Are hot neptunes partially evaporated hot jupiters?

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and

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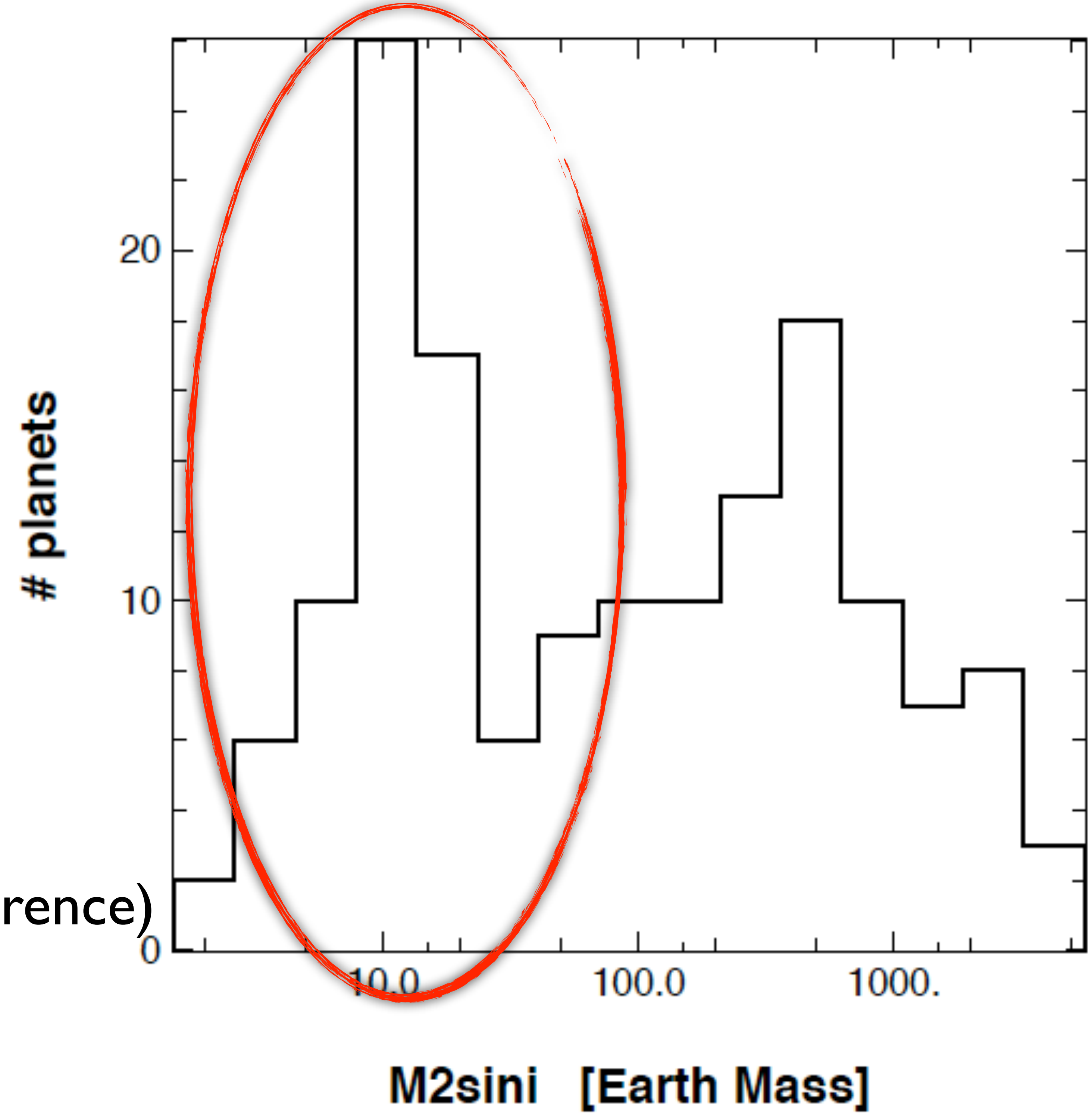
With the support from:

Neptunes and super-Earths

~80 with mass below 20 M_{Earth} known to date

Planet detections in HARPS and CORALIE samples



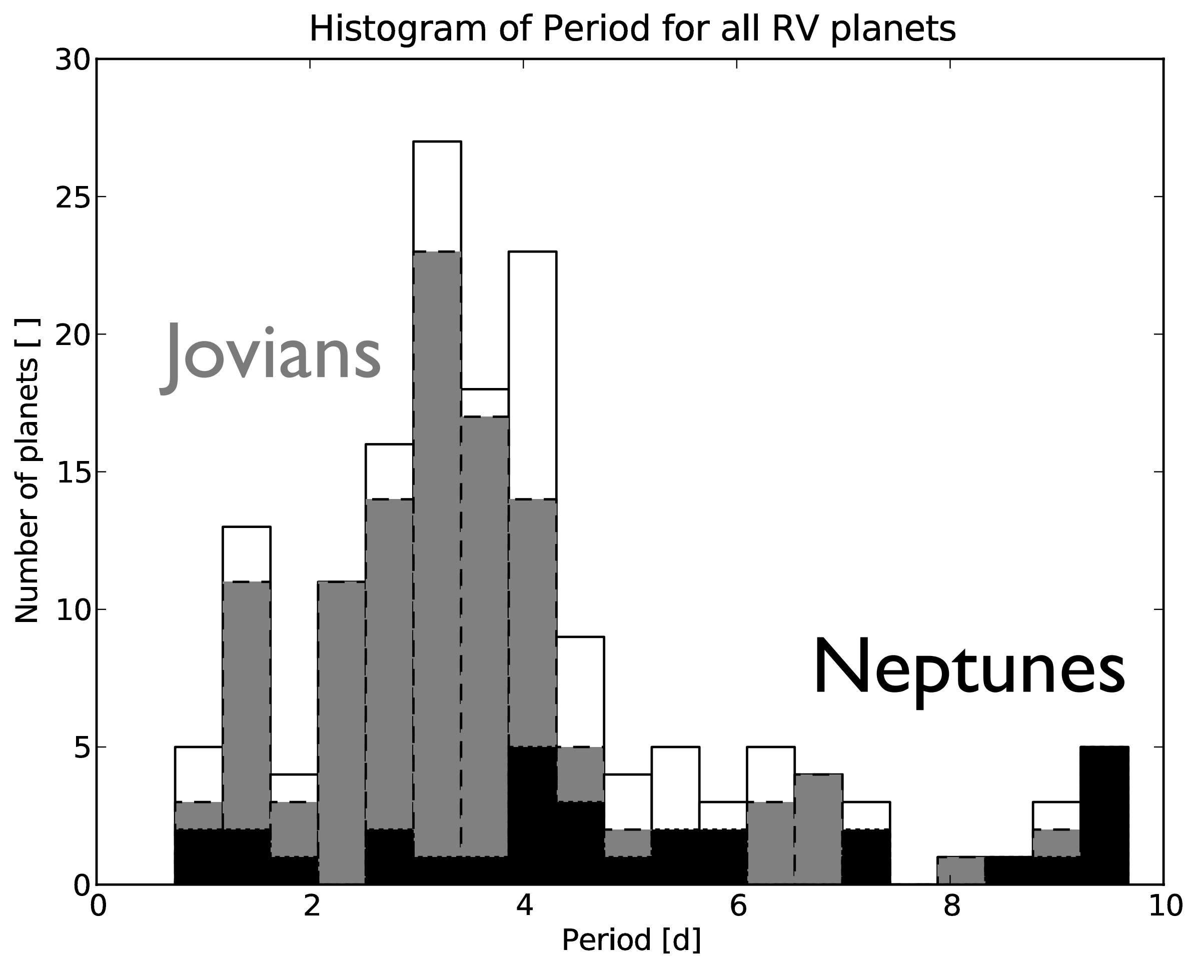
Mayor et al. (2011, this conference)

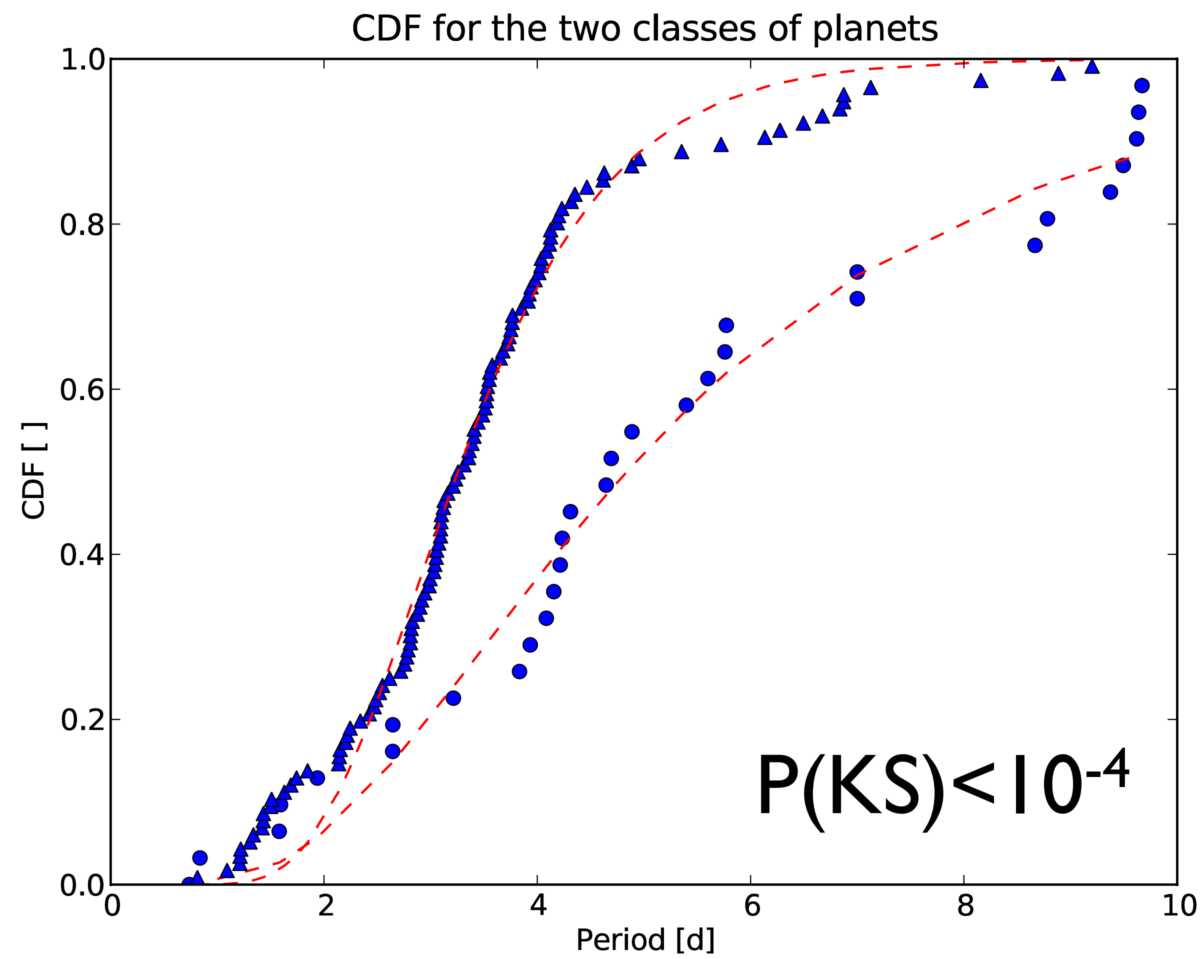
Hot-neptunes and super-earths: what is their origin and nature?

