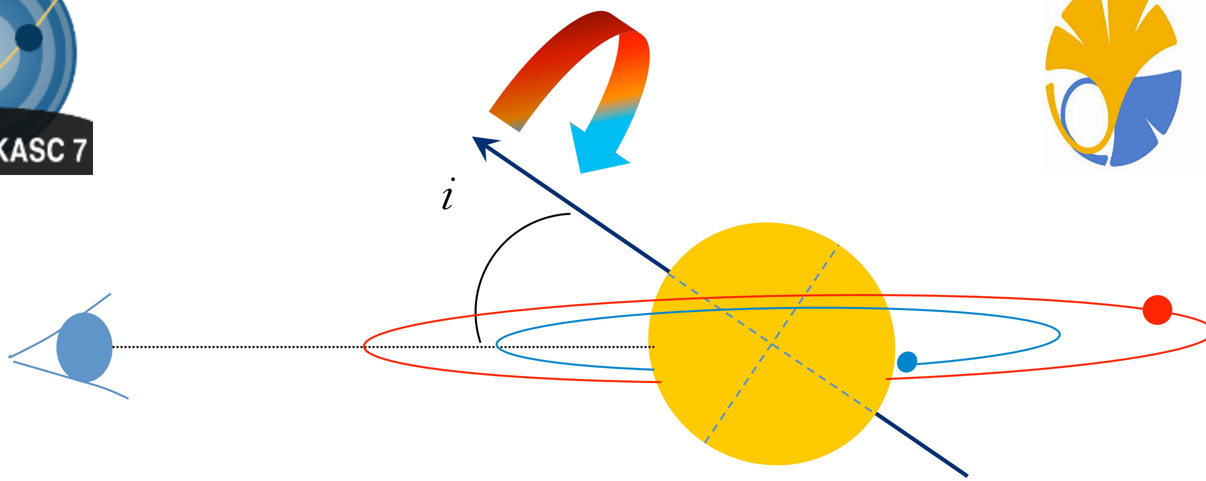
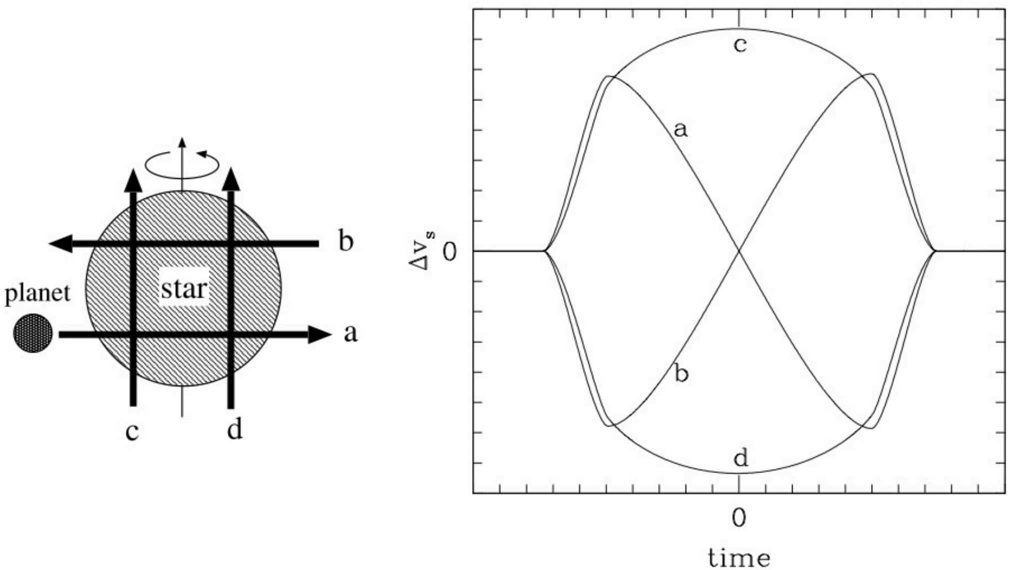


Three dimensional spin-orbit determination: joint analysis by asteroseismology, transit lightcurve and Rossiter-McLaughlin effect

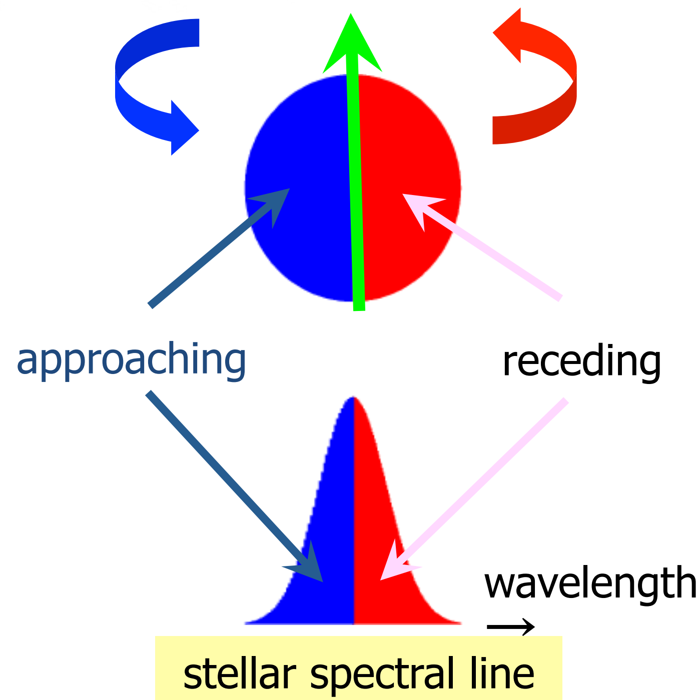
Benomar et al. (2014), accepted in PASJ

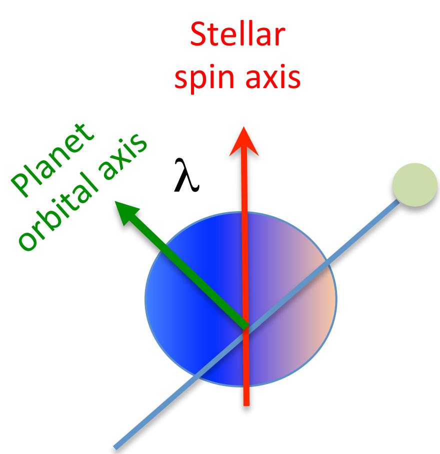
In collaboration with: Kento Masuda, Hiromoto Shibahashi, Yasushi Suto

