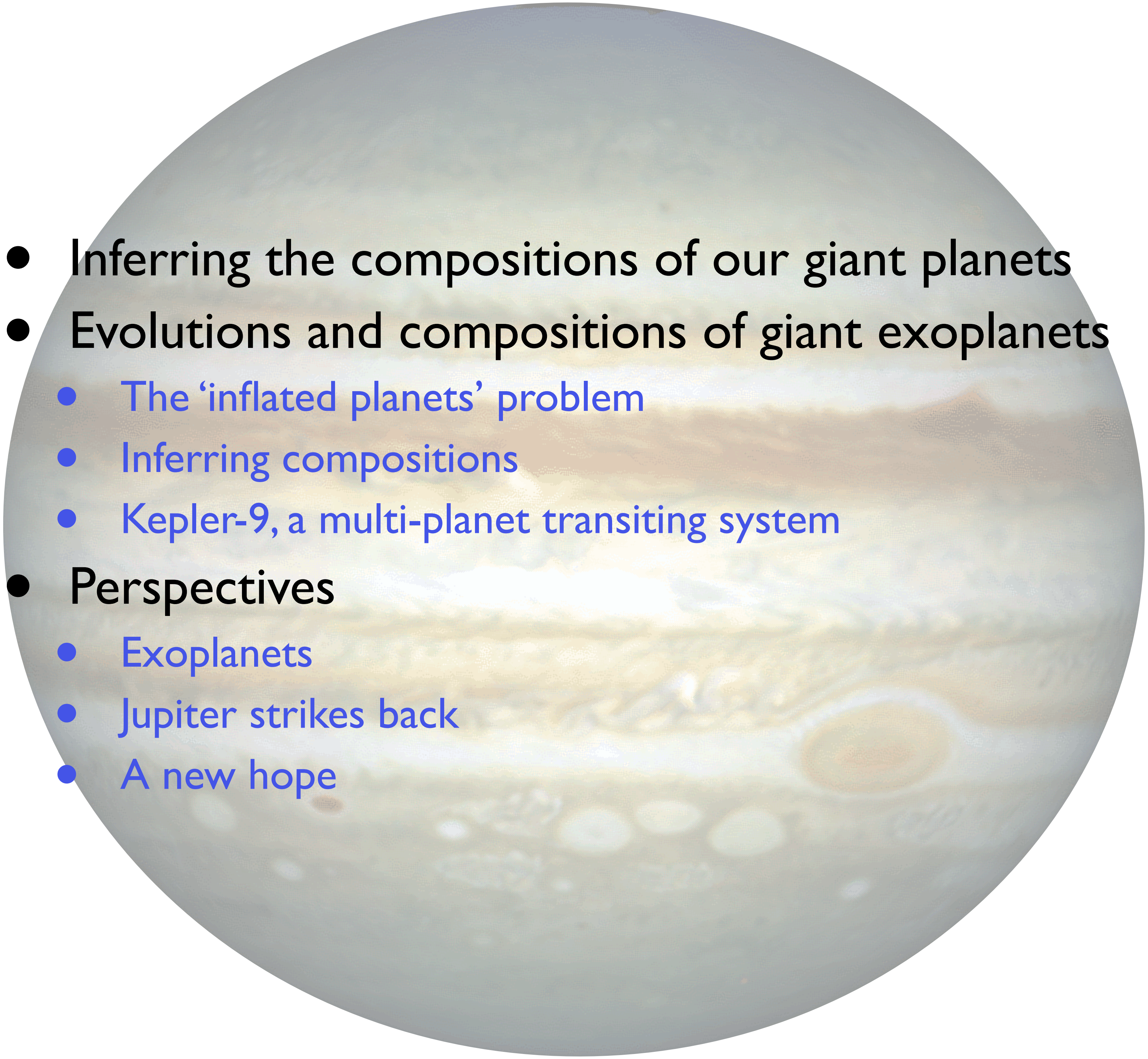
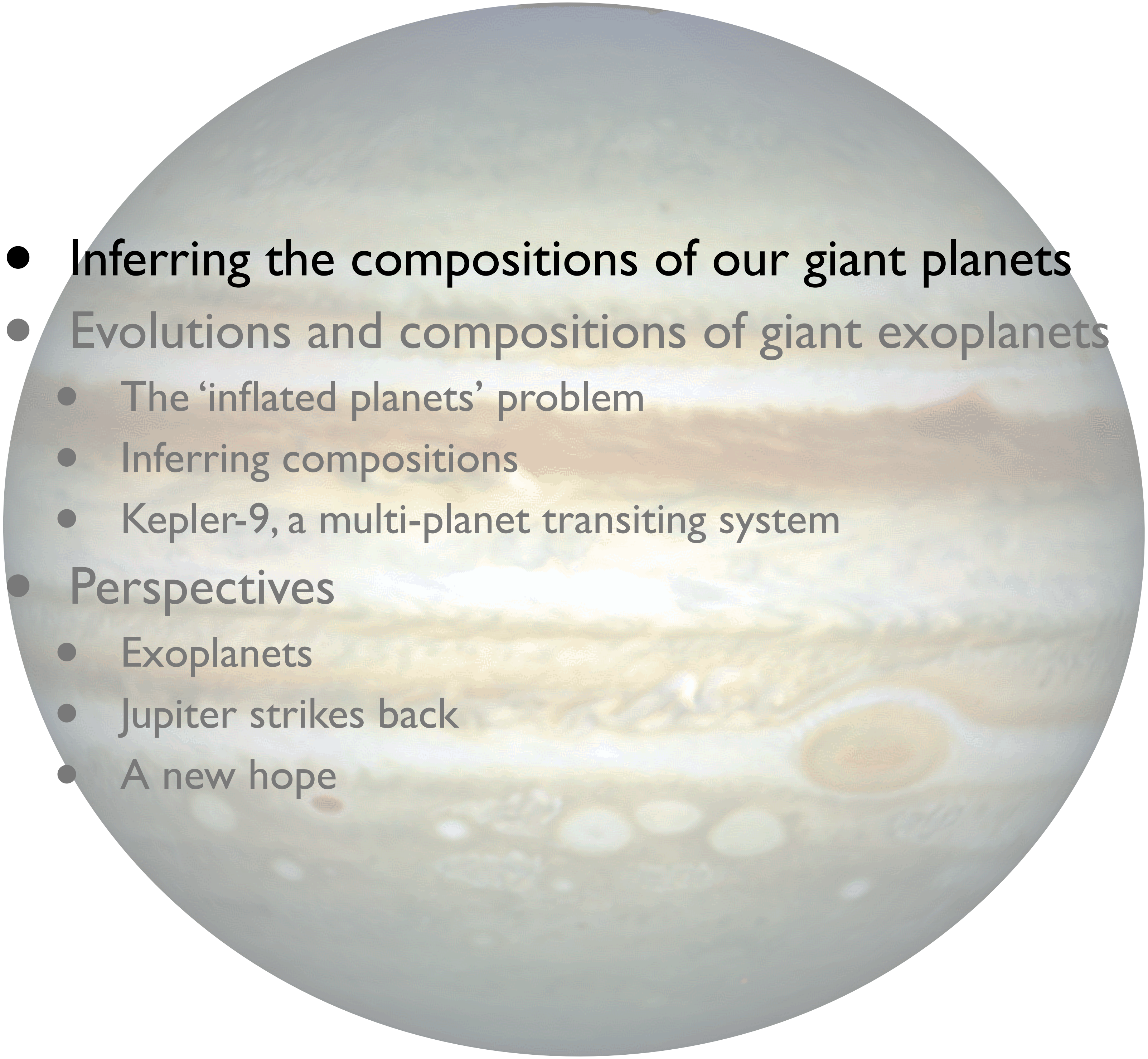
Evolution & Compositions of Giant Planets

Tristan Guillot
Observatoire de la Côte d'Azur, Nice



- Inferring the compositions of our giant planets
- Evolutions and compositions of giant exoplanets
  - The ‘inflated planets’ problem
  - Inferring compositions
  - Kepler-9, a multi-planet transiting system
- Perspectives
  - Exoplanets
  - Jupiter strikes back
  - A new hope



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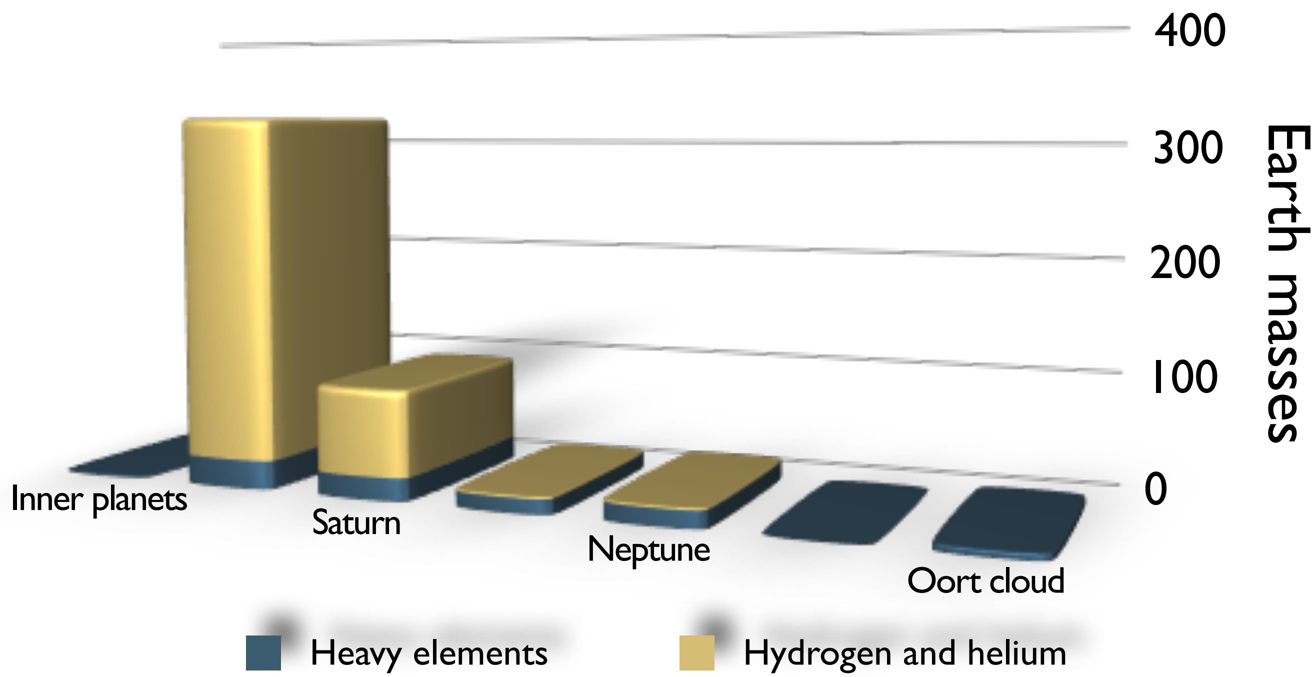
Global inventory of the Solar System

Giant planets possess 99.5% of all other objects in the Solar System except the Sun



Probing deep...

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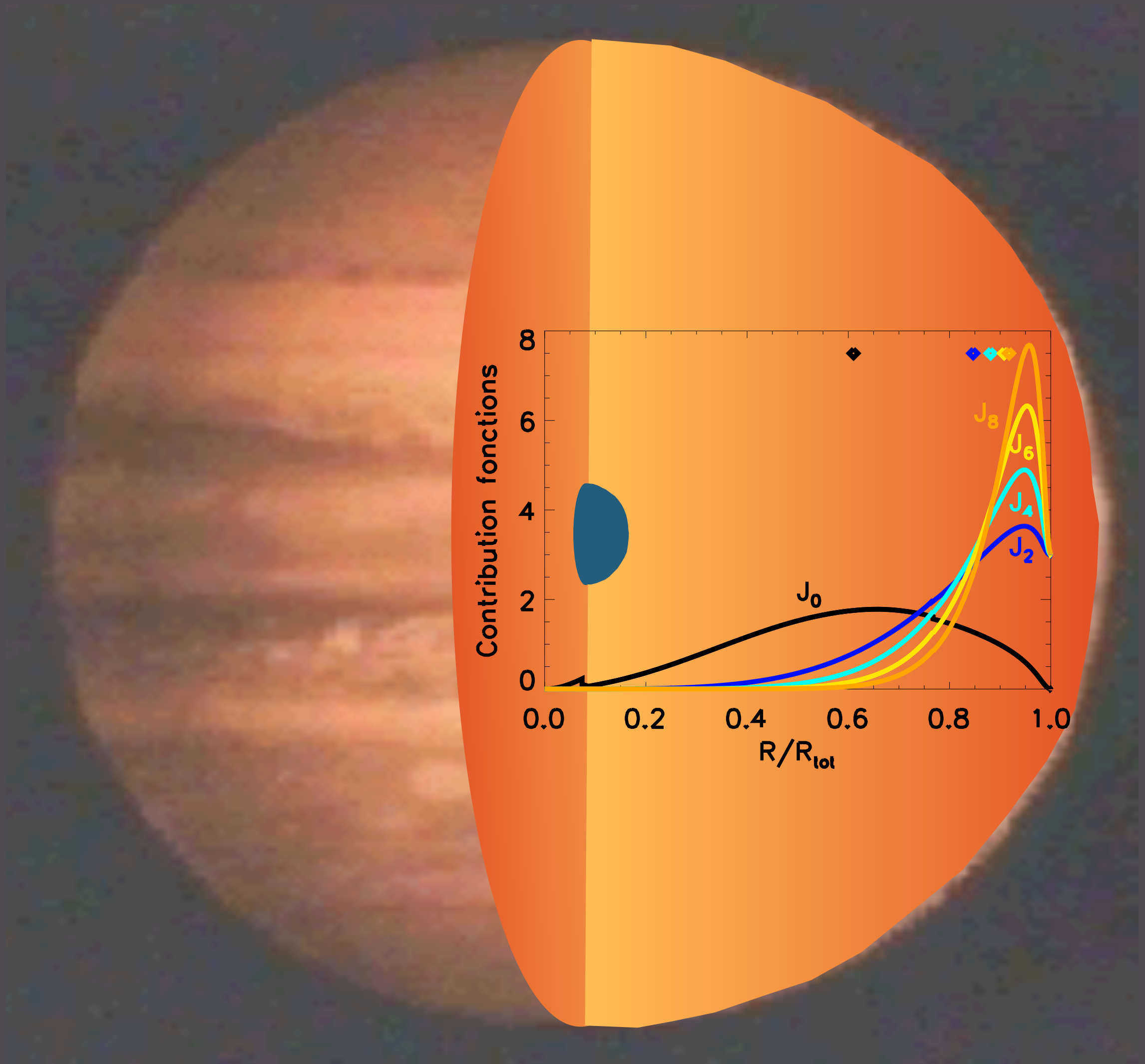
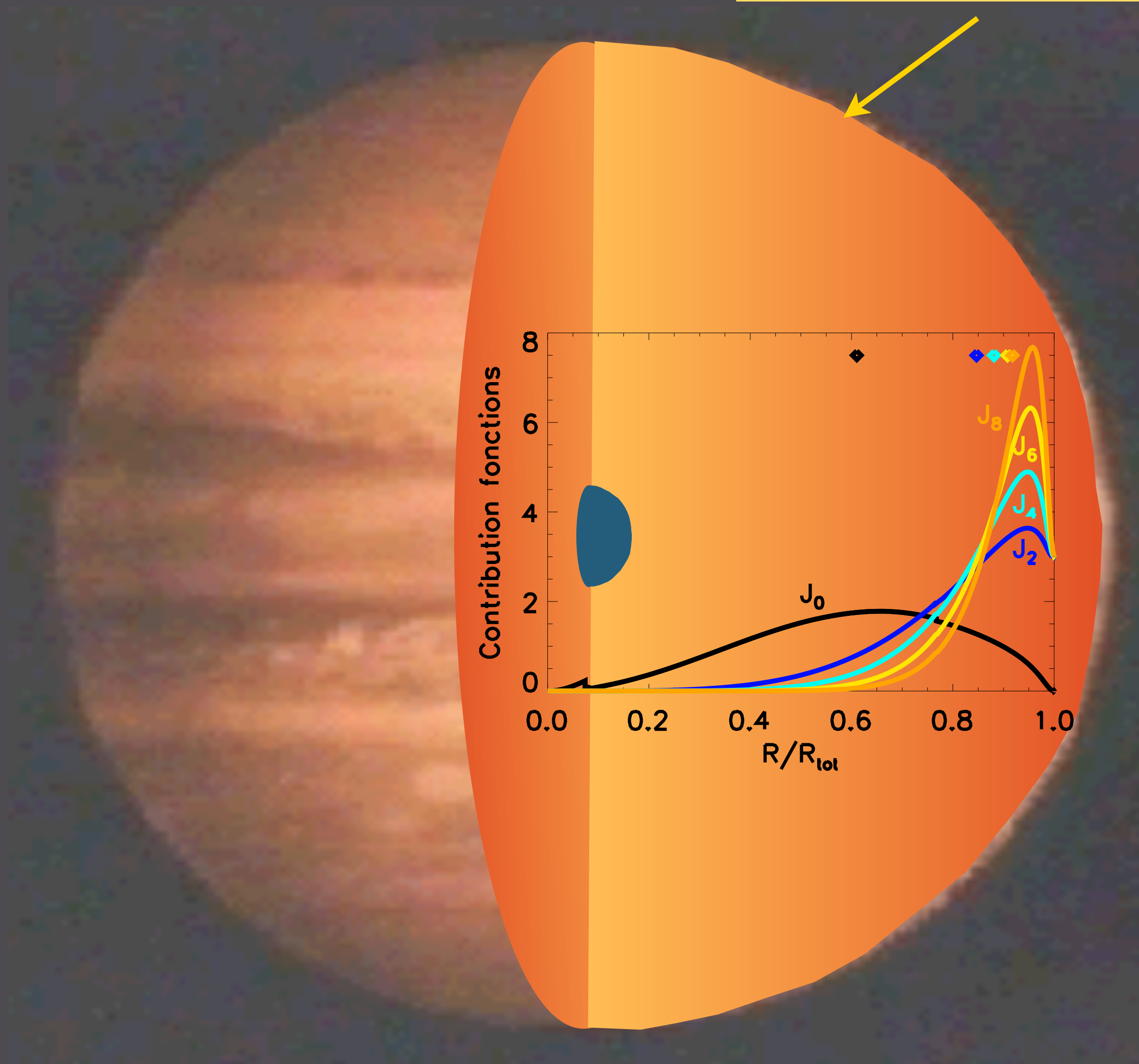


Probing deep...

Atmospheric probes (spectroscopy, in situ):
skin-deep measurement of the composition



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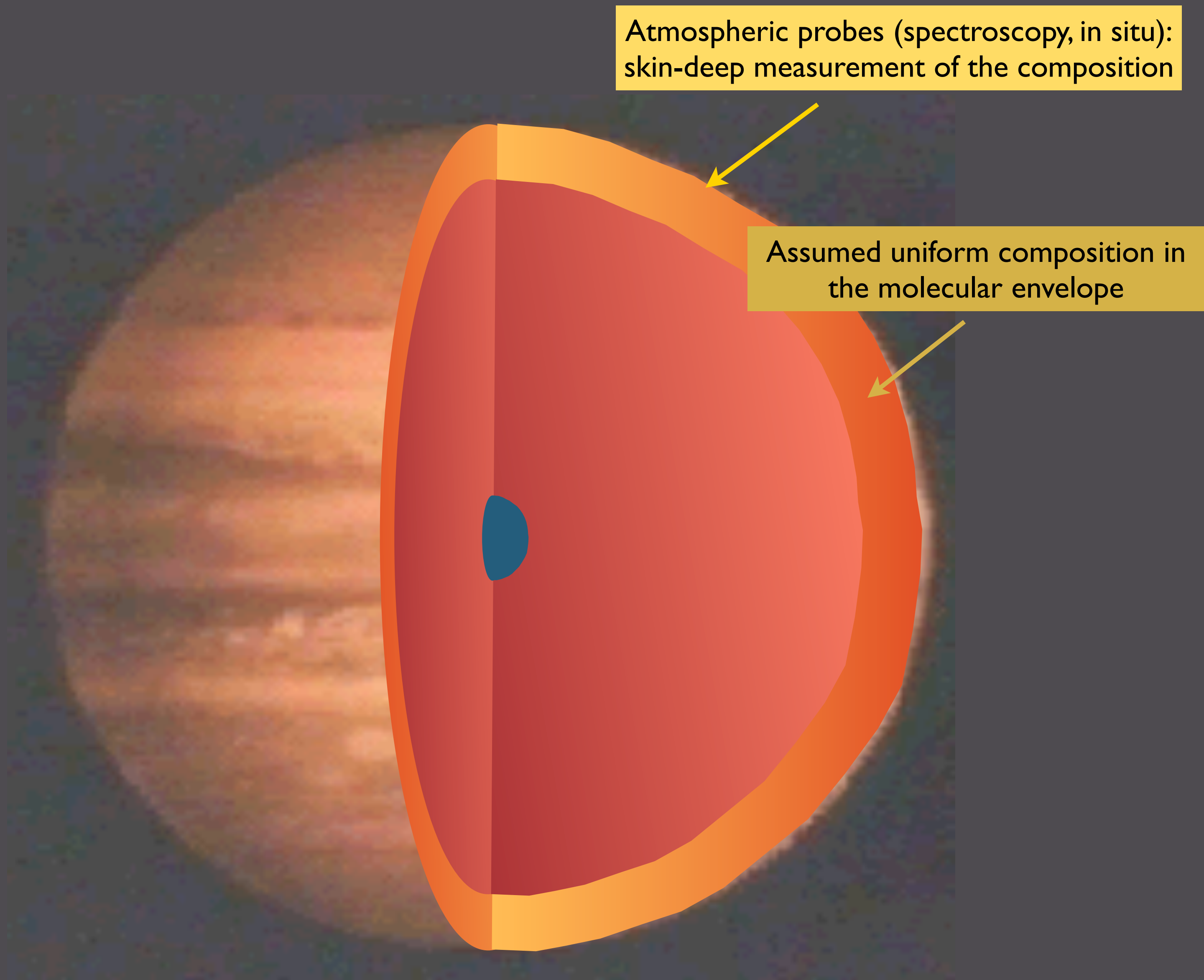

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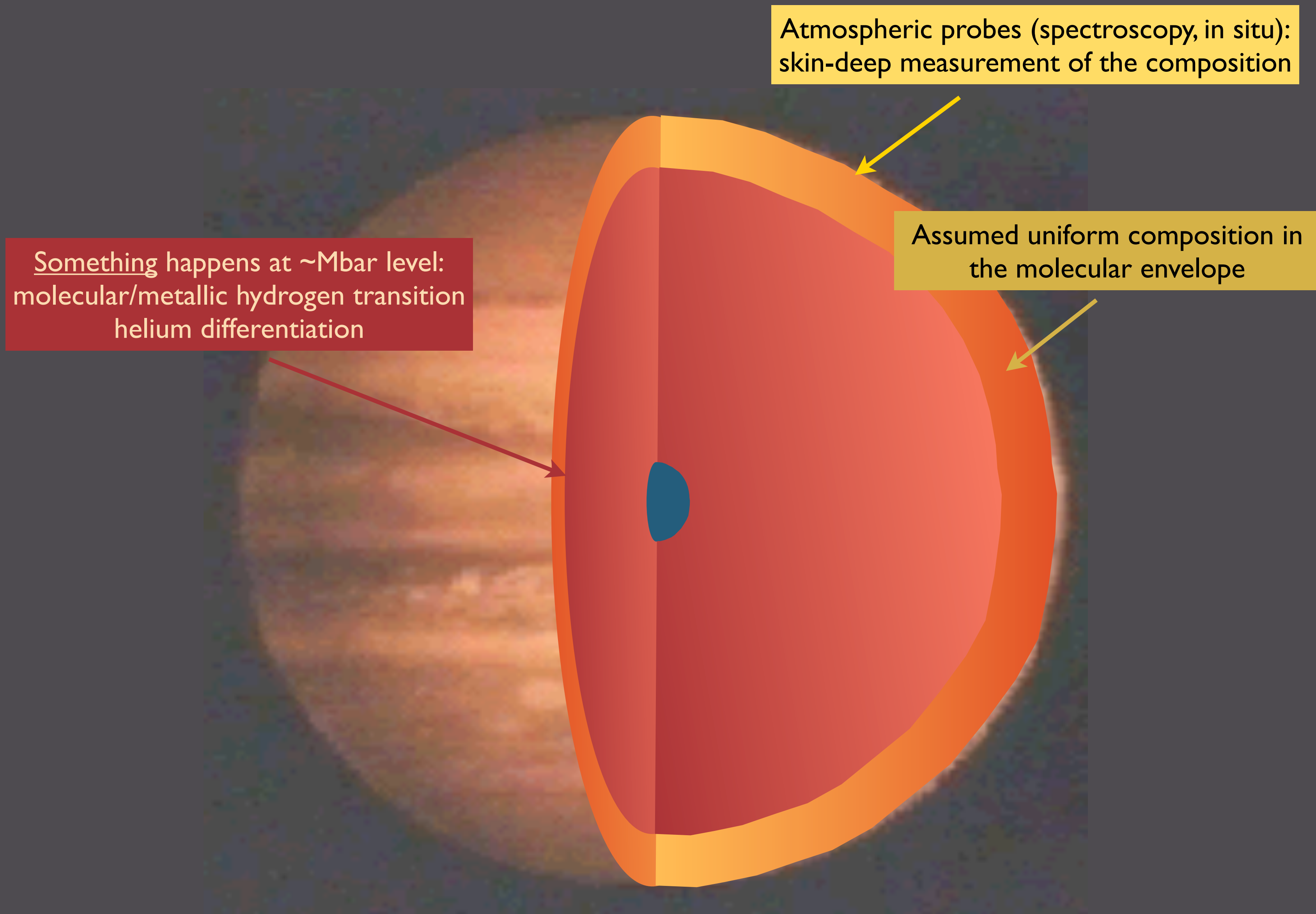

