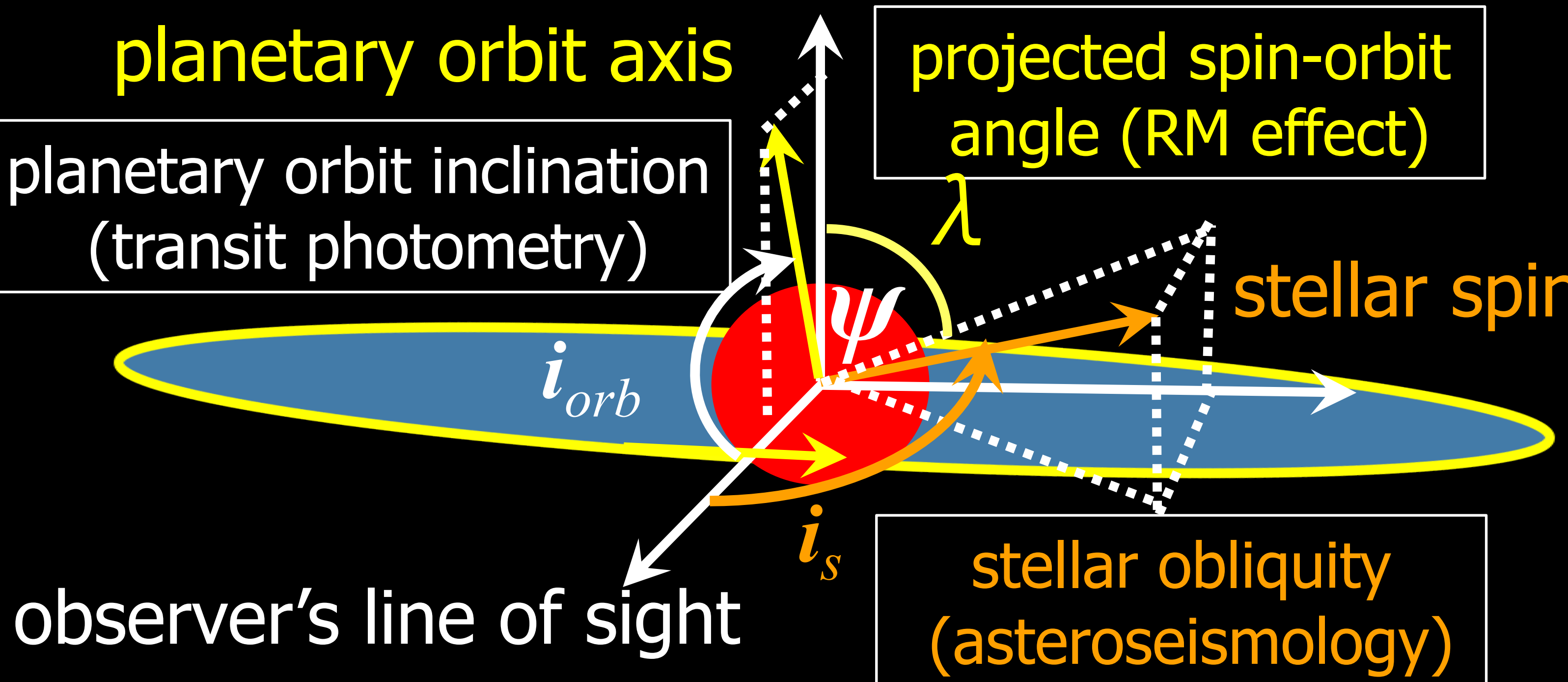
Reliability of the asteroseismic measurement of the stellar obliquity



Yasushi Suto

Department of Physics and RESCEU, The University of Tokyo

Planet discussion group meeting

June 11, 2018 @ Princeton University

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

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

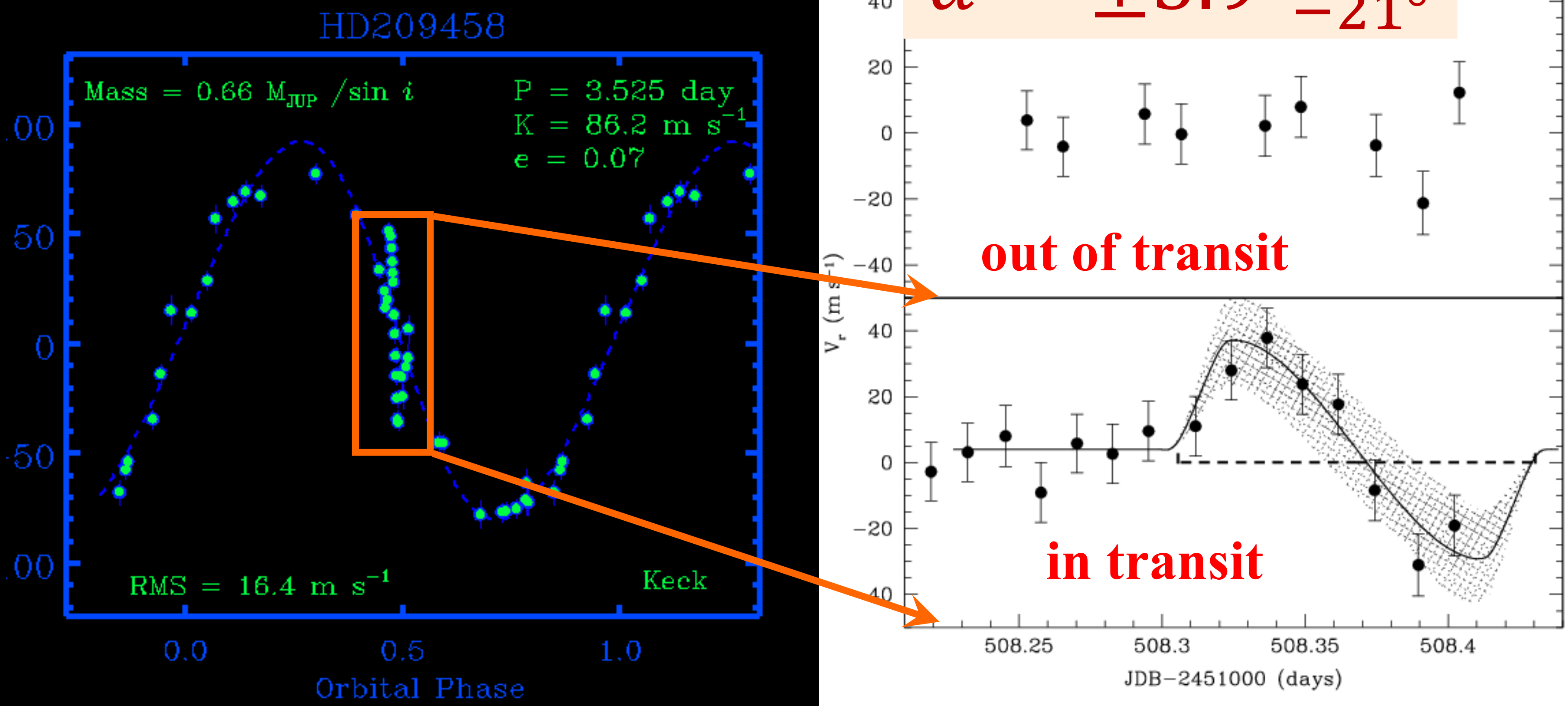
$$\alpha = \pm 3.9^\circ {}^{+18^\circ}_{-21^\circ}$$

- 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 generalizing and applying Ohta et al.(2005)

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/
(This is not their original data)

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

The Astrophysical Journal, 622:1118–1135, 2005 April 1

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

THE ROSSITER-McLAUGHLIN EFFECT AND ANALYTIC RADIAL VELOCITY CURVES FOR TRANSITING EXTRASOLAR PLANETARY SYSTEMS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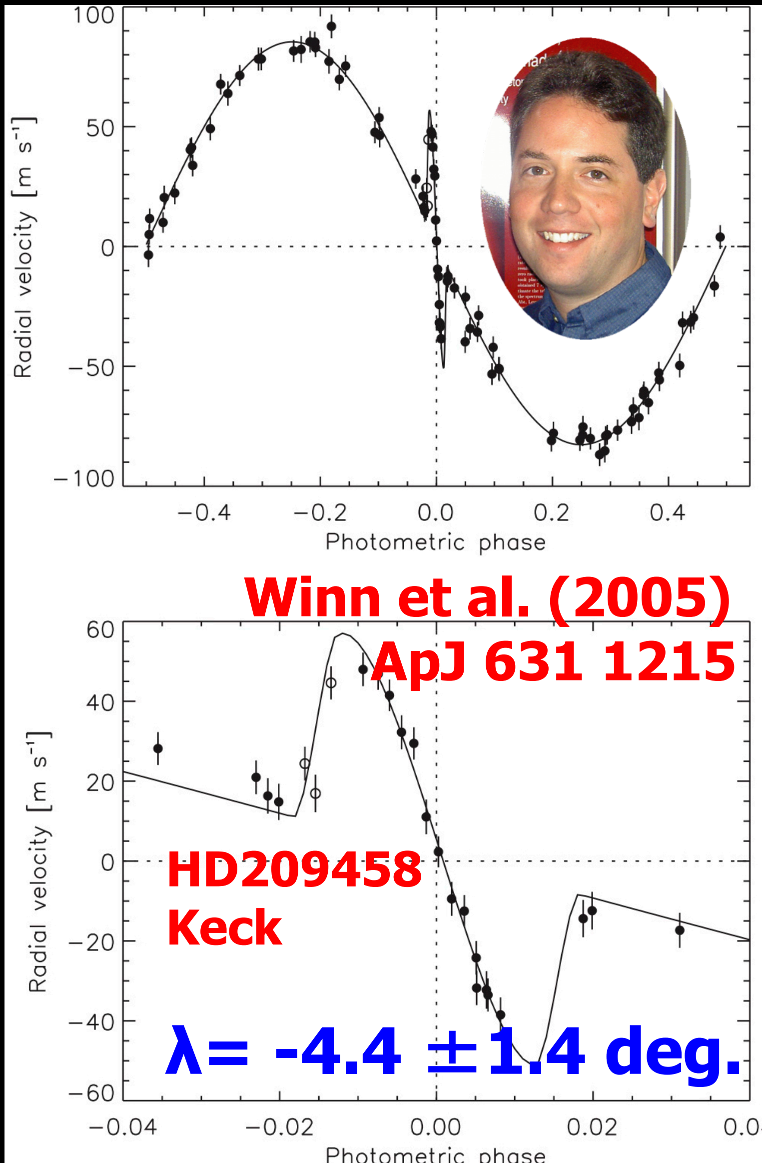
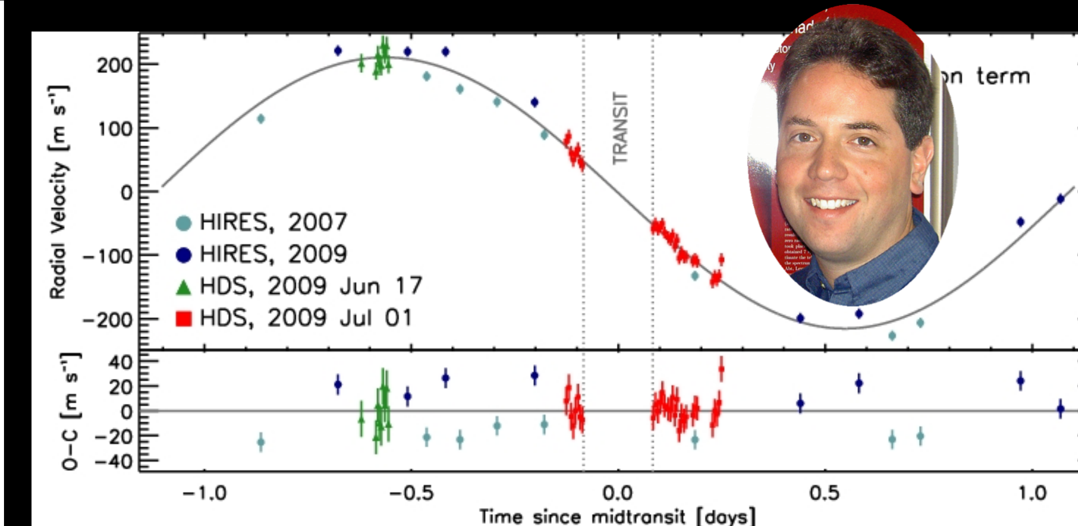
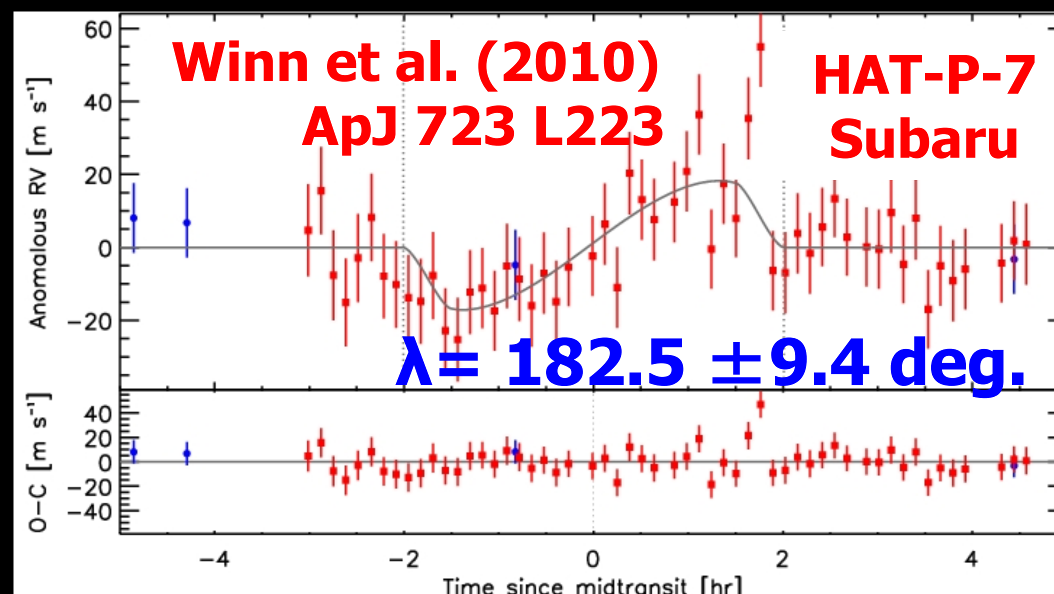
planetary orbit and the stellar rotation share the same direction as discovered for the HD 209458 system, it would be an important confirmation of the current view of planet formation out of the protoplanetary disk surrounding the protostar. If not, the result would be more exciting and even challenge the standard view, depending on the value of the misalignment angle λ.