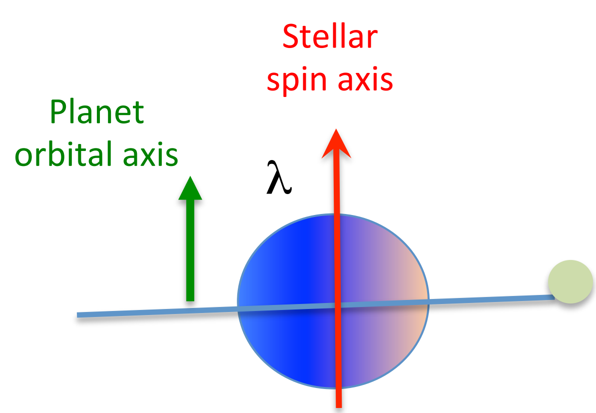
Rossiter McLaughlin effect



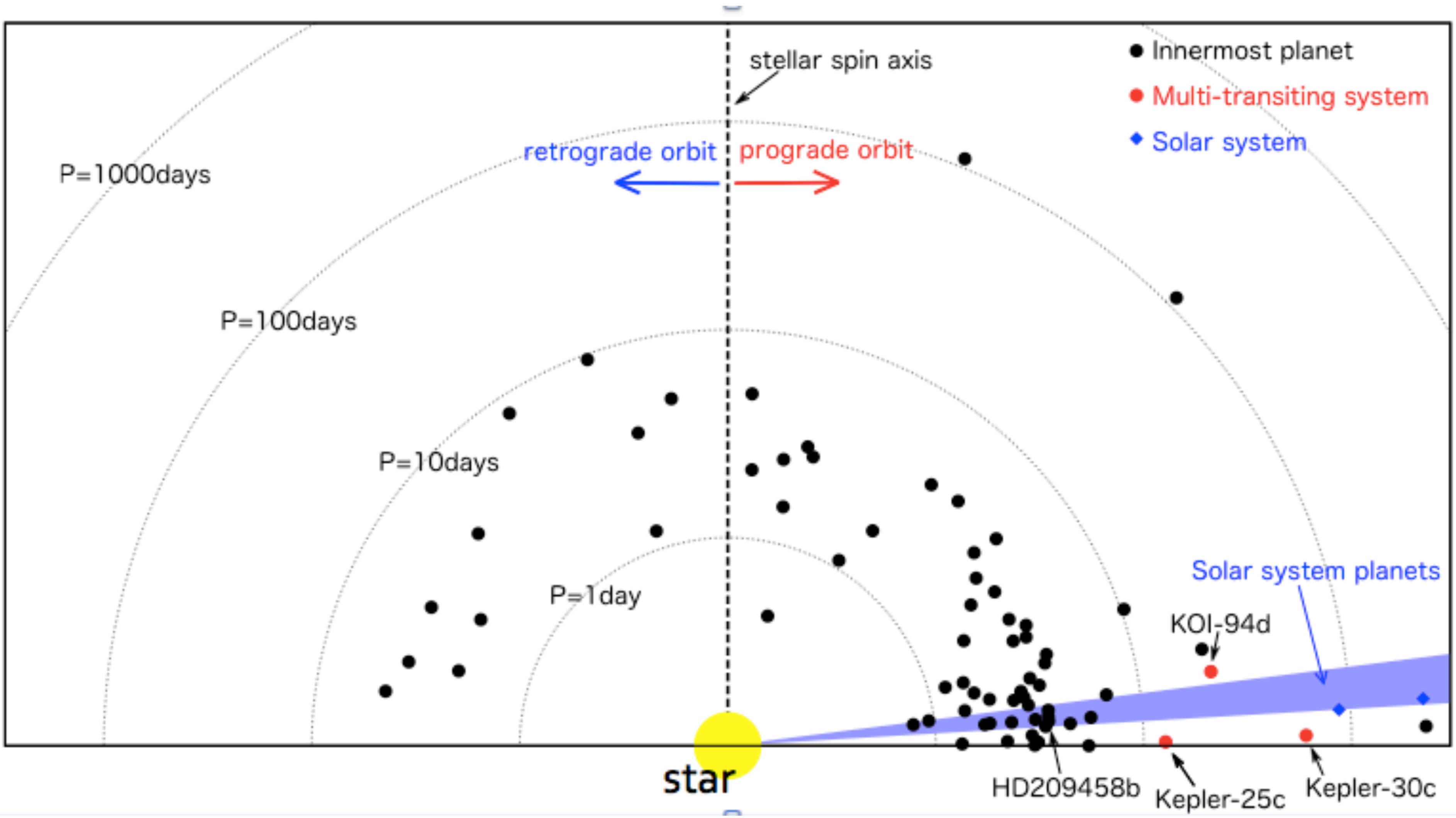
Ohta, Taruya & Suto, 2005





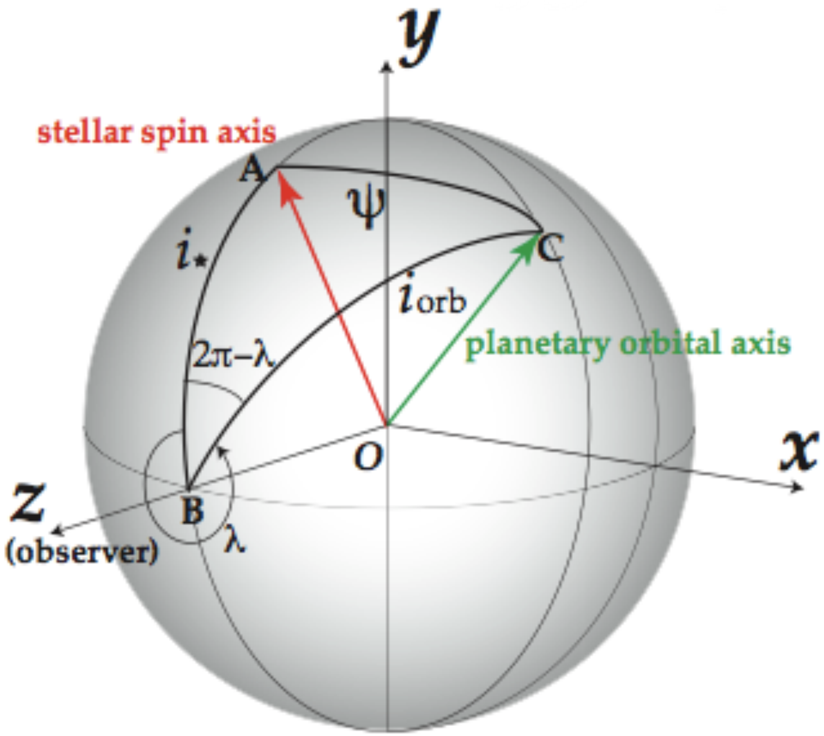


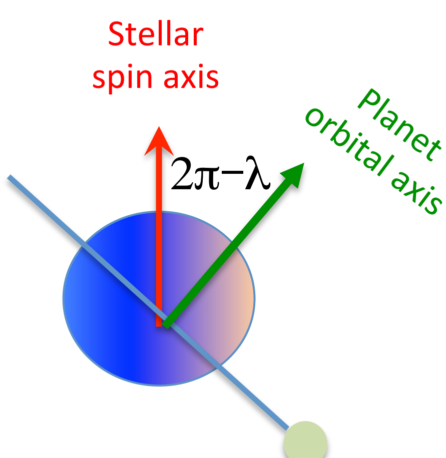
Proxy of misalignment using RM effect (λ)



Xue et al. (2014)

3D spin-orbit angle





Ψ : Planet orbital plan relative to the stellar spin axis

λ : Projection of Ψ into the sky plane

i_{orb}: angle between the orbital plan and the observer

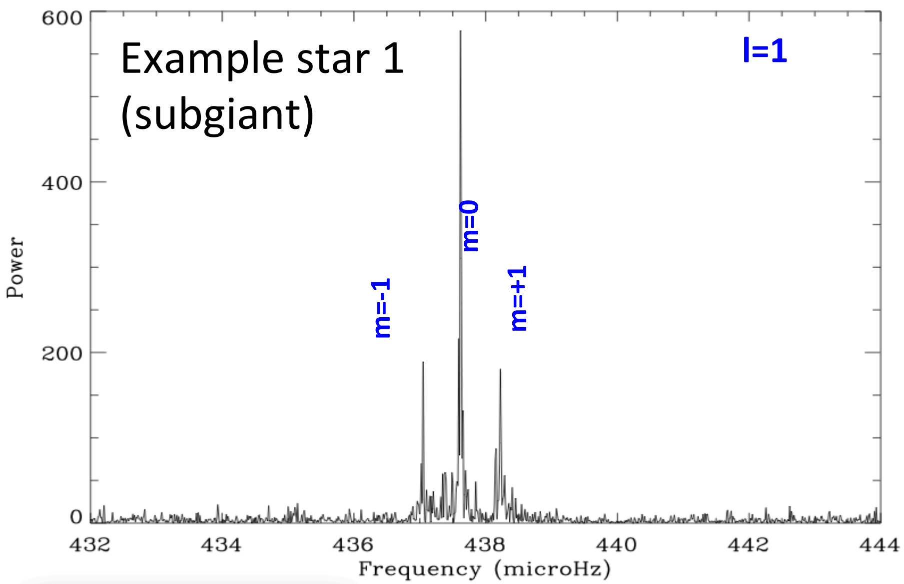
i_* : angle between observer and stellar spin axis