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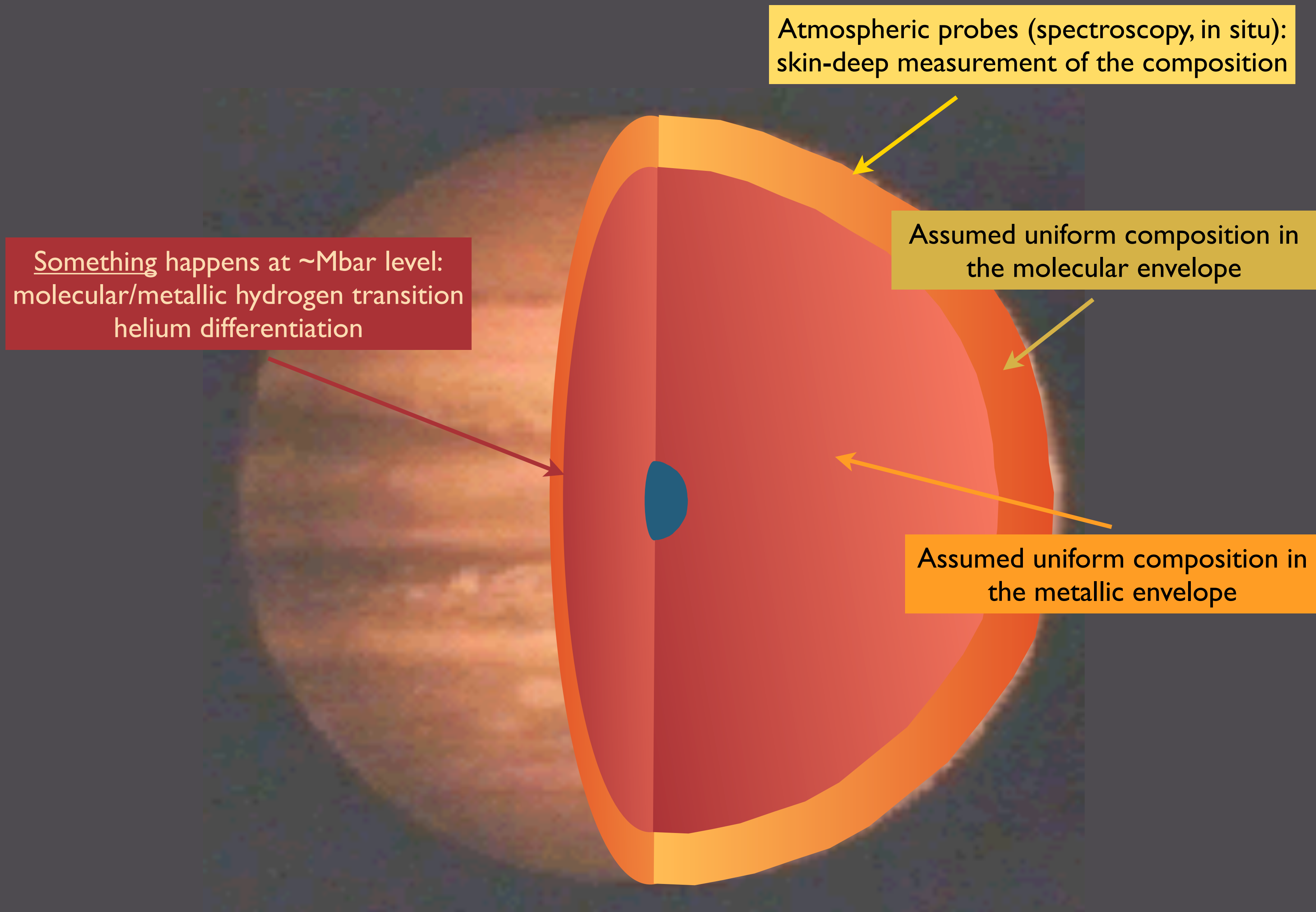

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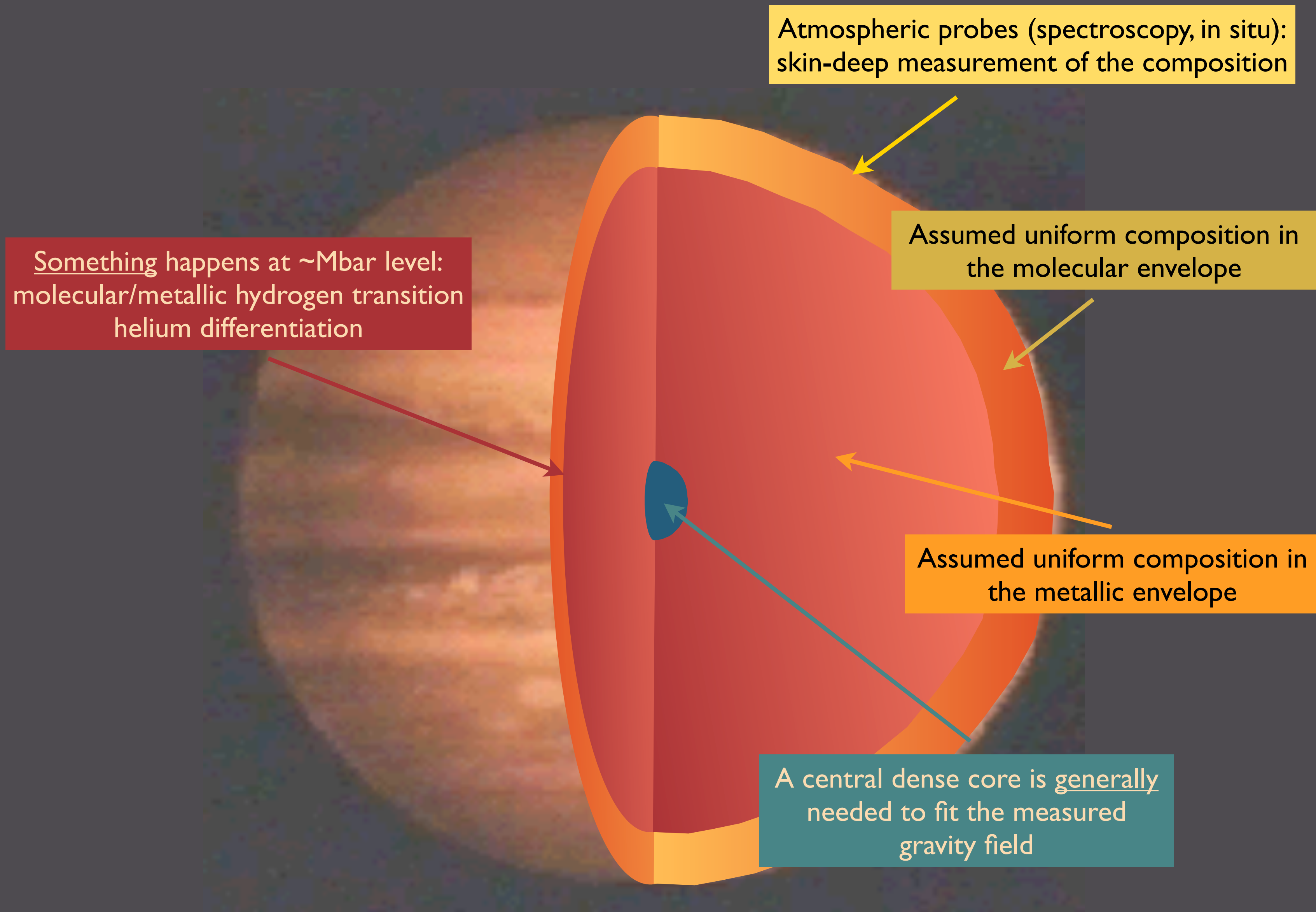
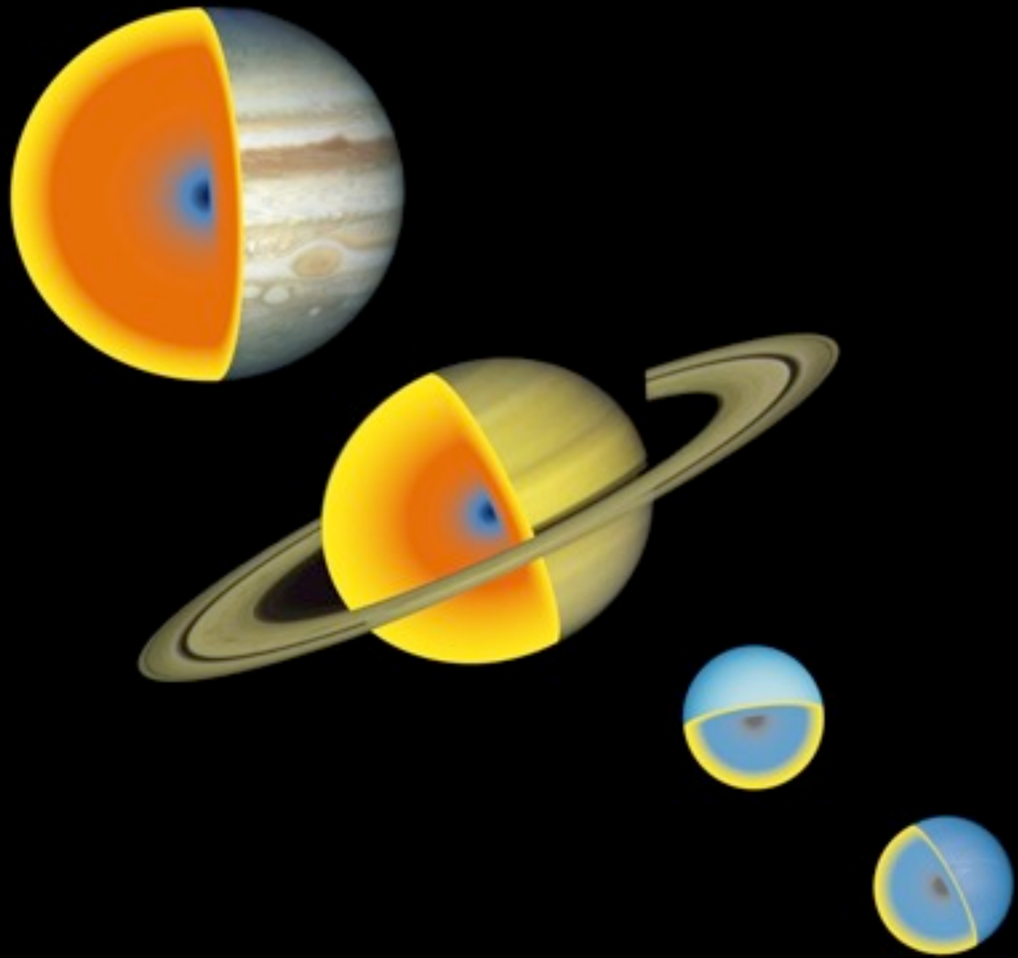


helium



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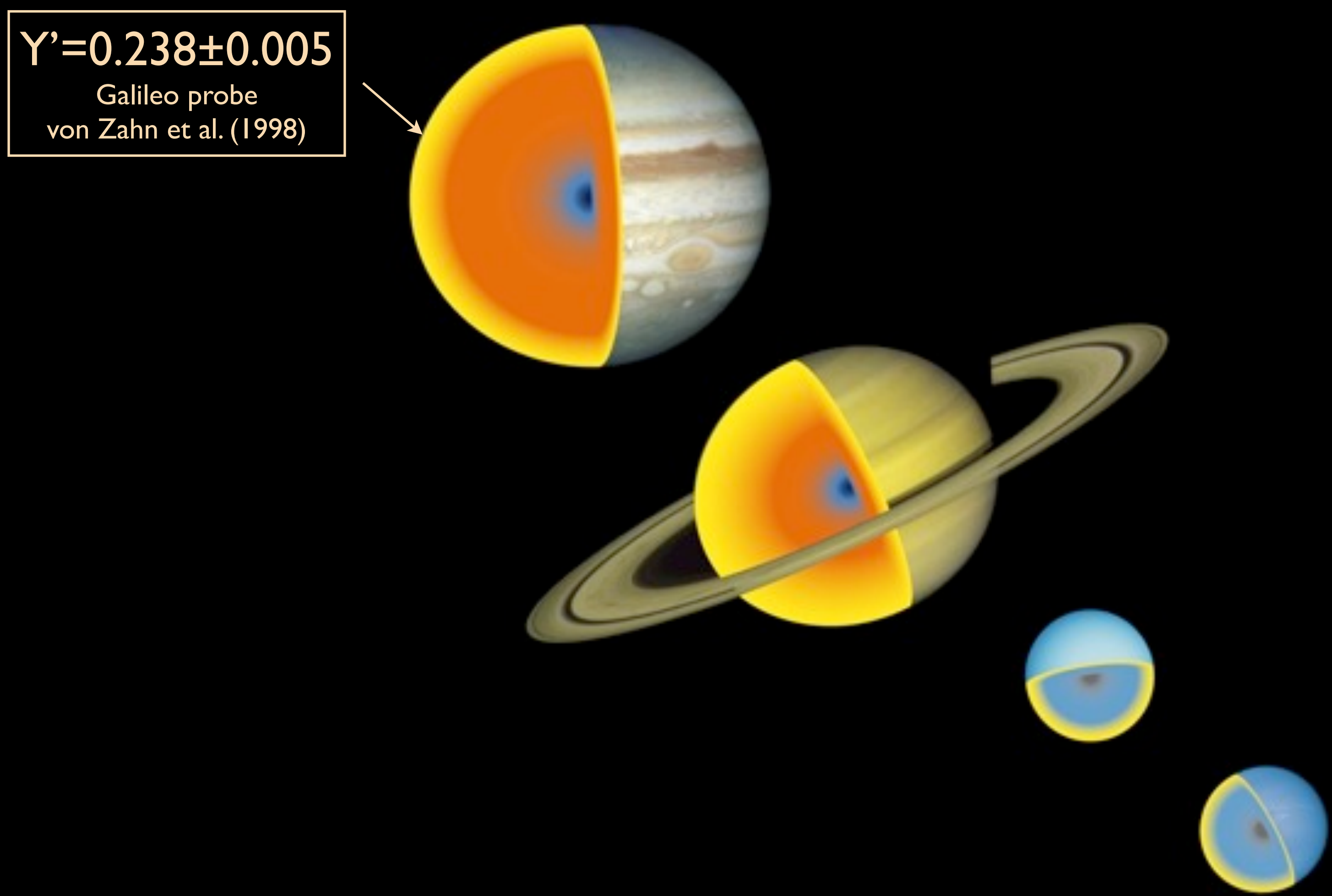
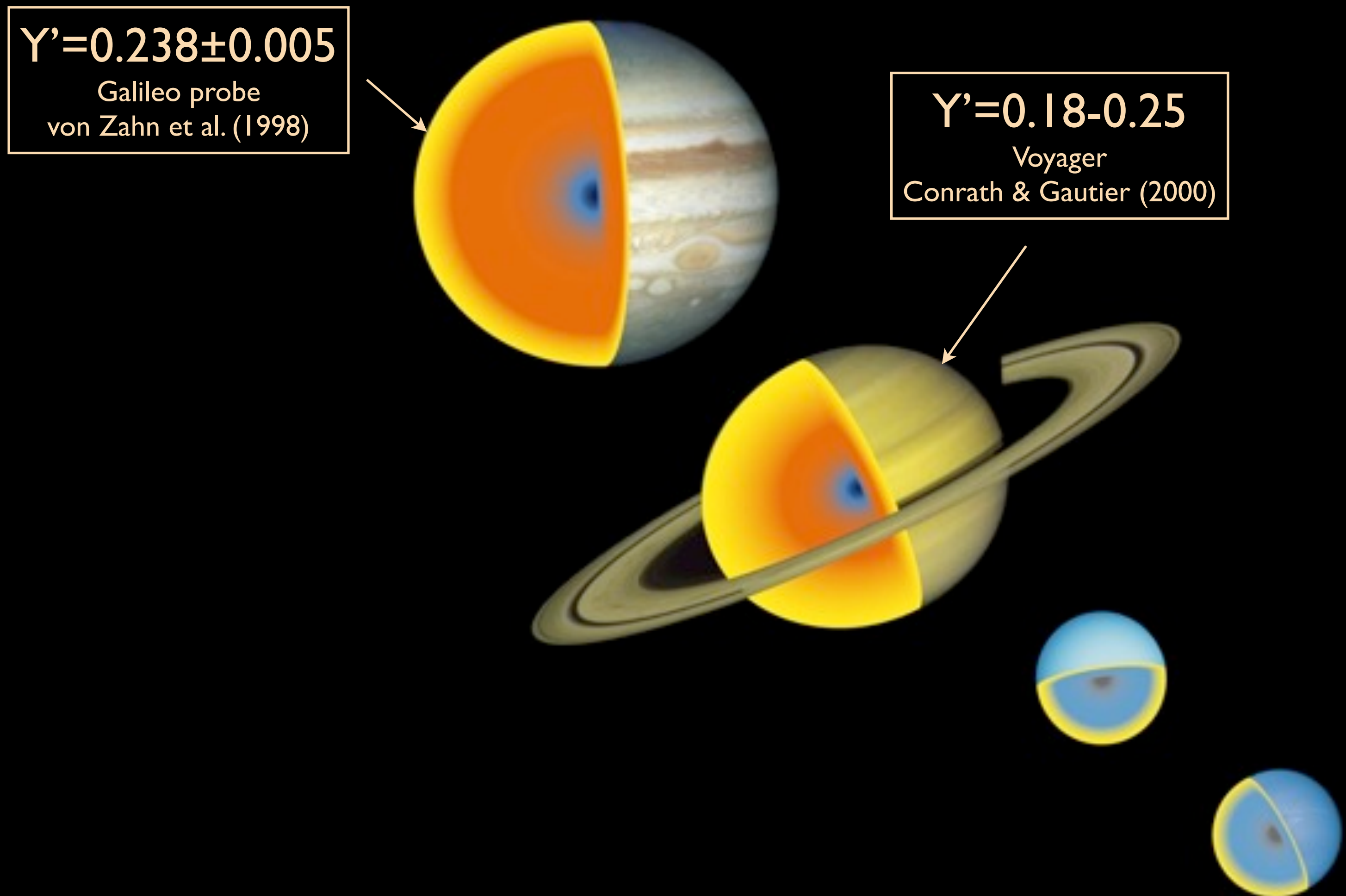
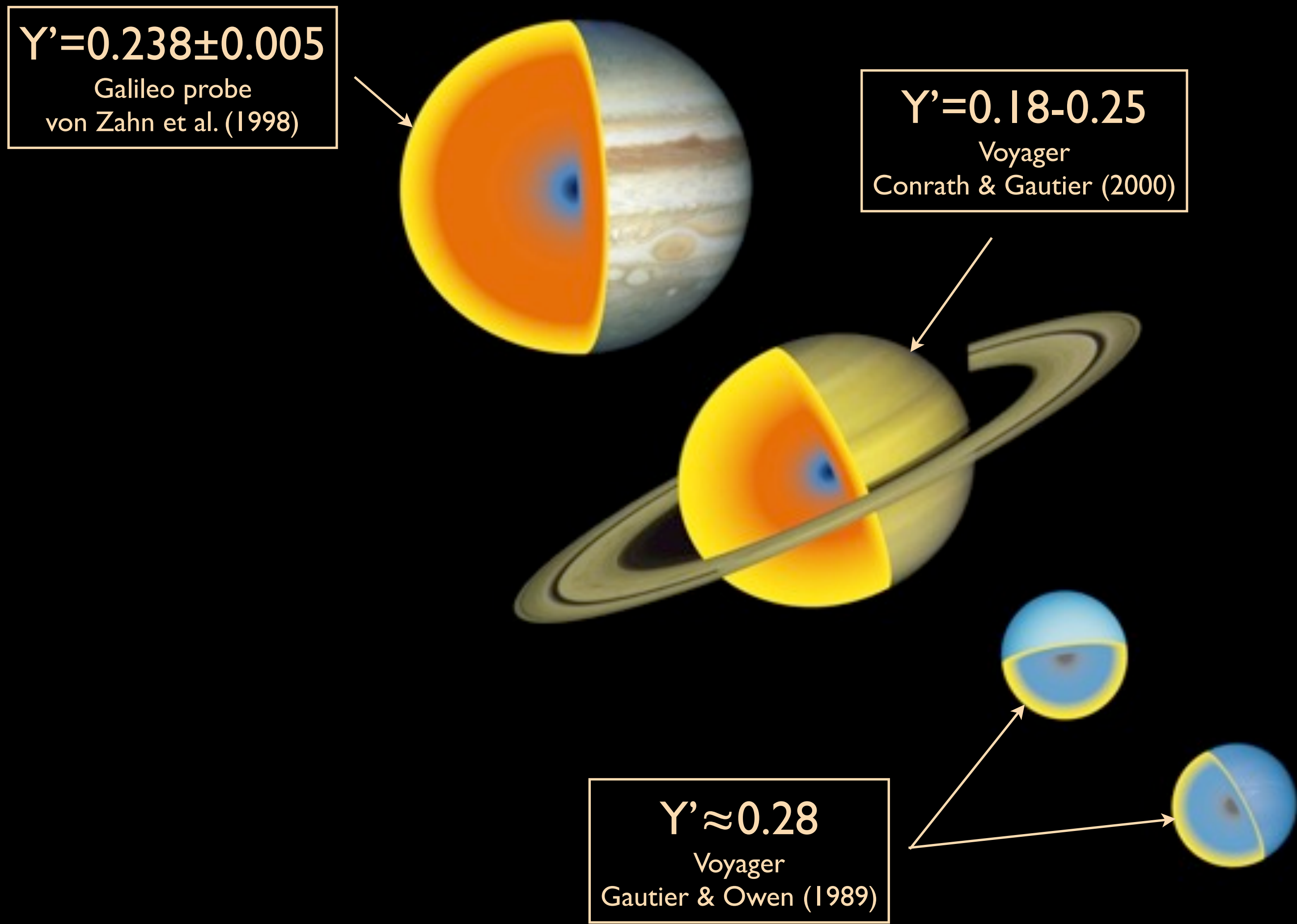


helium


Y'=0.238±0.005
Galileo probe
von Zahn et al. (1998)
Y'=0.18-0.25
Voyager
Conrath & Gautier (2000)

helium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Y'≈0.28
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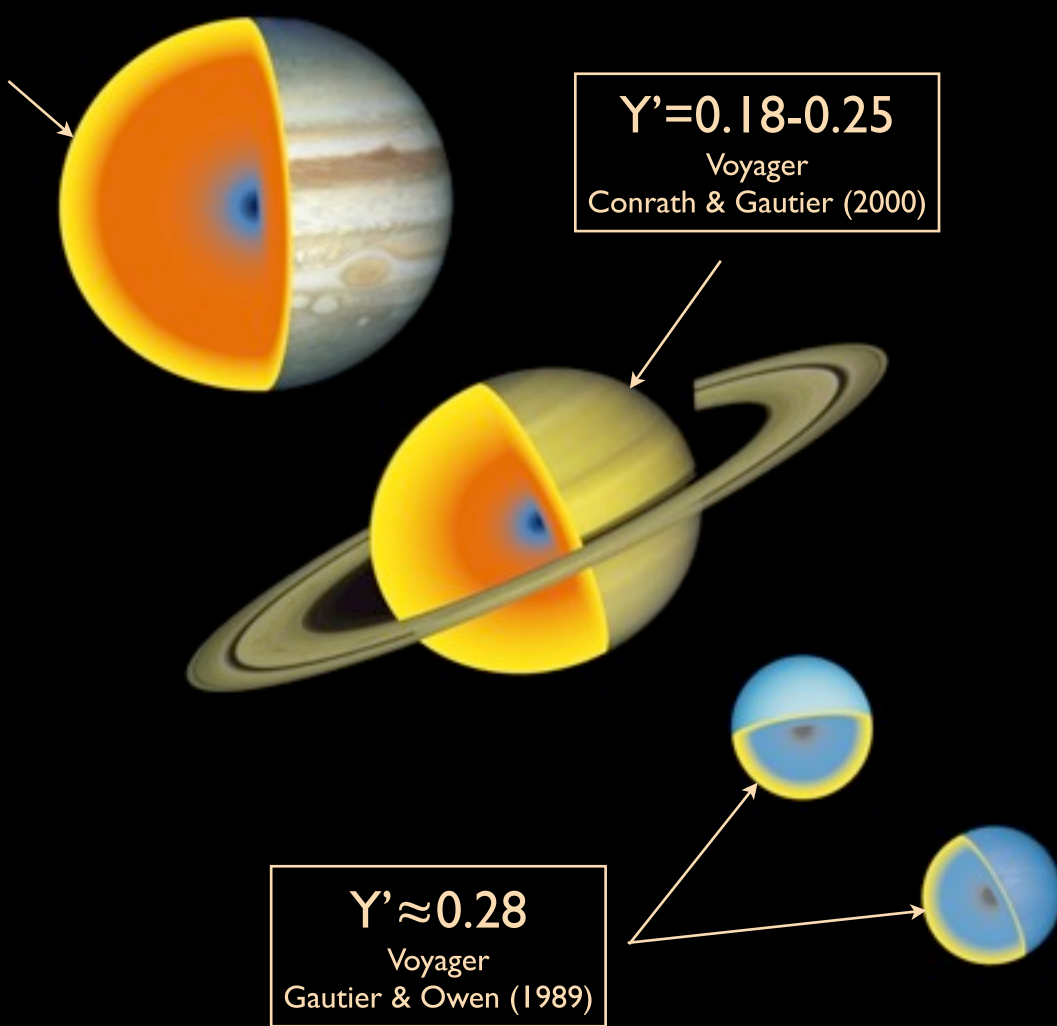
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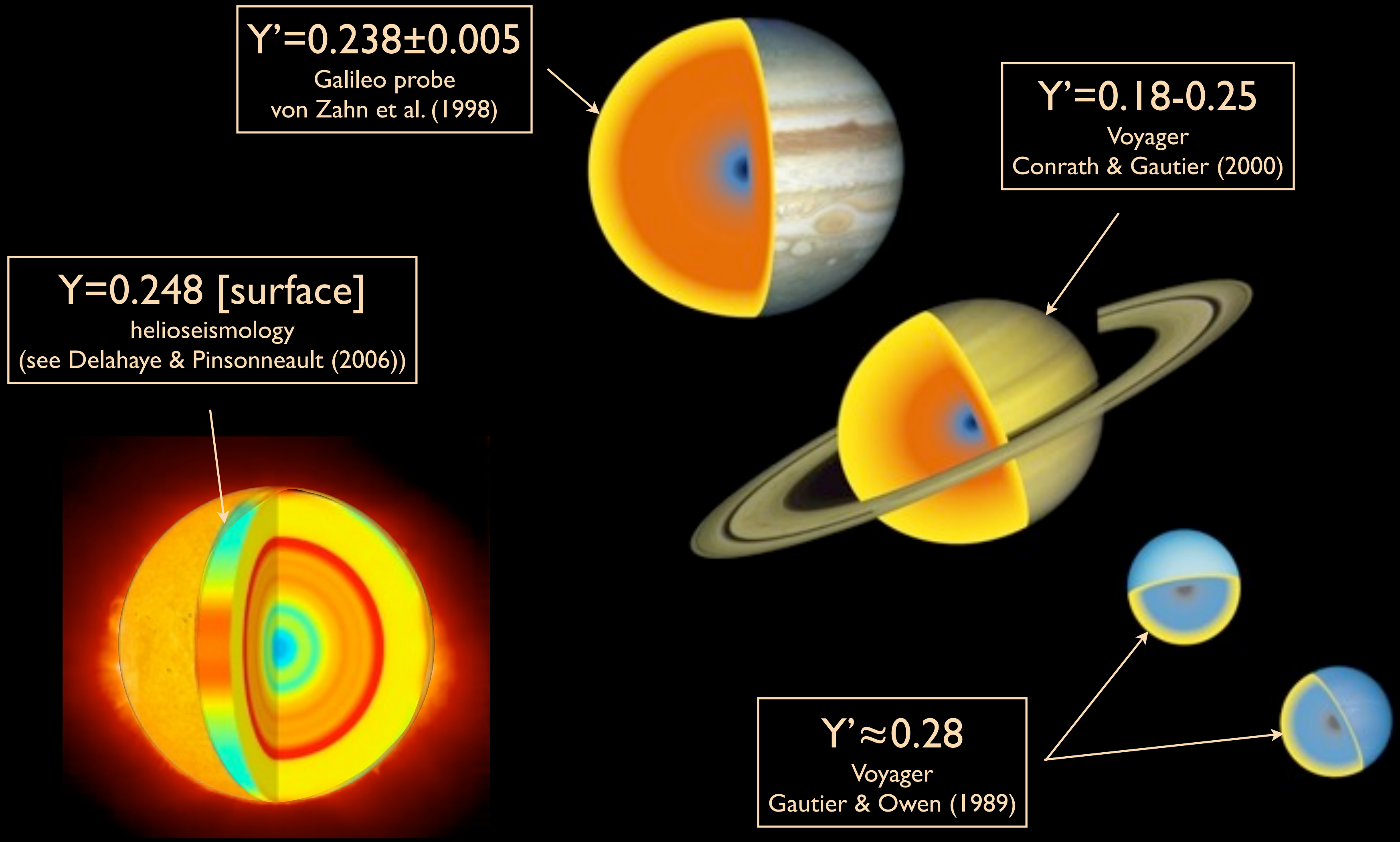

