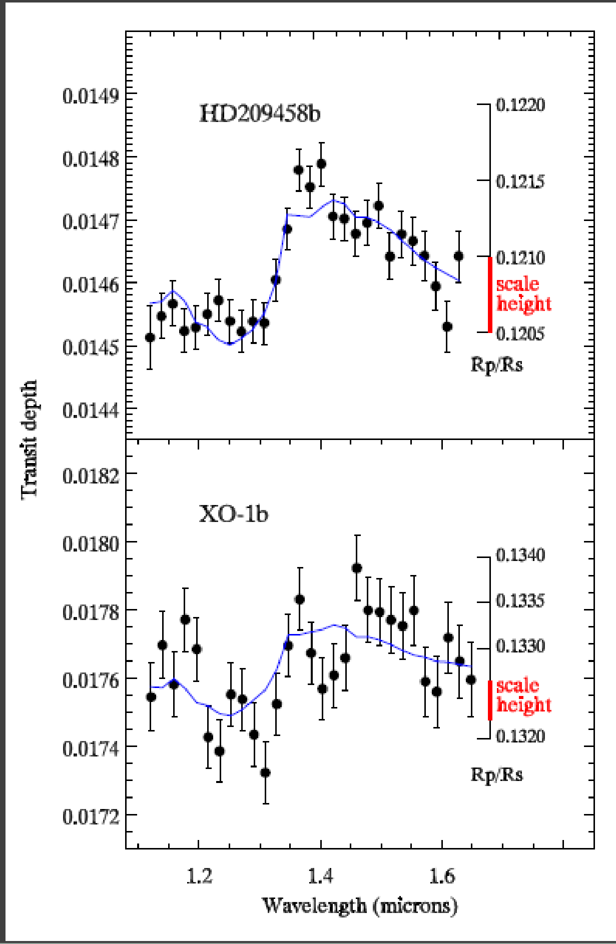
1804.07357

Sensitivity of the method



It is easier to detect the signal from planets around M-dwarfs due to a smaller stellar radius.

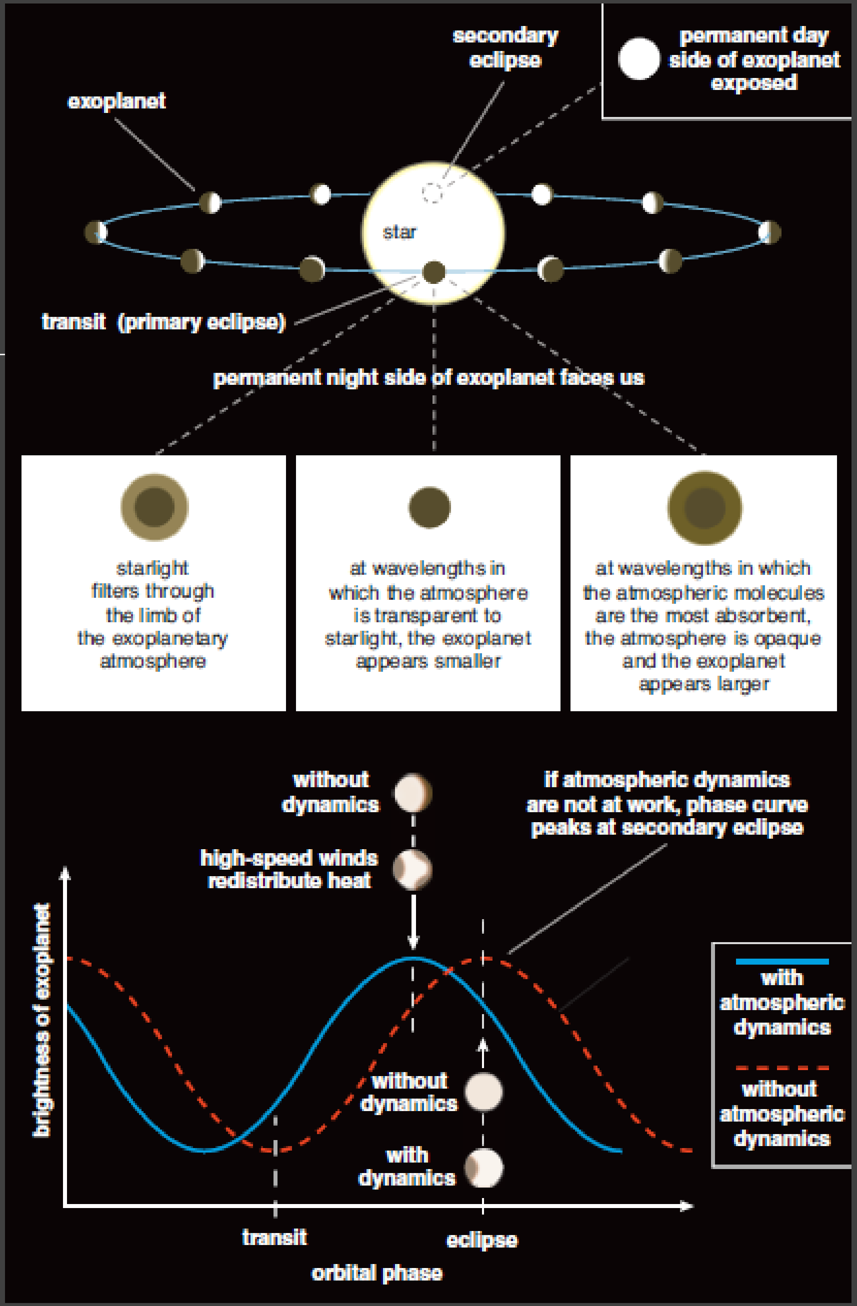
Transits and atmospheres



Transit observations in different wavelengths allow to determine properties of the planet atmosphere.

Size can be different in different wavelengths.

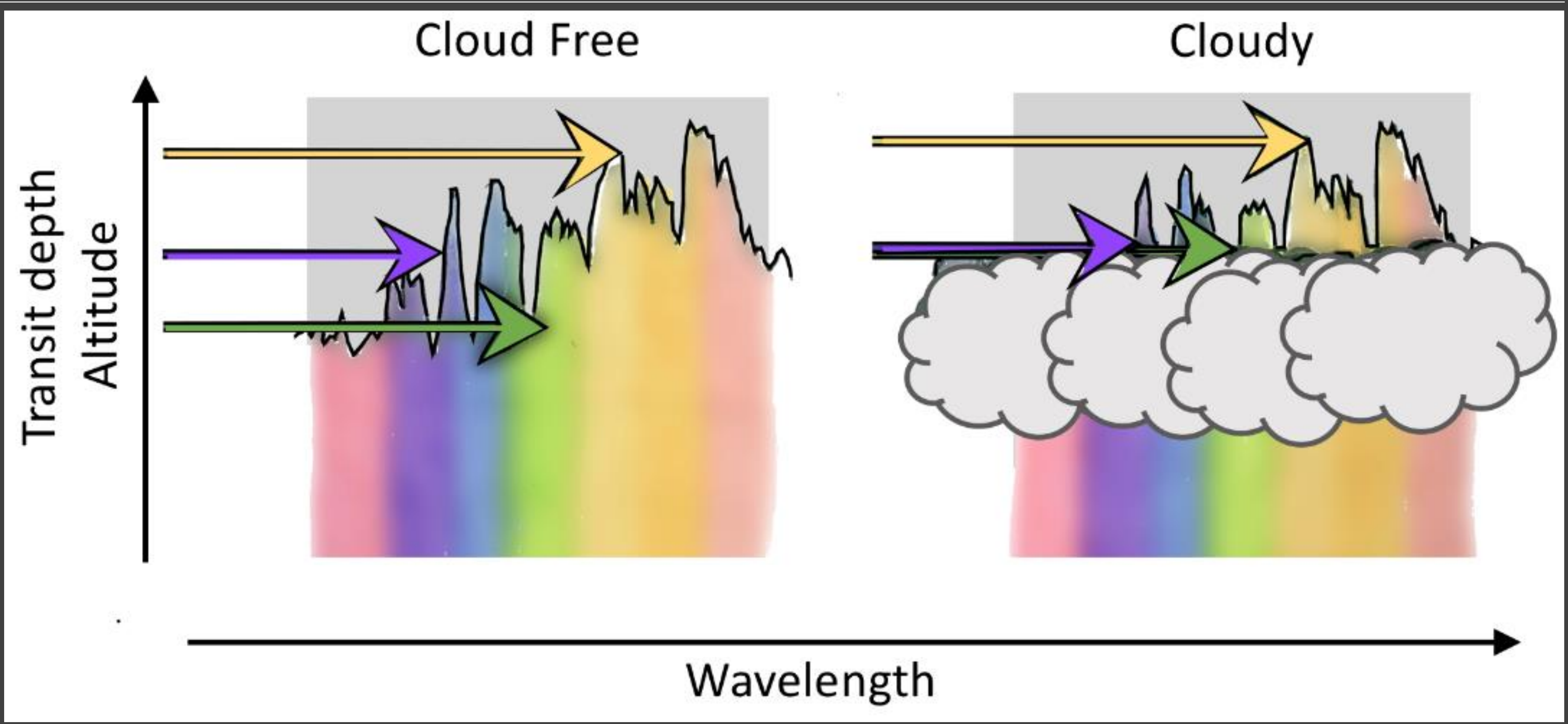
In addition, light curve can look different due to atmospheric dynamics. Heat redistribution due to strong winds modifies the flux from the planet.



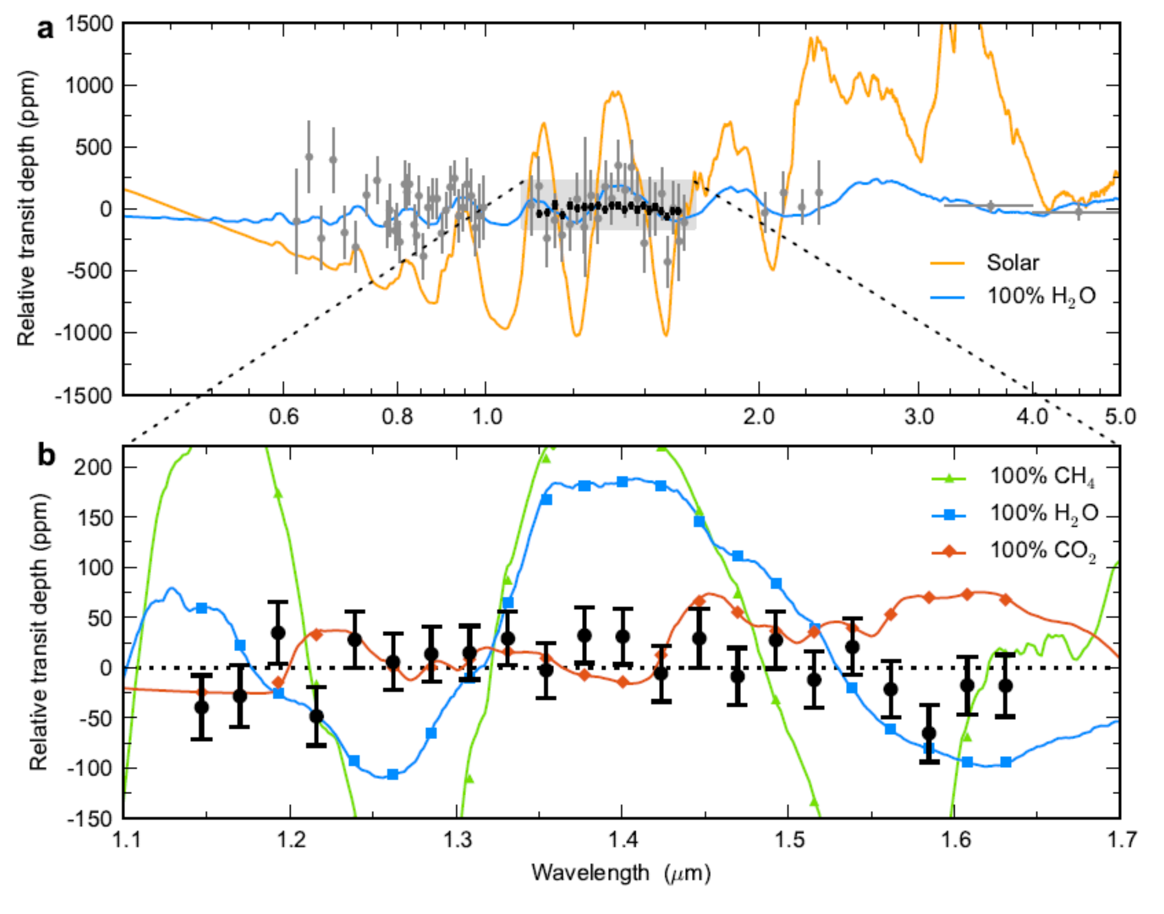
1302.1141

1407.4150

Obscured by clouds



Featureless spectrum of GJ 1214b



Obscured by clouds.

Hubble space telescope spectrum shows no details.

This is interpreted as the result of the presence of a thick cloud layer in the outer atmosphere of the planet.

Phase dependence

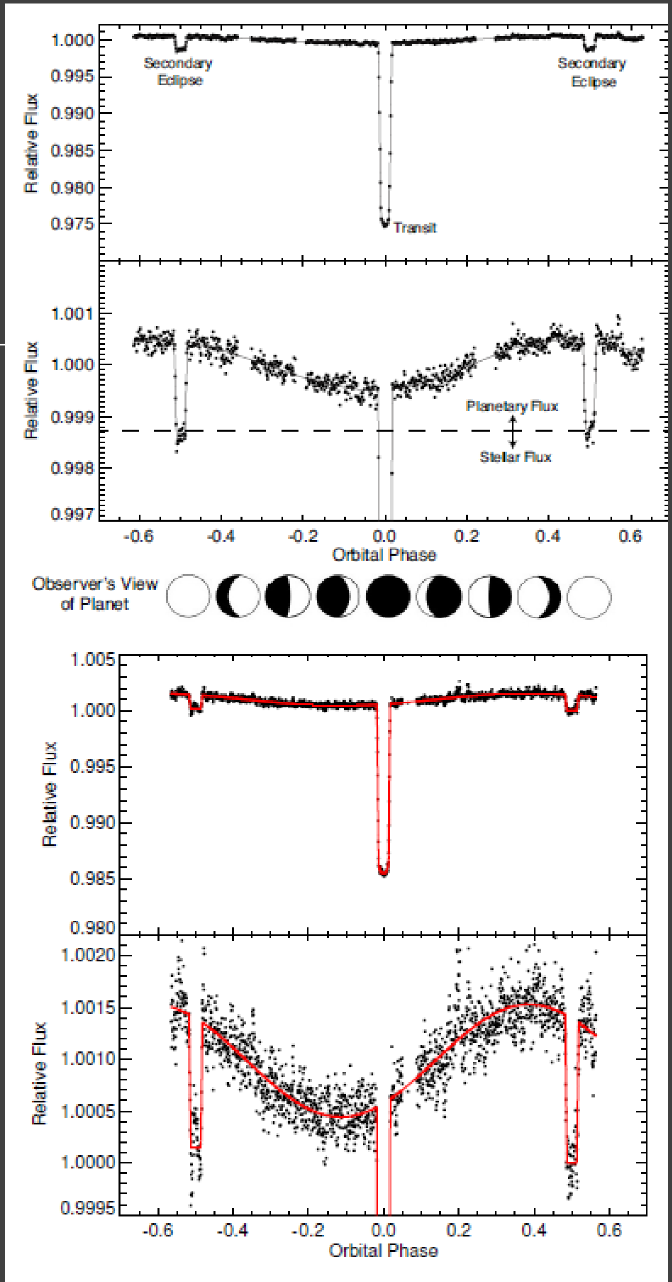
Depending on the phase we observe different parts of a disc.

Results of observations correspond to:

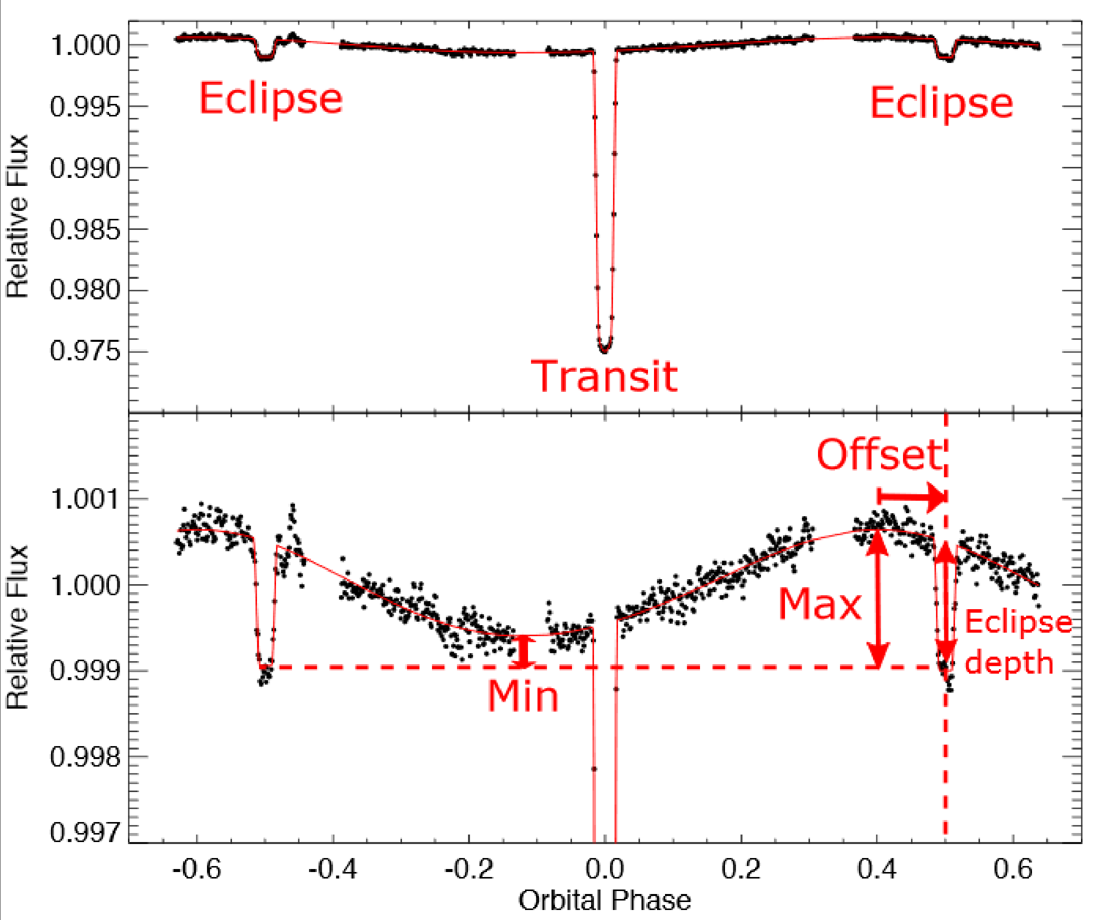
HD 189733b – upper panel;
HD 209458b – lower panel.

