Investigating the Role of Stellar Tides in Hot Jupiters' Origin and Fate.

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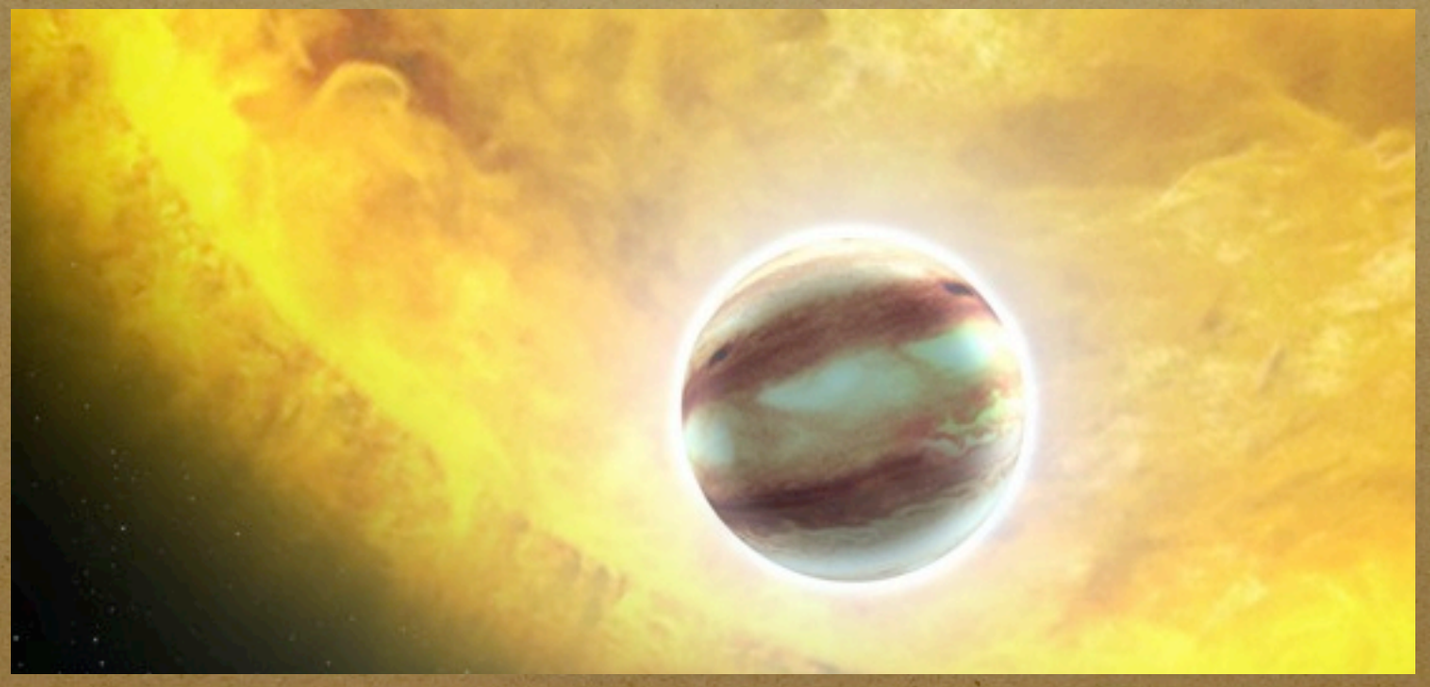

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Why Do We Care?

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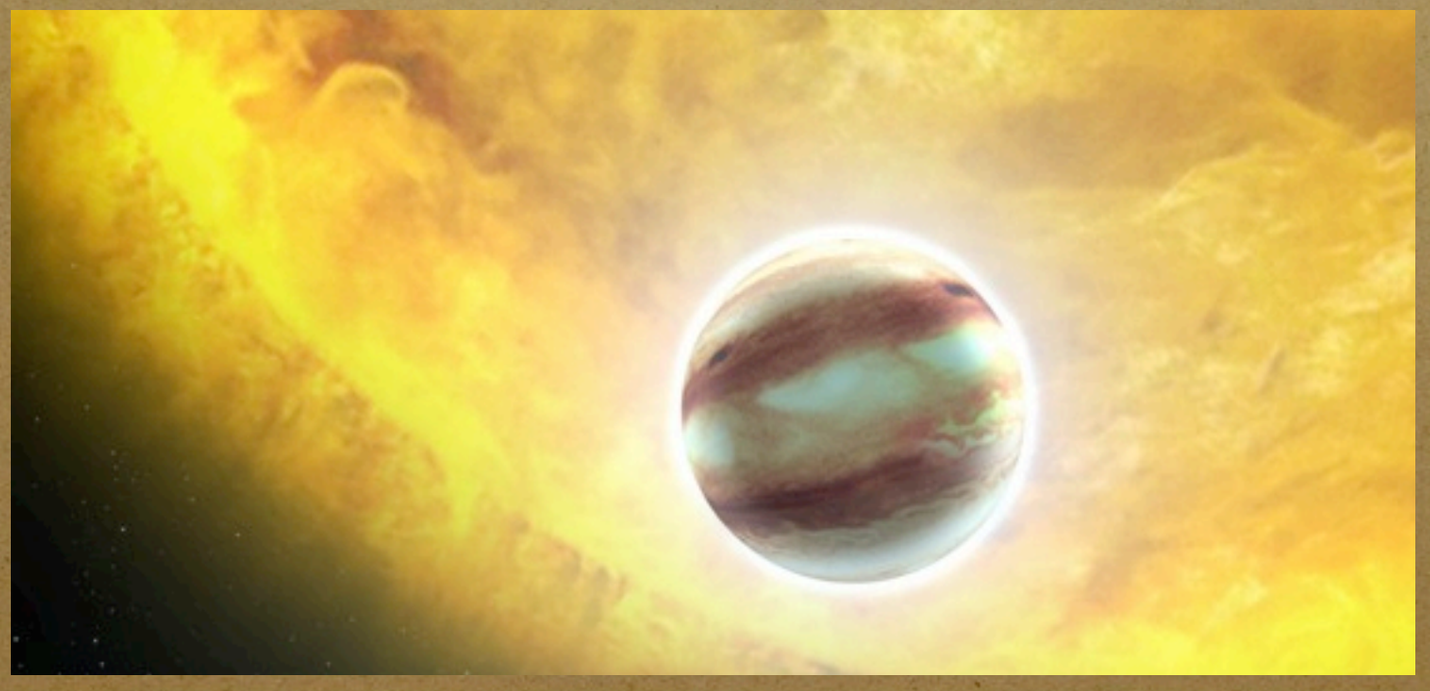
As of now:
(NASA Exoplanet Archive)

~2,000 confirmed planets
~4,000 candidates from NASA's *Kepler* satellite

Hot Jupiters: $M_{pl} \sim M_J$ & P_{orb} ~ few days

~ 200



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Why Do We Care?

CIERA

- Learn About Formation Models:

- Learn About Physical Mechanisms:

The Formation

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Created at several AUs

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(e.g. Goldreich & Tremaine '80; Ward '97; Murray+98; Lin+96)

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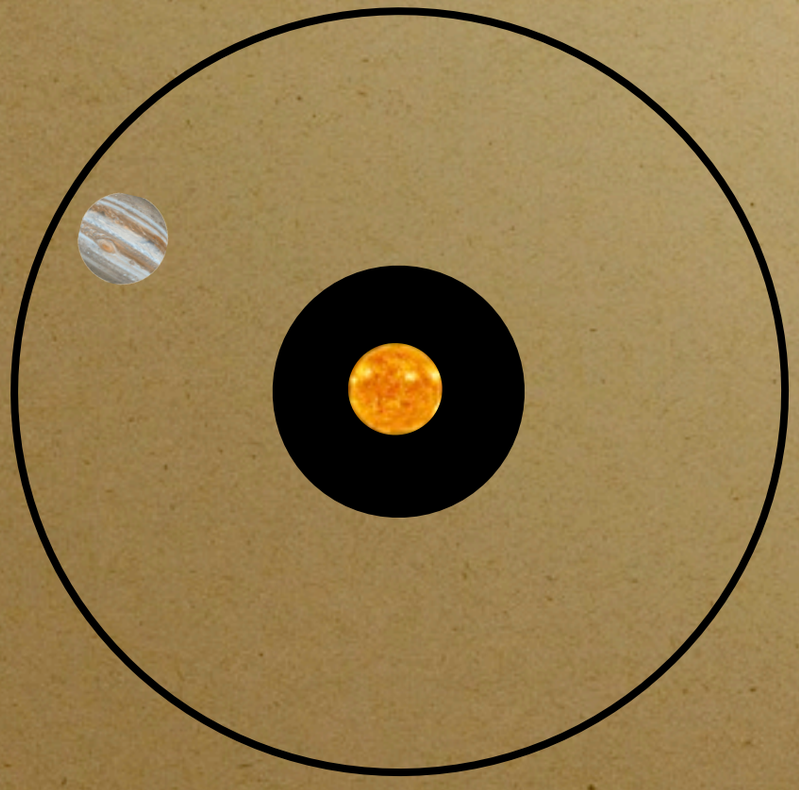

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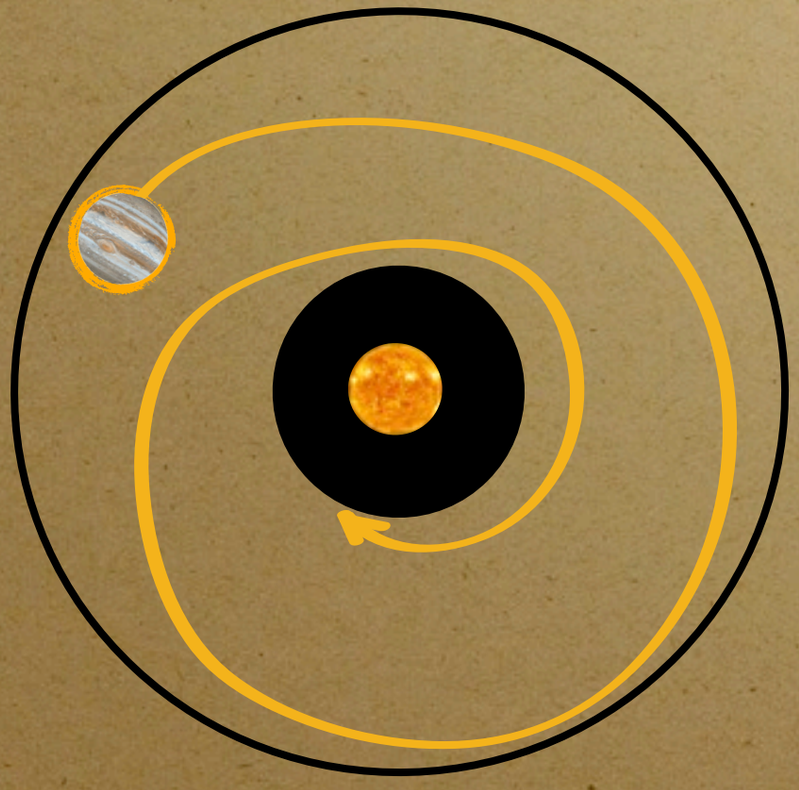

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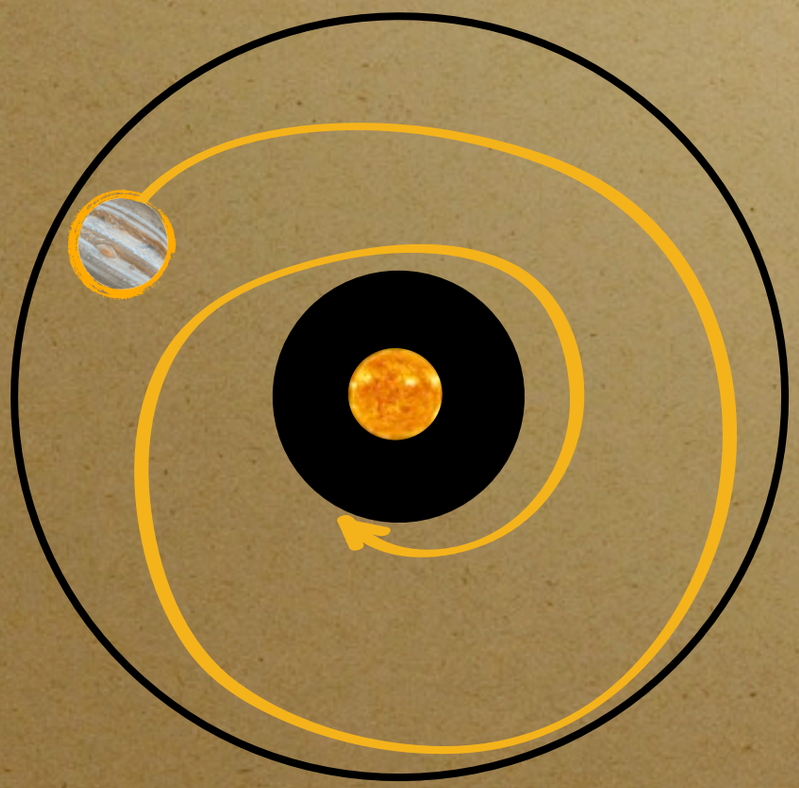

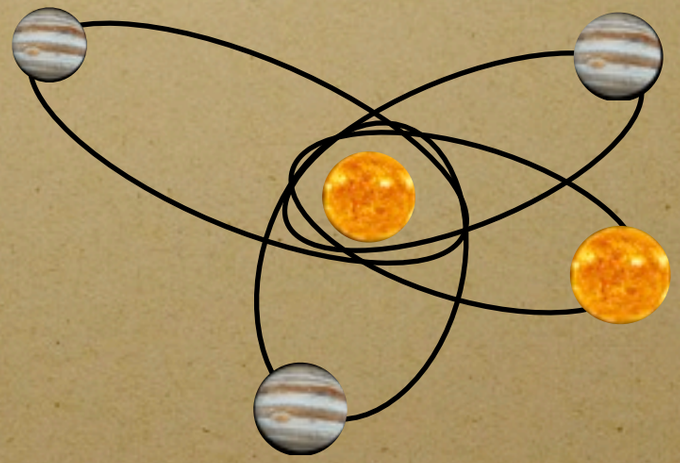

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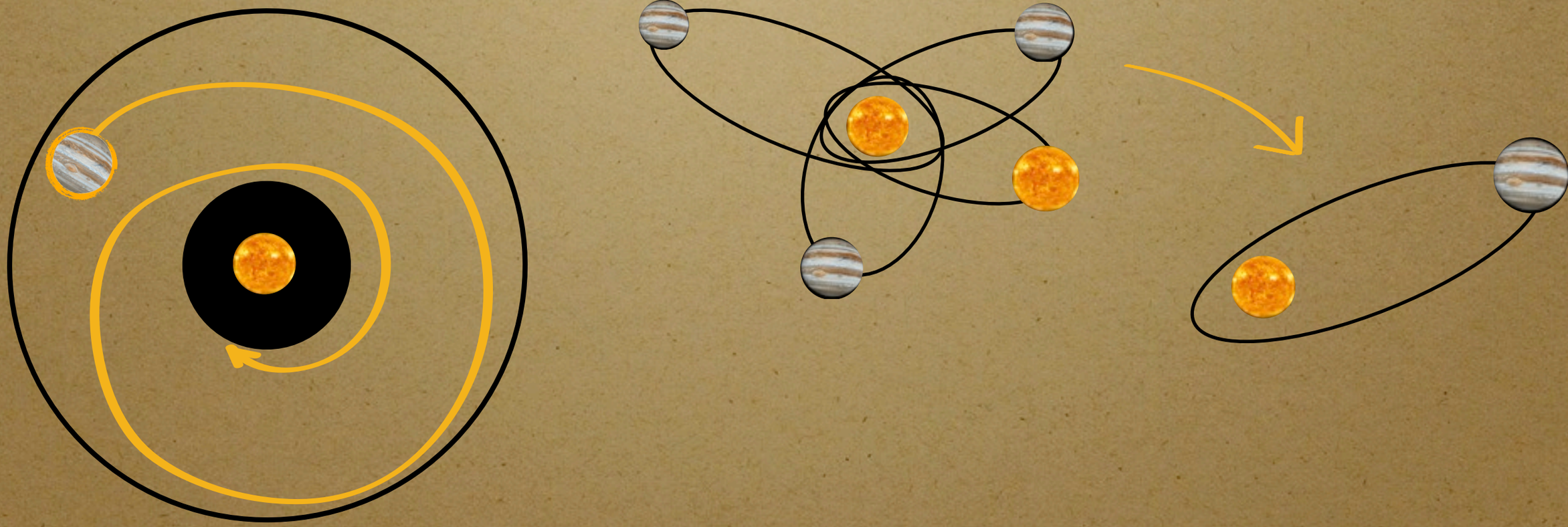

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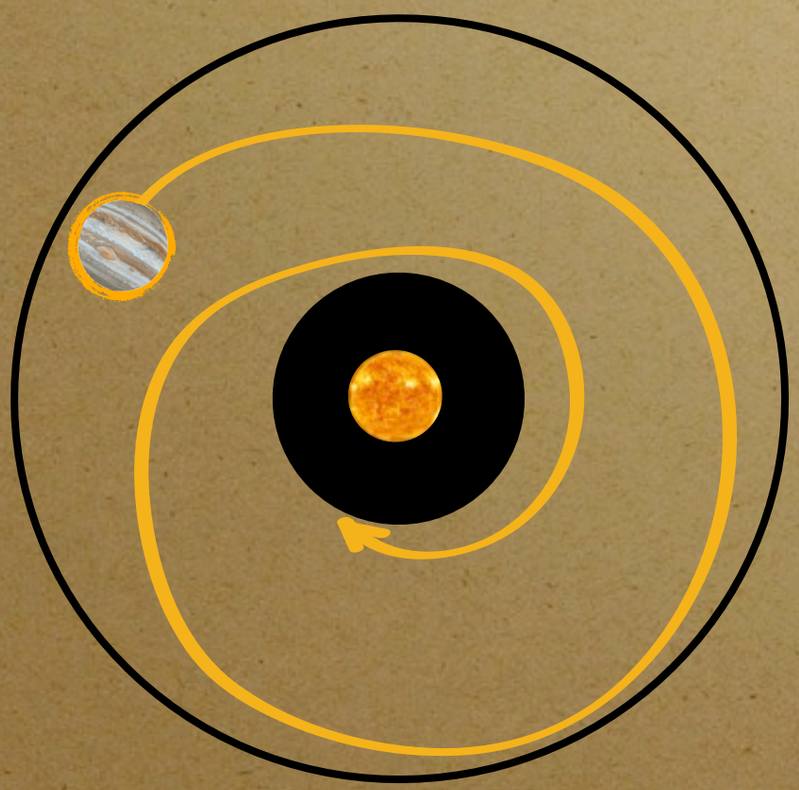

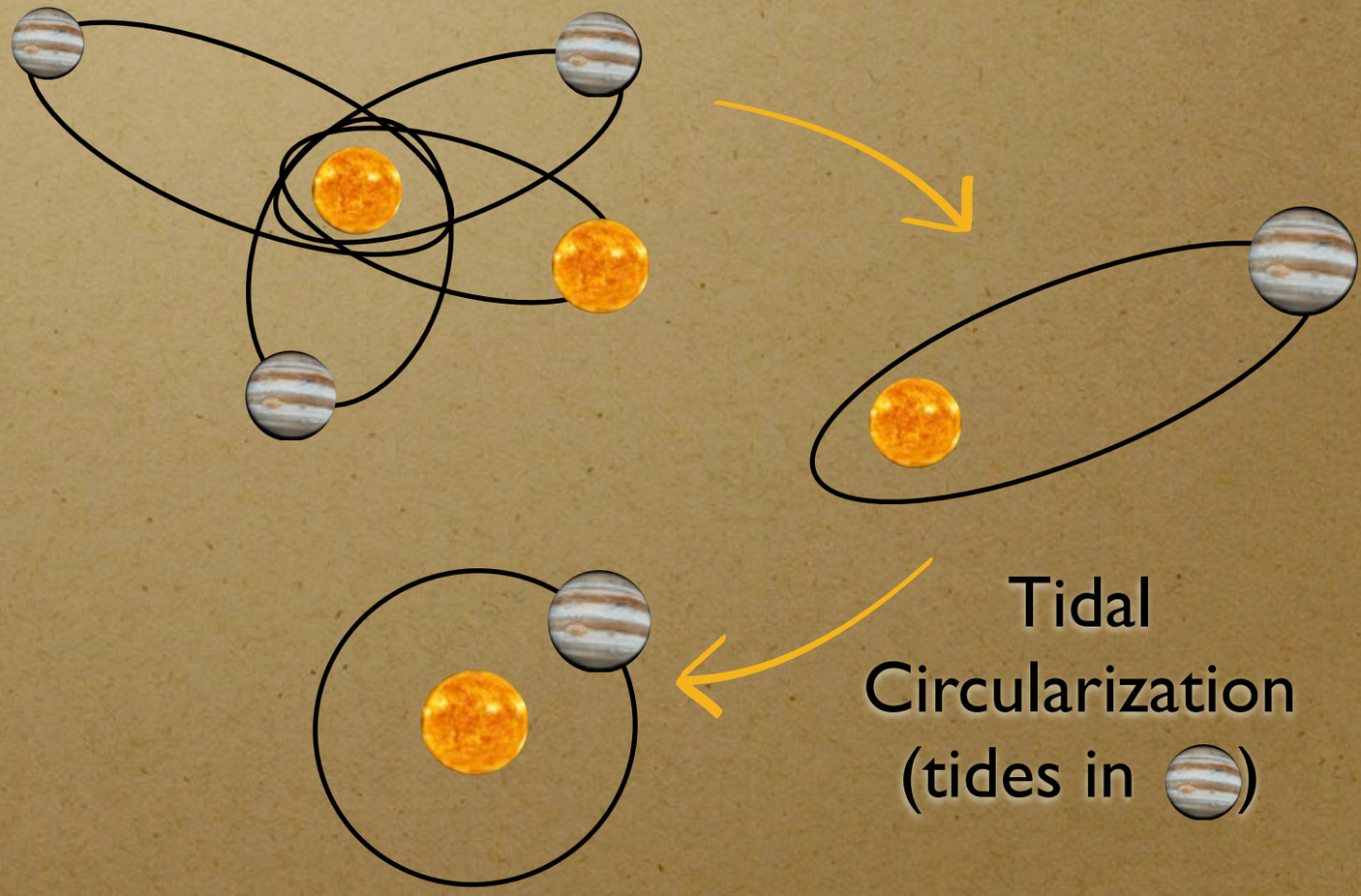

Tidal Circularization (tides in)

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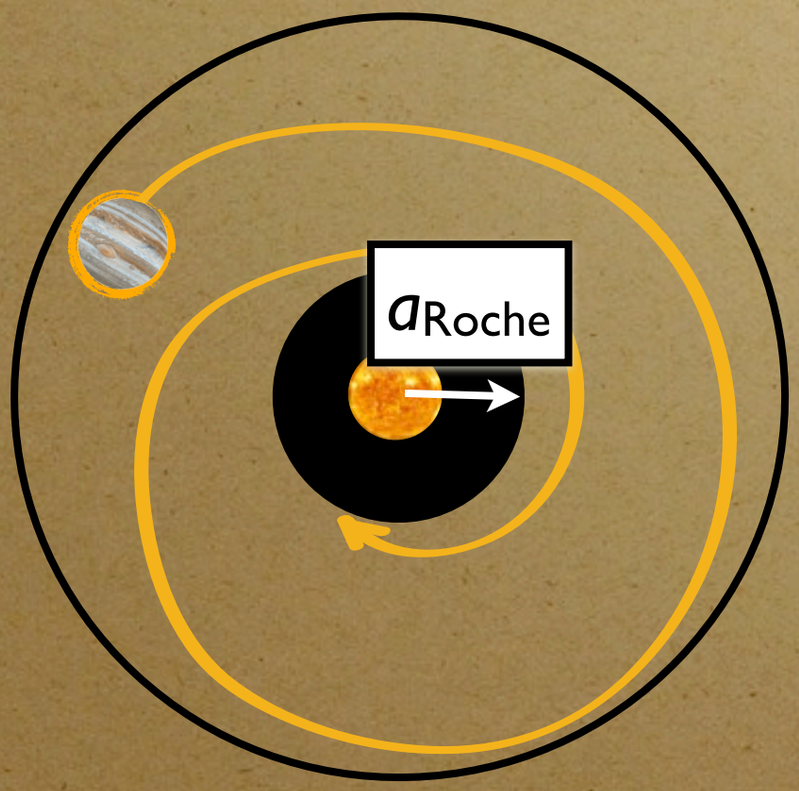