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

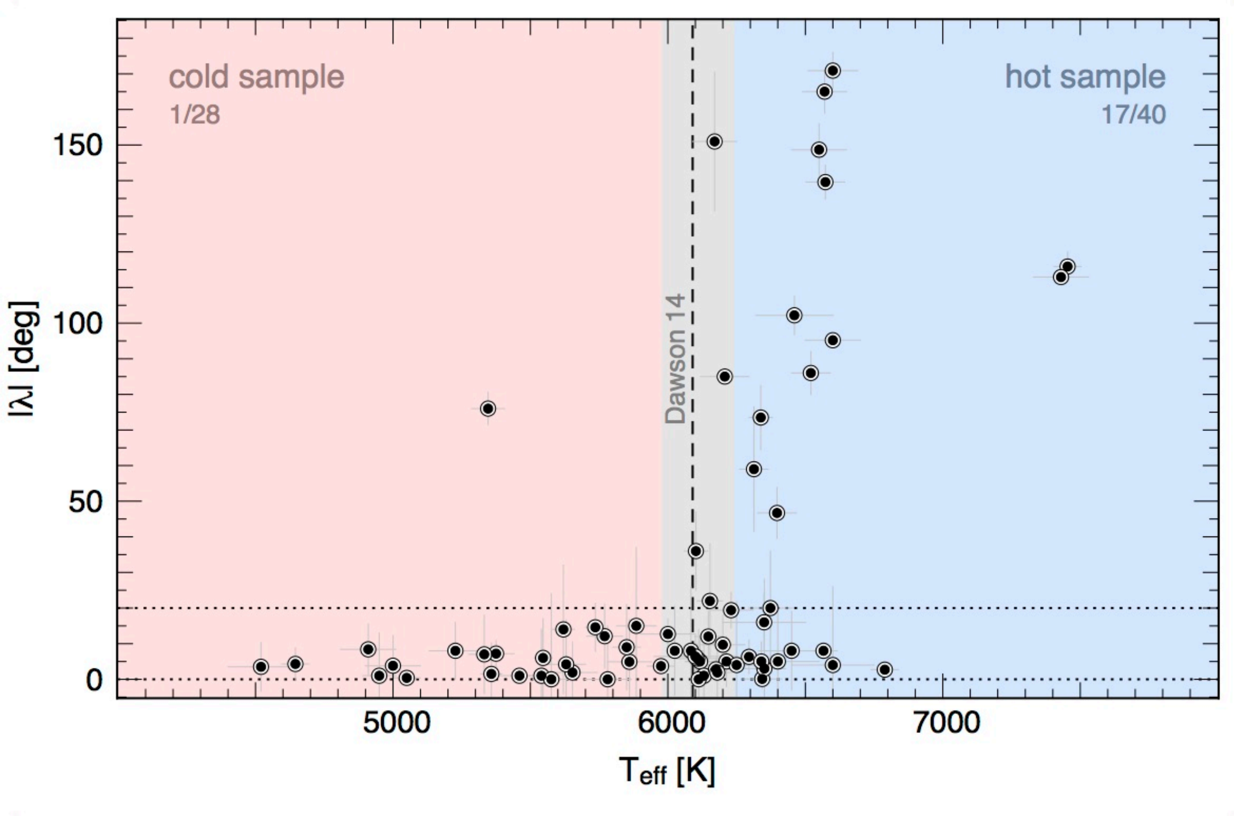
Prograde and retrograde orbits







Projected misalignment vs. stellar effective temperature



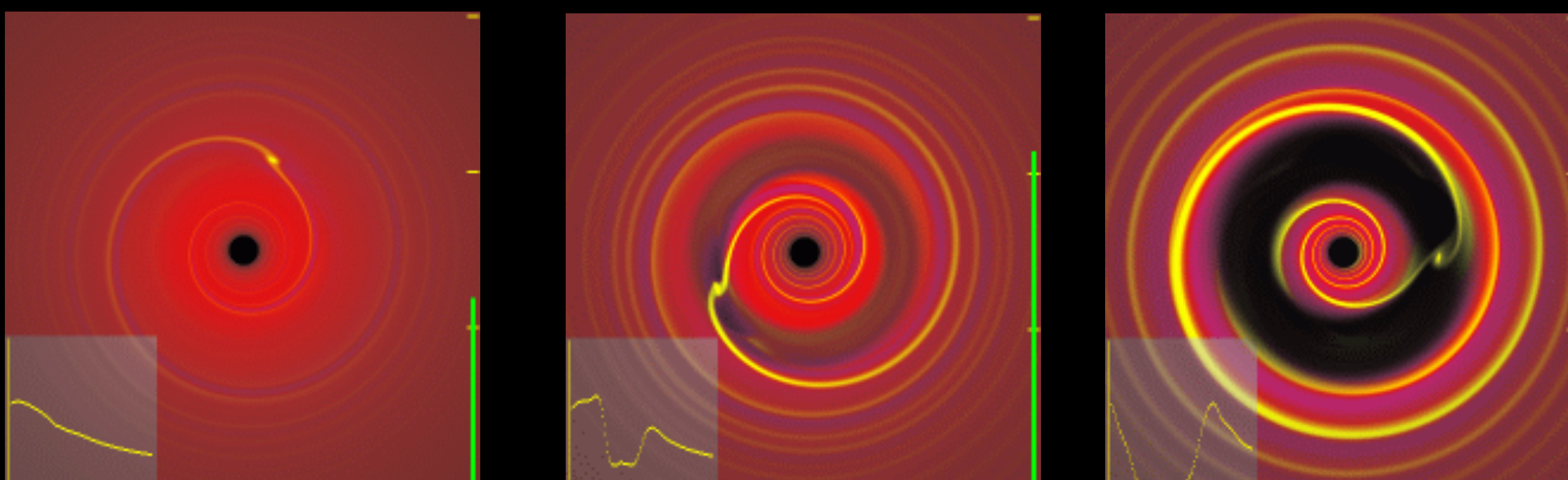
Triaud arXiv:1709.06376

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 migration channels

- Type I migration
  - Low-mass planet - spiral wave in the gas disk
- Type II migration
  - High-mass planet - gap in the disk
- Gravitation scattering
  - Planet - planet

Simulation by Phil Armitage

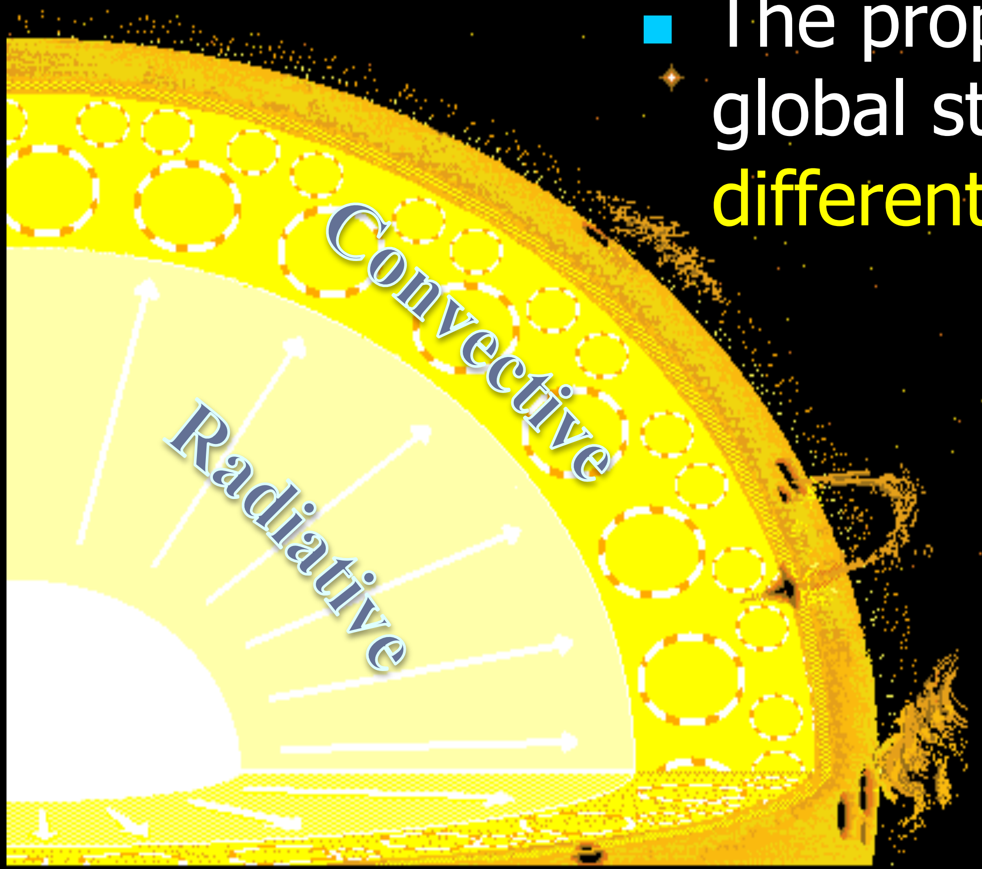


To confirm/falsify the migration scenarios

- 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

Oscillations of Sun-like stars
$(0.8M_\odot < M < 2.5\ M_\odot)$

- Convection triggers oscillation waves inside stars
- The propagating waves form global standing waves with different eigenmode frequencies