Both planets are hot jupiters.

Note, that in the case of HD 209458b planetary disc
is strongly non-symmetric in terms of the emitted flux.

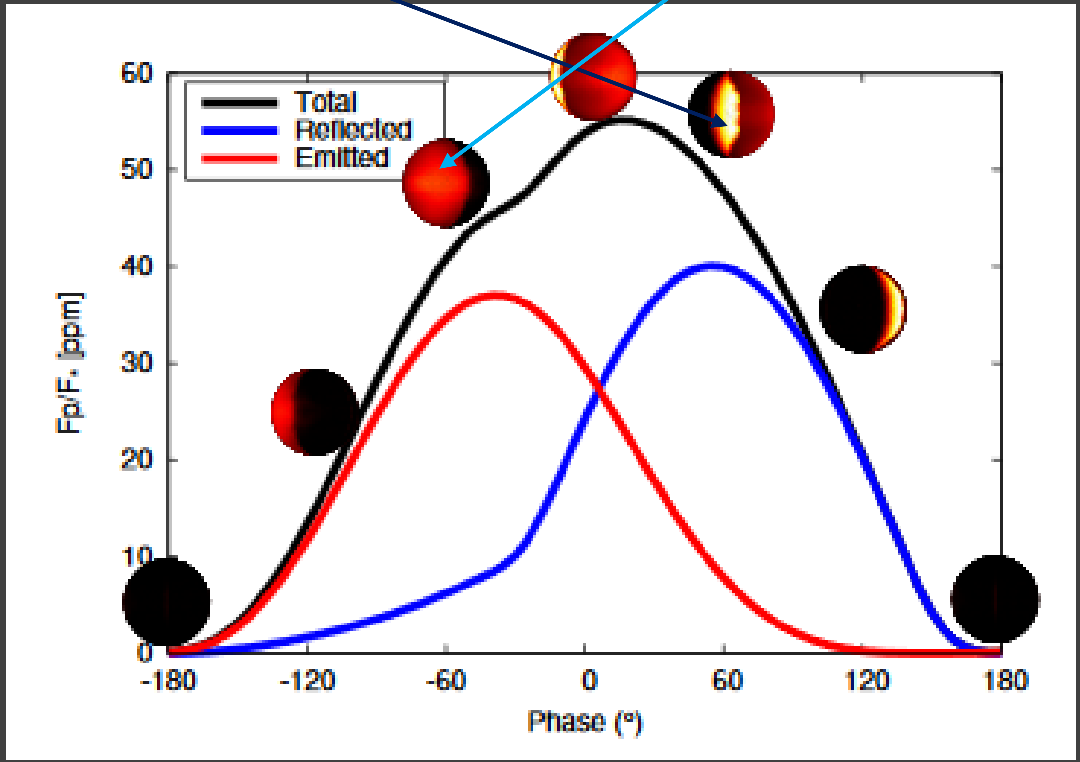


Phase light curves



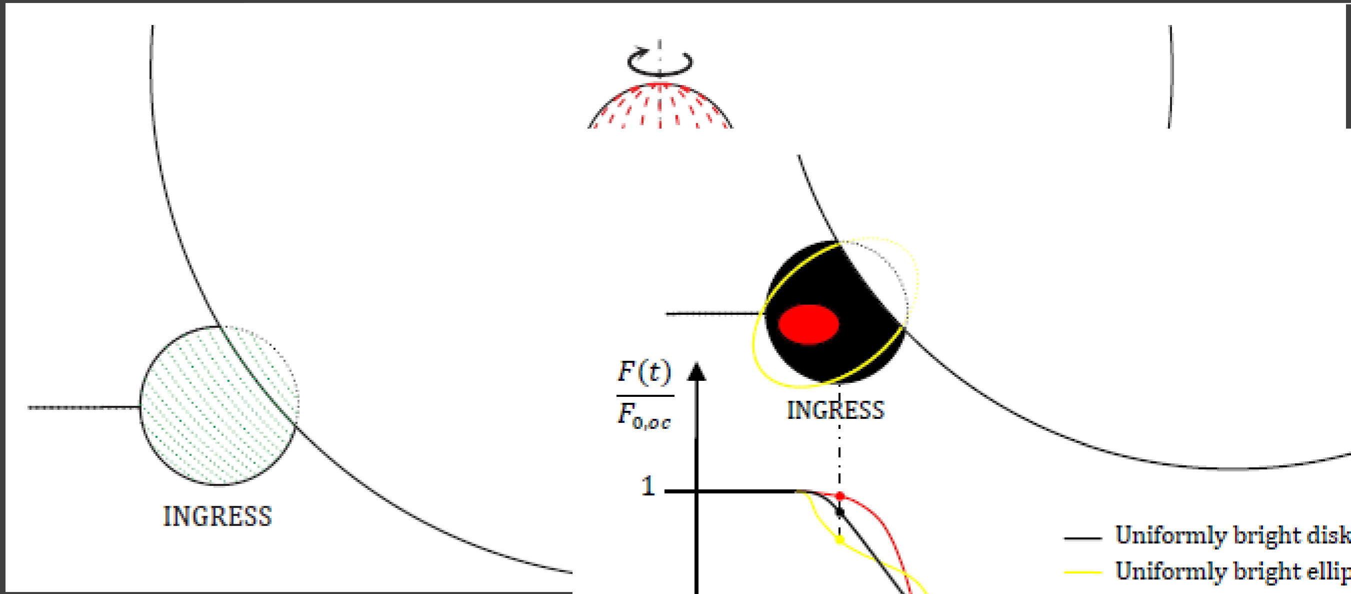
Bright cloud reflect light

Global winds produce non-symmetric temperature distribution



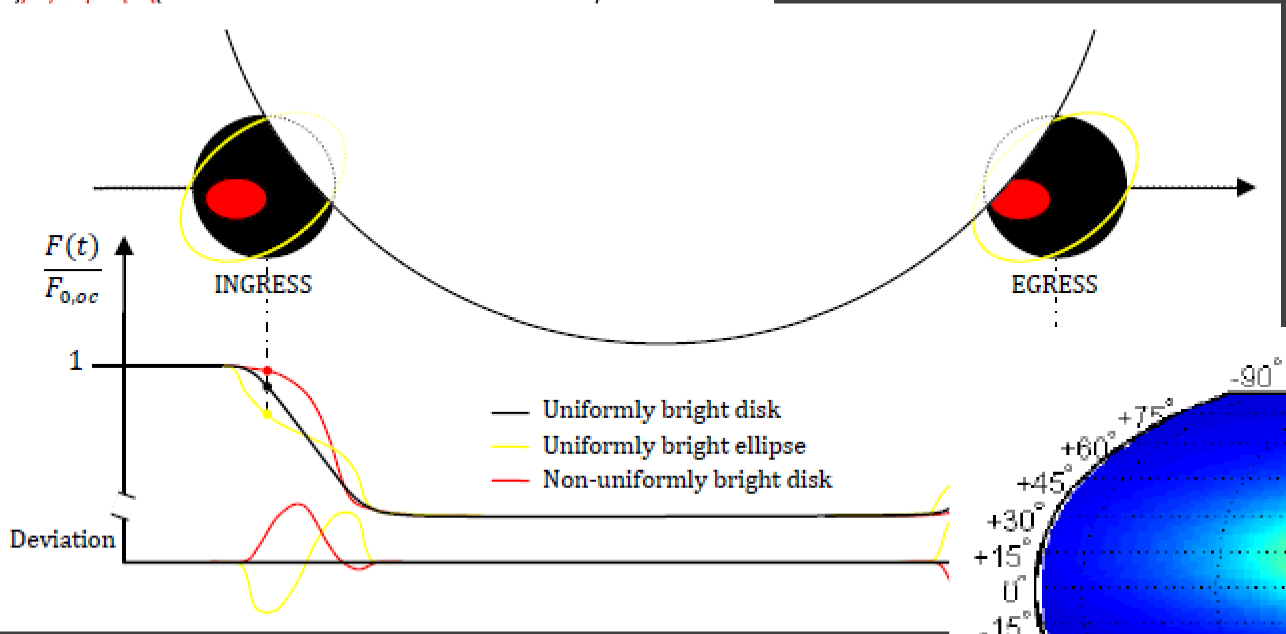
1711.07696

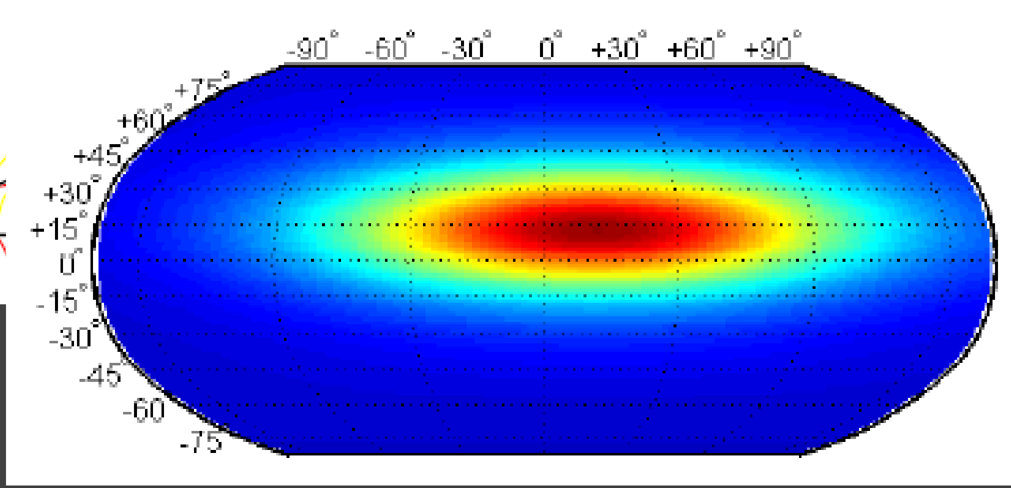
Scanning planetary discs



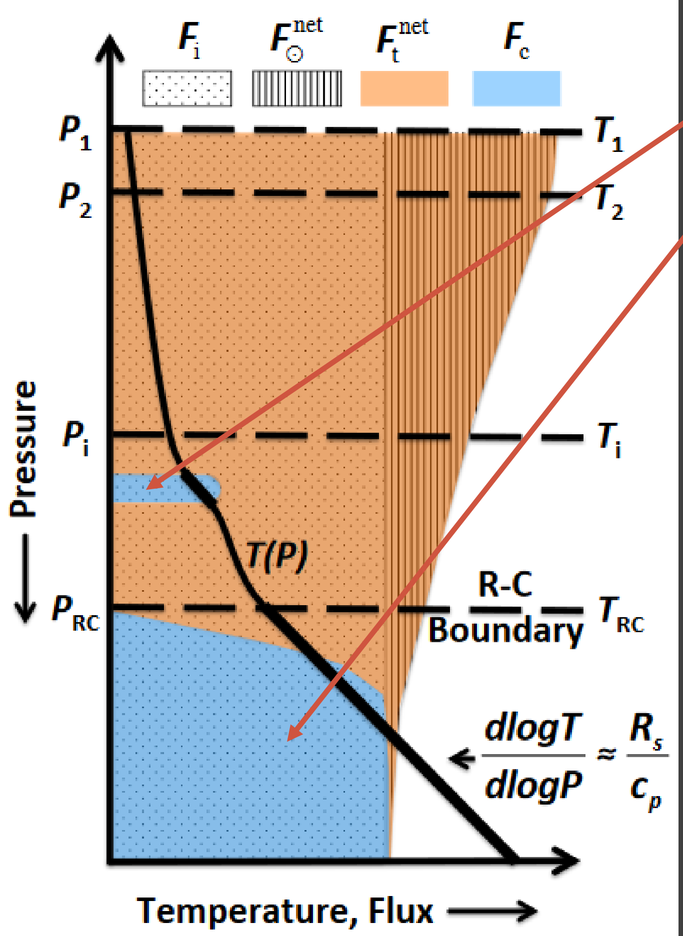
Spitzer space telescope

HD189733b

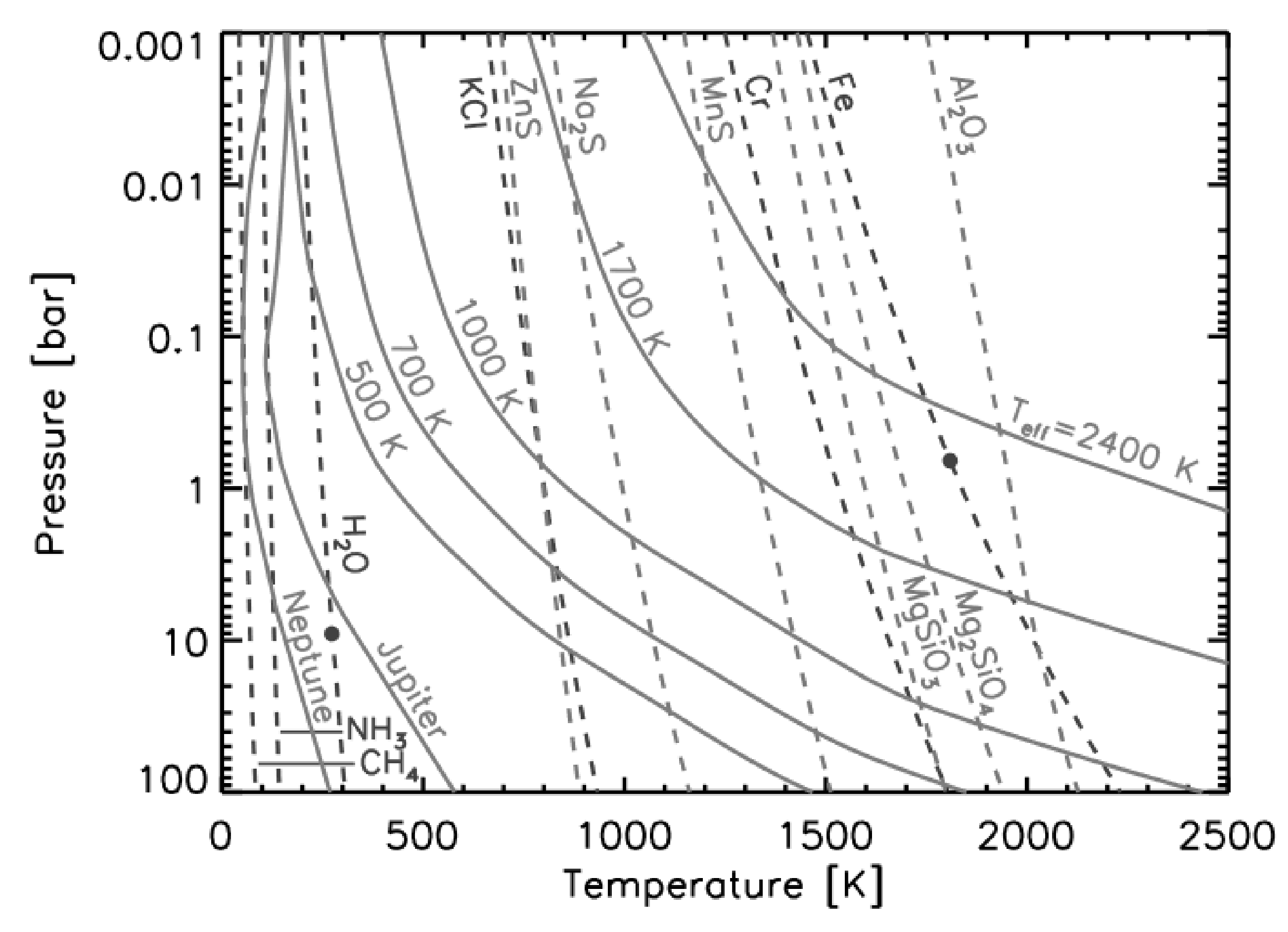




Modeling of planets atmospheres

