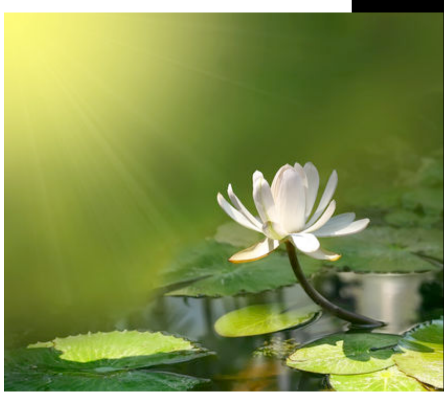
Observational methods and properties of Exoplanets

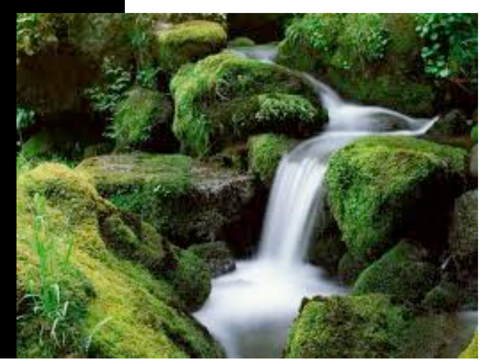
Douglas Lin
IAS THU, KIAA PKU, NSSC CAS, DAA UCSC

Institute for Advanced Studies, Tsinghua University
2014.05.07

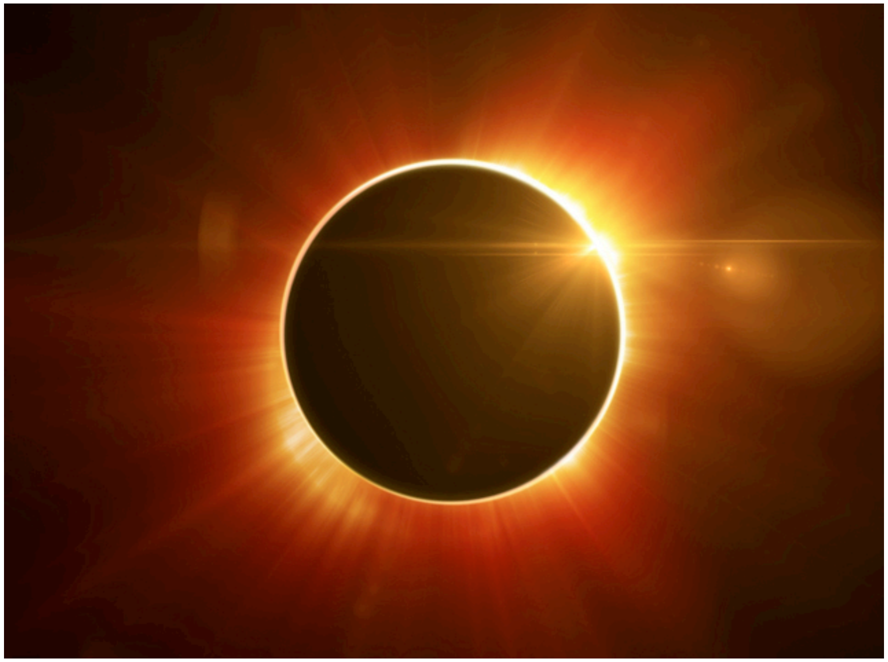
29 slides

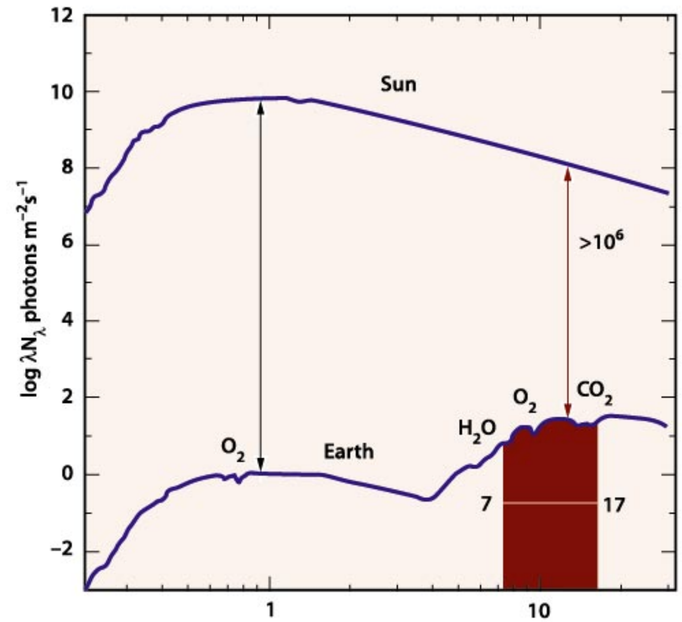
In Search of Faint Blue Dots (Mayor)

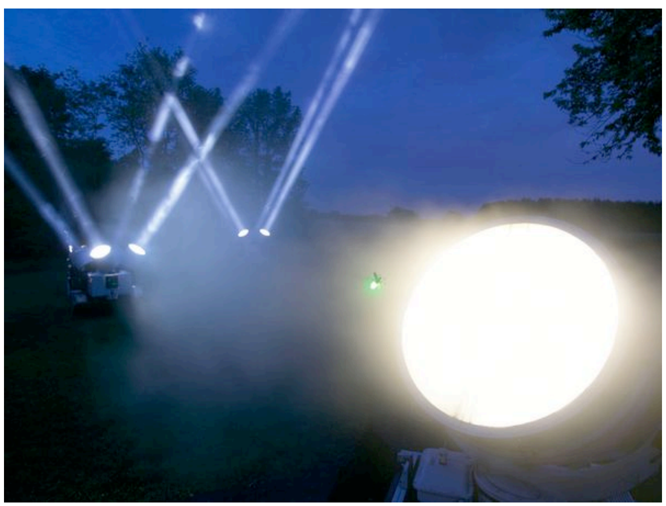


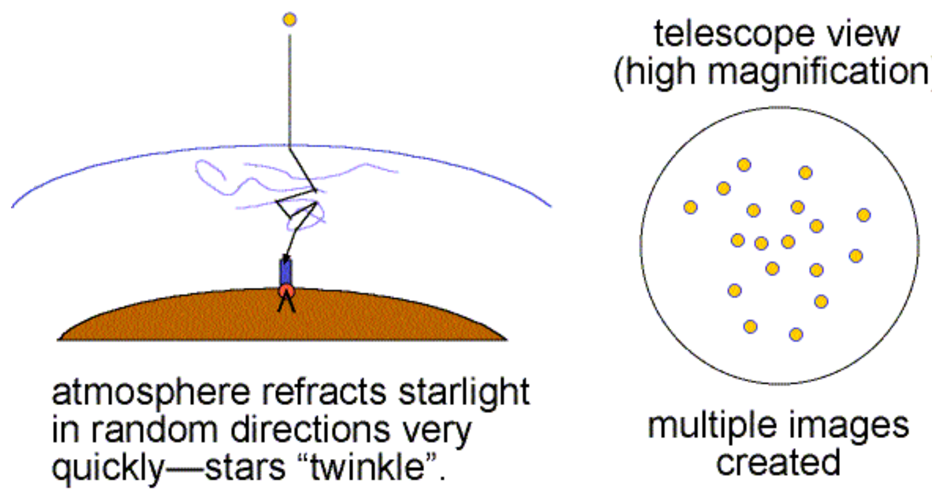


1. 系外行星直接成像的挑战

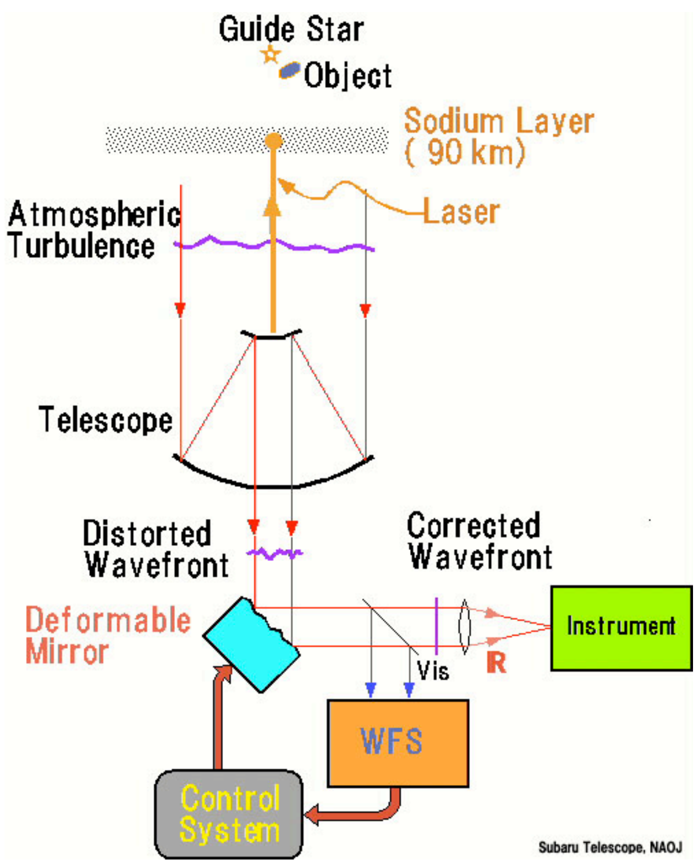


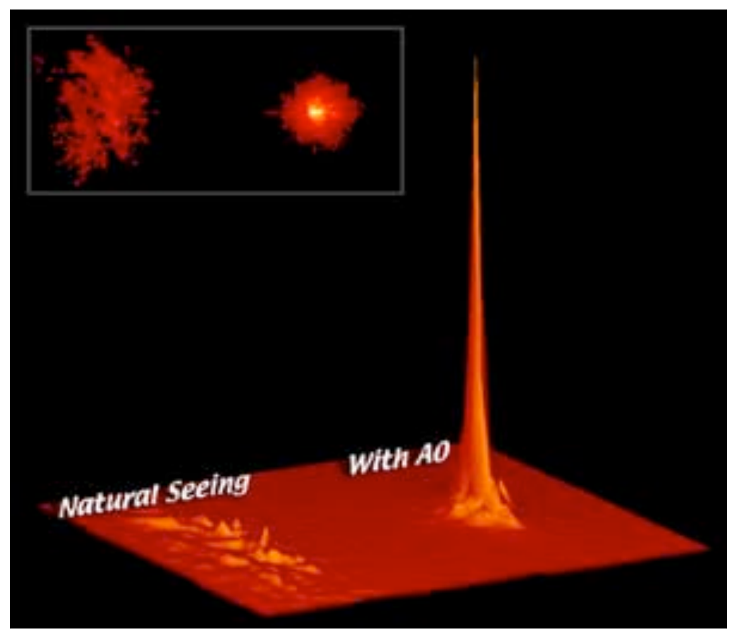






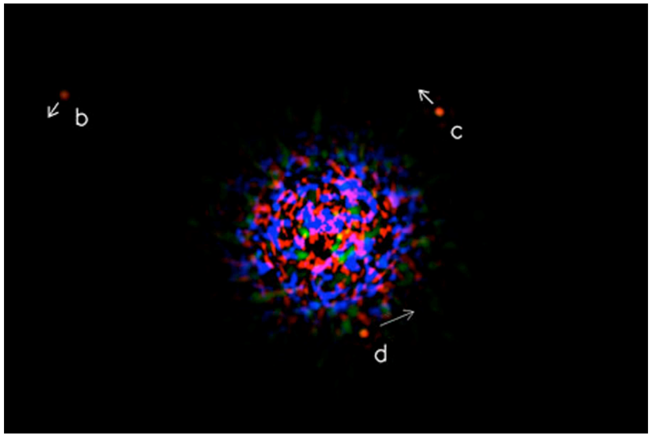
系外行星直接成像的解决方法

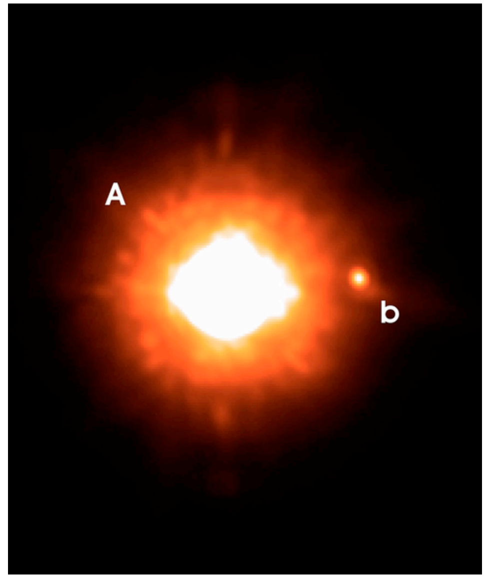


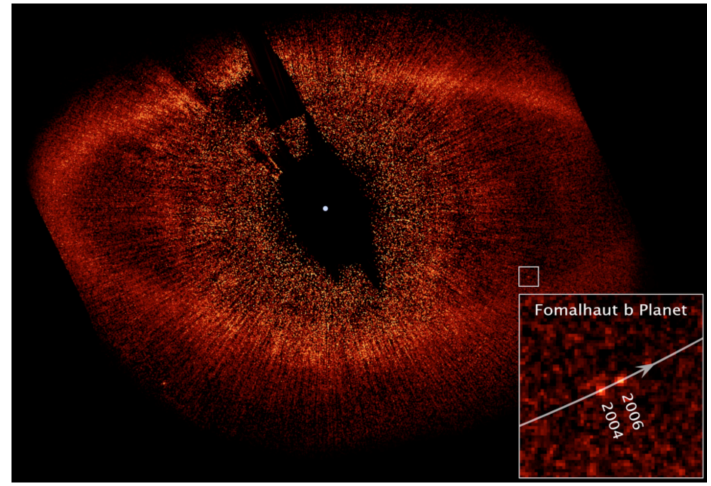


先决条件：自适应光学

系外行星直接成像（亮点）

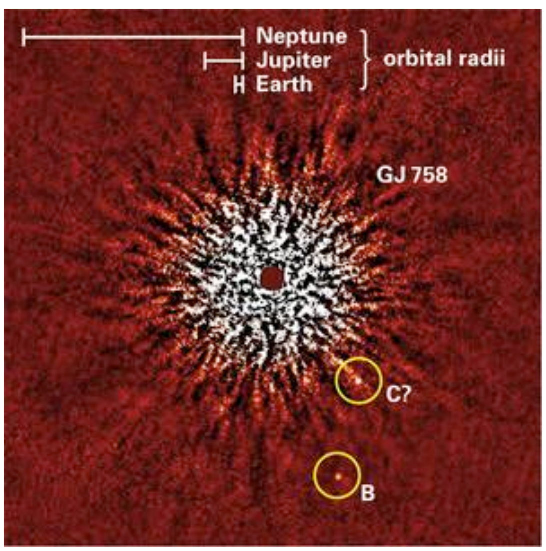


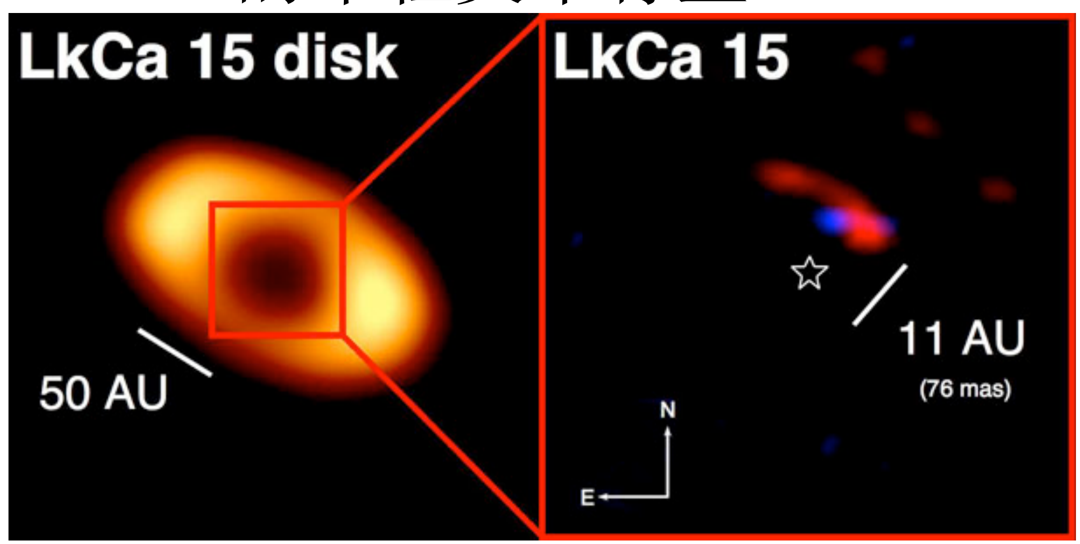




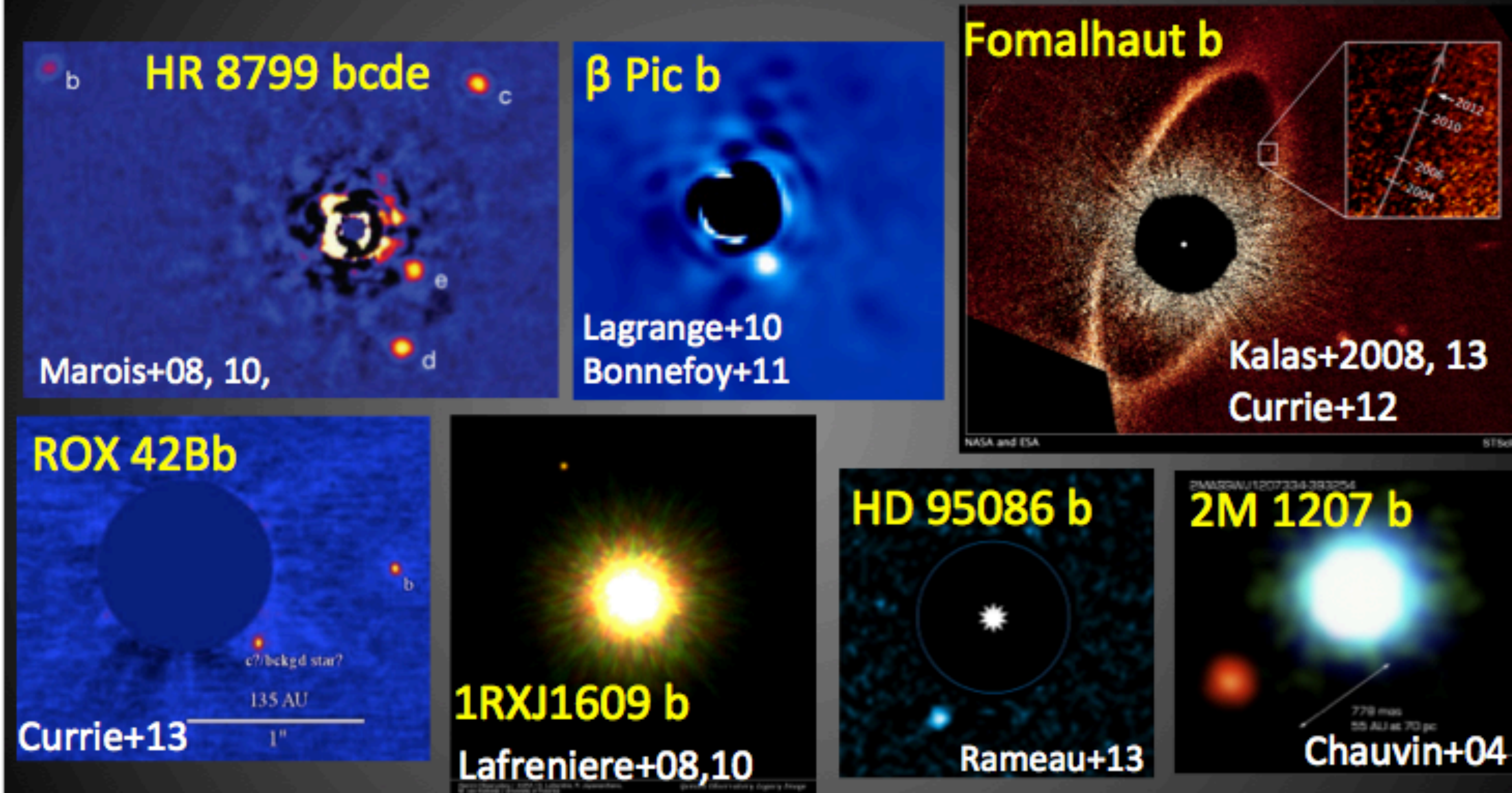
长周期、大质量、年轻类木行星，多行星系统

在原恒星盘与岩屑盘中的年轻类木行星





Examples of Directly Imaged Planets



Wide-Orbit planets can be detected only by direct imaging;
Limited number of detections => Unknown about wide-orbit planets

SEEDS Planet Discovery: GJ 504b

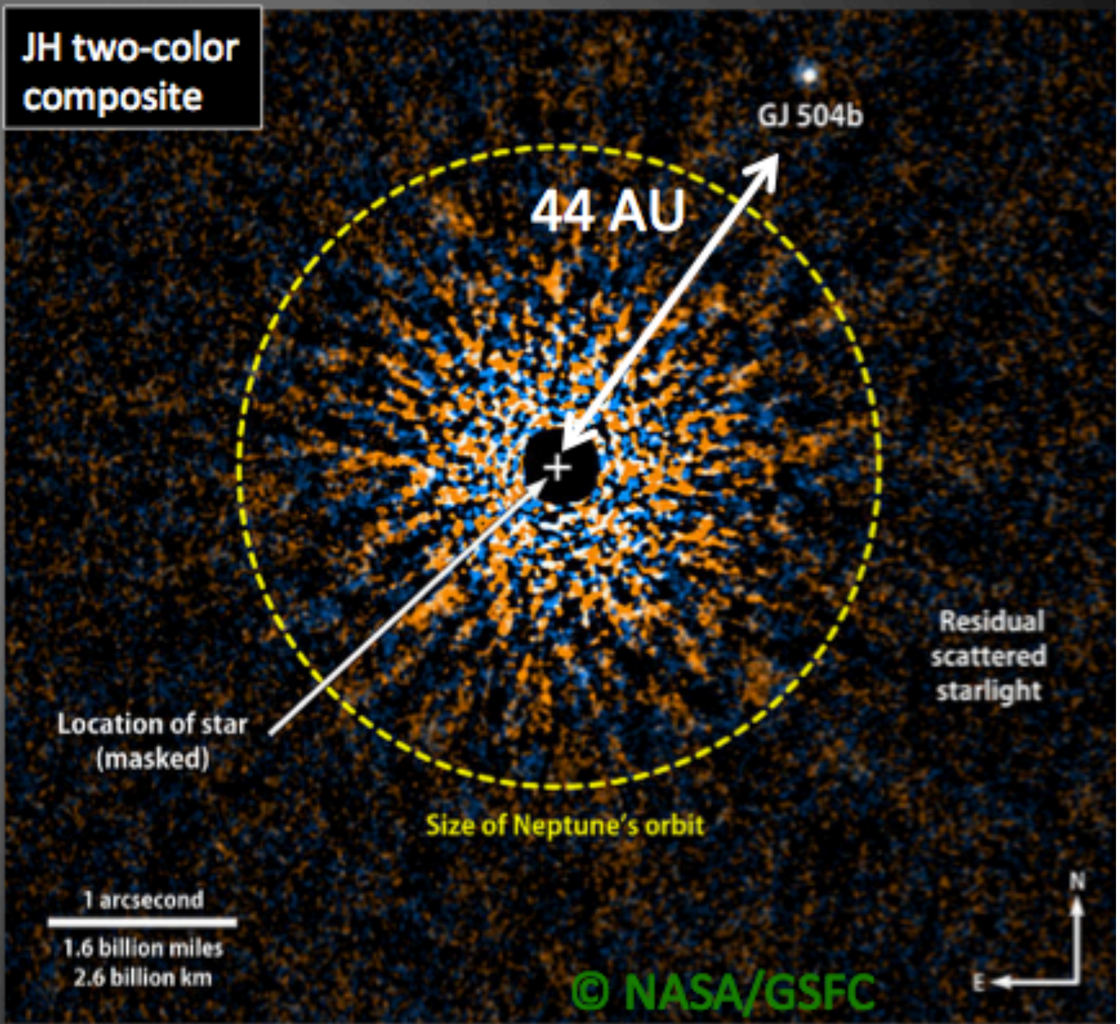
Kuzuhara+2013, ApJ

As a highlight, we report an exoplanet detection around the Sun-like star GJ 504.