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Galileo probe
von Zahn et al. (1998)
Y'=0.18-0.25
Voyager
Conrath & Gautier (2000)
Y=0.248 [surface]
helioseismology
(see Delahaye & Pinsonneault (2006))
Y'≈0.28
Voyager
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helium

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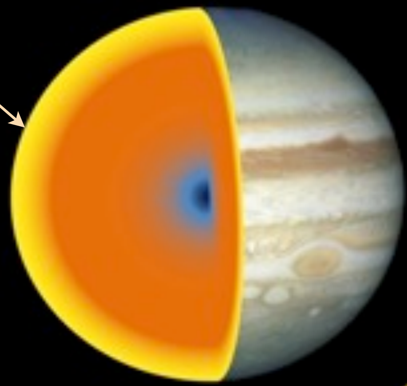

Y'=0.18-0.25
Voyager
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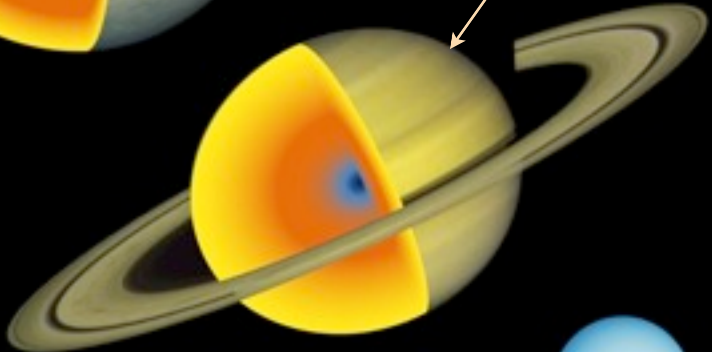
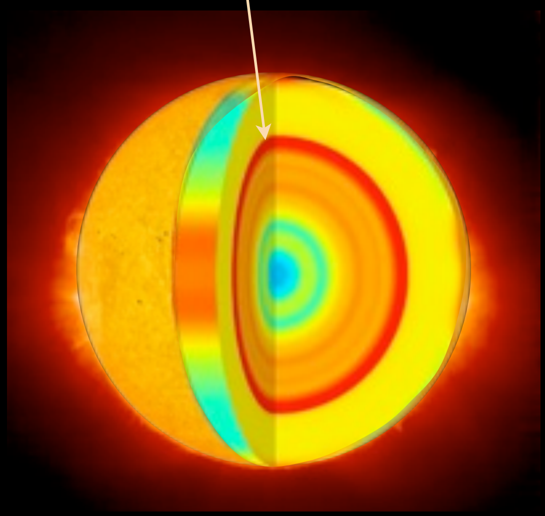
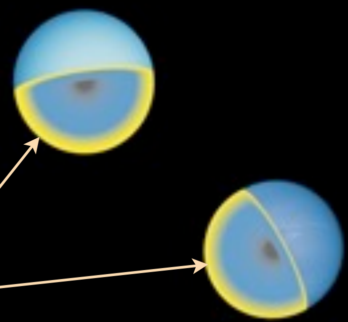


Y=0.275±0.01 [protosolar]
helioseismology+evolution models
(see e.g. Lodders (2004))





Y'≈0.28
Voyager
Gautier & Owen (1989)

Modeling rotating planets

Equations of state

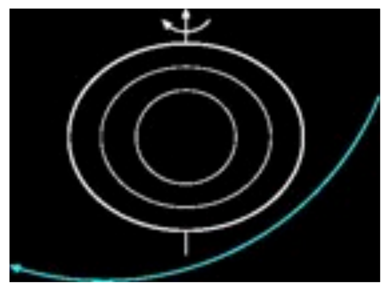
Opacities

Mass,
surface temperature…etc.

Hydrostatic equations
(rotation to 4th order)

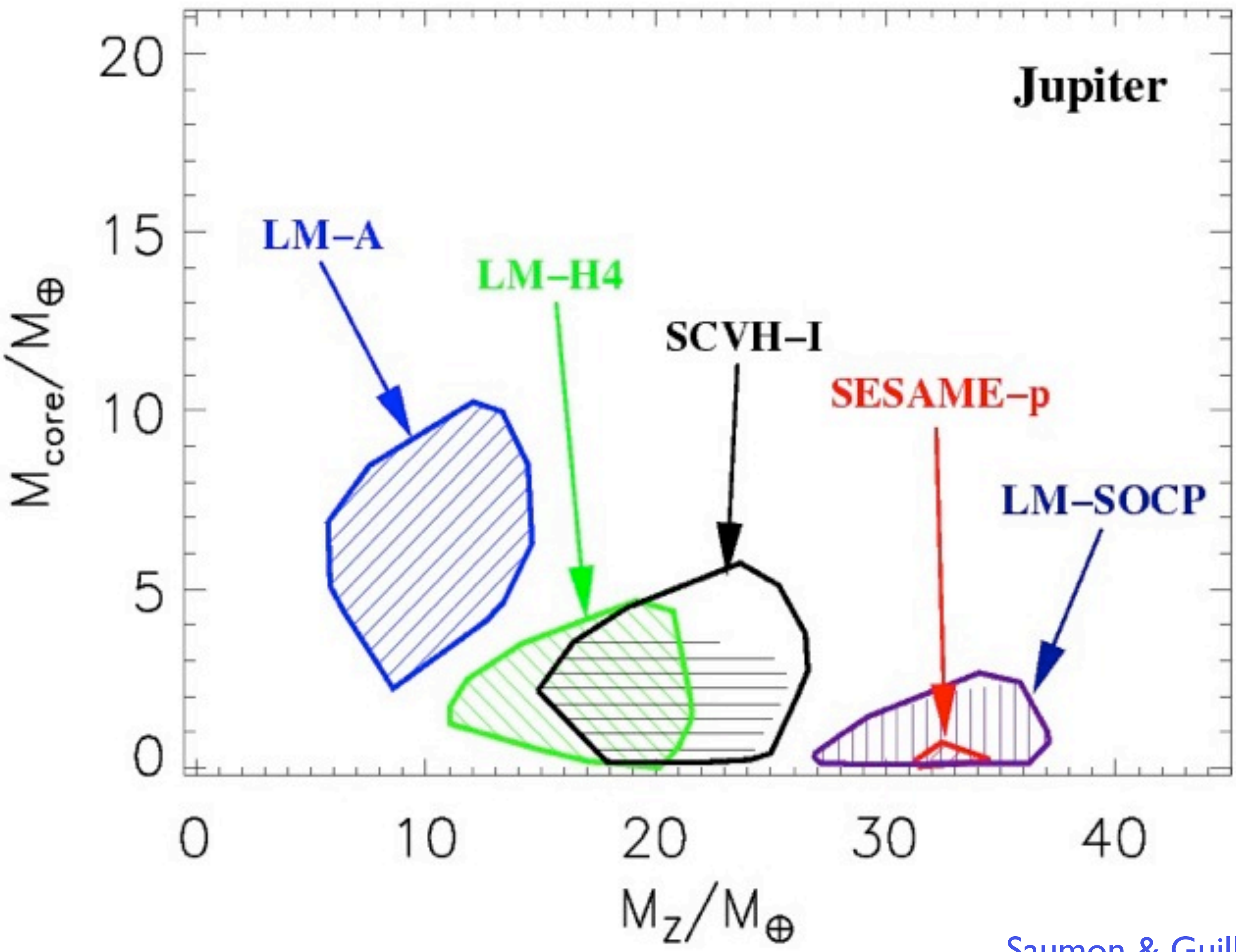
Theoretical gravitational
moments: J2, J4, J6,J8

Measured gravitational
moments: J2, J4, J6



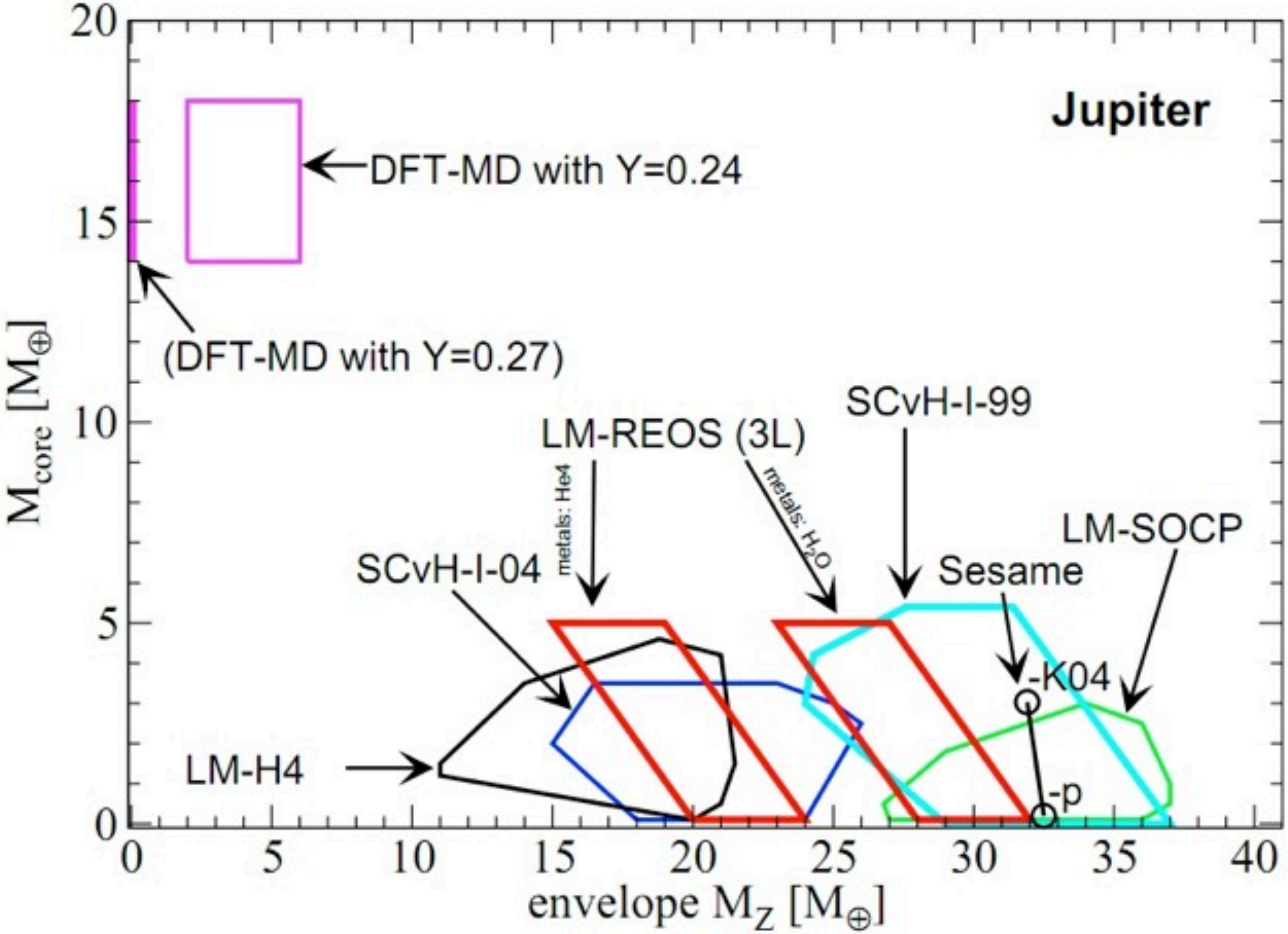
Mass of the rock/ice core
Y+Z in the metallic region
Y+Z in the molecular region

Results for Jupiter



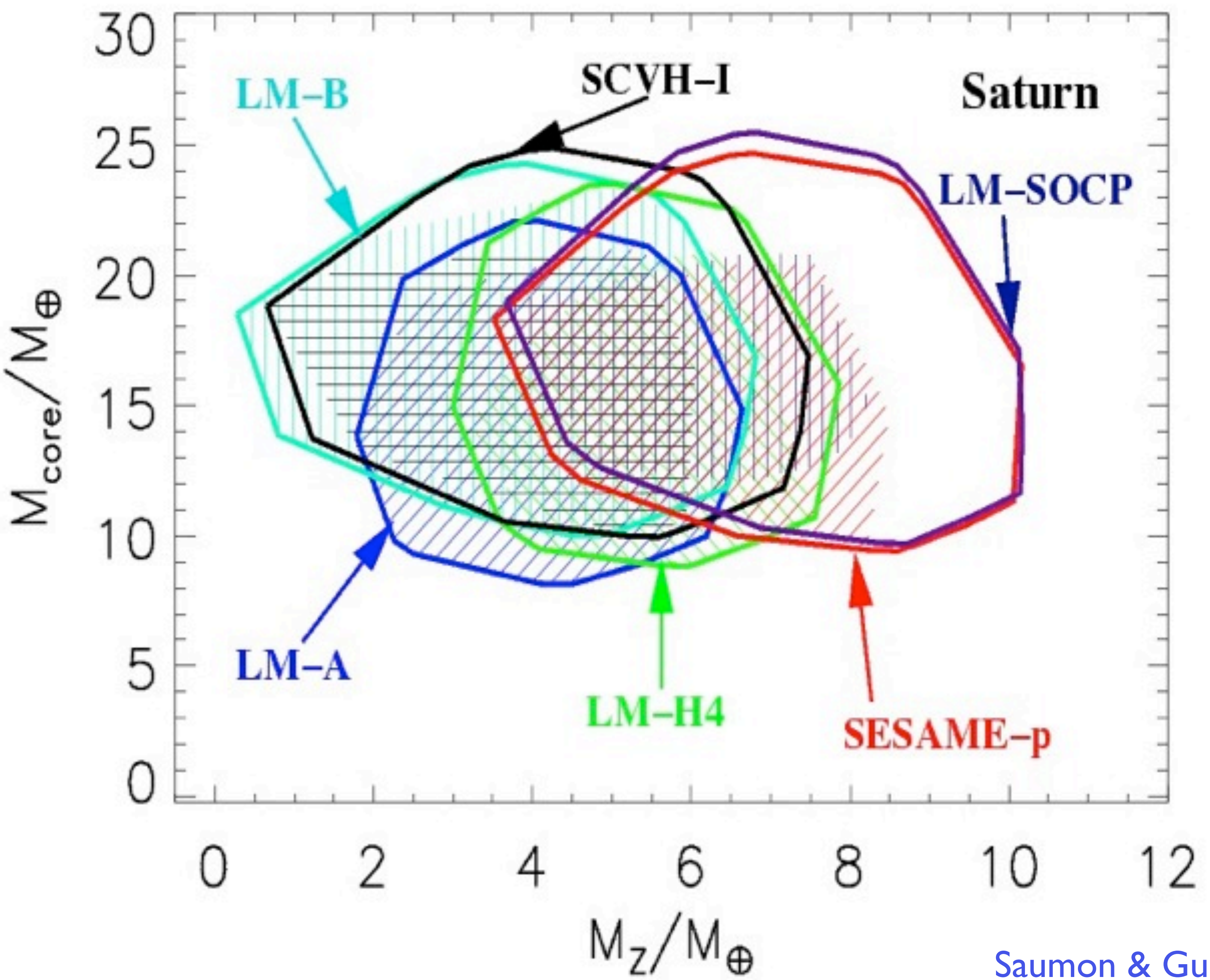
Saumon & Guillot 2004

Results for Jupiter



Fortney & Nettelmann 2010

Results for Saturn



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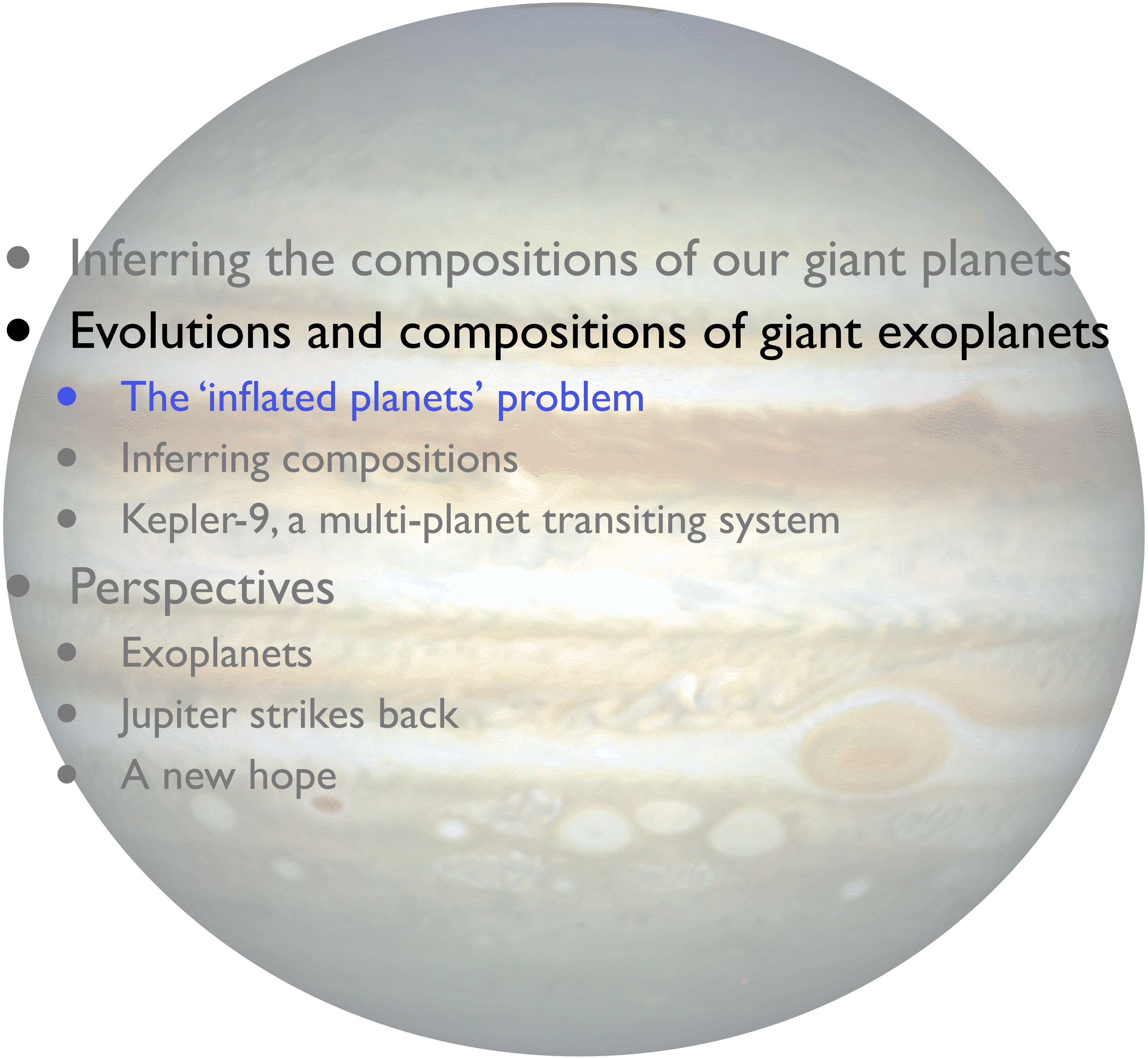

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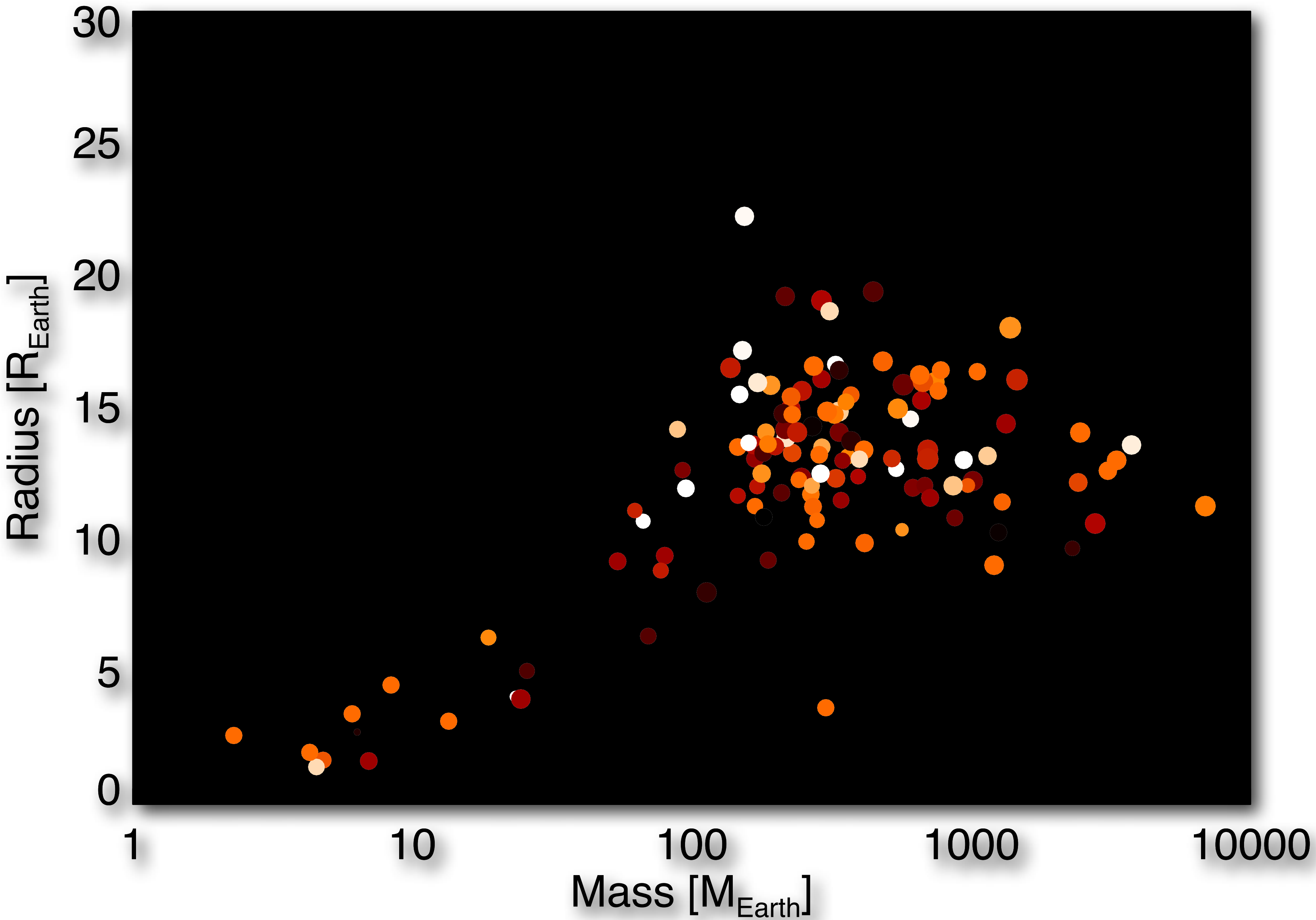
Transiting exoplanets: May 2011



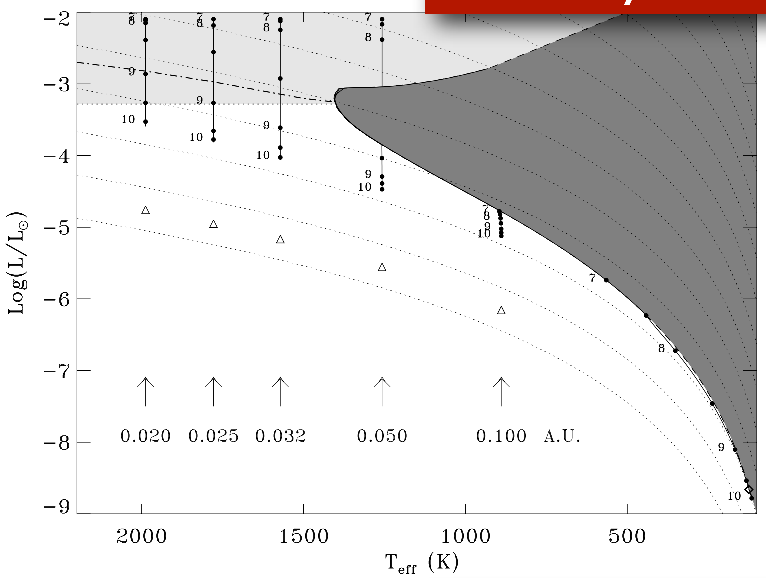
Principle

Giant planets gradually contract & cool
(Hubbard 1977)

Irradiated planets develop a deep radiative zone and contract more slowly
(Guillot et al. 1996)

More heavy elements implies smaller planets
(e.g. Guillot 2005- see however Baraffe et al. 2008, Spiegel et al. 2010, Burrows et al. 2011)

Planetary HR diagram



Mass-radius relation

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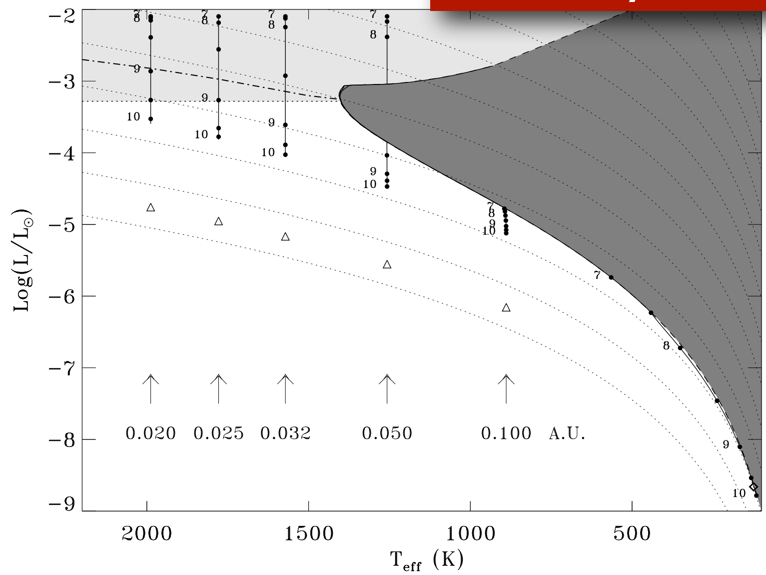