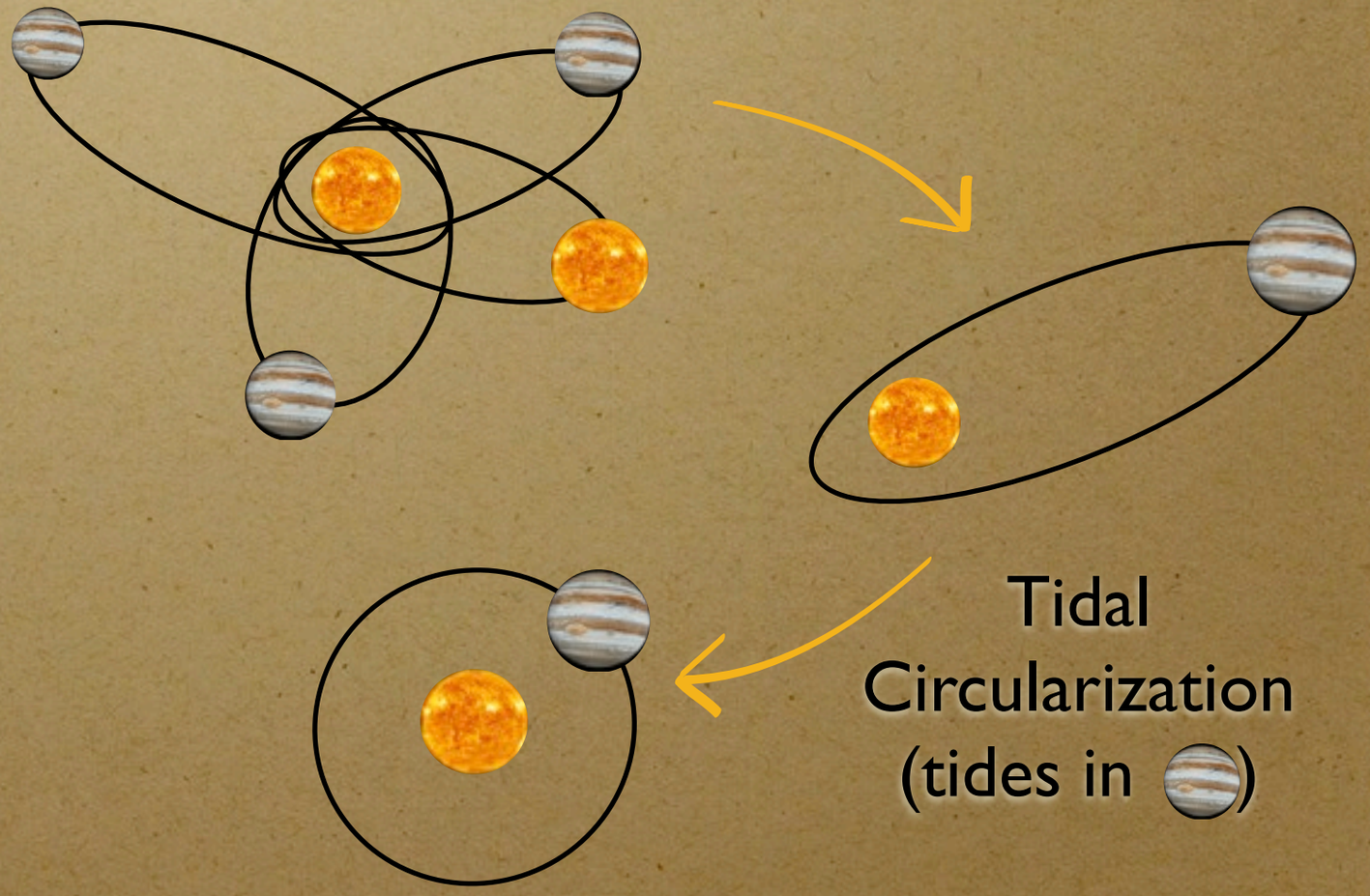

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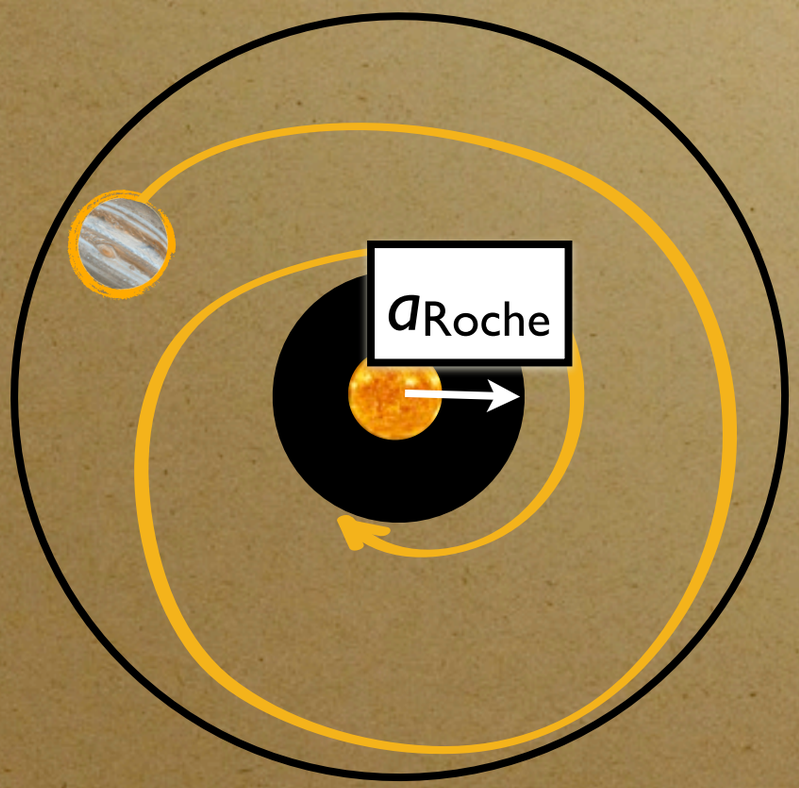

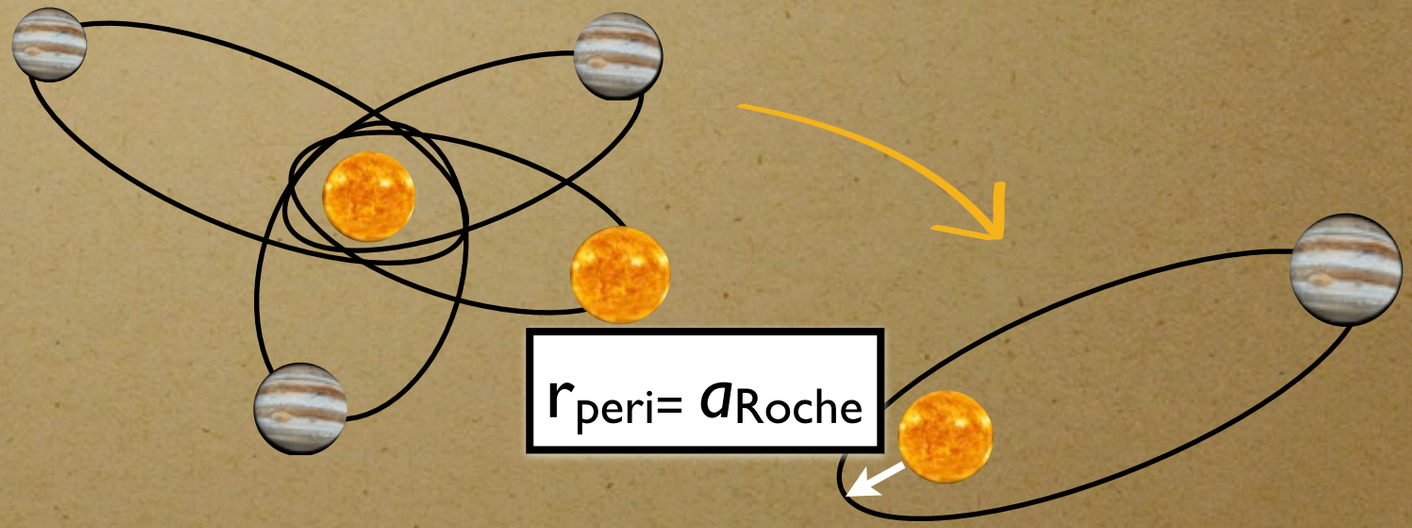

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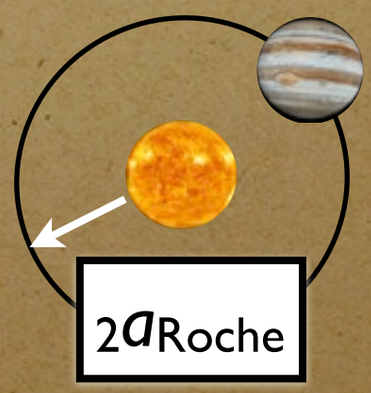

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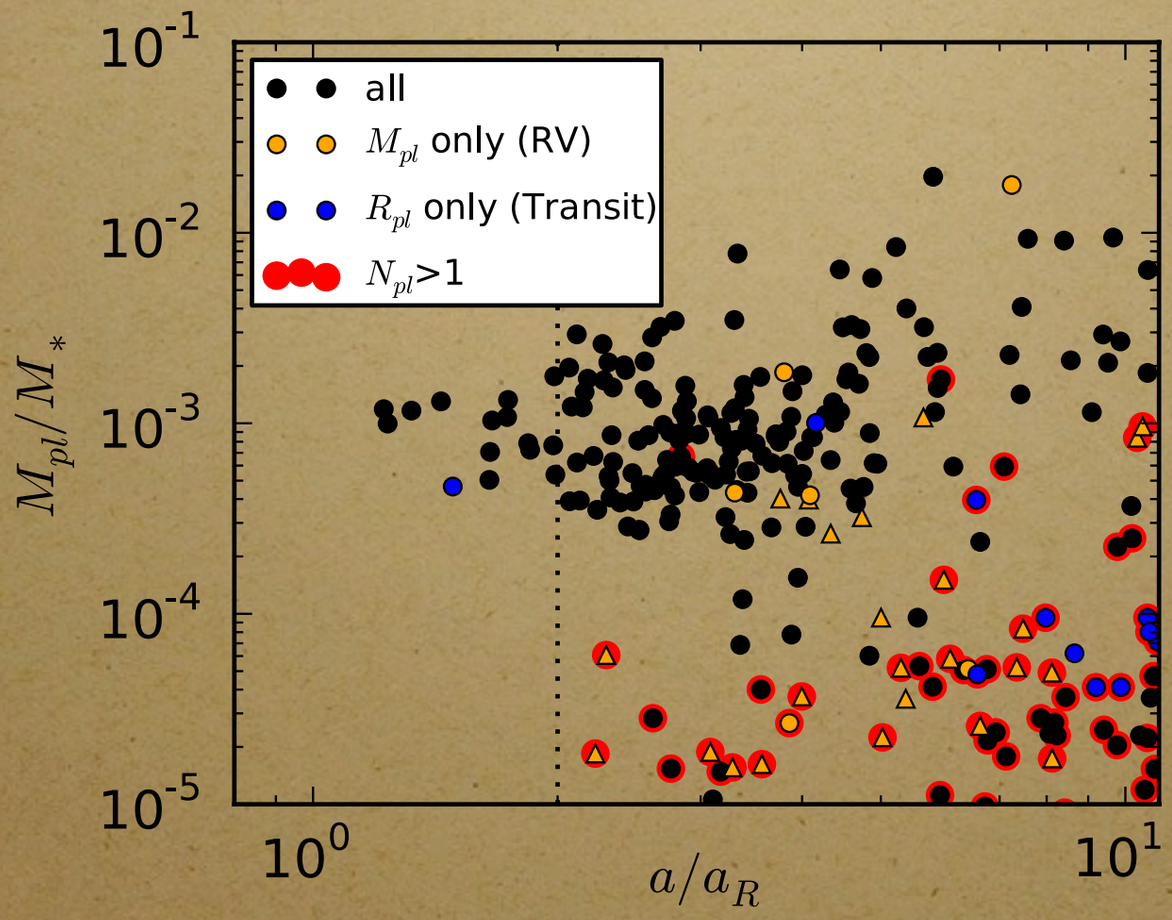

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$a_R \sim R_{PL} (M_{PL}/M_*)^{-1/3}$
(Paczynski's '71)

NASA Exoplanet Archive,20 February 2014

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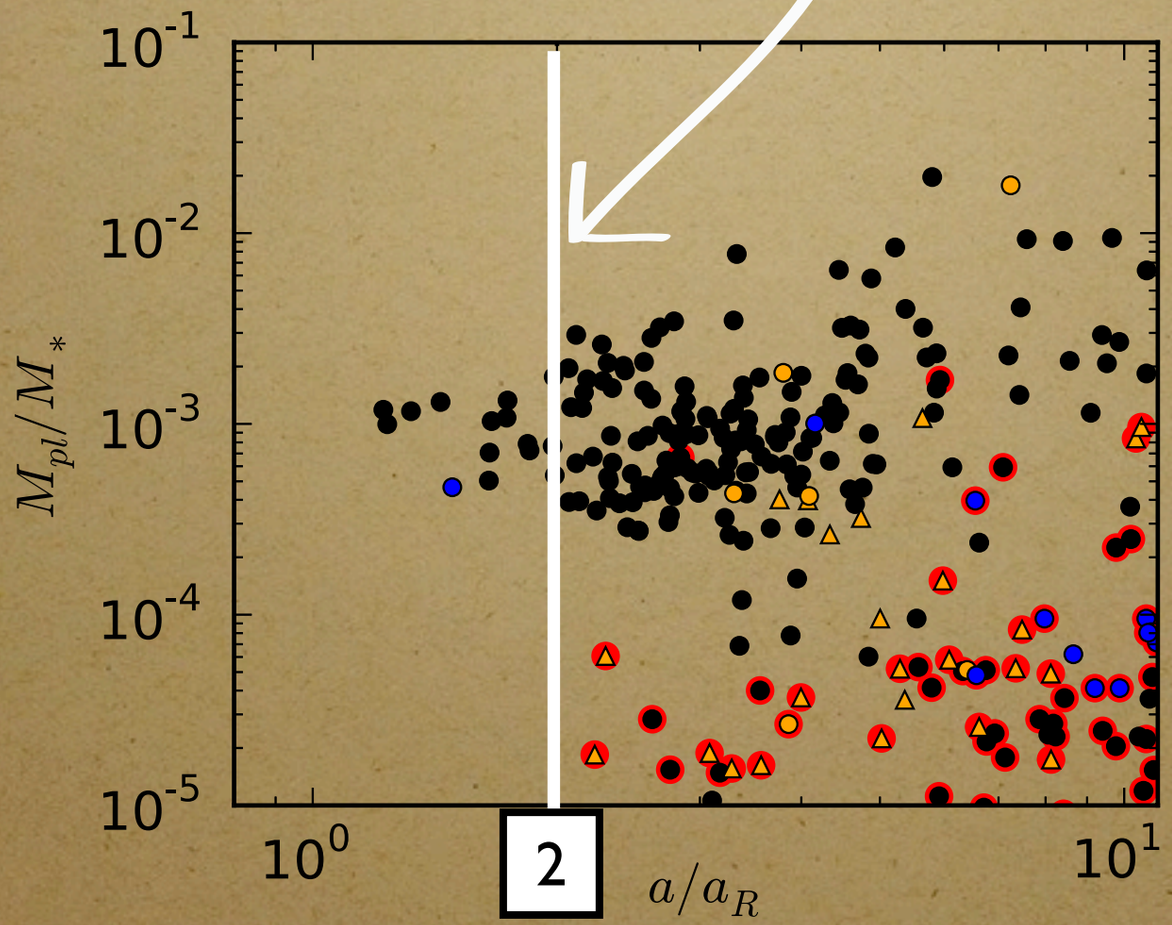

Valsecchi & Rasio '14b

Ford & Rasio06

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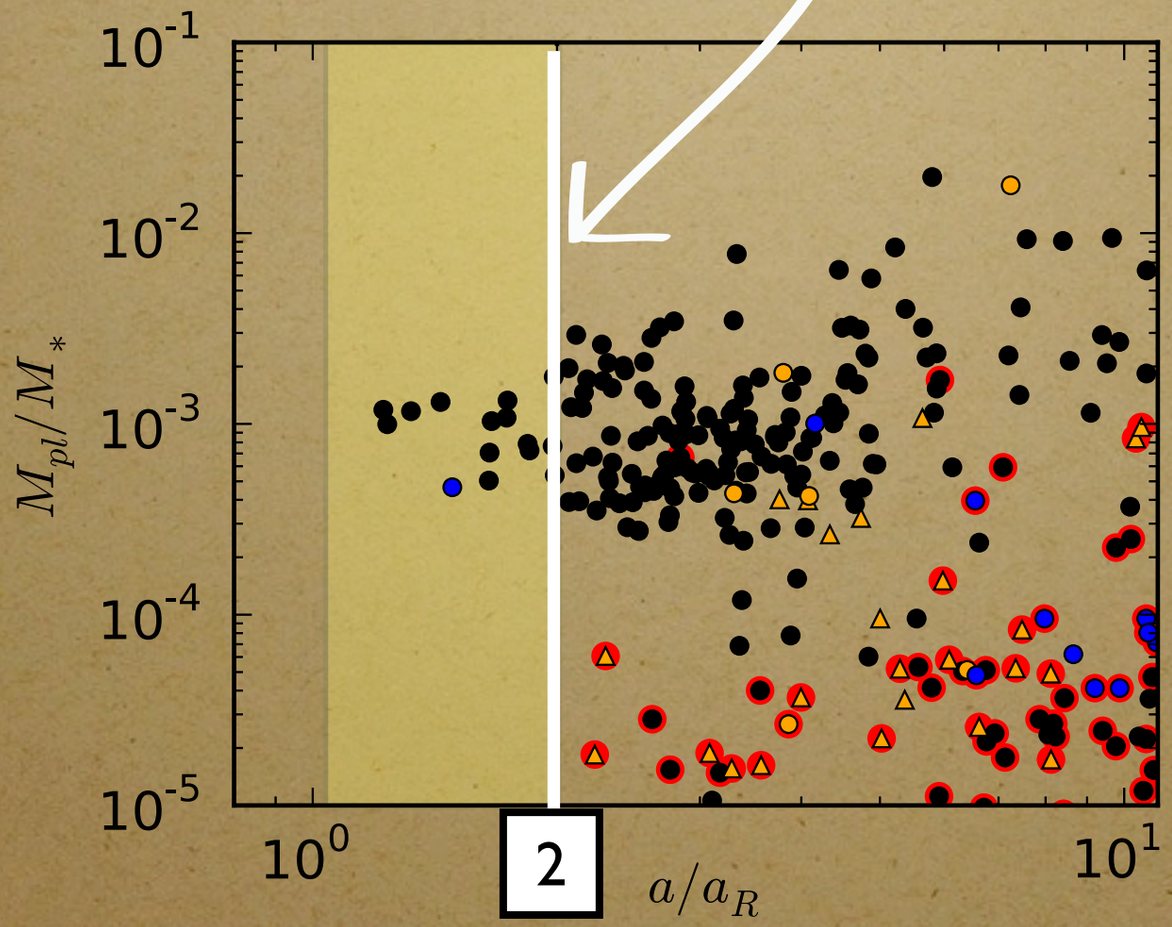

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Ford & Rasio06

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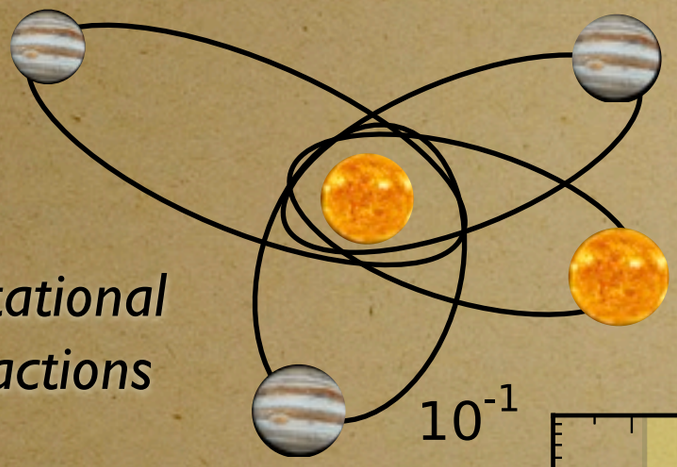
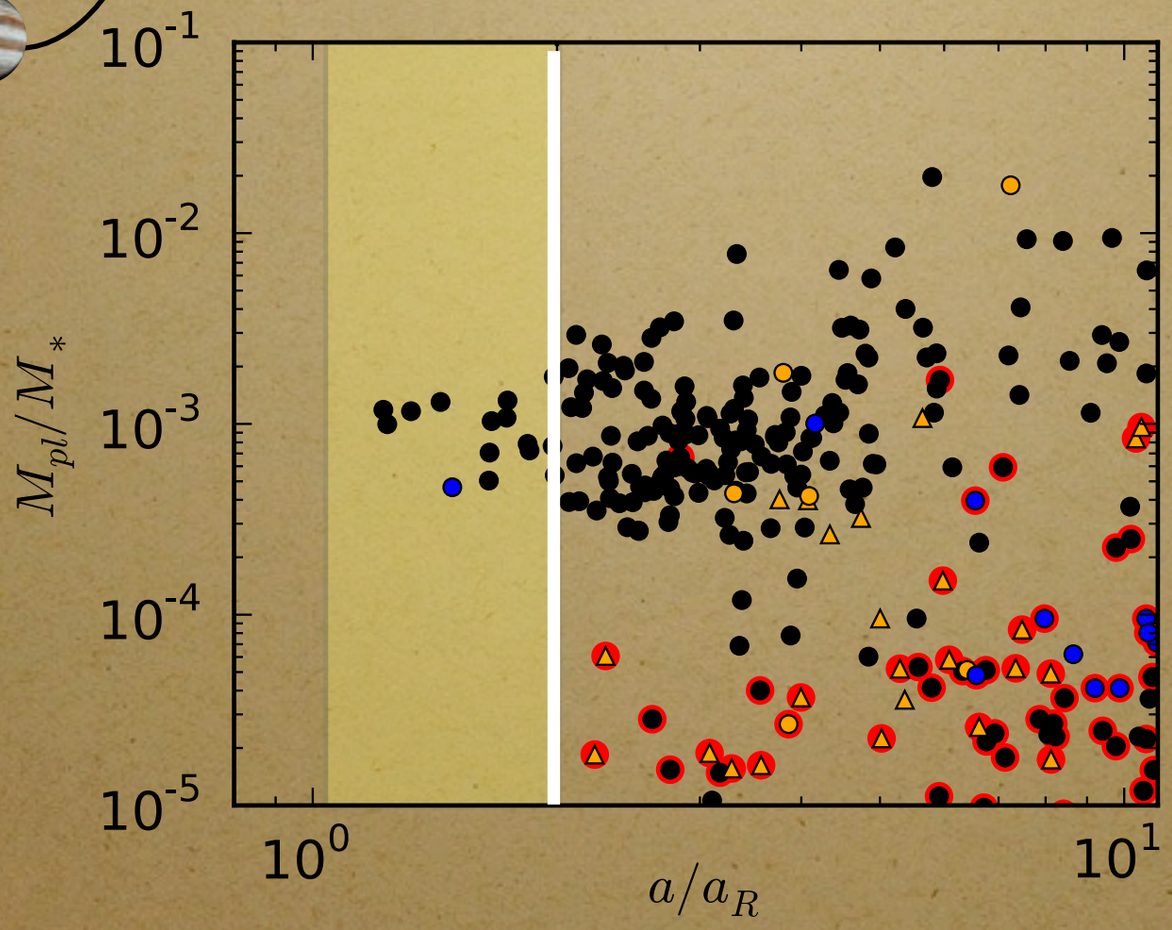
High-e Migration



Gravitational Interactions



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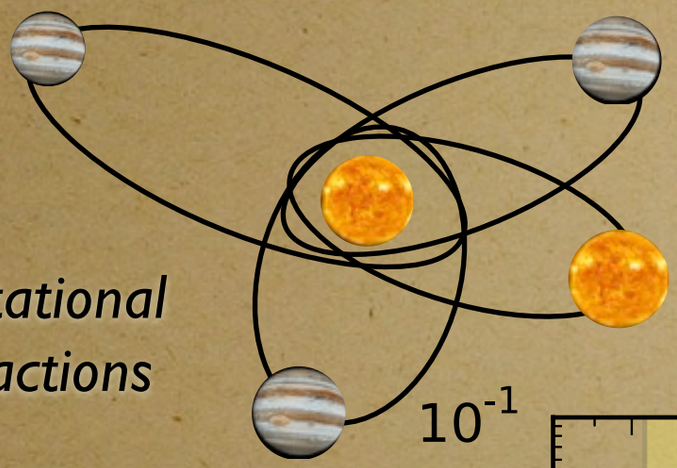

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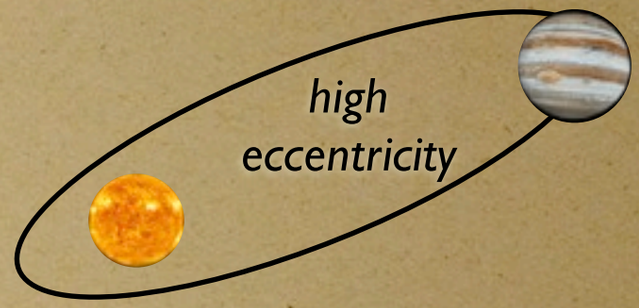

