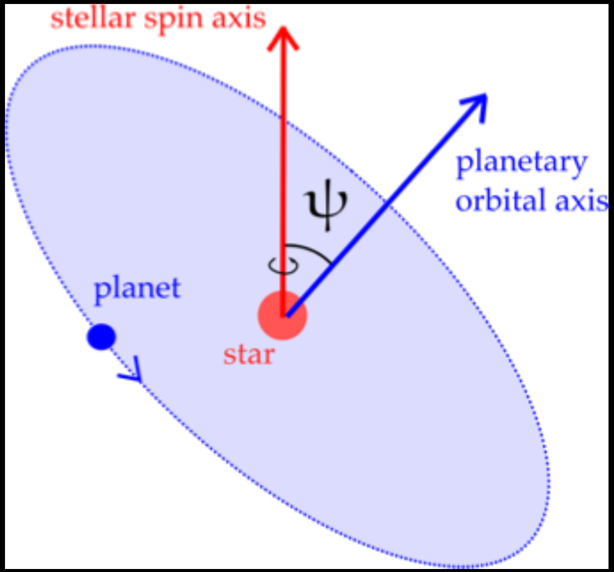
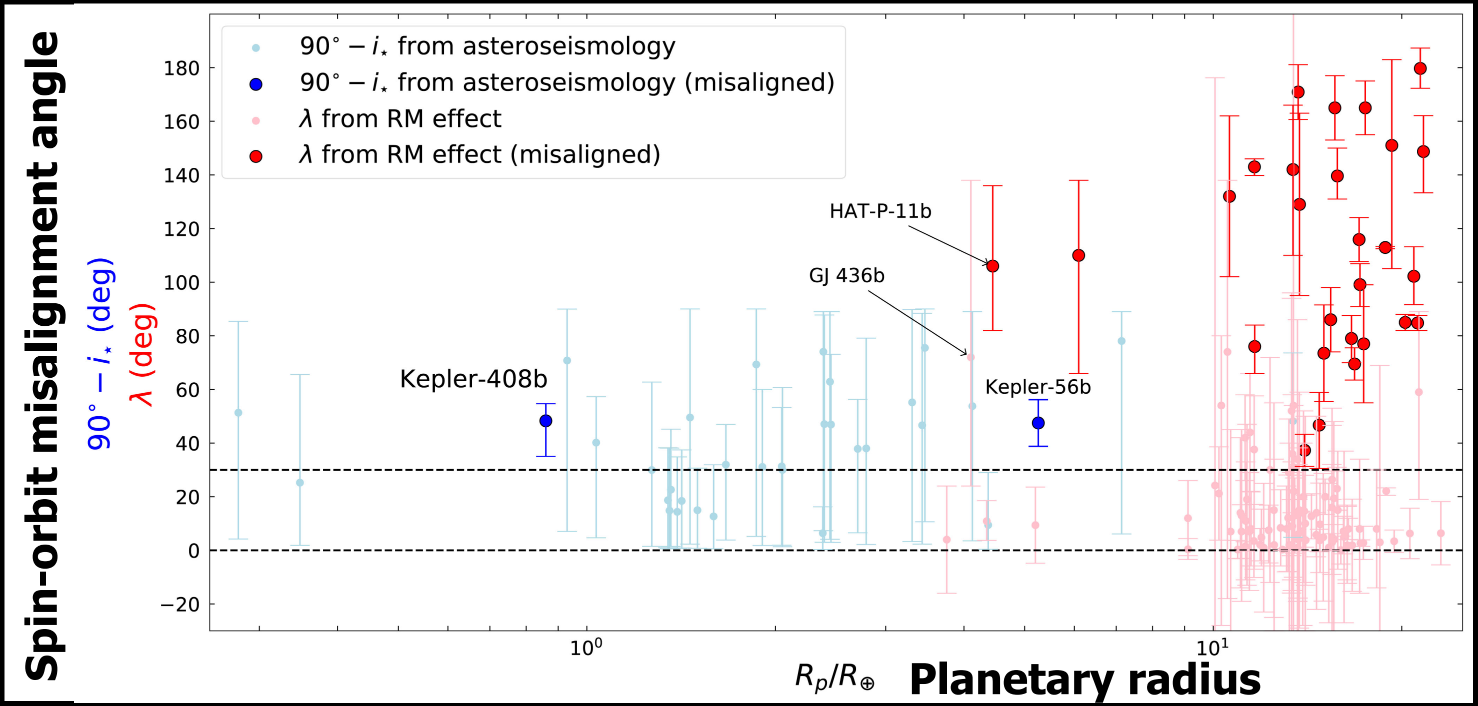
Origin and evolution of spin-orbit architectures of exoplanetary systems





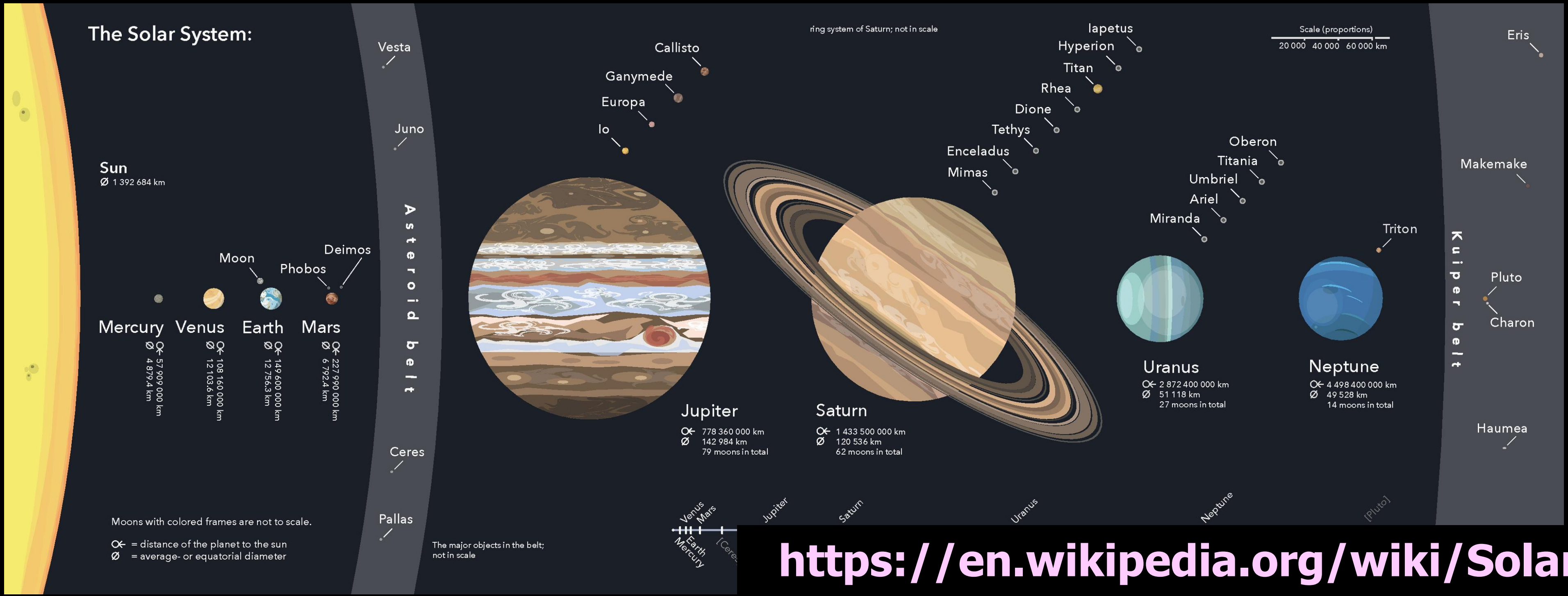
Yasushi Suto

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

16:30-17:30 January 29, 2019, JAXA seminar@ISAS, Sagamihara

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 fairly common
  - A planet with life and (advanced) civilization

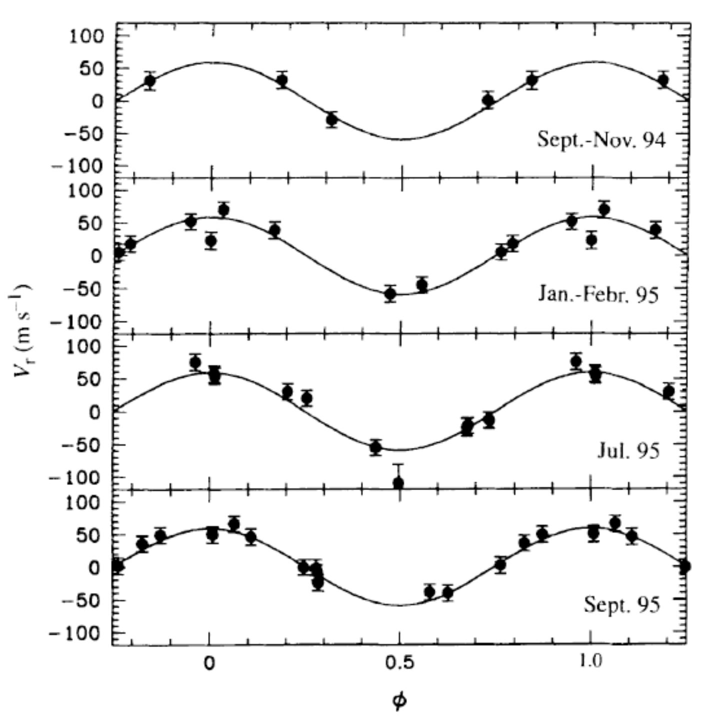
Surprising diversity of exoplanetary systems

A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz **Nature 378(1995)355**

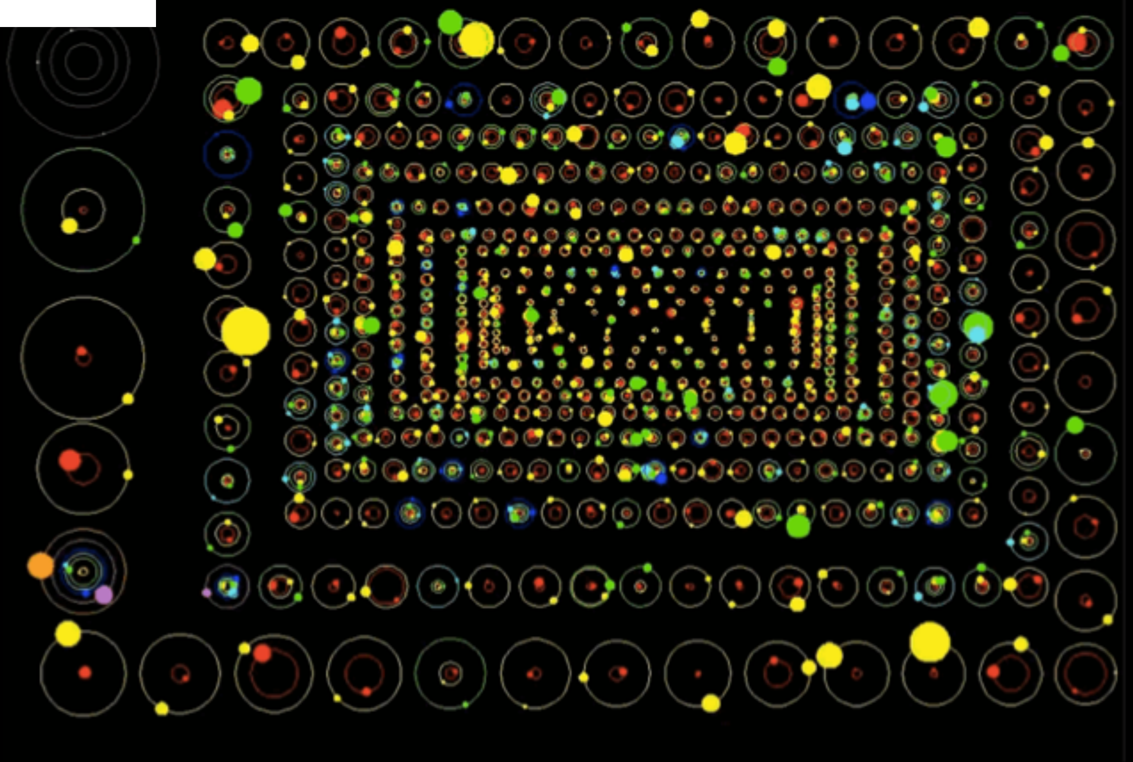
Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

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.



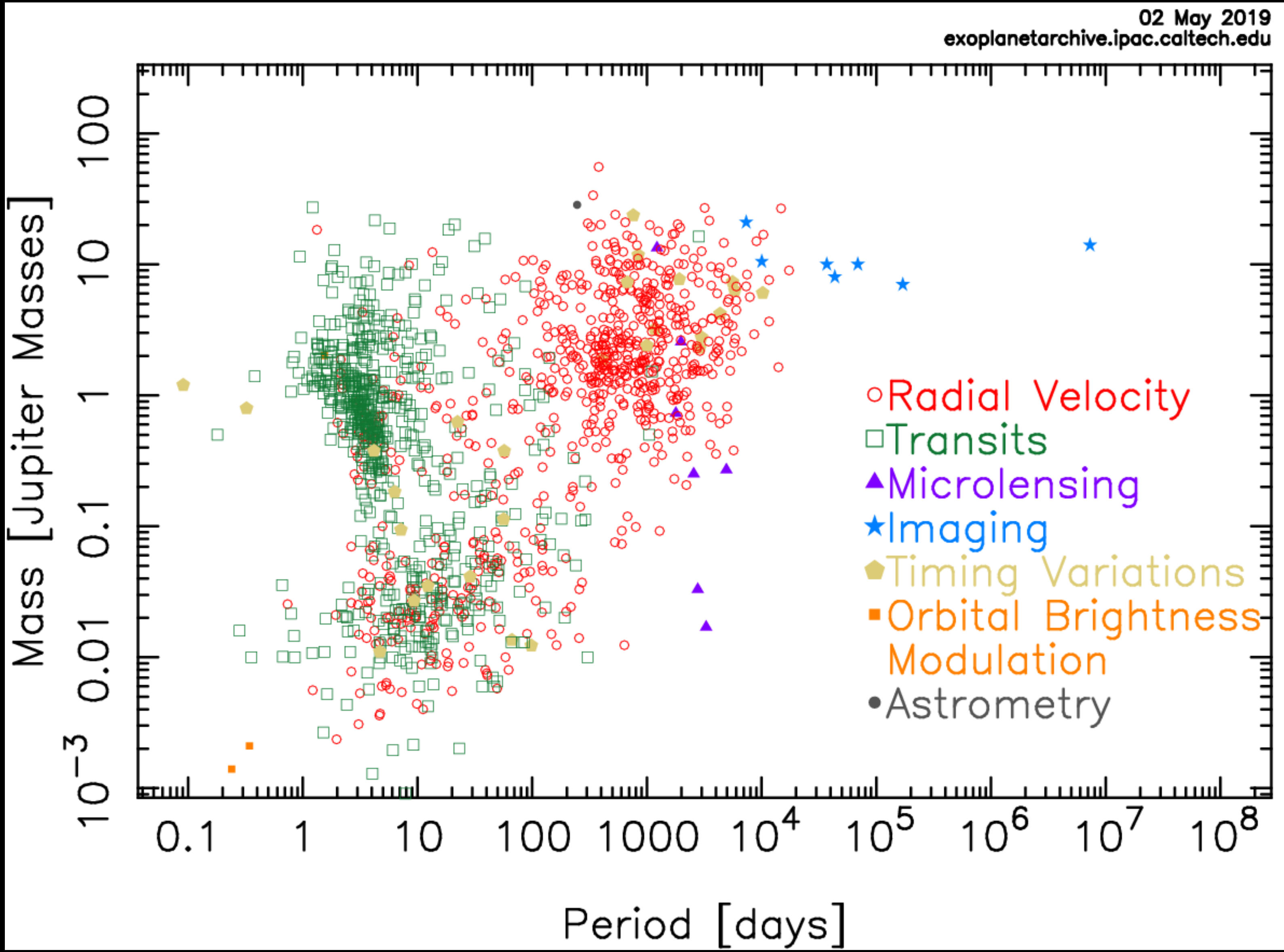
The first detected exoplanet around a Sun-like star 51Peg b (P_{orb}=4.2days)