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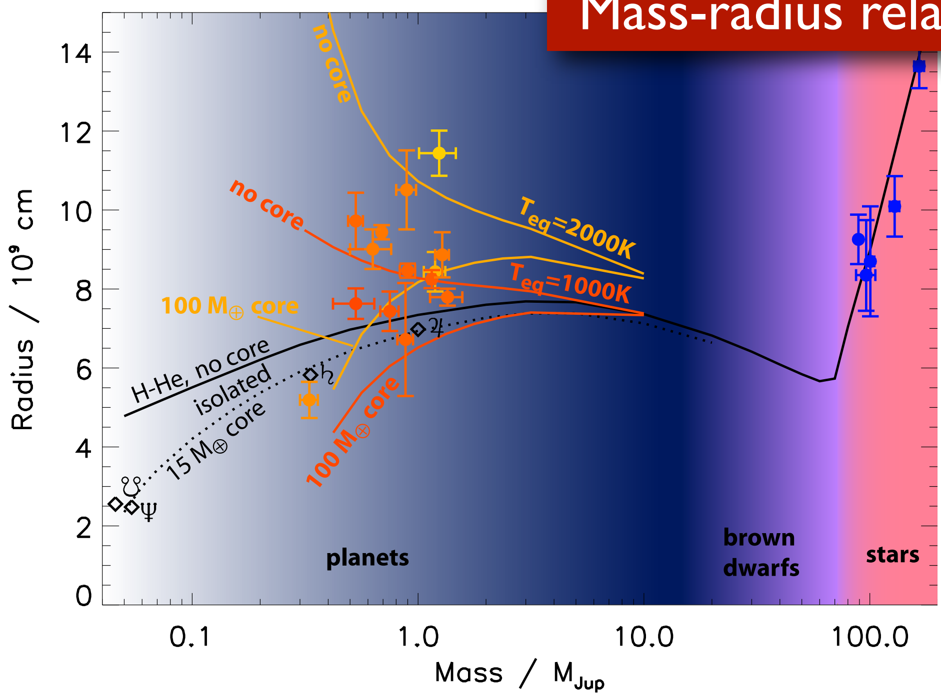

The radius anomaly: description

HD209458b was shown to be anomalously large
Bodenheimer et al. (2001)
Guillot & Showman (2002)
Baraffe et al. (2003)

The radius anomaly of an exoplanet is defined as the difference between the observed radius and the theoretical size of a solar-composition planet of the same mass and age
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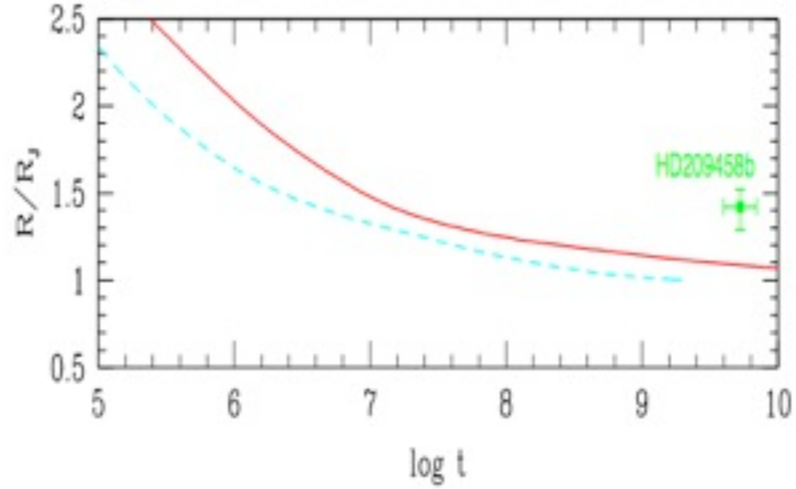
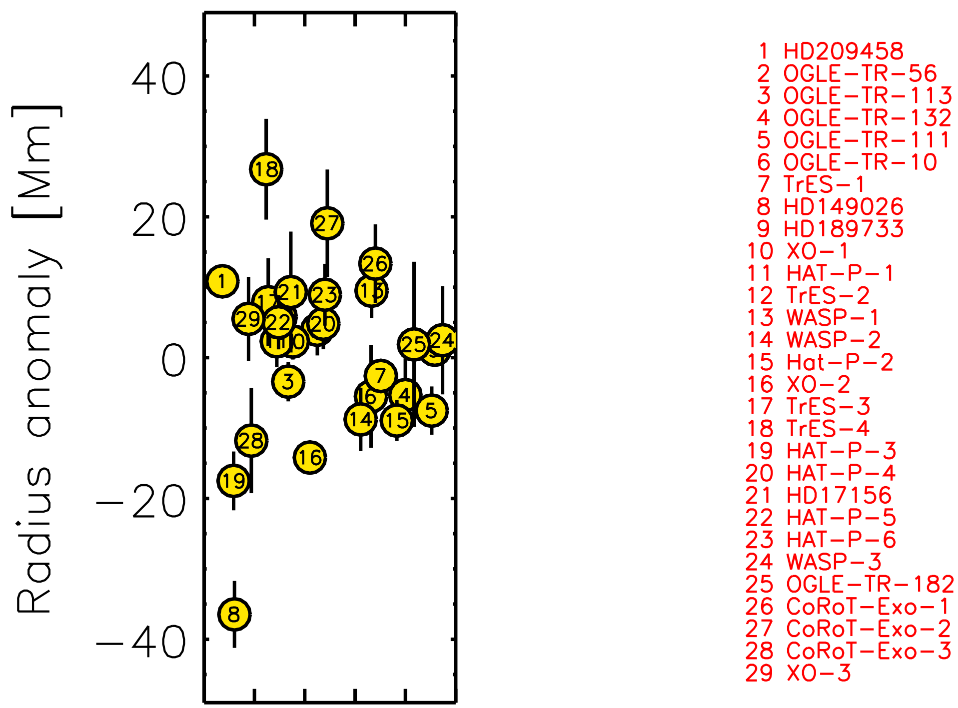
A large fraction of known transiting exoplanets have a positive radius anomaly
Guillot et al. (2006), Burrows et al. (2007), Guillot (2008), Laughlin et al. (2011)





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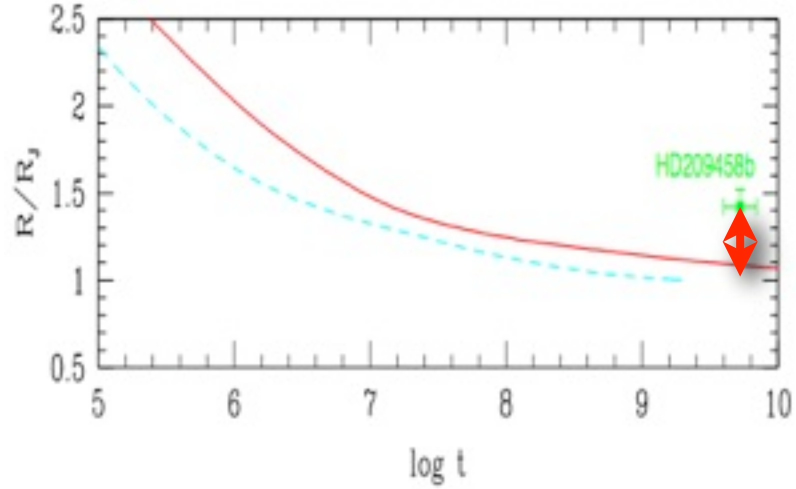
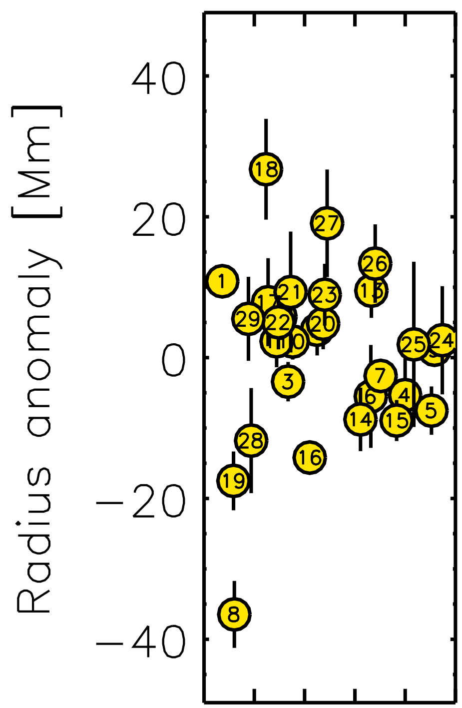


Radius anomaly



1 HD209458
2 OGLE−TR−56
3 OGLE−TR−113
4 OGLE−TR−132
5 OGLE−TR−111
6 OGLE−TR−10
7 TrES−1
8 HD149026
9 HD189733
10 XO−1
11 HAT−P−1
12 TrES−2
13 WASP−1
14 WASP−2
15 Hat−P−2
16 XO−2
17 TrES−3
18 TrES−4
19 HAT−P−3
20 HAT−P−4
21 HD17156
22 HAT−P−5
23 HAT−P−6
24 WASP−3
25 OGLE−TR−182
26 CoRoT−Exo−1
27 CoRoT−Exo−2
28 CoRoT−Exo−3
29 XO−3

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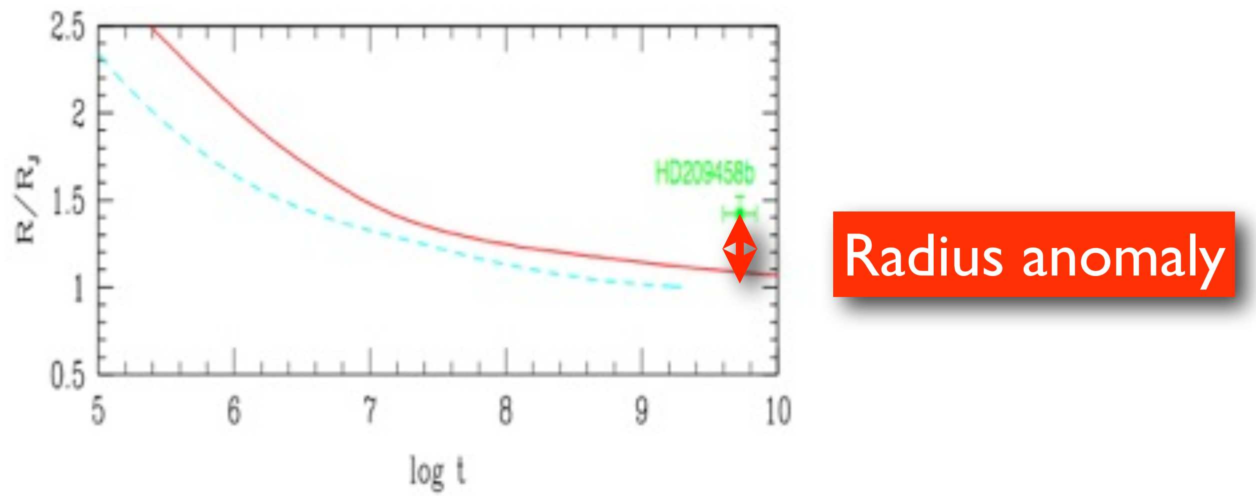

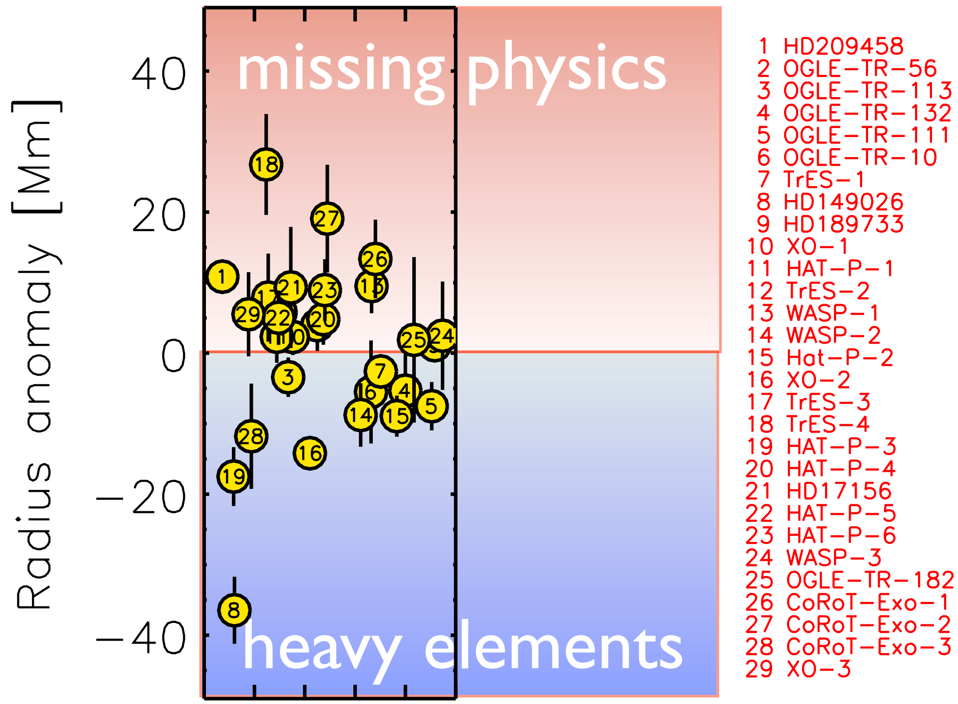

Possible explanations

Binding energy: $E_B \sim GM^2/R \sim 10^{43}$ erg for HD209458b

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1. Slow the cooling

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2. Transport irradiation energy deep

Stellar irradiation:

$L \sim 3 \times 10^{29}$ erg/s

The energy received in 1Ma is 10^{43} erg

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The energy received in 1Ma is 10^{43} erg

3. Tap from orbital energy reservoir

Orbital energy

$E = GM_{star}M/2a \sim 3 \times 10^{44}$ erg

The spin energy for a 10h rotation is

$E_s \sim 1/5\, MR^2\omega^2 \sim 10^{42}$ erg

Possible explanations

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1. Slow the cooling

Increased interior opacities:

Guillot (2005), Guillot et al. (2006)

Increased atmospheric opacities:

Burrows et al. (2007), Guillot (2010), Burrows et al. (2011)

Semi-convection:

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"Weather noise" model:

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Ohmic dissipation:

Laine, Lin & Dong (2009), Batygin & Stevenson (2010)

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Thermal tides:

Arras & Socrates (2010)

(but Gu & Ogilvie 2009; Goodman astroph)

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Circularisation by tides:

Bodenheimer et al. (2001)

Gu et al. (2003),

Jackson et al. (2008, 2009),

Ibgui et al. (2009),

Ibgui & Burrows (2010),

Miller et al. (2009)

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but:

Leconte et al. (2010)

(see also Barker & Ogilvie 2009)

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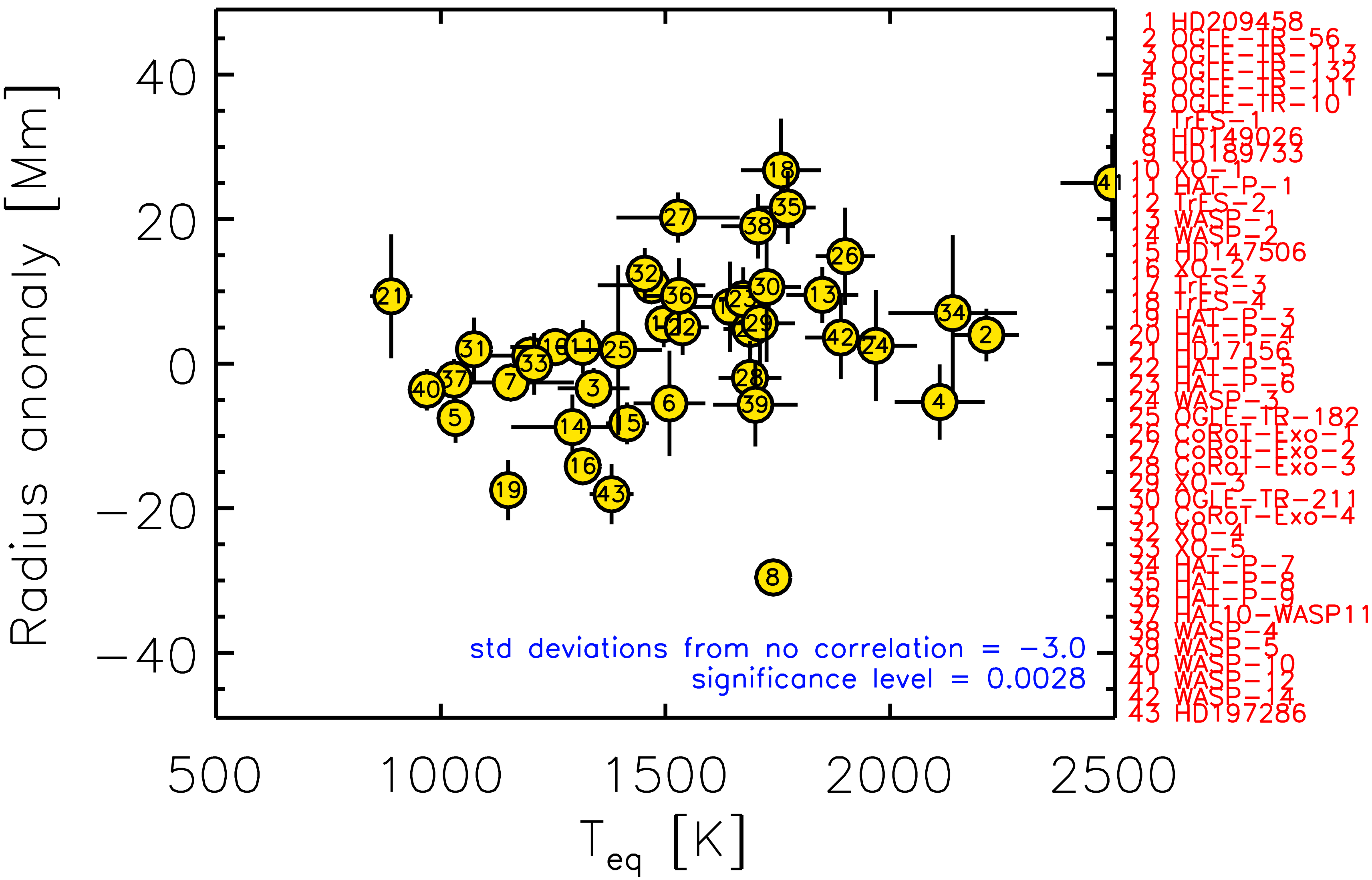
T_{eq} vs radius anomaly



Models from Guillot (2008)

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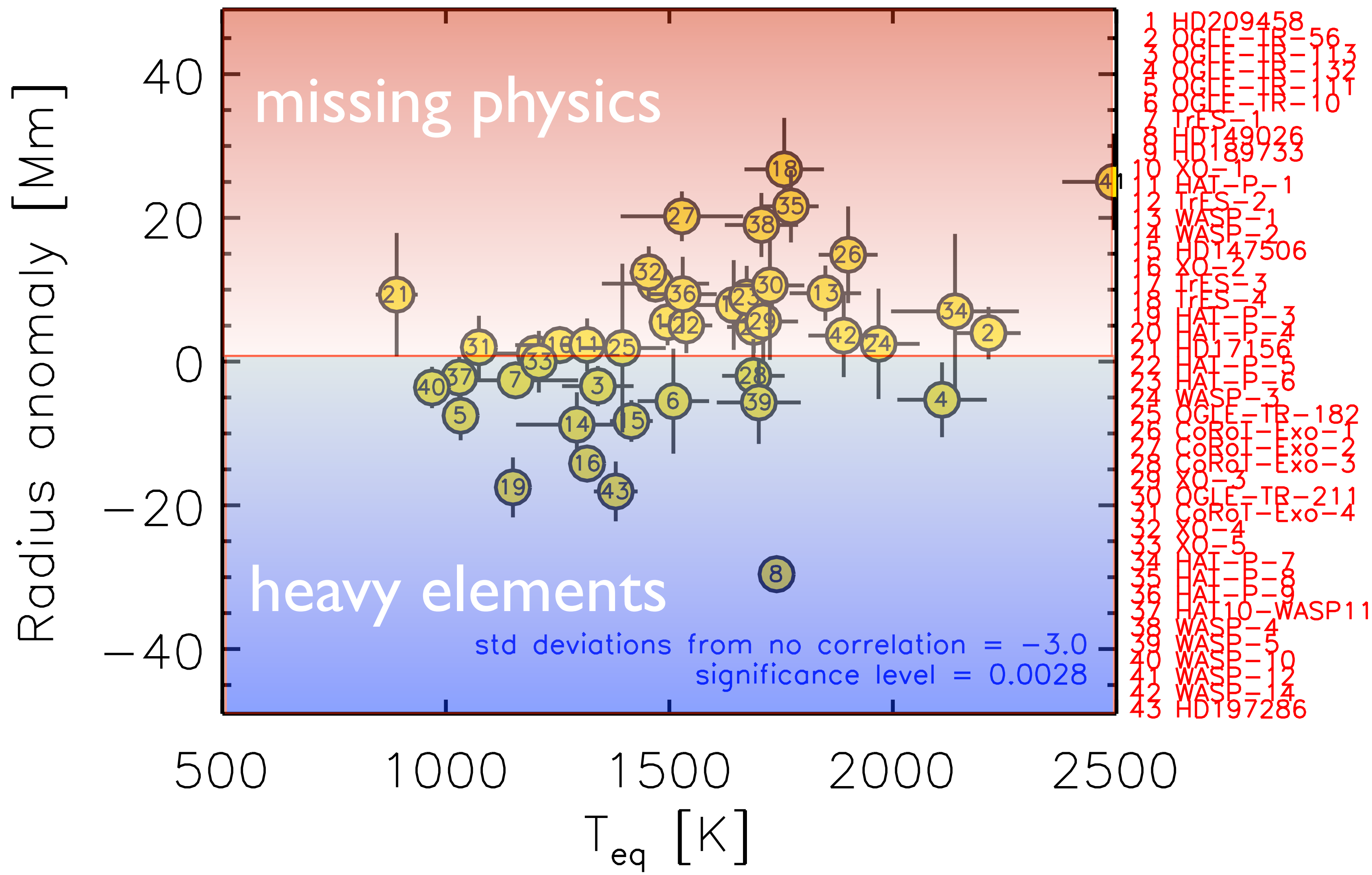

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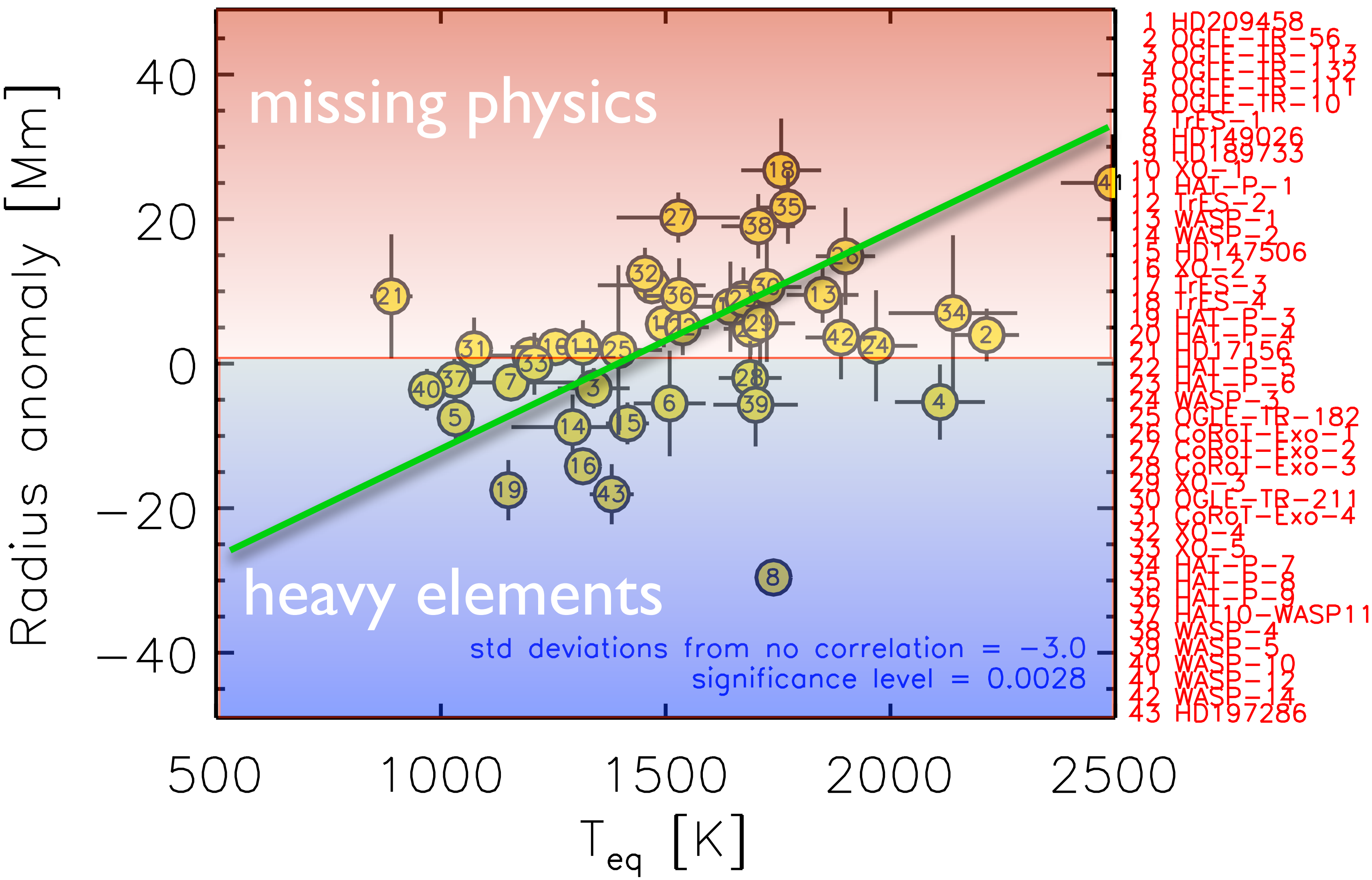

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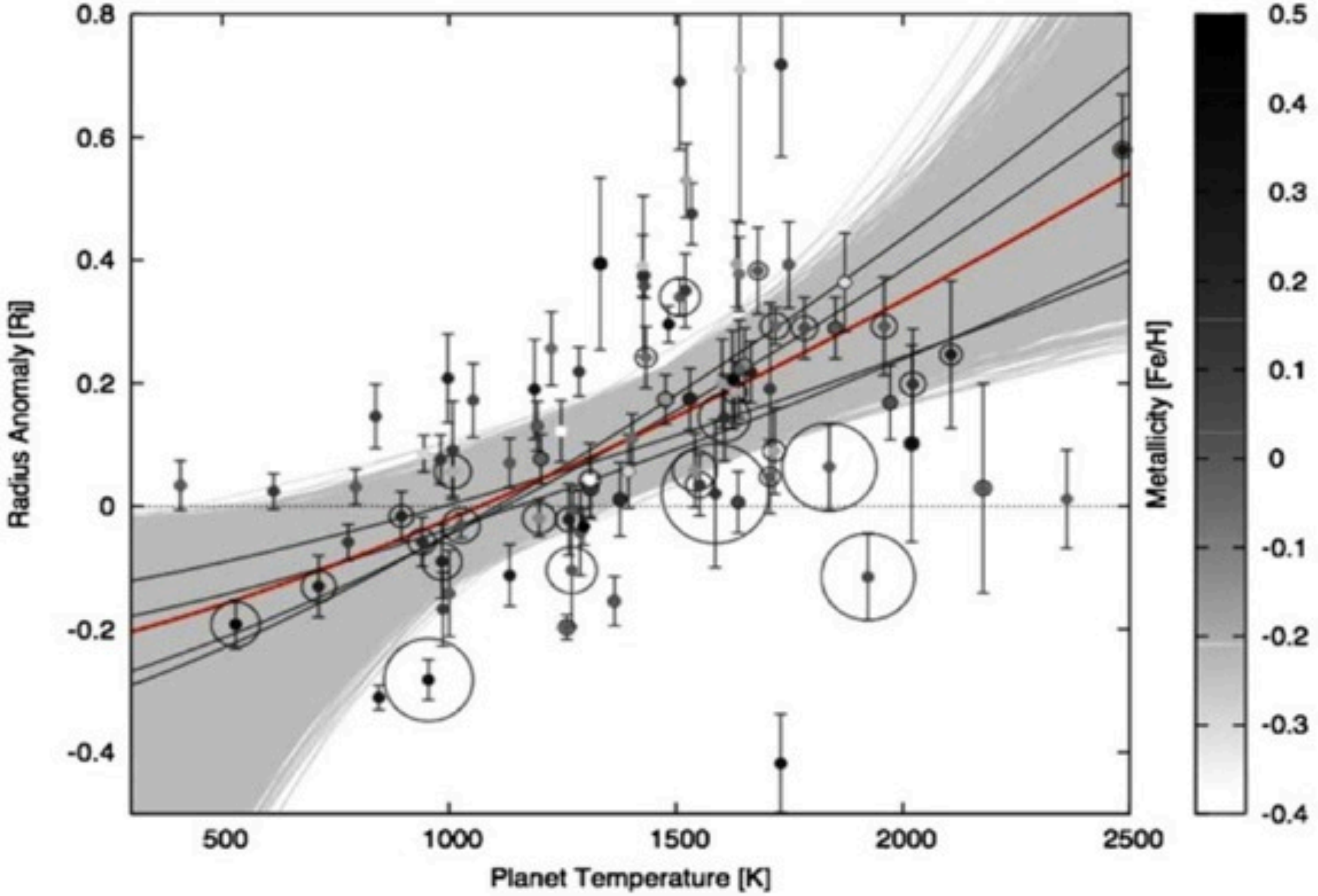

Laughlin et al. (2011): $\mathcal{R} \propto \mathrm{Teq}^{1.4\pm0.6}$

- ~ok for ohmic dissipation.
- Too strong for «pure kinetic energy deposition»?