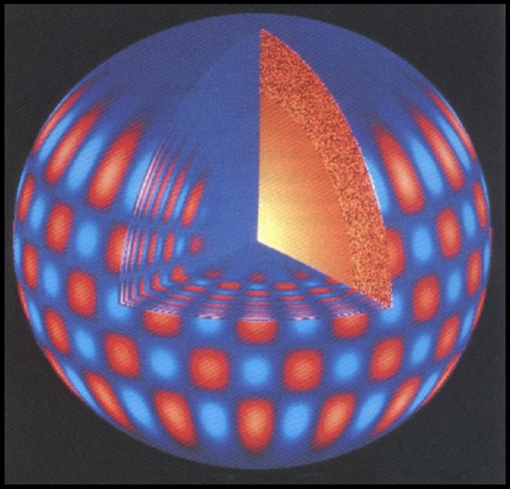
- The induced temperature perturbations are measured through the stellar photometric pulsation

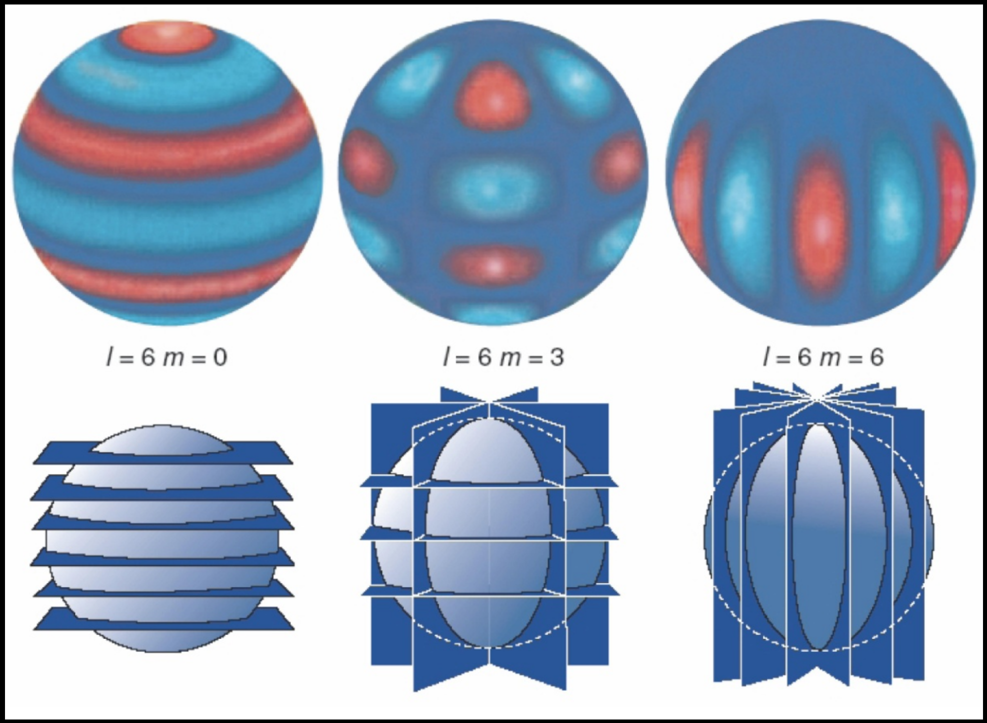
Characterizing the pulsations

- Expansion in terms of spherical harmonics

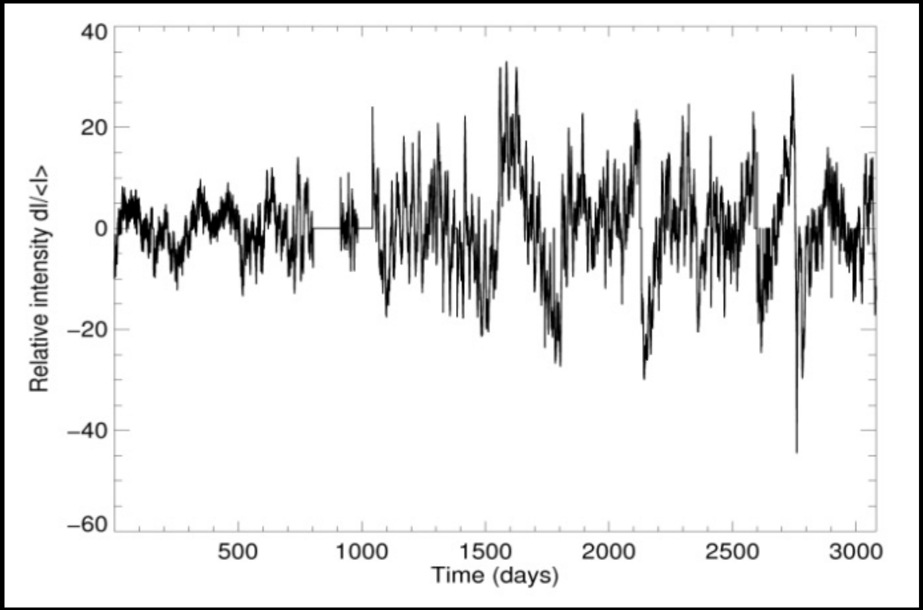
$$Y_{lm}(\theta,\varphi) \propto P_l^{|m|}(\cos\theta)e^{im\varphi}$$

- Three integers to characterize the mode
  - ***n*** radial order
  - ***l*** angular degree
  - ***m*** azimuthal order





