Evolution & Compositions of Giant Exoplanets

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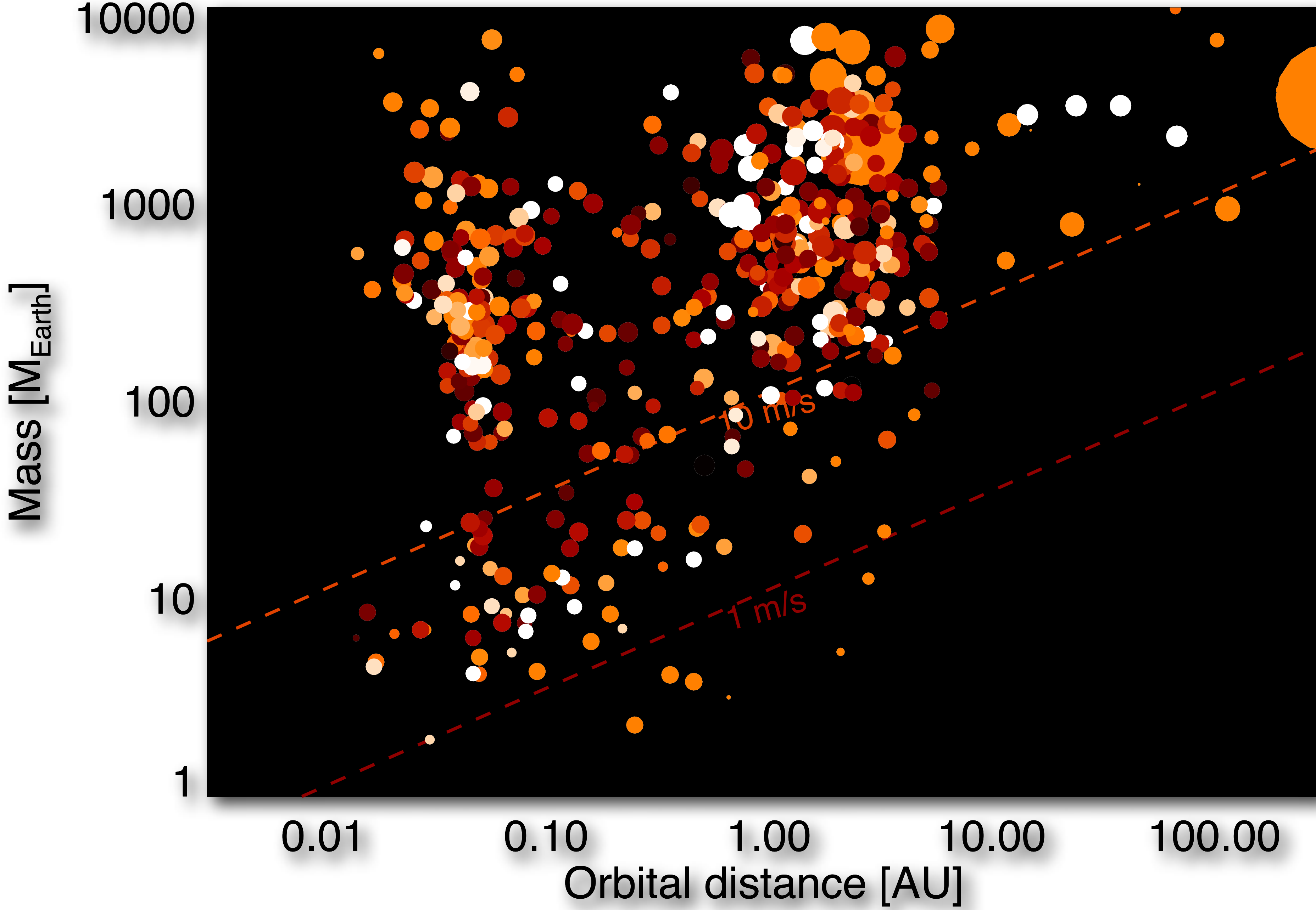
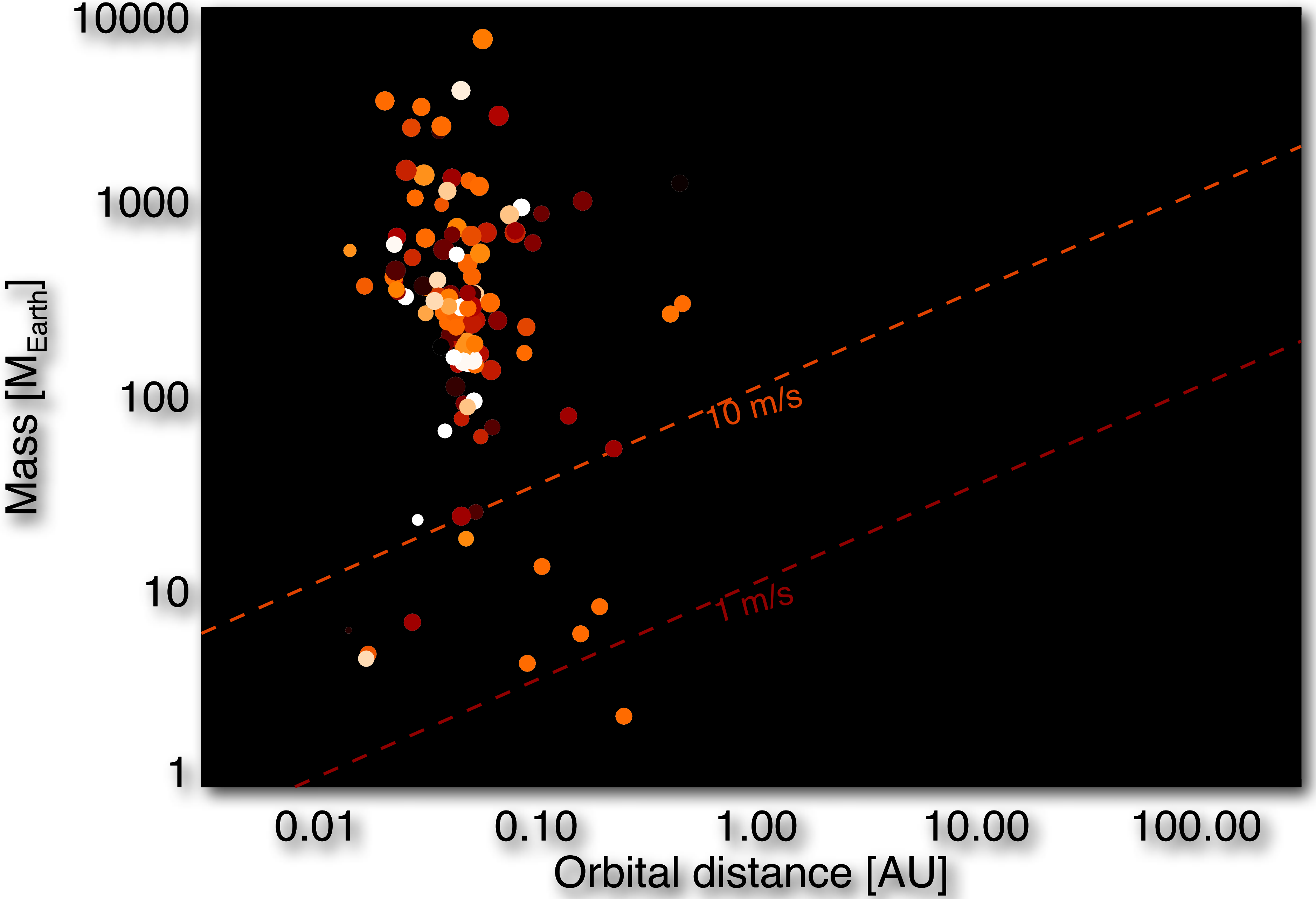
All exoplanets: May 2011



Transiting exoplanets: May 2011



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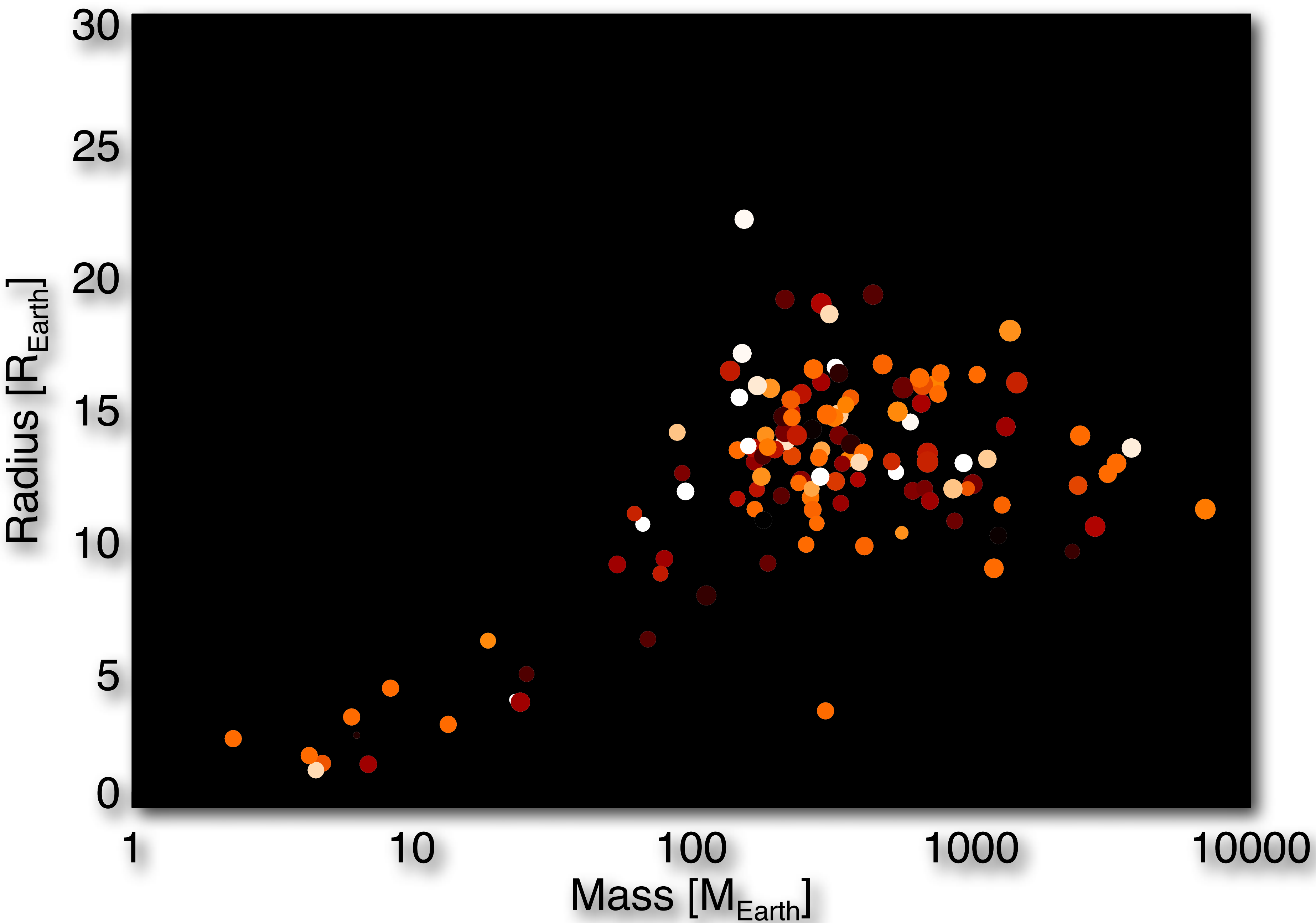

- Principle
- The 'inflated planets' problem
  - Kinetic energy heating, Ohmic dissipation & statistical tests
- Inferring compositions
  - Mz values and the Mz,[Fe/H] correlation
- The young/fast rotating G dwarfs
  - CoRoT-2 and CoRoT-18
- A multi-planet transiting system
  - Kepler-9

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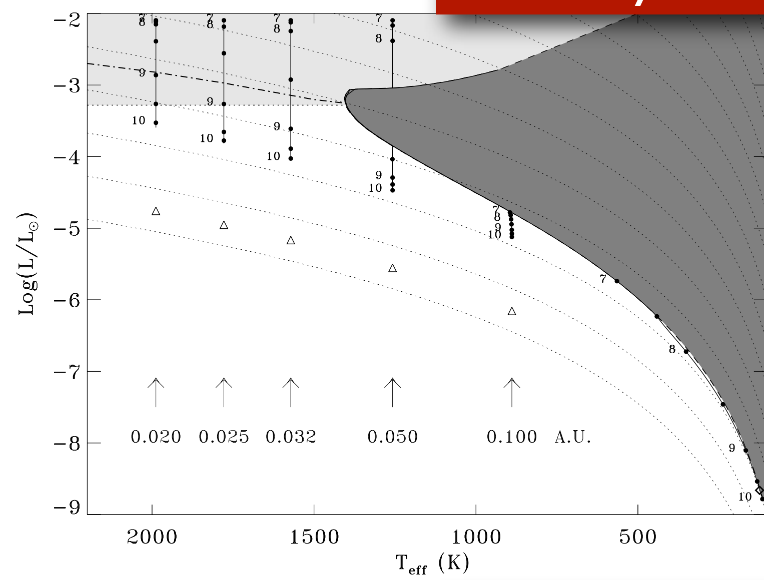
Principle

Giant planets gradually contract & cool
(Hubbard 1977)

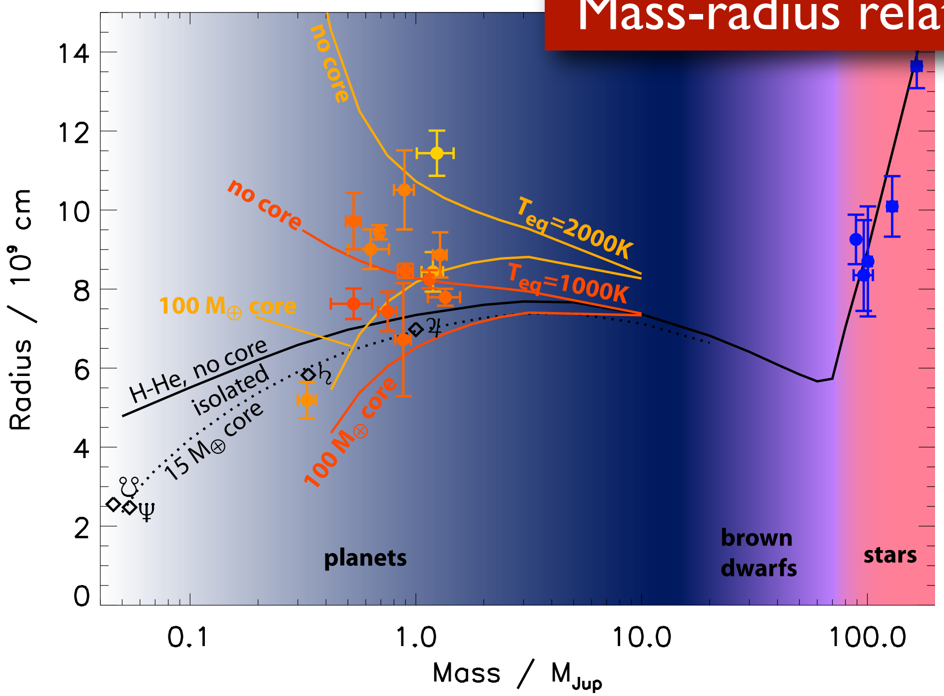
Irradiated planets develop a deep radiative zone and contract more slowly
(Guillot et al. 1996)

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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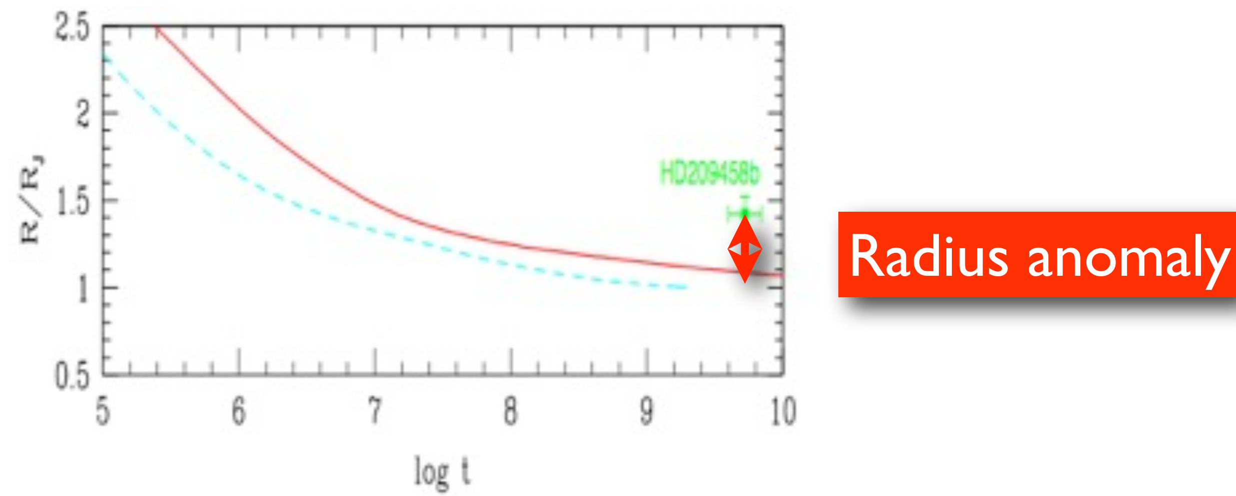
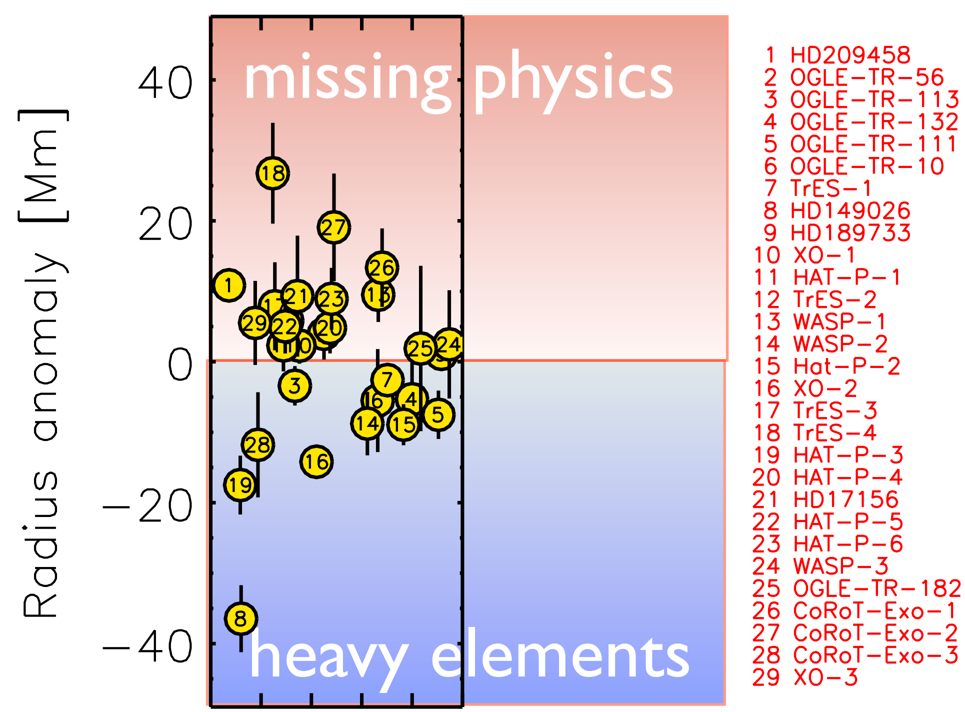
The radius anomaly: description