- Failed cores that migrated inwards (e.g. *Ida & Lin 2004, Mordasini et al. 2009)*
- In-situ formation by accretion of planetesimals (e.g. *Brunini & Cionco 2005; Hansen 2009)*
- Embryo formation in compact system and subsequent migration through scattering (e.g. *Ida & Lin 2010)*
- Tidal downsizing of migrating embryo (e.g. *Nayakshin 2011)*
- Evaporated hot-jupiters? *(e.g. Baraffe et al. 2004)*

Hints from the observations: the period distribution

Comparison of period distribution for planets with mass below 5 $M_{Jupiter}$ separated in two groups: mass above and below 2 $M_{Neptune}$ (35+116 planets, respectively)
Only "single" systems are considered (for P<10 days)





In brief...

- Jovian period distribution has average value of 3.5-days (sigma=1.6-days)
- Neptune period distribution has average value of 5.2 days (sigma=2.7-days)
- Statistically significantly different period distributions
- Confirmed with Kepler observations *(Latham et al. 2011)*
  - Previous studies have also shown that there seems to be a mass-period relation in giant transiting planets (e.g. *Mazeh et al. 2005, Southworth et al. 2007, Davis et al. 2009, Benitez-Llambay et al. 2011)*

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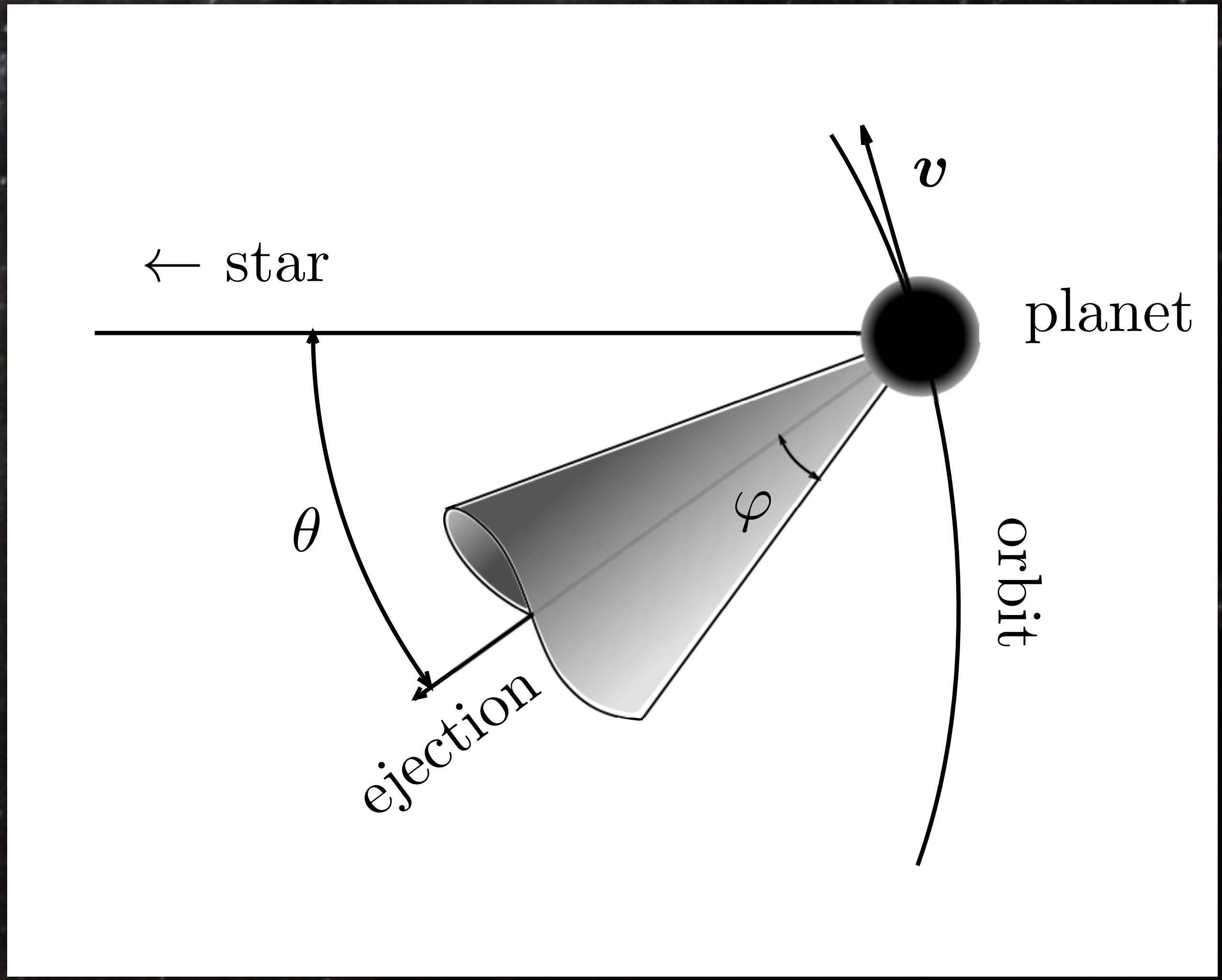
- *Can evaporation of a Jupiter into a Neptune explain the observed difference?*