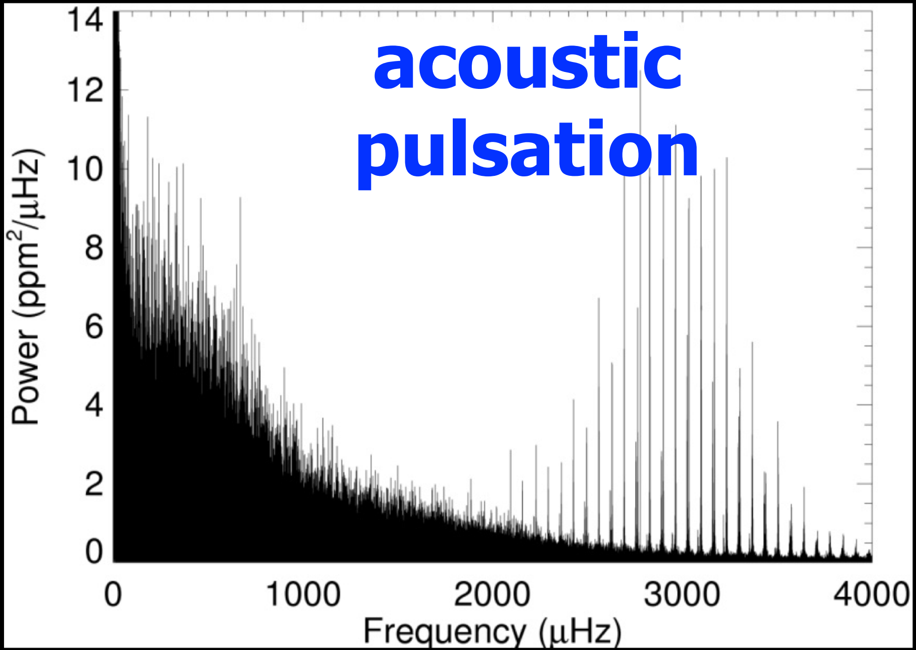
From lightcurve to power spectrum



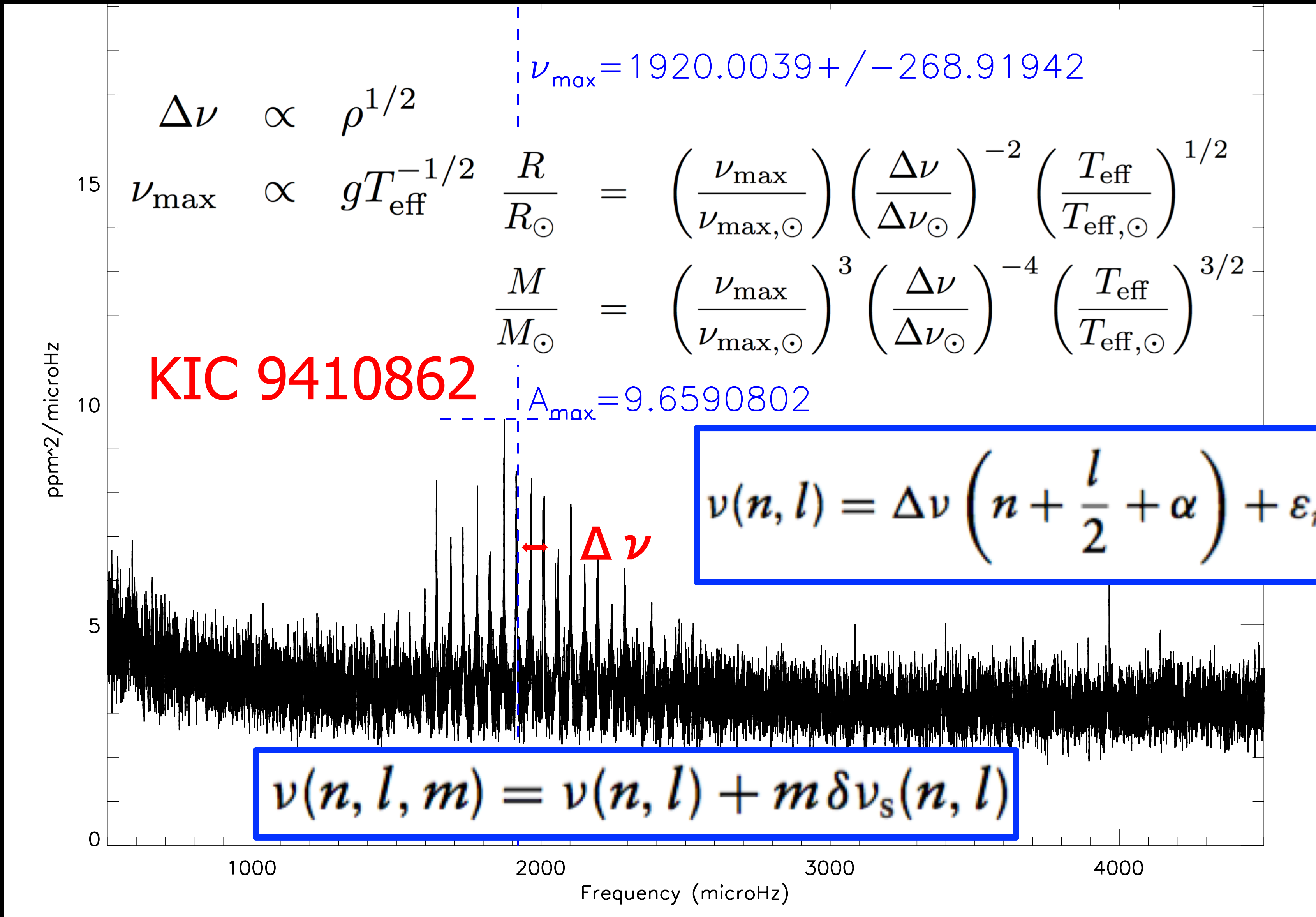
Lightcurve
in time domain

Fourier
Transform

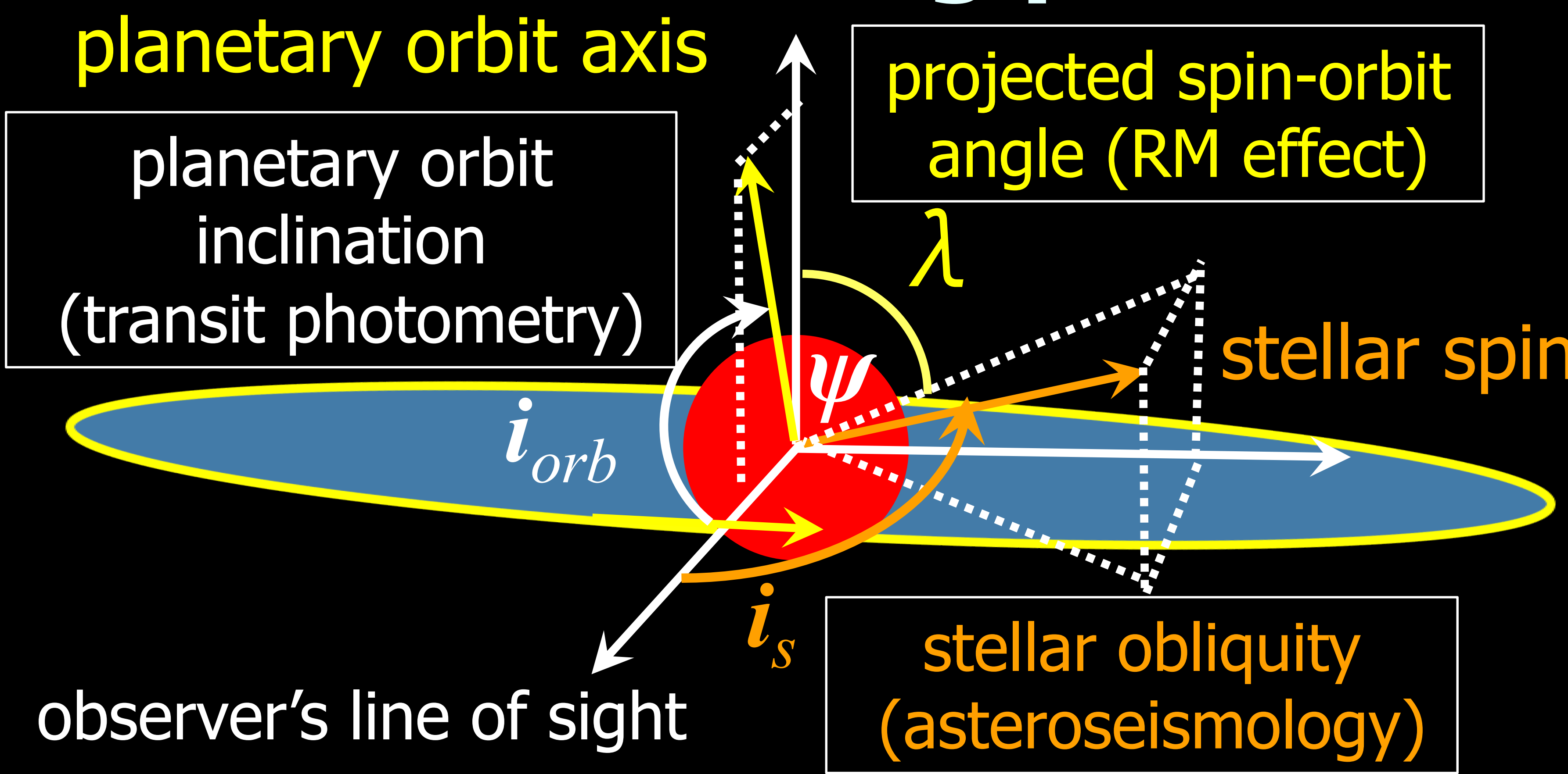
Power spectrum
in frequency domain



From oscillations to mass and radius



Spin-orbit angles of a transiting planet



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

Stellar rotation and obliquity

- Oscillation in the corotating frame of the star:

$$e^{i2\pi\nu(n,l)t}$$

- Oscillation frequency observed in the inertial frame:

$$Y_{lm}(\theta,\varphi) \propto P_l^{|m|}(\cos\theta)\, e^{im\varphi} \;\propto e^{im2\pi\delta\nu_*(n,l)t}$$

$$\nu(n,l,m) = \nu(n,l) + m\,\delta\nu_{\mathrm{s}}(n,l)$$

- Obliquity changes the amplitude of modes

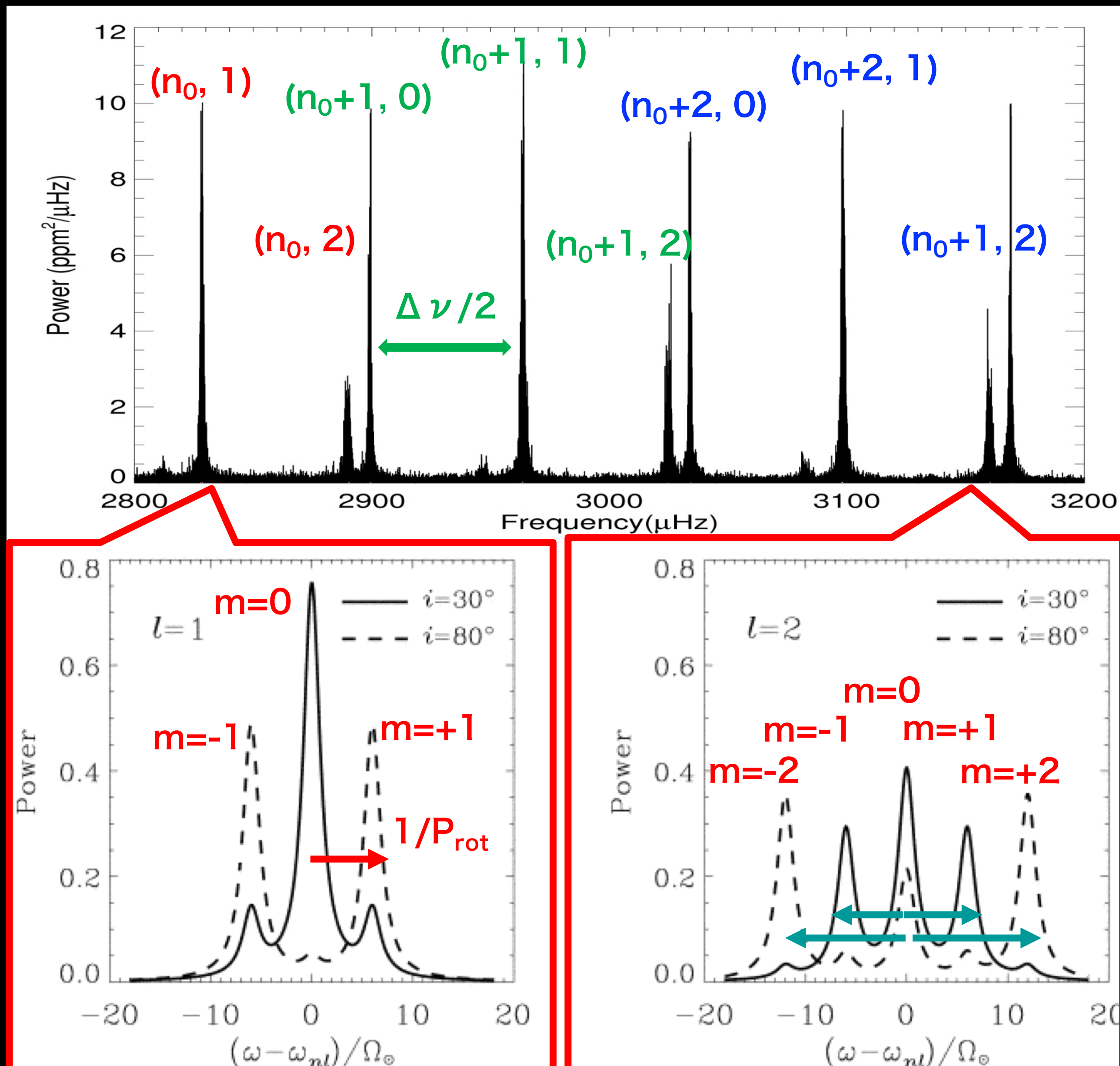
$$P(\nu) = \sum_{n,l}\sum_{m=-l}^{l} \frac{\mathcal{E}(l,m,i_\star)H(n,l)}{1+4[\nu-\nu(n,l,m)]^2/\Gamma^2(n,l,m)}$$

$$\mathcal{E}(l,m,i_\star) = \frac{(l-|m|)!}{(l+|m|)!}\left[P_l^{|m|}(\cos i_\star)\right]^2$$

Stellar rotation splits m-modes

$$\nu(n,l) = \Delta\nu\left(n + \frac{l}{2} + \alpha\right) + \varepsilon_{n,l}$$

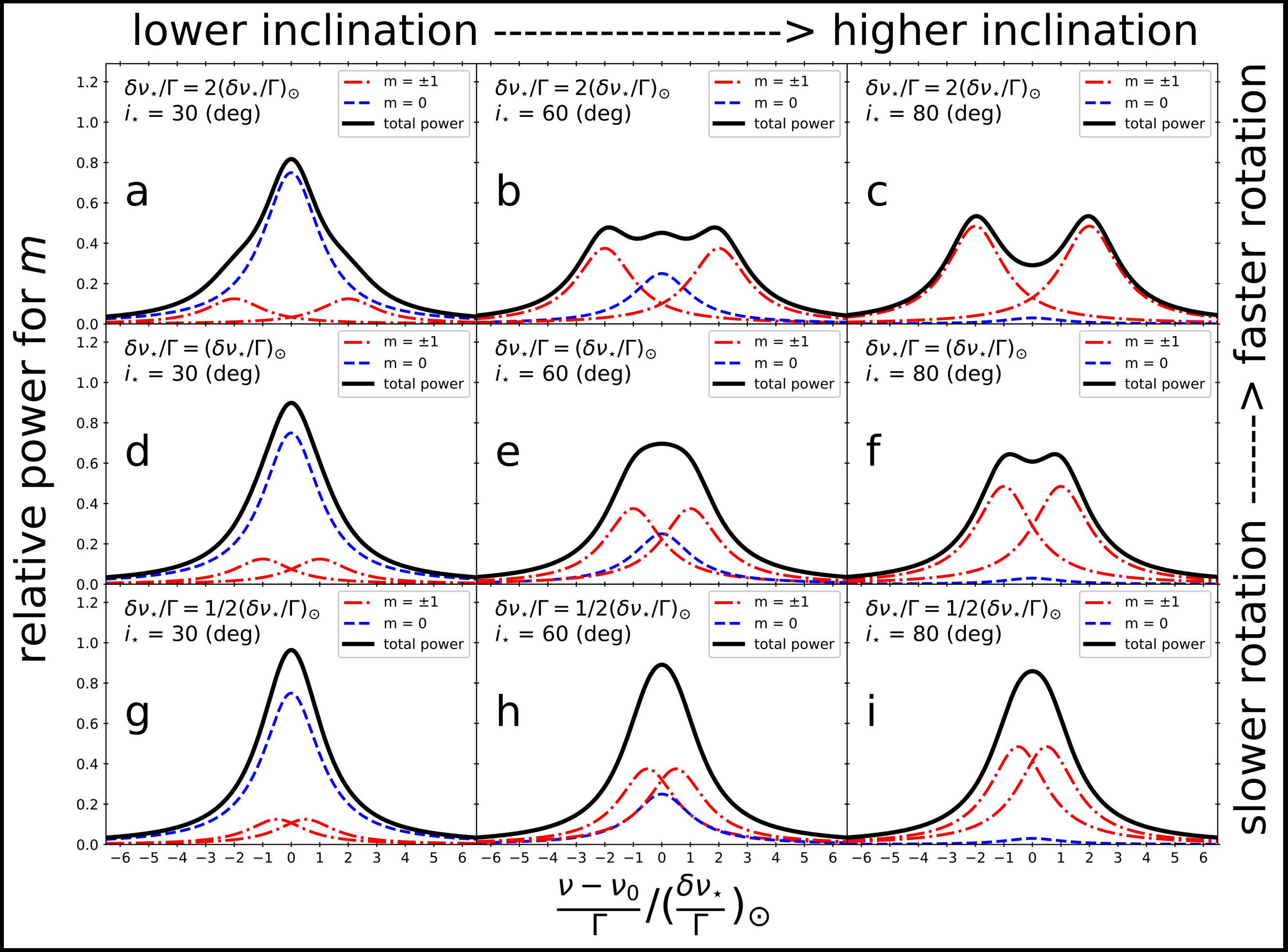
$$\nu(n,l,m) = \nu(n,l) + m\,\delta\nu_s(n,l)$$