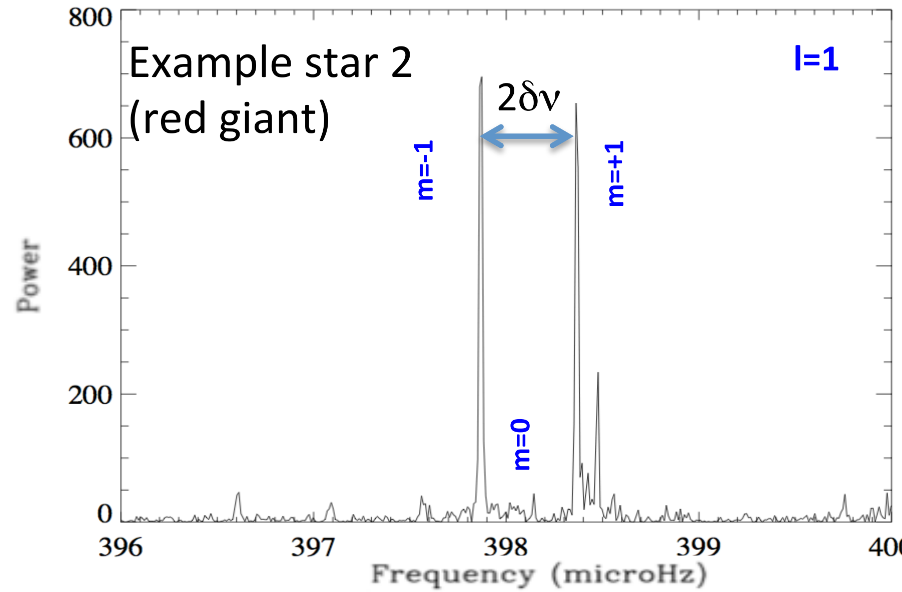
<u>Observations give us:</u>

- λ: Rossiter Mclaughin effect
- i_{orb}: The transit imposes i_{orb} ~ 90 degree
- i_* : Asteroseismology

Measure of the stellar inclination

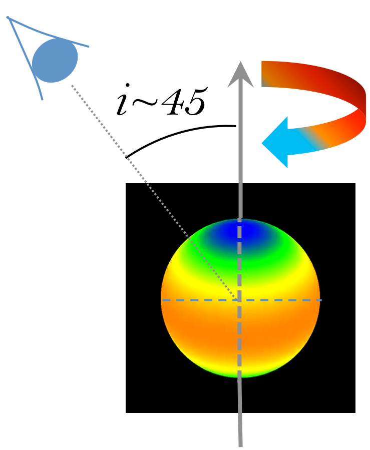
$$\nu_{n,l,m} = \nu_{n,l,0} + m\delta\nu_{n,l}$$

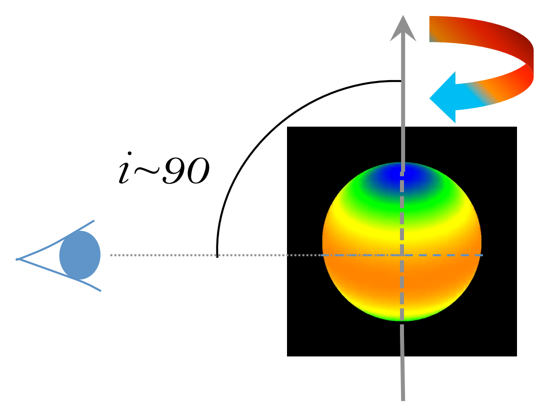




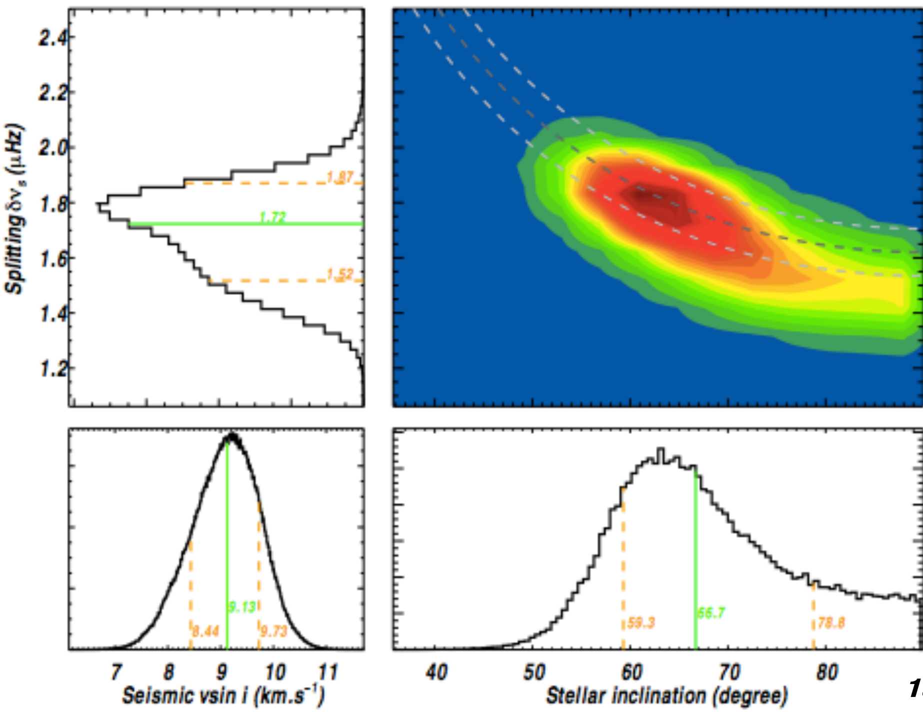
Why different amplitudes for the m-components of these l=1?

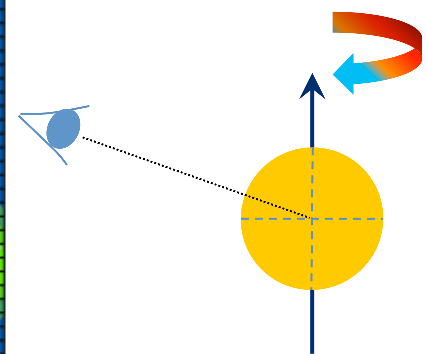
The star seen from different point of views





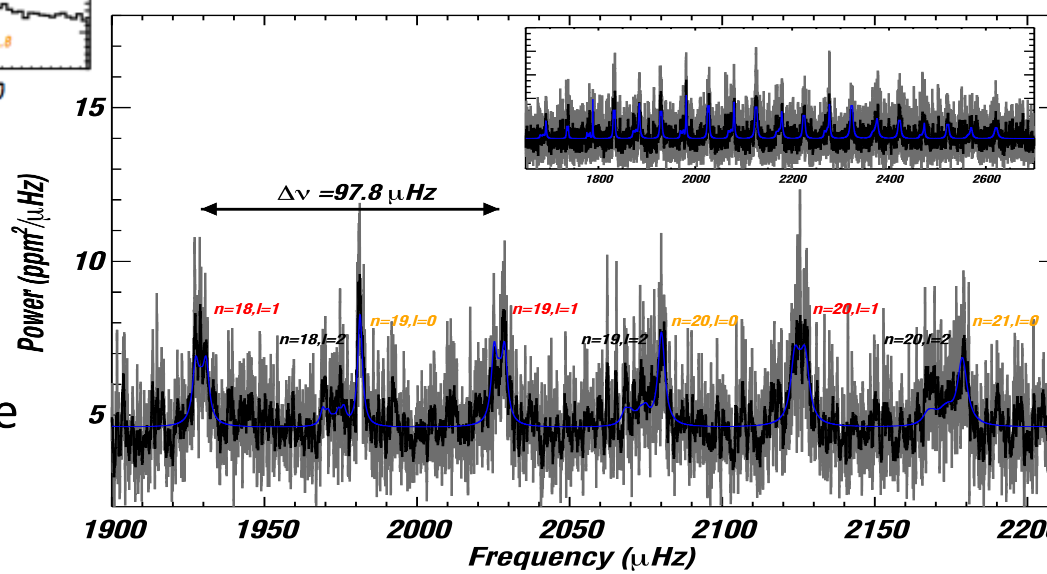
Kepler 25: Two neptunes in transit + one non-transiting planet