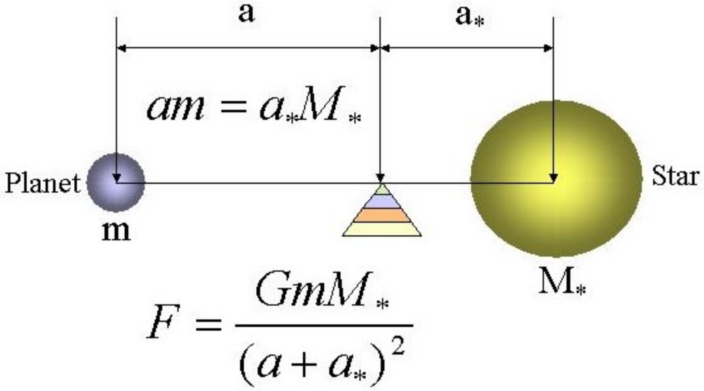
□ Property of GJ 504

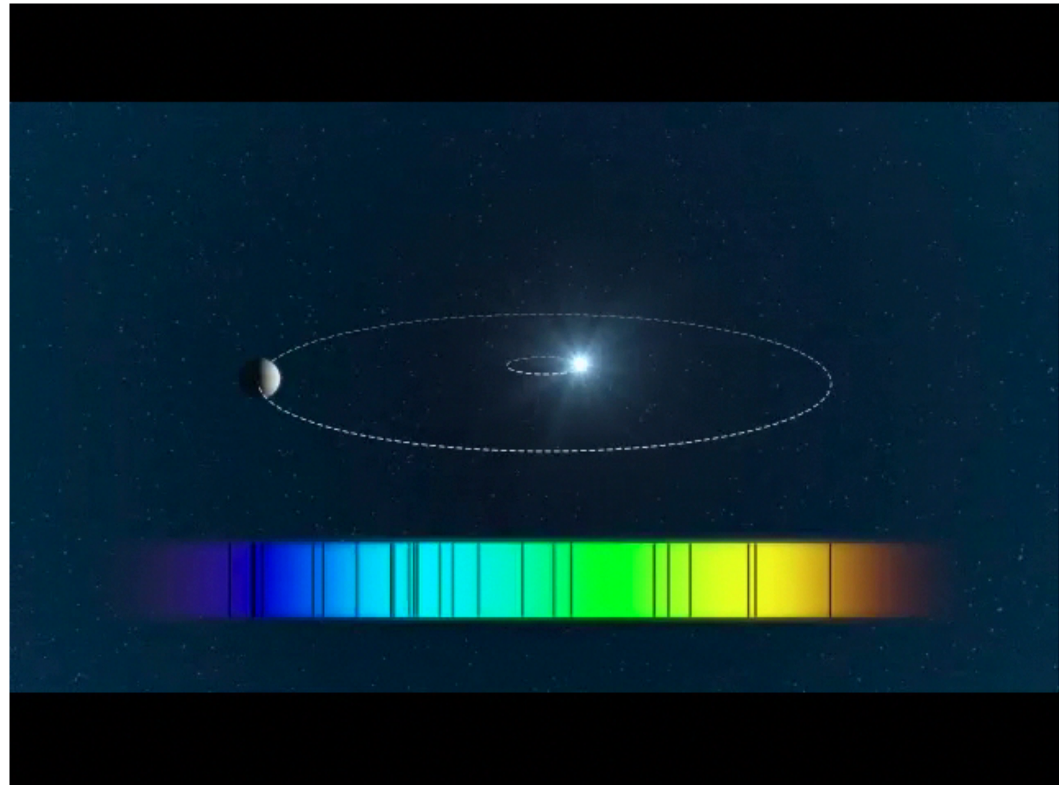
- Distance: ~17.6 pc
- Spectral type: G0
- Mass ~1.2 M_{sun}
- Age: 160 [+350, -60] Myr
- Metallicity [Fe/H]: 0.1–0.3 (Valdes+04, Takeda+07, Valenti+Fischer 05)

□ Reports of 9 detections
=> Confirmation of common proper motion, and detection or a part of orbit

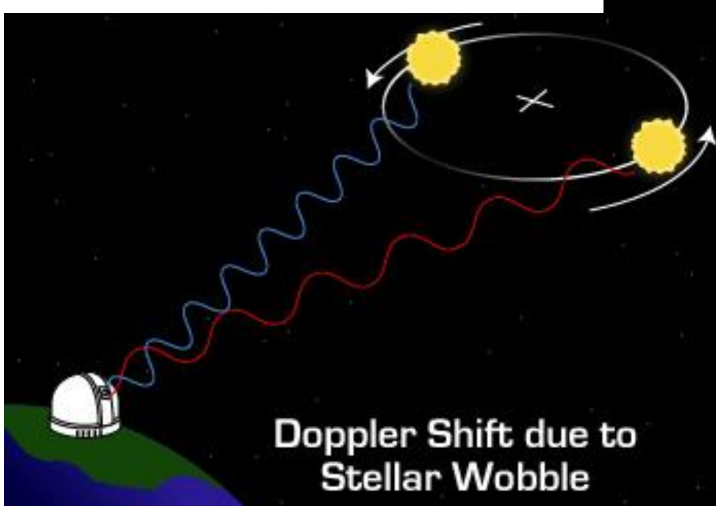


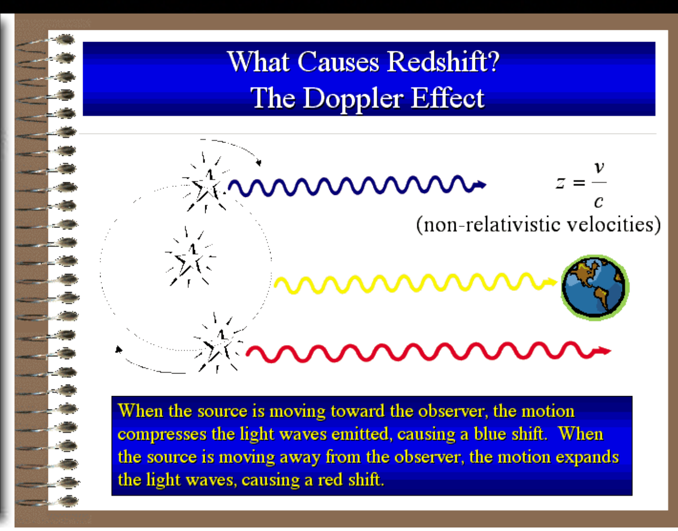
2. 视向速度巡天的挑战



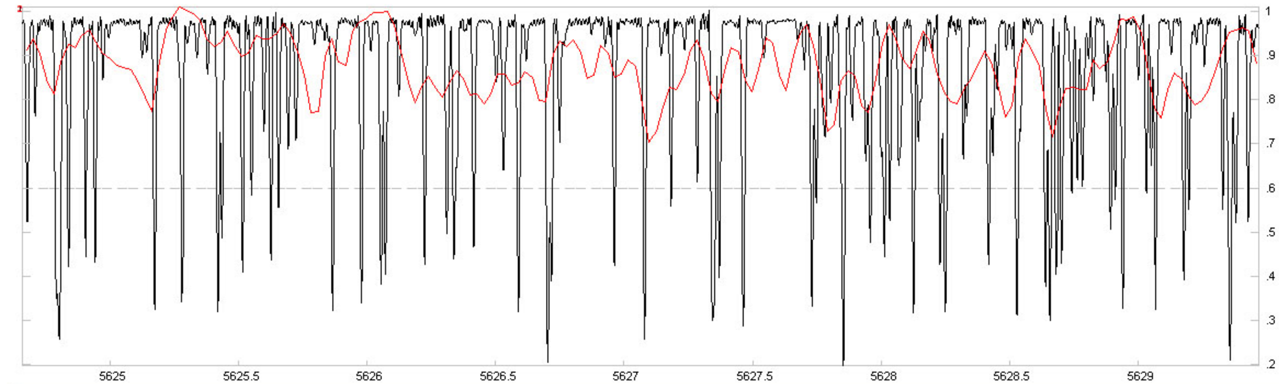


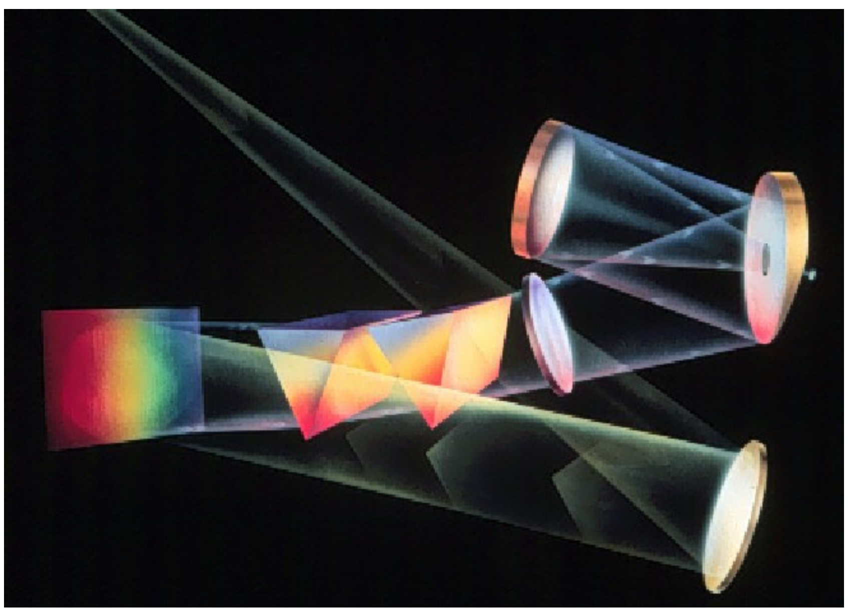
Femtometer Doppler shift
In individual lines