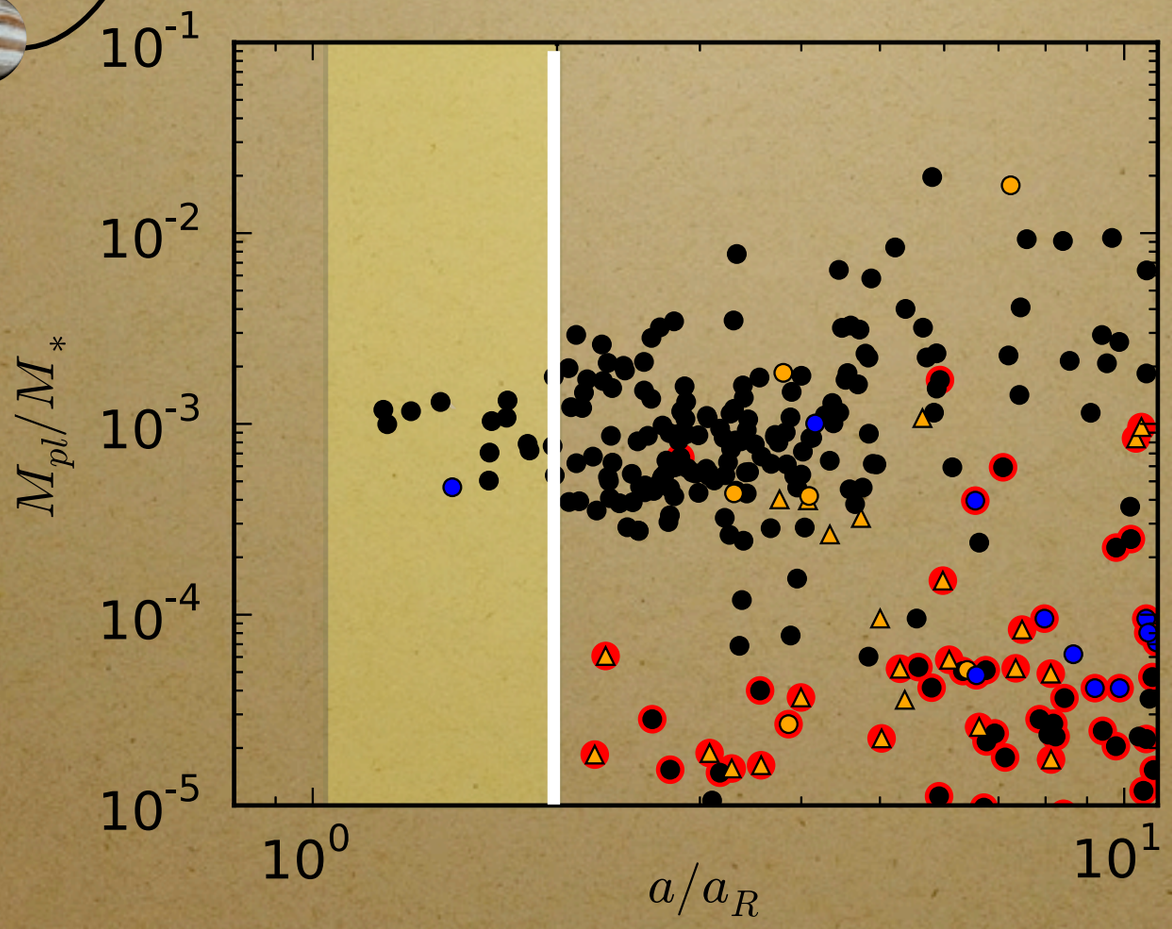

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High-e Migration

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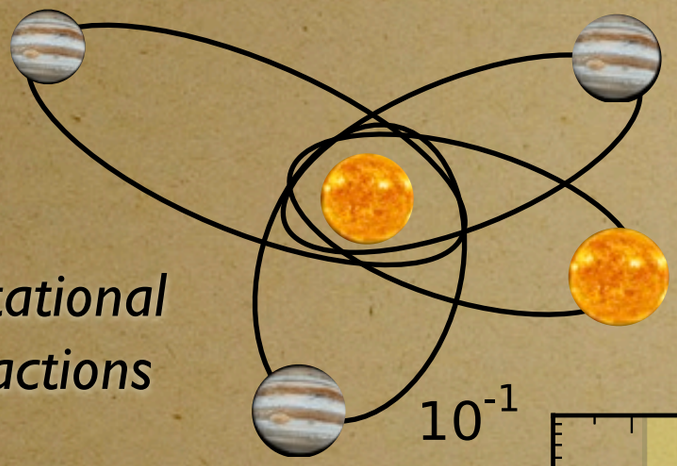

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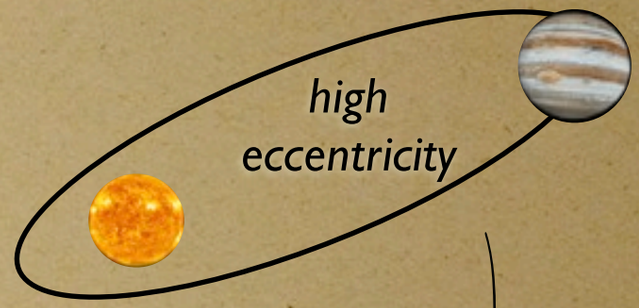
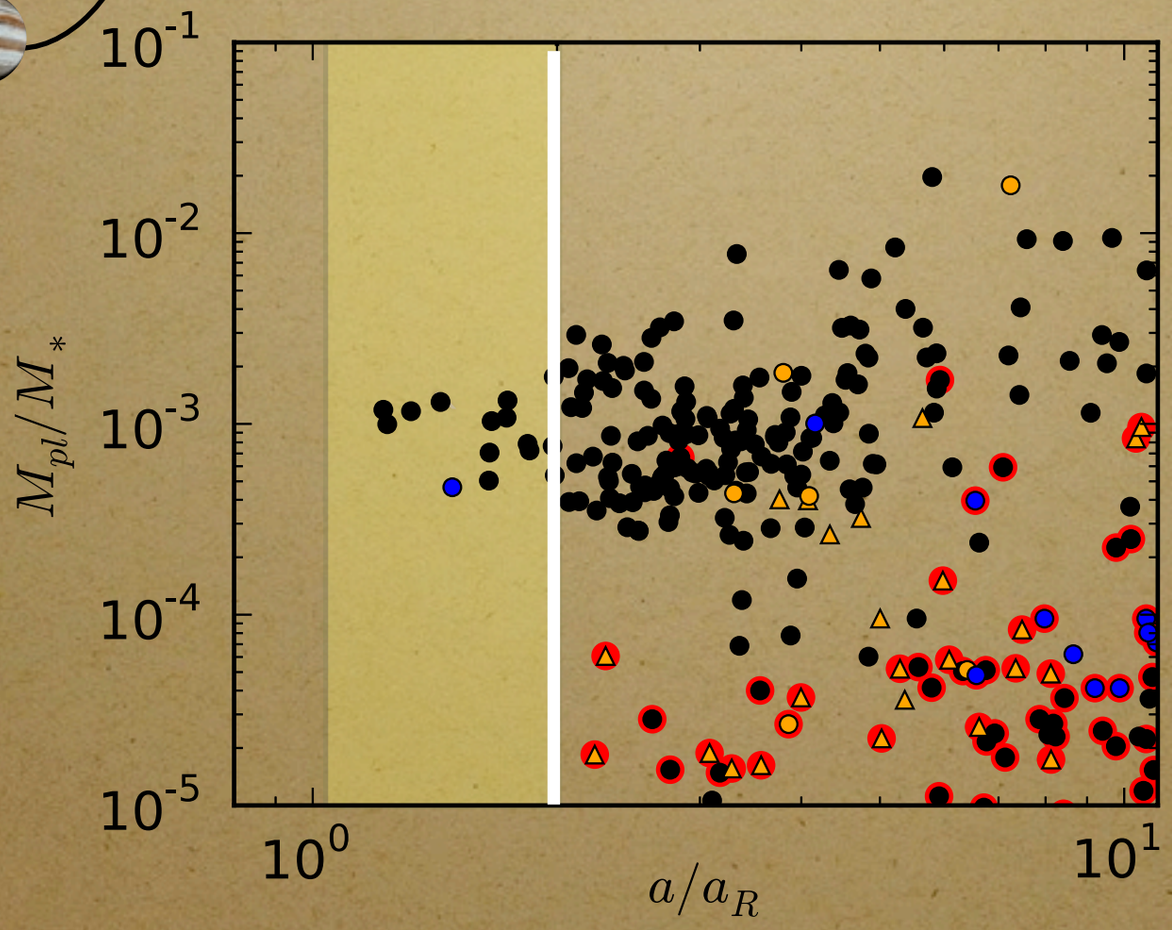
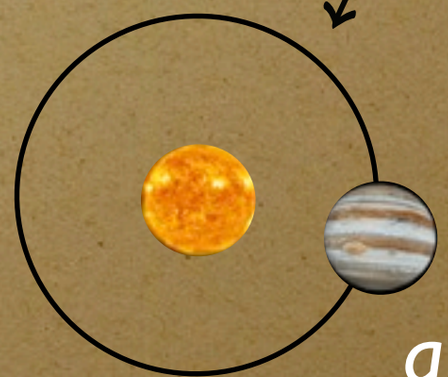




Tidal Circularization (tides in)

$a\downarrow$ $e\downarrow$



e = 0

$a/a_R \gtrsim 2$

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High-e Migration

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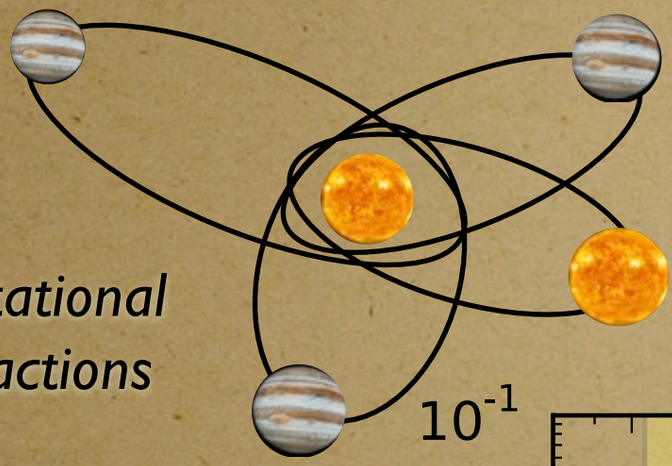

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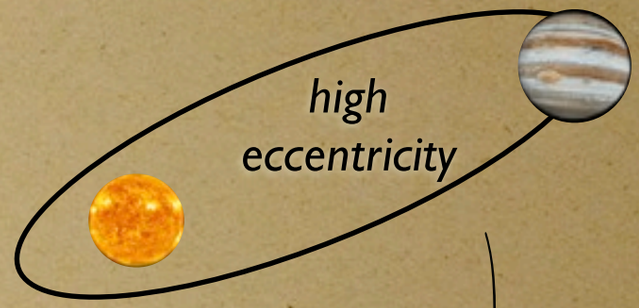
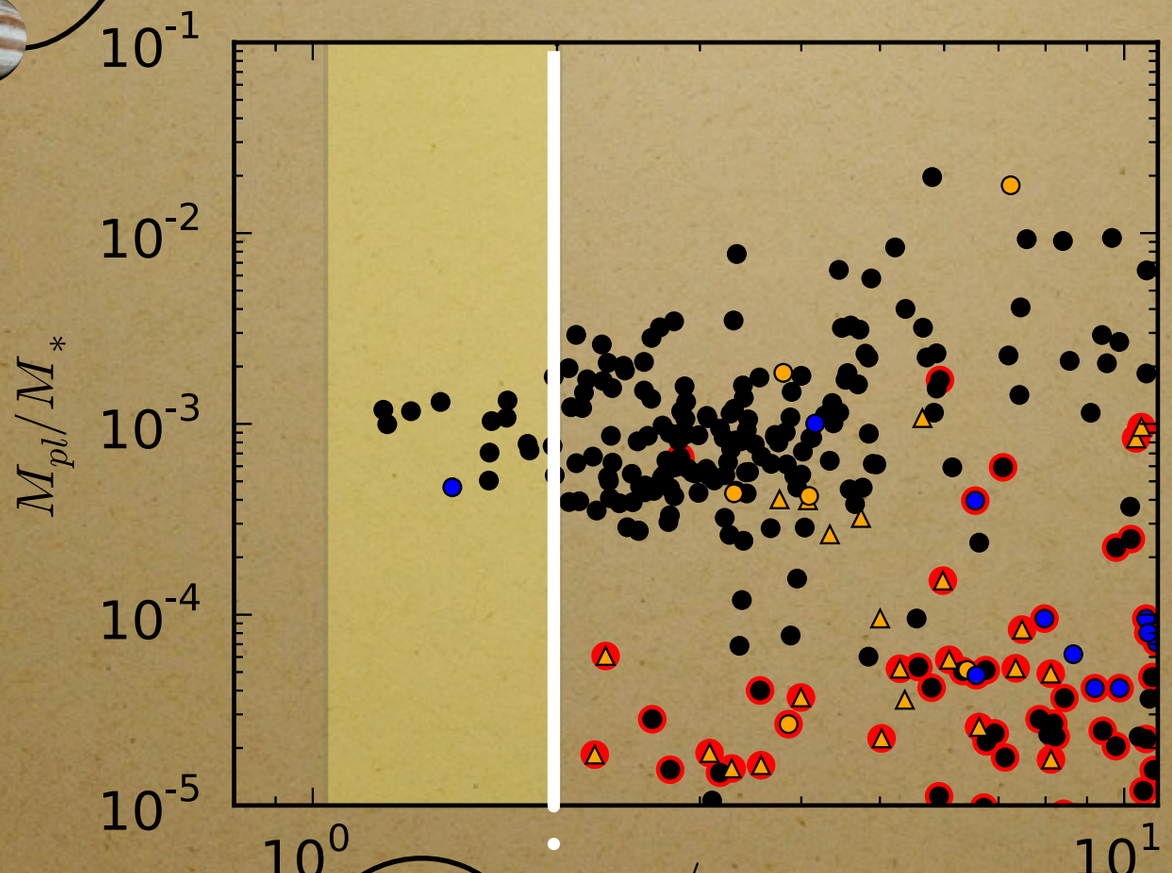
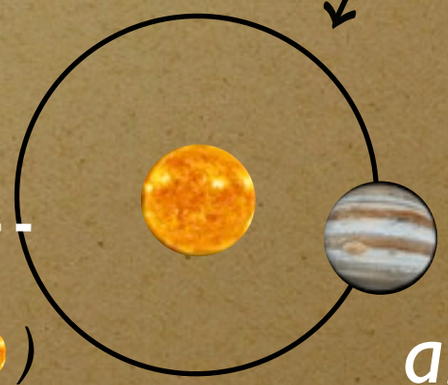




Tidal Circularization
(tides in)
a↓ *e*↓



e = 0
$a/a_R \gtrsim 2$

Tidal Decay
(tides in slowly spinning)
a↓

$a/a_R < 2$

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Disk migration

High-eccentricity migration:

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Our Orbital Evolution Code
- **Stellar tides** (Lai12, Zahn66,89, Goldreich & Nicholson77) - Stellar evolution (MESA, Paxton+11, 13) - Magnetic braking (Skumanich72)

The Physics

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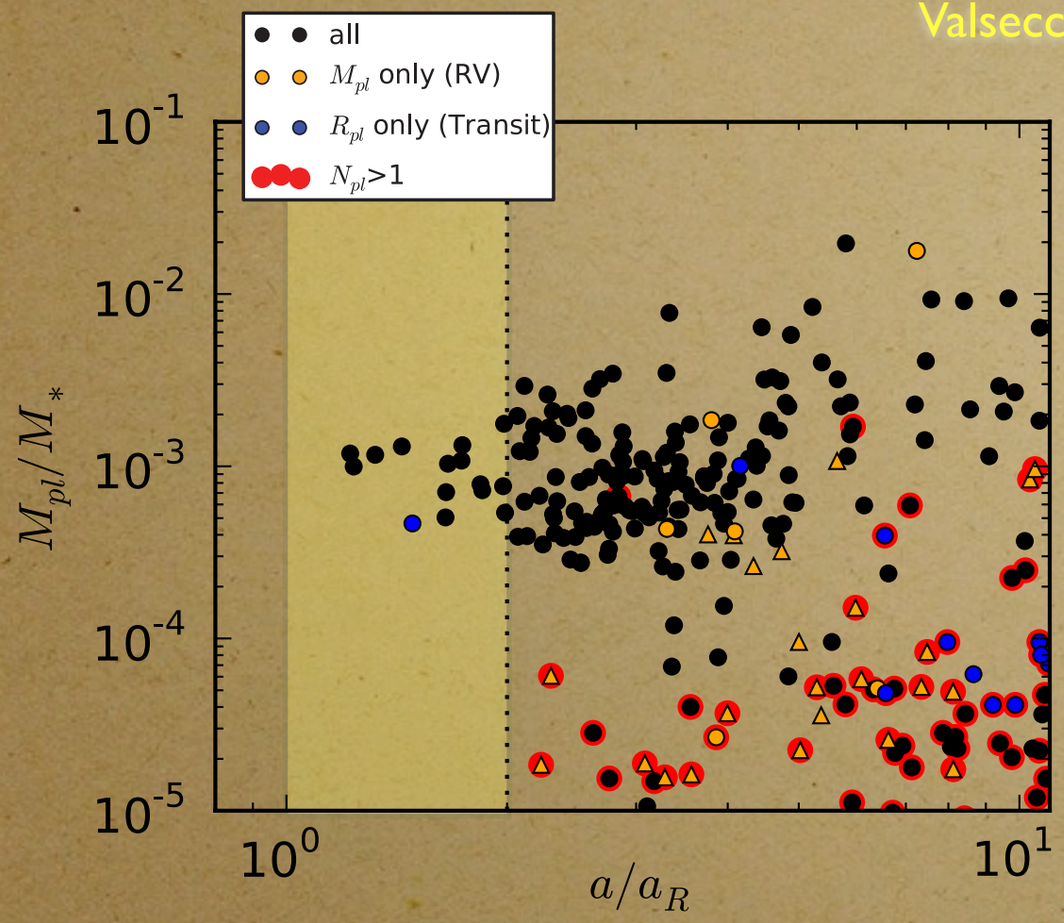

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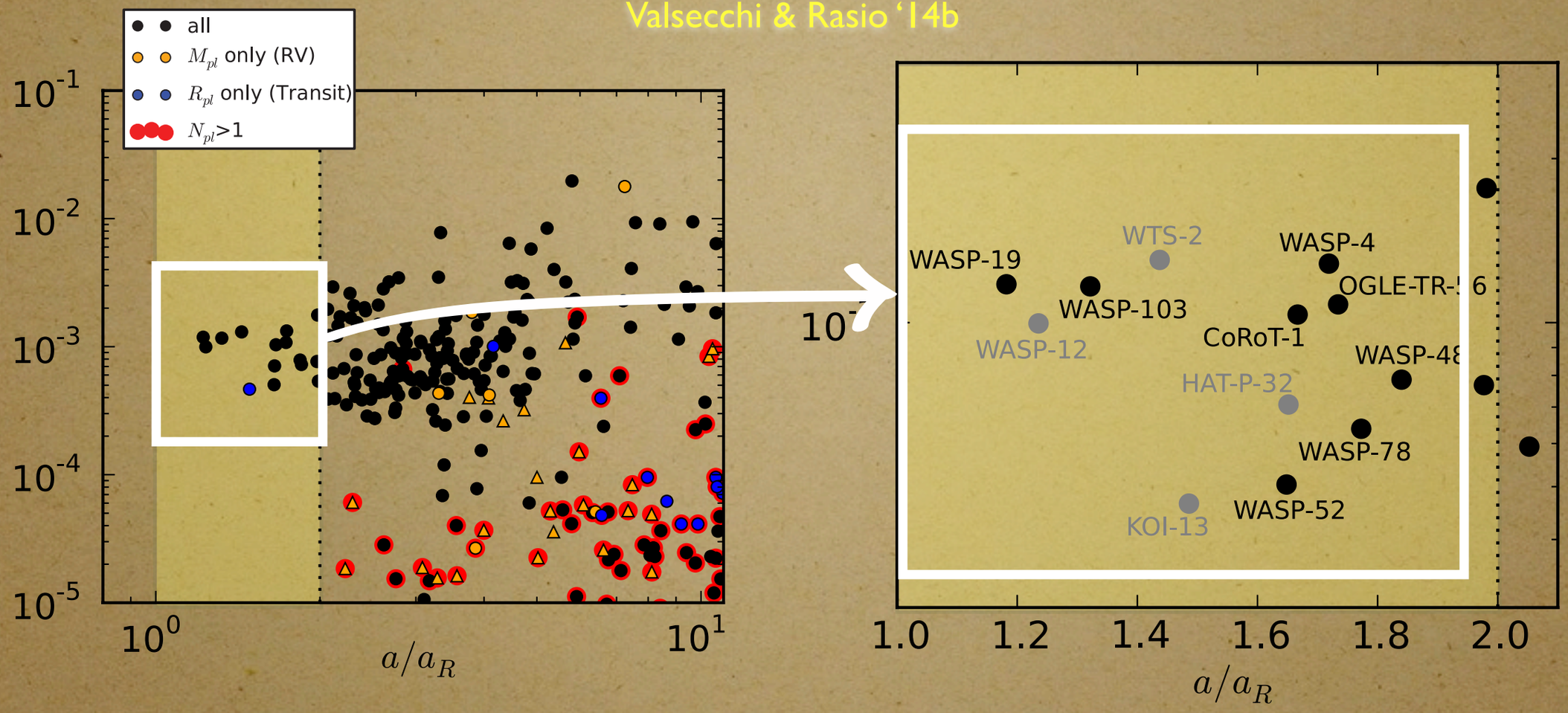

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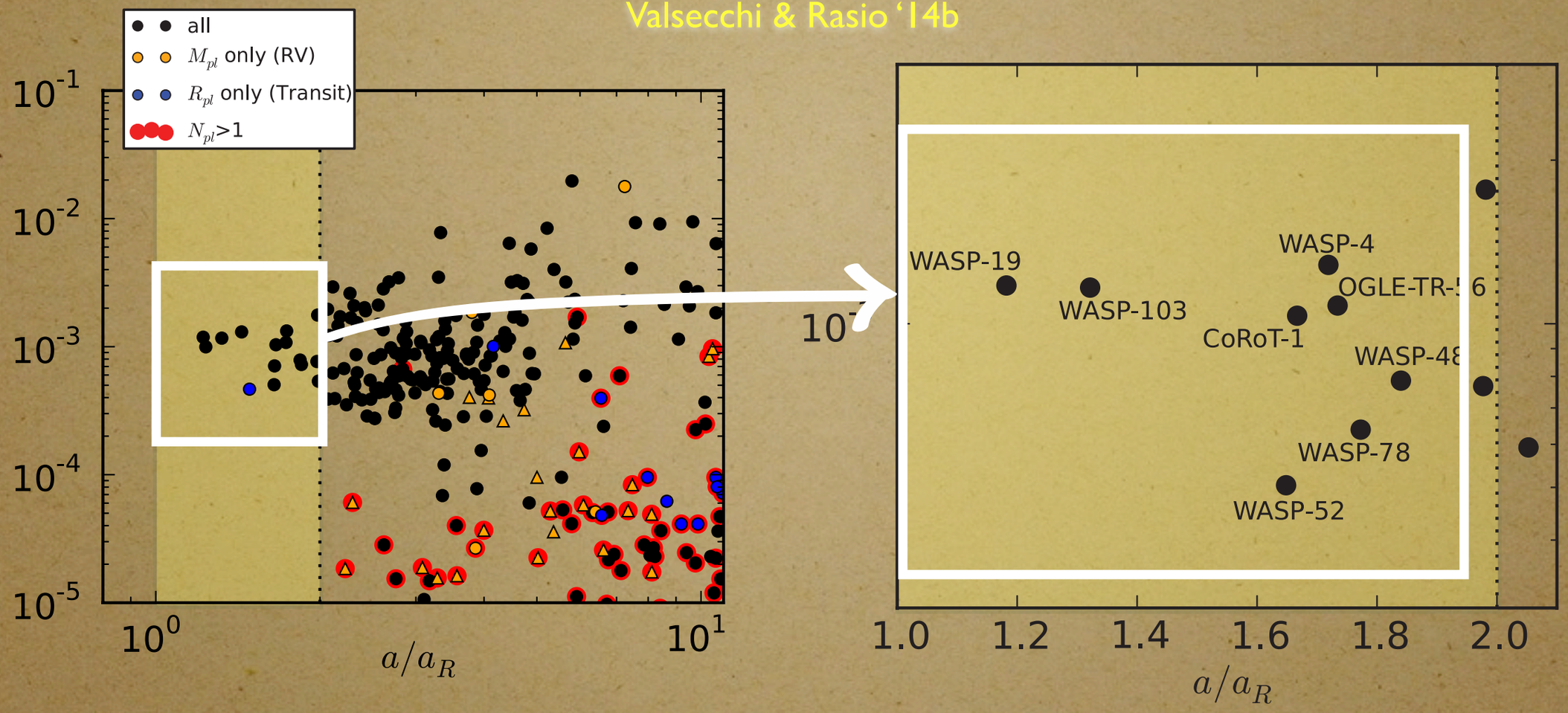