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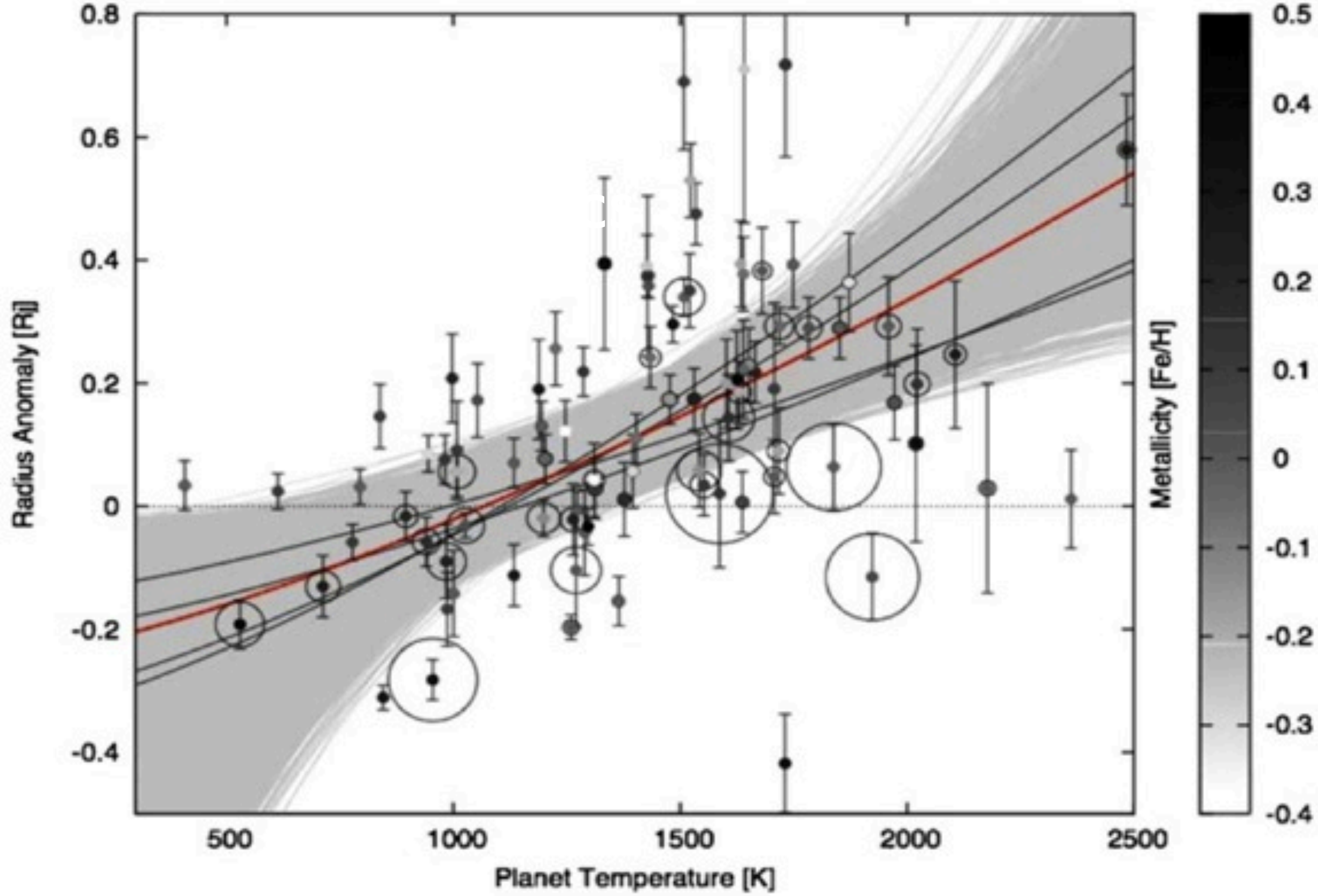

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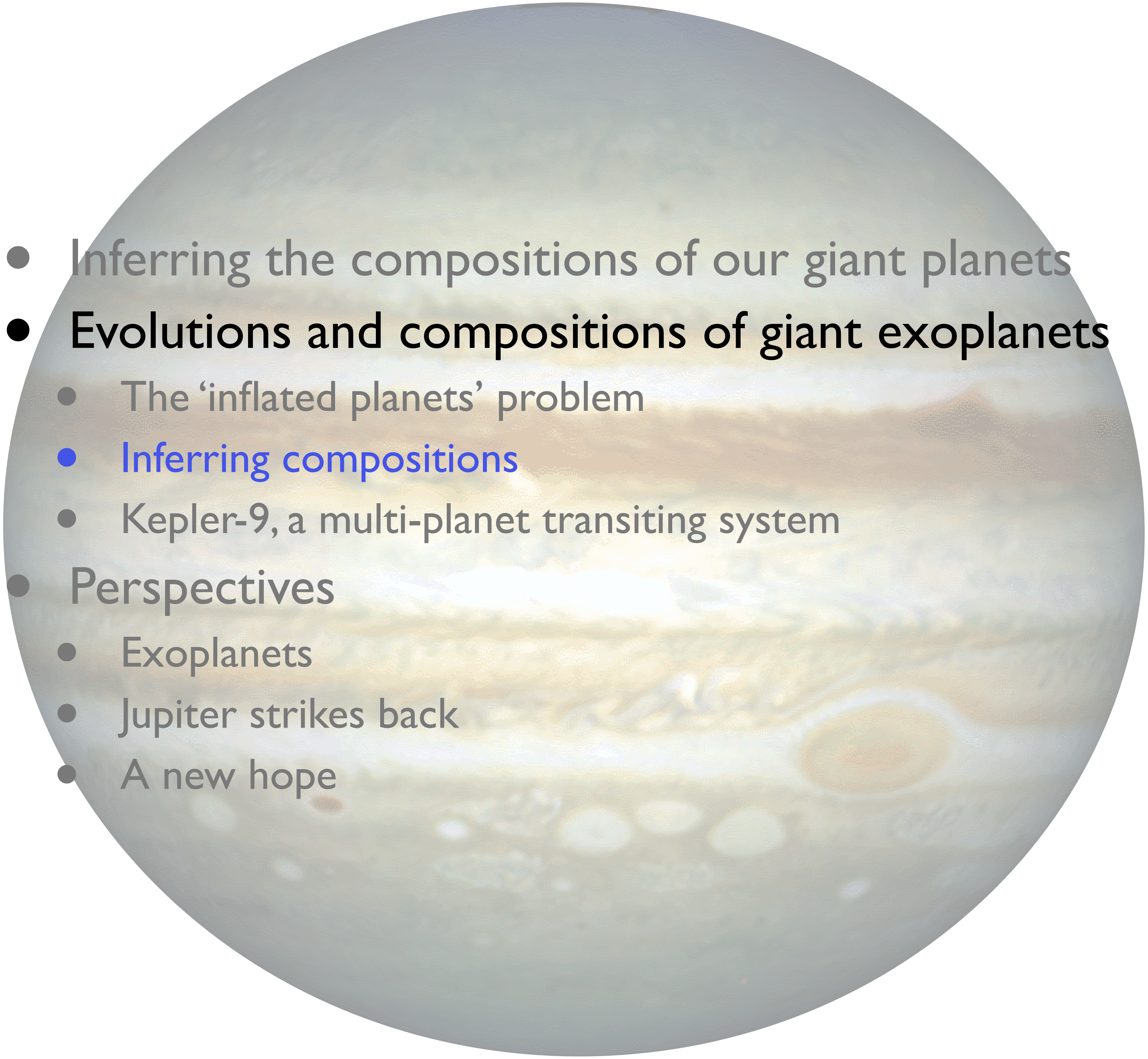
Missing physics: Summary

	magnitude	frequency	a dependence	[Fe/H] dependence	age dependence	Refs
interior/ atmosphere opacities	√	√	~	yes	weak	Guillot et al. (2006), Burrows et al. (2007), Guillot(2008)
Semi-convection	√	?	X	yes	weak	Chabrier & Baraffe (2007)
K.E. model	√	√	√	no	no	Guillot & Showman (2002), Burkert et al. (2005), Guillot et al. (2006, 2008)
Ohmic dissipation	√	√	√	yes	no/yes	Laine et al. (2009), Batygin & Stevenson (2010)
Thermal tides	√	√	√	no	no	Arras & Socrates (2010), [but see Gu & Ogilvie (2009), Goodman (astroph)]
Obliquity tides	?	X	√	no	weak	Winn & Holman (2005), Levrard et al. (2006), Fabrycky et al. (2006)
Eccentricity tides	√	?	√	no	strong	Bodenheimer et al. (2001), Gu et al. (2003), Jackson et al. (2008a,b), Ibgui & Burrows (2009), Miller et al. (2009)



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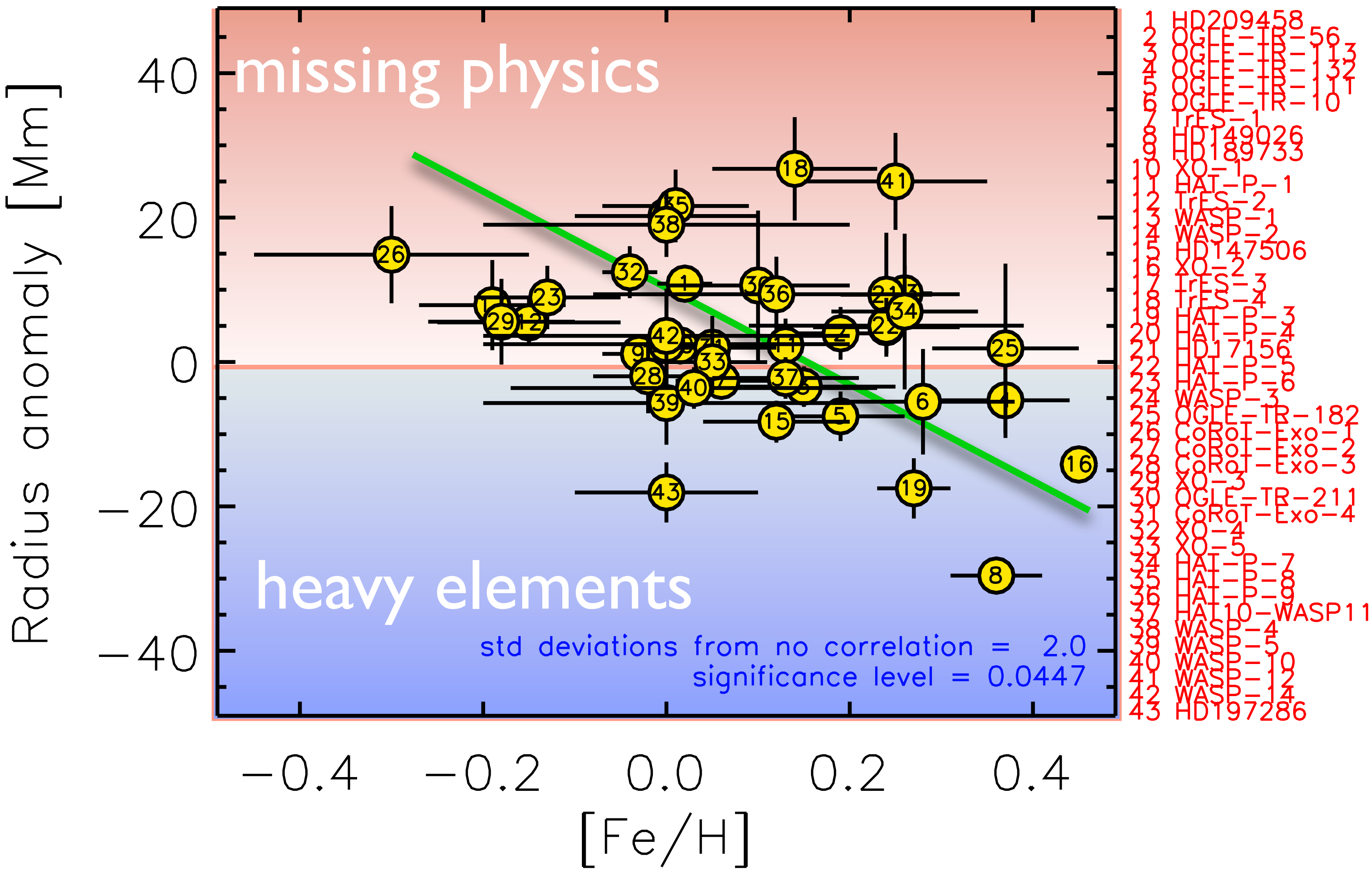
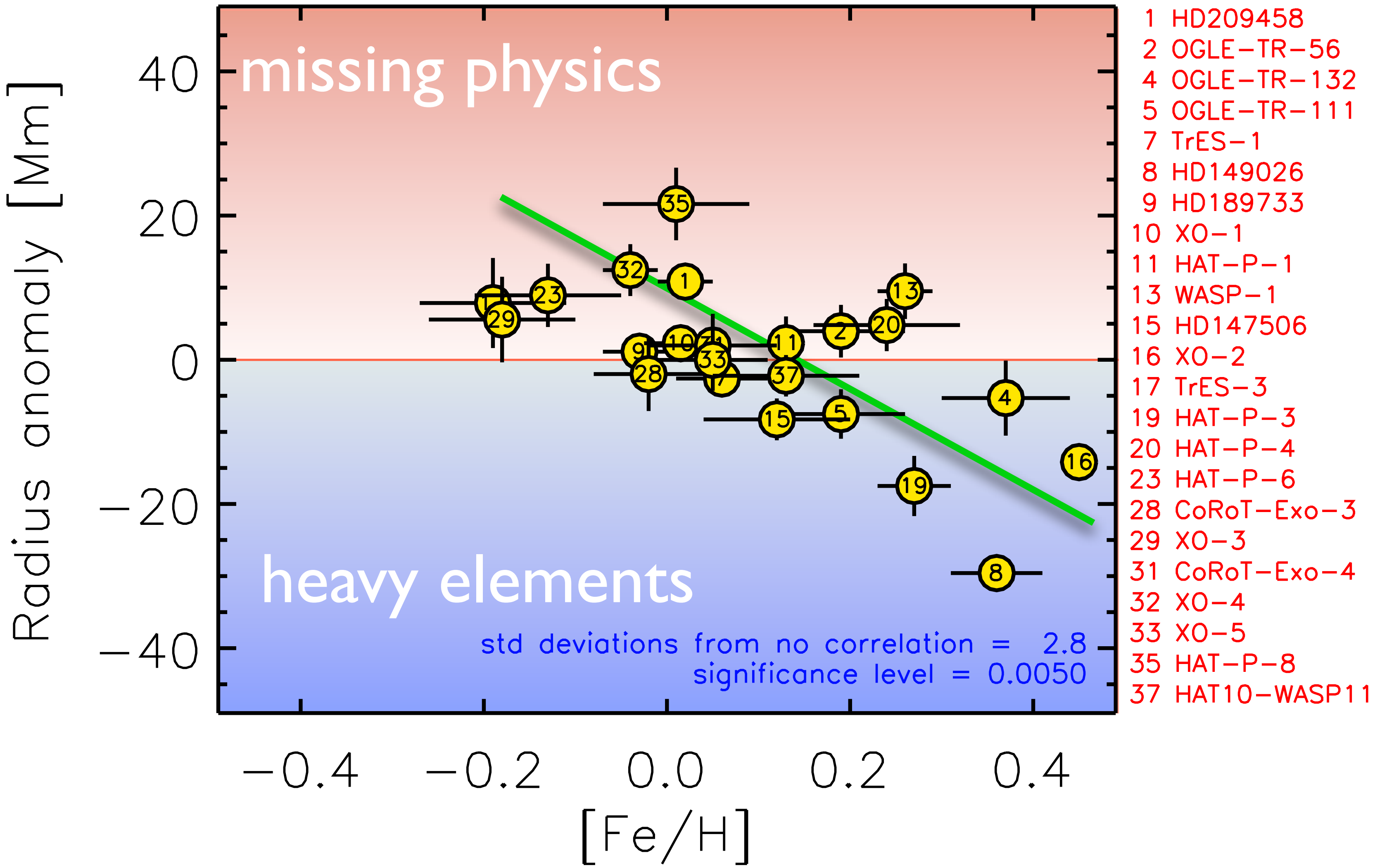
[Fe/H] vs radius anomaly



updated from Guillot 2008

see also Guillot et al. 2006, Burrows et al. 2007

[Fe/H] vs radius anomaly

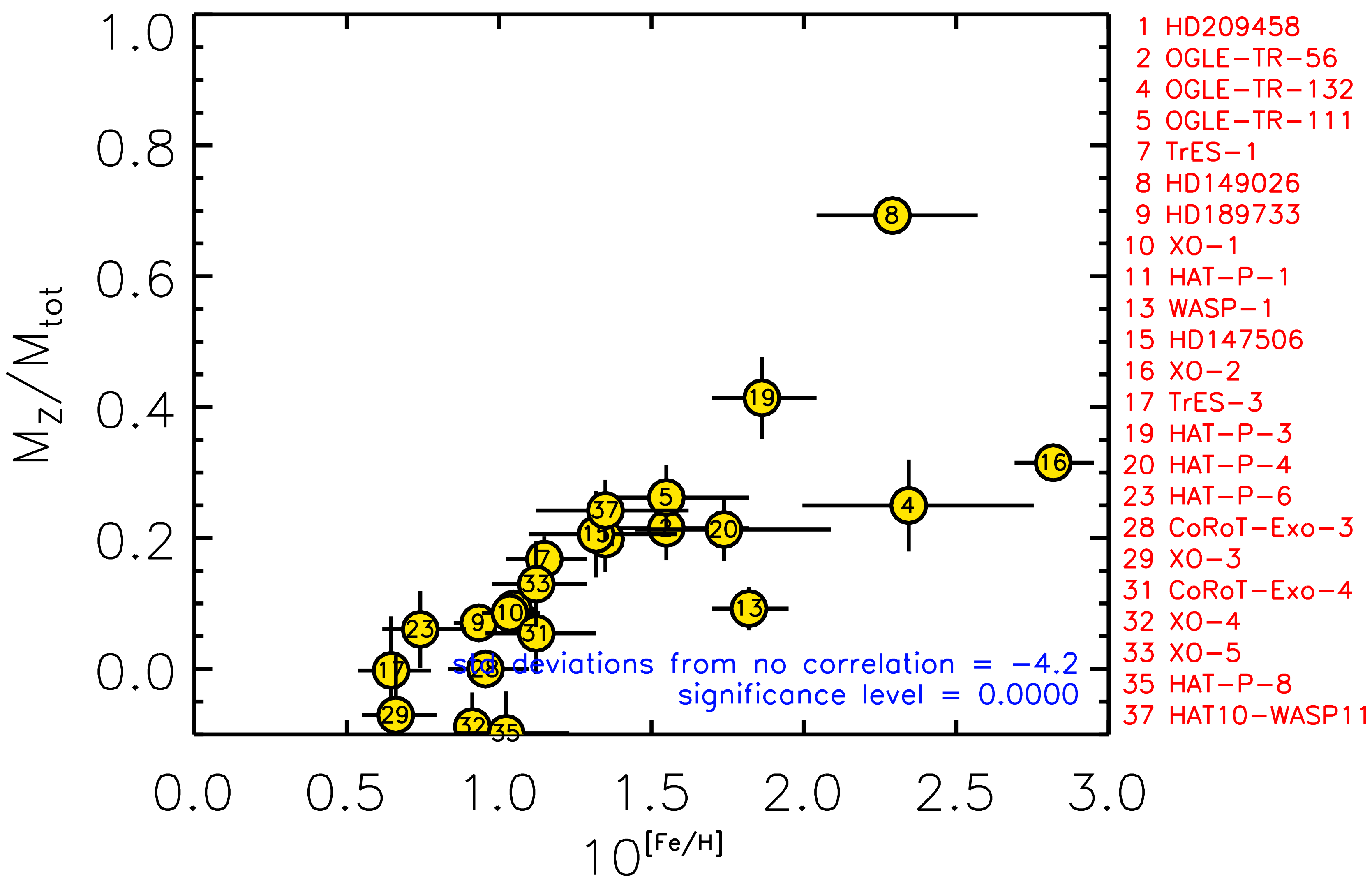


updated from Guillot 2008

see also Guillot et al. 2006, Burrows et al. 2007

(stellar) [Fe/H] vs. (planetary) Mz/Mtot

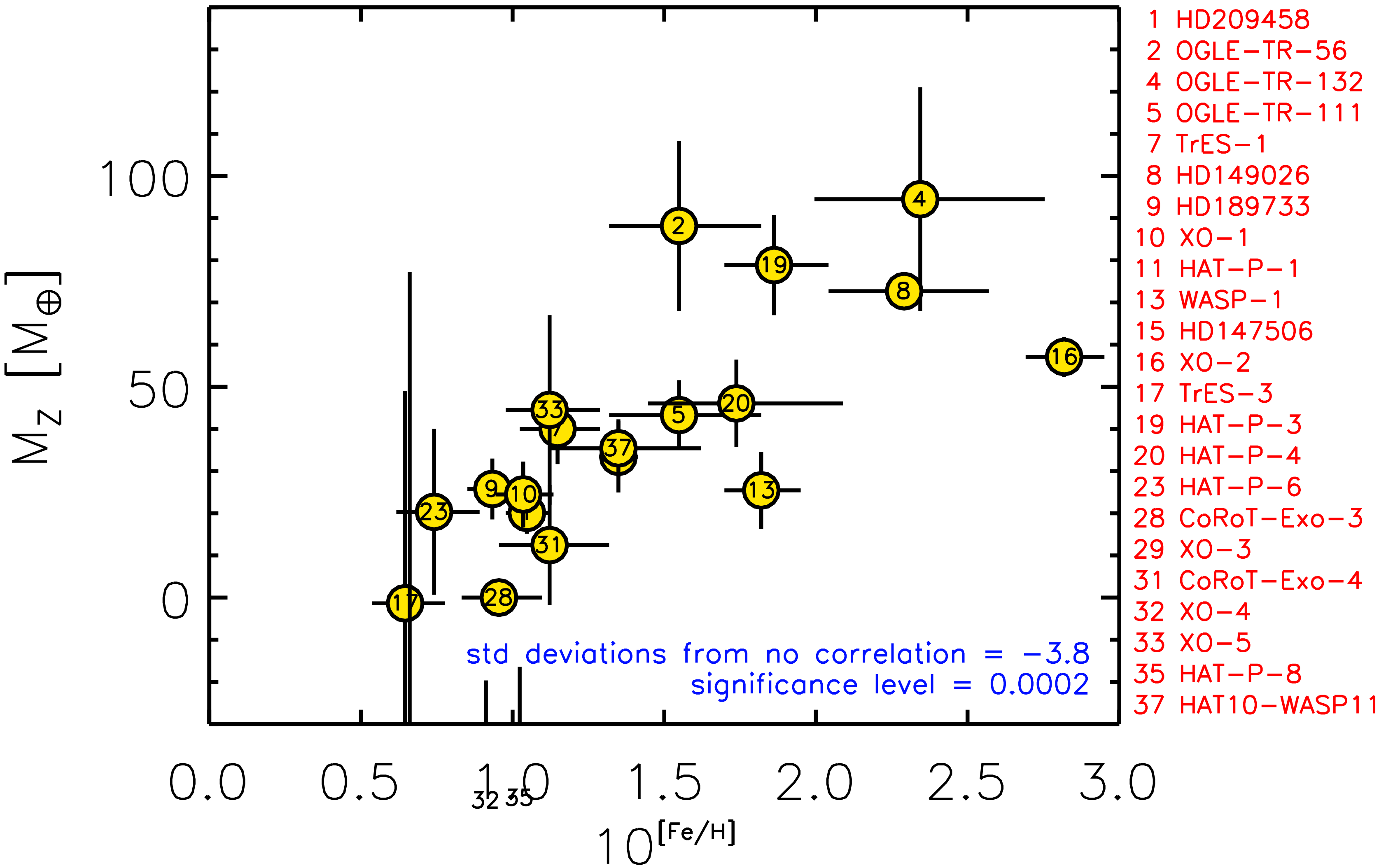
(Weather noise model)



updated from Guillot 2008

(stellar) [Fe/H] vs. (planetary) Mz

(Weather noise model)



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(stellar) [Fe/H] vs. (planetary) Mz