Kepler planets (August 3, 2015)
NASA/Daniel Fabrycky

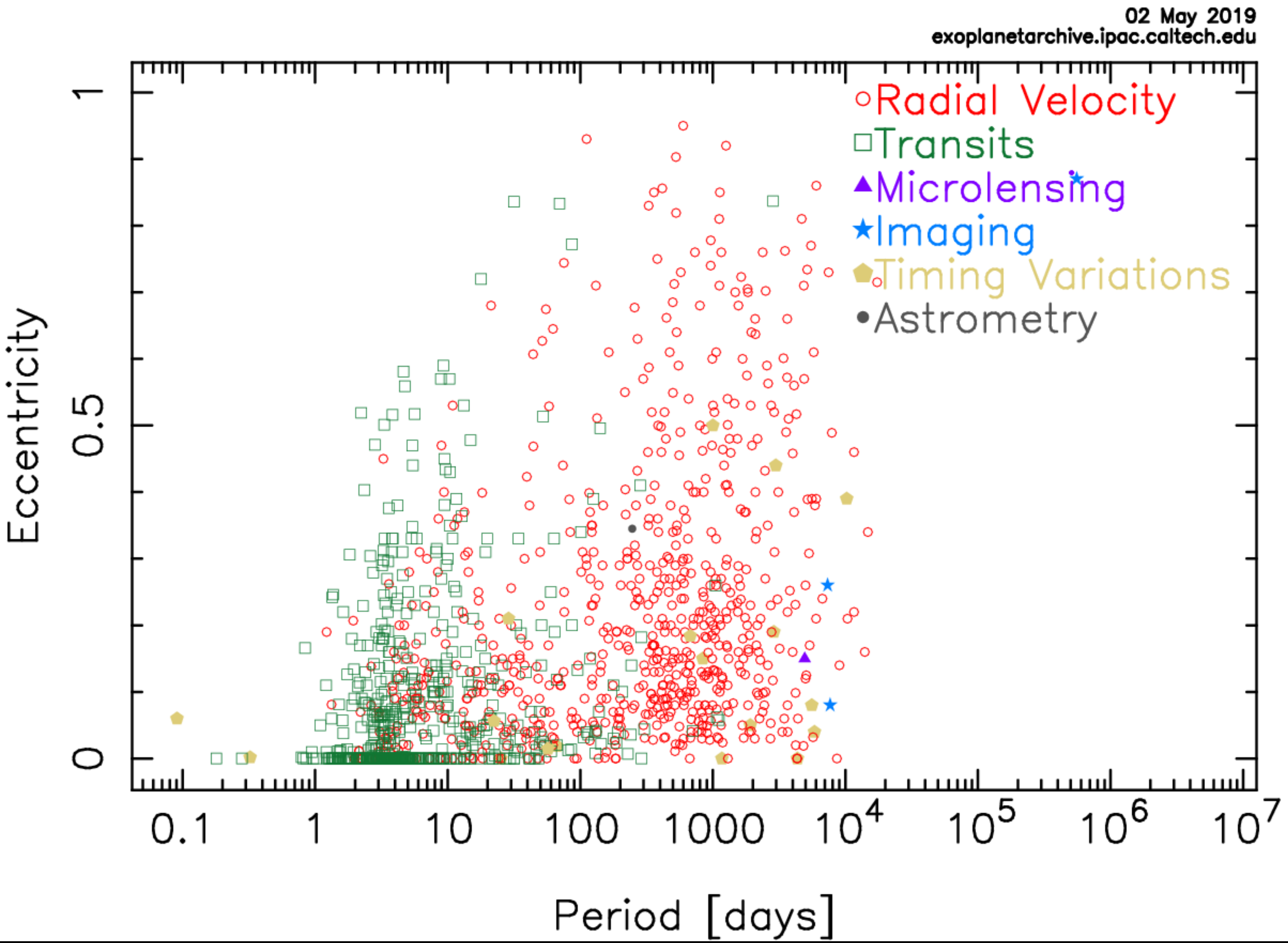


https://solarsystem.nasa.gov/resources/311/kepler-orrery-iii/

Diversity of planets: orbital period vs. mass



Diversity of planets: orbital period vs. eccentricity

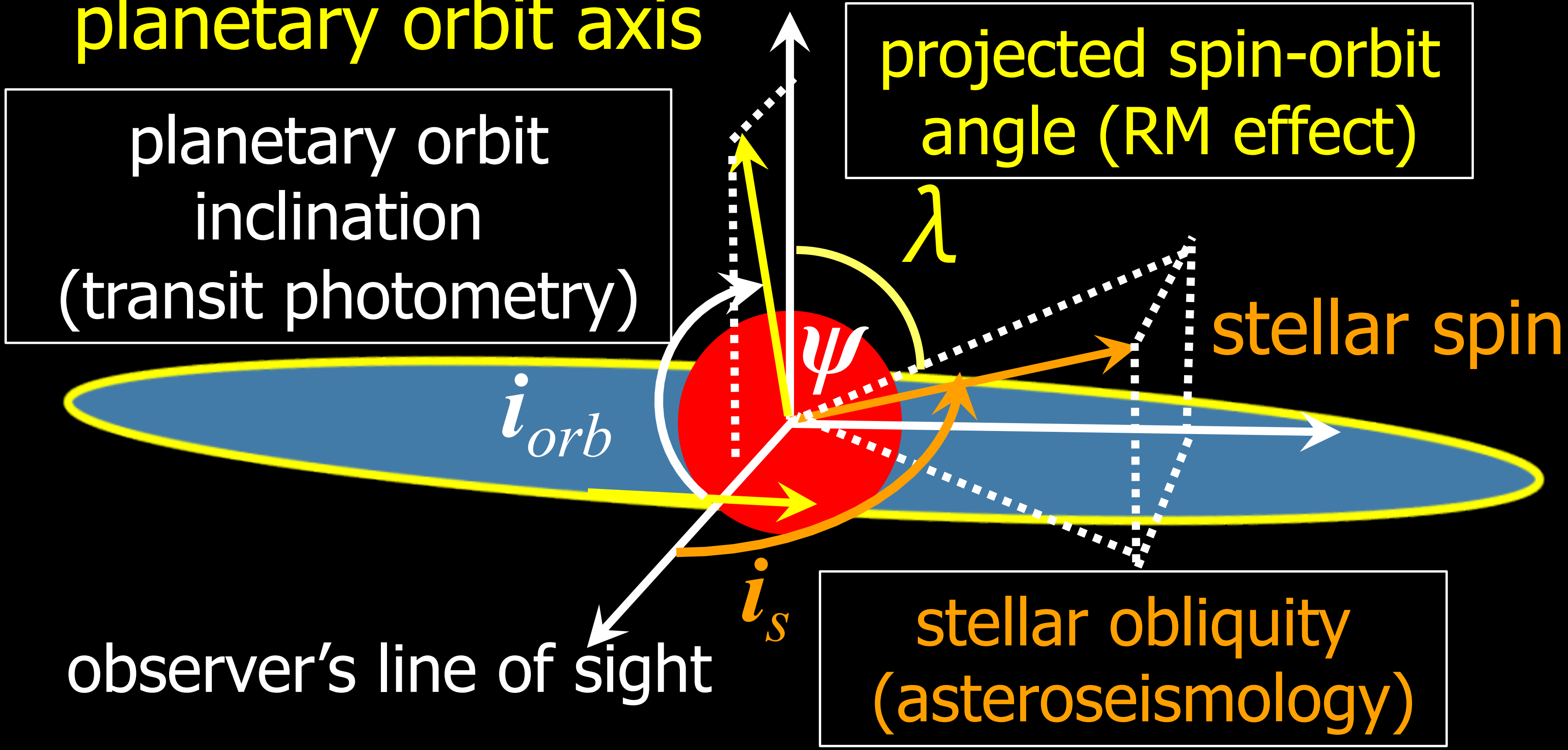


What we have learned so far

- Planets exist universally
  - Around 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
  - 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



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

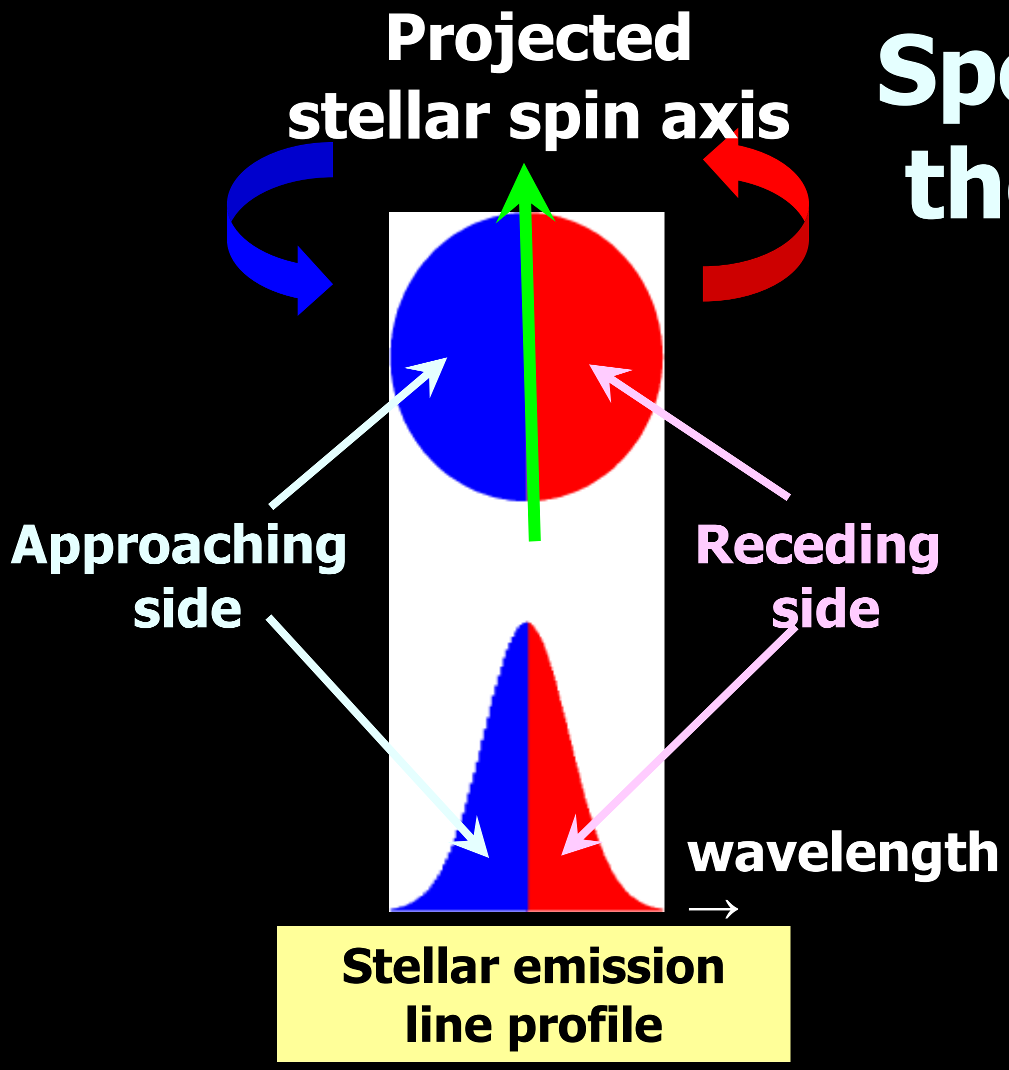
$$\cos\Psi = \sin i_s \sin i_{orb} \cos\lambda + \cos i_s \cos i_{orb}$$