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
Guillot et al. (2006)

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)





Possible explanations

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

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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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Stellar irradiation:

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

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

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

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:

Chabrier & Baraffe (2007)

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"Weather noise" model:

Guillot & Showman (2002)

Ohmic dissipation:

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

Perna, Menou & Rauscher (2010)

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)

Ibgui et al. (2010)

but:

Leconte et al. (2010)

(see also Barker & Ogilvie 2009)

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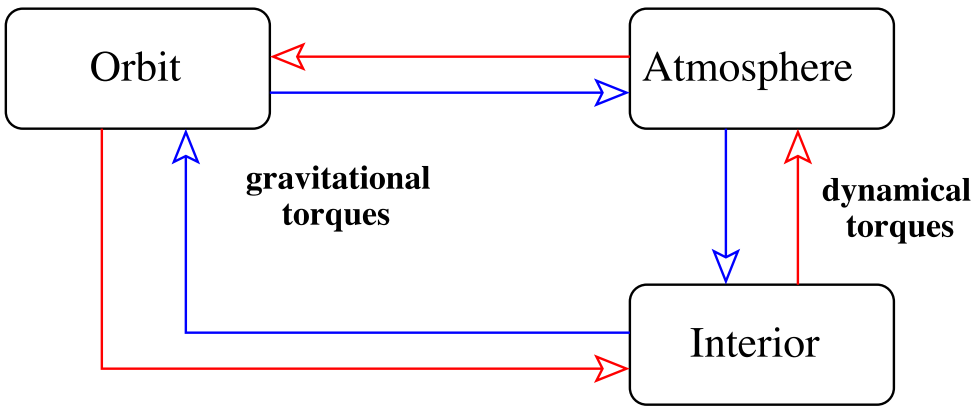
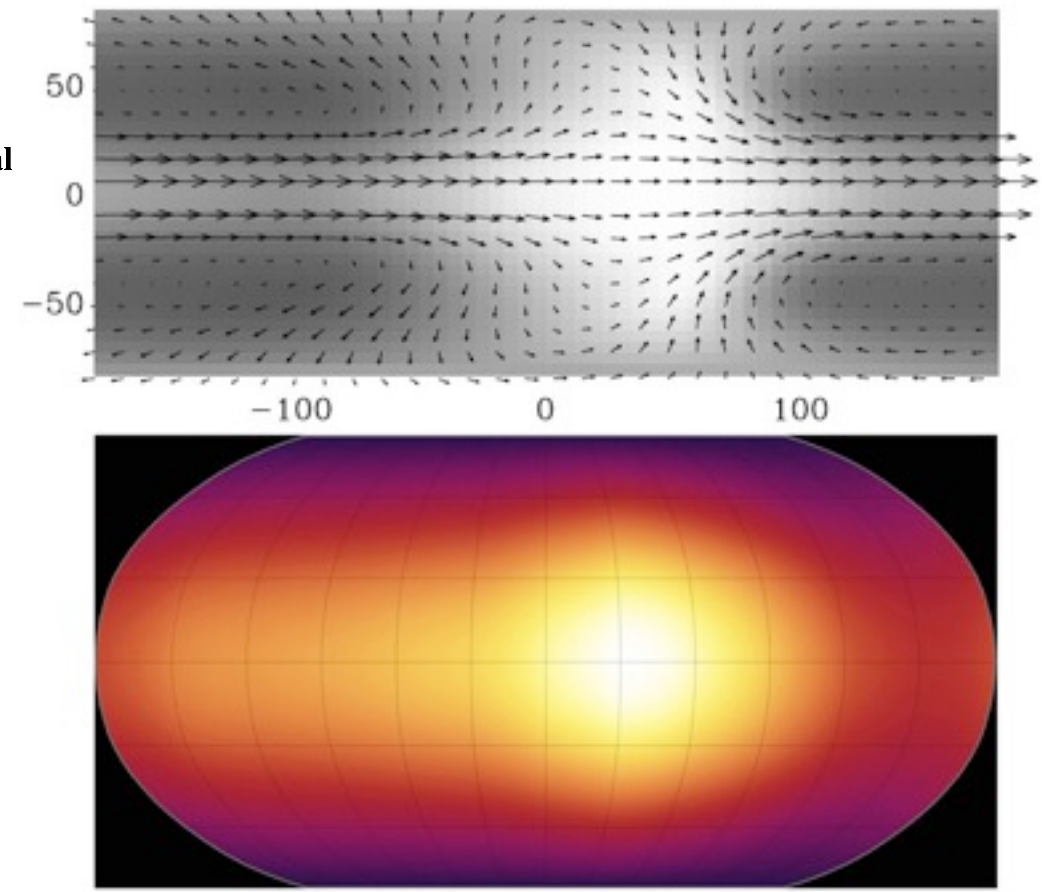
“Weather noise”





stellar photons heat the atmosphere

↓

Kinetic energy is generated

↓

Penetrates to deep levels

↓

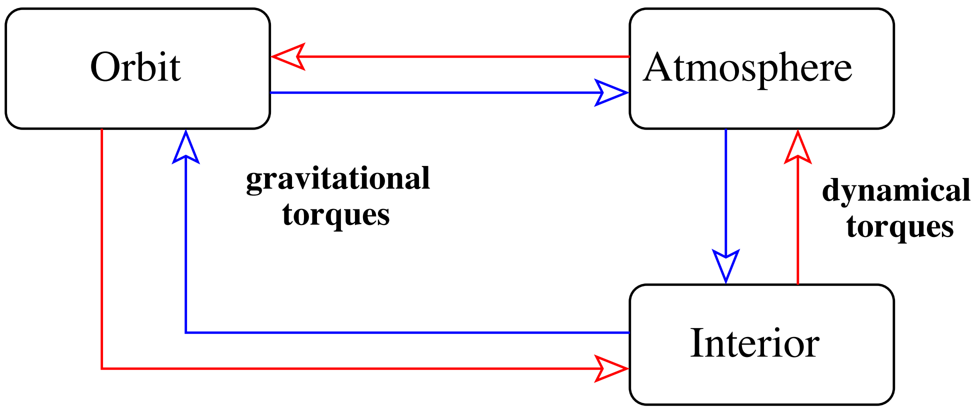
Is dissipated there

Knutson et al. 2007

but: Burkert et al. (2005) ?

"Weather noise"

Guillot & Showman (2002)



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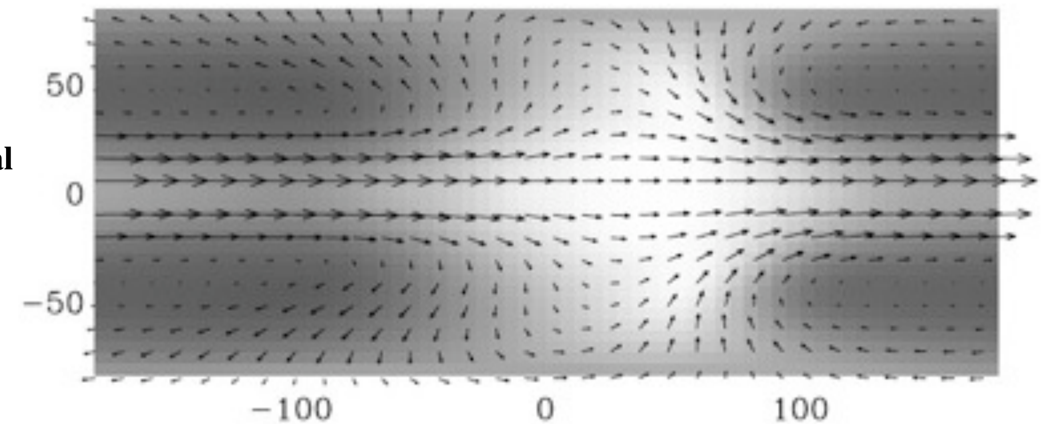
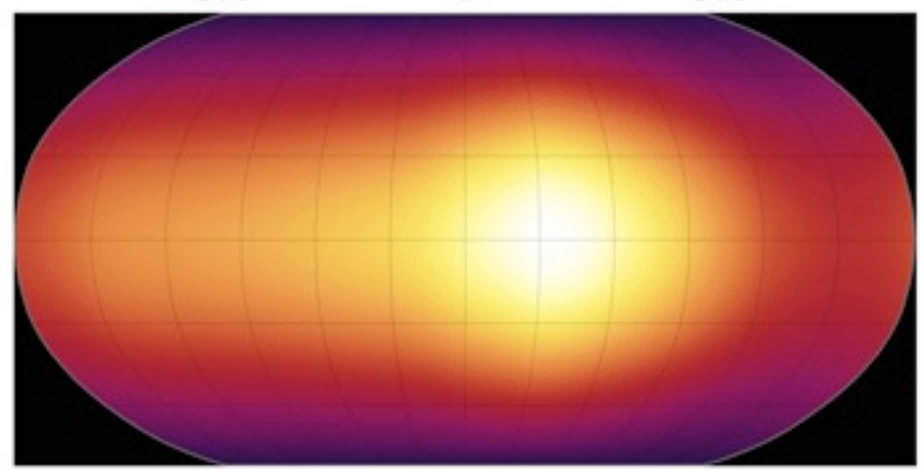
Showman & Guillot (2002)





Knutson et al. 2007

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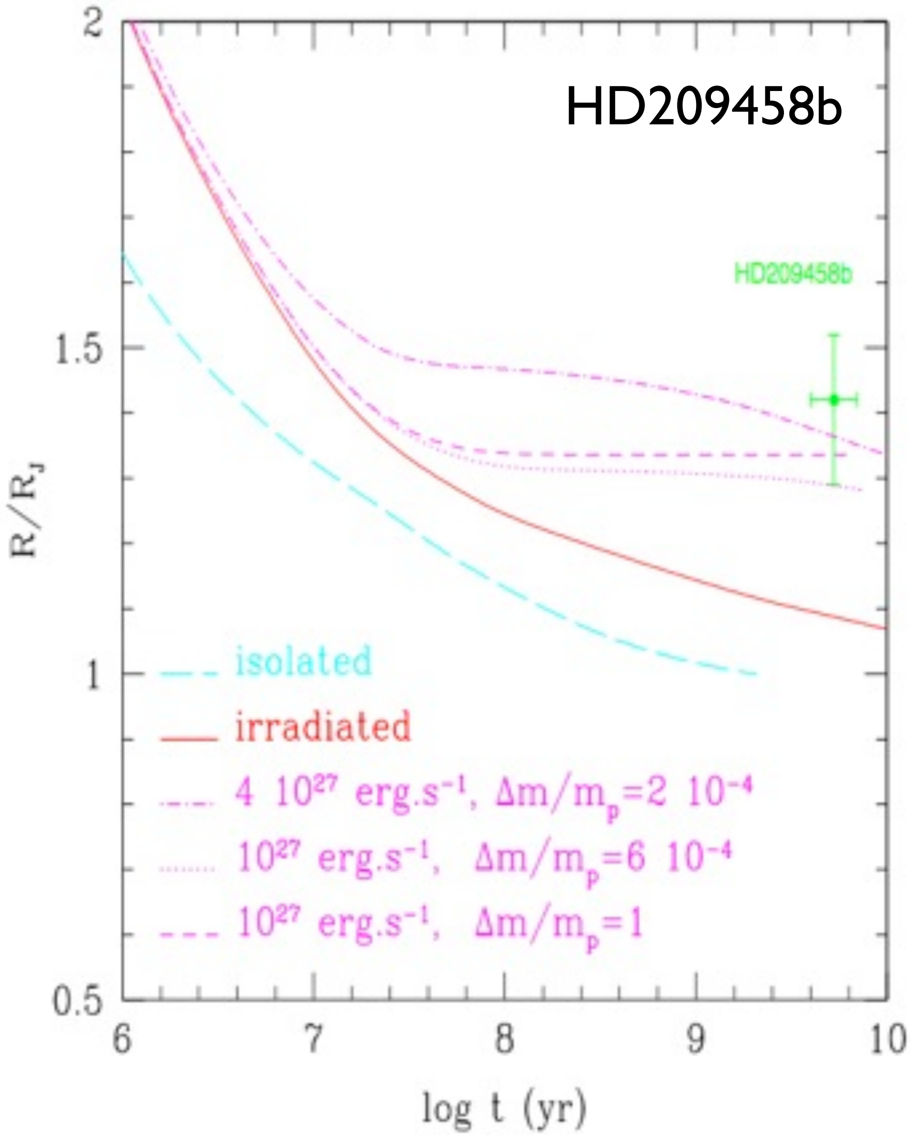
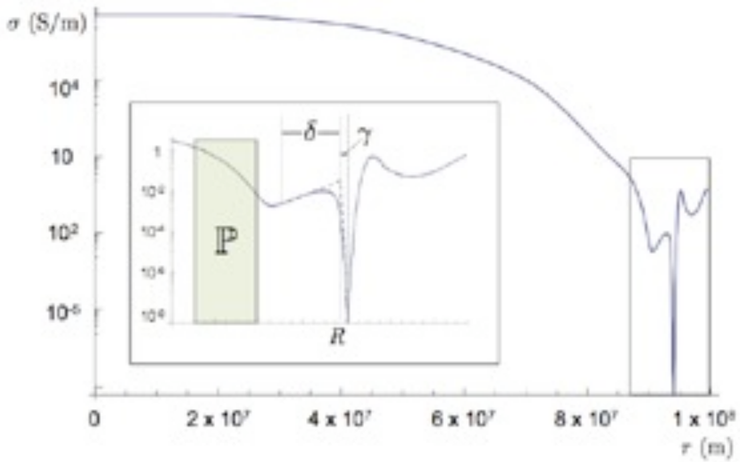


Baraffe et al. 2003

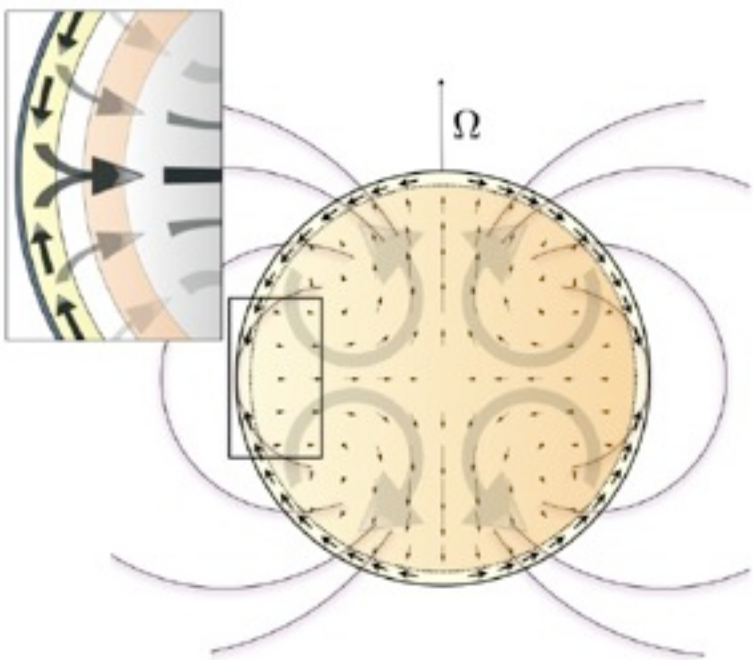
transporting deep ~1% of the stellar flux is enough to explain the size of most transiting planets

See also:
Bodenheimer et al. (2001) (orbital energy)
Guillot & Showman (2002)

