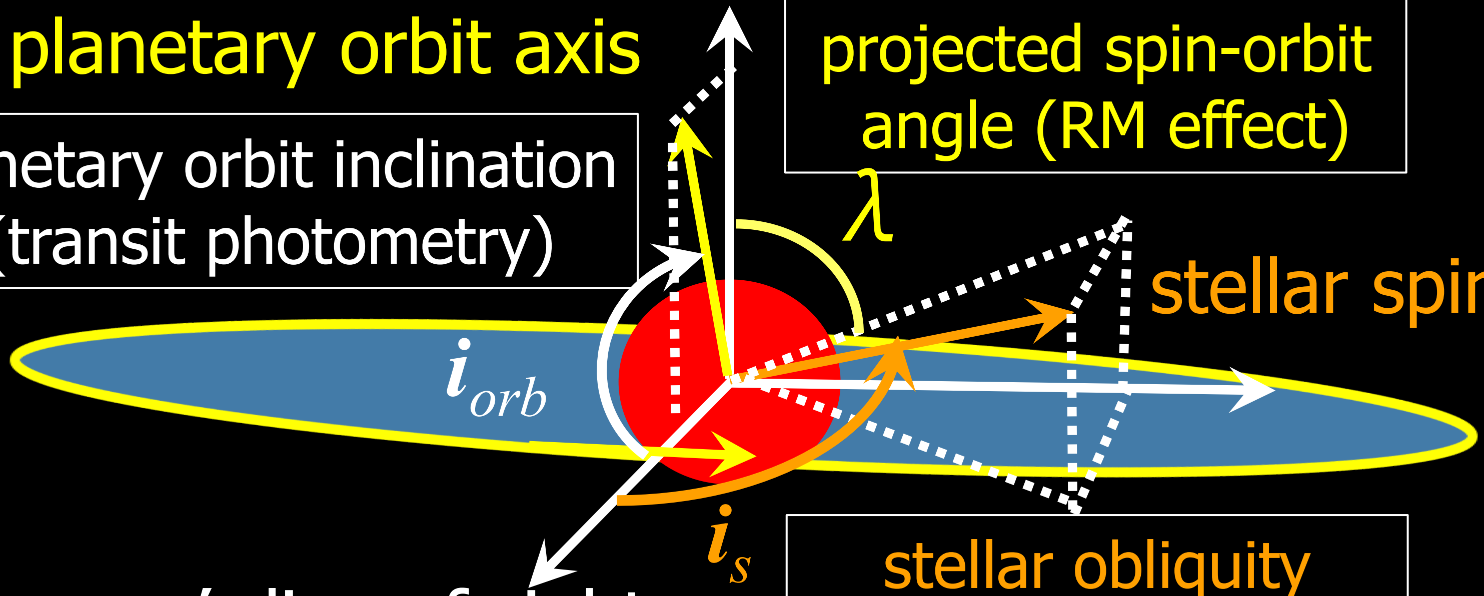
Reliability of the asteroseismic measurement of the stellar obliquity



planetary orbit axis

planetary orbit inclination
(transit photometry)

projected spin-orbit
angle (RM effect)

λ

stellar spin

i_{orb}

i_s

observer's line of sight

stellar obliquity
(asteroseismology)

Yasushi Suto

Department of Physics and RESCEU ,The University of Tokyo

"Asteroseismology and its impact on other branches of astronomy"
14:30-15:00 March 20, 2018 @ University of Tokyo

Spin-orbit (mis)alignment of exoplanetary systems

- Spin of the Sun and orbital angular momenta of Solar planets are aligned within several degrees
  - Primordial alignment between the central star and the proto-planetary disk
  - Subsequent quiescent dynamical evolution to keep the initial architecture
- Is this alignment universal or exceptional ?

I thought that spin-orbit misalignment for exoplanets is very unlikely

- Queloz et al. (2000)
  - First RM result for HD209458

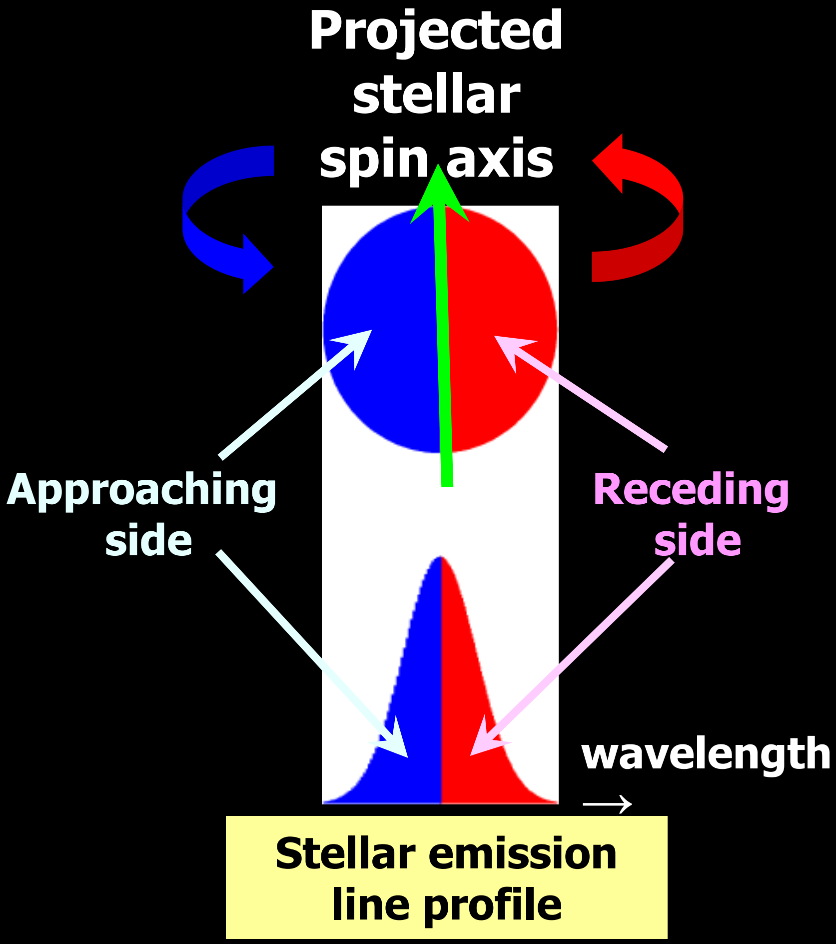
$$\alpha = \pm 3.9^{\circ}{}^{+18^{\circ}}_{-21^{\circ}}$$

- Ohta, Taruya + YS (2005)
  - Perturbative analytic formula for the RM effect
  - spin-orbit angle should be small according the standard planet formation (Hayashi) model
  - If not, it indicates a new non-standard formation channel for exoplanets
- Winn et al. (2005)

$$\lambda = -4.4^{\circ} \pm 1.4^{\circ}$$

  - Significantly improved the RM measurement accuracy for HD209458 on the basis of OTS approach