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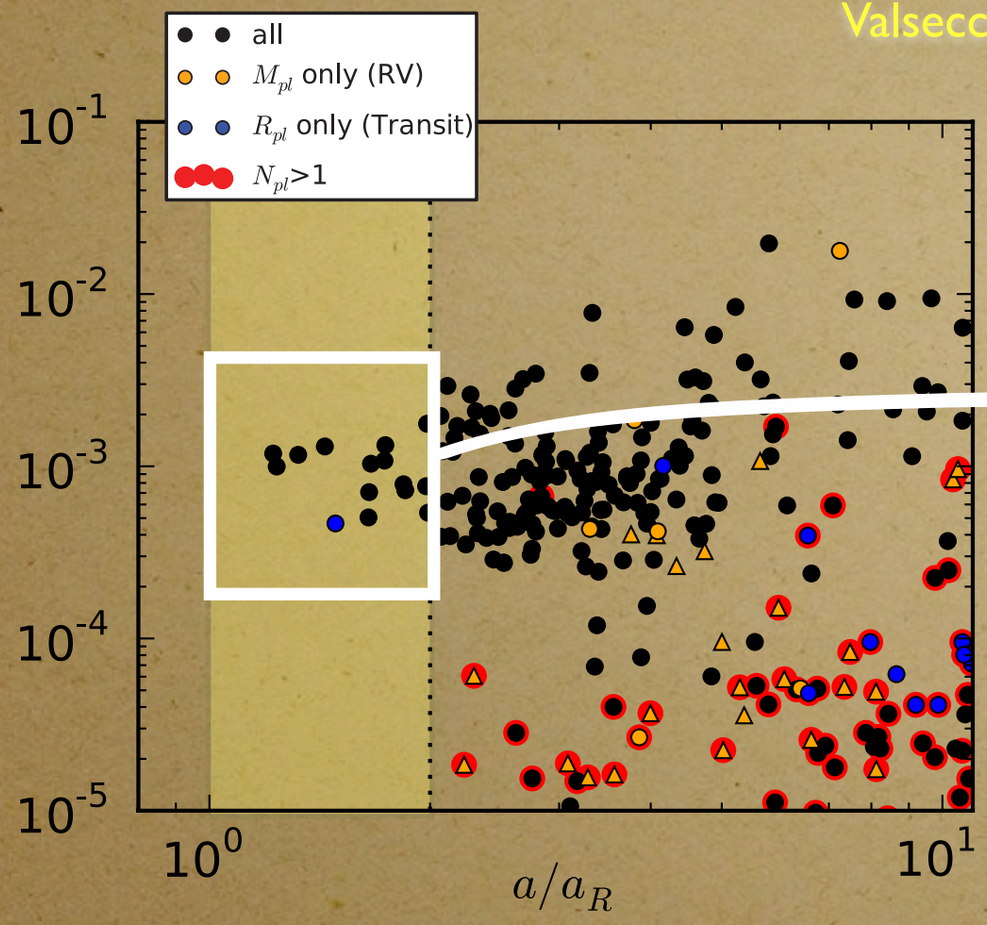

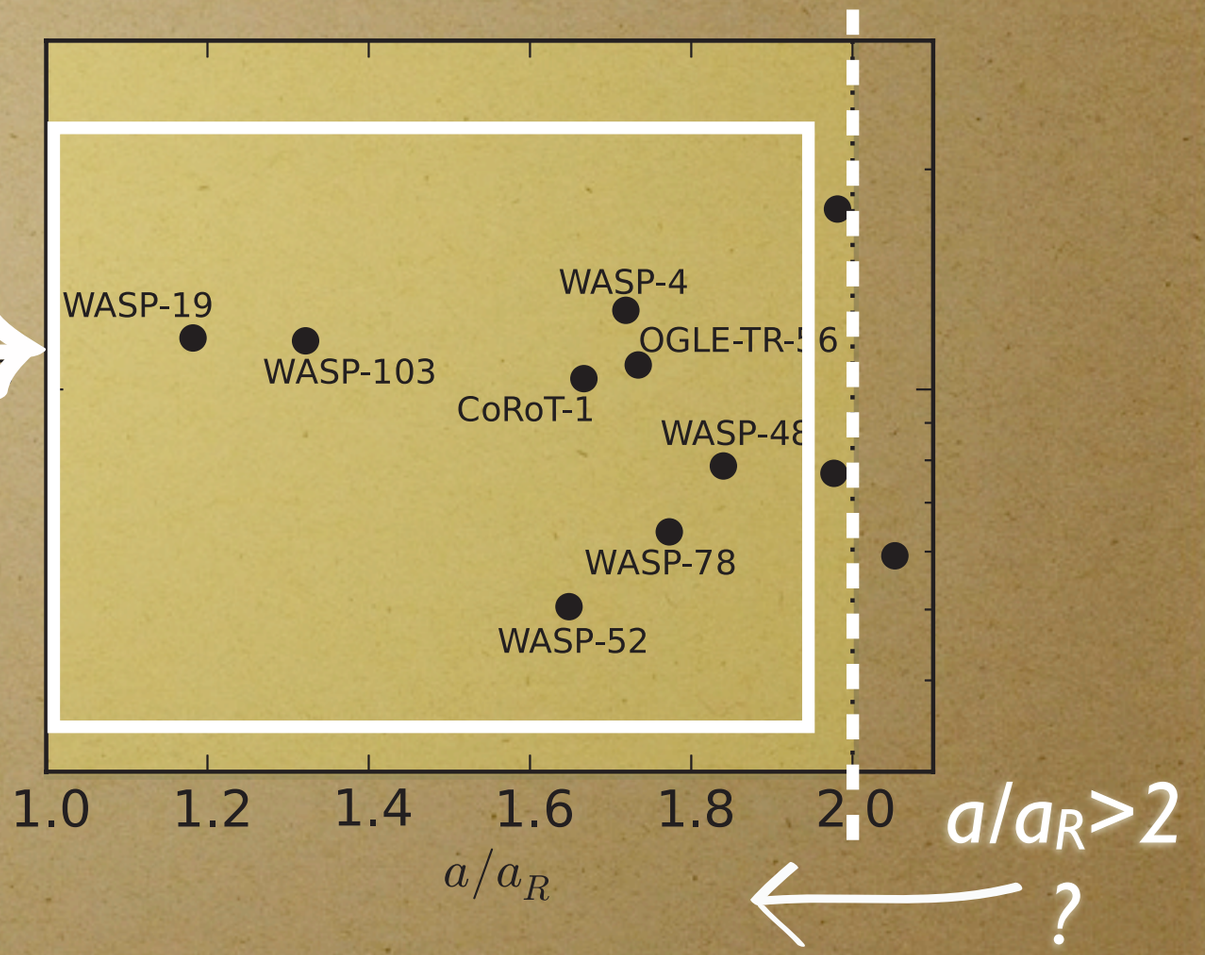

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"Achilles' Heel of Tidal Theory"

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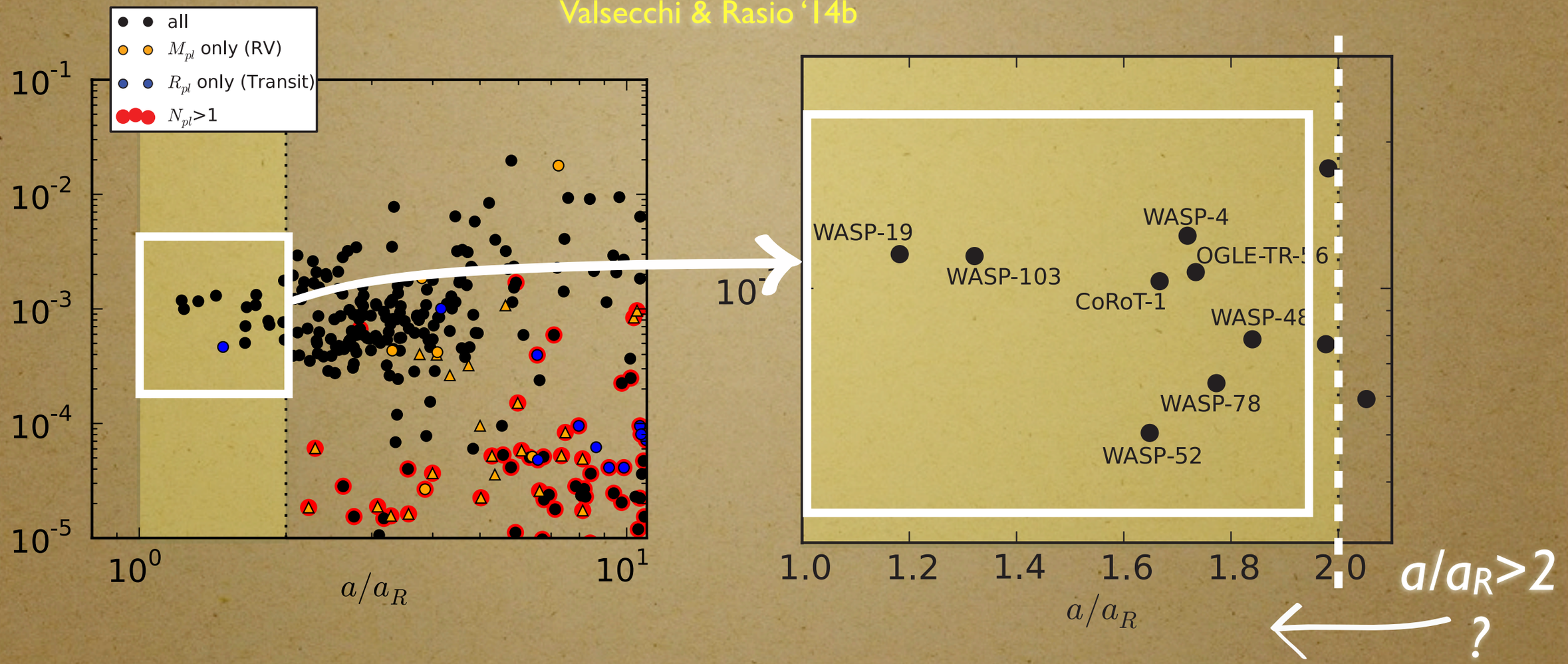

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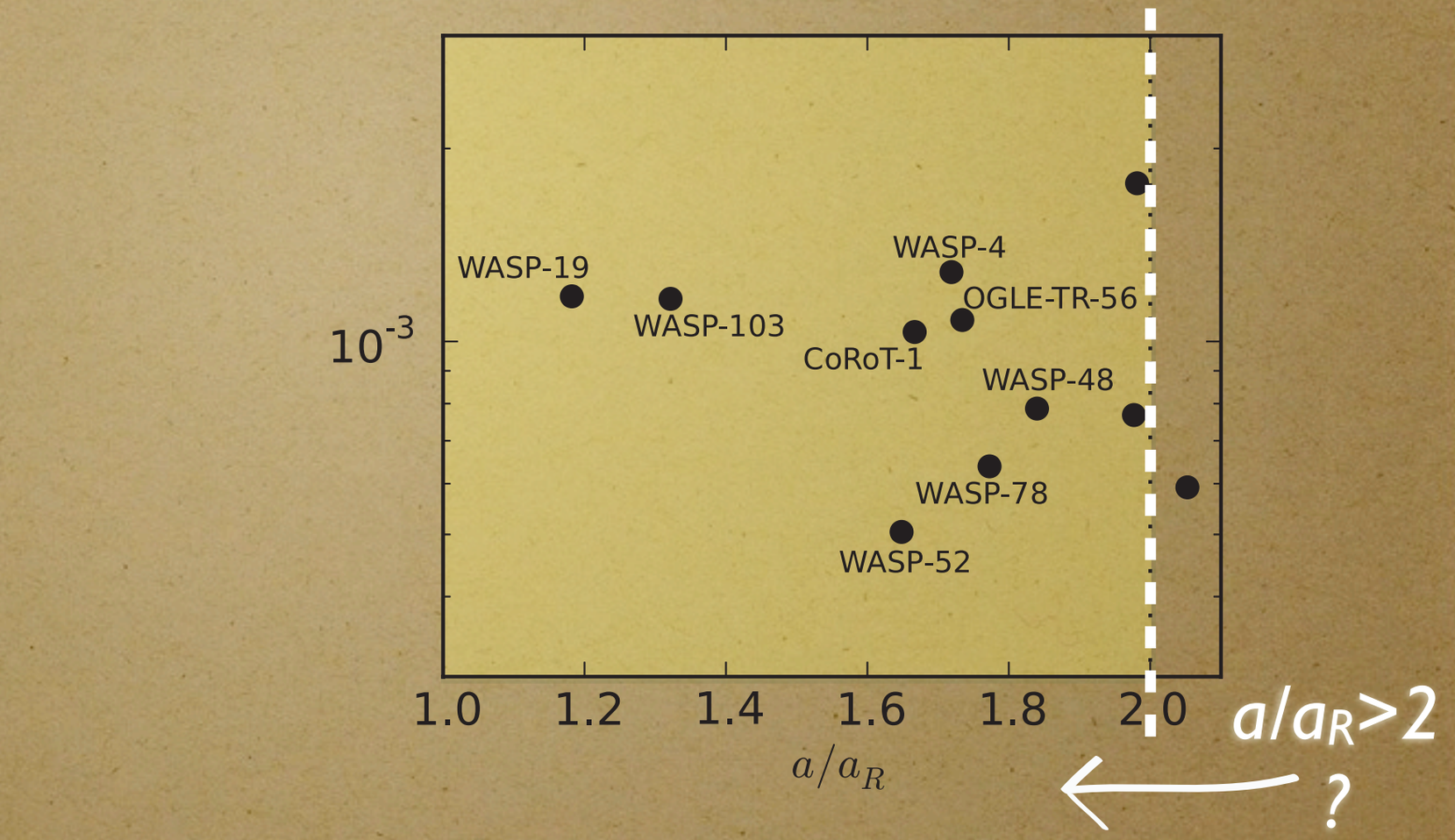

- Stellar tides $\frac{1}{\tau_{decay}} \sim min\left[1, \left(\frac{P_{tide}}{\tau_{convection}}\right)^s\right]$

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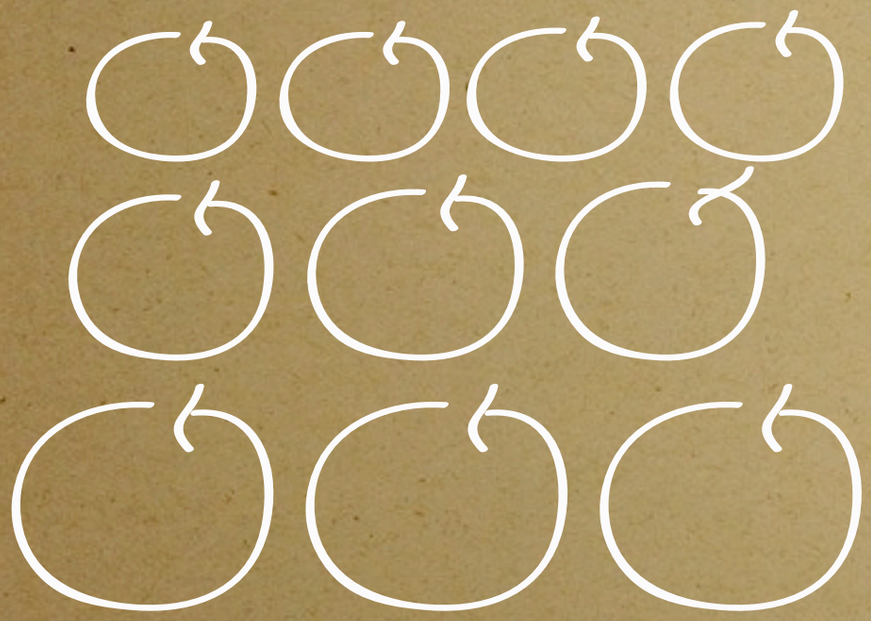

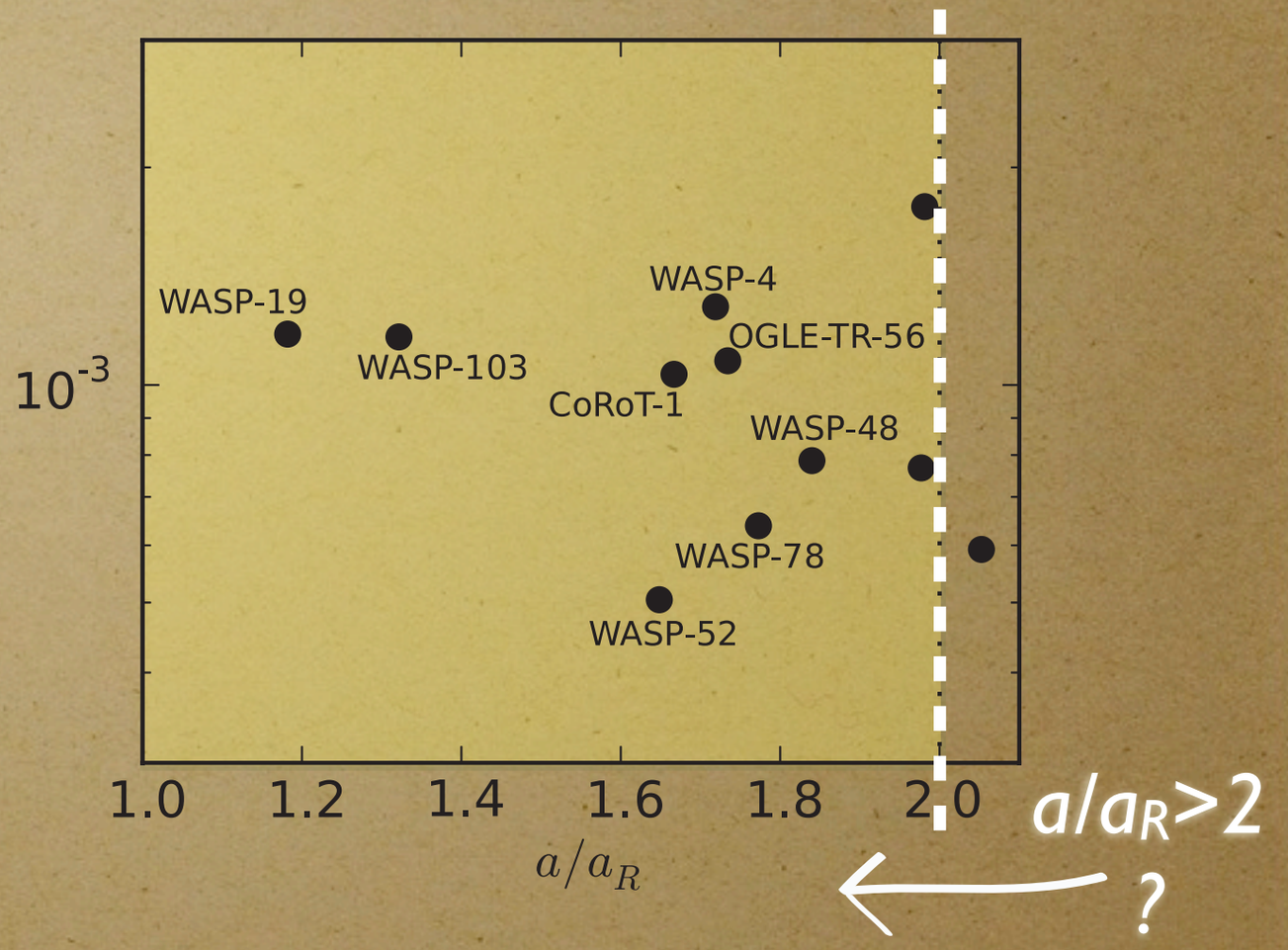

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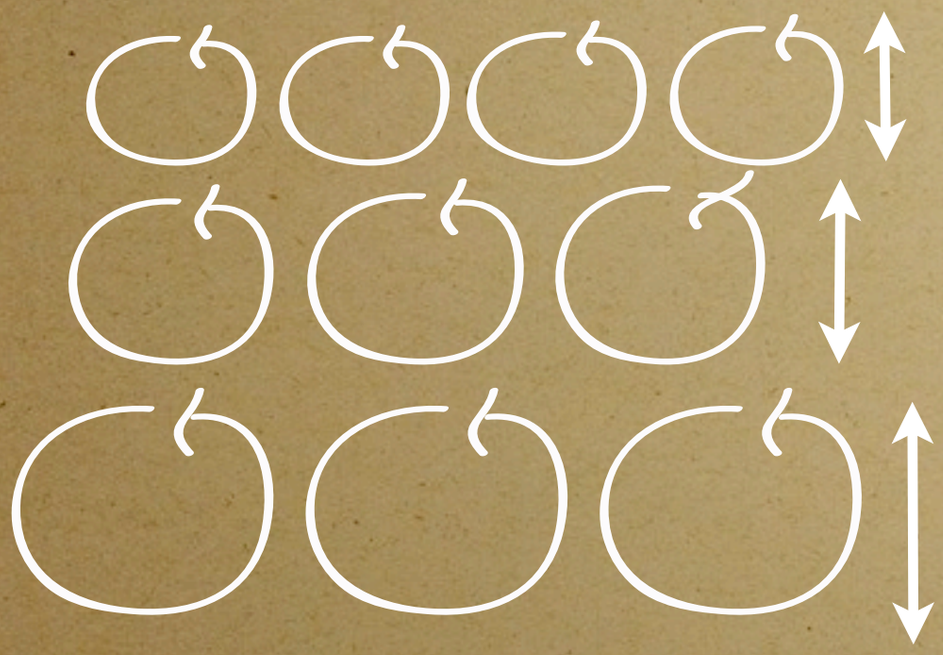

