# Observational Planetary Evolution Revealed by Statistical Studies of Exoplanets

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2025-10-21，Hangzhou

# Outline

1. **Research Background**

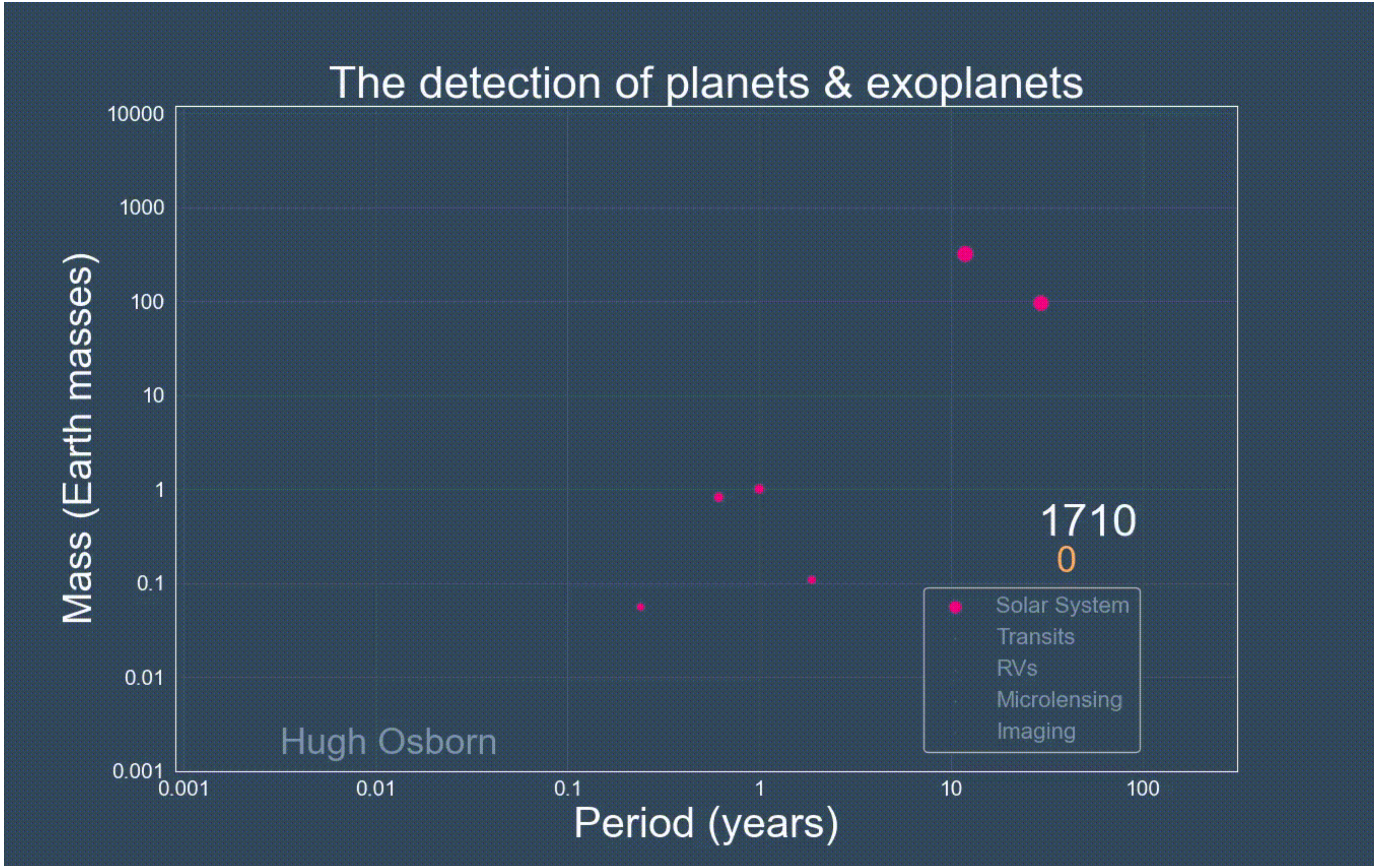
    Importance and Important Progresses of Planetary Statistics

2. **Exoplanet Statistical Research Based on LAMOST**

    Research highlight of the "PAST"（穿越）Series

3. **Prospects and Summary**

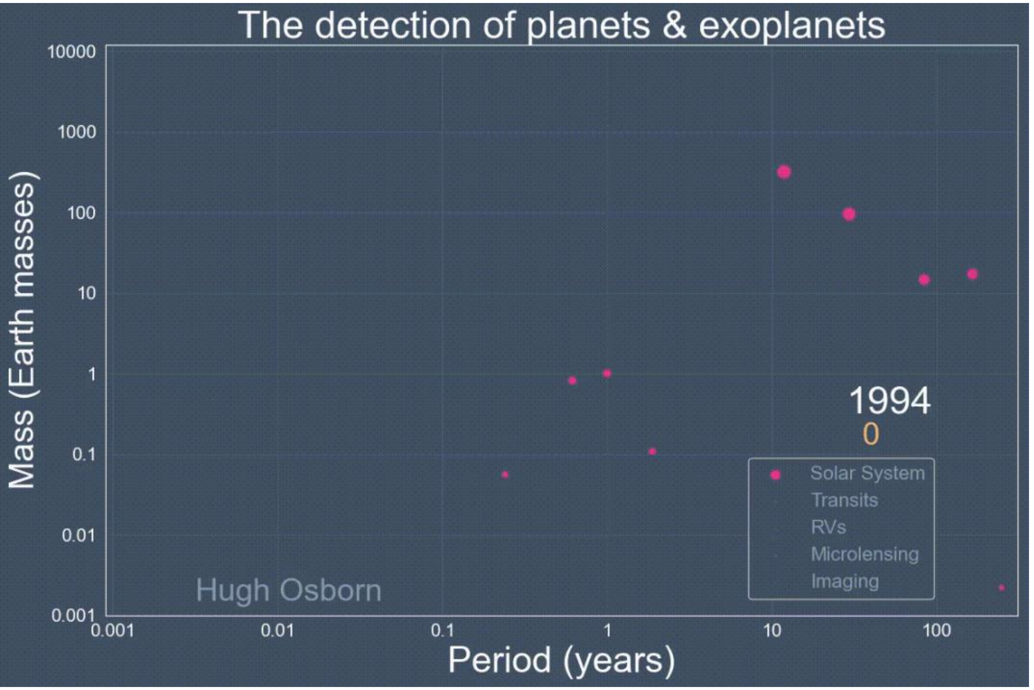
# A short history of Planets and Exoplanets

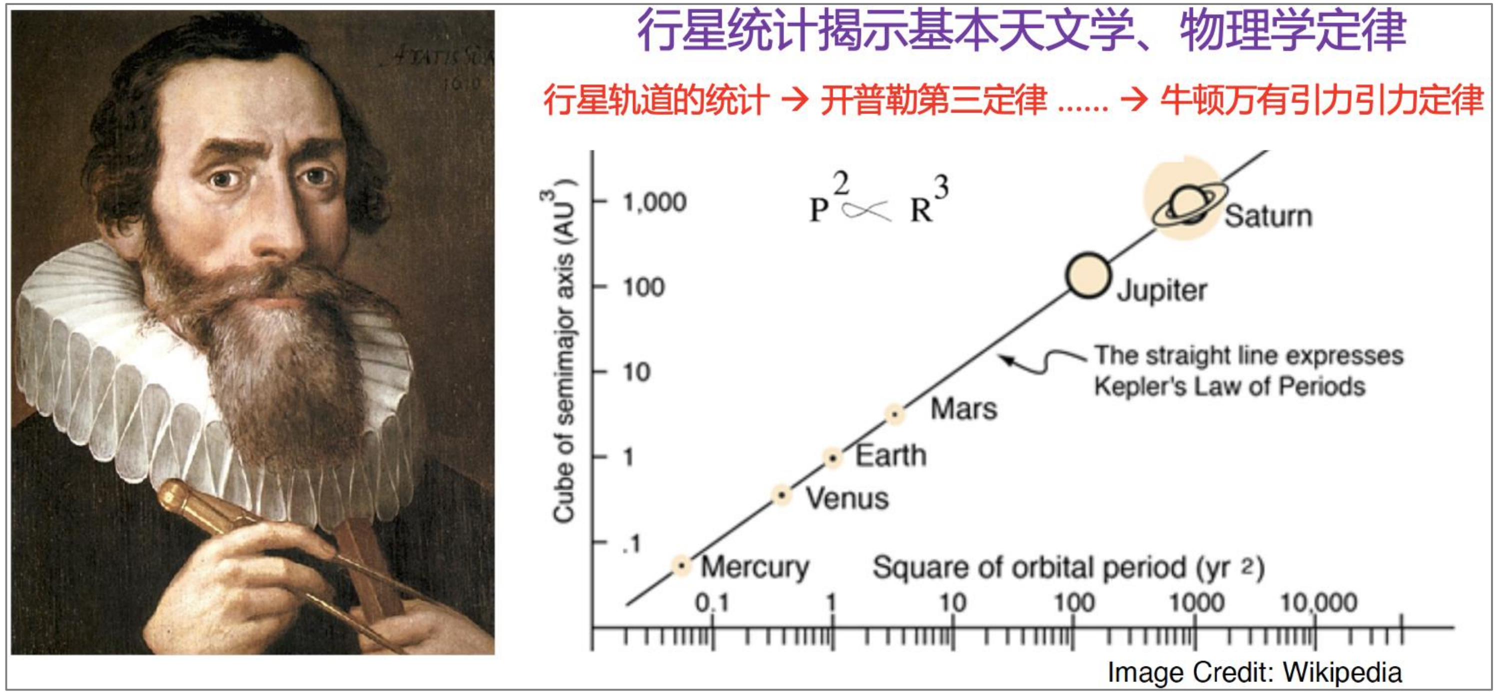


# Important Progresses of Planetary Statistics

## Era of the Solar System Planets (Pre-1995)

1995年之前



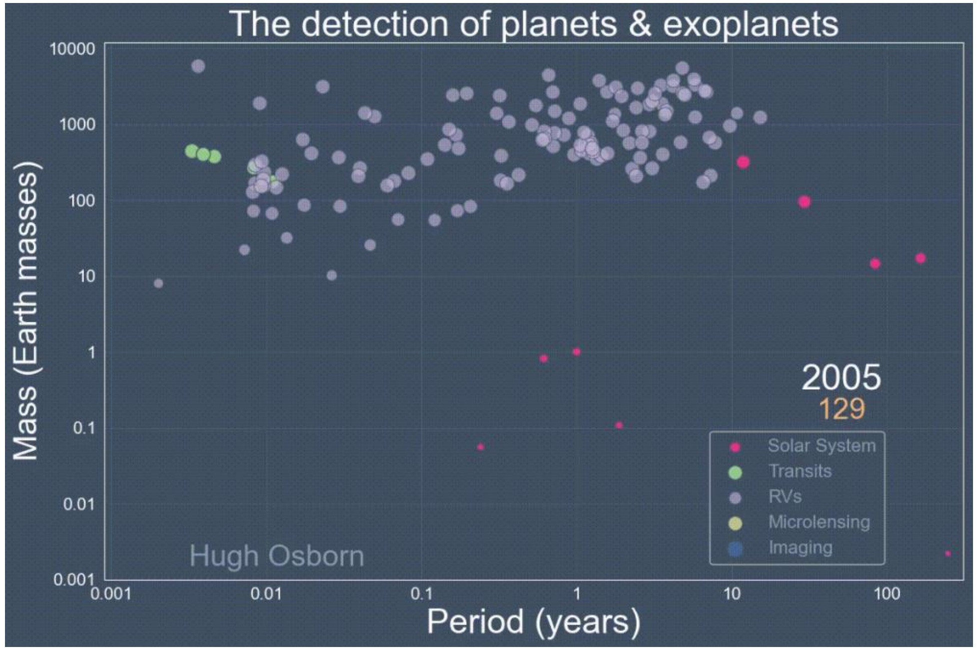



# Important Progresses of Planetary Statistics

Era of Exoplanets (1995-)

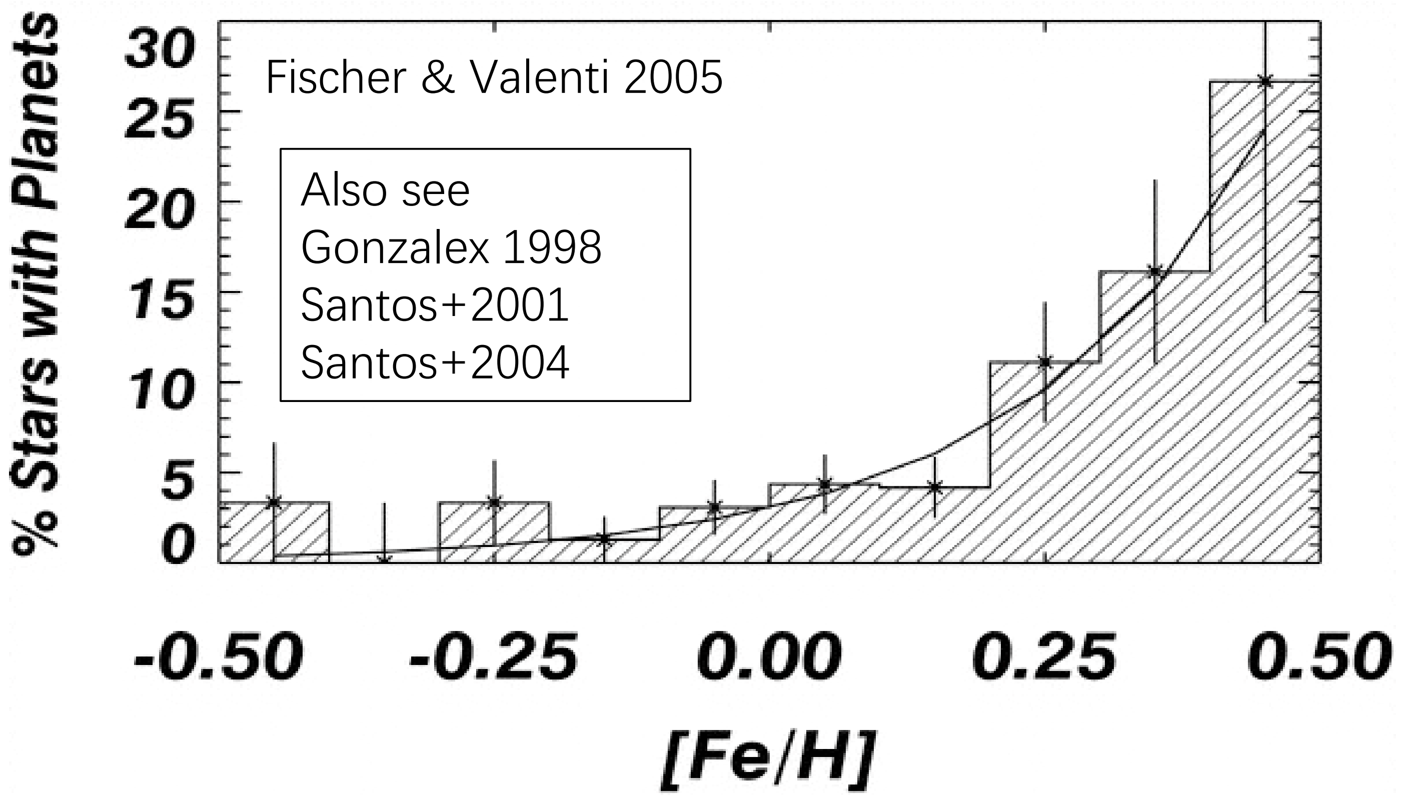
Jupiter-like Planets

1995-2010 年




giant planets - stellar metallicity correlation

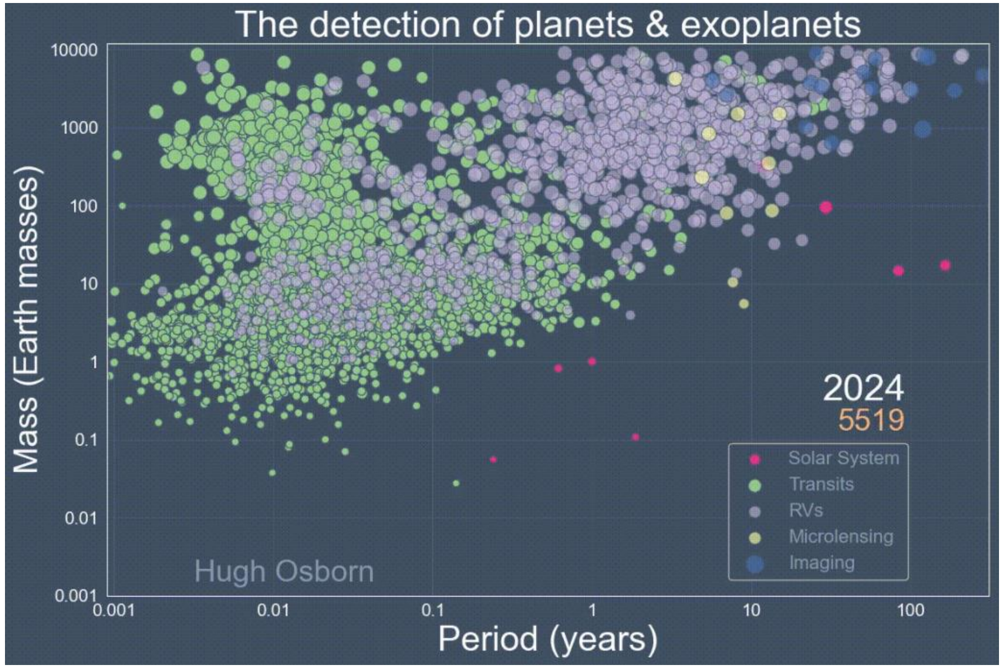
- observational foundation for the theory of planet formation (Core Accretion)