i_*~65 degree

M=1.26 +/- 0.03 Msun
R= 1.34 +/- 0.01 Rsun
Age=2.75 +/- 0.30 Gyrs



- vsini (Marcy et al. 2014) compatible with maximum of joint-probability

Kepler 25: Two neptunes in transit + one non-transiting planet

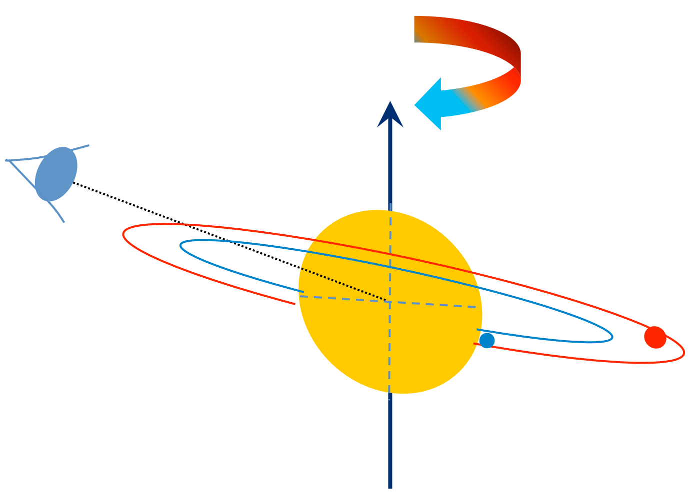
$i_* = 65.4^{+10.6}_{-6.4}$ degree

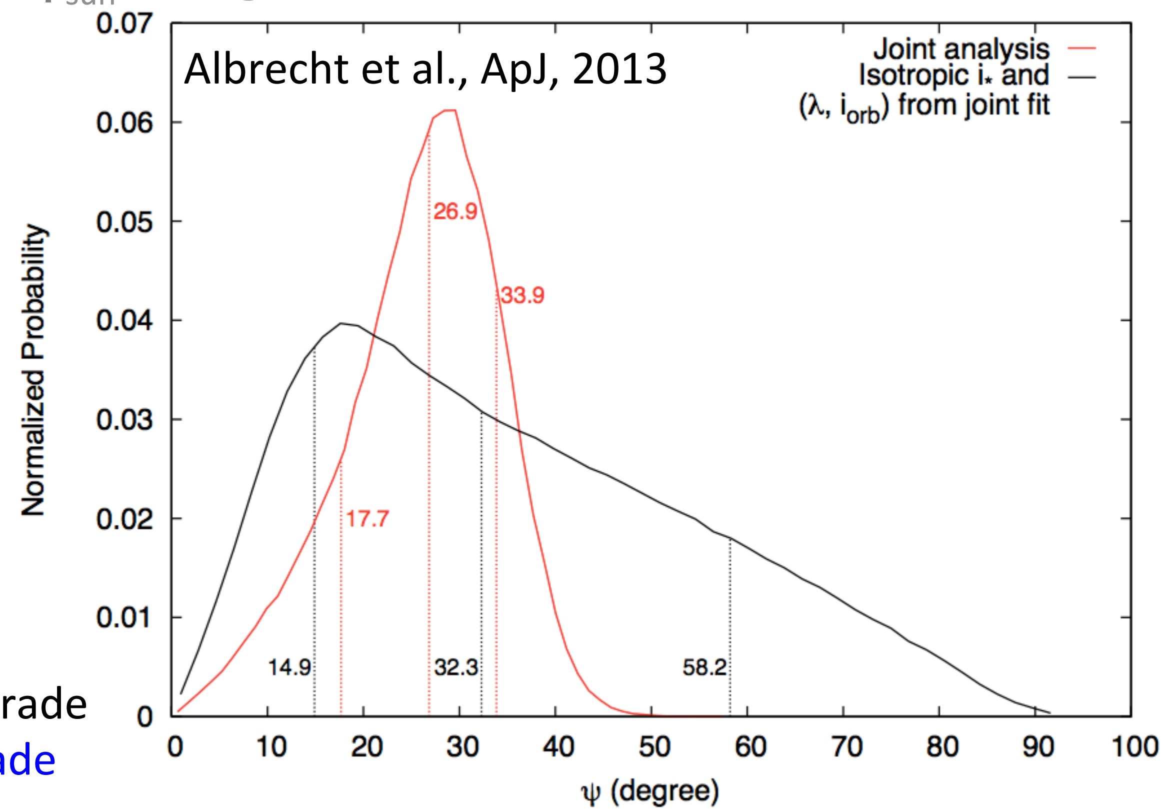
$\cos i_{orb} \sim 0.04788(38)$

$\lambda \sim 9.4 \pm 7.1$ (reanalysis of RM from Albrecht et al. 2013) ➔ suggests a flat system

$\psi \sim 26.9^{+7.0}_{-9.2}$ degree ➔ Not so flat!