Spectroscopic transit signature: the Rossiter-McLaughlin effect



Projected stellar spin axis

Approaching side

Receding side

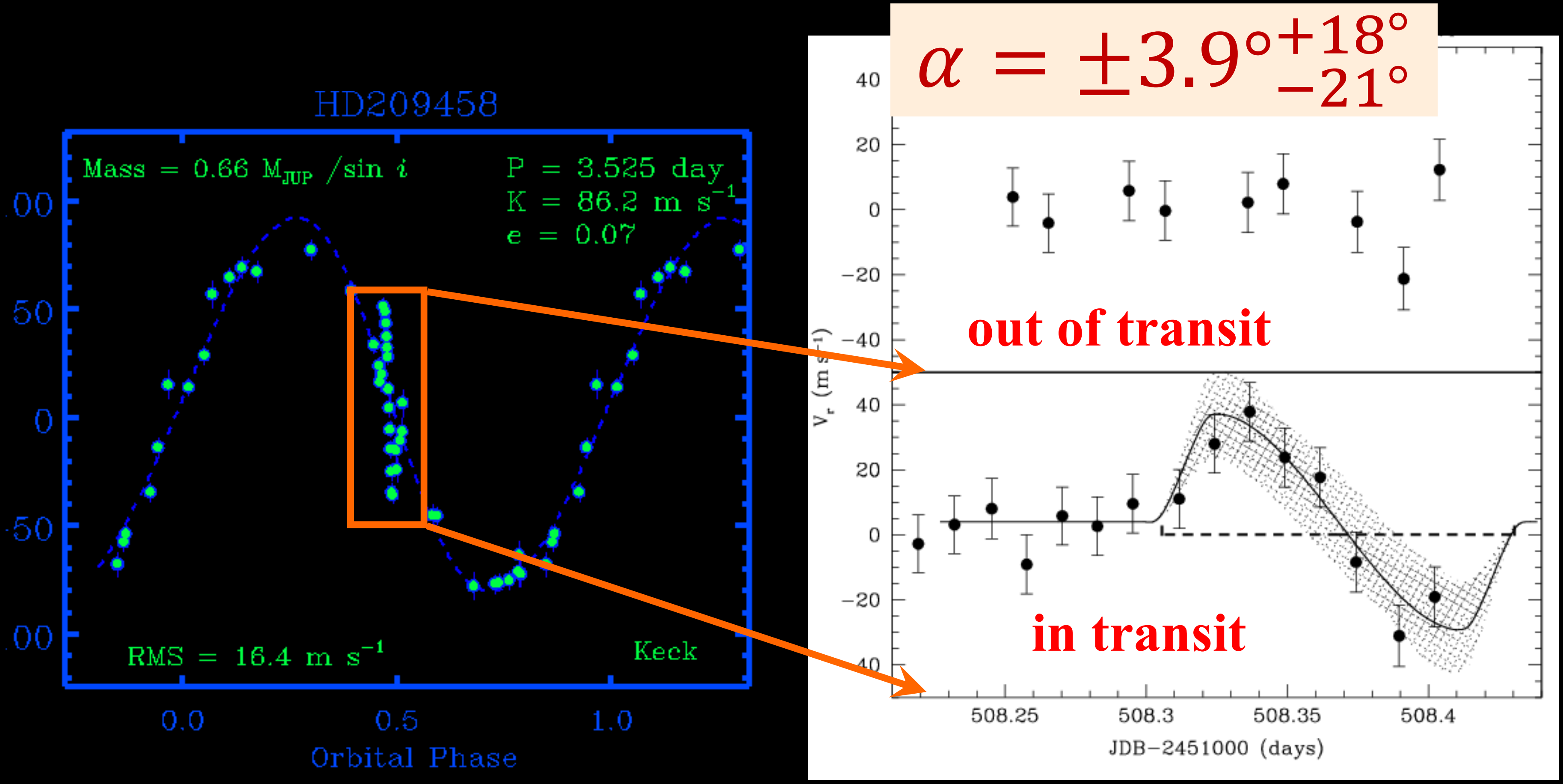
wavelength →

Stellar emission line profile

- Time-dependent asymmetry in the stellar Doppler broadened line profile
  - apparent anomaly of the stellar radial velocity
- originally proposed for eclipsing binaries

Holt (1893), Rossiter, ApJ 60(1924)15; McLaughlin, ApJ 60 (1924)20
Hosokawa, PASJ 5(1953)88; Ohta, Taruya + YS, ApJ 622(2005)1118

The first detection of the Rossiter-McLaughlin effect: HD209458

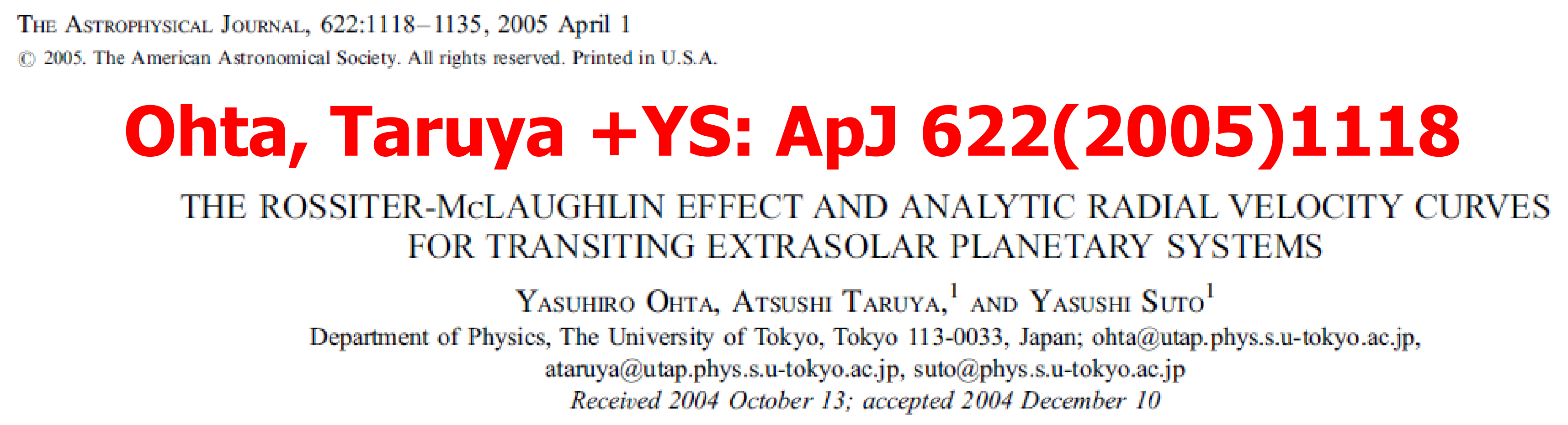


$$\alpha = \pm 3.9^{\circ}{}^{+18^{\circ}}_{-21^{\circ}}$$

HD209458 radial velocity data
http://exoplanets.org/

Stellar rotation and planetary orbit
Queloz et al. (2000) A&A 359, L13
ELODIE on 193cm telescope

Ohta, Taruya +YS: ApJ 622(2005)1118



THE ASTROPHYSICAL JOURNAL, 622:1118–1135, 2005 April 1

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THE ROSSITER-McLAUGHLIN EFFECT AND ANALYTIC RADIAL VELOCITY CURVES FOR TRANSITING EXTRASOLAR PLANETARY SYSTEMS

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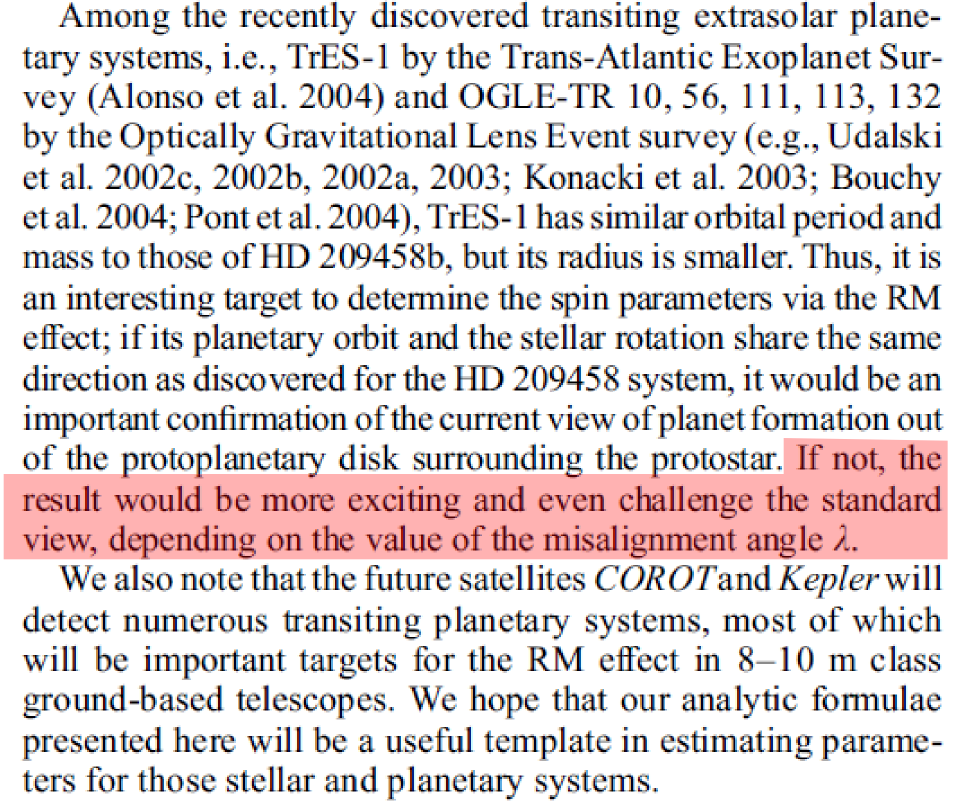
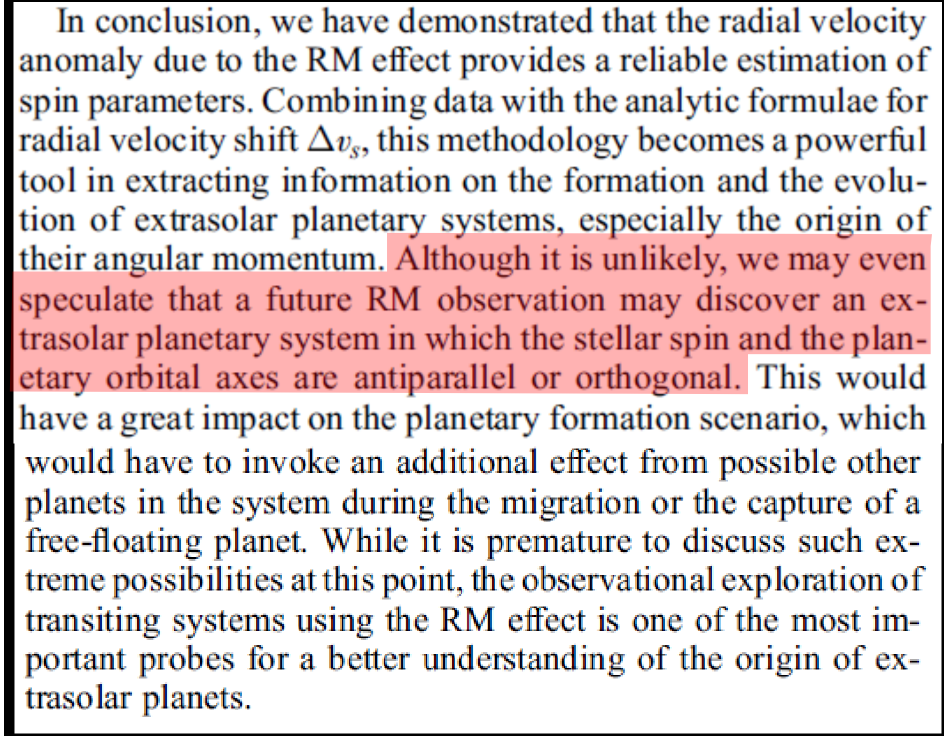