Stellar obliquity from asteroseismology

- Complementary probe of spin-orbit angles of exoplanetary systems

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



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)

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

  - see Campante et al. (2016) $i_s = 80.6°^{+6.5°}_{-9.3°}$ $\Psi = 12.6°^{+6.7°}_{-11.0°}$
  - 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 Huber et al. (2013) , Campante et al.(2016)

Analytic criteria for measurable i_*

- Identify m=±1 modes: lower limit of i_*

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

δf: oscillation frequency resolution
Γ: width of oscillation profile
SNR: line height to background ratio

- Identify m=0 mode: upper limit of i_*

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

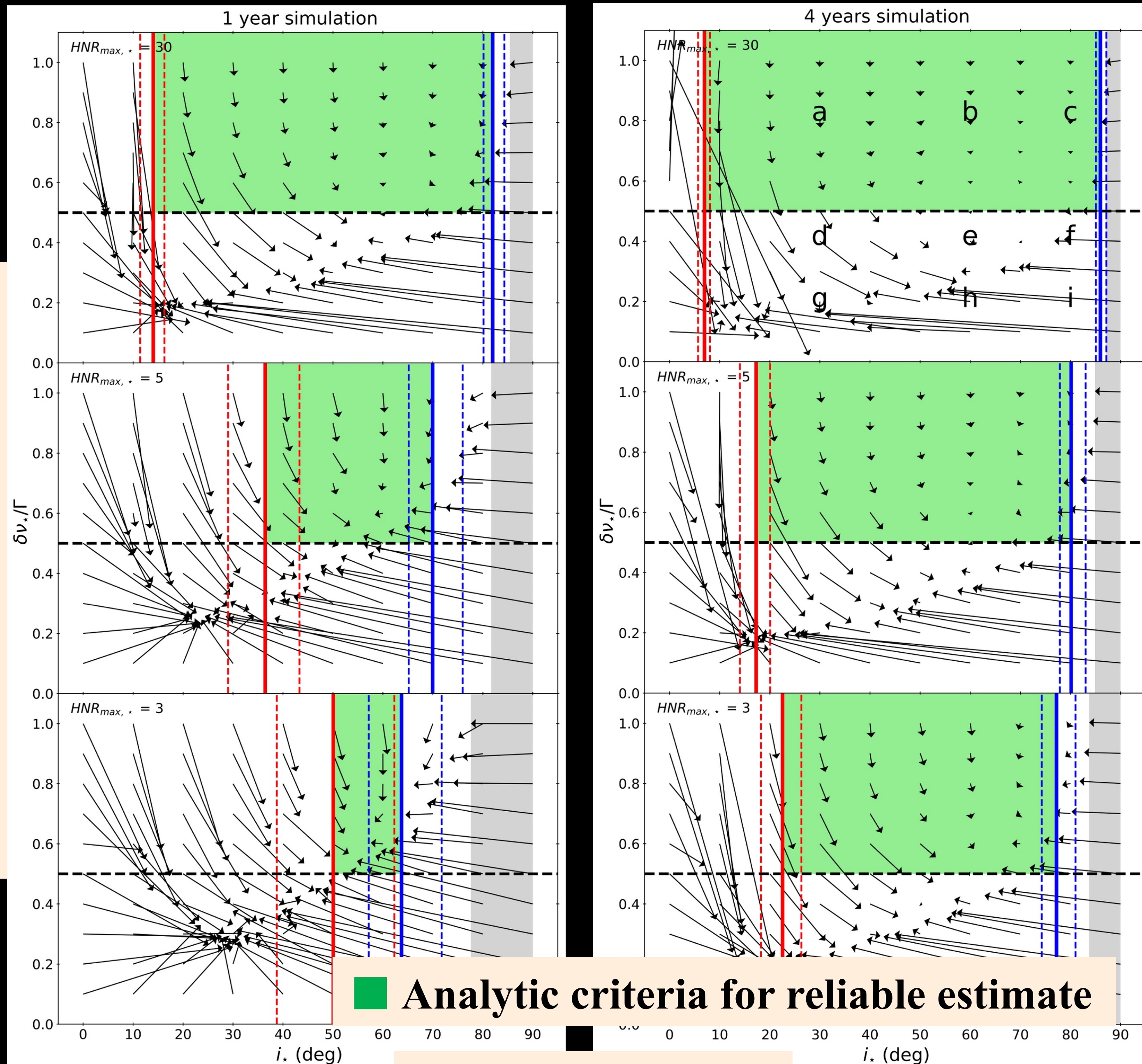
α, β: numerical fudge factors
$\delta\nu_*$: rotational splitting ($\cong 1/P_{rot,*}$)

- Distinguish m=±1 modes: rotational separation

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

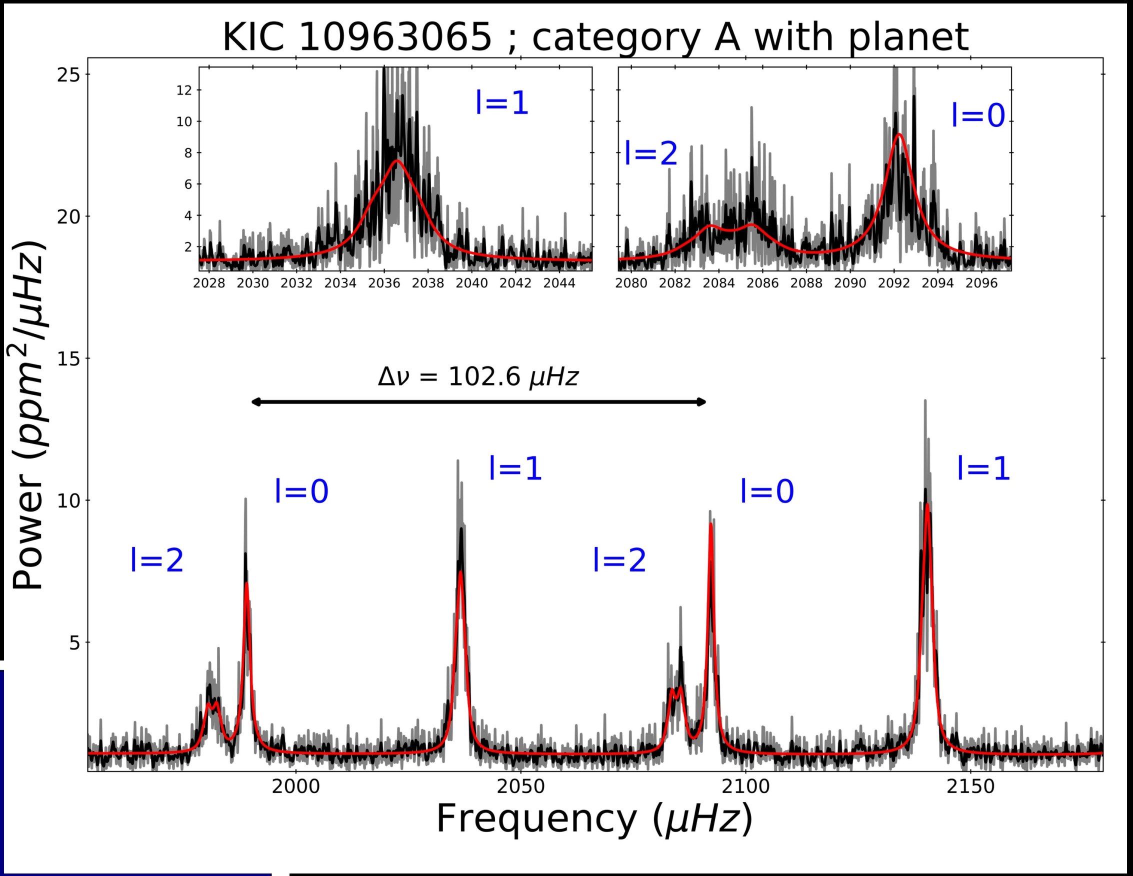
Kamiaka, Benomar + YS, arXiv:1805.07044
MNRAS (2018)

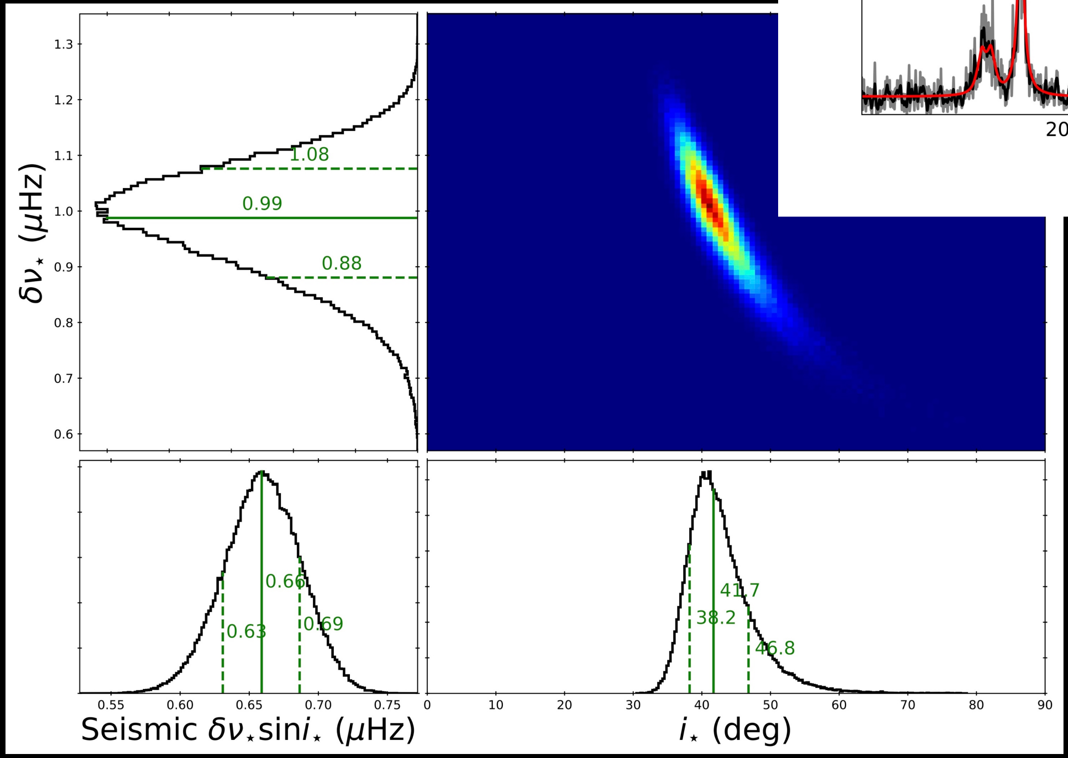
Simultaneous fit of many different modes