Ohmic dissipation



$$\mathbb{P} = \int\int\int \frac{\vec{J}^2}{\sigma(r)} dV.$$

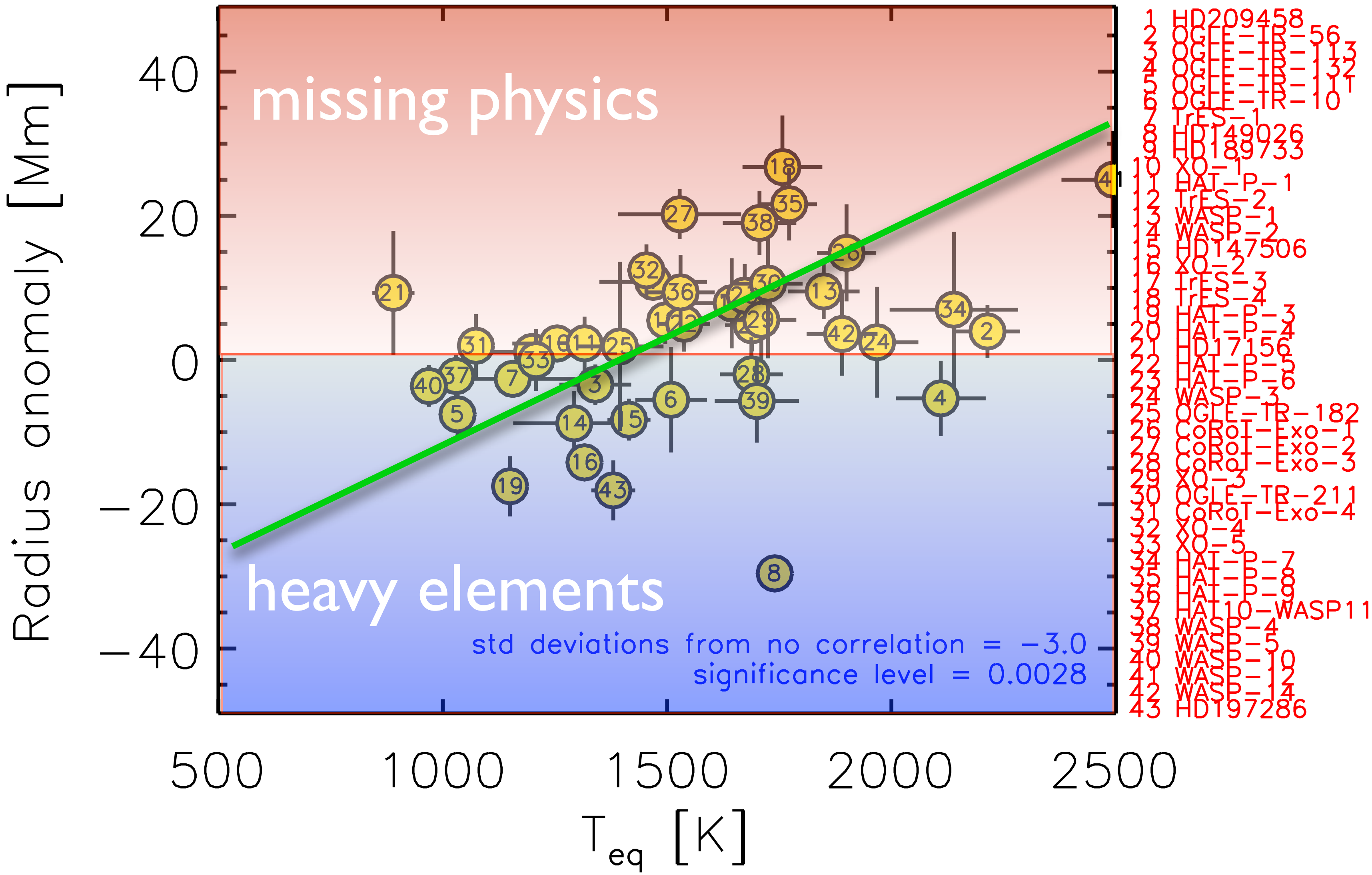


Currents generated in the hot, (partially) conducting interior and due to induction between the atmospheric circulation and the planetary magnetic field can dissipate ~10^{23} to 10^{28} erg/s

see also
Perna, Menou & Rauscher (2010)
Laine, Lin & Dong (2009)

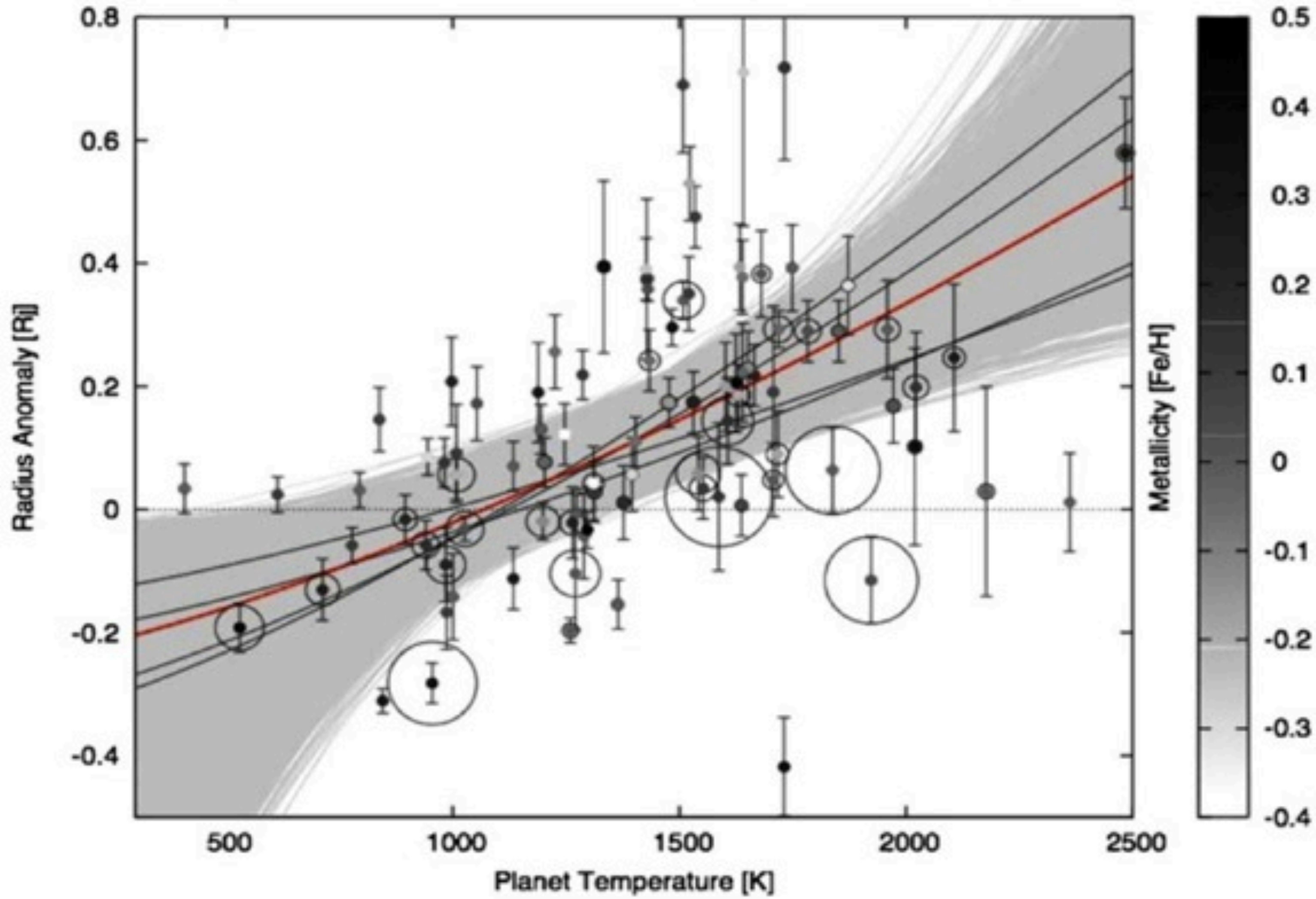
Batygin & Stevenson (2010)

T_{eq} vs radius anomaly



Models from Guillot (2008)

T_{eq} vs radius anomaly



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

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

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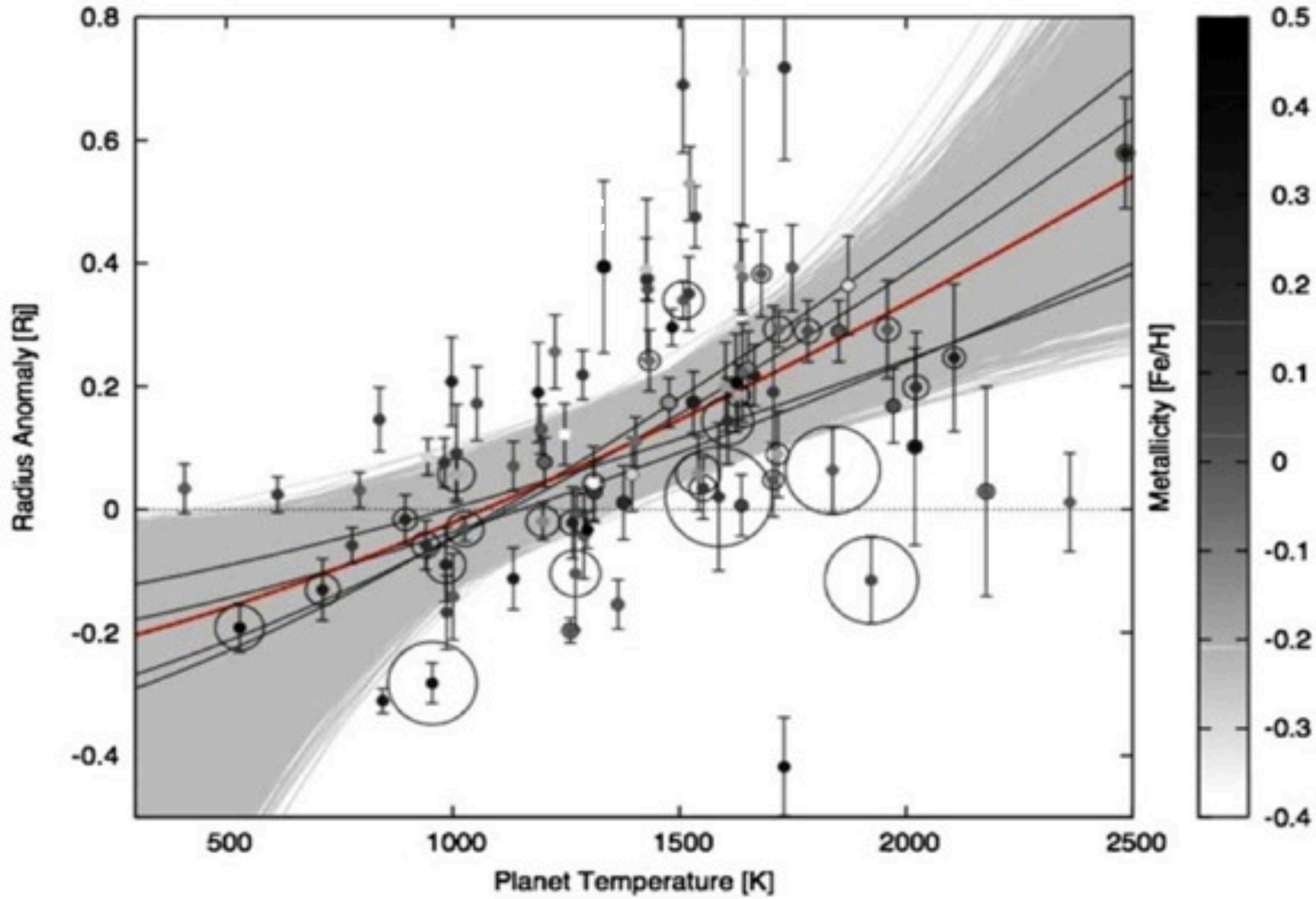

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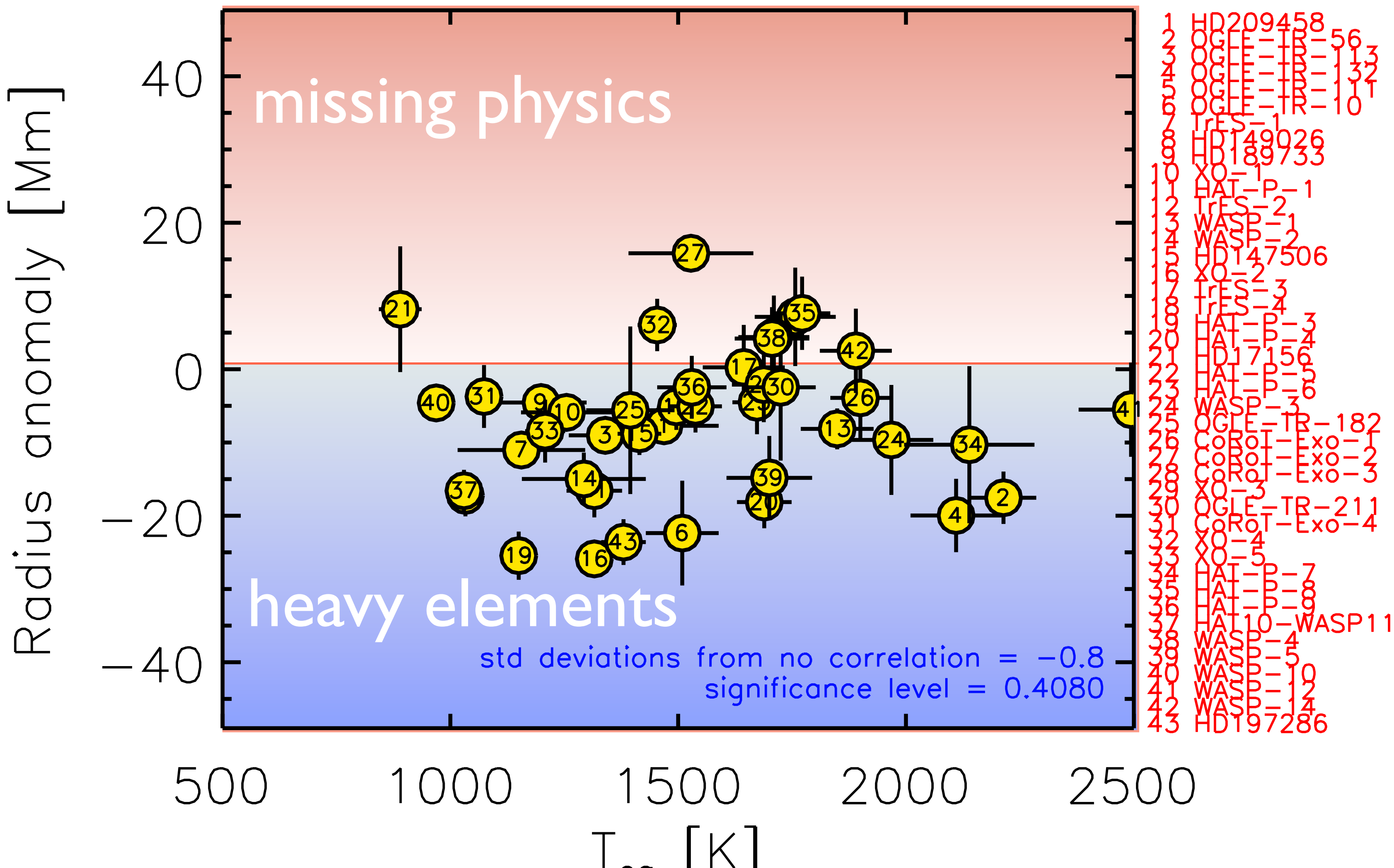
T_{eq} vs radius anomaly*

weather noise (0.5% of incoming stellar flux)



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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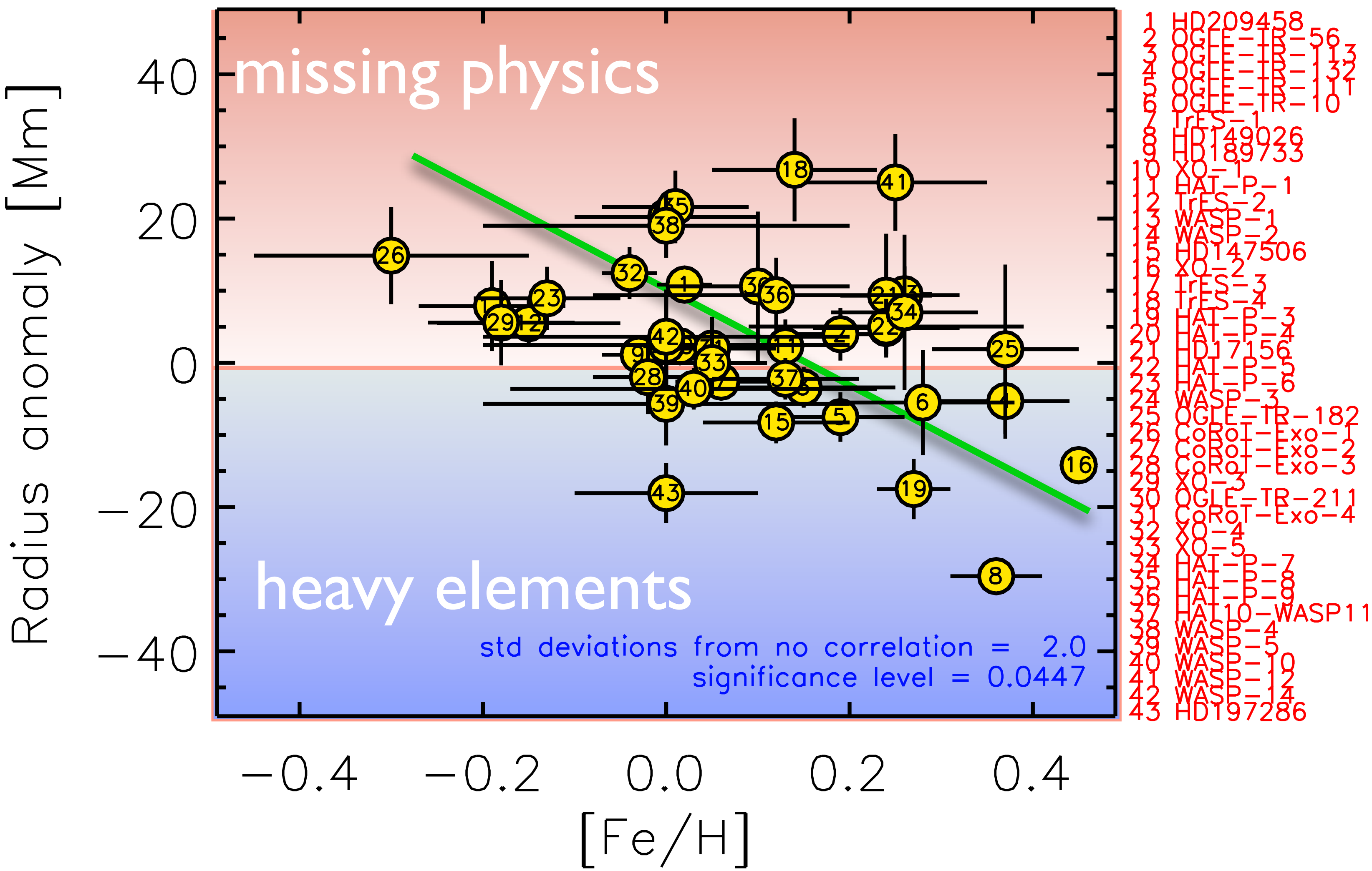
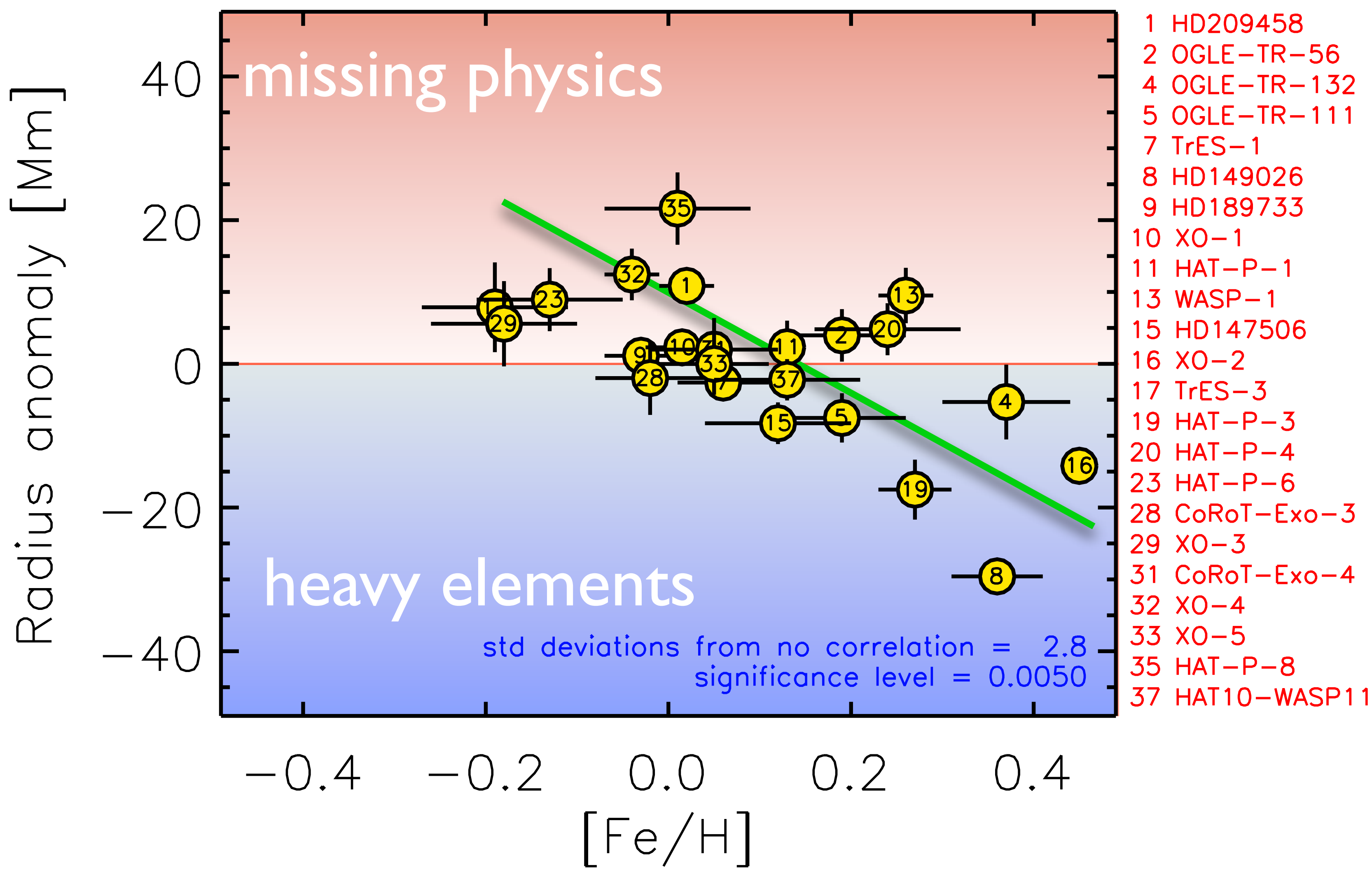
[Fe/H] vs radius anomaly