Among the recently discovered transiting extrasolar planetary systems, i.e., TrES-1 by the Trans-Atlantic Exoplanet Survey (Alonso et al. 2004) and OGLE-TR 10, 56, 111, 113, 132 by the Optically Gravitational Lens Event survey (e.g., Udalski et al. 2002c, 2002b, 2002a, 2003; Konacki et al. 2003; Bouchy et al. 2004; Pont et al. 2004), TrES-1 has similar orbital period and mass to those of HD 209458b, but its radius is smaller. Thus, it is an interesting target to determine the spin parameters via the RM effect; if its planetary orbit and the stellar rotation share the same direction as discovered for the HD 209458 system, it would be an important confirmation of the current view of planet formation out of the protoplanetary disk surrounding the protostar. If not, the result would be more exciting and even challenge the standard view, depending on the value of the misalignment angle λ.

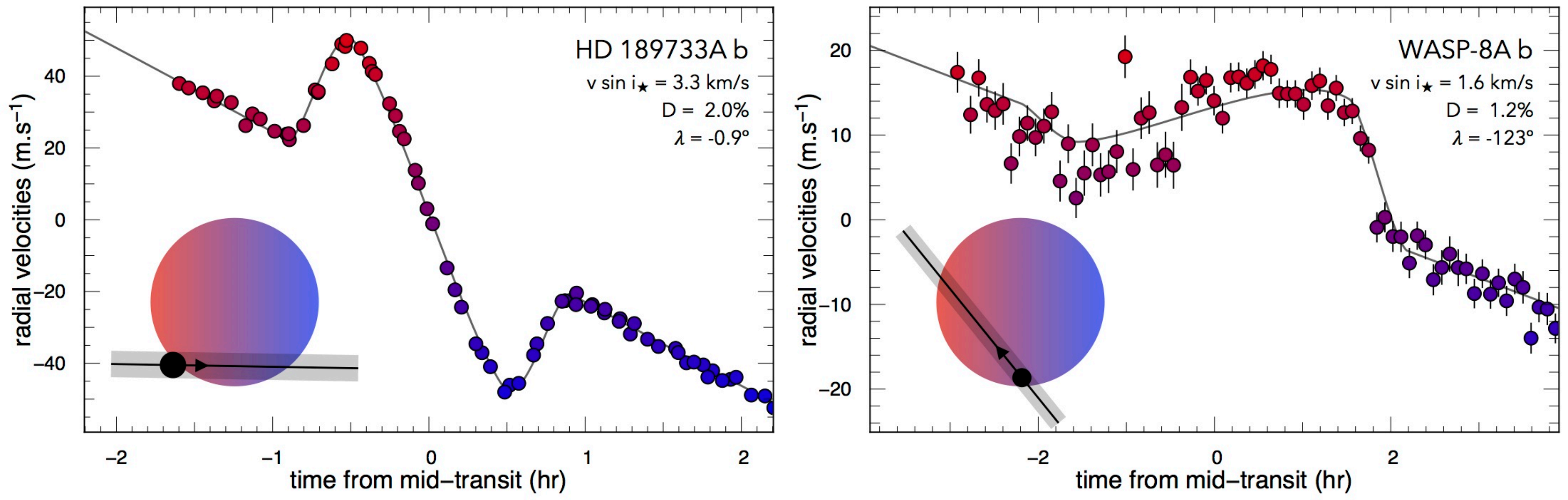
We also note that the future satellites *COROT* and *Kepler* will detect numerous transiting planetary systems, most of which will be important targets for the RM effect in 8–10 m class ground-based telescopes. We hope that our analytic formulae presented here will be a useful template in estimating parameters for those stellar and planetary systems.



In conclusion, we have demonstrated that the radial velocity anomaly due to the RM effect provides a reliable estimation of spin parameters. Combining data with the analytic formulae for radial velocity shift Δv_s, this methodology becomes a powerful tool in extracting information on the formation and the evolution of extrasolar planetary systems, especially the origin of their angular momentum. Although it is unlikely, we may even speculate that a future RM observation may discover an extrasolar planetary system in which the stellar spin and the planetary orbital axes are antiparallel or orthogonal. This would have a great impact on the planetary formation scenario, which would have to invoke an additional effect from possible other planets in the system during the migration or the capture of a free-floating planet. While it is premature to discuss such extreme possibilities at this point, the observational exploration of transiting systems using the RM effect is one of the most important probes for a better understanding of the origin of extrasolar planets.

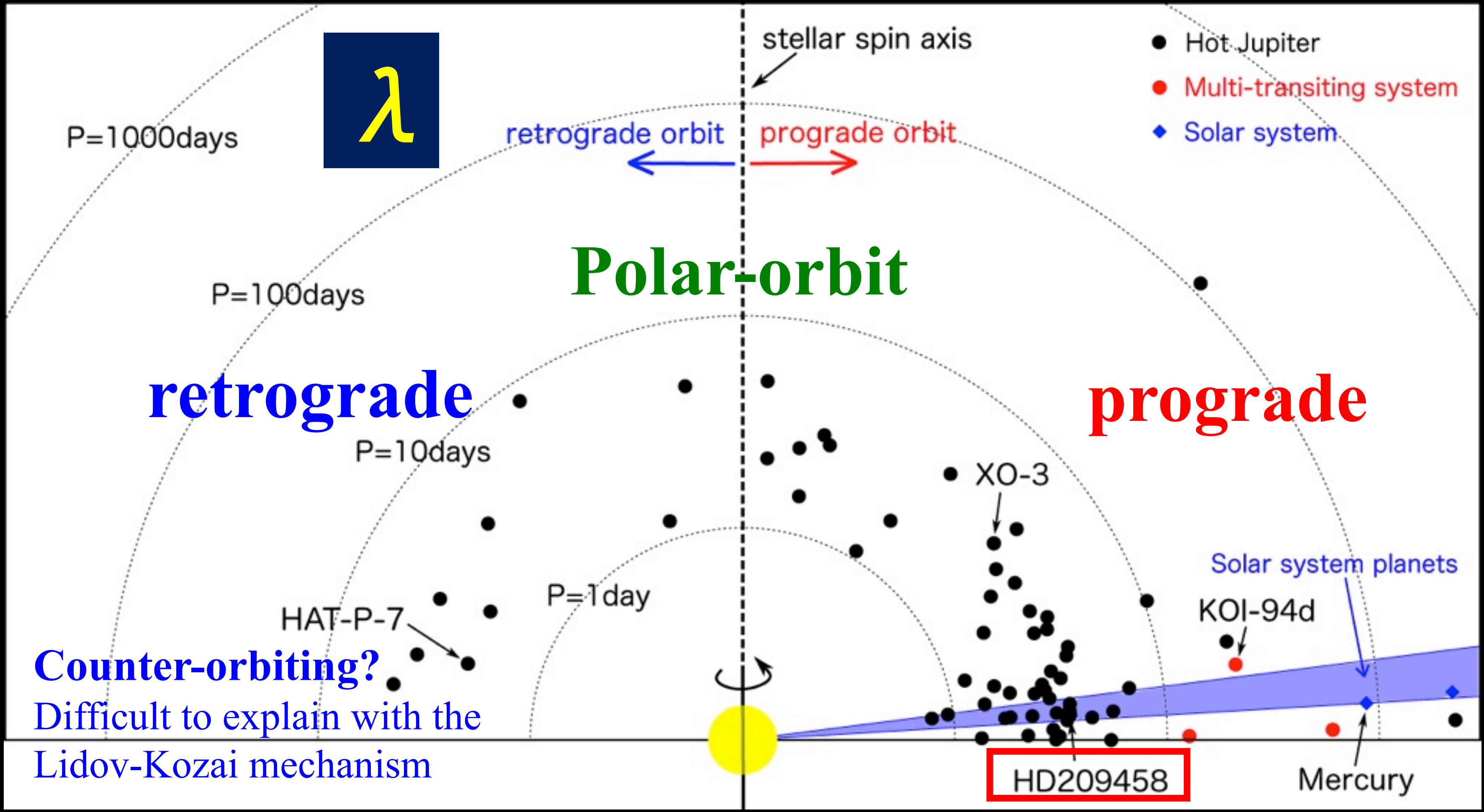
Examples of RM velocity anomaly

Aligned case **Misaligned case**



Ohta, Taruya, & YS, ApJ 622(200591118
Fabrycky & Winn, ApJ 696(2009)1230
Winn & Fabrycky, ARA&A 53(2015)409
Triaud arXiv:1709.06376