Kamiaka et al. arXiv:1805.07044

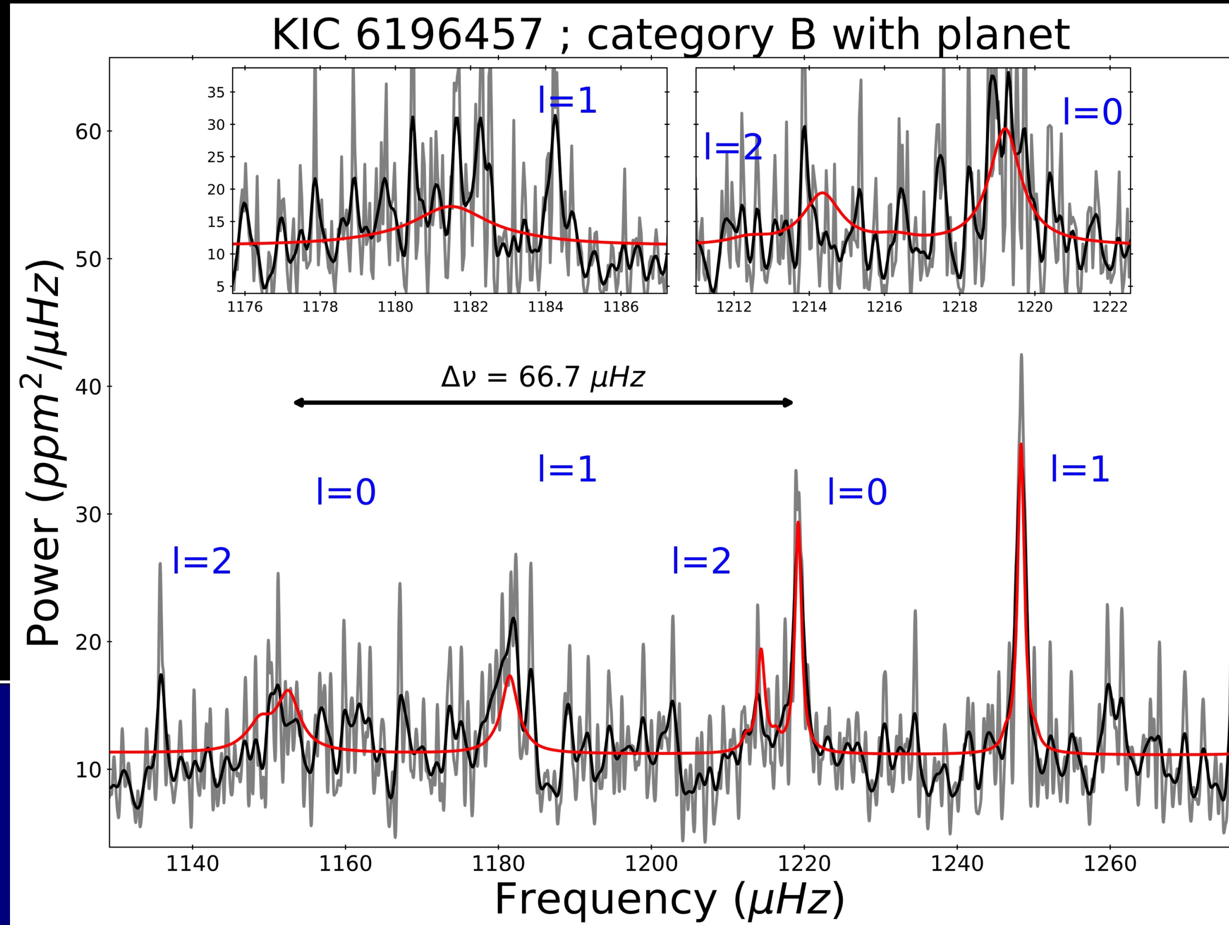
A reliable example

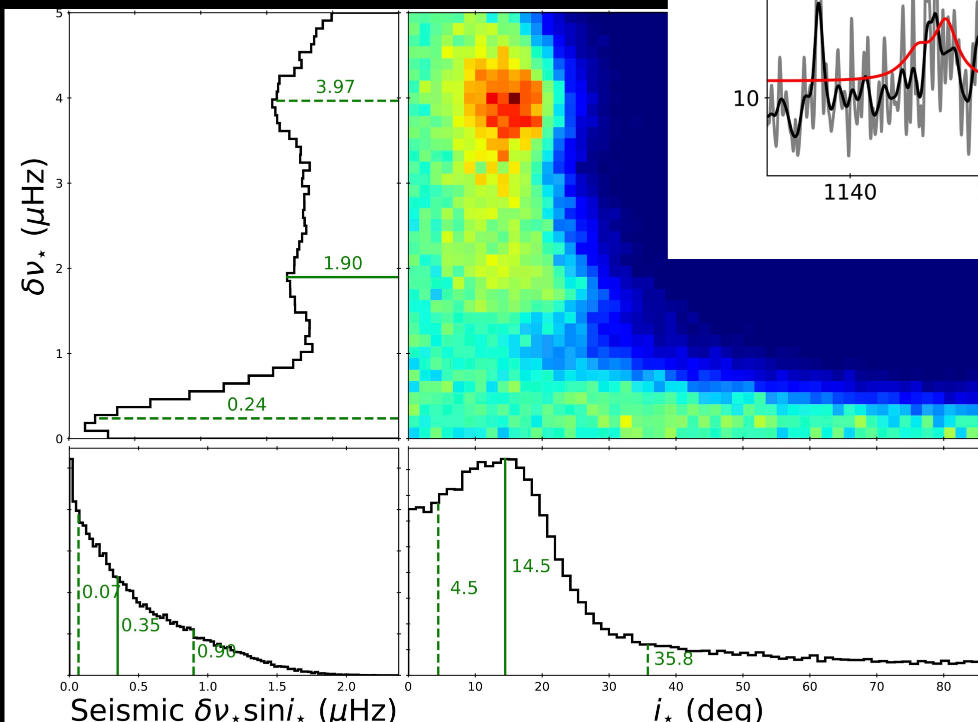




Kamiaka et al. arXiv:1805.07044

An unreliable example

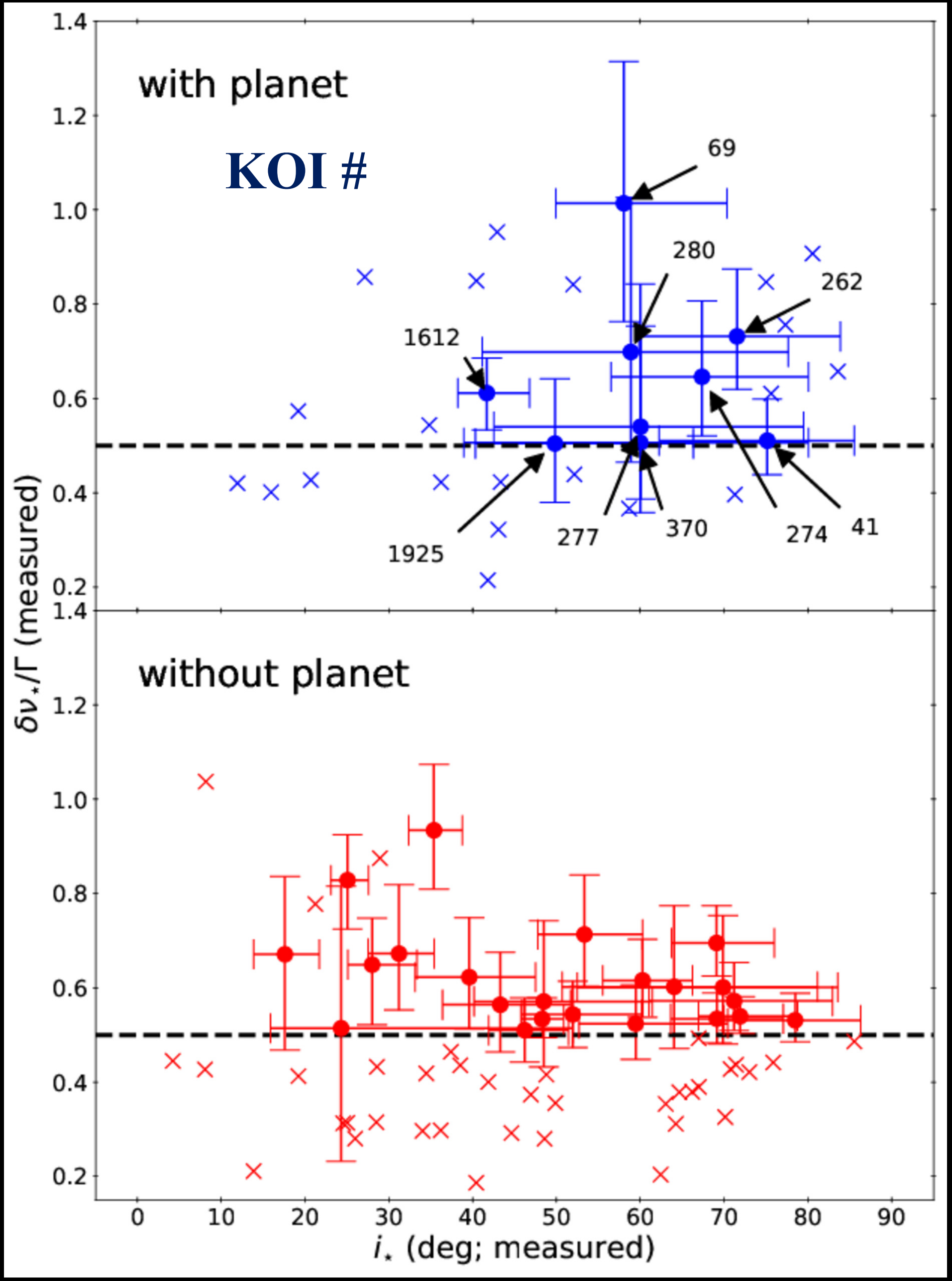




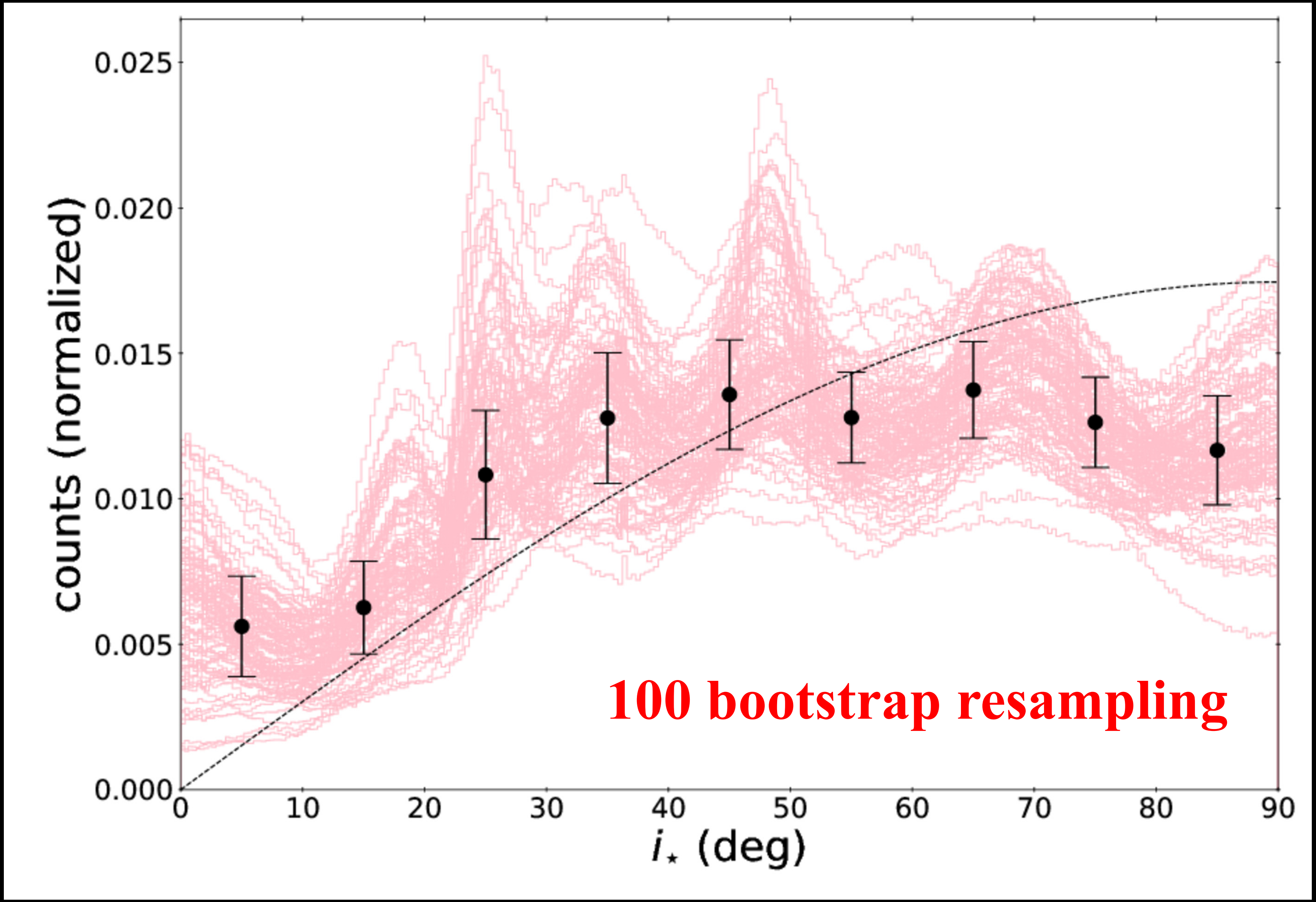
Kamiaka et al. arXiv:1805.07044

i_* from asteroseismology: with/without planets

