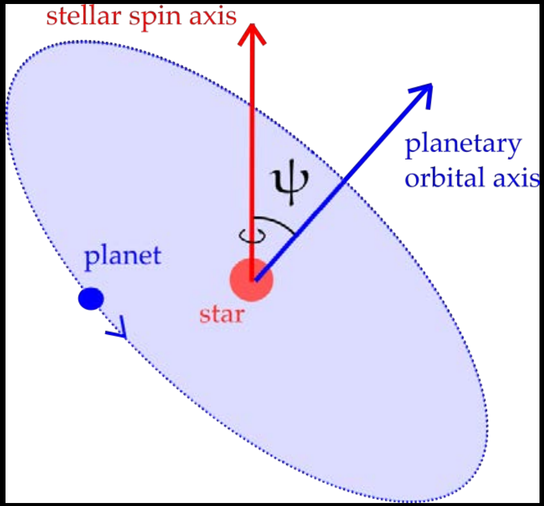
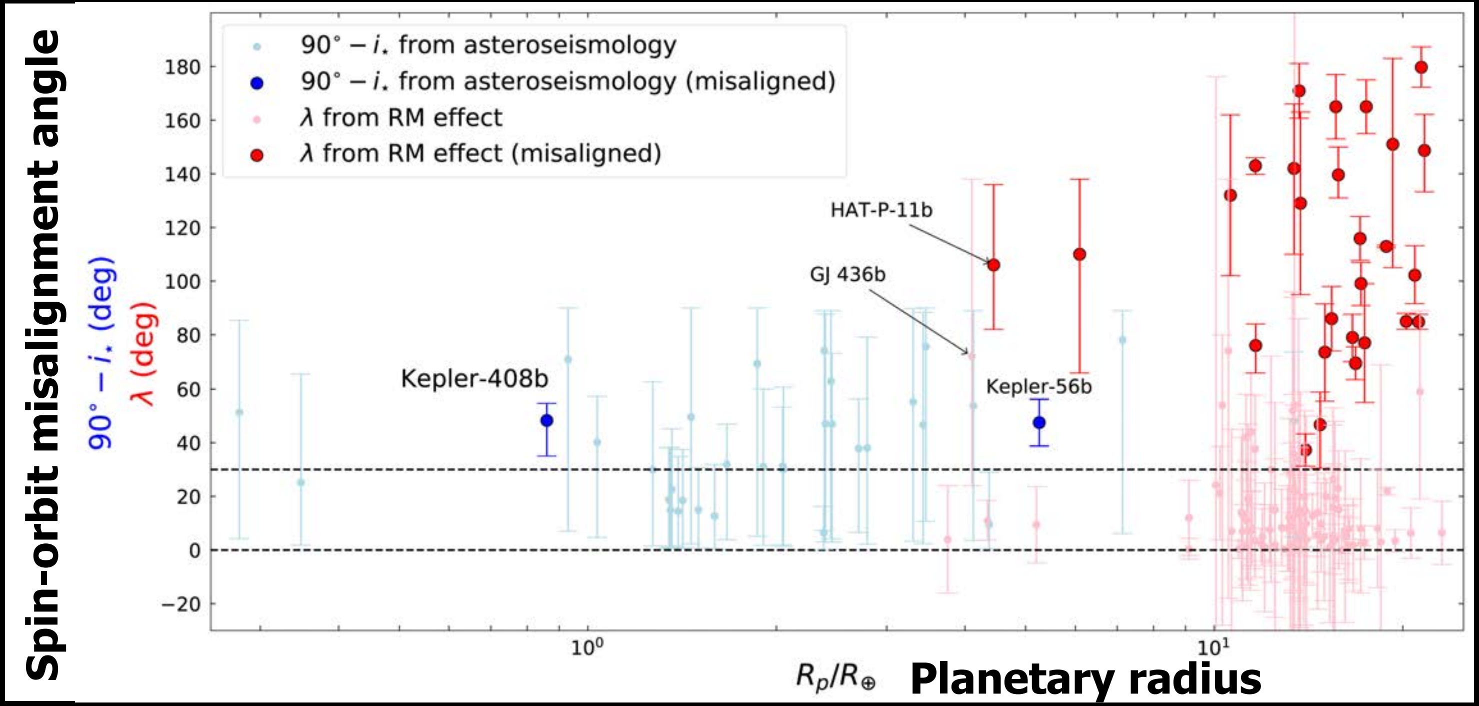
Spin-orbit architectures of transiting planetary systems: Rossiter-McLaughlin effect and asteroseismology





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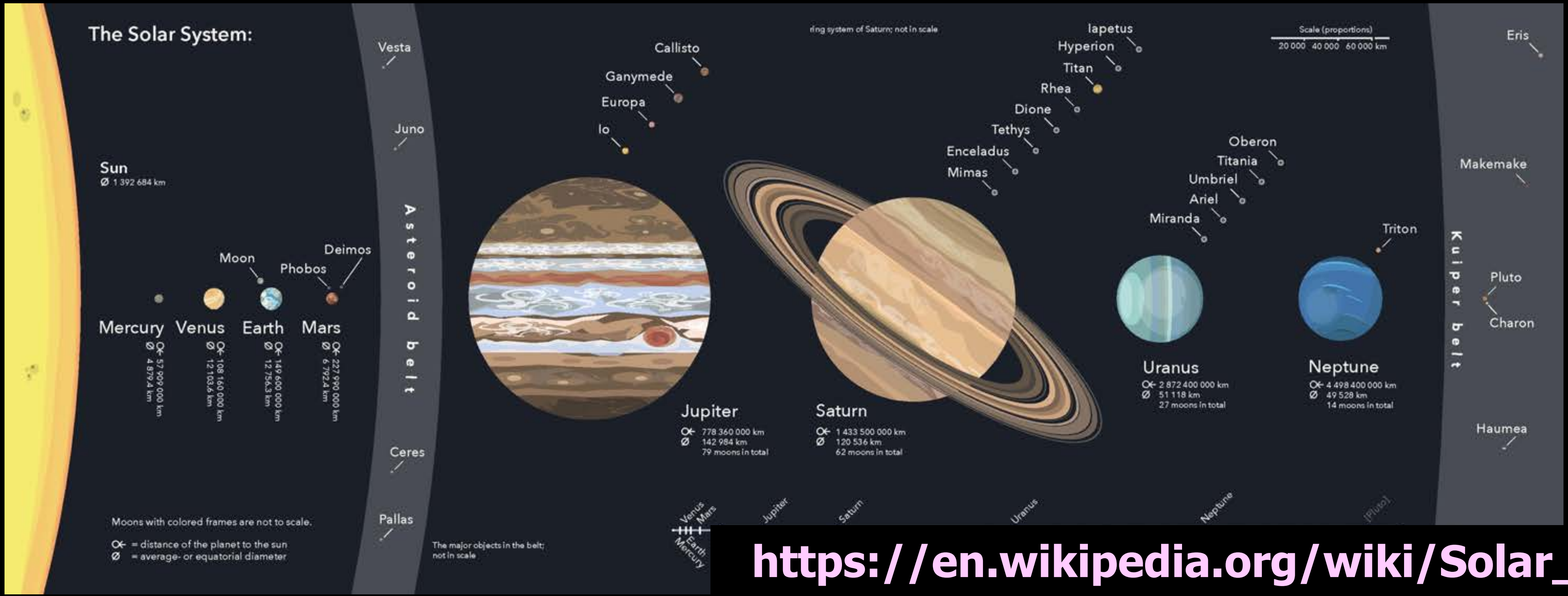
14:20 March 14, 2023@National Taiwan University (国立台湾大学)

Today's talk

1. Universality and diversity of exoplanetary systems
2. Spin-orbit angles from the Rossiter-McLaughlin effect
3. Origin of the spin-orbit misalignment
4. Spin-orbit angles from asteroseismology
5. Evolution of spin-orbit angle: Nature or Nurture?

1 Universality and diversity of exoplanetary systems

Architecture of the Solar system



https://en.wikipedia.org/wiki/Solar_System

- Our Solar system is typical or atypical ?
  - Very stable multiplanetary systems on nearly co-planar and circular orbits
  - Rocky inner planets + Gaseous outer planets
  - satellites and rings are common
  - ***Hosts a planet with life and (advanced) civilization***

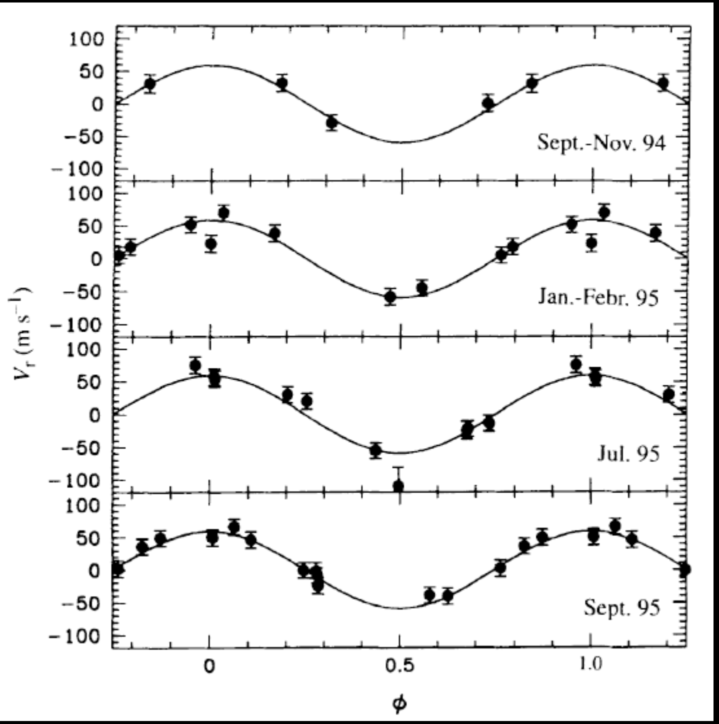
Exoplanet discovery history

A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz
Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

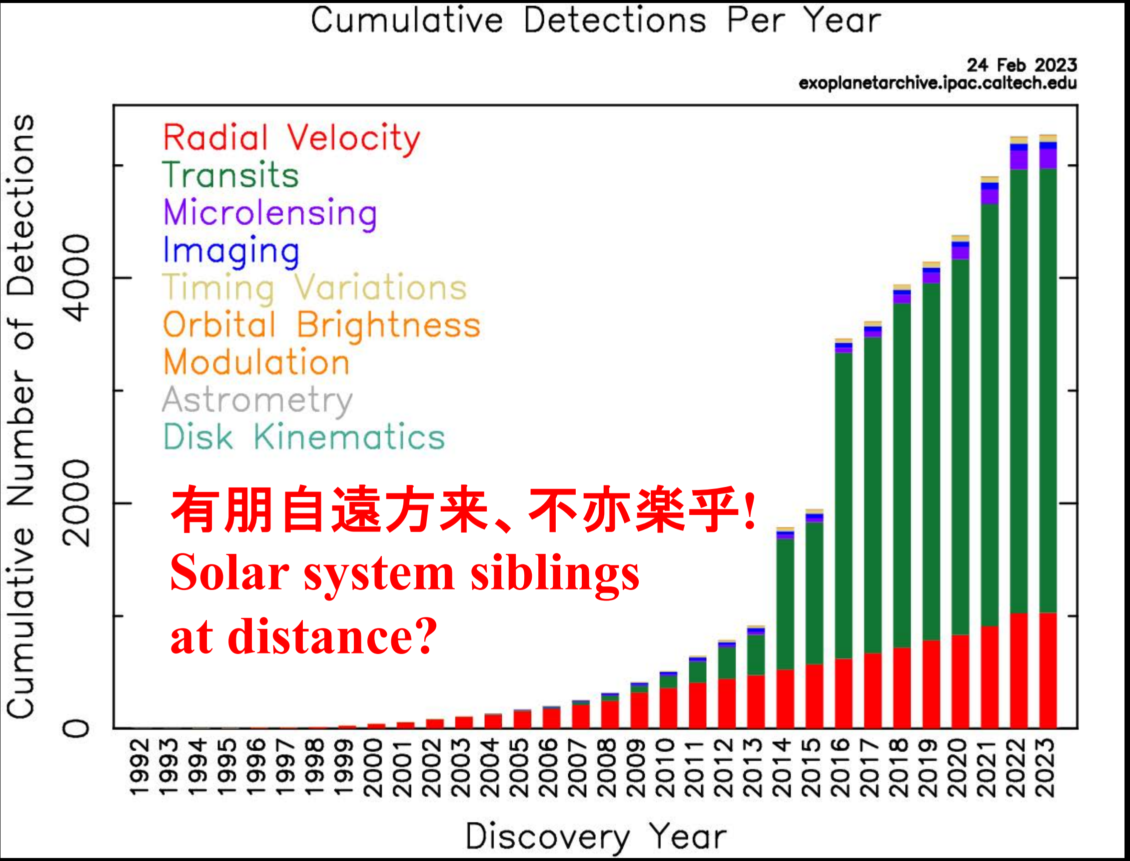
Nature 378(1995)355

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.



The first detected exoplanet around a Sun-like star 51Peg b (P_{orb}=4.2days)

Nobel Prize in Physics 2019



Kyoto Prize in 2015 awarded for Michel Mayor

What we have learned so far

- Planets exist universally
  - More than 70% of Sun-like (FGK) stars have planets
  - More than 20% of planetary systems host multi-planets
- A broad diversity
  - Hot-Jupiters: giant gas planets of P_{orb}<1 week
  - Ultra-Short-Period planets of P_{orb}<1 day
  - Super-earths: R < a few earth radius
  - A significant fraction of eccentric planets
  - Habitable planets: $0°C<T_{surface}<100°C$
- Universality and diversity ⇒ Physics
- Potential sites for extra-terrestrial life ⇒ Astrobiology

2 Spin-orbit angles from the Rossiter-McLaughlin effect

From Saturnian model to atomic model

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

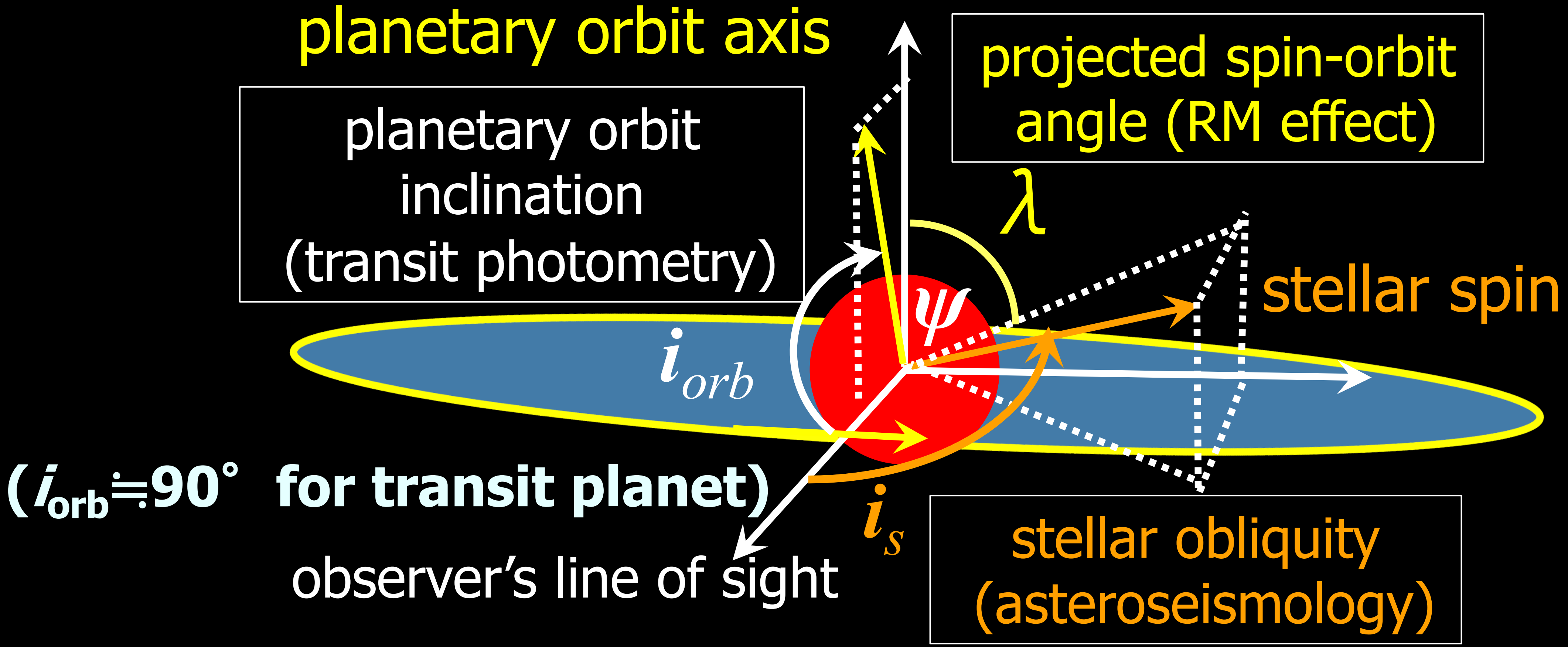
Ernest Rutherford: *The Scattering of α and β Particles by Matter and the Structure of the Atom* Phil. Mag. 6(1911) 669

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

Spin-orbit architecture of a planetary system



true angle ψ

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

Stellar inclination i_s **Projected angle** λ

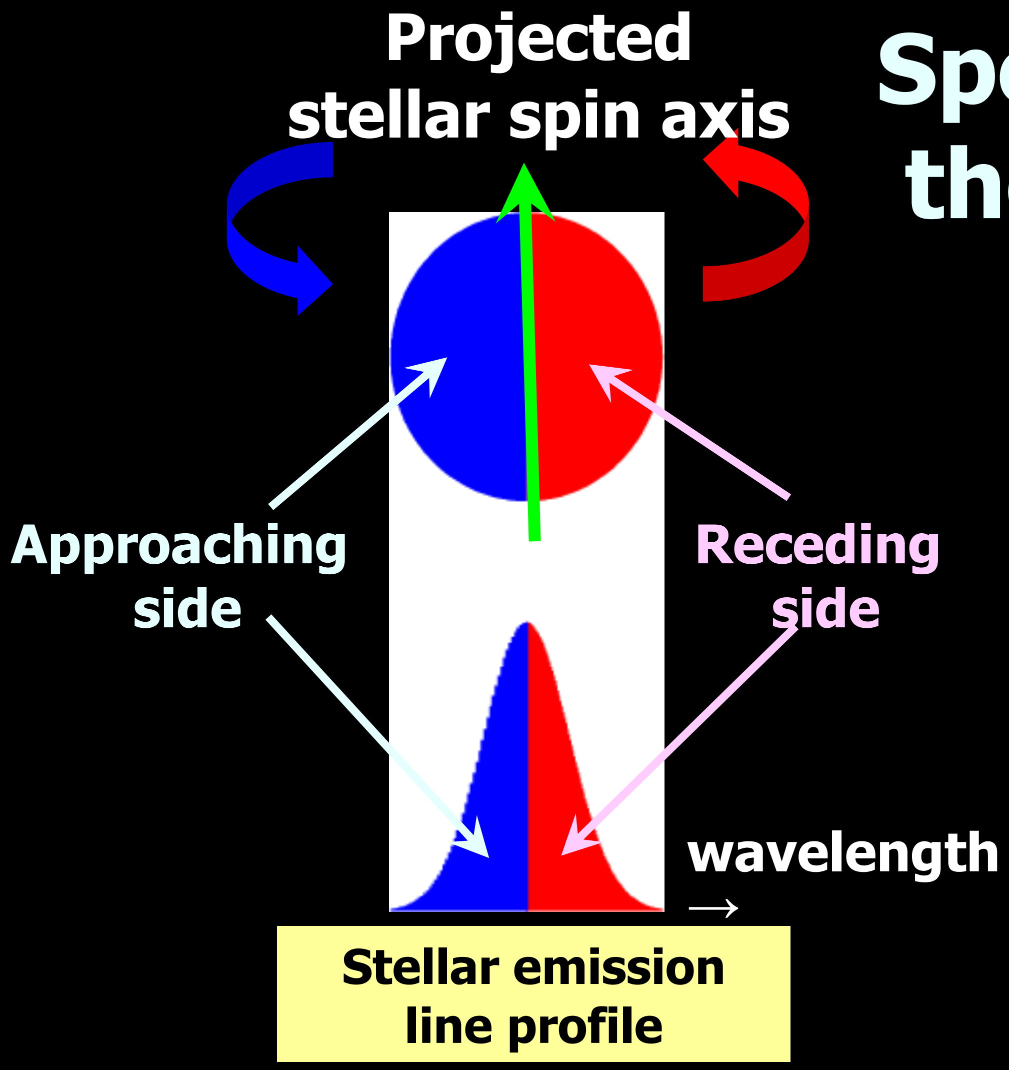
Three observables for spin-orbit architecture

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

True spin-orbit angle (unobservable)

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

- i_{orb}: orbital inclination for the observer
  - transit curve modeling ($\approx \pi/2$)
- λ: projected angle between stellar spin and planetary orbital angular momentum
  - Rossiter-McLaughlin effect
- i_s: stellar spin inclination for the observer
  - asteroseismology

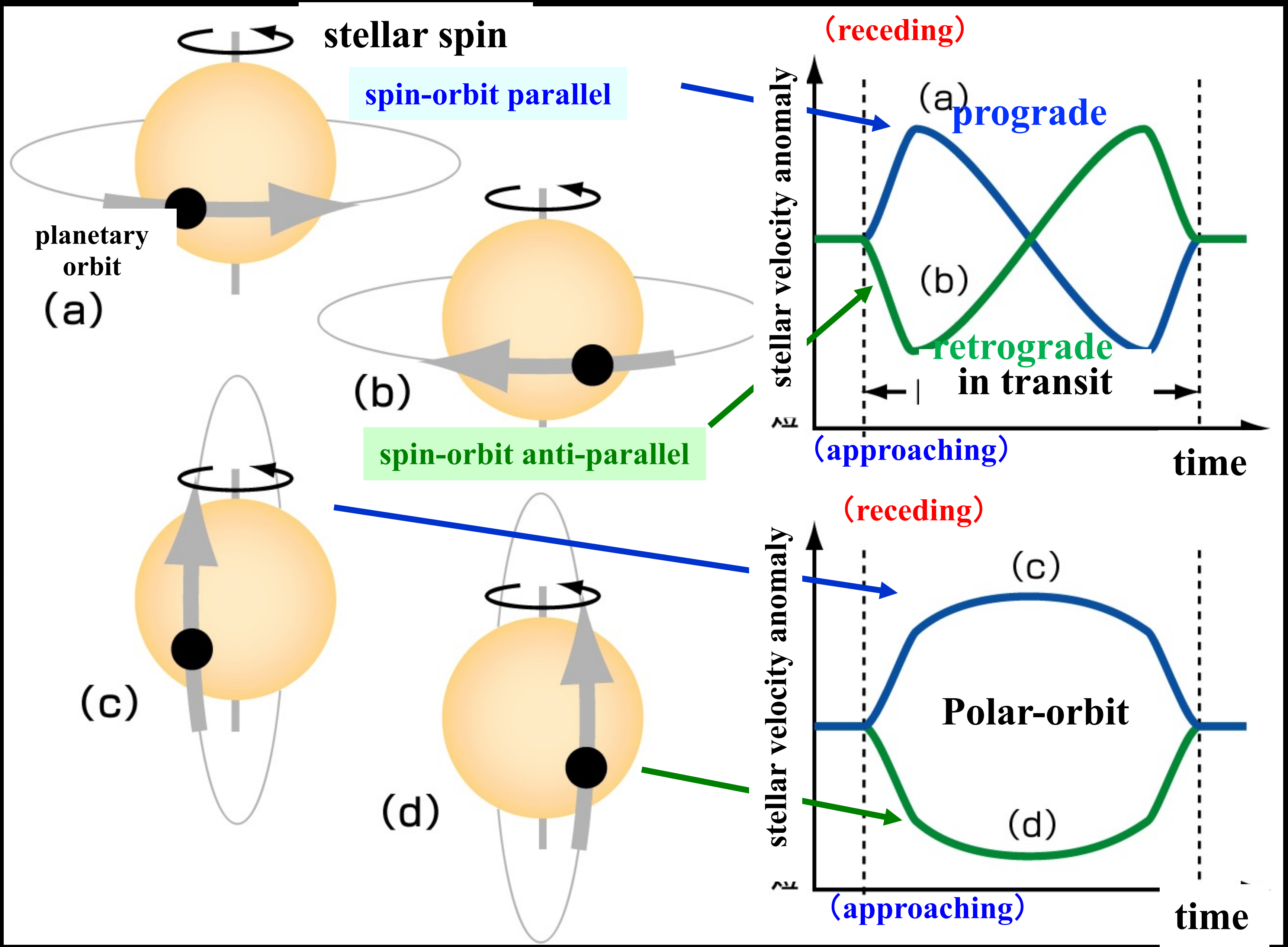


Spectroscopic transit signature: the Rossiter-McLaughlin effect

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

Holt, Astronomy and Astrophysics 12(1893)646
Rossiter, ApJ 60(1924)15; McLaughlin, ApJ 60 (1924)20
Ohta, Taruya + YS, ApJ 622(2005)1118

Velocity anomaly due to the RM effect



Early results of the Rossiter-McLaughlin effect

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

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

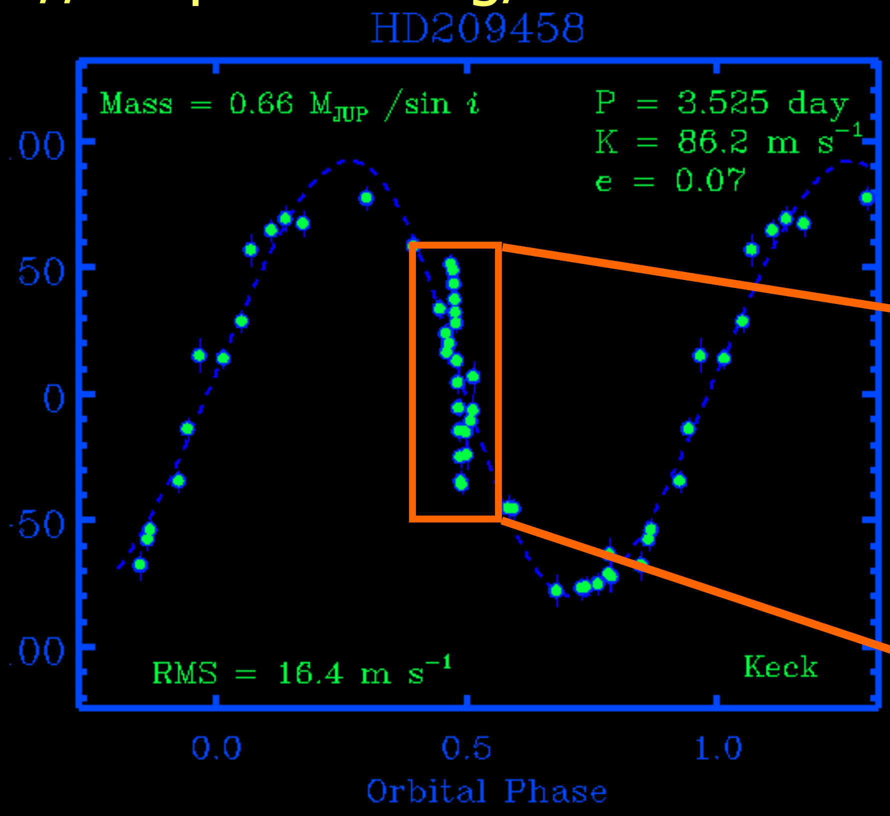
- Ohta, Taruya + YS (2005) 太田泰弘、樽家篤史、須藤靖
  - Perturbative analytic formula for the RM effect that helps the precision of modeling
  - introduced the commonly used symbol λ for the projected spin-orbit angle
- Winn et al. (2005)

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

  - Significantly improved the RM measurement accuracy for HD209458 applying and improving the OTS approach

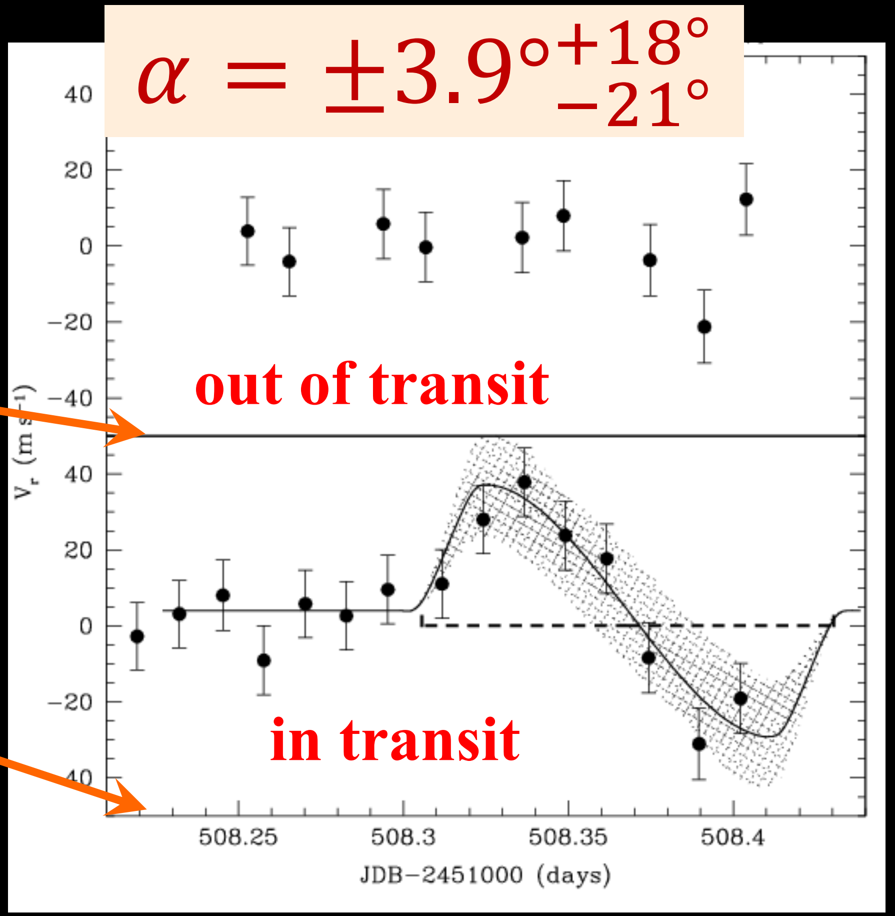
The first detection of the RM effect: HD209458

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



(This is not their original data in 2000)

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



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

Yasuhiro Ohta, Atsushi Taruya,[1] and Yasushi Suto[1]
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Received 2004 October 13; accepted 2004 December 10

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.

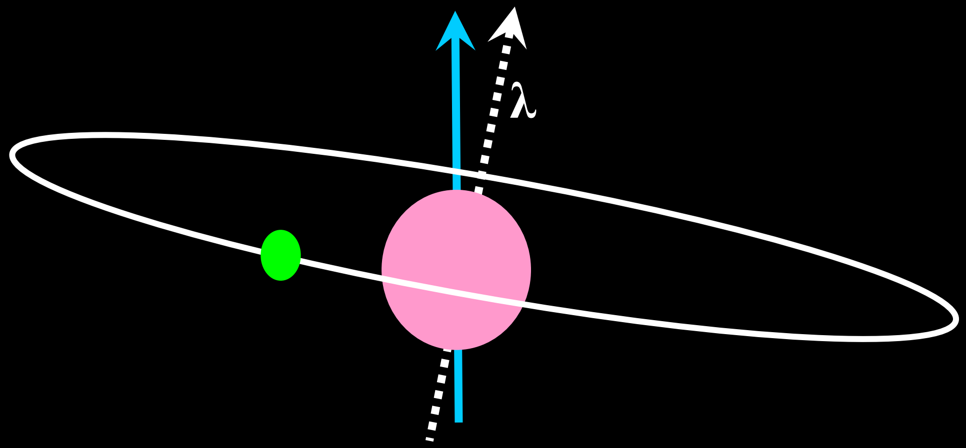
their angular momentum. Although it is unlikely, we may even speculate that a future RM observation may discover an extrasolar planetary system in which the stellar spin and the planetary orbital axes are antiparallel or orthogonal. This would have a great impact on the planetary formation scenario, which

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)



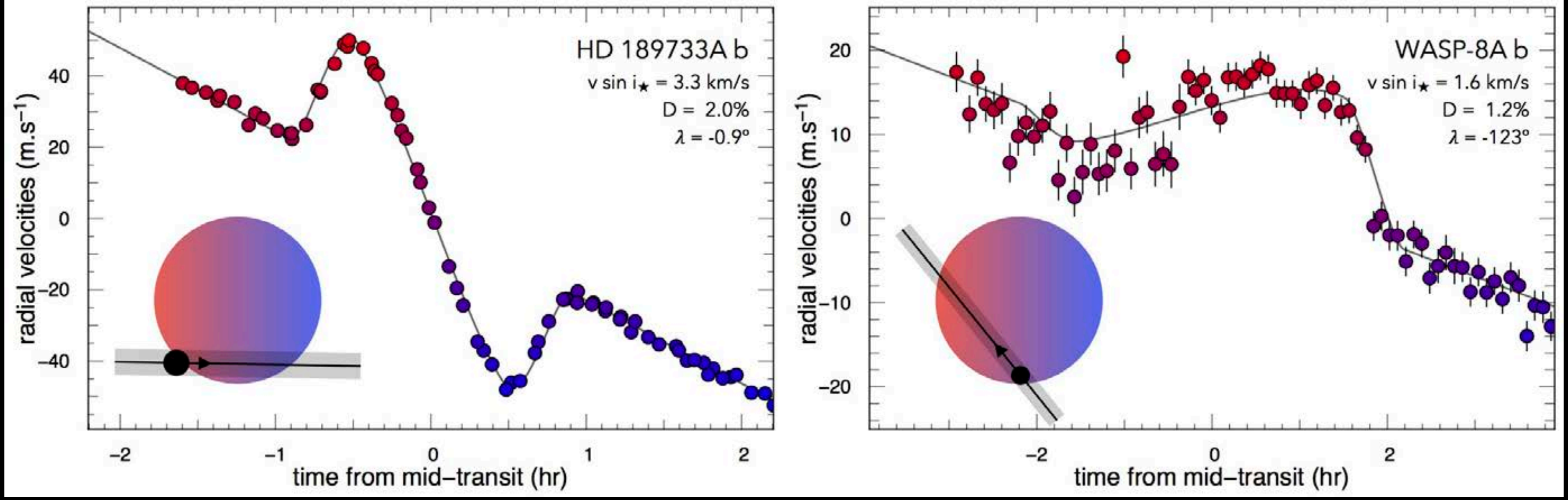
$$\lambda = -4.4° \pm 1.4°$$



HD209458: Keck data + velocity anomaly template based on the perturbation formula by Ohta, Taruya & YS (2005)

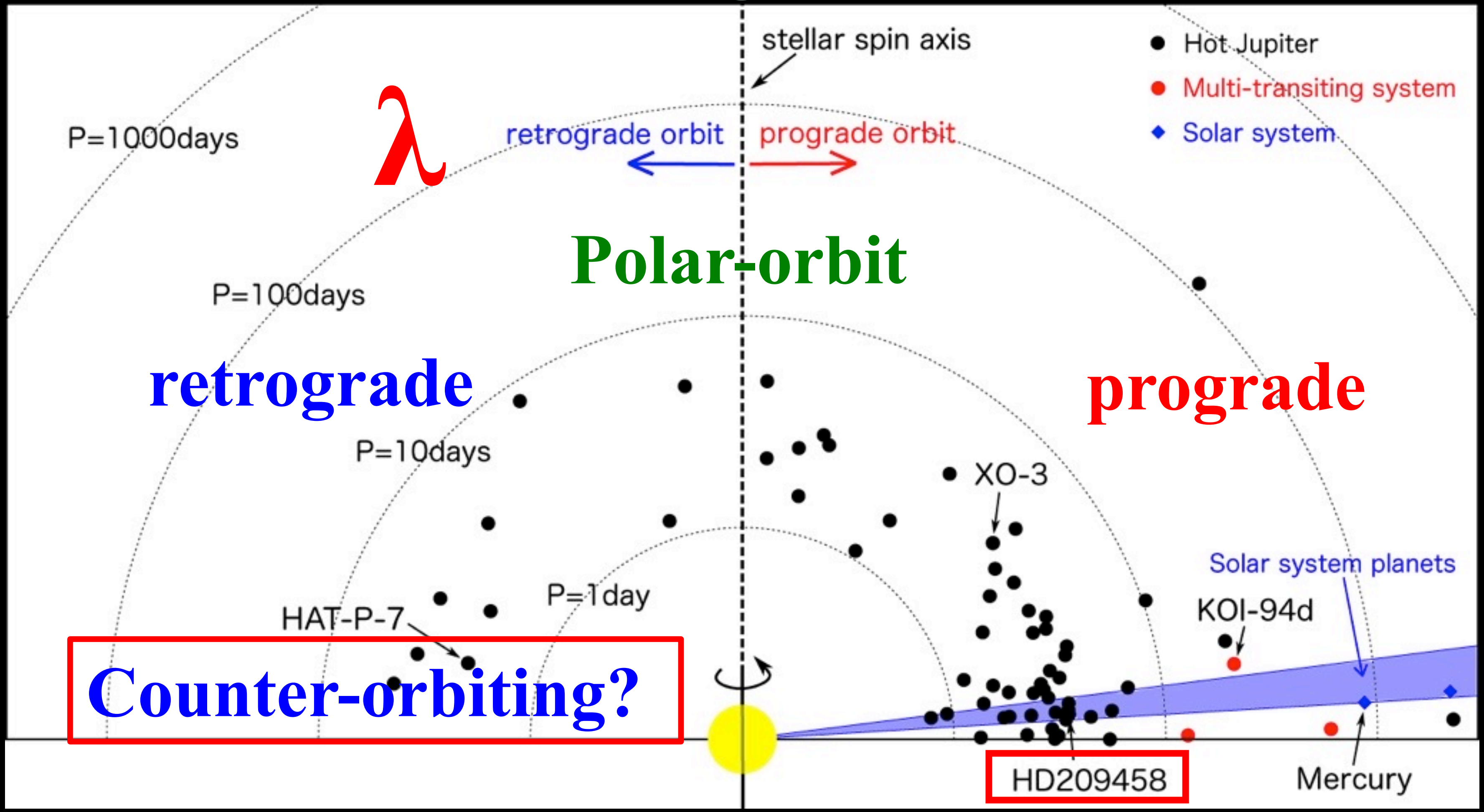
Examples of the RM velocity anomaly

Aligned case **Misaligned case**



Ohta, Taruya, & YS, ApJ 622(2005)1118
Winn et al. ApJ 631(2005)1215
Fabrycky & Winn, ApJ 696(2009)1230
Winn & Fabrycky, ARA&A 53(2015)409
Triaud arXiv:1709.06376

Projected spin-orbit angle distribution (mostly for single HJ systems)



As of June 2013, 29 out of 70 HJ systems were known to have $\lambda > \pi/8$

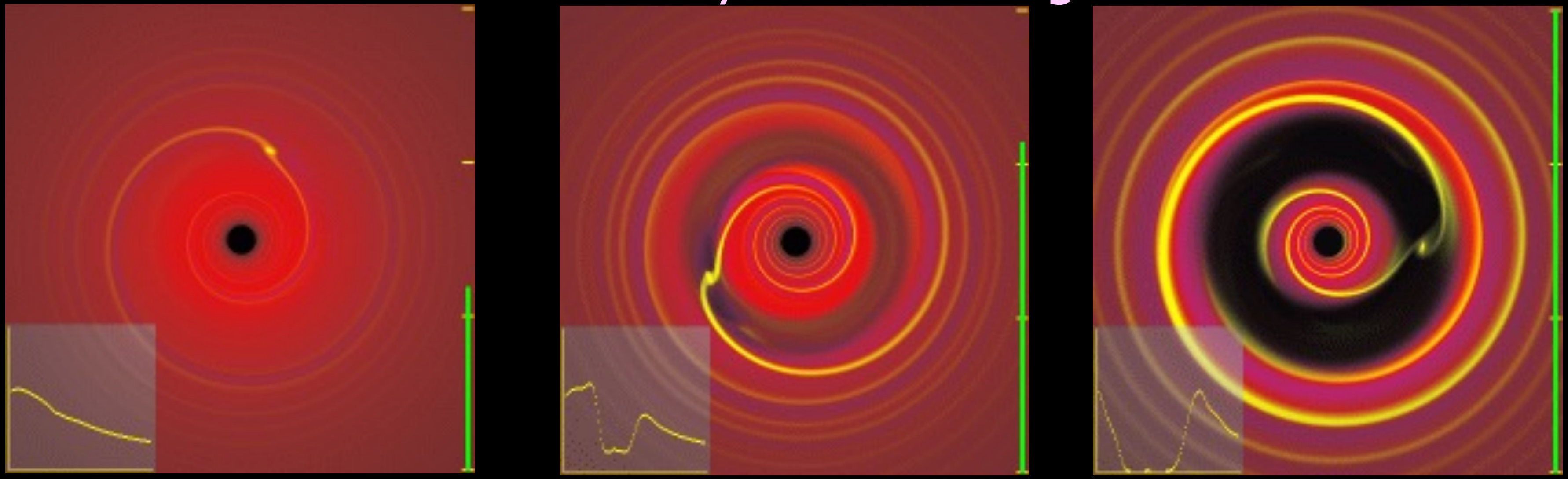
薛钰新 Xue, Y.S., Tayura, Hirano, Fujii, and Masuda, ApJ 784(2014)66

3 Origin of the spin-orbit misalignment

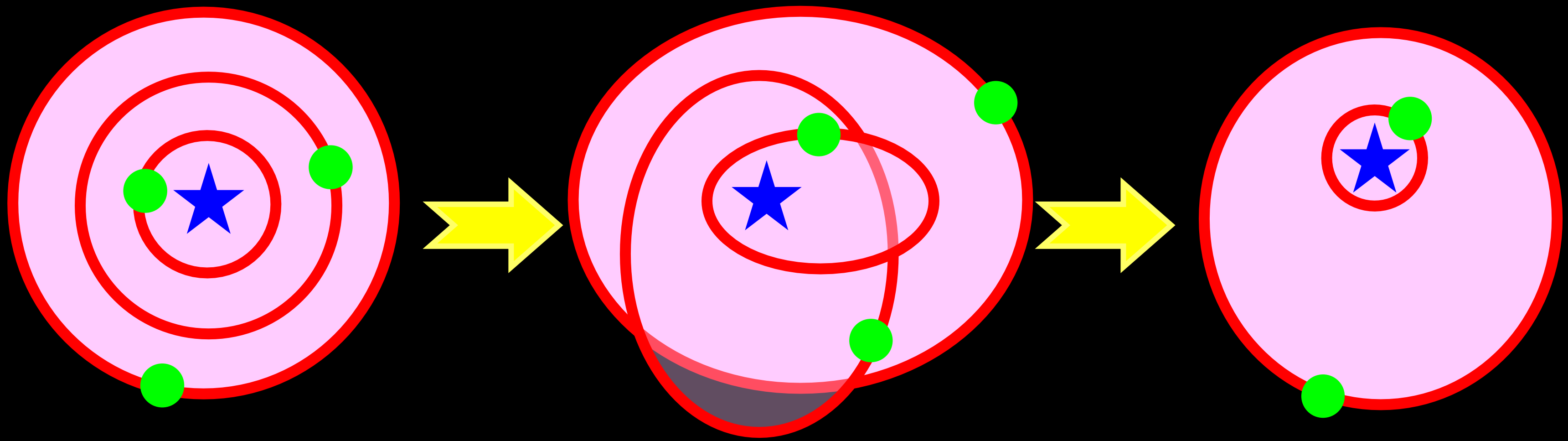
Planet migration channels

- Type I migration (fast)
  - Low-mass planet - spiral wave in the gas disk
- Type II migration (slow)
  - High-mass planet - gap in the disk
- Gravitational scattering (chaotic)
  - Planet - planet

Simulation by Phil Armitage



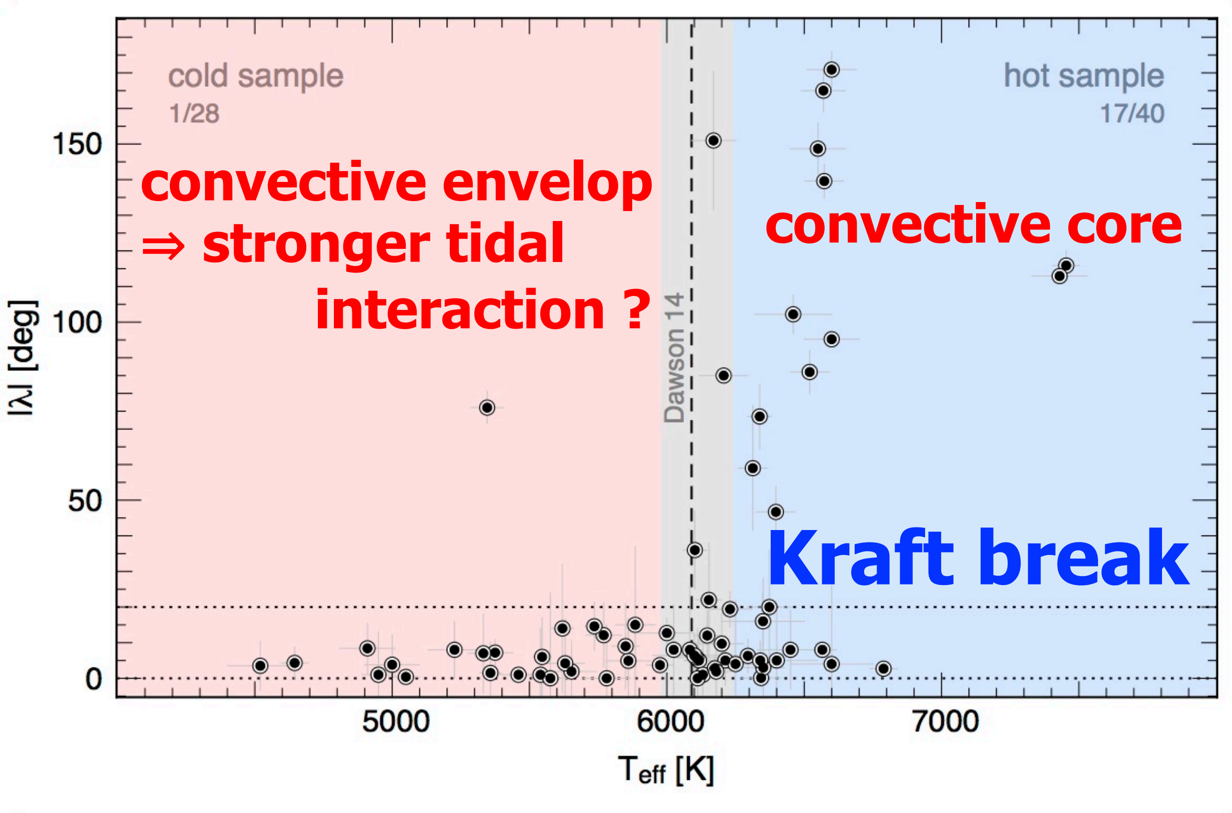
Planet-planet gravitation scattering + star-planet tidal interaction = circularized and misaligned Hot Jupiters



- 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)　長澤真樹子、井田茂
- Insensitive to the initial architecture of multi-planets

Spin-Orbit realignment?

λ vs. stellar effective temperature

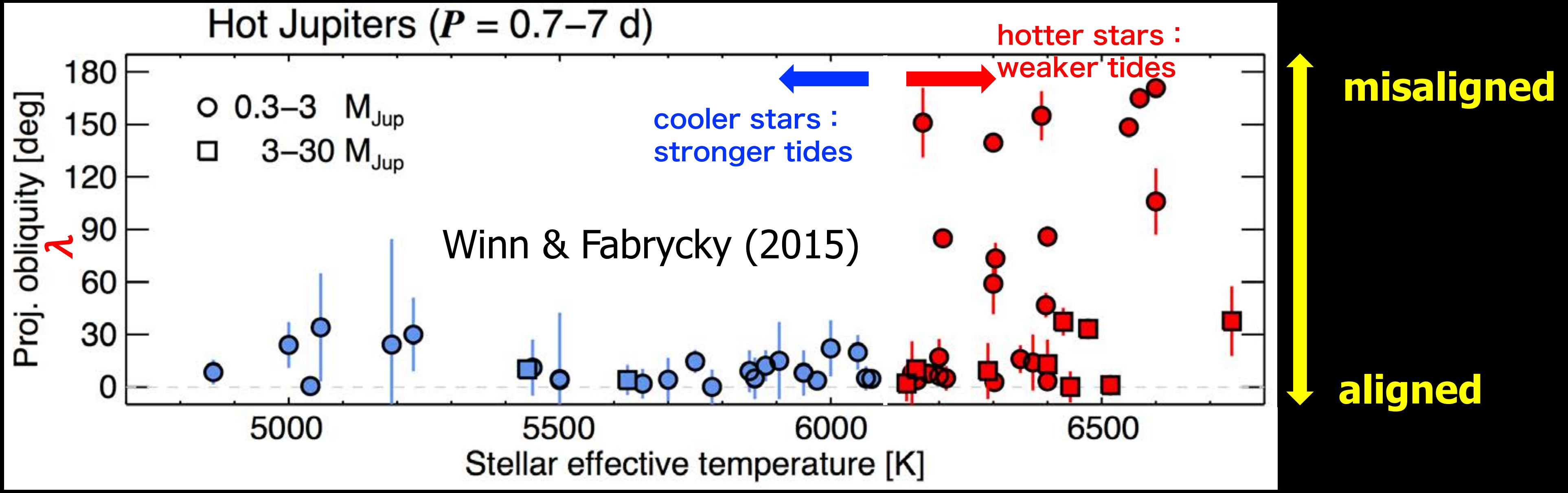


Triaud arXiv:1709.06376

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

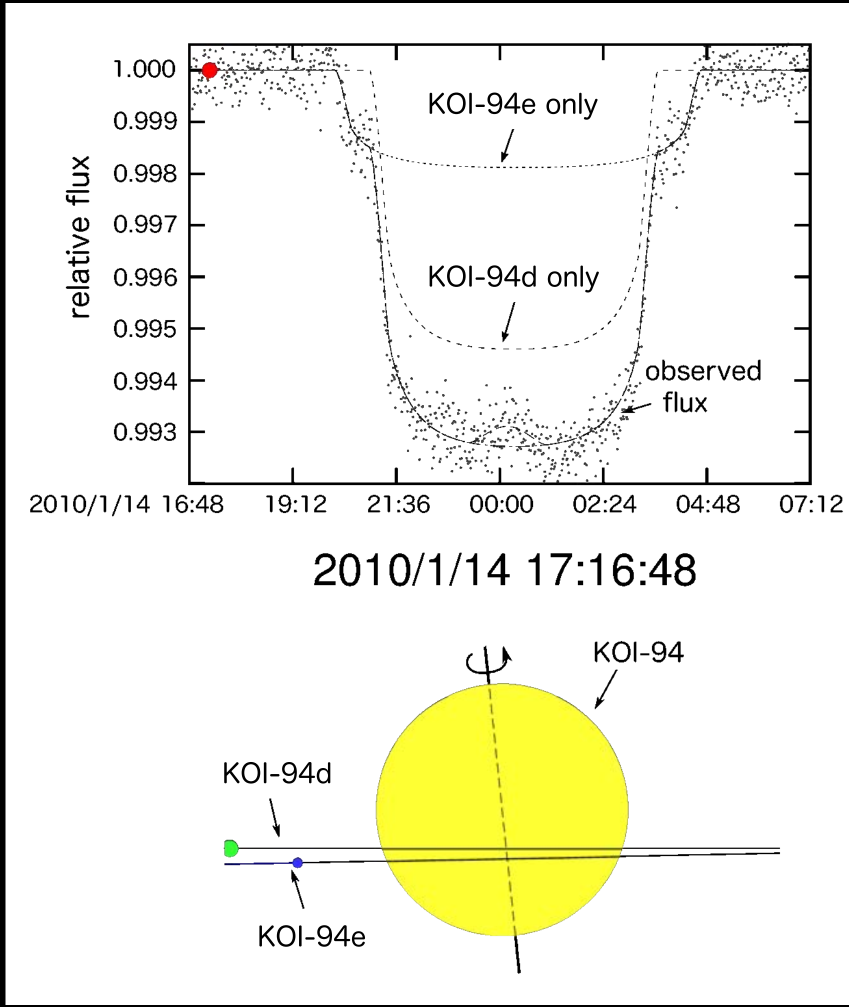
(Winn et al. 2010)

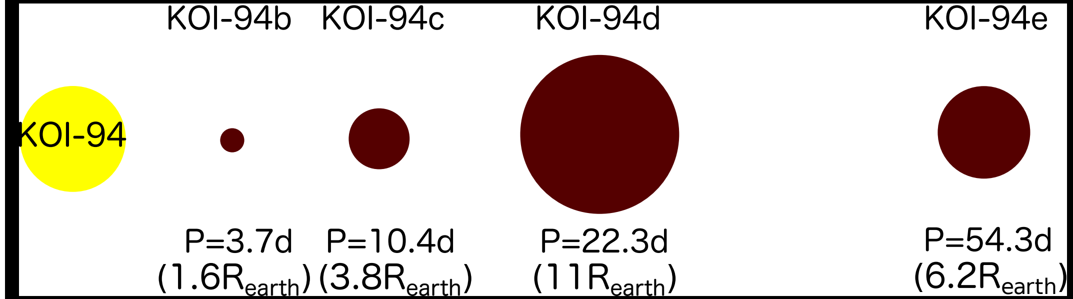
Star-orbit misalignment is more common ?



- It is not easy to explain why misalignments are preferentially in hotter host stars *in the primordial origin alone*
- Subsequent star-planet tidal interaction realigns the spin-orbit angle for cooler stars with convective envelops
- Primordial misaligned systems may be even more common ?

First discovery of planet-planet eclipse: KOI-94 (Kepler-89) with 4 transiting planets



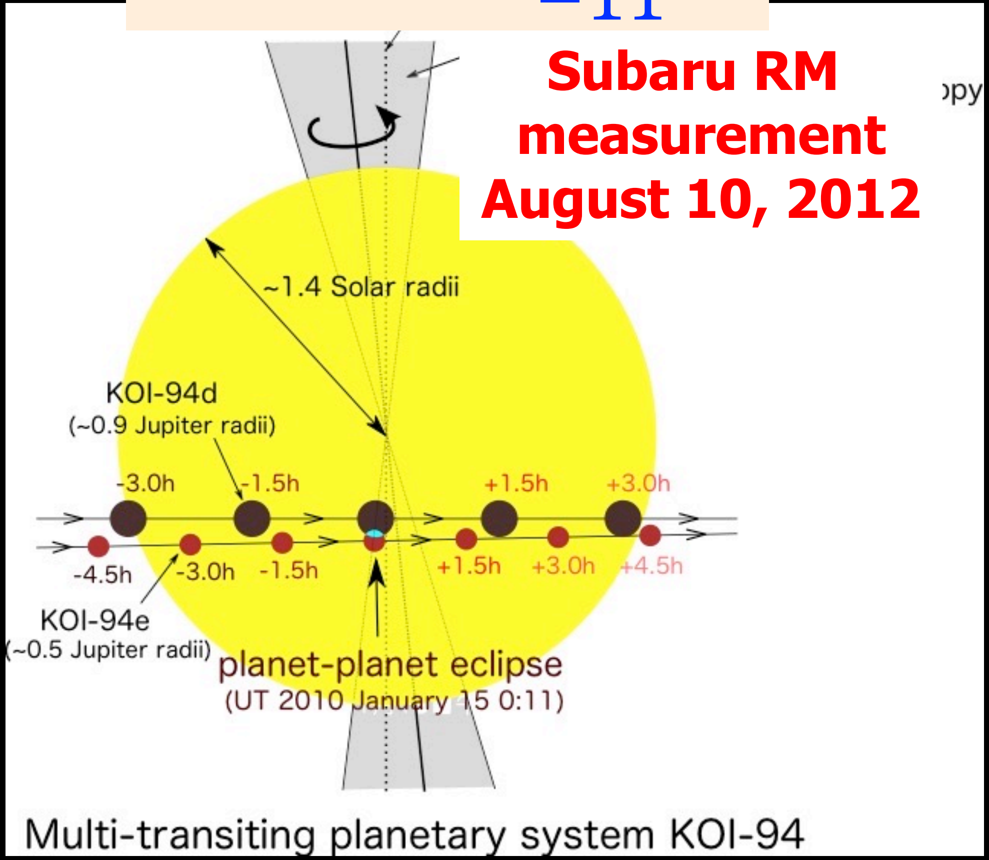


- First detection of planet-planet eclipse !
  - The orbital planes of those planets are amazingly coplanar
  - The initial architecture is supposed to be well preserved (not disturbed by subsequent dynamical evolution)
  - Its spin-orbit angle should retain the initial value (?)

Hirano et al. ApJL 759 (2012) L36

Spin-orbit alignment of KOI-94 (Kepler-89)

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



- First measurement of the RM effect for multiple-coplanar planets
  - Very well aligned
- Plausible interpretation
  - The spin-orbit angle is initially well aligned, and significantly disturbed later by dynamical evolution (e.g., chaotic planet-planet scattering) leaving a single close-in planet?

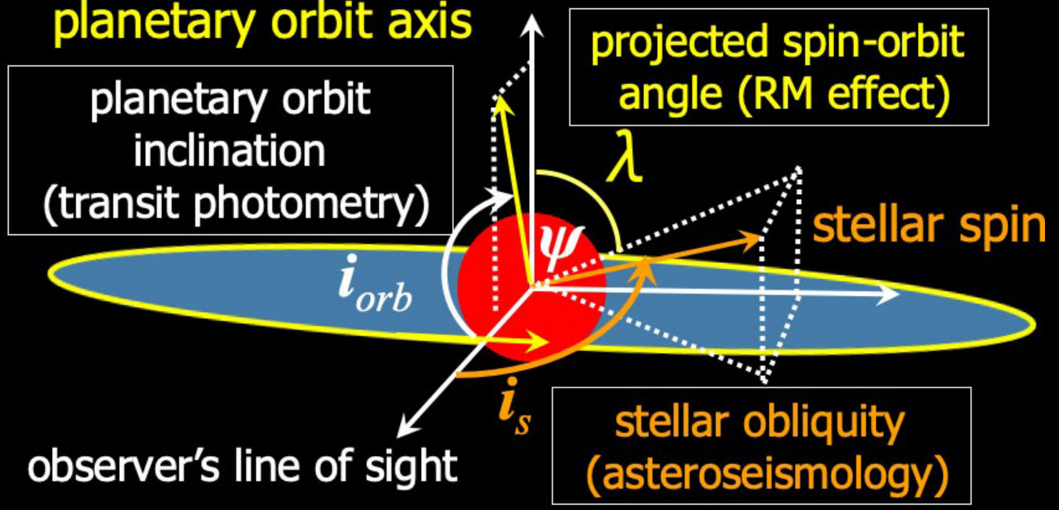
平野照幸　Hirano et al. ApJL 759 (2012) L36

増田賢人　Masuda et al. ApJ 778 (2013) 185

4 Spin-orbit angles from asteroseismology

Surprise ! : a misaligned multi-planetary system Kepler-56, revealed by asteroseismology

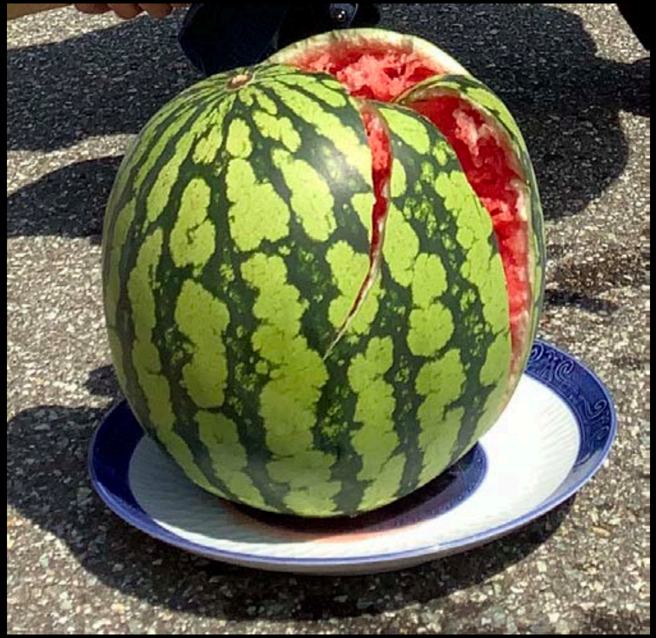
- Asteroseismology found a significantly misaligned system (i_s=47±6°) with two transiting planets, Kepler-56 !
  - Kepler-56: red giant (1.3M_s, 4.3R_s) + two transiting planets (10.5day, 20.4day) Huber et al. (2013)



- **Primordial origin for the misalignment ?**
- **Nature vs. Nurture ?**

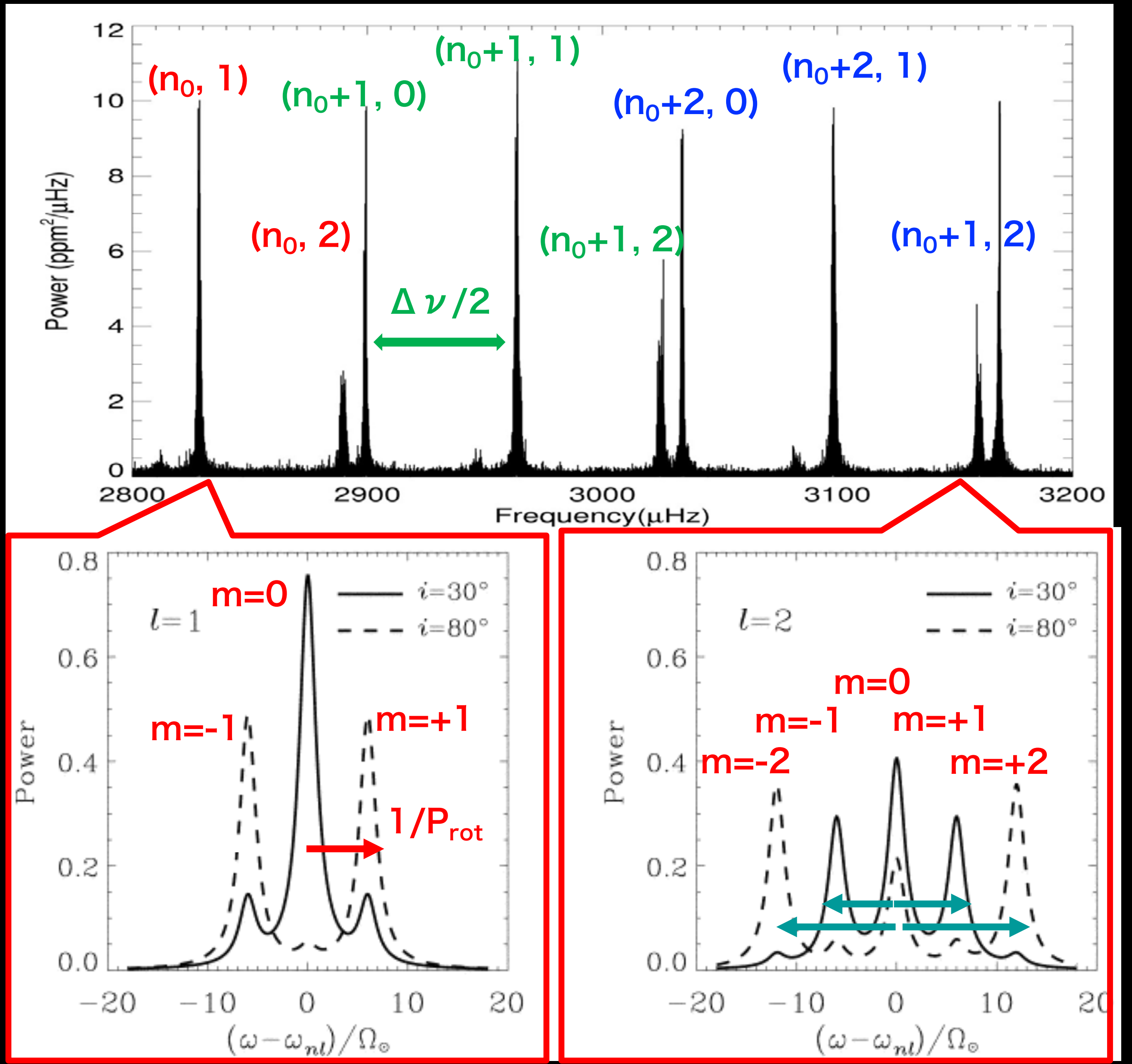
Asteroseismology in a nutshell

- Beating a watermelon to find a good one
  - oscillation eigen-mode analysis to understand the internal structure without destroying it
- Helioseismology- Solar neutrino puzzle
  - pp-chain reaction rate $\propto T^4$
  - neutrino deficit due to an overestimate of the internal temperature of the Sun from theory ?
  - Helioseismology confirmed the standard Solar model, leading to the discovery of the neutrino oscillation and neutrino mass eventually (SuperKamiokande: T.Kajita, Nobel Prize in 2015)



Why can asteroseismology measure i_s?

- **Stellar version of the Zeeman effect** (magnetic field ⇔ rotation)
  - Stellar pulsation eigen-modes have *(n,l,m)* using $Y_{lm}(\theta,\varphi)$
  - degeneracy of the eigen-frequency with respect to *m* of the same *l* is broken due to the stellar rotation
  - observed pulsation amplitudes of different *m*-modes depend on the stellar inclination



Larmor's theorem vs. the Zeeman effect

- Lagrangian for a particle of mass m and charge q under scalar potential φ

$$L = \frac{1}{2}mv^2 - q\varphi(r,z)$$

- frame rotation around z-axis with frequency Ω

$$L = \frac{1}{2}mv^2 - q\varphi(r,z) + m\Omega(xv_y - yv_x) + \frac{1}{2}m\Omega^2 r^2$$

- Homogeneous magnetic field B along z-axis

$$\begin{aligned} L &= \frac{1}{2}mv^2 - q\varphi(r,z) + q\boldsymbol{v}\cdot\boldsymbol{A} \\ &= \frac{1}{2}mv^2 - q\varphi(r,z) + \frac{qB}{2}(xv_y - yv_z) \end{aligned}$$

- Frame rotation is equivalent to magnetic field (B=2m Ω/q)
  - B breaks the degeneracy of m-level (Zeeman effect)
  - Classical asteroseimology ⇔ quantum Zeeman effect

Stellar obliquity and power spectrum

- **Oscillation in the corotating frame of the star**

$$\Psi_{nlm}(r,\theta,\varphi,t) = R_n(r)Y_{lm}(\theta,\varphi)e^{-iw_{nl}t} \propto e^{i(m\varphi - w_{nl}t)}$$

- **Oscillation frequency in the observer's frame**

$$\Psi_{nlm'}(r,\theta+i_*,\varphi-\Omega_* t,t) \propto e^{i(m'\varphi - m'\Omega_* t - w_{nl}t)}$$

- **Obliquity changes the amplitude of modes**

$$P(w) = \sum_{n,l}\sum_{m=-l}^{l} \frac{\mathcal{E}_{lm}(i_s)H_{nl}(w)}{1+4(\nu-\nu_{nlm})^2/\Gamma^2_{nlm}}$$

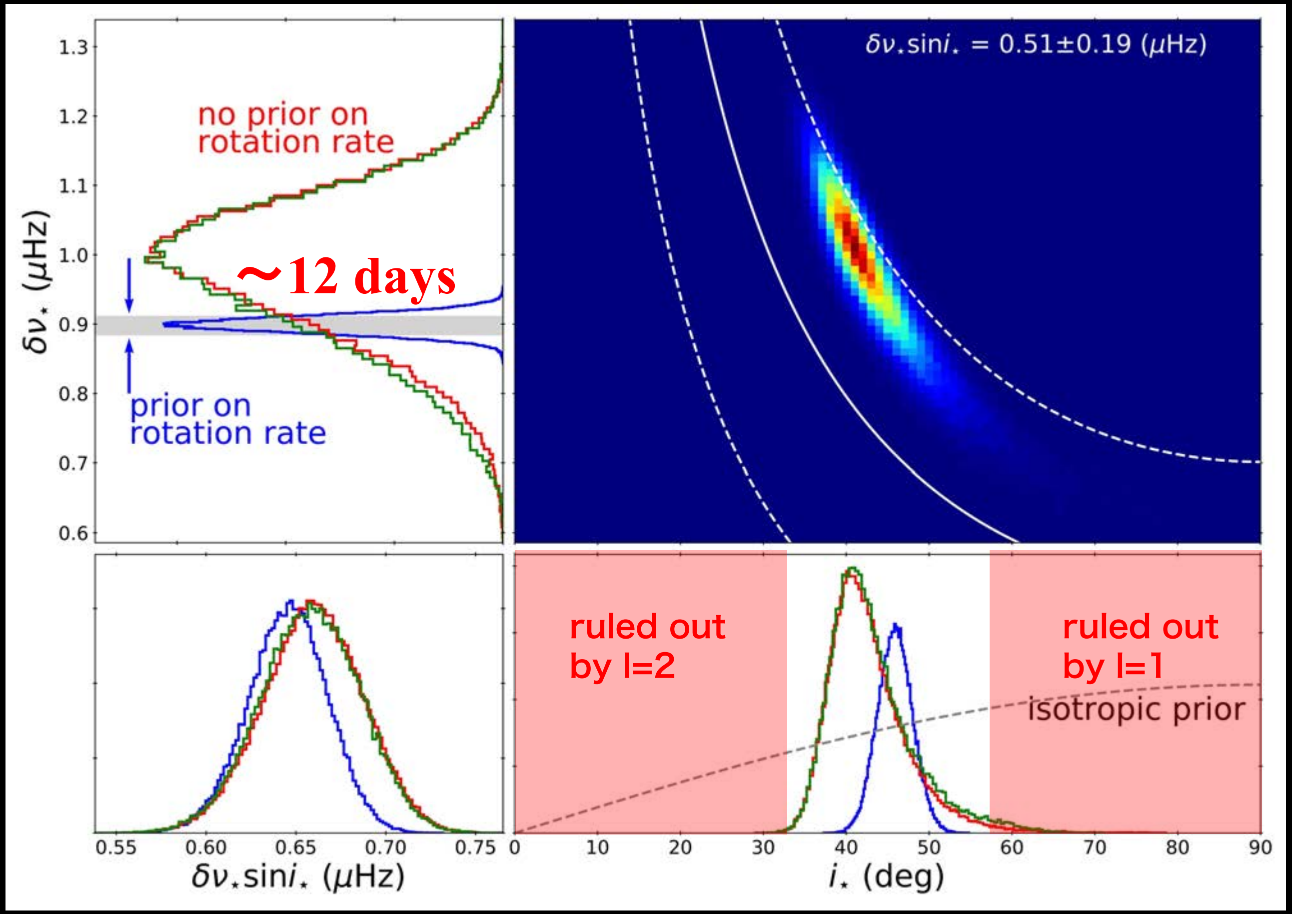
Toutain & Gouttebroze, (1993)
Gizon & Solanki (2003)
Kamiaka, Benomar & Suto (2018)

m-dependence of the mode amplitude $$\mathcal{E}_{lm}(i_s) = \frac{(l-|m|)!}{(l+|m|)!}\left[P_l^{|m|}(\cos i_s)\right]^2$$

m-dependence of the mode frequency $$\nu_{nlm'} = \nu_{nl} + m\,\delta\nu_*(1-C_{nl})$$

$\delta\nu_*$: stellar rotation C_{nl}: small correction factor

Asteroseismic constraints on i_s for Kepler-408



- **Kepler-408**
  - Star: 6100K, $1.05M_{sun}$ & $1.25R_{sun}$
  - Planet: sub-Earth size $0.86R_E$, 2.5day orbital period

上赤翔也

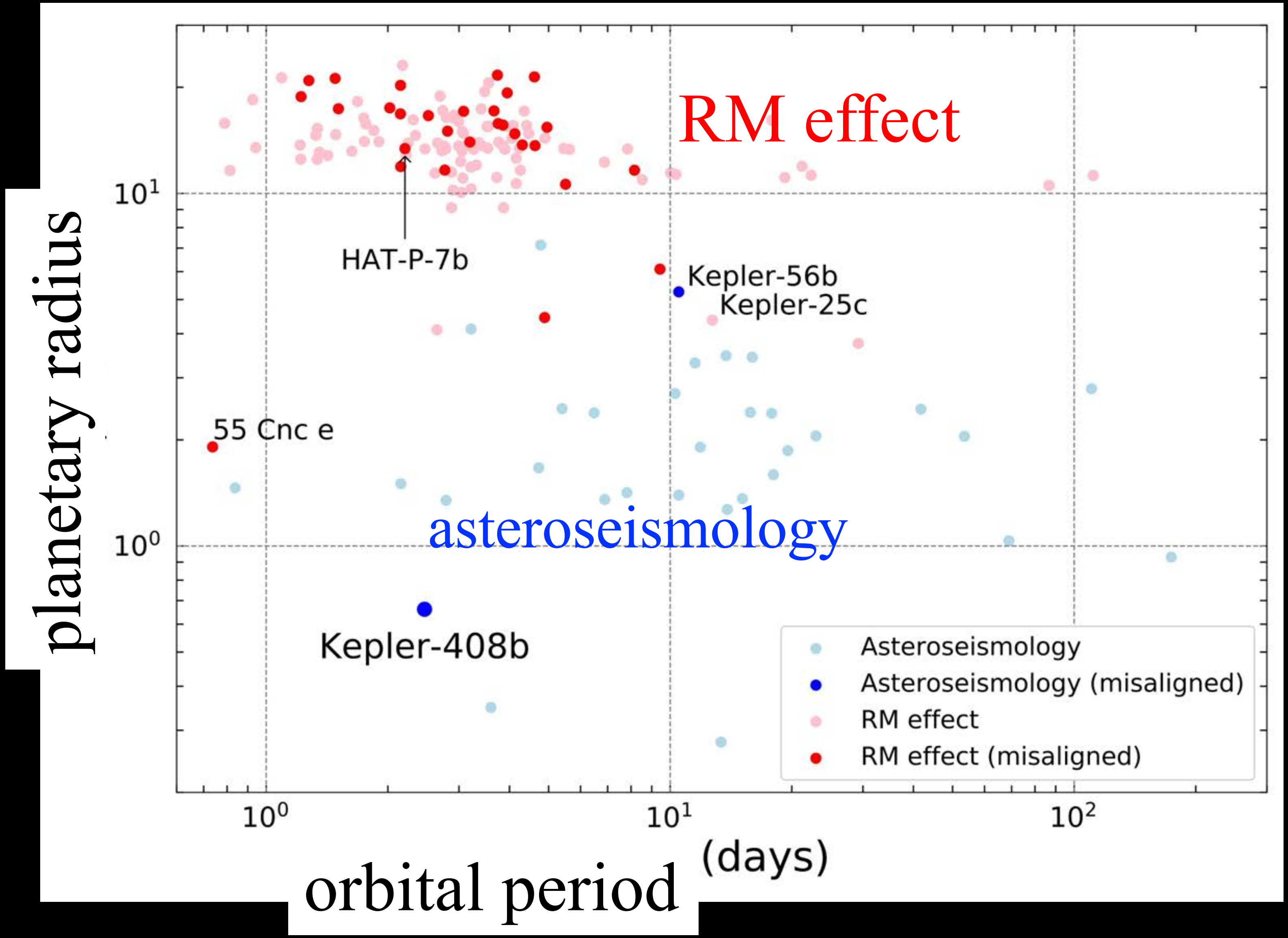
Kamiaka, Benomar, YS, Dai, Masuda & Winn AJ 157(2019)137

- Consistent with the independent estimate
  - Photometric rotation period：P_{rot}
  - Doppler line broadening：$v_{rot}\sin i_\star$

$$i_\star = \sin^{-1}\left(\frac{v_{\rm rot}\sin i_\star}{2\pi R_\star/P_{\rm rot}}\right) = 44^{+20}_{-15}\,(\mathrm{deg})$$

- The smallest-size planet in an oblique orbit

Complementarity between the RM effect and asteroseismology

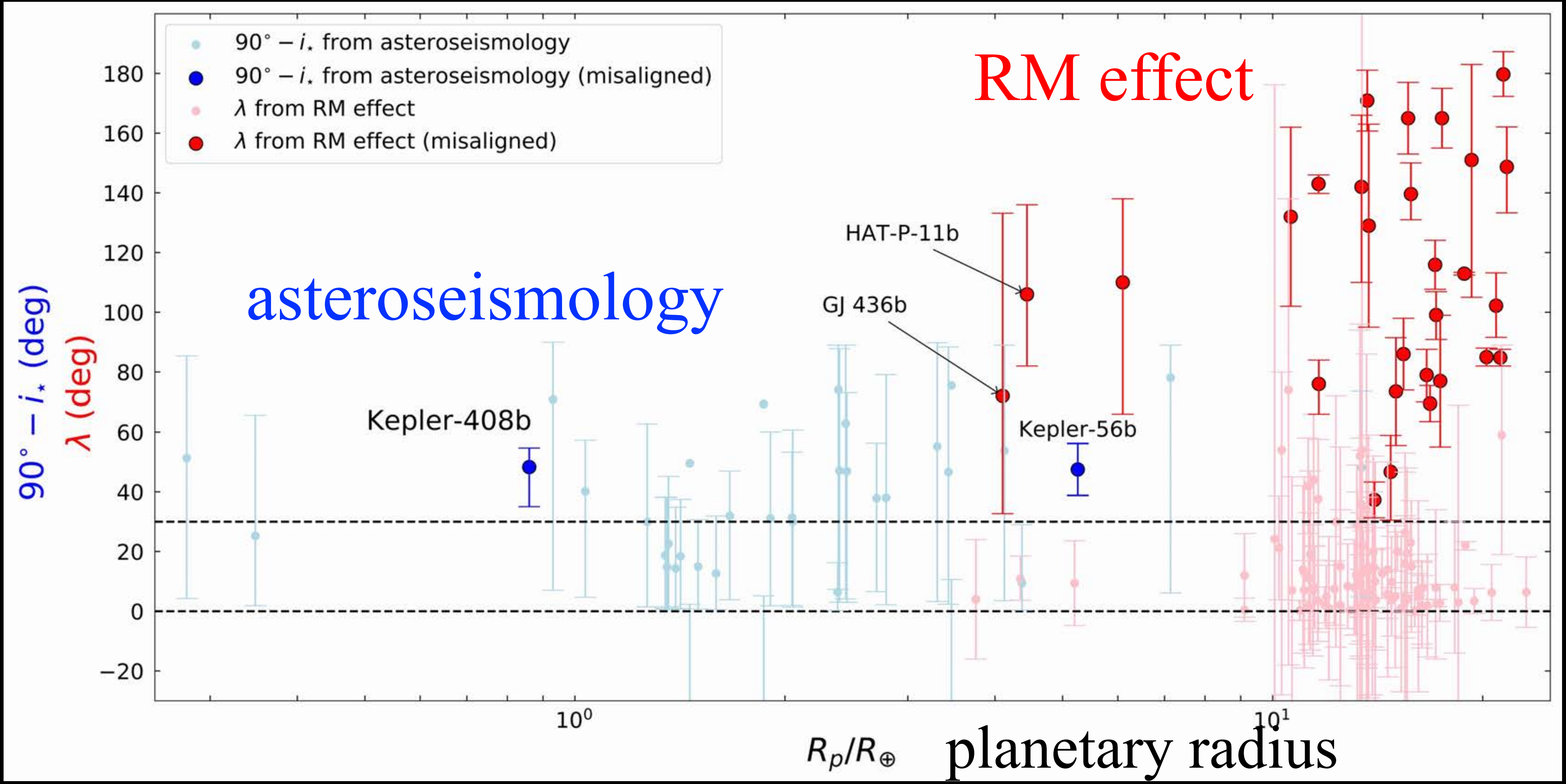


- **RM effect**
  - Prefers short-period and large planets
- **Asteroseismology**
  - independent of the properties of planets

Kamiaka, Benomar & YS MNRAS 479 (2018) 391
Kamiaka, Benomar, YS, Dai, Masuda, & Winn AJ 157(2019)137
YS, Kamiaka & Benomar AJ 157(2019)172

Lu, Benomar, Kamiaka & YS, ApJ 941(2022)175

Spin-orbit angles against R_p



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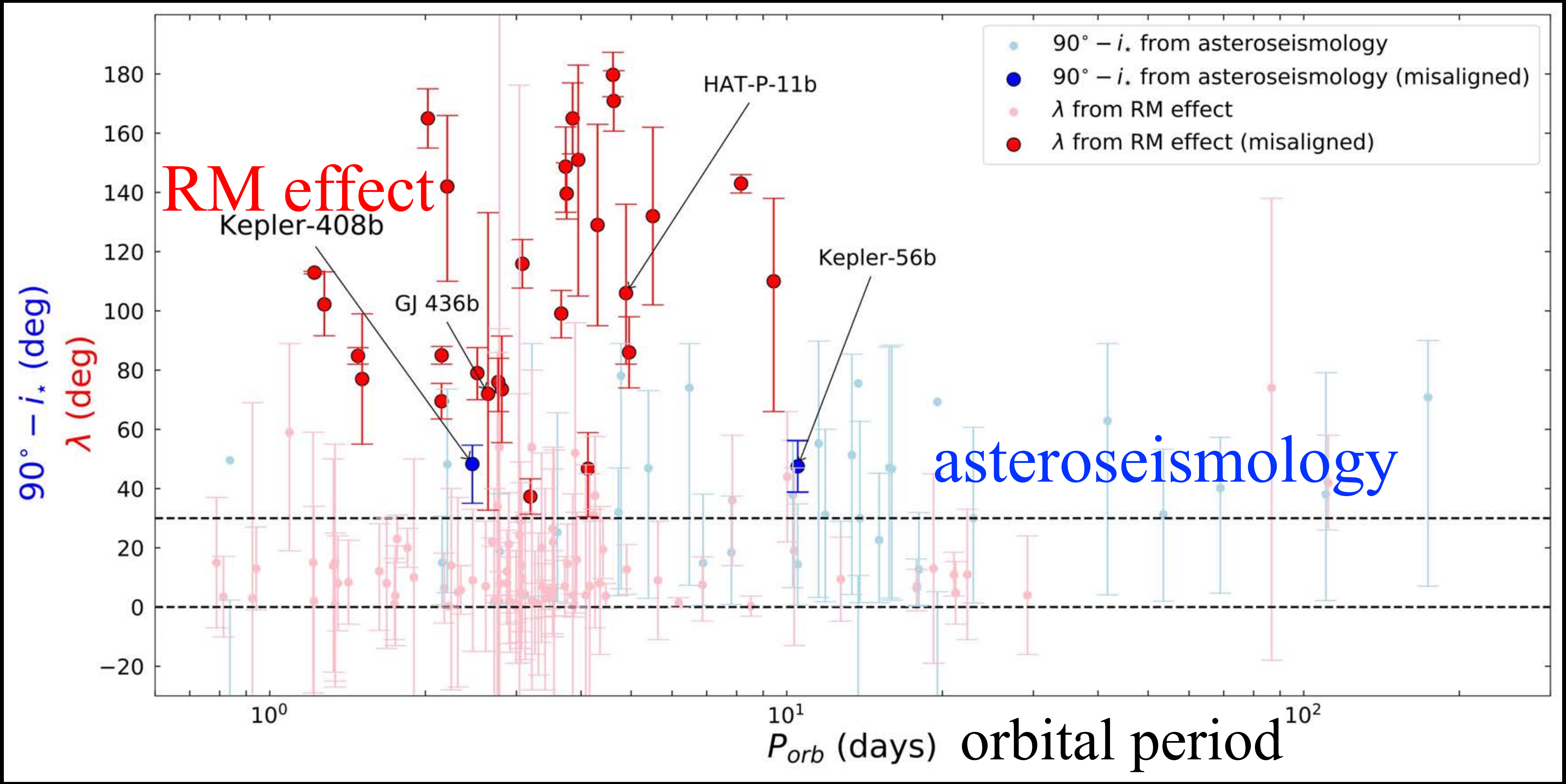
Spin-orbit angles against P_{orb}



上赤翔也　Kamiaka, Benomar, YS, Dai, Masuda, & Winn, AJ 157(2019)137

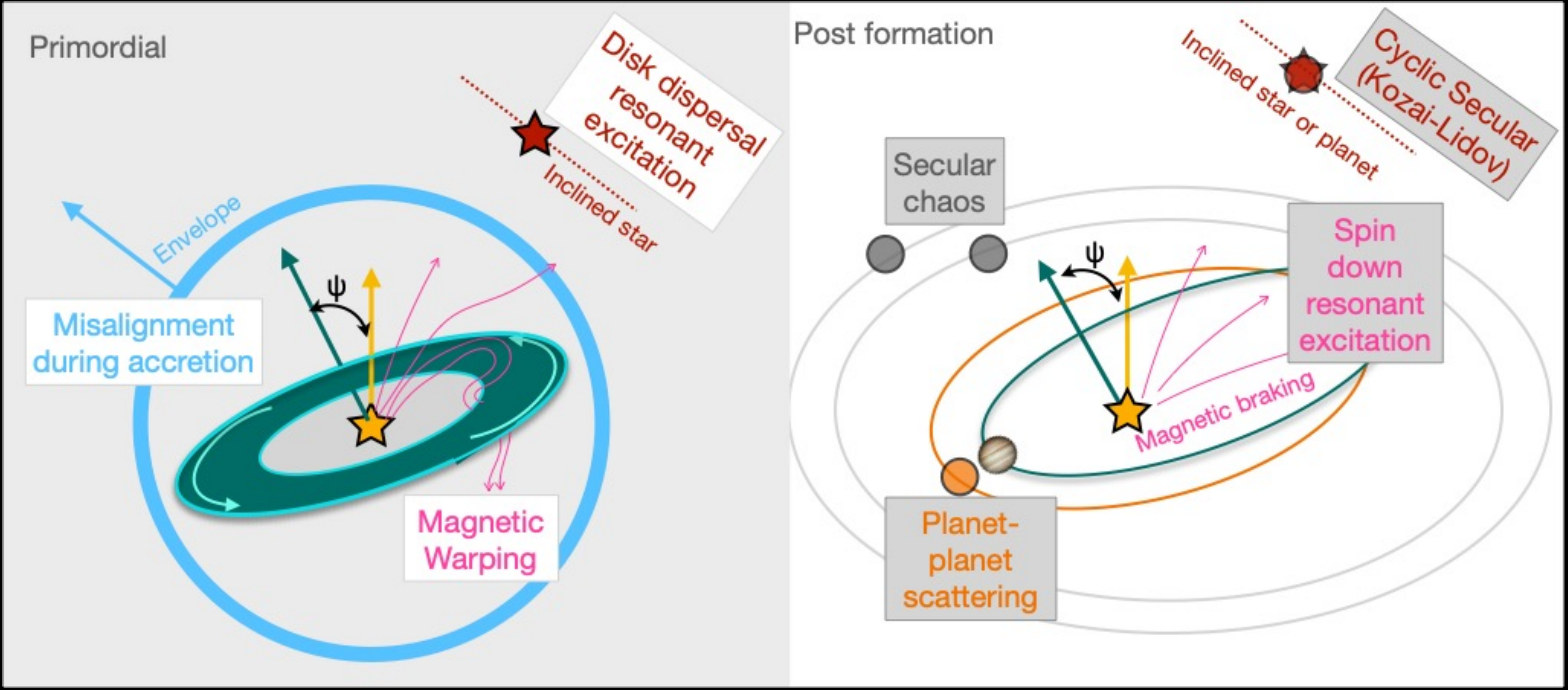
5 Evolution of spin-orbit angle: Nature or Nurture?

Proposed models for the misalignment

- Primordial misalignment between the protostar and the protoplanetary disk
  - Bate, Lodato & Pringle (2010)
  - Takaishi, Tsukamoto & YS (2020) MNRAS 492, 5641; arXiv:2001.05456
- Precession of the protoplanetary disk due to the external perturber
  - Batygin (2012)
- Planet-planet scattering
  - Nagasawa, Ida, & Bessho (2008), Gratia & Fabrycky (2017)

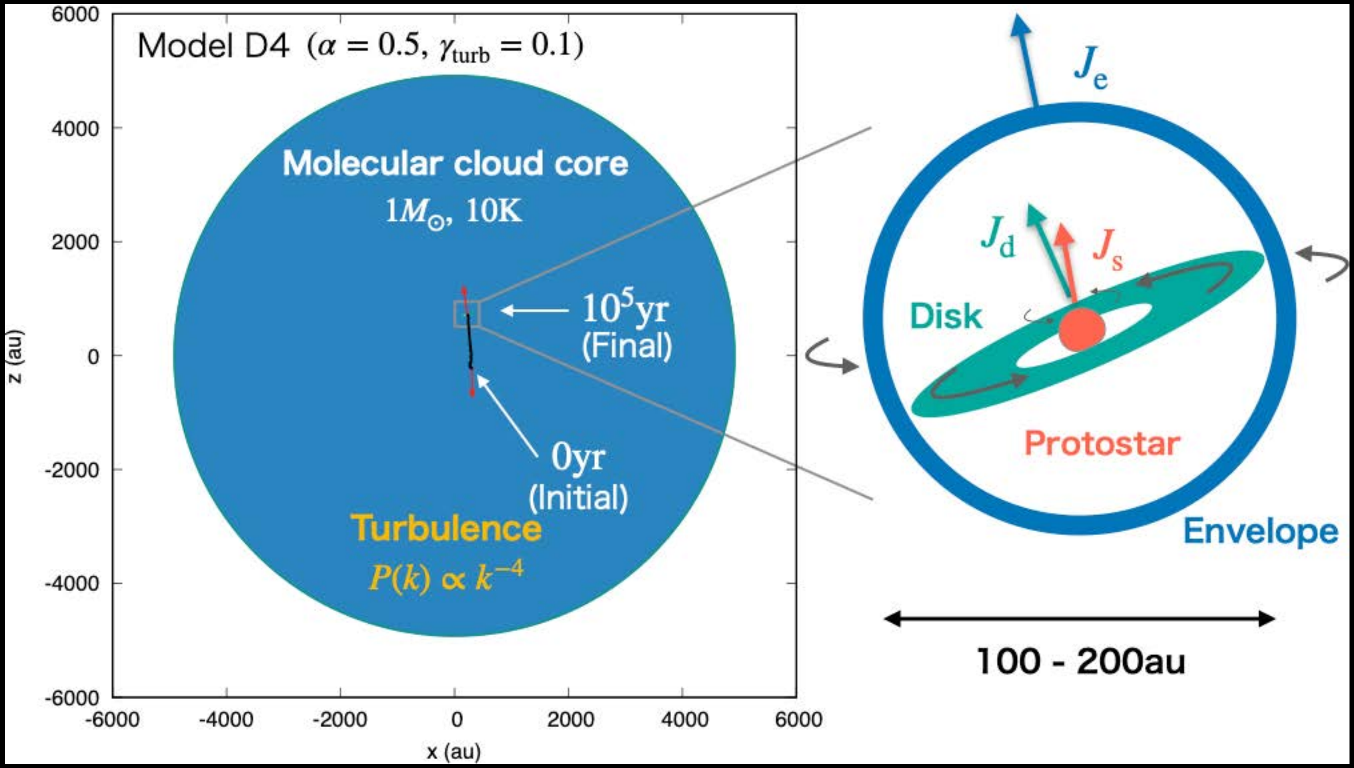
No consensus ⇒ many opportunities for further studies

Nature or Nurture?



Albrecht, Dawson, & Winn; Publications of the Astronomical Society of the Pacific, 134 (2022) 082001

Primordial star-disk alignment in turbulent molecular cloud cores

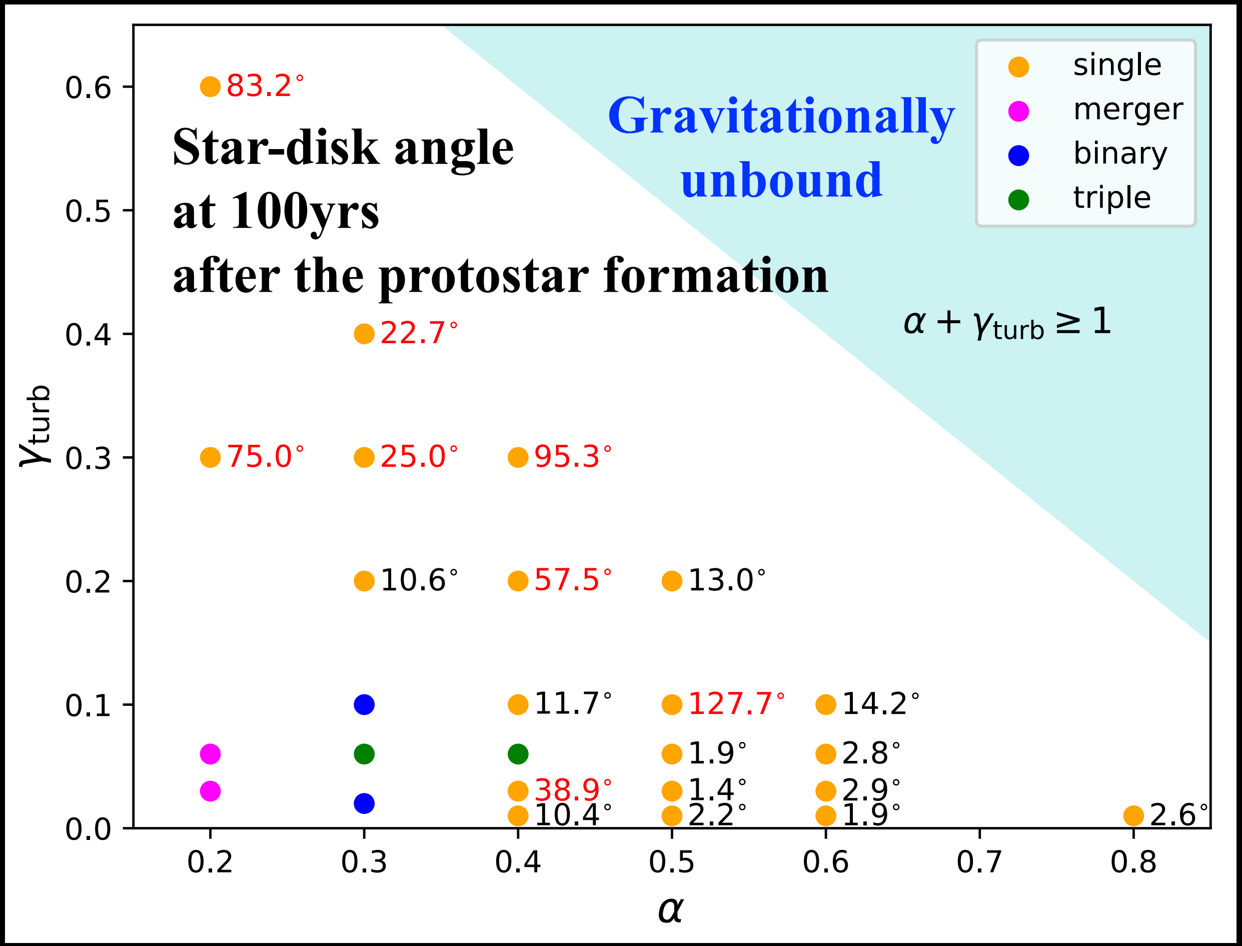


- **SPH simulation**
  - 1million SPH particles + sink particle method to approximate protostars
  - isothermal turbulent cloud cores of $1M_{sun}$
  - neglect magnetic field

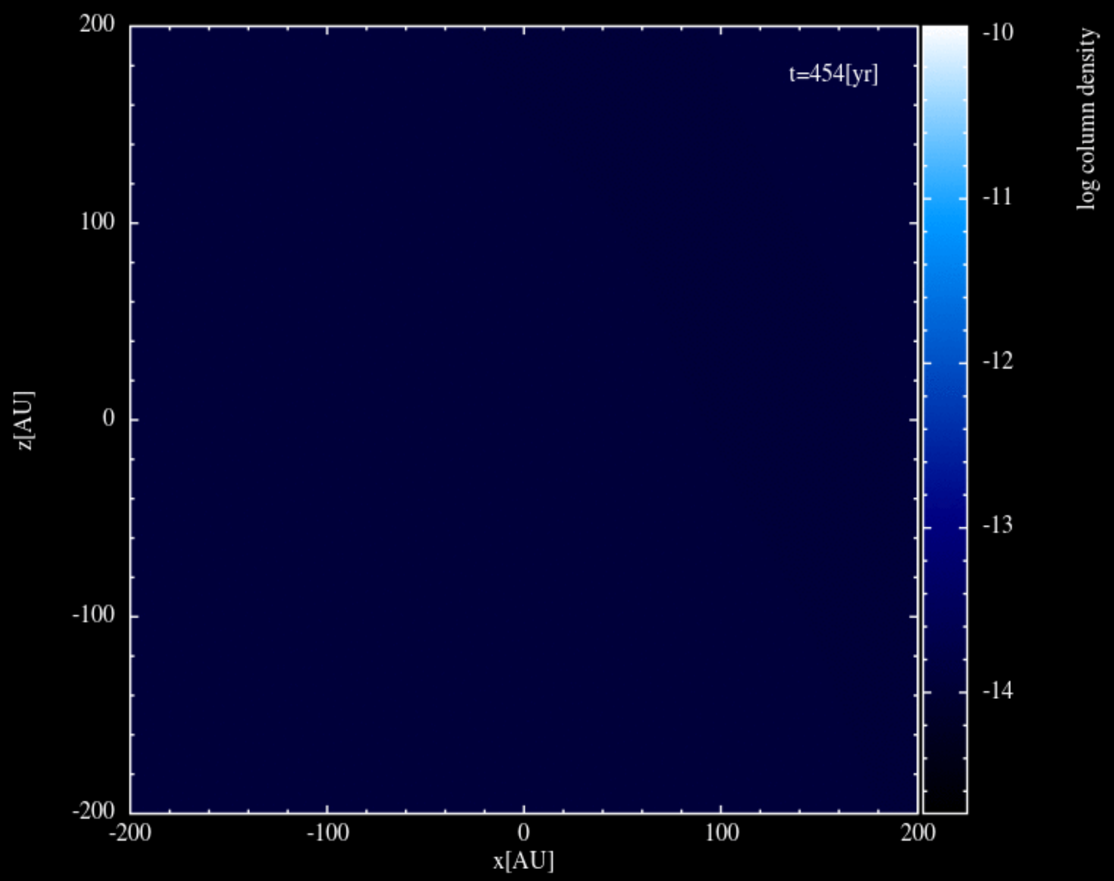
Takaishi, Tsukamoto + YS, MNRAS 492 (2020),5641
高石大輔　塚本祐介　arXiv:2001.05456

Initial star-disk (mis)alignment angles

Turbulence energy/Gravitational energy

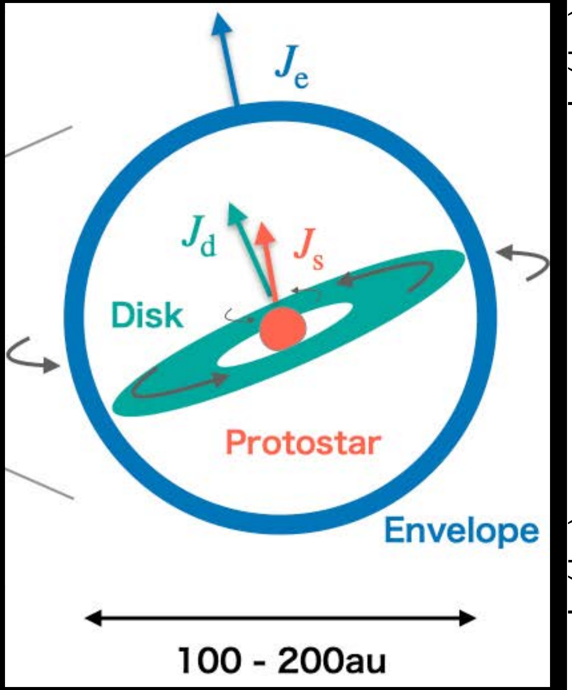


Thermal energy/Gravitational energy

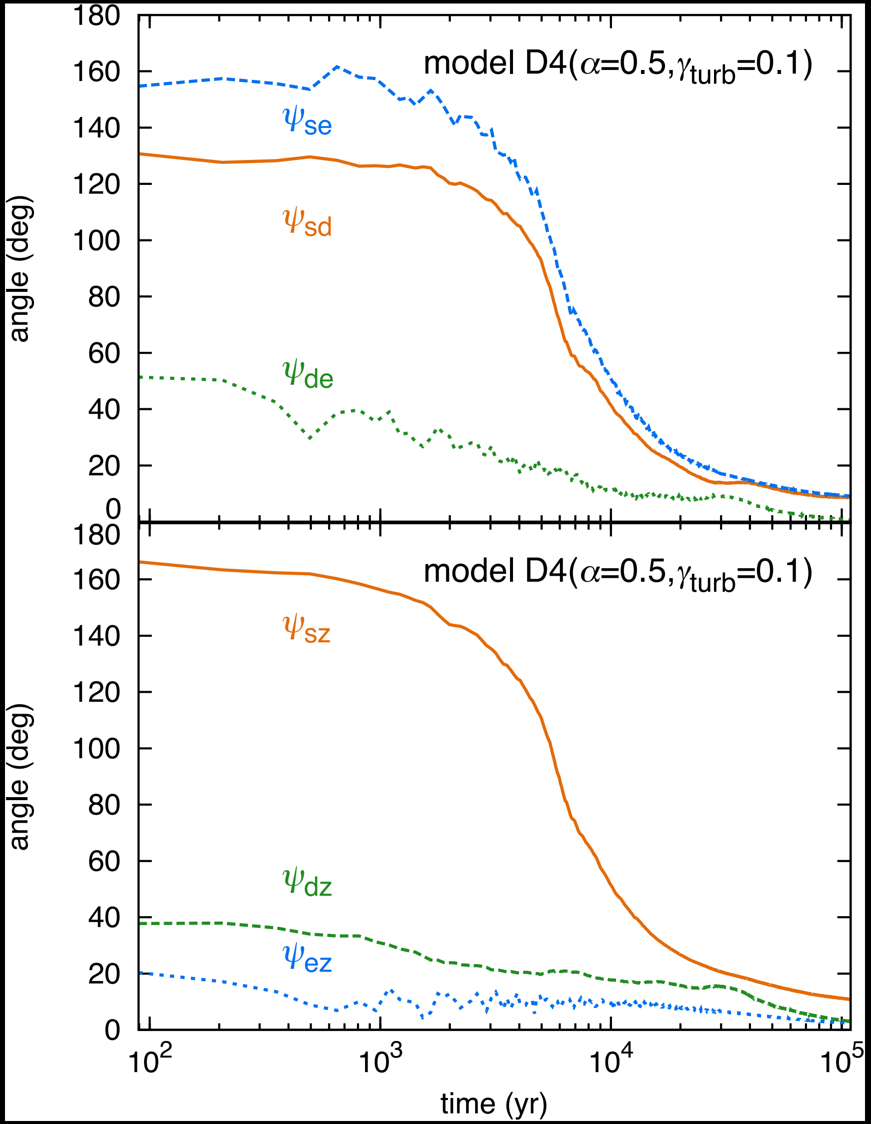


Takaishi, Tsukamoto + YS (2020)

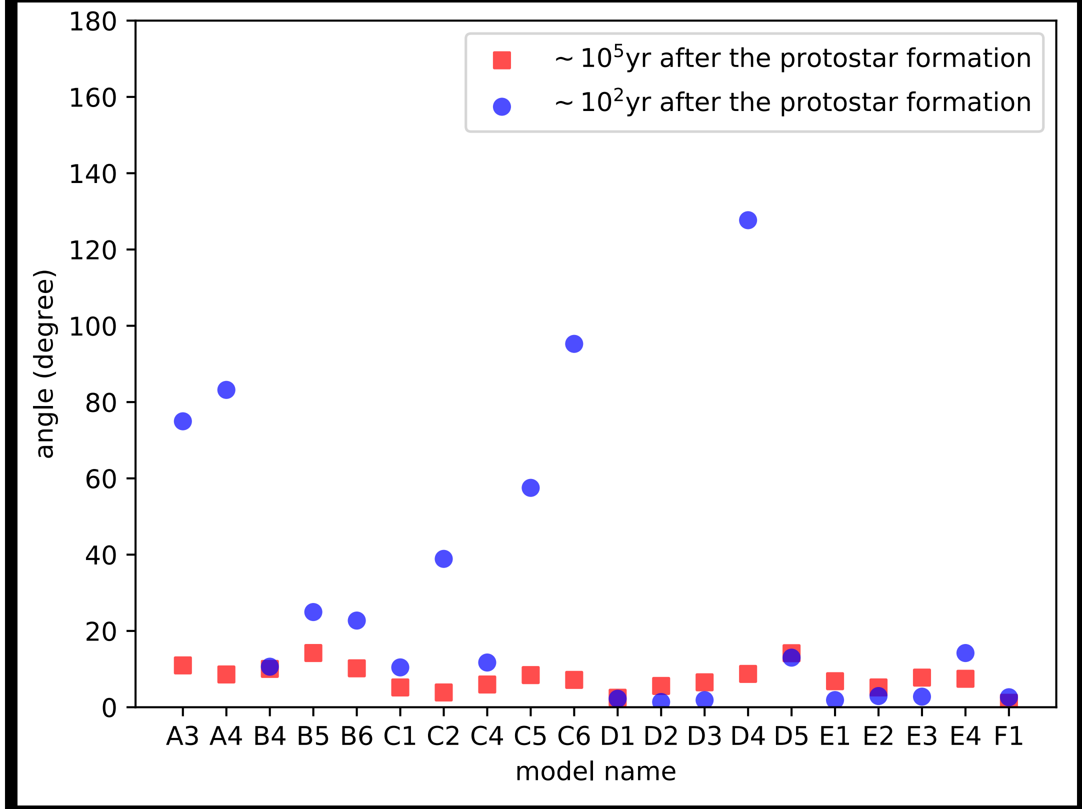
Protostar and disk tend to be aligned!



Misalignment for multiple star formation ?



Primordial star-disk angles are less than 20 degrees



Takaishi, Tsukamoto + YS (2020)

Summary: ***Nature or Nurture ?***

- Spin-orbit architecture of exoplanetary systems exhibits an unexpectedly large diversity
  - important probe of the initial conditions and migration/orbital evolution of planetary systems
- Challenging unsolved puzzles
  - Primordial misalignment imprinted in protoplanetary disks ?
  - Disk precession due to external perturbers ?
  - Chaotic dynamics triggered by planet-planet interaction ?
  - Tidal interaction between the host star and planets ?
- Significant opportunities for further study and discovery