The model: orbit evolution in a generic case where a planet is evaporating

- Define two parameters:
  - angle between star and direction of ejection (θ)
  - opening angle of the ejection stream (φ)
- Consider a given ejection velocity (V_{esc}): typical values are between 10-20 km/s *(Murray-Clay et al. 2009)*
- Assume circular orbit



$$\dot{m} = -\frac{B(t)}{r^2} ,$$

$$\kappa(t) = \eta(\varphi)\frac{B(t)}{m(t)}V_{\rm esc} ,$$

$$\frac{d\mathbf{e}}{dt} = -\left(\frac{\mathbf{r}}{r} + \mathbf{e}\right)\frac{\dot{\mu}}{\mu} + \frac{\kappa \sin\theta}{\mu r^3}(\ell \mathbf{r} + r^2 \mathbf{v} \times \mathbf{k}) ,$$

$$\eta(\varphi) = \frac{\int_0^\varphi \cos\varphi' \sin\varphi' \, d\varphi'}{\int_0^\varphi \sin\varphi' \, d\varphi'} = \frac{1+\cos\varphi}{2} = \cos^2\frac{\varphi}{2} .$$

$$\frac{1}{2}v^2 - \frac{\mu(t)}{r} = -\frac{\mu(t)}{2a} ,$$

$$m\frac{d\mathbf{v}_p}{dt} = -\frac{Gm_\star m}{r^3}\mathbf{r} + \dot{m}\mathbf{V}_{\rm str} ,$$

$$m_\star\frac{d\mathbf{v}_\star}{dt} = +\frac{Gm_\star m}{r^3}\mathbf{r} ,$$

$$\mathbf{e} = \frac{\mathbf{v} \times (\mathbf{r} \times \mathbf{v})}{\mu(t)}$$

$$\mu(t) = G(m_\star + m(t)) .$$

$$\frac{d\mathbf{v}}{dt} = -\frac{\mu(t)}{r^3}\mathbf{r} + \sin\theta\frac{\kappa(t)}{r^3}\mathbf{k} \times \mathbf{r} ,$$

A few equations later...

$$\tau = \eta(\varphi)\sin\theta\frac{V_{\rm esc}}{v_0}$$

$$B(t) = -a^2 \langle \dot{m} \rangle_M .$$

$$\left\langle \frac{d\mathbf{e}}{dt} \right\rangle_M = \frac{n\kappa \sin\theta}{\mu(1+\sqrt{1-e^2})}\mathbf{e} .$$

$$P = P_0\left(1 - \tau \ln\frac{m_0}{m}\right)^{-3} .$$

$$\left\langle \frac{da}{dt} \right\rangle_M = -2\tau\frac{v_0}{v}\frac{\langle \dot{m} \rangle_M}{m}a .$$

$$B(t) = \frac{3}{16\pi}\left(\frac{R_X}{R_p}\right)^2 \frac{\varepsilon L_{XUV}}{\ldots} .$$

$$\frac{da}{dt} = a\left(1 - 2\frac{a}{r}\right)\frac{\dot{\mu}}{\mu} + 2\frac{a^2\kappa\ell}{\mu r^3} ,$$

$$\frac{da}{dt} = -\frac{\dot{m}}{m+m_\star}a - 2\tau\frac{v_0}{v}\frac{\dot{m}}{m}a ,$$

$$\left\langle \frac{da}{dt} \right\rangle_M = -a\frac{\dot{\mu}}{\mu} + 2\frac{na\kappa \sin\theta}{\mu(1-e^2)} ,$$

$$\frac{P_{\rm Nep}}{P_{\rm Jup}} = \left(1 - \tau \ln\frac{M_{\rm Jup}}{M_{\rm Nep}}\right)^{-3} .$$

$$a = a_0\left(1 - \tau \ln\frac{m_0}{m}\right)^{-2} ,$$

$$\kappa \sin\theta = -\tau v_0 a^2 \frac{\langle \dot{m} \rangle_M}{m} .$$

$$\left\langle \frac{da}{dt} \right\rangle_M = -a\frac{\dot{\mu}}{\mu} + 2\frac{na\kappa \sin\theta}{\mu} , \qquad \left\langle \frac{de}{dt} \right\rangle_M = 0 .$$