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

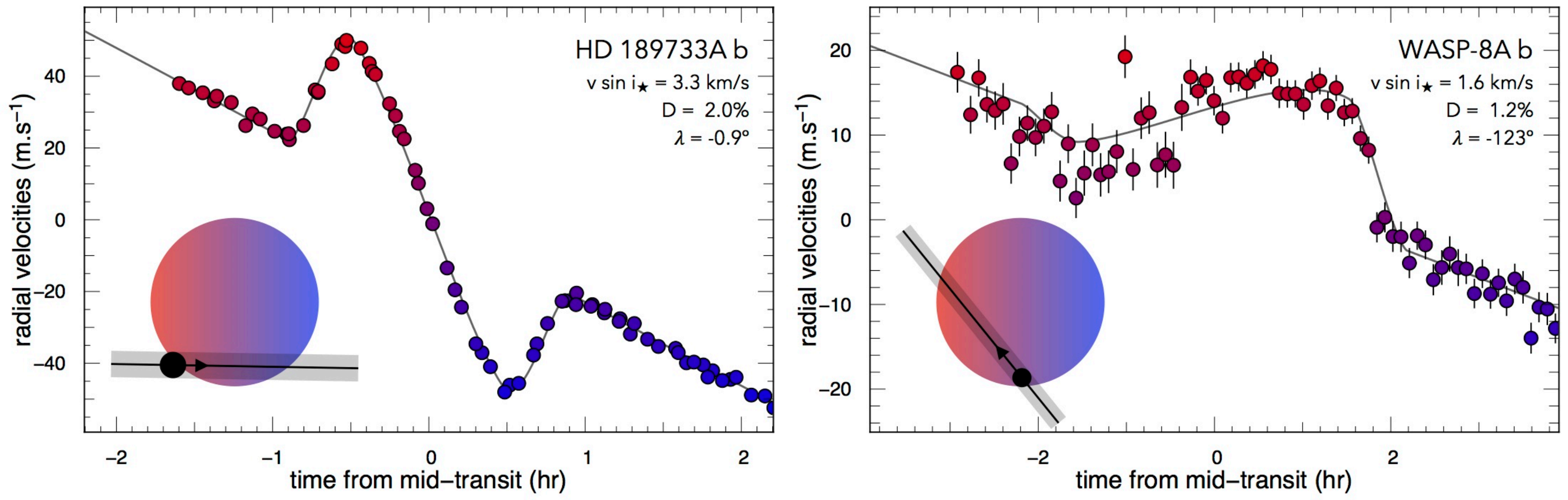


- Time-dependent asymmetry in the stellar Doppler-broadened line profile due to the planetary transit
  - apparent anomaly of the stellar radial velocity
- originally proposed for eclipsing binaries

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 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

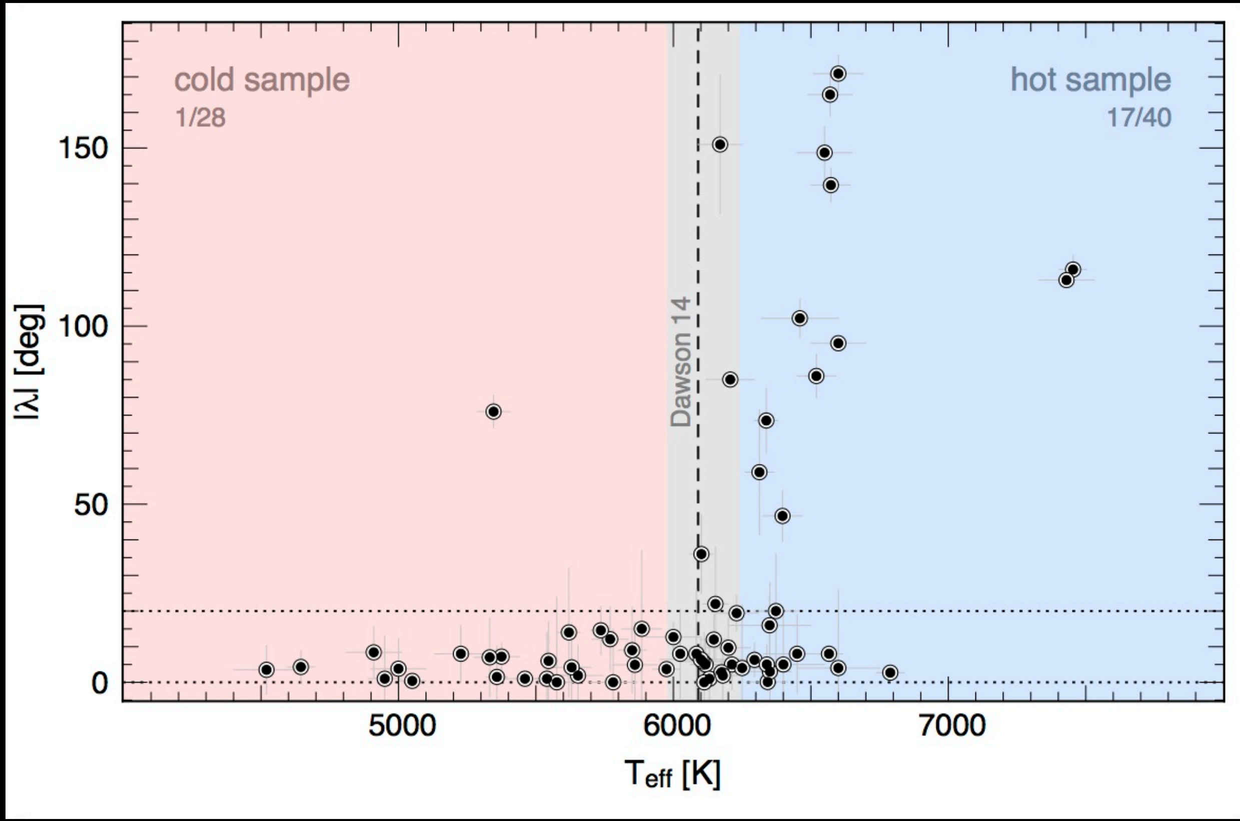
$$\alpha = \pm 3.9^{\circ}{}^{+18^{\circ}}_{-21^{\circ}}$$

- Ohta, Taruya + YS (2005)
  - 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 on the basis of OTS approach

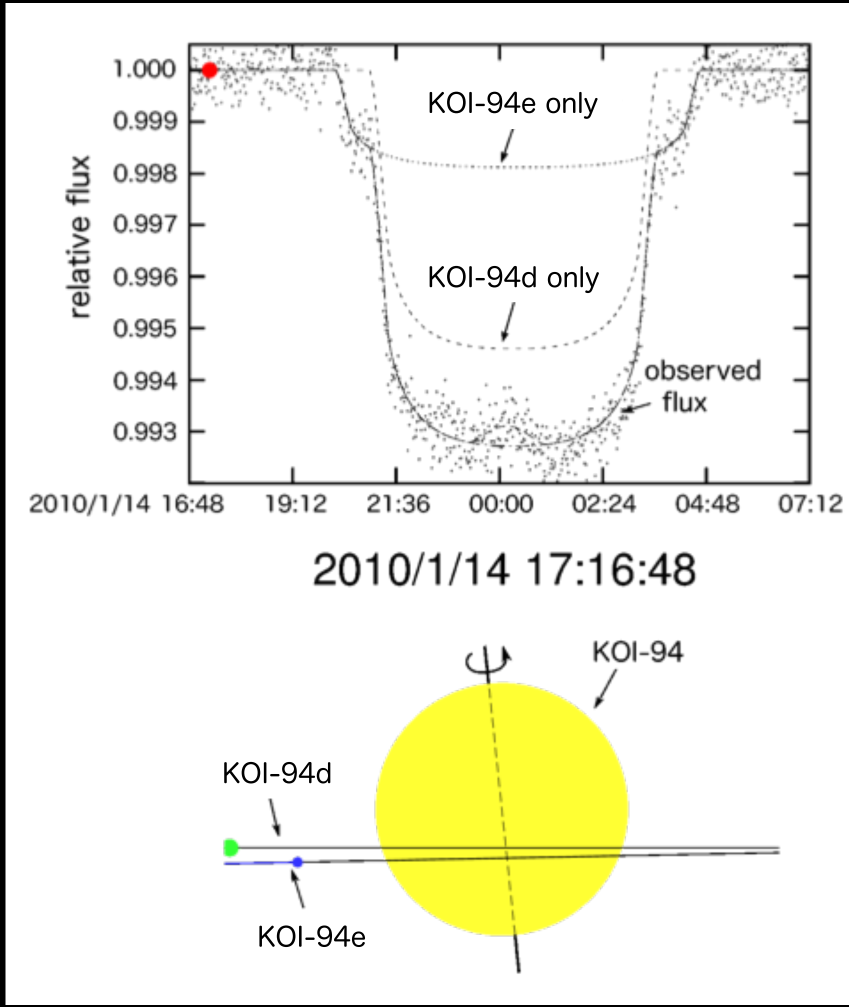
Orbital evolution: projected misalignment vs. stellar effective temperature

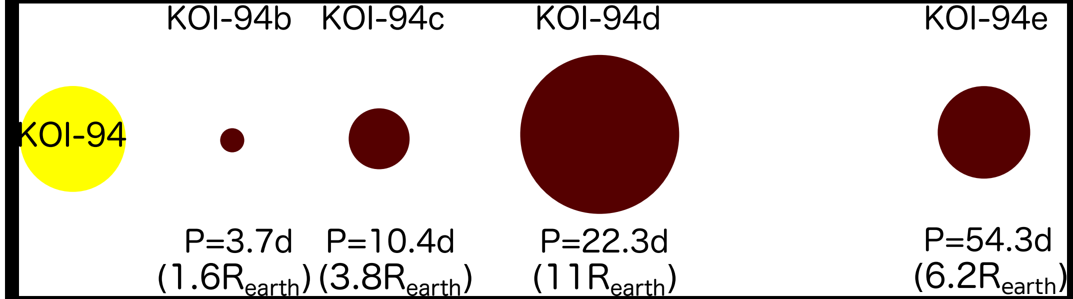


Triaud arXiv:1709.06376

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)