# Important Progresses of Planetary Statistics

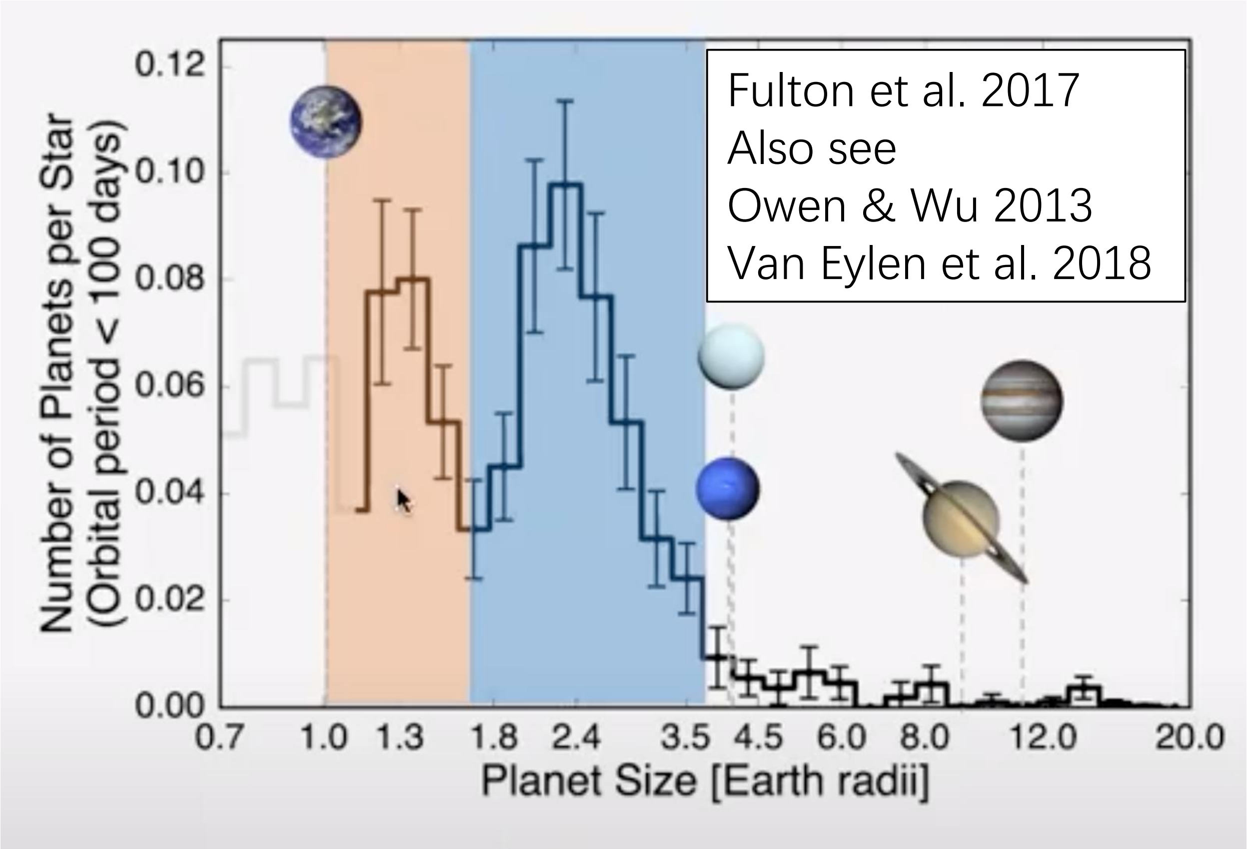
## Era of Exoplanets (1995-)
## Super Earths/Sub-Neptunes

1995-2010 年



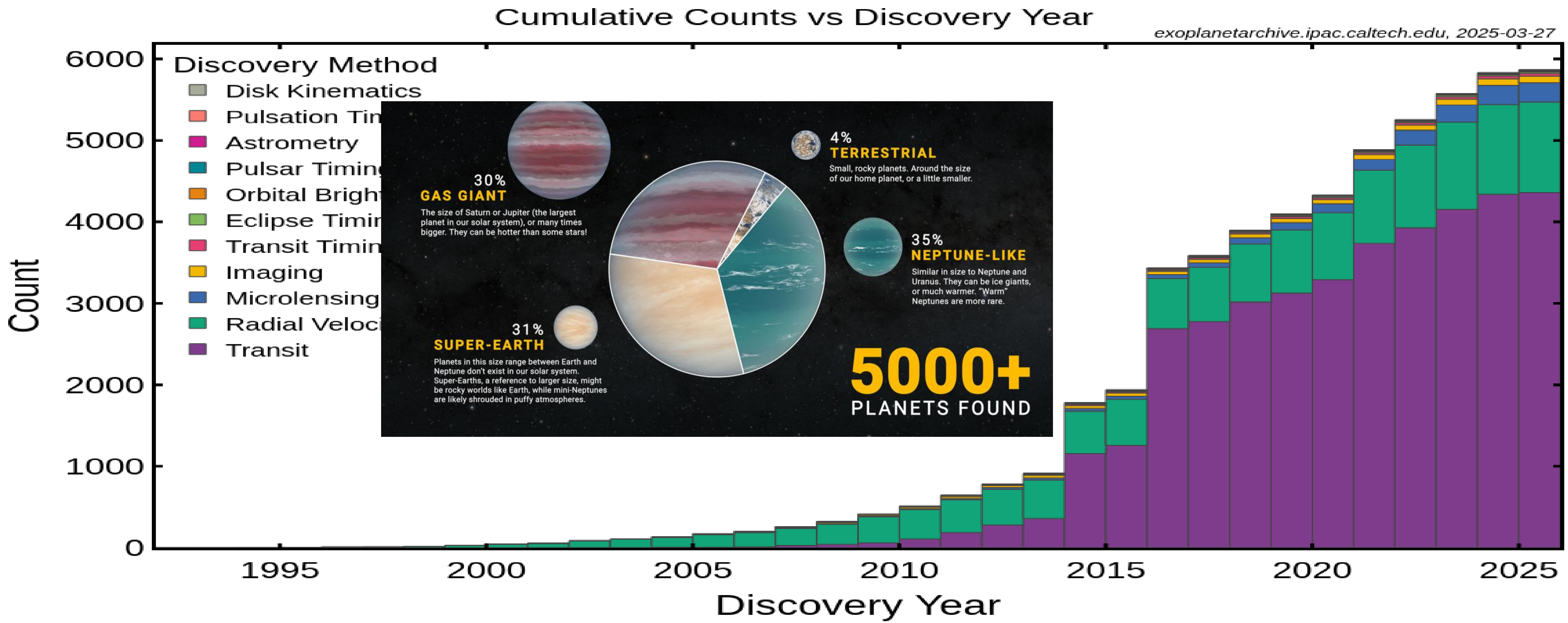

## the Planet Radius Valley

- Revealing the formation and evolution of different planet populations



# Exoplanets: the Era of Planet Census

**By finding thousands of planets, exoplanet field has been revolutionized and entered a new era of exoplanet census.**



# Outline

1. **Research Background**

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# LAMOST

Large sky Area Multi-Object Fiber Spectroscopy Telescope


- Features: Large field of view (20 square degrees), Multi-object (4000 fibers).
- over 20 million spectra, nearly 3 times the sum of other international survey telescopes).
- 2012-2017: first phase of scientific observations.
- 2018-2023: second phase of scientific observations.
- 2024- : third phase of scientific observations.

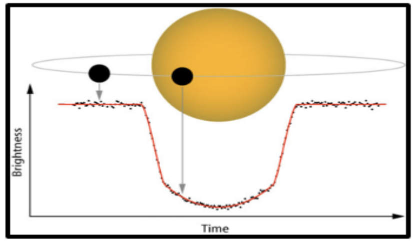
# Why LAMOST ?

**Exoplanet census needs star census**

Know thy star, know thy planet

(1) To accurately characterize planets (2) To reveal the star-planet relations

**Photometry**

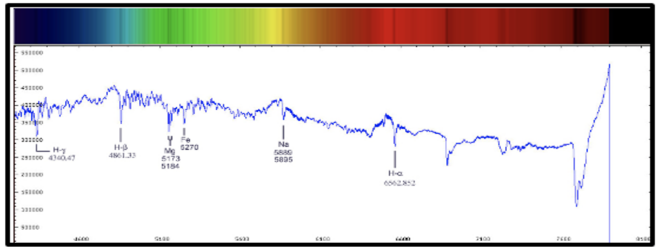



Ground ： WASP, HATNet
Space ： CoRot, Kepler, TESS

Find candidates …

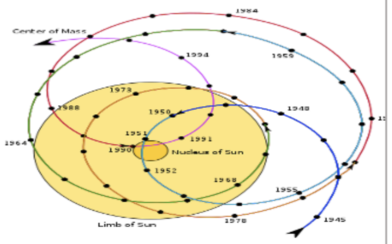
Something is there

**Spectroscopy**



Ground ： LAMOST, HARPS, KecK …
Space ： HST, JWST

**Astrometry**




Gaia …

What (why) they are

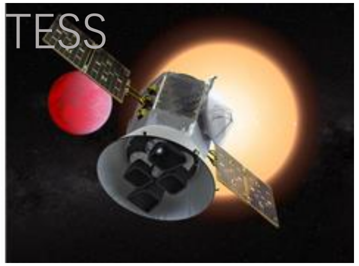
Planetary physical properties （mass， radius）
Planetary orbital properties （a, e, i ..）
Stellar Host properties （mass, age, Fe/H, activity, RV, dis）
Stellar environments (thin/thick disk, halo)

# LAMOST – Kepler– Gaia Synergy

## 光谱Spectroscopy

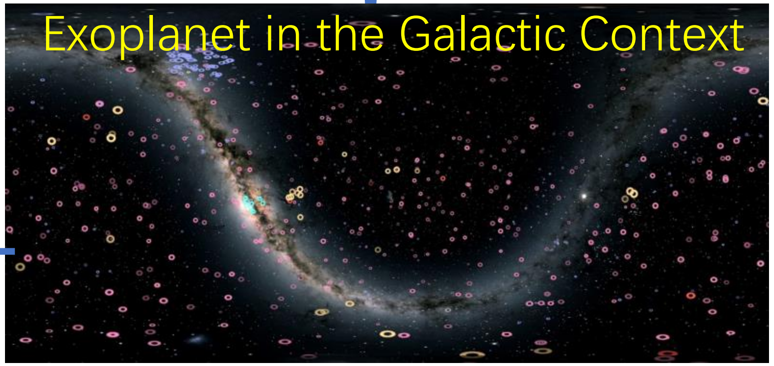

Teff,
logg,
RV,
Fe/H
…

## 测光 Photometry


## 天测Astrometry

Distance,
Proper
Motion
…


**Planet Census**
**In the Milky Way**

银河系的大背景下
行星普查

- Planetary Properties as functions of Galactic Environments (e.g., Thin/Thick disks)
- Planetary Properties as functions of Time (Kinematic age, Isochrone age, Rotation age)

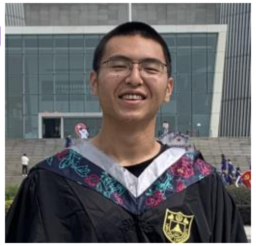
# NJU Exoplanet Census Team: "PAST" Group

Di-Chang CHEN
陈迪昌

Joined SYSU

Jia-Yi YANG
杨佳祎

Pei-Wei TU
涂培玮

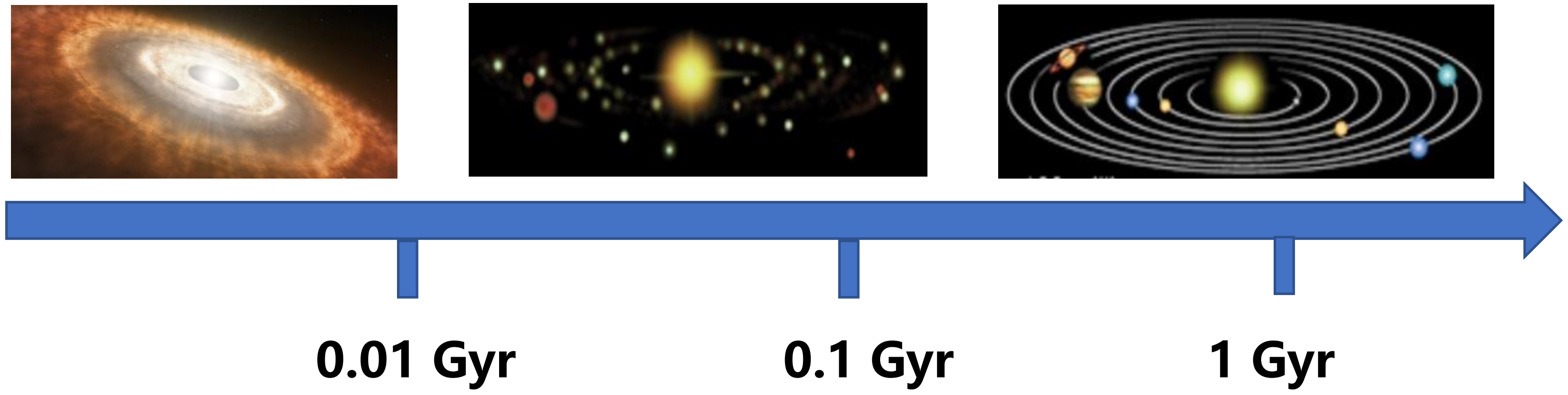


Di WU
武迪

“穿越”系列

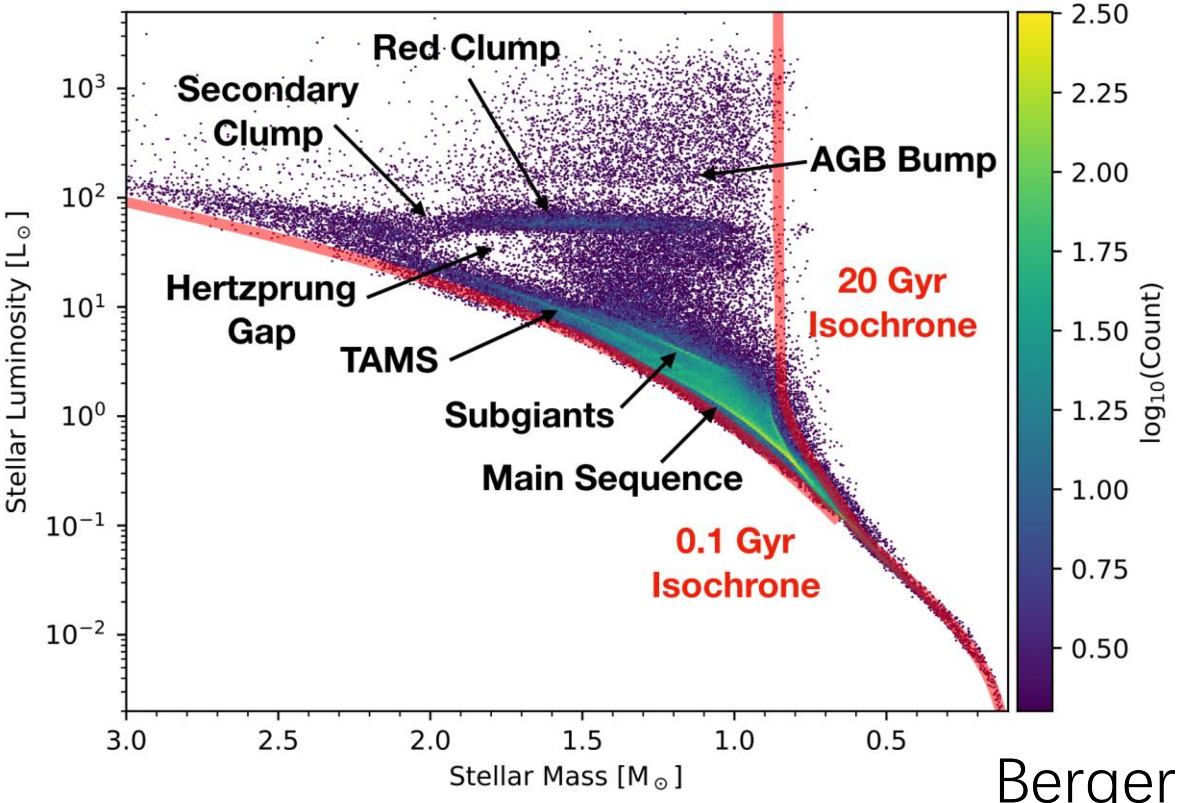
**P**lanets **A**cross **S**pace and **T**ime (**PAST**)

**To Reveal the Observational Evidences of Planetary Evolution**

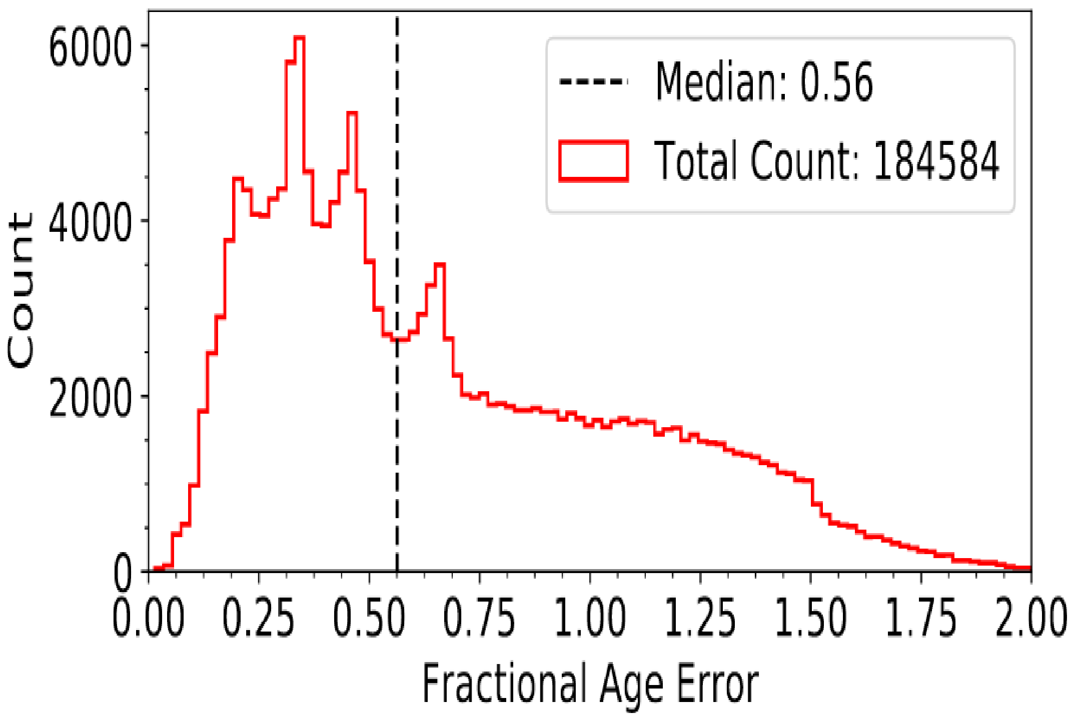


# Challenges of the Research

Age is crucial, but estimating age, especially the age of exoplanet host stars (main sequency), is not an easy task.