updated from Guillot 2008
see also Guillot et al. 2006, Burrows et al. 2007

[Fe/H] vs radius anomaly

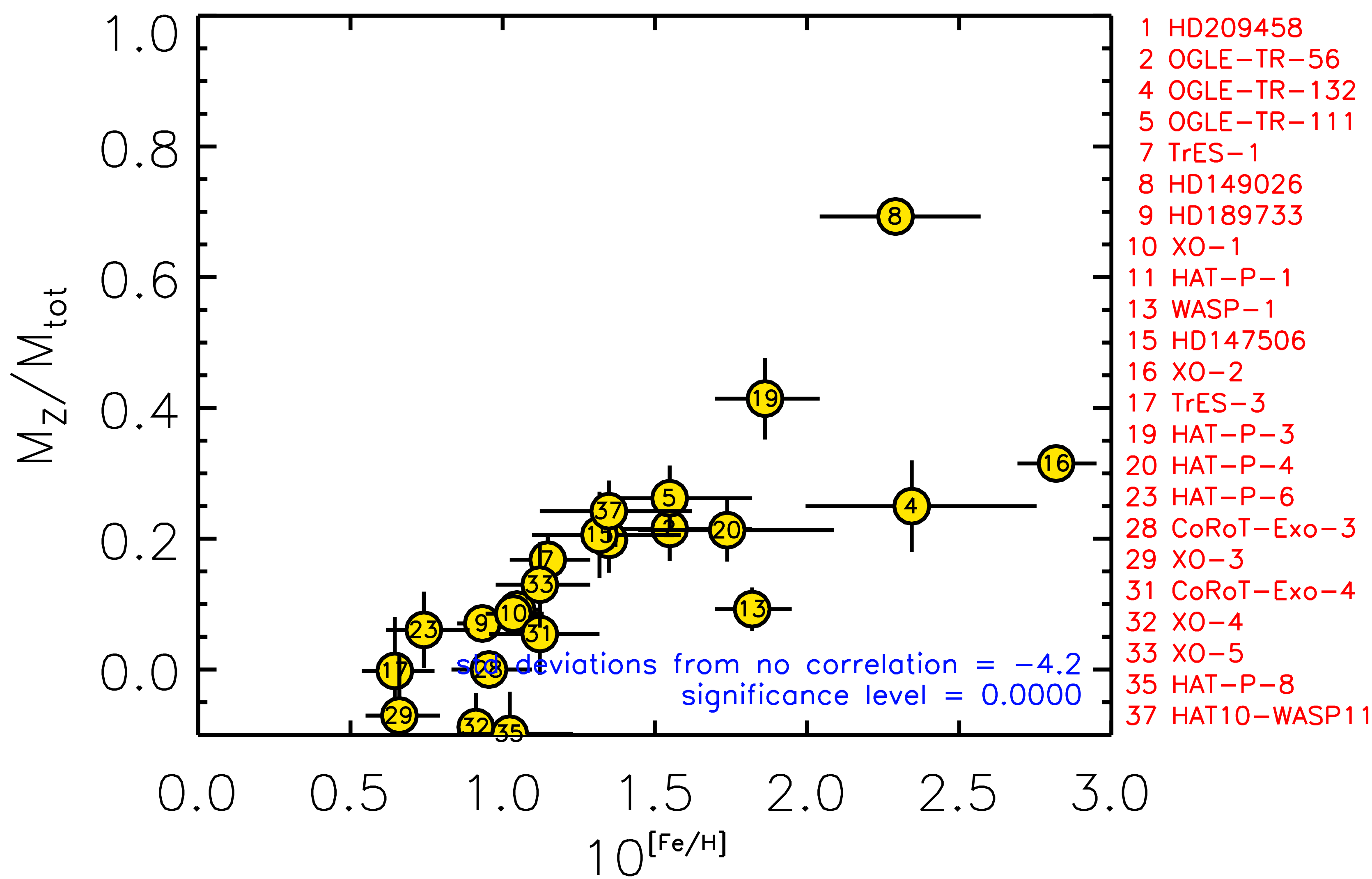


updated from Guillot 2008

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

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

(Weather noise model)



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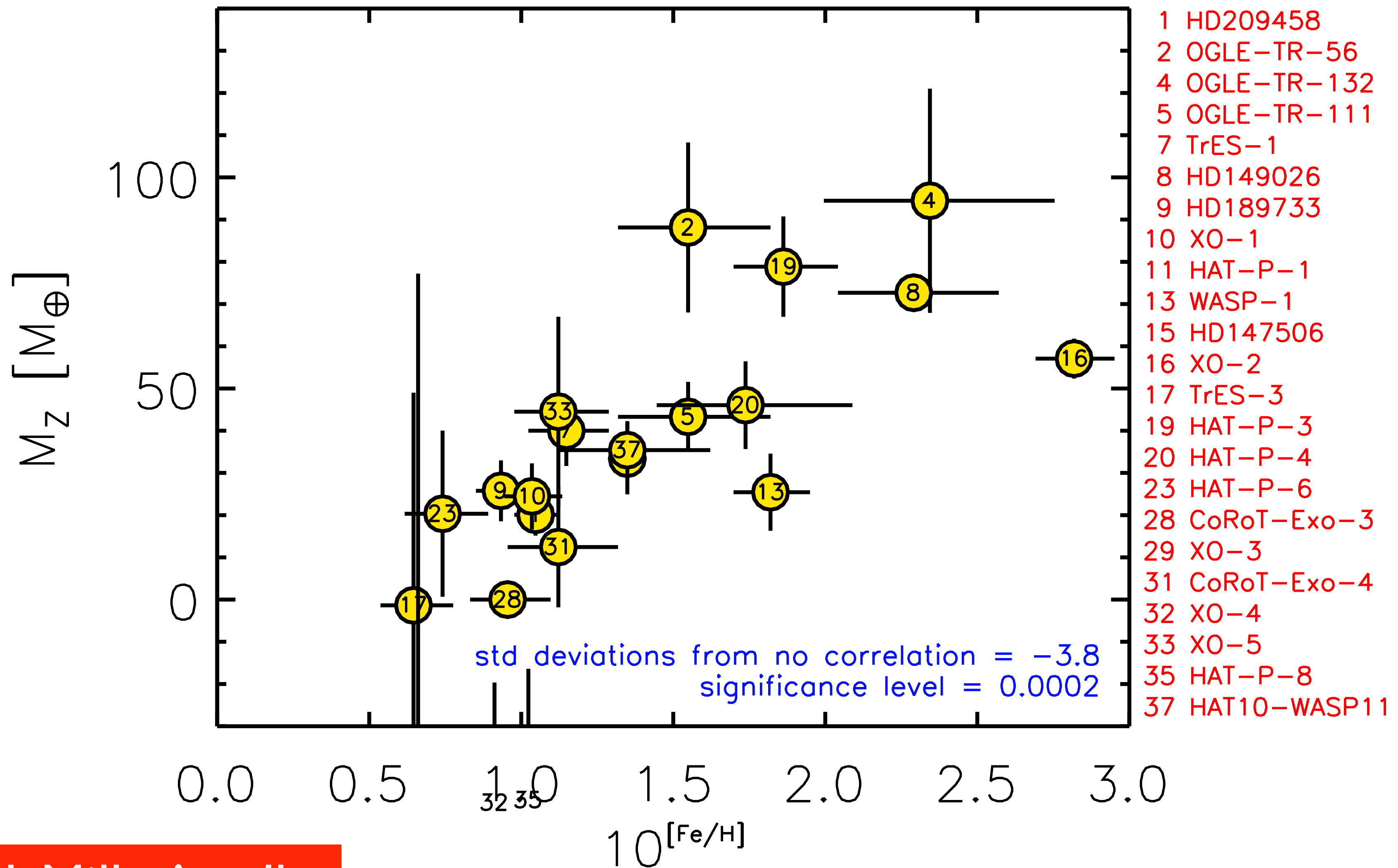
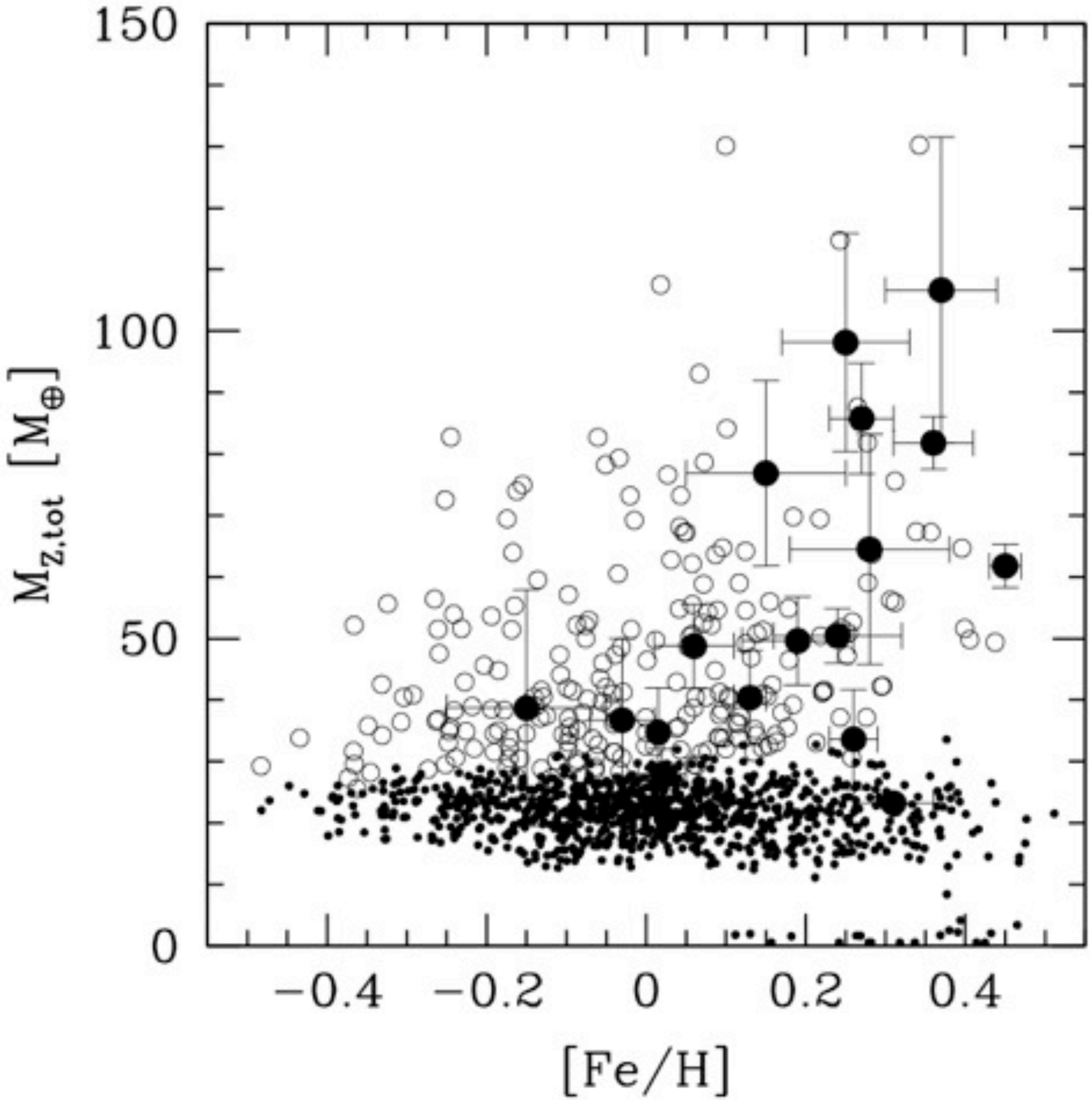


See N. Miller's talk on Friday

updated from Guillot 2008
see also Guillot et al. 2006, Burrows et al. 2007

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



Mordasini et al. (2009)