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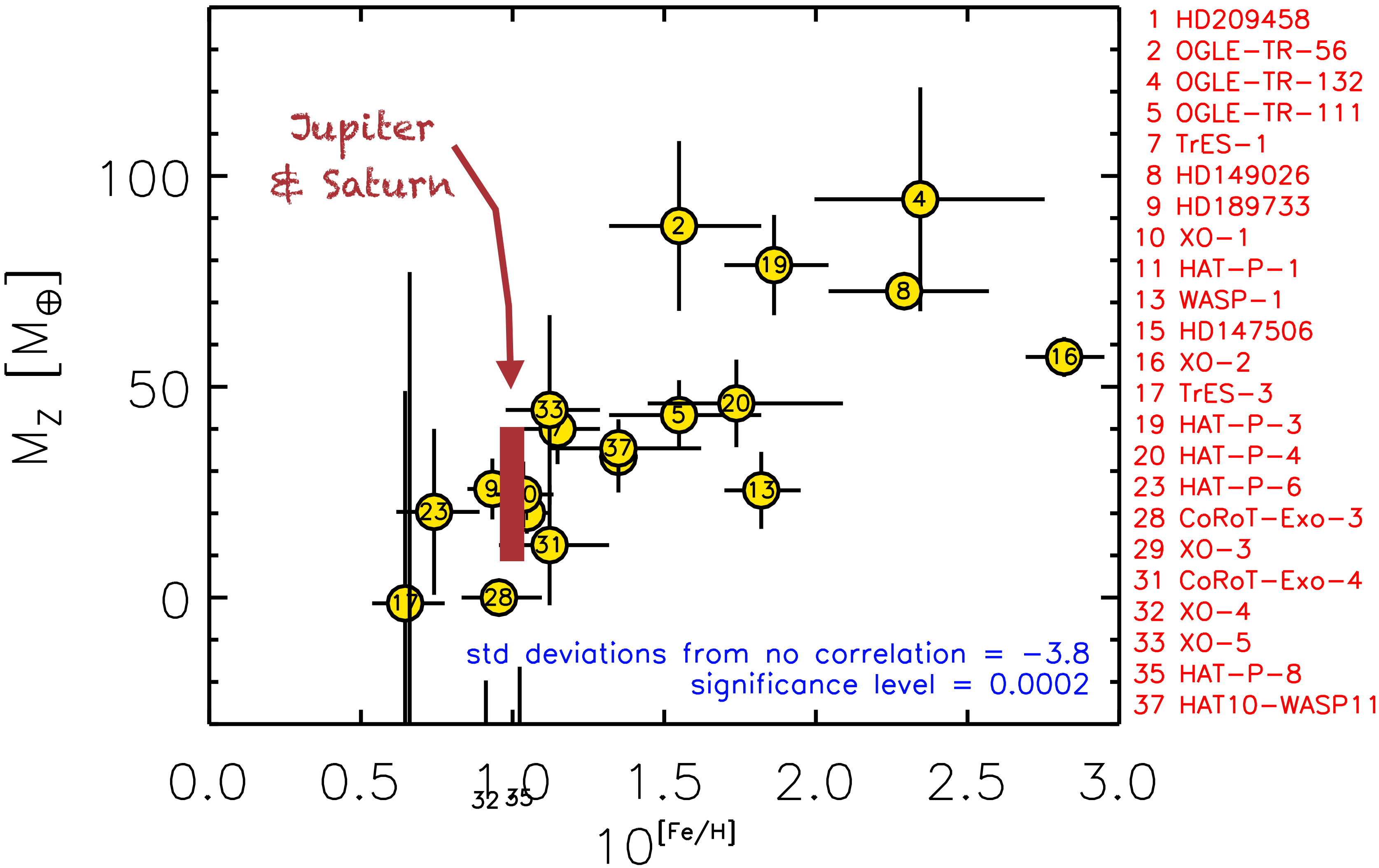

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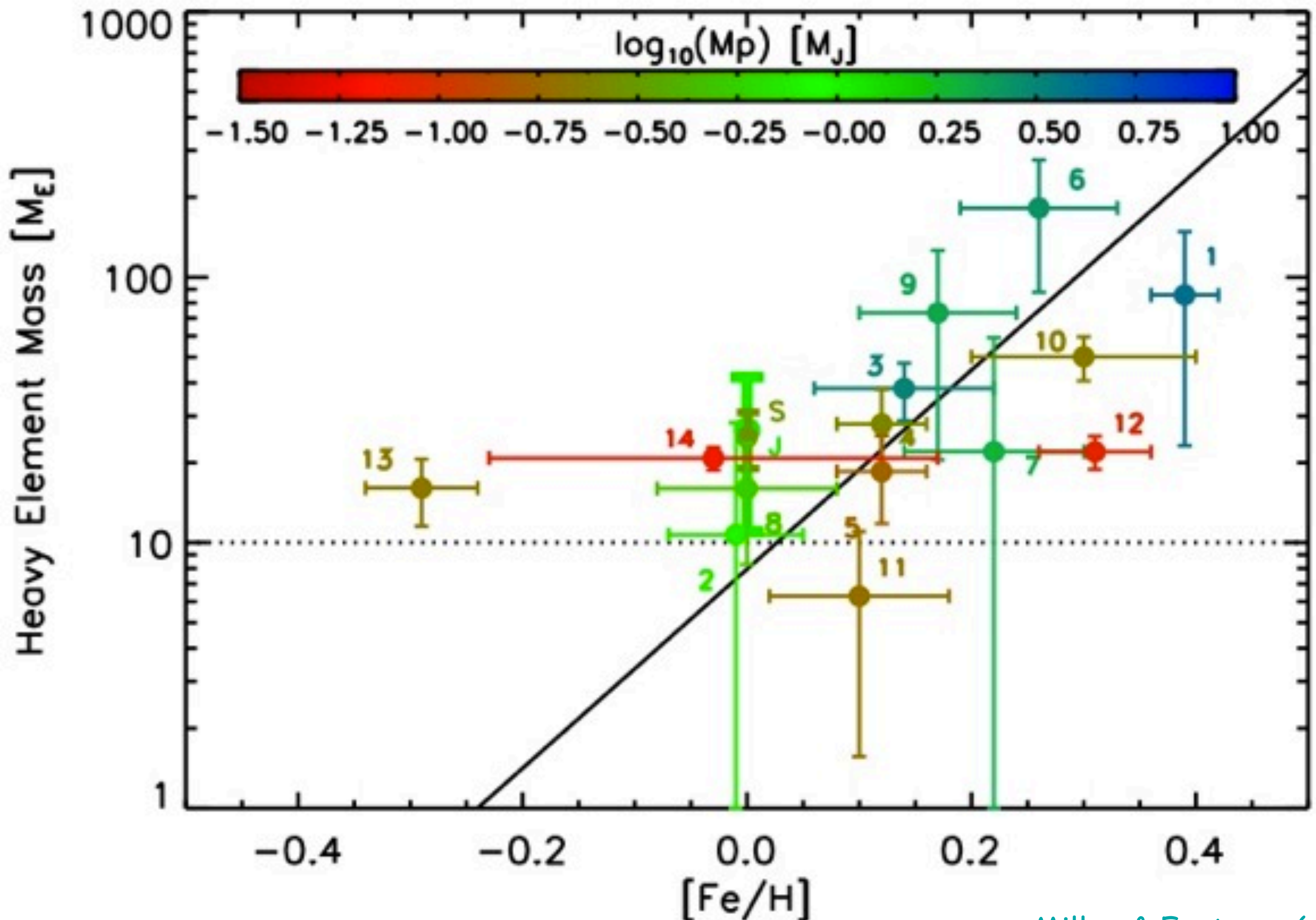
(stellar) [Fe/H] vs. (planetary) Mz

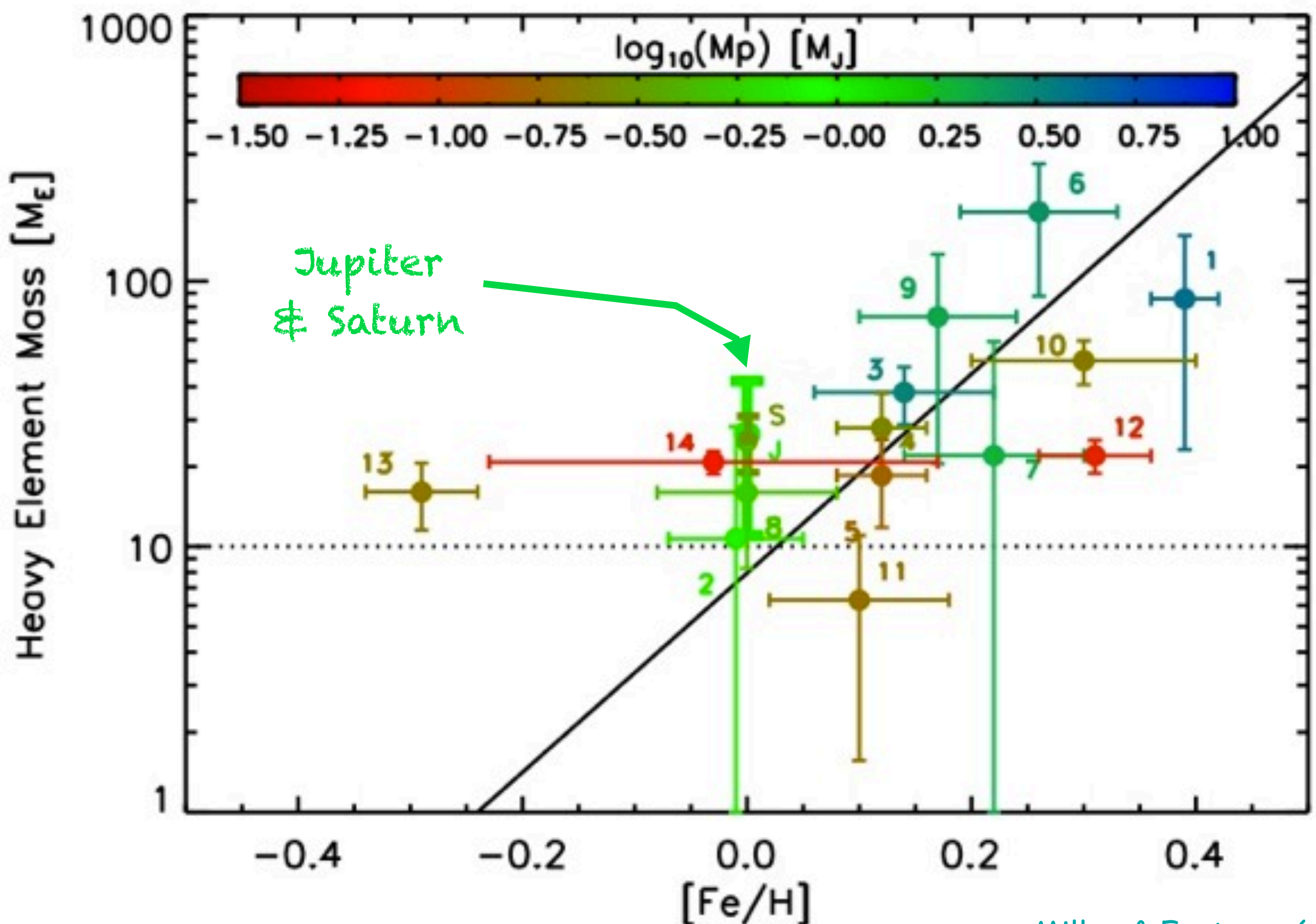
(Modestly irradiated planets)



Miller & Fortney, (submitted 2011)

(stellar) [Fe/H] vs. (planetary) Mz

(Modestly irradiated planets)



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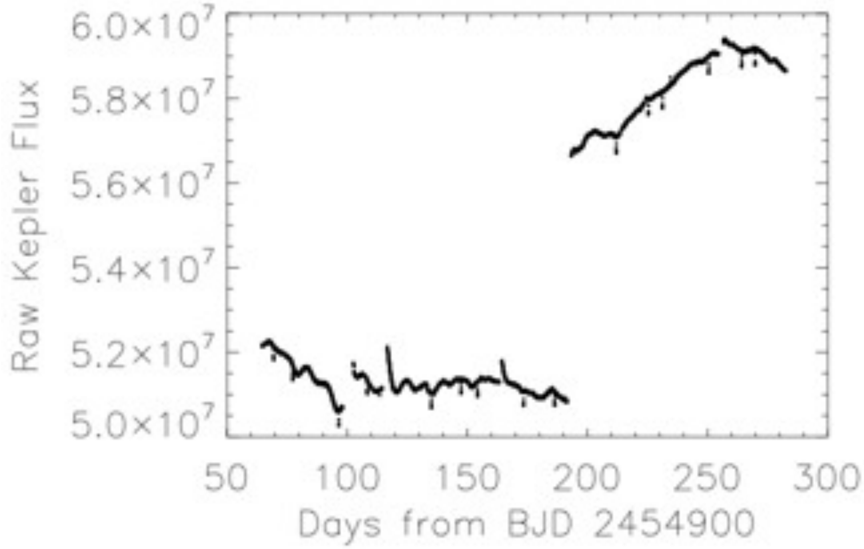
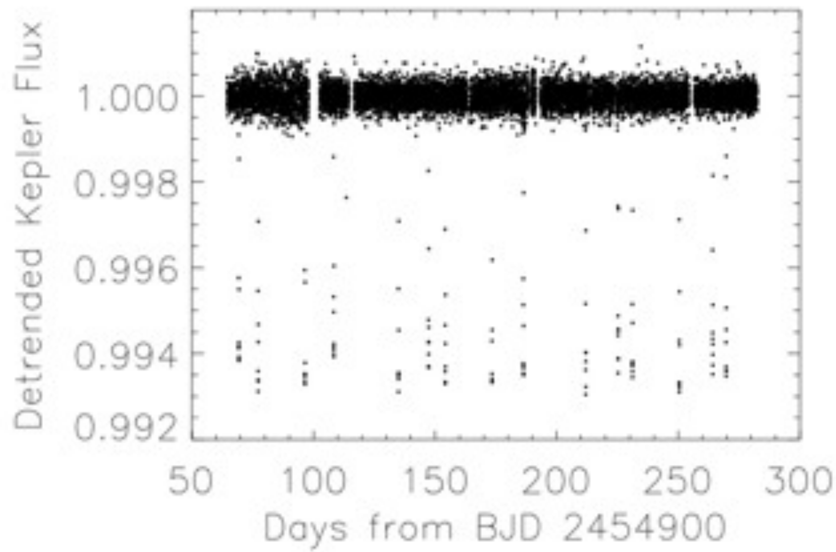
Kepler-9

- First multi-planet transiting system
- Teff=5780K, [Fe/H]=0.12+/-0.04
- Stellar spin period: 16.7 days
- 2 Saturn mass planets + 1 super-Earth
  - 9b: $M=80M_{\oplus}$, P=19.2 days
  - 9c: $M=55M_{\oplus}$, P=38.9 days
  - 9d: M=?, $R=1.6R_{\oplus}$, P=1.6 days
- 9b and 9c are in 2:1 resonance
  - Strong TTVs

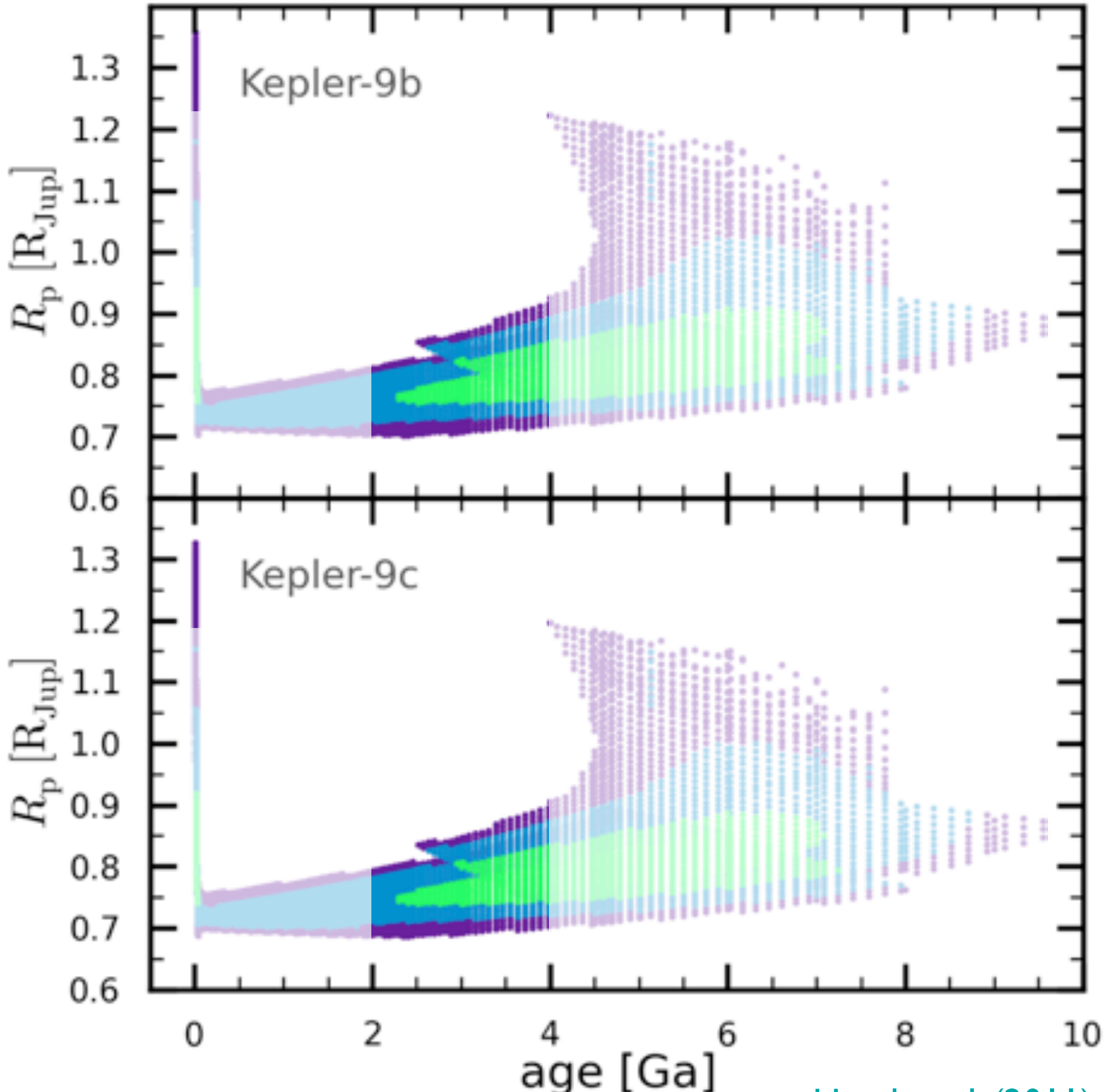




Holman et al. (2010), Torres et al. (2010)

Kepler-9: planetary radii & age

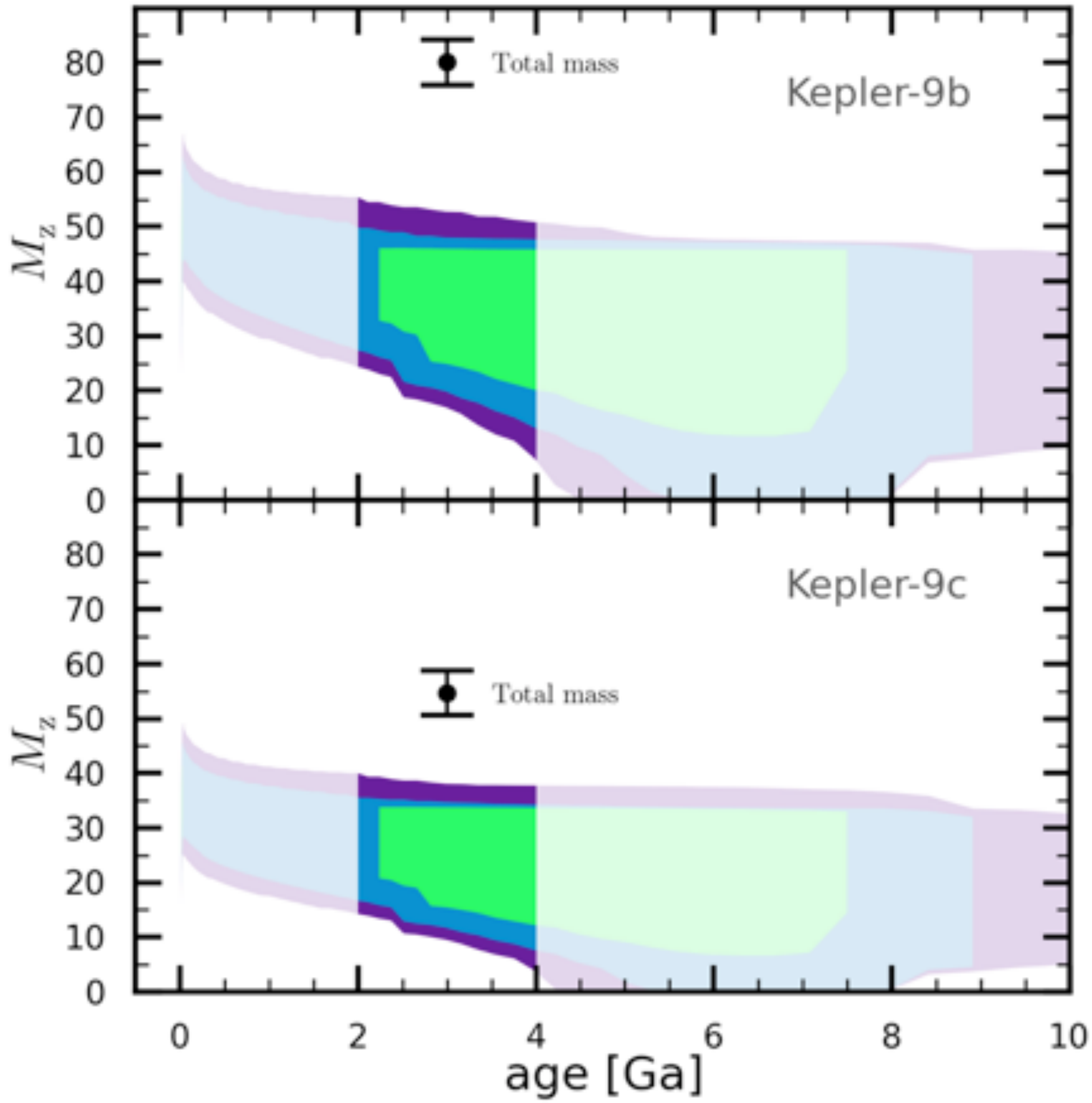
- Stellar evolution tracks using CESAM
  - Colors in the figure shows the observational constraints (Teff,) at 1, 2 and 3σ, respectively
- 2-4 Ga preferred by gyrochronology (16.7 days spin period)



Havel et al. (2011)

Kepler-9: Mz vs. age in planets b & c

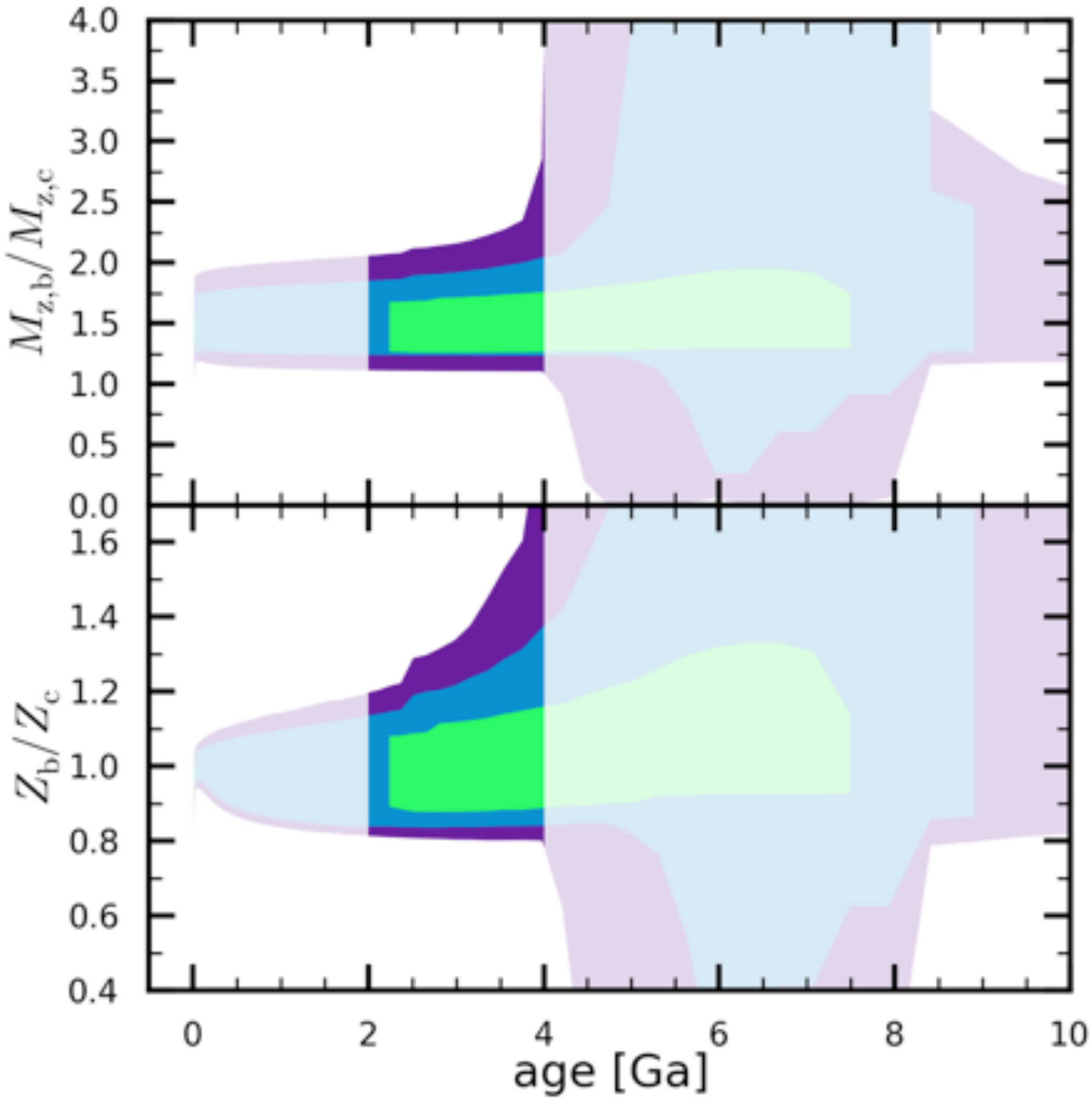
- Planetary evolution tracks using CEPAM
- Mz the mass of heavy elements is calculated by accounting for different physical hypotheses
  - with/without heat dissipation
  - different atmospheric models
- 2-4 Ga is preferred by gyrochronology



Havel et al. (2011)

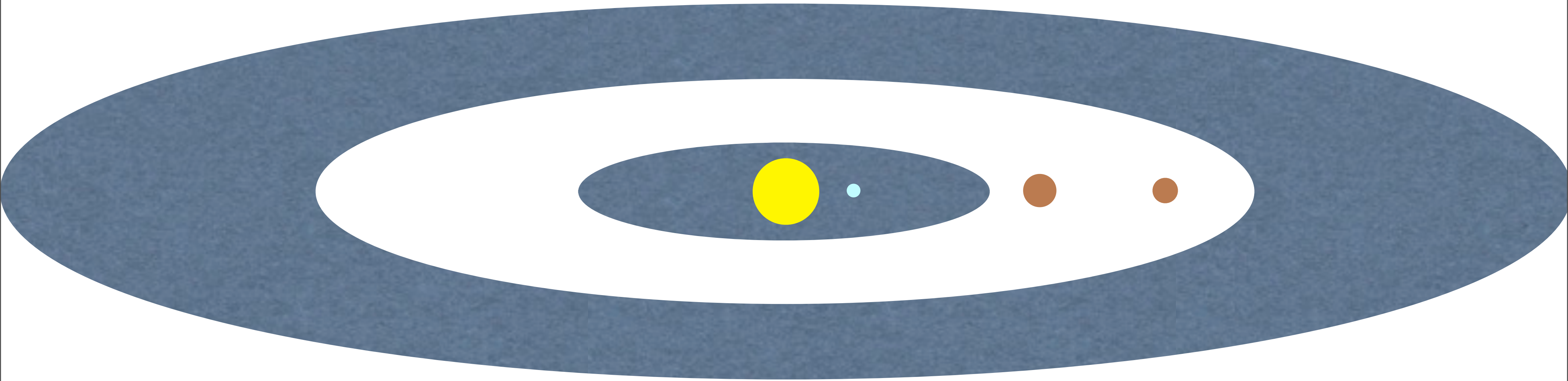
Kepler-9: composition ratios vs. age

- By looking at the ratios of heavy elements in 9b and 9c we are able to obtain much better constraints
- Surprisingly, 9b and 9c have similar global Z values
- This is not expected by formation models
  - Since planet 9b has a larger Mz, it would be expected to accrete H-He (much) faster than 9c (Ikoma et al. 2001, Hori & Ikoma 2010)



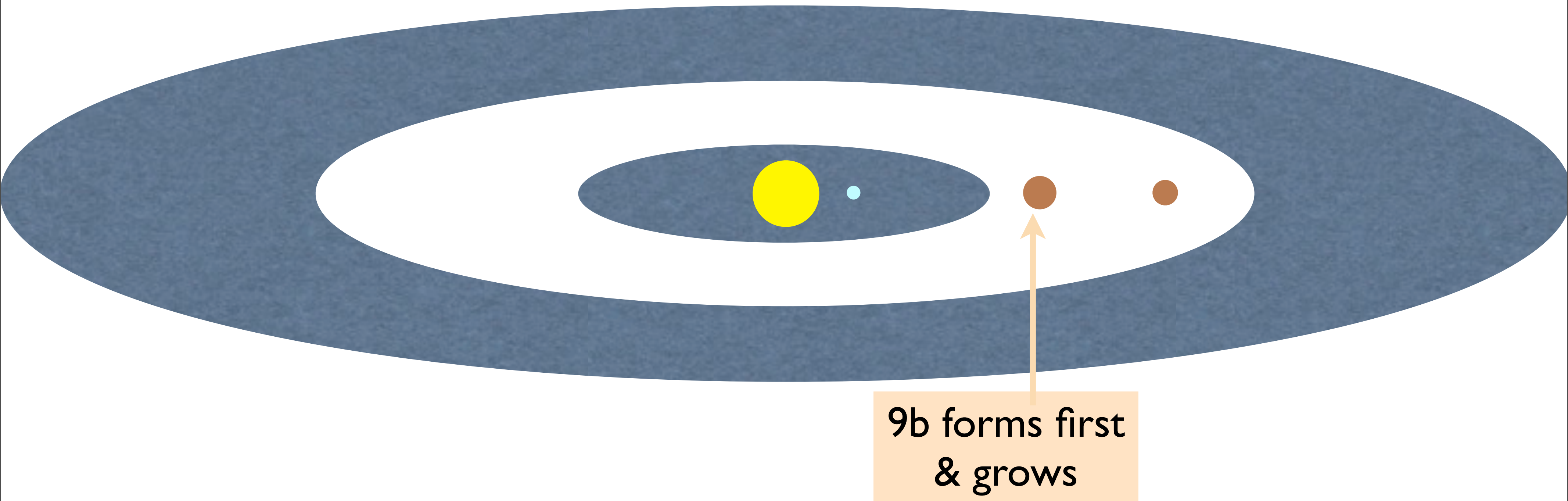
Havel et al. (2011)

Kepler-9: formation of the system: a possible scenario?