Model results

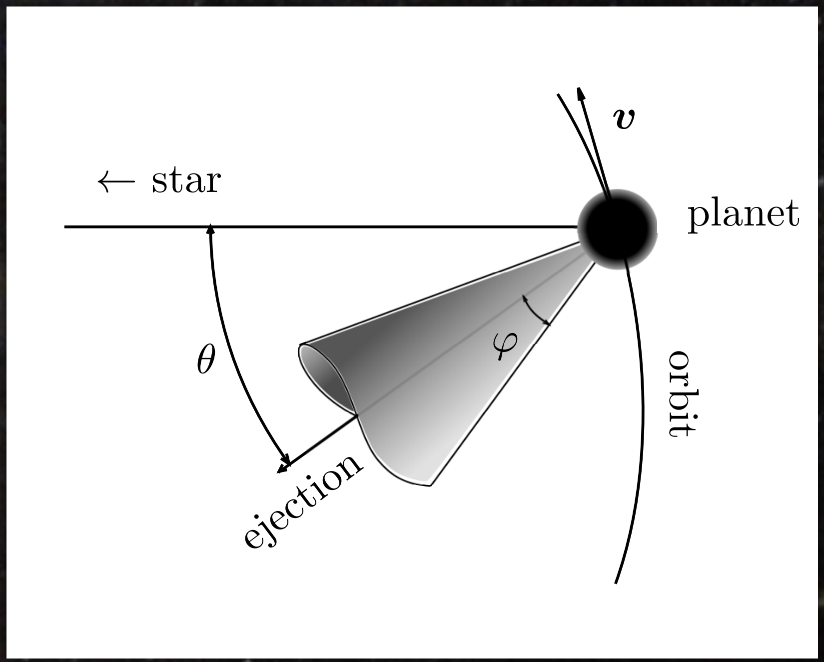
- It can be shown that under such conditions, the evolution of the orbit is given by:

$$\frac{da}{dt} = -\frac{\dot{m}}{m_\star + m} a - 2\tau \frac{v_0}{v} \frac{\dot{m}}{m} a \ ,$$

Where the "migration efficiency" parameter τ is defined as:

$$\tau = \cos^2 \frac{\varphi}{2} \sin\theta \frac{V_{\rm esc}}{v_0} \ .$$

- If evaporation is isotropic (φ=180°) or radial (θ=0°), no migration occurs
- Maximum efficiency for collimated evaporation with θ=90°



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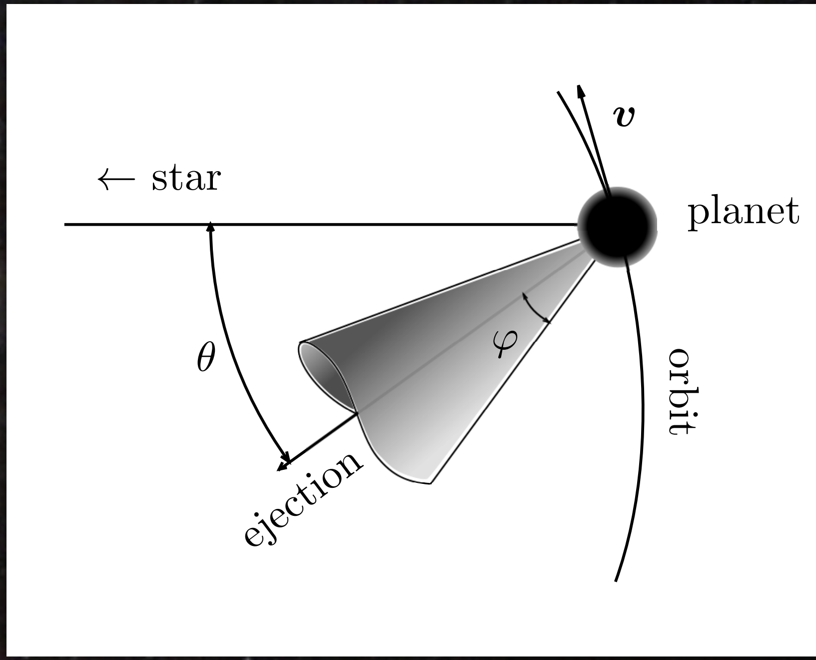
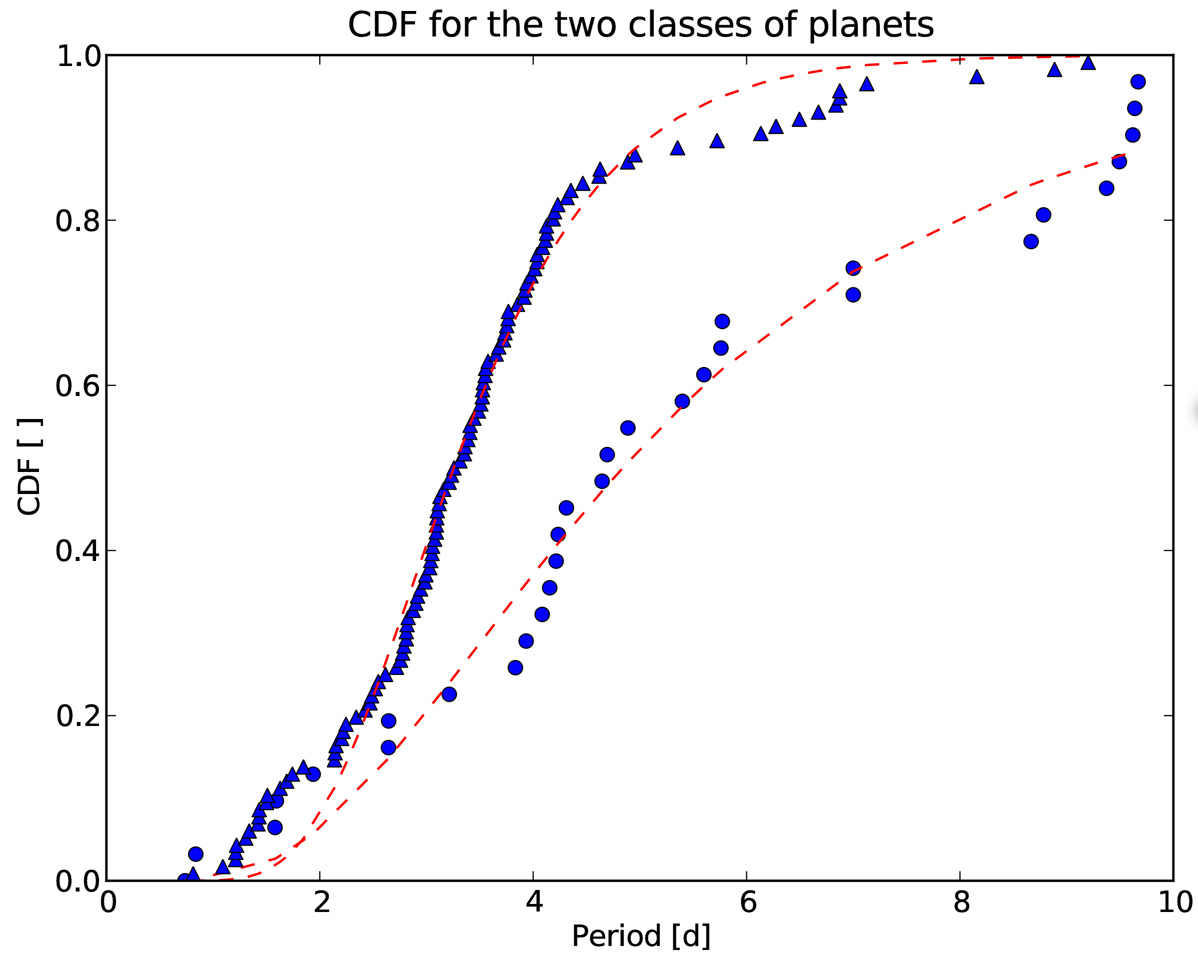