Projected spin-orbit angle distribution



λ

Polar-orbit

retrograde

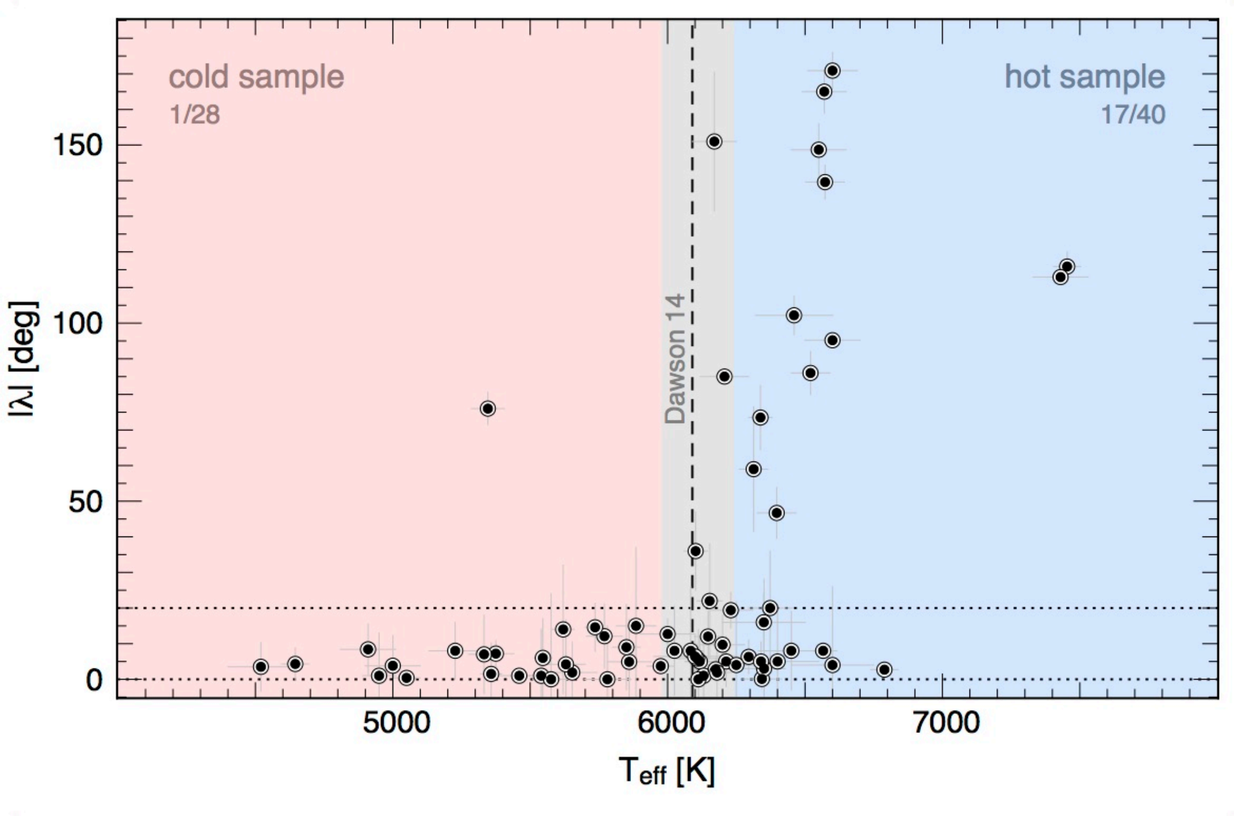
prograde

Counter-orbiting?
Difficult to explain with the
Lidov-Kozai mechanism

As of June 2013, 29 out of 70 planets have $\lambda > \pi/8$

Xue et al. (2014)

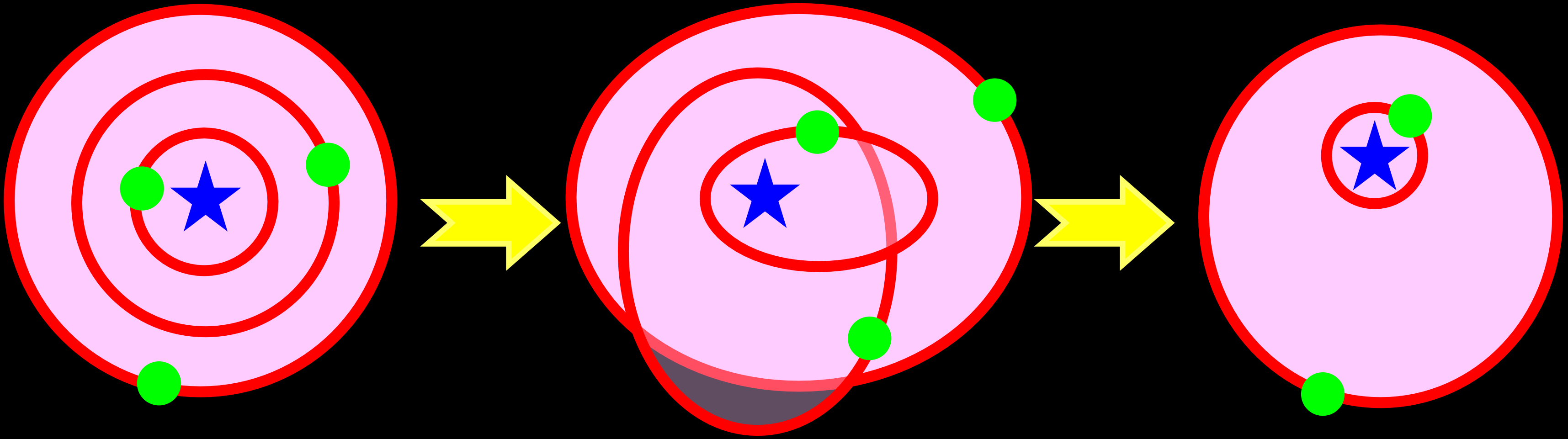
Projected misalignment vs. stellar effective temperature



Triaud arXiv:1709.06376

More efficient spin-orbit “realignment” through star-planet tidal interaction due to the thicker convective zones of cool stars with T_{eff}<6100K ? (Winn et al. 2010)

Planet-planet gravitation scattering
+ star-planet tidal interaction
= circularized but misaligned Hot Jupiters

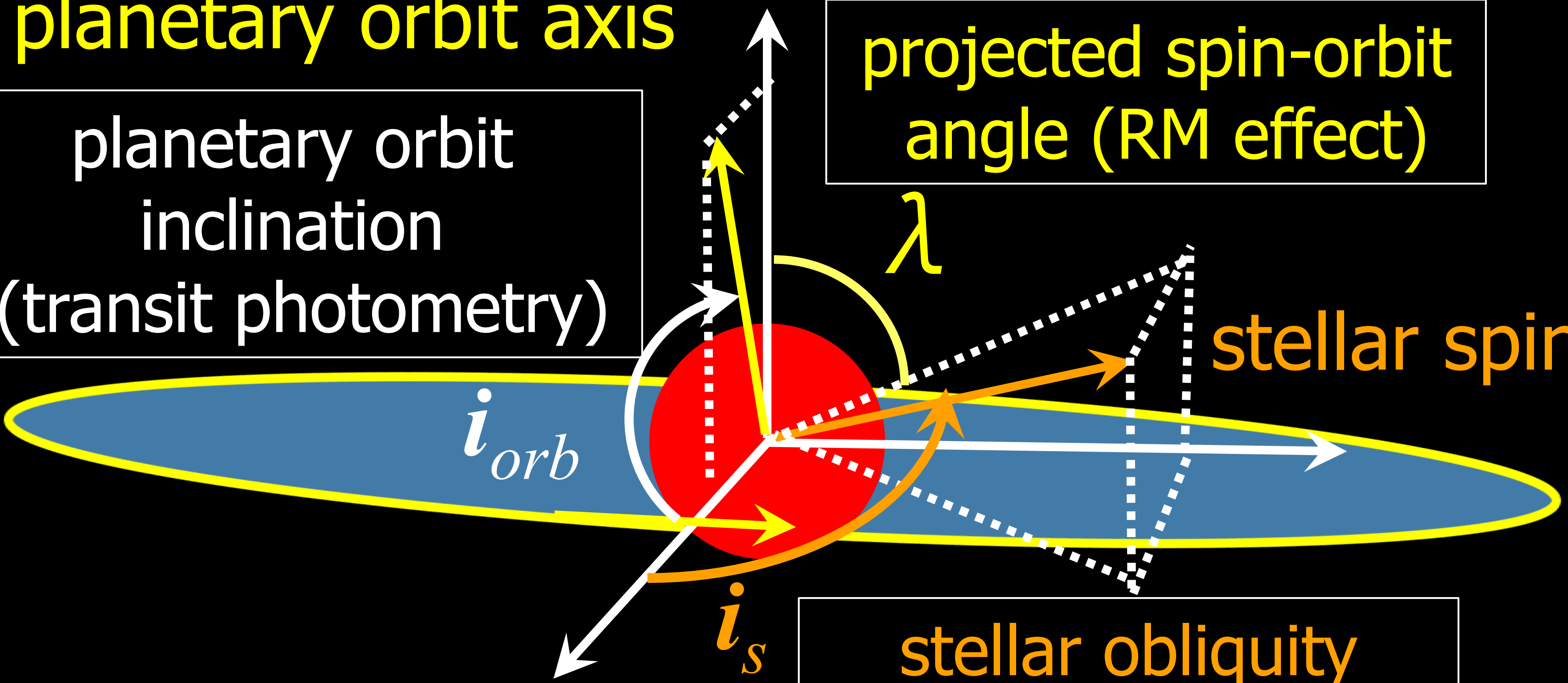


- Broad distribution of spin-orbit angles is generated due to planet scattering, the Lidov-Kozai effect and tidal circularization (e.g., Nagasawa, Ida + Bessho 2008)