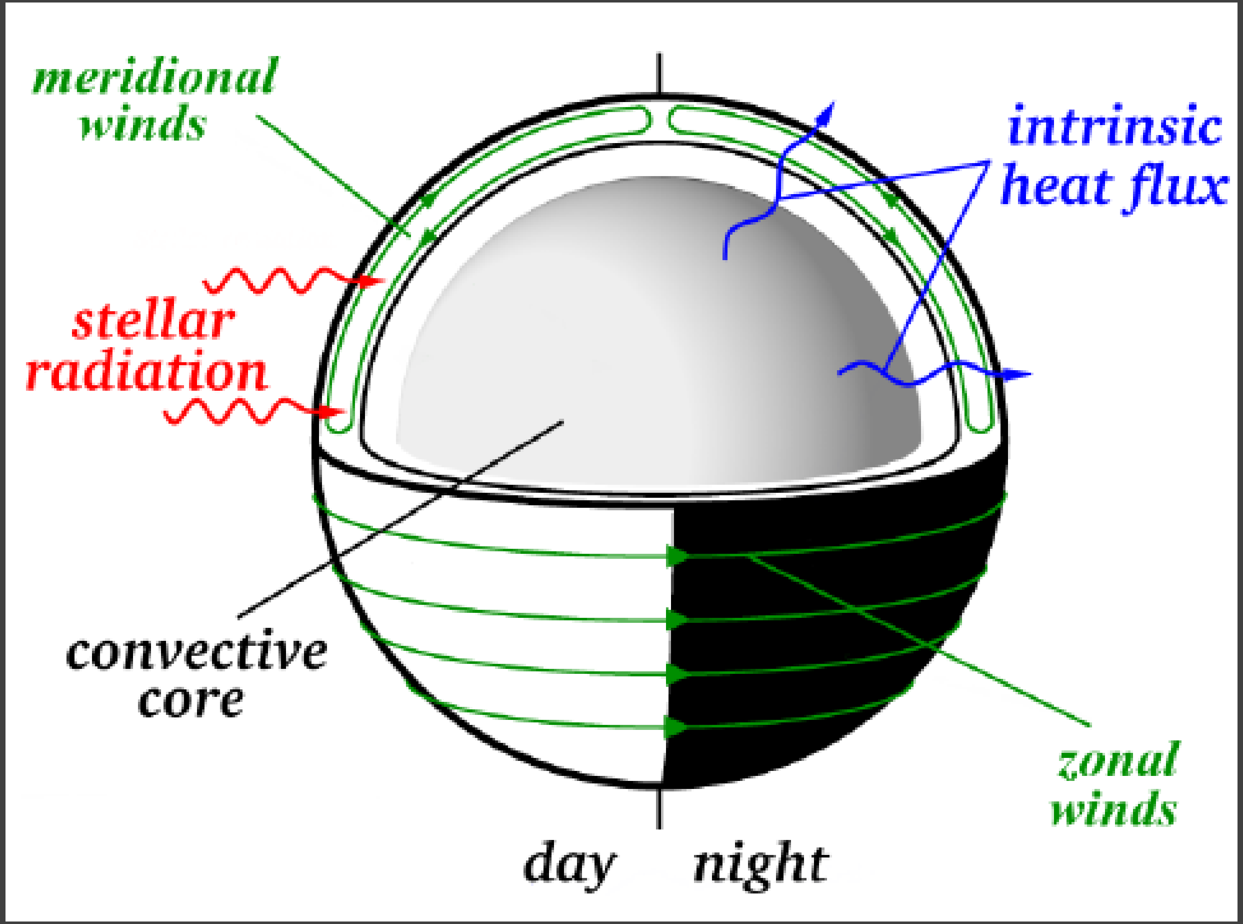


Convection



1804.08149

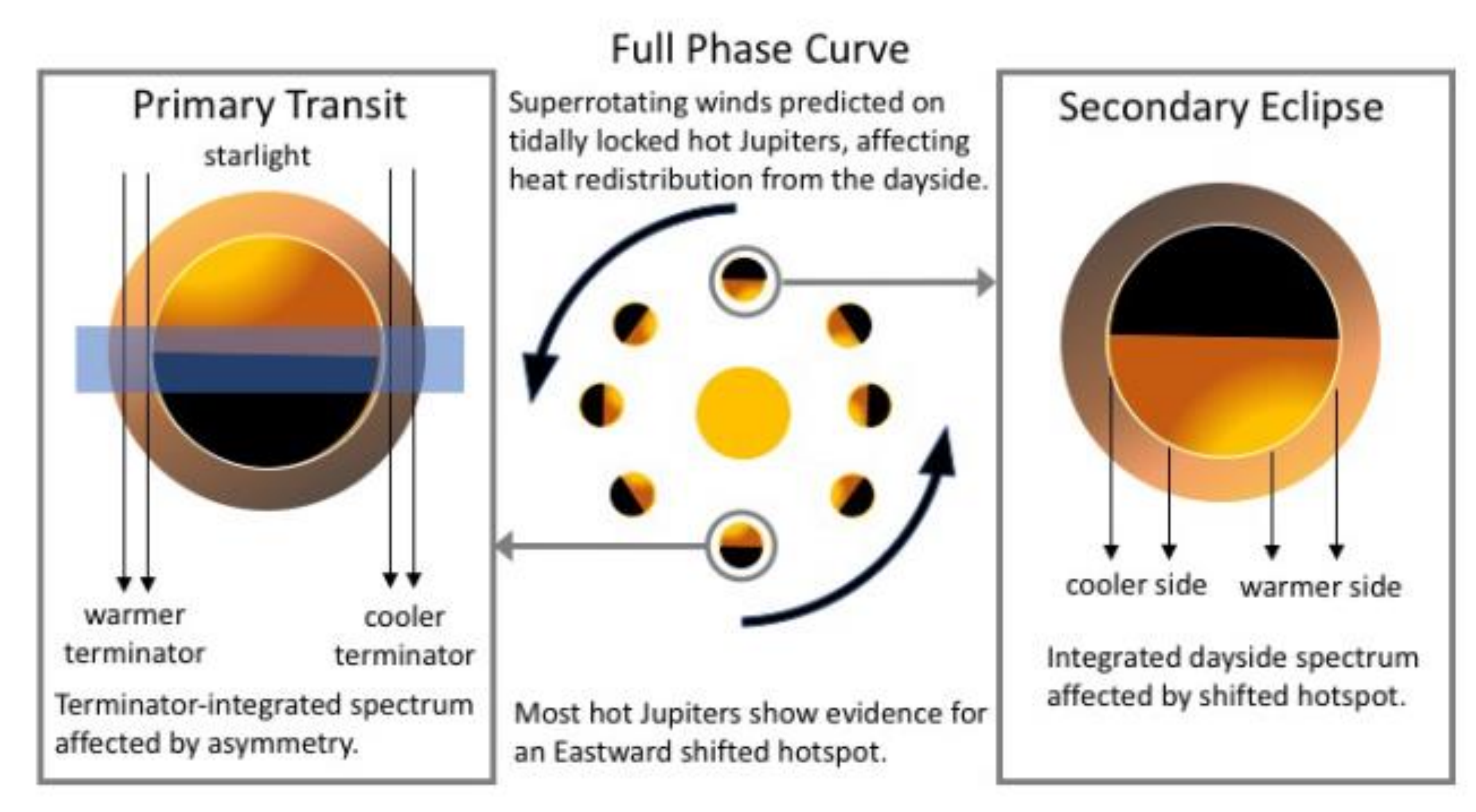
Dynamics of outer layers of hot jupiters



Planet has internal and external heat sources.

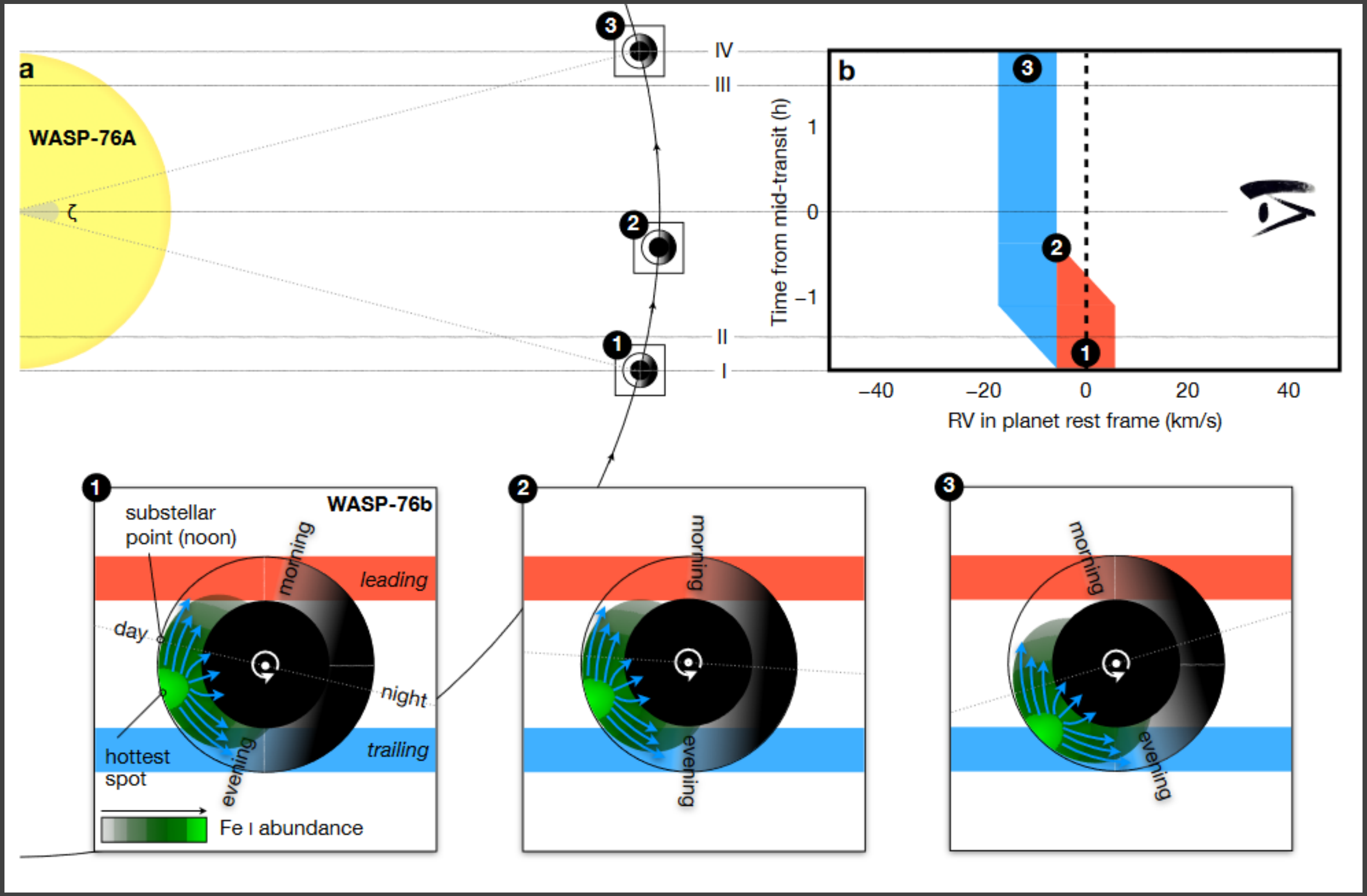
This results in violent winds and convection in the outer gas envelope.

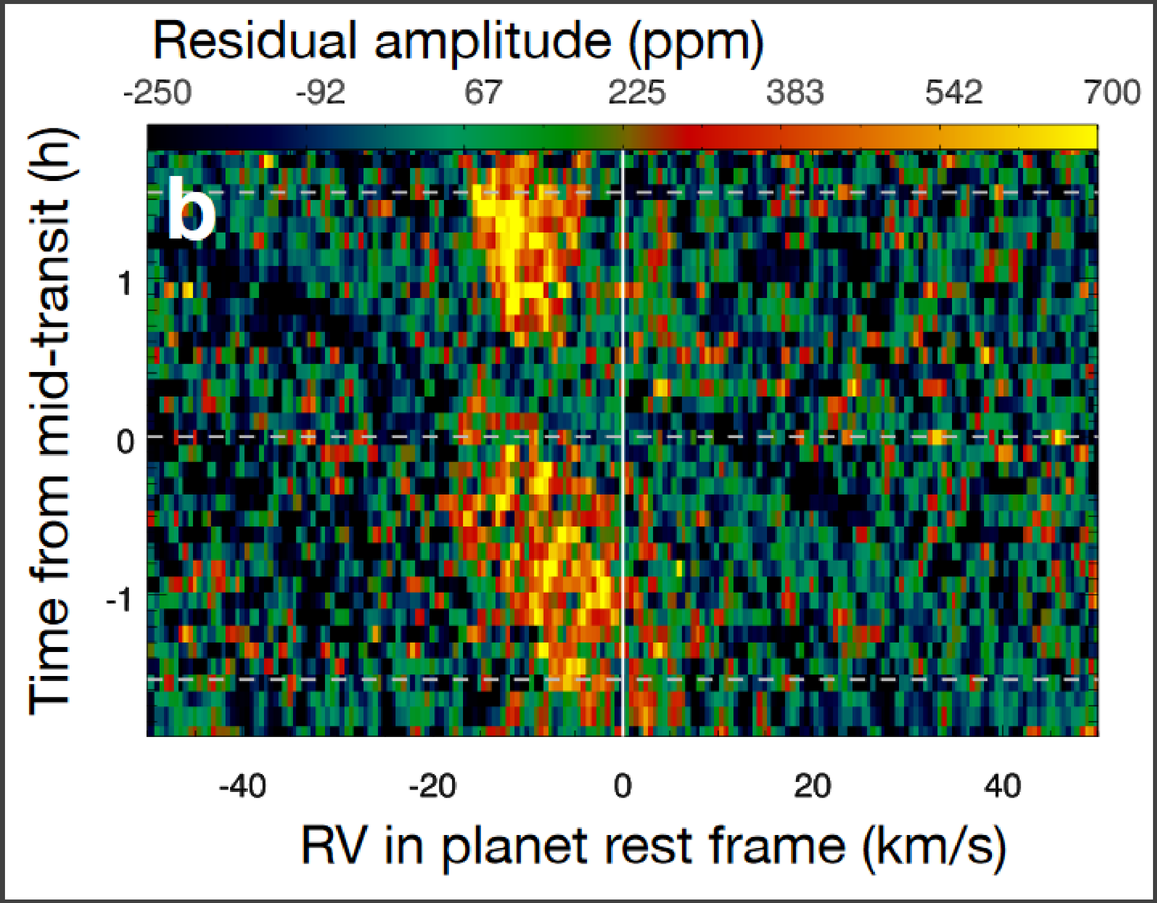
Shift of the hottest point from the noon point



2003.14311

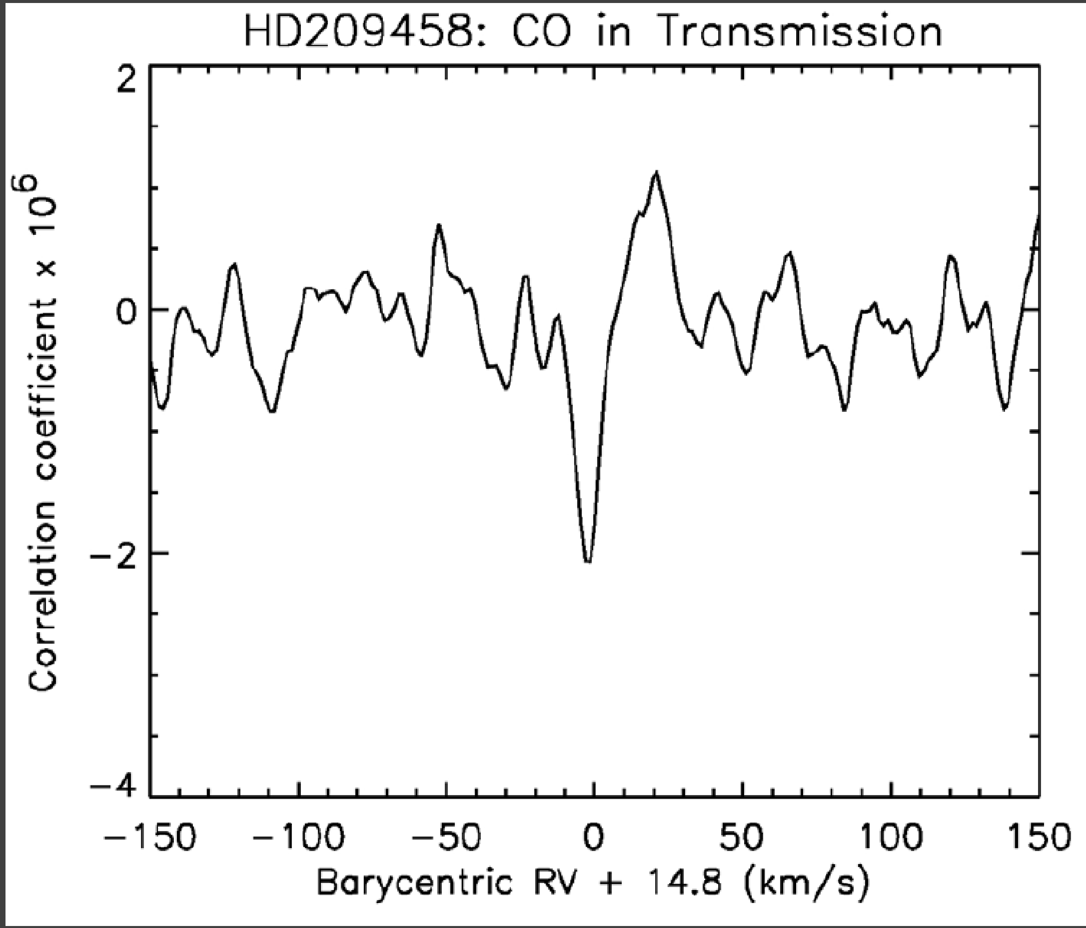
Nightside condensation of iron





2003.05528

Wind on HD 209458

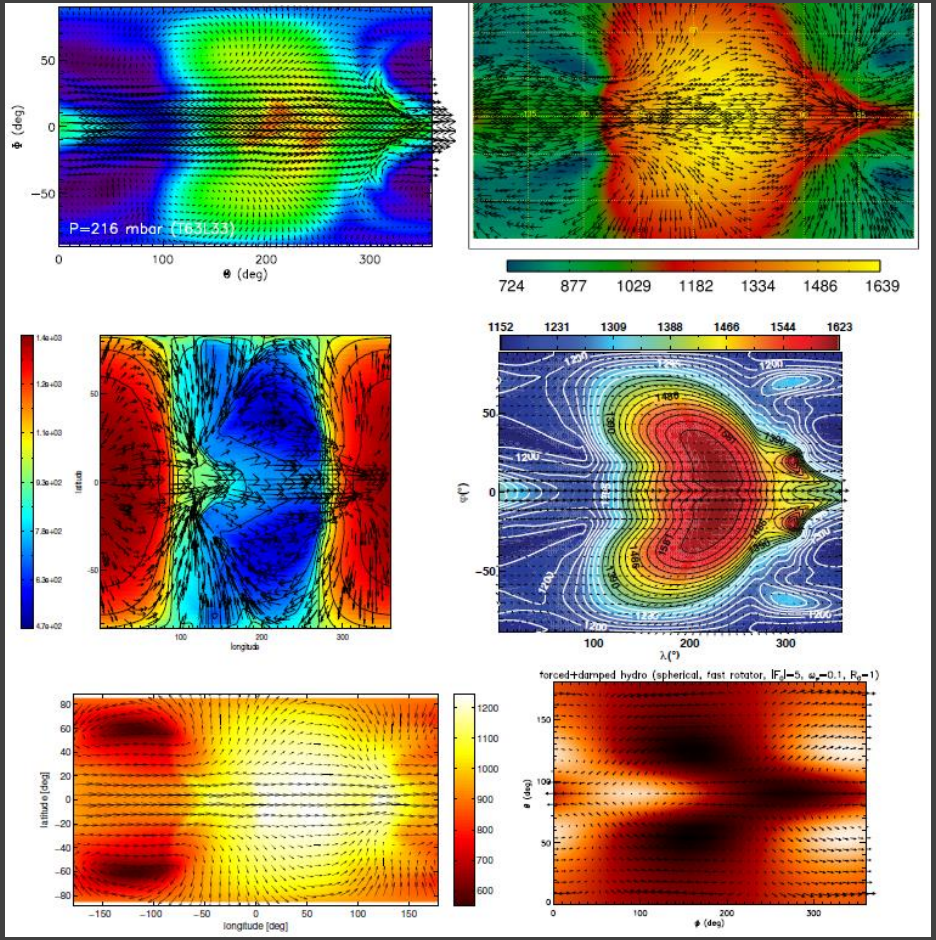


Wind velocity can be directly (!) measured.

The planet is a VERY hot Jupiter.