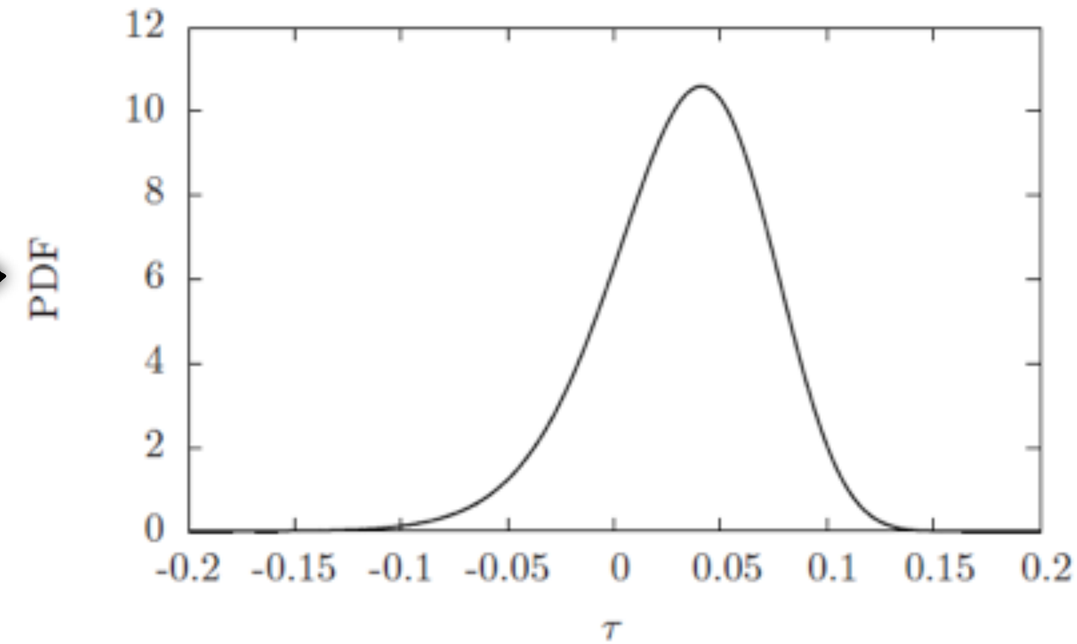
- The equation above implies that the initial and final periods of a neptune that is the result of an evaporated hot jupiter are related by:

$$\frac{P_{\rm Nep}}{P_{\rm Jup}} = \left(1 - \tau\ln\frac{M_{\rm Jup}}{M_{\rm Nep}}\right)^{-3} \ ,$$

The distribution of τ

Using the observed period distributions (assuming log-normal distributions) and the equation above, we can constrain the probability distribution function of τ