$\psi_{sun} \sim 7$ degree

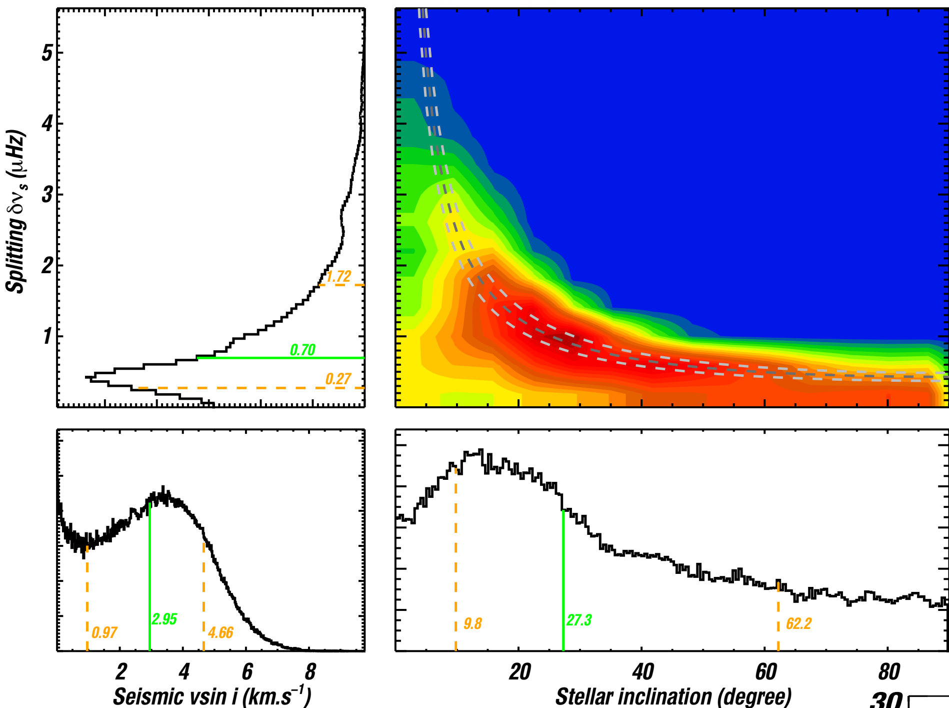


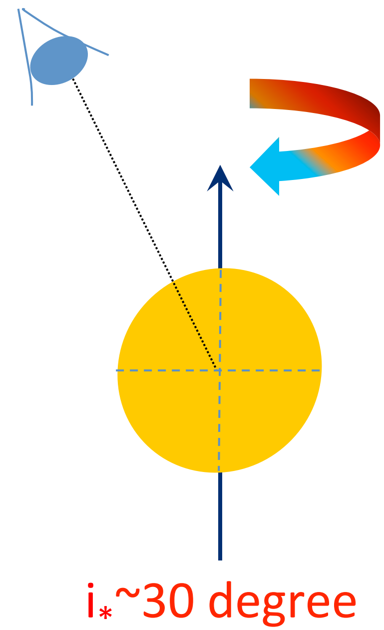


➔ If $|\Psi|>90$ then the orbit is retrograde

➔ If $|\Psi|<90$ then the orbit is prograde

HAT-P-7: a system with a hot Jupiter





M=1.59 +/- 0.03 Msun

R= 2.02 +/- 0.02 Rsun

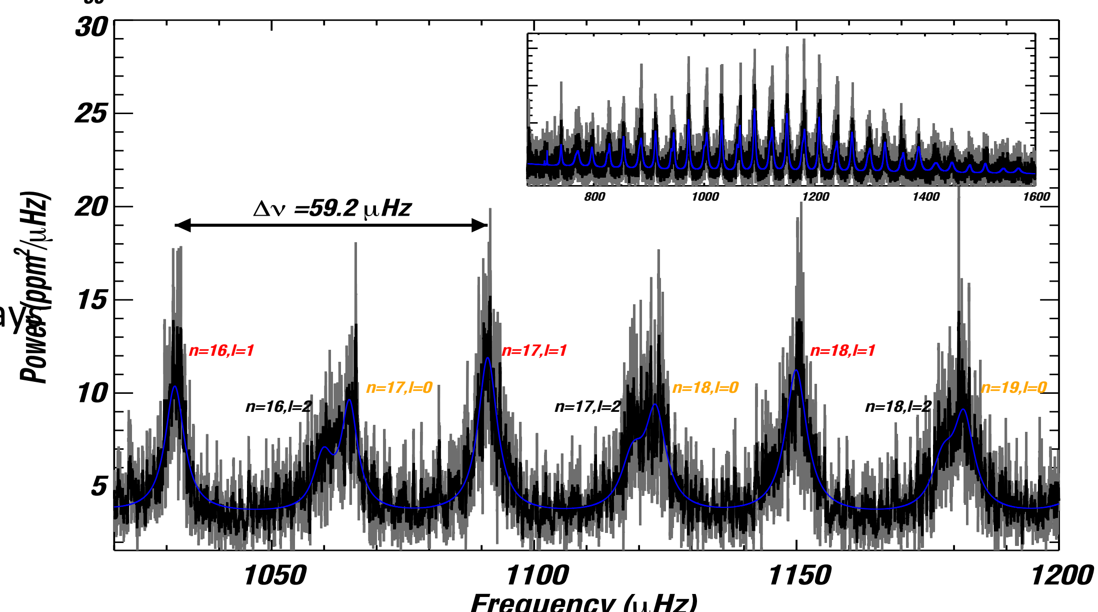
Age=1.7 +/- 0.1 Gyrs

Weak constrain on i_*:

Broad modes

Rotation unusually slow for a F-star : ~ 16 days

- ➔ Modes overlap!
- ➔ Hard to disentangle l=0, 2
- ➔ Hard to disentangle m-components



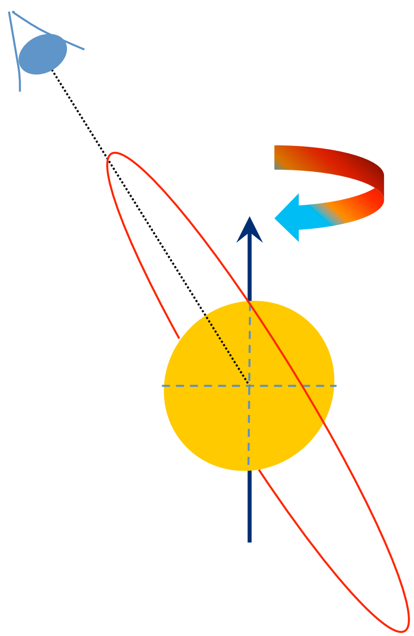
HAT-P-7: a system with a hot Jupiter

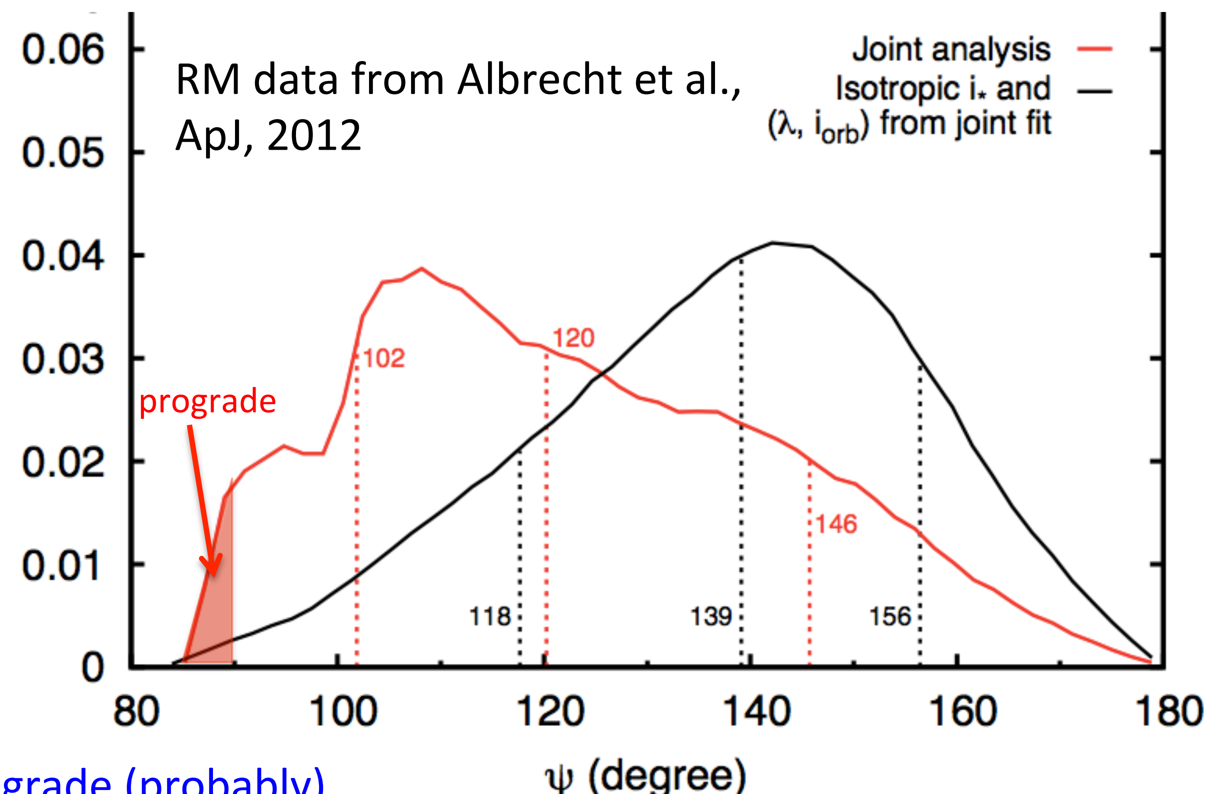
$i_* = 33^{+34}_{-20}$ degree

$\cos i_{orb} \sim 0.12145(81)$

λ ~ [157 – 220] (depends RM data) degree ➔ suggests a oblique, retrograde system

$\psi \sim 120^{+26}_{-18}$ degree ➔ quasi-polar orbit





➔ If |Ψ|>90 then the orbit is retrograde (probably)

➔ If |Ψ|<90 then the orbit is prograde (possible)

Conclusion

- If for a system we have:
  - The Rossiter McLaughlin effect
  - A transiting planet
  - Solar-like pulsations