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



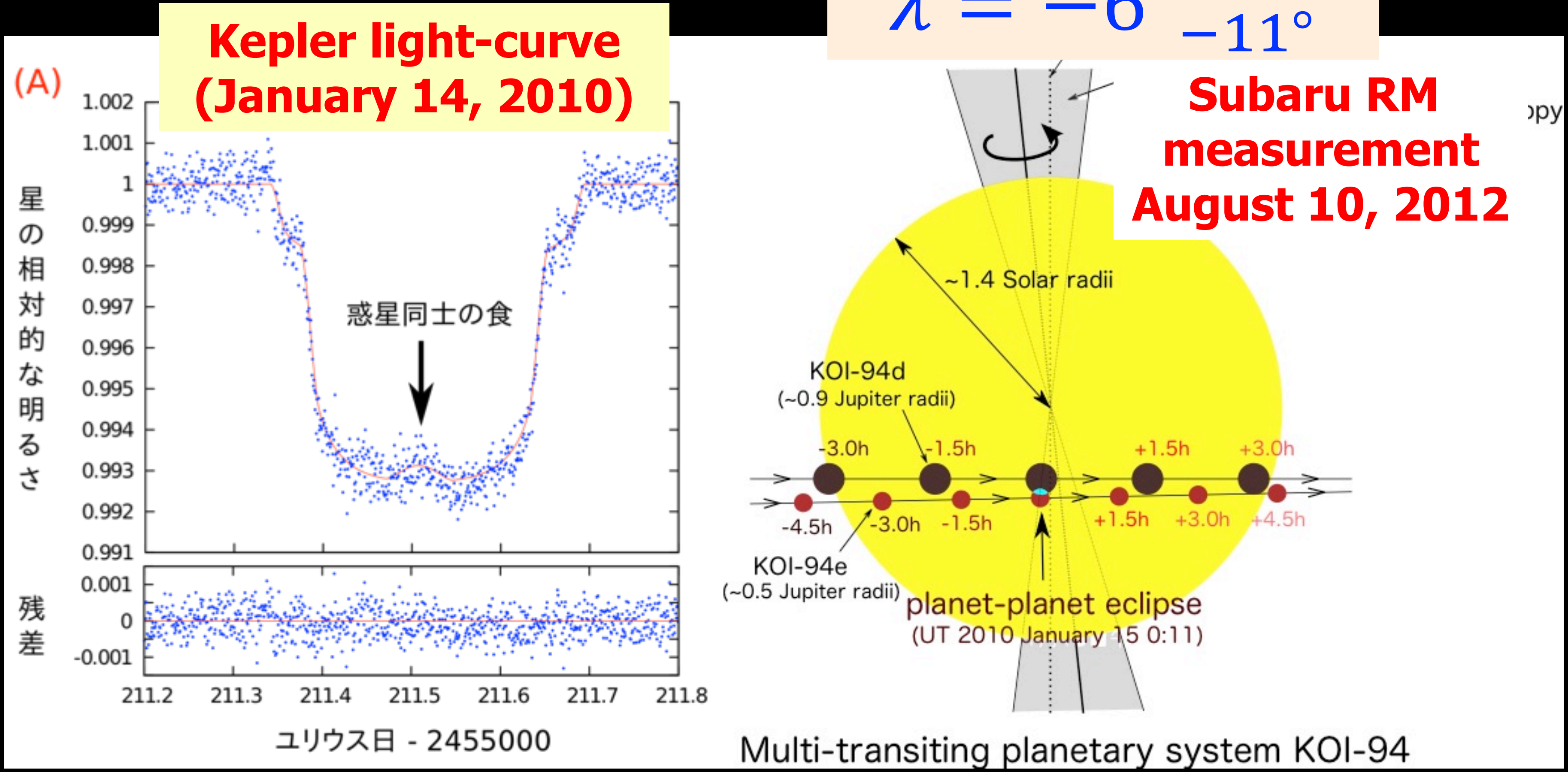


Hirano et al. ApJL 759 (2012)L36

- 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

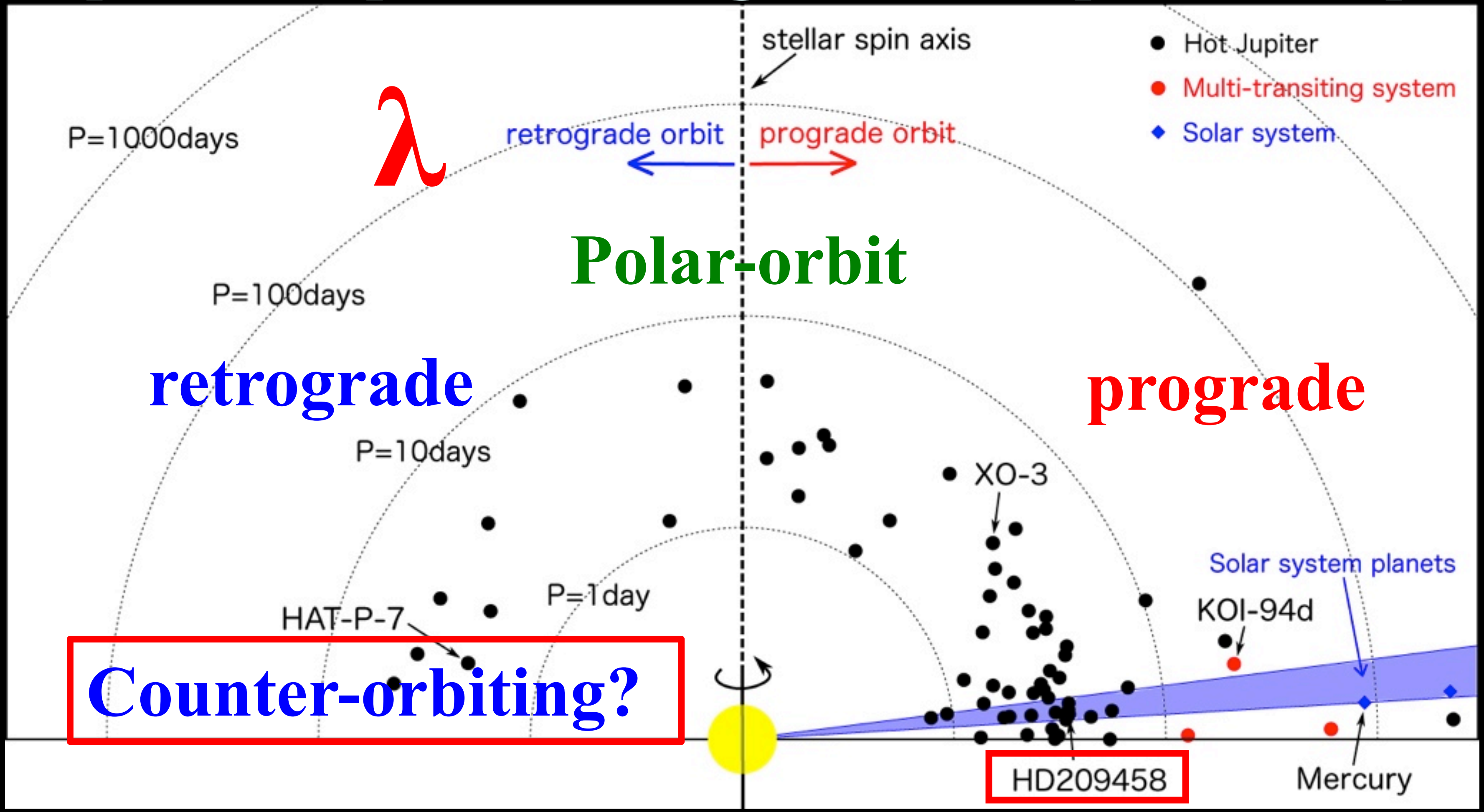
Spin-orbit alignment of KOI-94

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



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

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

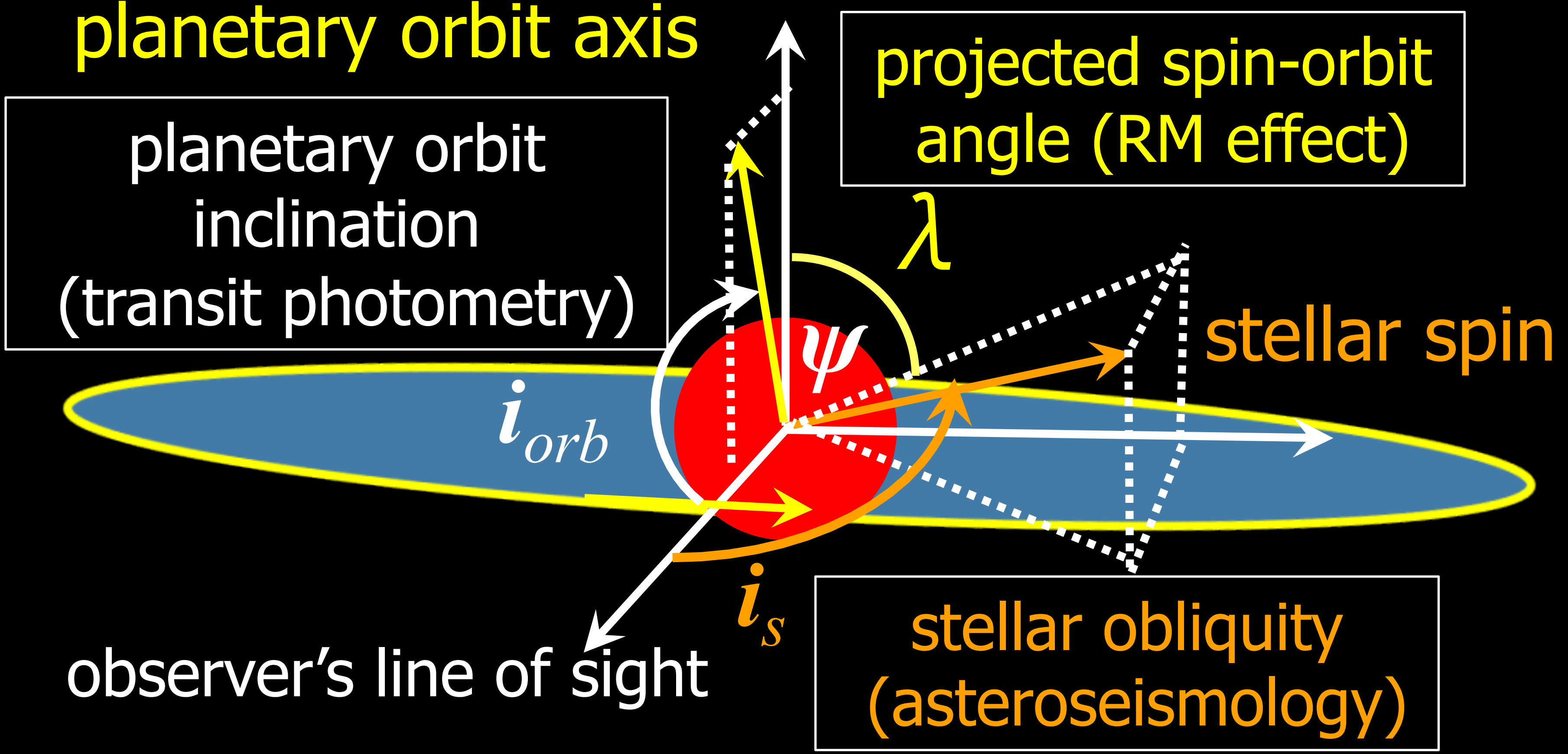


As of June 2013, 29 out of 70 planets were known to have $\lambda > \pi/8$

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

Spin-orbit (mis)alignment from asteroseismology

Spin-orbit architecture of a planetary system



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True spin-orbit angle (unobservable) $\approx \sin i_s \cos\lambda$

- i_{orb}: orbital inclination for the observer
  - transit curve modeling ($\approx \pi/2$)
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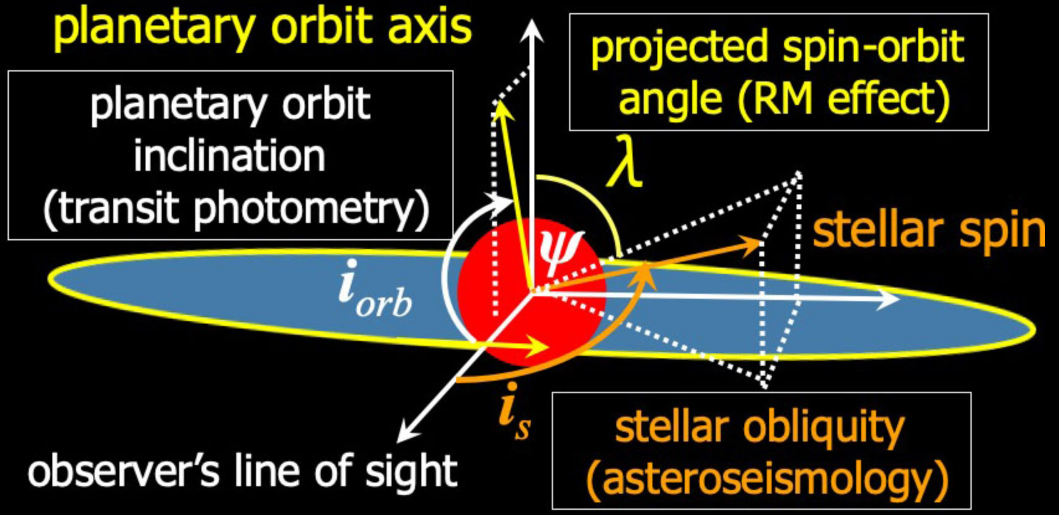
  - Rossiter-McLaughlin effect
- i_s: stellar spin inclination for the observer
  - asteroseismology

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 (T.Kajita, Nobel Prize in 2015)

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

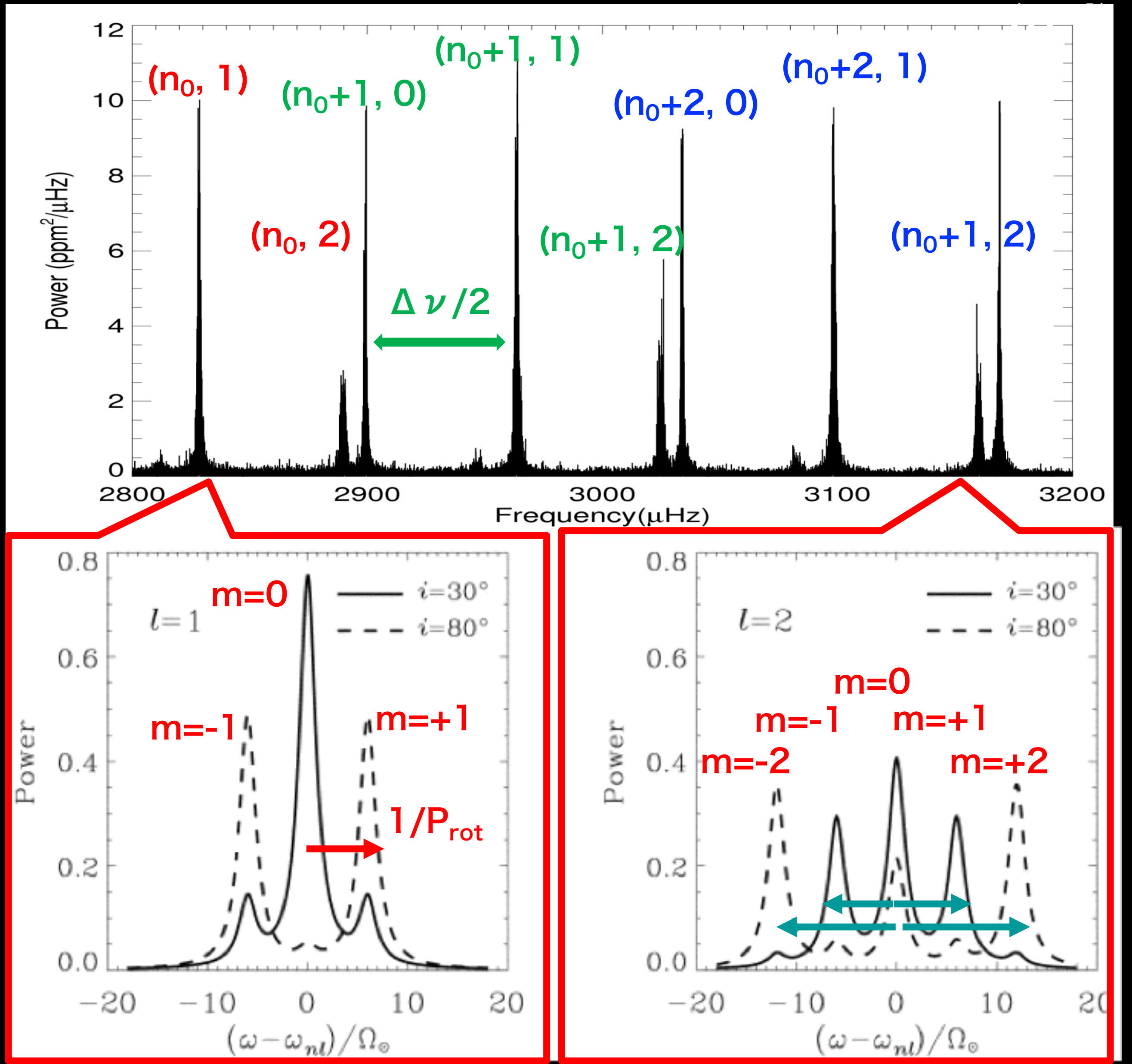
- Asteroseismology found a significantly misaligned system (i_s=47±6°) with two transiting planets, Kepler-56 !
  - Kepler-56: red giant (1.3M_s, 4.3R_s) + two transiting planets (10.5day, 20.4day) Huber et al. (2013)



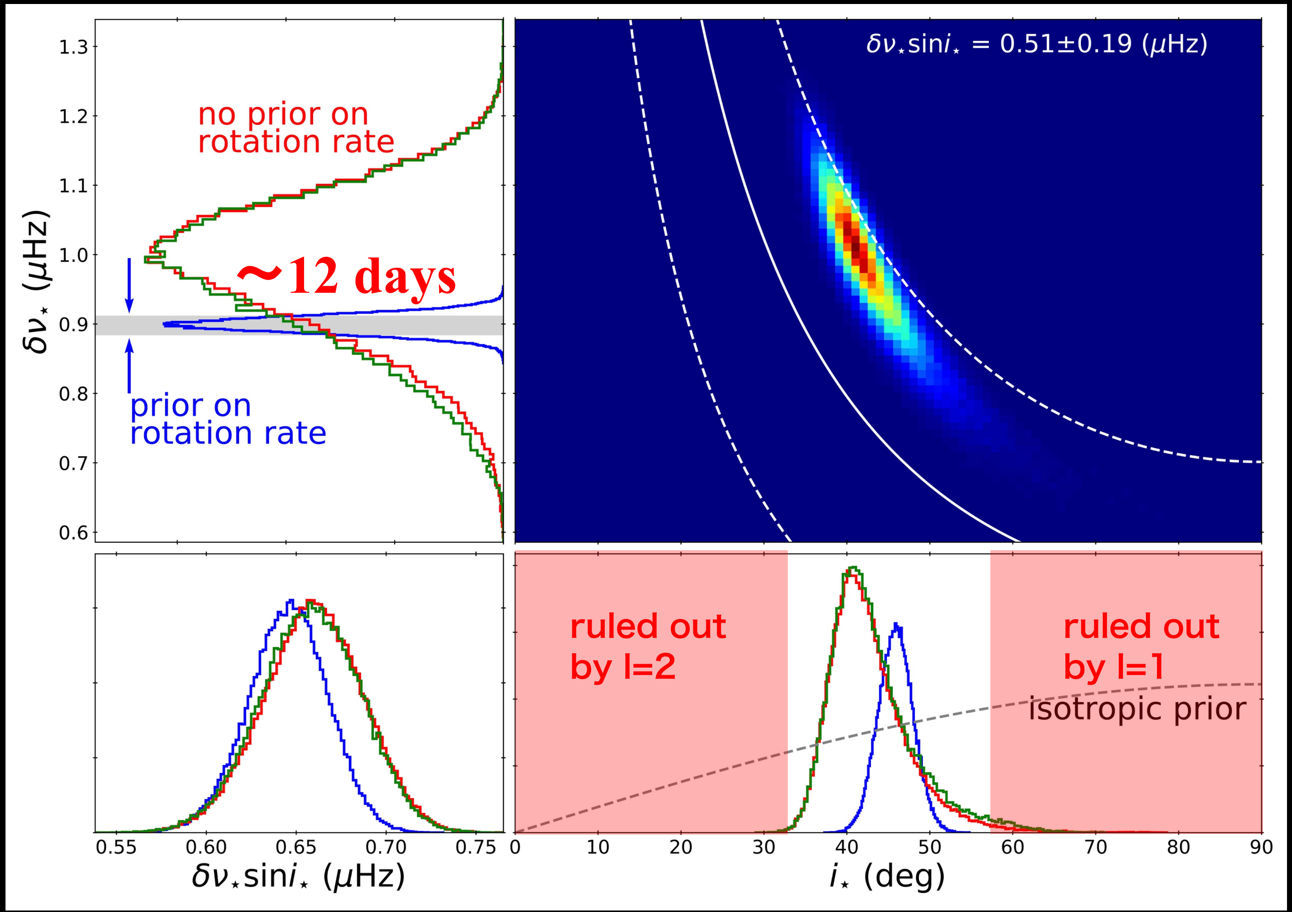
- **Primordial origin for the misalignment ?**
- **Nature vs. Nurture ?**

Why can asteroseismology measure i_s ?