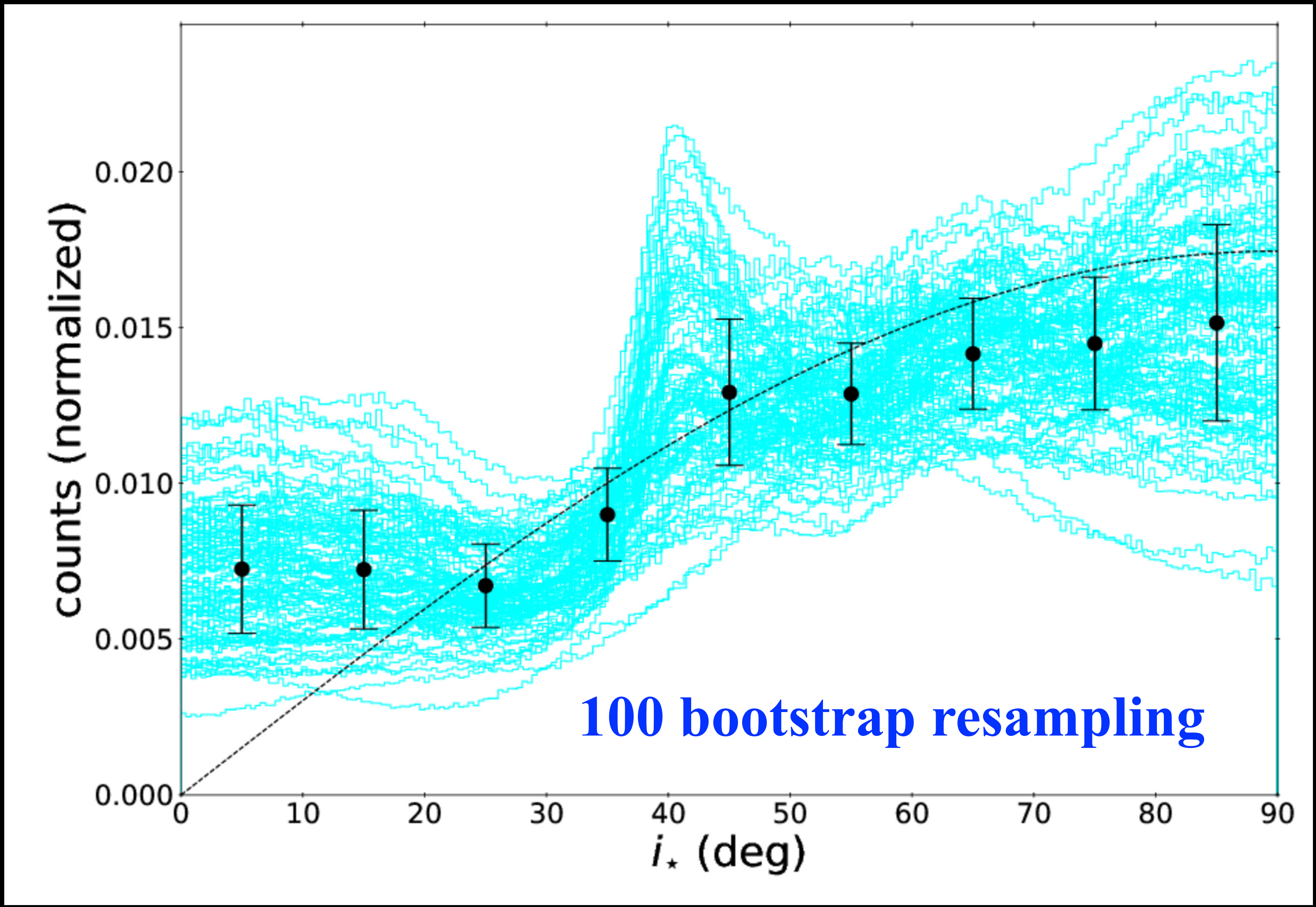
- 94 Kepler main-sequence stars
  - 33 with planets
  - 61 without planets
- Planet-host stars have systematically larger stellar obliquities



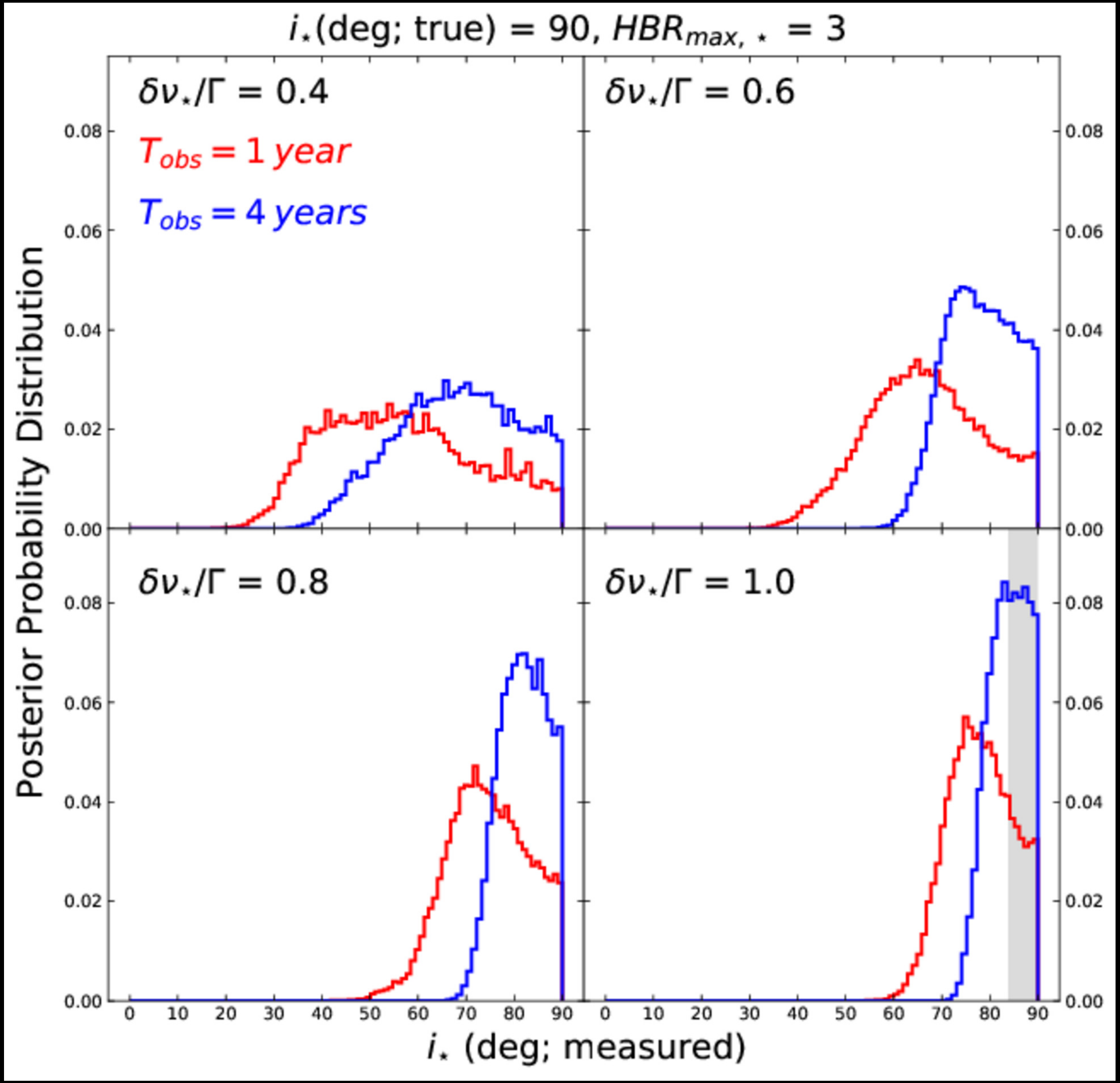
Inclination PDF for 61 stars w/o planets



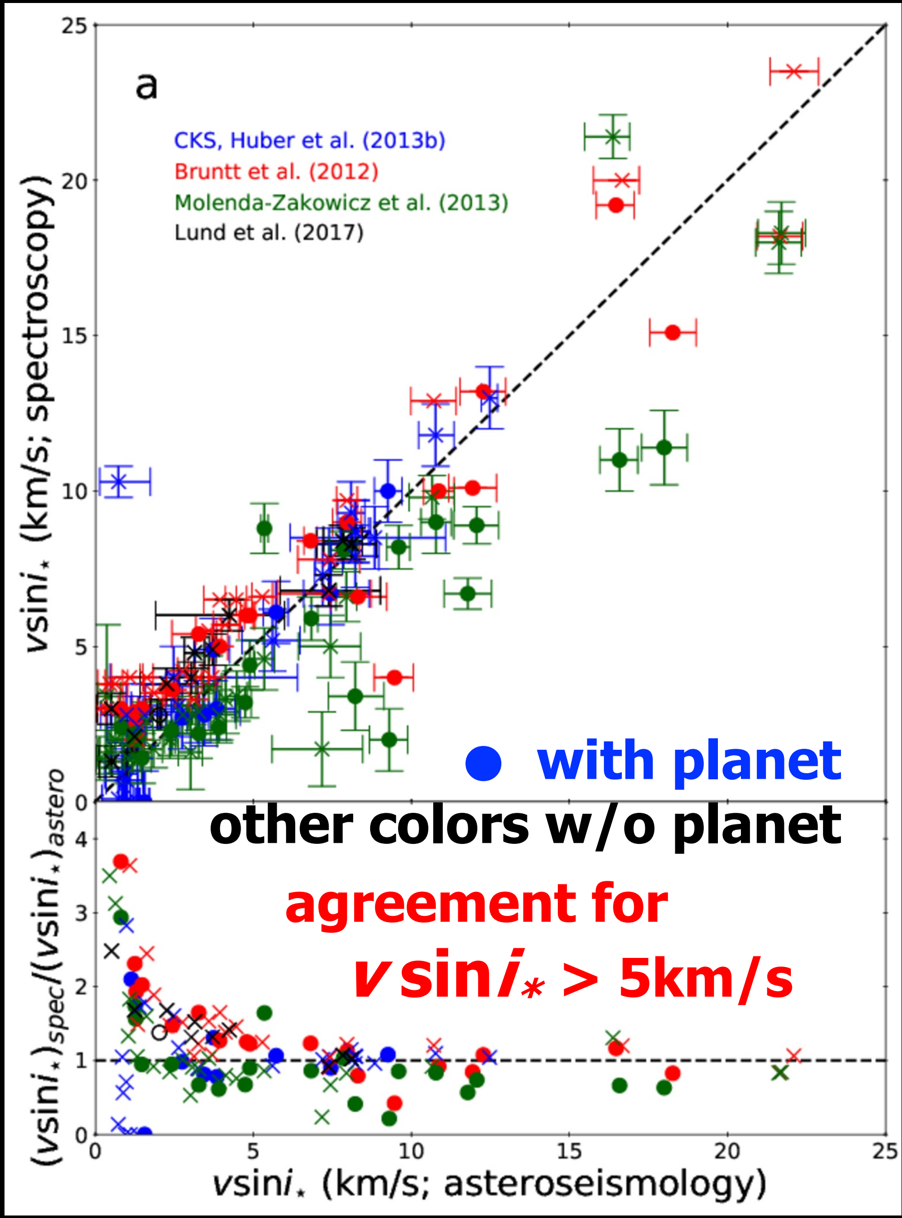
Inclination PDF for 33 stars with planets