To confirm/falsify the planet-planet scattering scenario

- Occurrence rate of misalignment from numerical simulations ? (large uncertainty of the initial configuration of planets)
- Efficiency of tidal realignment by convective zone of stars with $T_{eff}<6100K$?
- Complementary statistics from stellar obliquity with/without planets → asteroseismology
- Difference between single- and multi-transiting planetary systems → asteroseismology

Spin-orbit angles of a transiting planet



planetary orbit axis

planetary orbit inclination (transit photometry)

projected spin-orbit angle (RM effect)

stellar spin

observer's line of sight

stellar obliquity (asteroseismology)

$$\cos\Psi = \sin i_s \sin i_{orb} \cos\lambda + \cos i_s \cos i_{orb}$$
$$\approx \sin i_s \cos\lambda$$

True spin-orbit angles from RM effect + asteroseismology

- Only two systems have both measurements of λ (RM) and i_s (asteroseismology)
  - Kepler-25 (F-star+ planets with 6 and 13days)

$\lambda = 9.4° \pm 7.1°$ $i_s = 65.4°^{+12.1°}_{-7.4°}$ $\Psi = 26.9°^{+7.0°}_{-9.2°}$

$\boldsymbol{i_s = 80.6°^{+6.5°}_{-9.3°}}$

  - HAT-P-7 (F-star + a single planet with 2.2 days)

$\lambda = 186°^{+10°}_{-11°}$ $i_s = 27°^{+35°}_{-18°}$ $\Psi = 122°^{+30°}_{-18°}$

Not a counter-orbiting planet !

Benomar, Masuda, Shibahashi + YS, PASJ 66(2014) 9421

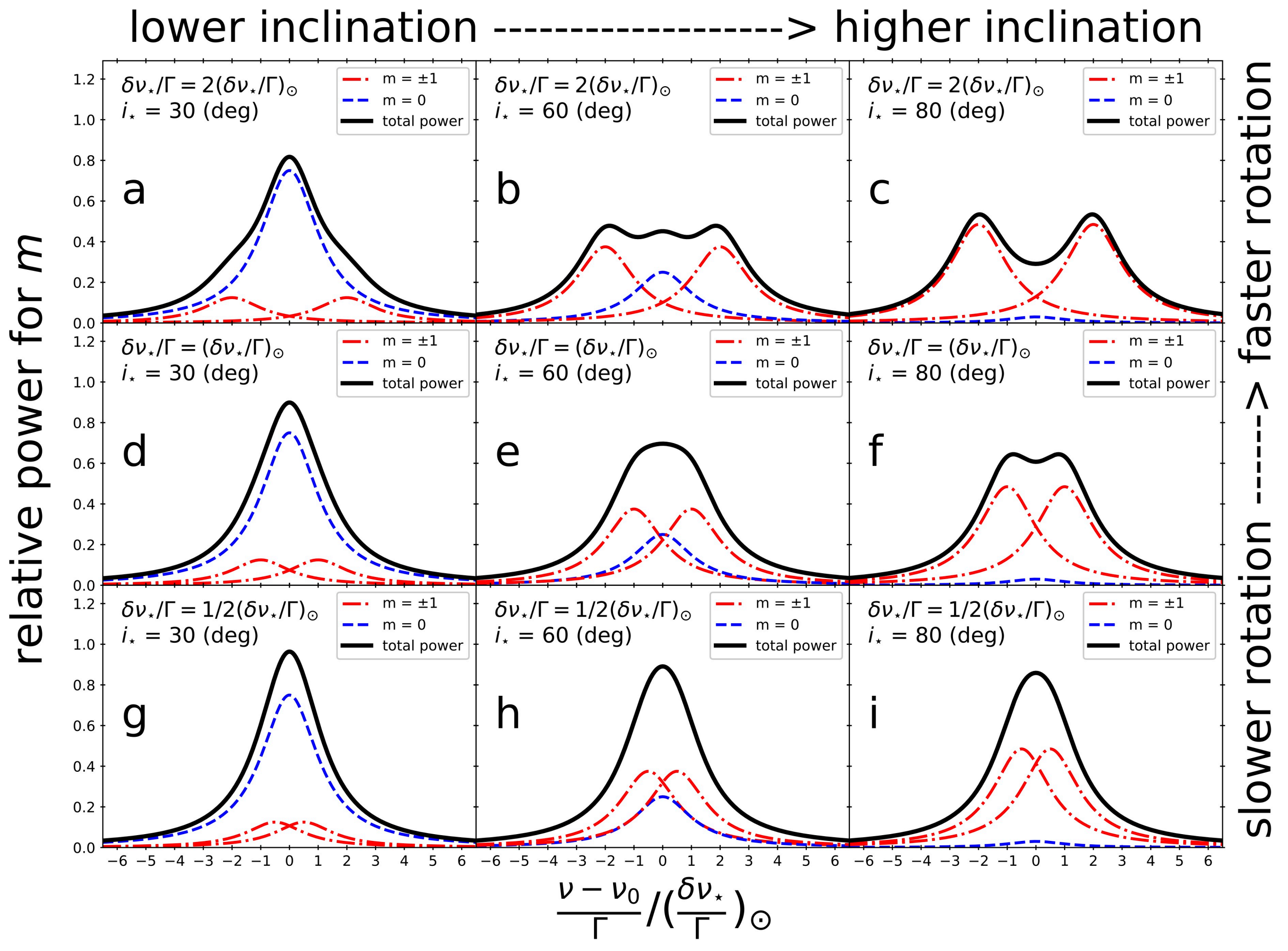
see also Kamiaka, Benomar + YS, submitted (2018)

Huber et al. (2013) , Campante et al.(2016)

Stellar obliquity from asteroseismology

- Complementary probe of spin-orbit angles of exoplanetary systems

Toutain & Gouttebroze, (1993)
Gizon & Solanki (2003)
Kamiaka, Benomar & Suto (2018)