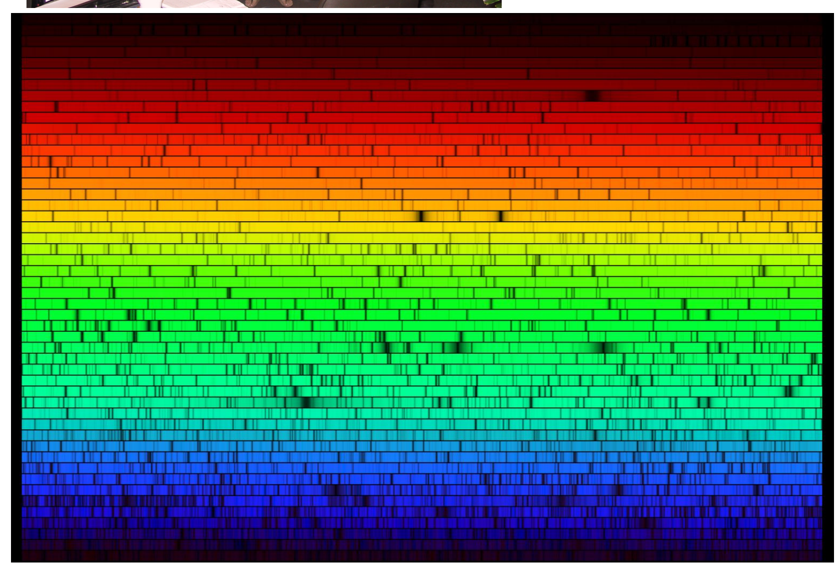




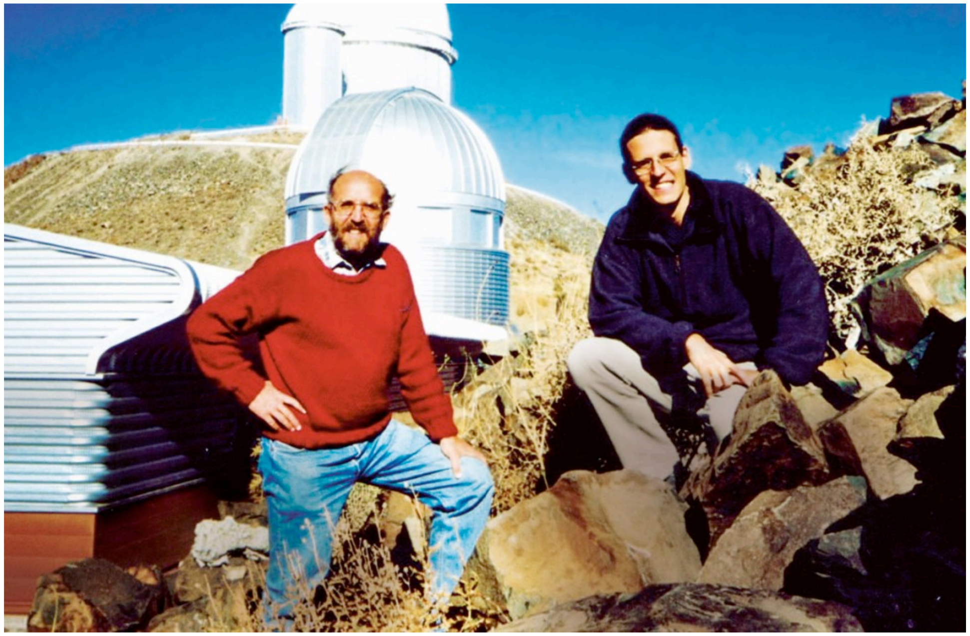
先决条件：高精度、稳定的光谱仪

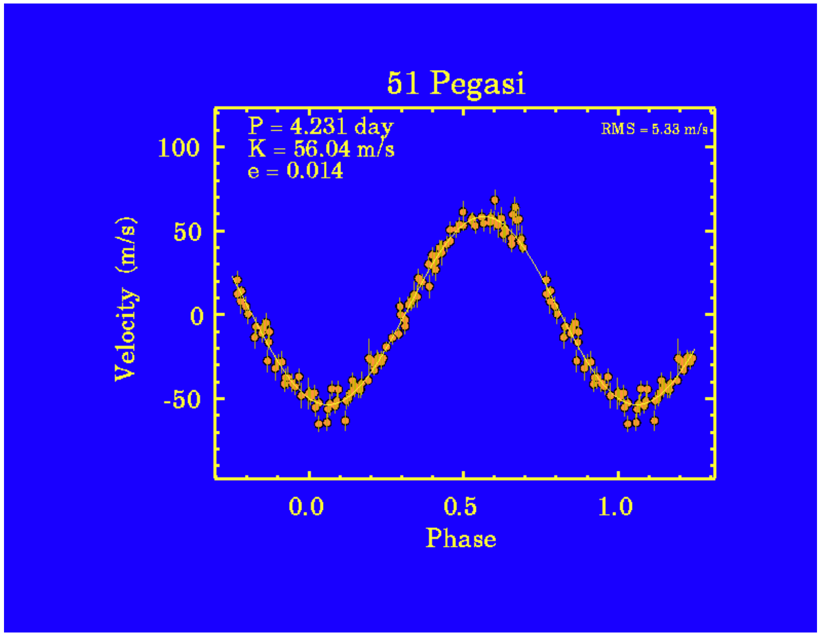


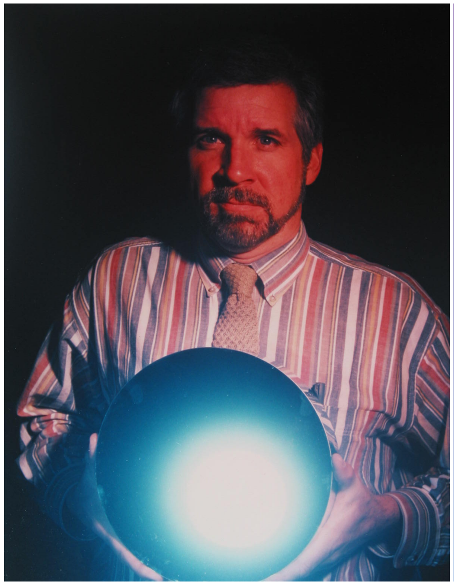


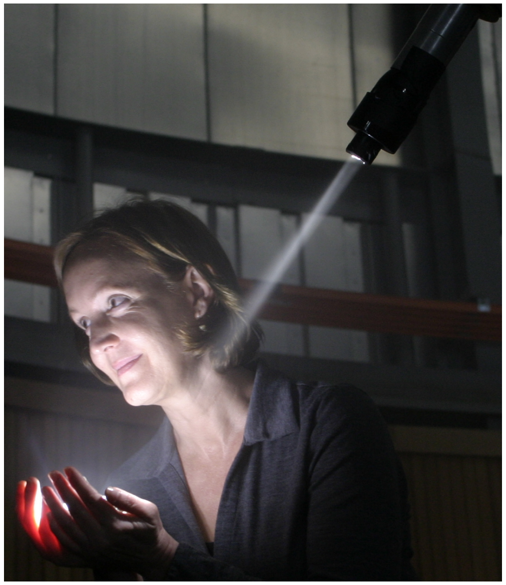


创新的视向速度巡天

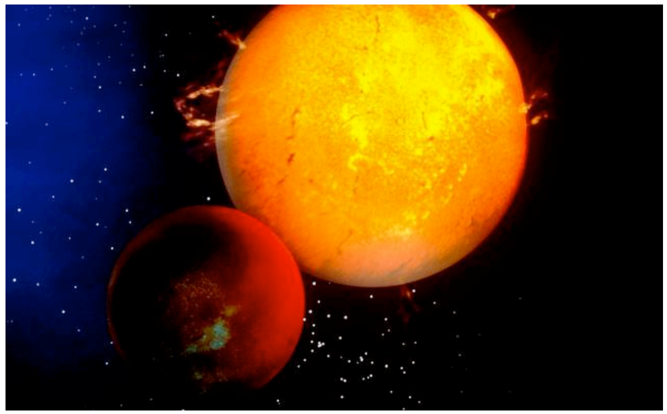


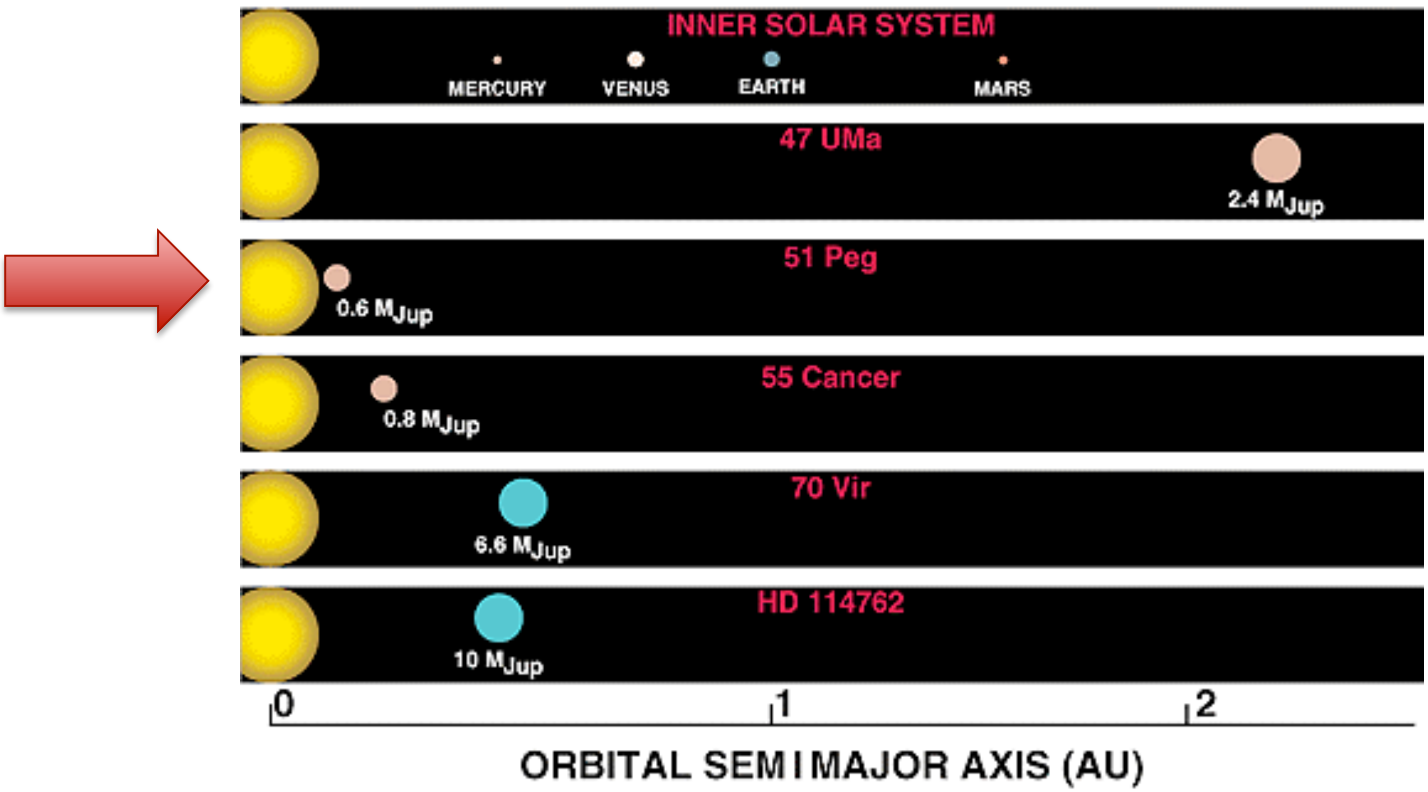

51 Pegasi
P = 4.231 day
K = 56.04 m/s
e = 0.014
RMS = 5.33 m/s
100
50
0
-50
Velocity (m/s)
0.0
0.5
1.0
Phase





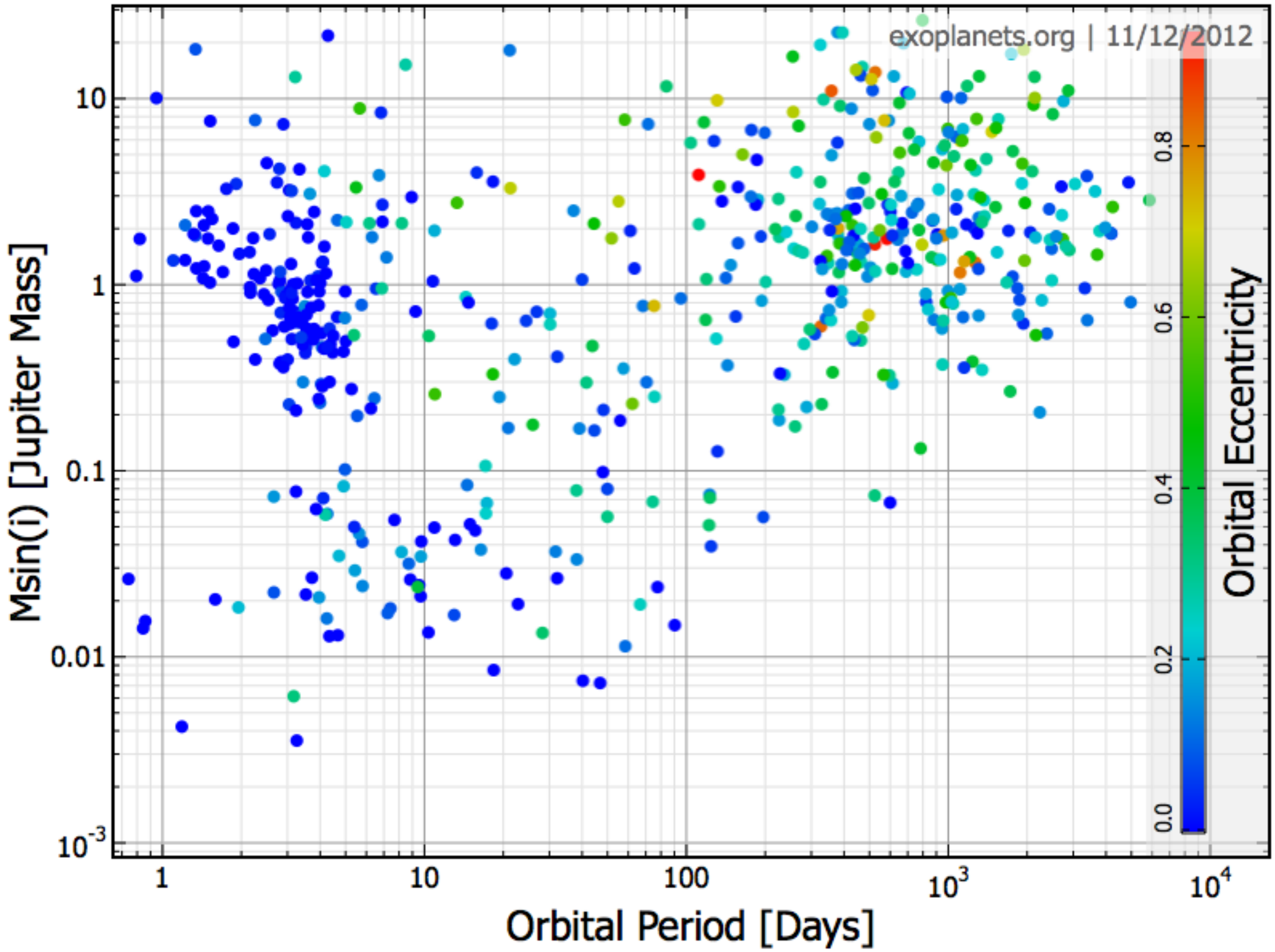
被发现的第一颗系外行星：51 Peg



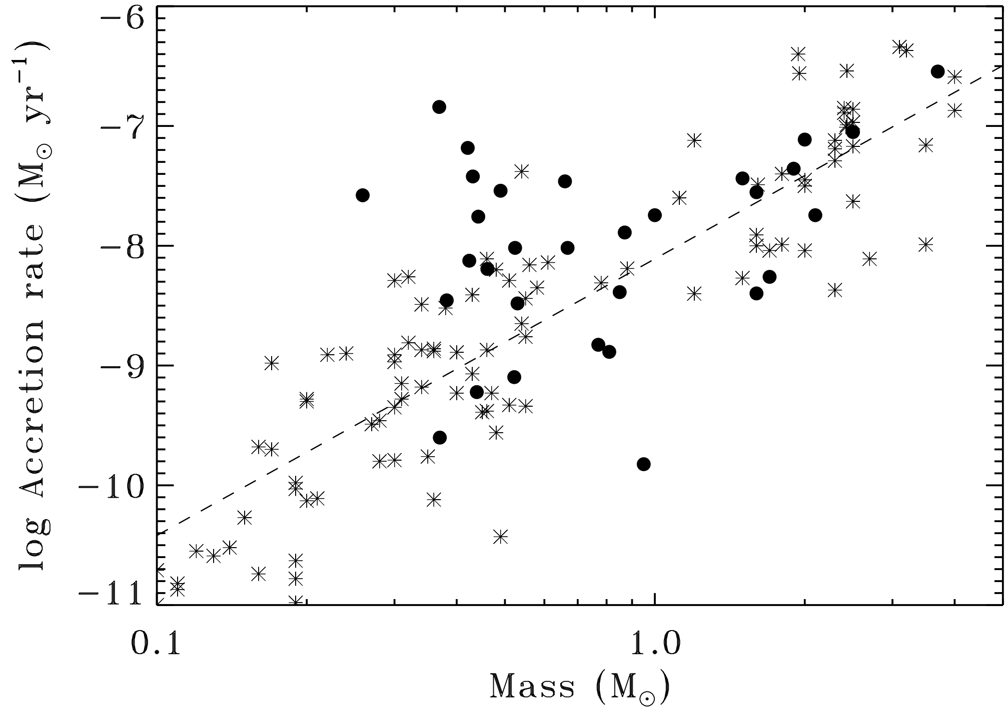


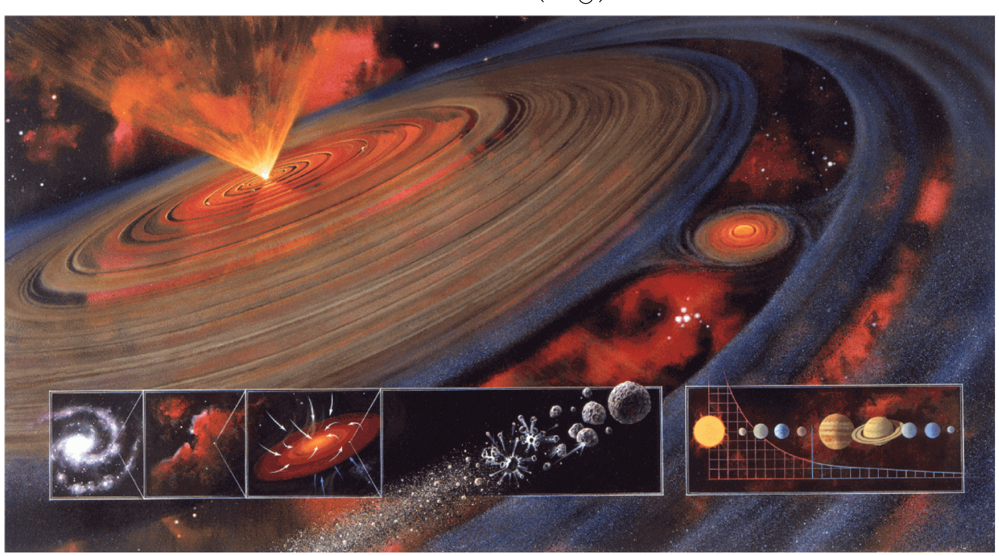
Gas giants: some key issues

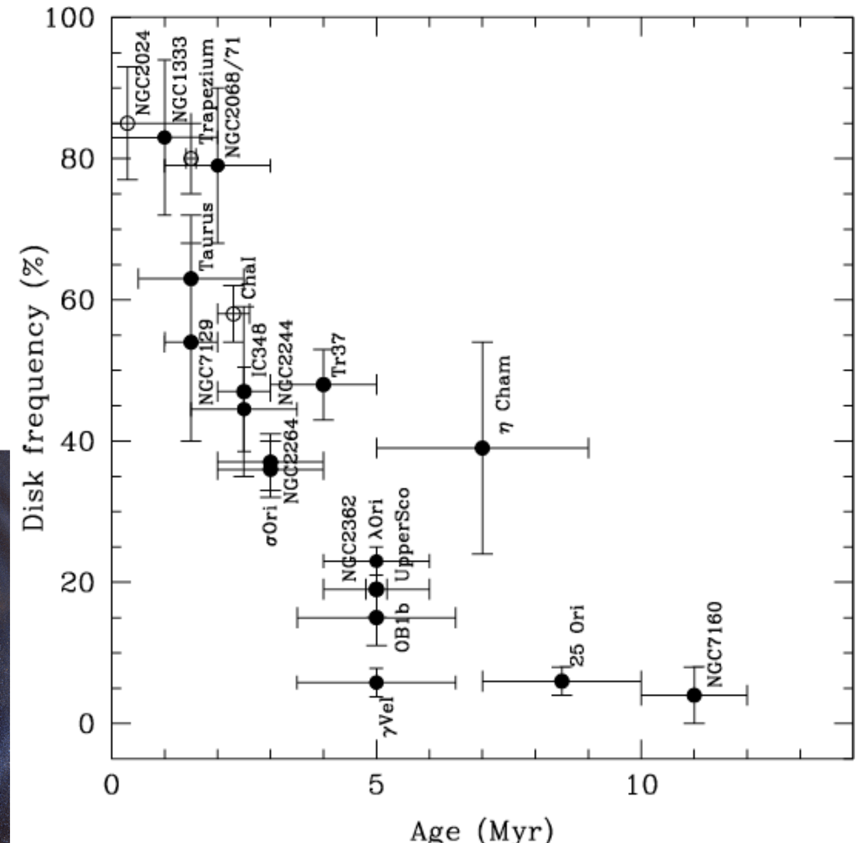
- Is there a prefer location for gas giant formation?



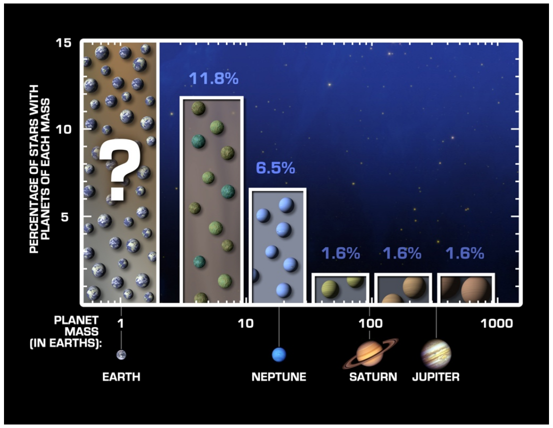
Protostellar disks

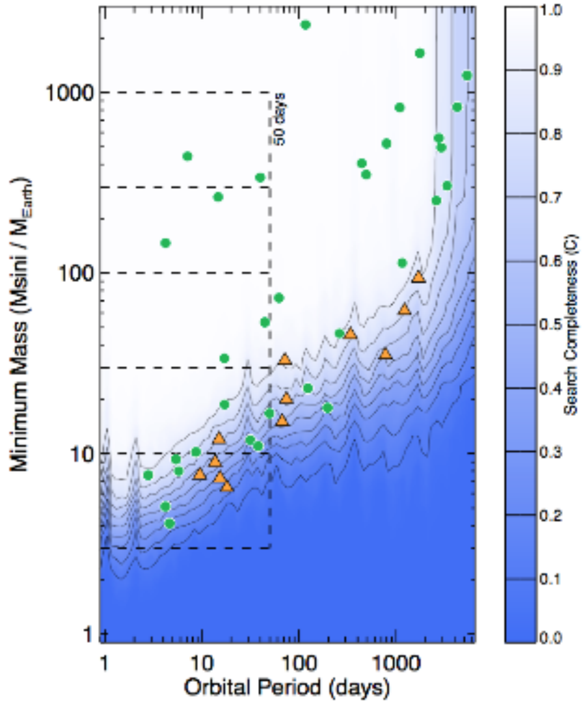


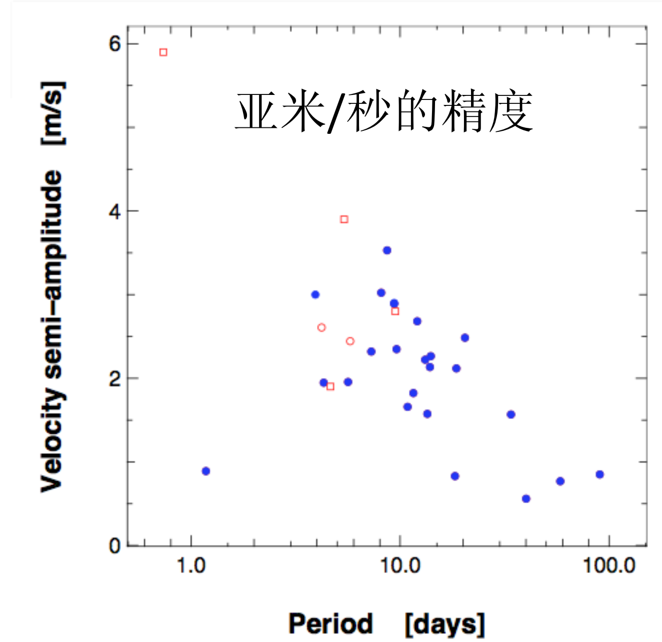




视向速度巡天（亮点1）

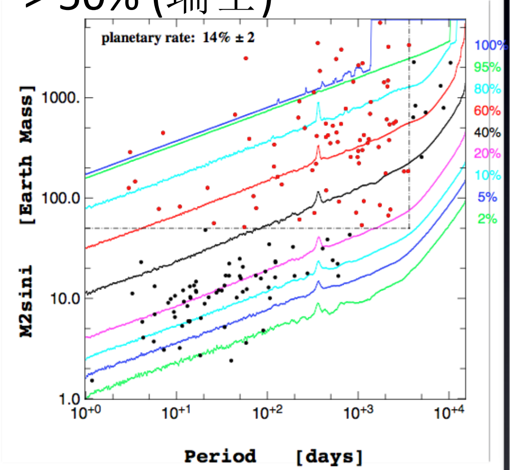


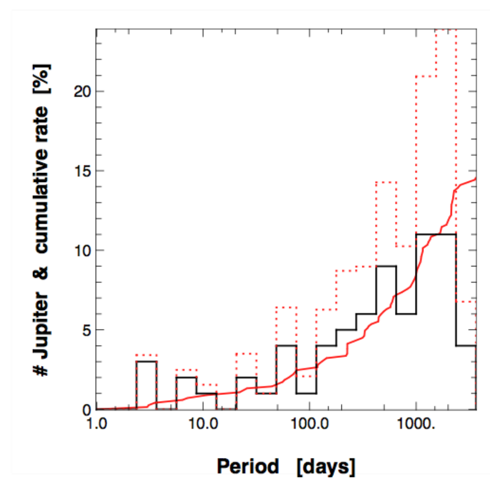




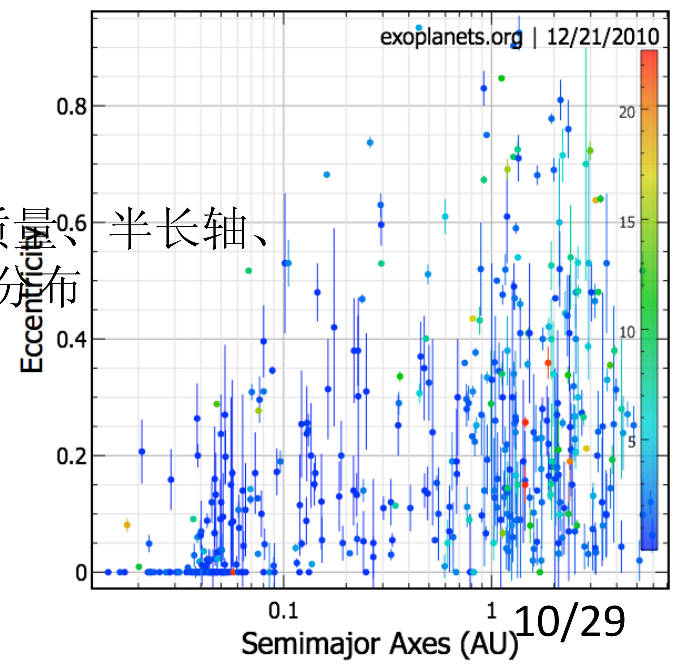
公认在~20%类日恒星的周围存在类木行星，其中1-2%是短周期热木星

类地行星的概率:
> 50% (瑞士)

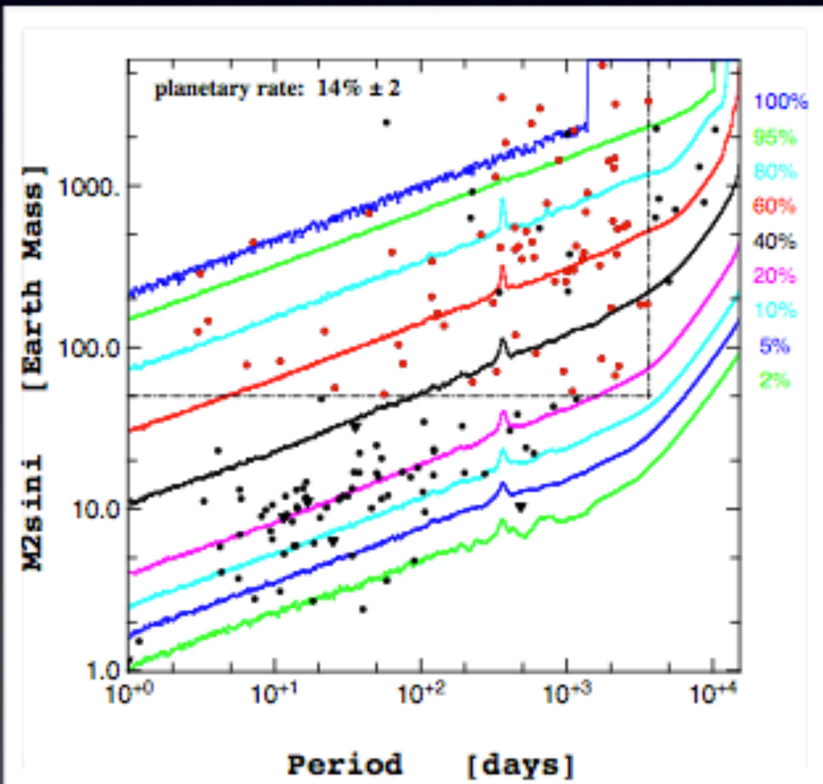


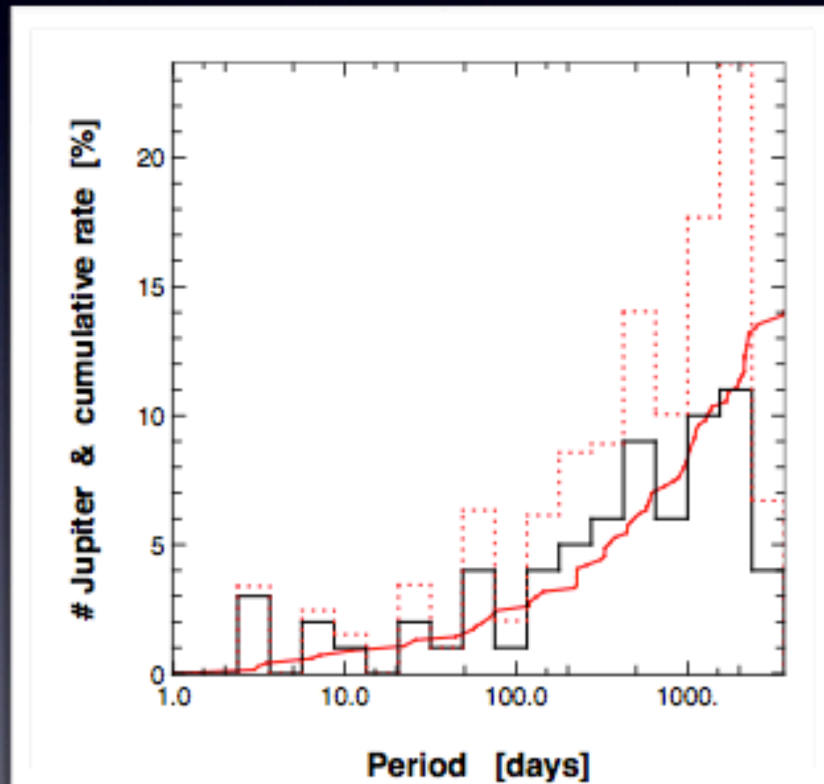


多元化: 质量、半长轴、偏心率的分布



Gaseous giant planets
(Msini > 50 Earth masses)

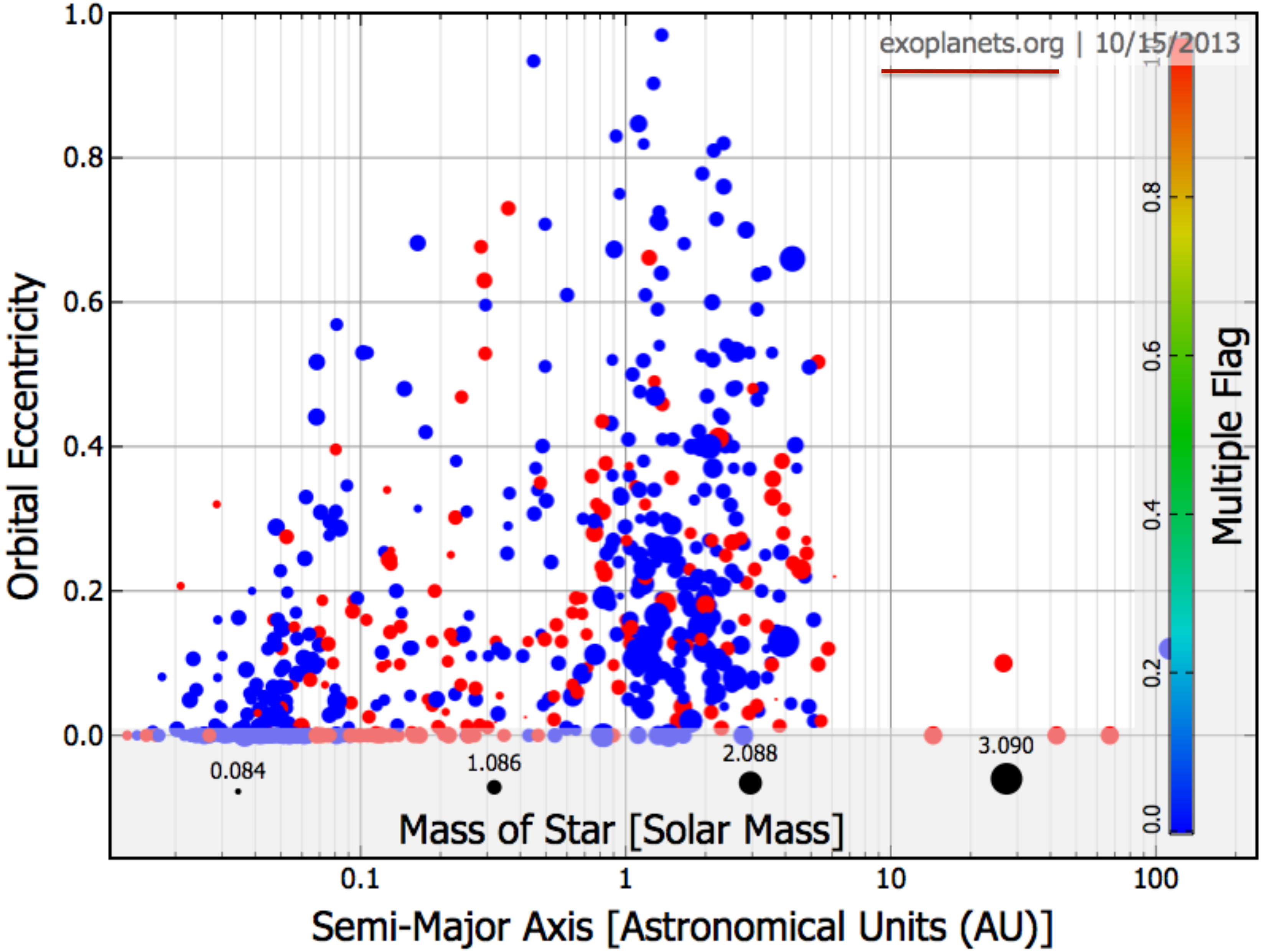




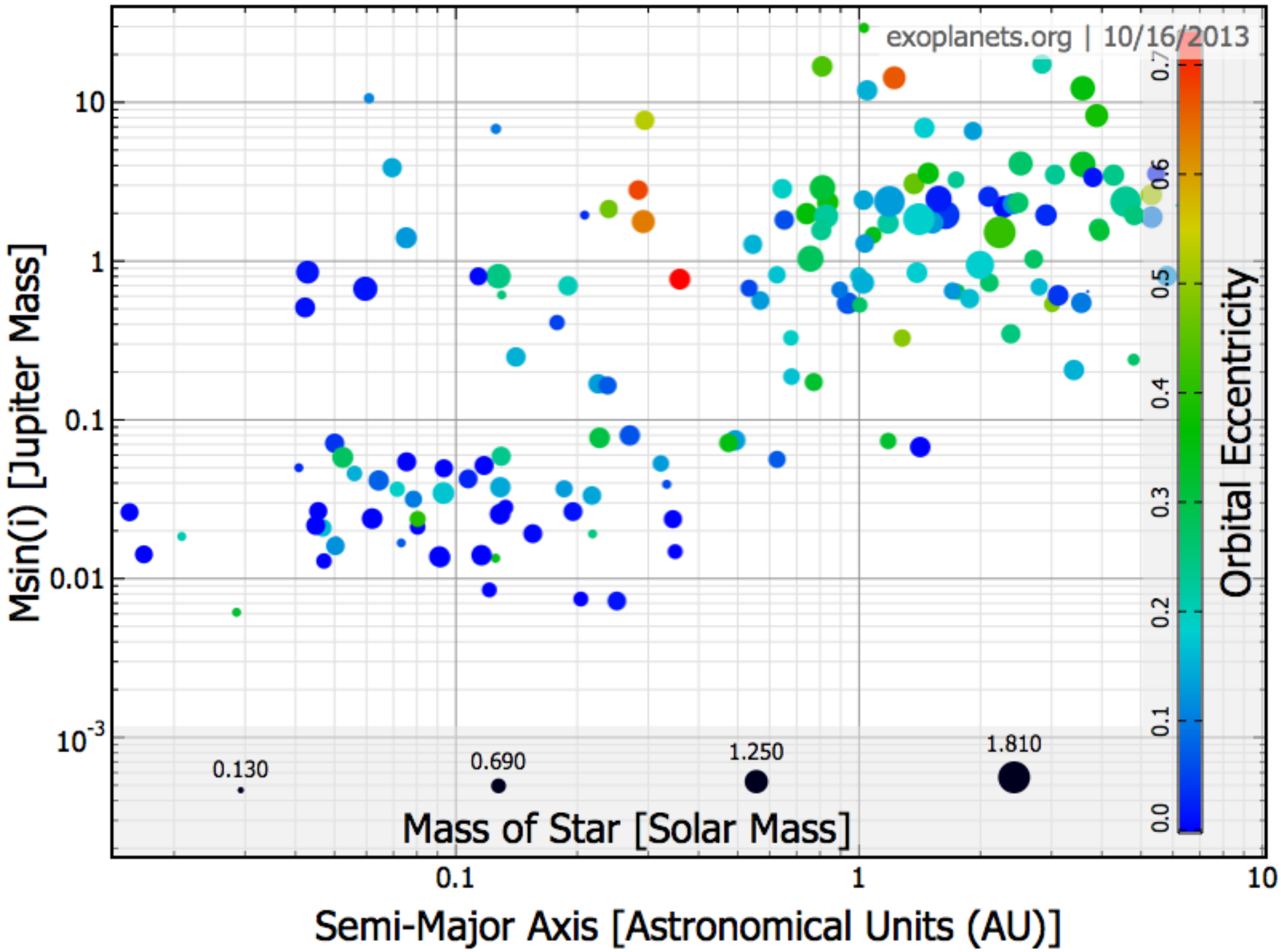
A short summary of the results (RV, Pepe)