- **Stellar version of the Zeeman effect**
  - 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

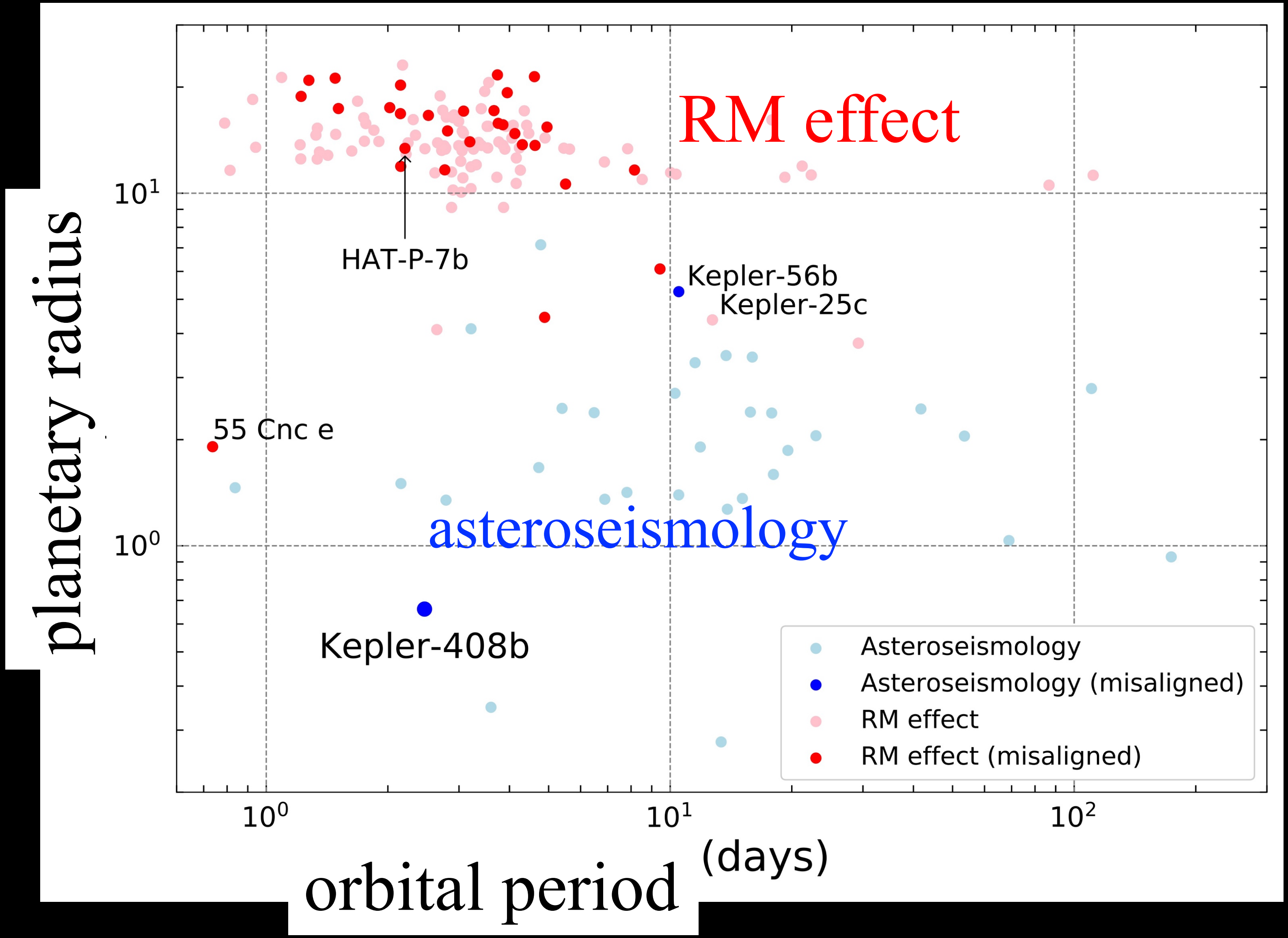
Kamiaka, Benomar, YS, Dai, Masuda, & Winn (2019)

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

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

- The smallest size planet in an oblique orbit

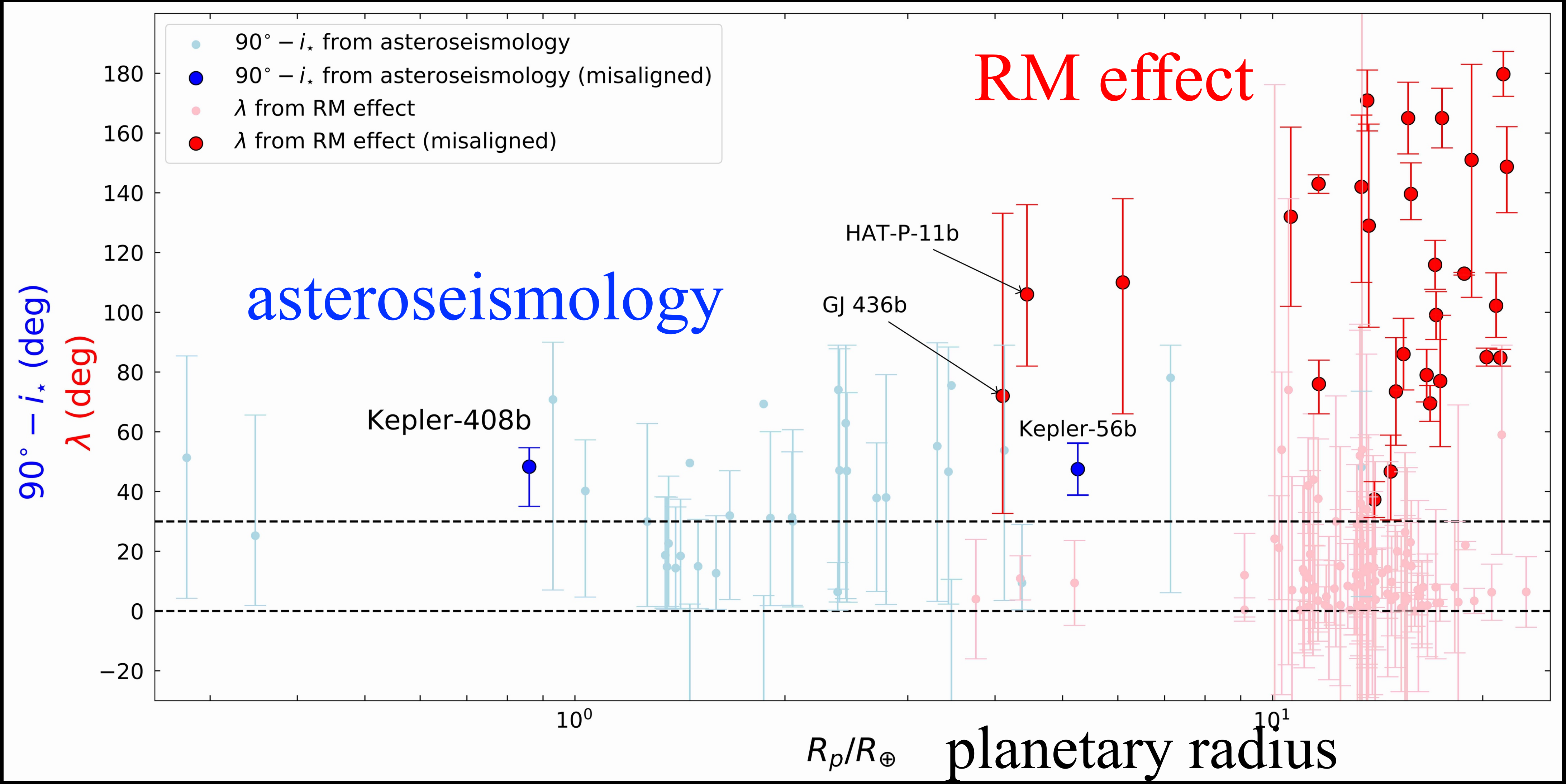
Complementarity between the RM effect and asteroseismology



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

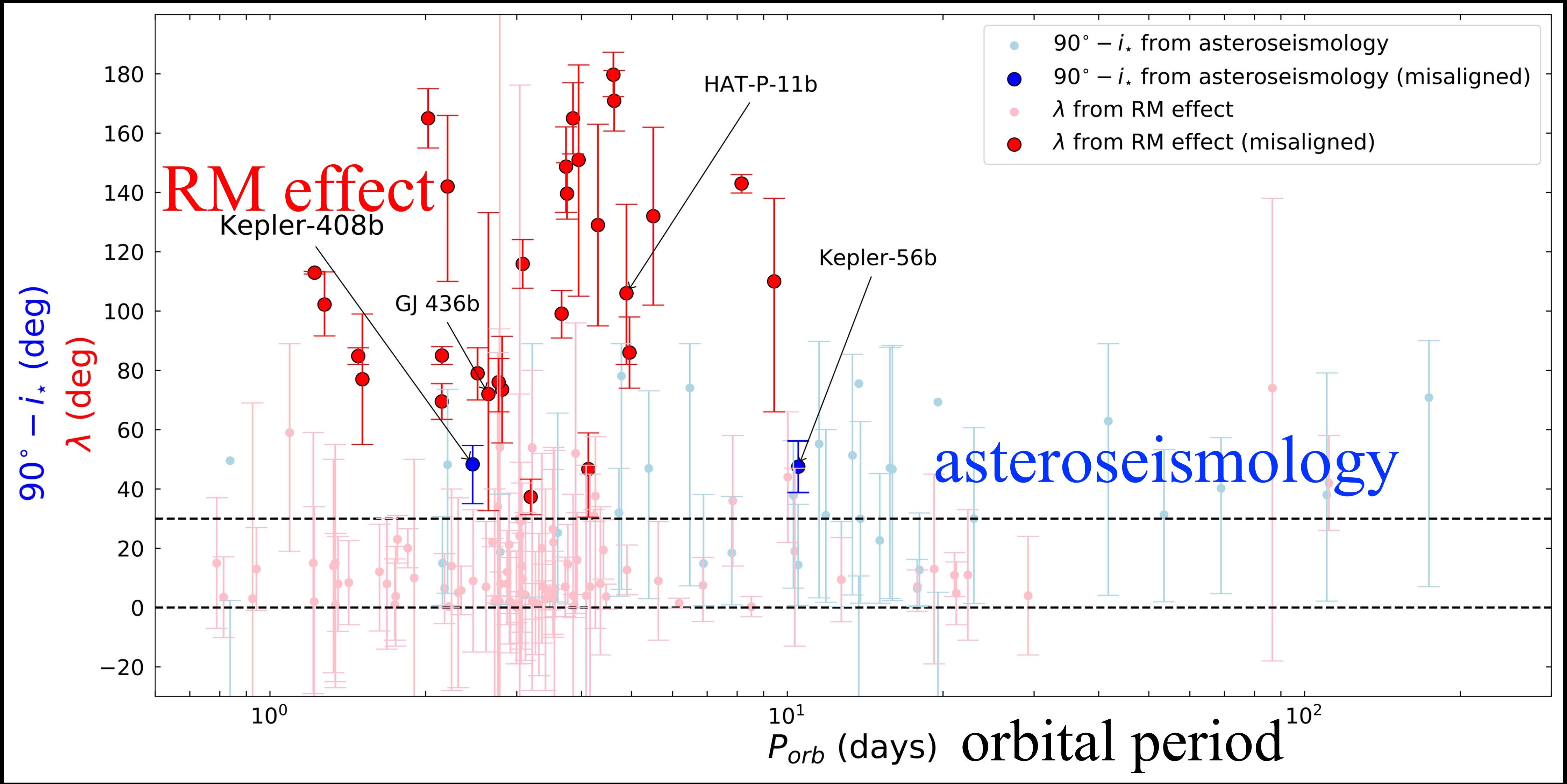
Kamiaka, Benomar & YS (2018)
Kamiaka, Benomar, YS, Dai, Masuda, & Winn (2019)
YS, Kamiaka & Benomar (2019)