Analytic criteria for measurable i_s

- Identify m=±1 modes: lower limit of i_s

$$i_* > \sin^{-1}\sqrt{\beta\frac{4}{SNR}\frac{\delta f}{\Gamma}}$$

- Identify m=0 mode: upper limit of i_s

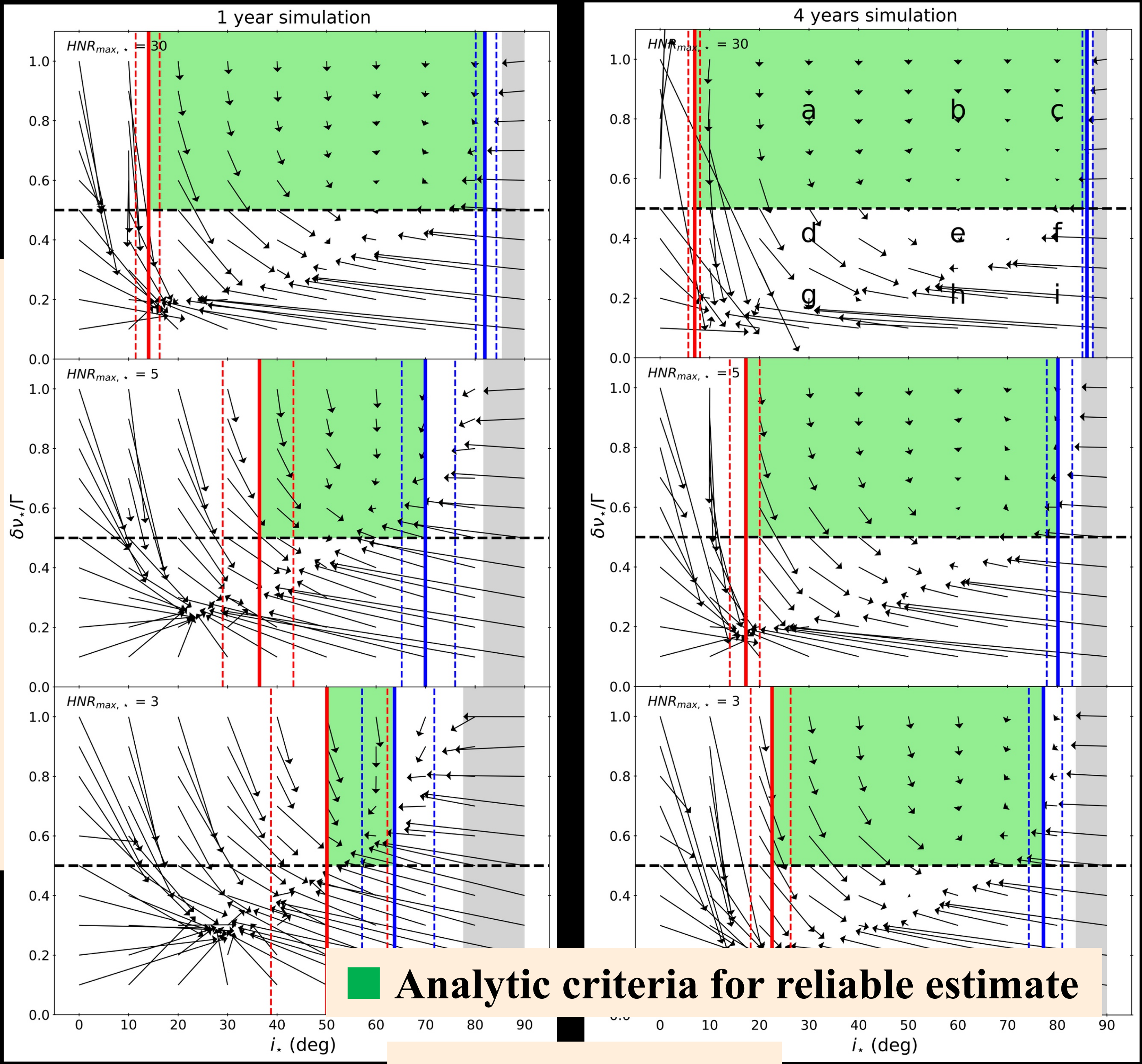
$$i_* < \cos^{-1}\sqrt{\alpha\frac{2}{SNR}\frac{\delta f}{\Gamma}}$$

- Distinguish m=±1 modes: rotational separation

$$\delta\nu_*/\Gamma > \frac{1}{2}$$

Kamiaka, Benomar + YS, submitted (2018)