Wind velocity is ~ 2 km/s
(line is blueshifted by 2 km/s)

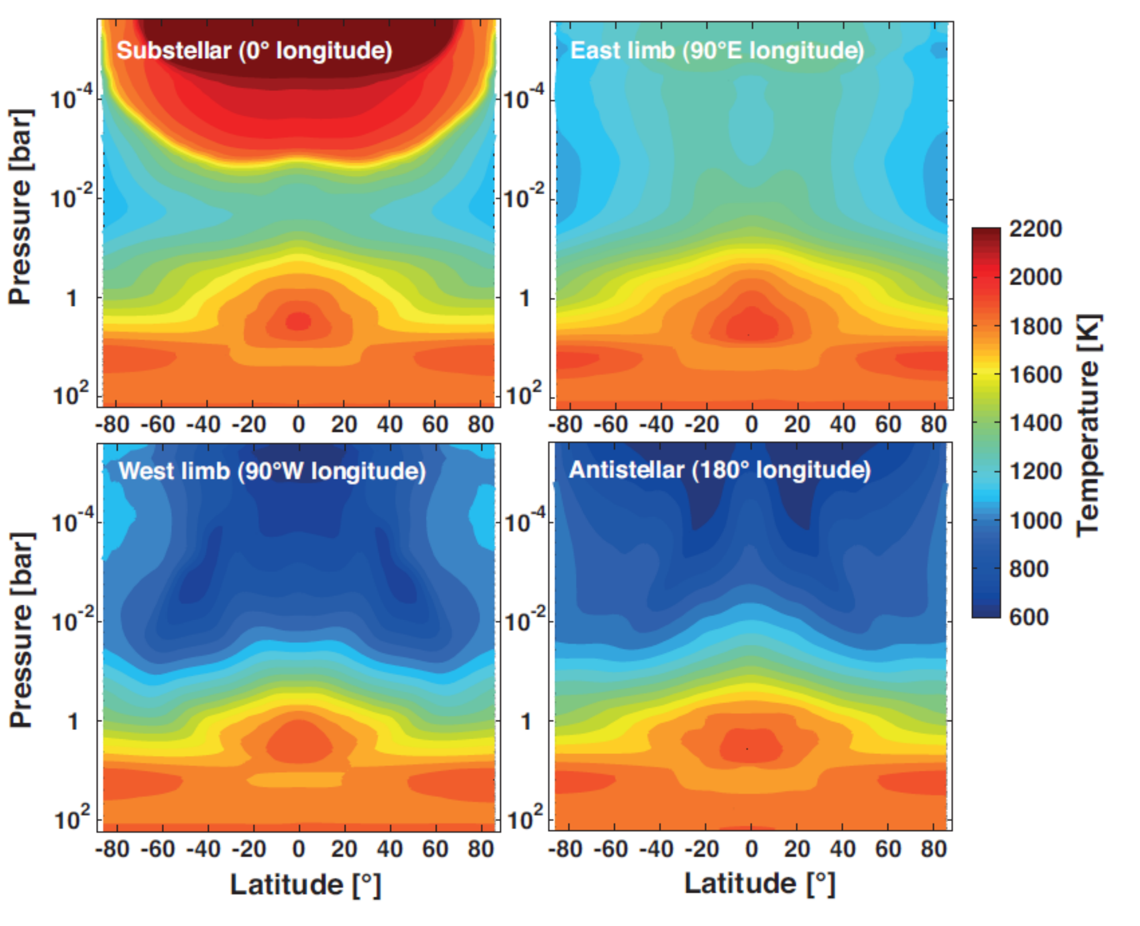
Modeling winds on hot jupiters

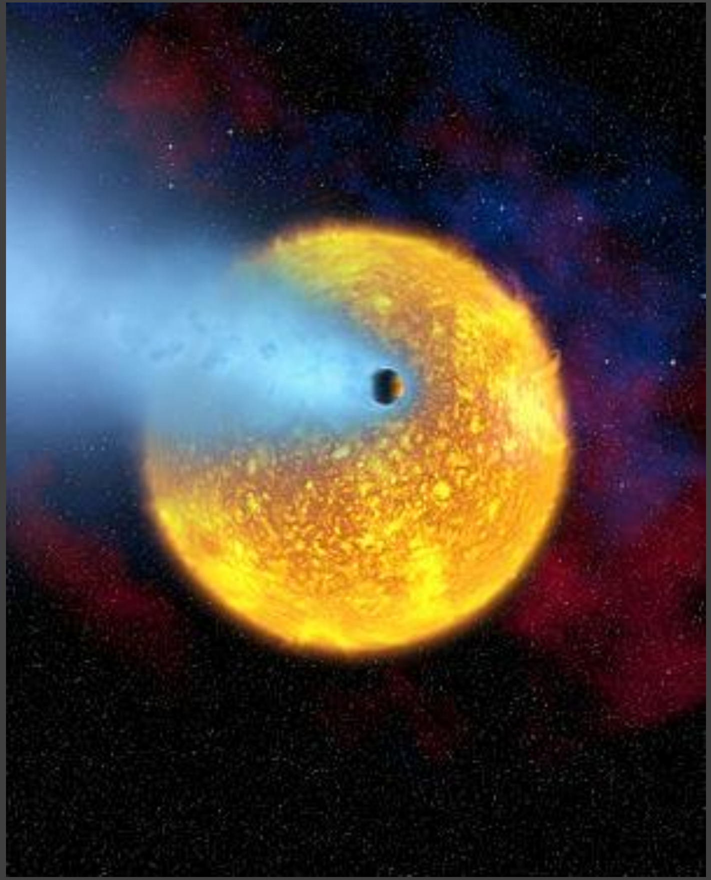


General property:

Strong equatorial wind from the West to the East.

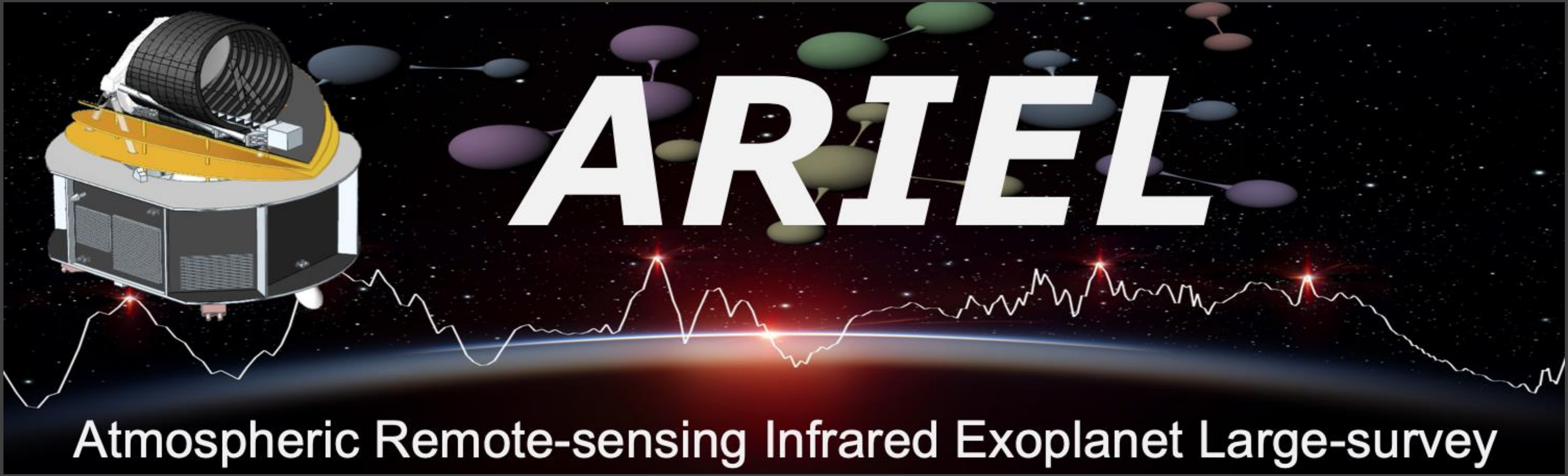
Modeling of HD209458 b





Osiris

Ariel

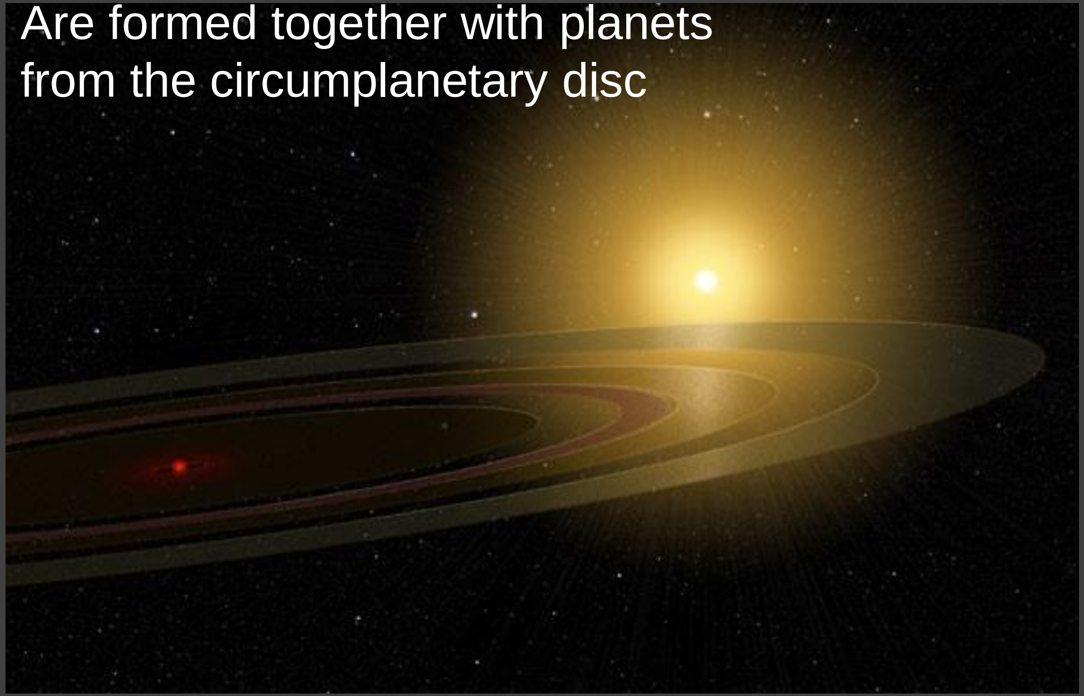


~1-meter telescope. ~2030 launch. ~1000 exoplanets to study.

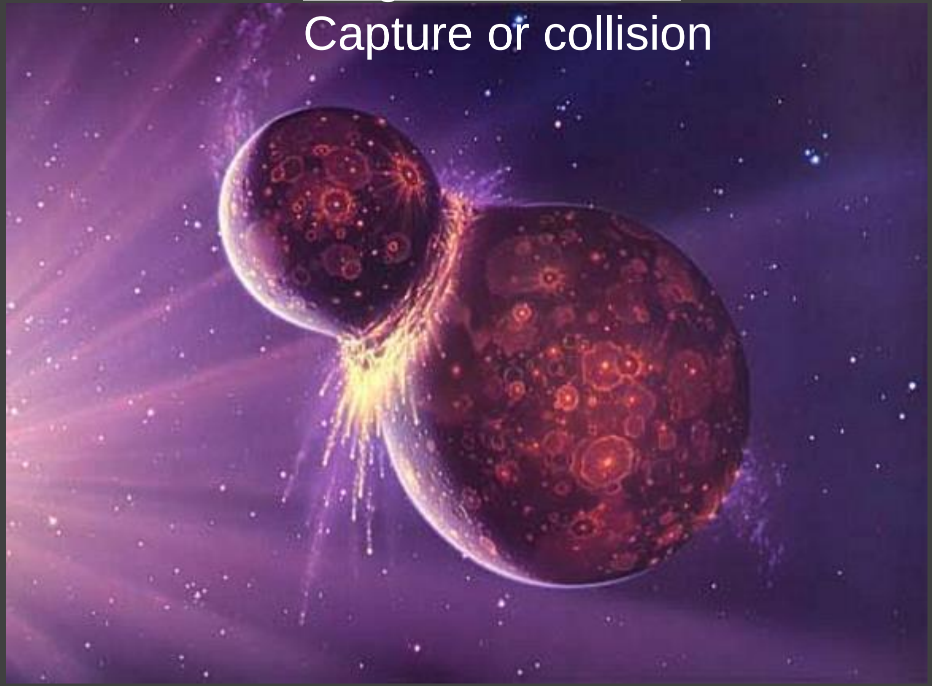
See a review of scientific goals related to atmospheric properties and interior composition in 2103.08481

Exomoons: how to form

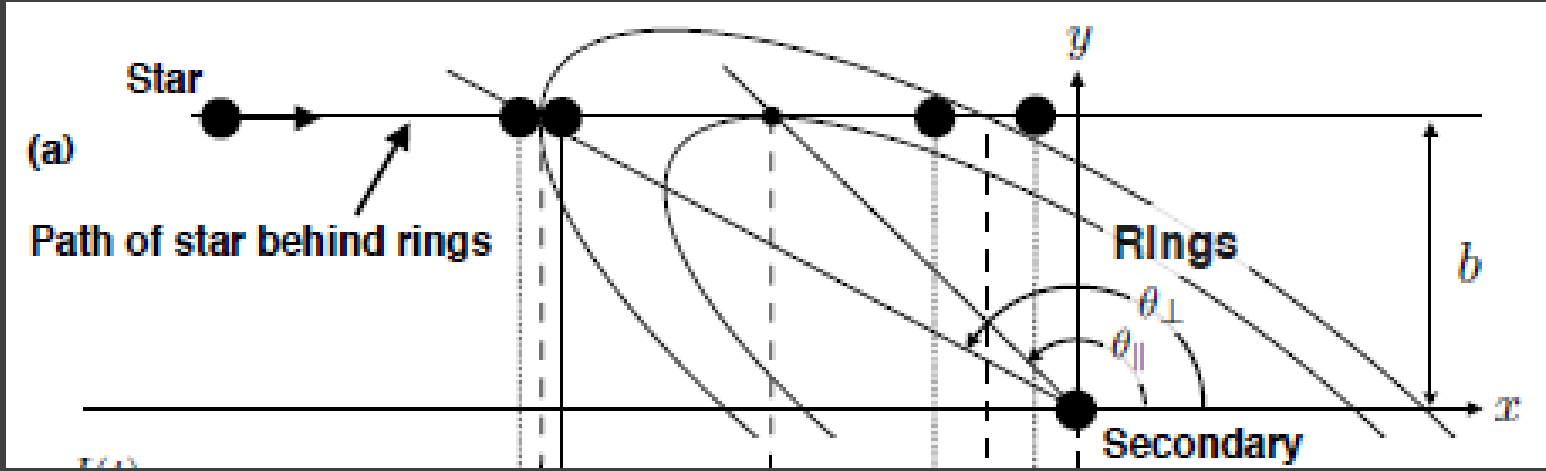
<u>Regular satellites</u>
Are formed together with planets from the circumplanetary disc



<u>Irregular satellites</u>
Capture or collision

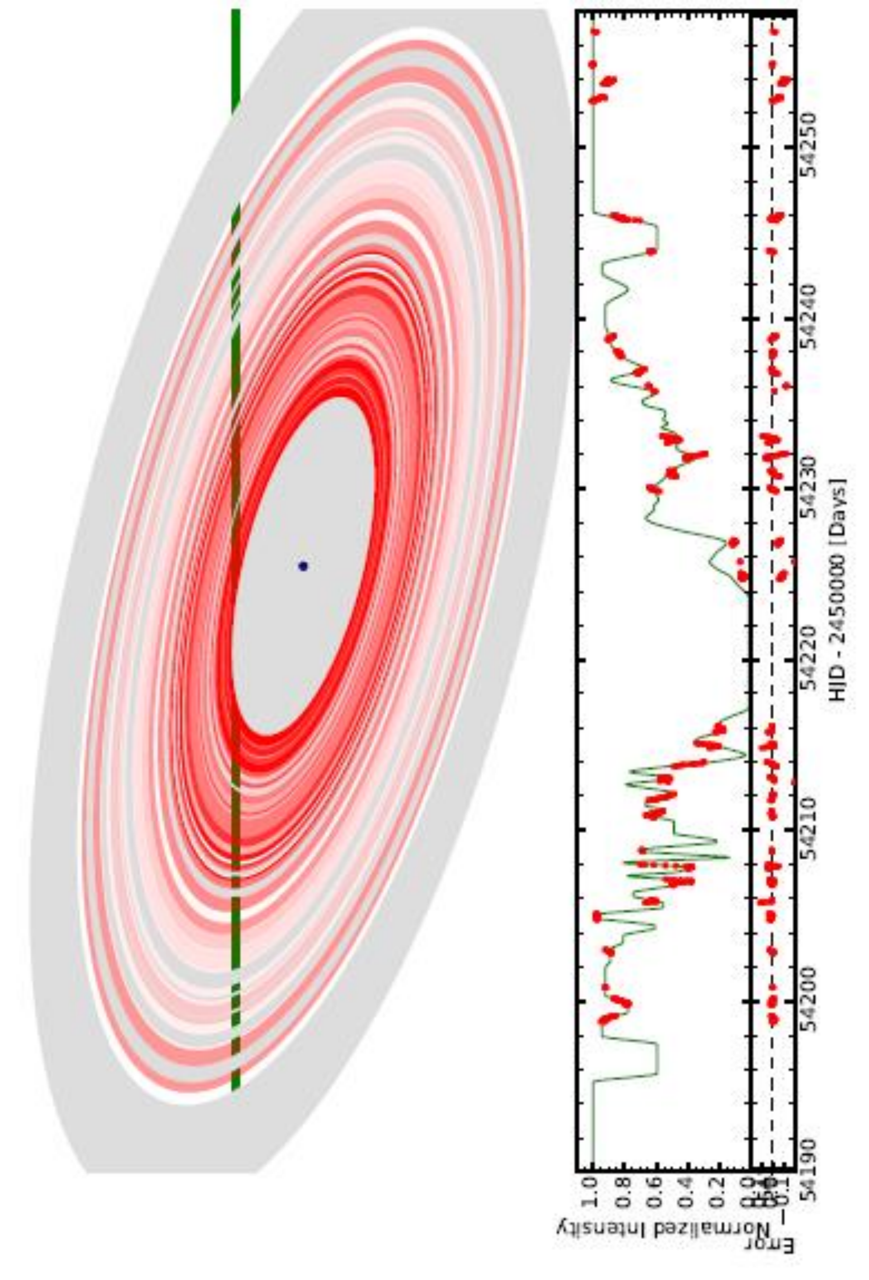


Giant ring system



System of 37 rings extending up to 0.6 AU around a stellar companion.

The star is young (16 Myrs), and so, probably, the system of rings is just forming. Satellites might regulate the shape of the ring system.



Which planets might have detectable satellites?

http://www.freemars.org/jeff/planets/Luna/Luna.htm

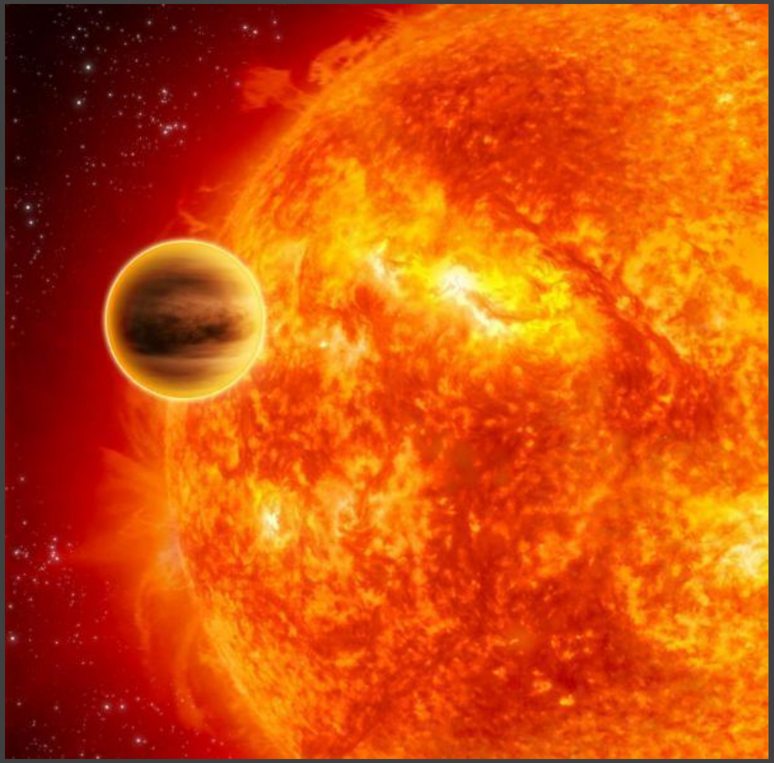
To be large respect to the host-planet
the satellite might be irregular.