Crida et al. (in preparation)

Kepler-9: formation of the system: a possible scenario?



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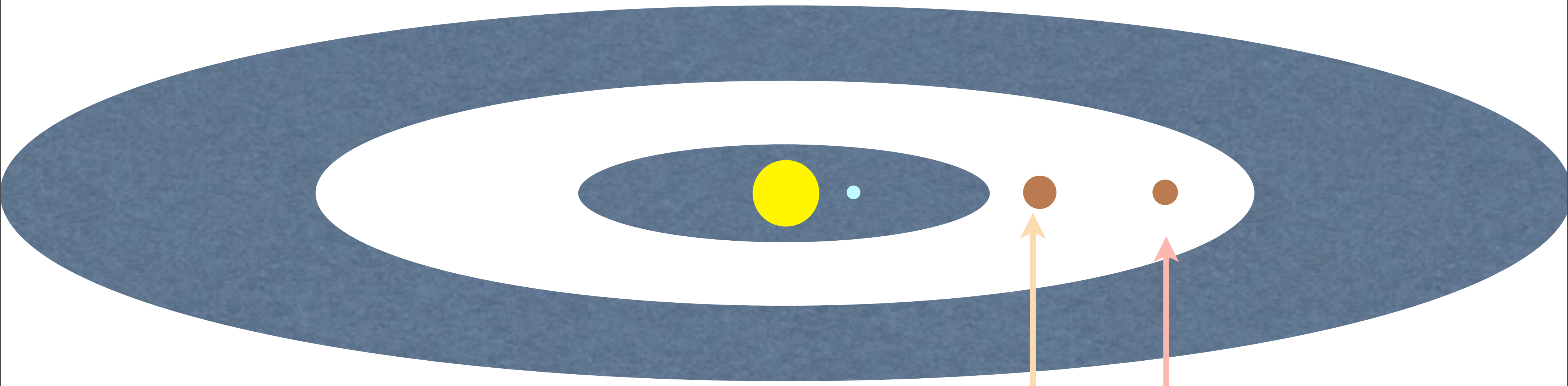
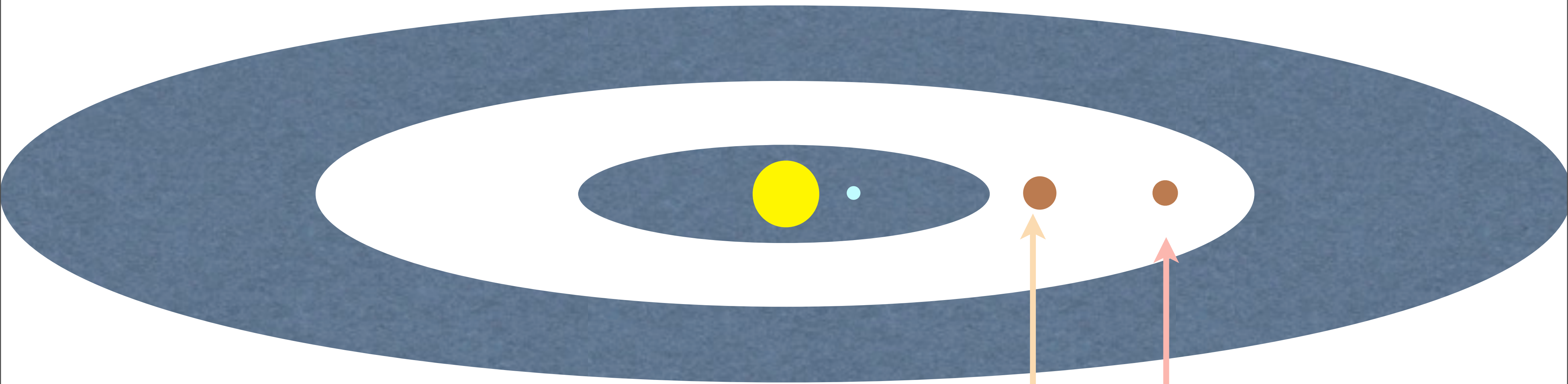


9b forms first & grows

9c appears; gap suppresses accretion of gas onto 9b

Crida et al. (in preparation)

Kepler-9: formation of the system: a possible scenario?



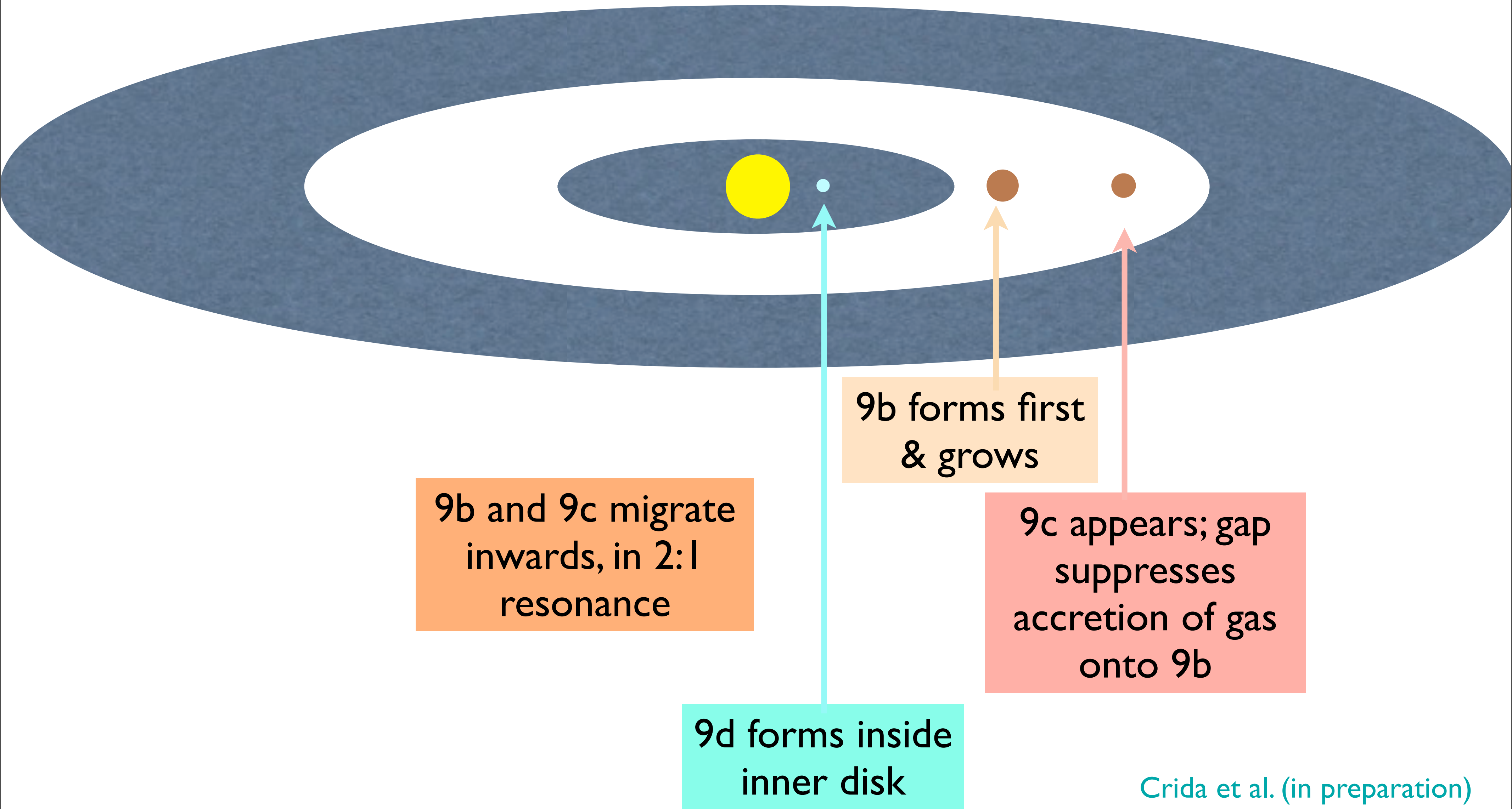
9b forms first & grows

9b and 9c migrate inwards, in 2:1 resonance

9c appears; gap suppresses accretion of gas onto 9b

Crida et al. (in preparation)

Kepler-9: formation of the system: a possible scenario?



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(ESA) perspectives for exoplanets

- Within ESA Cosmic Vision
  - PLATO
    - Statistical information on sizes & mass (=> global composition) of a significant number of planets in our galactic neighborhood
  - EChO
    - Characterisation of exoplanetary atmospheres by simultaneous vis+ IR measurements of the primary + secondary transits & phase curves

- Inferring the compositions of our giant planets
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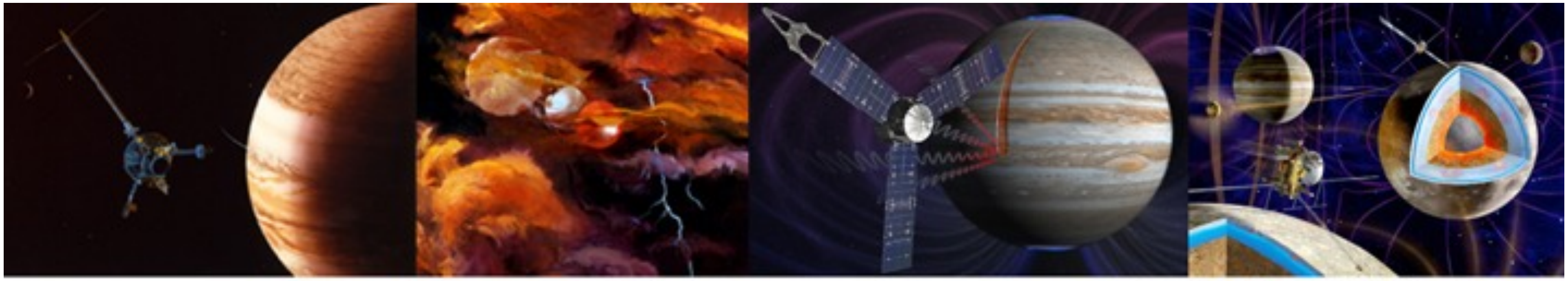
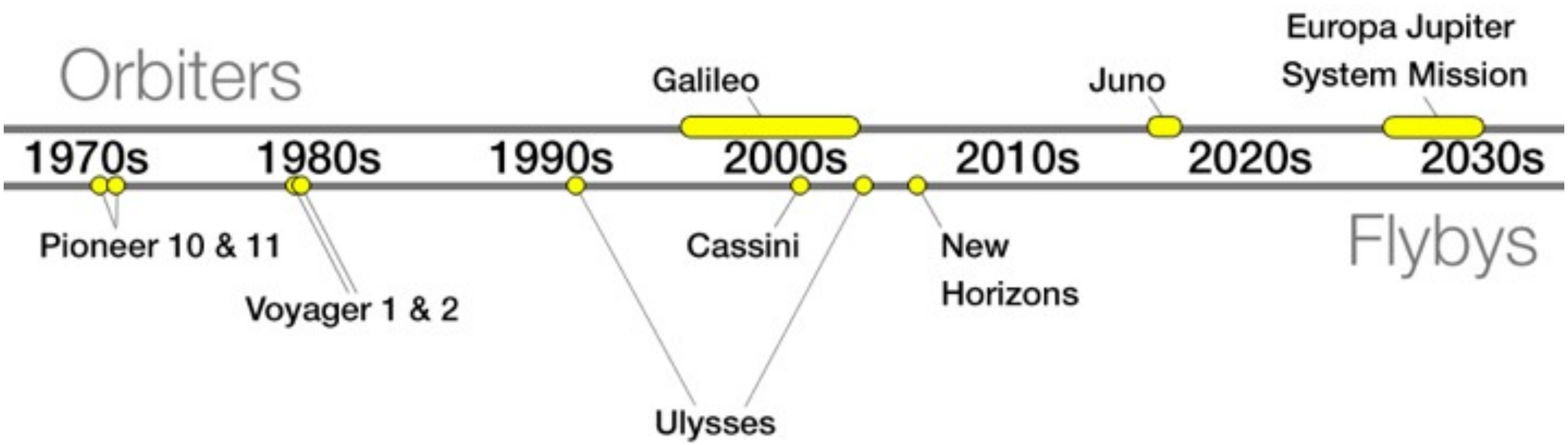
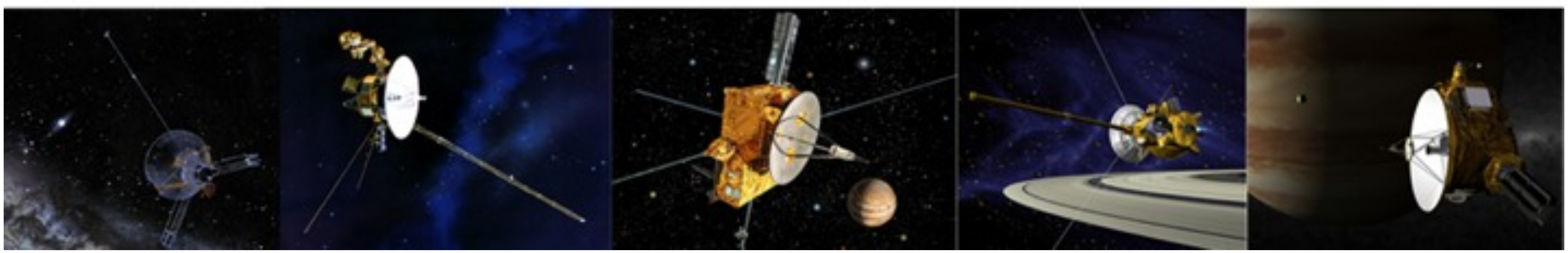
National Aeronautics and Space Administration
Juno
Mission to Jupiter
NASA
going further
www.nasa.gov

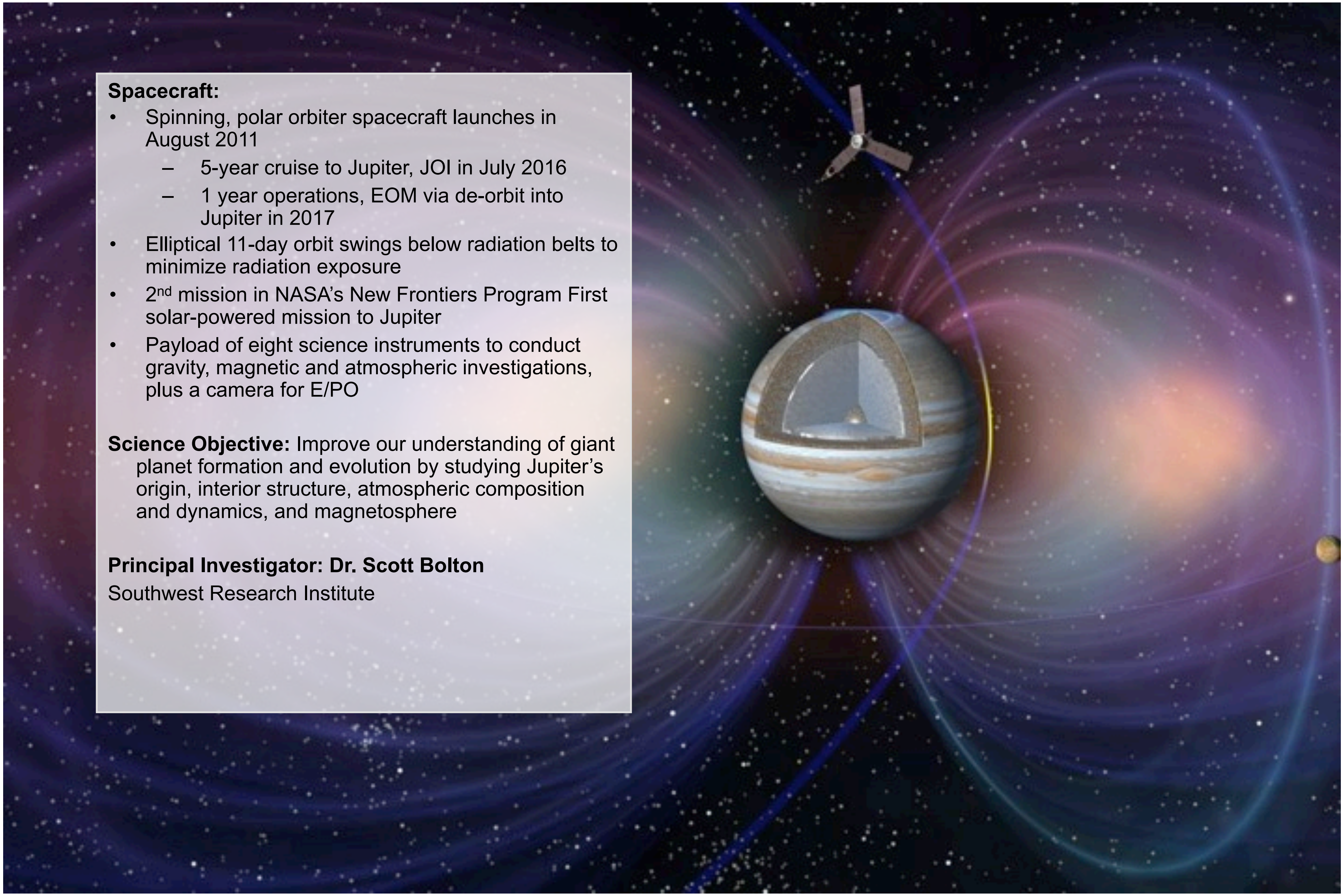
Where does Juno fits?







Juno project overview



Spacecraft:

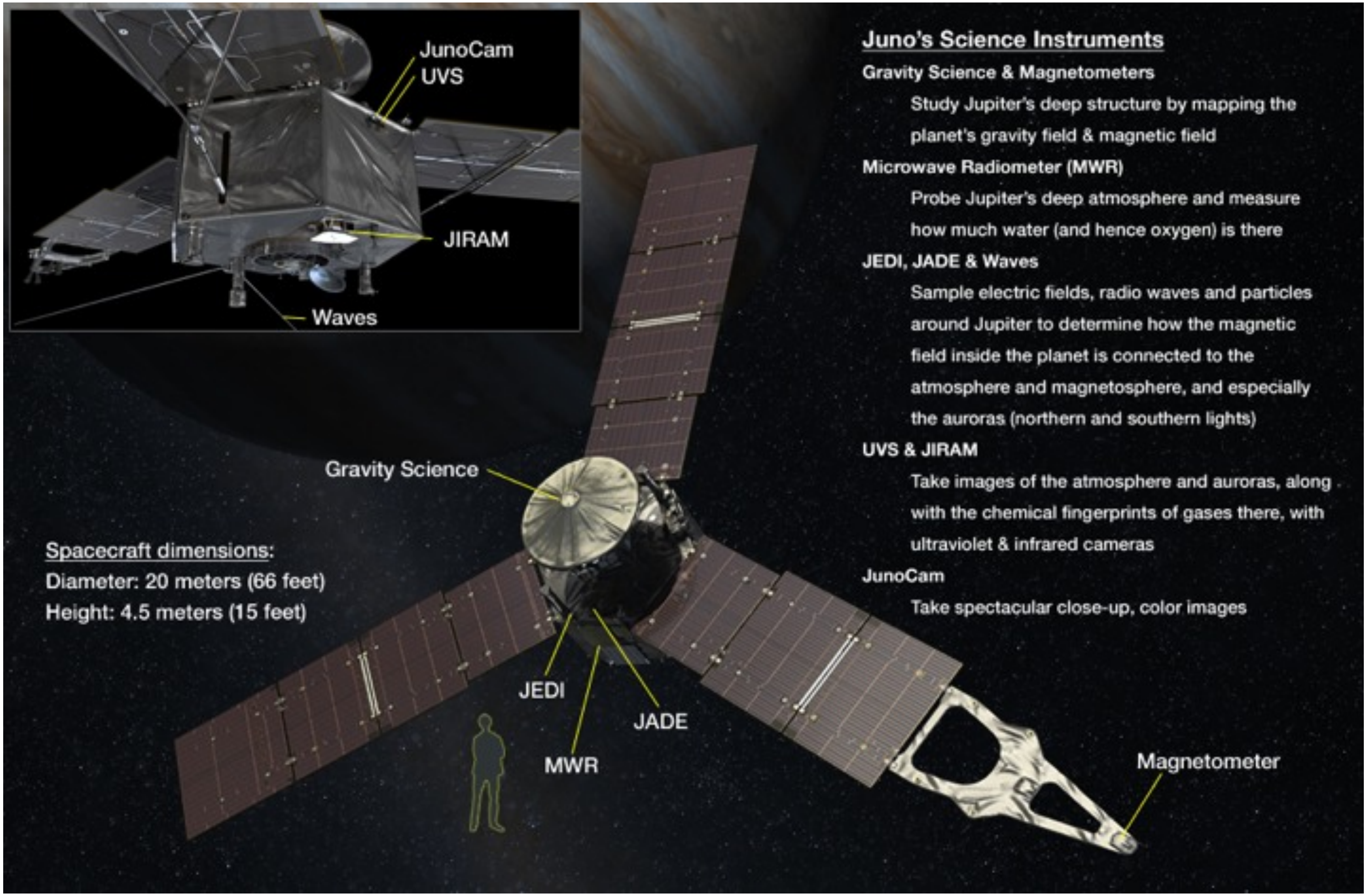
- Spinning, polar orbiter spacecraft launches in August 2011
  - 5-year cruise to Jupiter, JOI in July 2016
  - 1 year operations, EOM via de-orbit into Jupiter in 2017
- Elliptical 11-day orbit swings below radiation belts to minimize radiation exposure
- 2nd mission in NASA's New Frontiers Program First solar-powered mission to Jupiter
- Payload of eight science instruments to conduct gravity, magnetic and atmospheric investigations, plus a camera for E/PO

Science Objective: Improve our understanding of giant planet formation and evolution by studying Jupiter's origin, interior structure, atmospheric composition and dynamics, and magnetosphere