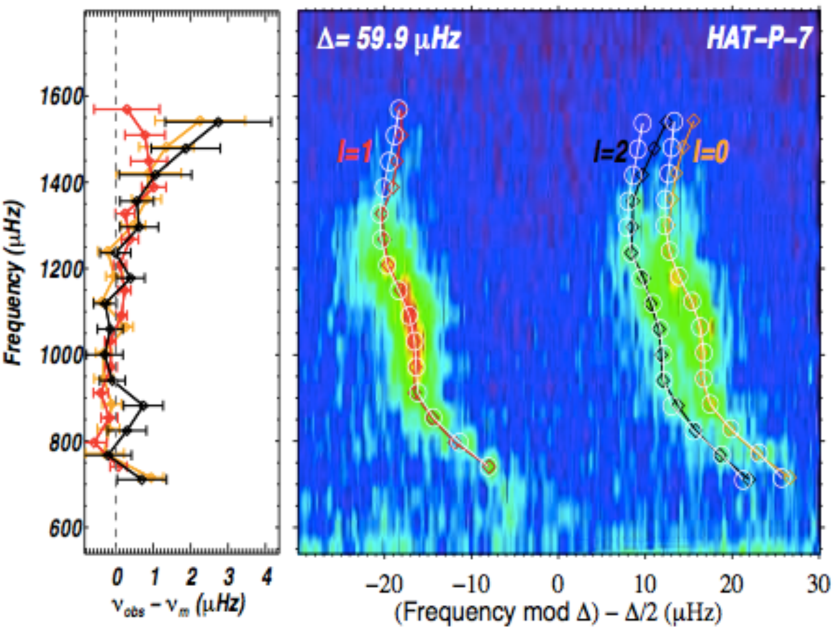
➔ Measure of the true spin-orbit is possible

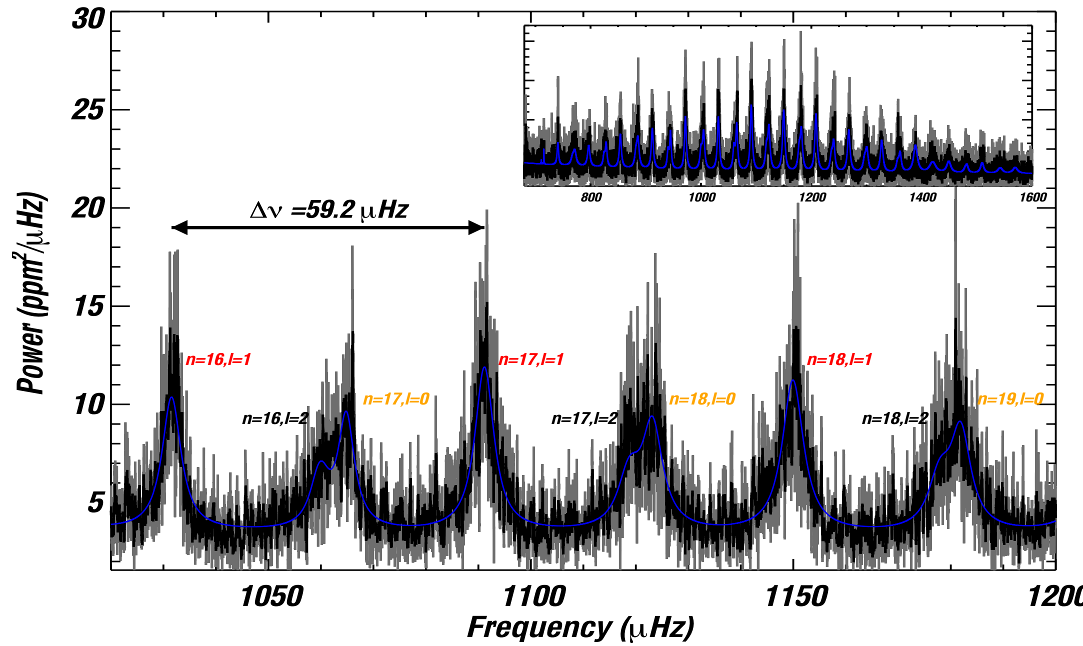
- Kepler 25:
  - Is the first system with multiple planets and a MS star to show significant obliquity
  - Only two systems with multiple planets are known to have high obliquities (Huber et al. 2013) ➔ Hard to conclude about the cause of obliquity in multiplanet systems.
- HAT-P-7:
  - Very likely to be on a quasi-polar orbit
  - Likely to be on a retrograde orbit but cannot rule out a prograde orbit

END

Questions?

HAT-P-7: a system with a hot Jupiter

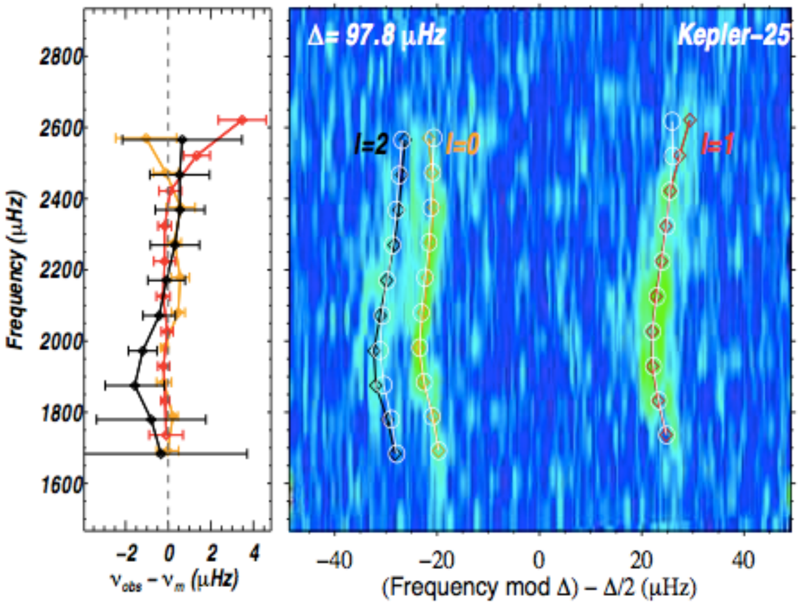


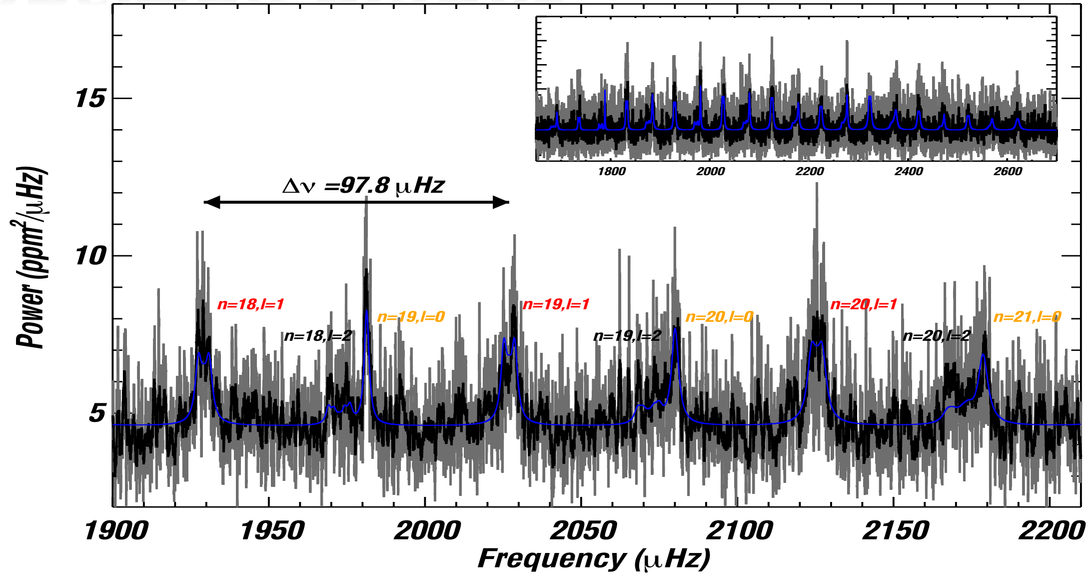


parameter	HAT-P-7
$M_\star$ $(M_\odot)$	1.59 ± 0.03
$R_\star$ $(R_\odot)$	2.02 ± 0.01
[Fe/H]	0.32 ± 0.04
$T_{\rm eff}$ (K)	6310 ± 15
Age (Myrs)	1770 ± 100
$\alpha_{\rm ov}$	$0.000^{+0.002}_{-0.000}$
$L/L_\odot$	5.84 ± 0.05
$\log g$ (cgs)	4.029 ± 0.002
$\rho_{\star,\rm m}$ $(10^3\,{\rm kg\,m^{-3}})$	0.2708 ± 0.0035
$\rho_{\star,\rm s}$ $(10^3\,{\rm kg\,m^{-3}})$	0.2696 ± 0.0011
reduced χ^2	1.73