Systems with many planets
are more favorable.

Larger planets have larger moons.

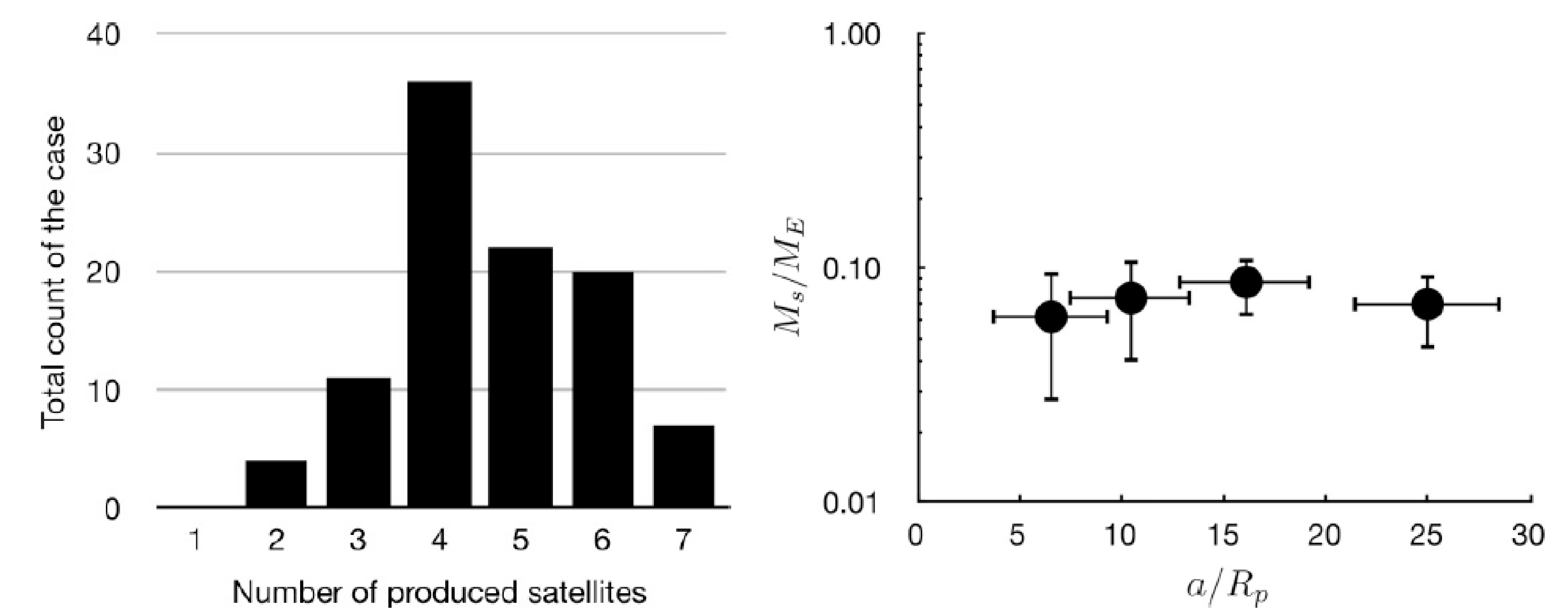
Hot jupiters (and neptunes) can
loose planets during migration.

Stability of exomoon orbits
was studied in 2105.12040.



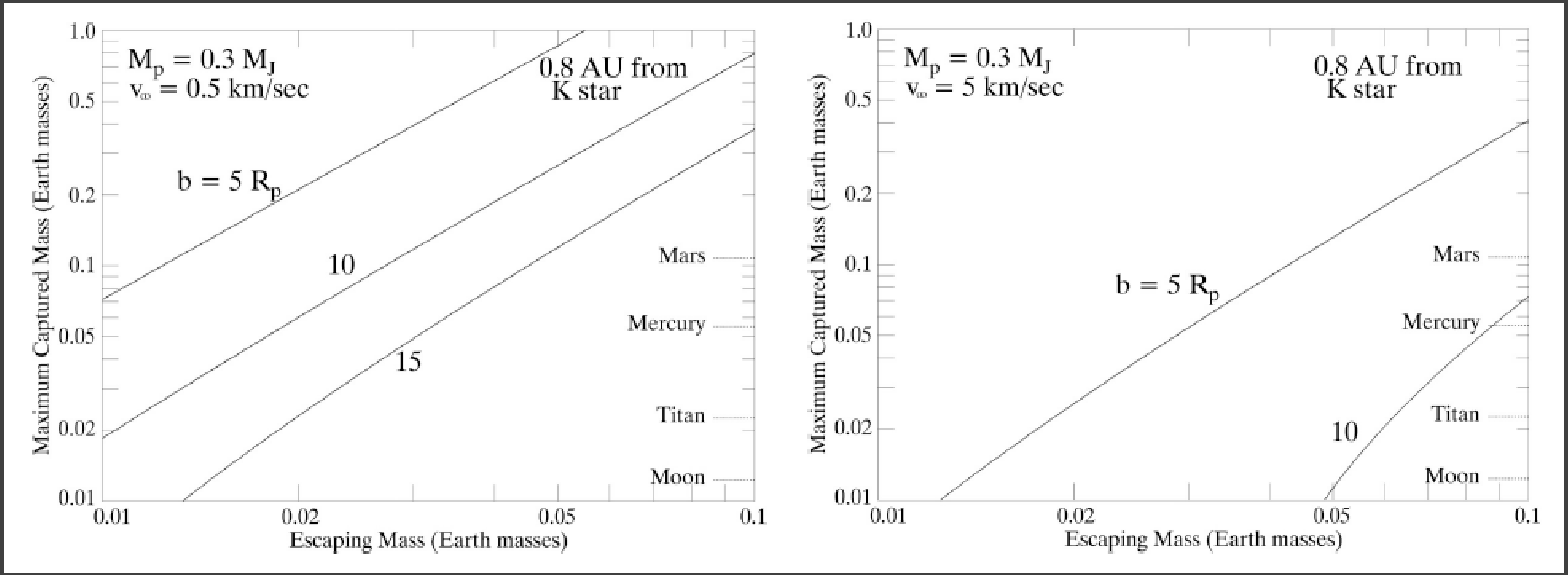
http://minerva.union.edu/parkashv/hotjupiters.html

Modeling satellite formation



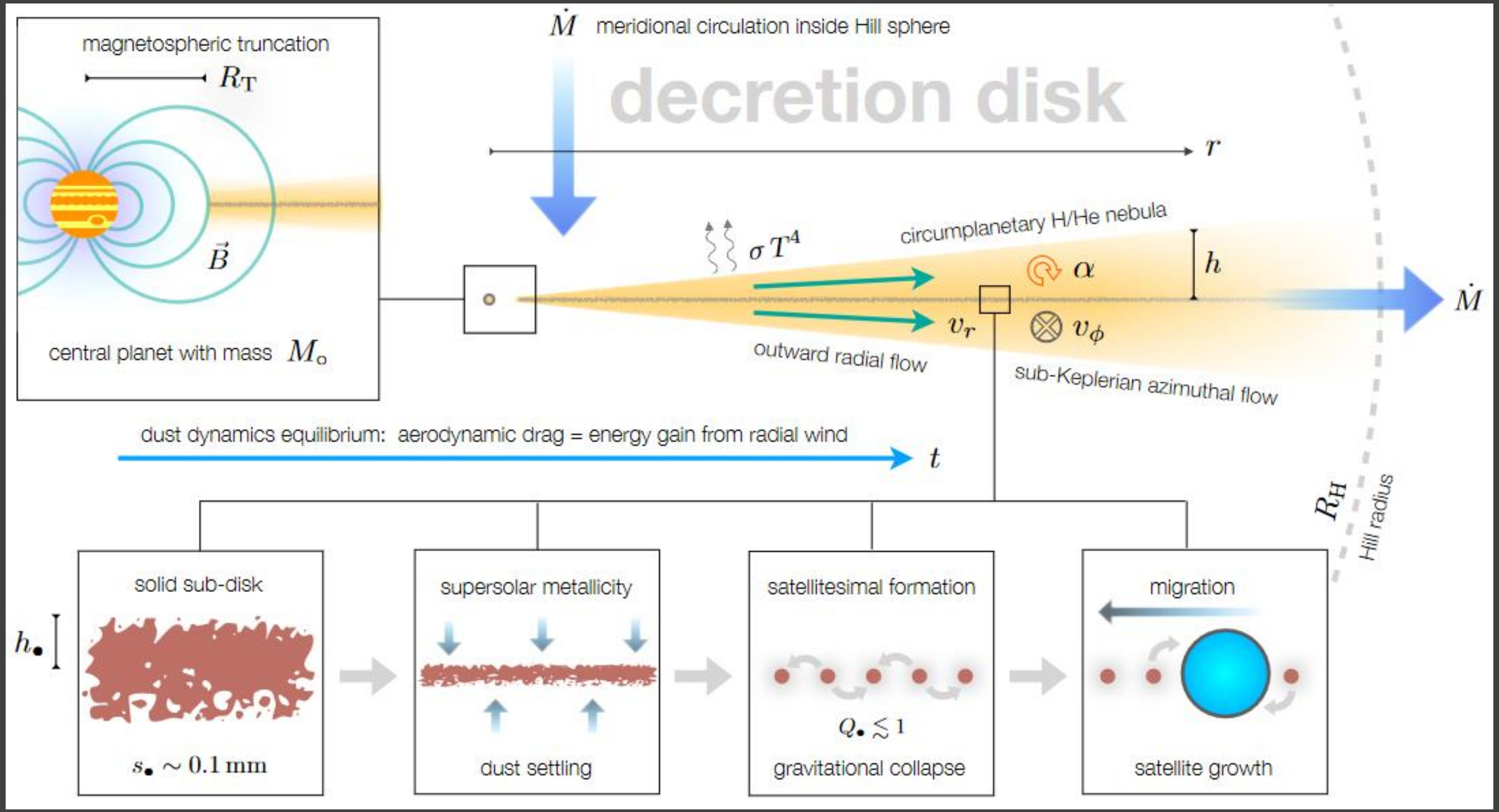
A massive planet: 10 $M_{jupiter}$

Satellite capture in three-body interaction



Results of modeling of a satellite capture. The body initially had a companion which was lost during three-body interaction. This scenario requires a massive planet. Such interactions can happen in the habitable zone.

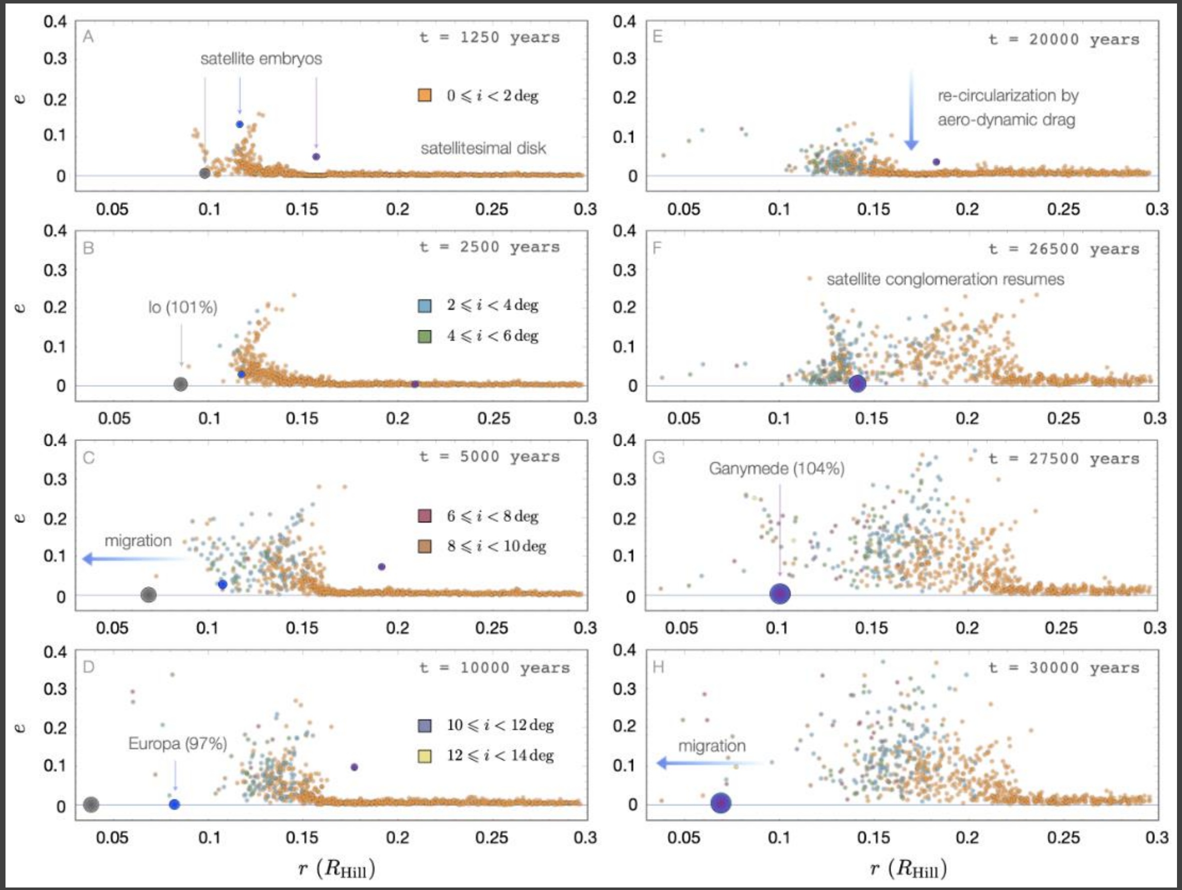
Detailed modeling of Jupiter satellites



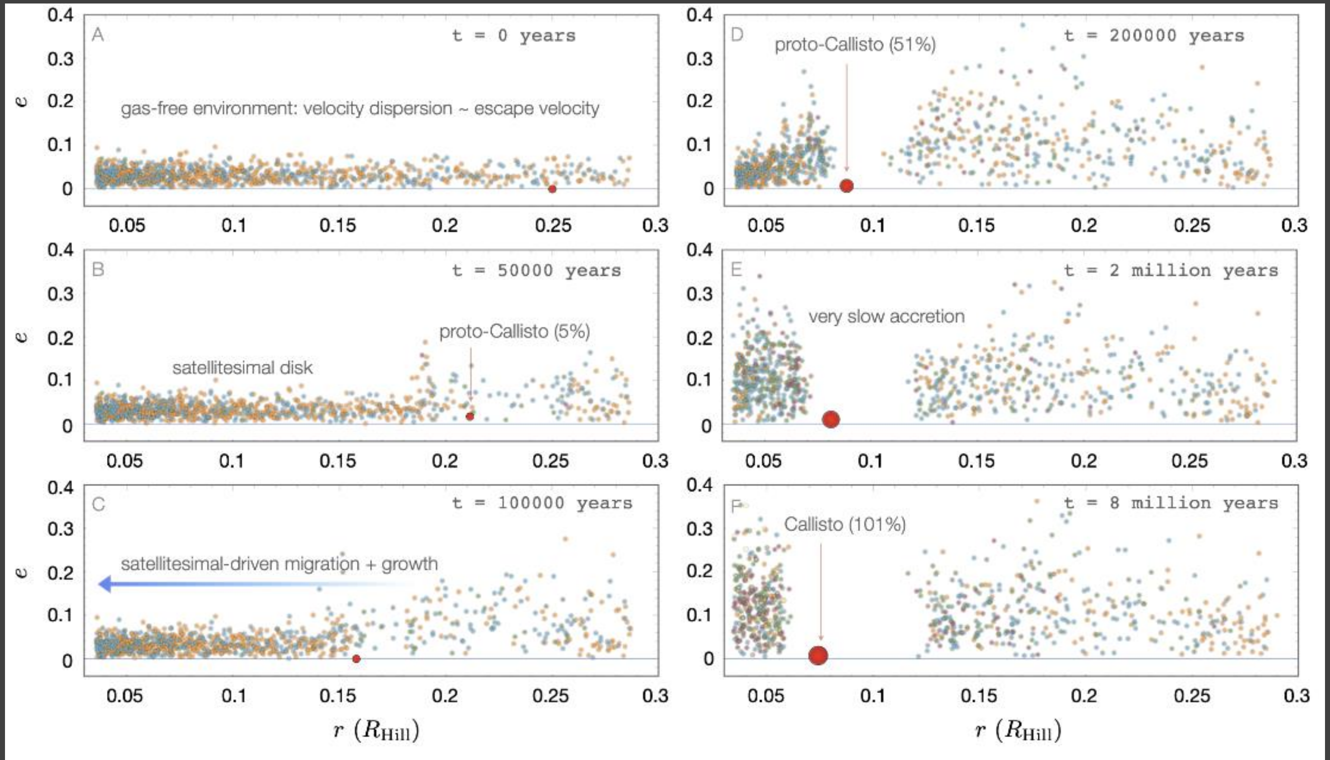
gradual accumulation of icy dust in a vertically-fed decretion disk

2005.08330

Jupiter family formation

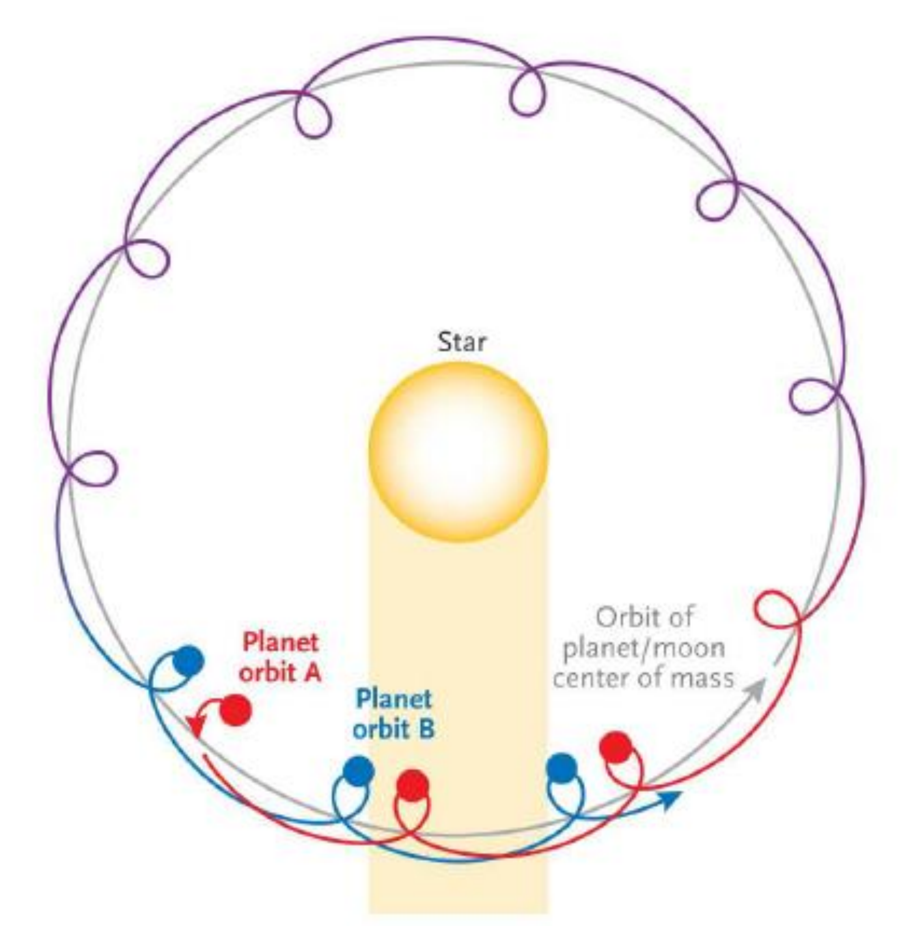


Formation of the three inner Galilean satellites



Formation of Callisto in a gas-free satellitesimal swarm

How to find an exomoon



Potentially, all methods for exoplanets discovery can work.