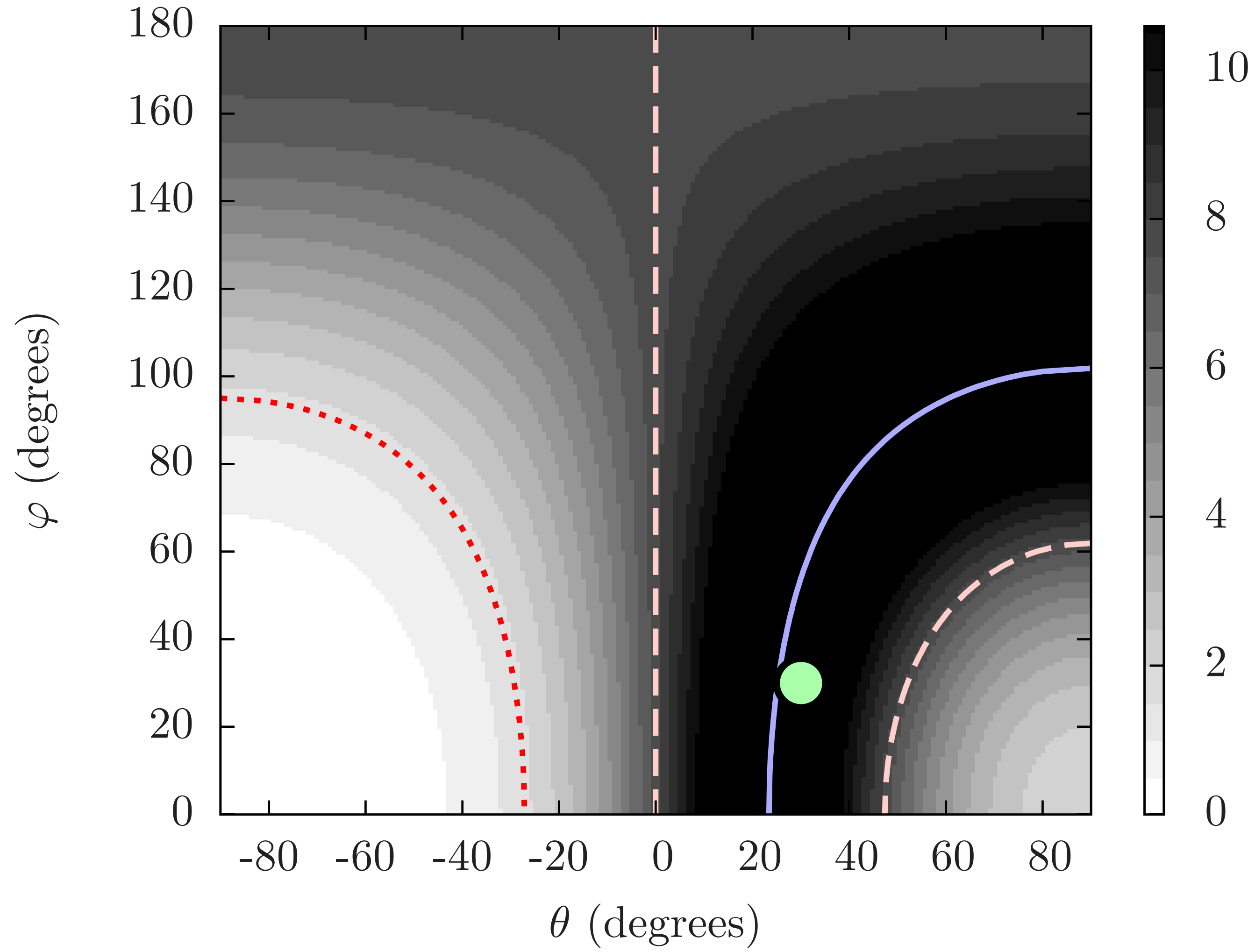
The distribution of τ

PDF of τ in the θ-φ diagram assuming:

V_{esc}=15 km/s (intermediate value)

v_0=145m/s (P=3.2days)

$$\tau = \cos^2 \frac{\varphi}{2} \sin\theta \frac{V_{\rm esc}}{v_0} \; .$$



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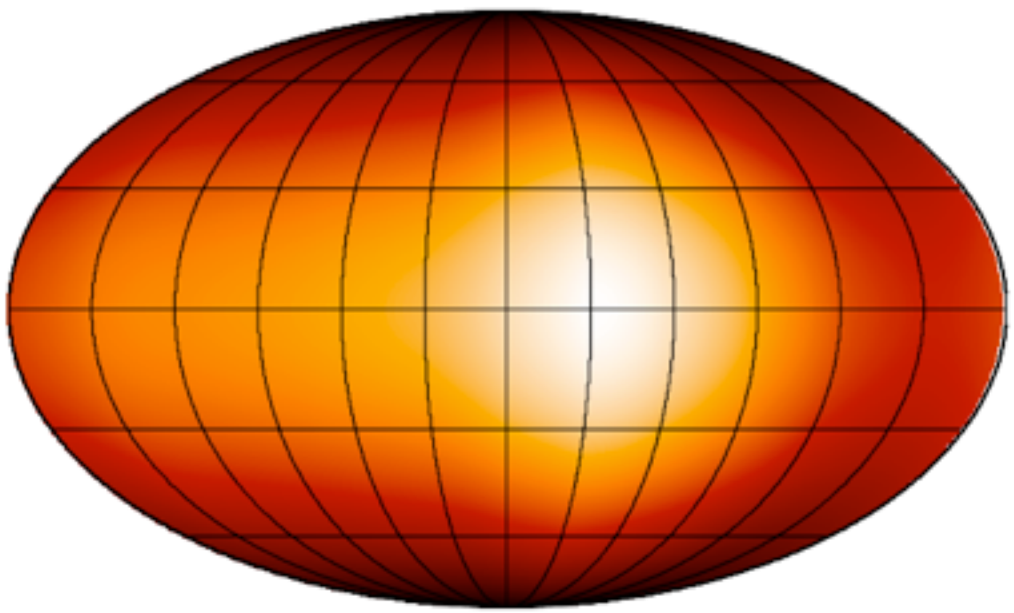