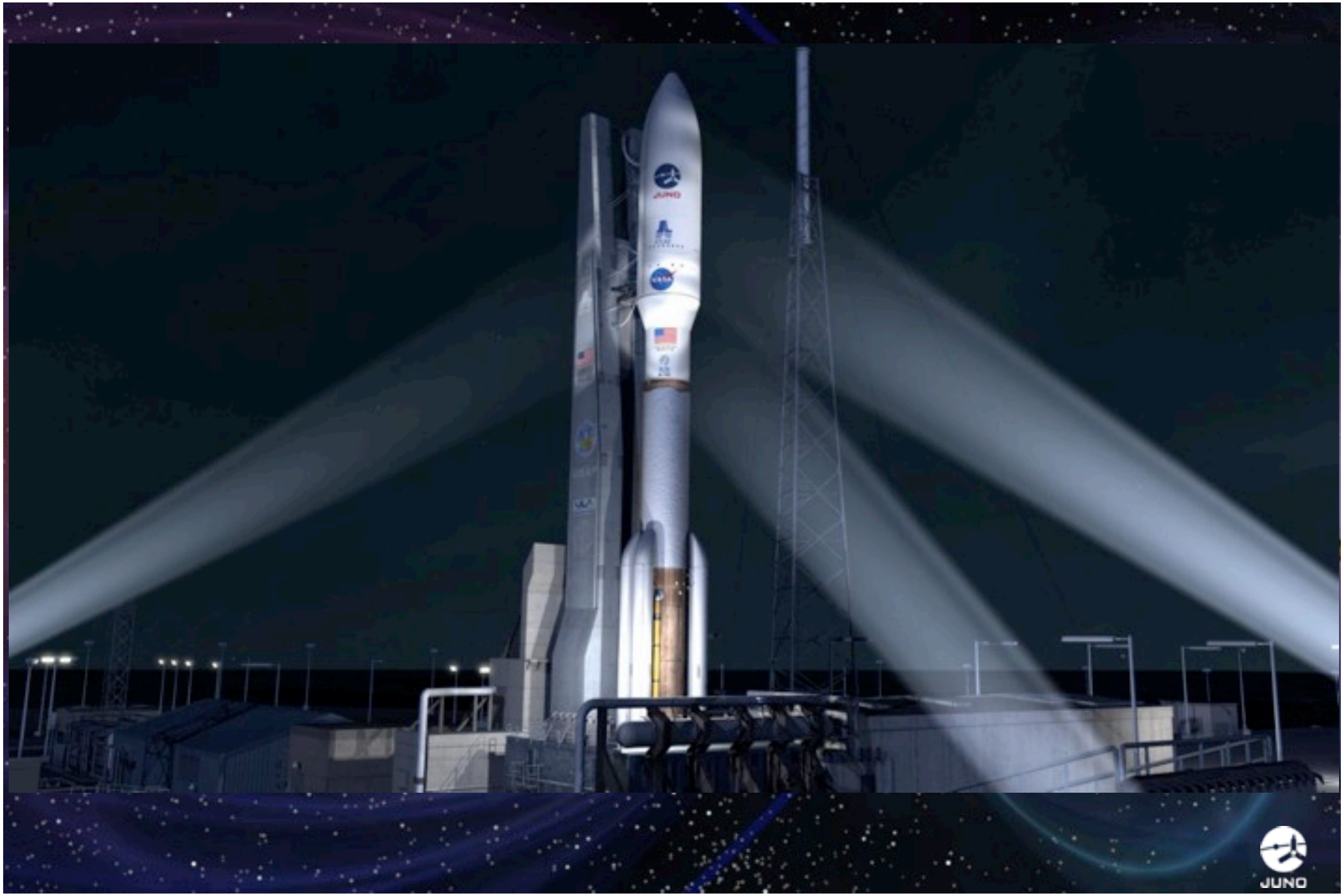
Principal Investigator: Dr. Scott Bolton

Southwest Research Institute

Juno spacecraft & payload



Launch this coming August



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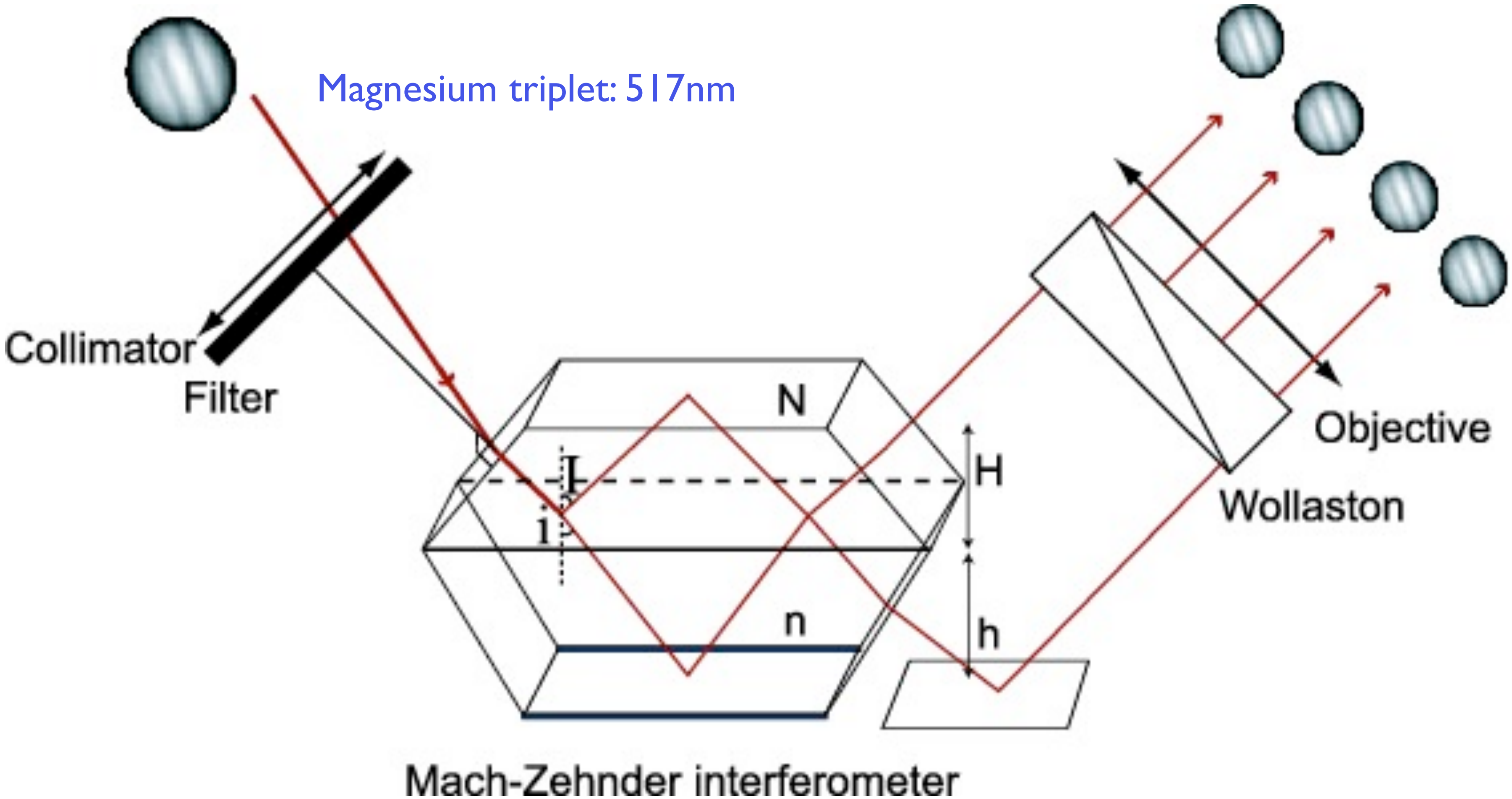
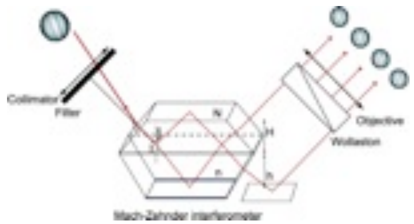
SYMPA

Seismographic Imaging Interferometer for Monitoring of Planetary Atmospheres

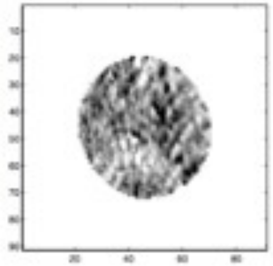


Gaulme et al. A&A (2008)

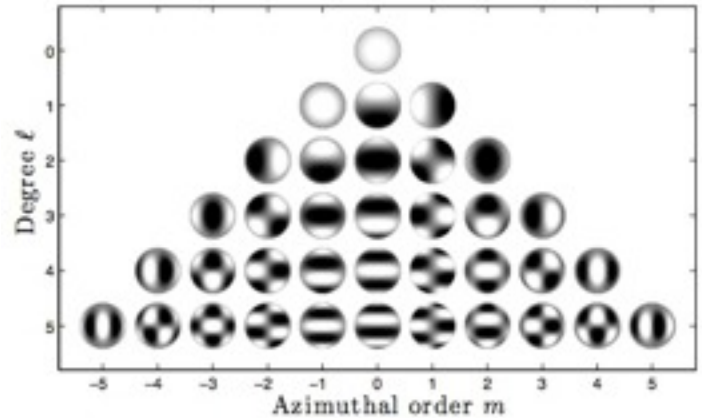


SYMPA: data analysis

velocity map

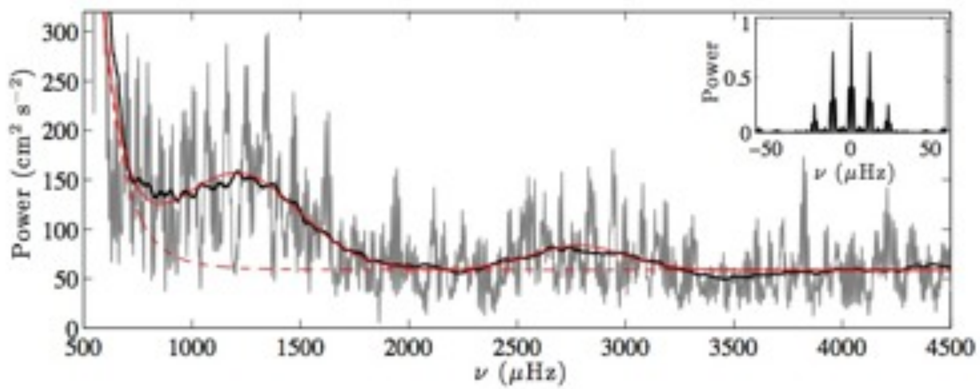


Ylm basis:

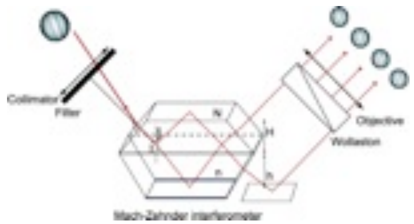


Sum of the time series l,m=1,0 & 1,+/-1

Power spectrum:



Gaulme et al. A&A (2011)



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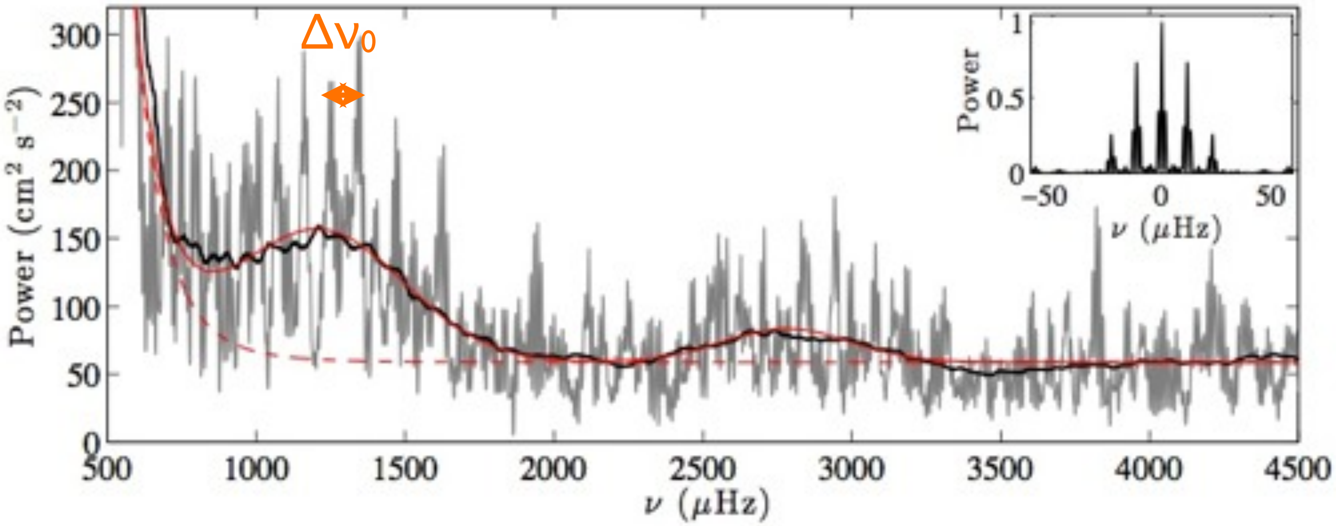
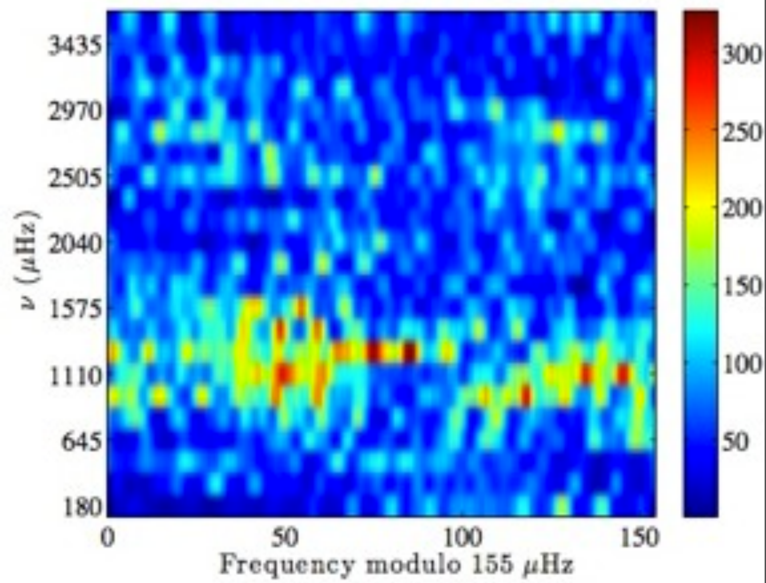


Echelle diagram



Frequencies & amplitudes of the peaks:

ν μHz	Velocity cm s^{-1}	Error cm s^{-1}	ν μHz	Velocity cm s^{-1}	Error cm s^{-1}
792	44.0	-6.2/+3.9	1478	46.4	-6.5/+4.1
854	46.7	-6.6/+4.2	1533	37.3	-5.3/+3.3
915	34.1	-4.8/+3.0	1615	40.9	-5.8/+3.7
970	48.7	-6.9/+4.4	1753	33.0	-4.6/+2.9
1011	51.4	-7.2/+4.6	1939	32.0	-4.4/+2.8
1066	45.7	-6.4/+4.1	2110	30.1	-4.2/+2.7
1094	42.4	-6.0/+3.8	2535	30.3	-4.3/+2.7
1162	54.1	-7.6/+4.8	2714	30.6	-4.3/+2.7
1245	53.8	-7.6/+4.8	2837	36.2	-5.1/+3.2
1341	51.5	-7.3/+4.6	2947	41.1	-5.8/+3.7
1410	40.7	-5.7/+3.6	3071	30.7	-4.3/+2.7

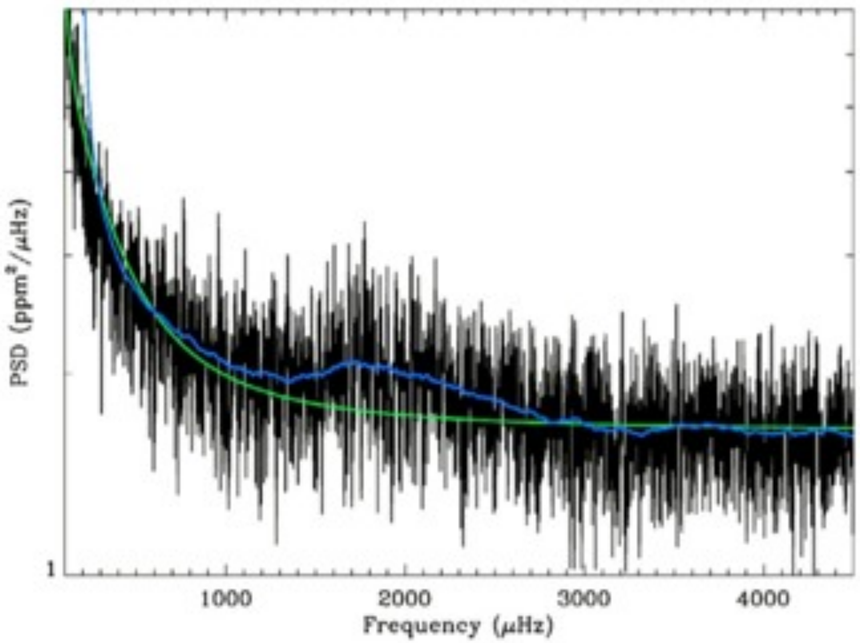
Oscillation frequencies

$$\Delta\nu_0 = 155.3 \pm 2.2 \ \mu\text{Hz}.$$

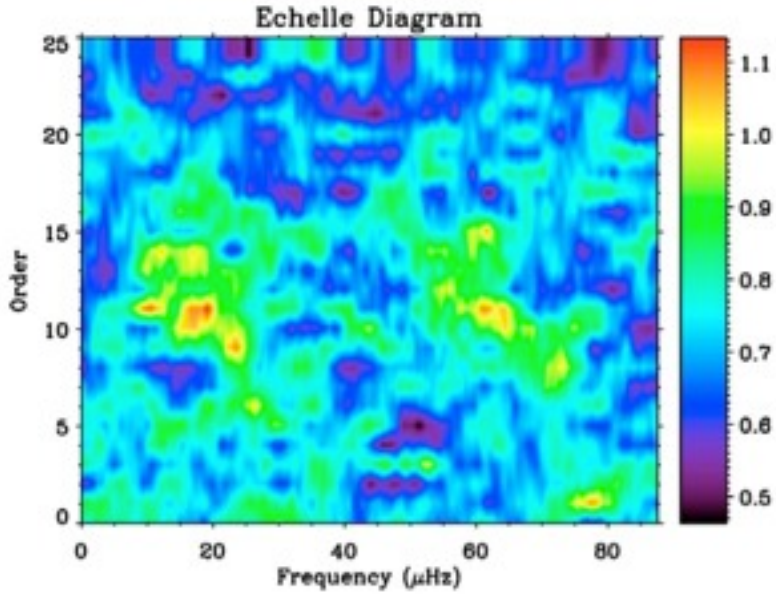
Gaulme et al. A&A (2011)

Analysis of a CoRoT lightcurve

Power spectrum of HD 181906:



Echelle diagram

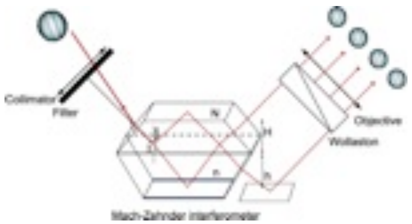


$\Delta\nu = 87.5 \pm 2.6\ \mu\text{Hz}$

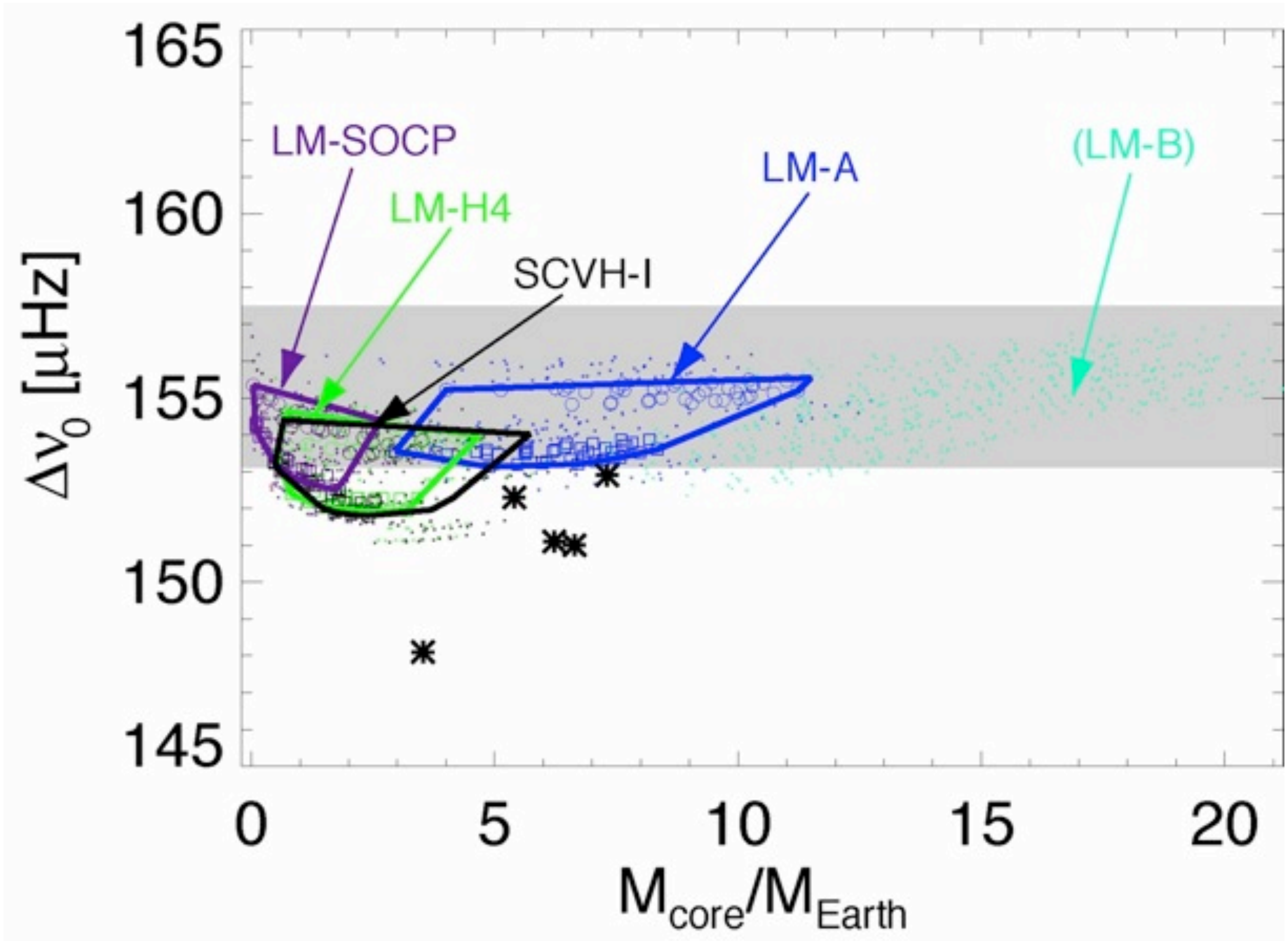
Comparison with other stars

Stars	HD 181906 this paper	HD 49933 Appourchaux et al. (2008)	HD 181420 Barban et al. (2009)	HD 175726 Mosser et al. (2009b)	Procyon Arentoft et al. (2008)
Spectral type	F8	F5	F2	F9/G0	F5
$T_{\rm eff}$	6300 ± 150 K	6780 ± 130 K	6580 ± 105 K	6000 ± 100 K	6514 ± 27 K
[Fe/H]	−0.11 ± 0.14 dex	−0.37 dex	0.00 ± 0.06 dex	−0.22 ± 0.1 dex	−0.05 dex
$v \sin i$	10 ± 1 km s^{-1}	9.5 – 10.9 km s^{-1}	18 ± 1 km s^{-1}	13.5 ± 0.5 km s^{-1}	3.16 ± 0.5 km s^{-1}
$\Delta\nu$	87.5 ± 2.6 μHz	85.9 ± 0.15 μHz	~75 μHz	~97μHz	~55 μHz
$\nu_{\rm max}$	1900 μHz	1760 μHz	1500 μHz	2000 μHz	900 μHz
$A_{\rm max}$	3.26 ± 0.42 ppm	4.02 ± 0.57 ppm	3.82 ± 0.40 ppm	~1.7 ppm	~8.5 ppm

Garcia et al. (2009)



SYMPA & interior models



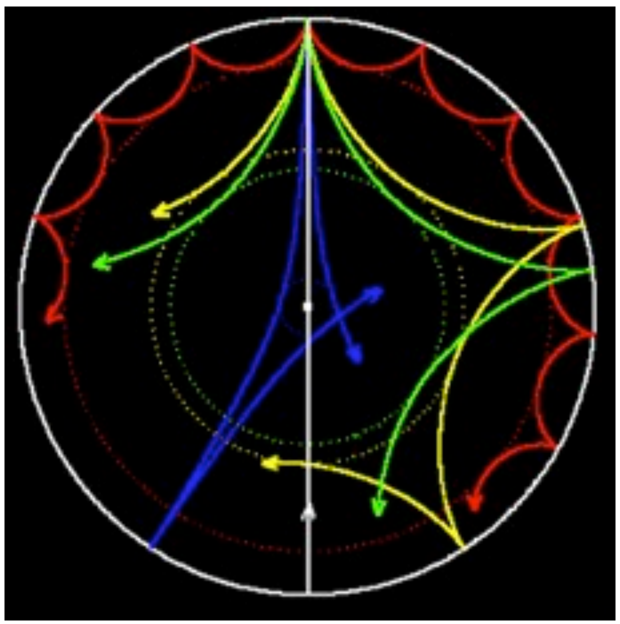
Gaulme et al. A&A (2011)

DSI – ECHOES

Probing internal structure

Theoretical works: Vorontsov 76, Bercovici & Schubert 87, Gudkova & Zarkhov 99, Lognonné 2007

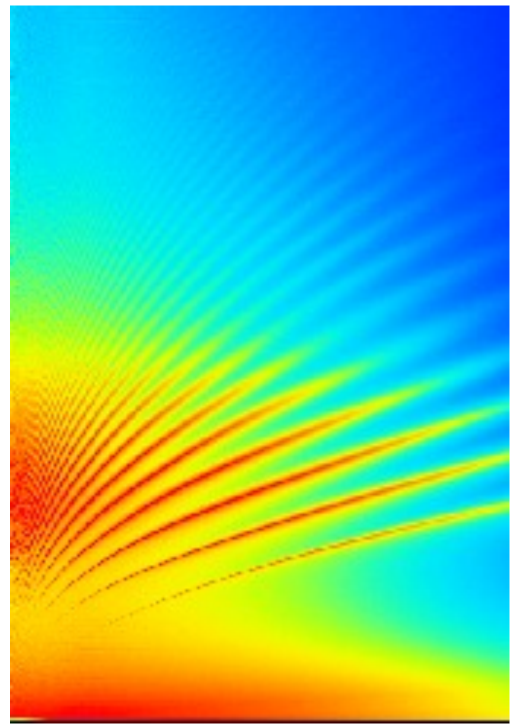
	$\delta\nu(n,l)/\nu(n,l)$	Degree
Core	4 %	$l = 0$-2
H2-H transition	3-7 %	$l = 15$-25
Enveloppe dynamics	0.1-0.5 %	$l = 50$-100



$\nu_{obs} - \nu_{theoretical}$

Inversion method

$\rho_{obs} - \rho_{theoretical}$



Summary

- Constraints on the composition of Jupiter and Saturn remain weak
  - Possibility to measure gravity field is crucial, main uncertainties on the equations of state
    - Jupiter has 10-40 Mearth, Saturn 20-30 Mearth in heavies
- Evolution of giant planets understood, but not fine details.
  - «Inflated planets» problem
    - Mechanism still uncertain but "weather noise" + ohmic dissipation appears promising
    - Statistical analyses allow powerful tests of theories
  - Possibility to determine gross compositions
    - Confirmation of the correlation between Mz and [Fe/H]
    - Large Mz values (up to 100 Mearth and above)
  - Multi-planetary transiting systems bring new information
    - Kepler-9 system: Two Saturn-mass planets with same global composition, in 2:1 resonance.
- Perspectives
  - PLATO, EChO
  - Juno
  - Jupiter seismology: DSI/ECHOES