However, presently methods related to transits seems to be more favorable:

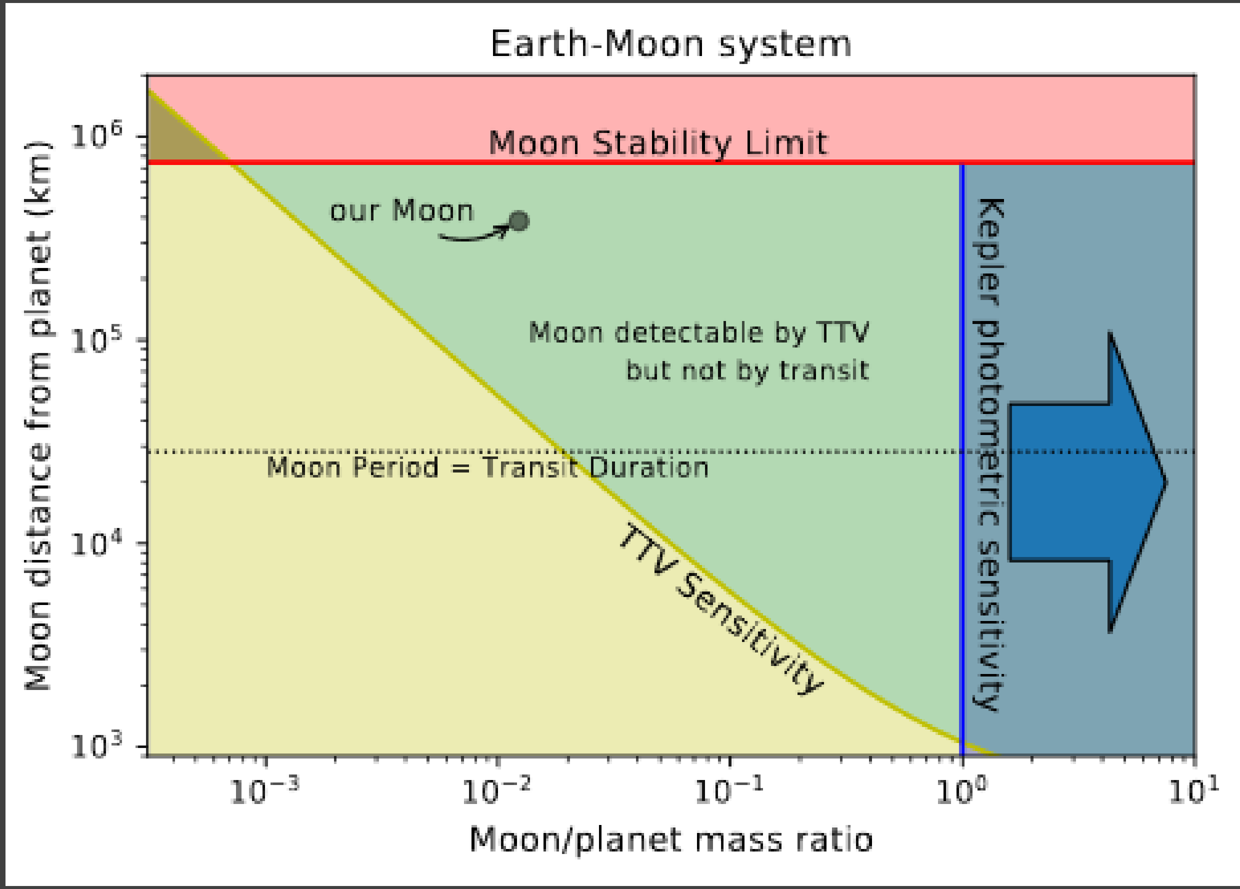
1. TTV (see 2004.02259)

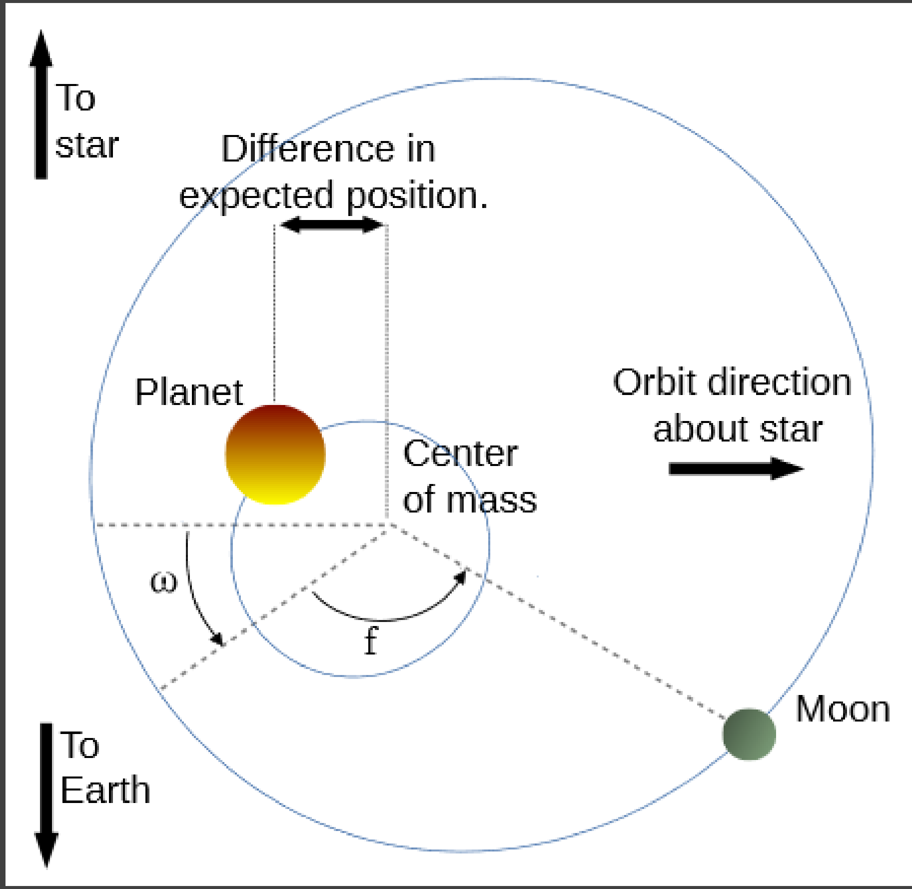
2. TDV (see 2004.02259)

3. TRV (radius variation, see 2004.02259)

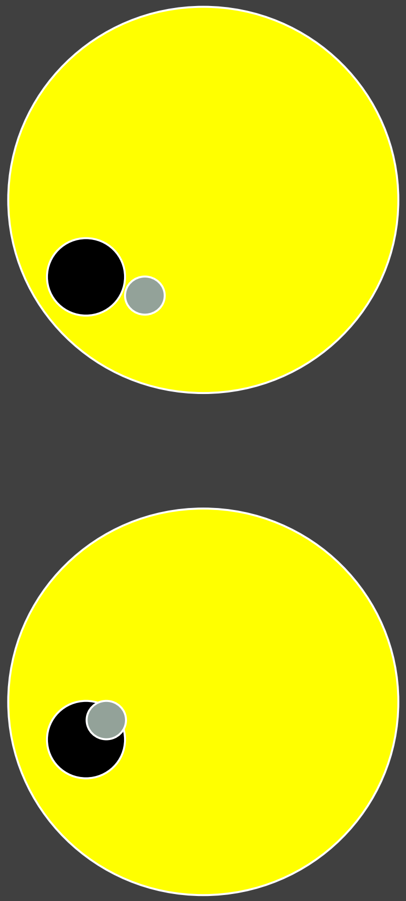
4. Orbital plane changes.

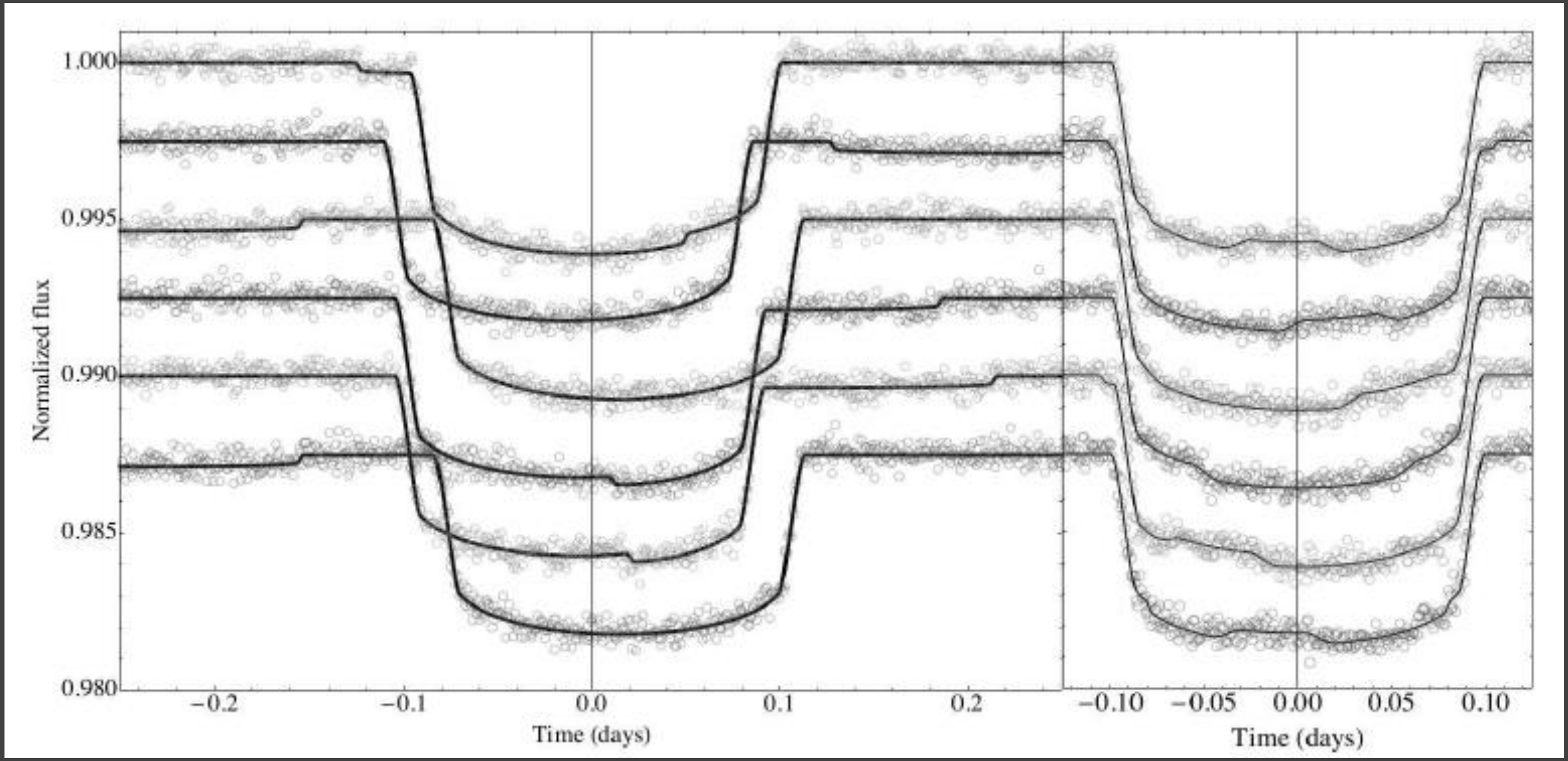
TTV and exomoons





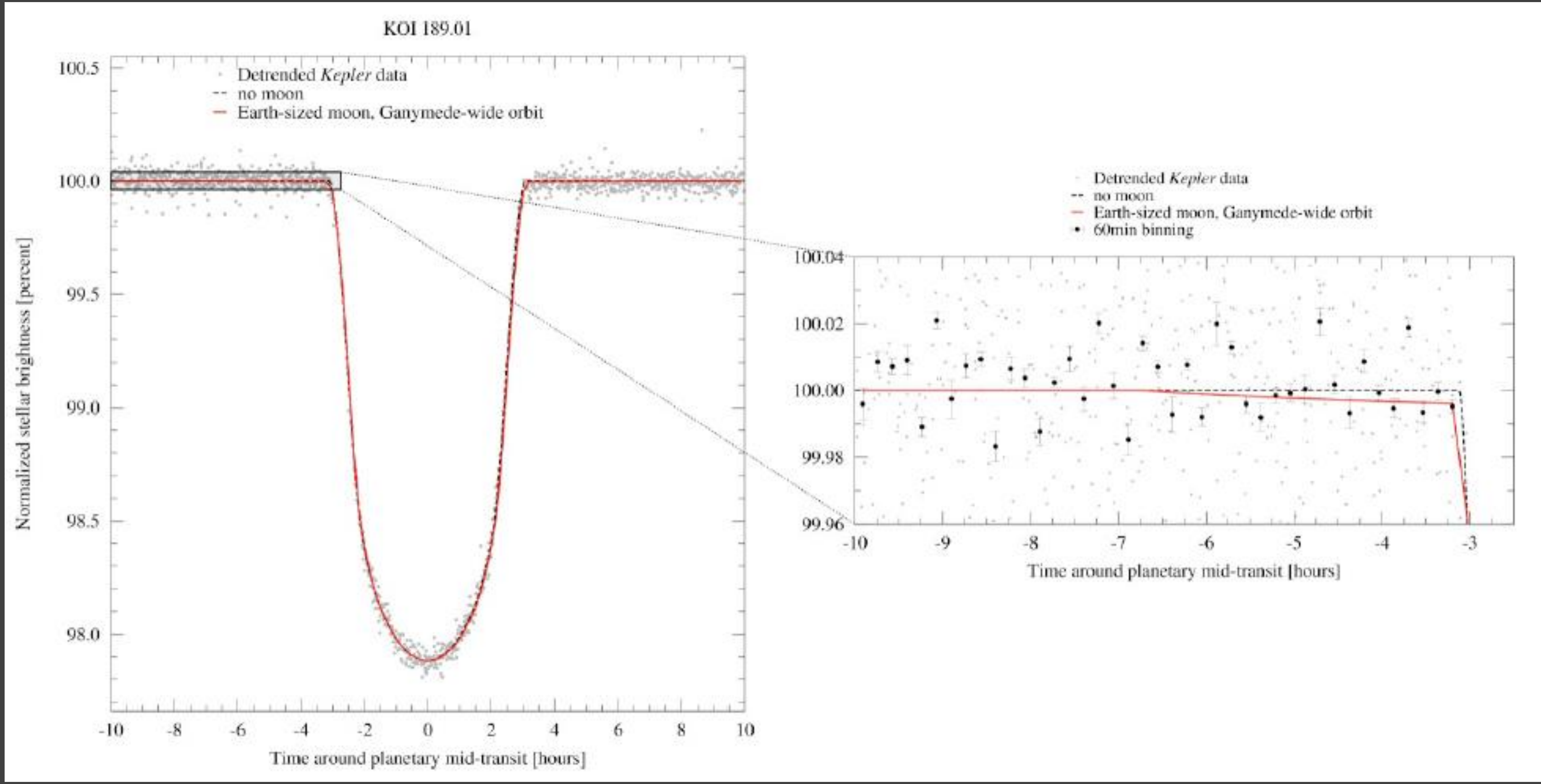
Joint transits





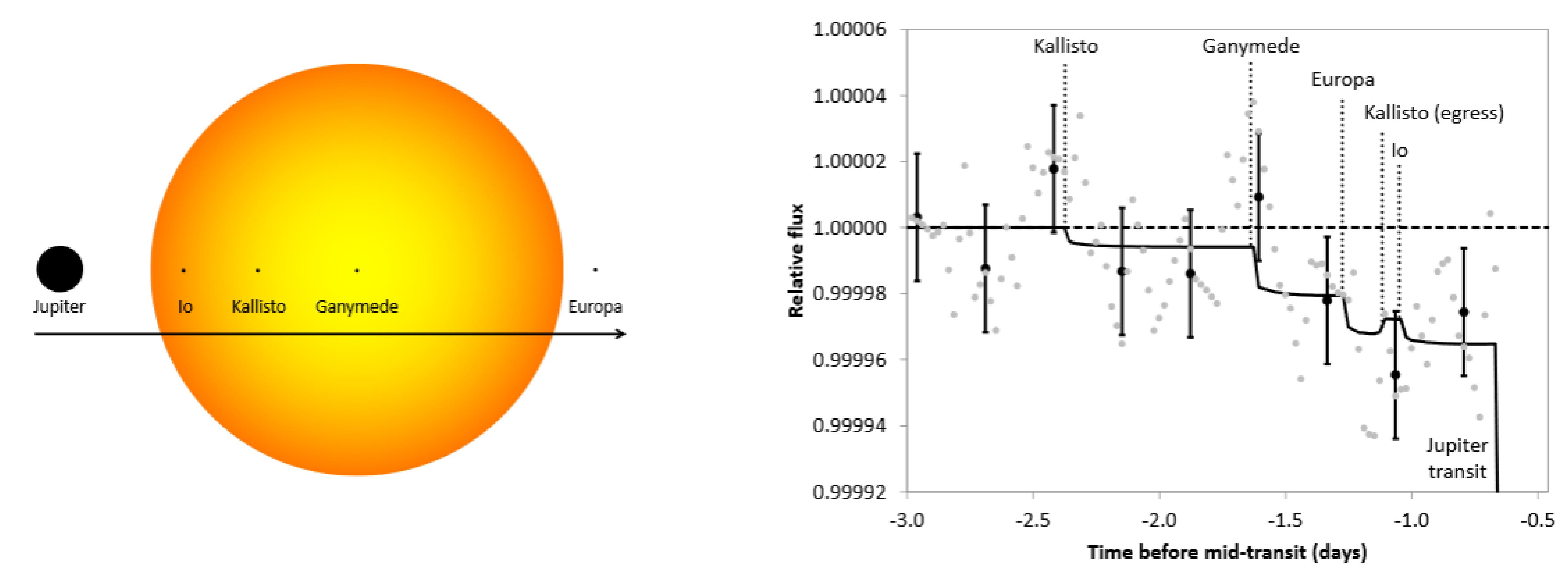
1405.1455

How strong is the effect?