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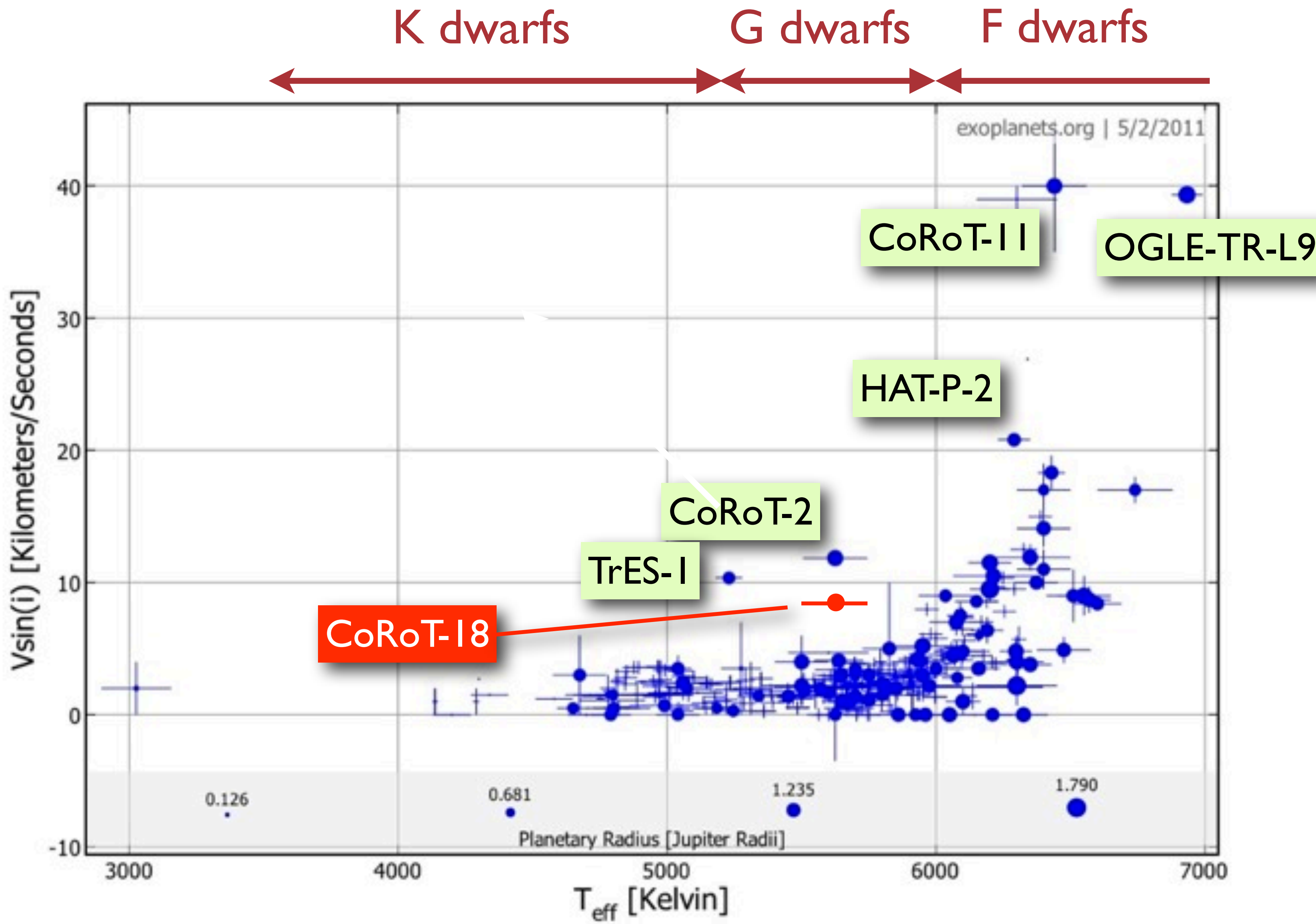
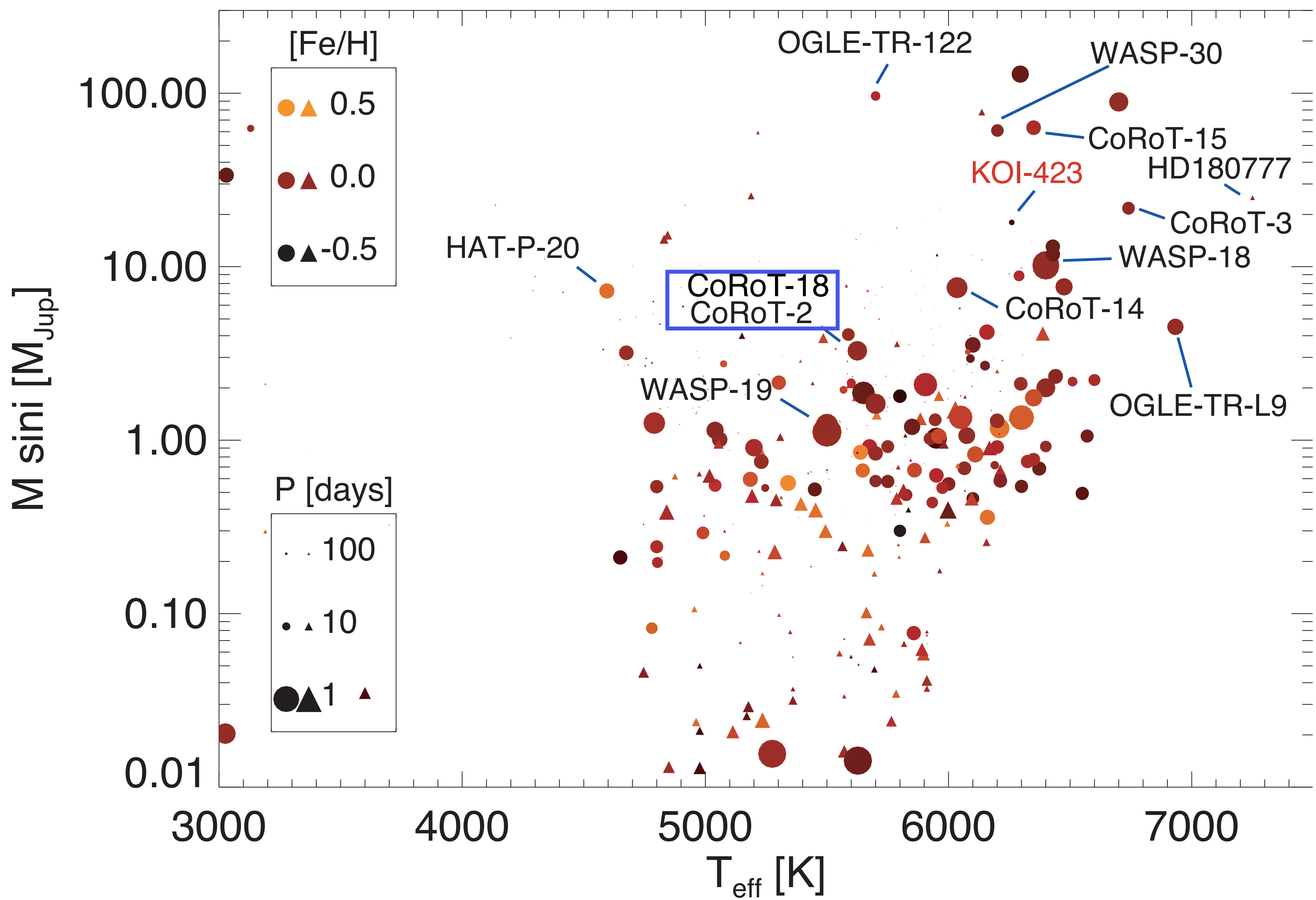
Spin rates of stars with planets

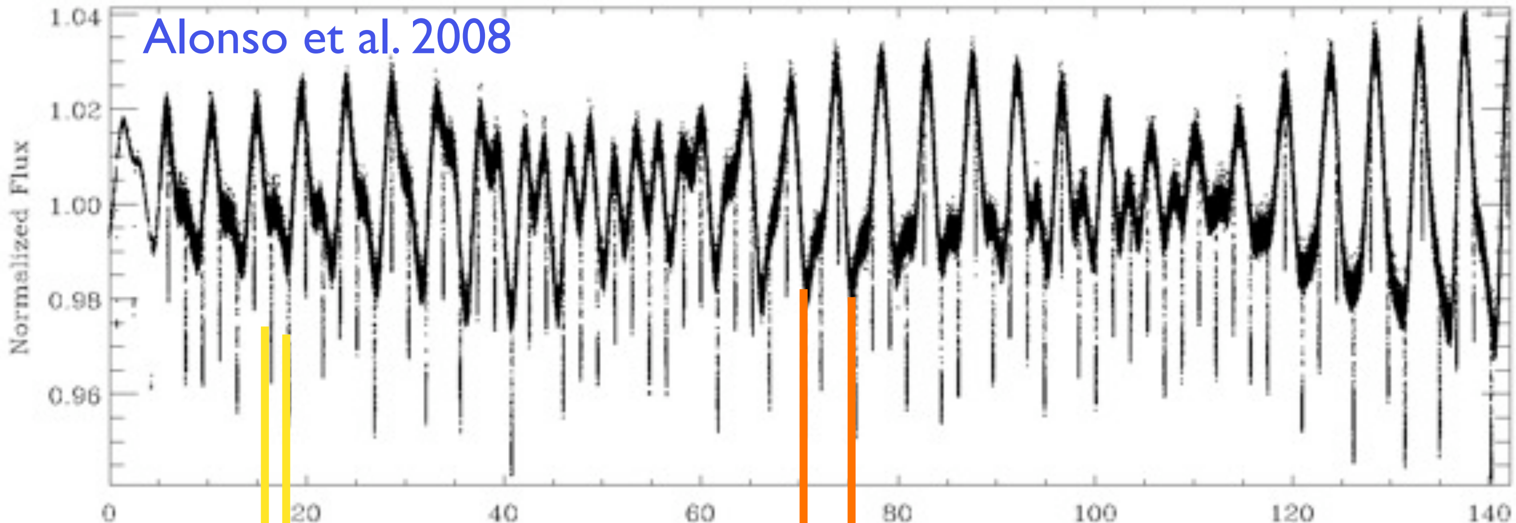


Link to tides?



Bouchy et al. (submitted to A&A)