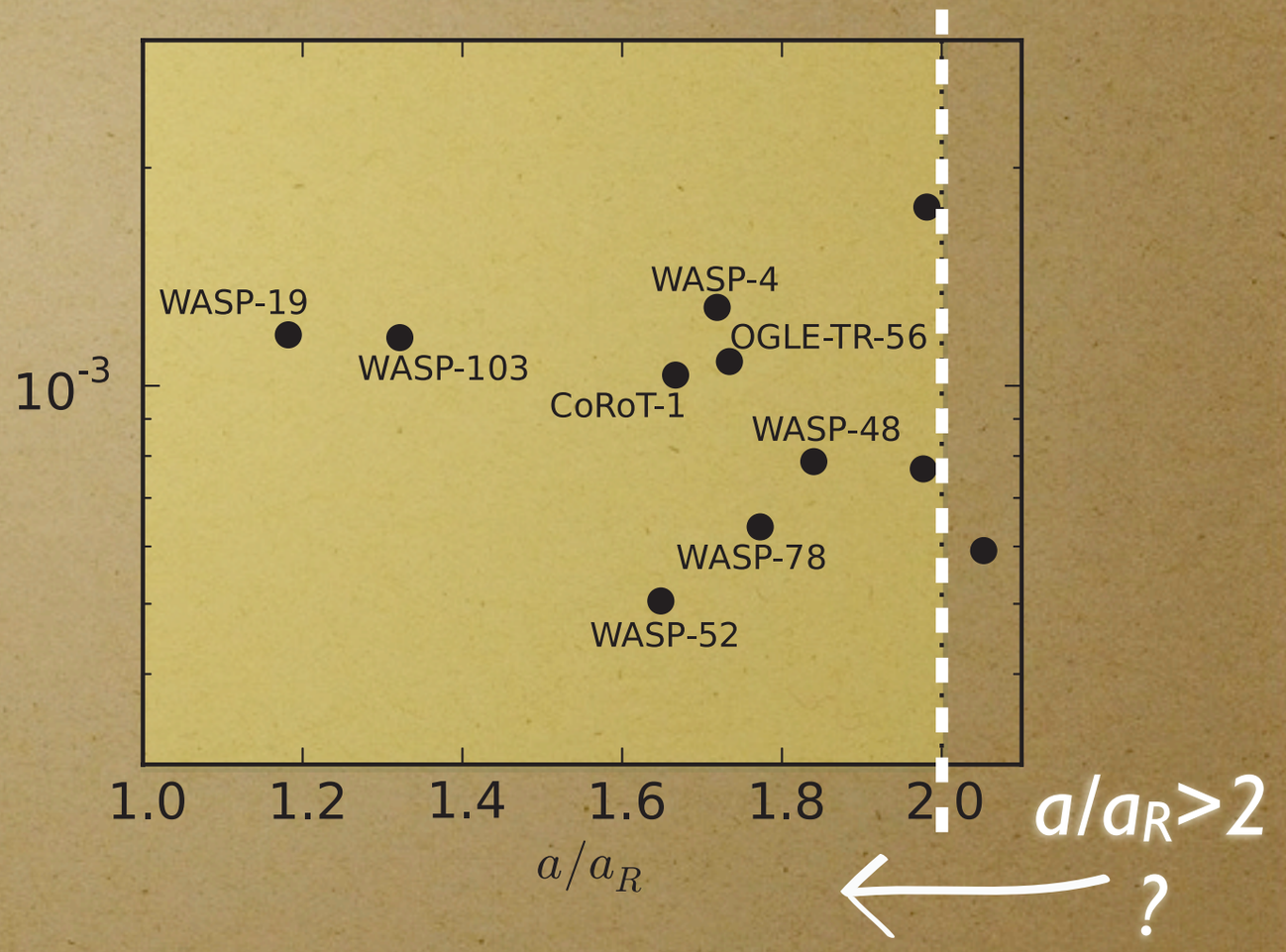

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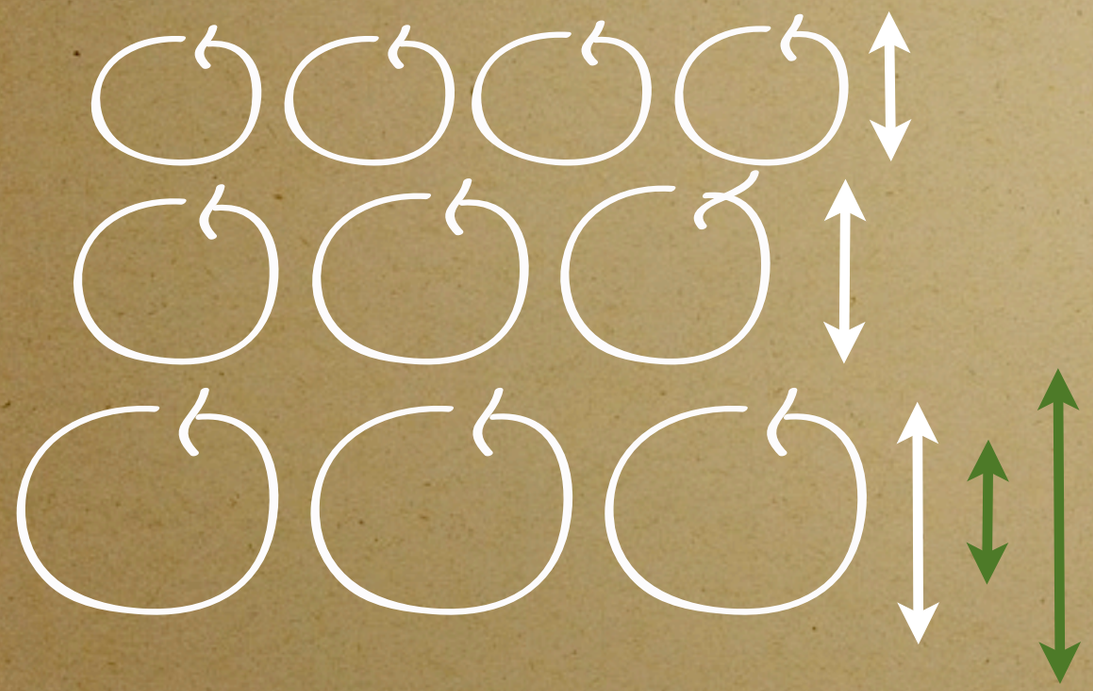
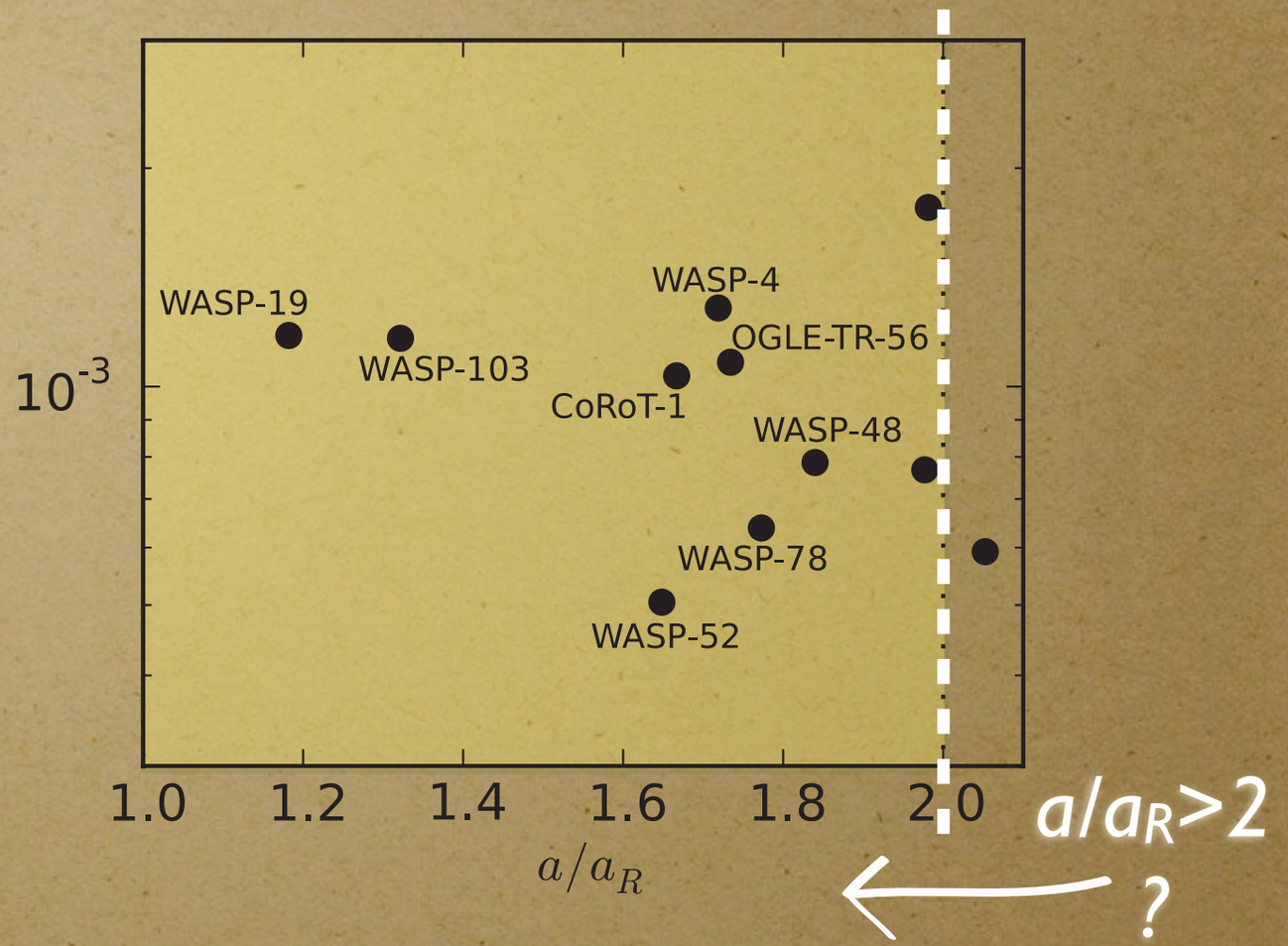
Valsecchi & Rasio '14b





- Stellar tides

$$\frac{1}{\tau_{decay}} \sim min\left[1, \left(\frac{P_{tide}}{\tau_{convection}}\right)^{s}\right]$$

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"Achilles' Heel of Tidal Theory"

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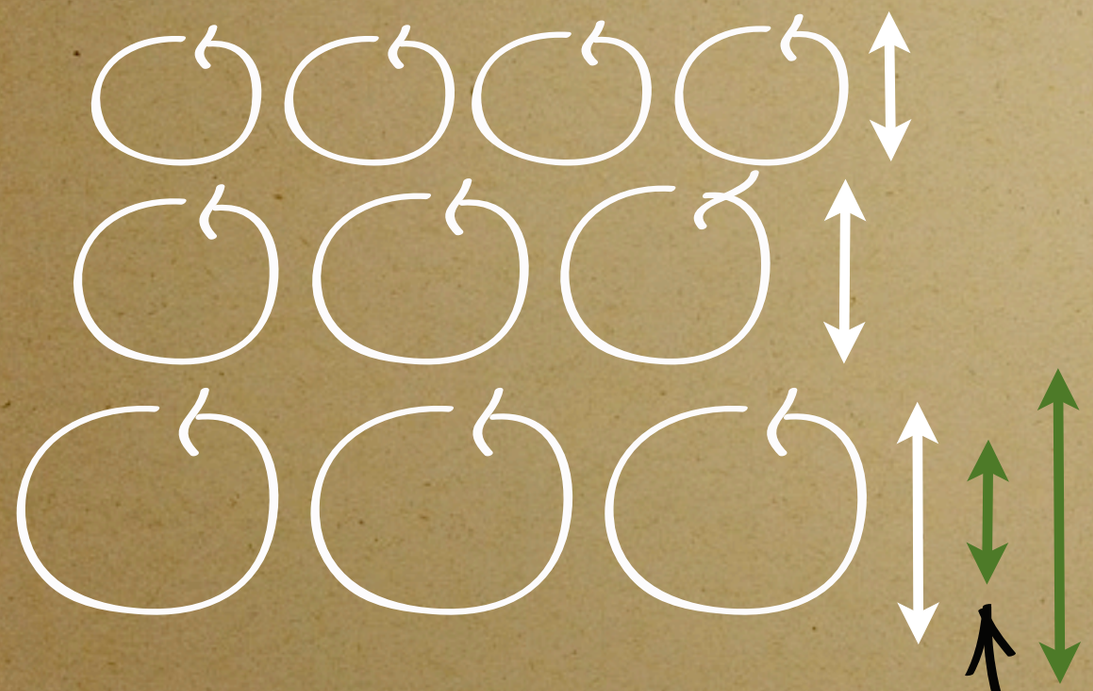
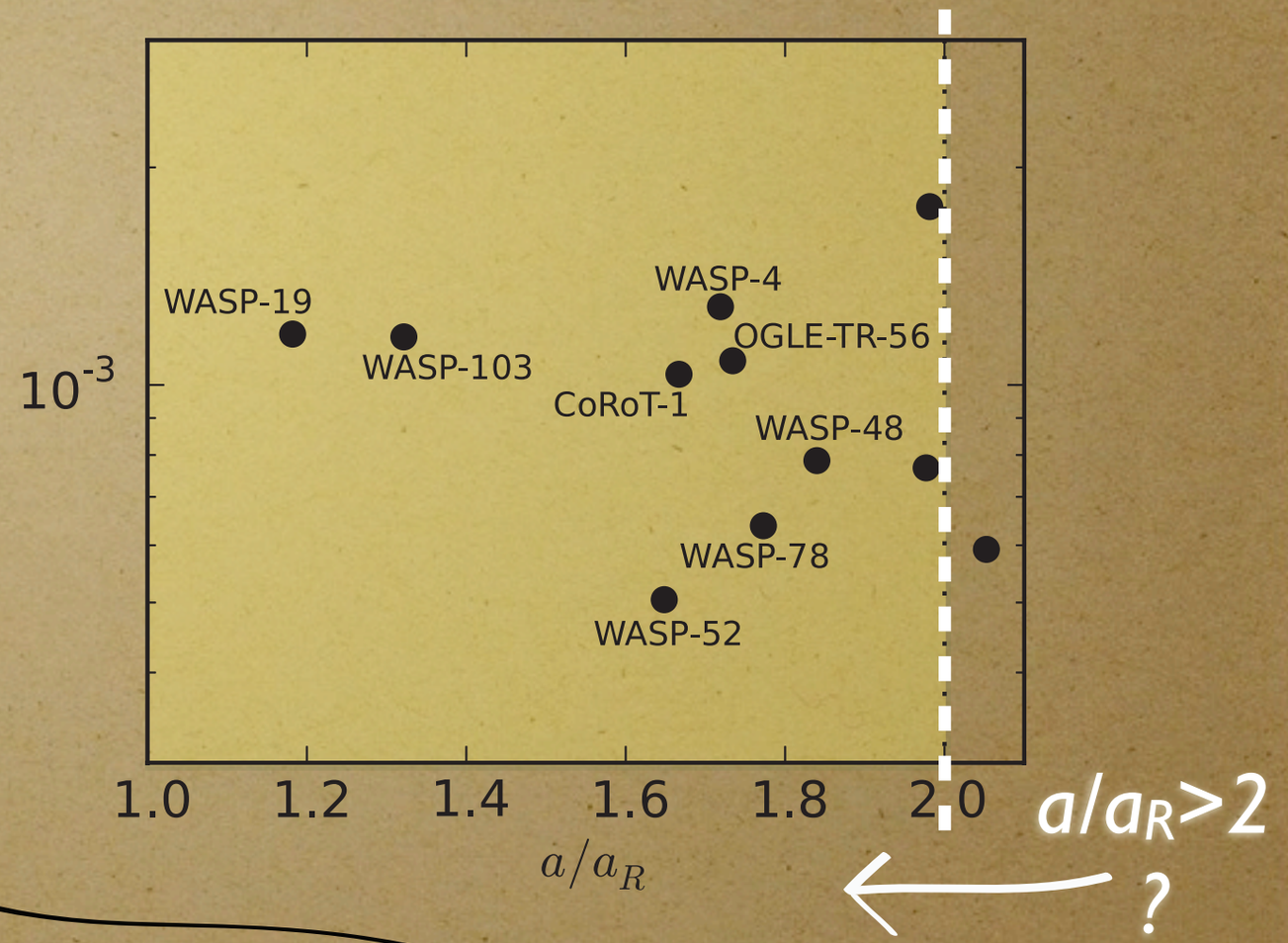
- J. P. Zahn

Valsecchi & Rasio '14b





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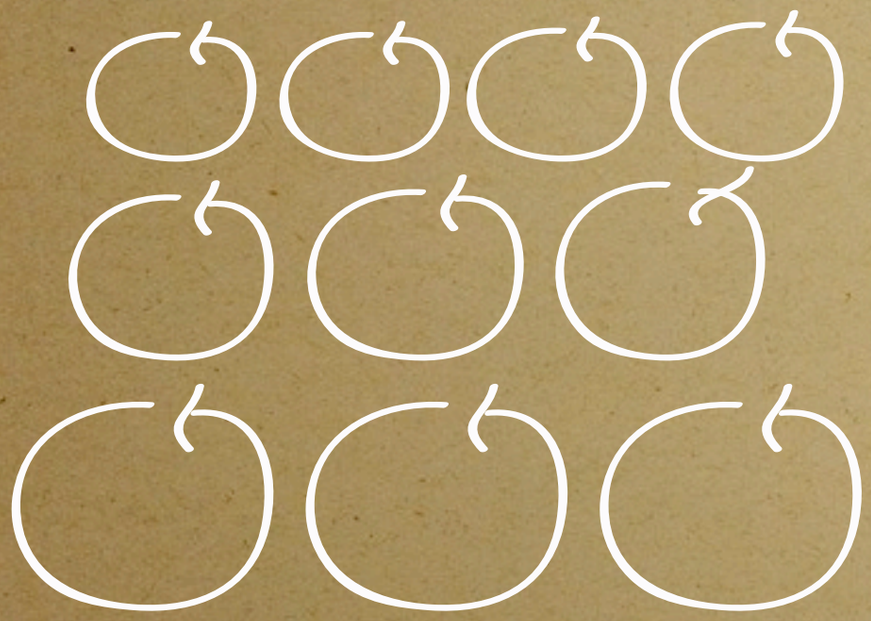

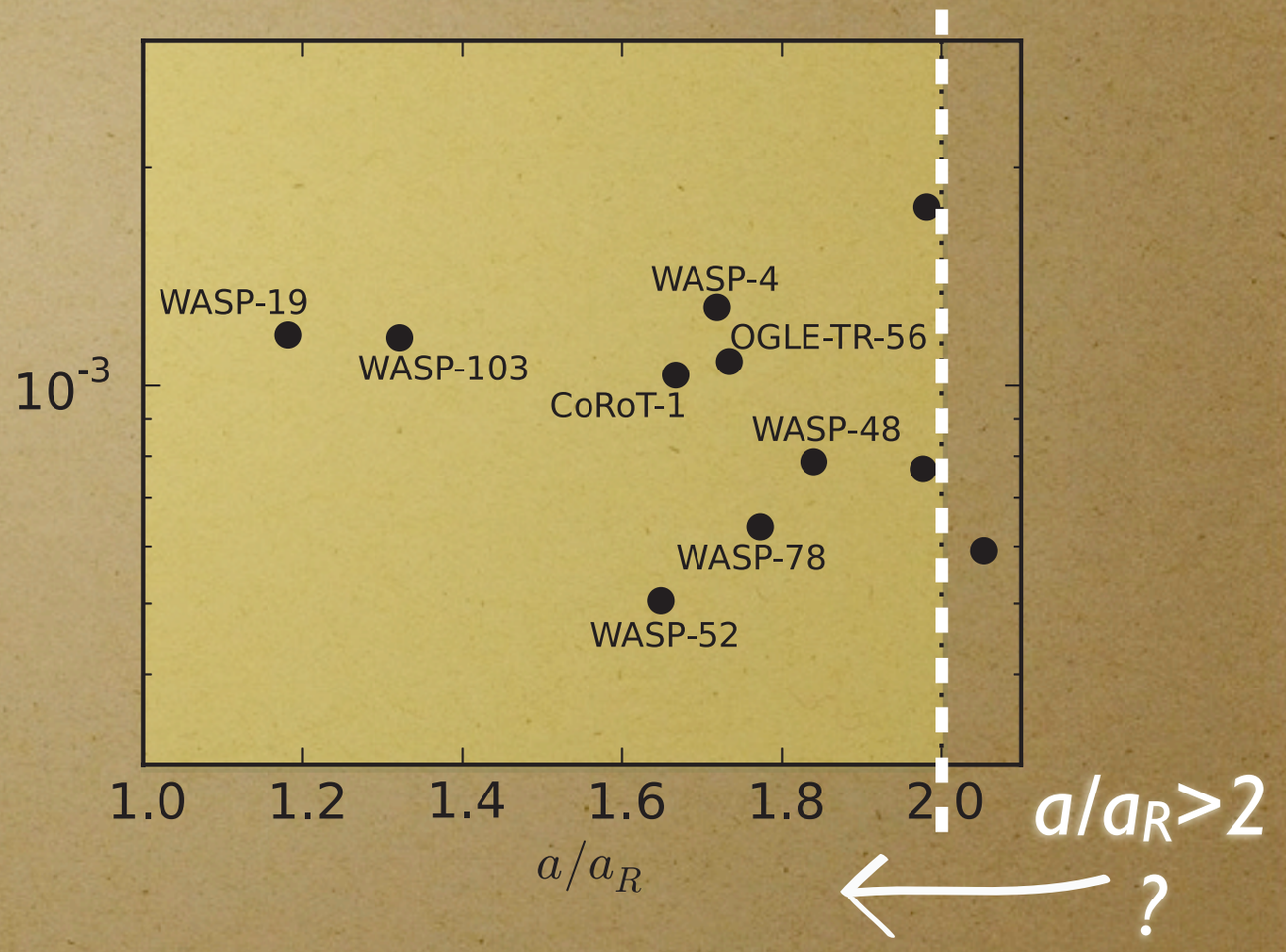

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Zahn ('66,'89)
s=1

Goldreich & Nicholson ('77)
s=2

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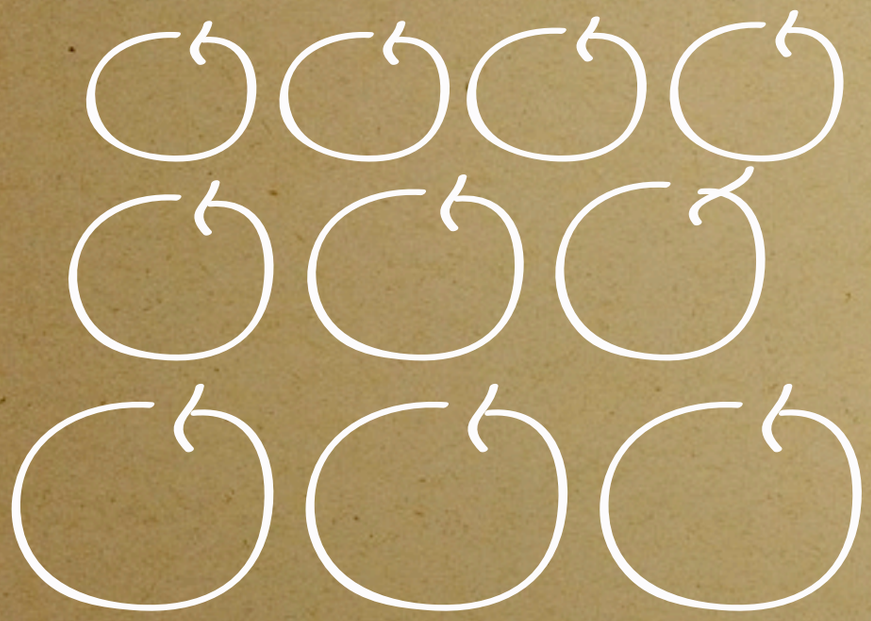

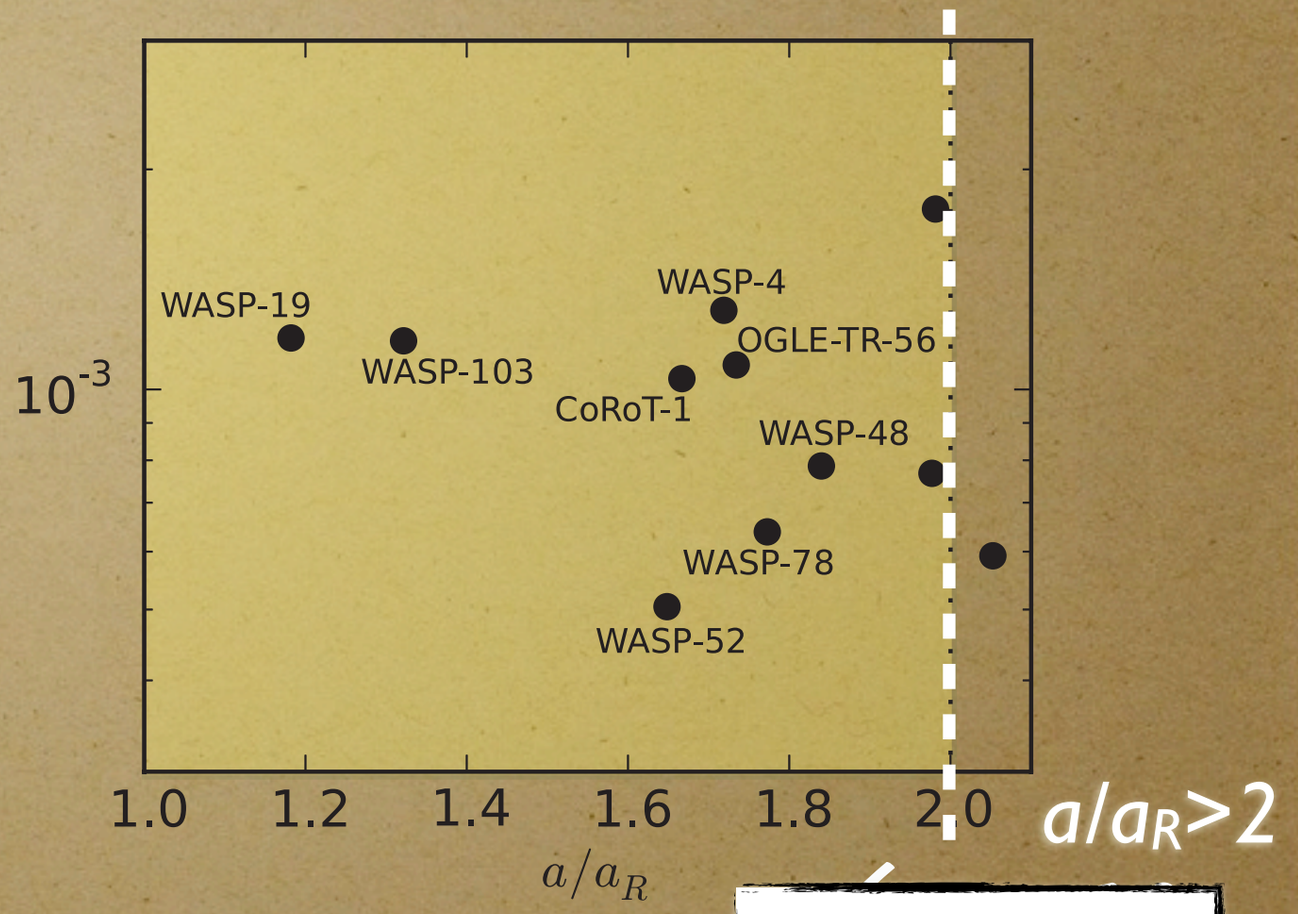

- Stellar tides

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Supported by 3-D numerical simulations
(Penev+07)

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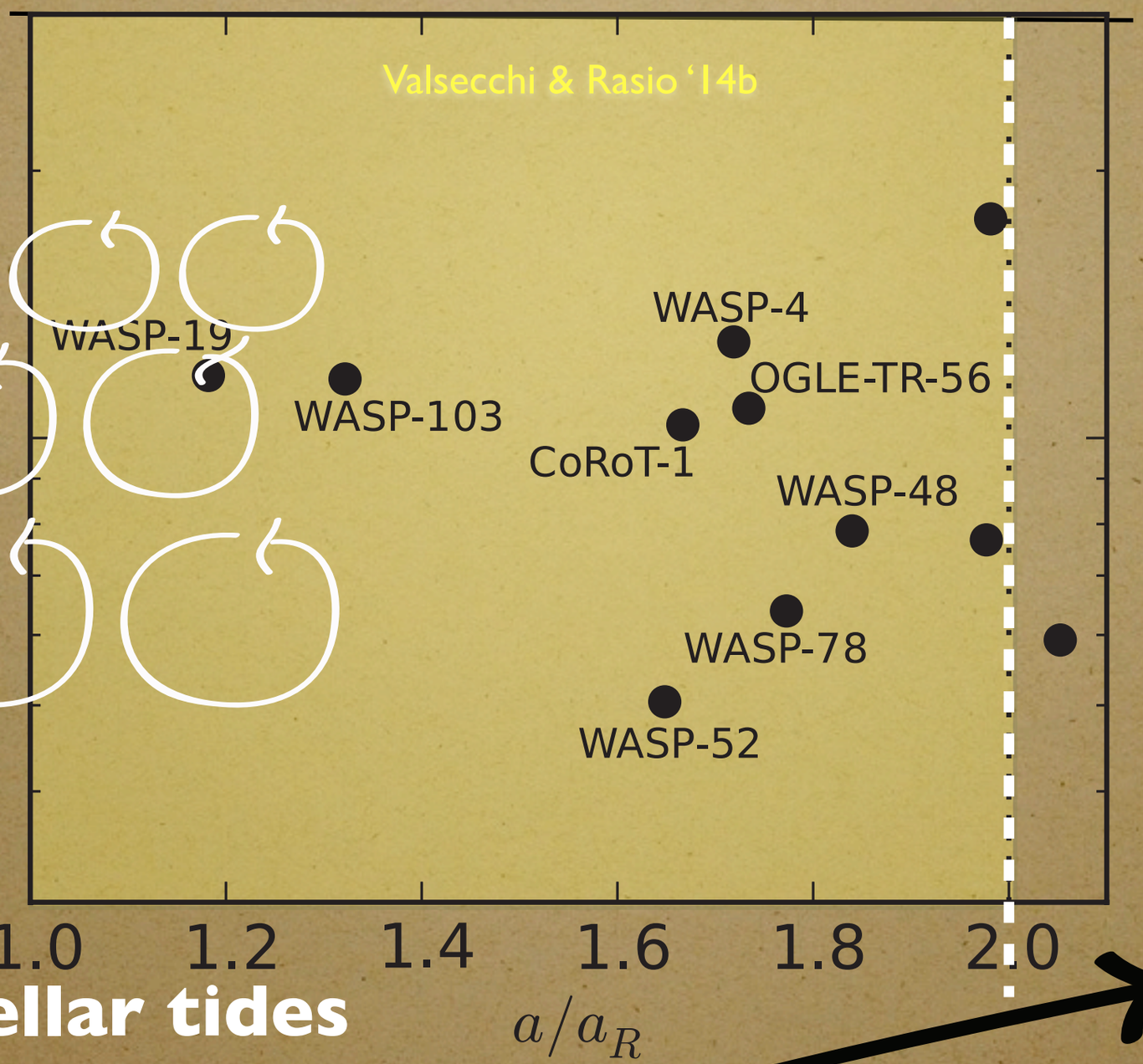
- J. P. Zahn