- 1% of stars have a hot Jupiter, more frequently around metal-rich stars
- 14% of stars host a giant planets at any period, more frequently around metal-rich stars
- 50 – 80% of stars orbit at least one planet of any kind
- 30% of stars have a planet within < 30 M_{Earth} and within 100 days period …
- More than 70 % of planetary systems with one planet of $m_P \sin i < 30\ M_{Earth}$ include more than one planet

Dynamical diversity

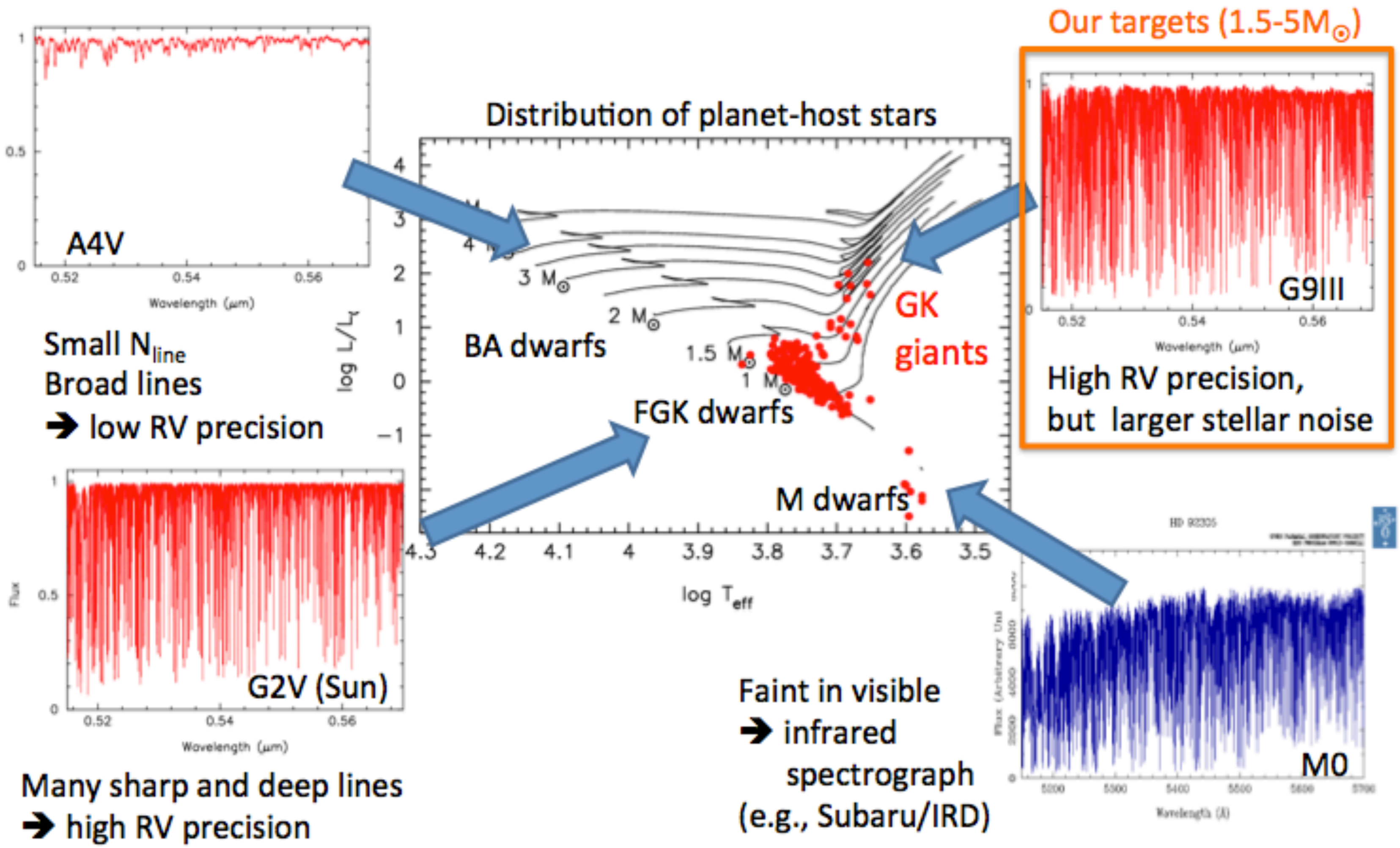


Multiple-gas-giant barrier: perturbation



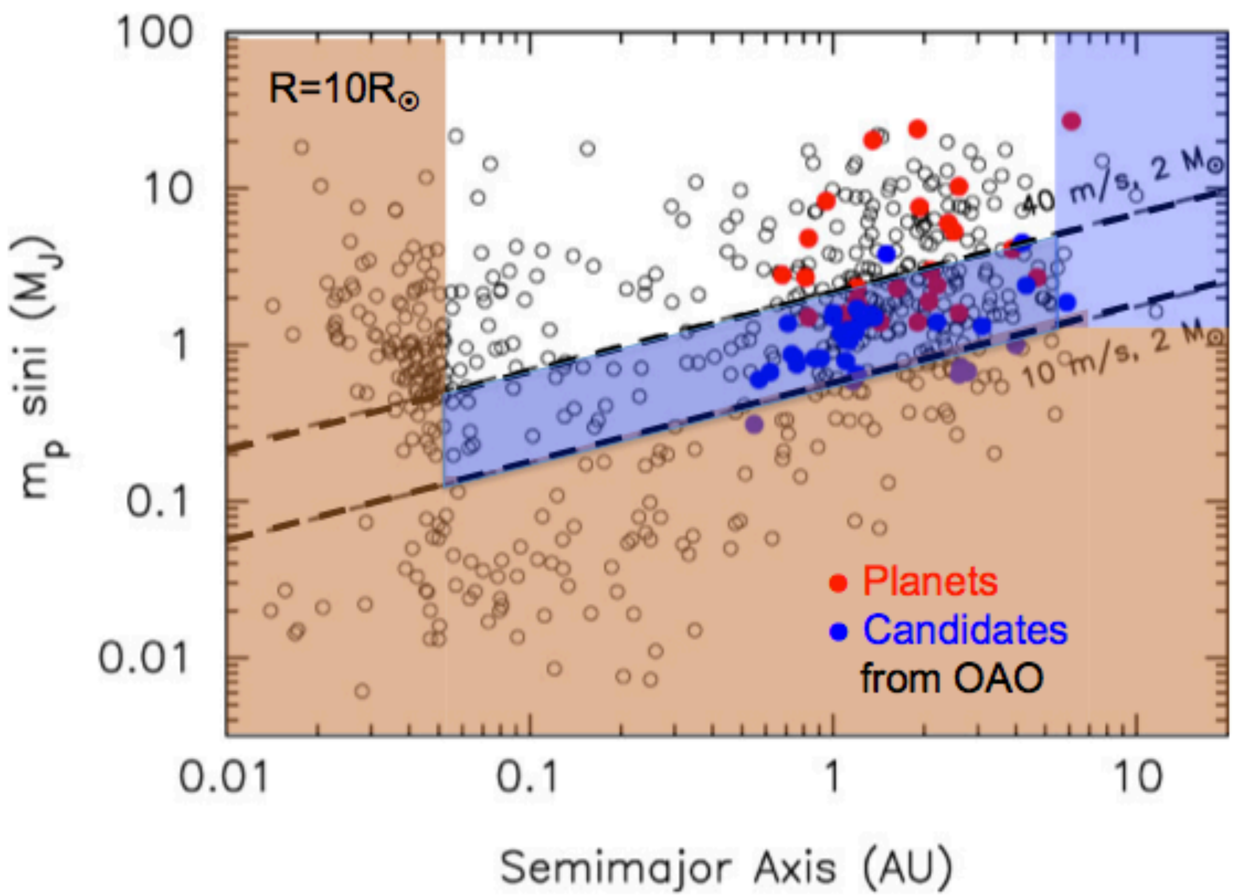
Confirmed members of multiple planet systems

Targeting Evolved Stars to Search for Planets around Intermediate-Mass Stars



Planets around massive stars (Sato)

Detection Limit for Planets around Giants



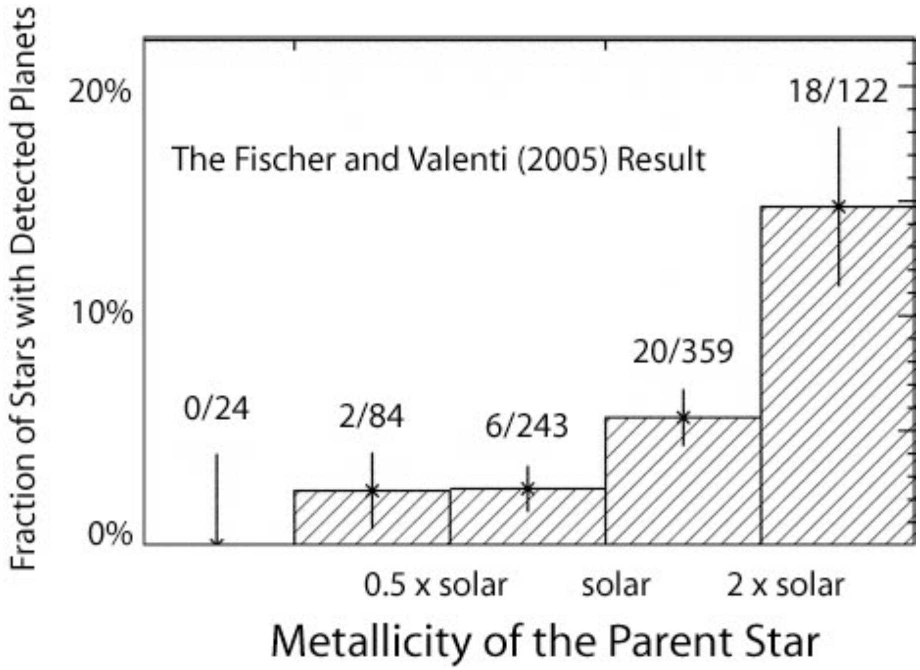
K_1=40m/s@2M⊙
Completeness
~100%

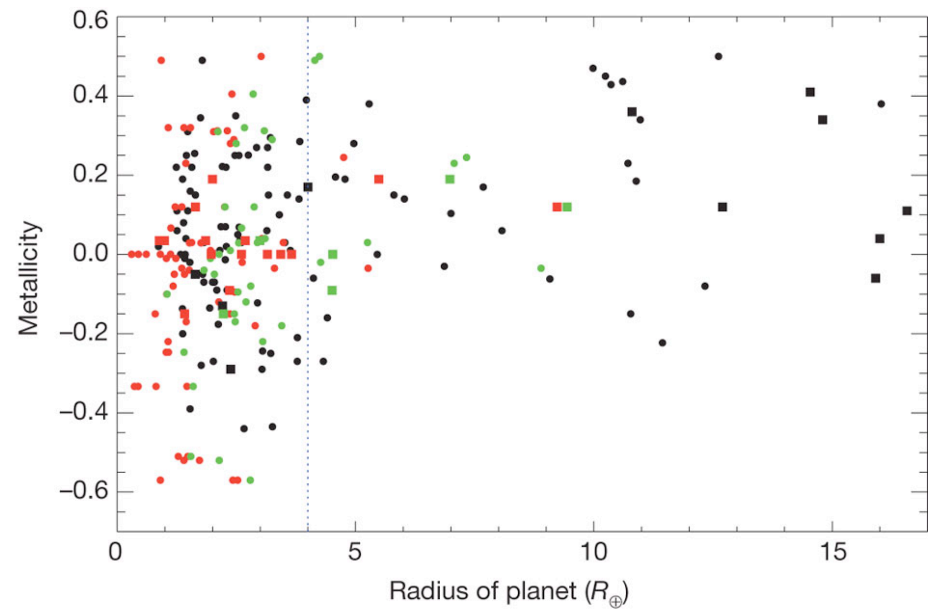
K_1=10m/s@2M⊙
Completeness
<30%

RV jitter of giants is 10-20 m/s

Unexplored or not-well explored region

Planetary mass & size vs stellar metallicity

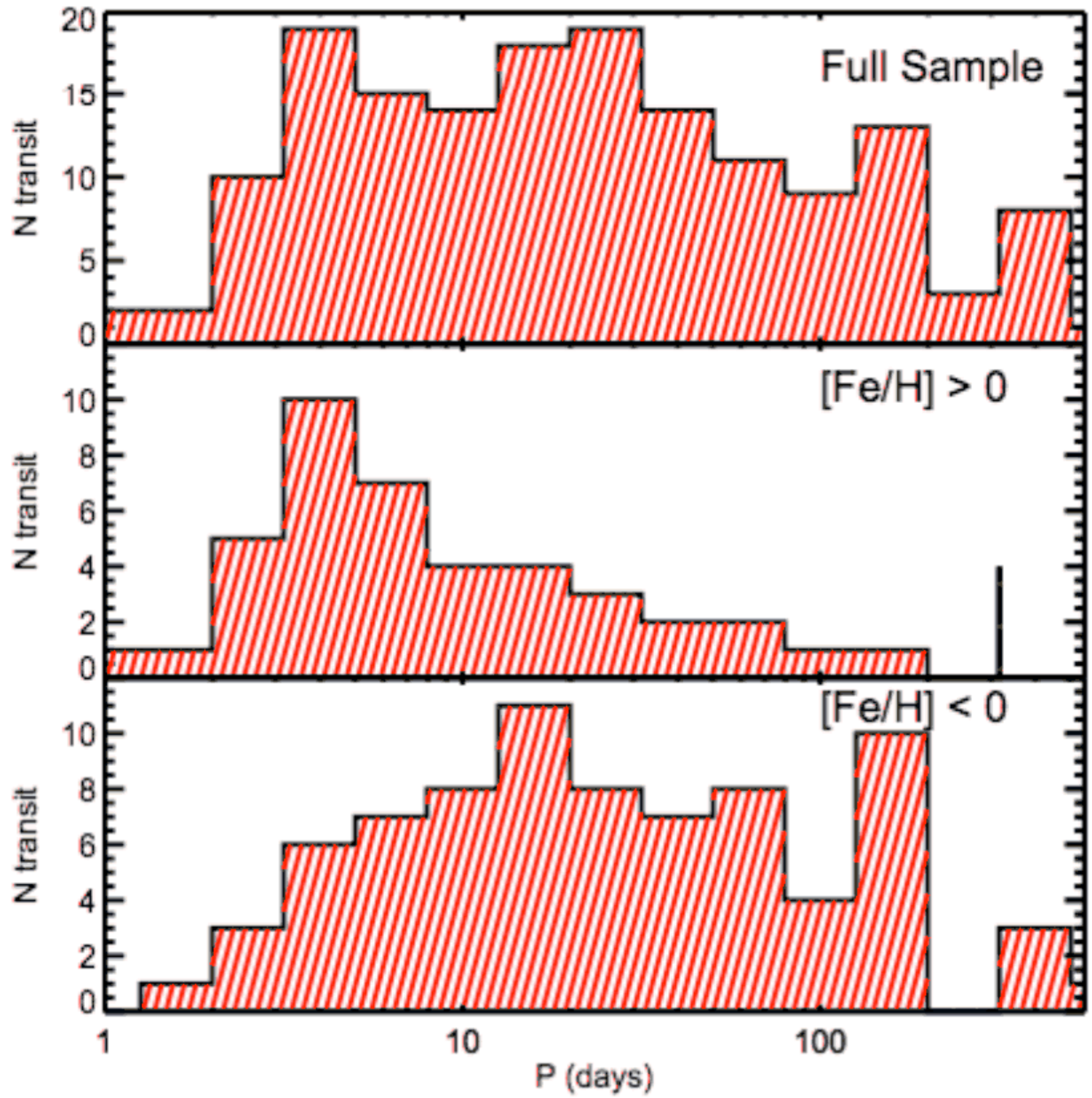




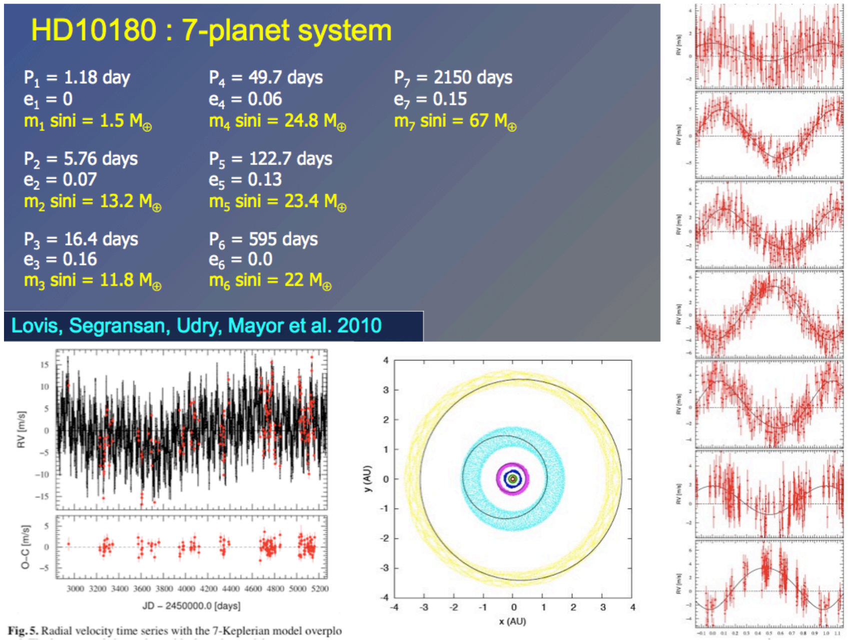
1) There is a strong correlation between η_{HJ} vs stellar metallicity.

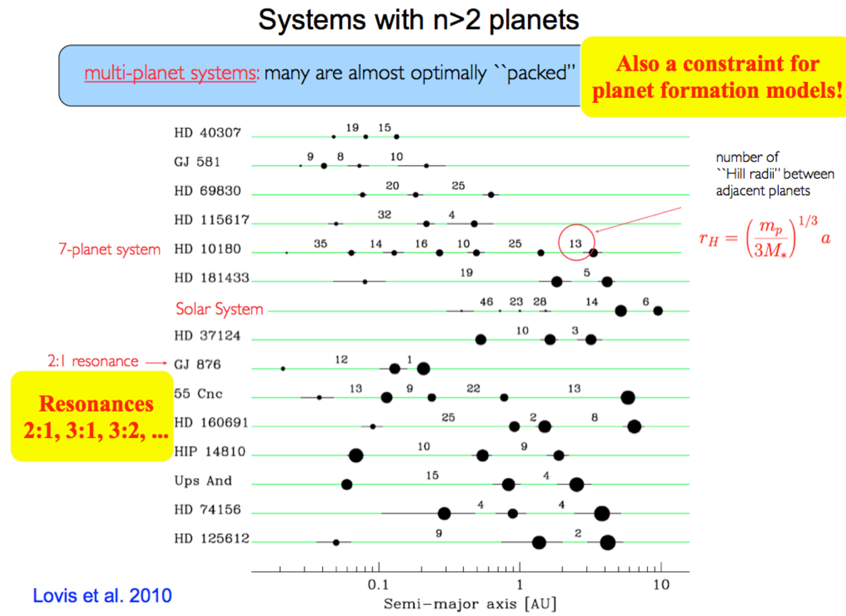
2) There is no shortage of super Earths around metal-poor stars

Period distribution of hot Jupiters: Dependence on stellar metallicity



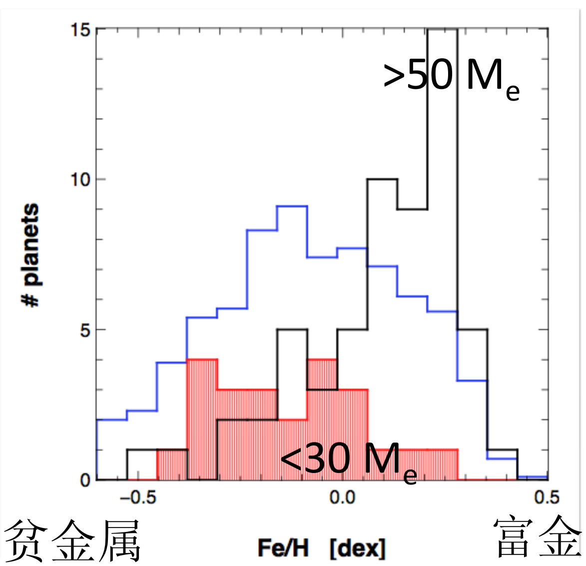
视向速度巡天（亮点2）



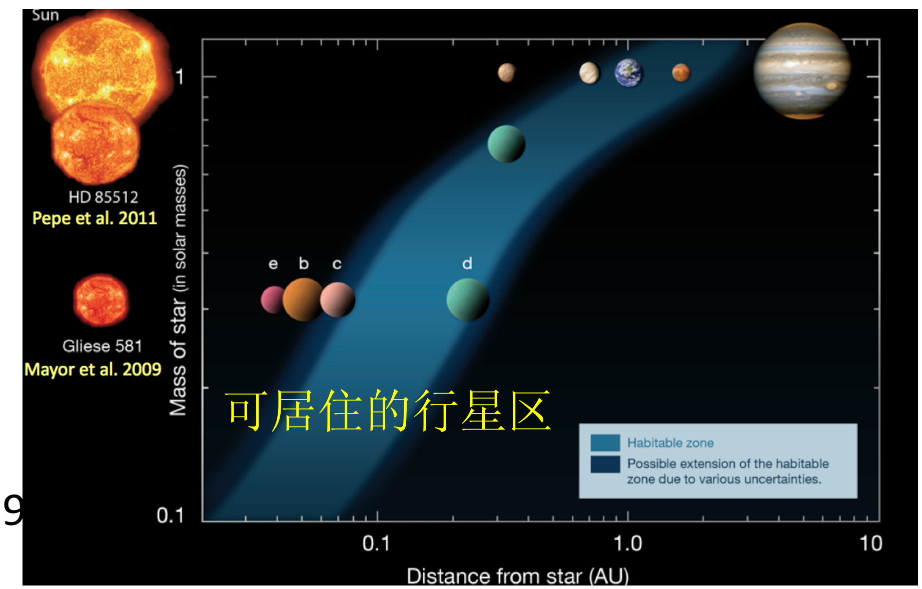


多成员的行星系统

共振的行星系统



贫金属 富金属



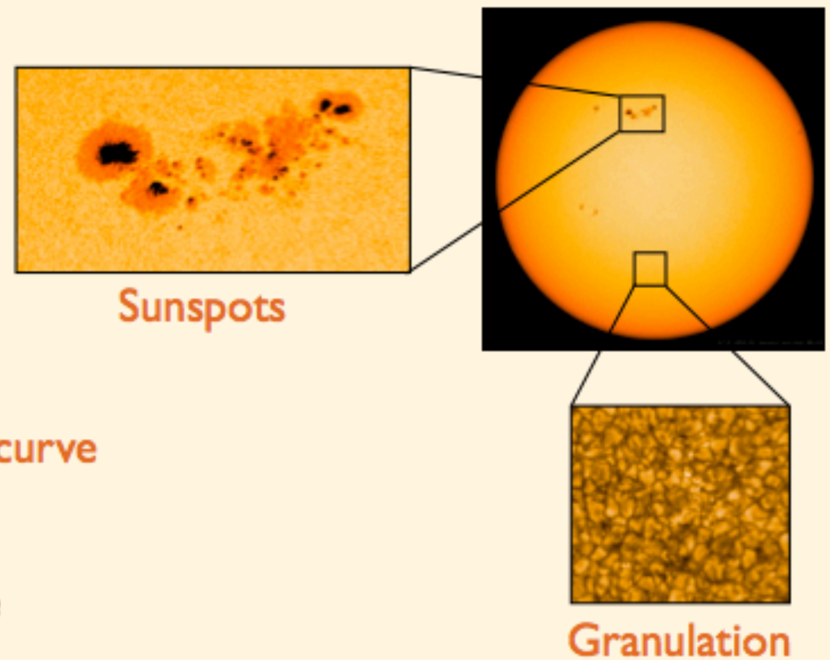
Outline of this work

- Monte Carlo Markov Chain (MCMC) code
- RV model:

$RV_{total} = RV_{planets} + RV_{activity}$

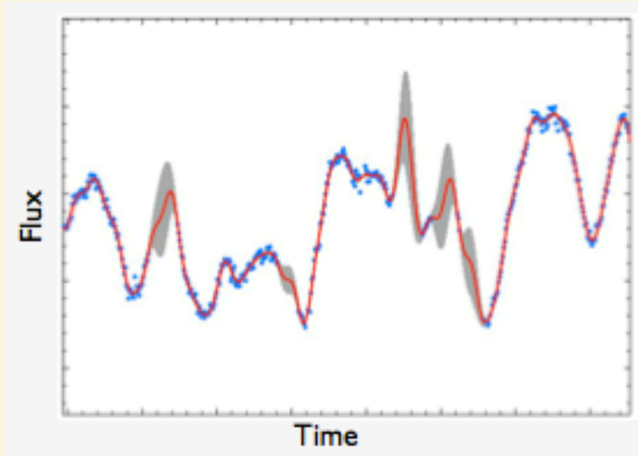
Basis functions derived from lightcurve
(*FF'* method of Aigrain 2012)

Gaussian process with covariance
properties of lightcurve
(Haywood et al., submitted)



Using a Gaussian process to fit data

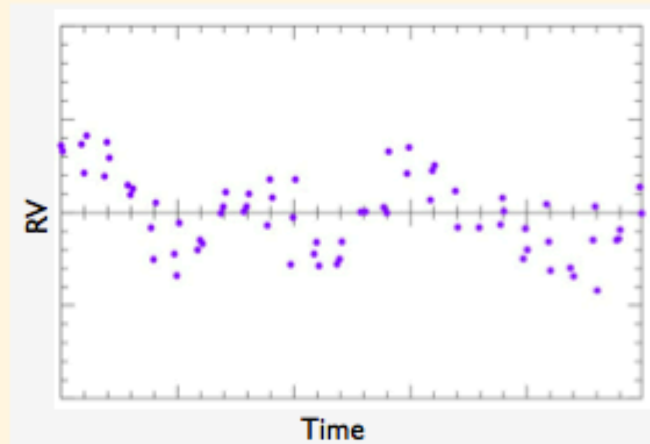
Lightcurve:
naturally has covariance properties of star's magnetic activity



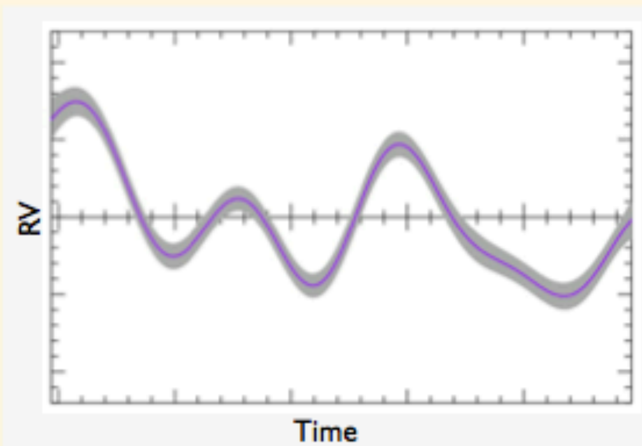
train GP: determine $\theta_1, \theta_2, \theta_3, \theta_4$ of covariance function through MCMC simulation

$k\,(t, t')$

+

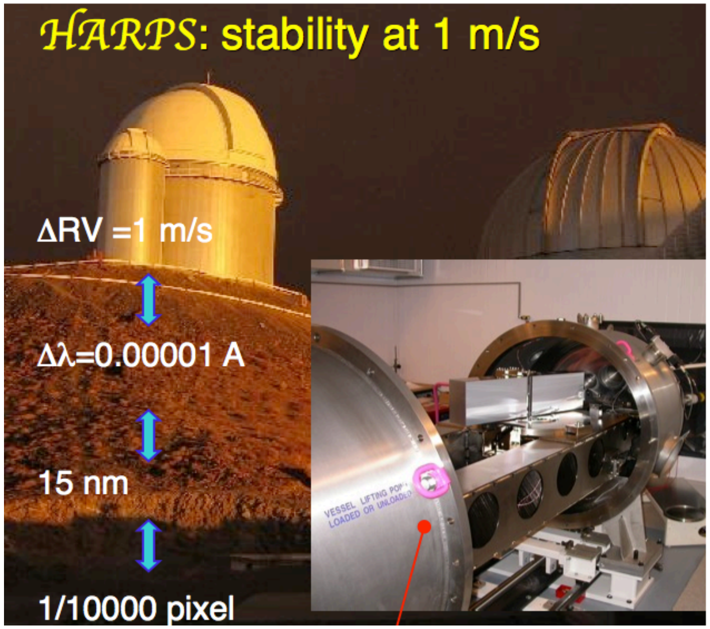


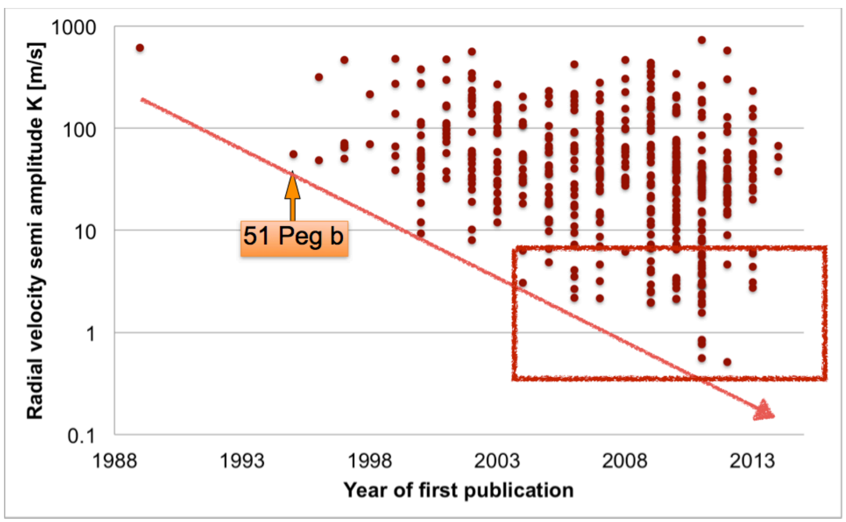
predict GP: compute covariance matrix using $k\,(t, t')$

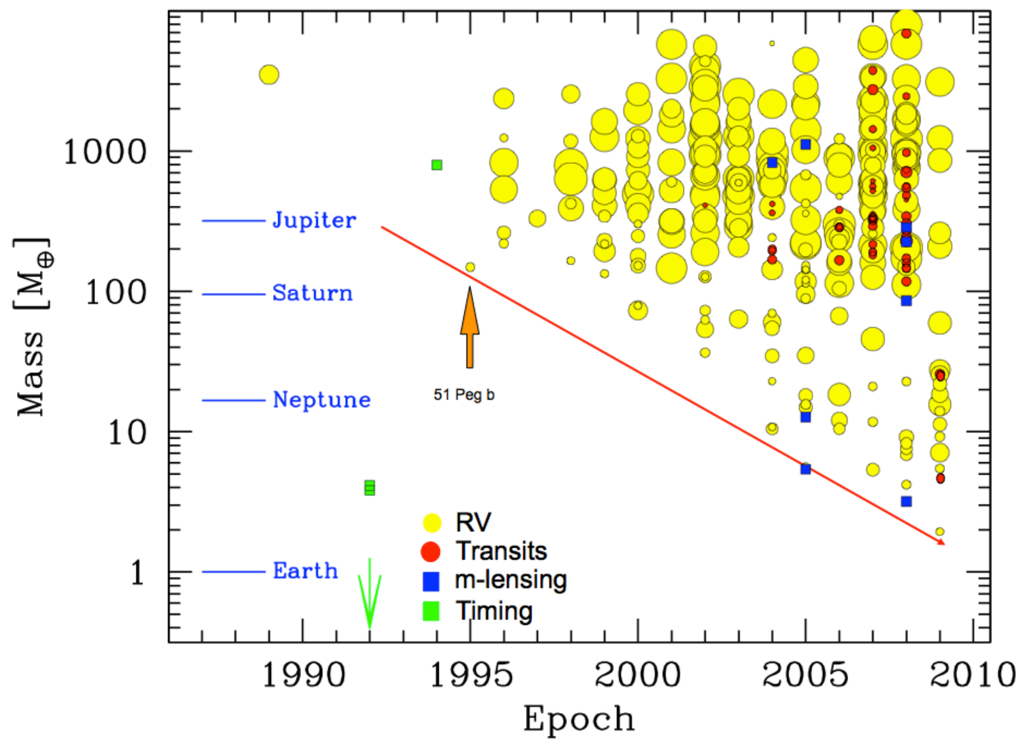


RV basis function with covariance properties of lightcurve

高精度、稳定的光谱仪，　激光梳

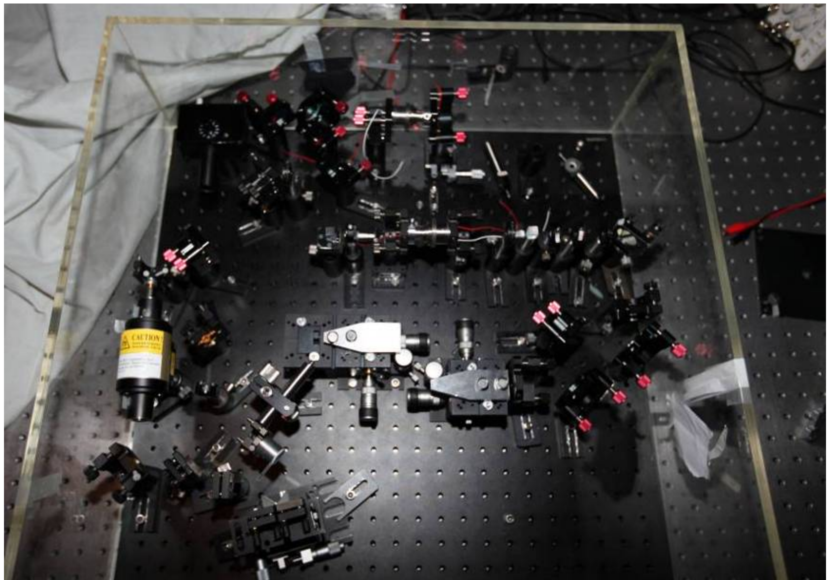


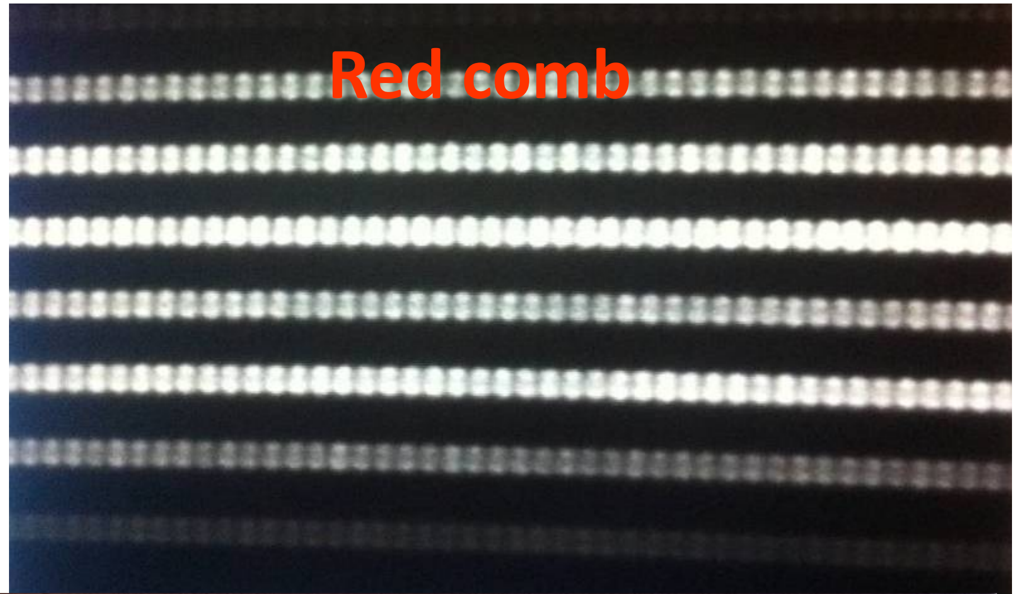


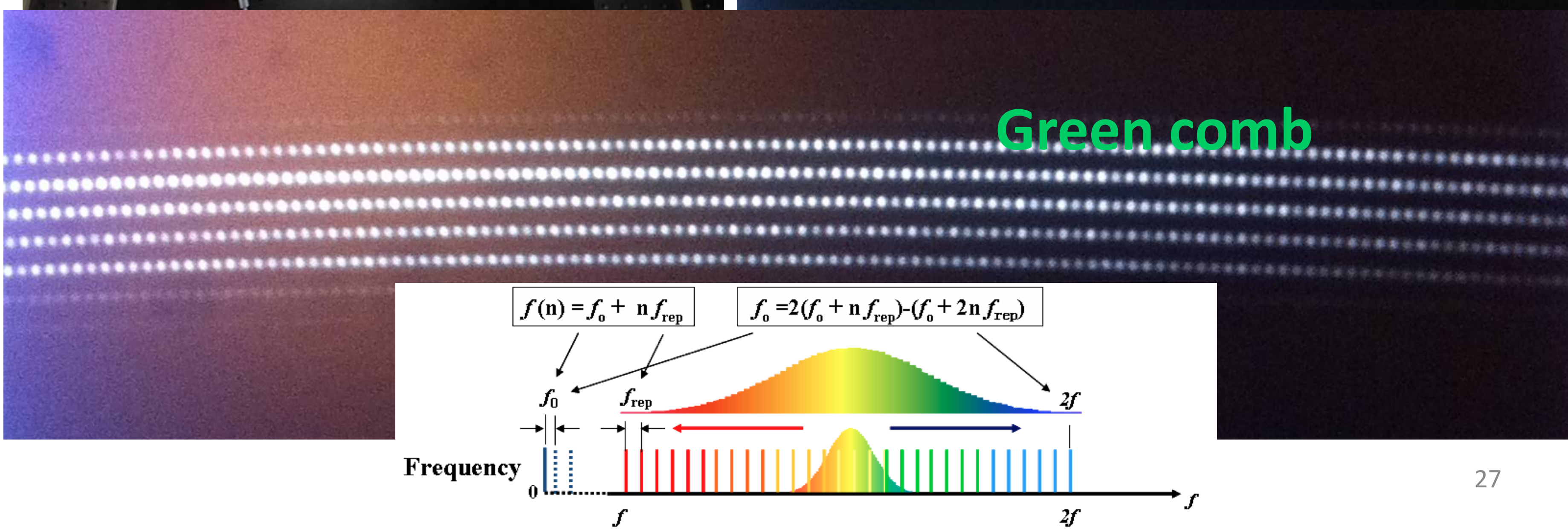


中小型望远镜: Swiss 1.2m Euler+coralie (>60 planets), Lick: 3m, Keck: 10m and Harps

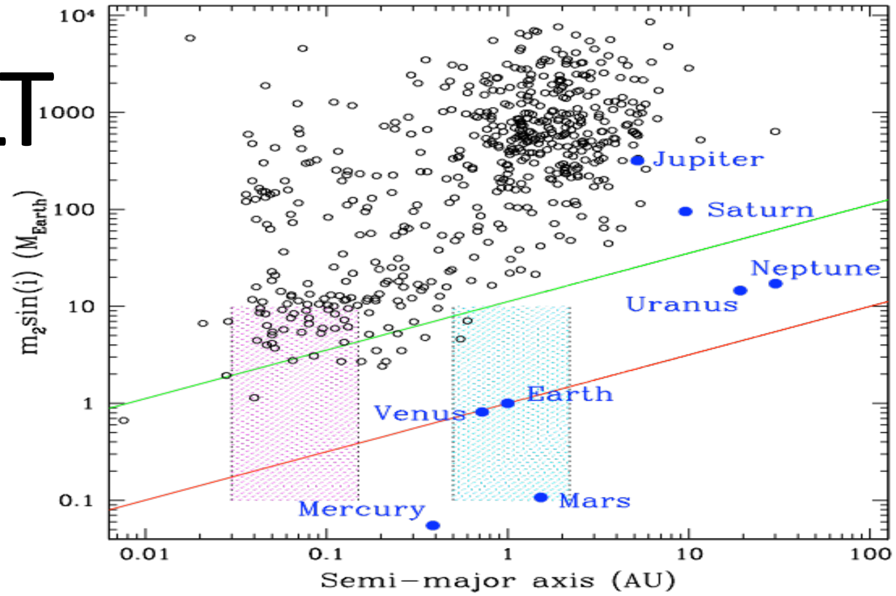
Comb line resolved in NAOC 2.16M



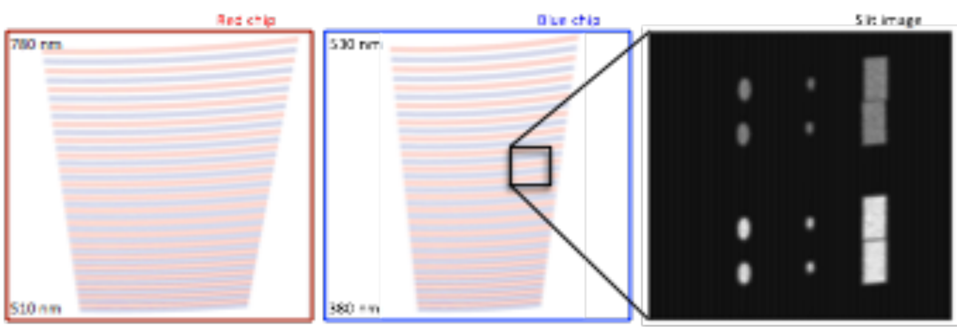




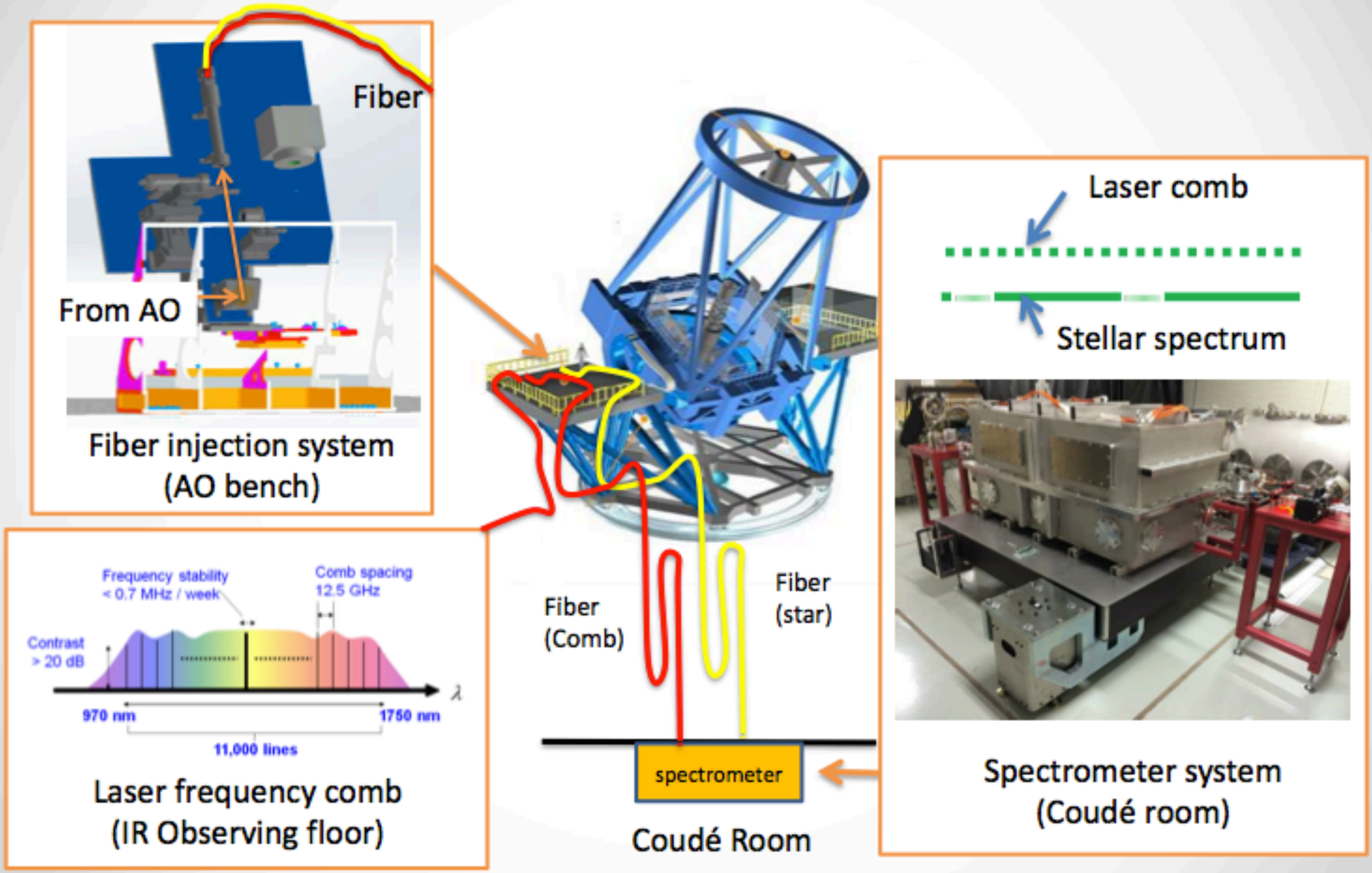
Expresso on the VLT



Parameter/Mode	singleHR (1 UT)	multiMR (up to 4 UTs)	singleUHR (1 UT)
Wavelength range	380-780 nm	380-780 nm	380-780 nm
Resolving power	134'000	59'000	225'000
Aperture on sky	1.0 arcsec	4x1.0 arcsec	0.5 arcsec
Spectral ampling (average)	4.5 pixels	5.5 pixels (binned x2)	2.5 pixels
Spatial sampling per slice	9.0 (4.5) pixels	5.5 pixels (binned x4)	5.0 pixels
Simultaneous reference	Yes (no sky)	Yes (no sky)	Yes (no sky)
Sky subtraction	Yes (no sim. ref.)	Yes (no sim. ref.)	Yes (no sim. ref.)
Total efficiency	11%	11%	5%
Instrumental RV precision	< 10 cm s^{-1}	~ 1 m s^{-1}	< 10 cm s^{-1}



IRD instruments (Kotani)



To find small planets :

One needs precise and efficient instrumentation and pipelines

One needs to characterize the star

Difficulty : no general analytical model and could evolve over time (stationarity issues)

1> Effort need to be made on the modeling part and statistical part

2> Take more data on many different time scales:

~days :granulation

~10-60 days : star rotation period and its harmonic : spots, plages

~500-5000 days : Activity Cycle

3> Avoid as much as possible sampling GAPS

Above all

To study the planetary content of quiet bright solar neighborhood stars one need :

Large number of measurements for each star !! ie. 200 meas.