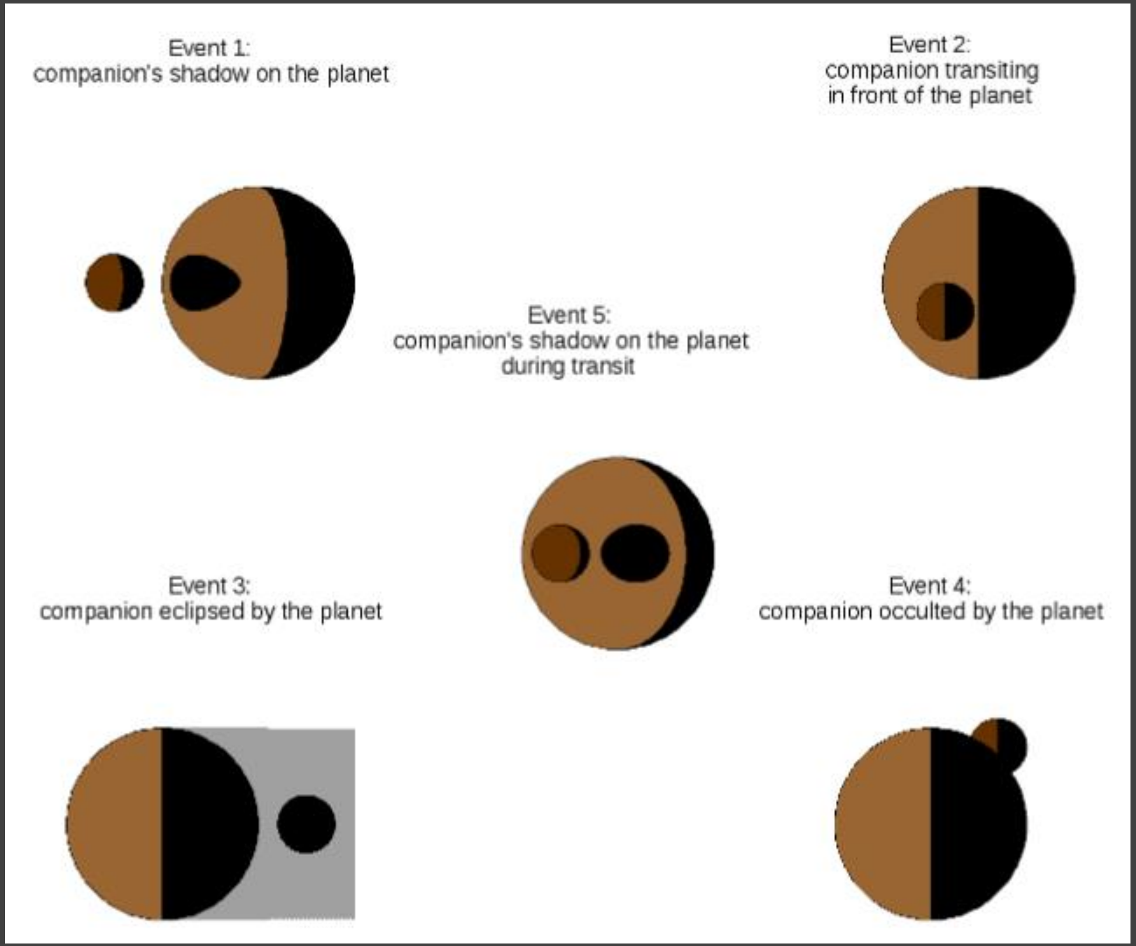
1408.6164

An example: Jupiter with satellites over the Sun



1503.03251

Other ways to see a moon

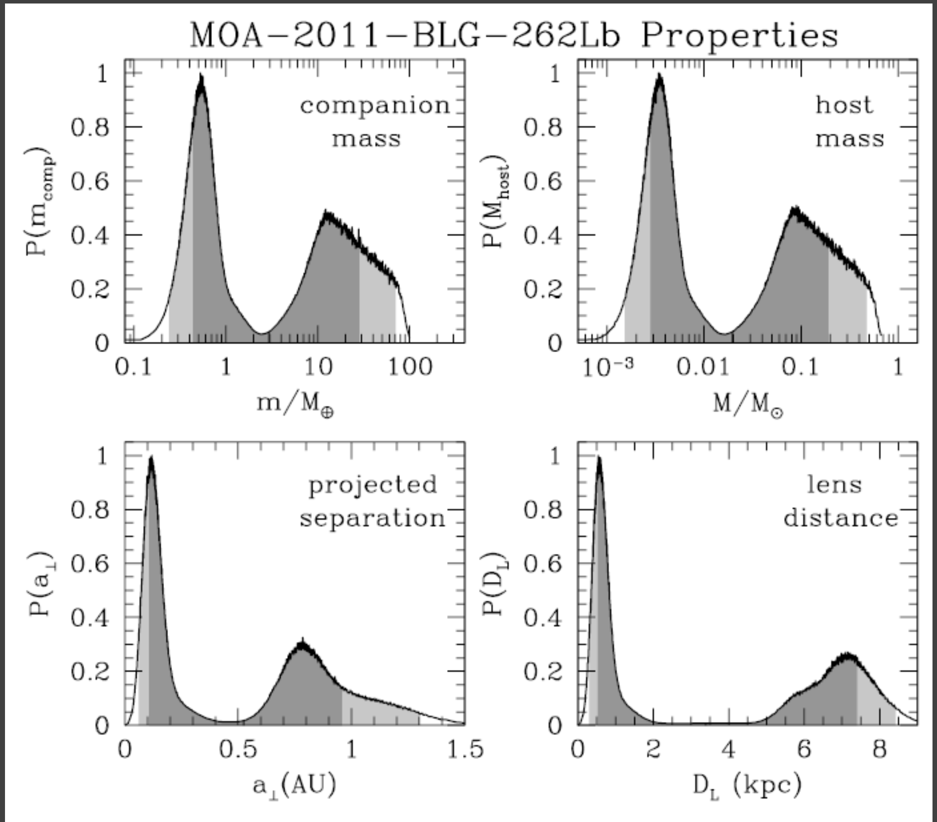


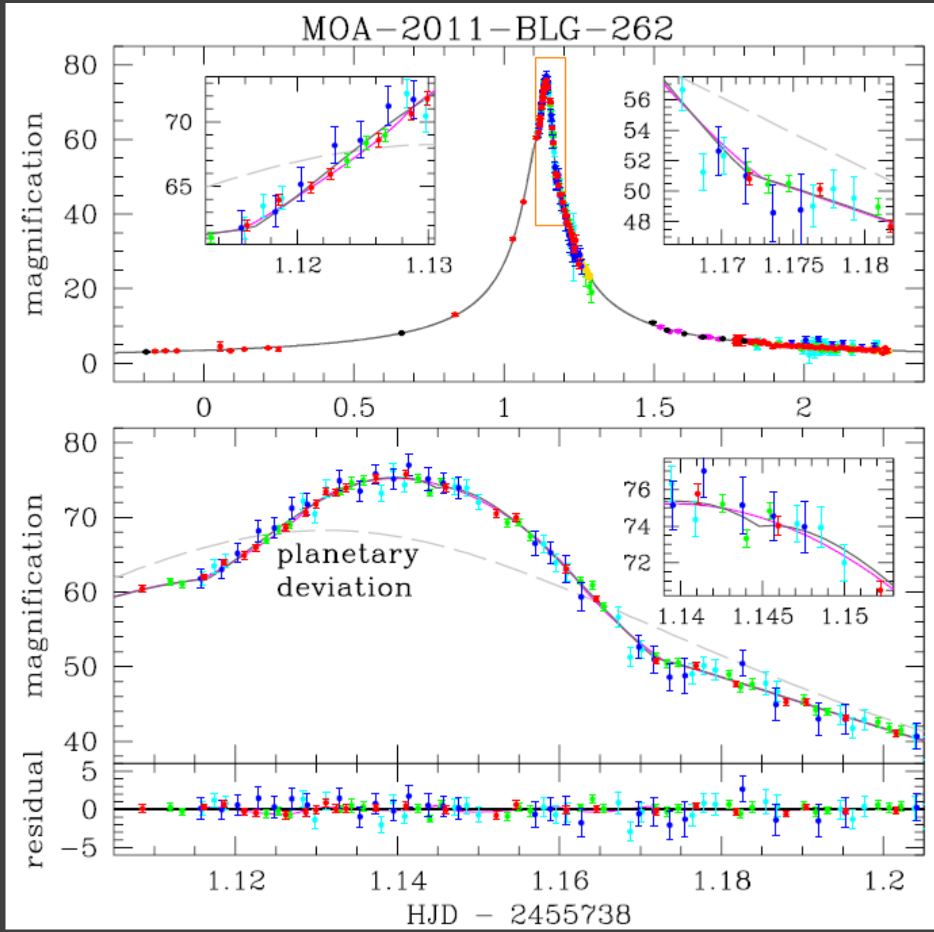
1806.10032

A planet with a moon …but without a star?

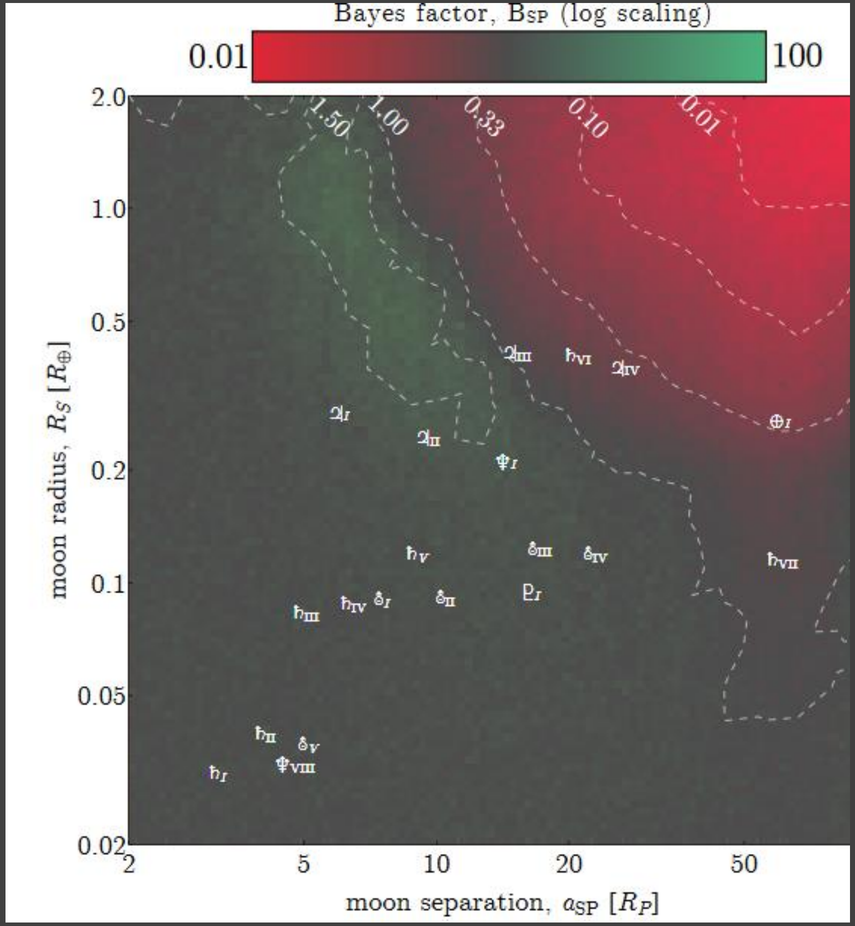
Microlensing.
Two solutions are possible:
1. $0.12M_{sun}+18M_{Earth}$
2. $4M_{Jup}+0.5M_{Earth}$

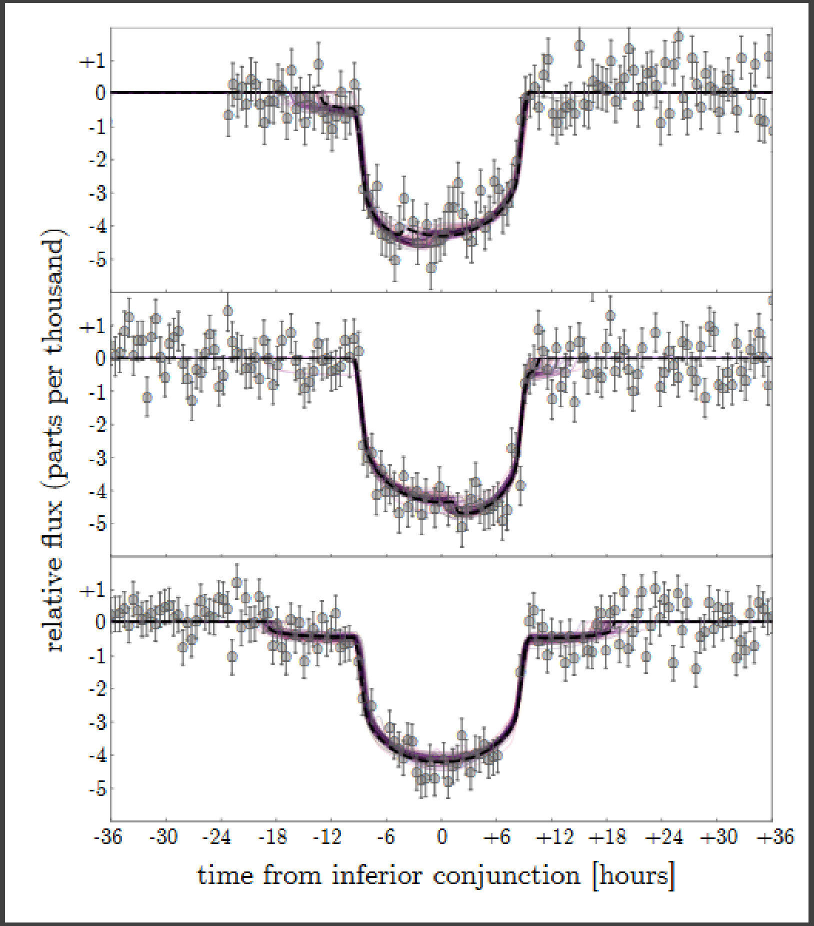
Uncertainty is related to unknown distance





A candidate?





Kepler-1625BI

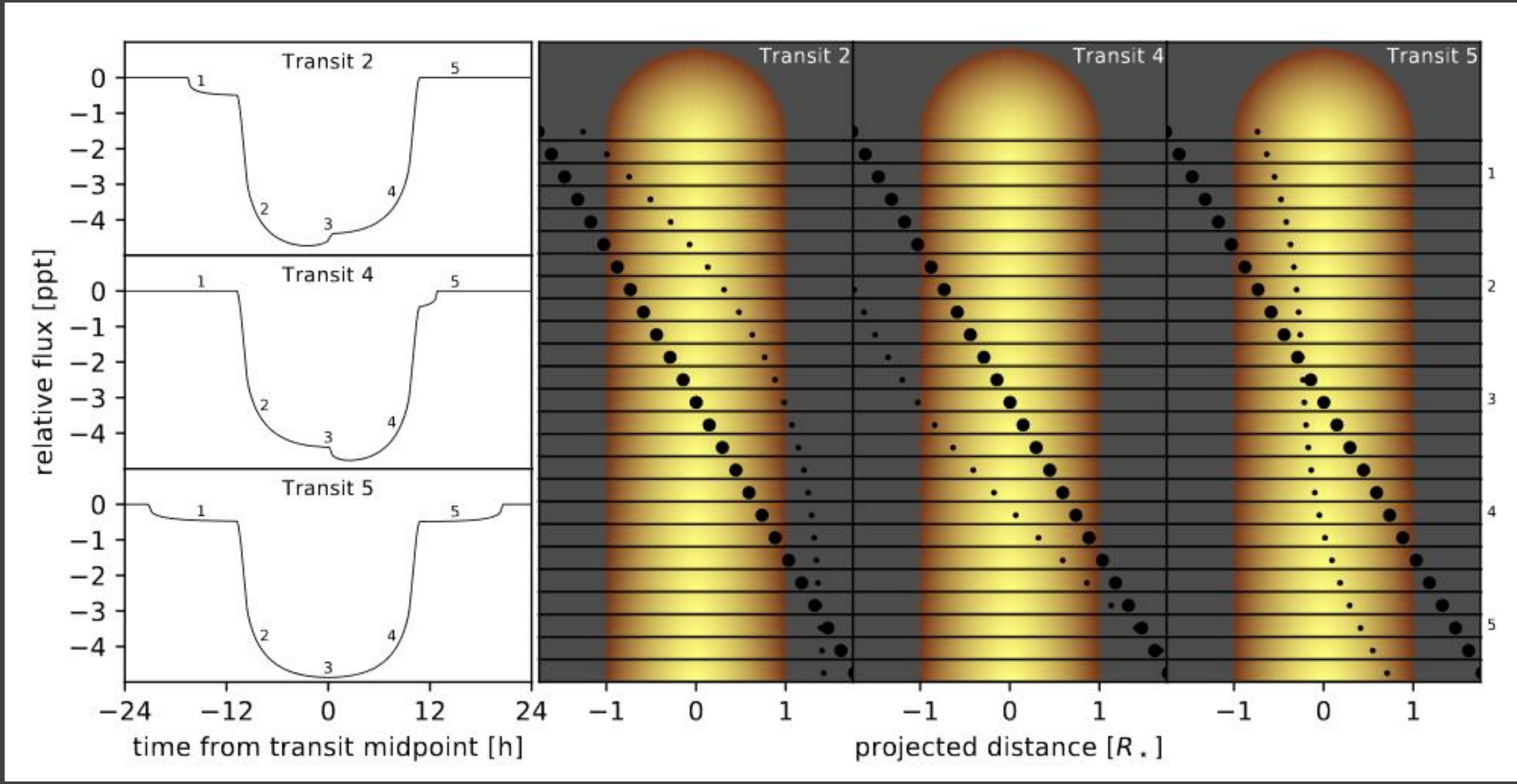
Semimajor axis: 20 planet radii.