- **Stellar tides**

a/a_R>2

Zahn ('66,'89)
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Supported by 3-D numerical simulations
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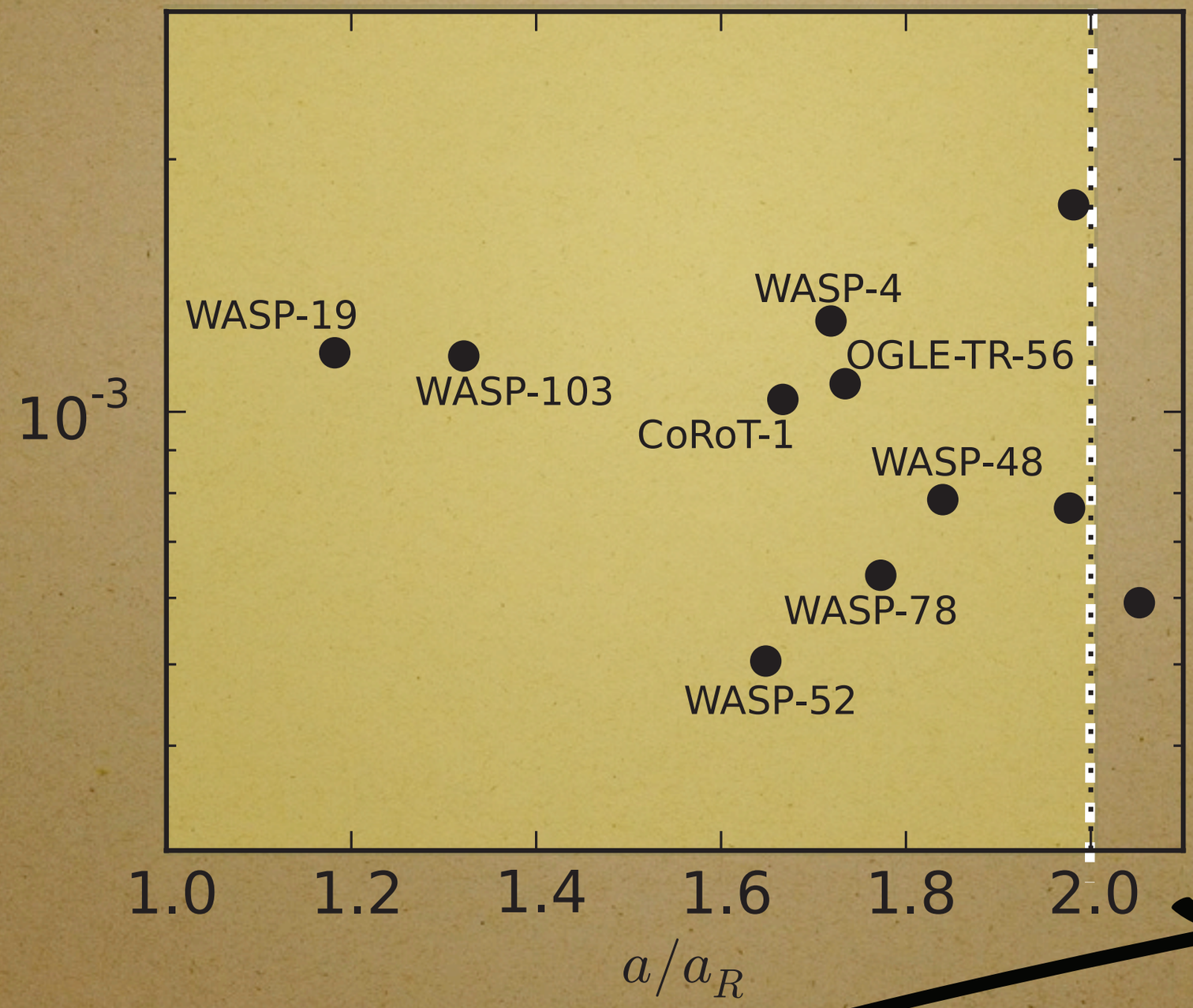

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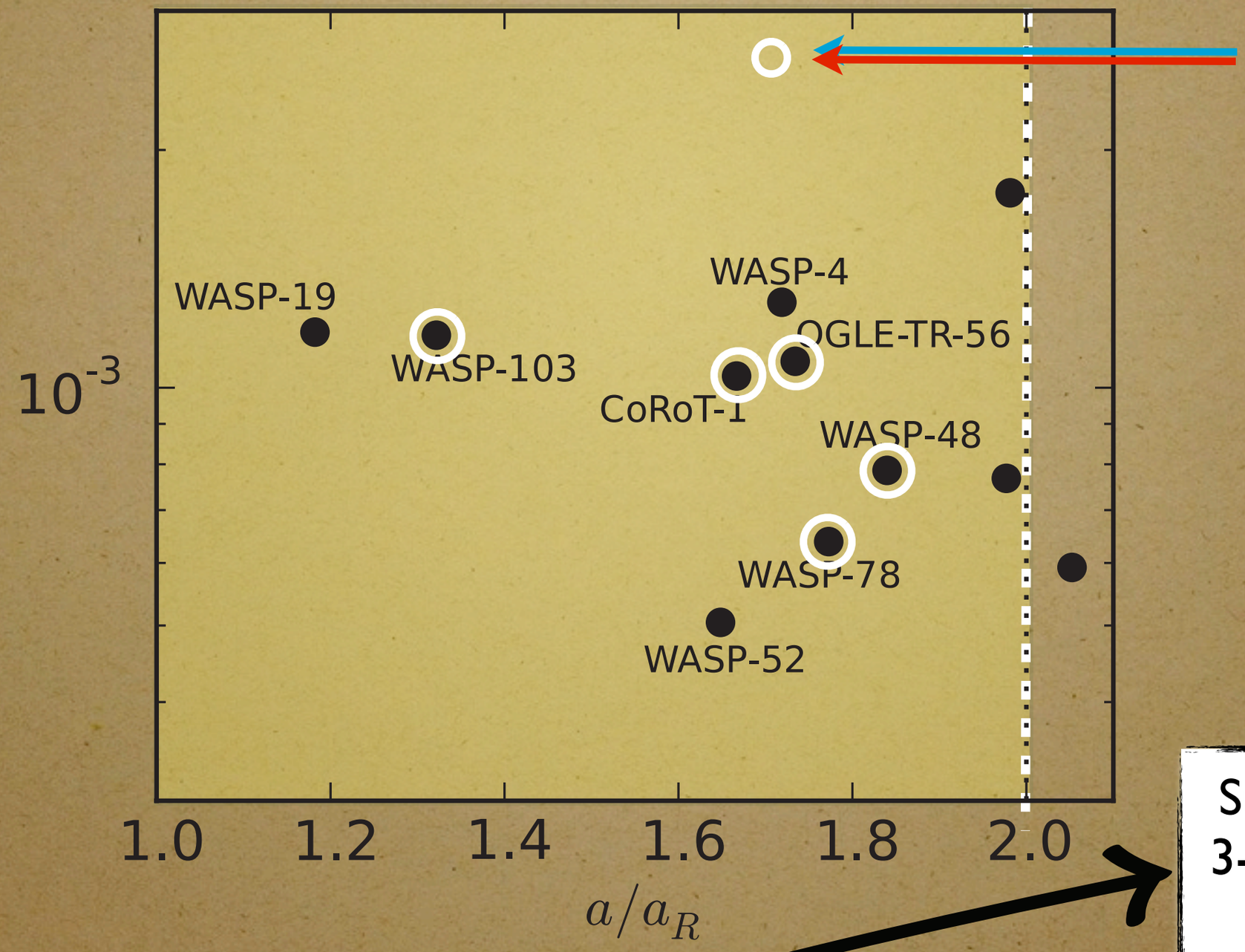

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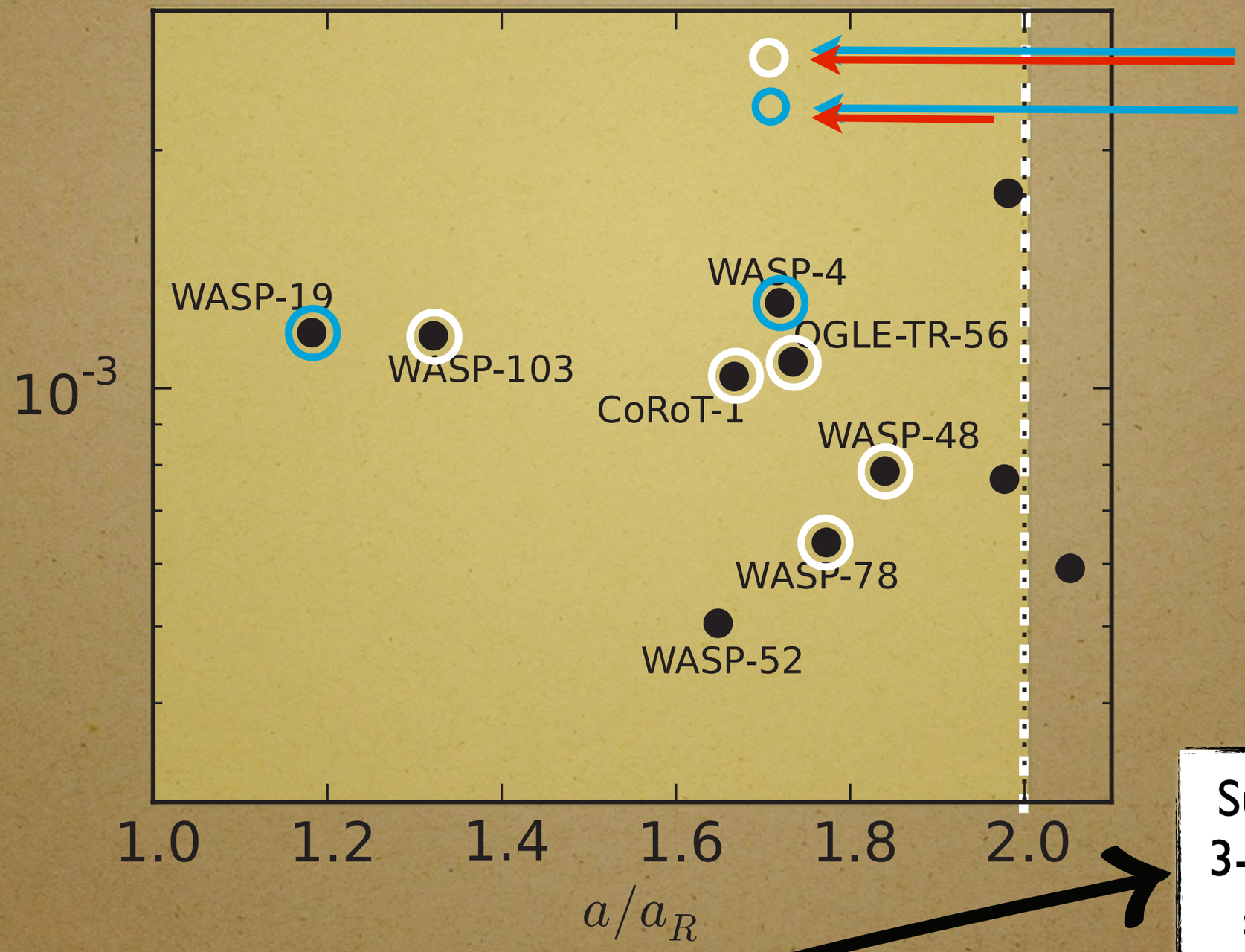

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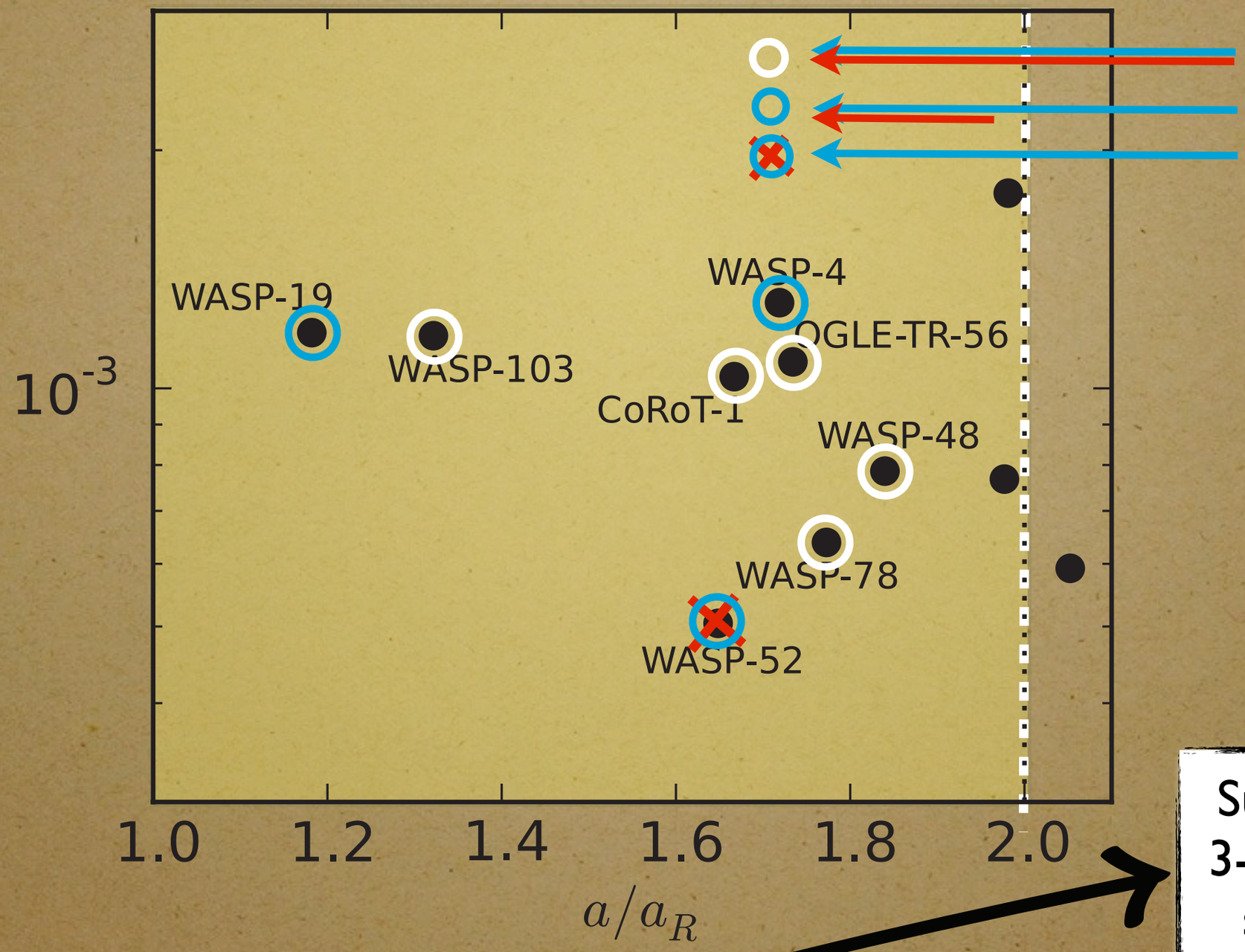
Valsecchi & Rasio '14b



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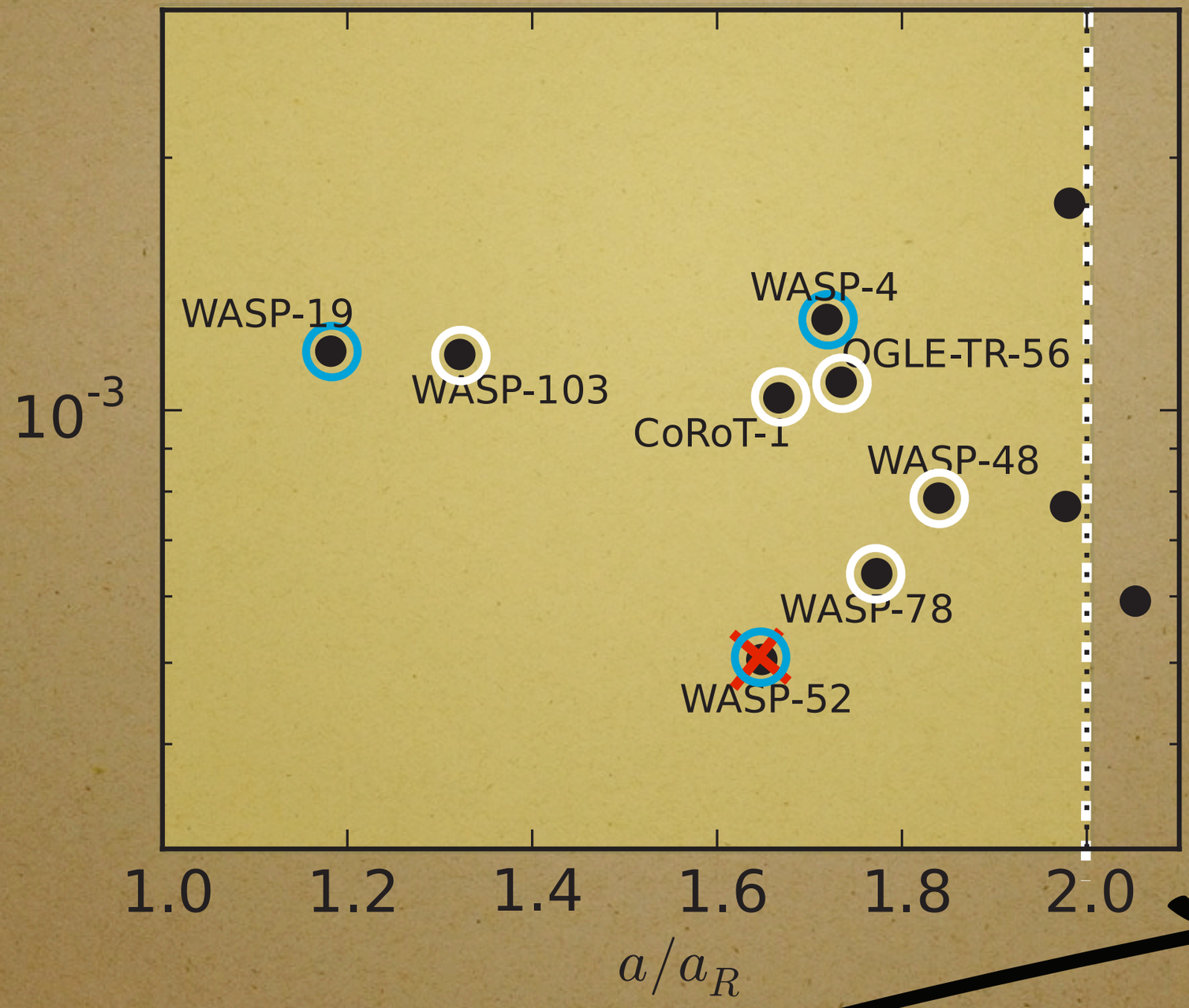

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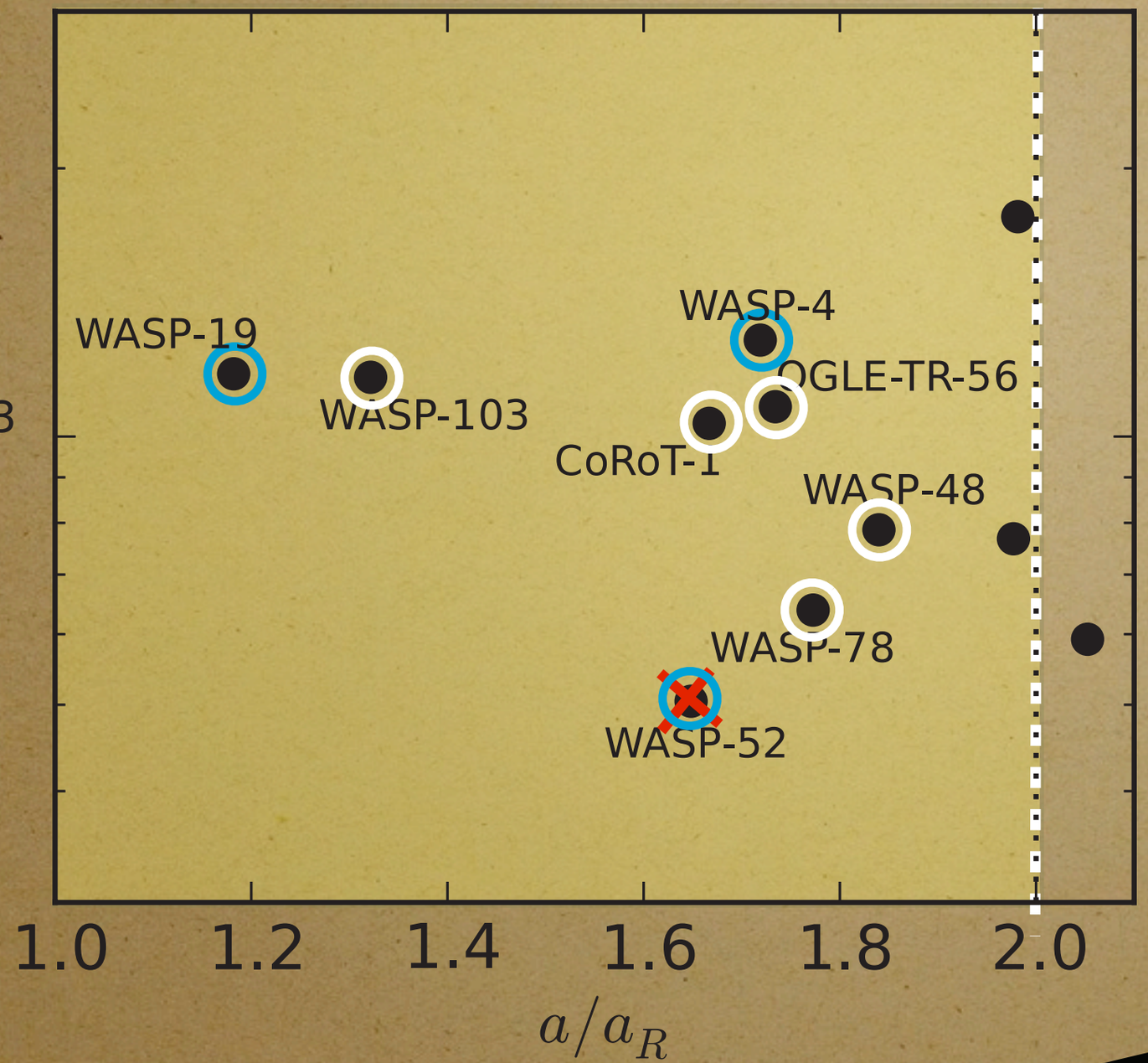
Valsecchi & Rasio '14b



Zahn ('66,'89)
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Goldreich & Nicholson ('77)
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Supported by 3-D numerical simulations
(Penev+07)