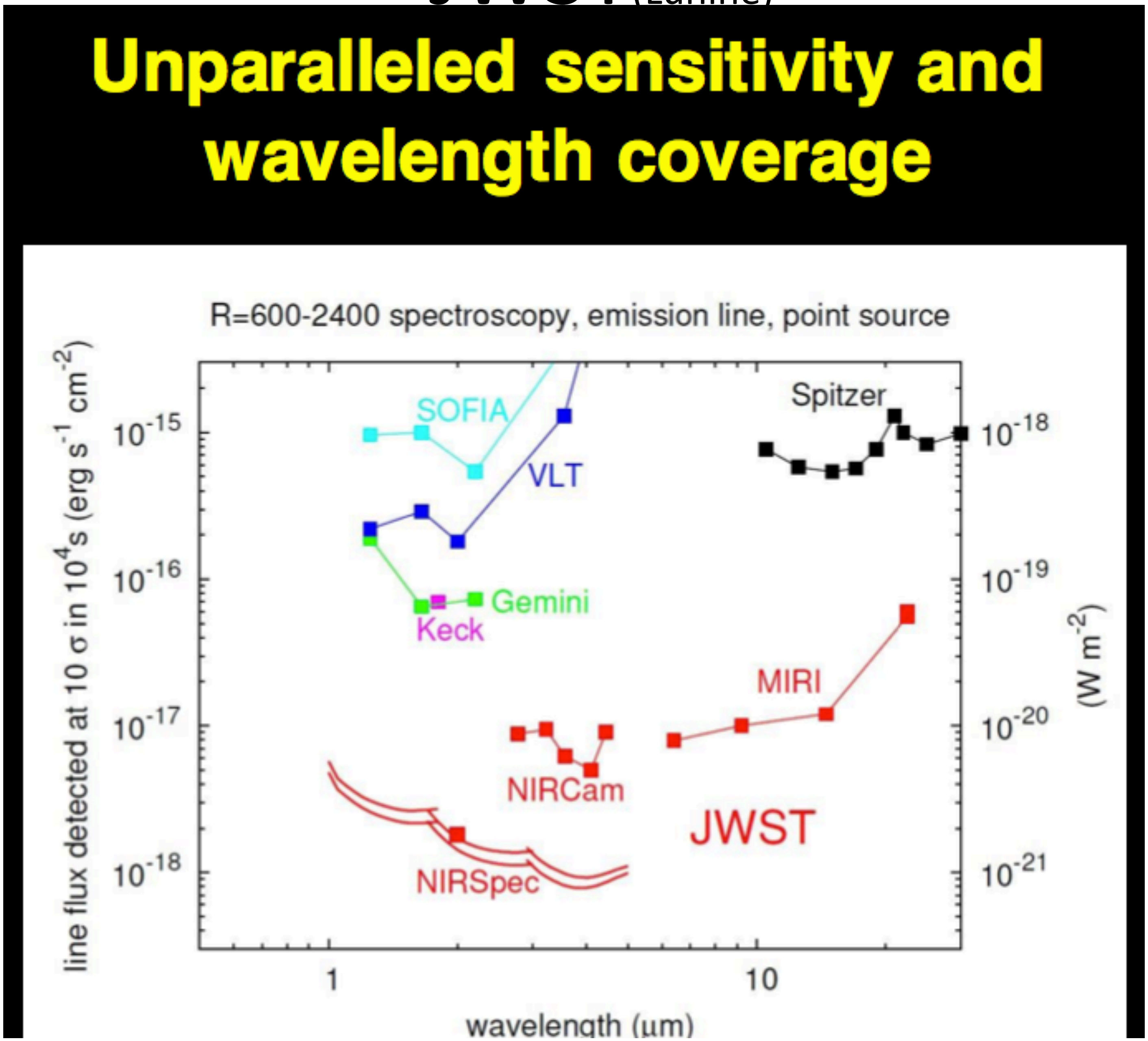
Bright and quiet objects

Dedicated telescopes

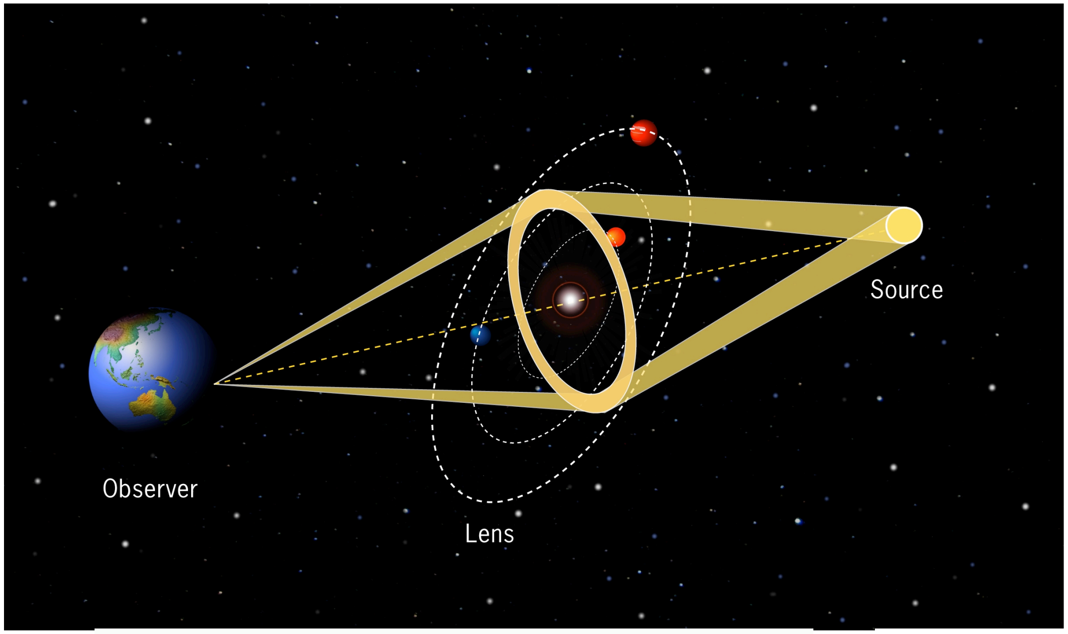
Take home message

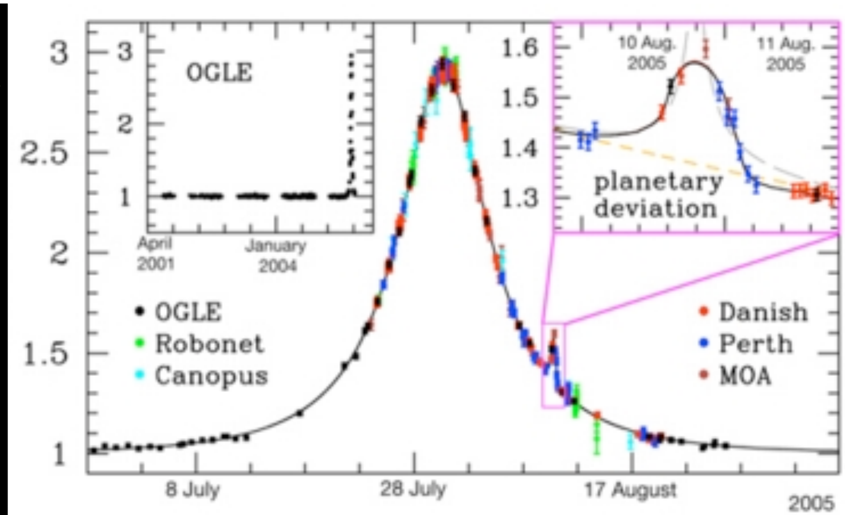
Many instruments like HARPS strongly needed, especially in the era of Kepler, TESS, Cheops, JWST, PLATO, …

JWST(Lunine)

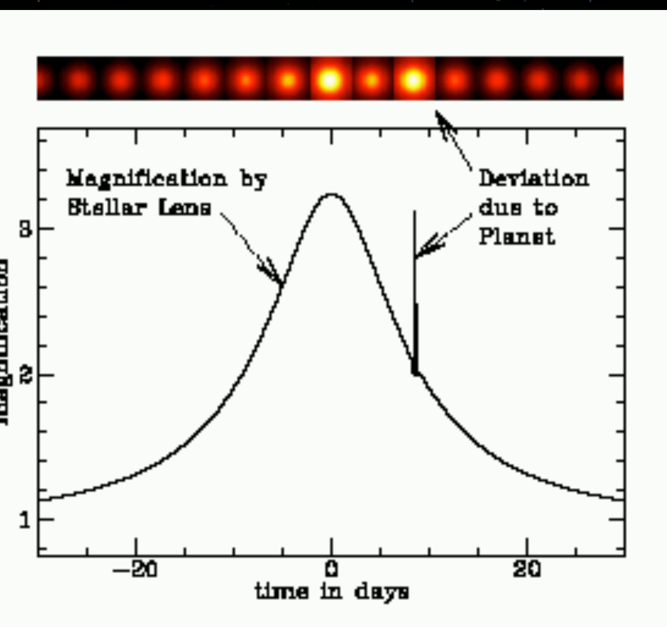

Unparalleled sensitivity and wavelength coverage
R=600-2400 spectroscopy, emission line, point source
line flux detected at 10 σ in 10^4 s (erg s^-1 cm^-2)
(W m^-2)
wavelength (μm)
10^-15
10^-16
10^-17
10^-18
10^-18
10^-19
10^-20
10^-21
1
10
SOFIA
VLT
Gemini
Keck
Spitzer
MIRI
NIRCam
NIRSpec
JWST

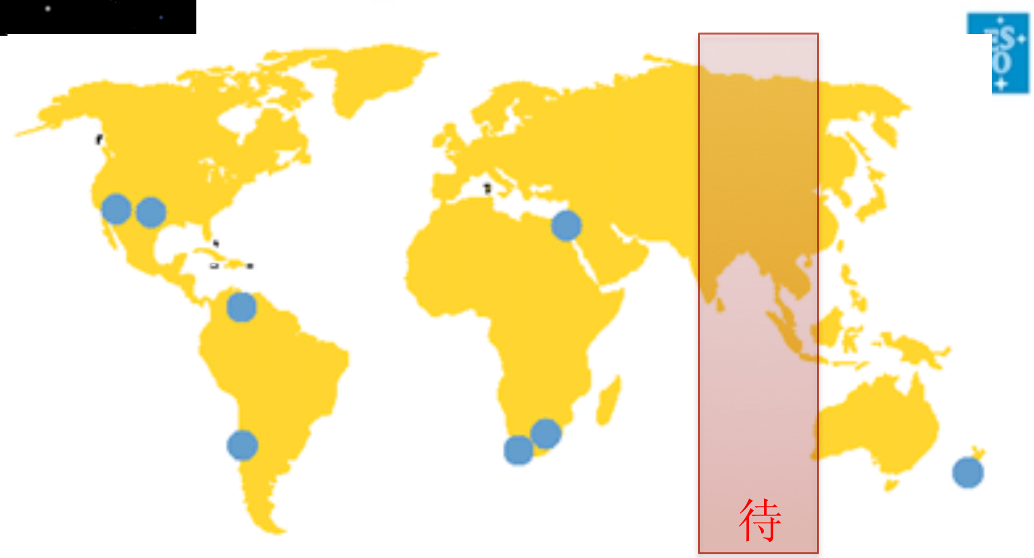
3. 微引力透镜（方法）





Light Curve of OGLE-2005-BLG-390

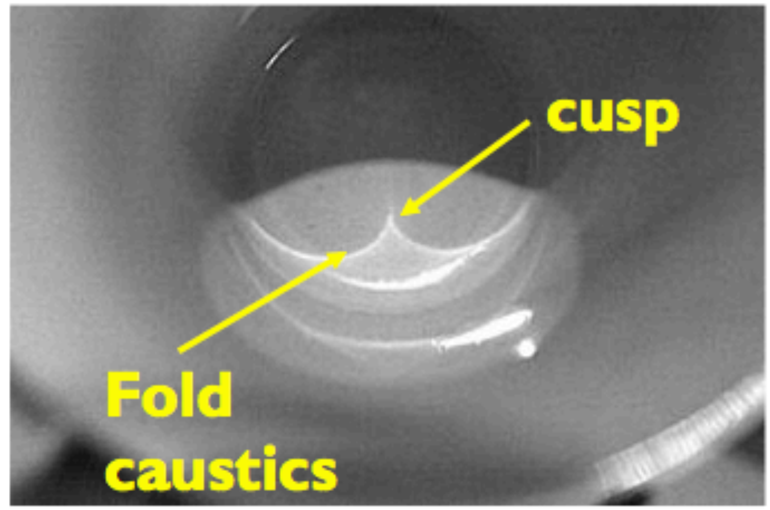




先决条件：全球布局的跟踪站

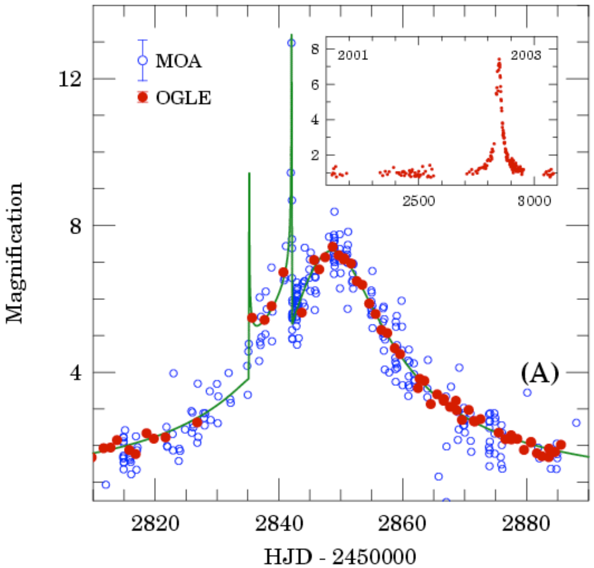
Caustics in the real world

Parallel rays from the Sun are piled into bright optical caustics by waves

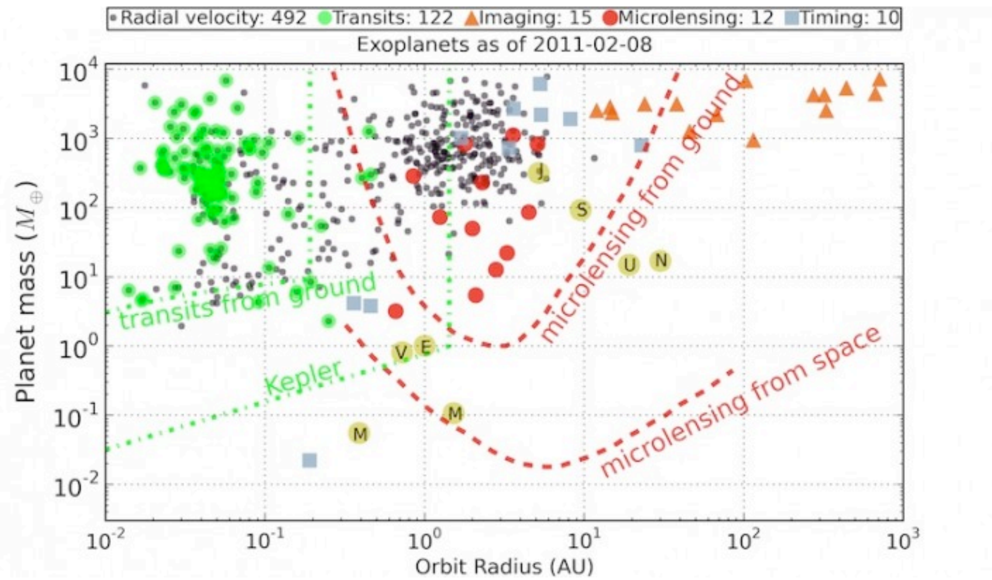


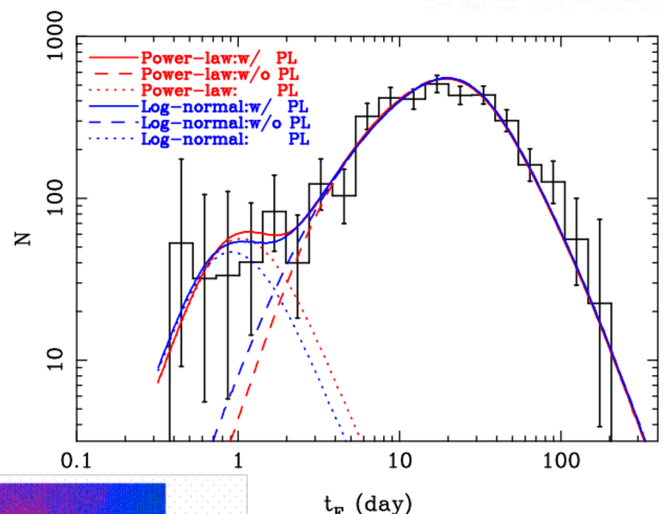
Wine glasses

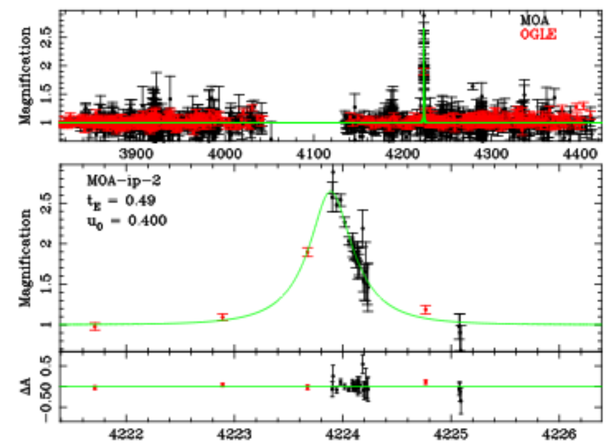
微引力透镜（亮点）

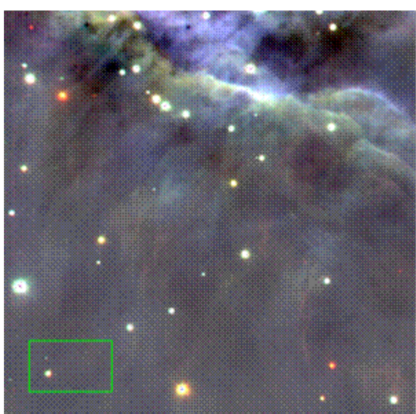


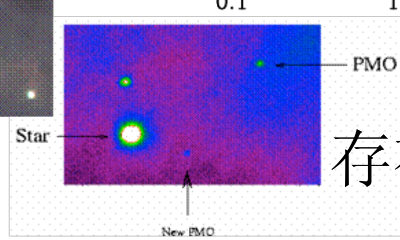
类地行星多
过类木行星







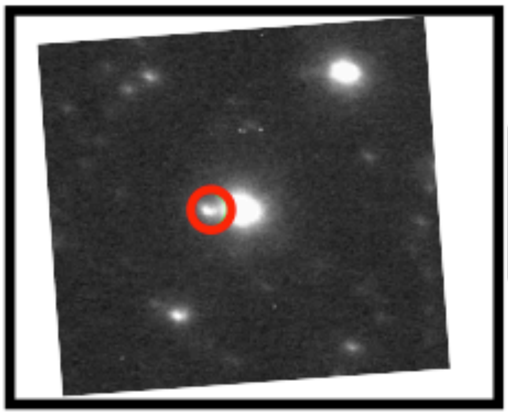




存在数量多于恒星、自由漂浮的类木行星族

Physical Properties

AO Imaging from Keck



Host:

Mass = 0.51 +/- 0.05 MSun

Luminosity ~ 5% LSun

Distance = 1510 +/- 120 pc

Planet b:

Mass = 0.73 +/- 0.06 MJup

Semimajor Axis = 2.3 +/- 0.5 AU

Planet c:

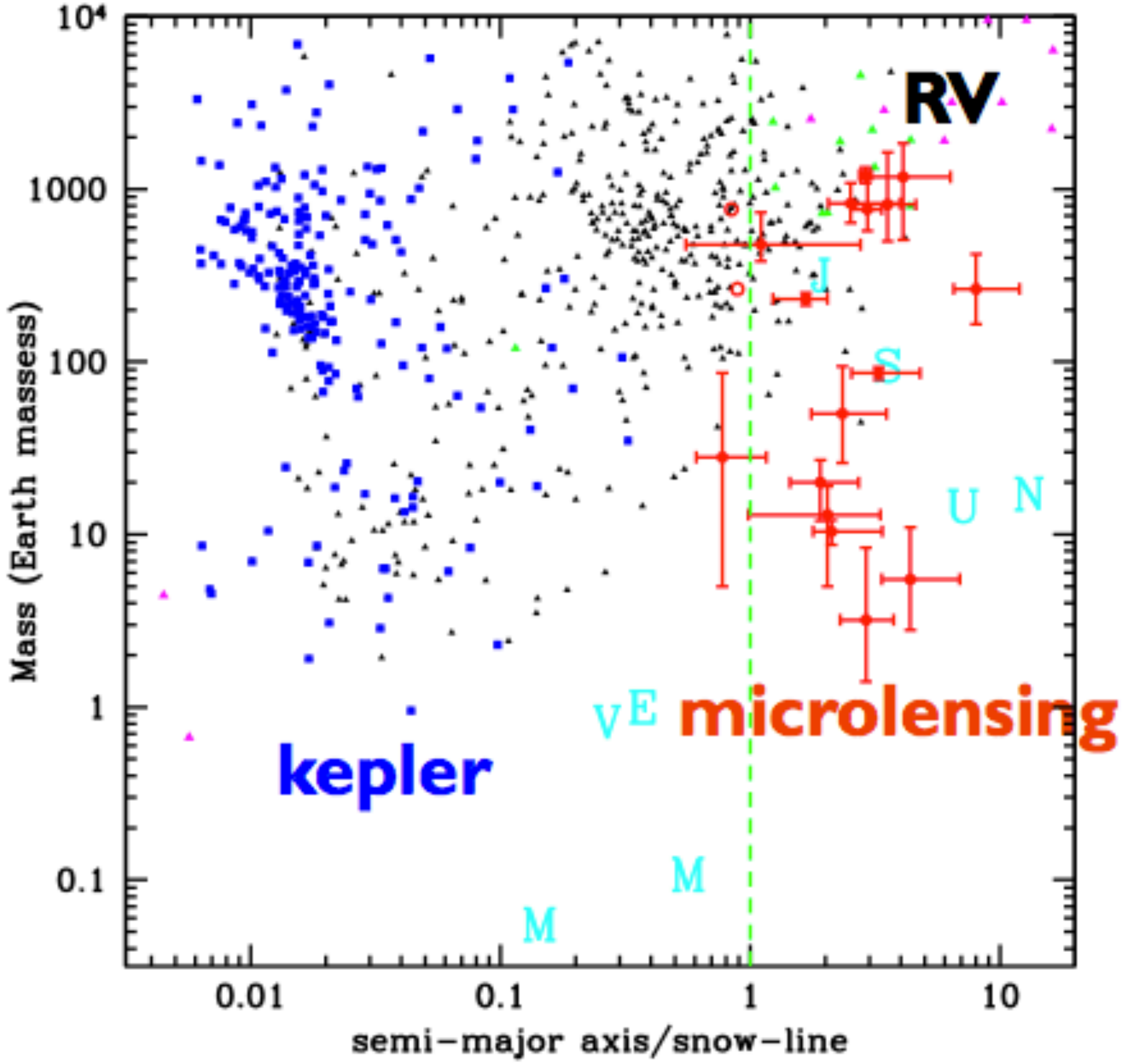
Mass = 0.27 +/- 0.02 MJup = 0.90

Semimajor Axis = 4.6 +/- 1.5 AU

Eccentricity = 0.15+0.17-0.10

Inclination = 64+4-7 degrees

Statistics in discovery space

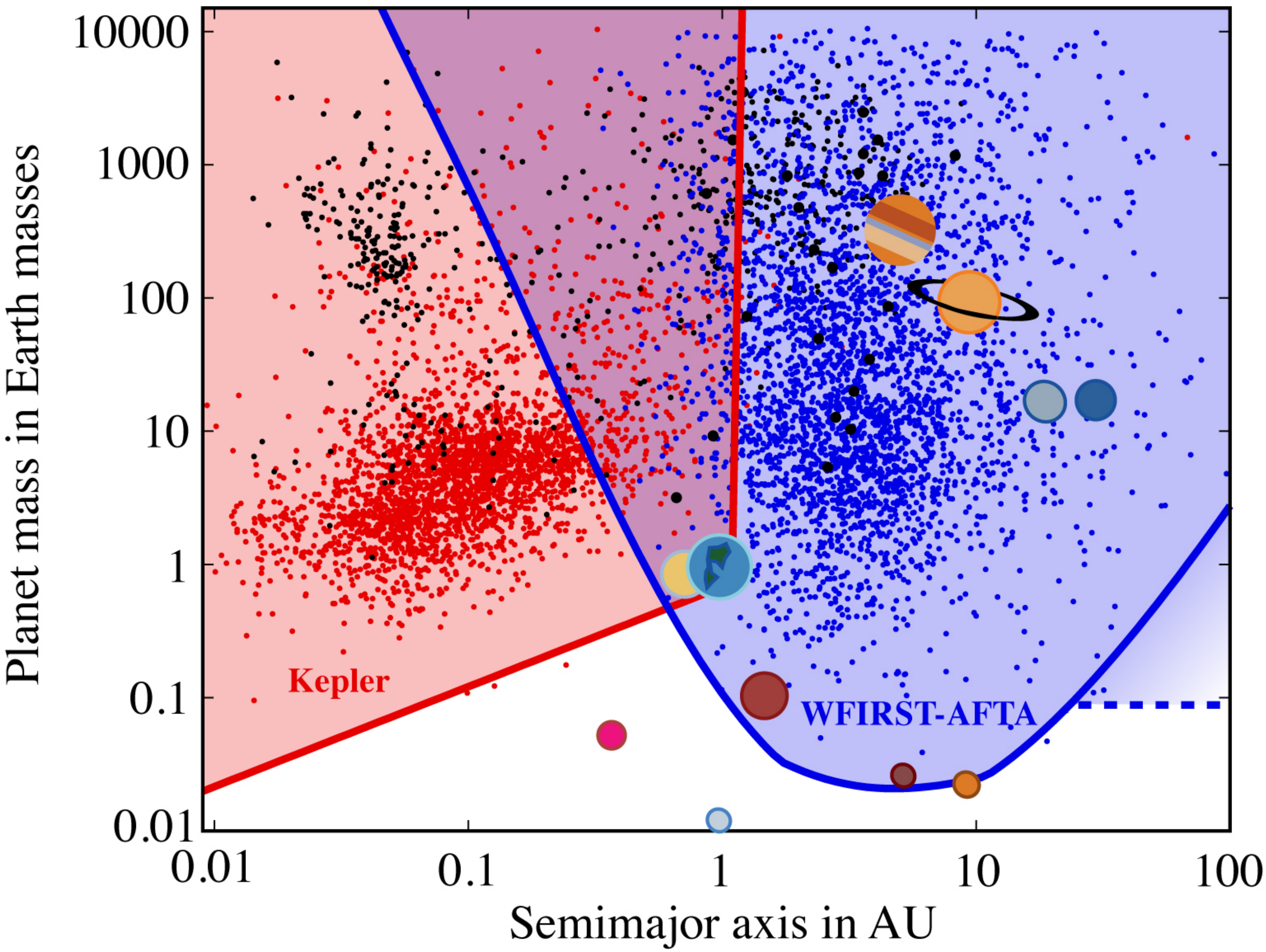


(Mao 2012)

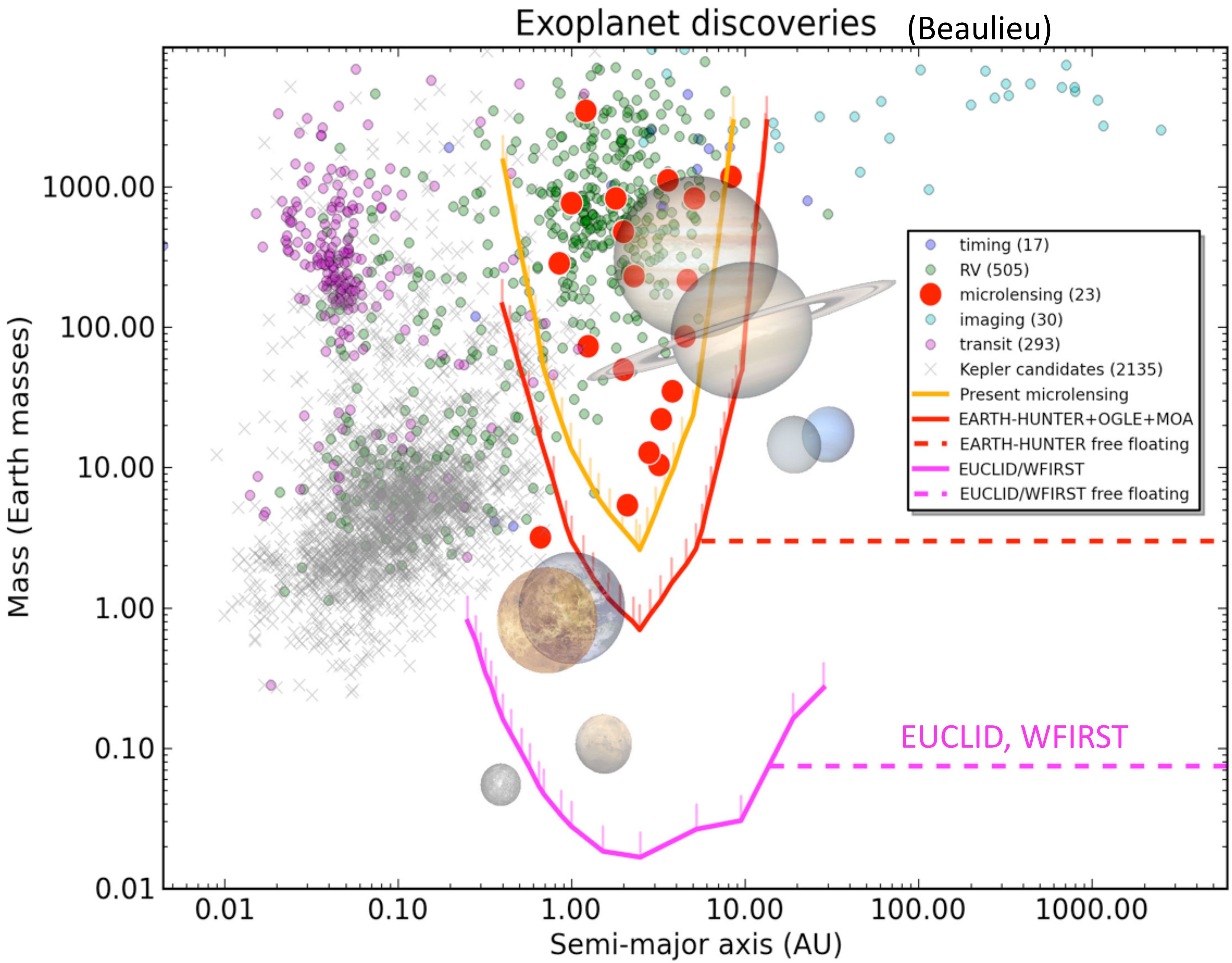
- **Mostly beyond snow line**
- **Low mass planets are more common**
- **Between 0.5-10 AU - 17% have Jupiters, 50% Neptune and Super-Earths**

Cassan et al. (2012); Gould (2006, 2010)

future

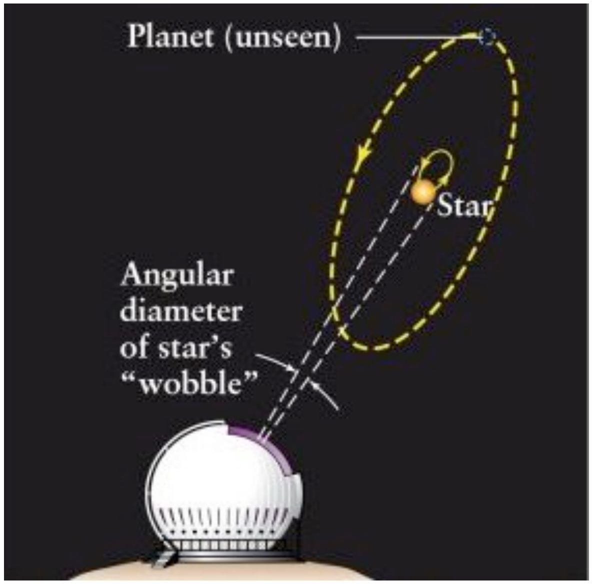


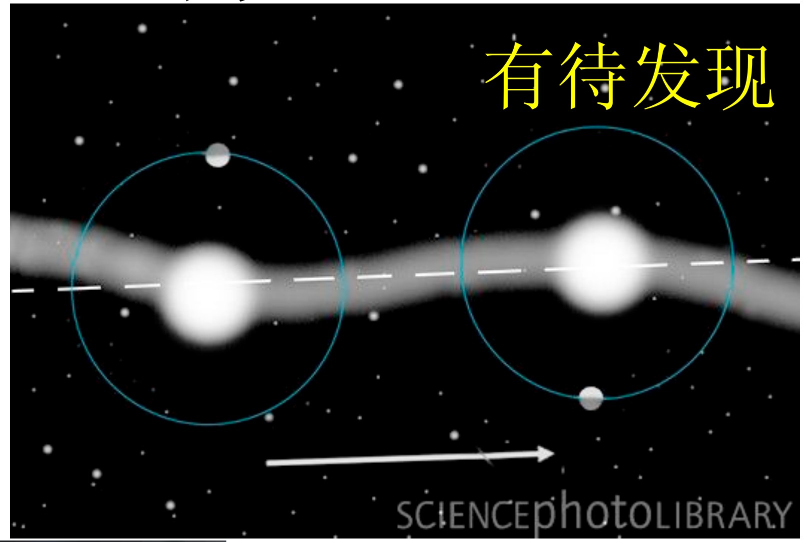
10000
1000
100
10
1
0.1
0.01
Planet mass in Earth masses
0.01
0.1
1
10
100
Semimajor axis in AU
Kepler
WFIRST-AFTA

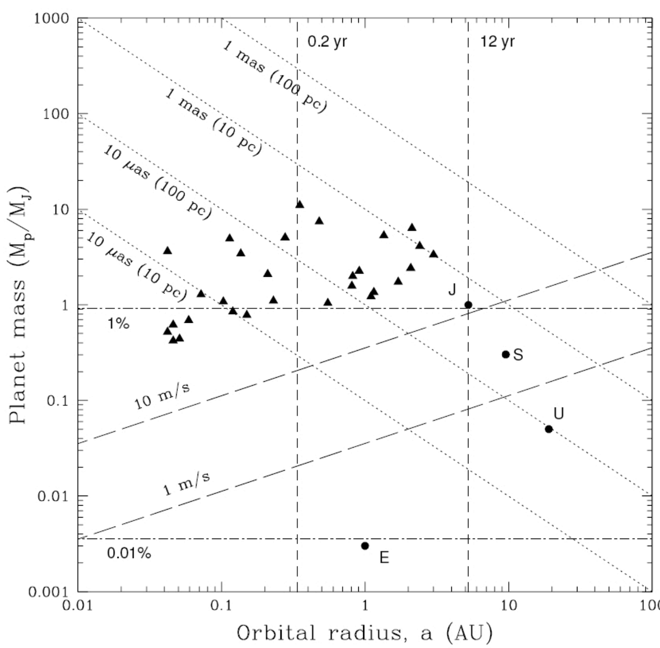


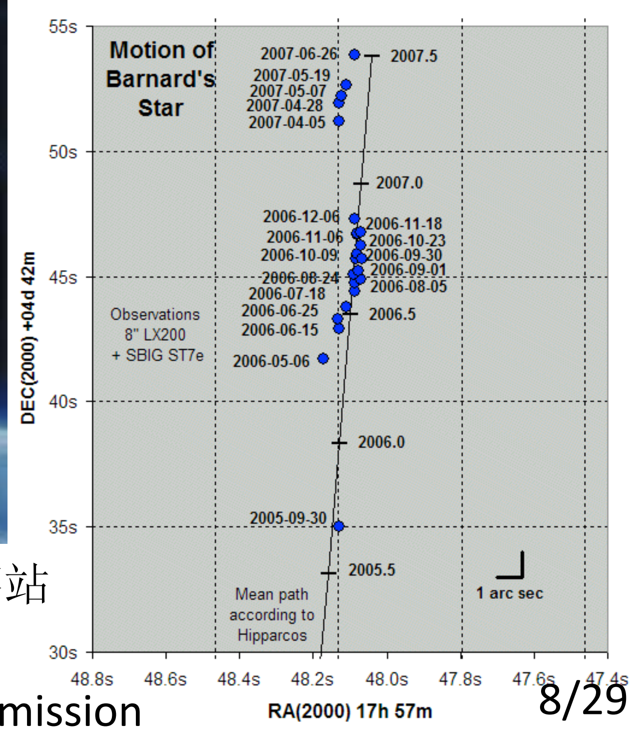
Exoplanet discoveries
(Beaulieu)
Mass (Earth masses)
Semi-major axis (AU)
0.01
0.10
1.00
10.00
100.00
1000.00
timing (17)
RV (505)
microlensing (23)
imaging (30)
transit (293)
Kepler candidates (2135)
Present microlensing
EARTH-HUNTER+OGLE+MOA
EARTH-HUNTER free floating
EUCLID/WFIRST
EUCLID/WFIRST free floating
EUCLID, WFIRST

4. 天体测量（方法）





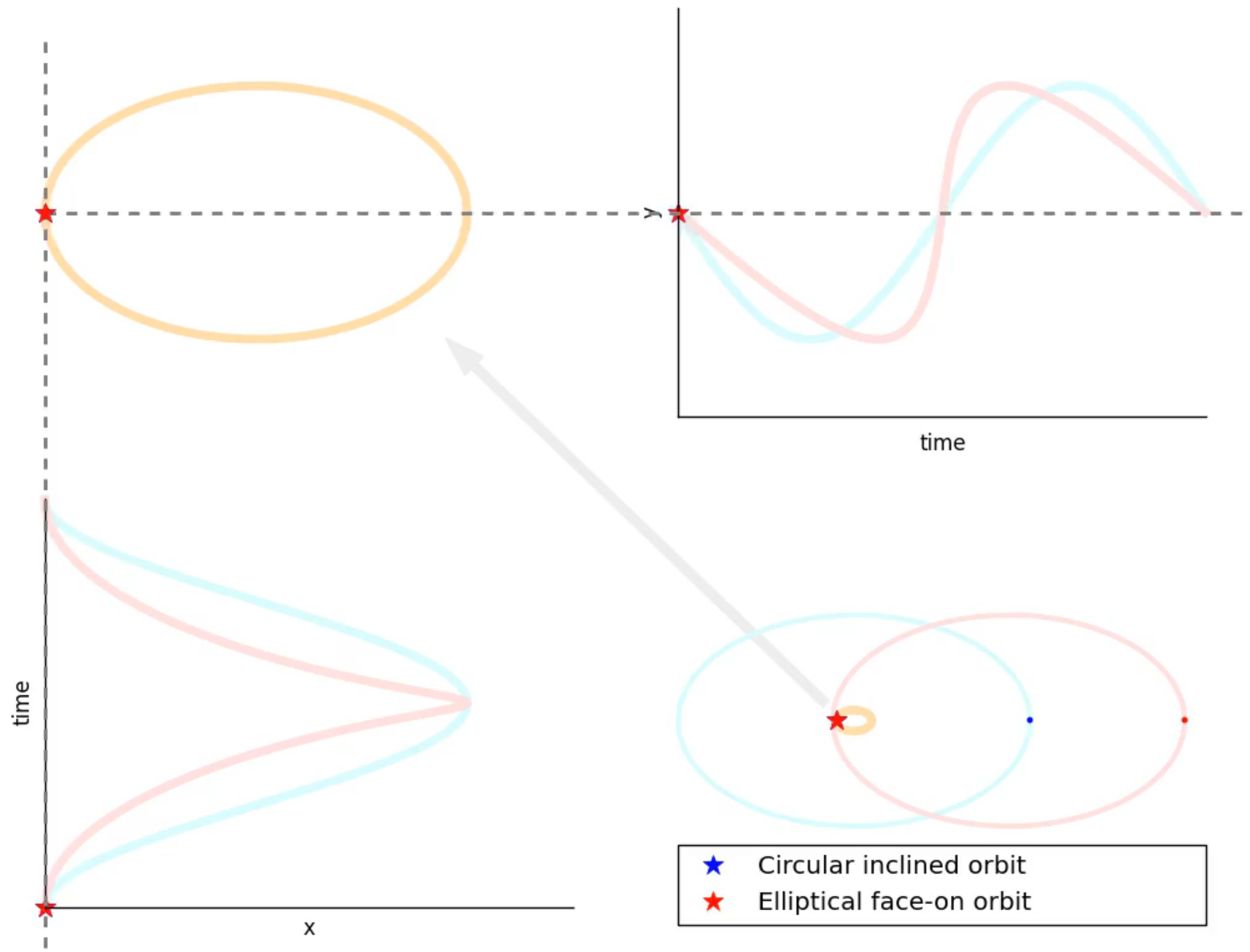




现决条件：空间观察站

STEP

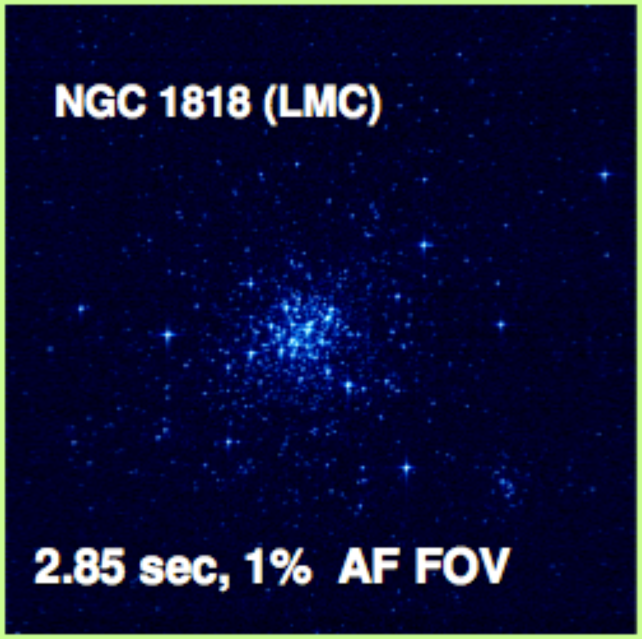
Space interferometer mission

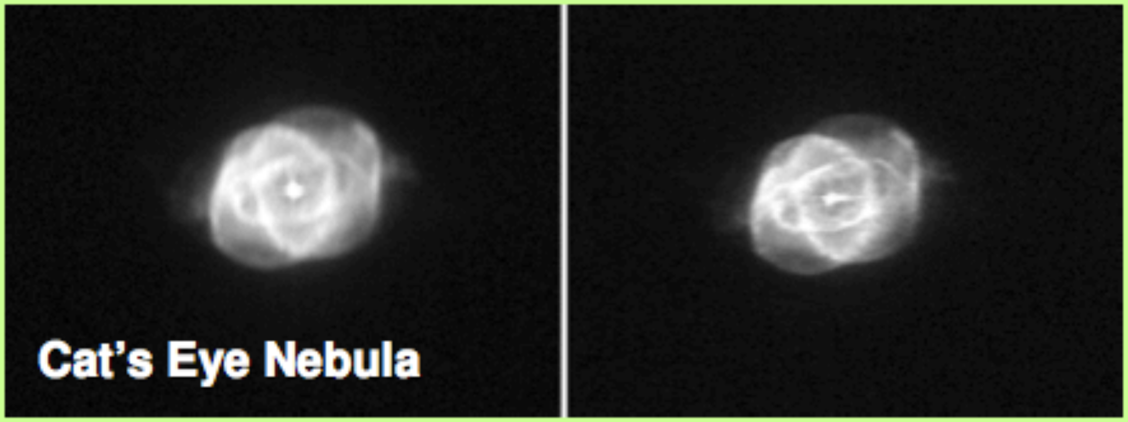


3D orbital reconstruction & accurate distance gaia (Sozzetti)

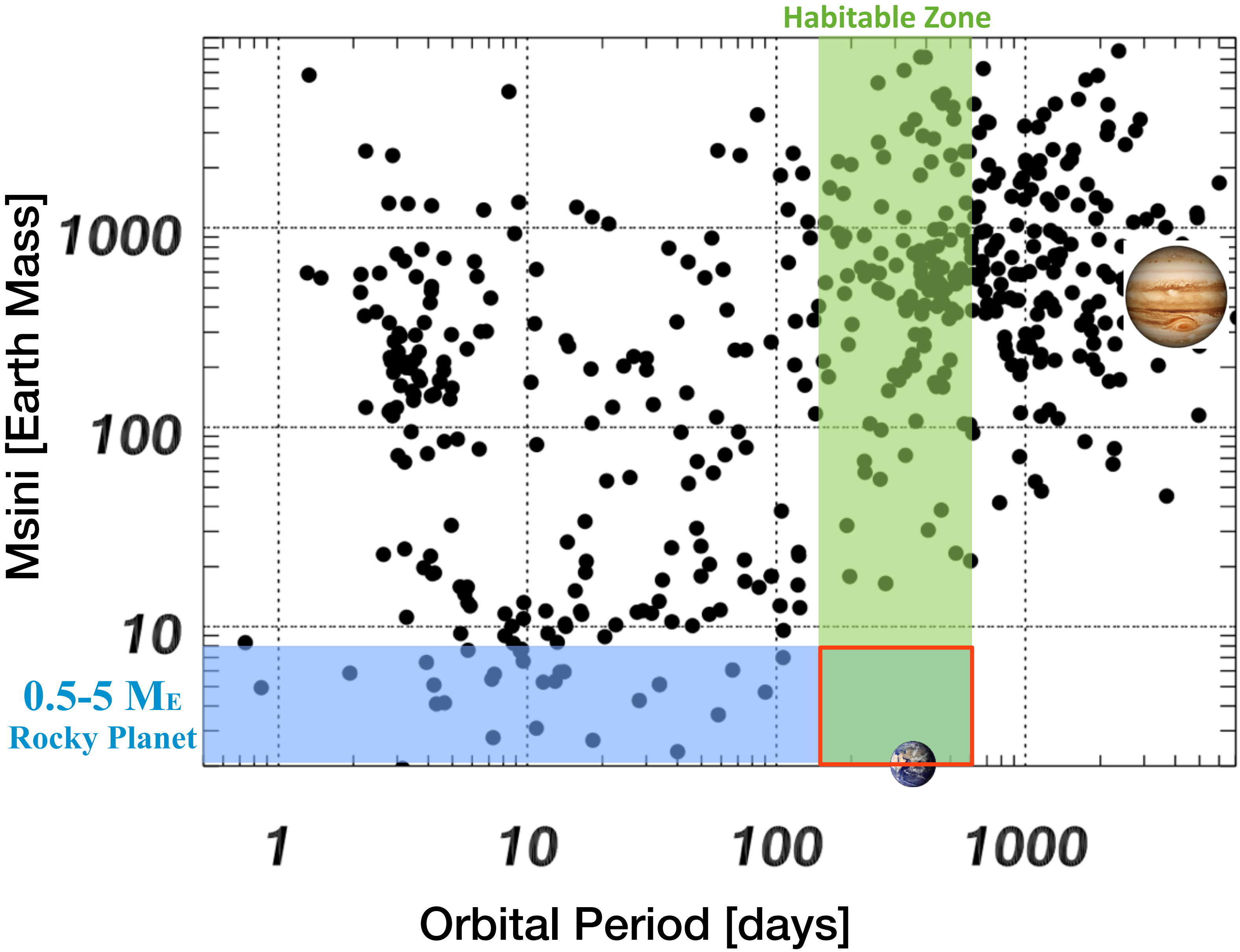
The Good News

- Perfect L2 orbit insertion (take that, Hipparcos!)
- Excellent image quality (focus and SL tuning up)