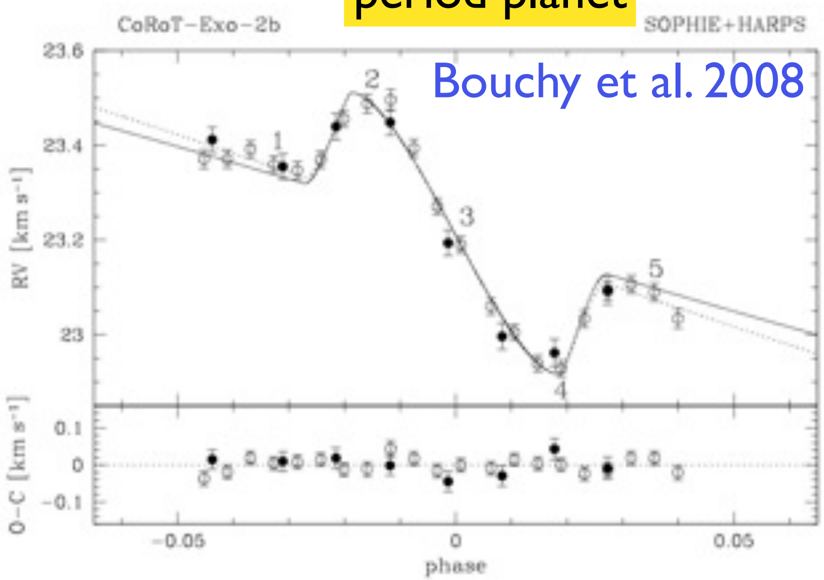
CoRoT-2a&b: observations

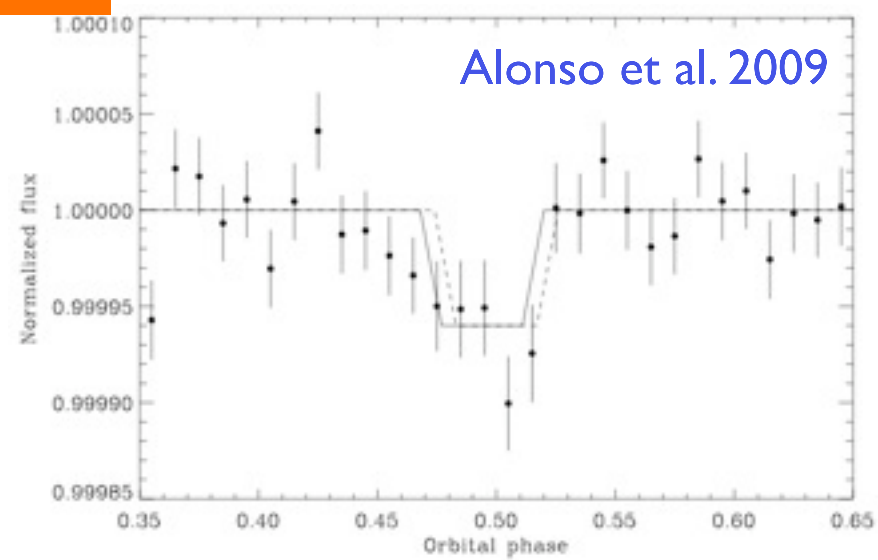


1.73 day period planet

4.5 day period star

Planet: ~3 Mjup, ~1.5 Rjup

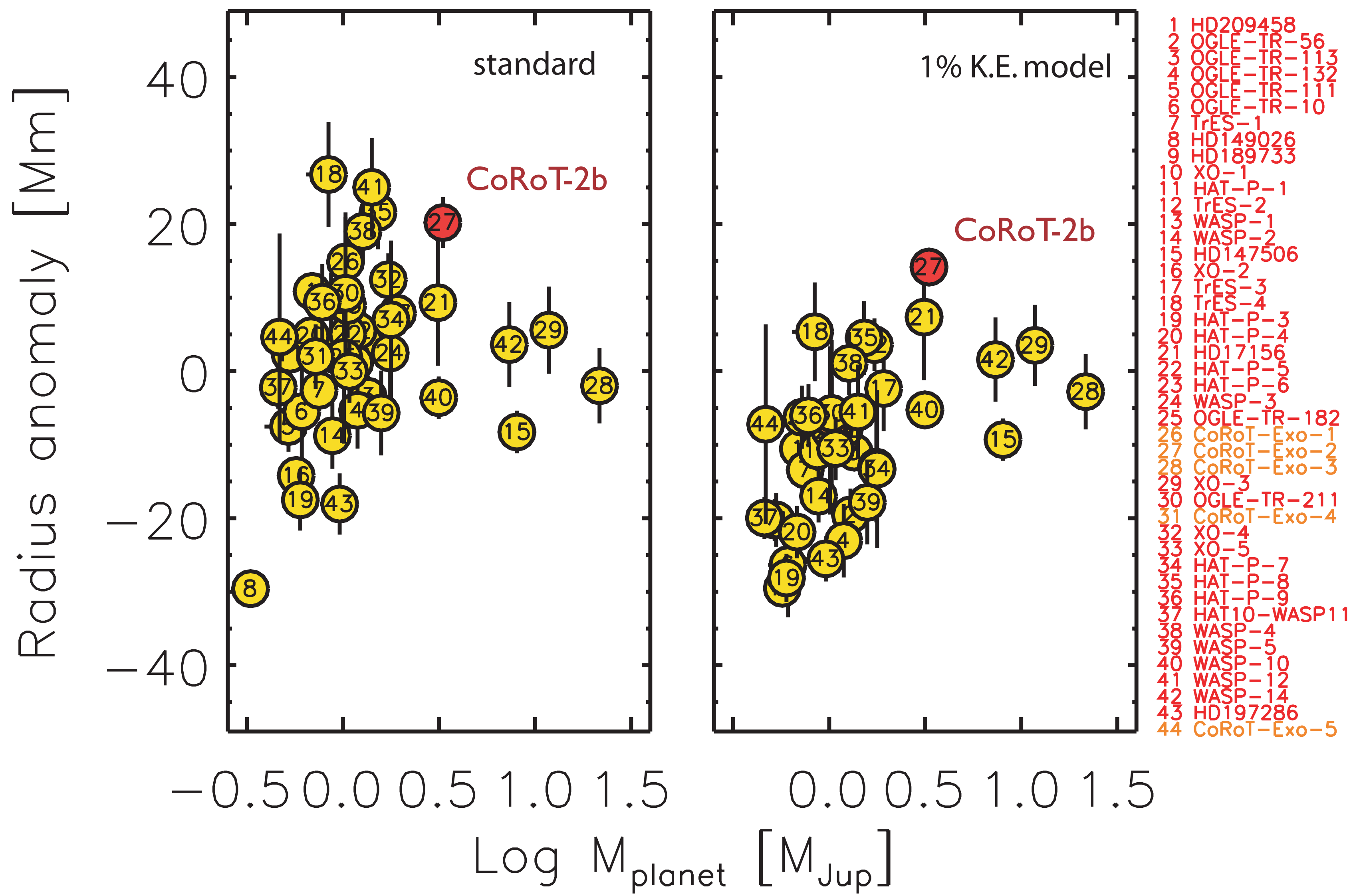




Rossiter: l=7.2° +/- 4.5°

Secondary transit: e=0.03 +/- 0.03

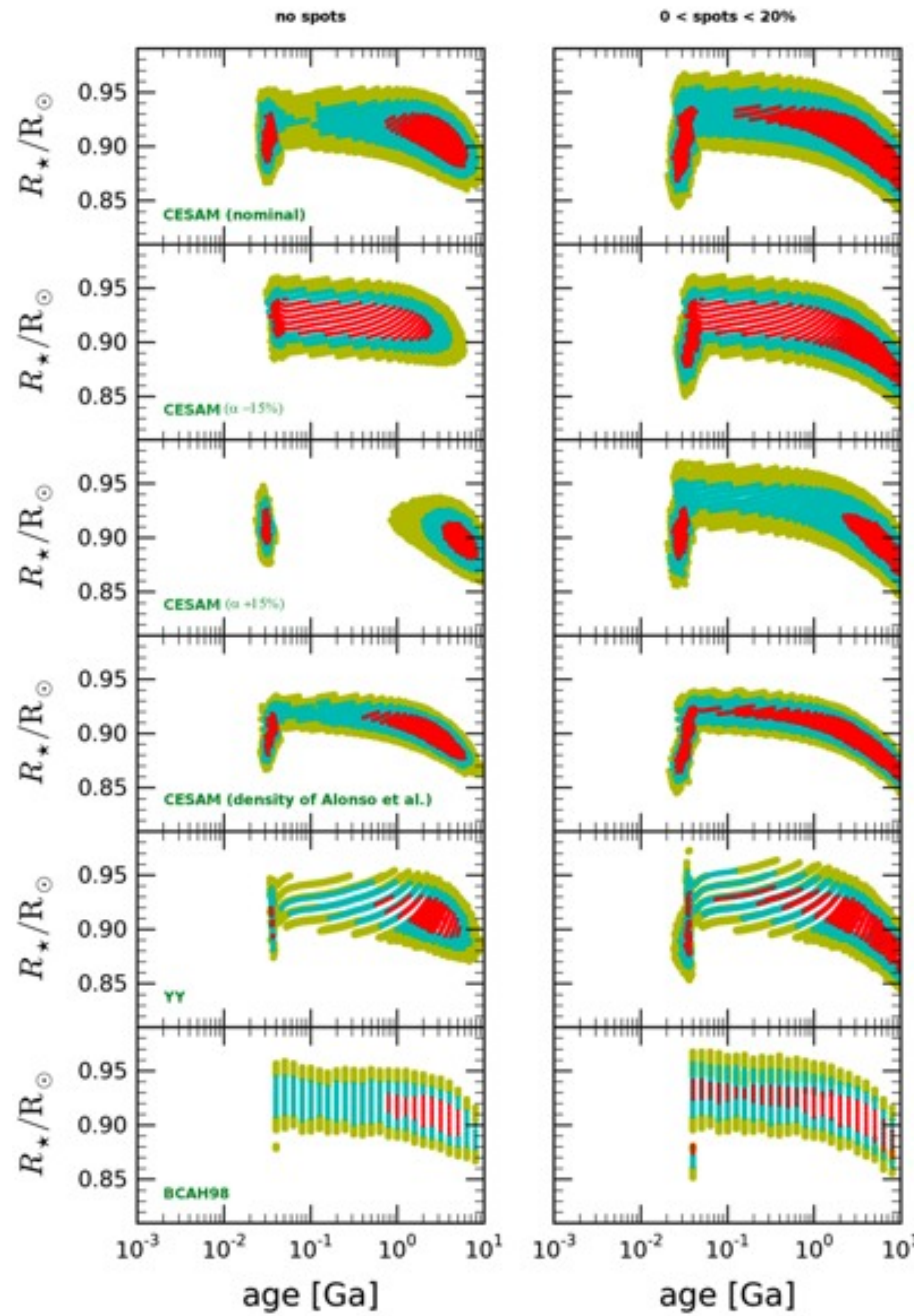
CoRoT-2b among its peers



updated from Guillot 2008

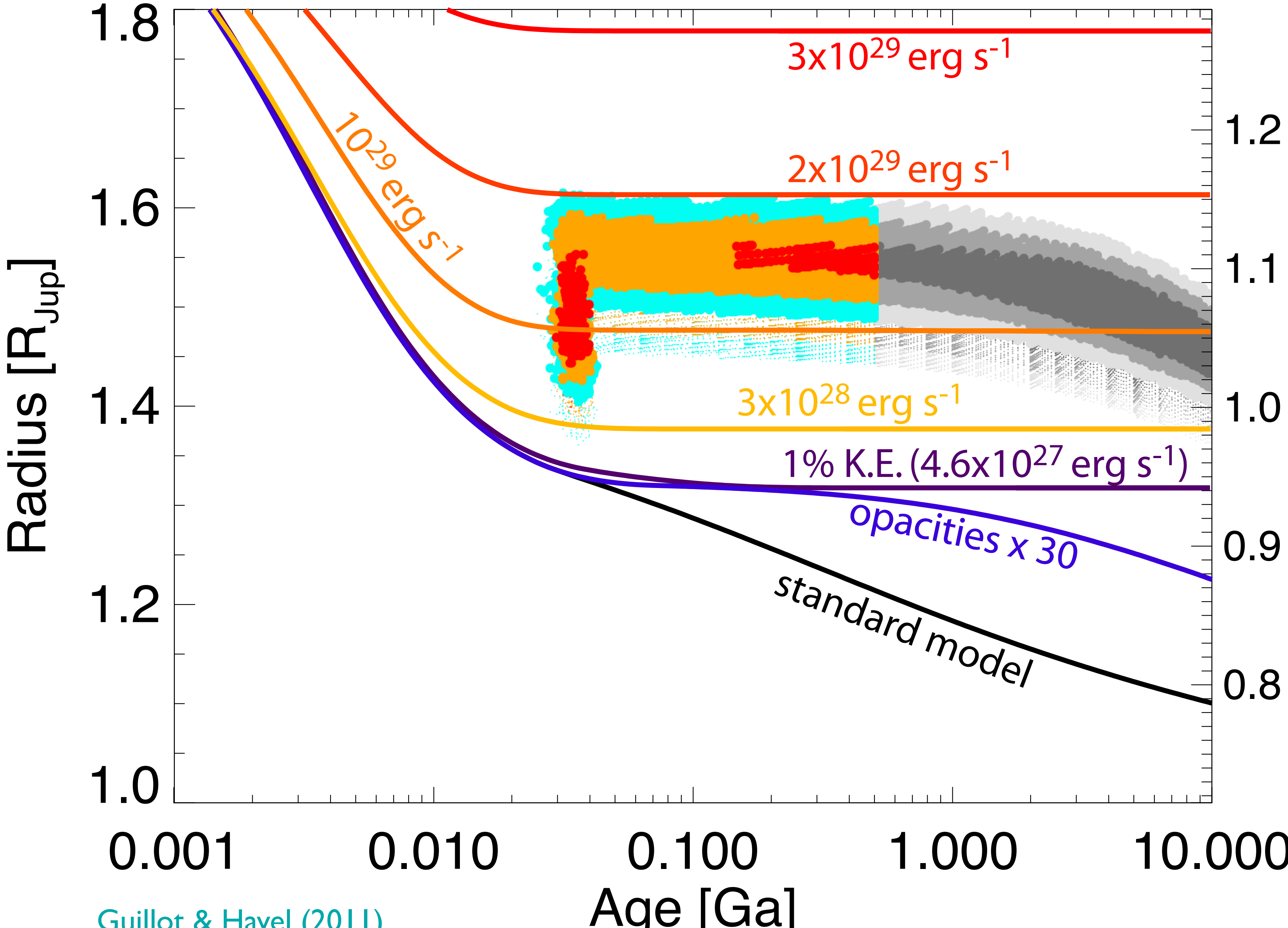
CoRoT-2a: evolution constraints

2 classes of solutions:
•on the pre-main sequence (30-40Ma)
•on the main sequence (>1Ga)



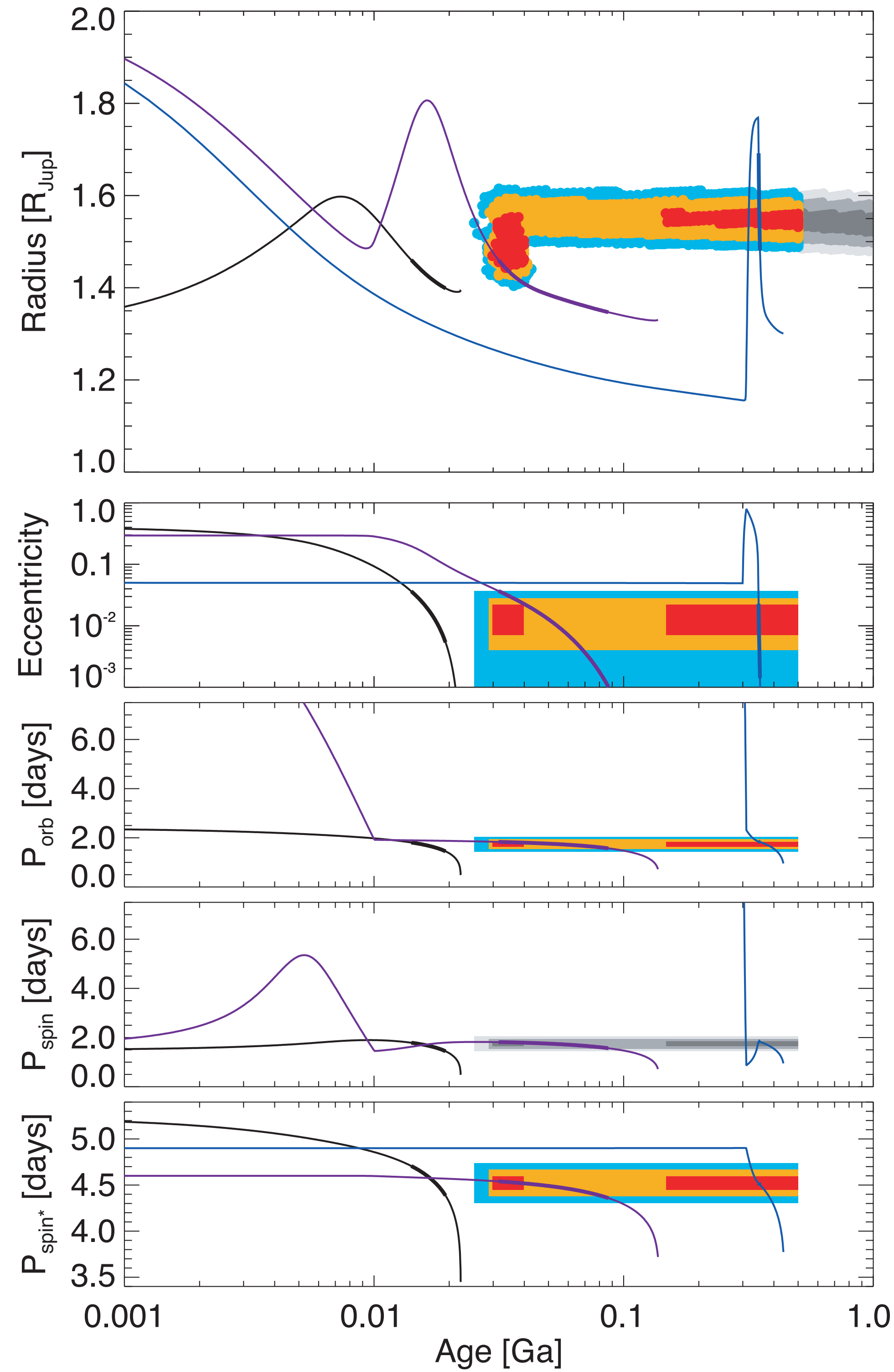
Guillot & Havel (2011)

CoRoT-2b: energy dissipation



Guillot & Havel (2011)

CoRoT-2b: tides? a recent giant impact?

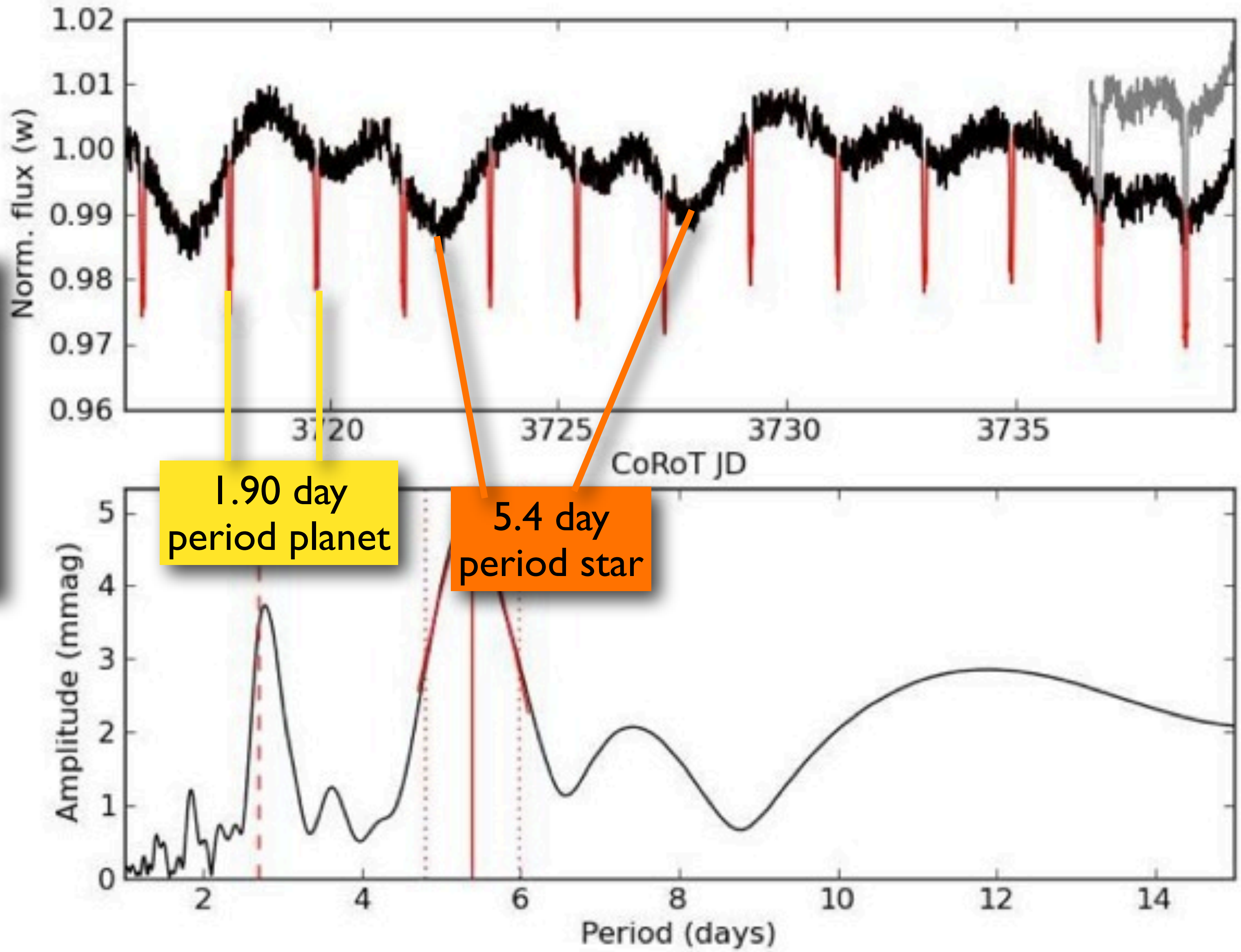


The measured size can be explained as a transient phenomenon

Guillot & Havel (2011)
(see also Gillon et al. 2010)

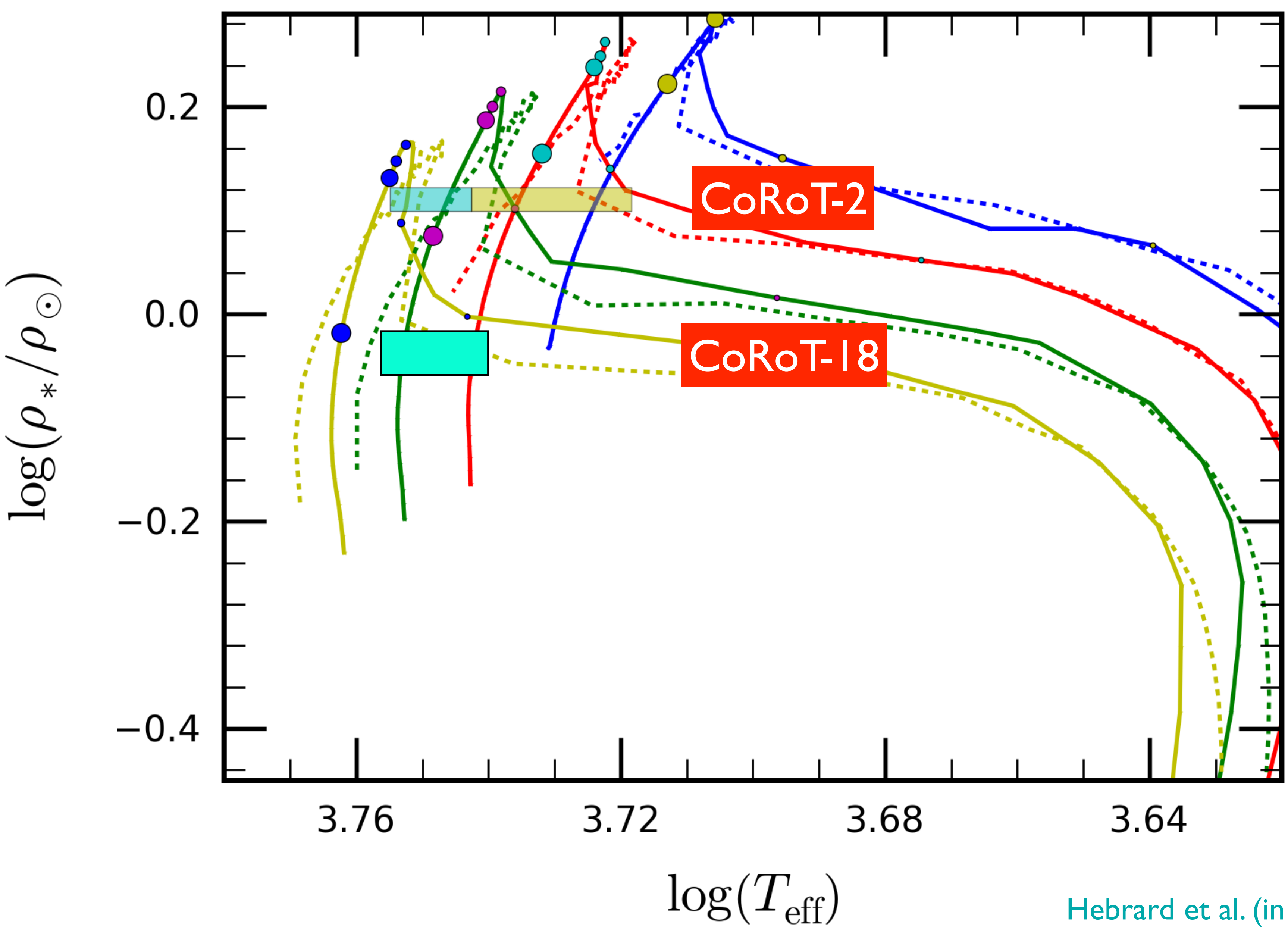
CoRoT-18

Very similar to CoRoT-2:
Active, solar-mass star, with high mass close-in planet (~3Mjup)



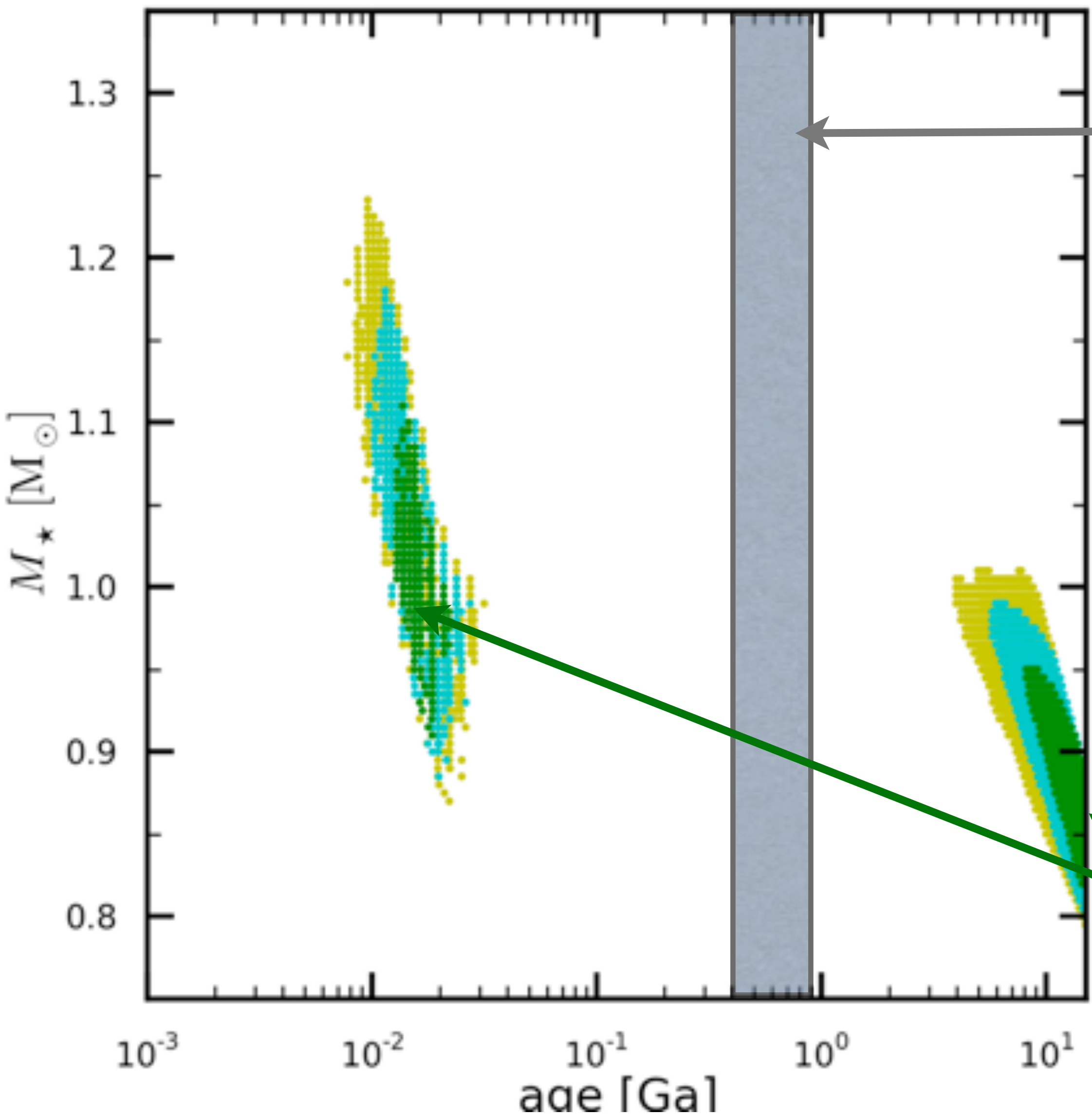
Hebrard et al. (in preparation)

CoRoT-18: HR tracks



Hebrard et al. (in preparation)

CoRoT-18



Age range from gyrochronology & Li abundance

Ages & Masses from stellar evolution tracks matching Teff, ρ*

Hebrard et al. (in preparation)

Planets around young stars

- CoRoT-2b is so large that either:
  - It was formed 30 to 40Ma ago, and the planet's atmosphere contains additional opacity sources
  - It was raised to a high eccentricity less than 20 Ma ago and has now been almost circularized but is still hot from that period
  - It suffered a giant impact with a Saturn to Jupiter mass planet less than 20 Ma ago.
- CoRoT-18 age determinations are not consistent
  - Problem with ρ^* determination in variable stars?
  - Do we understand the physics of young stars?