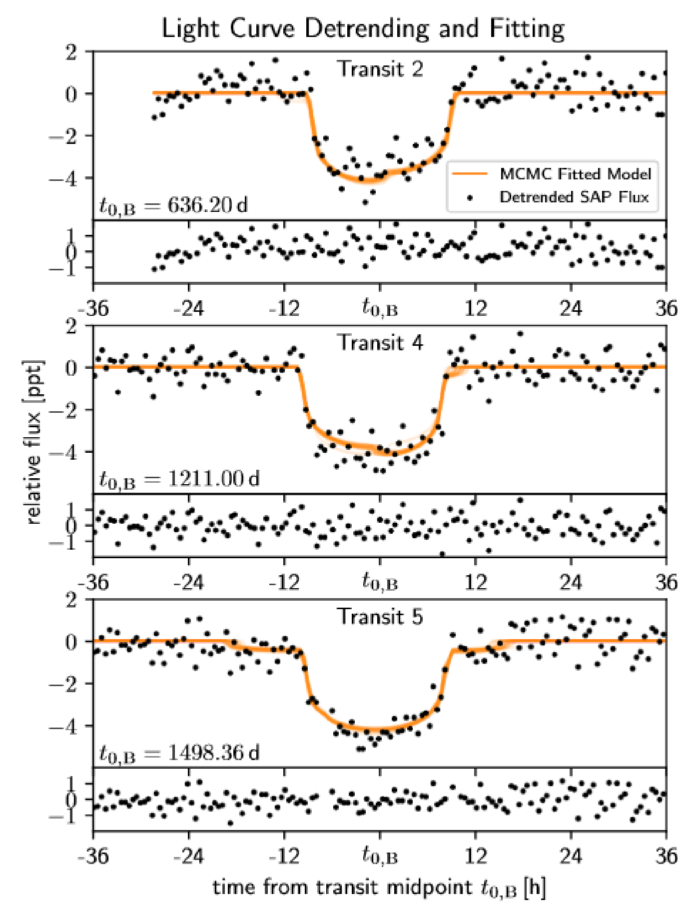
Jupiter-like planet.

Planet orbit: 0.8 AU

1707.08563

Confirmation of the candidate

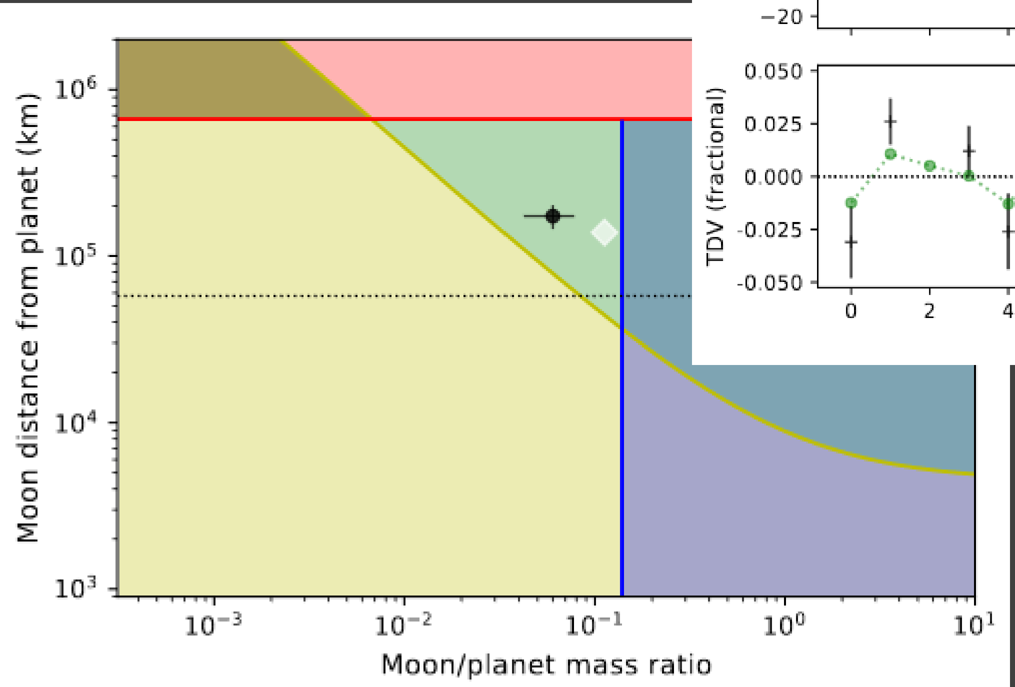


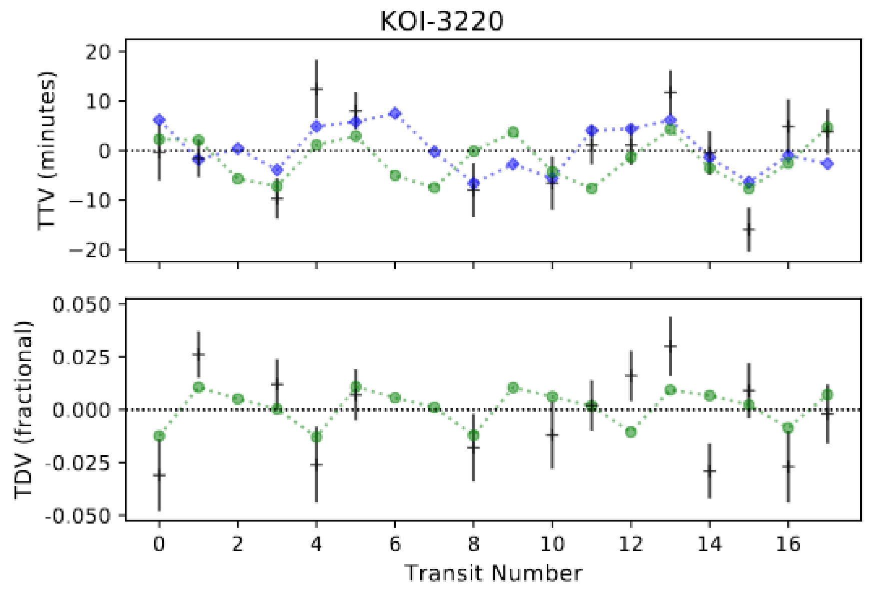


1806.04672

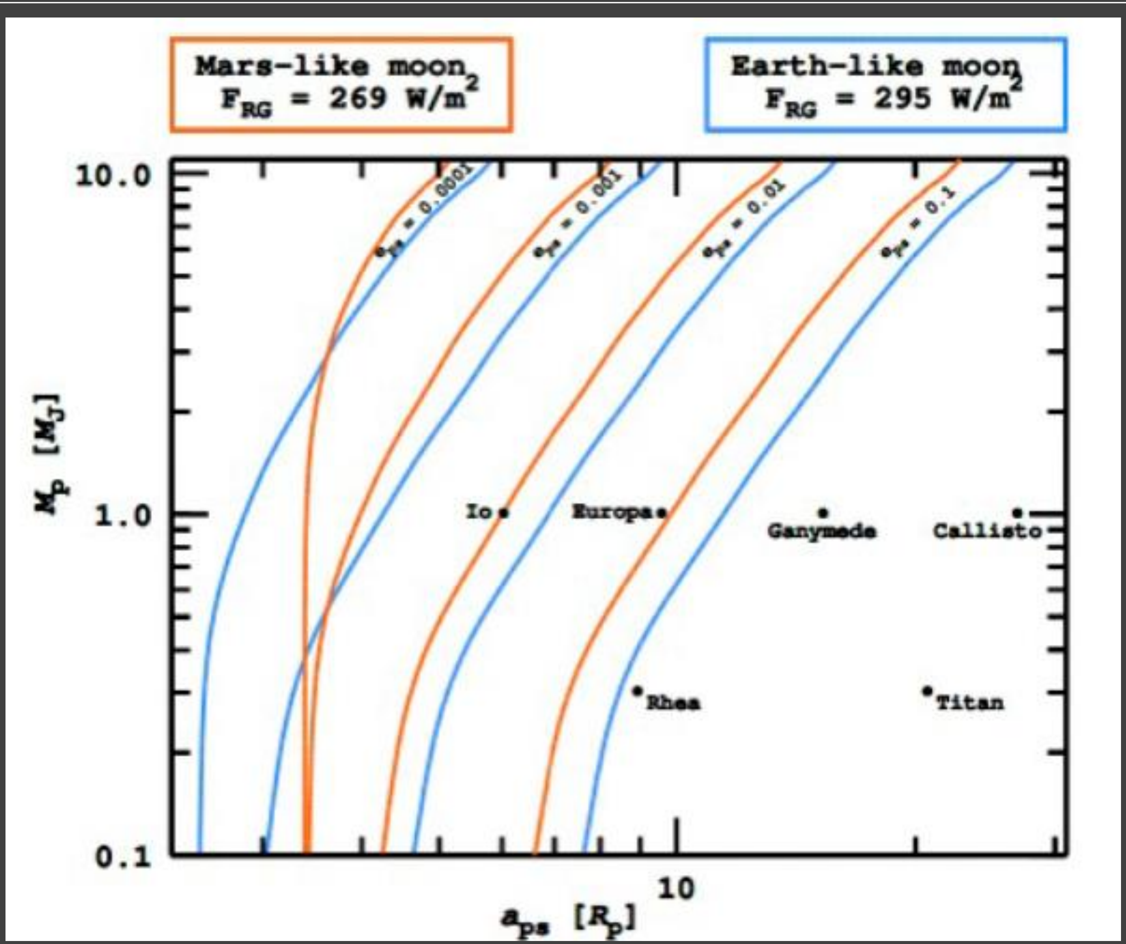
Exomoon candidates from TTV

KOI	# Data Points	TTV SNR (min)	Planet χ^2/N	Moon χ^2/N	Likely Cause of TTVs
268.01	11	2.37	0.579	1.514	planet or moon
303.01	21	1.56	0.581	0.793	planet or moon
1503.01	10	1.56	0.181	0.629	planet
1888.01	12	1.84	0.883	0.682	planet or moon
1925.01	11	1.57	0.656	0.622	planet or moon
1980.01	15	1.69	0.313	0.644	planet
2728.01	20	1.71	0.427	0.748	planet or moon
3220.01	14	1.67	0.566	0.826	planet or moon





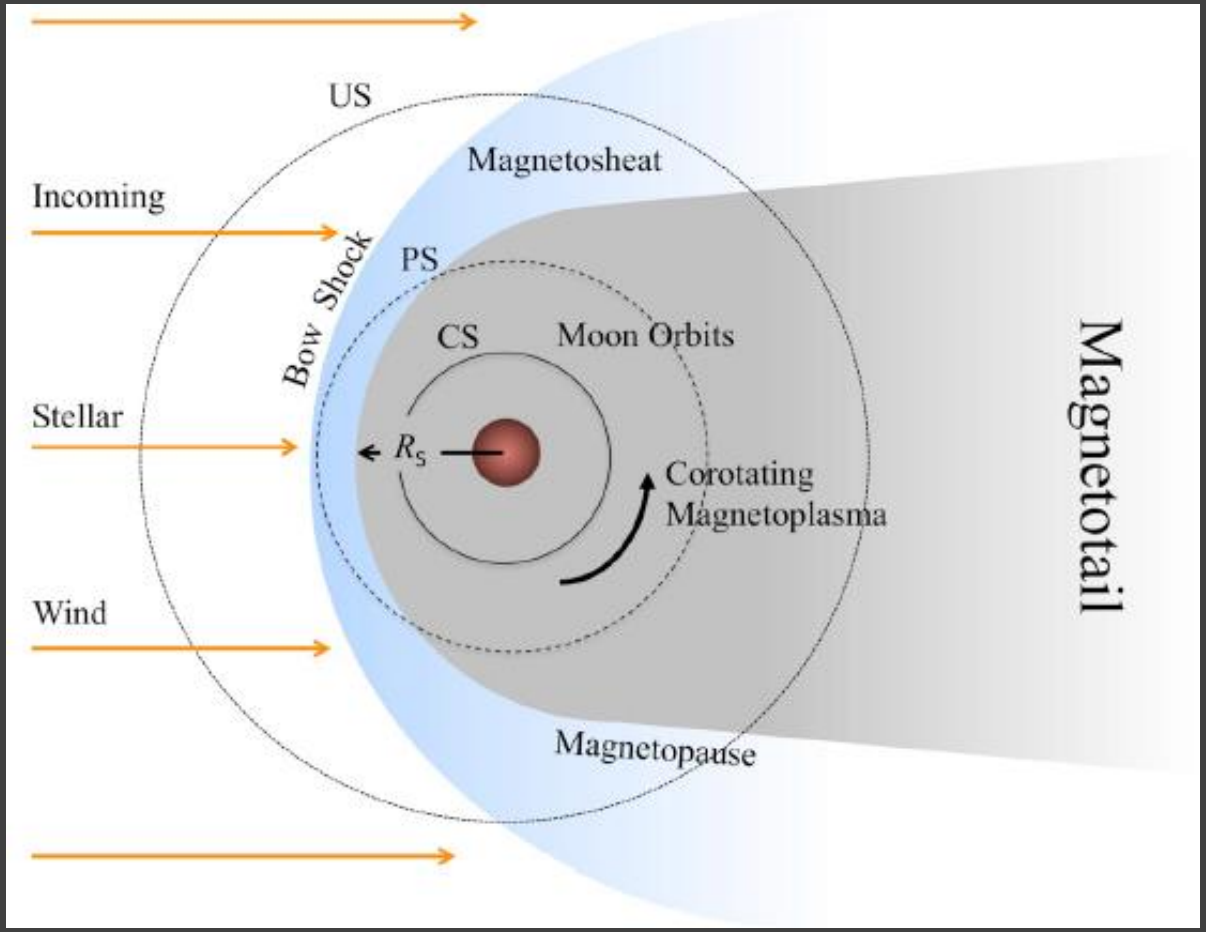
Tidal heating



Satellites can be heated by tides.

Effect can be so strong,
that a satellite with an atmosphere
can experience the greenhouse effect.

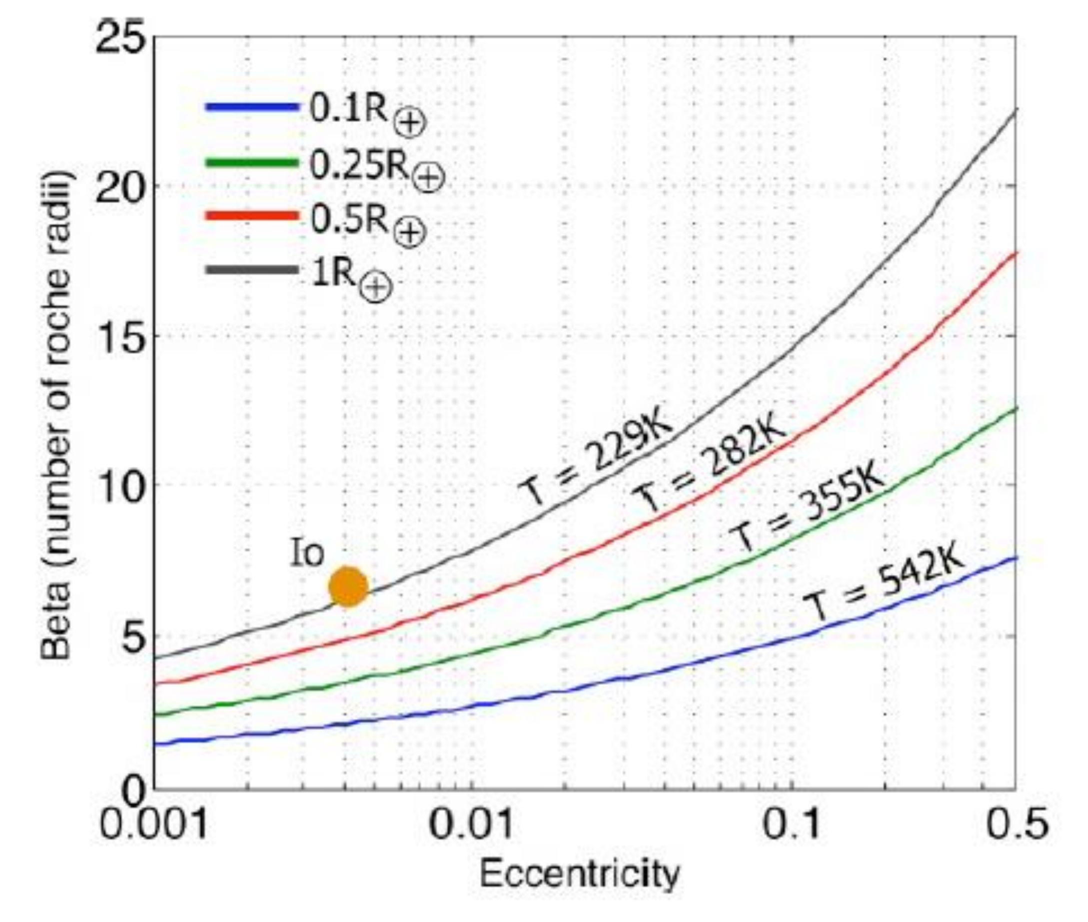
Planetary magnetospheres

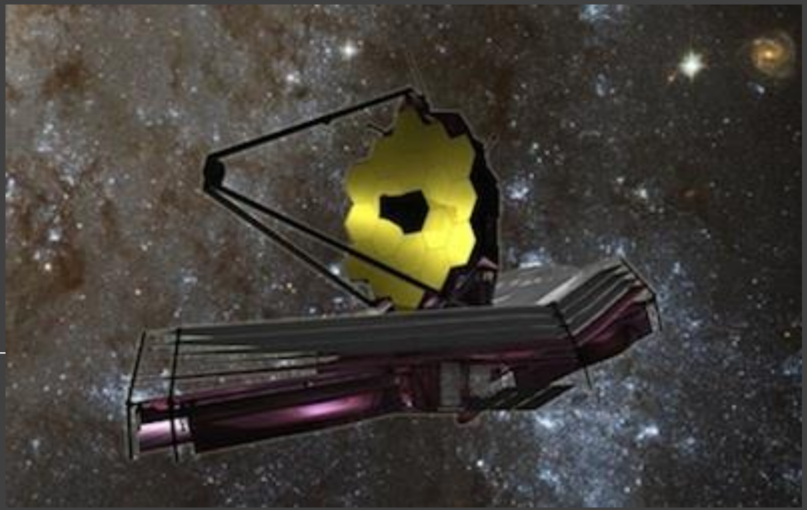


It is argued that magnetic shield
can be important for life.
A satellite can ``use'' the planetary field.

However, if the satellite is too close
to the planet – then tides can heat it up.
If it is too far – it can be out of the magnetosphere.

Can JWST see exomoons?





A satellite might be large (as the Earth) and warm (also as the Earth, at least).

Potentially, such satellites can appear around massive planets far from the star, where it is easier to see them.
A satellite can be heated by tides.

Literature

- arxiv:1604.06092 Exoplanetary Atmospheres - Chemistry, Formation Conditions, and Habitability
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- arxiv:1312.3323 The Structure of Exoplanets
- arxiv:1501.05685 Exoplanetary Geophysics -- An Emerging Discipline
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- arxiv:1411.1740 Seismology of Giant Planets
- arxiv:1709.05941 Exoplanet Atmosphere Measurements from Transmission Spectroscopy
- arxiv:1810.04175 How to characterize the atmosphere of a transiting exoplanet
- arXiv:1904.03190 Exoplanetary atmospheres
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