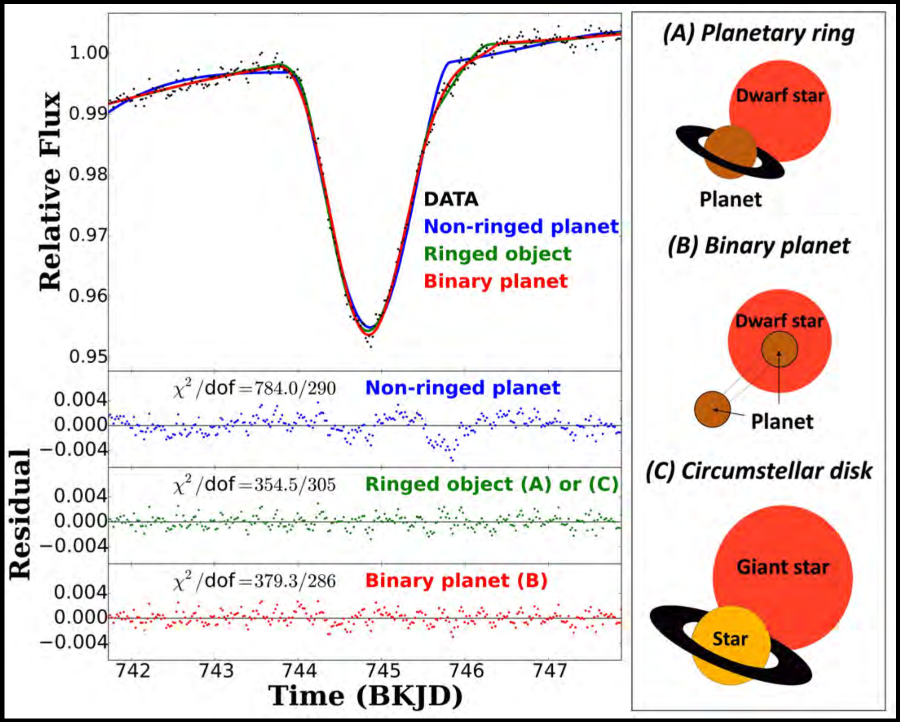
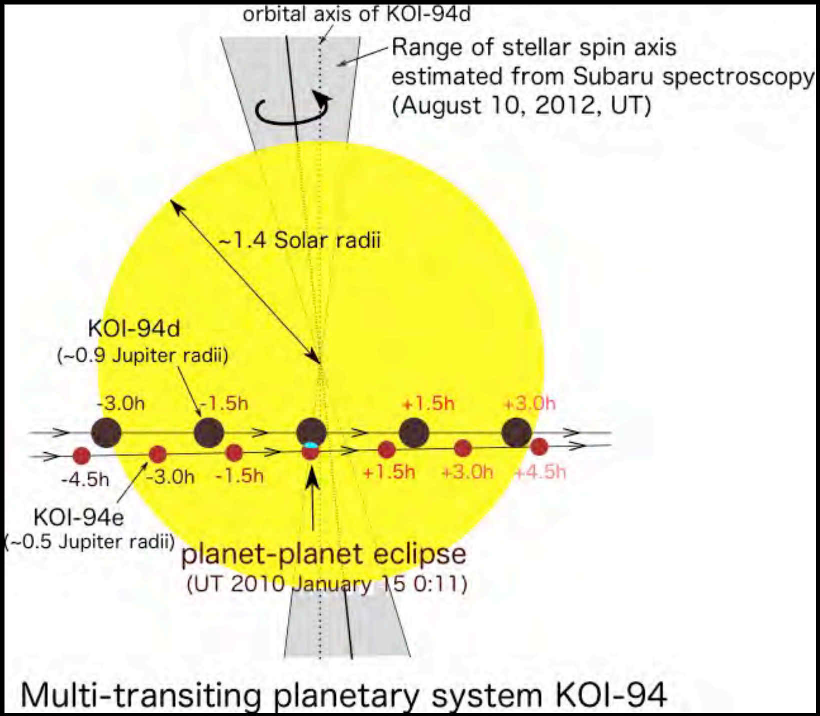
Architecture of spin and orbital angular momenta in exoplanetary systems





Yasushi Suto

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(REsearch Center for the Early Universe) The University of Tokyo

15:00-16:00, October 25, 2017 @ Observatoire de la Côte d'Azur

From Saturnian model to atomic model

- Saturnian architecture inspired the model of atomic structure
  - H.Nagaoka: Phil. Mag. 7(1904) 445

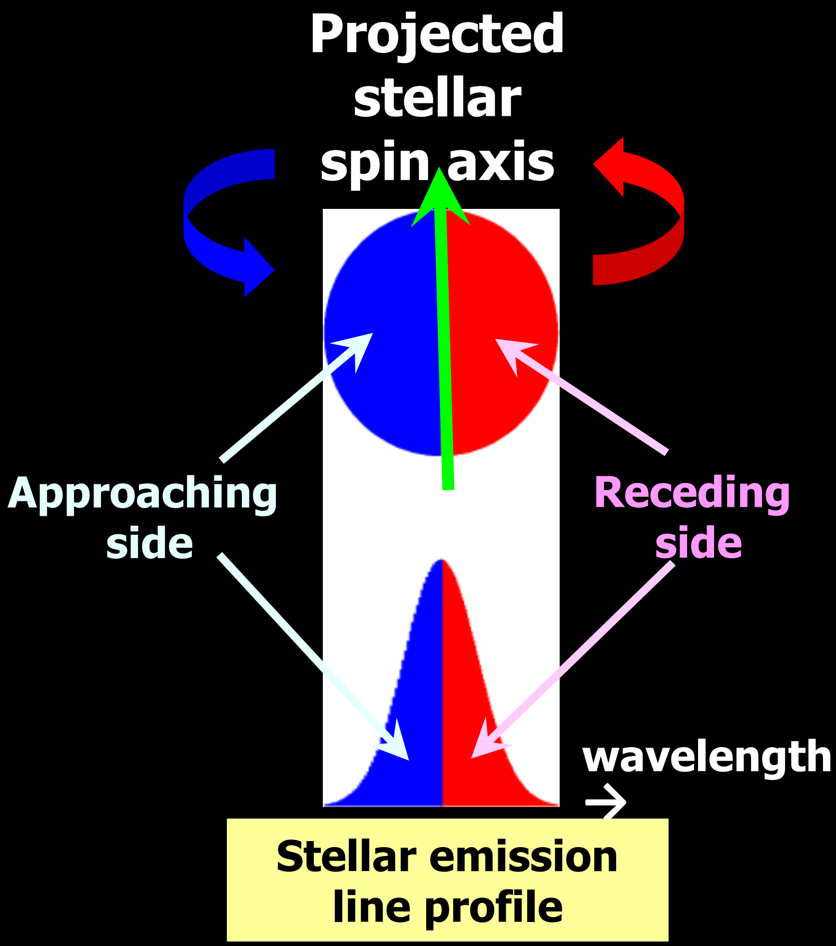
Ernest Rutherford: *The Scattering of α and β Particles by Matter and the Structure of the Atom* Phil. Mag. 6(1911) 669

It is of interest to note that Nagaoka * has mathematically considered the properties of a "Saturnian" atom which he supposed to consist of a central attracting mass surrounded by rings of rotating electrons. He showed that such a system was stable if the attractive force was large. From the point of view considered in this paper, the chance of large deflexion would practically be unaltered, whether the atom is considered to be a disk or a sphere.

From atomic model to architecture of exoplanetary systems

Ang. Mom.	Atomic system	Exoplanetary system
L	Quantized energy levels Emission/absorption line transition	Spectroscopic radial velocity Transit photometry, Microlensing Orbital period, semi-major axis, eccentricity, planetary mass
S	Spin of nucleus Hyperfine structure splitting	Rossiter-McLaughlin effect Asteroseismology Stellar spin - planetary orbit angle Stellar spin obliquity
s	Spin of electrons Fine structure splitting	Tidal interaction between star and planet Planetary spin, planetary ring

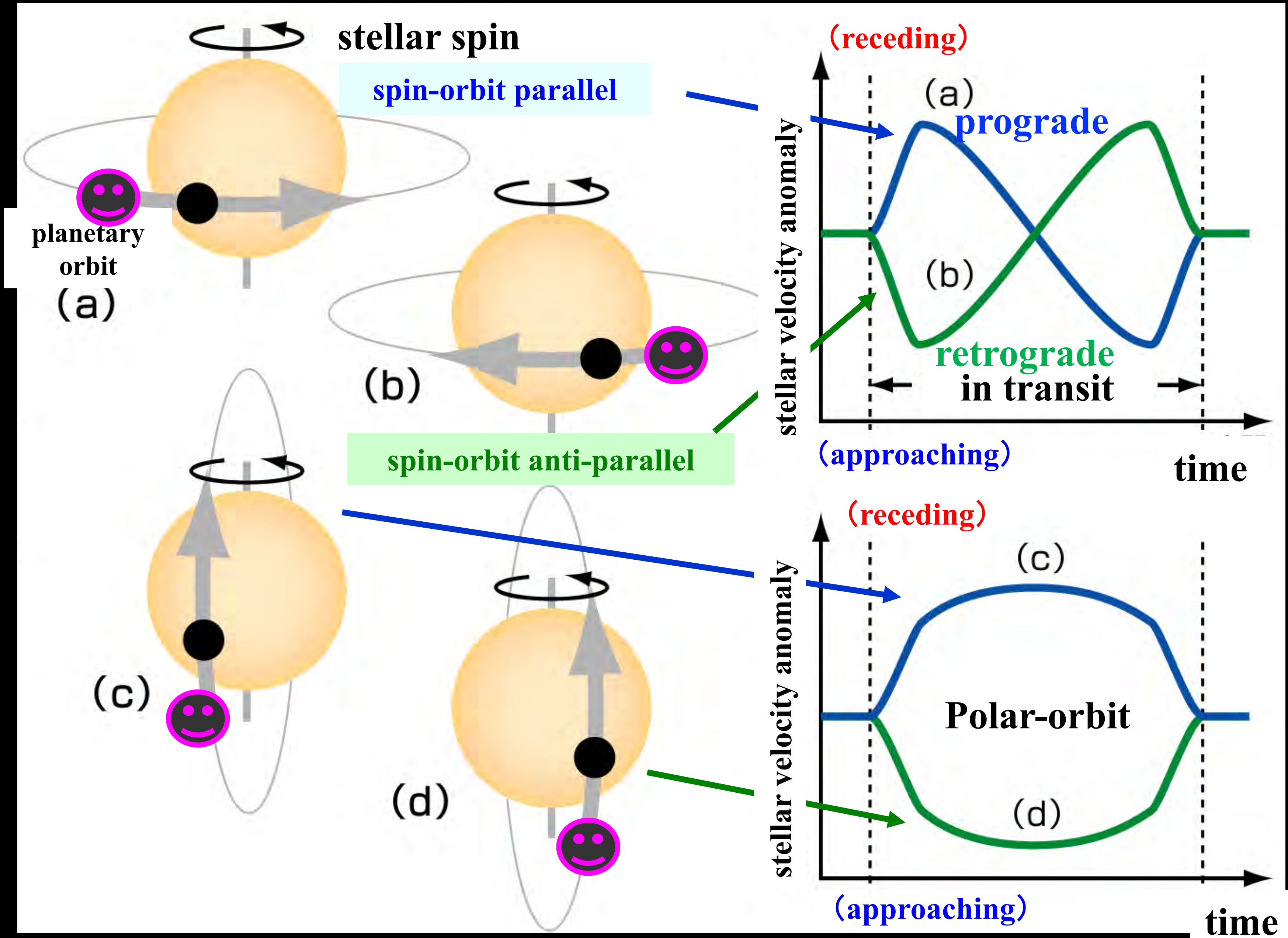
Spectroscopic transit signature: the Rossiter-McLaughlin effect



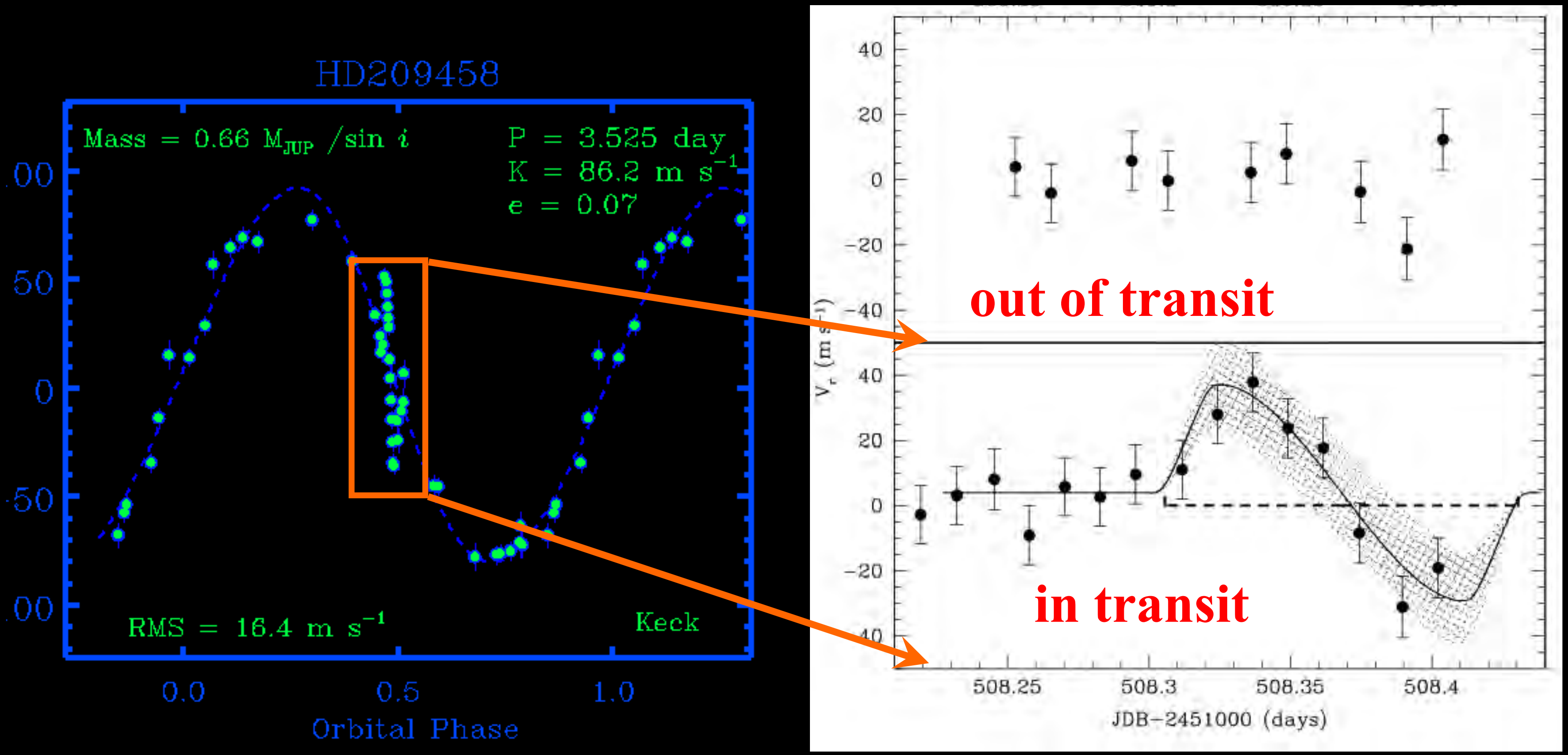
- Time-dependent asymmetry in the stellar Doppler broadened line profile
  - apparent anomaly of the stellar radial velocity
- originally proposed for eclipsing binaries