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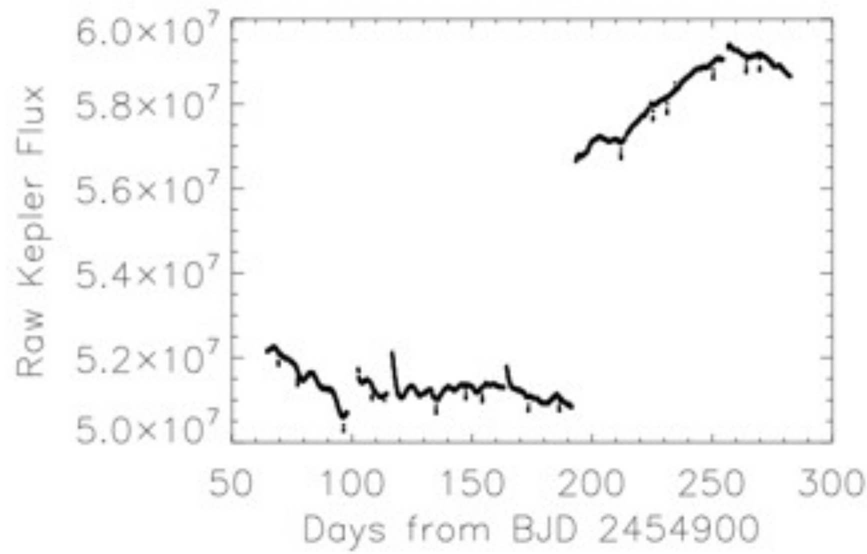
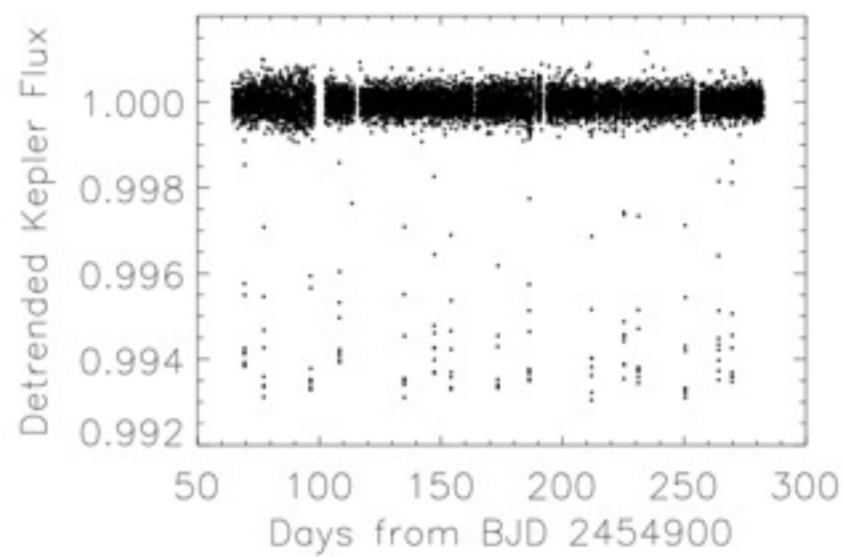
Kepler-9

- 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

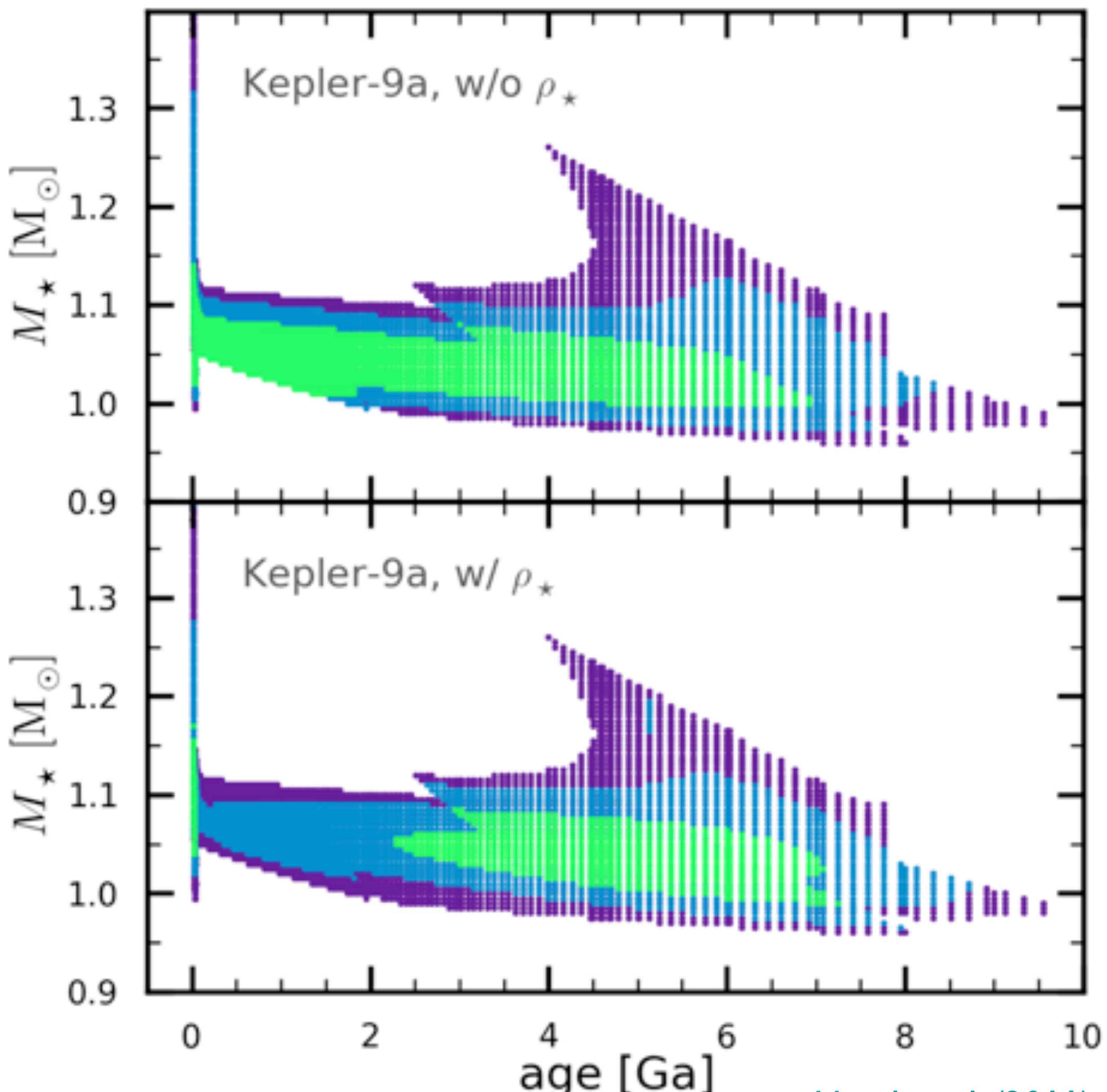




Holman et al. (2010), Torres et al. (2010)

Kepler-9: stellar mass & 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: planetary radii & age

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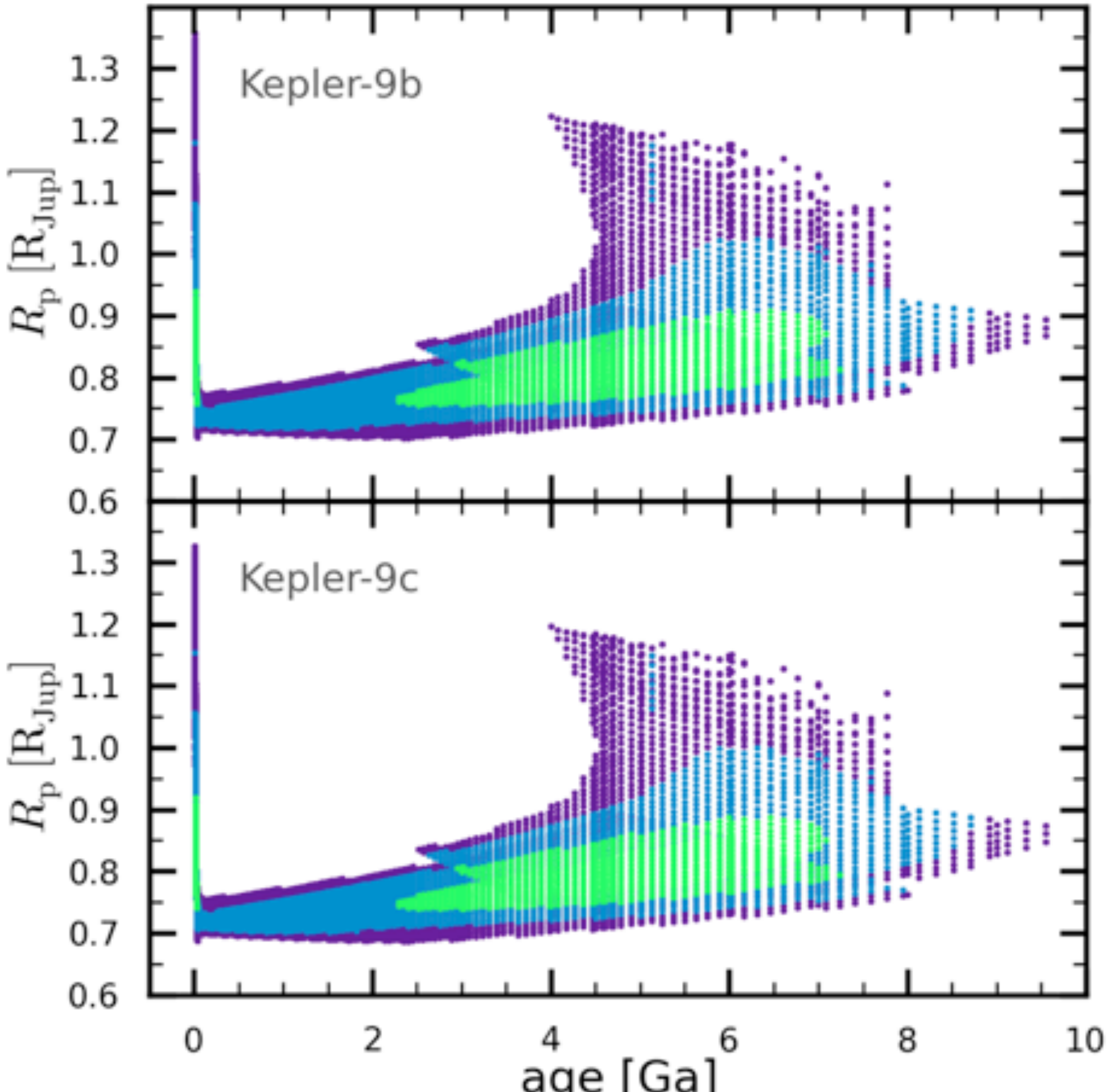
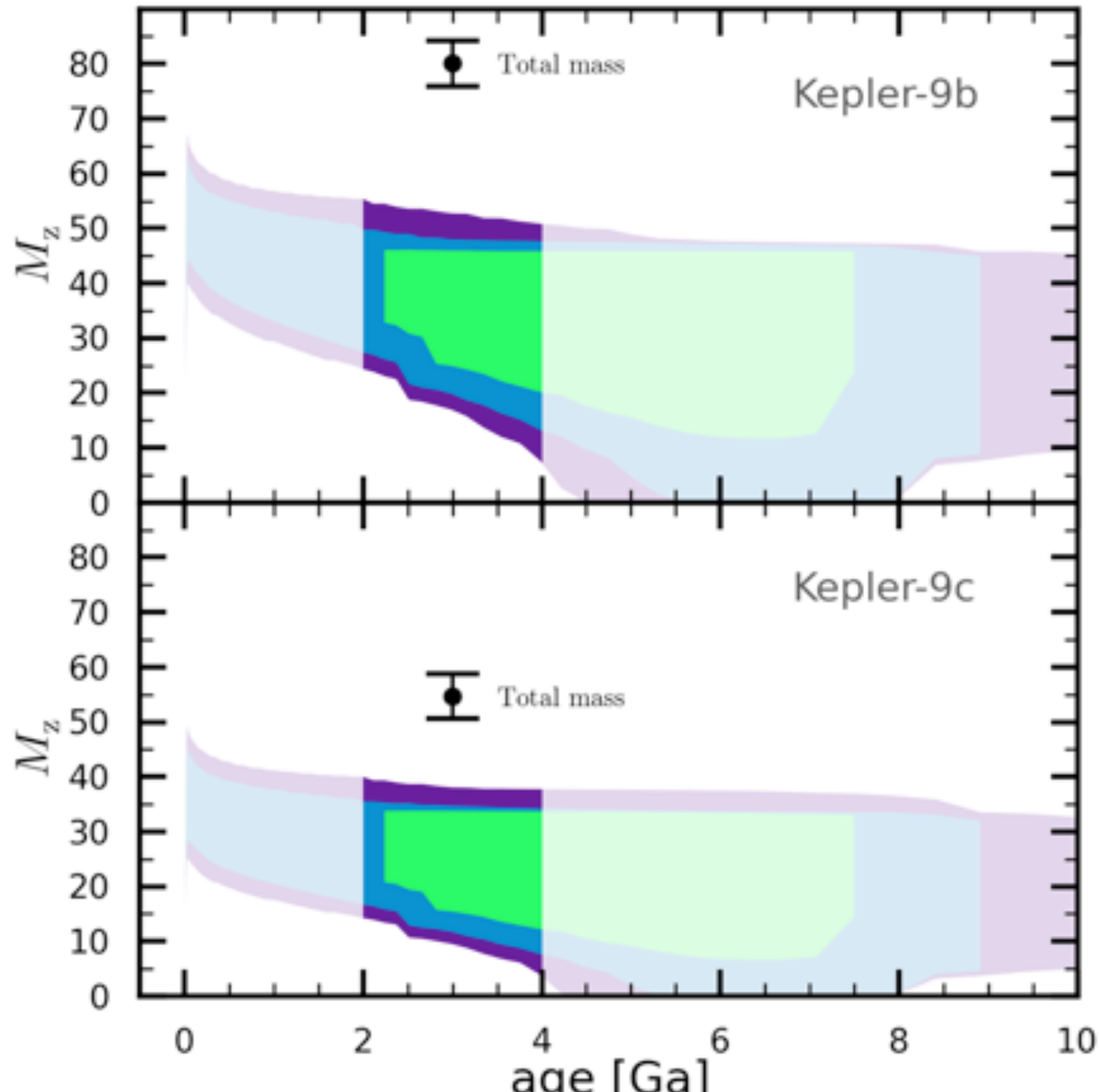
    - Colors in the figure shows the observational constraints (Teff,) at 1, 2 and 3σ, respectively
- 2-4 Ga preferred by gyrochronology (16.7 days spin period)



Havel et al. (2011)