Spin-orbit angles against R_p



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

Spin-orbit angles against P_{orb}



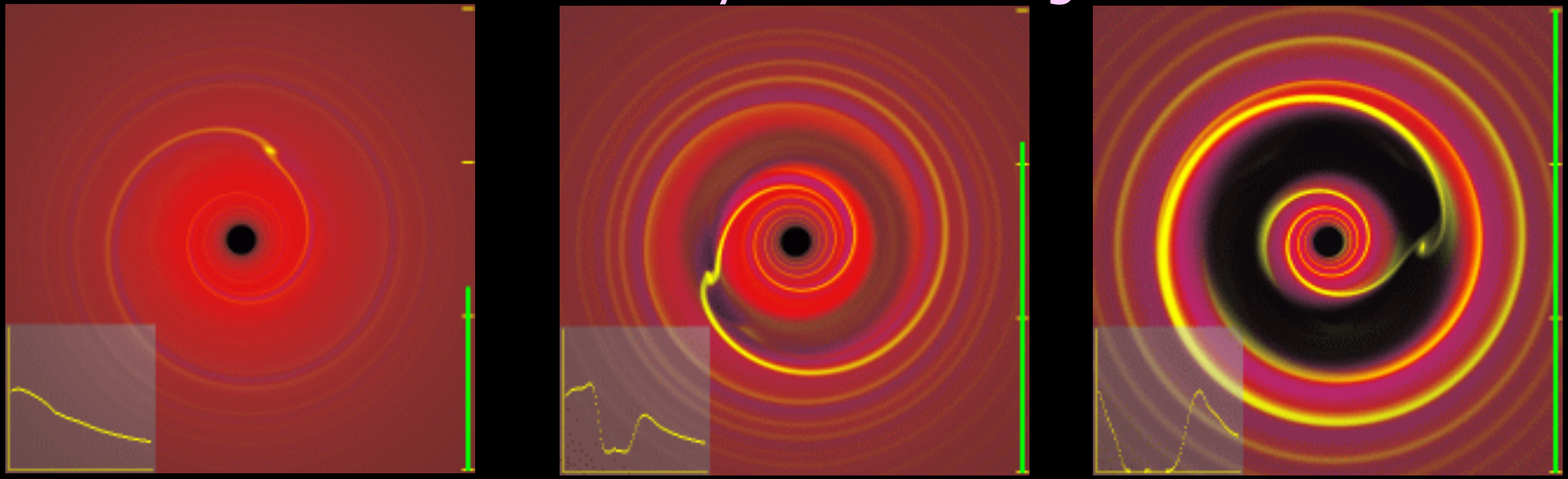
Kamiaka, Benomar, YS, Dai, Masuda, & Winn, AJ 157(2019)137

Origin of the spin-orbit misalignment

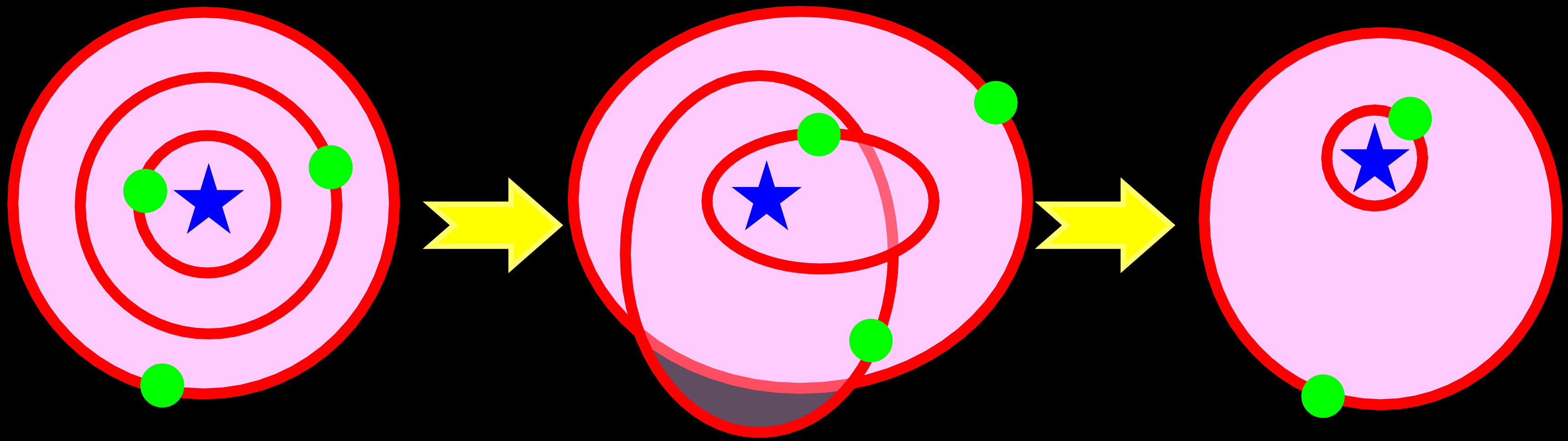
Planet migration channels

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

Simulation by Phil Armitage

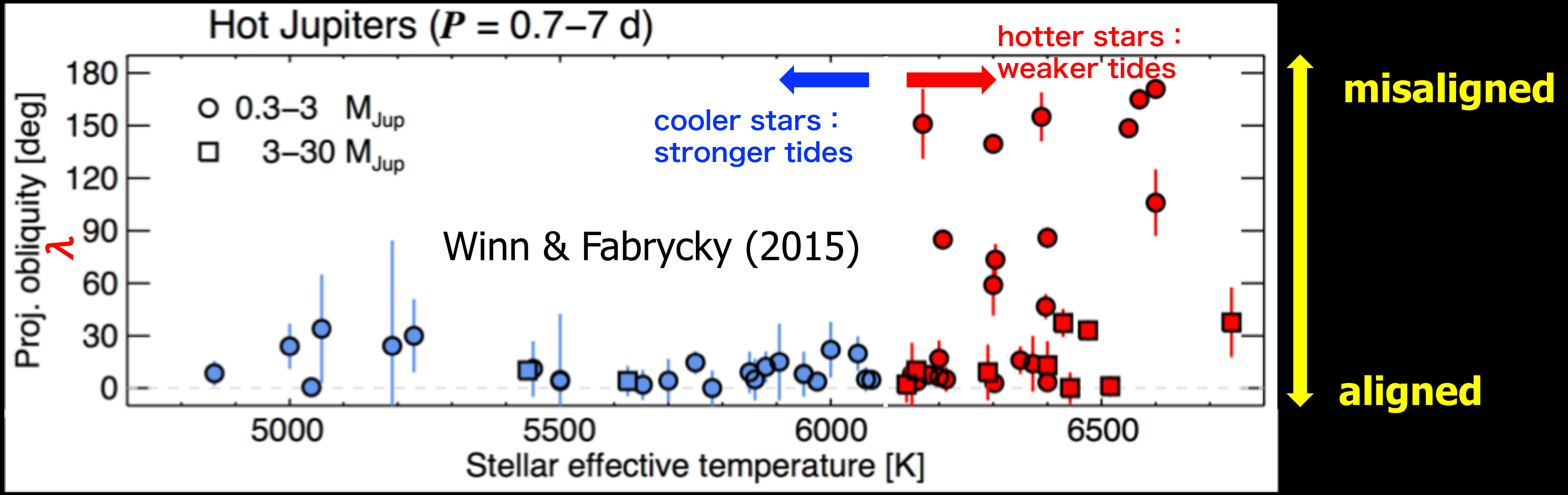


Planet-planet gravitation scattering + star-planet tidal interaction = circularized but misaligned Hot Jupiters



- 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)
- The initial architecture of multi-planets is not clear at all

Star-orbit misalignment is more common ?

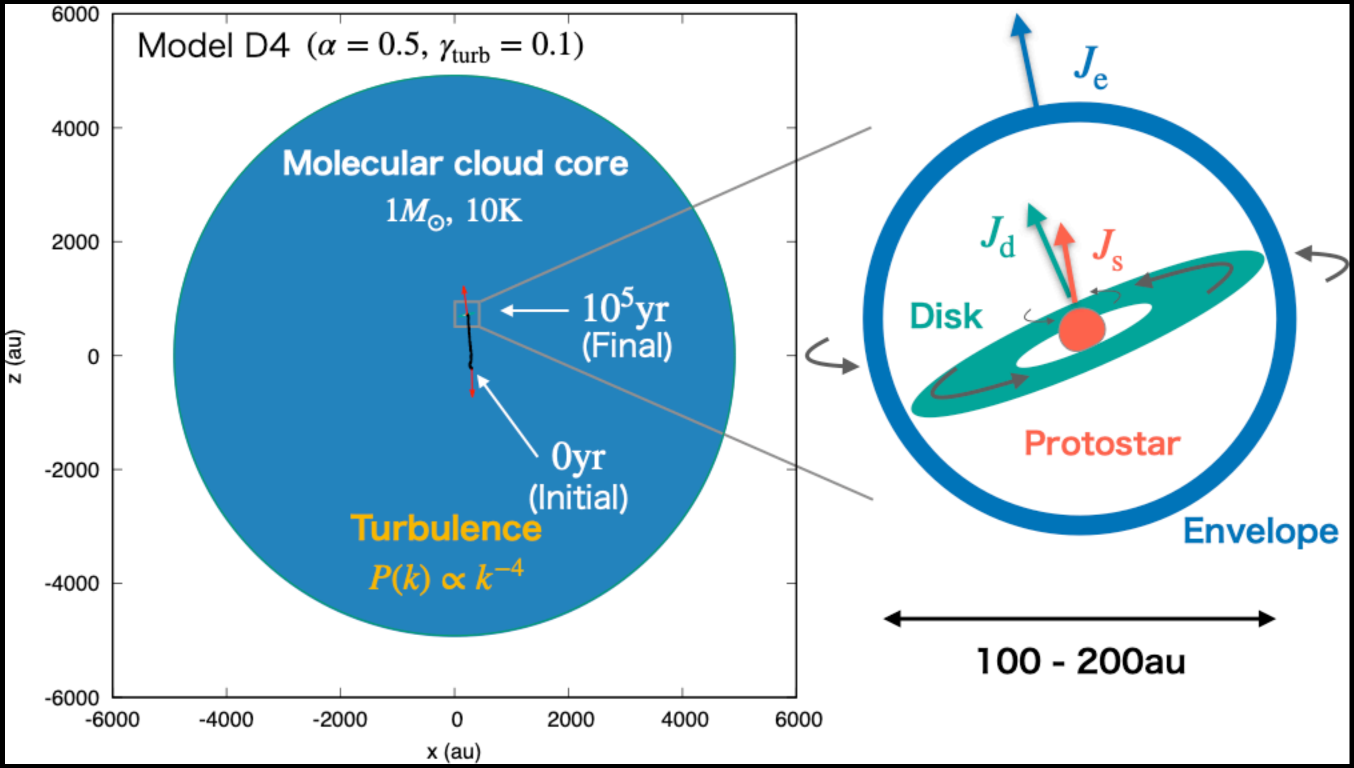


- It is not easy to explain why misalignments are preferentially in hotter host stars in the primordial origin alone
- Subsequent star-planet tidal interaction realigns the spin-orbit angle for cooler stars with convective envelops
- Primordial misaligned systems may be even more common ?

Proposed models for the misalignment

- Primordial misalignment between the protostar and the protoplanetary disk
  - Bate, Lodato & Pringle (2010)
  - Takaishi, Tsukamoto & YS (2020) MNRAS in press, 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, submitted

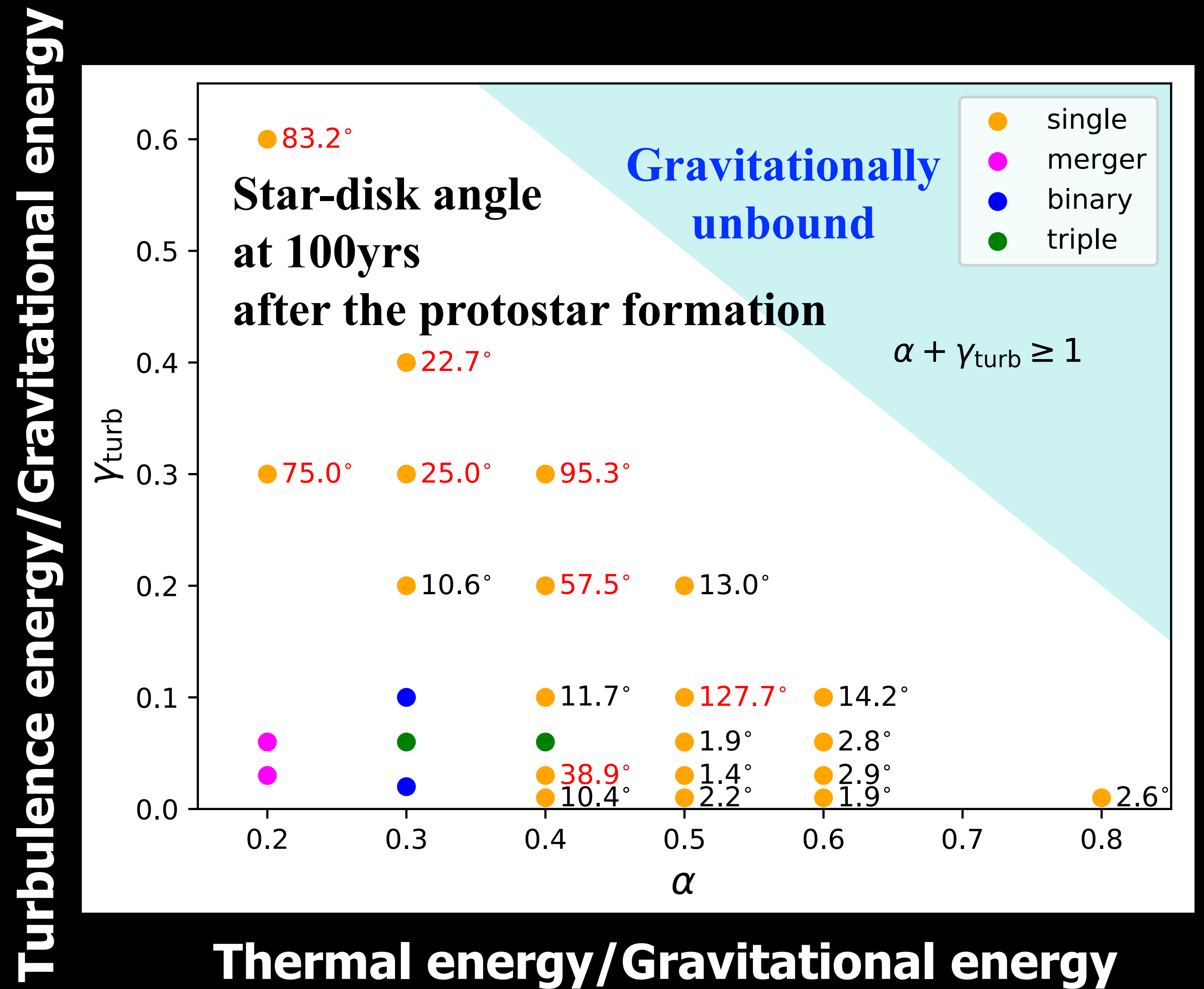
Primordial star-disk alignment in turbulent molecular cloud cores