Mock simulations



Stellar rotation/line width

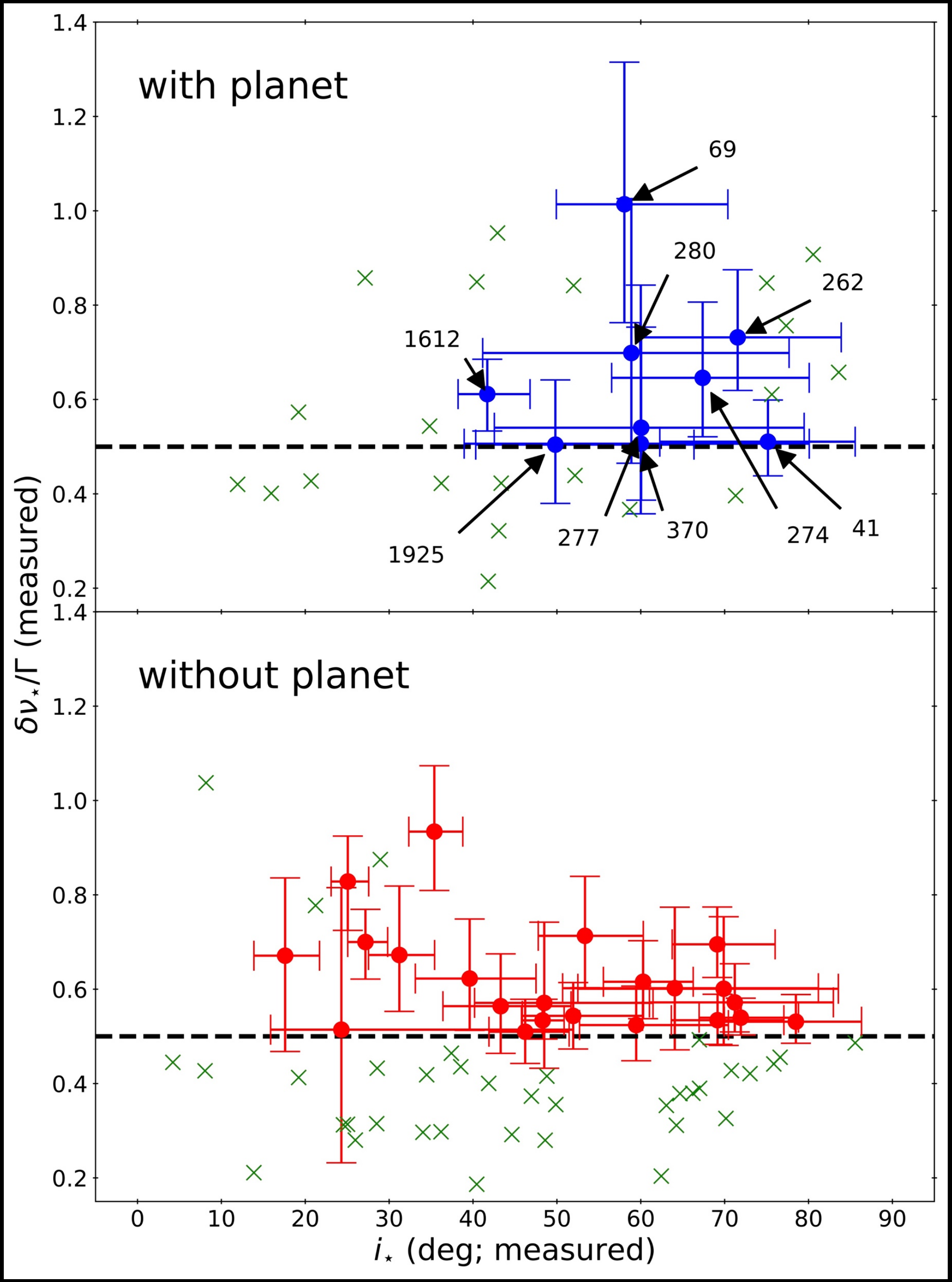
Stellar obliquity

🟩 **Analytic criteria for reliable estimate**

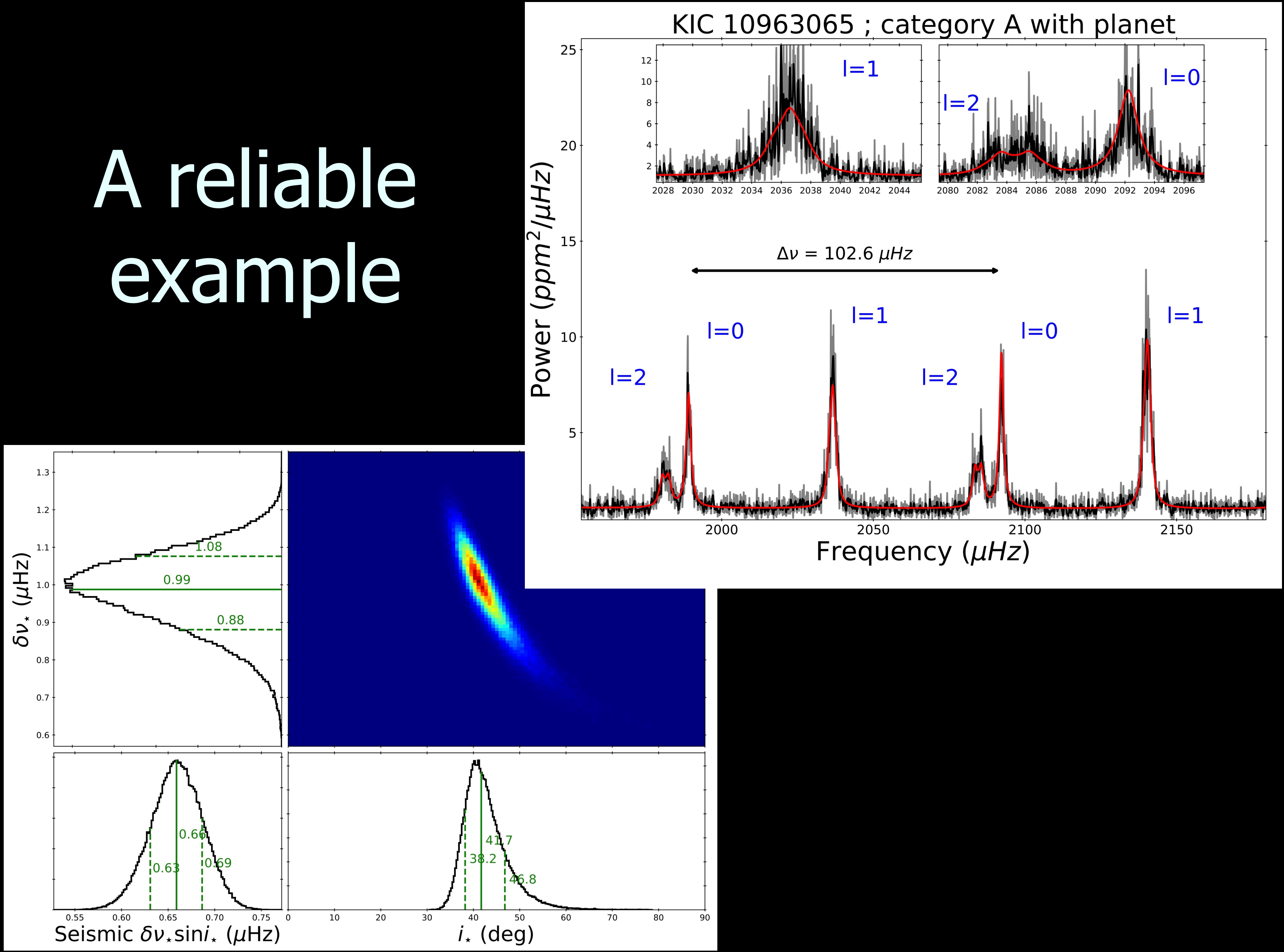
higher signal-to-noise ratio →

i_s of Kepler stars from asteroseismology: with/without planets

- 94 Kepler main-sequence stars
  - 33 with planets
  - 61 without planets
- Planet-host stars have systematically larger stellar obliquities