**median error 56%**

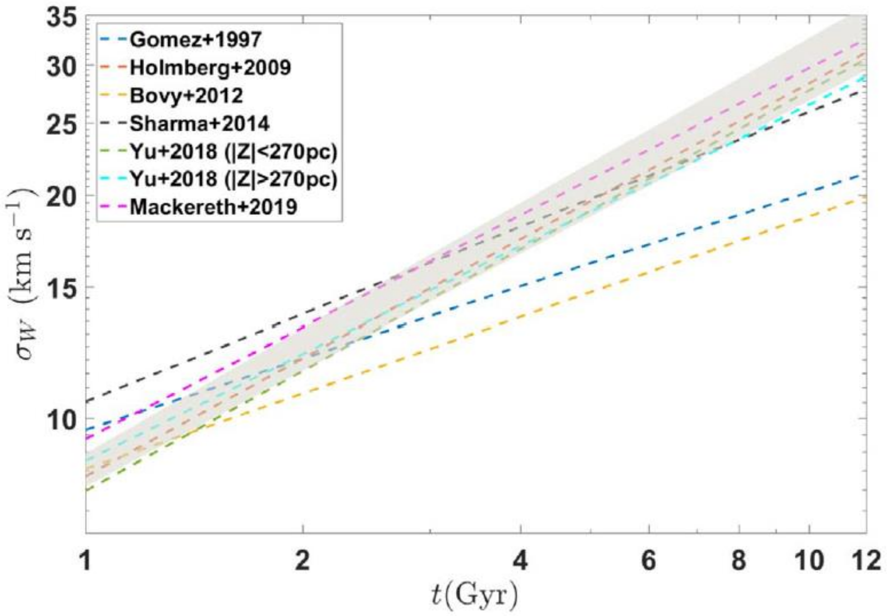



Berger et al. 2020

# PAST Approach: Kinematic Age

## A Well Calibrated Age-Velocity Relation based on LAMOST and Gaia

Reducing the age error from approximately 50% to 15%




Chen et al. 2021 ApJ


**Table 6**
The Typical Relative Uncertainties of Parameters and Kinematic Ages Derived by the AVR Using Data from Holmberg et al. (2009) and This Work

| | | This Work | Holmberg et al. (2009) |
|---|---|---|---|
| $U$ | $\Delta k/k$ | 2.6% | 10.1% |
| | $\Delta\beta/\beta$ | 4.4% | 20.5% |
| | $\Delta\sigma/\sigma$ | 2.0% | 2.0% |
| | $\Delta t/t$ | 9.7%–14.1% | 31.6%–64.1% |
| $V$ | $\Delta k/k$ | 3.7% | 9.4% |
| | $\Delta\beta/\beta$ | 4.1% | 13.8% |
| | $\Delta\sigma/\sigma$ | 3.5% | 3.5% |
| | $\Delta t/t$ | 11.8%–20.1% | 23.32%–44.4% |
| $W$ | $\Delta k/k$ | 5.2% | 14.1% |
| | $\Delta\beta/\beta$ | 3.7% | 12.3% |
| | $\Delta\sigma/\sigma$ | 4.1% | 4.1% |
| | $\Delta t/t$ | | |
| $V_{tot}$ | $\Delta k/k$ | | |
| | $\Delta\beta/\beta$ | | |
| | $\Delta\sigma/\sigma$ | 2.4% | 2.4% |
| | $\Delta t/t$ | 9.2%–16% | 27.4%–54.1% |

reduce the internal error !

vs

# Plan of the PAST

## Methods and Catalogs

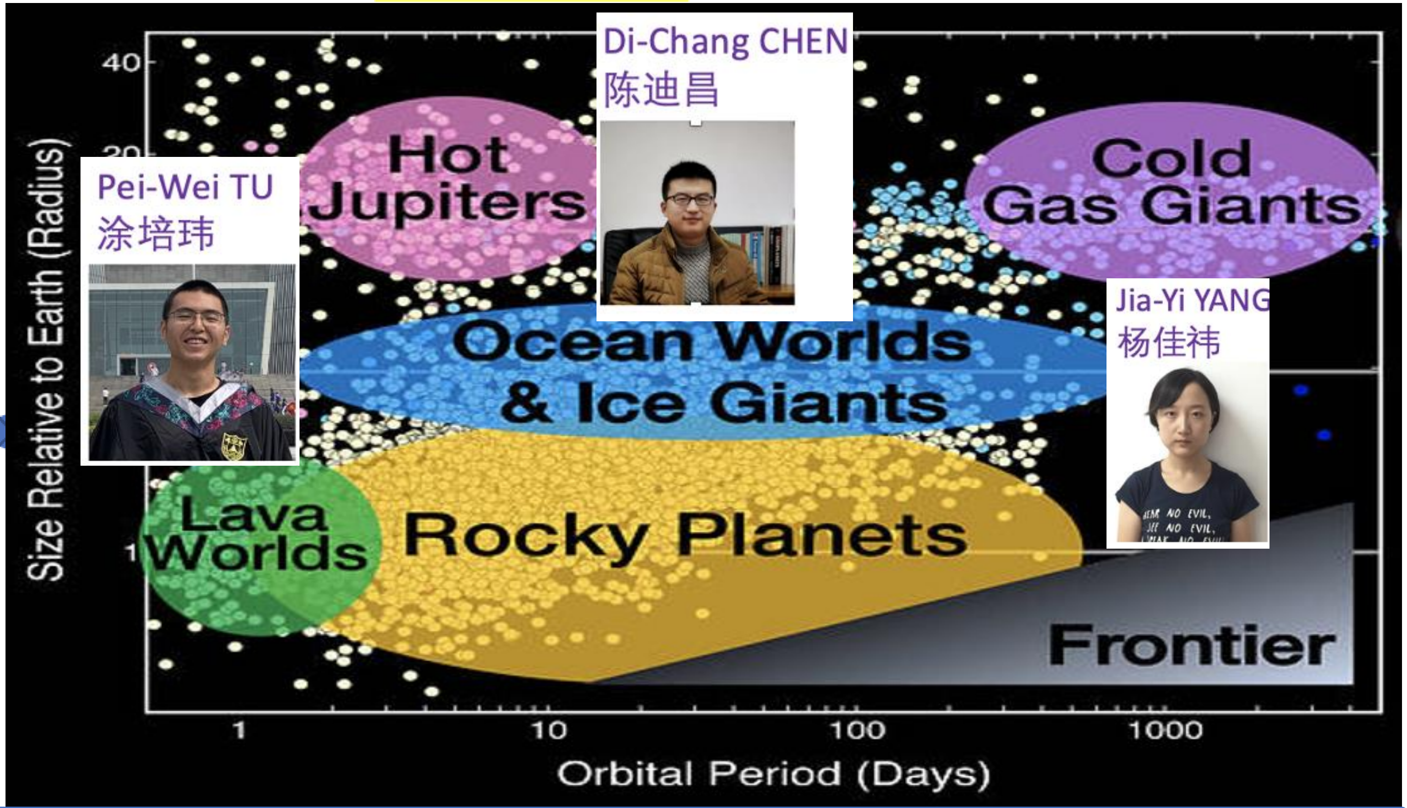
**PAST-1**: Characterizing the Memberships of Galactic Components and Stellar Ages: Revisiting the Kinematic **Methods** and Applying to Planet Host Stars

Chen +2021 ApJ

**PAST-2**: **Catalog** and Analyses of the LAMOST-Gaia-Kepler Stellar Kinematic Properties

Chen + 2021 AJ

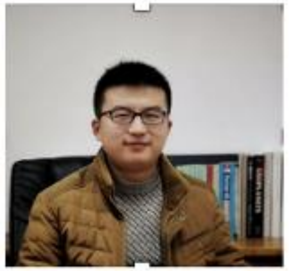
## Applications



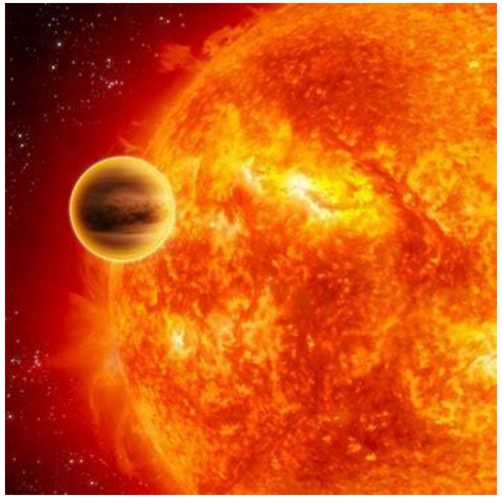

**PAST-3 & 4:** Applications to Super-Earths & Sub-neptunes; (Chen+2022 AJ, Yang+2023 AJ)
**PAST-5 & 7:** Applications to Hot Jupiters; (Chen+2023 PNAS, Chen+2025 Accepted by Nature Astronomy)
**PAST-6:** Application to USP planets (Tu+2025 Nature Astronomy)

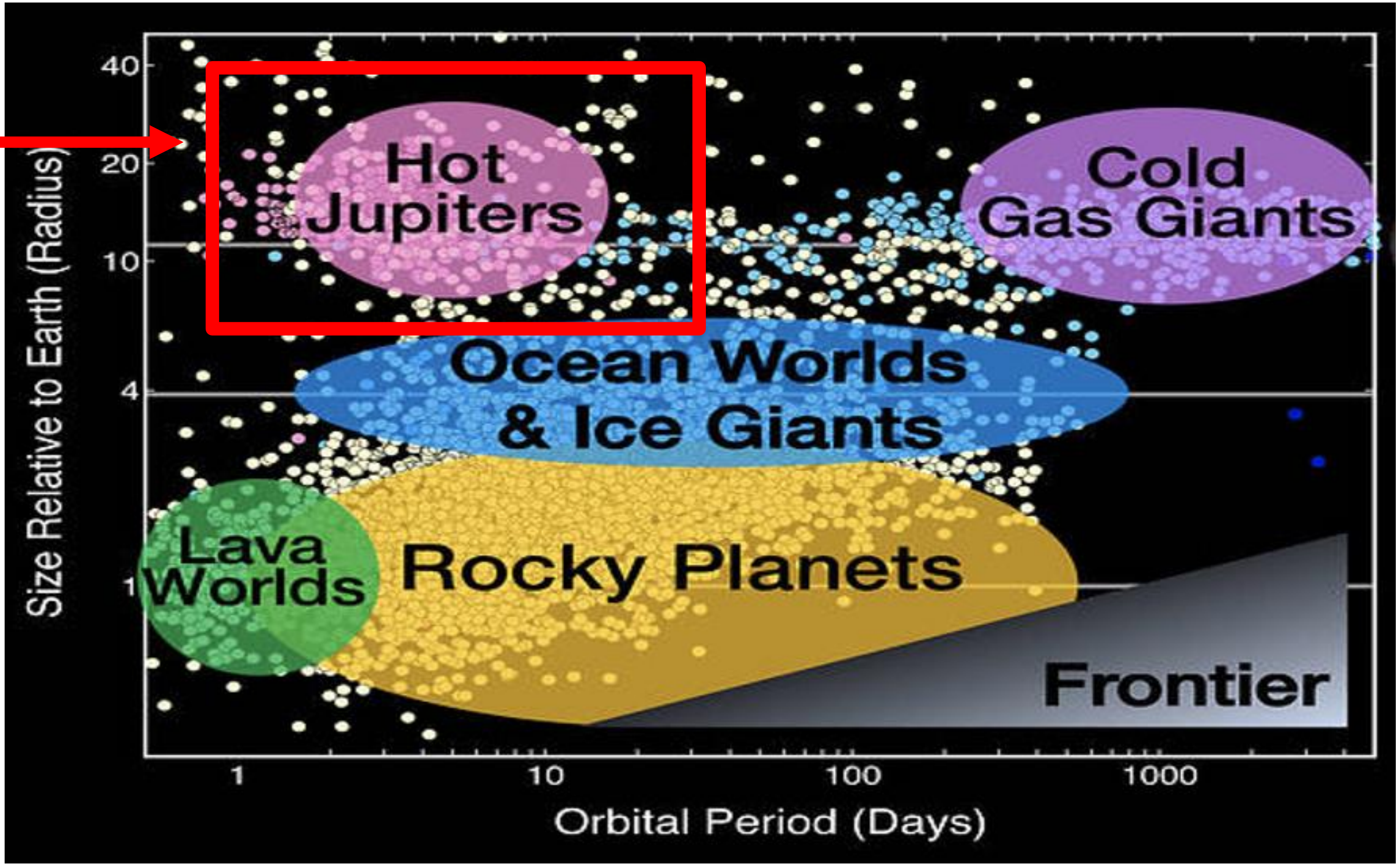
# Hot Jupiters

Di-Chang CHEN
陈迪昌



LAMOST Fellow





# The First Discovery of Hot Jupiter

nature
International journal of science

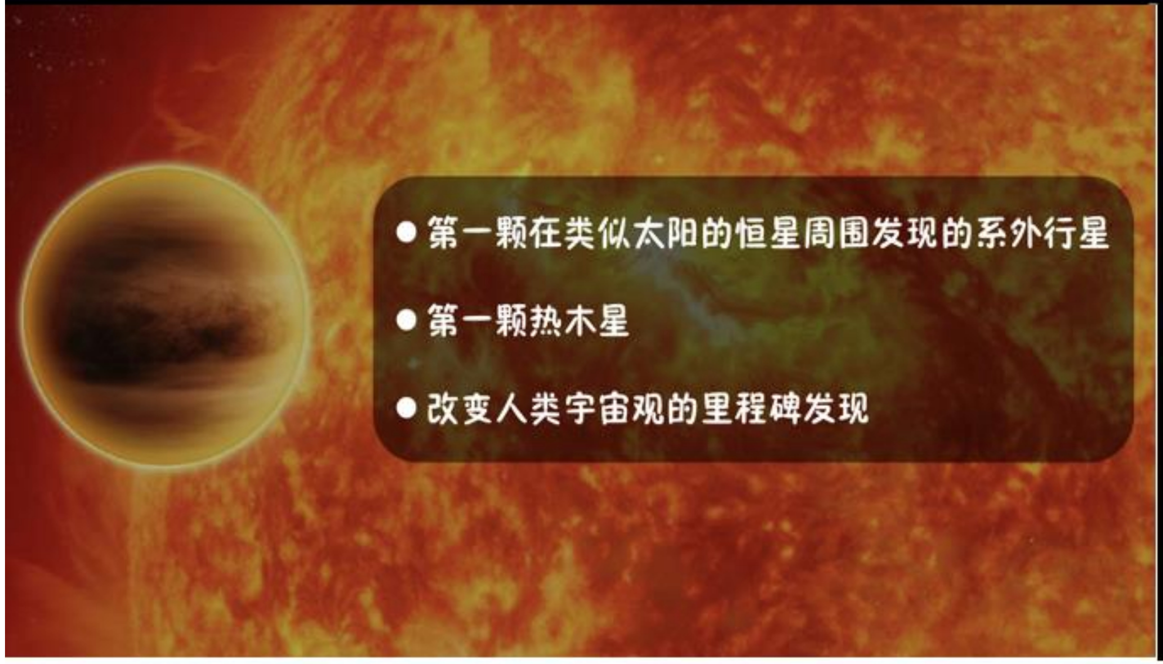
2019诺贝尔物理学奖

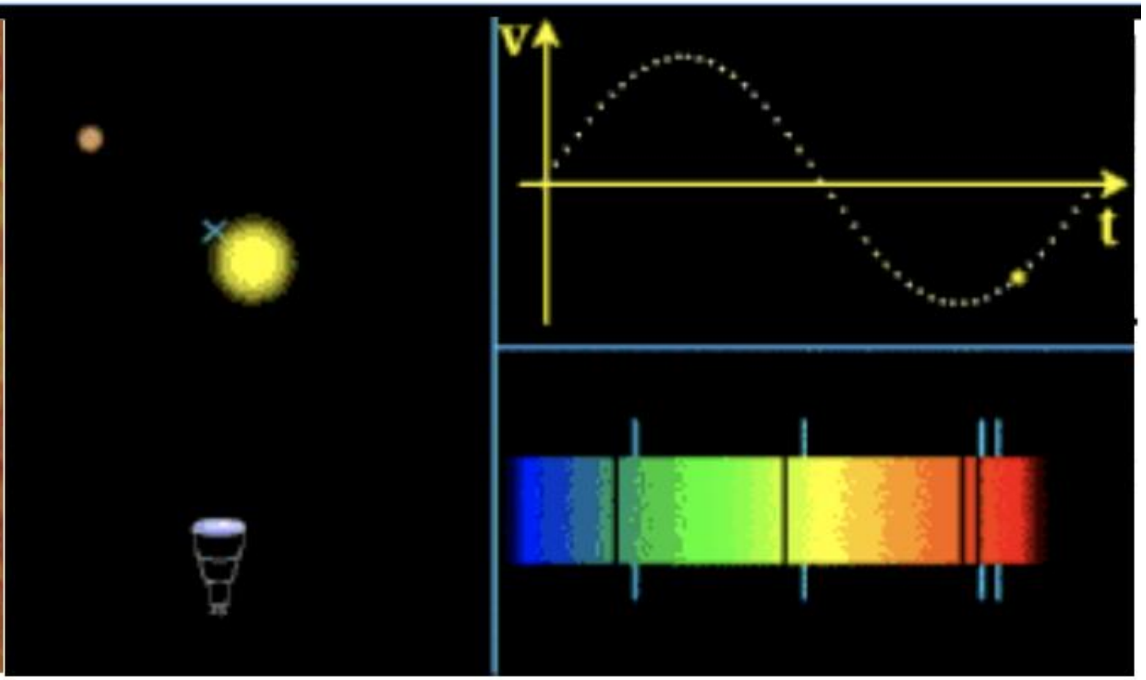
Article | Published: 23 November 1995

## A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

揭开了系外行星探测研究的序幕

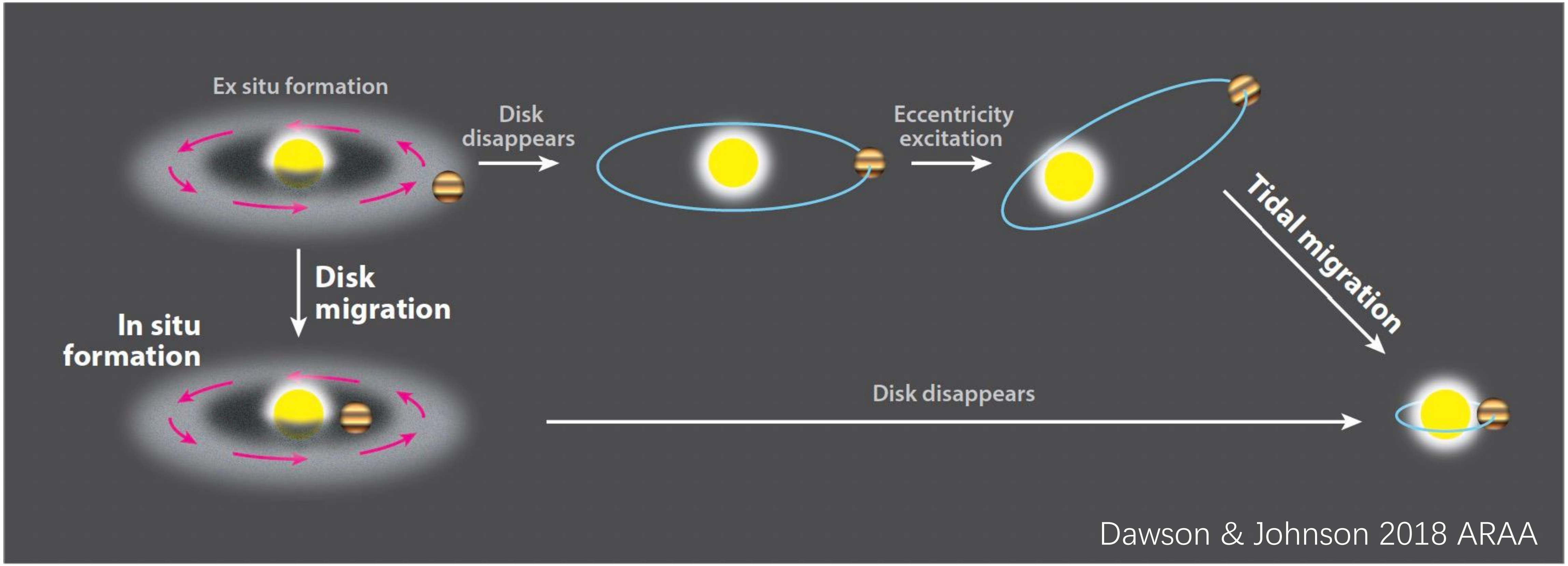


# The Mystery of Hot Jupiters (1)

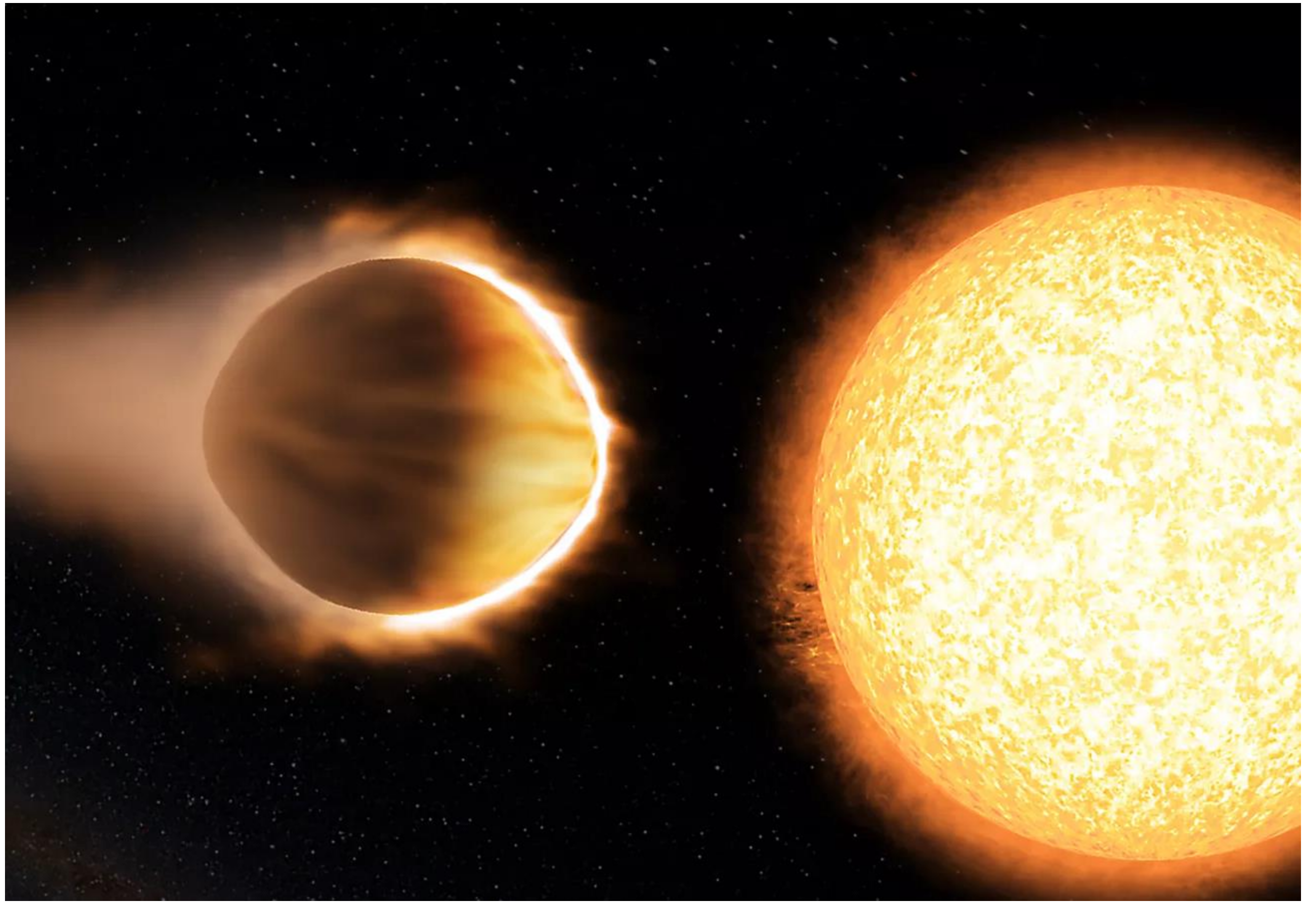
## How do hot Jupiters form?

lack of important observational evidences to distinguish between various models



# The Mystery of Hot Jupiters (2)

Will Hot Jupiters crash into the Stars ?



**Tidal theory：YES!**

BUT：lack large-sample observational evidence

WASP-12 b is currently the only one with solid evidence on orbital decay (Yee et al. 2020)

# The Mystery of Hot Jupiters (3)

## Contradiction on the Occurrence of Hot Jupiter

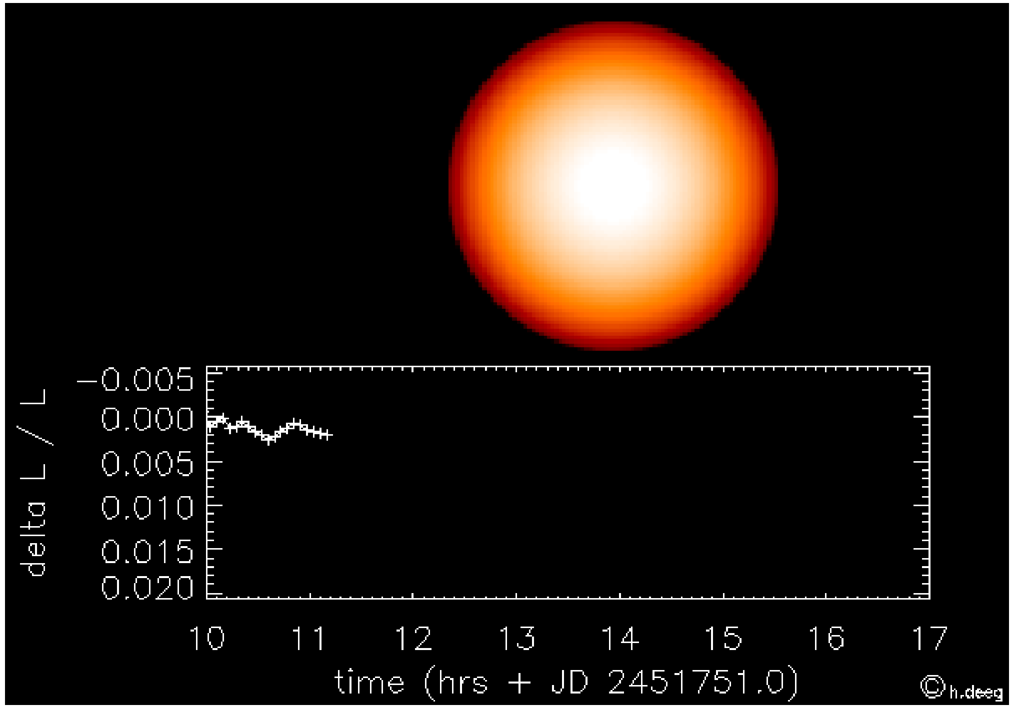
Gould+06, Howard+12, Santerne+16

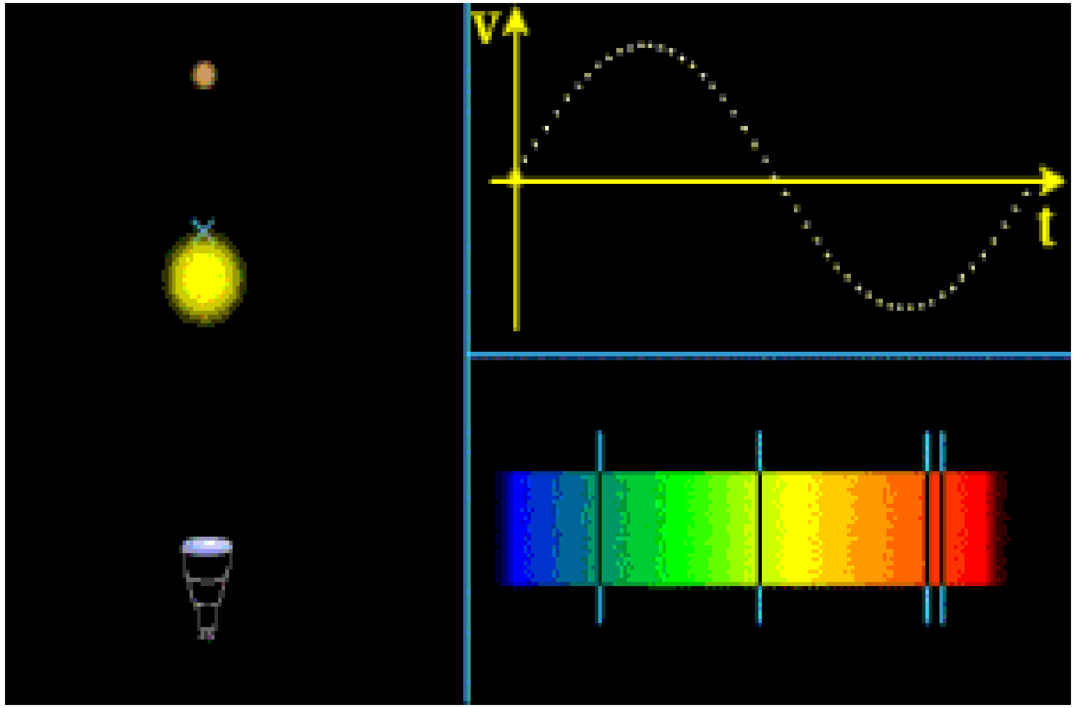
**Transit: $F_{HJ} \sim 0.5\%$**

≠

Cumming+08, Mayor+11, Wright+12

**Radial Velocity: $F_{HJ} \sim 1\%$**

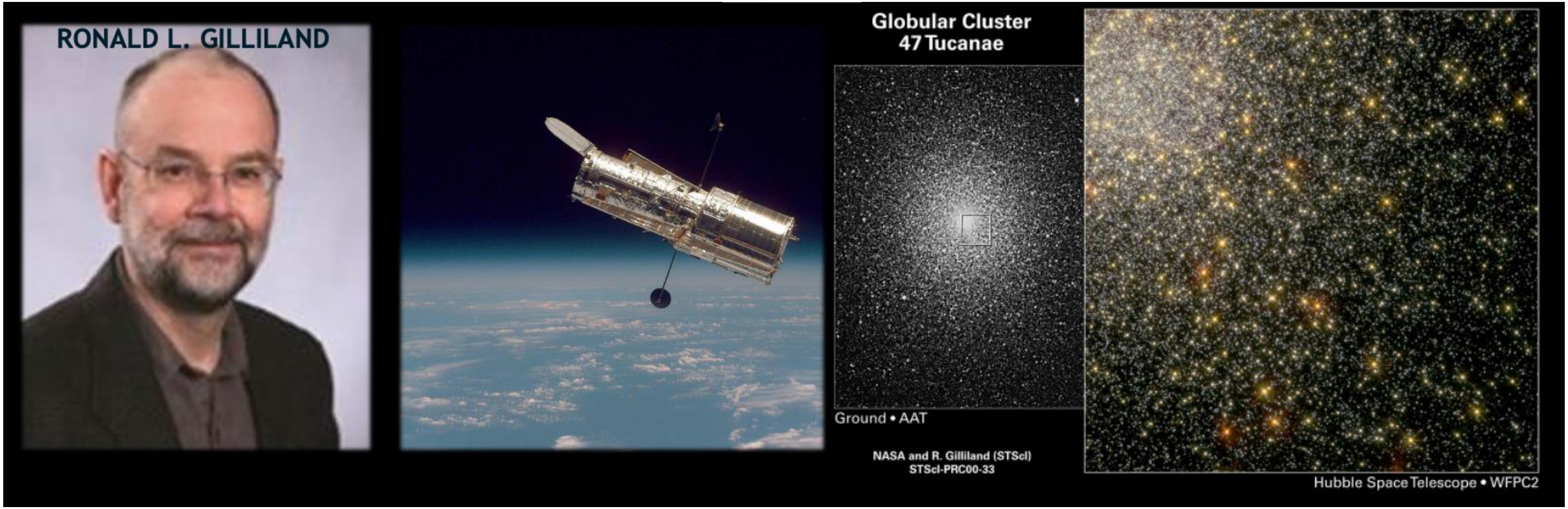


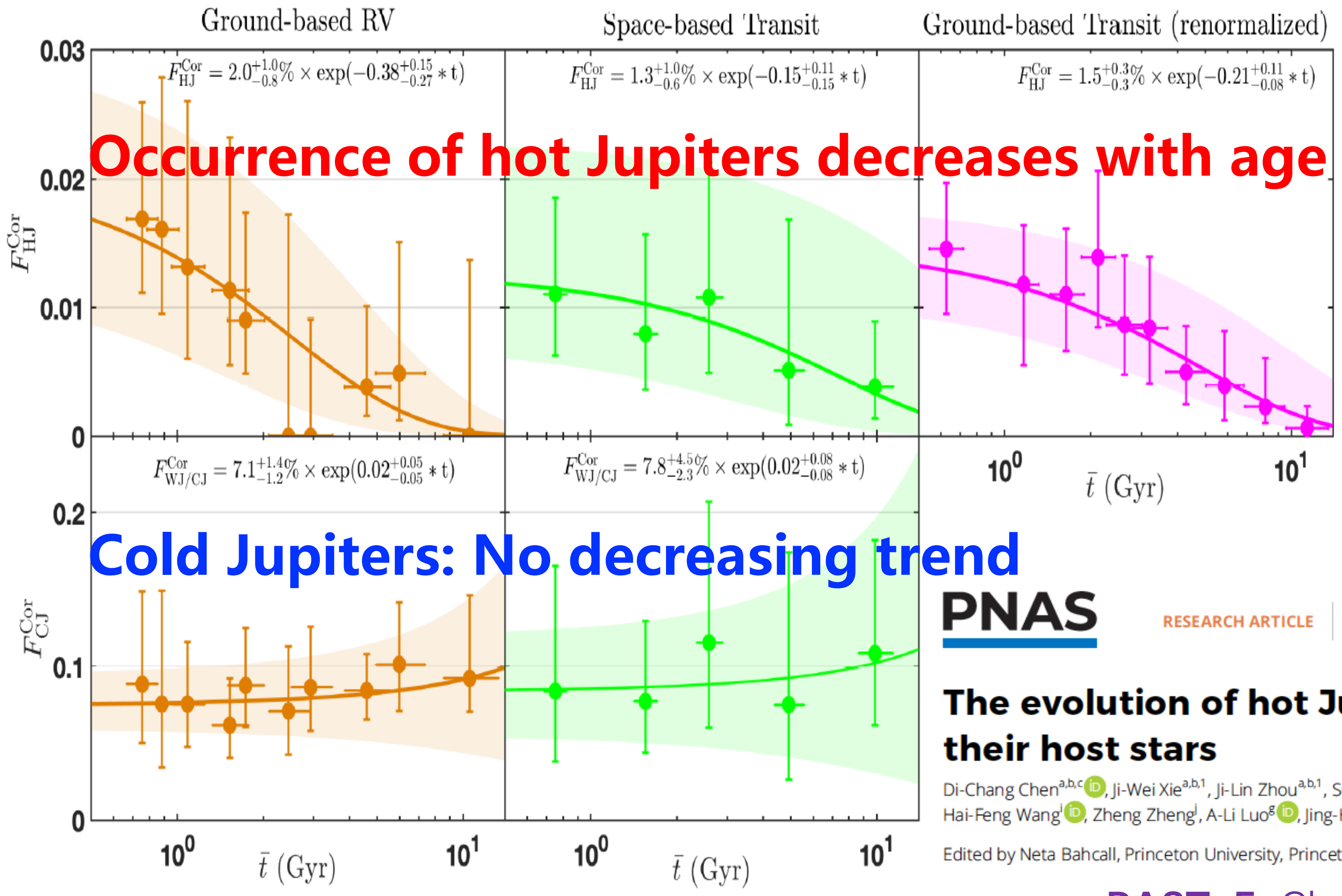
# The Mystery of Hot Jupiters (4)

## Searching for hot Jupiters in Globular Clusters

**Expected： 17 ≠ Result： 0 !** Gilliland et al. (2003)

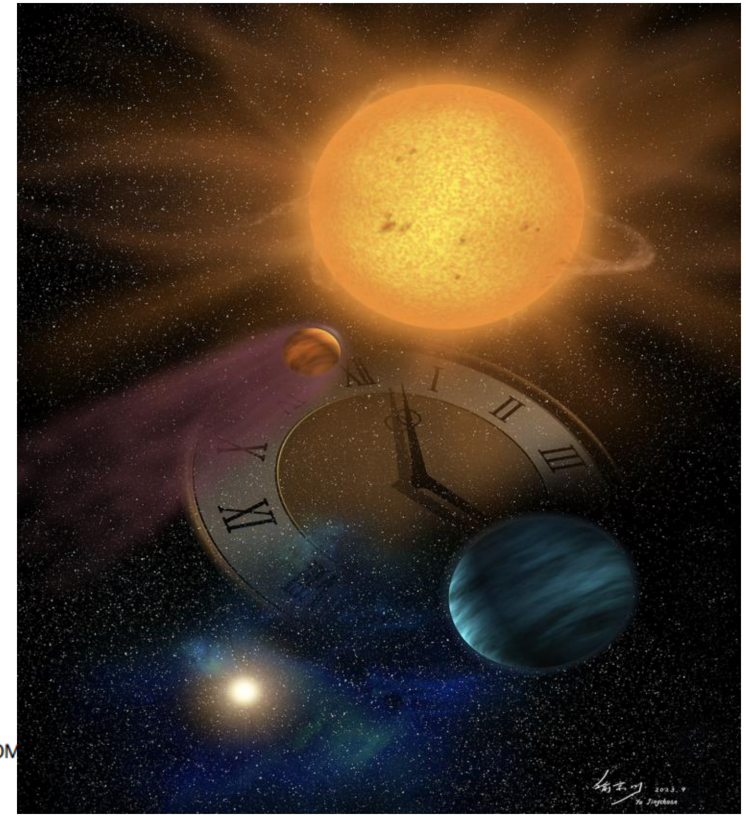


# Hot Jupiters are Decaying




**Occurrence of hot Jupiters decreases with age**

**Cold Jupiters: No decreasing trend**



PNAS RESEARCH ARTICLE | ASTRONOM

Check for updates

## The evolution of hot Jupiters revealed by the age distribution of their host stars


Di-Chang Chen[a,b,c], Ji-Wei Xie[a,b,1], Ji-Lin Zhou[a,b,1], Subo Dong[d,e,1], Jia-Yi Yang[a,b], Wei Zhu[f], Chao Liu[g], Yang Huang[g,h], Mao-Sheng Xiang[g], Hai-Feng Wang[i], Zheng Zheng[j], A-Li Luo[g], Jing-Hua Zhang[g], and Zi Zhu[a,b]



Edited by Neta Bahcall, Princeton University, Princeton, NJ; received March 15, 2023; accepted August 15, 2023

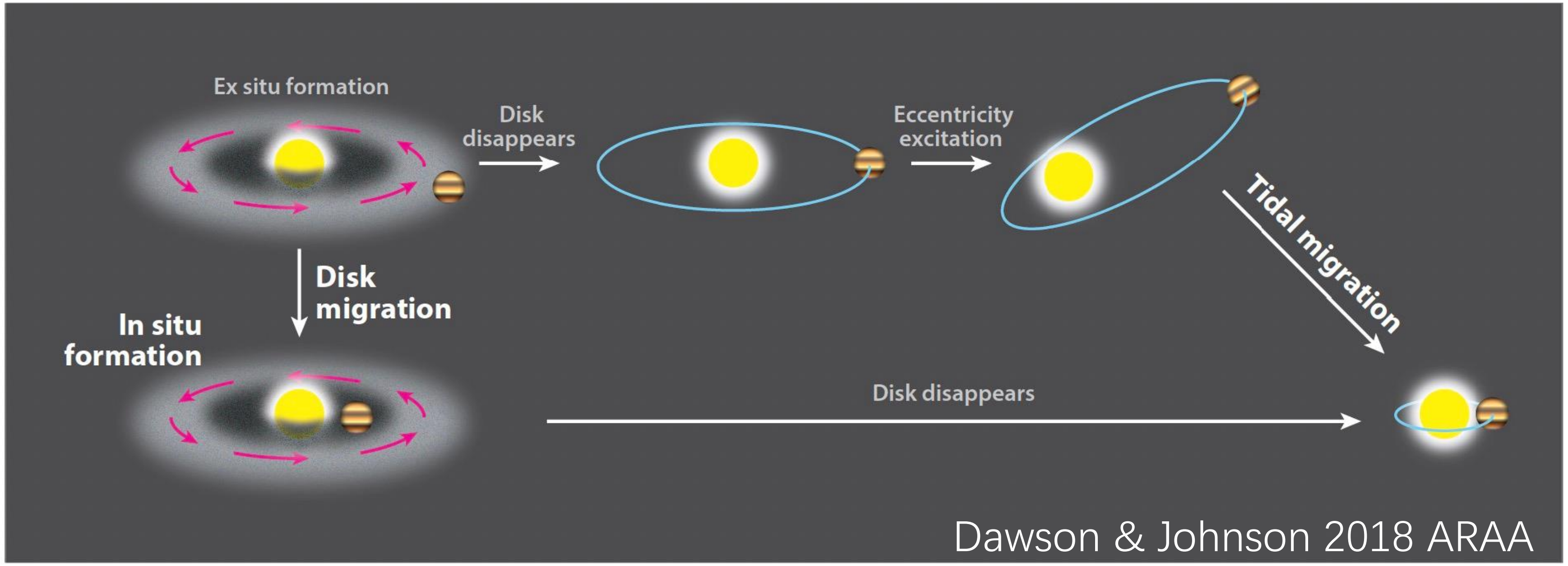

**PAST-5**: Chen, **Xie** & Zhou et al. 2023 **PNAS**

# Implications

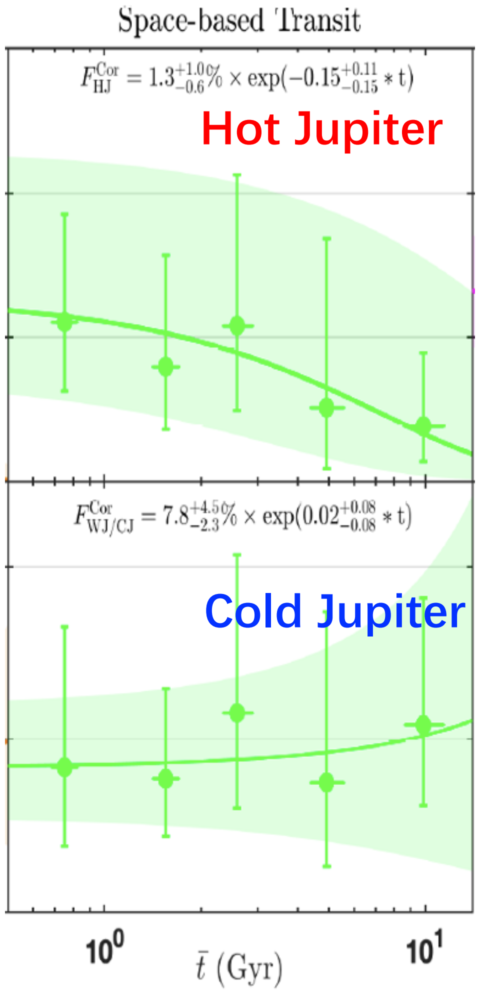
**Mystery(1): How do HJ form?**

**PAST-5:** Chen, **Xie** & Zhou et al. 2023 **PNAS**

**Answer (1) : Providing time constraint for the formation mechanism, and the majority of hot Jupiters should form within ~1 Gys**




Dawson & Johnson 2018 ARAA

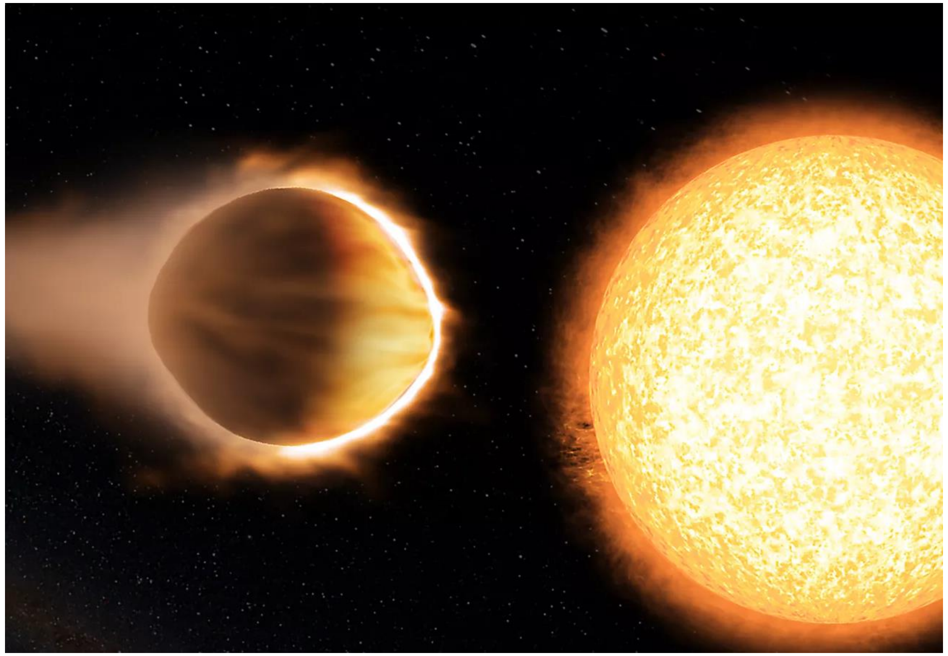


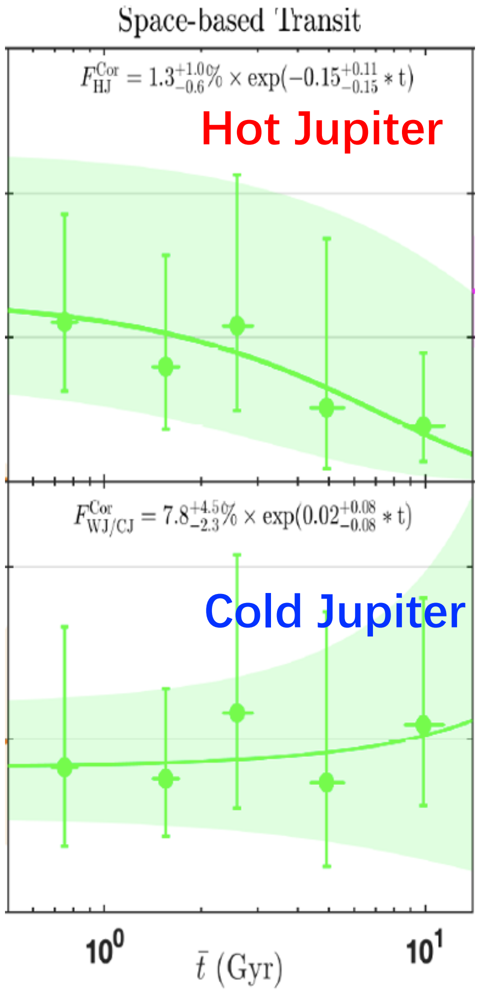
# Implications

PAST-5: Chen, **Xie** & Zhou et al. 2023 **PNAS**

## Mystery(2): HJ crash into the Stars ?

**Answer (2):** **Yes! Providing large-sample evidence of hot Jupiters being engulfed due to tidal evolution. Provide observational constraints for stellar tidal factors.**





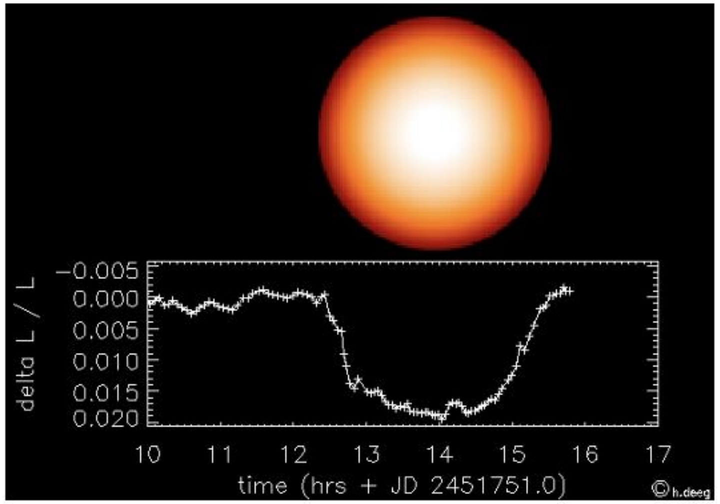
# Implications

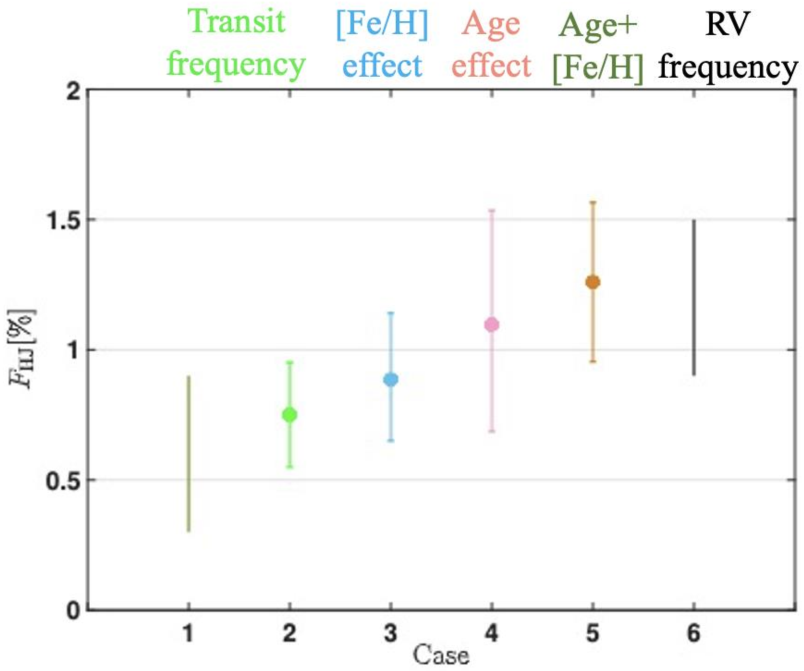
**Mistery (3): Why are the occurrence rates for HJ different?**

**Answer (3): Because the RV sample are metal richer and younger.**

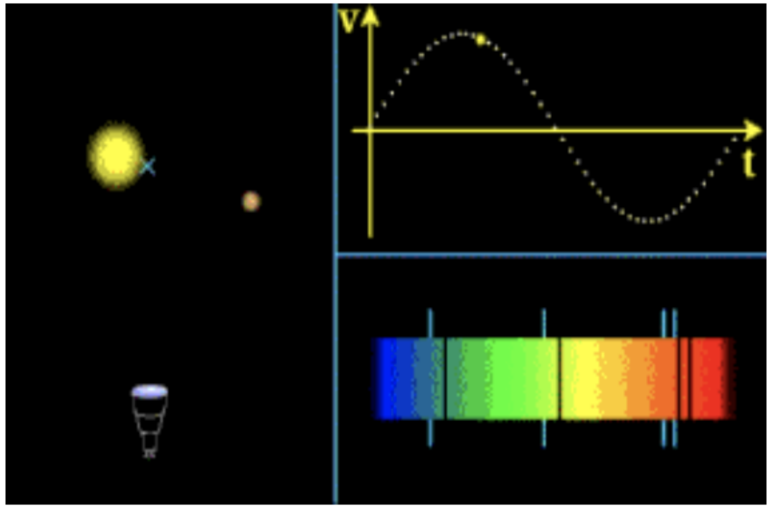
PAST-5: Chen, **Xie** & Zhou et al. 2023 **PNAS**

**Transit: $F_{HJ}$ ~ 0.5%**




**Radial Velocity: $F_{HJ}$ ~ 1%**

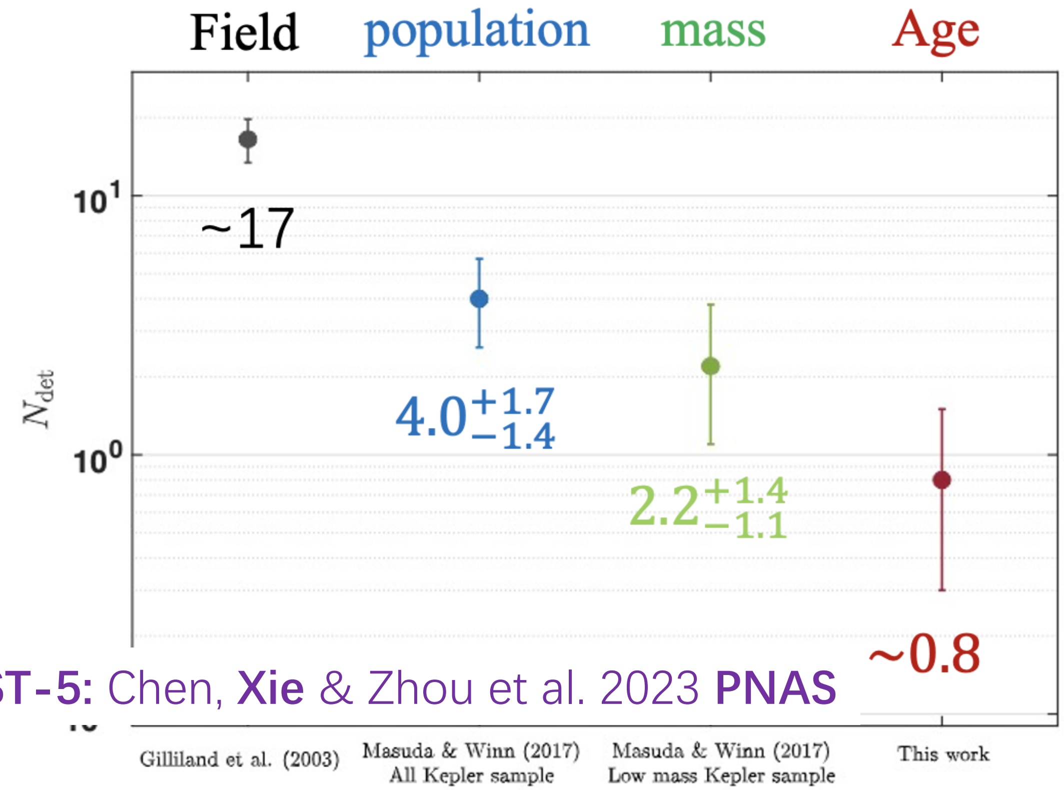


# Implications

**Mystery(4)： Zero detection of HJ in globular cluster ？**

**Answer (4)： Because globular clusters are too old, and most hot Jupiters have already been engulfed.**

47 Tucanae : Globular cluster ,
low [Fe/H] , low-mass, ～11.6 Gyr

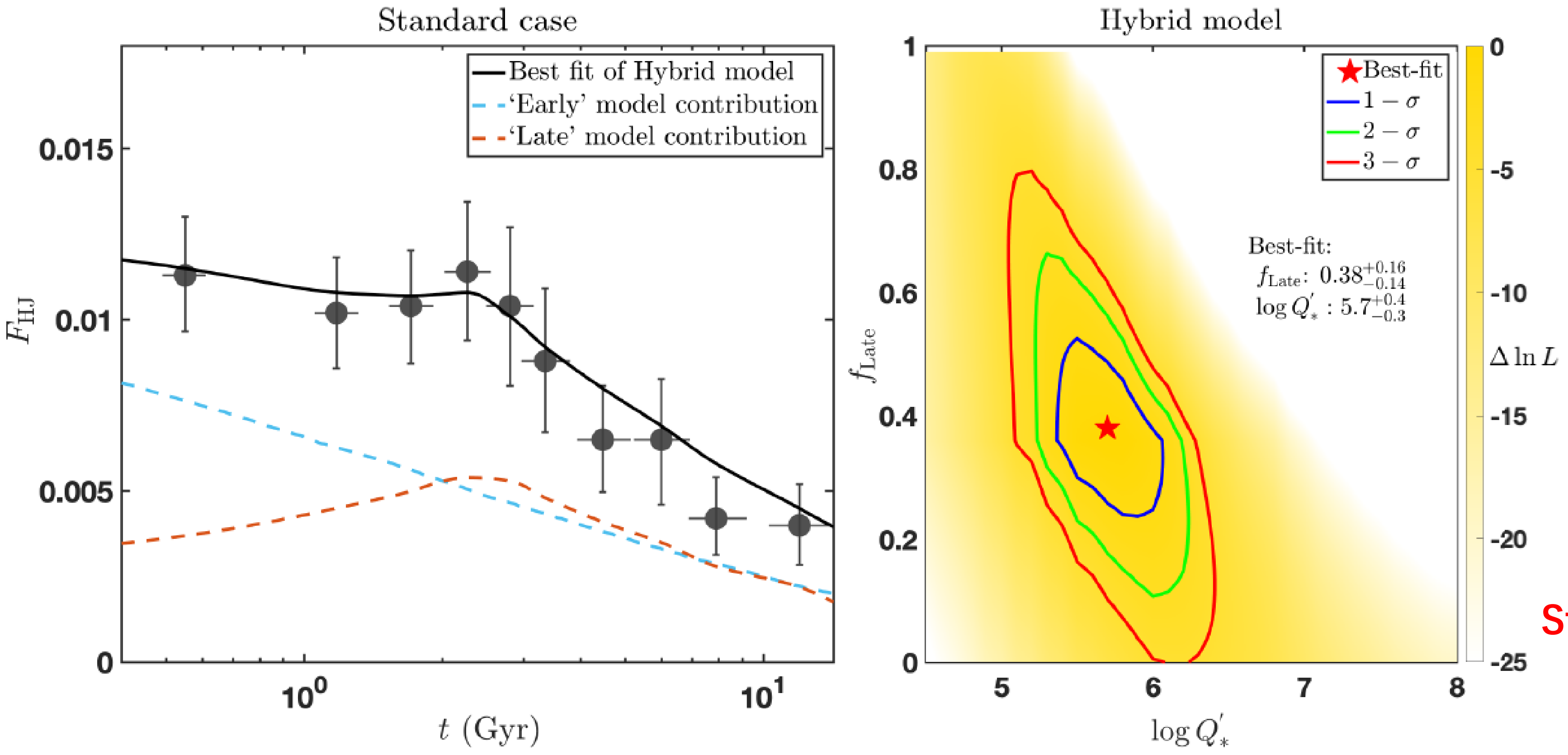



**PAST-5:** Chen, **Xie** & Zhou et al. 2023 **PNAS**

# New Progress !

Hot Jupiter Origin and Tidal Evolution
Constrained by a Broken Age–Frequency Relation

**PAST-7:** Chen, **Xie***, Zhou et al. 2025 **Nature Astronomy**, accepted

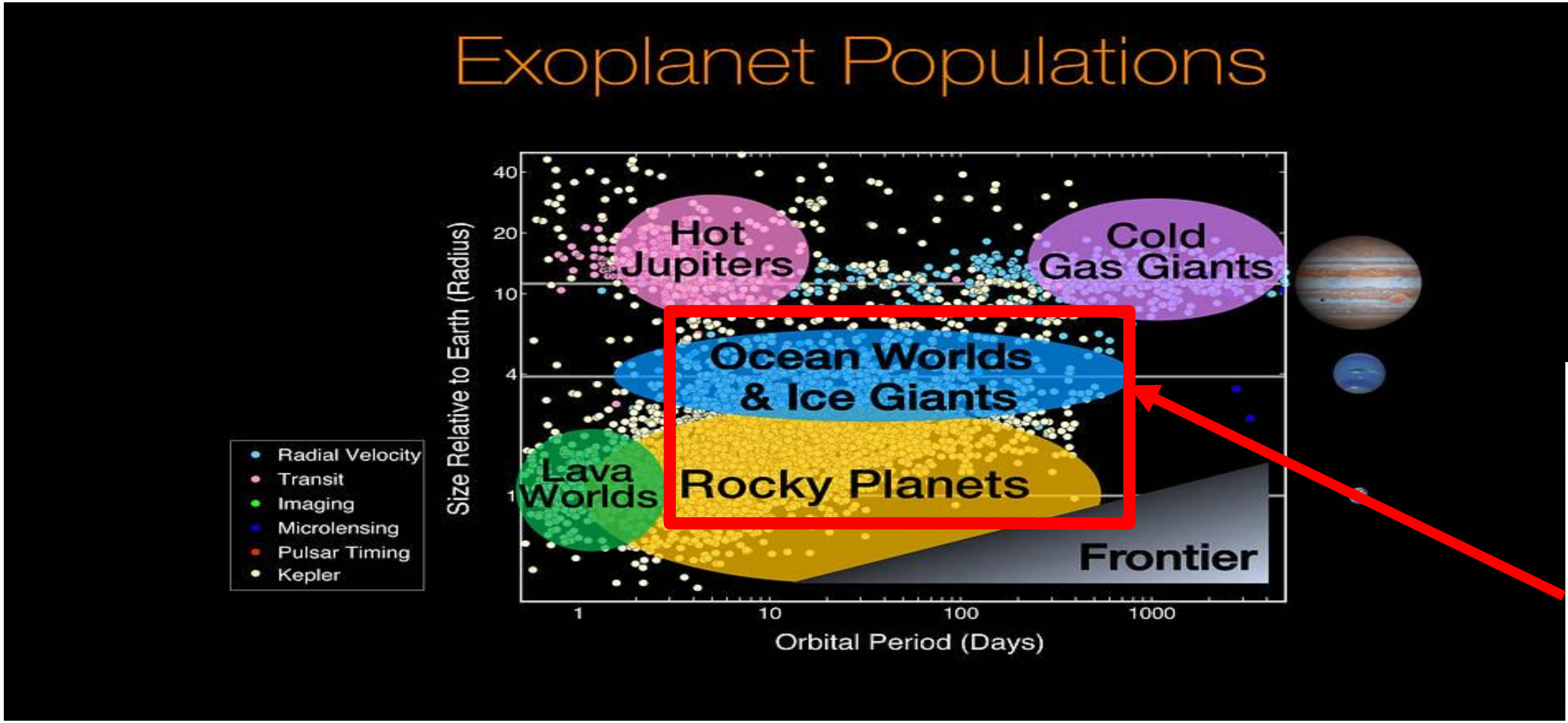



Quick model: ~ 60%
Timescale within < 0.1 Gyr
In-situ formation, disk migrarion
planet scattering/Kozai-Lidov

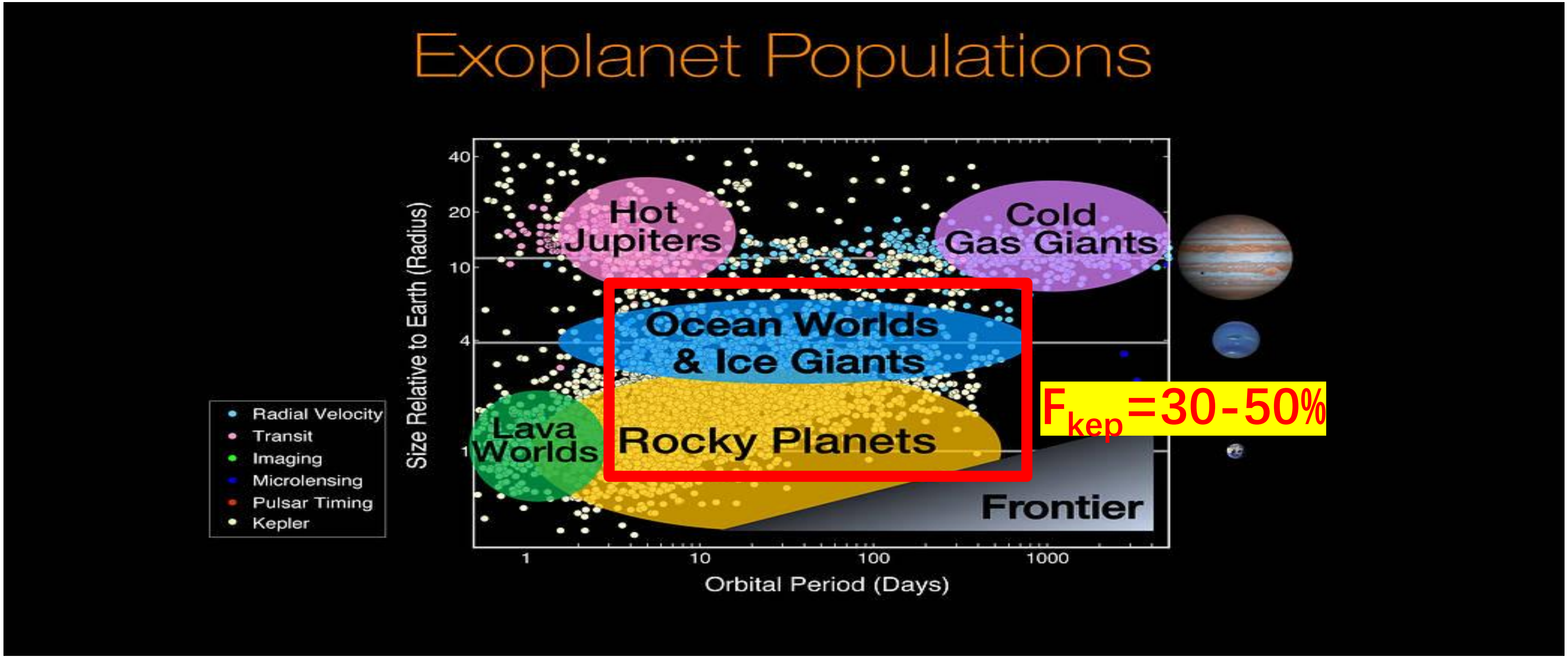
Slow model: ~40%
Timescale from ~0.1-10 Gyr
Secular chaos in multiple systems

**Stellar tidal factor: $\log Q'_* = 5.7^{+0.4}_{-0.3}$**

# Super-Earths / Sub-Neptunes




# Super-Earths / Sub-Neptunes

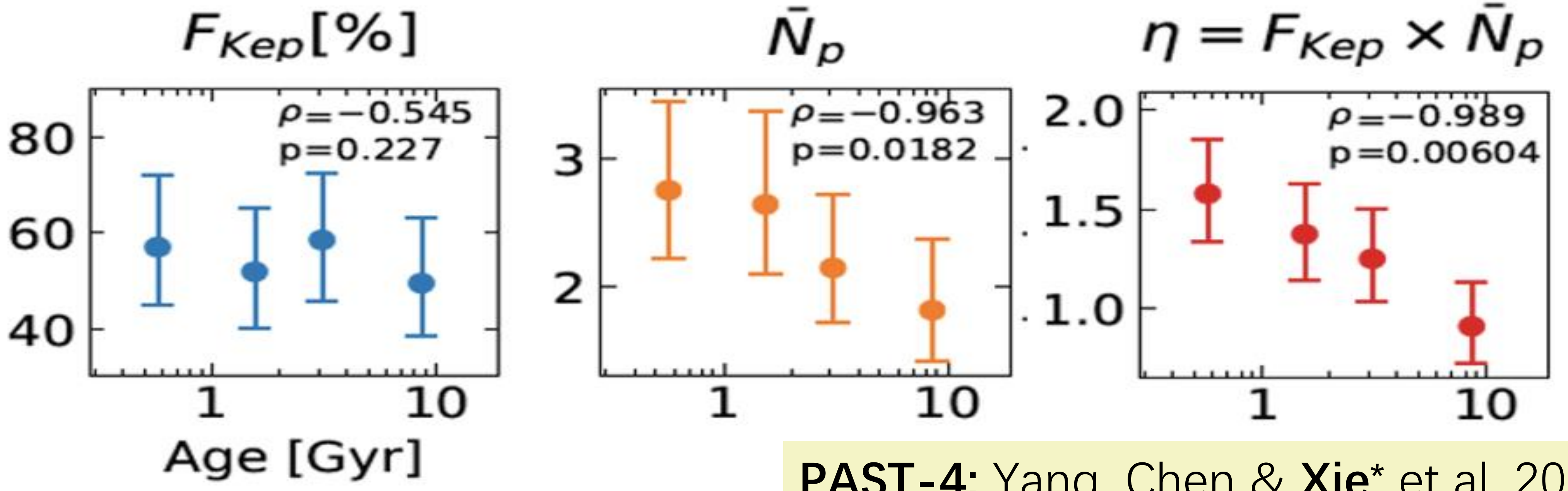



$F_{kep}$=30-50%

see review by Zhu & Dong 2021

# Age dependence of Occurrence and Architecture

**Planet formation is robust and stable across the Galaxy history.**




**PAST-4:** Yang, Chen & **Xie*** et al. 2023 **AJ**

Fraction of stars with Kepler-like planets ($F_{kep}$) is relatively stable around 50%.

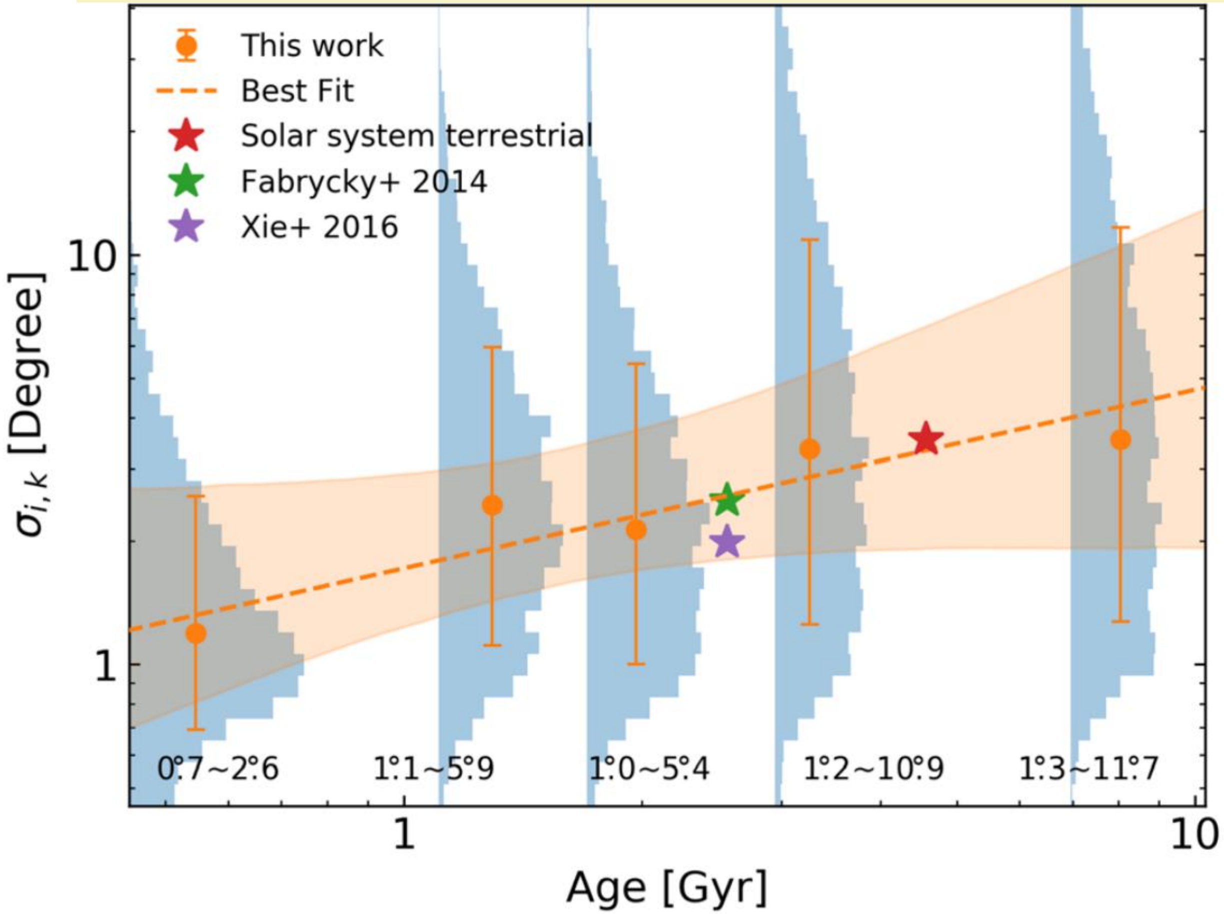
Average planet multiplicity ($Np$) decreases ( ~2σ significance) with age.

Number of planets per star ($\eta$) decreases (~3σ significance) with age.

# Age dependence of Occurrence and Architecture

Orbital inclination dispersion ($\sigma_{i,k}$) generally increases with age.

**PAST-4**: Yang, Chen & **Xie*** et al. 2023 **AJ**



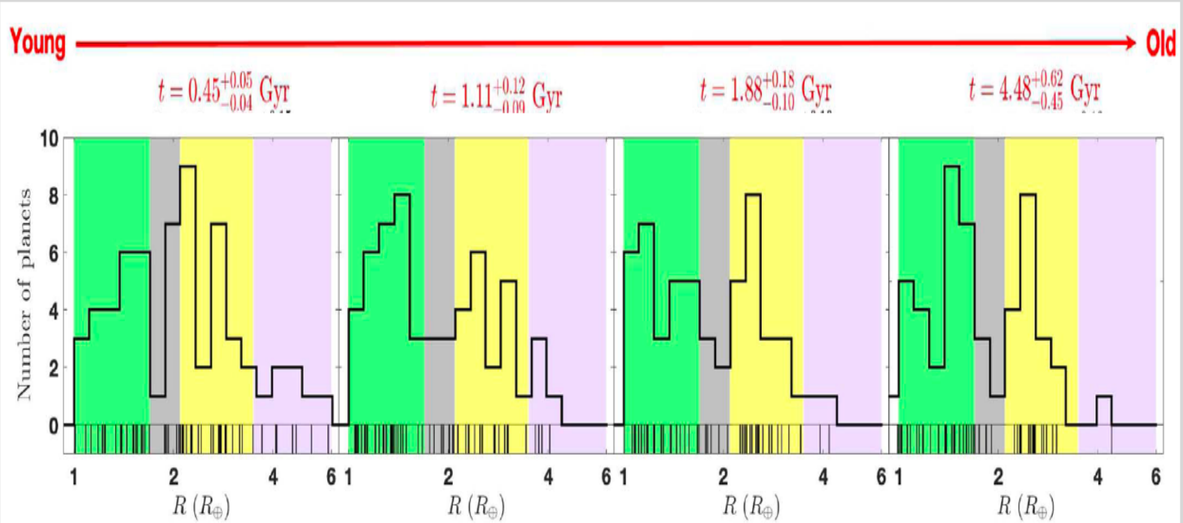

**Inference** →

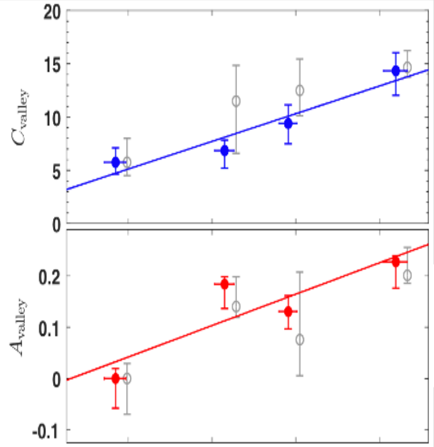
Early Solar System:
more coplanar?
more planets ?

**e.g.， The Planet V model**
(Chambers & Lissauer 02;
Chambers 07; Brasser & Morbidelli)

# The "Radius Valley" is Evolving

**PAST-3**: Chen, **Xie*** et al. 2022 **AJ**




The radius valley emerged before 1 Gyr and the contrast ($C_{valley}$, number ratio of super-Earths plus sub-Neptunes to the valley planets) increase with time.

The asymmetry ($A_{valley}$, the number ratio in logarithm of super-Earths to sub-Neptunes) increase with time.

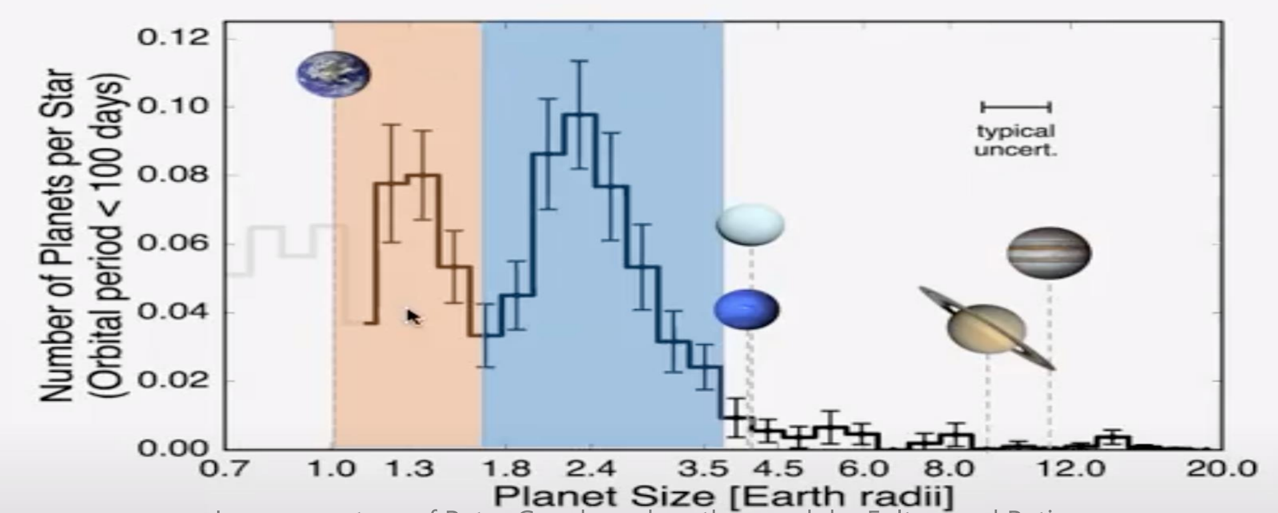
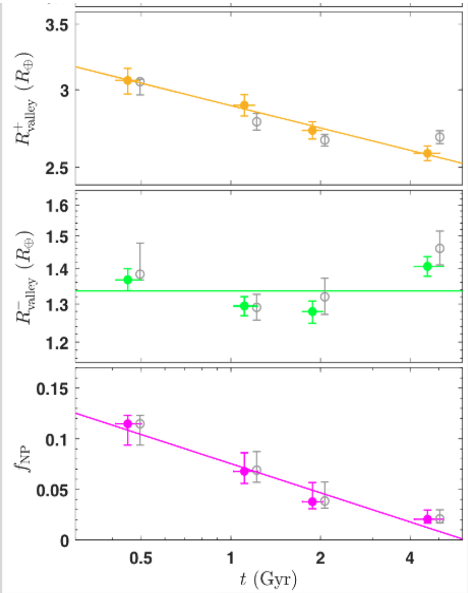



Image courtesy of Peter Gao, based on the graph by Fulton and Petigura



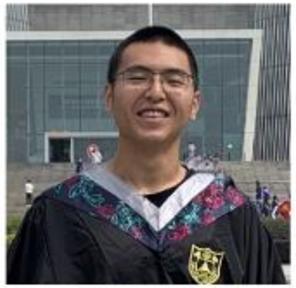

The $R^+_{valley}$ (average radius of planets with size larger than Valley planets) Decrease with time.
(sub-Neptunes are shrinking! Due to cooling?)

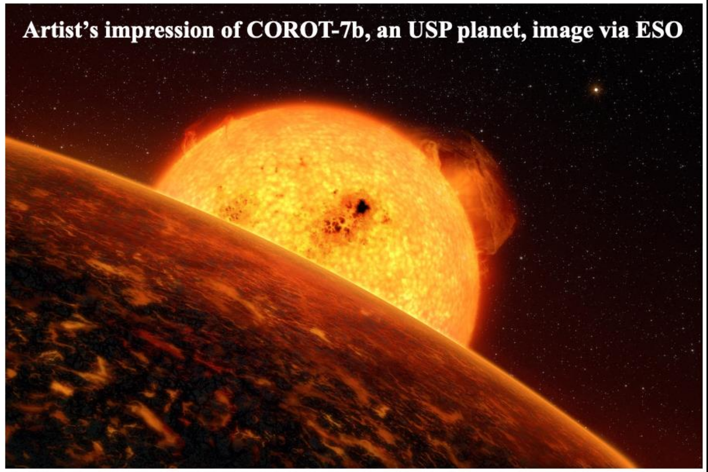
The $R^-_{valley}$ (average radius of planets with size smaller than Valley planets. i.e., super-Earths) does not change significantly.

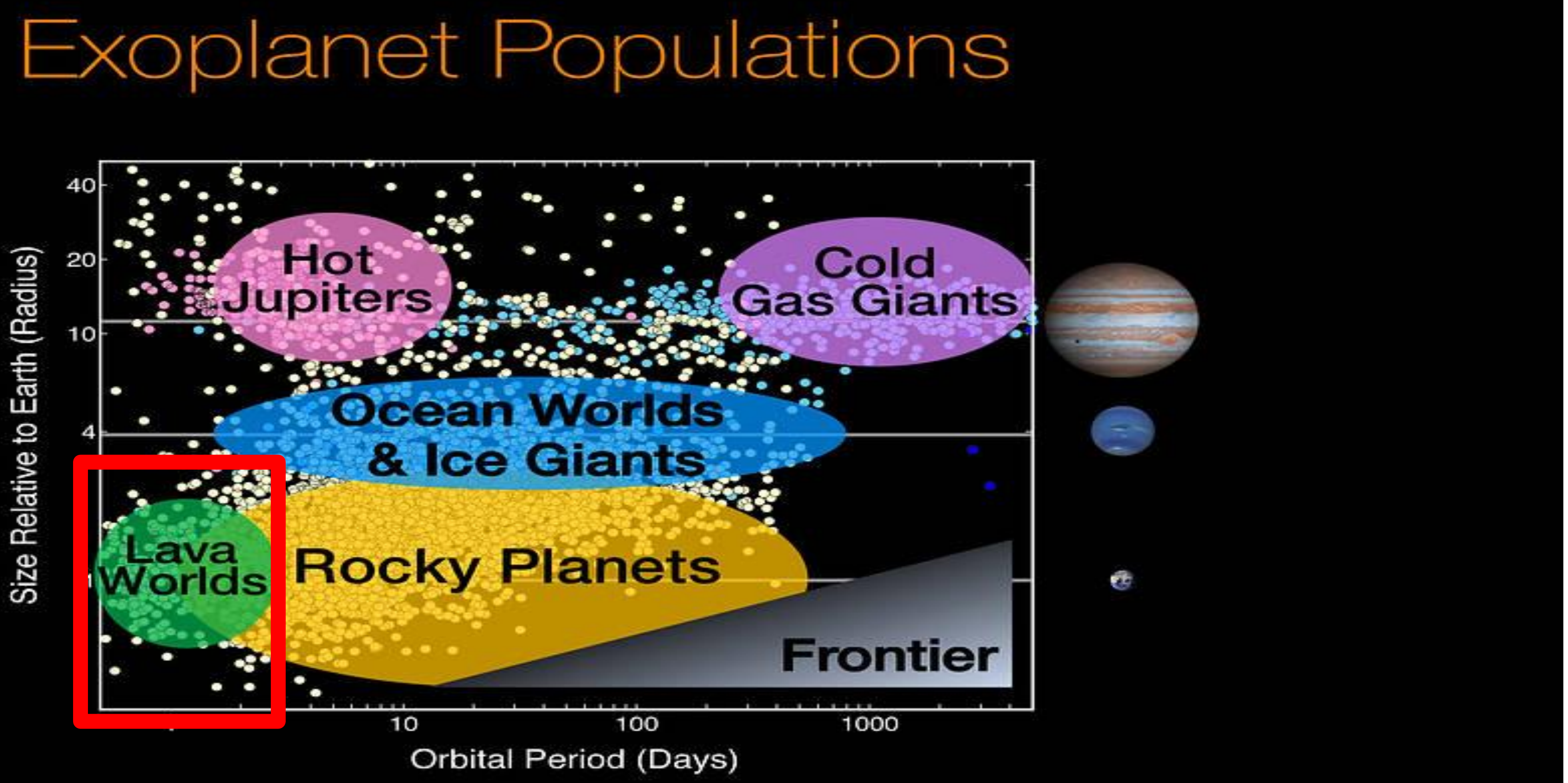
Fraction of Neptune sized planets ($f_{NP}$) decreases with time.

# Ultra Short Period (USP) Planets

Pei-Wei TU
涂培玮



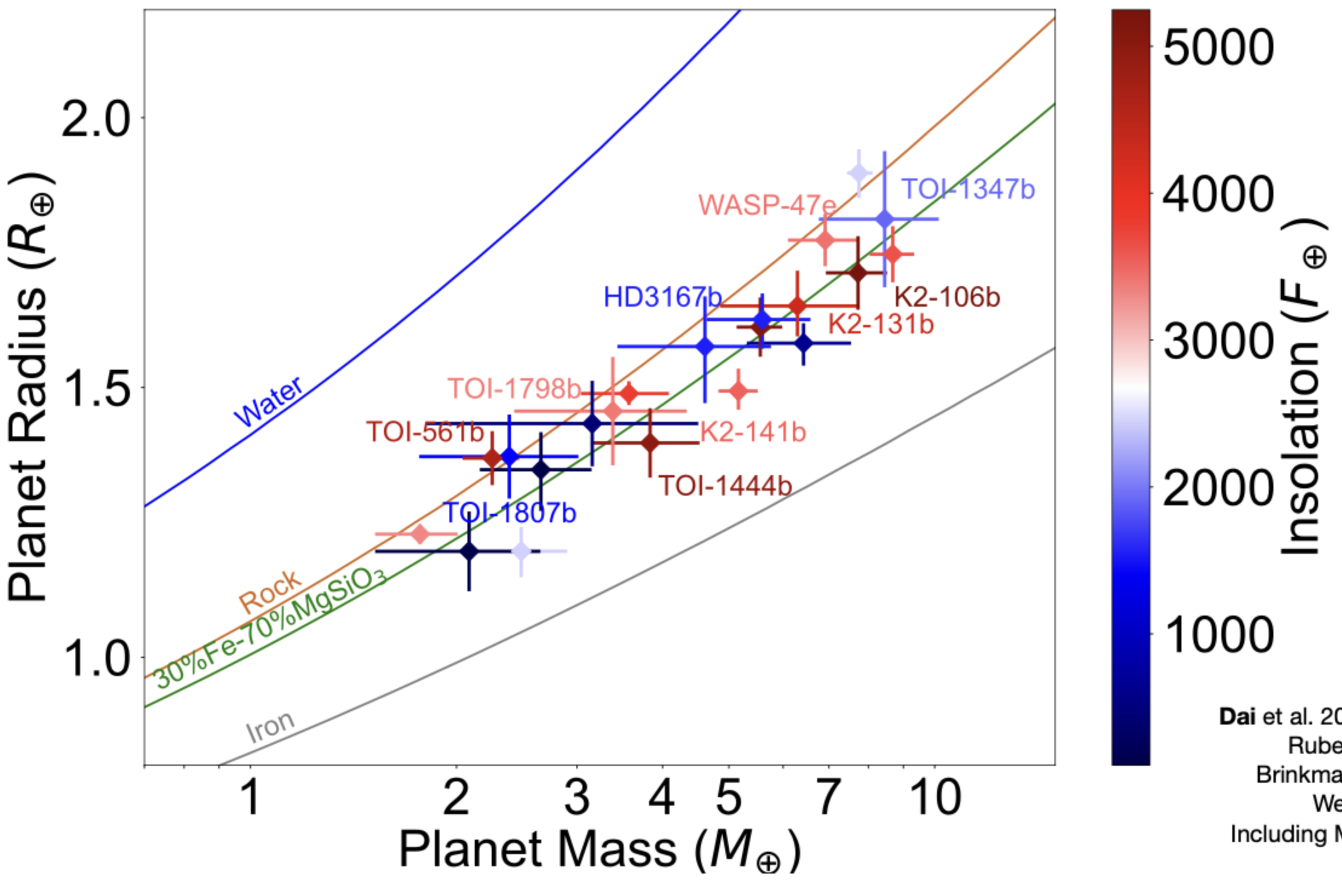


# Ultra Short Period (USP) Planets

- Earth-sized or super-Earth planets with orbital period **< 1 day**.
- Occurs around **0.51 ± 0.07%** of Sun-like stars **Winn et al. 2018**
- $T_{eq}$ = 1000K-2000K —— Lava worlds!

A population-wide 0.32±0.04 CMF



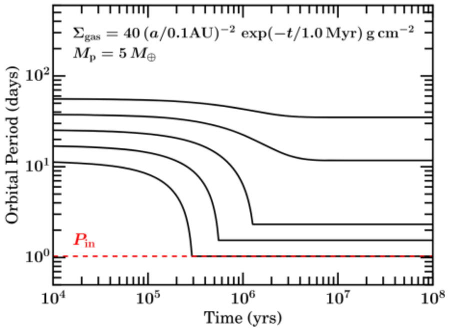

They are rocky!

**Dai** et al. 2015, 2017, 2018, 2019, 2021
Rubenzahl, **Dai** et al. 2023
Brinkman, Weiss, **Dai** et al. 2022
Weiss, **Dai** et al. 2021
Including Murphy, Scarsdale, Batalha

# Migration forms USP planets

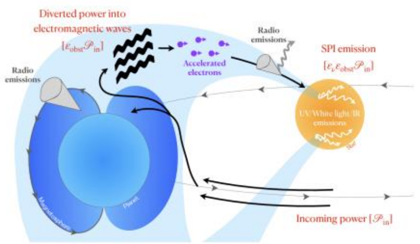
**Arrival time at the USP's orbit**

## ≪ ~ 1 Gyr




disk migration

Becker et al. 2021, Lee & Chiang 2017

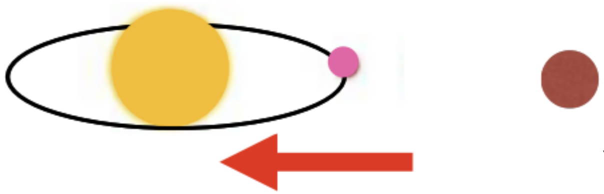



magnetic effects

Strugarek et al. 2017, 2025
Colle et al. 2025 Lee & Owen 2025

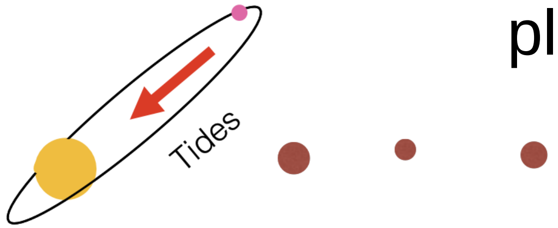
See also Eve J. Lee and Douglas Lin's talk on April 23

## Myrs to Gyrs, depend on initial conditions



stellar tides

Schlaufman et al. 2010, Lee & Chiang 2017




Eccentric, Inclined Orbit

planetary eccentricity tides

Petrovich et al 2019, Pu & Lai 2019

planetary obliquity tides

Millholland & Spalding 2020

**USP planets' origins remain enigmatic**

# Evolution of USP Occurrence Rate and Architecture


nature astronomy

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Article | Published: 28 April 2025

**Age dependence of the occurrence and architecture of ultra-short-period planet systems**

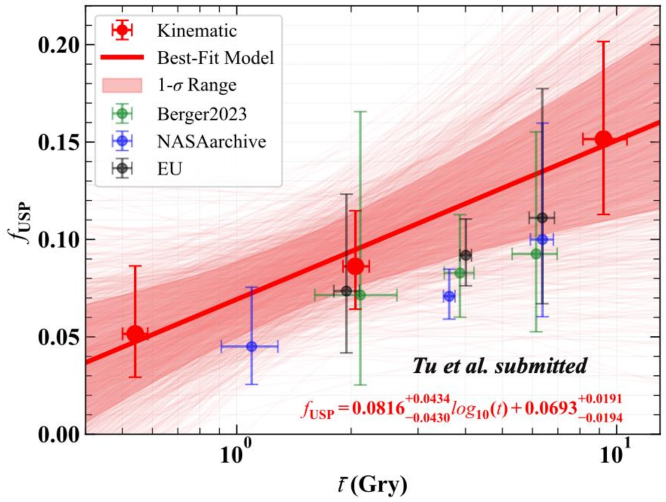
Pei-Wei Tu, Ji-Wei Xie, Di-Chang Chen & Ji-Lin Zhou

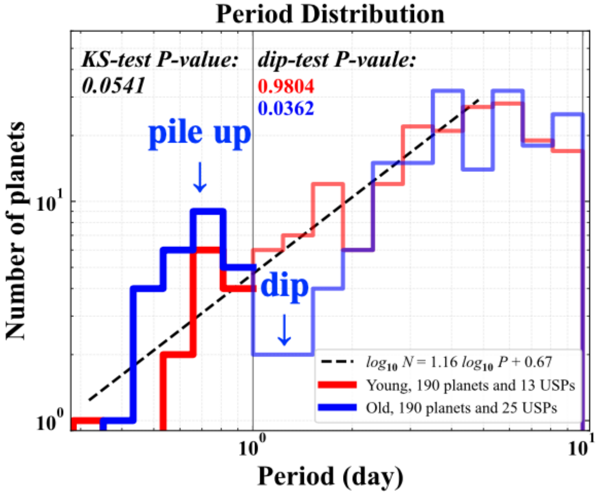
**PAST-6**: Tu, **Xie***, et al. 2025 **Nature Astronomy**

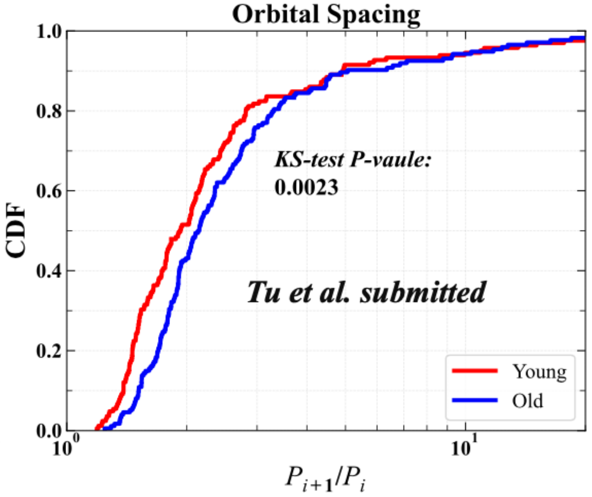
USP migration formation spans billions of years, formation rate increases over time.

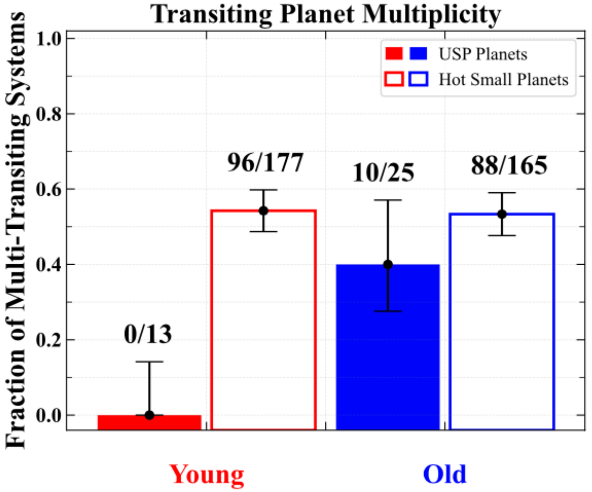
Early-formed (≲ 1 Gyr) USPs have larger orbital inclinations => violent formation process.