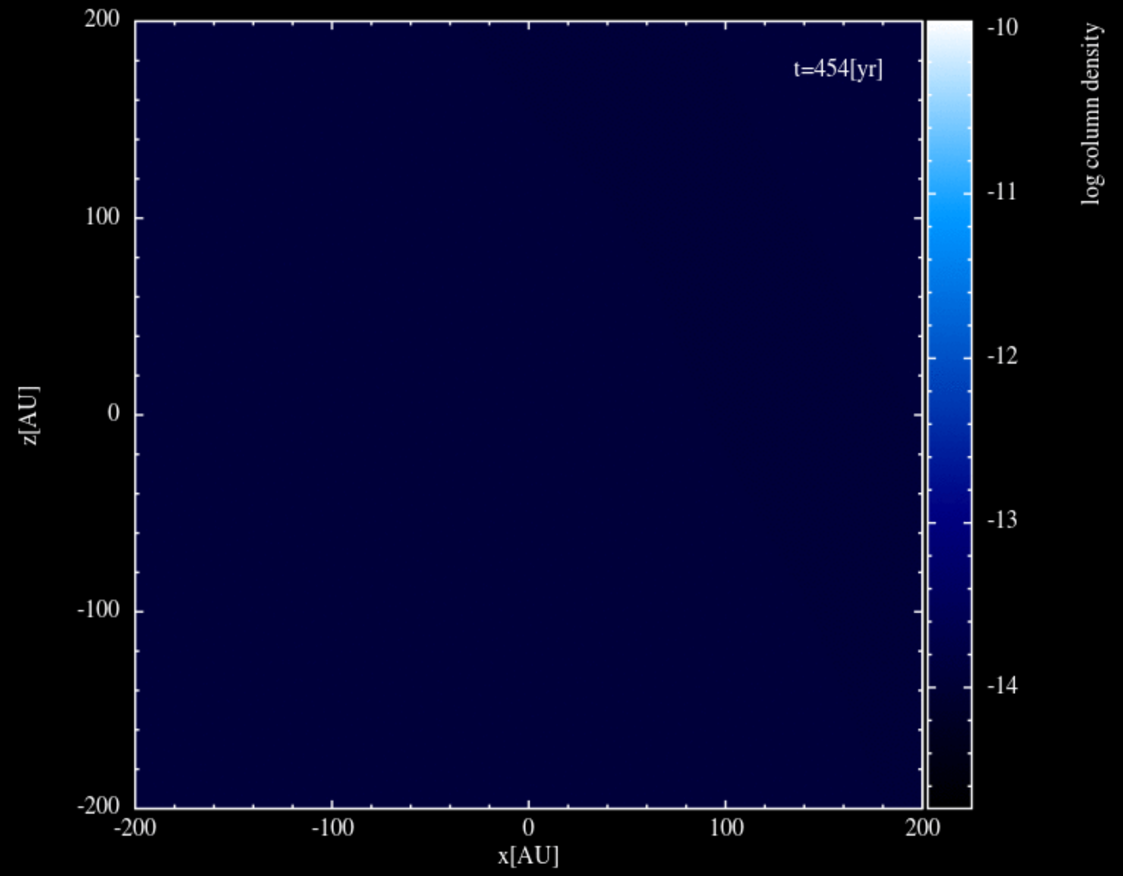


- **SPH simulation**
  - 1million SPH particles + sink particle method to approximate protostars
  - isothermal turbulent cloud cores of $1M_{sun}$
  - neglect magnetic field

Takaishi, Tsukamoto + YS (2020) MNRAS arXiv:2001.05456

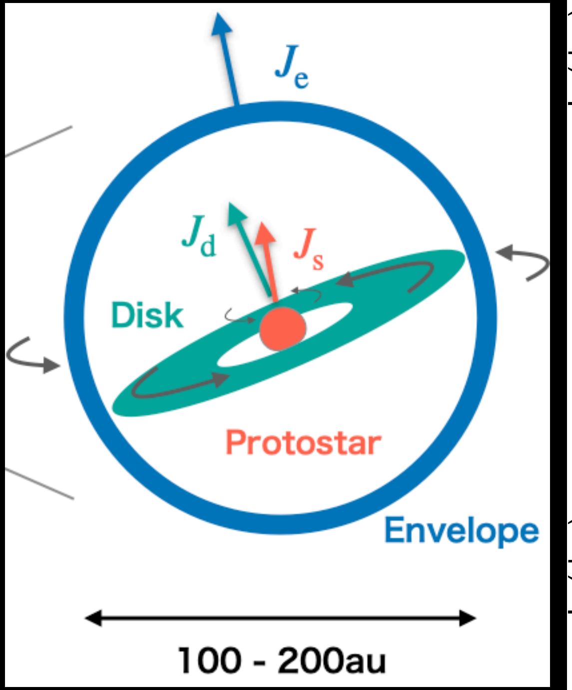
Initial star-disk (mis)alignment angles

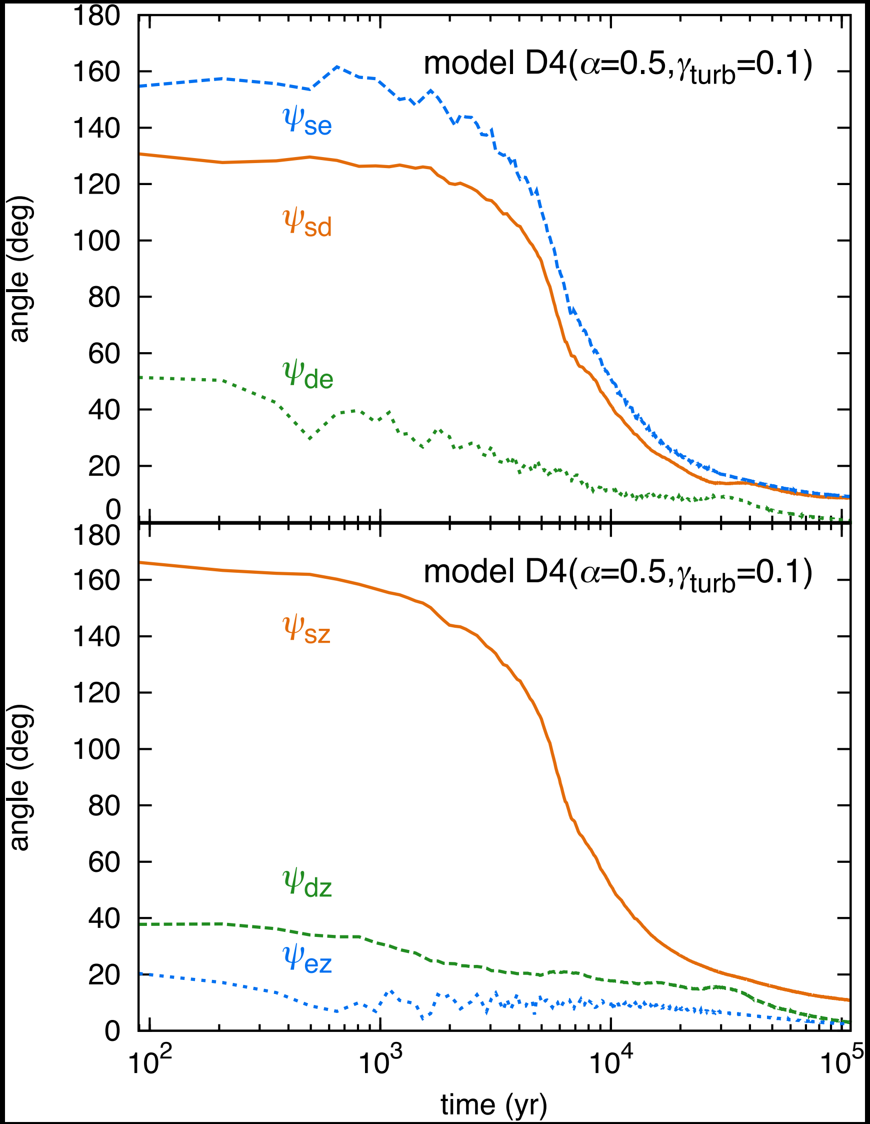




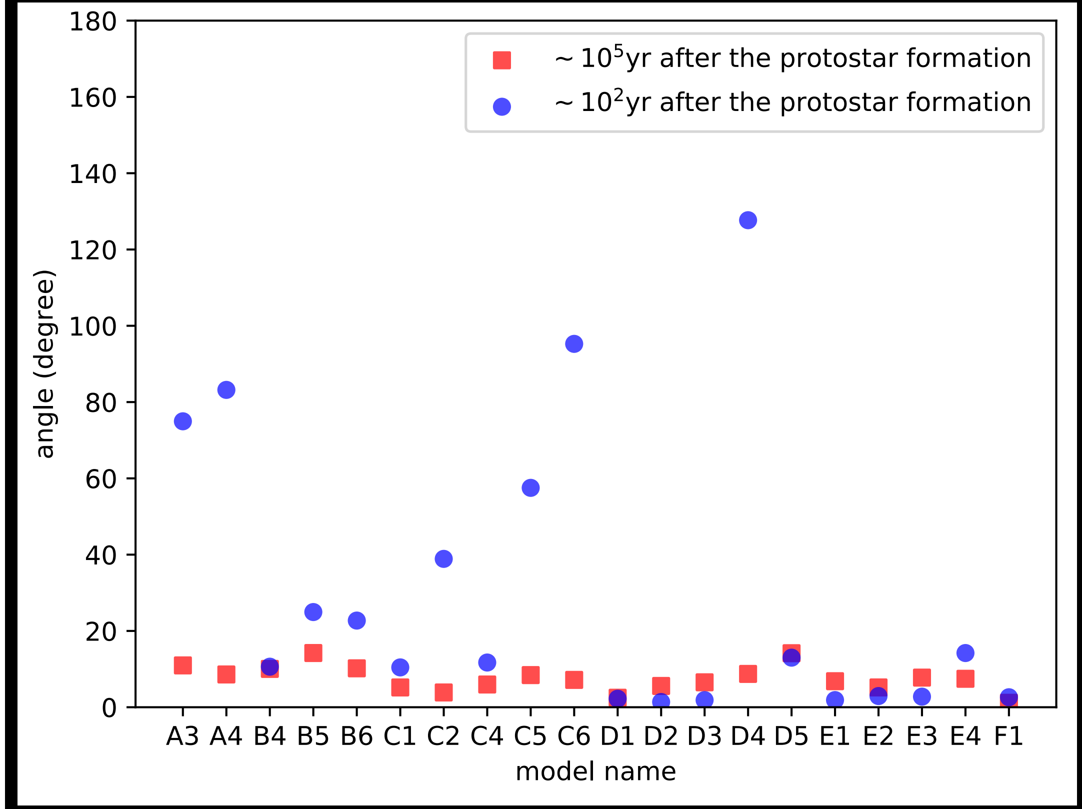
Takaishi, Tsukamoto + YS (2020)

Evolution of the star-disk angles





Primordial star-disk angles are less than 20 degrees



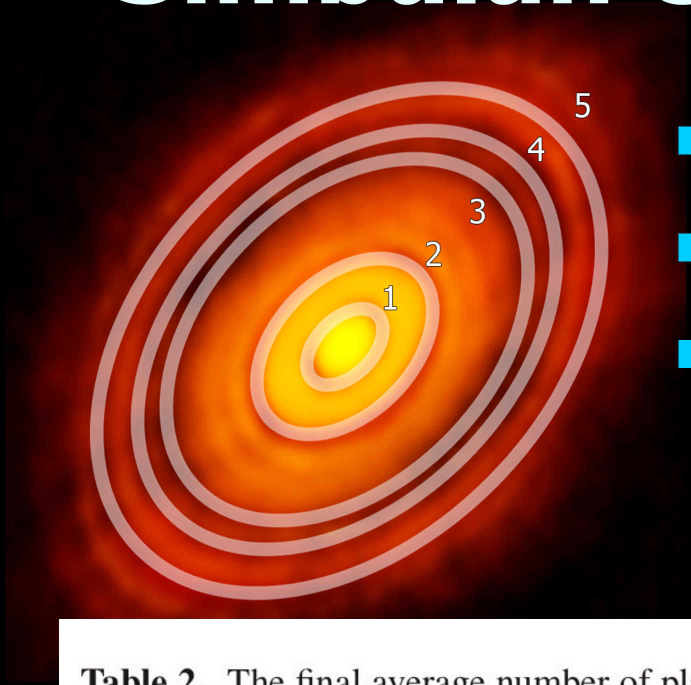
Takaishi, Tsukamoto + YS (2020)

The ALMA view of the protoplanetary disk HL-Tau

www.eso.org

Credit: ALMA (ESO/NAOJ/NRAO)/NASA/ESA/N. Risinger (skysurvey.org)