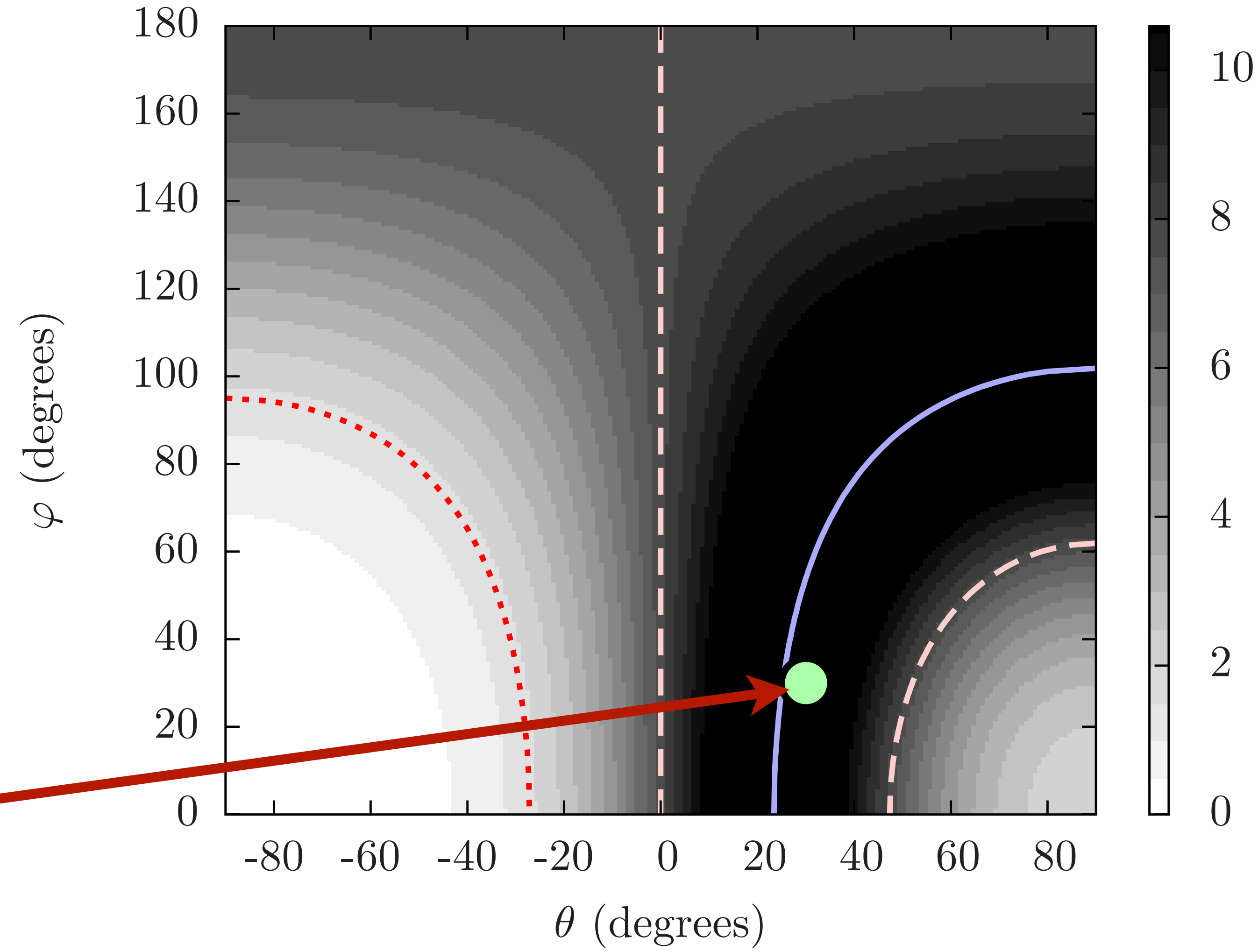

Estimated hot spot position of HD189733b
(Knutson et al. 2007)

Some remarks...

- The necessary evaporation properties may indeed exist in the real world:
  - Hot spots - not necessarily oriented towards the star - have been observed and predicted *(Knutson et al. 2007, Showman et al. 2011)*
  - Planets may have time to evaporate
    - If star is young (T Tauri), there may be enough radiation to explain the escape velocities needed *(Ribas et al. 2005, Murray-Clay et al. 2009)*
    - If the planet is young (bloated) evaporation times may be short enough! *(Mordasini et al. 2009, Erkaev et al. 2007)*

Conclusions

- We present a model that explains the formation of hot-neptunes as evaporated hot-jupiters
- Model naturally explains the different observed period distributions
- Model is time-independent: only depends on total ejected mass and on the geometry of the ejection

Thank you!

For details: Boué et al. 2011 (today in astro-ph)

With the support from: