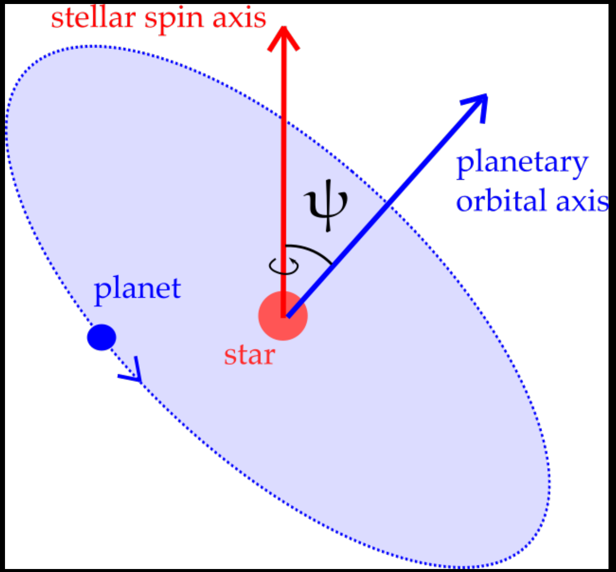
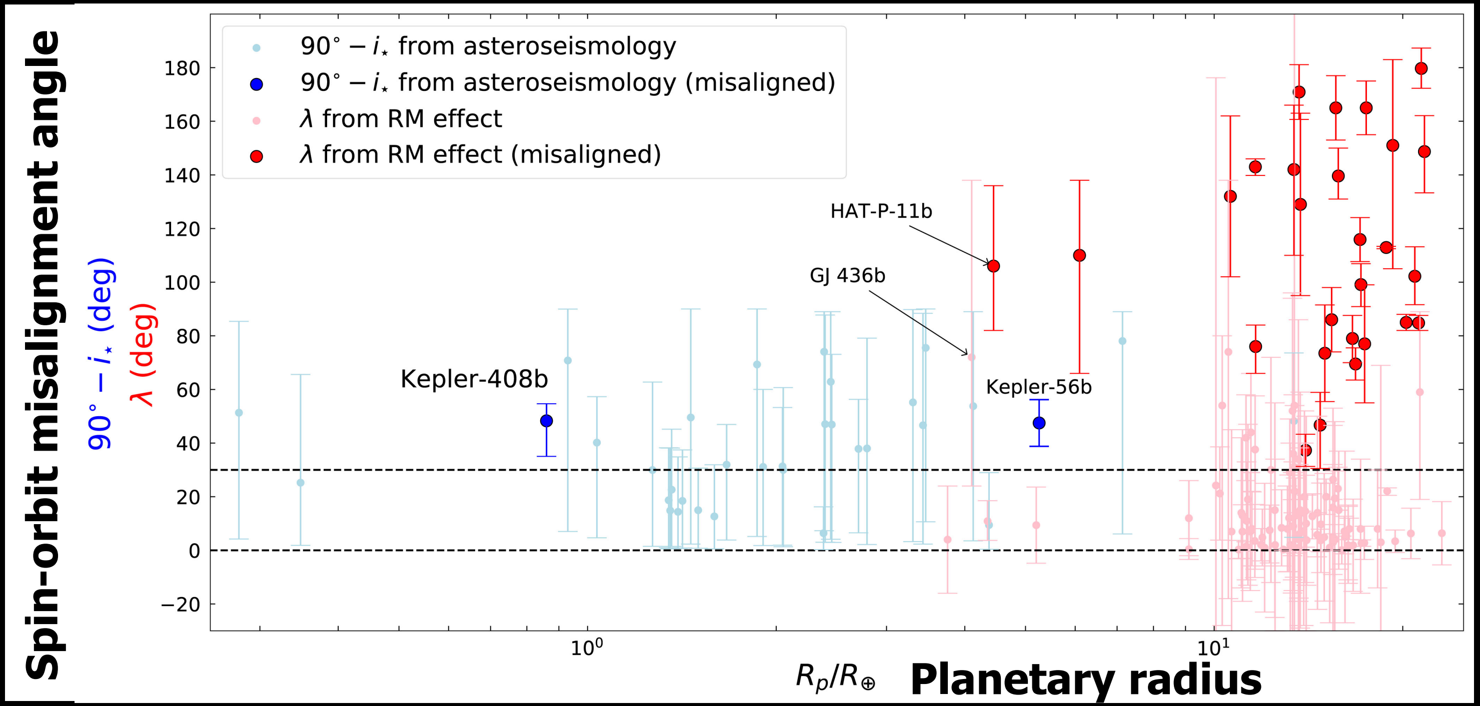
Unveiling spin-orbit architectures of exoplanetary systems





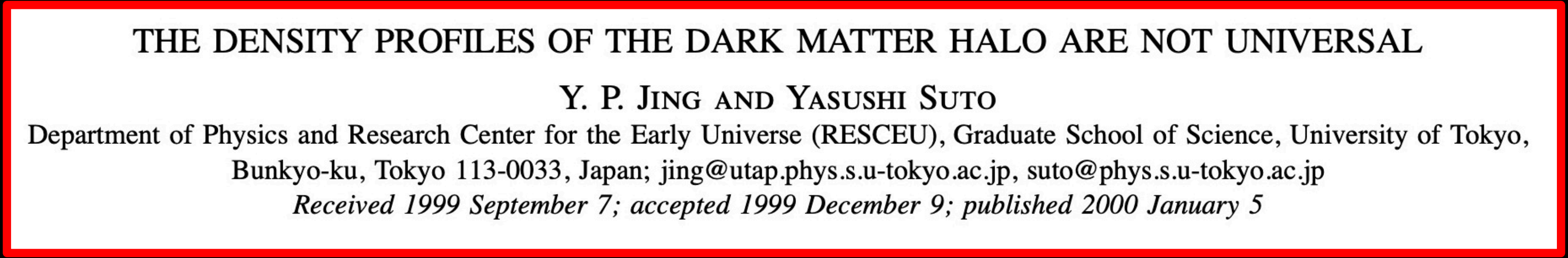
Yasushi Suto （須藤 靖）

Department of Physics and Research Center for the Early Universe , The University of Tokyo

14:00-15:00 September 28, 2020@上海交通大学天文学科

有朋自遠方来、不亦楽乎

Of course, we did science together, not only enjoying Chinese food !



THE DENSITY PROFILES OF THE DARK MATTER HALO ARE NOT UNIVERSAL

Y. P. Jing and Yasushi Suto

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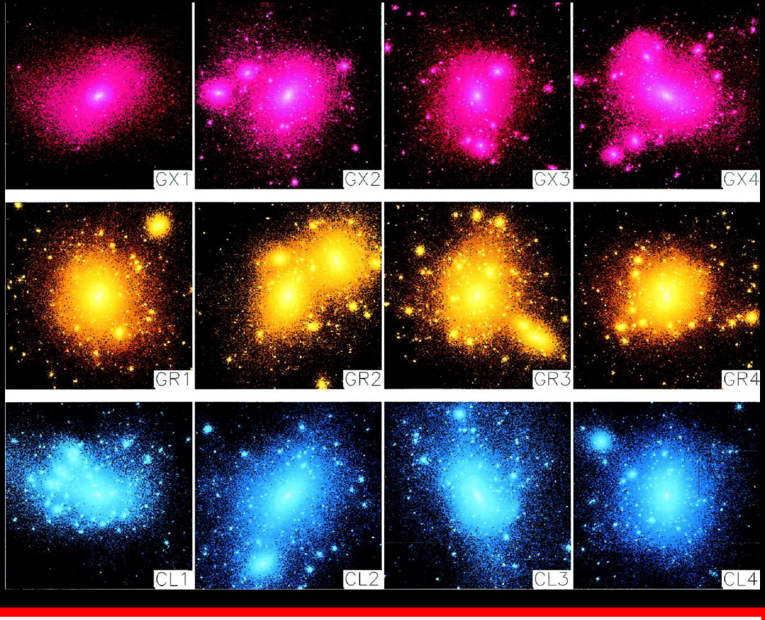
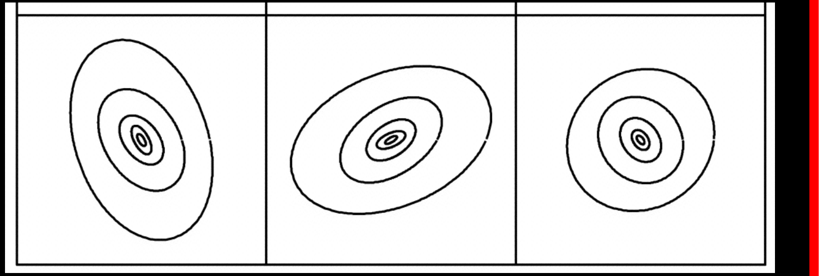
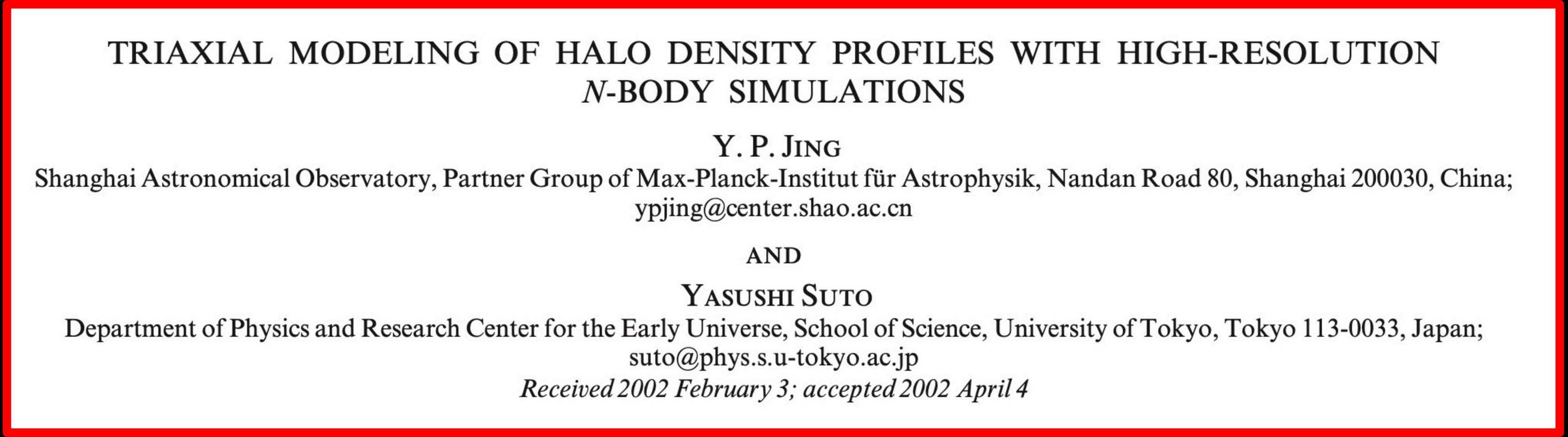
Received 1999 September 7; accepted 1999 December 9; published 2000 January 5







TRIAXIAL MODELING OF HALO DENSITY PROFILES WITH HIGH-RESOLUTION *N*-BODY SIMULATIONS

Y. P. Jing

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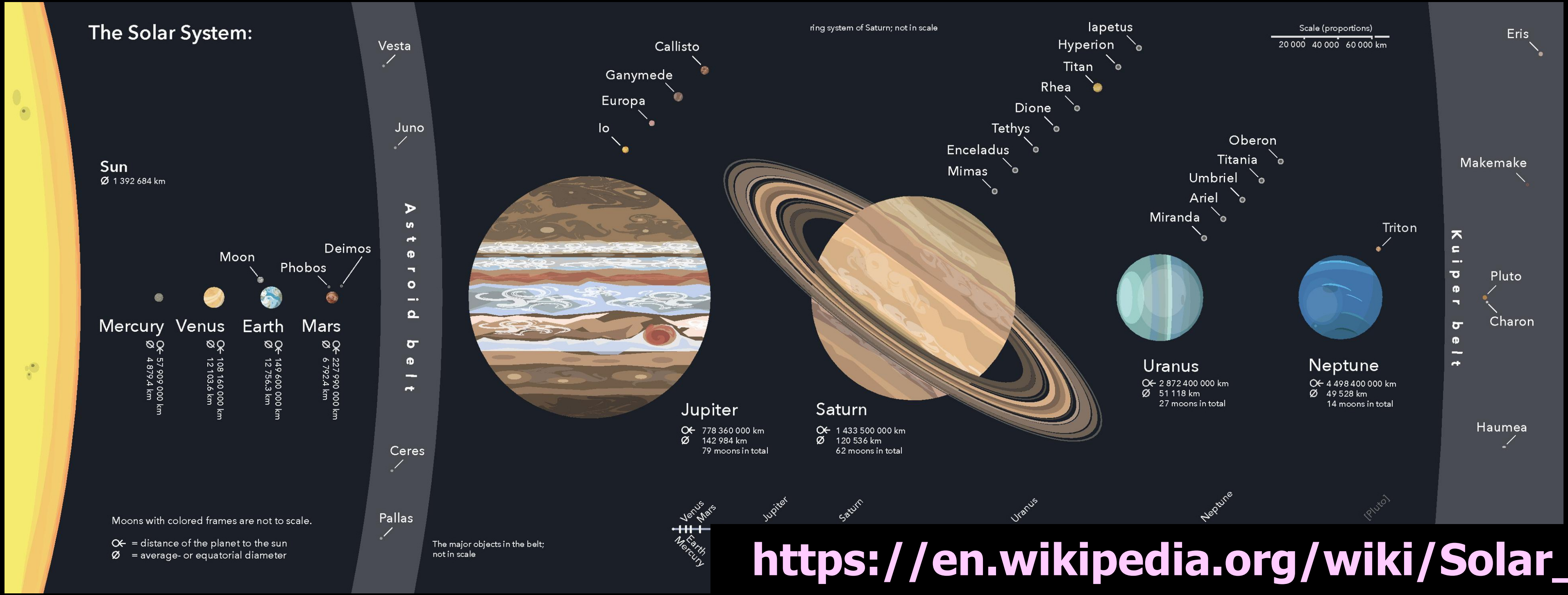
Received 2002 February 3; accepted 2002 April 4

Introduction

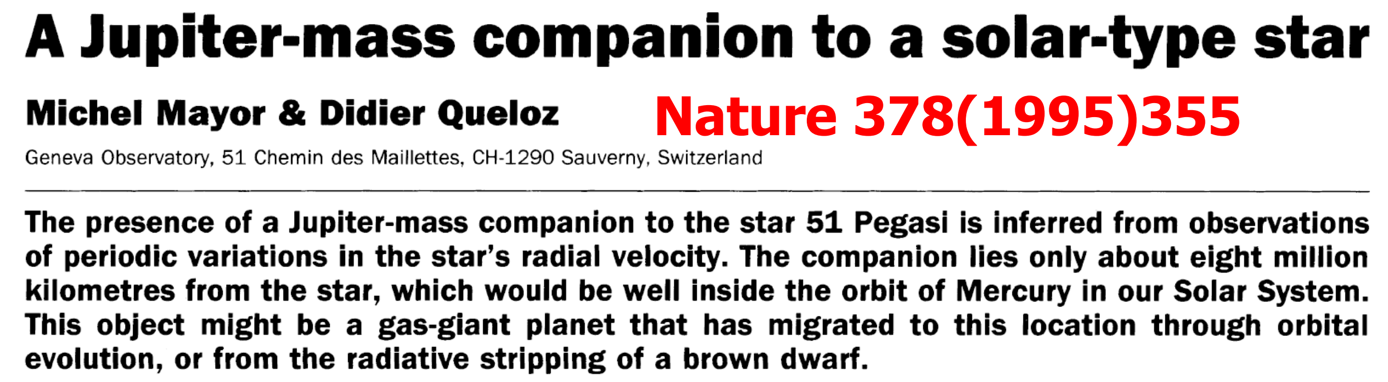
Architecture of the Solar system



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
  - ***Host a planet with life and (advanced) civilization***

Exoplanet discovery history



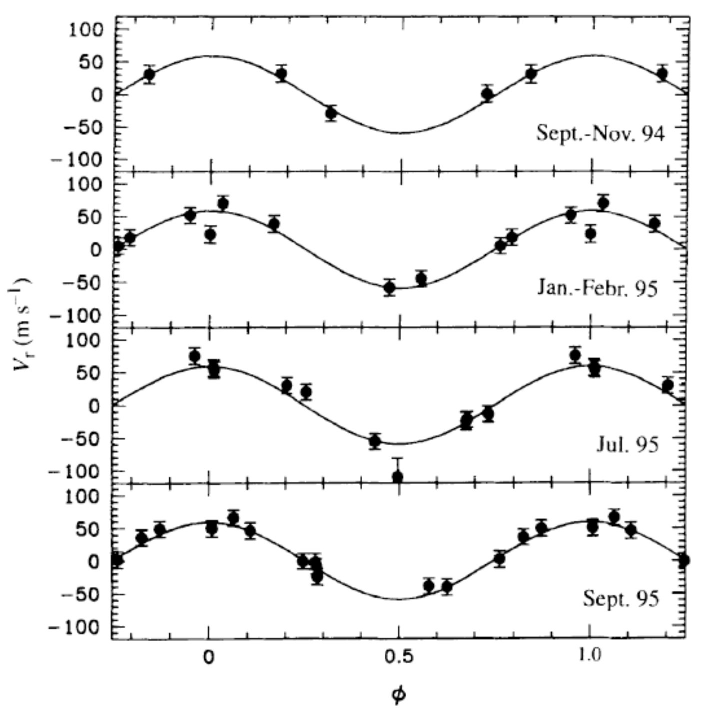
A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz Nature 378(1995)355

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

---

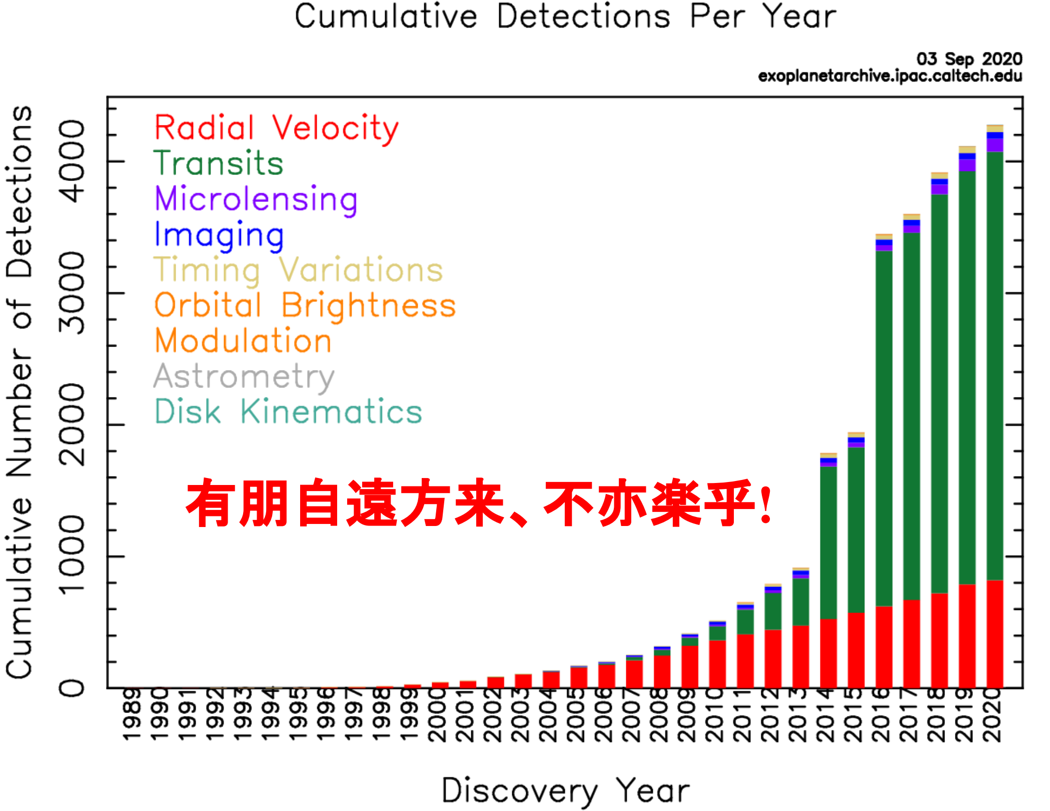
The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might 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

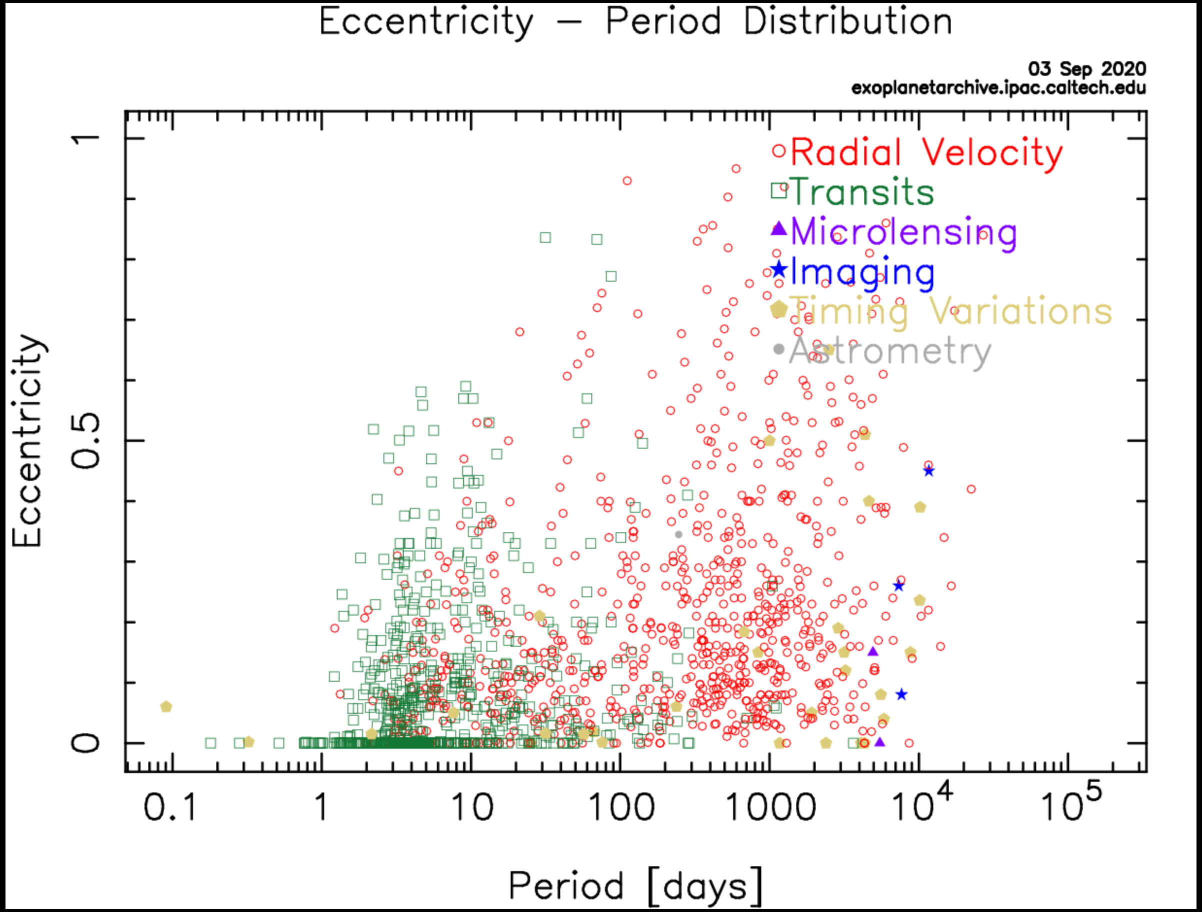
（P_{orb}=4.2days）

Nobel Prize in Physics 2019



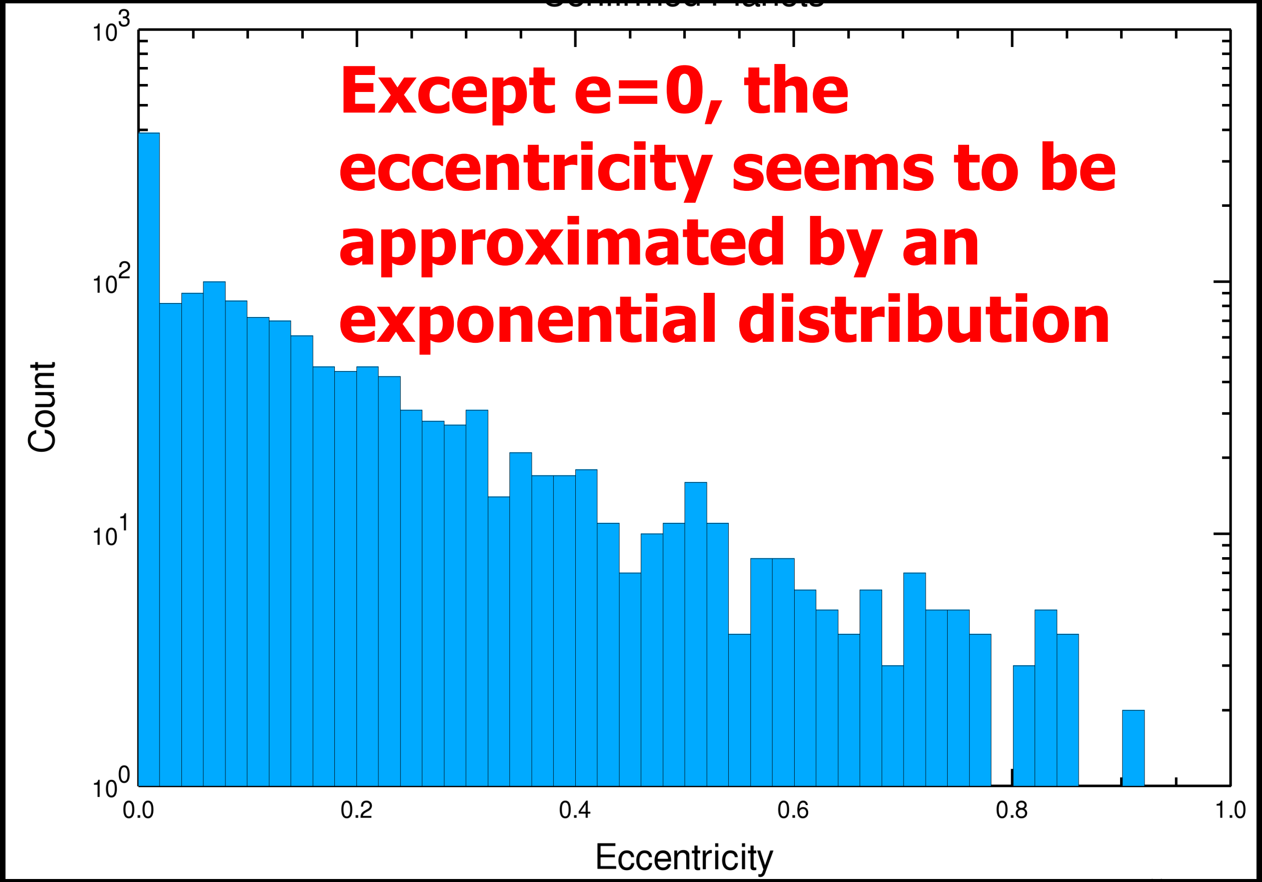
有朋自遠方来、不亦楽乎!

Diversity of planets: orbital period vs. eccentricity



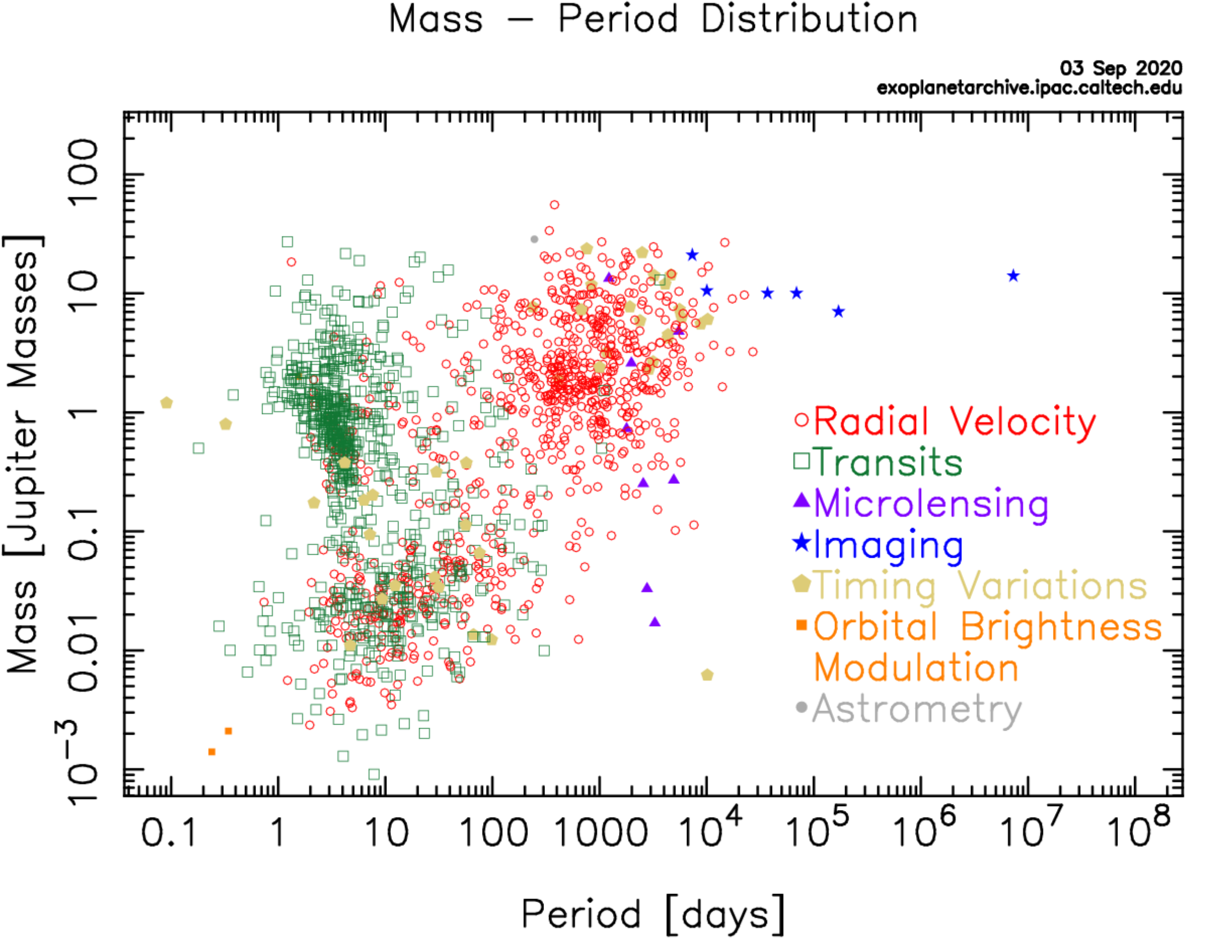
Eccentricity – Period Distribution

03 Sep 2020
exoplanetarchive.ipac.caltech.edu



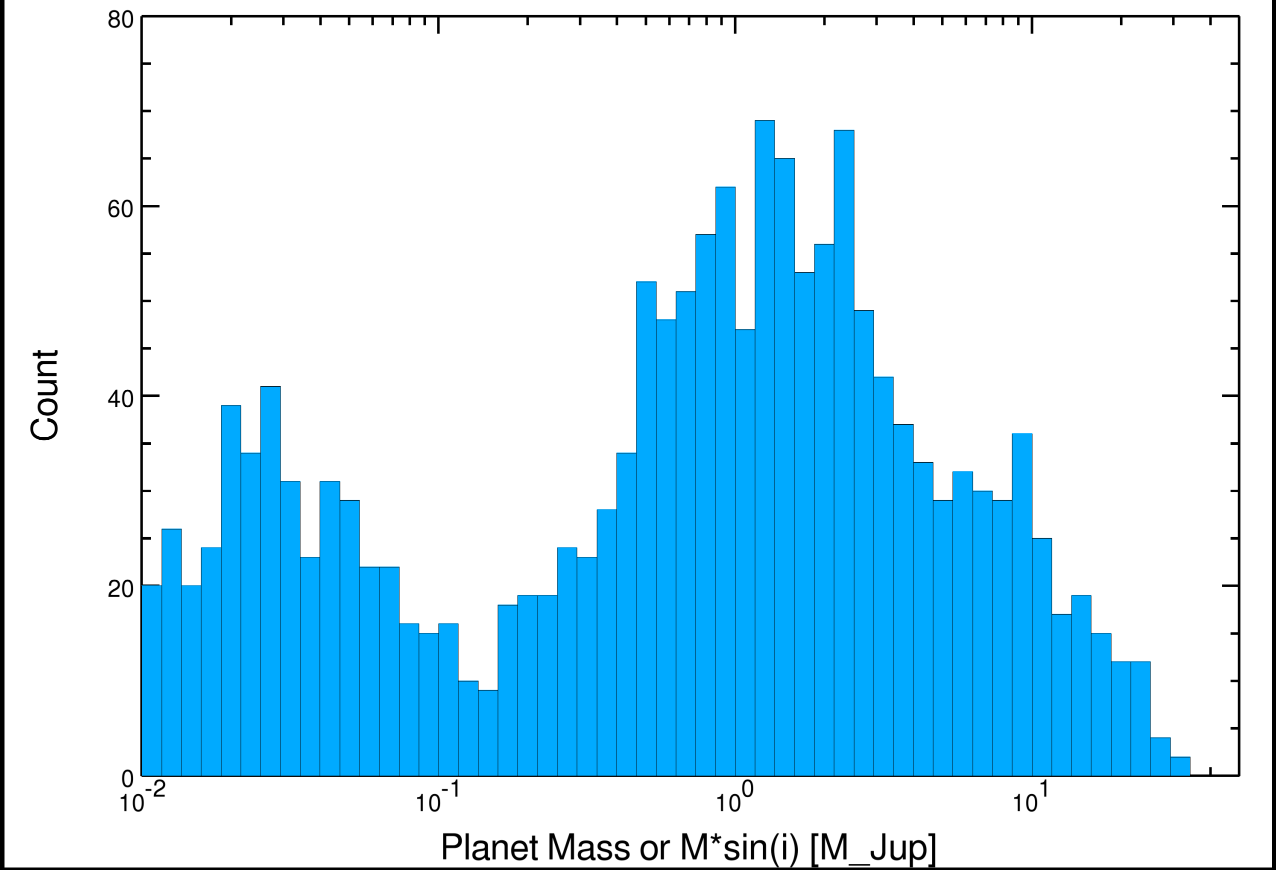
Except e=0, the eccentricity seems to be approximated by an exponential distribution

Diversity of planets: orbital period vs. mass

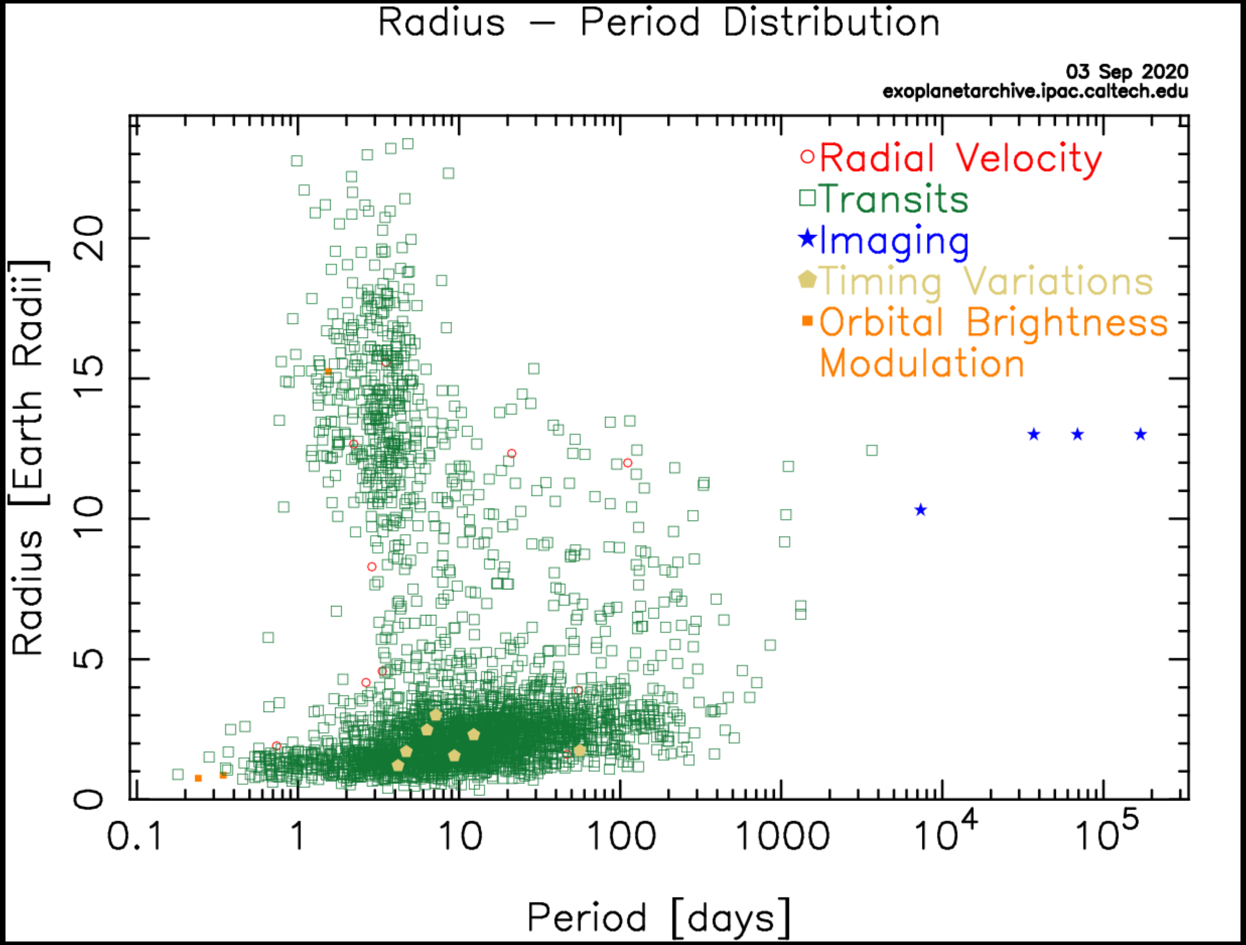


Large selection bias ?

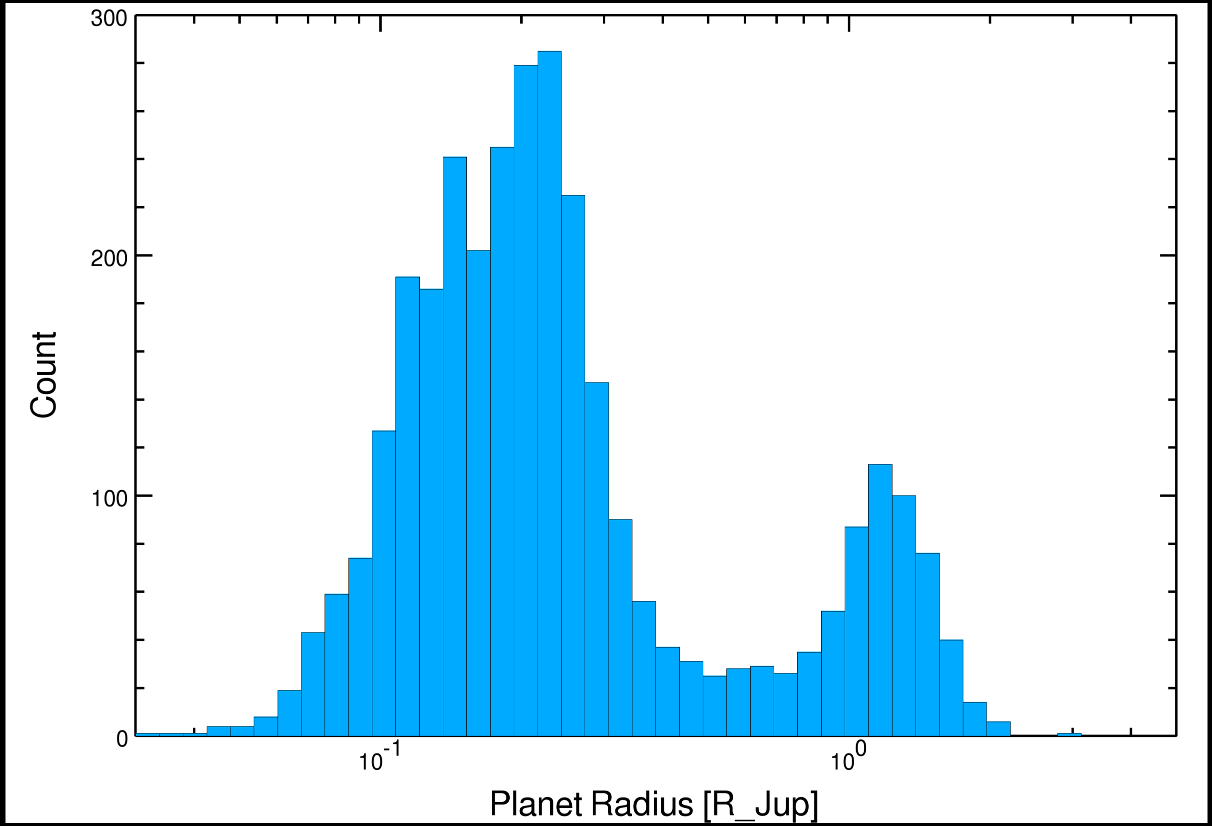
Bimodal distribution around the Jupiter and Neptune mass ?



Diversity of planets: orbital period vs. radius



Bimodal distribution around the Jupiter and Neptune radius ?



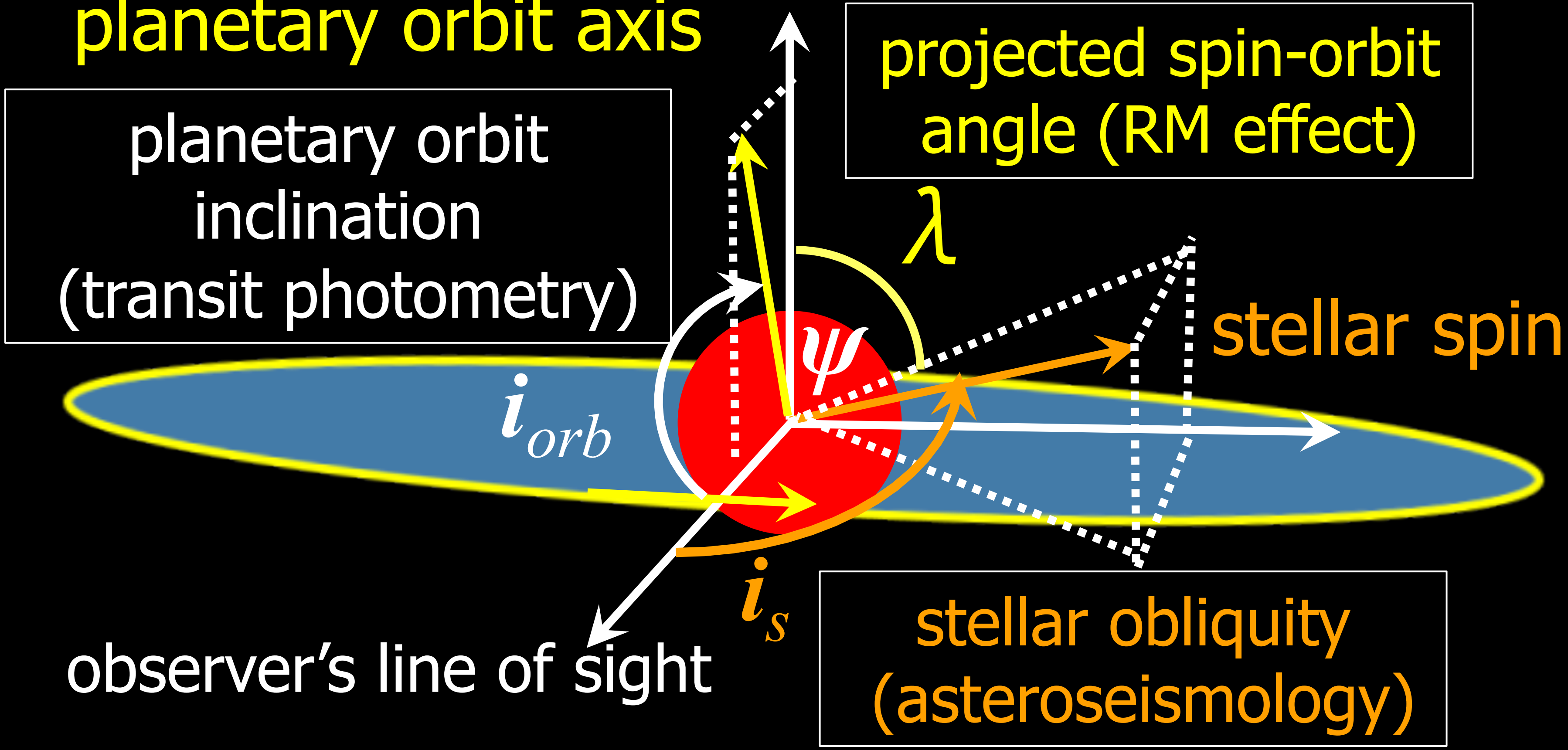
Large selection bias ?

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

Spin-orbit (mis)alignment from the Rossiter-McLaughlin effect

Spin-orbit architecture of a planetary system



planetary orbit axis

planetary orbit inclination (transit photometry)

projected spin-orbit angle (RM effect)

stellar spin

observer’s line of sight

stellar obliquity (asteroseismology)

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

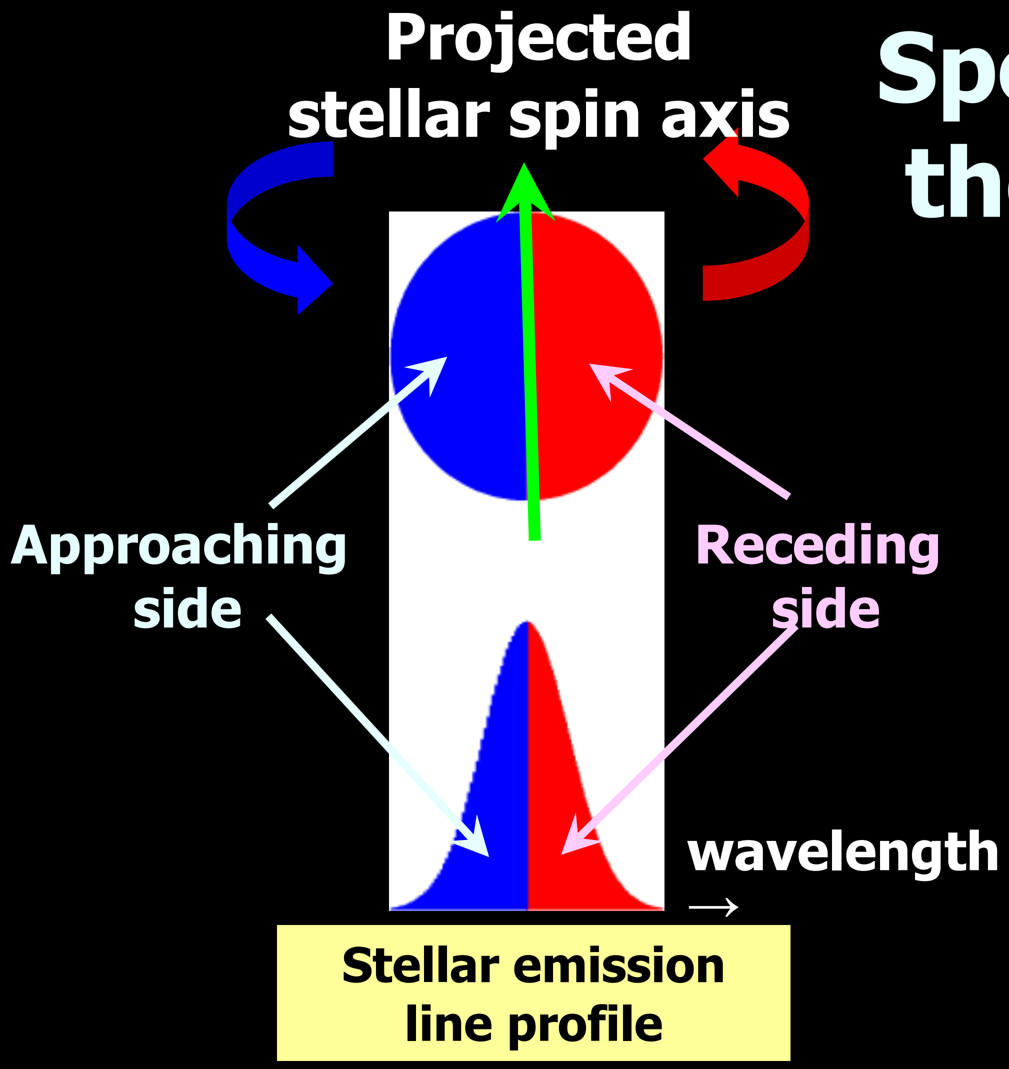
$$\cos\Psi = \sin i_s \sin i_{orb} \cos\lambda + \cos i_s \cos i_{orb}$$

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

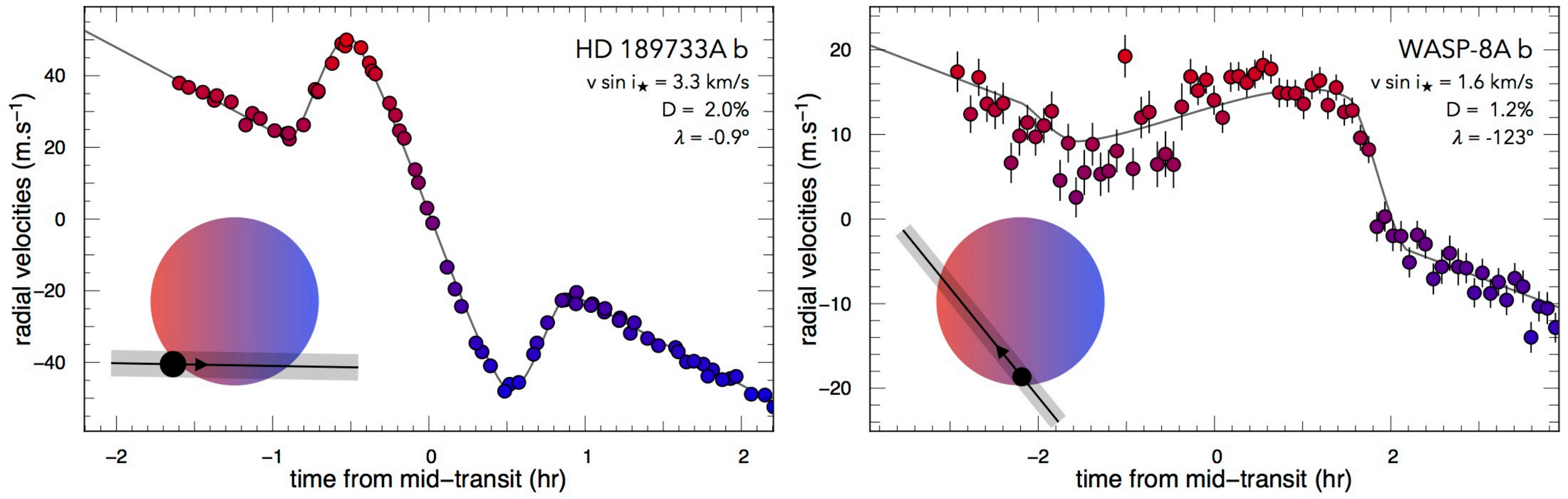


- Time-dependent asymmetry in the stellar Doppler-broadened line profile due to the planetary transit
  - apparent anomaly of the stellar radial velocity
- originally proposed for eclipsing binaries

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

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

Early results of the Rossiter-McLaughlin effect

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

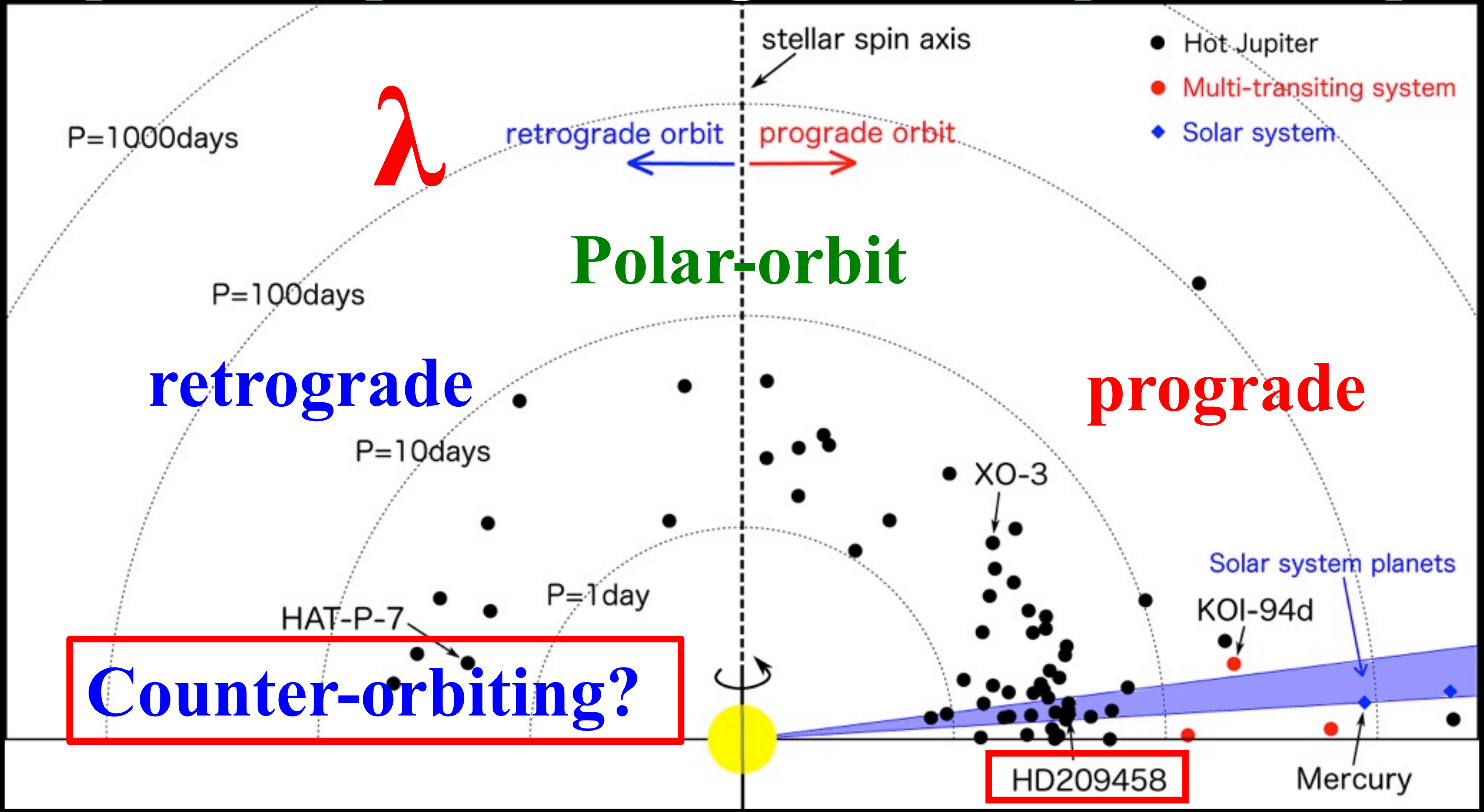
$$\alpha = \pm 3.9^{\circ}{}^{+18^{\circ}}_{-21^{\circ}}$$

- 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

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



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

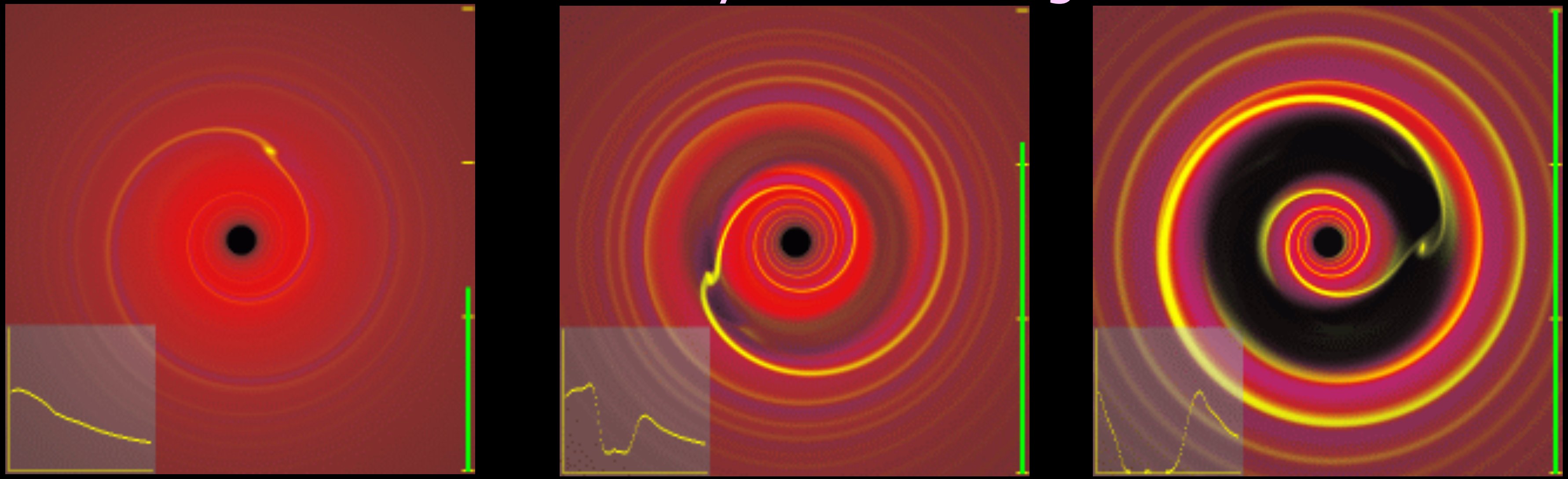
薛鈺新 Xue, Y.S., Tayura, Hirano, Fujii, and Masuda, ApJ 784(2014)66

Origin of the spin-orbit misalignment

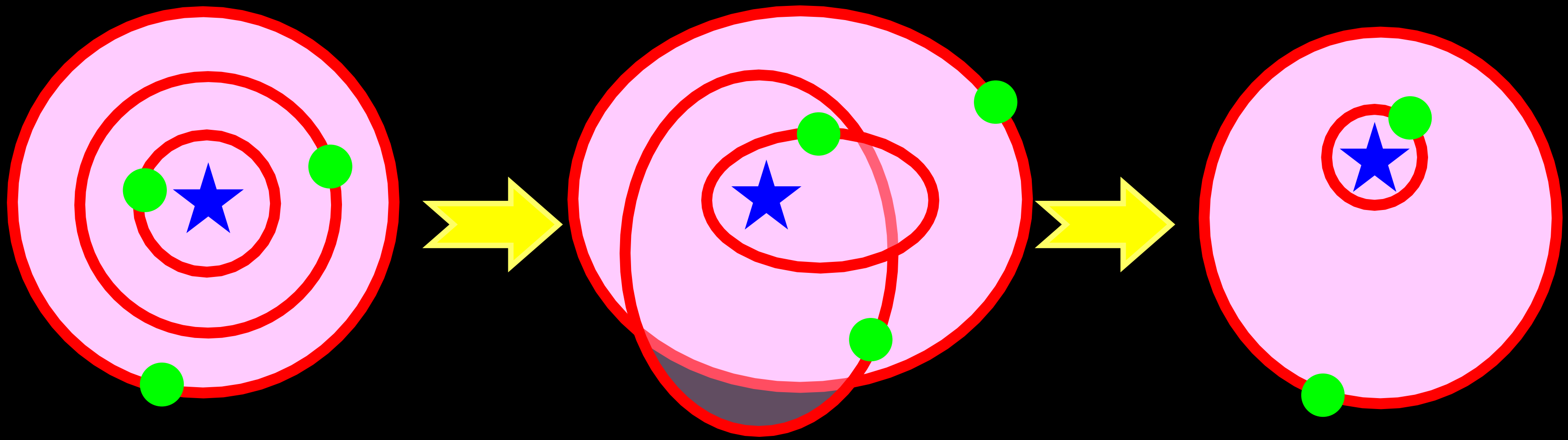
Planet migration channels

- 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



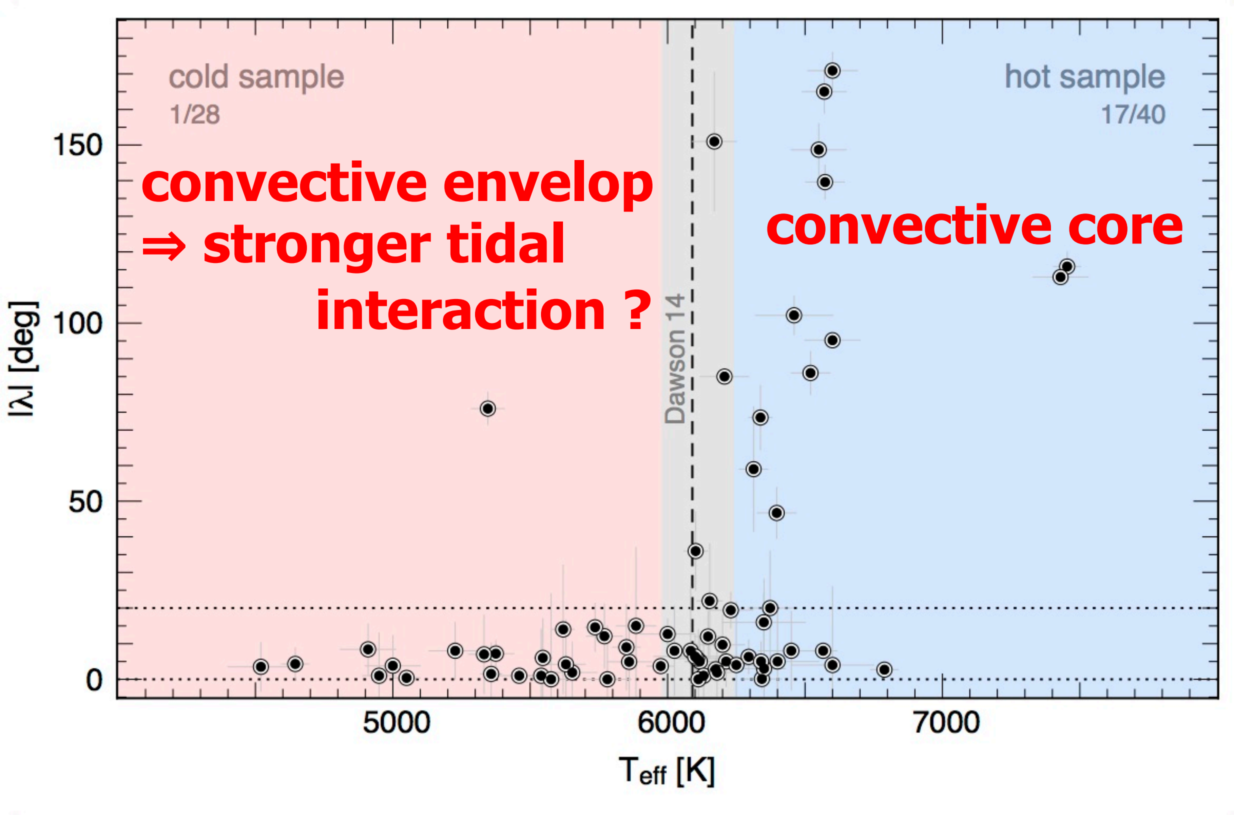
Planet-planet gravitation scattering
+ star-planet tidal interaction
= circularized and misaligned Hot Jupiters



- 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



convective envelop
⇒ stronger tidal interaction ?

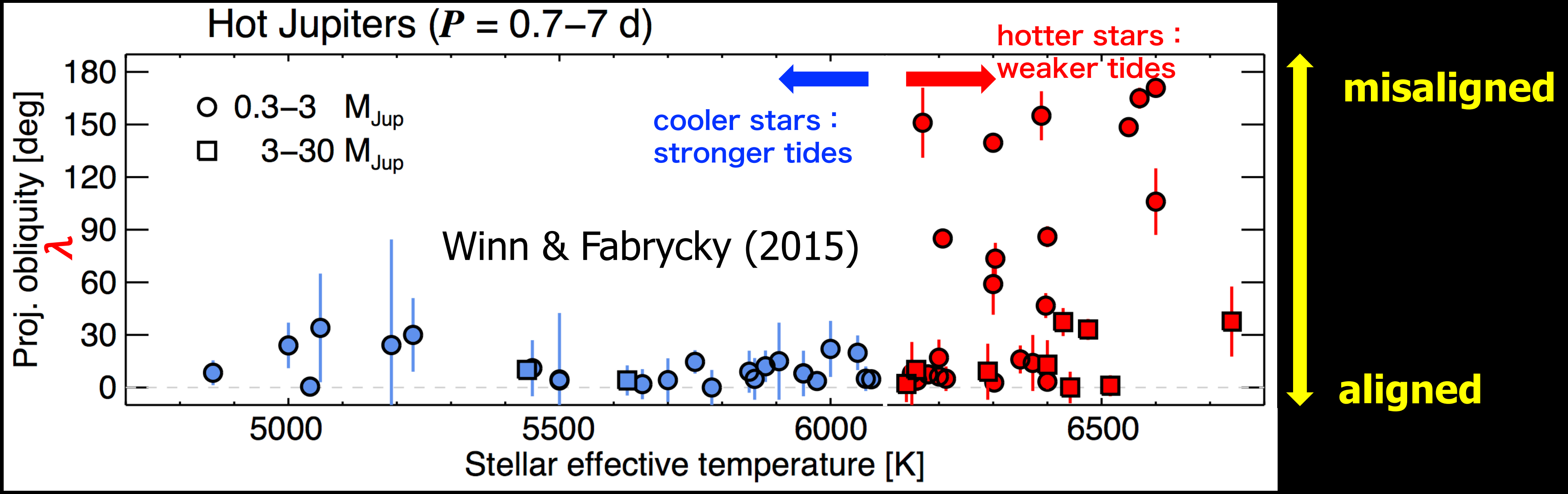
convective core

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 ?

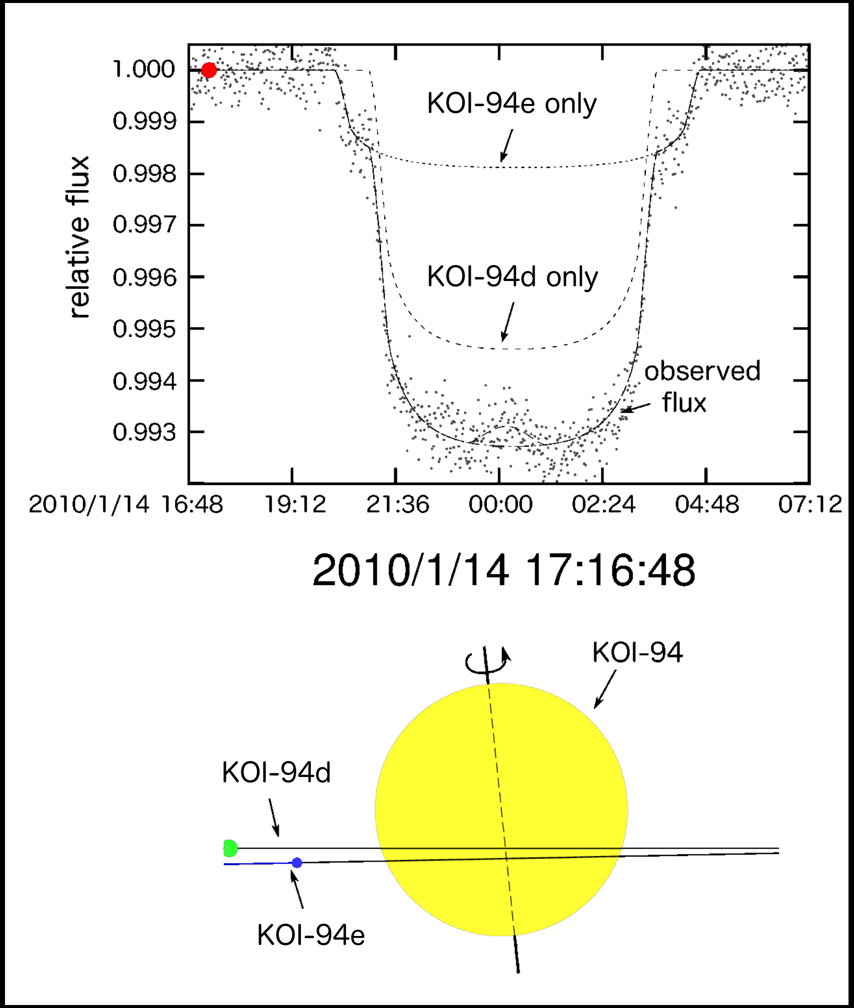
(Winn et al. 2010)

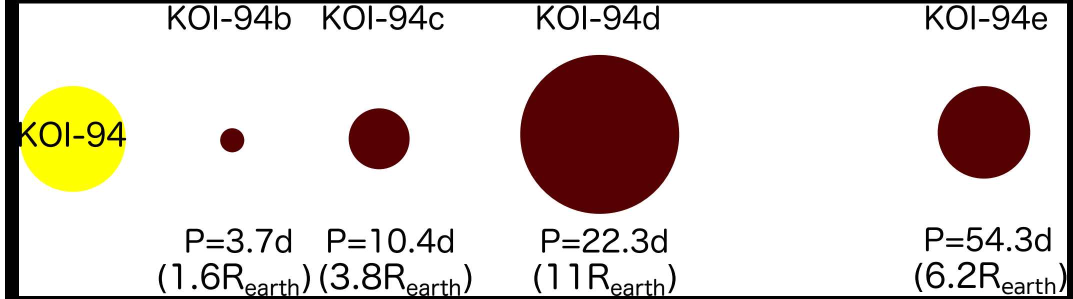
Star-orbit misalignment is more common ?



- 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



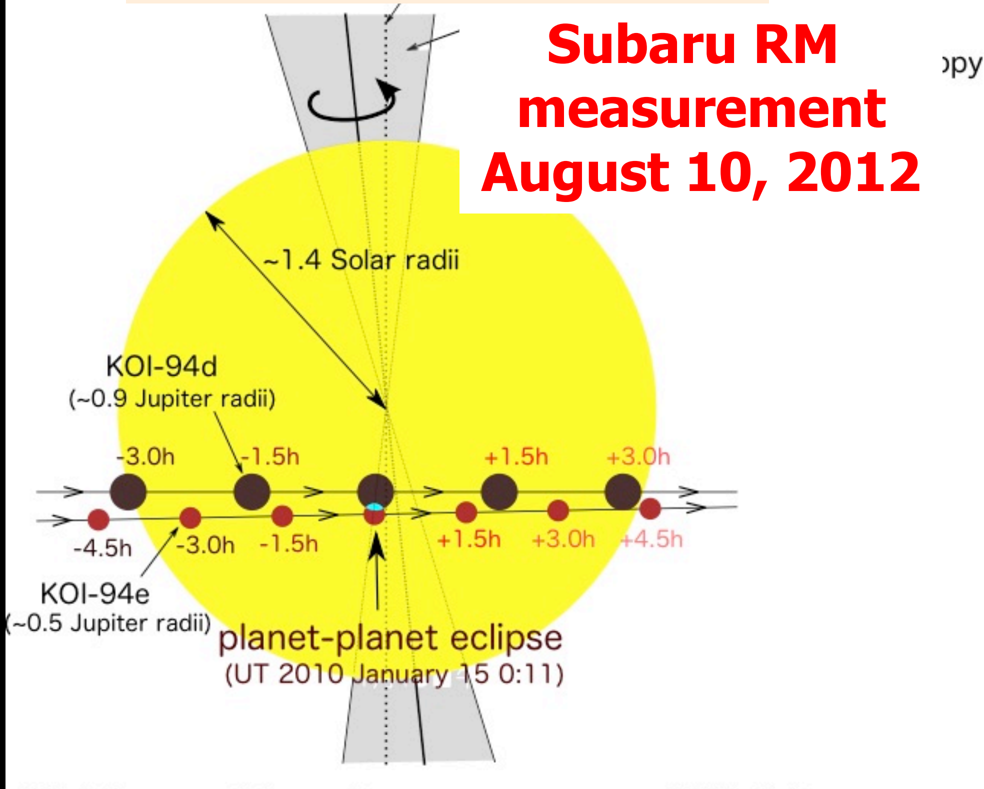


- First detection of planet-planet eclipse !
  - The orbital planes of those planets are amazingly coplanar
  - The initial architecture is supposed to be well preserved (not disturbed by subsequent dynamical evolution)
  - Its spin-orbit angle may also remember the initial value ?

Hirano et al. ApJL 759 (2012) L36

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

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



Subaru RM measurement August 10, 2012

Multi-transiting planetary system KOI-94

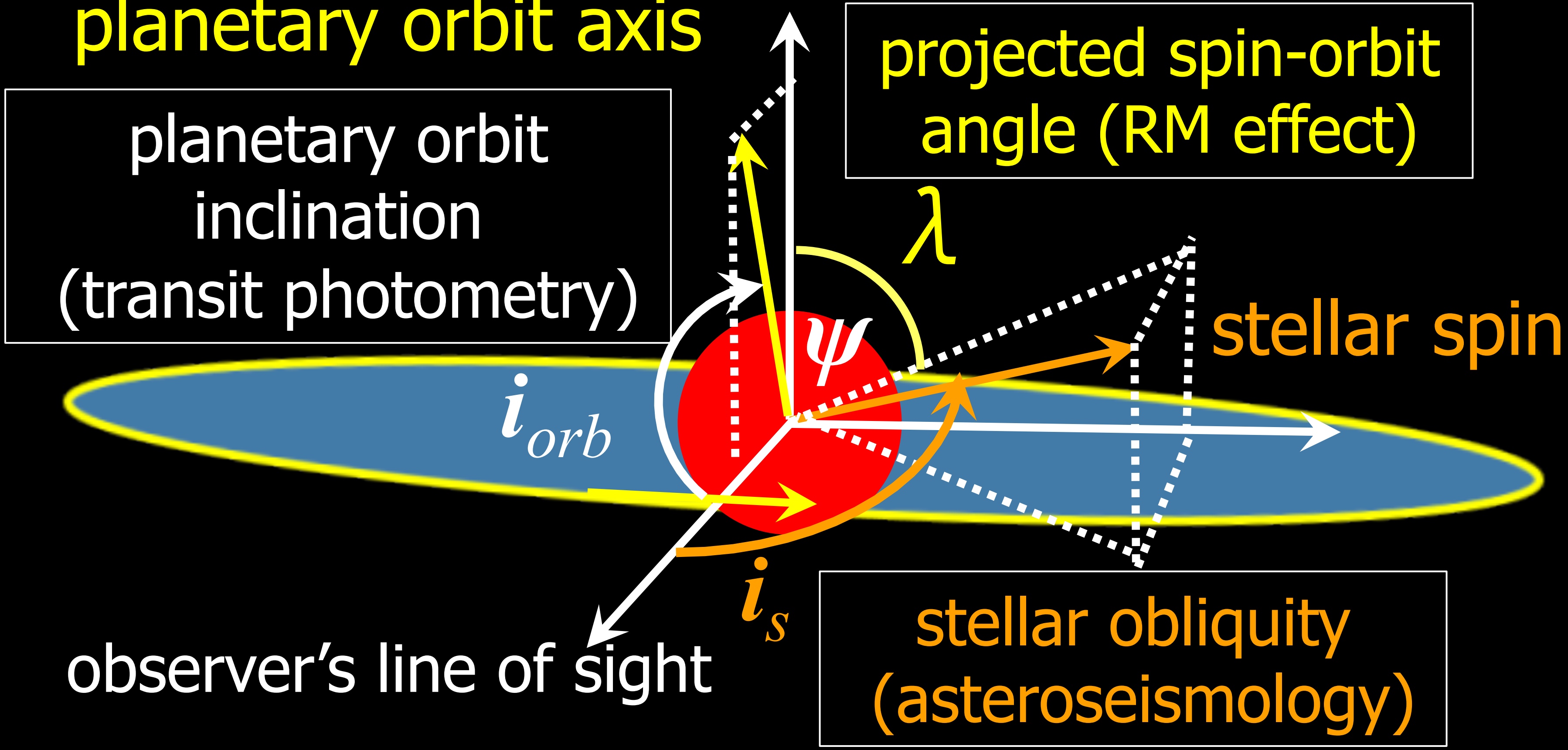
- First measurement of the RM effect for multiple-coplanar planetary systems
- Very well aligned
- The spin-orbit angle is initially well aligned, and significantly disturbed later by dynamical evolution (e.g., chaotic mutual planet-planet scattering) ?

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

増田賢人 Masuda et al. ApJ 778 (2013) 185

Spin-orbit (mis)alignment from asteroseismology

Spin-orbit architecture of a planetary system



planetary orbit axis

planetary orbit
inclination
(transit photometry)

projected spin-orbit
angle (RM effect)

stellar spin

observer's line of sight

stellar obliquity
(asteroseismology)

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

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

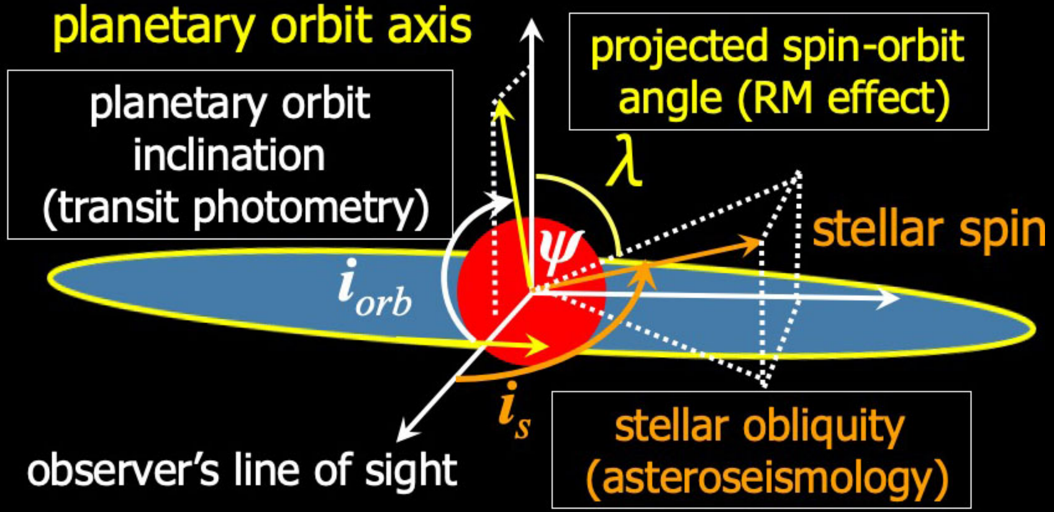
True spin-orbit angle (unobservable)

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

- 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

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

- Asteroseismology found a significantly misaligned system ($i_s=47 \pm 6^\circ$) 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)



planetary orbit axis

planetary orbit inclination (transit photometry)

projected spin-orbit angle (RM effect)

stellar spin

stellar obliquity (asteroseismology)

observer's line of sight

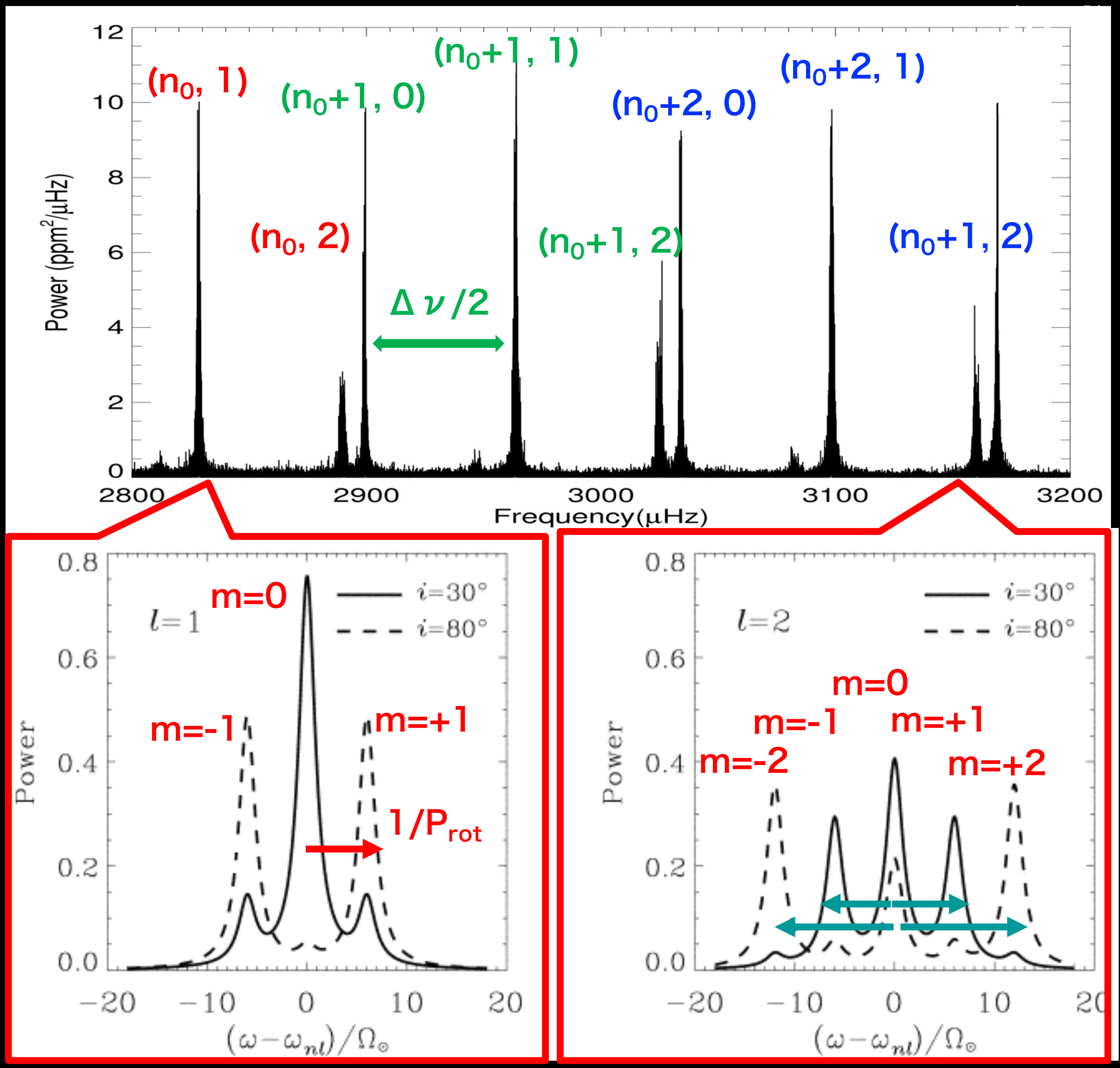
- **Primordial origin for the misalignment ?**
- **Nature vs. Nurture ?**

Asteroseismology in a nutshell

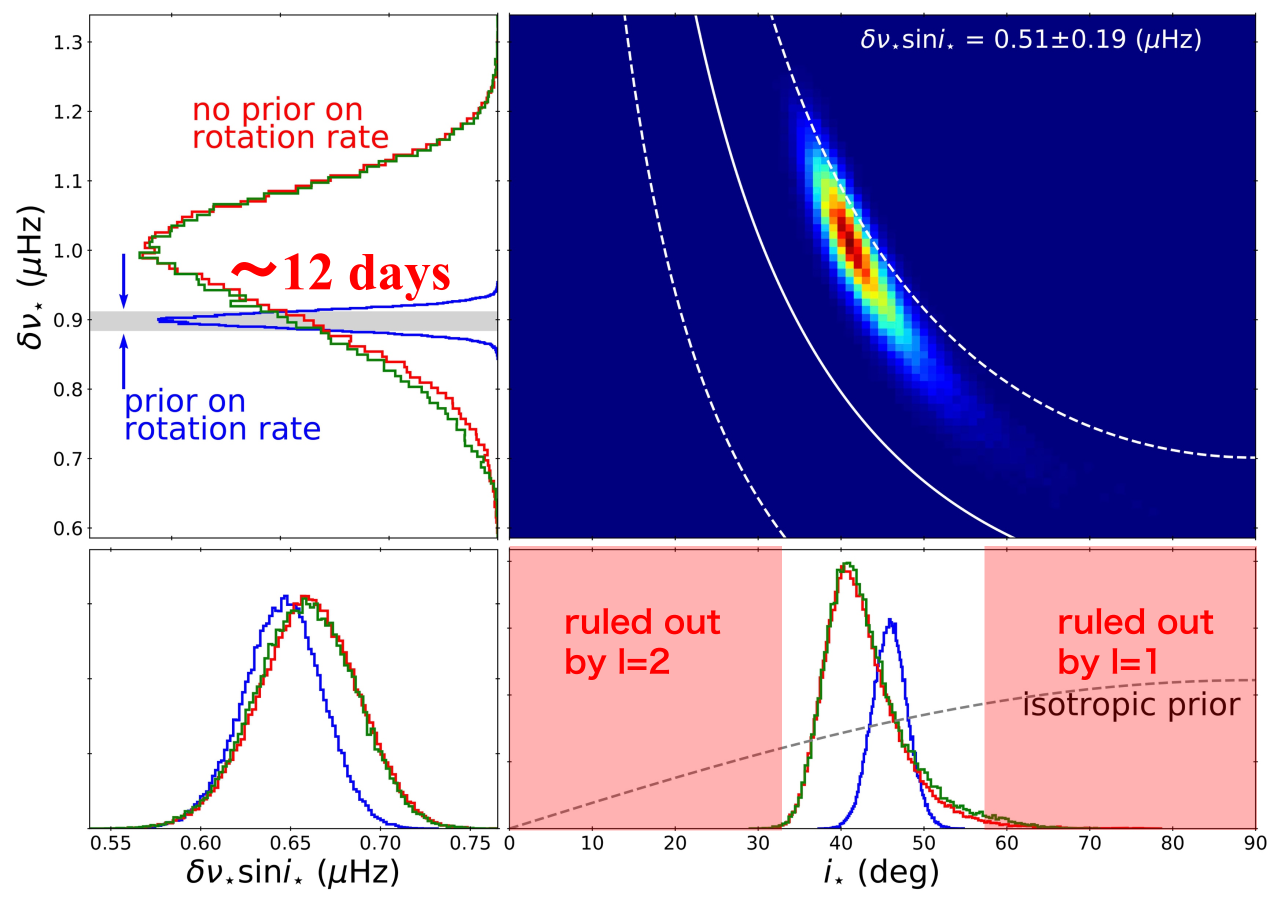
- Beating a watermelon to find a good one
  - oscillation eigen-mode analysis to understand the internal structure without destroying it
- Helioseismology- Solar neutrino puzzle
  - pp-chain reaction rate $\propto T^4$
  - neutrino deficit due to an overestimate of the internal temperature of the Sun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



Asteroseismic constraints on i_s for Kepler-408



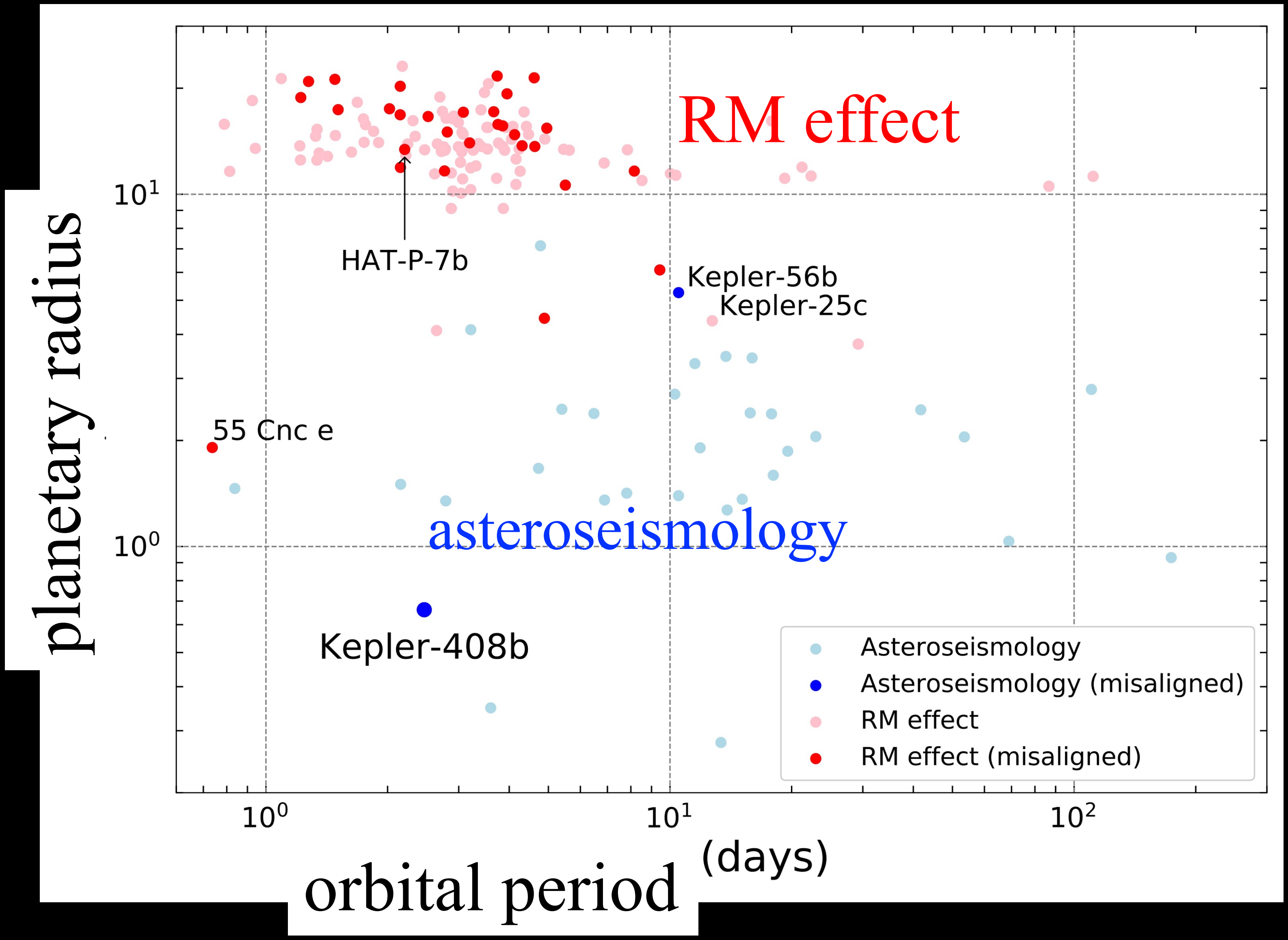
- **Kepler-408**
  - Star: 6100K, $1.05M_{sun}$, $1.25R_{sun}$
  - Planet: sub-Earth size $0.86R_E$, 2.5day orbital period

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

- Consistent with the other estimate
  - Photometric rotation period : P_{rot}
  - Doppler line broadening : $v_{rot}\sin i_\star$
- The smallest size planet in an oblique orbit

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

Complementarity between the RM effect and asteroseismology

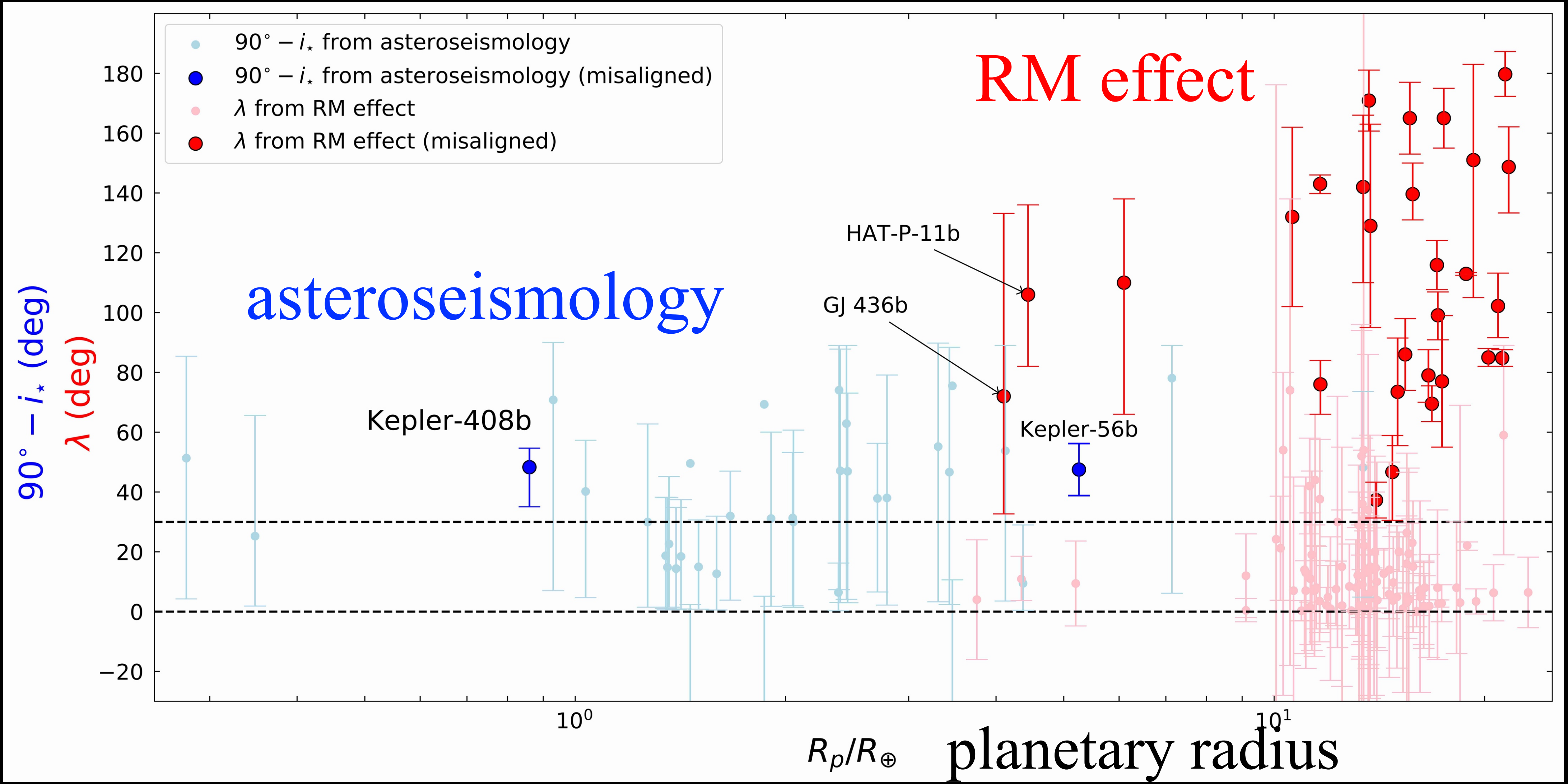


- **RM effect**
  - short-period and large planets
- **Asteroseismology**
  - independent of the properties of planets

上赤翔也

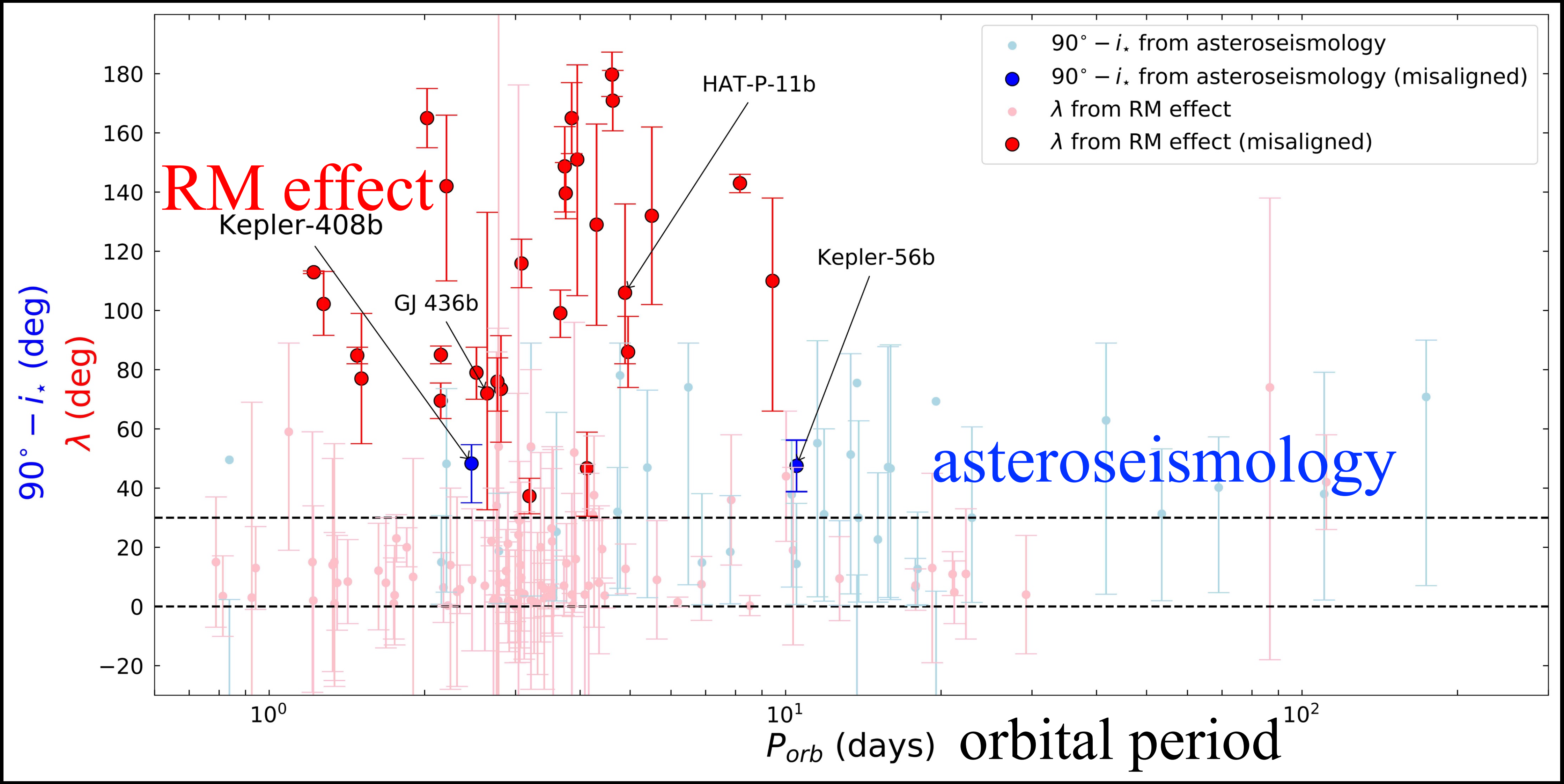
Kamiaka, Benomar & YS (2018)
Kamiaka, Benomar, YS, Dai, Masuda, & Winn (2019)
YS, Kamiaka & Benomar (2019)

Spin-orbit angles against R_p



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

Spin-orbit angles against P_{orb}



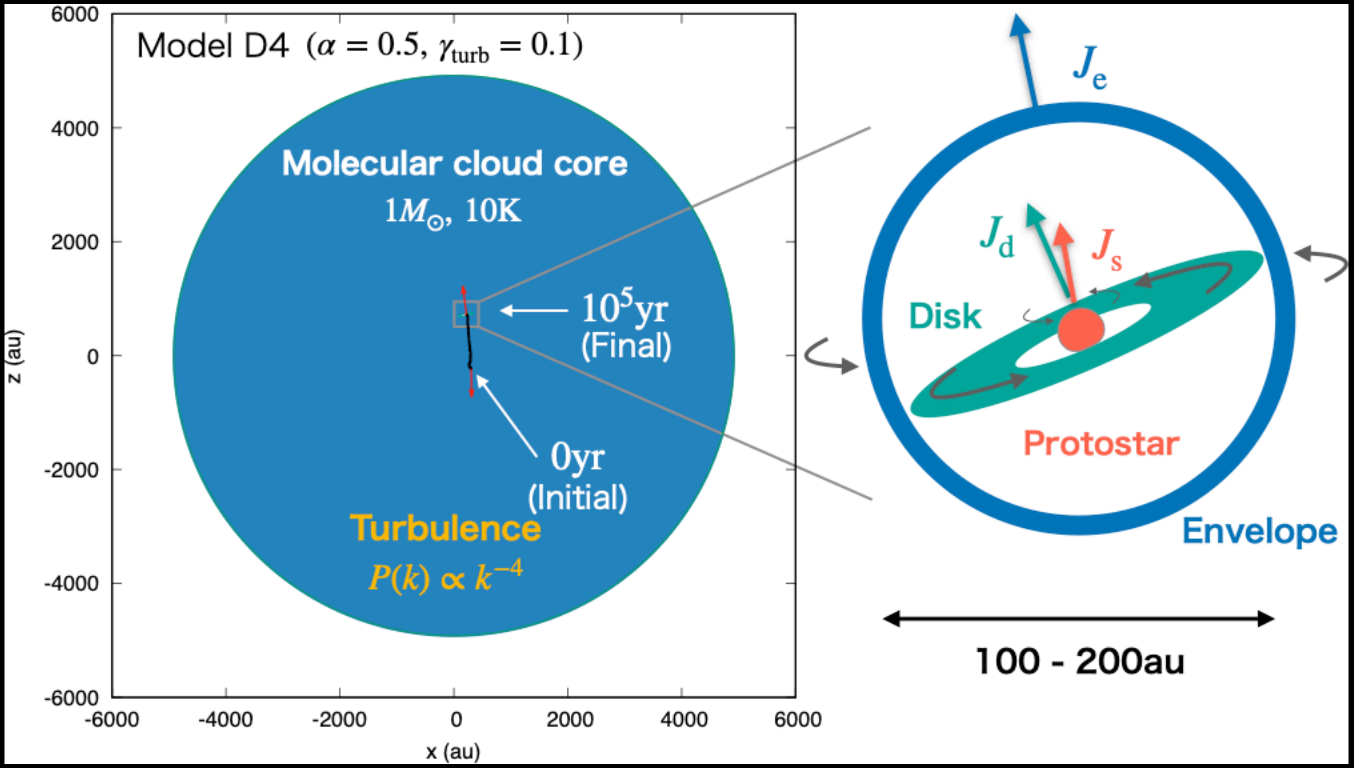
上赤翔也　Kamiaka, Benomar, YS, Dai, Masuda, & Winn, AJ 157(2019)137

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)
- Implication from the observed HL-tau system
  - Simbulan et al. (2017) MNRAS, 469, 3337
  - Wang, Kanagawa, Hayashi & YS (2020) ApJ, 891, 166; arXiv:2002.08036
    汪士杰、金川和弘、林利憲、須藤靖

Primordial star-disk alignment in turbulent molecular cloud cores

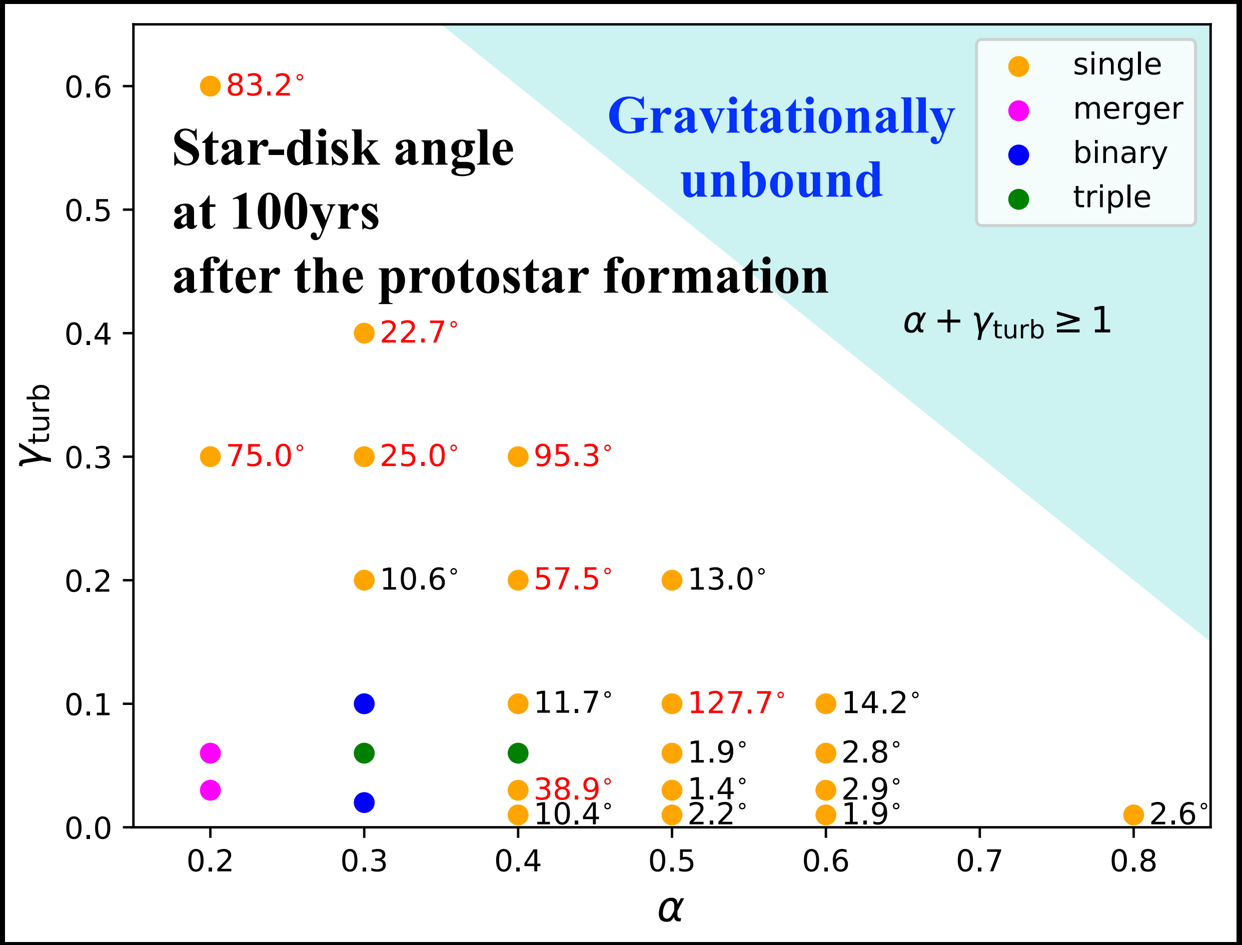


- **SPH simulation**
  - 1million SPH particles + sink particle method to approximate protostars
  - isothermal turbulent cloud cores of $1M_{\rm sun}$
  - neglect magnetic field

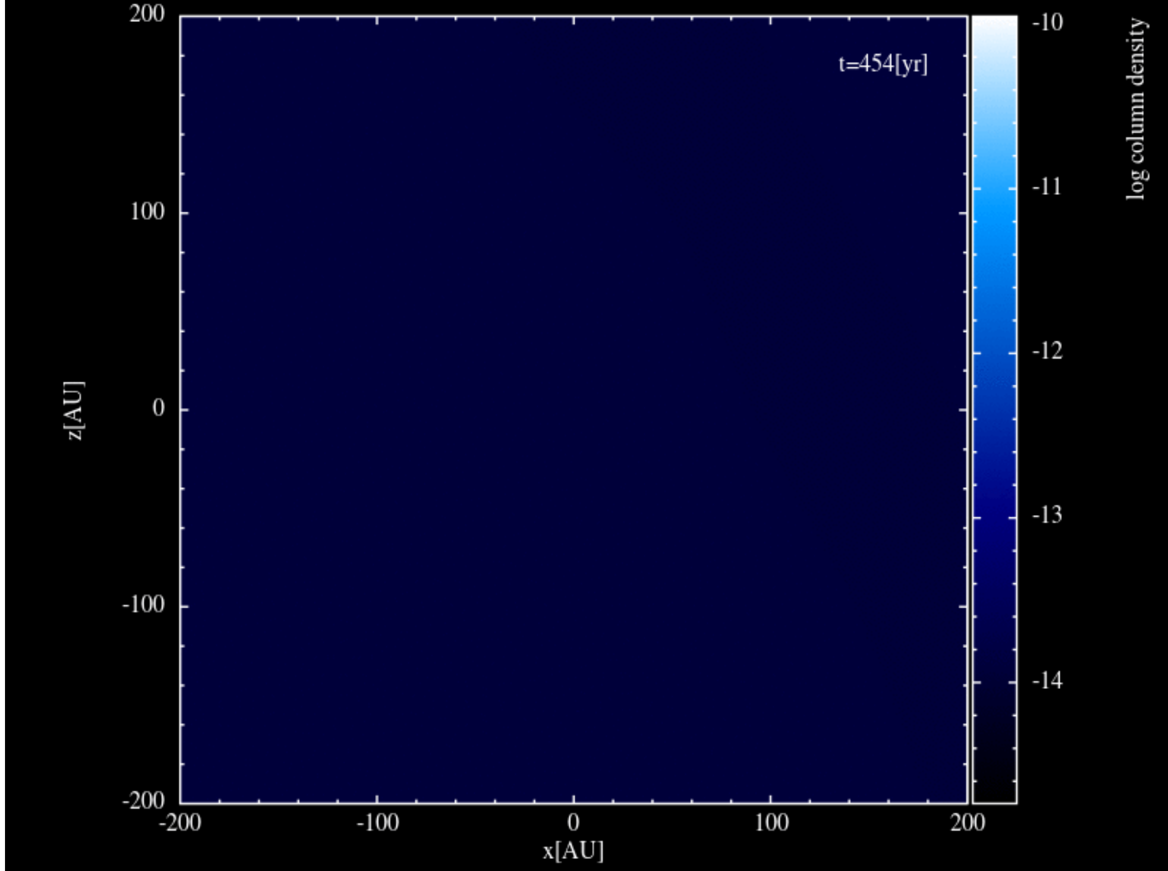
Takaishi, Tsukamoto + YS (2020) MNRAS 492, 5641
高石大輔
arXiv:2001.05456

Initial star-disk (mis)alignment angles

Turbulence energy/Gravitational energy

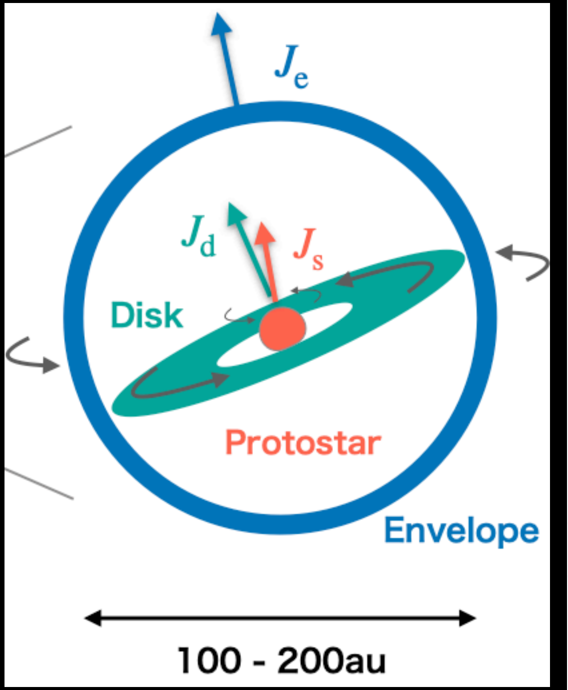


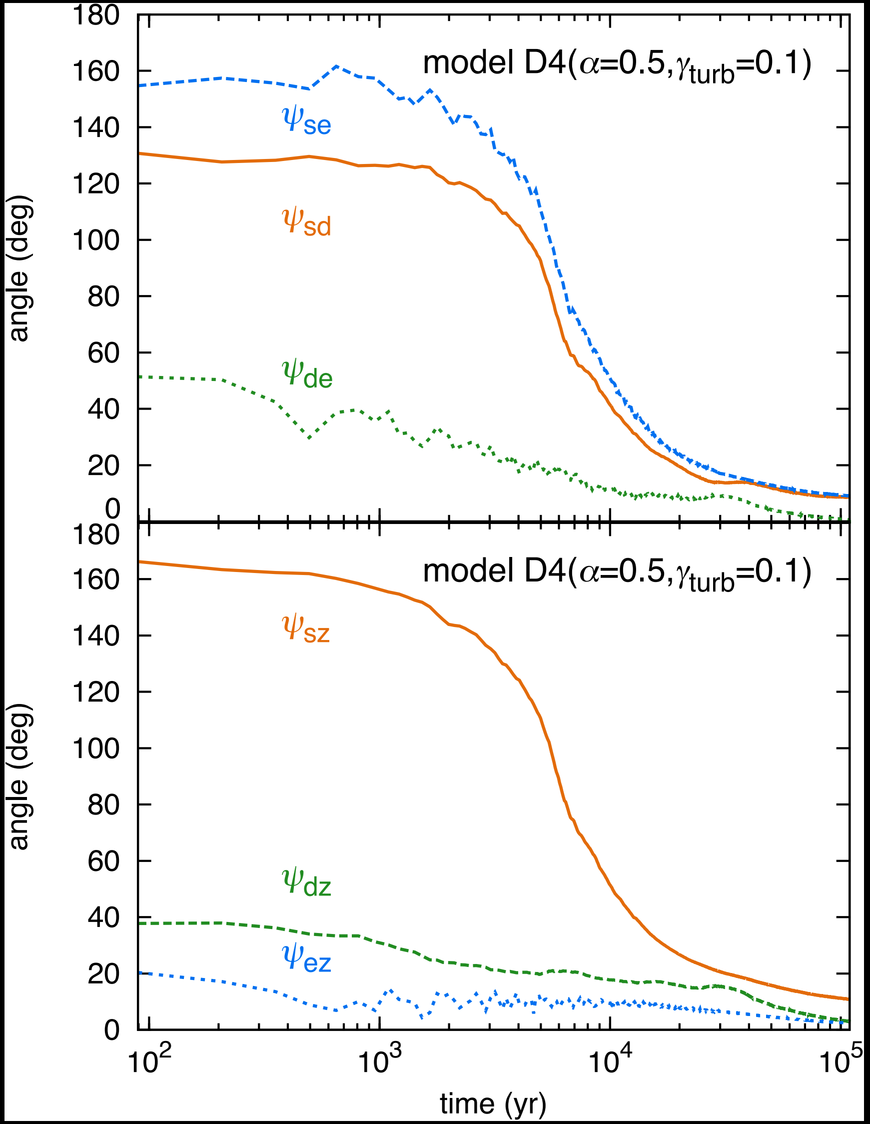
Thermal energy/Gravitational energy



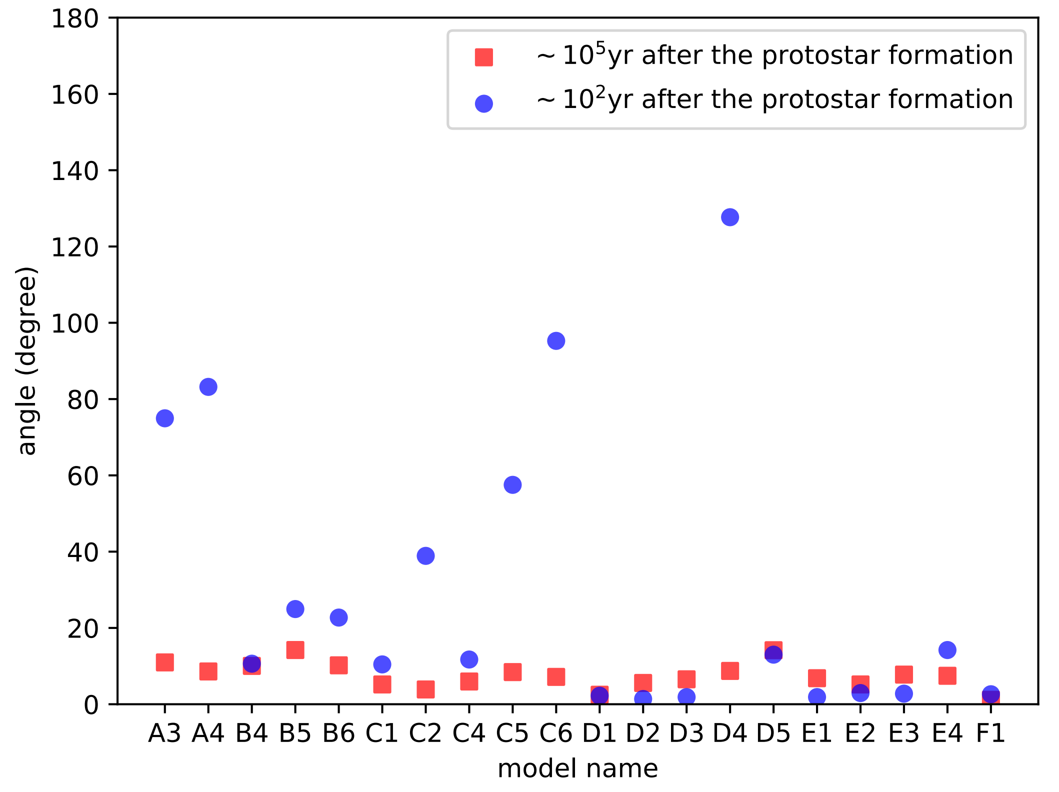
Takaishi, Tsukamoto + YS (2020)

Protostar and disk tend to be aligned!



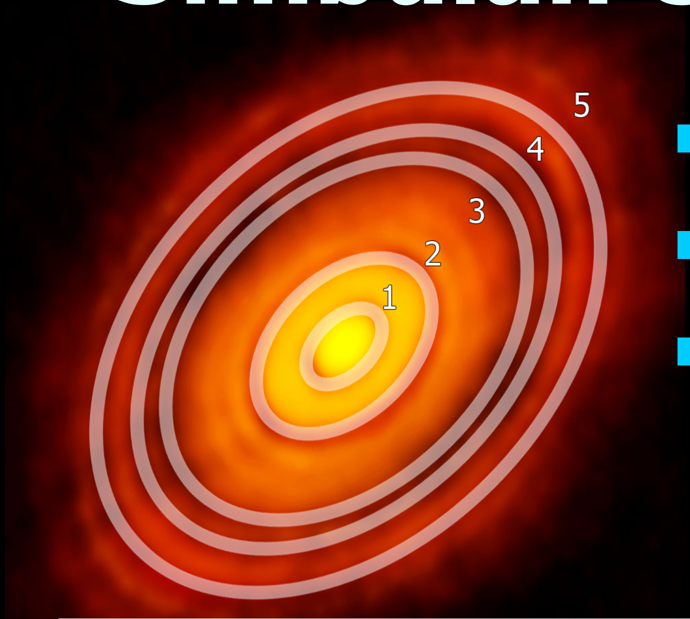


Primordial star-disk angles are less than 20 degrees



Takaishi, Tsukamoto + YS (2020)

Simbulan et al. MNRAS 469(2017)3337



- Multi-planets allocated at the observed gaps
- Intentionally start with unstable configurations
- Significant misalignments due to gravitationally chaotic planet-planet scattering

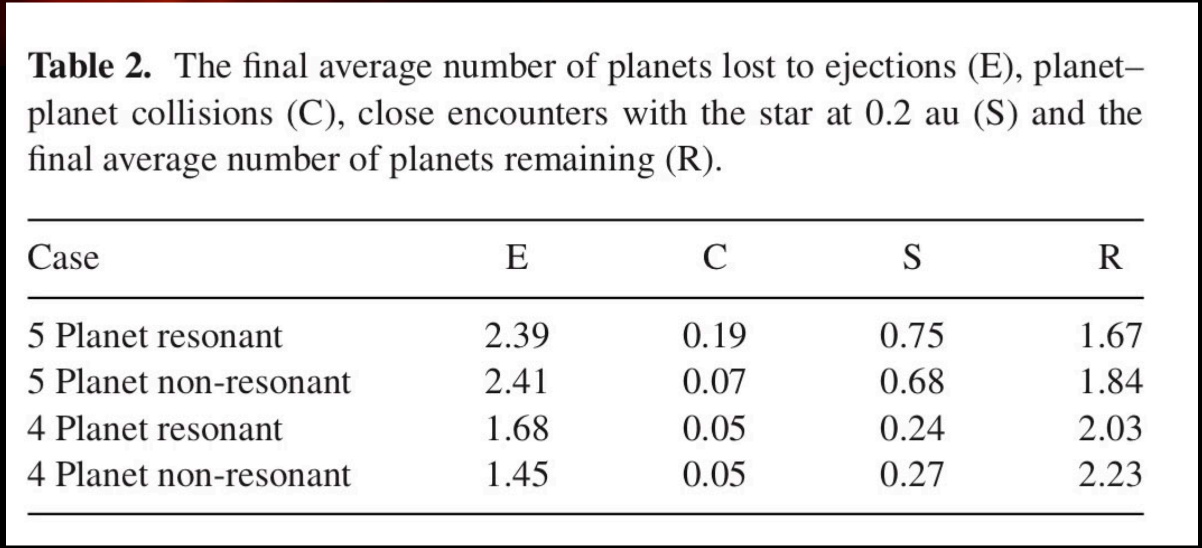
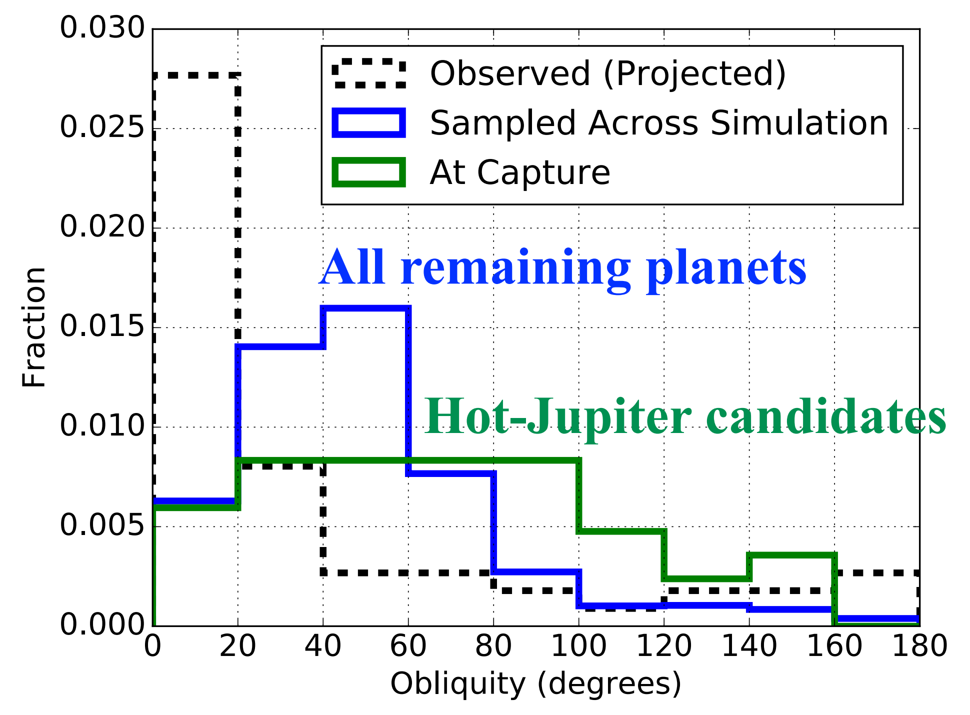


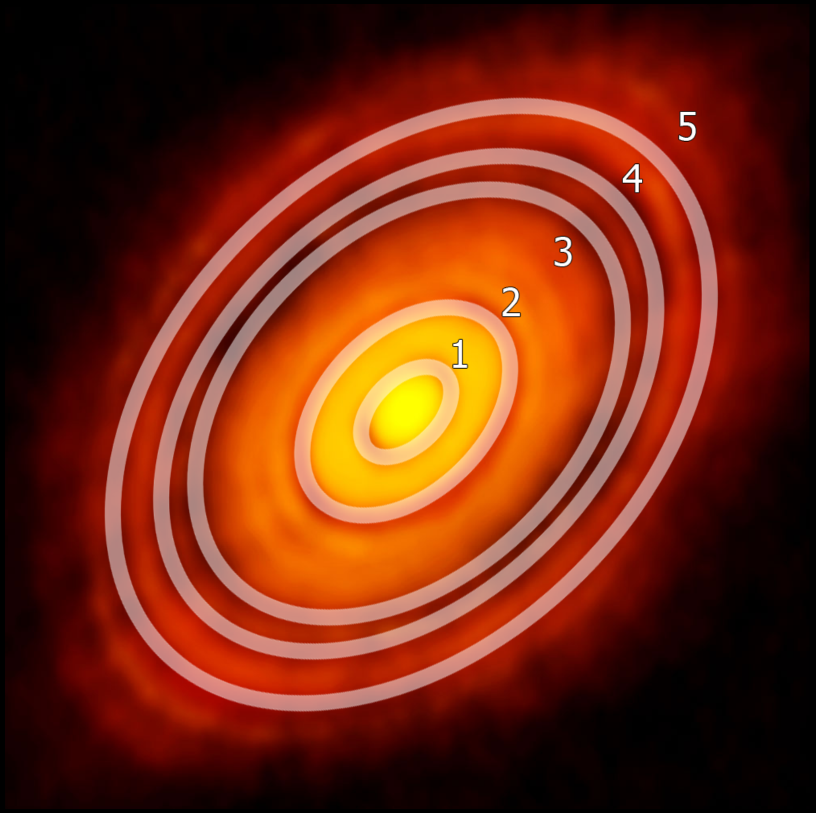
Table 2. The final average number of planets lost to ejections (E), planet–planet collisions (C), close encounters with the star at 0.2 au (S) and the final average number of planets remaining (R).

Case	E	C	S	R
5 Planet resonant	2.39	0.19	0.75	1.67
5 Planet non-resonant	2.41	0.07	0.68	1.84
4 Planet resonant	1.68	0.05	0.24	2.03
4 Planet non-resonant	1.45	0.05	0.27	2.23



Improved disk-planet migration model

- Empirical Type I and II migration models calibrated by 2D hydro-simulation (Kanagawa et al. 2018)
- Initially 3 planets are located at the major three gaps (1, 2, and 4) in the HL tau disk (Dipierro et al. 2015, Jin et al. 2016, Dong et al. 2017, 2018)
- 70 out of 75 simulated runs are stable
- chaotic orbital evolution is rare, at least for HL tau



汪士杰 Wang, Kanagawa, Hayashi & YS (2020) ApJ 891, 166

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
- Misalignment remains as a challenging puzzle
  - 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