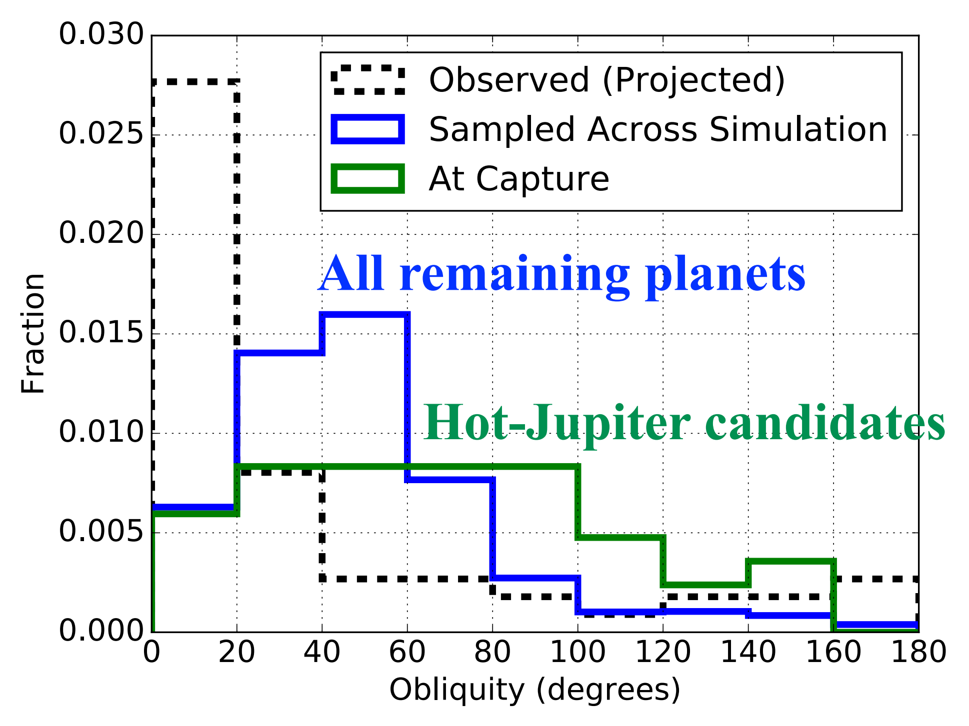
Simbulan et al. MNRAS 469(2017)3337



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

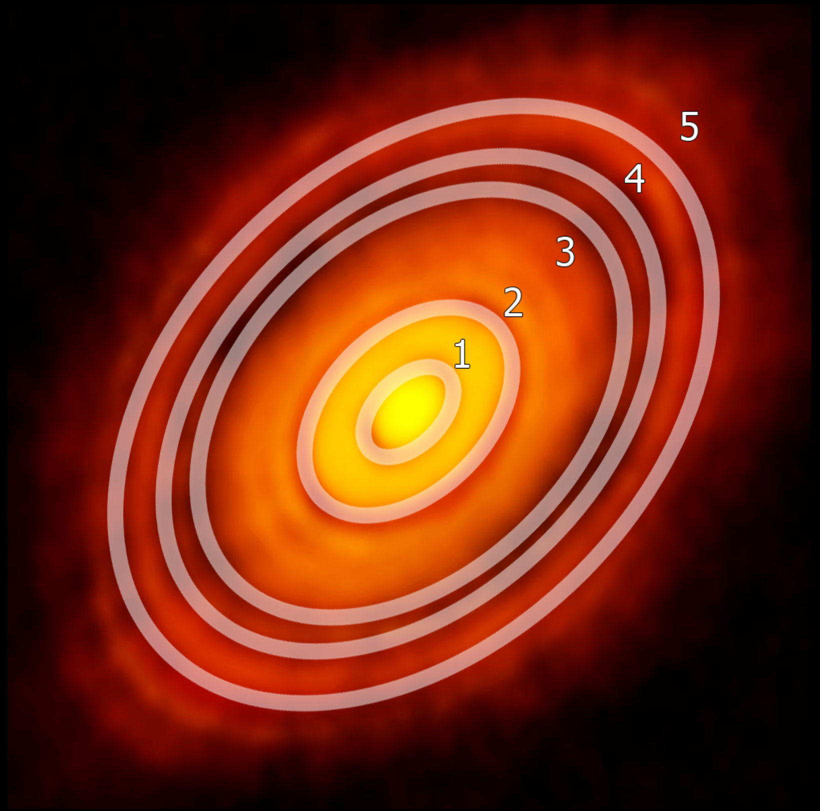
Table 2. The final average number of planets lost to ejections (E), planet–planet collisions (C), close encounters with the star at 0.2 au (S) and the final average number of planets remaining (R).

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



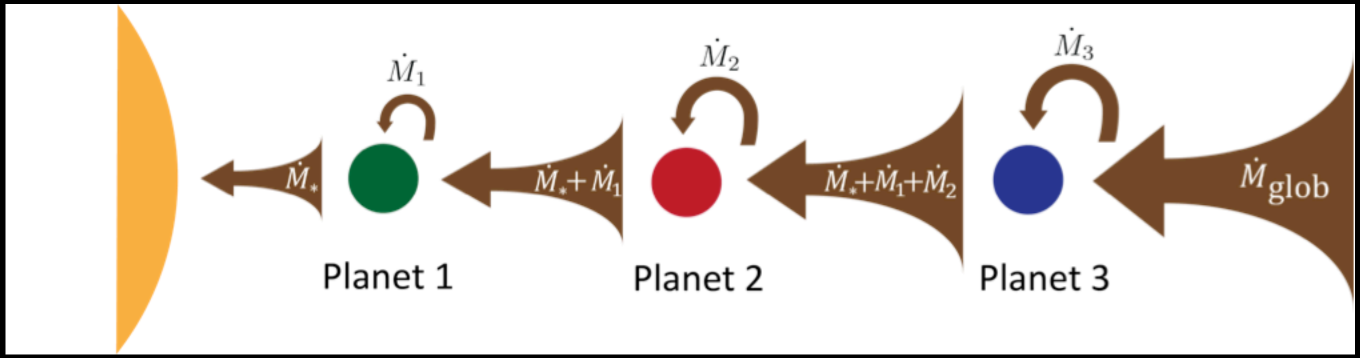
Improved disk-planet migration model

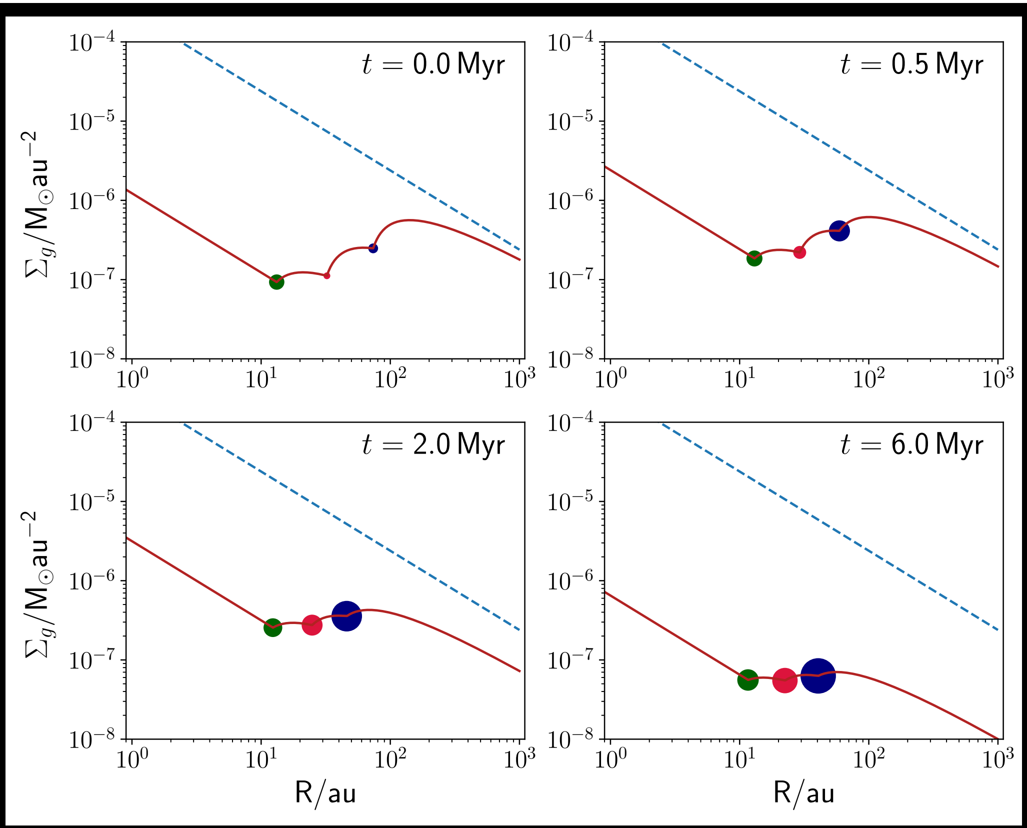
- Empirical Type I and II migration models calibrated by 2D hydro-simulation (Kanagawa et al. 2018)
- Initially 3 planets are located at the major three gaps (1, 2, and 4) in the HL tau disk (Dipierro et al. 2015, Jin et al. 2016, Dong et al. 2017, 2018)
- 70 out of 75 simulated runs are stable
- chaotic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

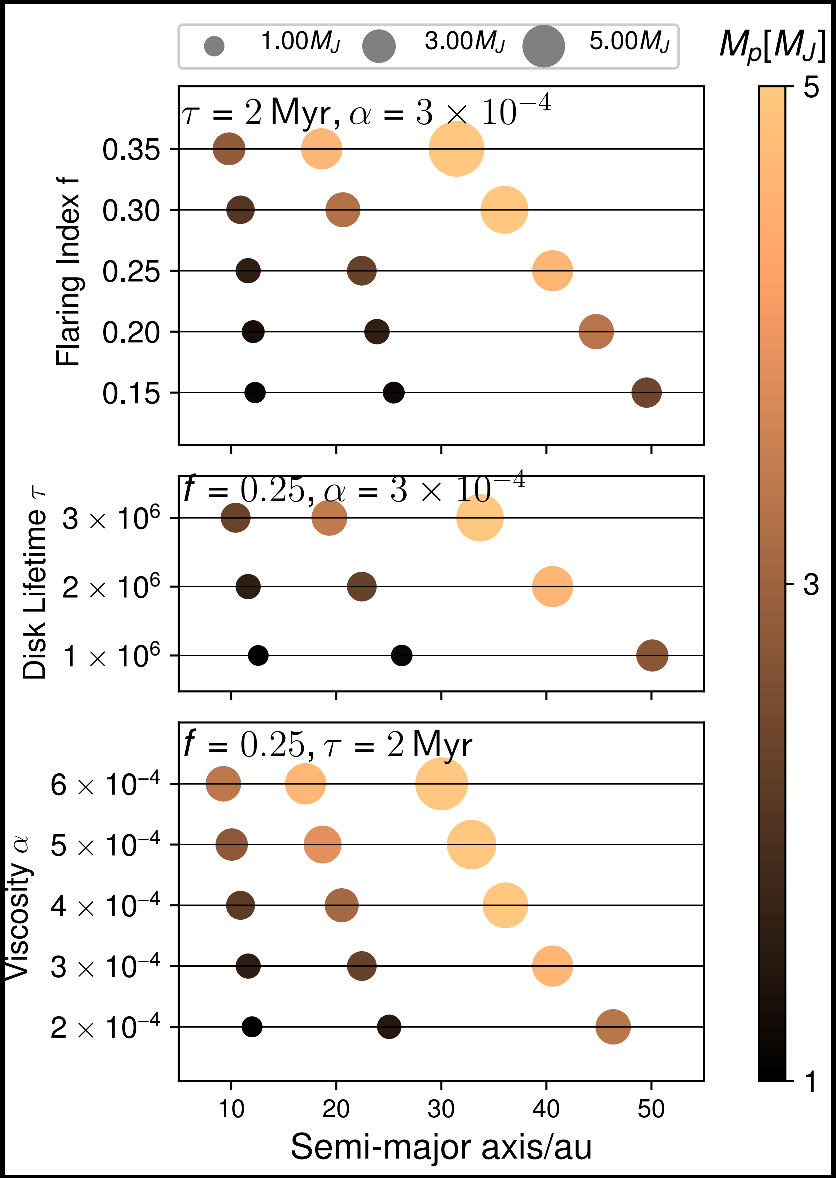


Wang, Kanagawa, Hayashi & YS (2020)

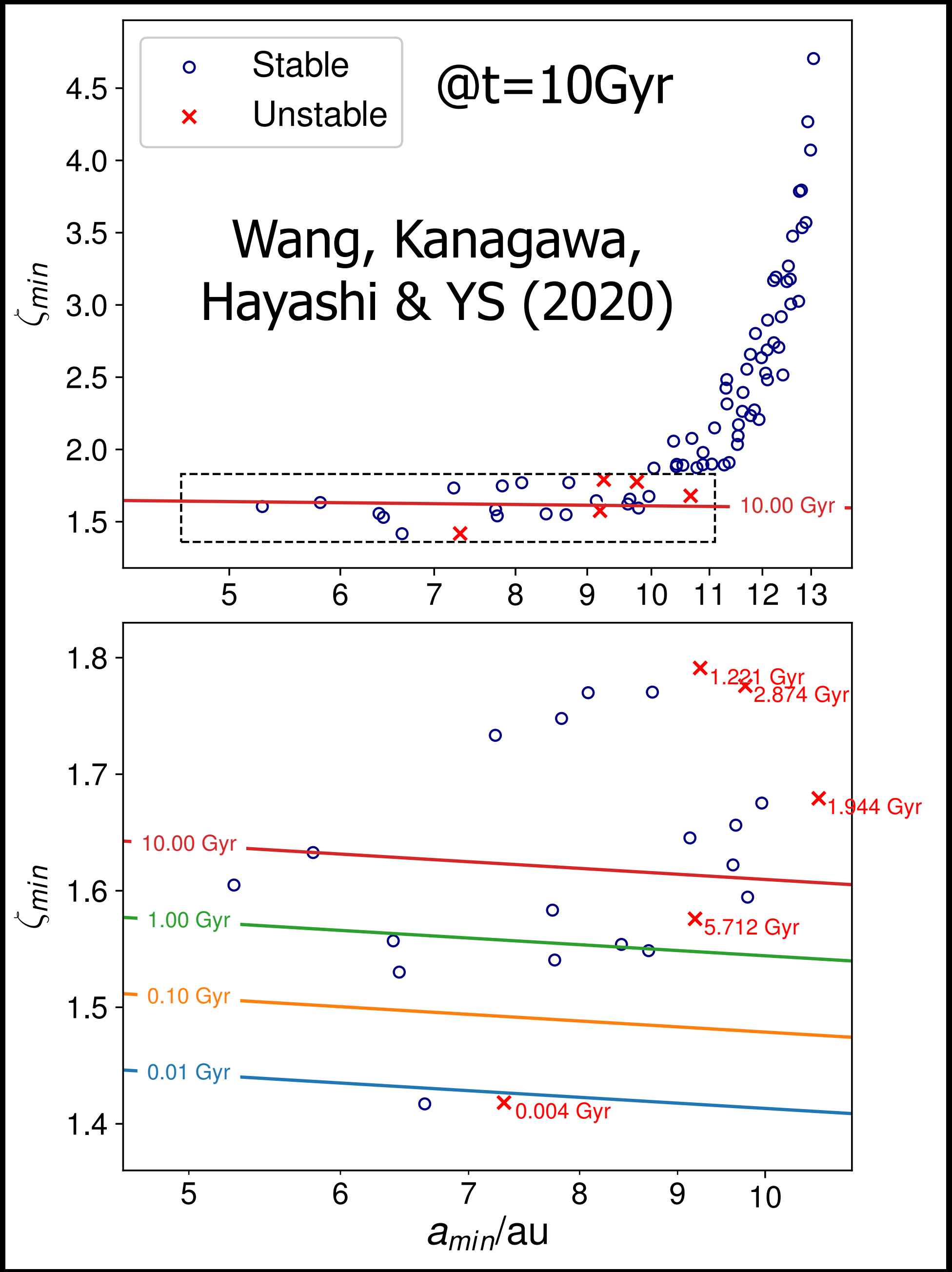
disk-planet migration evolution







Orbital stability of multi-planet systems in purely gravitational interaction



ζ_{min}: minimum separation of adjacent planet-pairs in units of their first-order mean resonance overlap scale

a_{min}: semi-major axis of the innermost planet

(Morrison & Kratter 2016)

Multi-planetary systems expected from the observed HL-tau disk configuration are largely stable

Wang, Kanagawa, Hayashi & 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
- Misalignment remains as an interesting unsolved 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 ?