- Modeling with MESA using:
  - Eigenfrequencies (this analysis, Q0-Q16)
  - Teff, [Fe/H], log(g), L/Lsun from Pal et al. (2008)

Kepler 25: Two neptunes in transit + one non-transiting planet

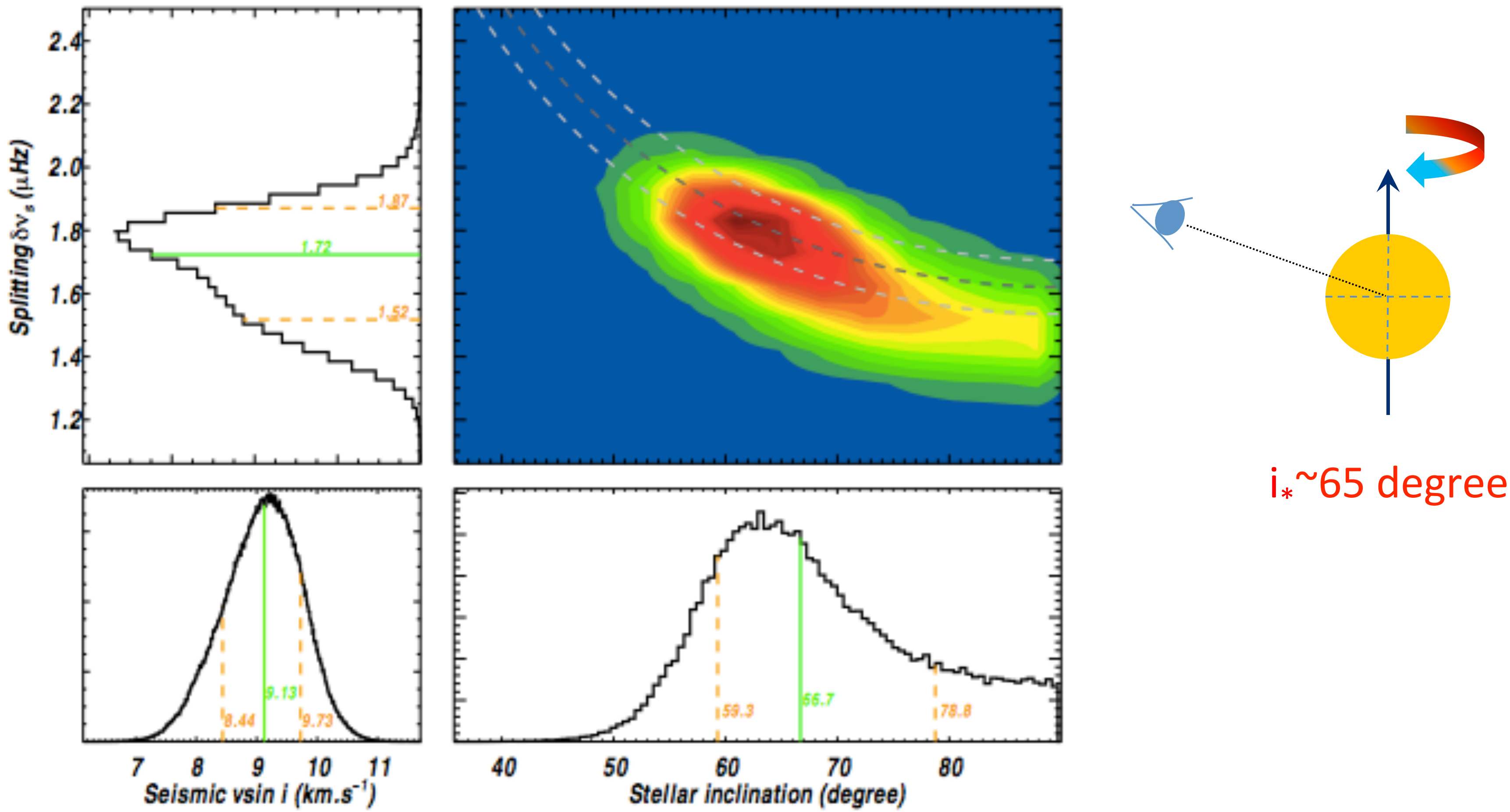




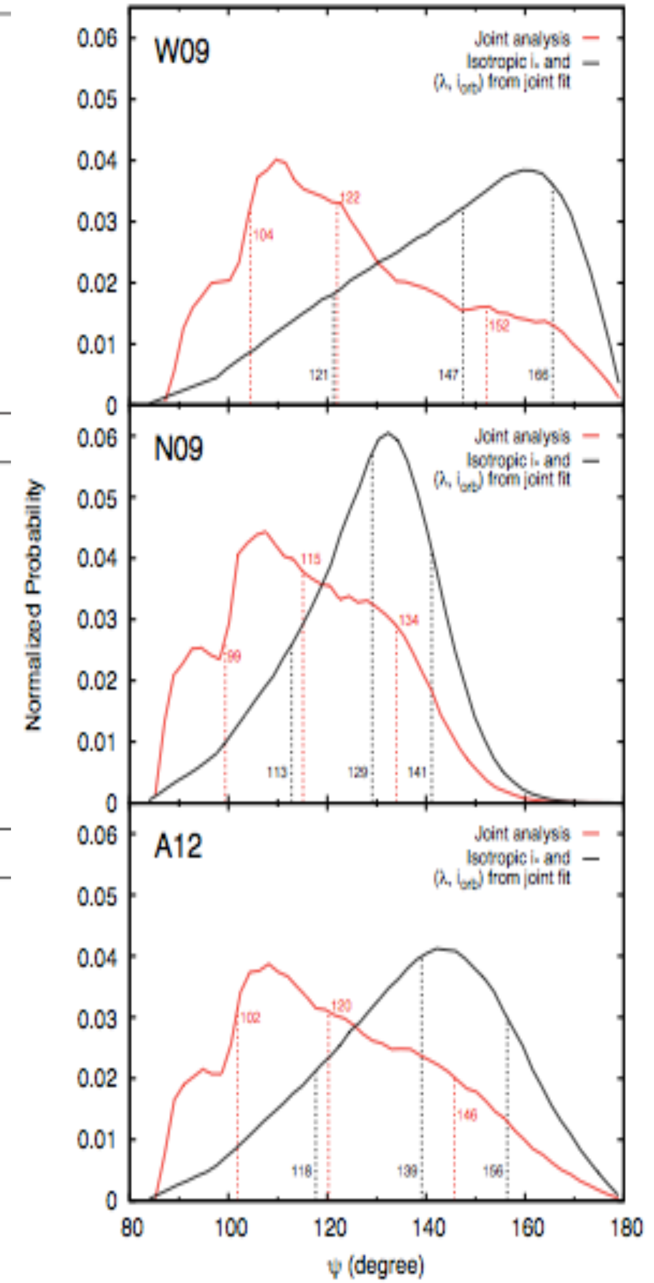
parameter	Kepler-25
$M_\star$ ($M_\odot$)	1.26 ± 0.03
$R_\star$ ($R_\odot$)	1.34 ± 0.01
[Fe/H]	0.11 ± 0.03
$T_{\rm eff}$ (K)	6354 ± 27
Age (Myrs)	2750 ± 300
$\alpha_{\rm ov}$	0.007 ± 0.003
$L/L_\odot$	2.64 ± 0.07
$\log g$ (cgs)	4.285 ± 0.003
$\rho_{\star,\rm m}$ ($10^3\,\rm kg\,m^{-3}$)	0.7367 ± 0.0137
$\rho_{\star,\rm s}$ ($10^3\,\rm kg\,m^{-3}$)	0.7356 ± 0.0030
reduced χ^2	1.03

- Modeling with MESA using:
  - Eigenfrequencies (this analysis, Q5-Q16)
  - Teff, [Fe/H], log(g)   from Marcy et al. (2014)