Late-formed (≳ 1 Gyr) USPs have smaller orbital inclinations => quiet formation process.



# Outline

1. **Research Background**

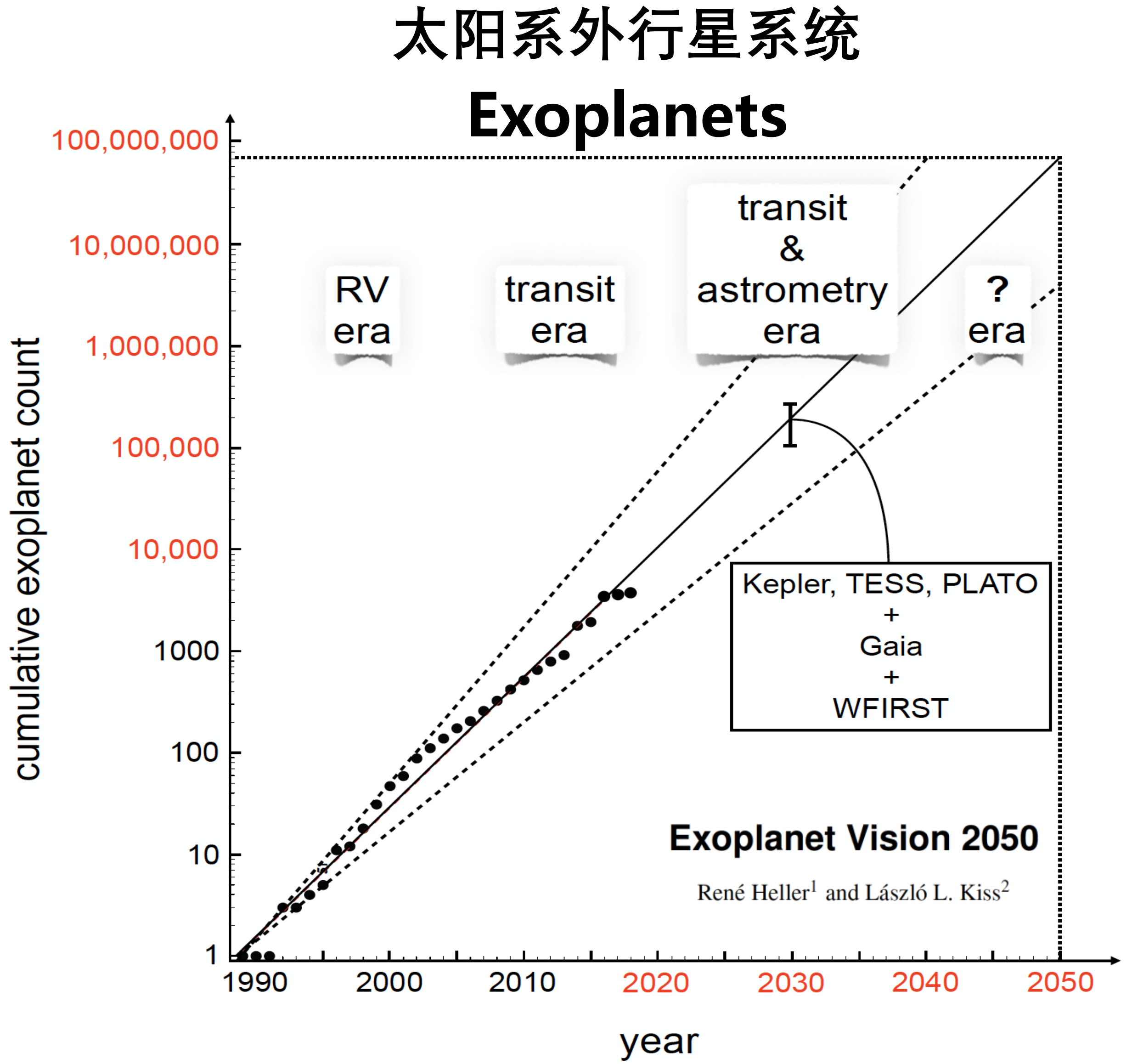
   Importance and Important Progresses of Planetary Statistics

2. **Exoplanet Statistical Research Based on LAMOST**

   Research highlight of the "PAST" （穿越） Series

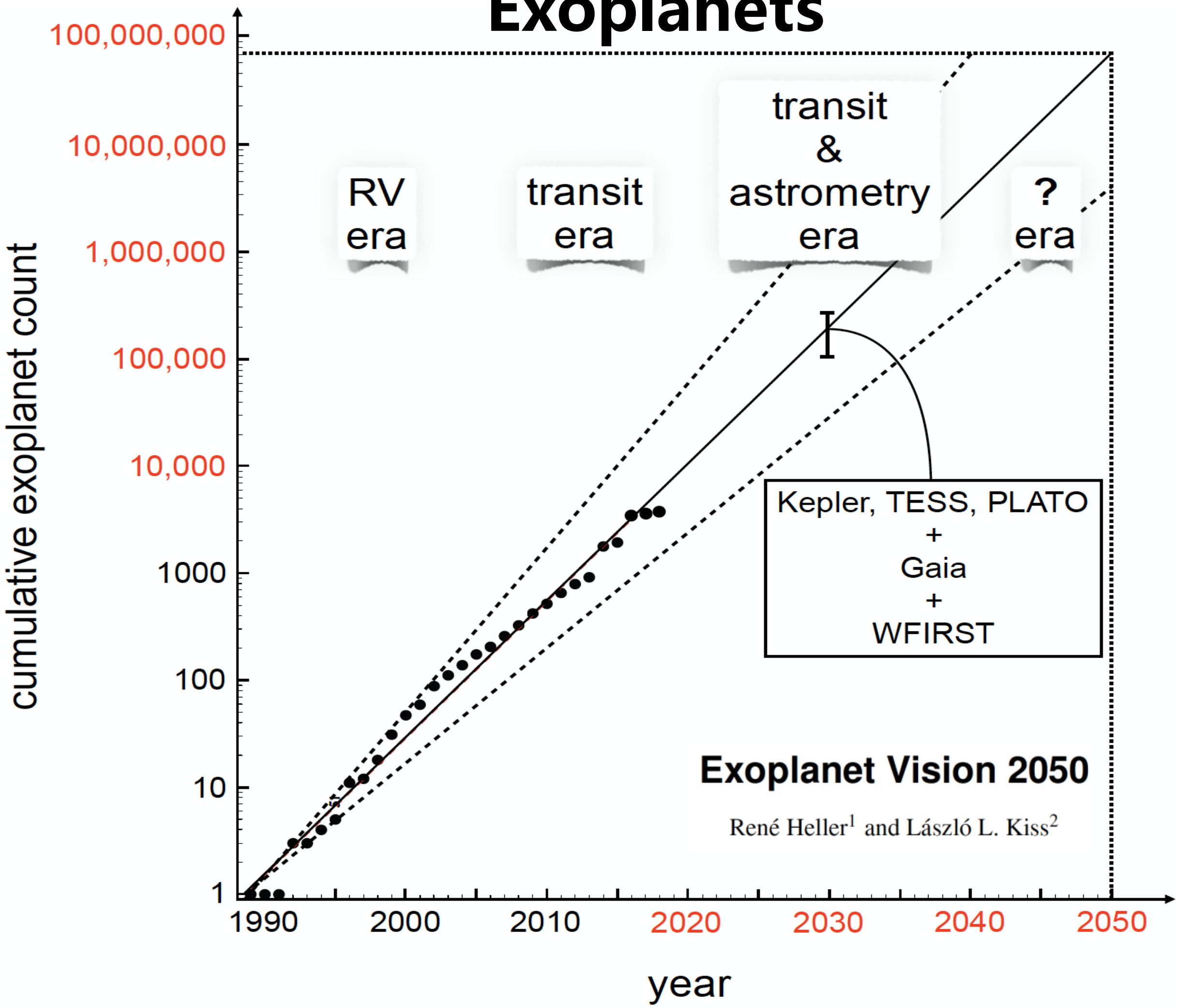
3. **Prospects and Summary**

# Bright Future of Exoplanet Statistics



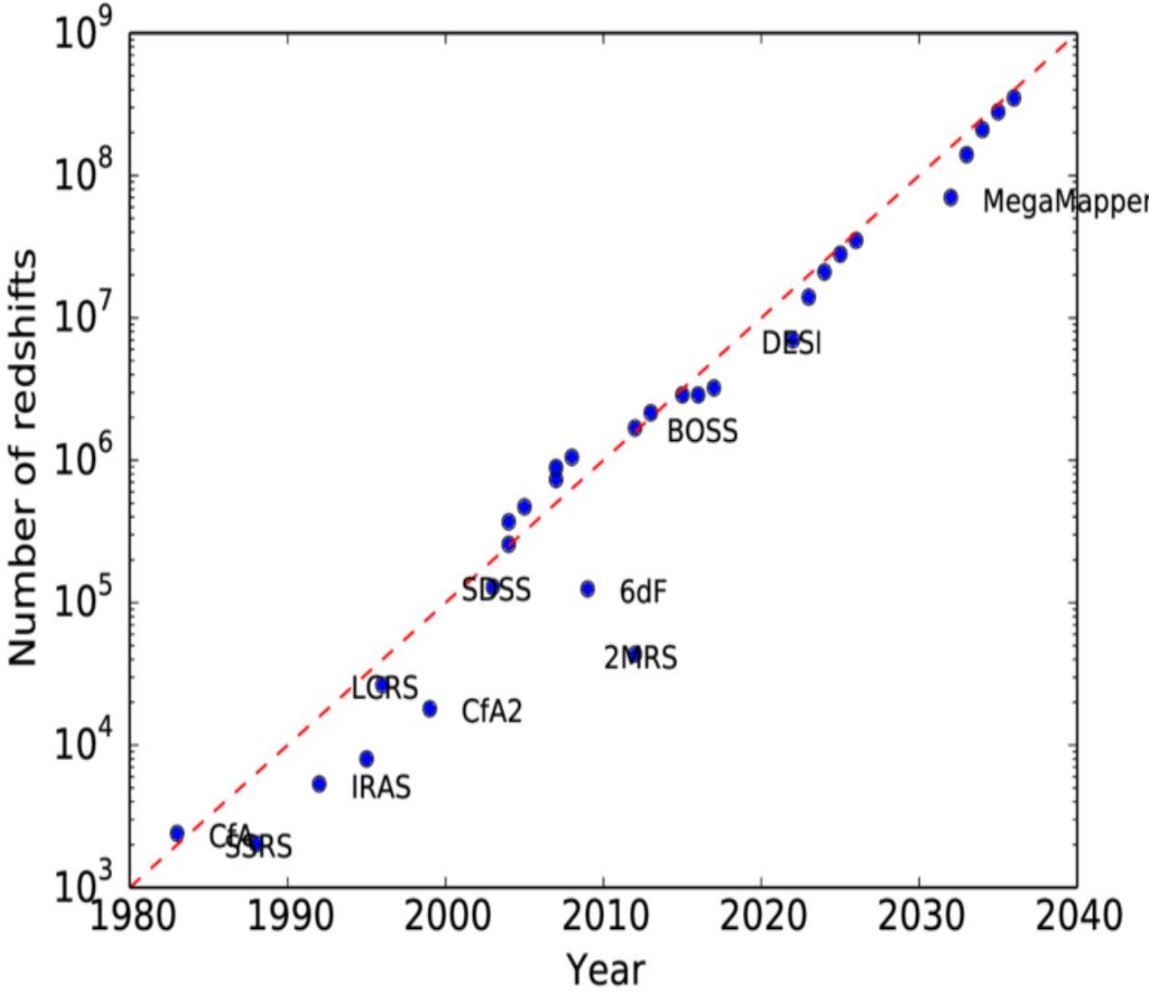
# Exoplanets vs. Galaxies

## 太阳系外行星系统
## Exoplanets




VS

## 银河系外恒星系统
## Galaxies

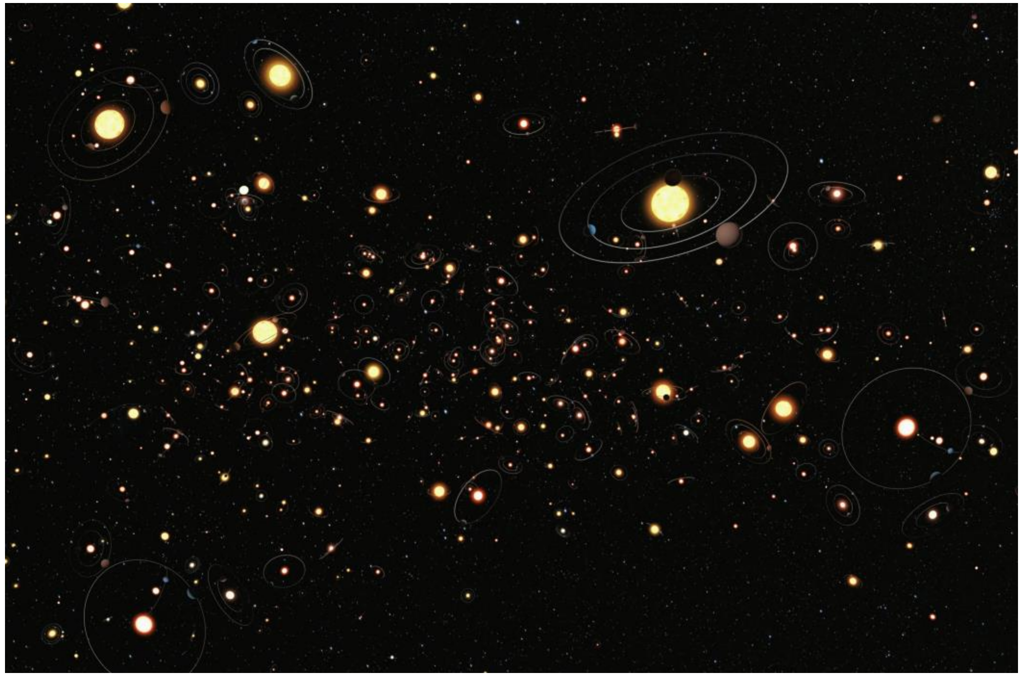


# Lessons from the extragalactic astronomy

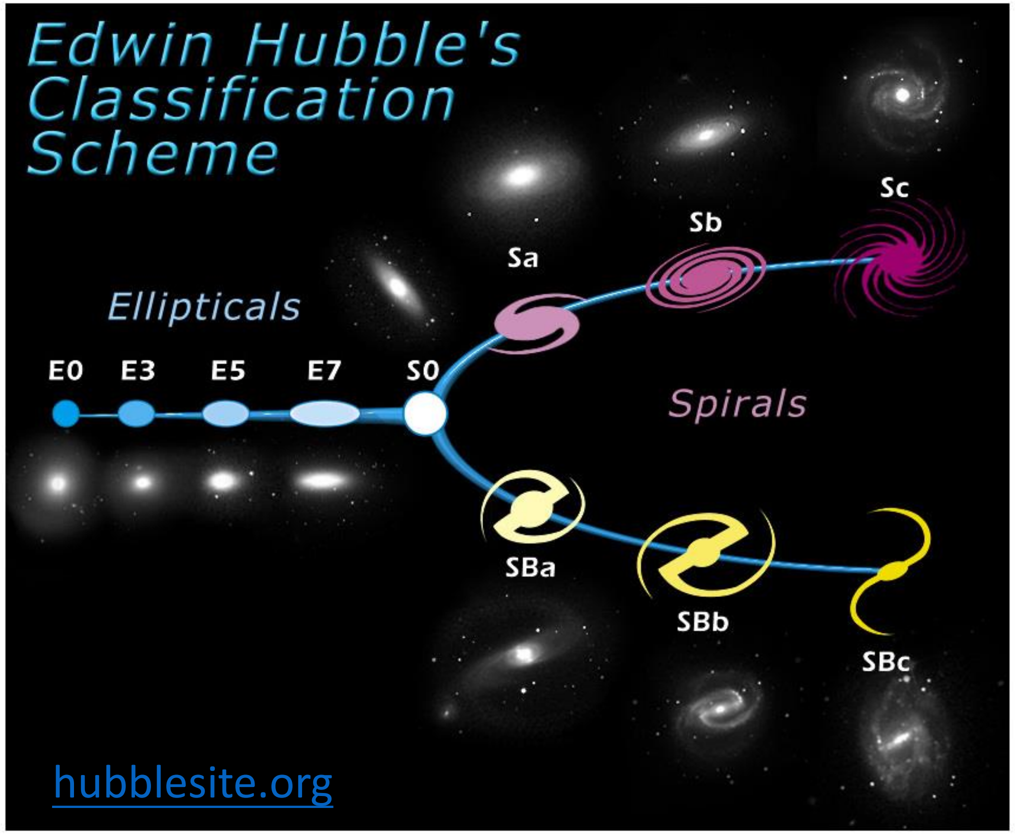
**太阳系外行星系统**
**Exoplanets**

**银河系外恒星系统**
**Galaxies**

See the future of the exoplanet field from the past of the galaxy field



VS




How to classify exoplanets **with AI**

# Future Plans and Layout: NJU Exoplanet Census Team

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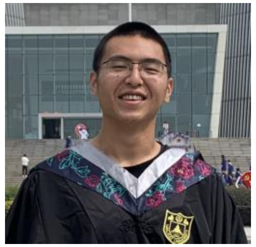
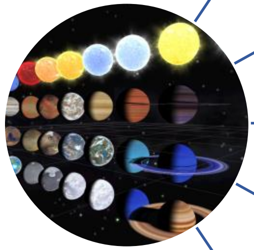


Di WU
武迪

Exoplanet census



- PAST — **P**lanets **A**cross **S**pace and **T**ime (**PAST**) “穿越”系列
- PET — **P**lanetary **E**dge **T**rends （**PET**） “宠物”系列
- POET — **P**lanetary **O**rbital **E**ccentricity **T**rends (**POET**) “诗人”系列
- DEB — **D**emographics of **E**xoplanets in **B**inaries (**DEB**) “新秀”系列
- CASH — **C**hemical **A**bundance **S**hapes **H**istory(**CASH**) “现金”系列

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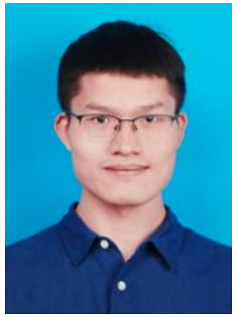
辛科霆

Dong-Shen An
安东升



# Summary

- The Future for **Exoplanet Census** is bright.
  系外行星普查统计前途光明

- Large scale **star survey（LAMOST） is essential** for planet census.
  大型恒星巡天（如LAMOST）是非常必要的

- **Time (or Age)** is an important dimension to explore → **observational planet evolution.**
  时间（年龄）维度方面的探索是关键 → 直接揭示行星演化