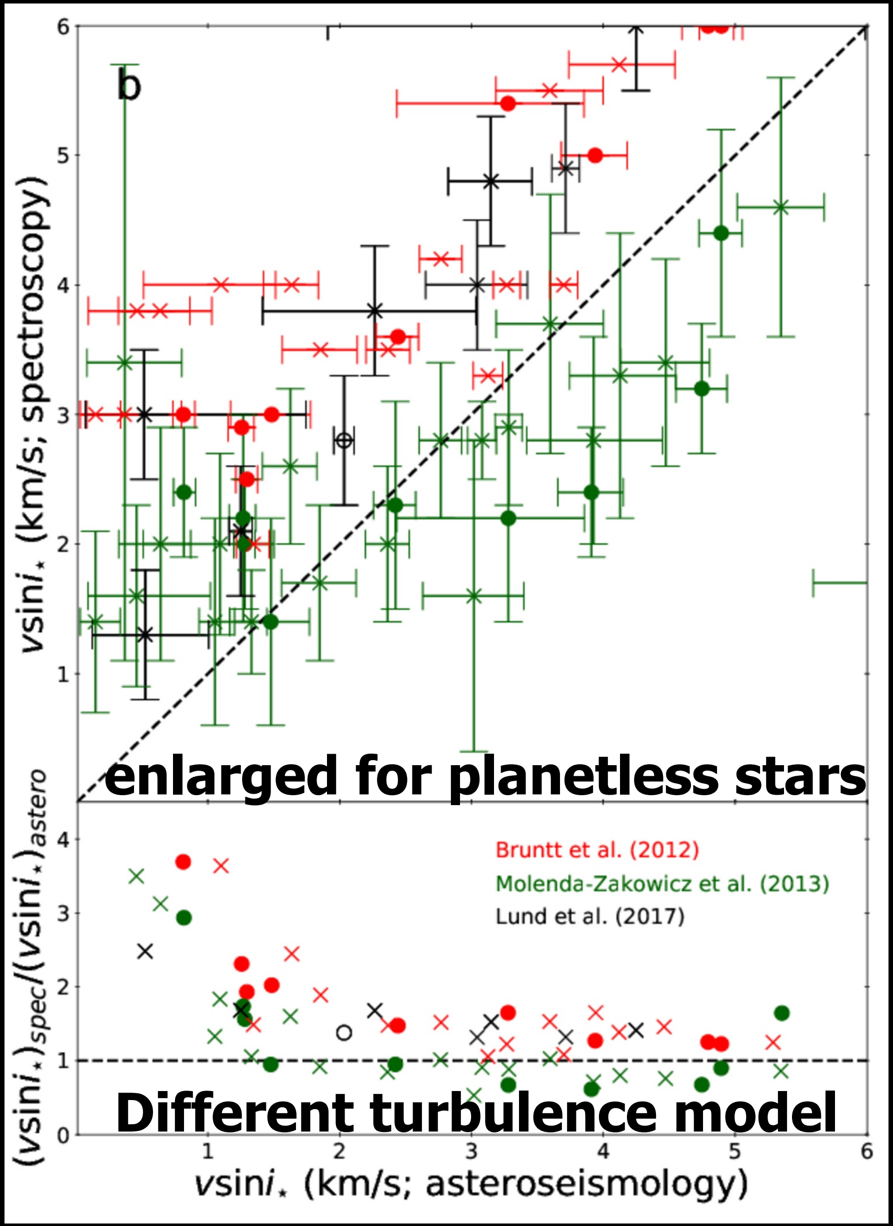


Posterior PDF of i_* for a simulated star

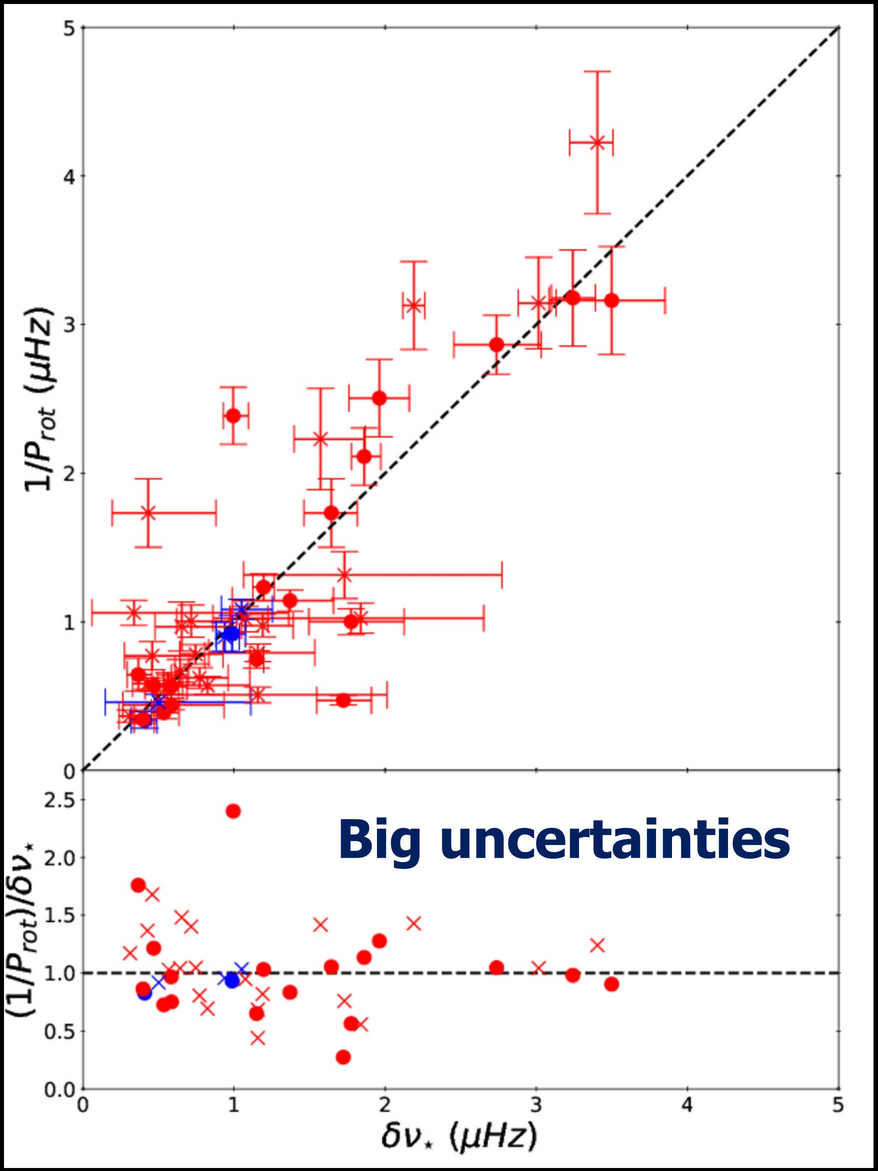


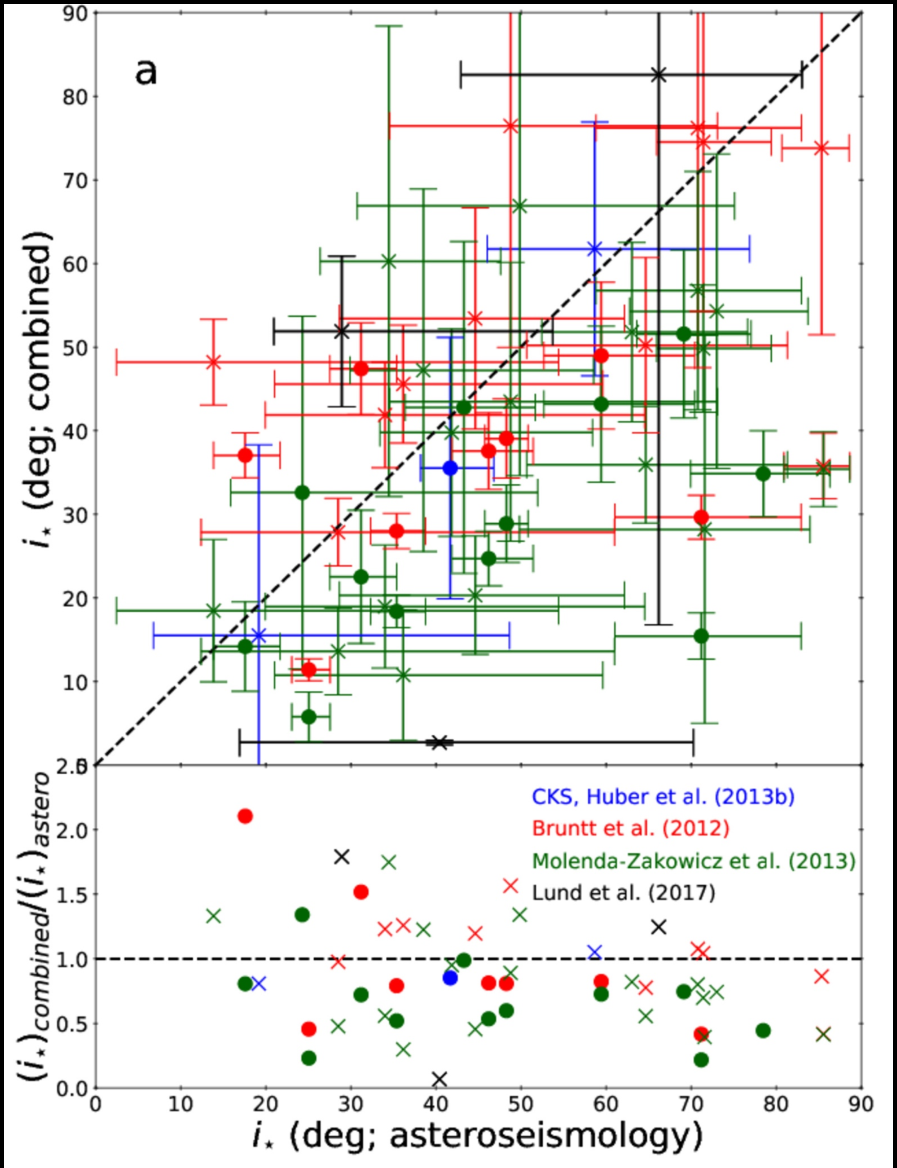
$v\sin i_*$: spectroscopy vs. seismology





P_{rot} and i_* from photometric variation





Conclusions

- Stellar obliquities i_s estimated from asteroseismology provide important/complementary clues to architecture of exoplanetary systems (independent of the nature of planets)
- We derived analytic criteria for i_s to be reliable, which were calibrated/confirmed by series of systematic simulations
- Asteroseismic measurements of i_s for most Kepler stars are reliable only for those in the range of $20^\circ < i_s < 80^\circ$
- We are trying to improve the fitting method