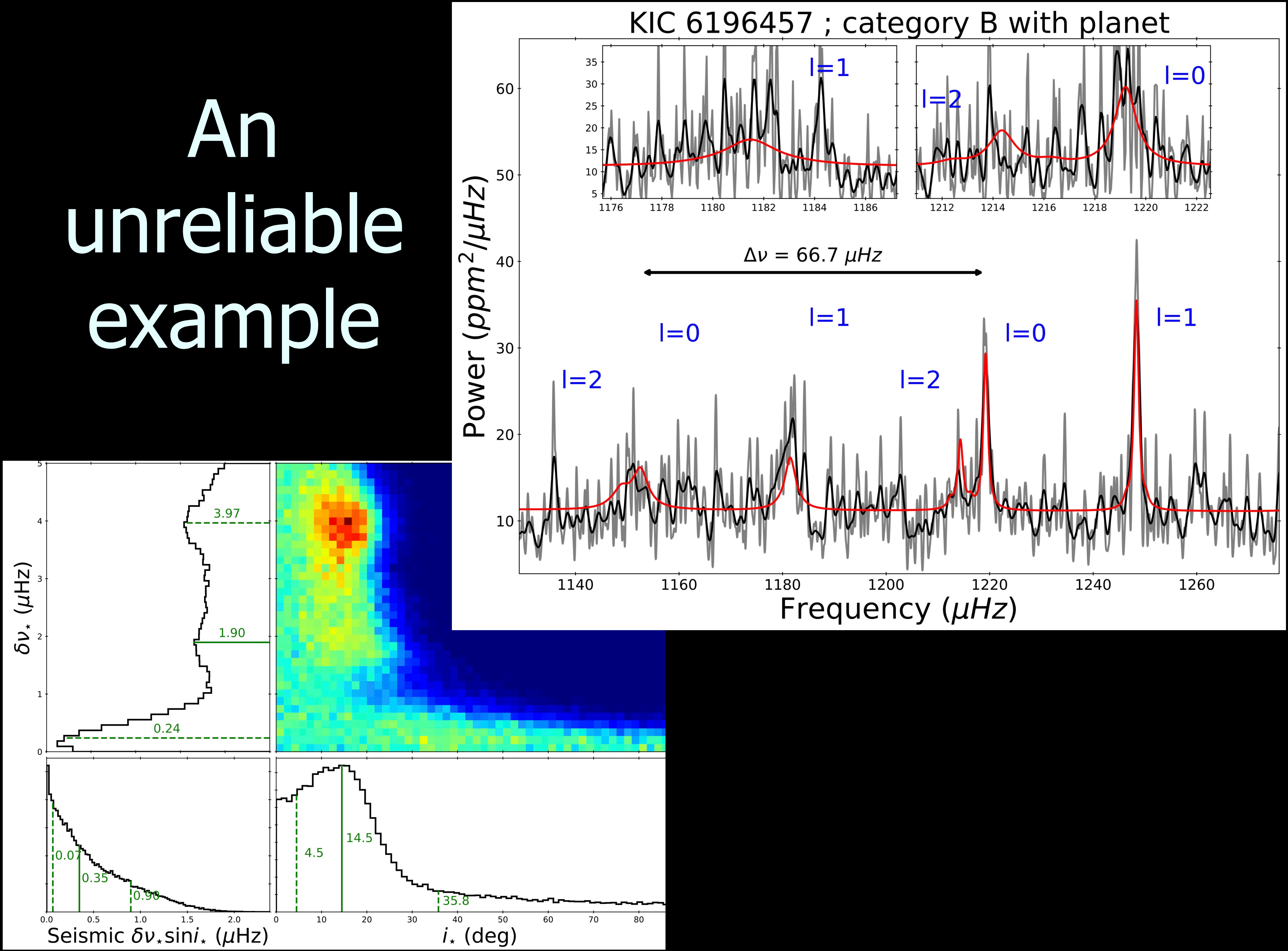


A reliable example

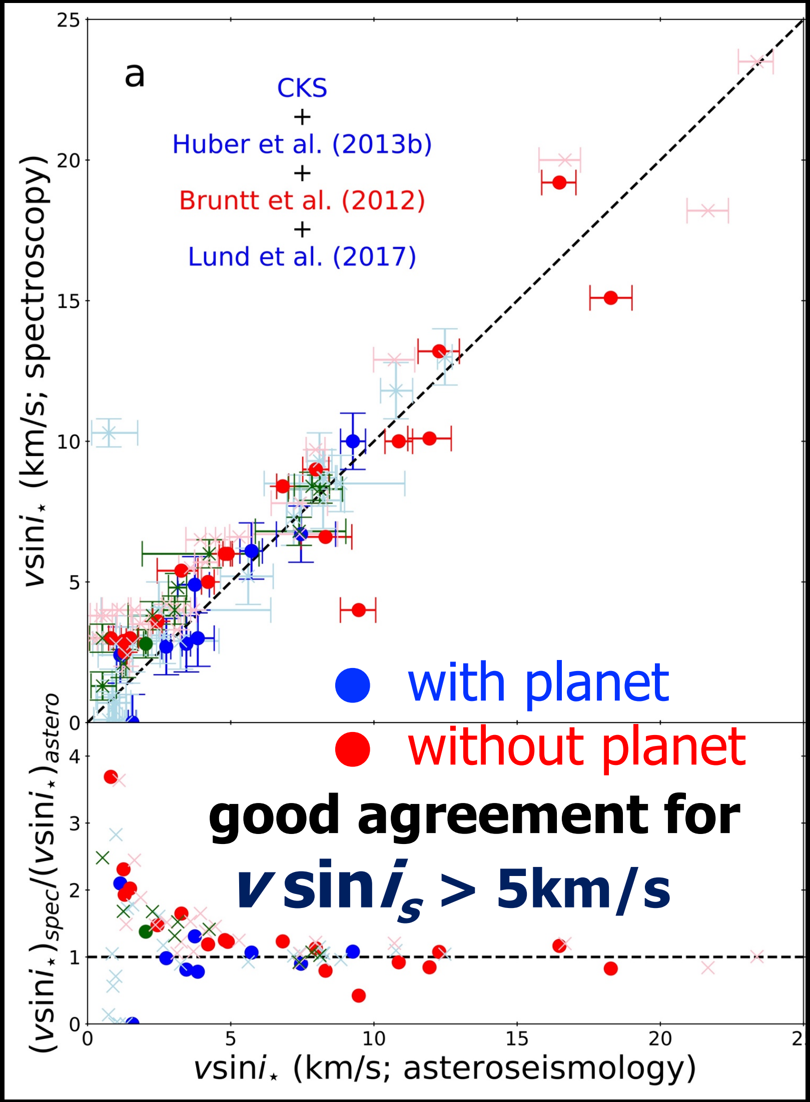


KIC 10963065 ; category A with planet

An unreliable example



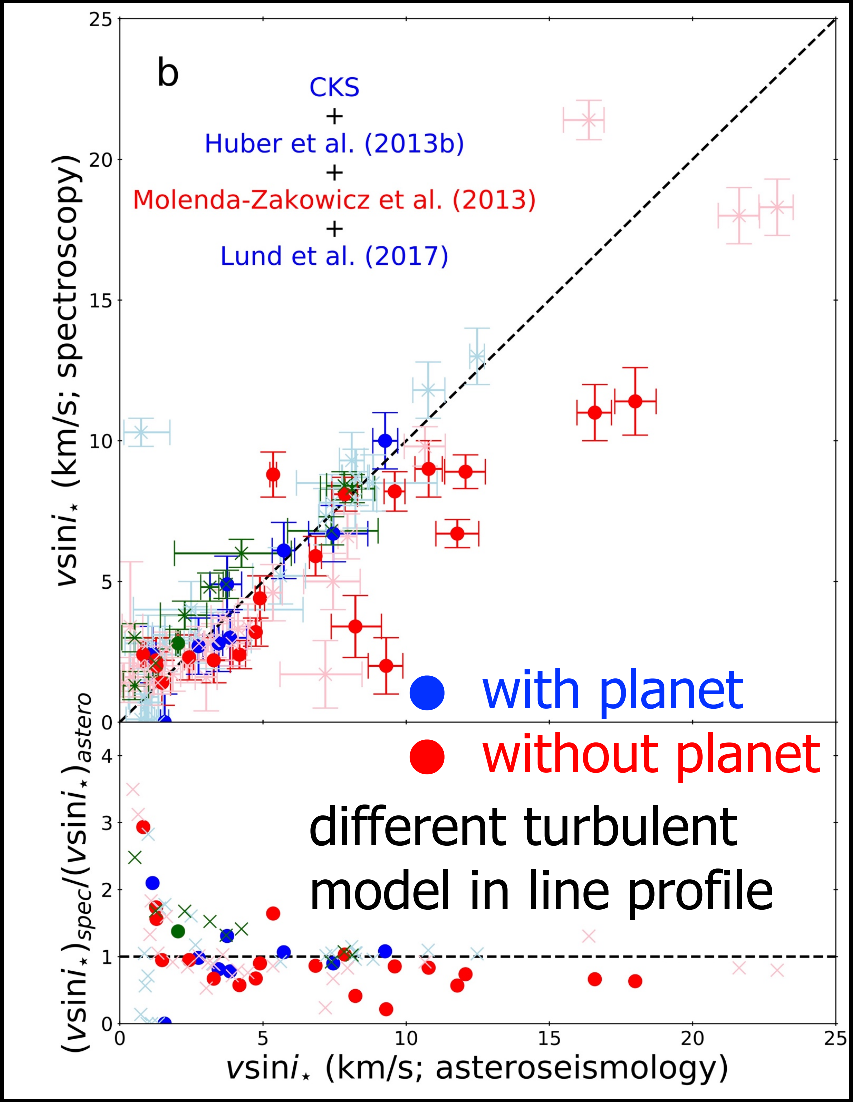
Comparison with $v \sin i_s$ from spectroscopic analysis



● with planet

● without planet

good agreement for $\boldsymbol{v \sin i_s > 5\mathrm{km/s}}$

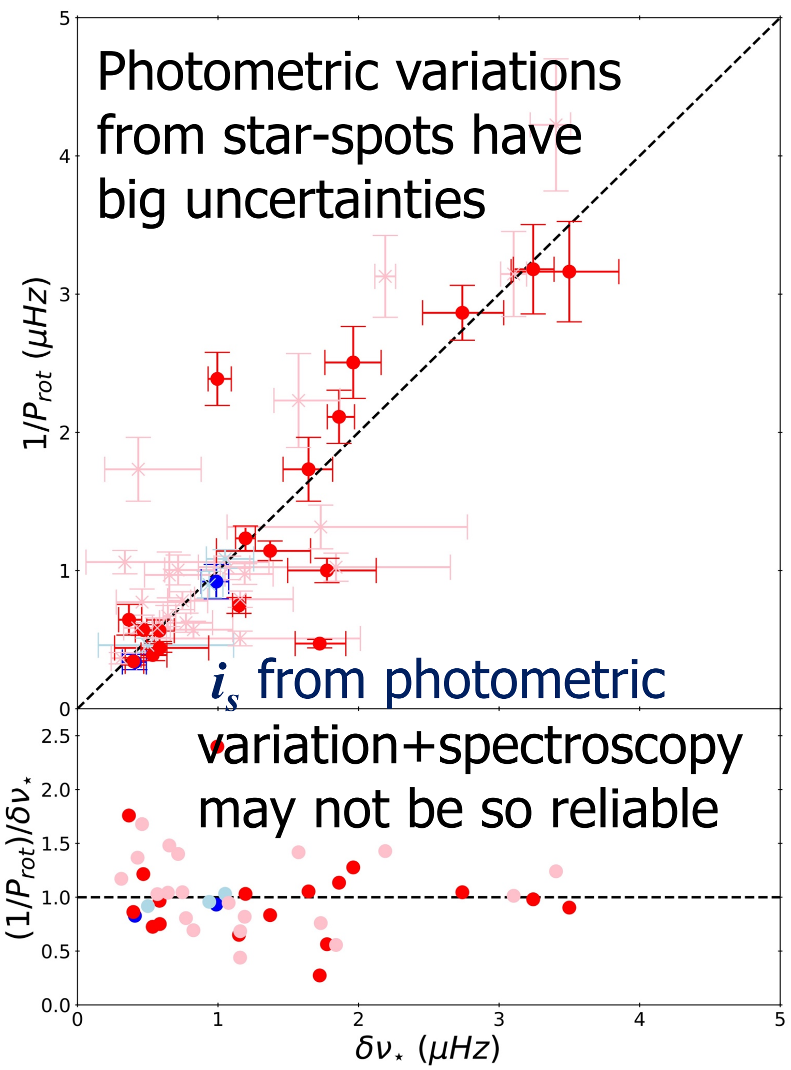


● with planet

● without planet

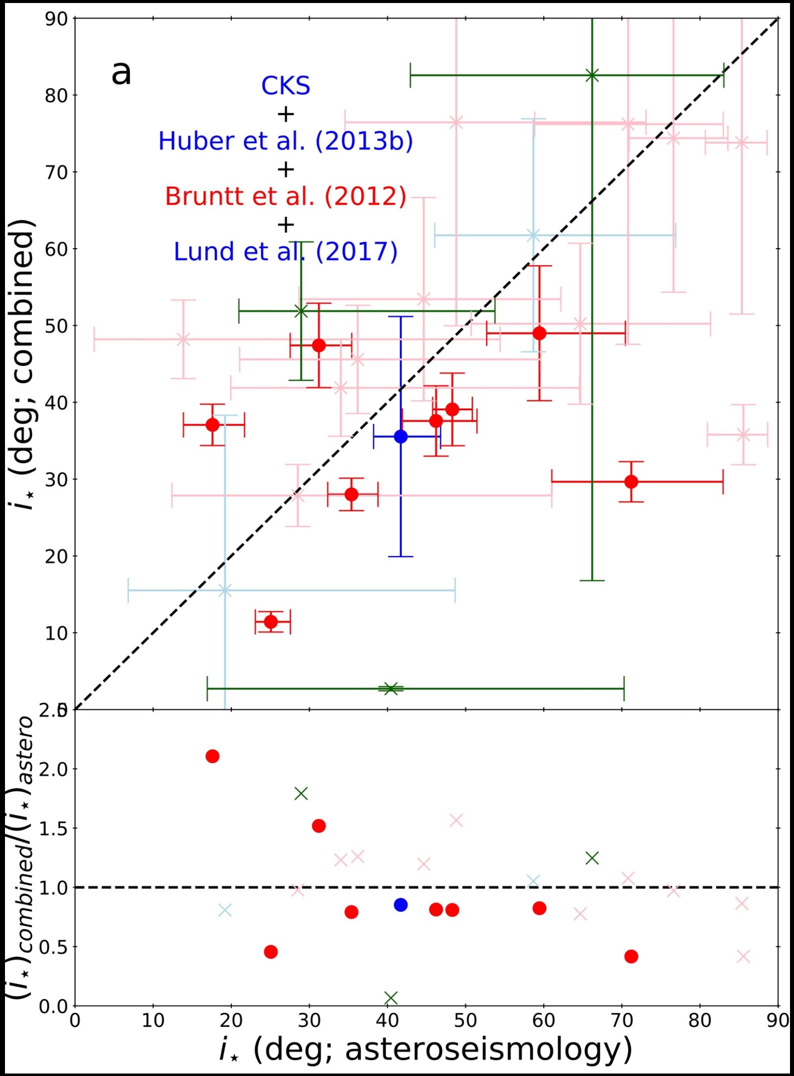
different turbulent model in line profile

Comparison with i_s and v_{rot} from photometric variation



Photometric variations from star-spots have big uncertainties

i_s from photometric variation+spectroscopy may not be so reliable



Conclusions

- Stellar obliquities i_s estimated from asteroseismology provide unique clues to architecture and orbital evolution of exoplanetary systems
- We derived analytic criteria for i_s to be reliable, which was confirmed by systematic numerical simulations
  - *$i_s < 20°$ tends to be overestimated and $i_s > 80°$ tends to be underestimated.*
  - We applied the criteria to judge the reliability of i_s measured for 94 Kepler stars
- How about Red giants ? (e.g., Kepler-56)