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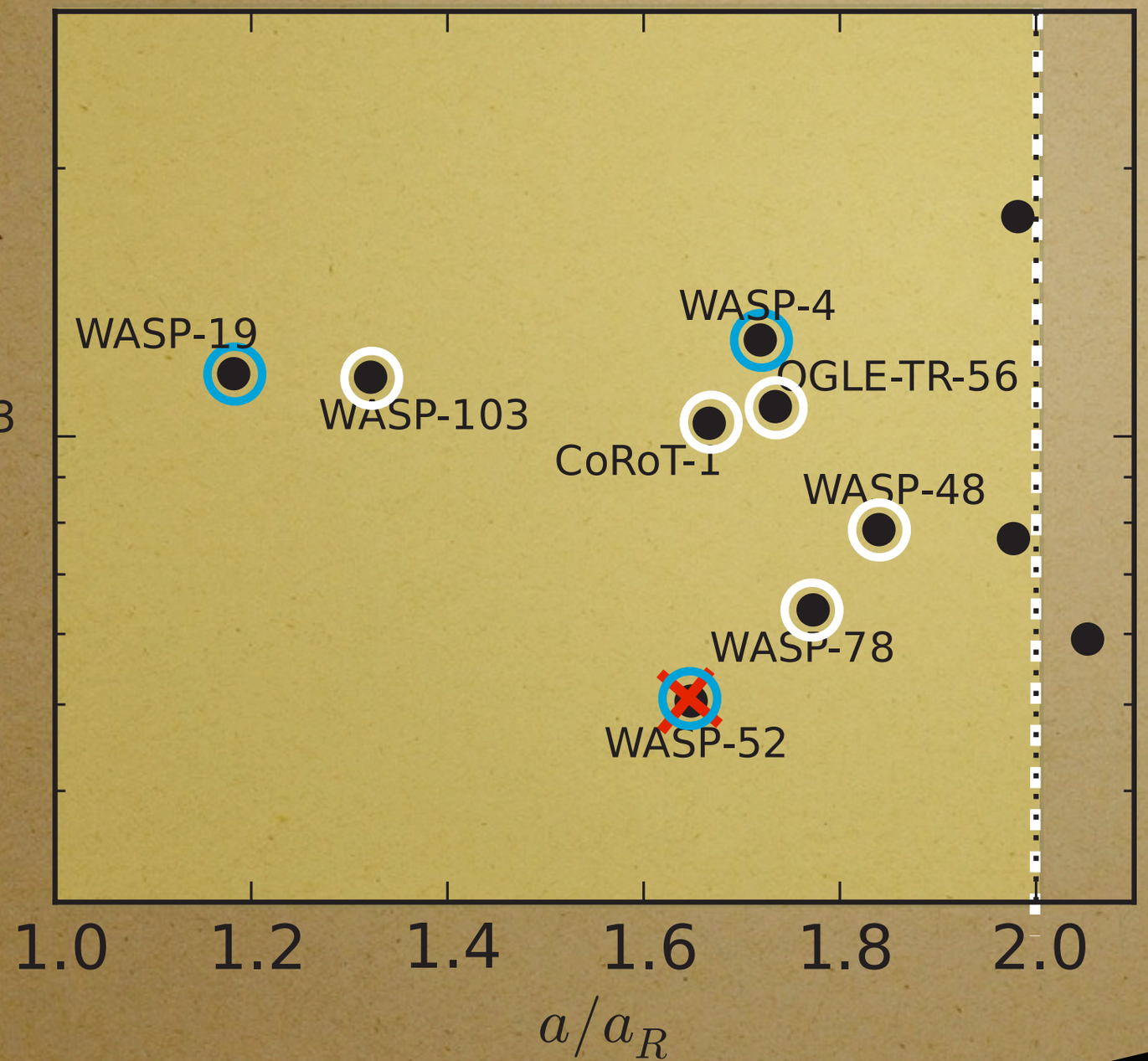
T_{shift} = Transit Arrival Time Shift (Birkby+14):

Valsecchi & Rasio '14b



Zahn ('66,'89)
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Goldreich & Nicholson ('77)
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Supported by 3-D numerical simulations
(Penev+07)

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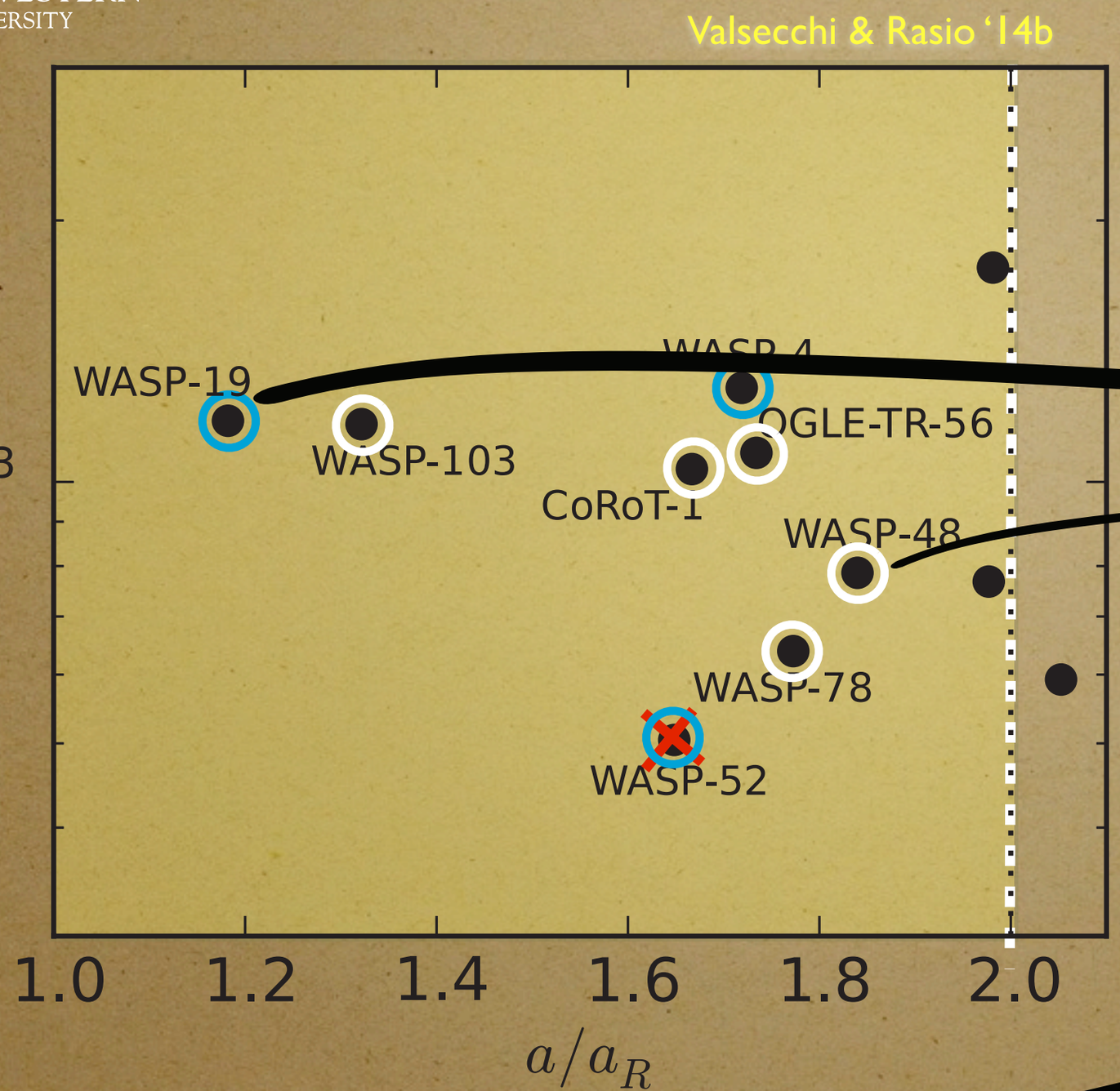
T_{shift} = Transit Arrival Time Shift (Birkby+14):



T_{shift} after 10 yr

~10 sec

~1sec

Zahn ('66,'89)
s=1

Goldreich & Nicholson ('77)
s=2

Supported by 3-D numerical simulations
(Penev+07)

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Orbital Decay to a_R

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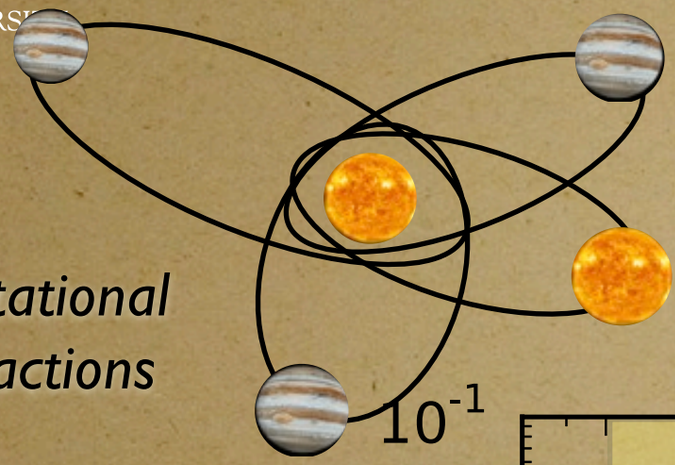
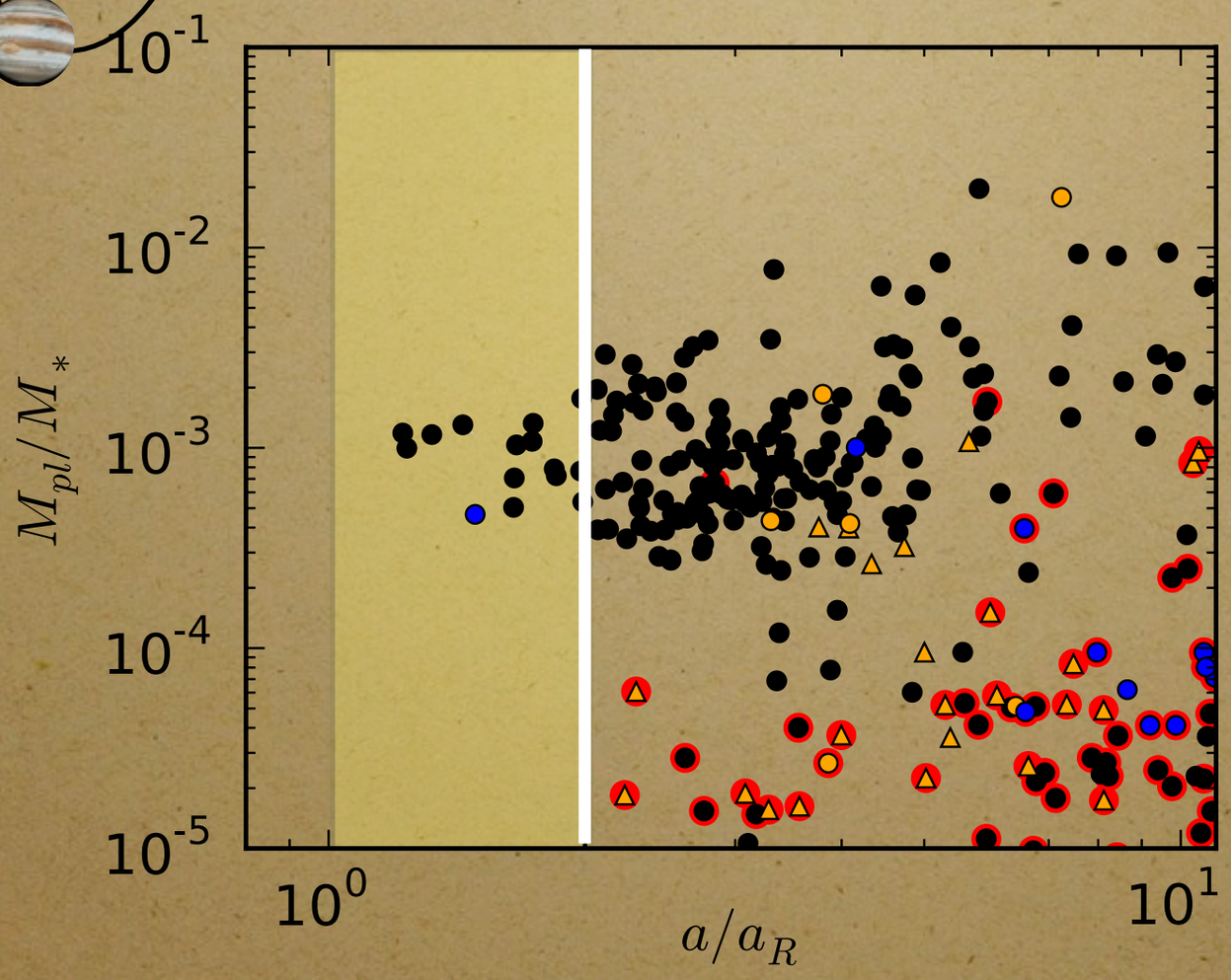
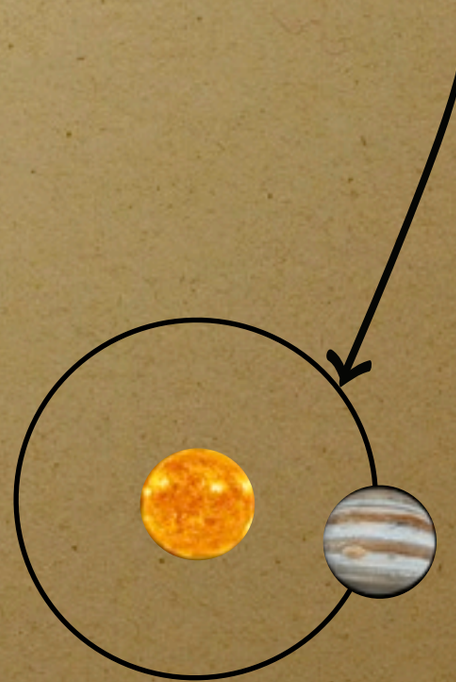


Gravitational Interactions



Tidal Circularization (tides in)

$a\downarrow$ $e\downarrow$



e = 0

$a/a_R \gtrsim 2$

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Orbital Decay to a_R

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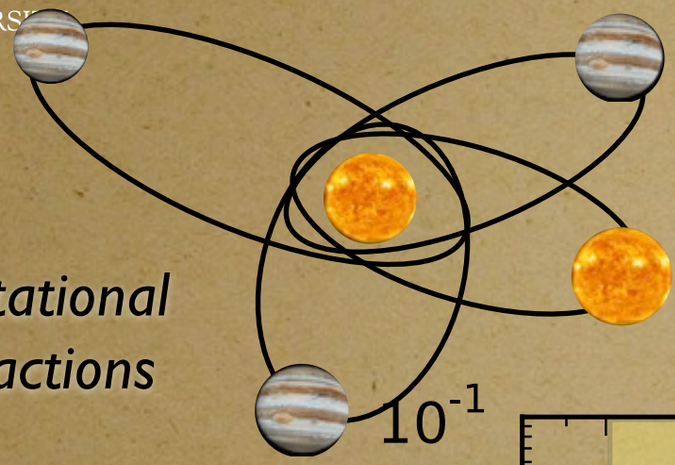
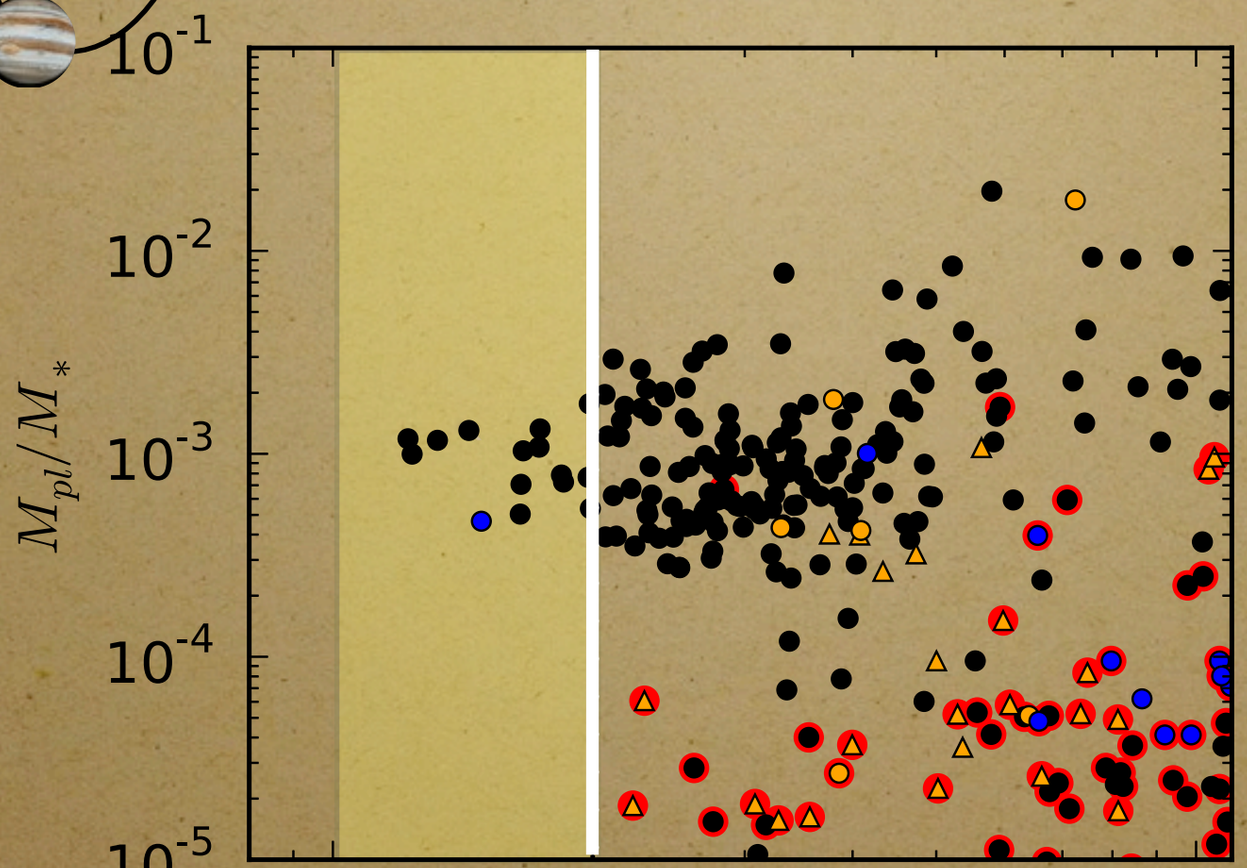


Gravitational Interactions

high eccentricity

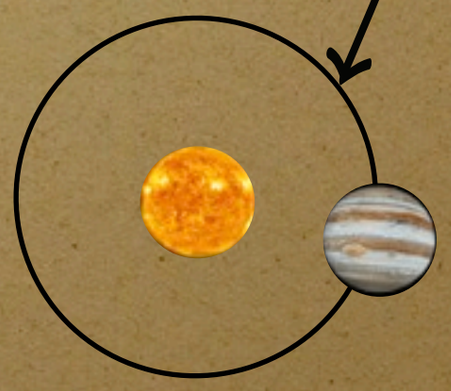
Tidal Circularization (tides in)

$a\downarrow$ $e\downarrow$



$a/a_R < 2$

Tidal Decay (tides in), $a\downarrow$



$e = 0$

$a/a_R \gtrsim 2$

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Orbital Decay to a_R

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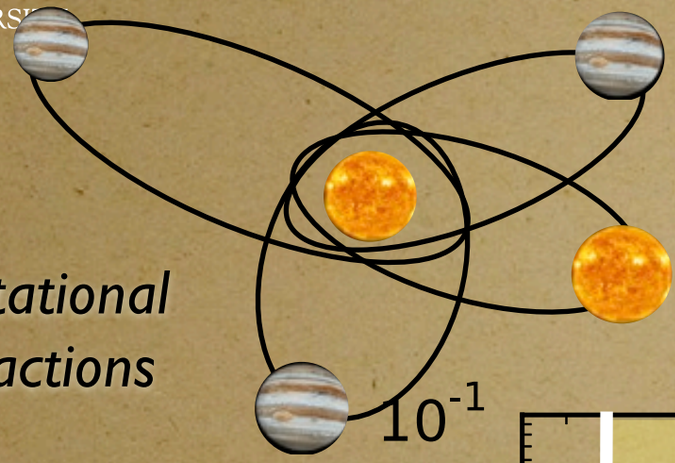
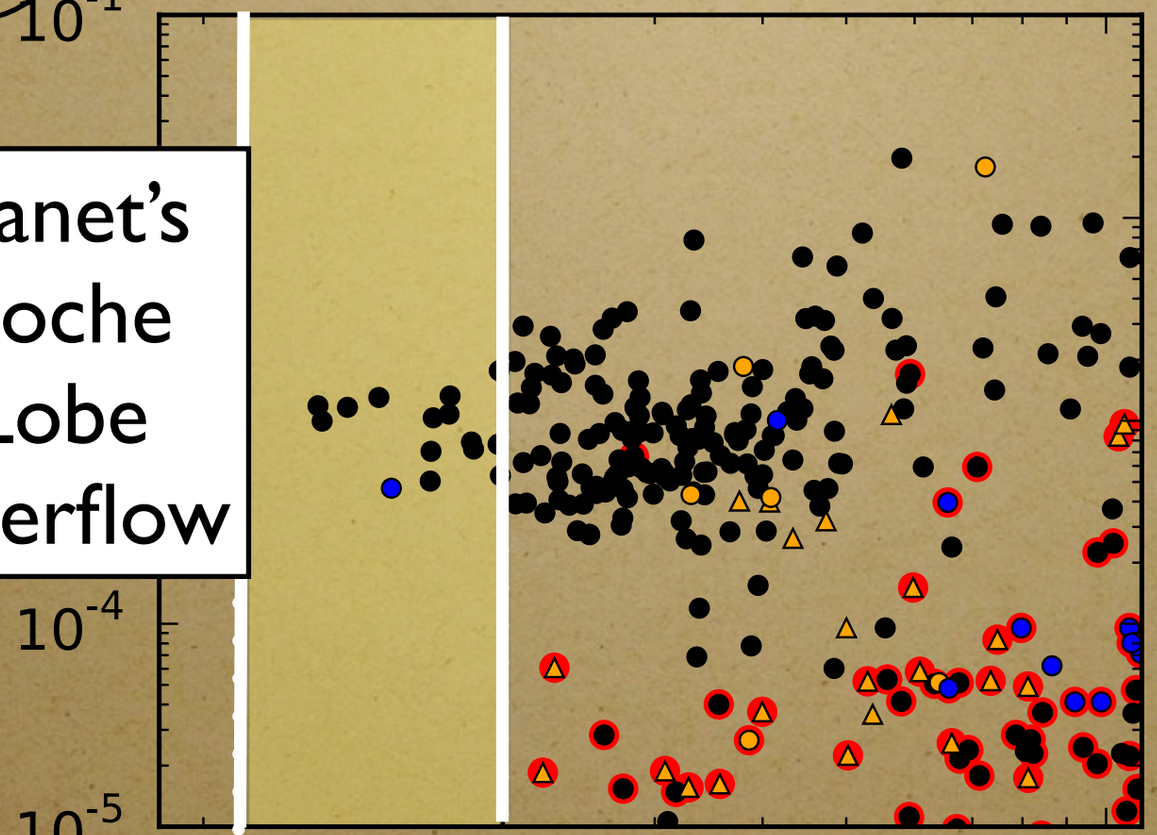
Gravitational Interactions



high eccentricity

Tidal Circularization (tides in)

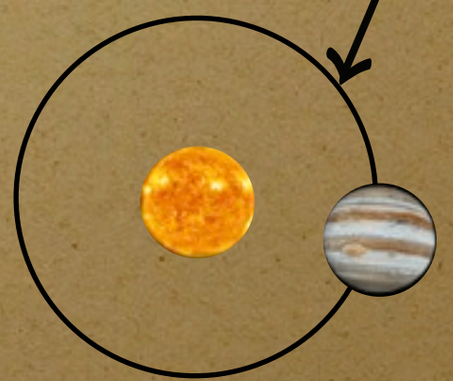
$a\downarrow$ $e\downarrow$



Planet's Roche Lobe Overflow

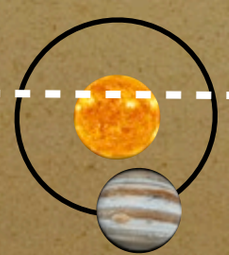
?