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

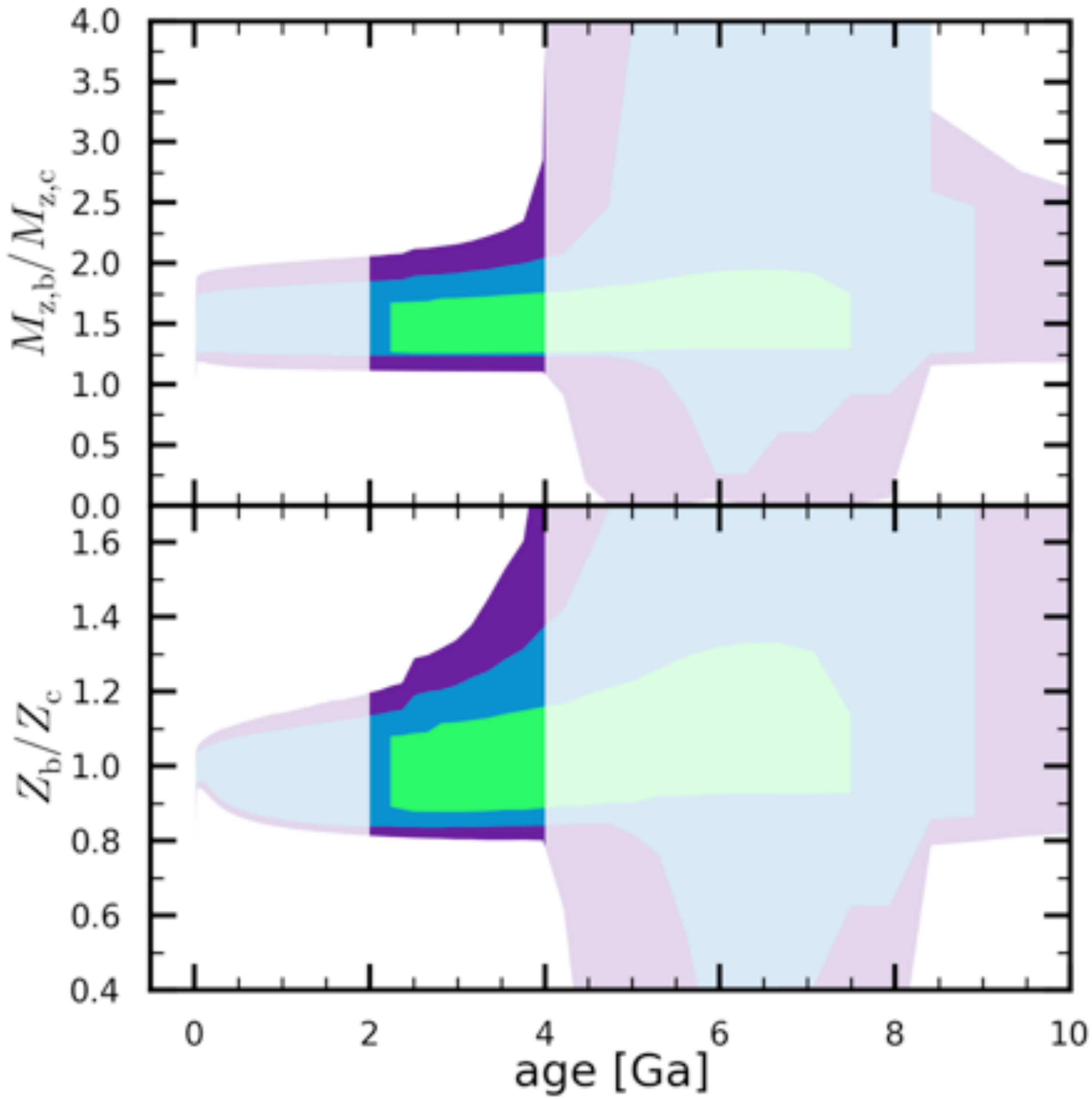
- Planetary evolution tracks using CEPAM
- Mz the mass of heavy elements is calculated by accounting for different physical hypotheses
  - with/without heat dissipation
  - different atmospheric models
- 2-4 Ga is preferred by gyrochronology



Havel et al. (2011)

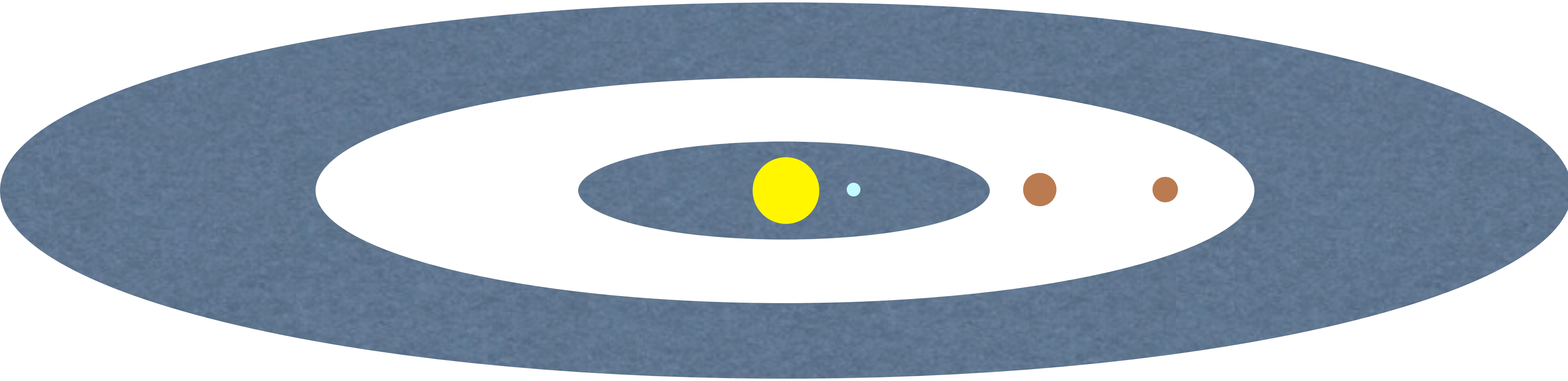
Kepler-9: composition ratios vs. age

- 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)



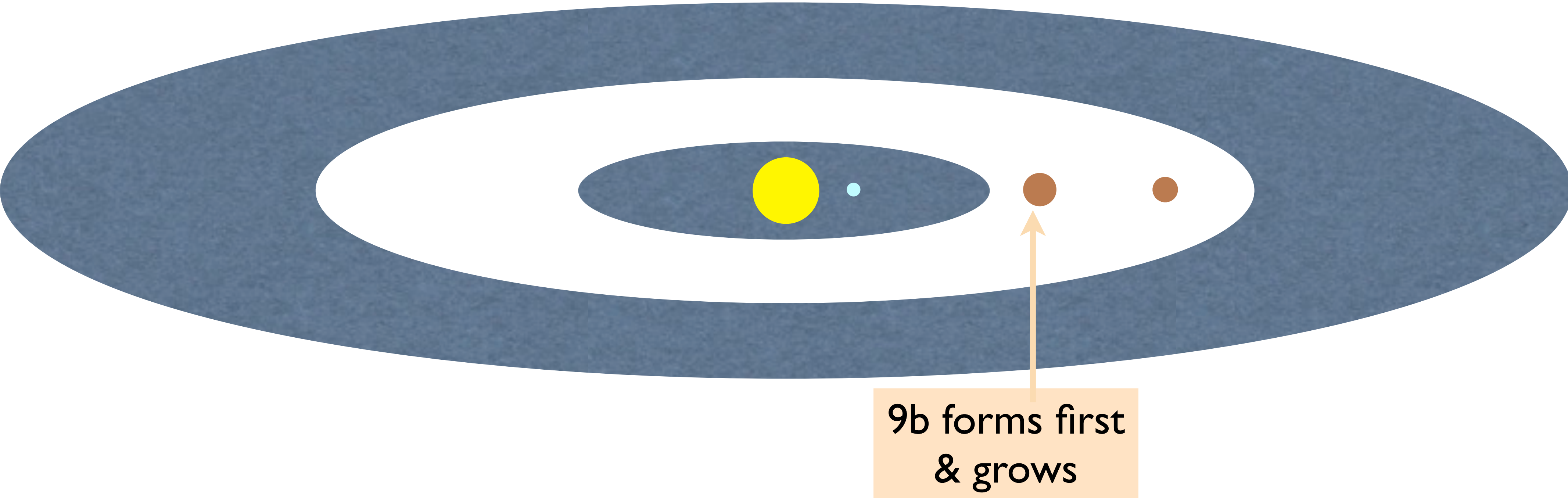
Havel et al. (2011)

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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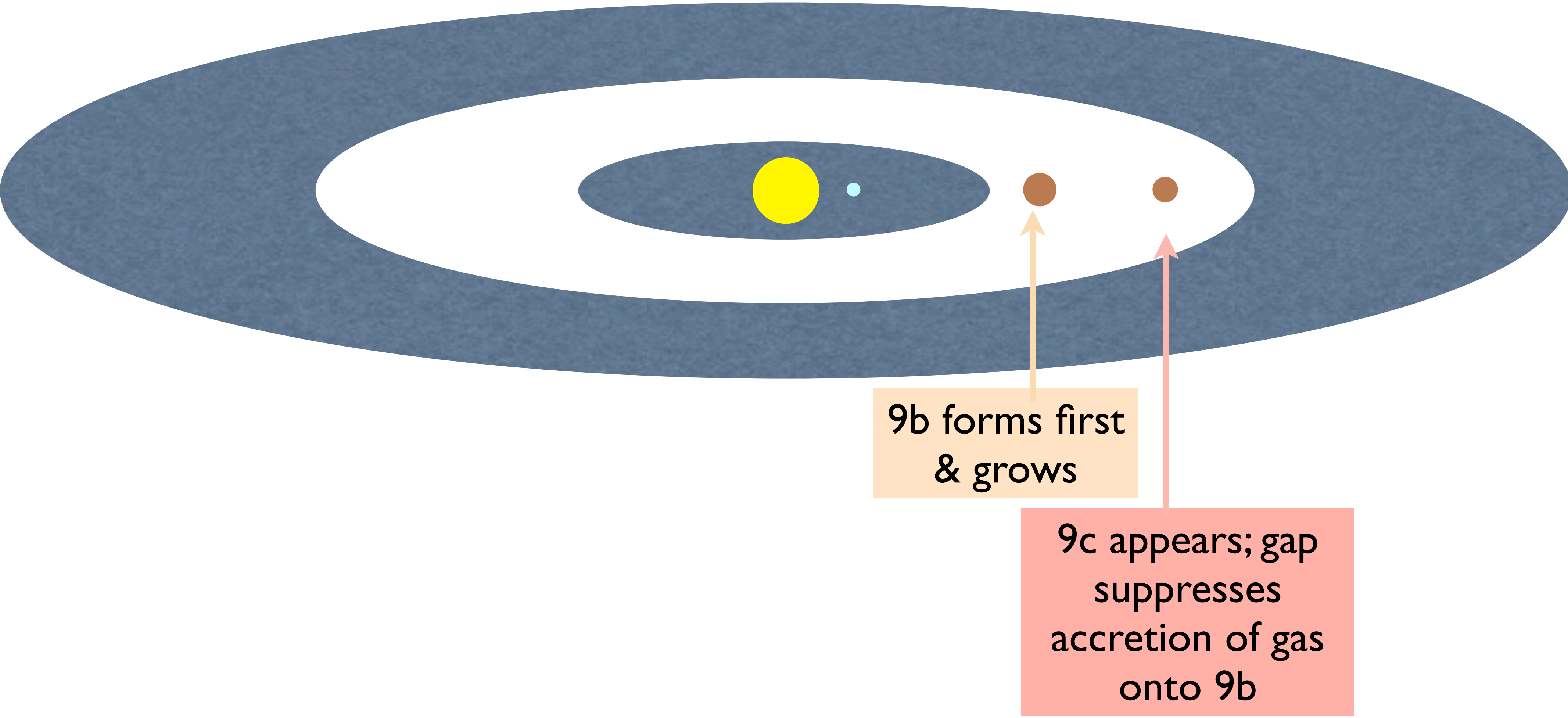

Crida et al. (in preparation)

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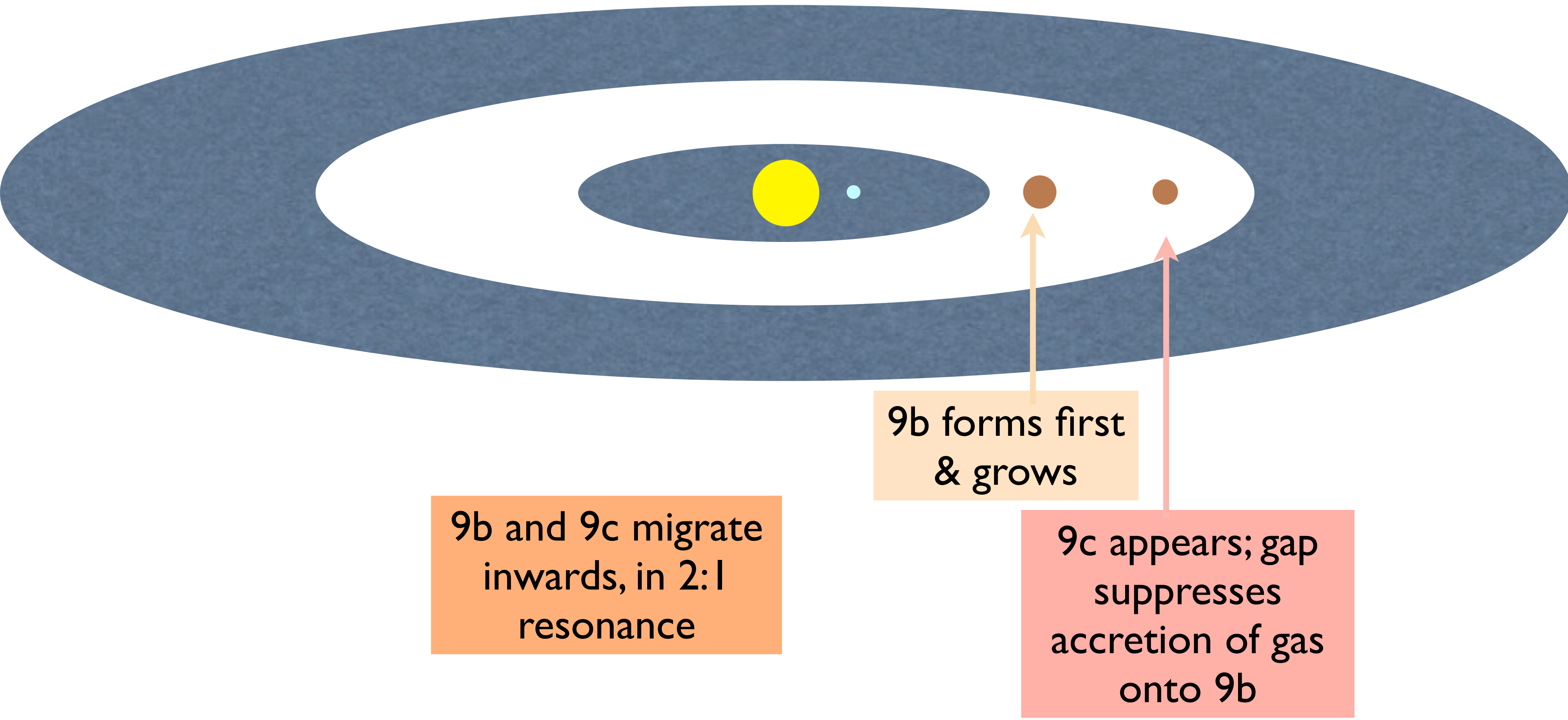

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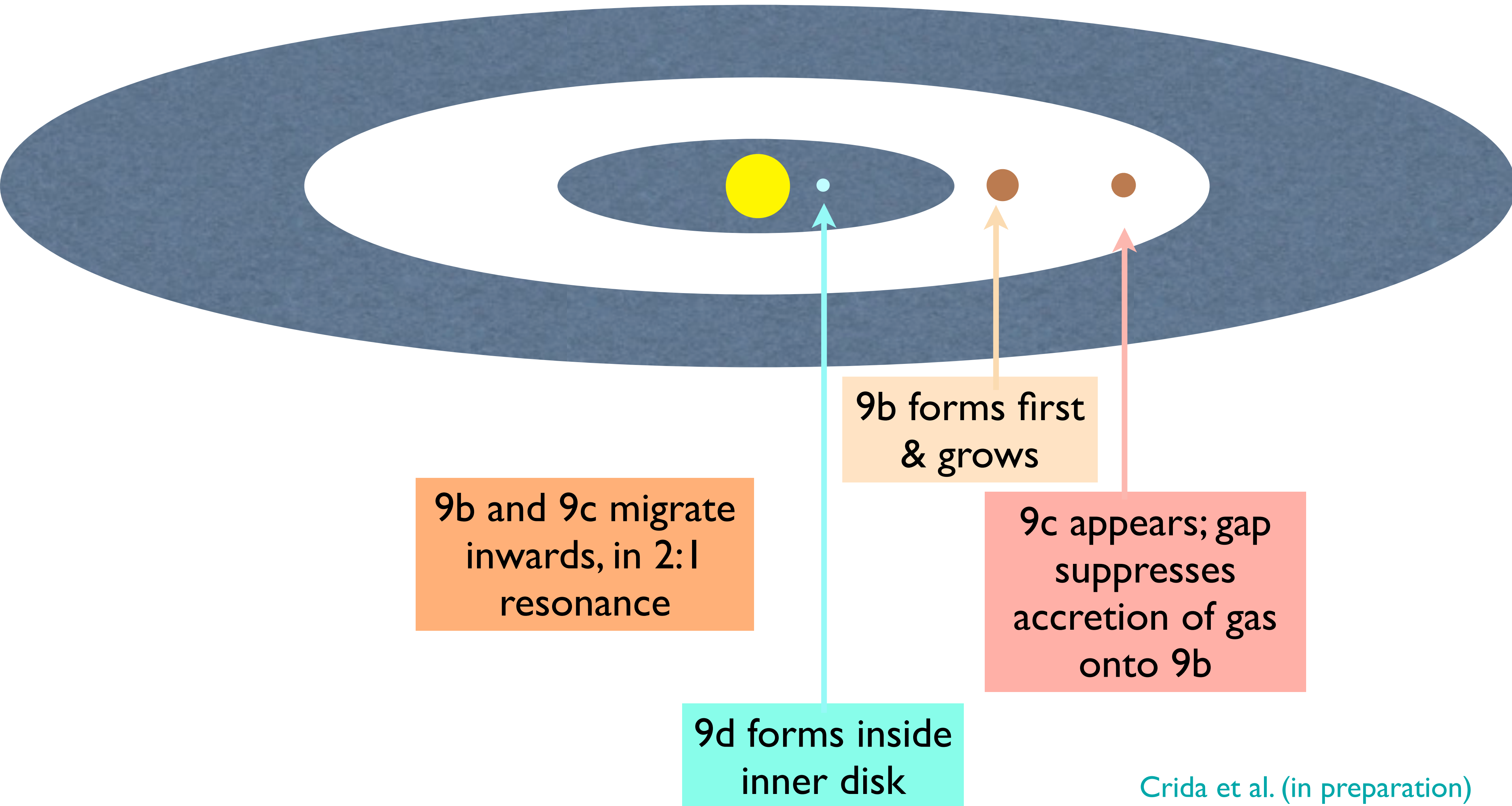

Crida et al. (in preparation)

Summary

- Evolution of giant planets understood, but not fine details.
  - «Inflated planets» problem
    - Mechanism still uncertain but "weather noise" + ohmic dissipation appears promising
  - Role of atmosphere?
- Statistical analyses of transiting exoplanets allow powerful tests of theories
  - Testing the source of the missing physics
  - Confirmation of the correlation between Mz and [Fe/H]
    - High Mz mass probably imply multiple (giant) impacts
- Young stars with transiting planets pose problems
  - CoRoT-2, CoRoT-18
    - Recent giant impacts? Different stellar physics?
- Multi-planetary transiting systems bring new information
  - Kepler-9 system: Two Saturn-mass planets with same global composition, in 2:1 resonance.