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

Velocity anomaly due to the Rossiter-McLaughlin effect



The first detection of the Rossiter-McLaughlin effect: HD209458



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

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

Evolution of my own prejudice 1

Spin-orbit misalignment for exoplanets is 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

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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Received 2004 October 13; accepted 2004 December 10

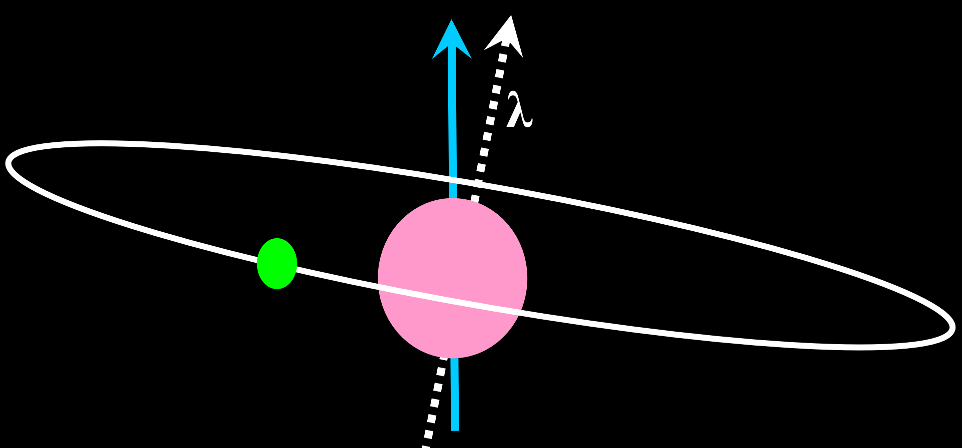
Among the recently discovered transiting extrasolar planetary systems, i.e., TrES-1 by the Trans-Atlantic Exoplanet Survey (Alonso et al. 2004) and OGLE-TR 10, 56, 111, 113, 132 by the Optically Gravitational Lens Event survey (e.g., Udalski et al. 2002c, 2002b, 2002a, 2003; Konacki et al. 2003; Bouchy 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.

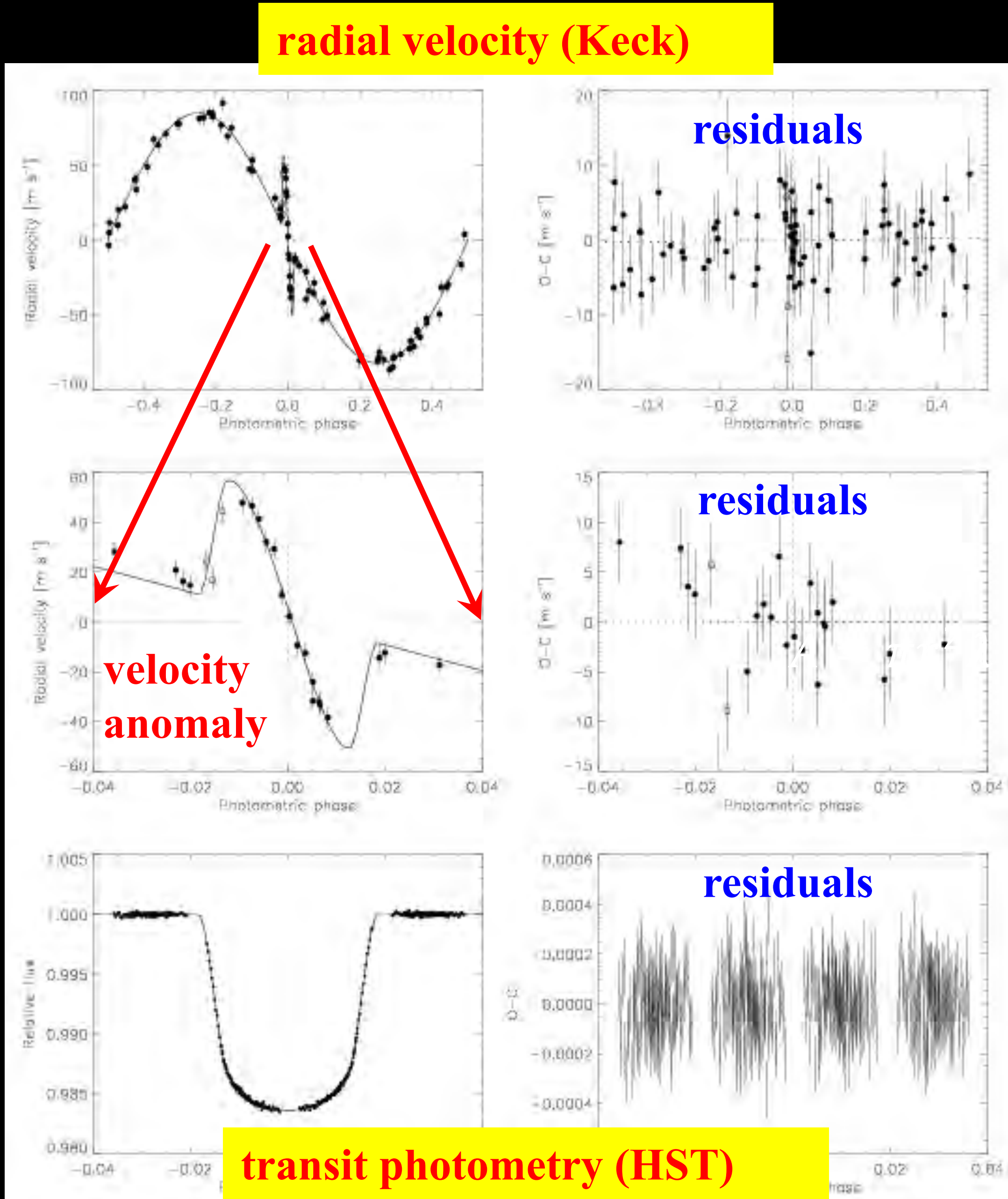
We also note that the future satellites *COROT* and *Kepler* will detect numerous transiting planetary systems, most of which will be important targets for the RM effect in 8–10 m class ground-based telescopes. We hope that our analytic formulae presented here will be a useful template in estimating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

Measurement of spin-orbit alignment in an extrasolar planetary system

- Joshua N. Winn, R.W. Noyes, M.J. Holman, D.B. Charbonneau, Y. Ohta, A. Taruya, Y. Suto, N. Narita, E.L. Turner, J.A. Johnson, G.W. Marcy, R.P. Butler, & S.S. Vogt
  - ApJ 631(2005)1215 (astro-ph/0504555)

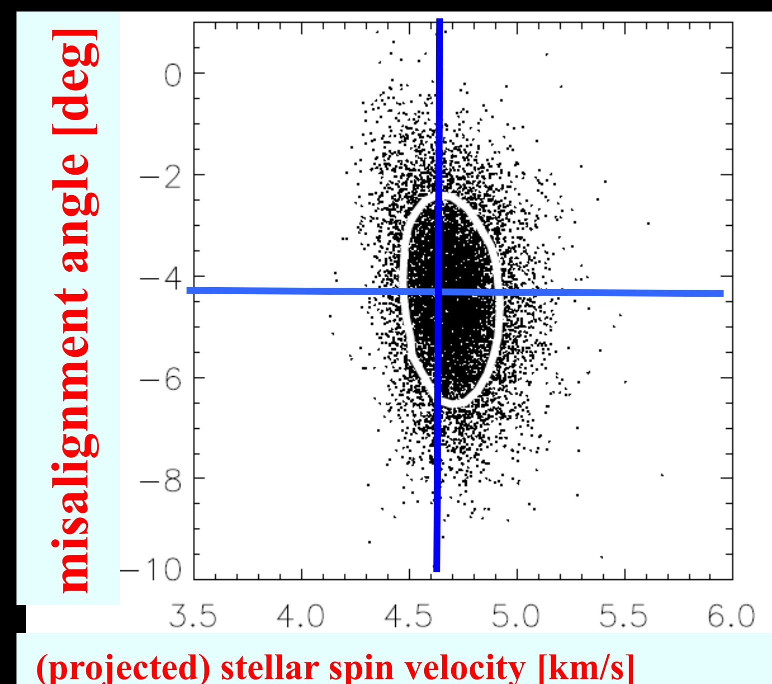




- First detection of small misalignment

$$\lambda = -4.4° \pm 1.4°$$

- Established precise RM measurement methodology



Winn et al. ApJ 631(2005)1215

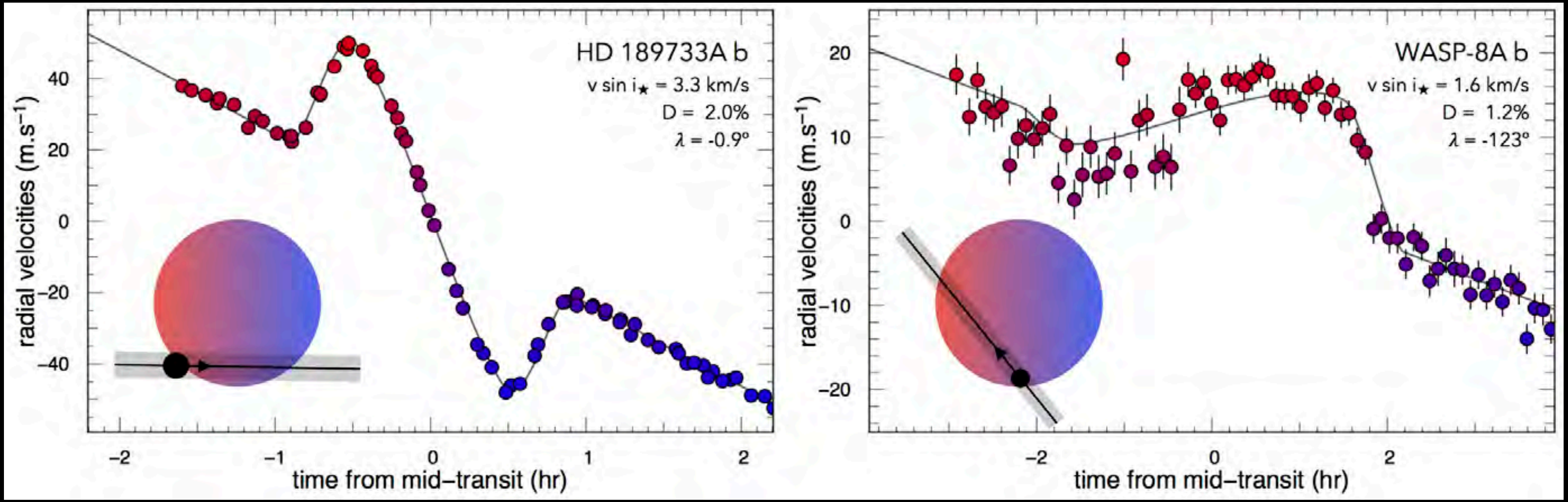
Evolution of my own prejudice 2

Spin-orbit misalignment may be common for Hot Jupiters, but should not for transiting multi-planetary systems

- Around 2010, it became clear that a fair fraction of the observed Hot-Jupiters exhibits large spin-orbit misalignment
- This cannot happen, however, in transiting multi-planetary systems, which is unlikely to have suffered from significant dynamical disturbance, and thus should keep the initial condition (e.g., our Solar system aligned within several degrees)
- Let us test this prediction with the RM measurement for a transiting multi-planet system !

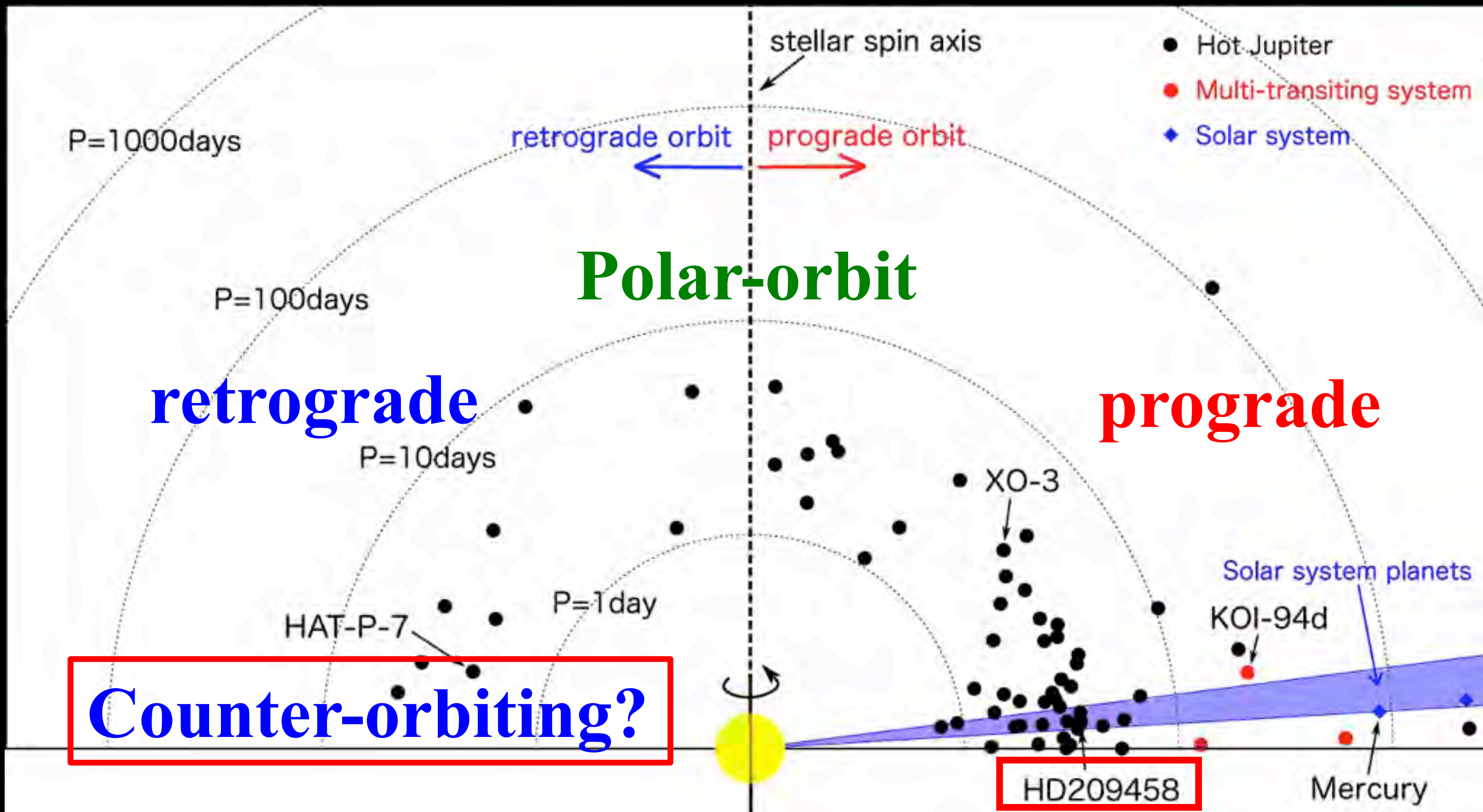
Examples of RM velocity anomaly

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

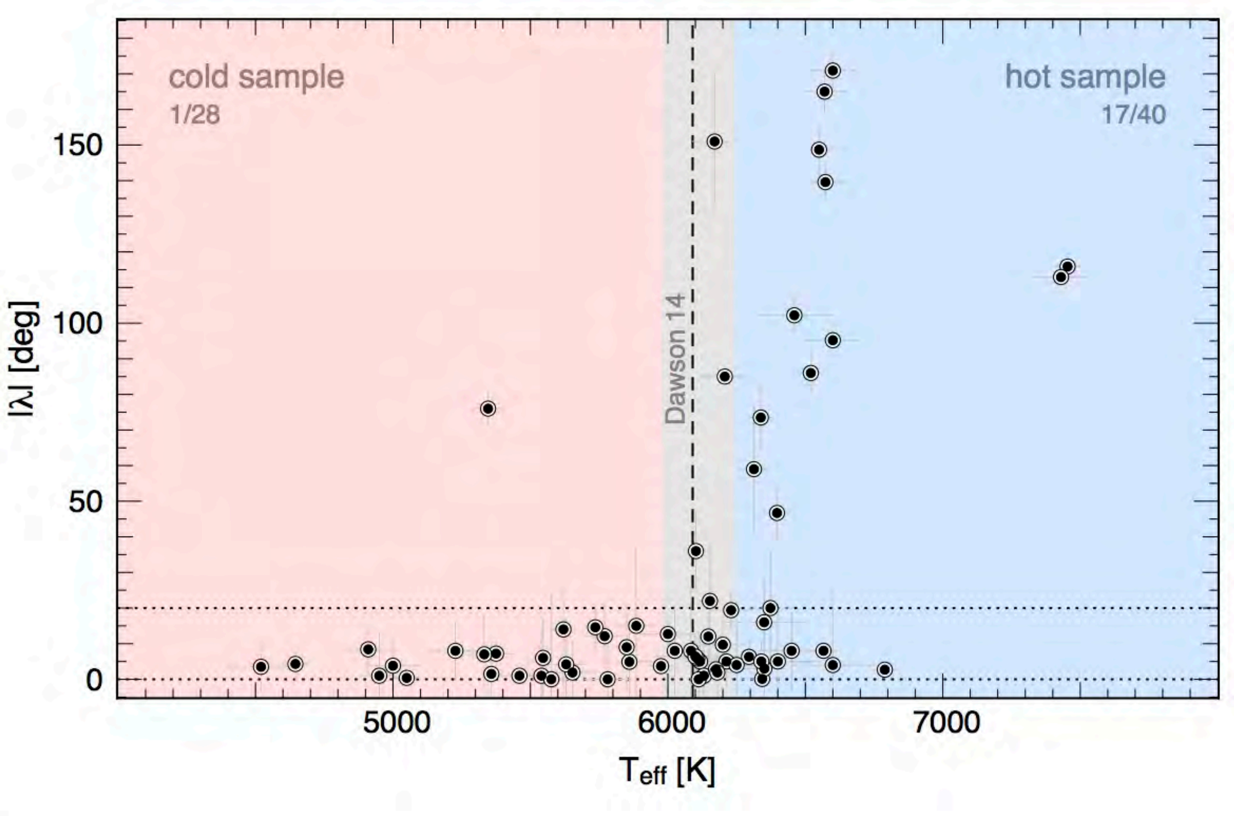
Projected spin-orbit angle distribution



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

Xue et al. (2014)

Projected misalignment vs. stellar effective temperature



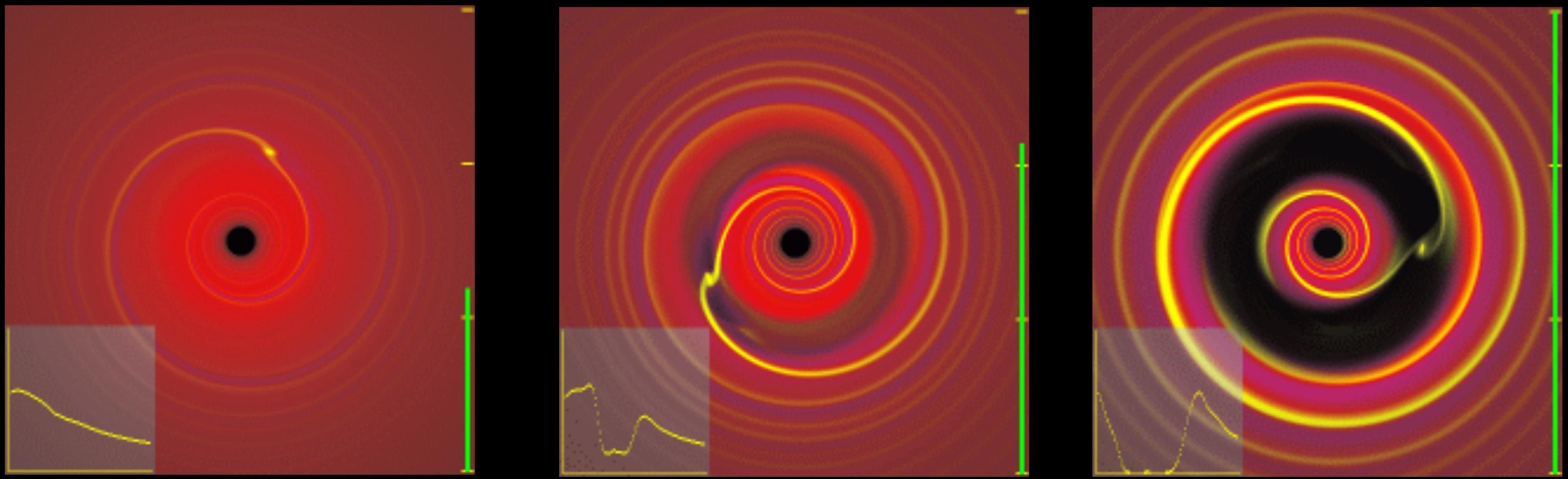
Triaud arXiv:1709.06376

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)

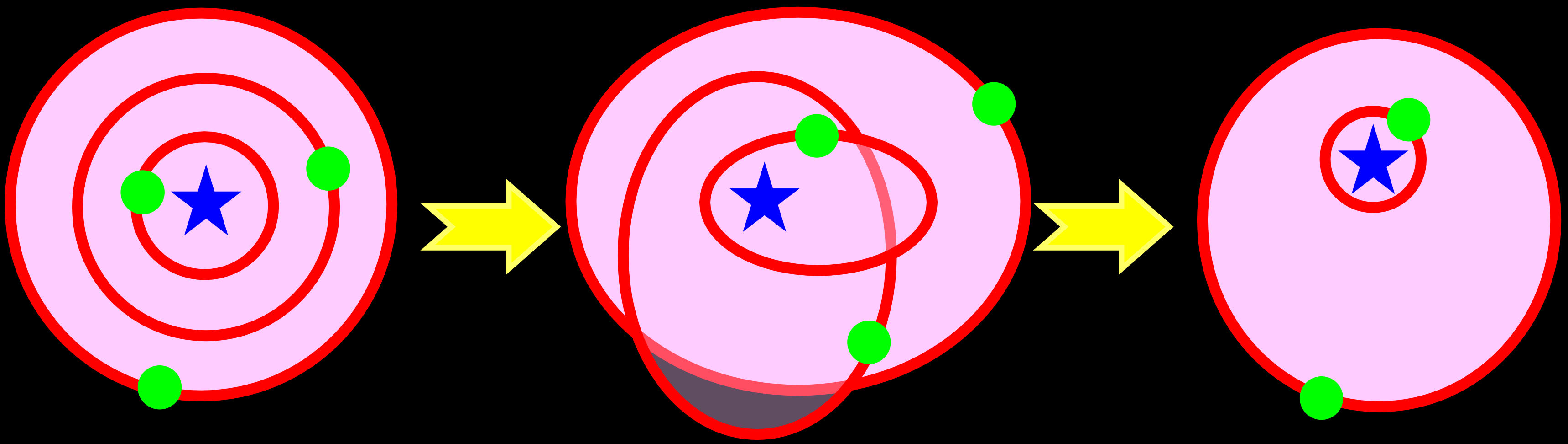
Planet migration scenarios

- 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

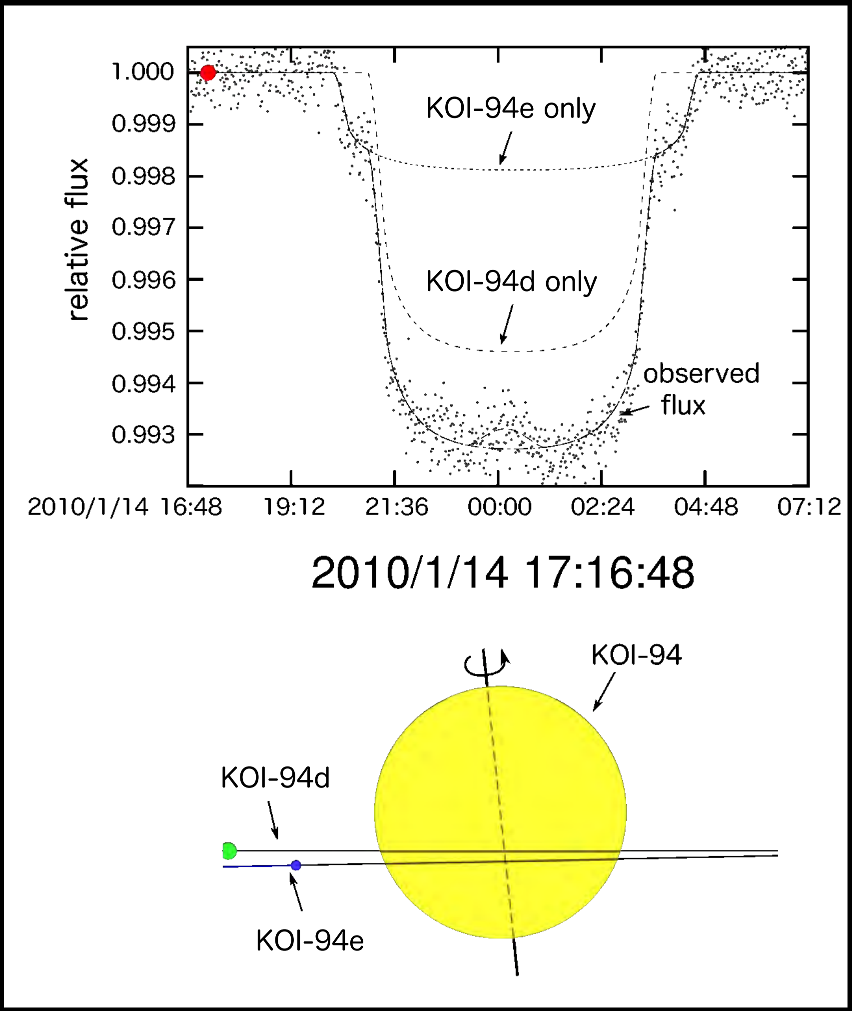


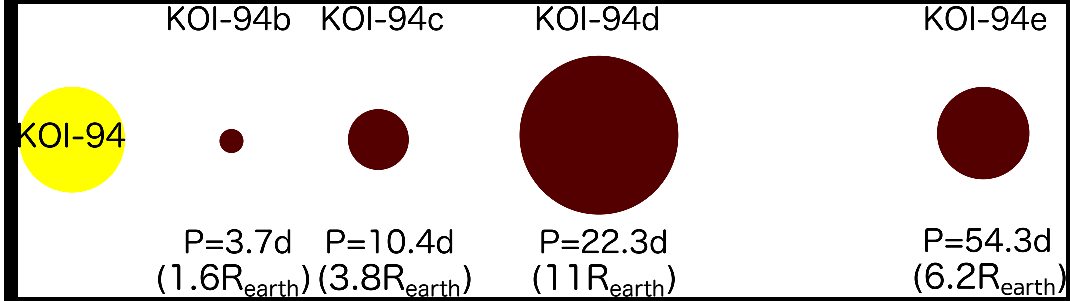
Planet-planet gravitation scattering
+ star-planet tidal interaction
= circularized but misaligned Hot Jupiters



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

RM observation of KOI-94 with Subaru: a system with 4 transiting planets





- First detection of planet-planet eclipse !
  - Even before we conduct the RM measurement in August 2012, we found an anomalous transit signature from Kepler archive on January 14, 2010
  - The orbital planes of those planets are well-aligned

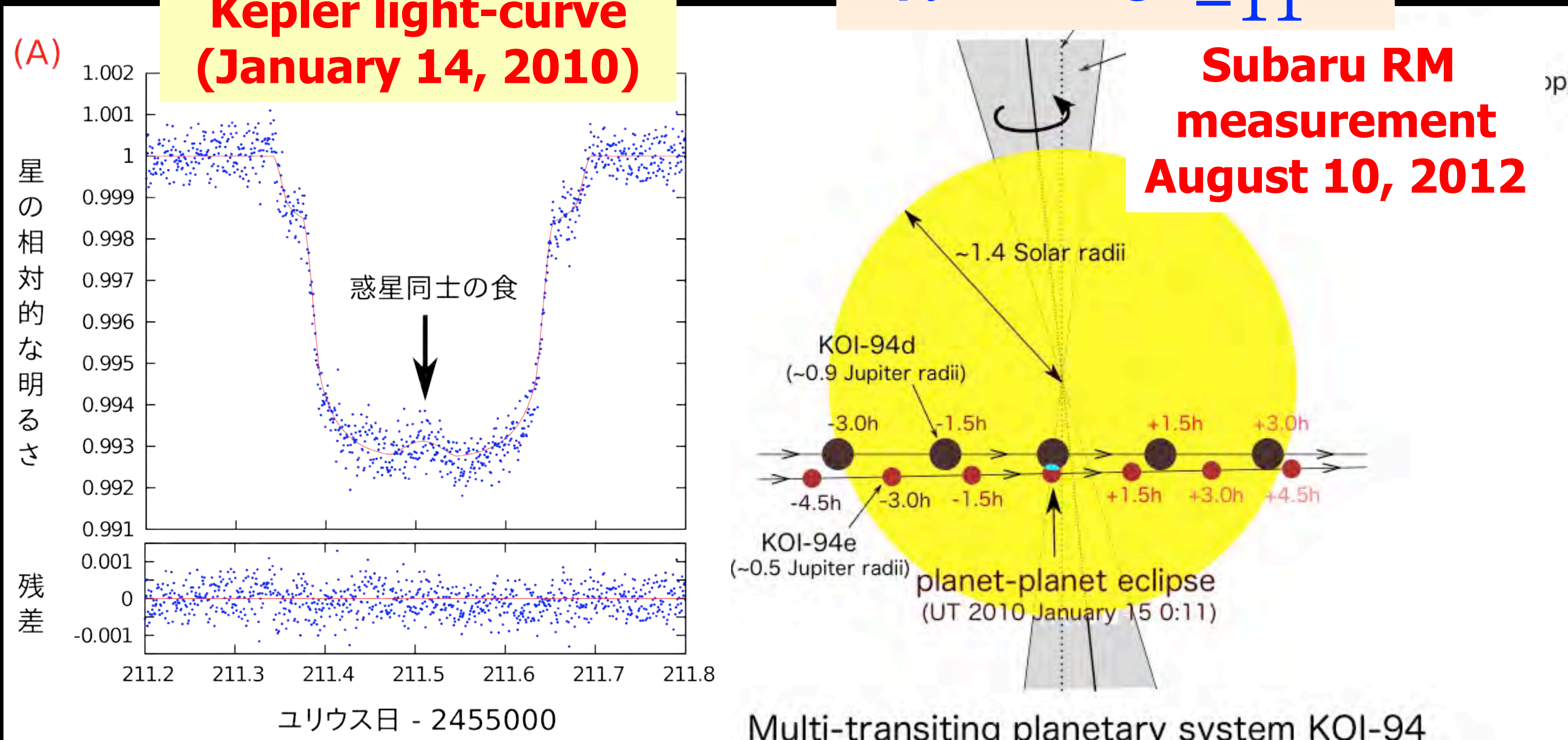
Hirano et al. ApJL 759 (2012)L36

Spin-orbit alignment of KOI-94

$$\lambda = -6^{\circ}{}^{+13^{\circ}}_{-11^{\circ}}$$

Kepler light-curve (January 14, 2010)

Subaru RM measurement August 10, 2012



Hirano et al. ApJL 759 (2012) L36
Masuda et al. ApJ 778 (2013) 185

Evolution of my own prejudice 3

Spin-orbit misalignment should not exist for transiting multi-planetary systems

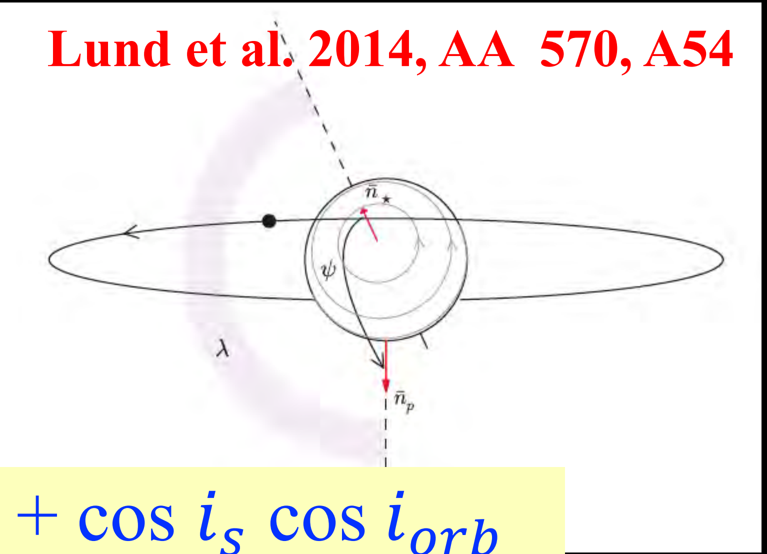
- Subaru spectroscopy + Kepler photometry of a transiting 4 planet system KOI 94 (Hirano et al. 2012, Masuda et al. 2013)
  - First measurement of RM effect for transiting multi-planet system
  - First discovery of planet-planet eclipse
  - KOI-94 was approved as Kepler-89
- Finally a reasonable picture established (?)

Evolution of my own prejudice 4

Stellar obliquity needs to be estimated to fully determine the true spin-orbit angle

- Asteroseismology indicated the stellar obliquity of 47±6 degree for Kepler-56
  - Kepler-56: red giant ($1.3M_s$, $4.3R_s$) + two transiting planets (10.5day, 20.4day)
  - Huber et al. Science 342(2013) 331

- RM effect measures the *projected spin-orbit angle*
  - Is this also the case for other multi-planet systems, especially with a main-sequence host star ?



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

Asteroseismology measurement of stellar obliquities of HAT-P-7 and Kepler-25

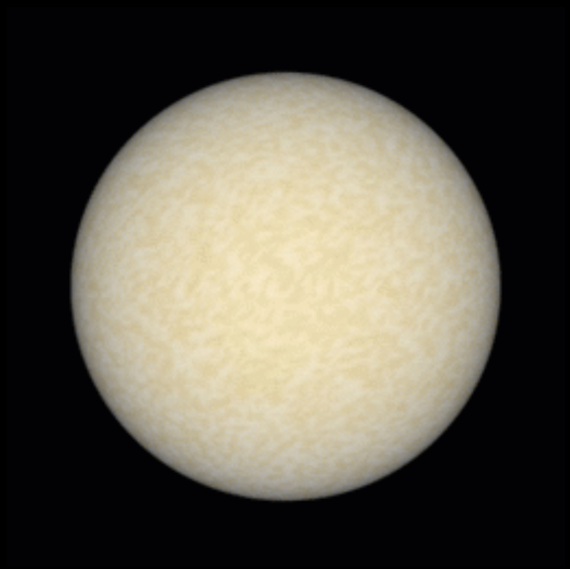
- Kepler-25 with projected spin-orbit angle $\lambda < 10$ degree
  - F-type star ($1.2M_s$, $1.4R_s$) + 6.2day and 12.7day transiting planets+ 123day non-transiting planet
- HAT-P-7 with projected spin-orbit angle $\lambda \fallingdotseq 180$ degree
  - Truly counter-orbiting planet in 3D ?

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

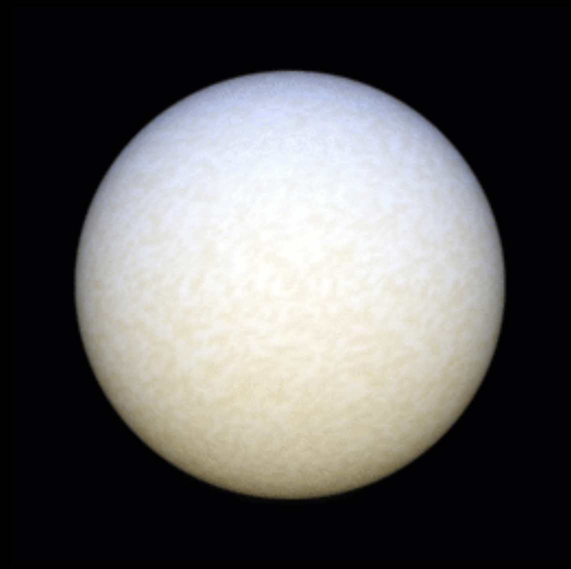
Non-radial oscillations $Y_{lm}(\theta,\varphi)$ (spherical degree l=1)

azimuthal order

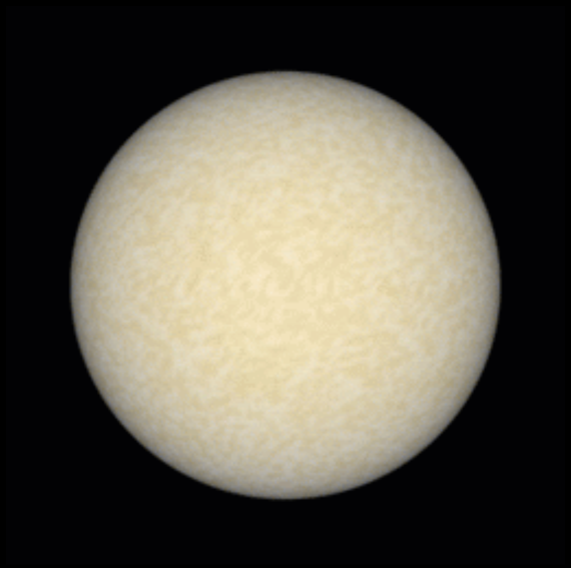
m=-1



m=0

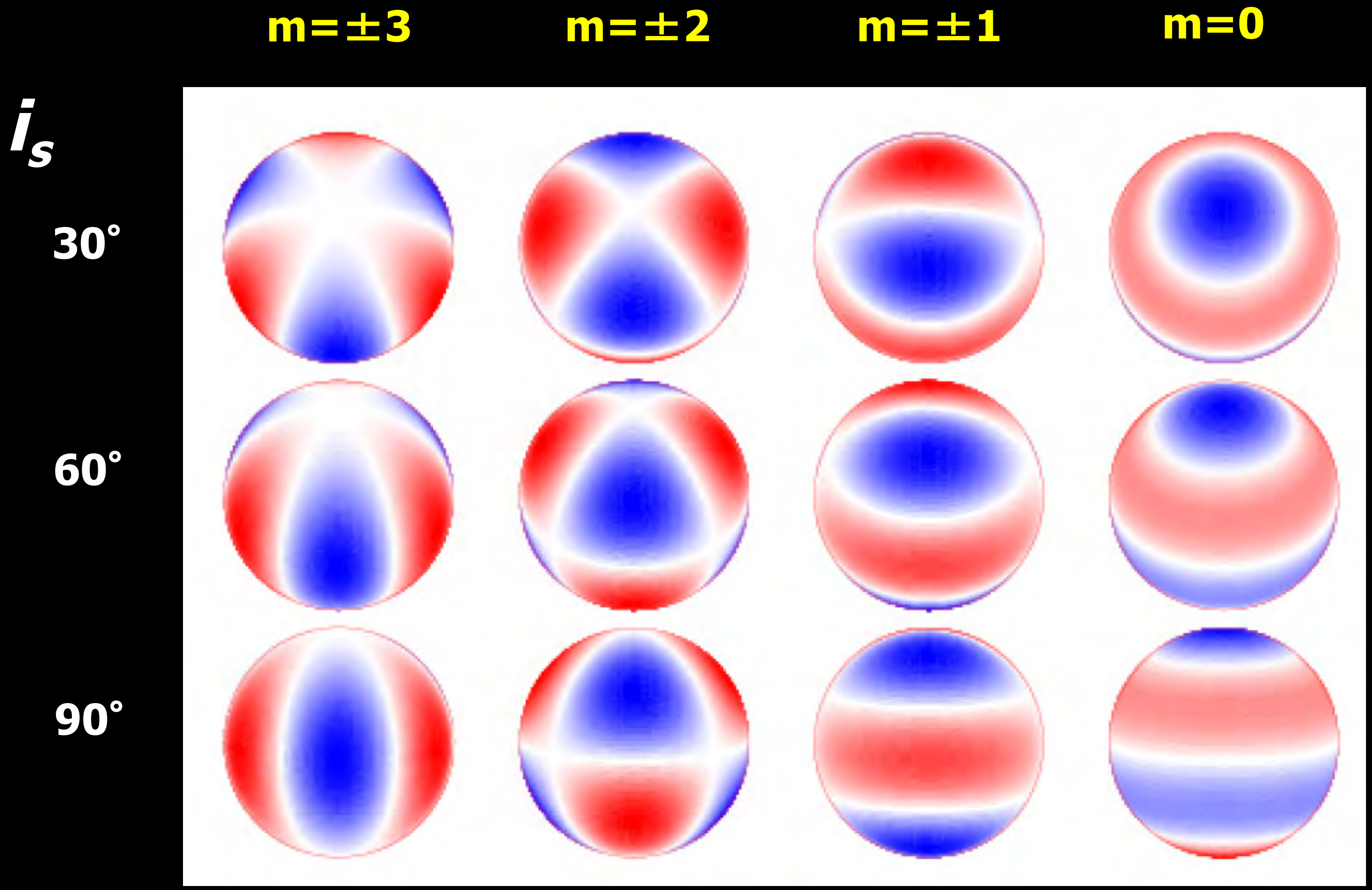


m=+1



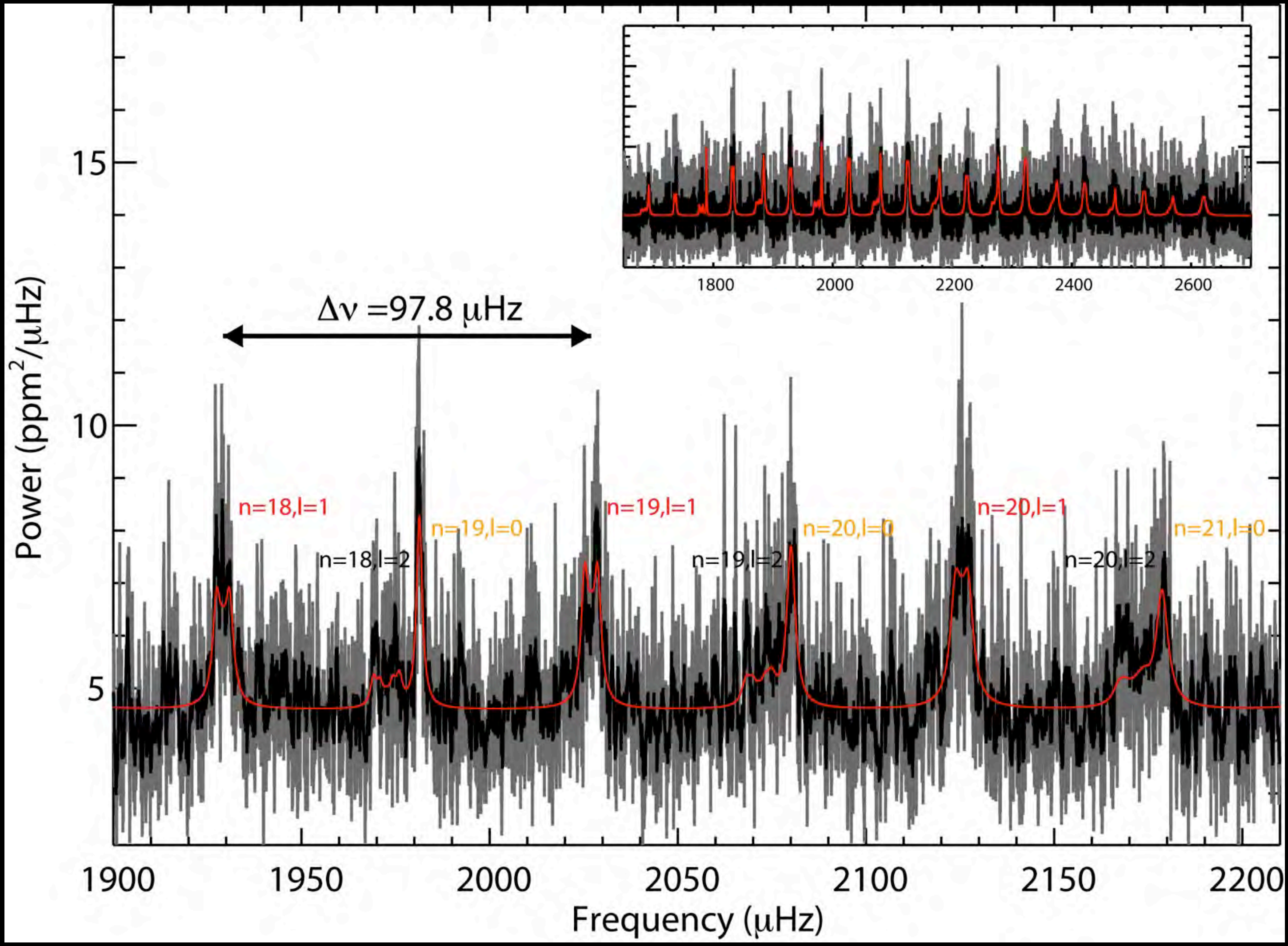
http://www.asteroseismology.org/

Stellar inclination (l=3)



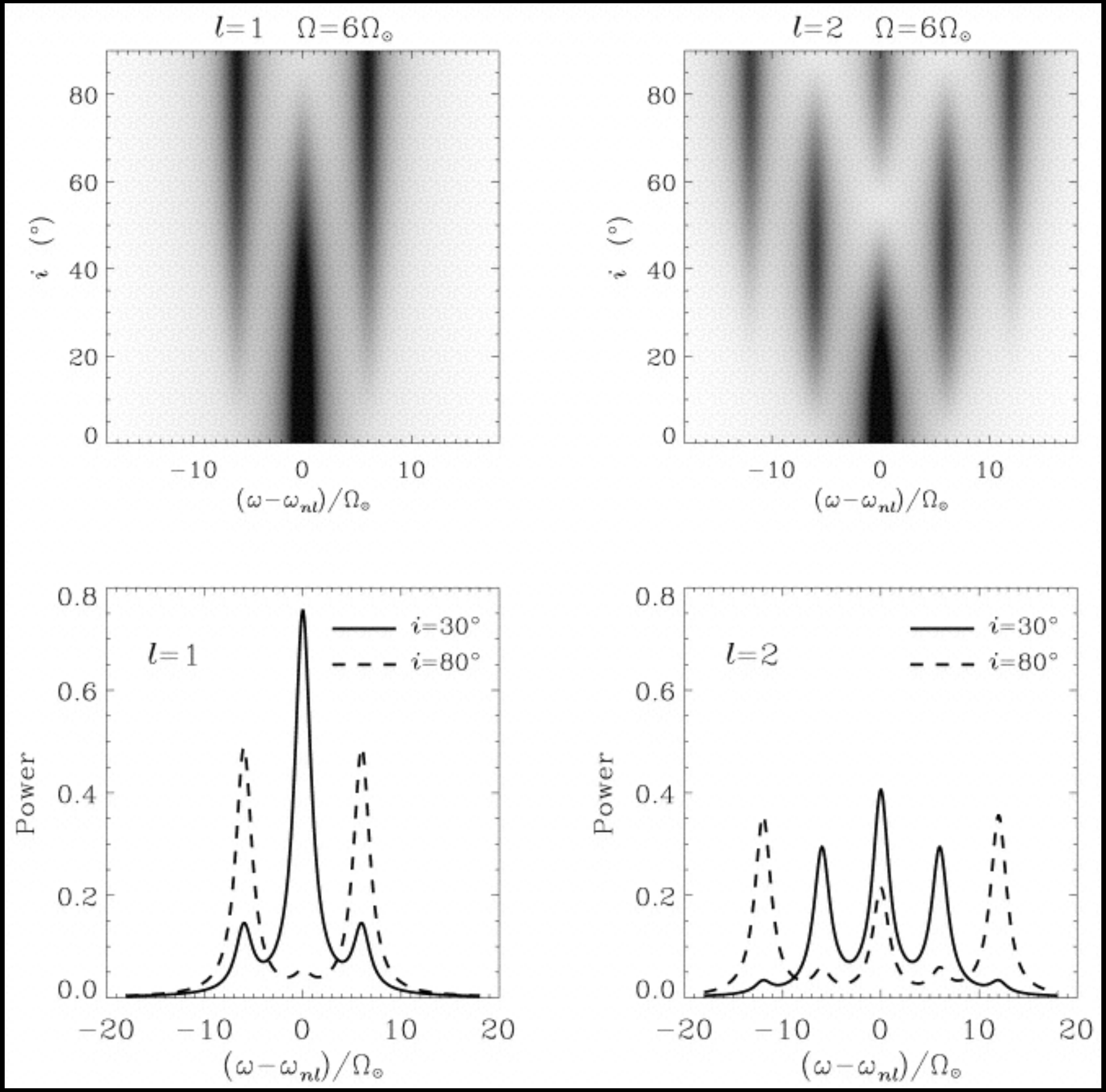
T.L. Campante, arXiv:1405.3145

Power spectra of Kepler-25



Benomar et al. 2014, PASJ 66, 9421, arXiv:1407.7332

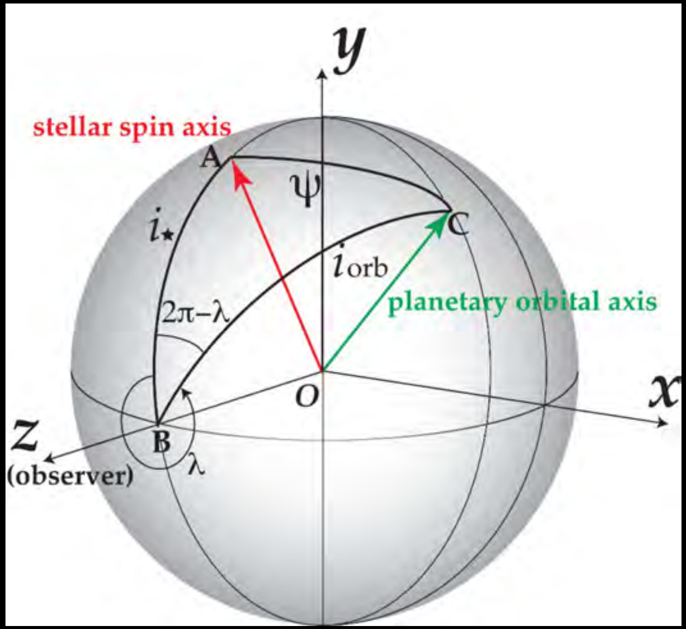
Power spectra of l=1 and 2 modes



Gizon & Solanki, ApJ 589 (2003)1009

Spin-orbit angle of Kepler-25

- Kepler-25 (with two transiting planets)
  - Projected spin-orbit angle: $\lambda = 9.4° \pm 7.1°$ (RM effect)
  - Stellar inclination: $i_s = 65.4°^{+12.1°}_{-7.4°}$ (asteroseismology)
  - True spin-orbit angle: $\Psi = 26.9°^{+7.0°}_{-9.2°}$



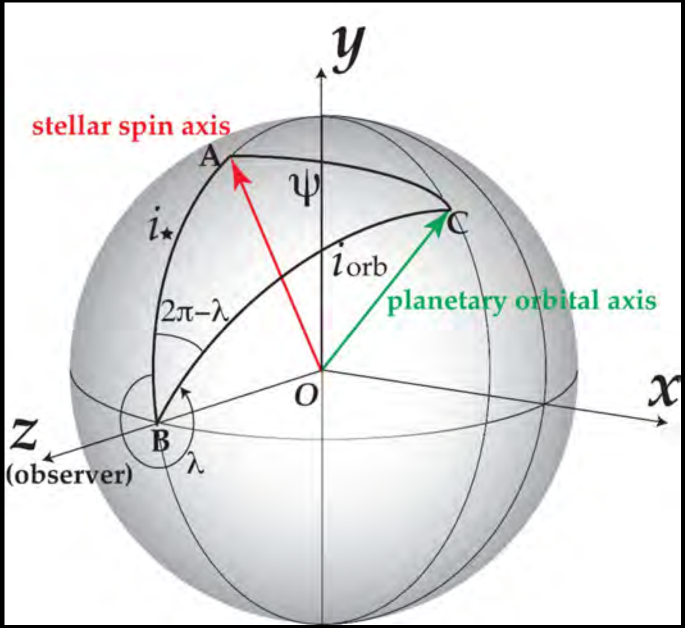
$$\cos\Psi \approx \sin i_s \cos\lambda$$

Benomar et al. 2014, PASJ 66, 94
arXiv:1407.7332

- Multi-planet systems may also show spin-orbit misalignment (primordial?)

Spin-orbit angle of HAT-P-7b

- HAT-P-7b (a retrograde planet on the sky plane)
  - Projected spin-orbit angle: $\lambda = 186°^{+10°}_{-11°}$ (RM effect)
  - Stellar inclination: $i_s = 27°^{+35°}_{-18°}$ (asteroseismology)
  - True spin-orbit angle: $\Psi = 122°^{+30°}_{-18°}$



$$\cos\Psi \approx \sin i_s \cos\lambda$$

Benomar et al. 2014, PASJ 66, 94
arXiv:1407.7332

- Several planets with $\lambda \fallingdotseq 180°$, but none with $\psi \fallingdotseq 180°$ (so far)
- Retrograde ≠ counter-orbiting

My current summary of spin-orbit misalignment of exoplanetary systems

- RM measurements indicate that 30 % of exoplanetary systems with hot host stars (T_{eff}>6100K) are misaligned $(|\lambda| > \pi/3)$, but not for cool host stars
- Asteroseismology revealed a couple of misaligned multiple transiting systems
- The origin of the misalignment would be violent orbital evolution, but could be primordial (at least partially)

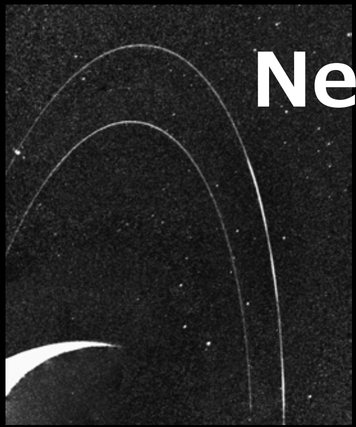
Search for exo-planetary ring: spin axis of planets

- Architecture of exo-planetary systems
  - Orbital angular momenta of planets
  - Stellar spin
  - Planetary spin
- Planetary rings are ubiquitous in the Solar system
  - First discovery of exo-ring is wonderful in itself
  - Precious tracer of planetary spin

Rings are common in our Solar system

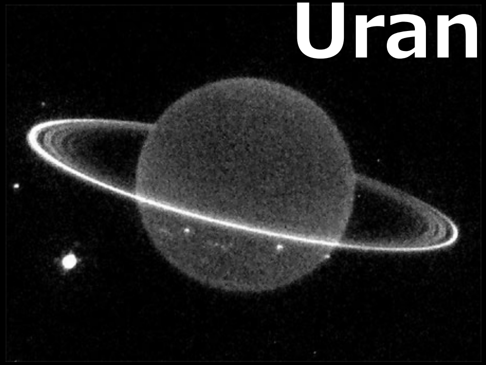
Saturn

Neptune



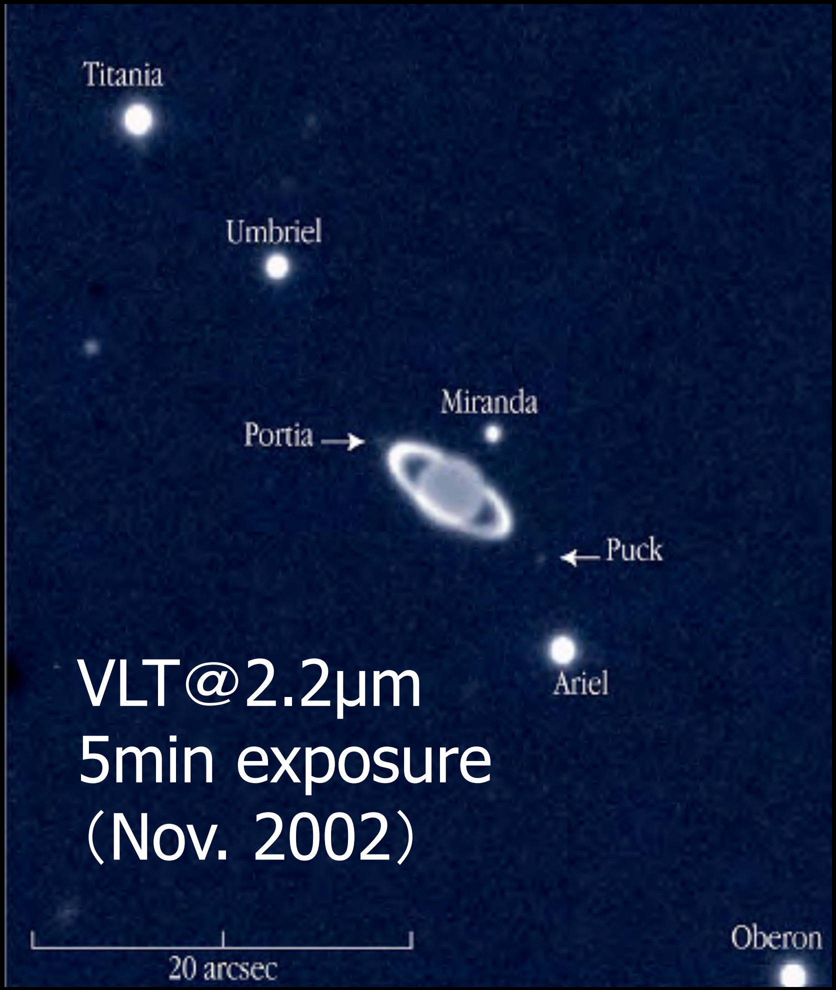
Jupiter

Uranus



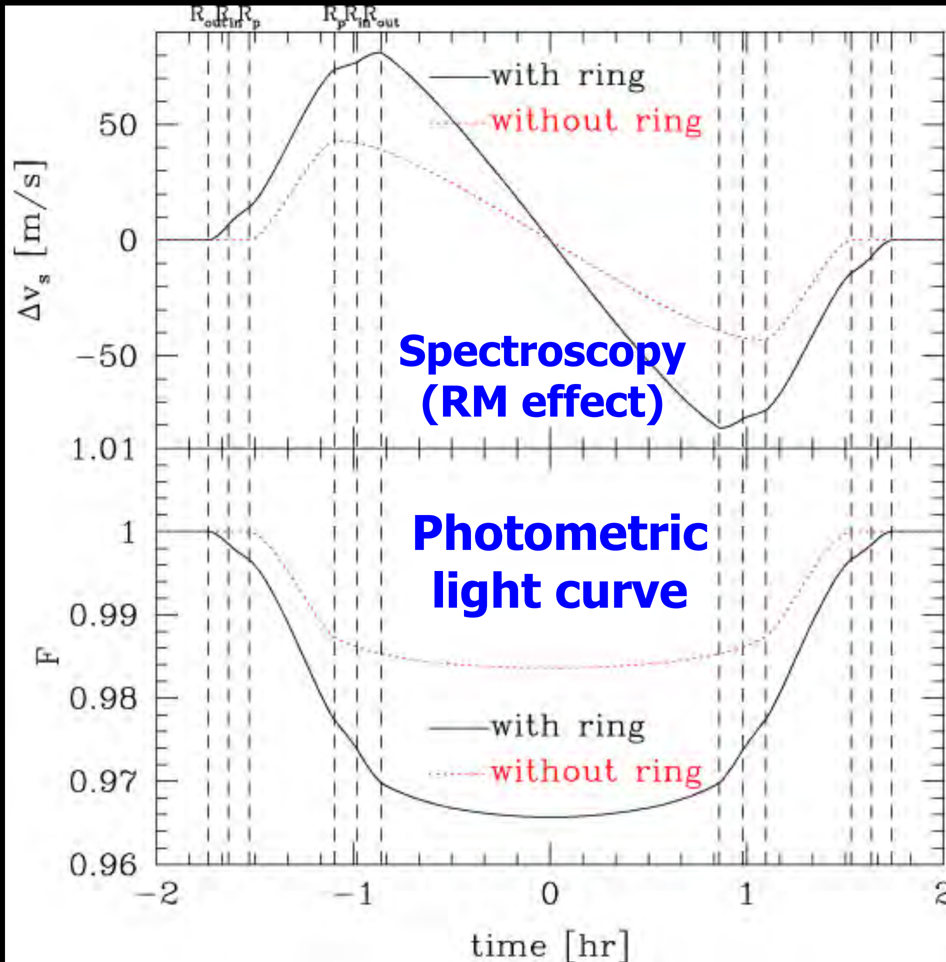
Are they also common in exo-planetary systems?

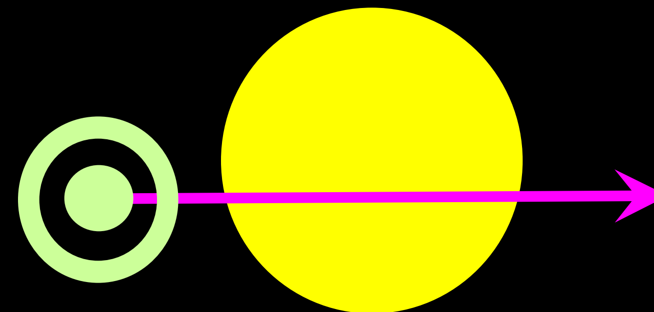
Discovery of the Uranus rings



- Serendipitous discovery
  - Uranus's transit against a background star (Elliot et al. 1977)
  - Neptune's ring was discovered also by transit in 1986
- Transit proved to be useful in detecting rings of the Solar planets !

Signatures of exo-rings

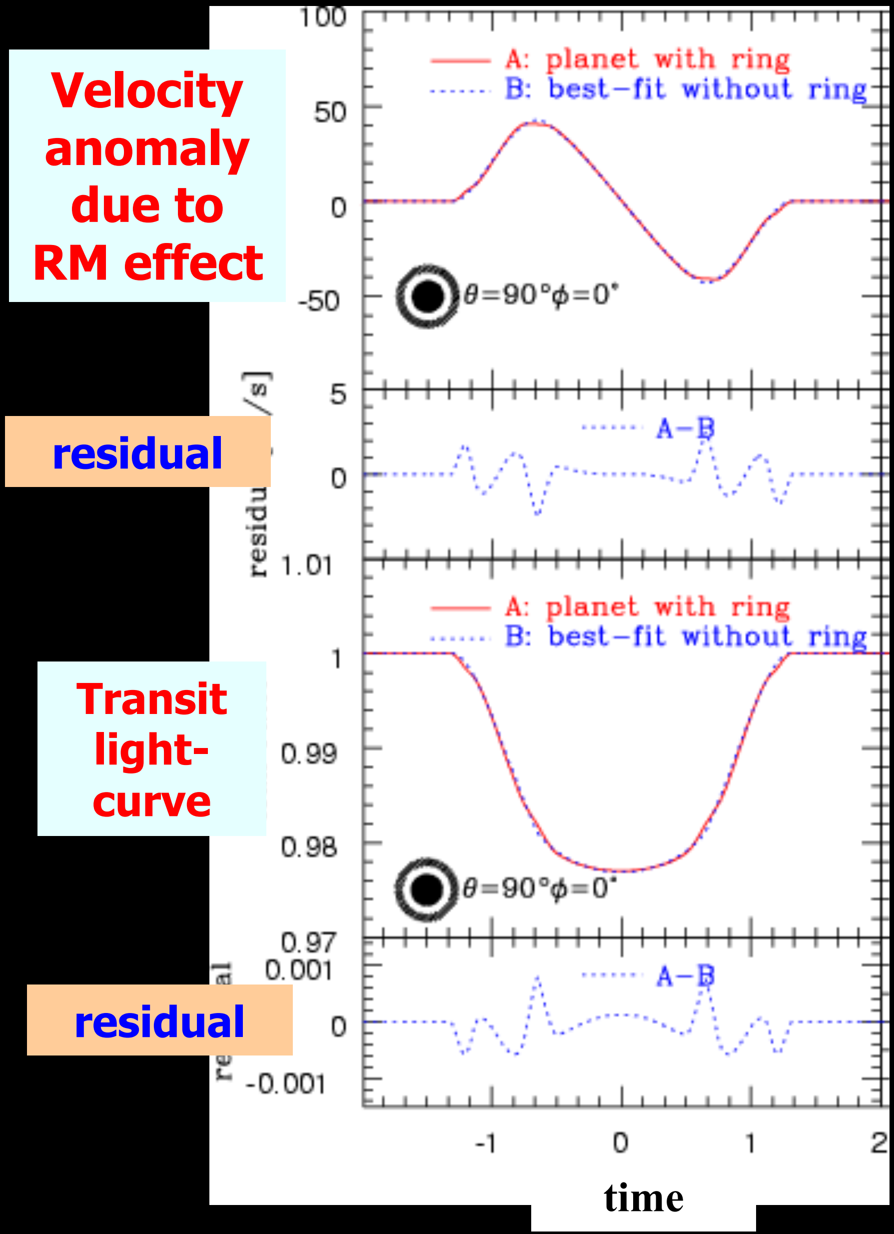




- Ring's inner and outer radii, gap, planet's radius imprints strong features in the photometric and spectroscopic data
- Statistical analysis of the residuals with respect to the best-fit ringless model

Ohta, Taruya +YS, ApJ 690(2009)1

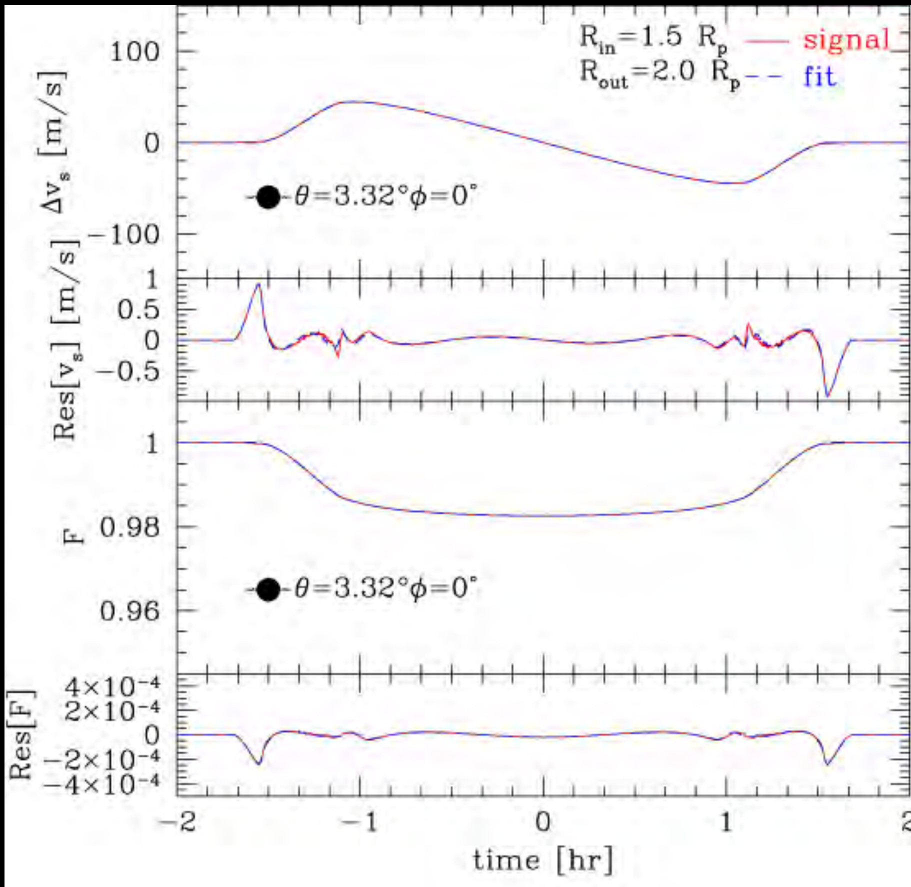
Detectability of a exo-ring

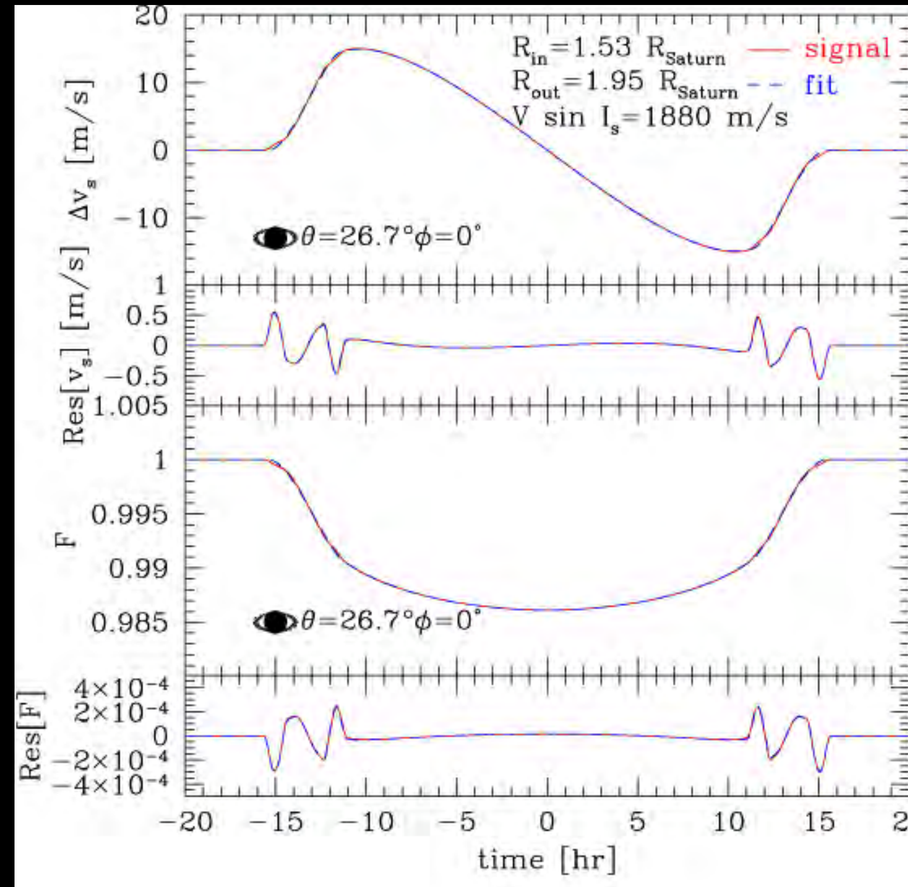


- a hypothetical ring around HD209458
  - $1.5R_{pl} < R_{ring} < 2R_{pl}$
  - deviation from a best-fit single planet
  - dv～1m/s
  - dF/F～0.1%
- Should be easily detectable if any !

Ohta, Taruya +YS
ApJ 690(2009)1

How about hot Jupiter and Saturn rings ?





Ohta, Taruya +YS, ApJ 690(2009)1

- **Hot Jupiter: edge-on rotation due to the tidal locking**
- **Saturn：30 deg. inclined, but spin of the Sun is small**
- **Still detectable potentially eve if not easy**

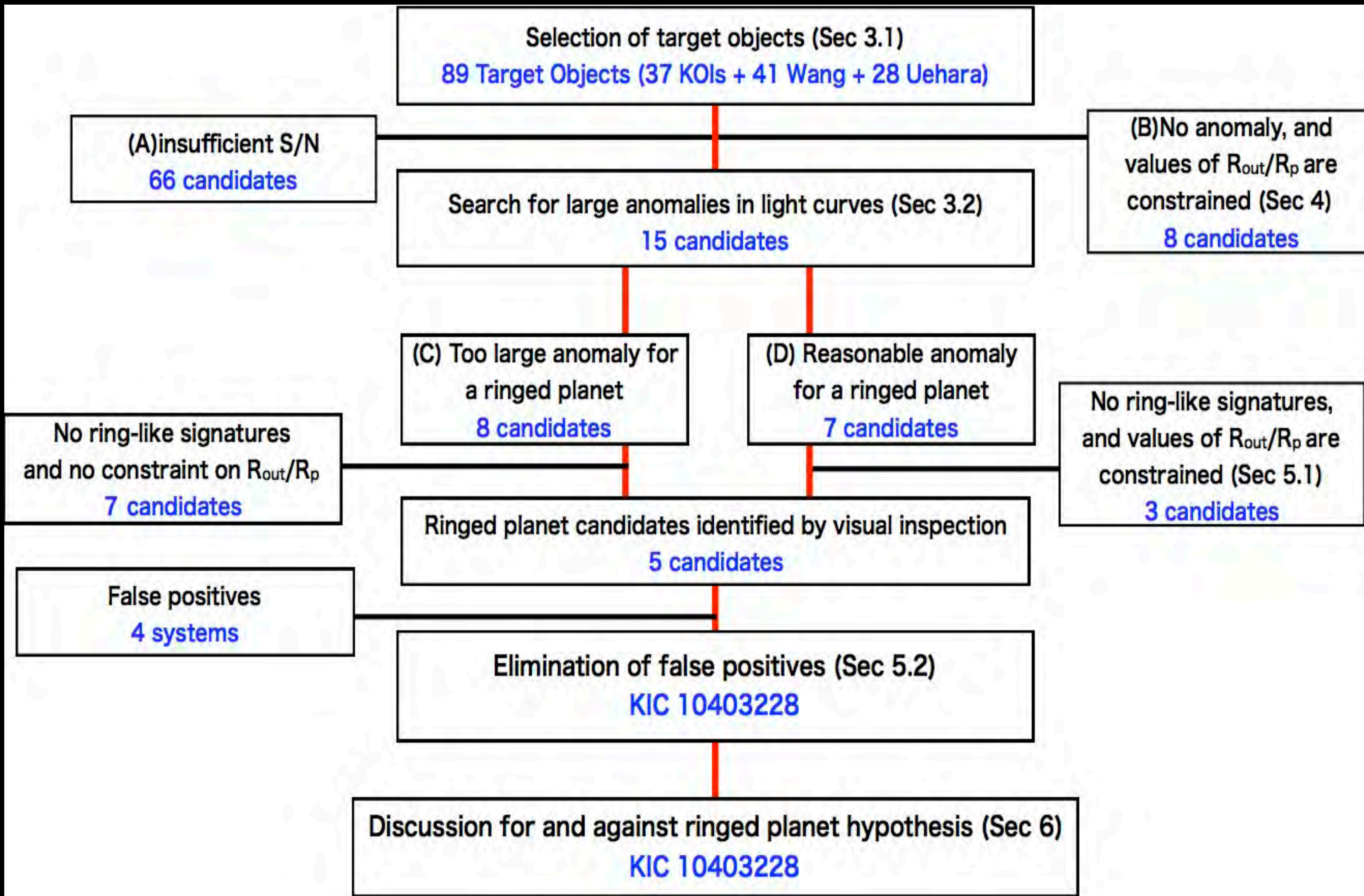
Searching for exoplanetary rings via the *Kepler* transit photometry

- 89 targets for our search from KOIs with T_{eq}<200K and other long-period planet candidates (Wang et al. 2015, Uehara et al. 2016)

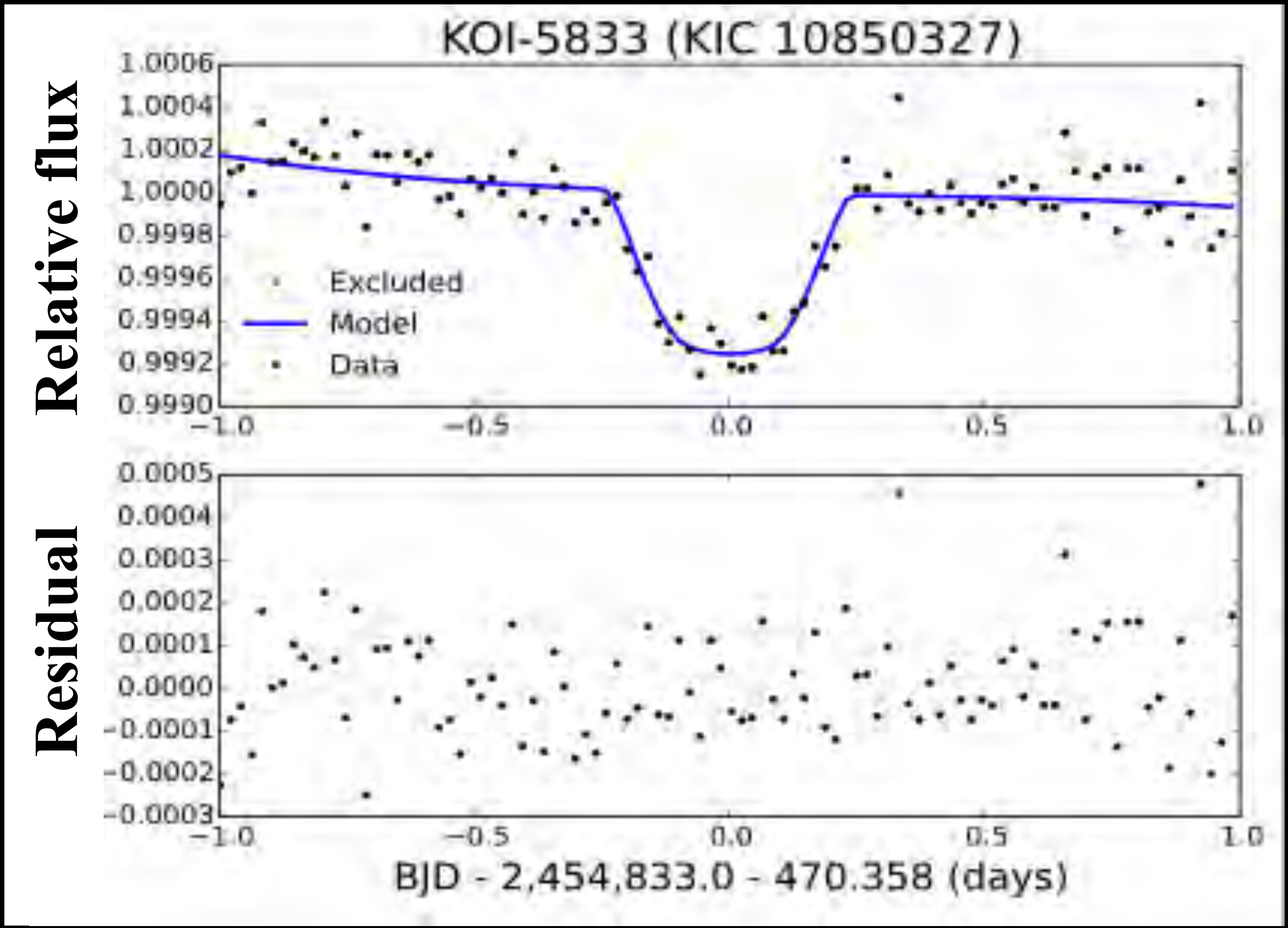
data	1 transit	2	≧3
KOIs with T_{eq}<200K	5	2	30
Wang et al. (2015)	17	14	10
Uehara et al. (2016)	21	0	0

Aizawa, Uehara, Masuda, Kawahara + YS
AJ 153(2017)193(23pp)

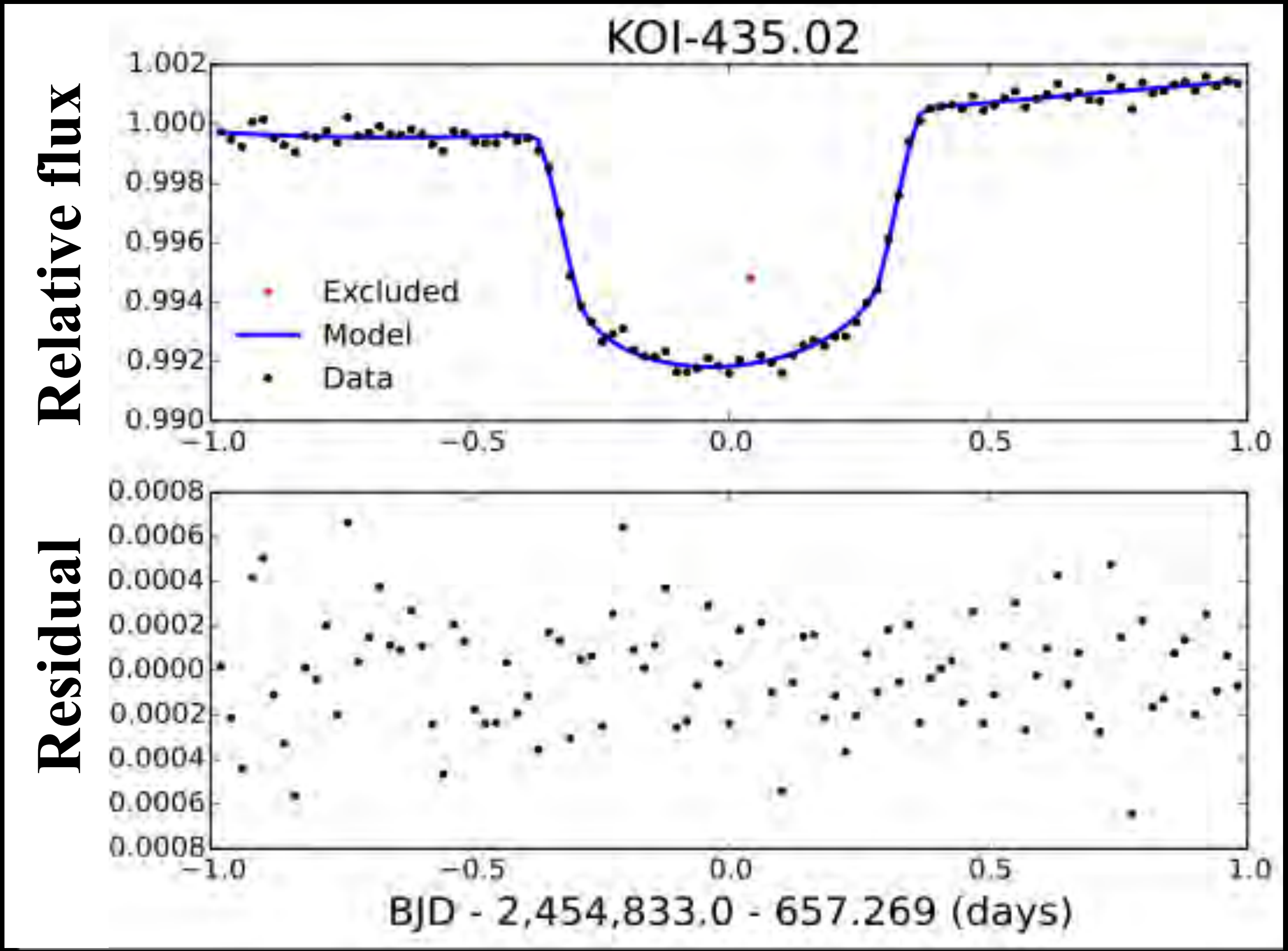
Exo-ring search methodology



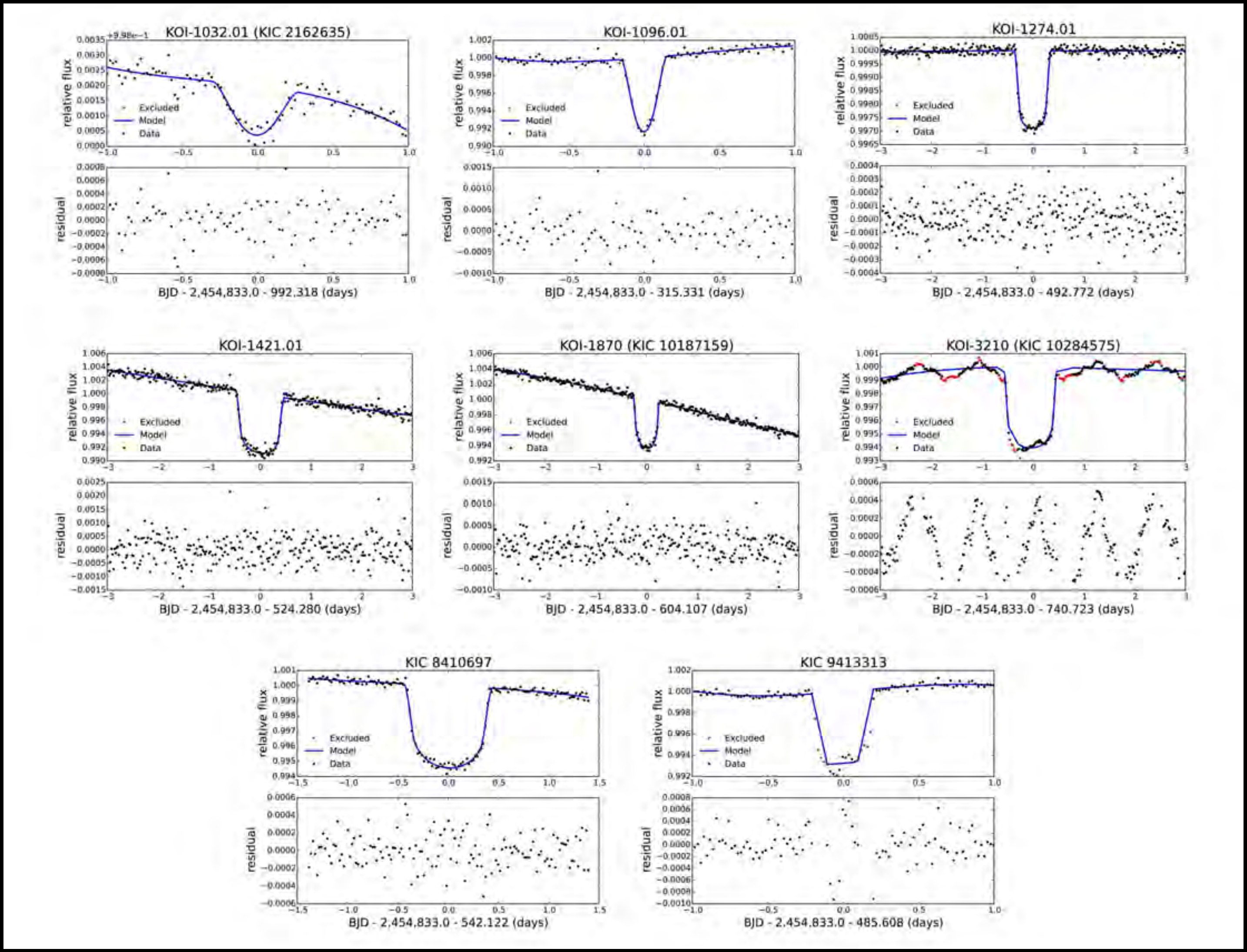
(A) Insufficient S/N: 66 out of 89 targets



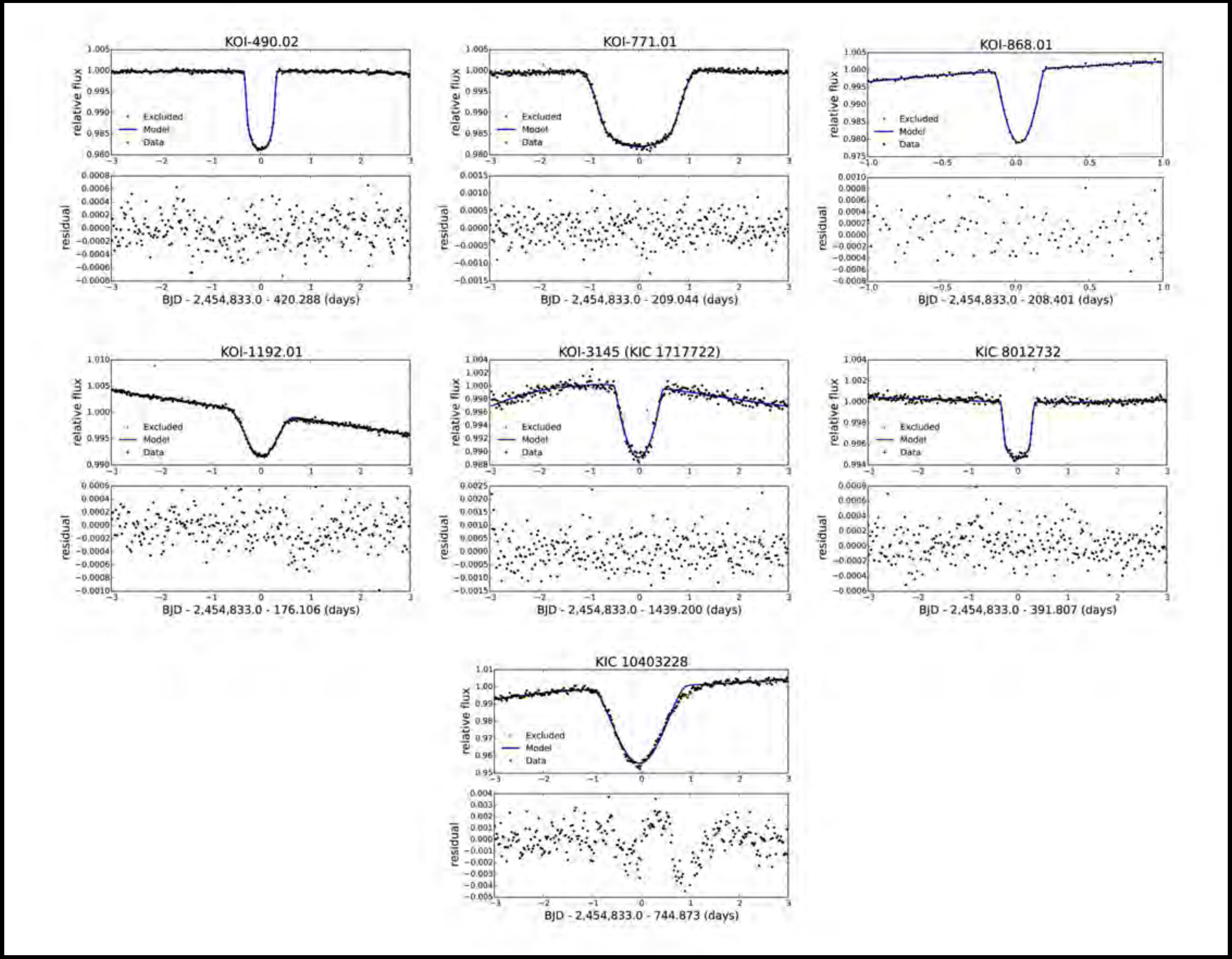
(B) Sufficient S/N, but without any detectable ring-like feature: 8 out of 89 targets →constraints on ring parameters