Kepler 25: Two neptunes in transit + one non-transiting planet



Parameter	Value (W09)	Value (N09)	Value (A12)
Parameters mainly derived from lightcurves (transit, occultation, asteroseismology)			
t_0(BJD) − 2454833		$121.3585049 \pm 0.0000049$	
P (days)		$2.204735427 \pm 0.000000013$	
$e\cos\omega$	0.00024 ± 0.00020	0.00024 ± 0.00020	0.00025 ± 0.00020
$e\sin\omega$	$0.0053^{+0.0022}_{-0.0021}$	$0.0057^{+0.0025}_{-0.0026}$	$0.0049^{+0.0026}_{-0.0030}$
u_1	0.3540 ± 0.0034	$0.3544^{+0.0033}_{-0.0034}$	$0.3545^{+0.0034}_{-0.0035}$
u_2	$0.1670^{+0.0055}_{-0.0054}$	$0.1663^{+0.0055}_{-0.0053}$	$0.1661^{+0.0056}_{-0.0055}$
$\rho_\star$ ($10^3\,\mathrm{kg\,m^{-3}}$)	0.2736 ± 0.0016	$0.2731^{+0.0021}_{-0.0018}$	$0.2737^{+0.0024}_{-0.0018}$
$\cos i_{\rm orb}$	$0.12149^{+0.00056}_{-0.00057}$	$0.12166^{+0.00063}_{-0.00068}$	$0.12145^{+0.00061}_{-0.00081}$
$R_{\rm p}/R_\star$	$0.077589^{+0.000020}_{-0.000021}$	0.077593 ± 0.000020	$0.077591^{+0.000020}_{-0.000021}$
δ		0.01171 ± 0.00010	
$t_{\rm c,tra}$ (days)		$-0.0000044^{+0.0000041}_{-0.0000042}$	
$i_\star$ (°)	31^{+33}_{-16}	33^{+34}_{-20}	33^{+34}_{-20}
Parameters mainly derived from RVs			
$K_\star$ ($\mathrm{m\,s^{-1}}$)	211.7 ± 2.3	213.2 ± 1.8	214.0 ± 4.6
γ_1 ($\mathrm{m\,s^{-1}}$)	-15.5 ± 3.0	-37.5 ± 1.5	$10.4^{+1.5}_{-1.6}$
γ_2 ($\mathrm{m\,s^{-1}}$)	-9.7 ± 1.7	-16.9 ± 1.4	–
$\dot{\gamma}$ ($\mathrm{m\,s^{-1}\,yr^{-1}}$)	21.5 ± 2.5	–	–
λ (°)	186^{+10}_{-11}	$220.3^{+8.2}_{-9.3}$	157^{+14}_{-13}
$v\sin i_\star$ ($\mathrm{km\,s^{-1}}$)	$4.15^{+0.38}_{-0.39}$	3.17 ± 0.33	$3.17^{+0.33}_{-0.34}$
β ($\mathrm{km\,s^{-1}}$)		3.0 (fixed)	
γ ($\mathrm{km\,s^{-1}}$)		1.0 (fixed)	
ζ ($\mathrm{km\,s^{-1}}$)	5.3 ± 1.5	5.5 ± 1.5	5.5 ± 1.5
$u_{\rm 1RM} + u_{\rm 2RM}$		0.70 ± 0.10	
$u_{\rm 1RM} - u_{\rm 2RM}$		−0.23 (fixed)	
Derived quantities			
ψ (°)	122^{+30}_{-18}	115^{+19}_{-16}	120^{+26}_{-18}
$a/R_\star$	$4.1269^{+0.0082}_{-0.0078}$	$4.1245^{+0.0103}_{-0.0092}$	$4.1277^{+0.0121}_{-0.0090}$
transit impact parameter ($R_\star$)	0.4987 ± 0.0013	0.4989 ± 0.0013	$0.4988^{+0.0013}_{-0.0014}$
$T_{14,\rm tra}$ (days)	0.164301 ± 0.000022	0.164303 ± 0.000023	0.164300 ± 0.000023
$T_{23,\rm tra}$ (days)	$0.133042^{+0.000049}_{-0.000048}$	$0.133034^{+0.000047}_{-0.000048}$	$0.133037^{+0.000052}_{-0.000048}$
$T_{\rm tra}$ (days)	$0.148672^{+0.000025}_{-0.000024}$	0.148668 ± 0.000024	$0.148669^{+0.000025}_{-0.000024}$
occultation impact parameter ($R_\star$)	$0.5040^{+0.0022}_{-0.0023}$	$0.5047^{+0.0025}_{-0.0028}$	$0.5039^{+0.0024}_{-0.0033}$
$T_{14,\rm occ}$ (days)	$0.16555^{+0.00051}_{-0.00050}$	$0.16566^{+0.00058}_{-0.00061}$	$0.16547^{+0.00060}_{-0.00070}$
$T_{23,\rm occ}$ (days)	$0.13385^{+0.00034}_{-0.00033}$	$0.13392^{+0.00039}_{-0.00040}$	$0.13379^{+0.00041}_{-0.00046}$
$T_{\rm occ}$ (days)	$0.14970^{+0.00042}_{-0.00041}$	$0.14979^{+0.00048}_{-0.00051}$	$0.14963^{+0.00050}_{-0.00058}$
occultation depth (ppm)		70.5 ± 0.6	
$M_{\rm p}(M_{\rm J})$	1.86 ± 0.03	1.87 ± 0.03	1.88 ± 0.05
$R_{\rm p}(R_{\rm J})$		1.526 ± 0.008	
$\rho_{\rm p}$ ($10^3\,\mathrm{kg\,m^{-3}}$)	0.65 ± 0.01	0.66 ± 0.01	0.66 ± 0.02



Parameter	Value (A13)
Parameters mainly derived from lightcurves (transit, asteroseismology)	
$t_0(\mathrm{BJD}) - 2454833$	$127.646558^{+0.000096}_{-0.000094}$
P (days)	$12.7203724^{+0.0000014}_{-0.0000013}$
$u_1 + u_2$	0.550 ± 0.018
$u_1 - u_2$	-0.27 ± 0.44
$\rho_\star$ ($10^3\,\mathrm{kg\,m^{-3}}$)	$0.733^{+0.013}_{-0.012}$
$\cos i_{\mathrm{orb}}$	$0.04788^{+0.00036}_{-0.00038}$
$R_\mathrm{p}/R_\star$	$0.03590^{+0.00054}_{-0.00046}$
$i_\star$ (°)	$65.4^{+10.6}_{-6.4}$
Parameters mainly derived from RVs	
$K_{\star,2011}$ ($\mathrm{m\,s^{-1}}$)	-13 ± 22
$K_{\star,2012}$ ($\mathrm{m\,s^{-1}}$)	-37 ± 30
γ_{2011} ($\mathrm{m\,s^{-1}}$)	-3.5 ± 1.3
γ_{2012} ($\mathrm{m\,s^{-1}}$)	2.0 ± 1.4
λ (°)	9.4 ± 7.1
$v \sin i_\star$ ($\mathrm{km\,s^{-1}}$)	$9.34^{+0.37}_{-0.39}$
β ($\mathrm{km\,s^{-1}}$)	3.0 (fixed)
γ ($\mathrm{km\,s^{-1}}$)	1.0 (fixed)
ζ ($\mathrm{km\,s^{-1}}$)	4.9 ± 1.5
$u_{1\mathrm{RM}} + u_{2\mathrm{RM}}$	0.69 ± 0.10
$u_{1\mathrm{RM}} - u_{2\mathrm{RM}}$	-0.0297 (fixed)
Derived quantities	
ψ (°)	$26.9^{+7.0}_{-9.2}$
$a/R_\star$	18.44 ± 0.11
transit impact parameter ($R_\star$)	0.8826 ± 0.0018
$T_{14,\mathrm{tra}}$ (days)	0.11925 ± 0.00025
$T_{23,\mathrm{tra}}$ (days)	$0.08528^{+0.00065}_{-0.00069}$
T_{tra} (days)	$0.10226^{+0.00036}_{-0.00037}$