Tidal Decay (tides in), $a\downarrow$



$e = 0$

$a/a_R \gtrsim 2$



$a/a_R < 2$

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Orbital Decay to a_R

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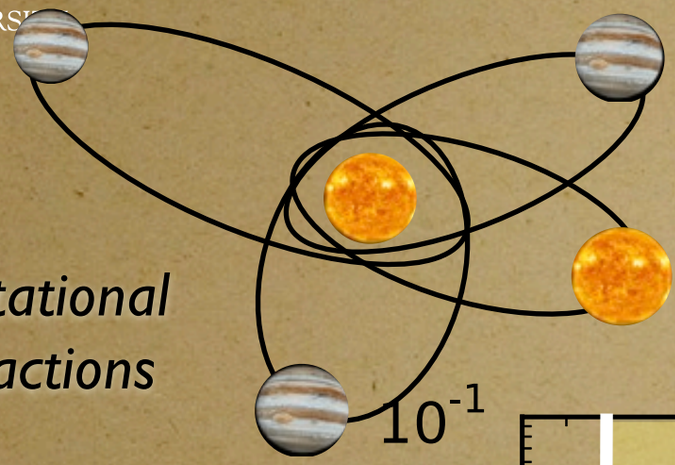
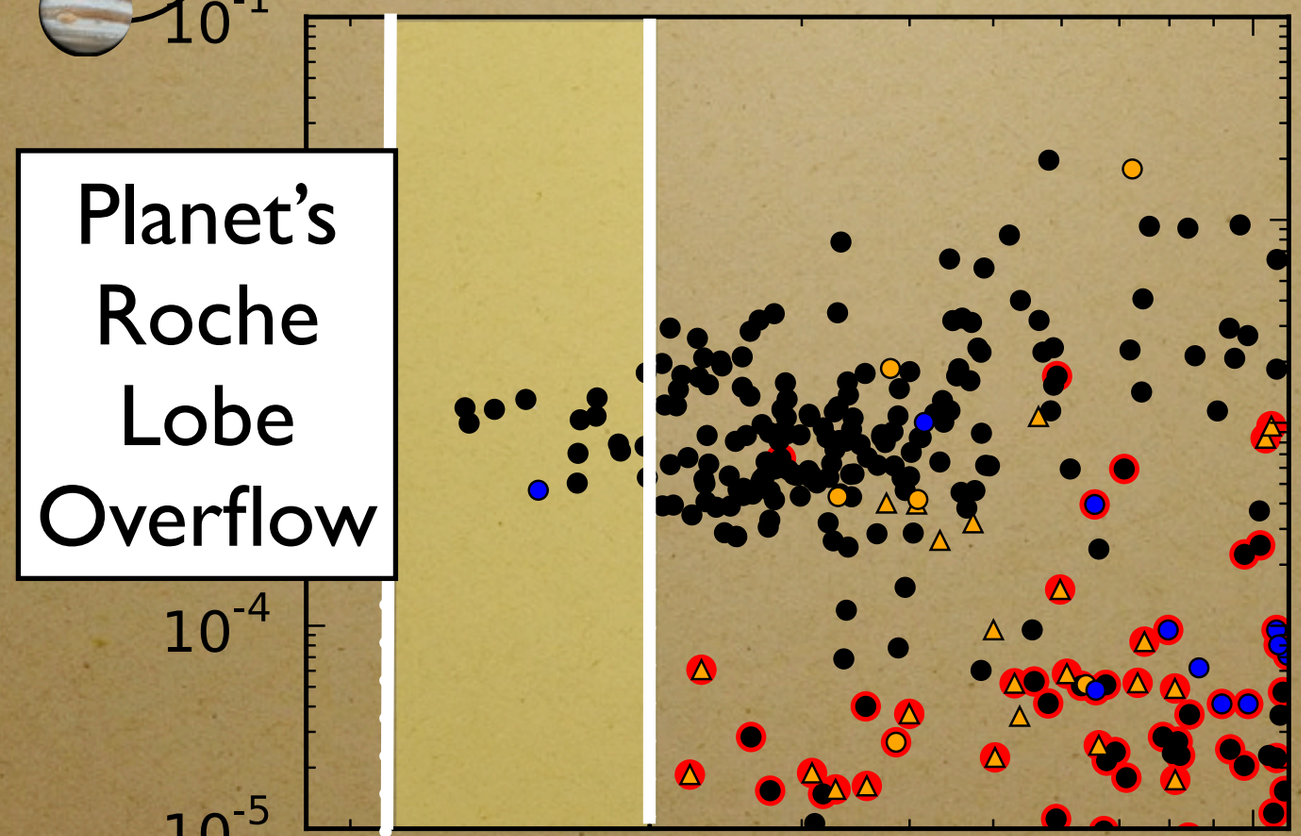


Gravitational Interactions

high eccentricity

Tidal Circularization (tides in ☉)

a↓ *e*↓



Jackson+09
Metzger+12
Schlaufman & Winn13
Teitler & Konigl14,
Zhang & Penev14;
McQuillan,Mazeh, & Aigrain13

?

a/*a*$_R$ < 2

Tidal Decay (tides in ☉), a↓

e = 0
a/*a*$_R$ ≳ 2

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Orbital Decay to a_R

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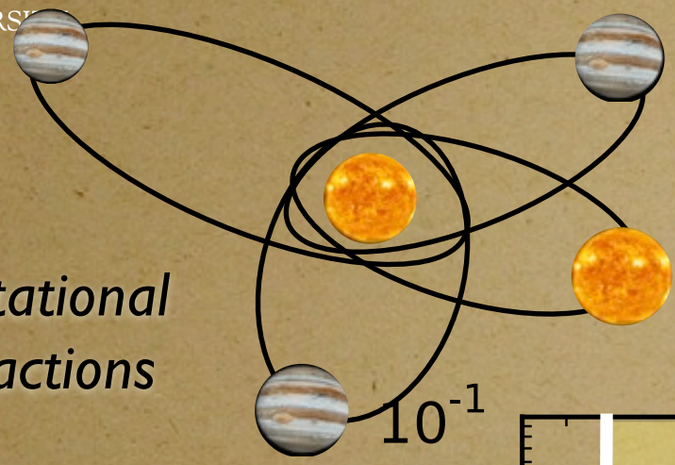

Gravitational Interactions

high eccentricity

Tidal Circularization (tides in)

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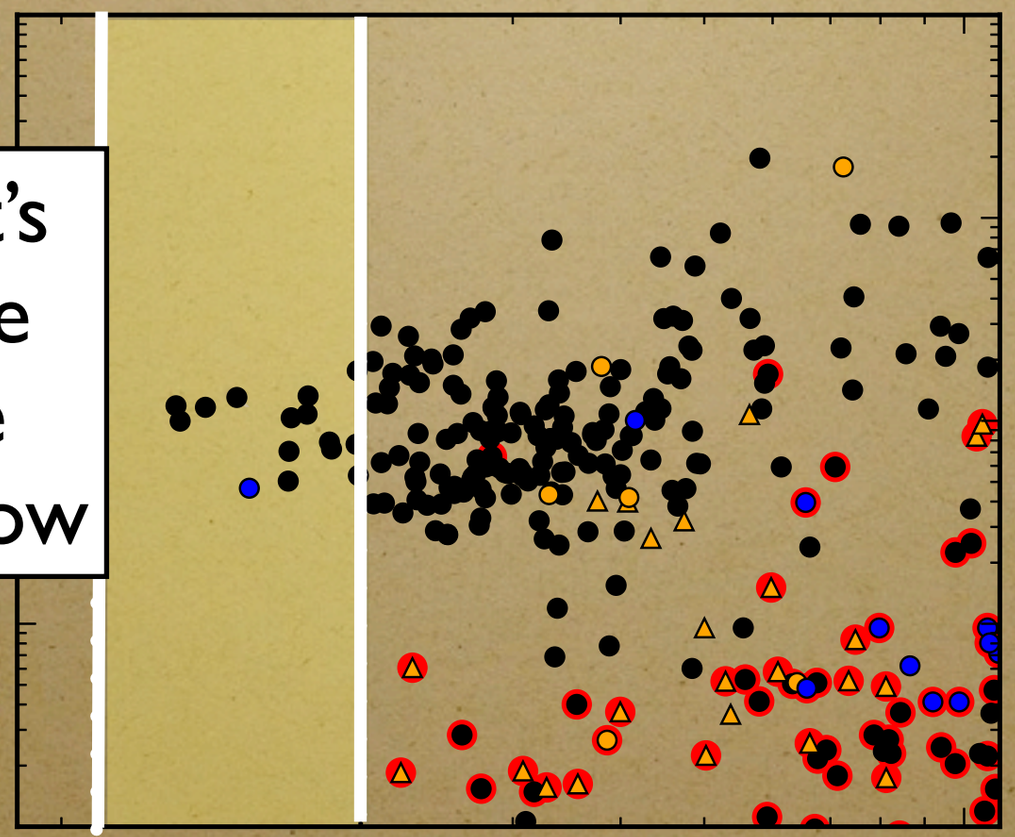
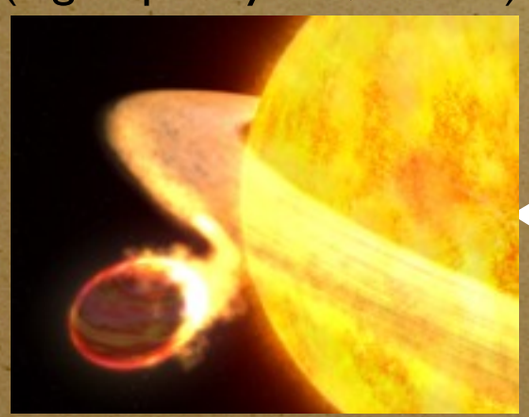


Planet's Roche Lobe Overflow

(e.g. Sepinsky+10, Lai+10)



NASA, ESA, G. Bacon, C. Haswell

$a/a_R < 2$

Tidal Decay (tides in), $a\downarrow$

$e = 0$

$a/a_R \gtrsim 2$

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Excess of isolated small planets in KOIs

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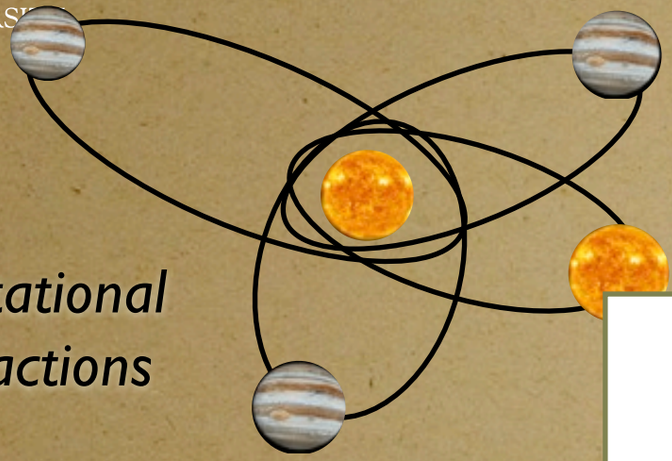
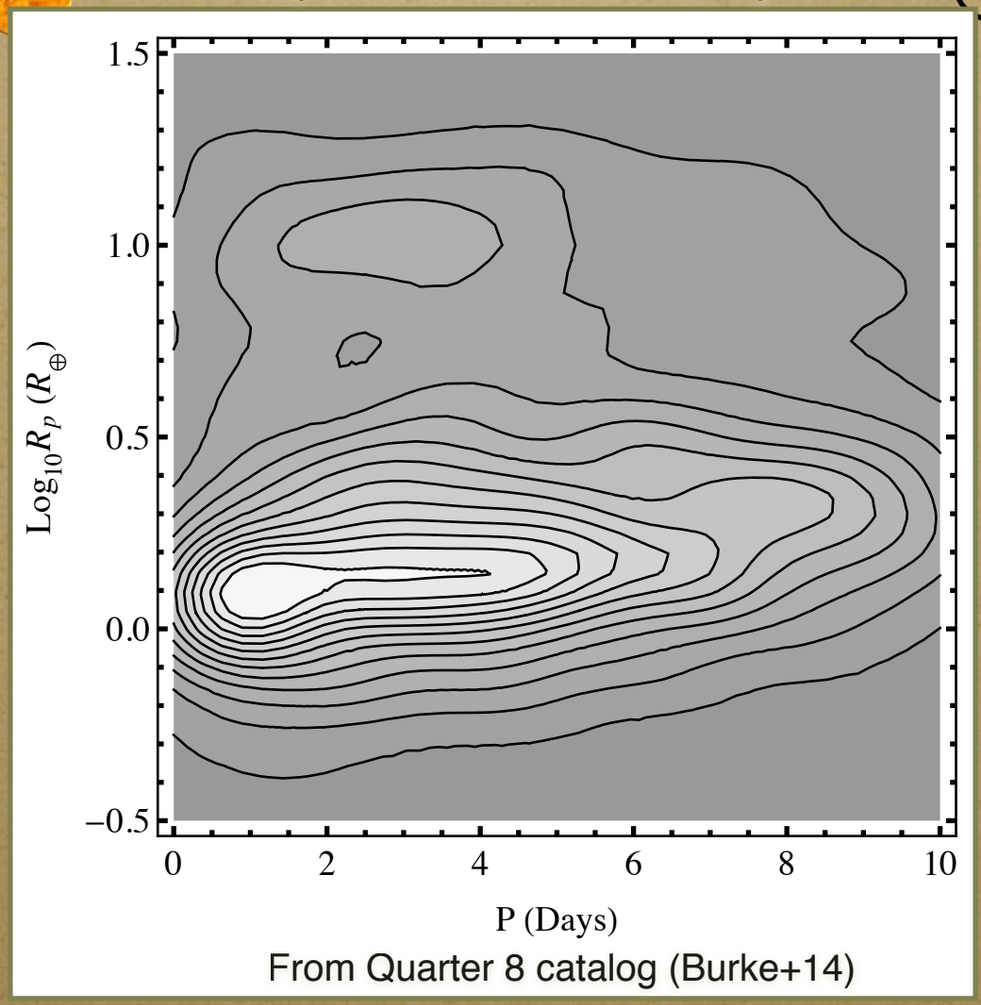
Gravitational Interactions



(Steffen & Farr '13)



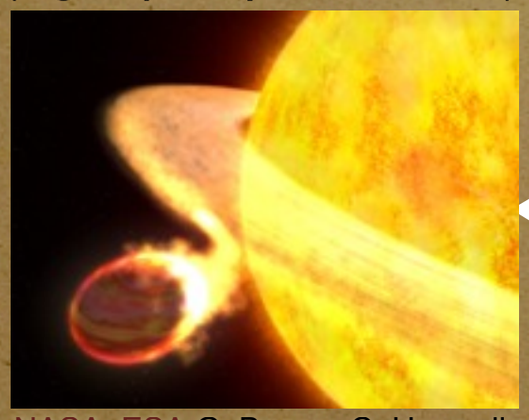
From Quarter 8 catalog (Burke+14)

high eccentricity

Tidal Circularization (tides in ●)

a↓ *e*↓

(e.g. Sepinsky+10, Lai+10)



NASA, ESA, G. Bacon, C. Haswell

a/*a*$_R$ < 2

Tidal Decay (tides in ●), a↓

e = 0

a/*a*$_R$ ≳ 2

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Mass Transfer Examples - Toy Model

(Valsecchi, Rasio, & Steffen '14c, following Rappaport et al. 1982)

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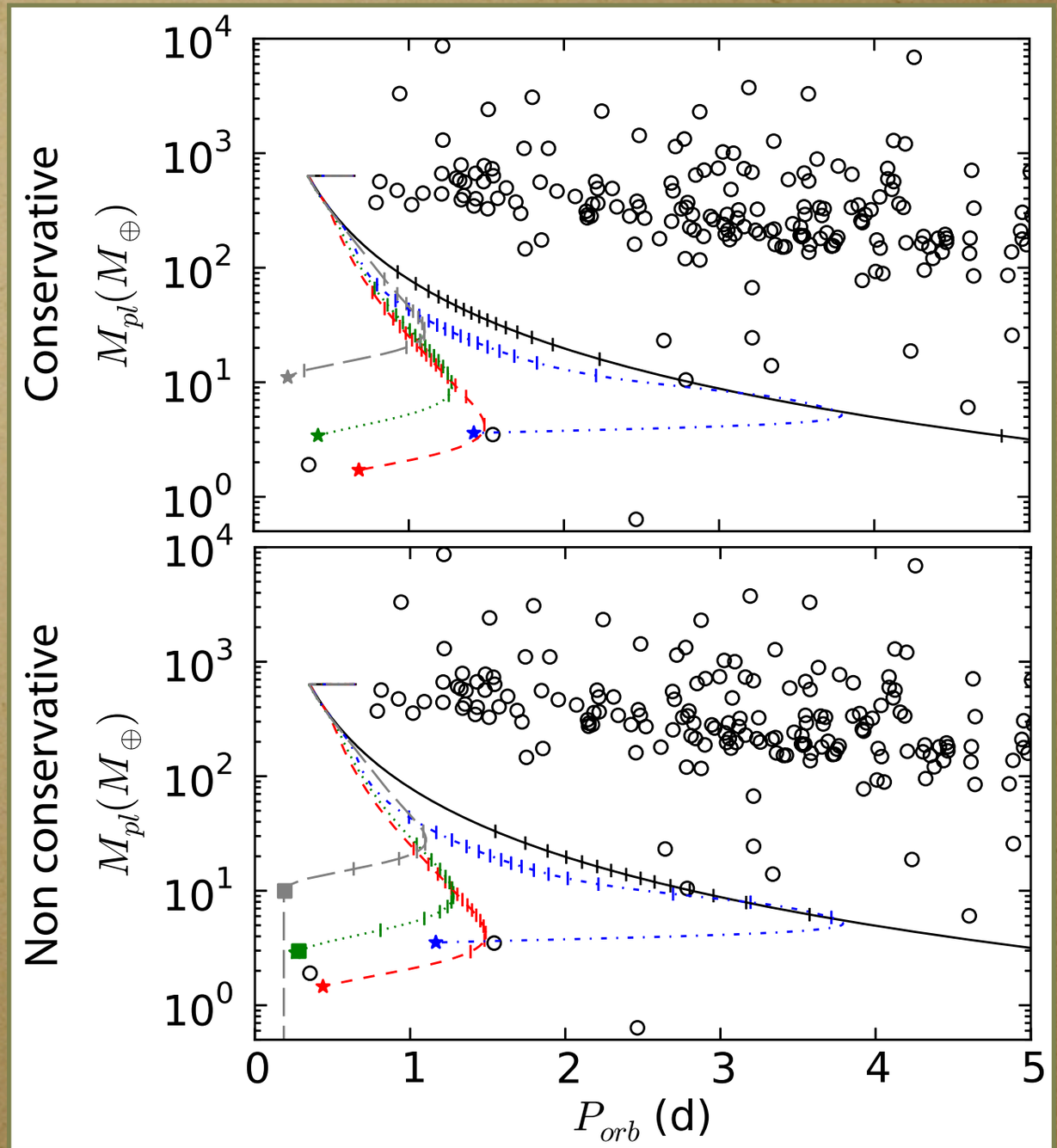
- M_{core}= 1 $M_\oplus$
- M_{core}= 3 $M_\oplus$
- M_{core}= 3 $M_\oplus$ with irradiation
- M_{core}= 10 $M_\oplus$ with irradiation
- core-less (n=1 polytrope)

(Batygin+13, Fortney+07)



Mass Transfer Examples - Toy Model

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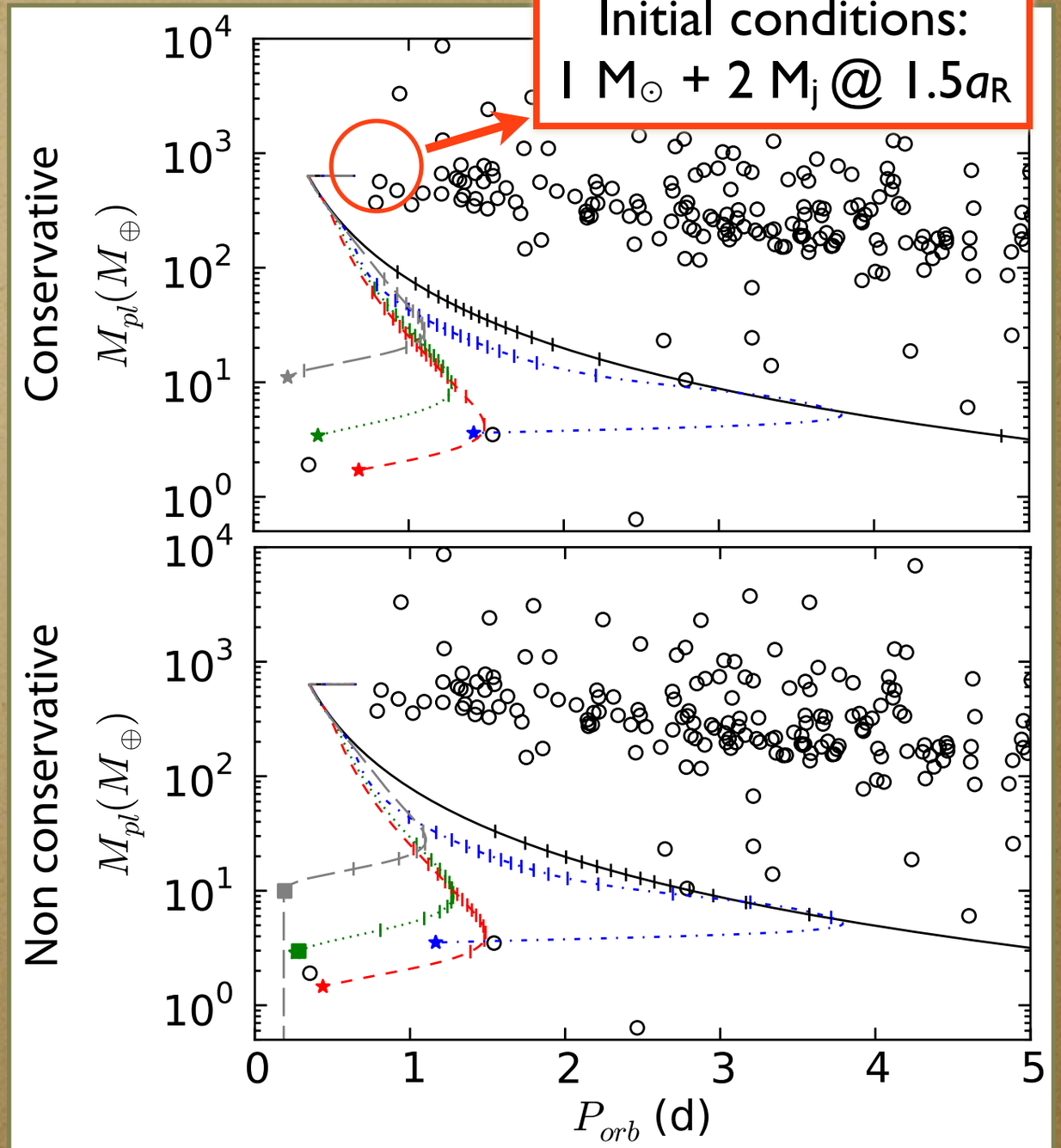

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Mass Transfer Examples - Toy Model

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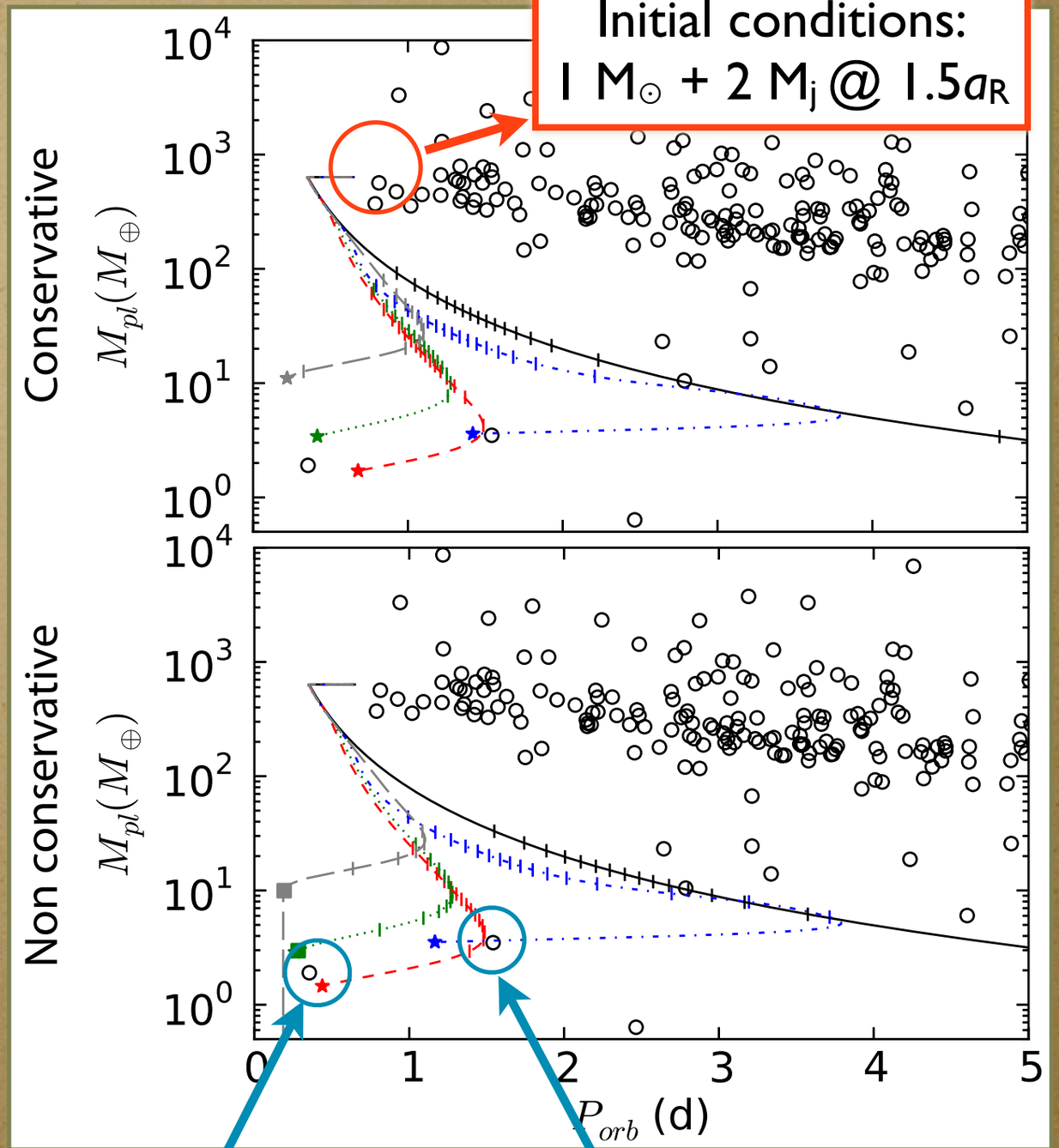
- M_{core}= 10 $M_\oplus$ with irradiation
- core-less (n=1 polytrope)

(Batygin+13, Fortney+07)

Initial conditions:
1 $M_\odot$ + 2 M_j @ 1.5a_R



Kepler-78

Kepler-98

Conclusions

- Hot Jupiters with $a<2a_R$ are consistent with high-e migration

- A hot Jupiter undergoing a phase of Roche lobe overflow could leave behind a hot super-Earths.

with more physics and MESA..

For more info:

http://arxiv.org/pdf/1402.3857

http://arxiv.org/abs/1403.1870

http://arxiv.org/abs/1408.3635