(C) Too large anomaly for possible rings: 8 out of 89 targets



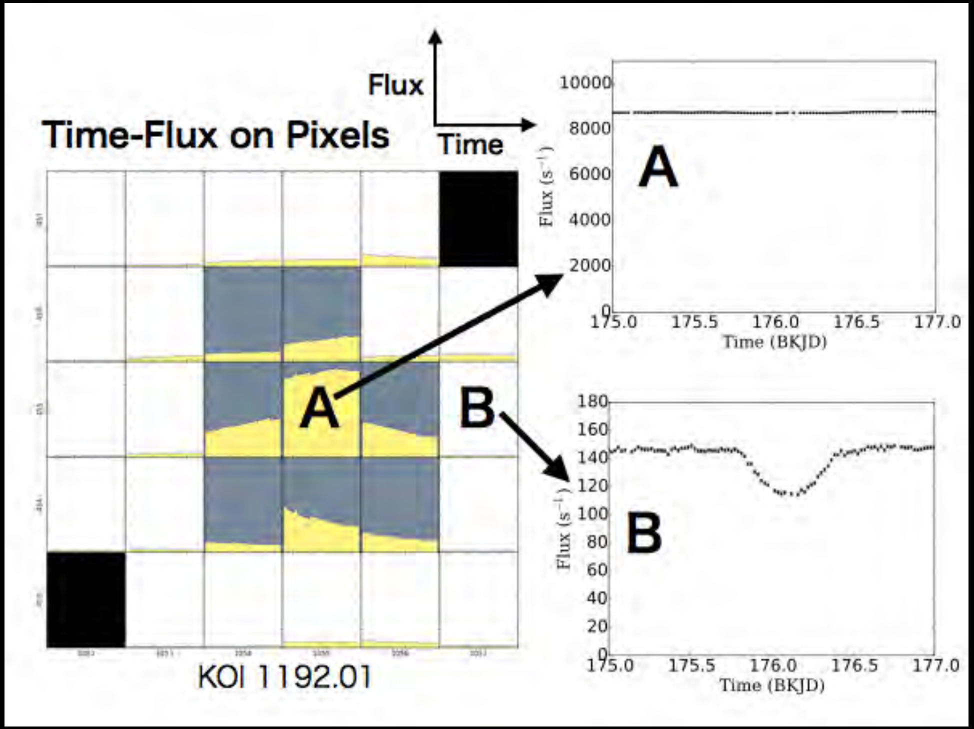
(D) With features consistent with rings: 5 out of 89 targets



Visual inspection and false-positive removal toward final candidates

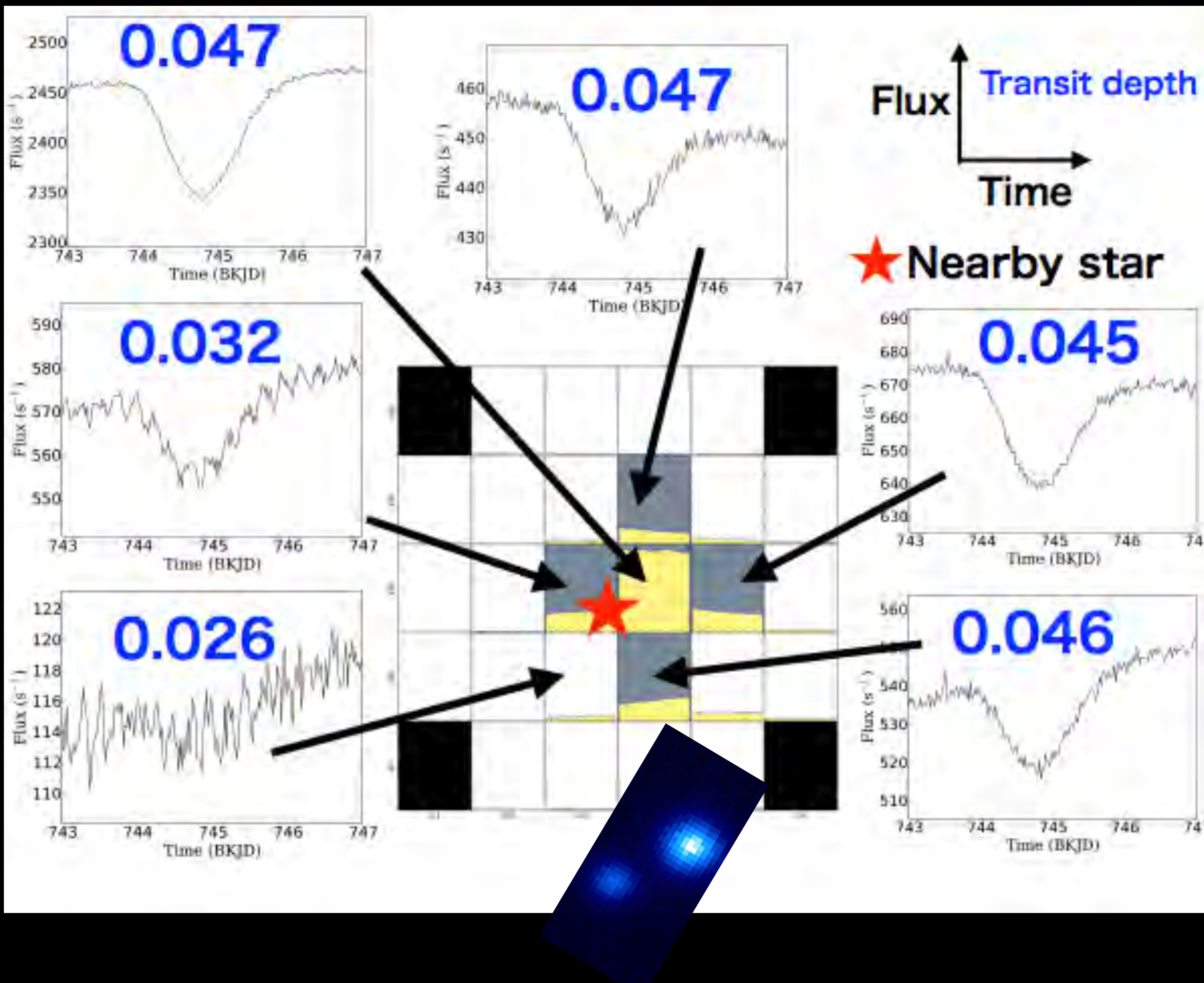
- Visual inspection of the 15 remaining targets leaves 5 tentative candidates

- Kepler pixel image inspection indicates that 4 out of the 5 candidates are false positive due to contamination of near-by stars



Aizawa et al.(2017)

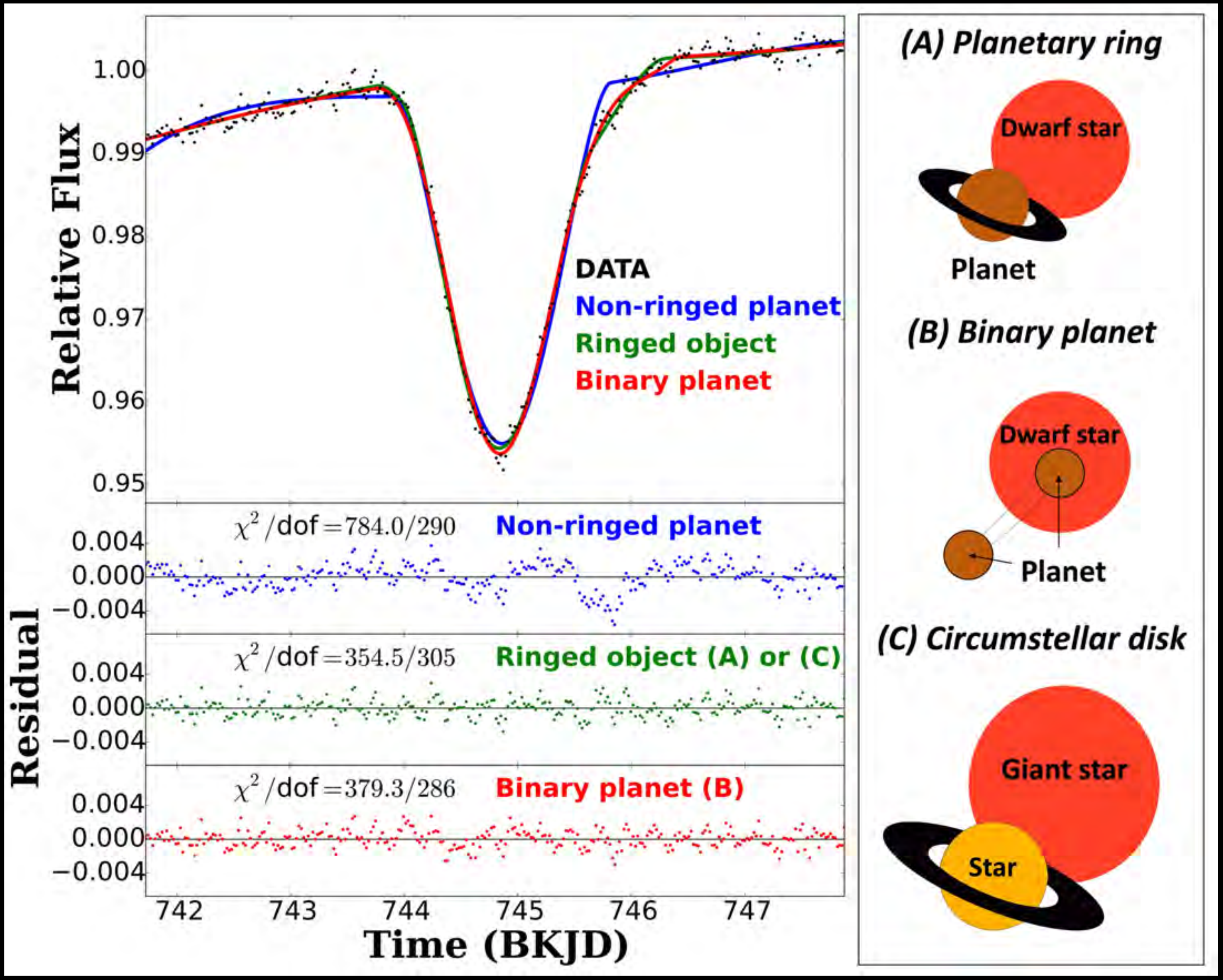
KIC 10403228: our final candidate



- All the adjacent pixels exhibit the similar transit-like signature
- No significant contamination of the nearby star

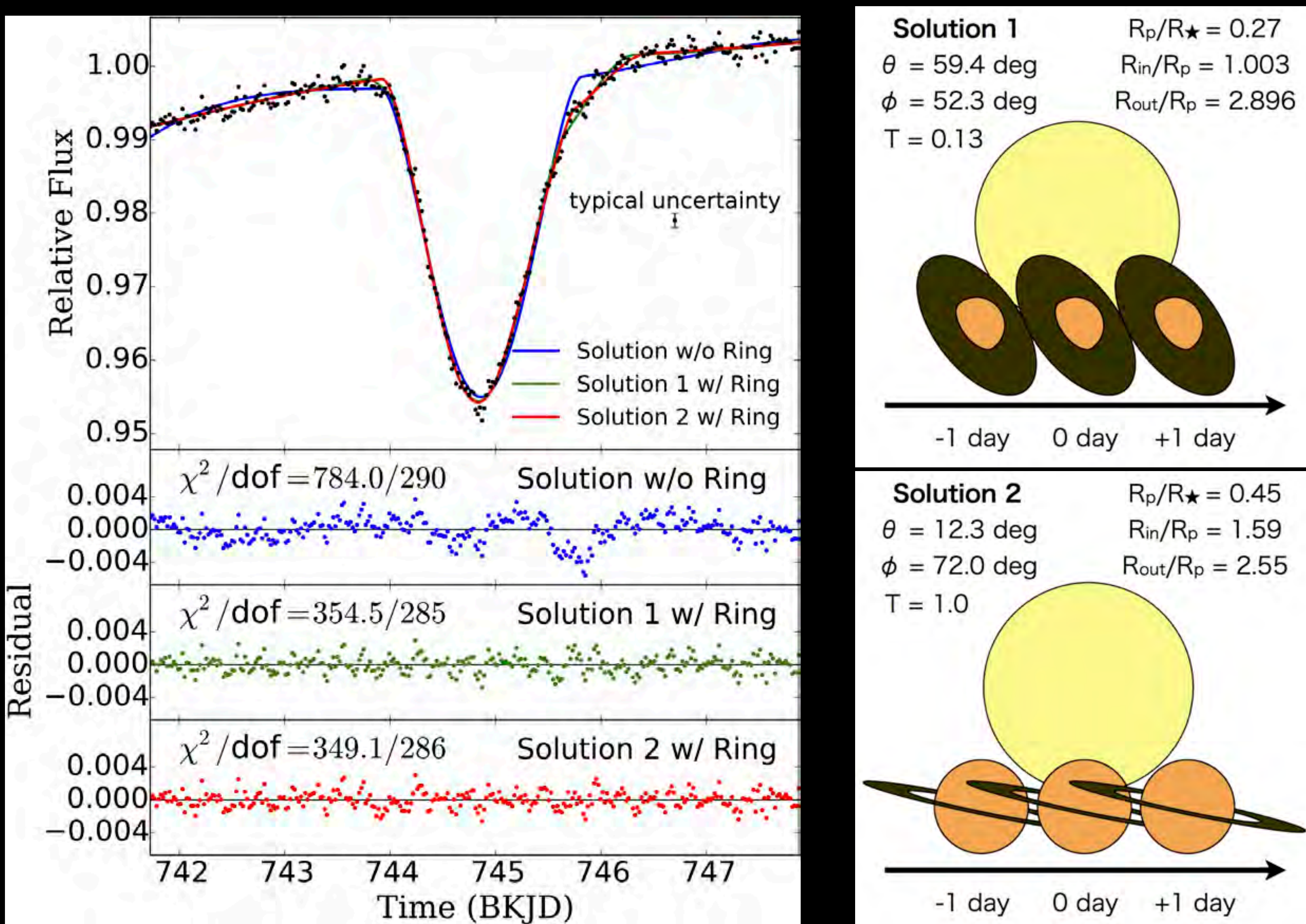
Aizawa et al.(2017)

KIC 10403228: best-fits for three possible interpretations



Aizawa et al.(2017)

Two possible solutions of a ringed planet scenario: KIC 10403228



Aizawa et al.(2017)

Alternative interpretations for KIC 10403228 ?

scenario	remark
Oblate planet	Unrealistic large oblateness (=0.2) is required
Gravity darkening	Rotation of the host star is too slow (P=40days) to produce the substantial gravity darkening
Spot-crossing	No bump-like feature characteristic of spot-crossing
Stellar activity	Out-of-transit light-curve does not show any strong activities

Aizawa et al.(2017)

Summary of our Saturnian ring interpretation of KIC 10403228

- **Final sec. of the Nagaoka paper**
  - There are various problems which will possibly be capable of being attacked on the hypothesis of a Saturnian system
  - The rough calculation and rather unpolished exposition of various phenomena above sketched may serve as a hint to a more complete solution of atomic structure

写真 2：長岡半太郎（1865－1950）

Conclusions

- RM measurements revealed that a significant fraction of exo-planetary systems exhibit large projected spin-orbit misalignments
- True (non-projected) spin-orbit angles will be estimated with a help of asteroseismology
- Detection of exo-rings will further add information of the planetary spin direction
- Those observational quests for the stellar and planetary spin and their orbital angular momenta provide important clues to the origin and evolution of exoplanetary systems