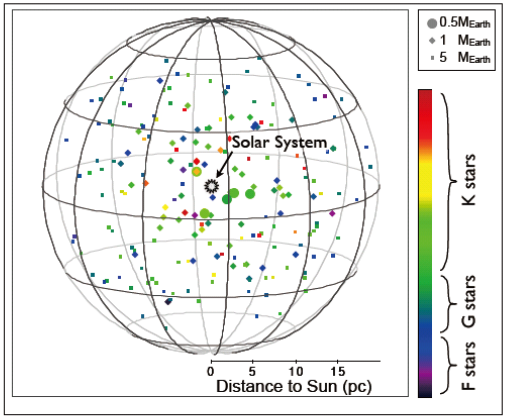
Search for Earth-twins

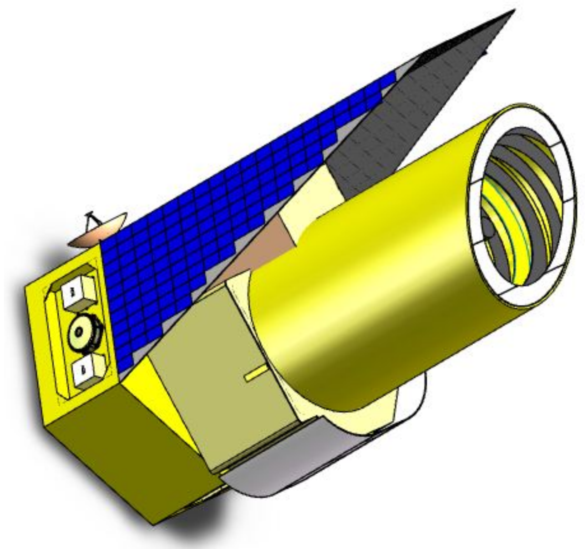


Overview of STEP

- **Satellite Specifications / Payloads:**
  - Orbit: Solar-earth L2 Halo
  - Mass: 500 kg   Life time: 5 year
  - Payloads: TMA Astrometry Telescope

    (Primary Aperture: 1.2m, f=50m, FOV: 0.44°)



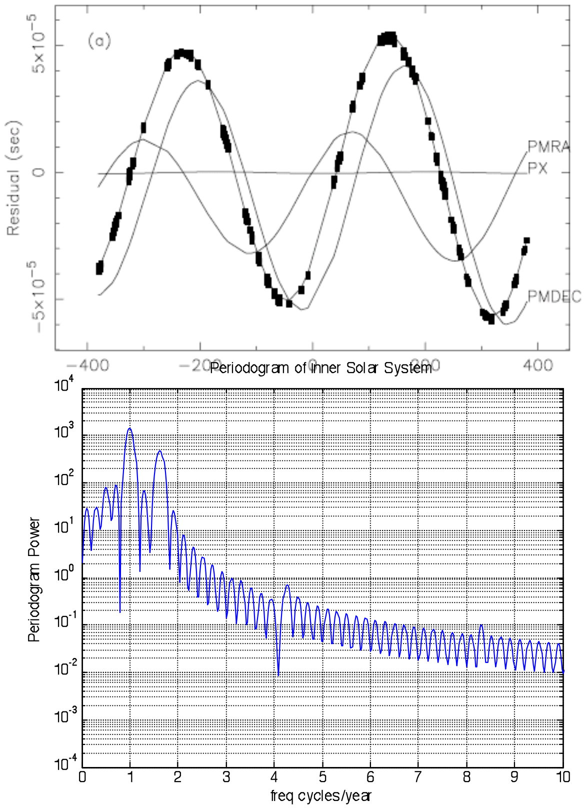


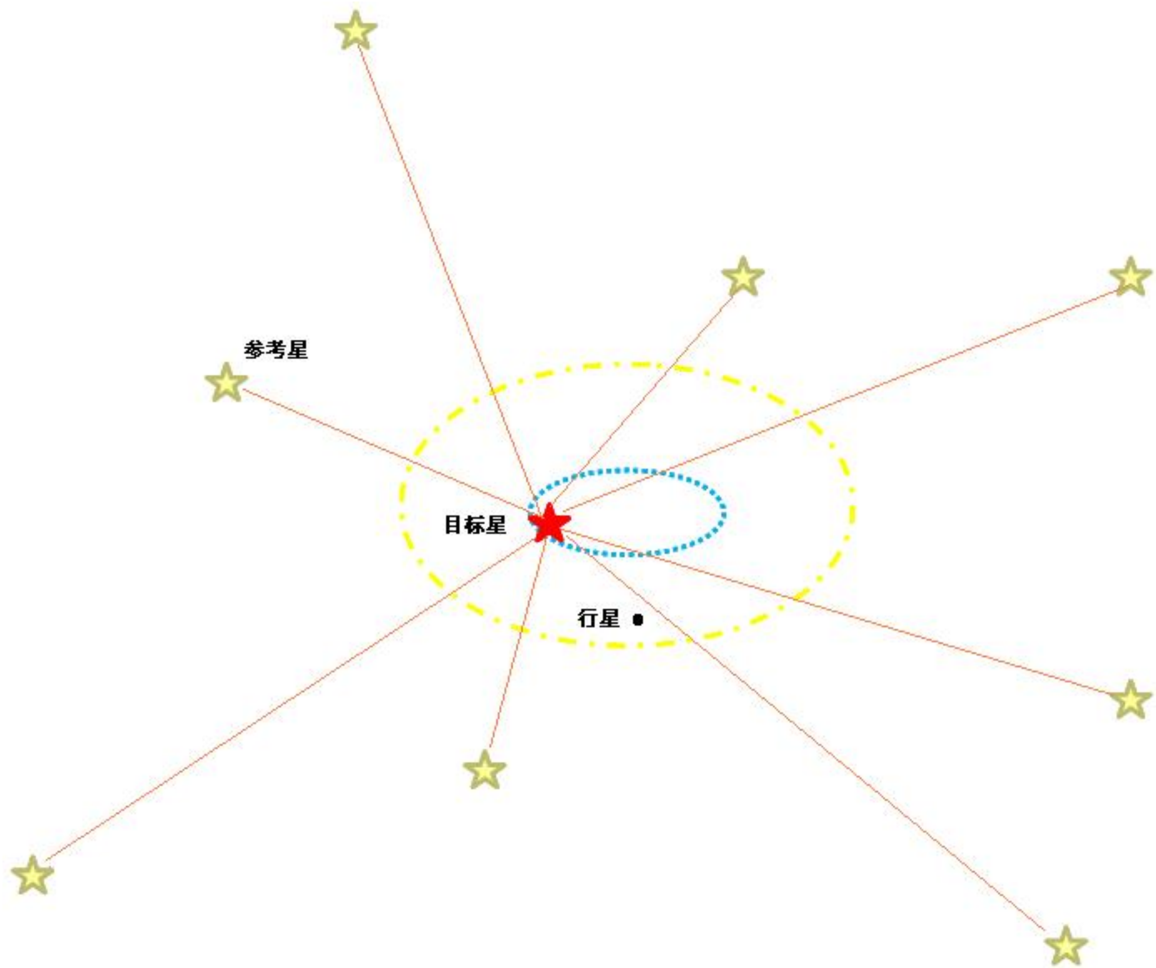
➢ Highlights

- ✓ Extremely-high-precision(0.5uas) astrometry space mission
- ✓ Able to detect the habitable planets at earth criterion
- ✓ Get the actual planetary masses and the full orbital geometry for all components of the detected planetary system

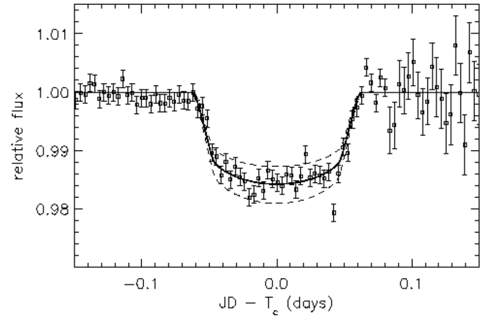
Approach

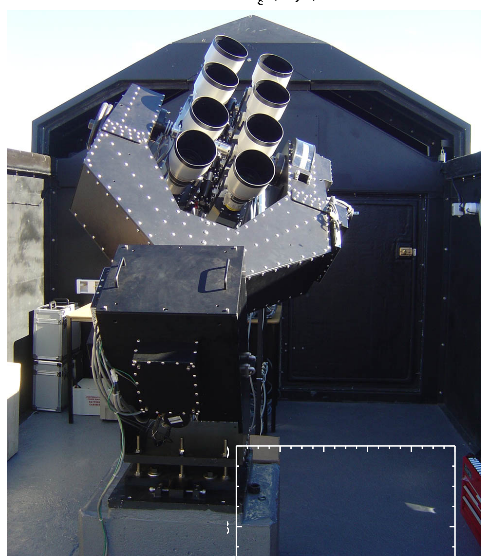
Astrometry

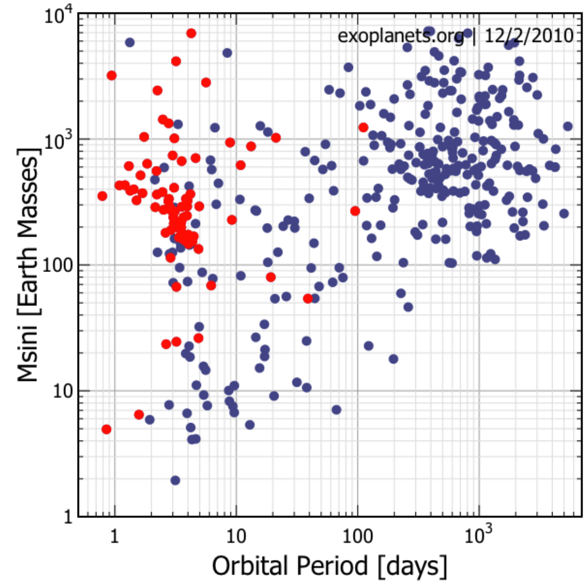




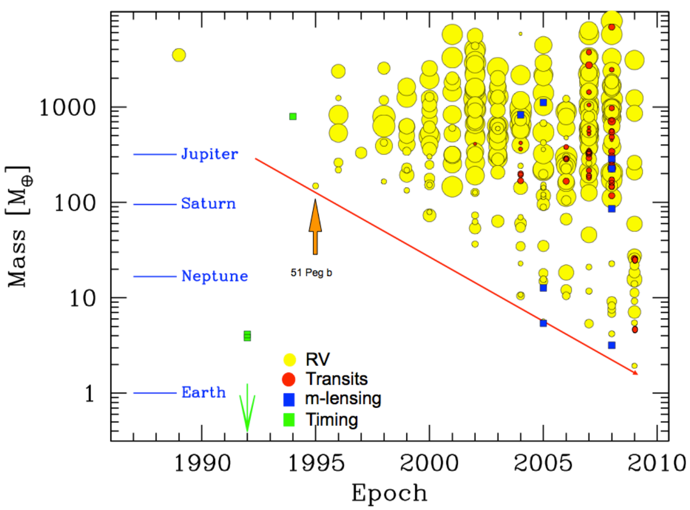
5. Transit searches 地面凌星观测

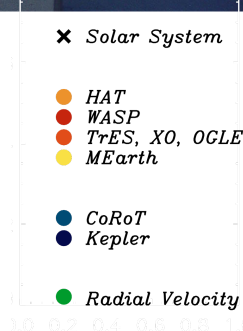


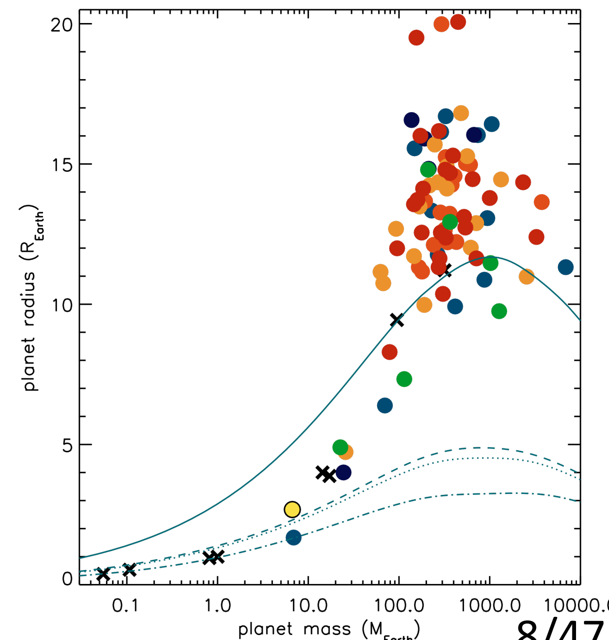




小型望远镜: SuperWASP (8x11cm), Ogle (1.3m), HATnet (6x11cm), Tres (3x10cm), Mearth (8x40cm)

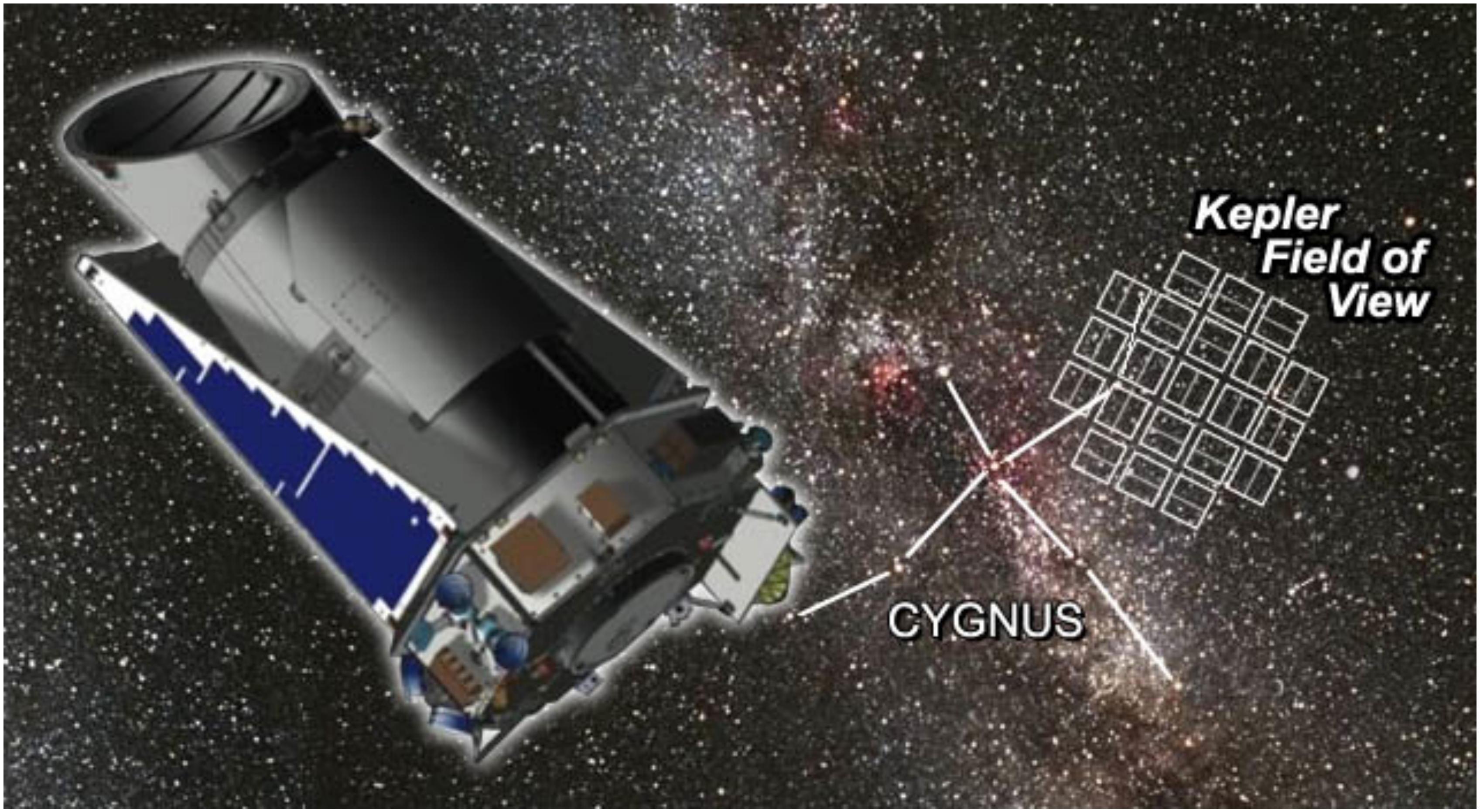




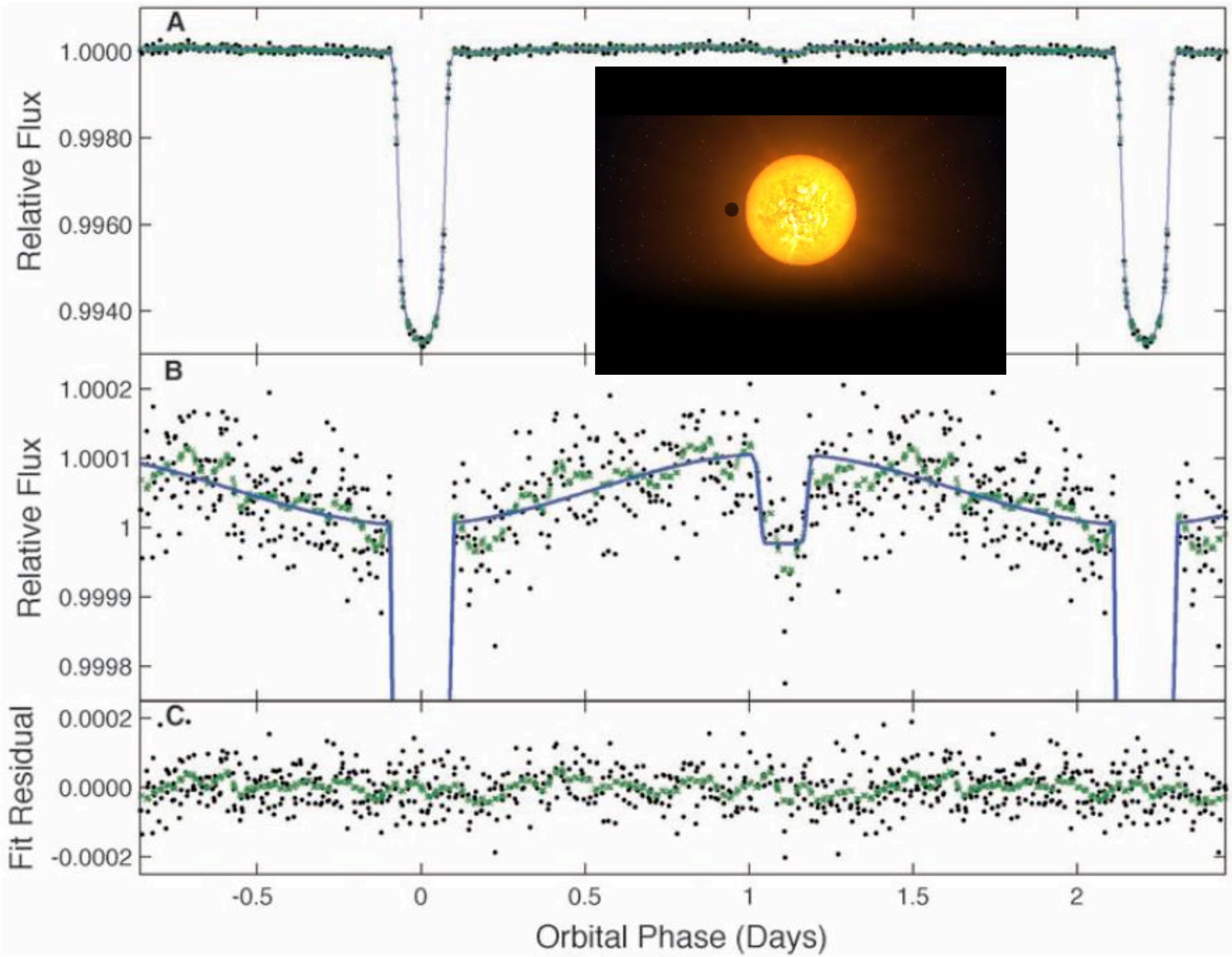


Kepler Mission (*NASA*)

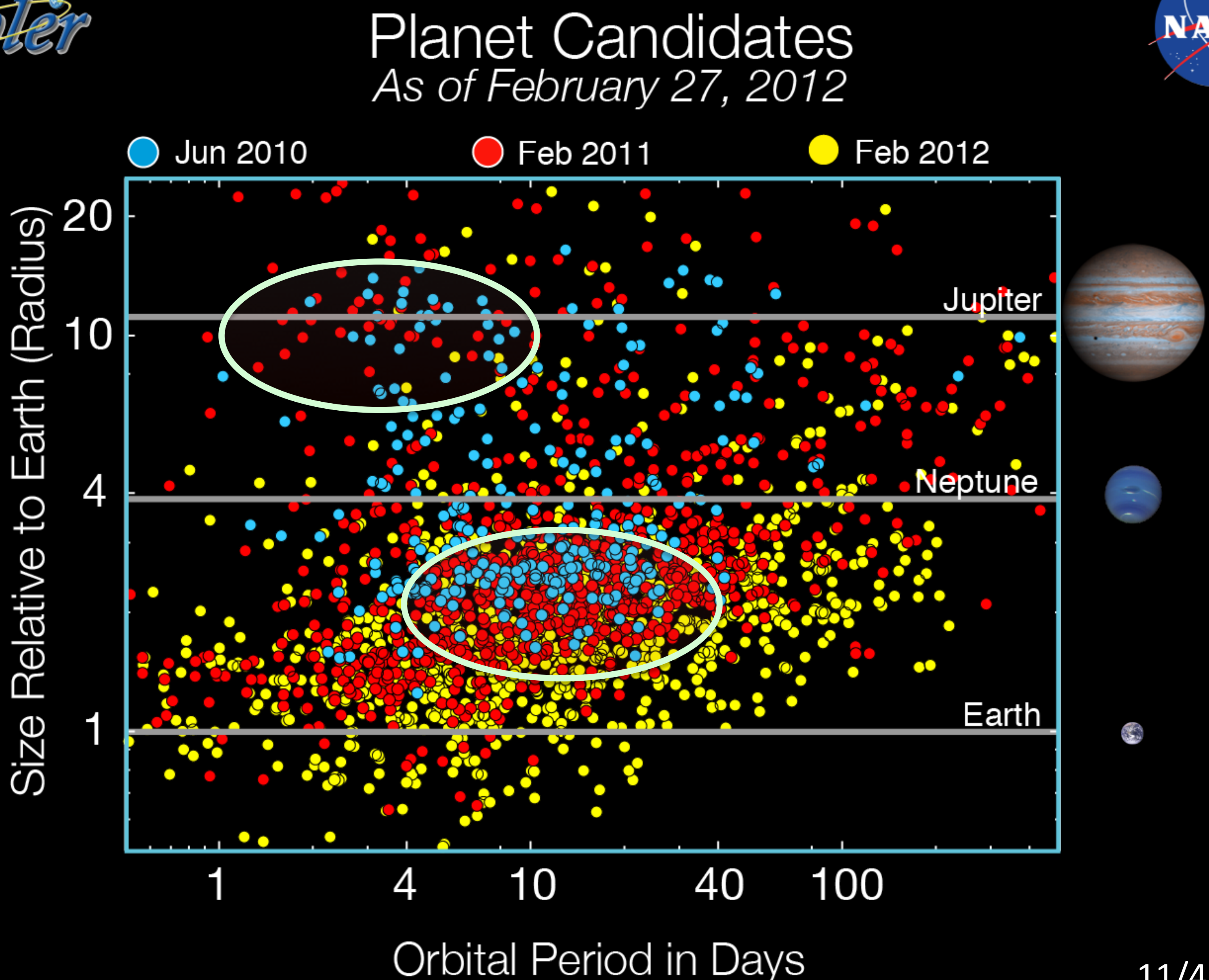
- Looking for Earth-like planets in transit
- Photometry of 150,000 stars
- ~40 ppm in 6 hours; 30 minute cadence



空间凌星观测

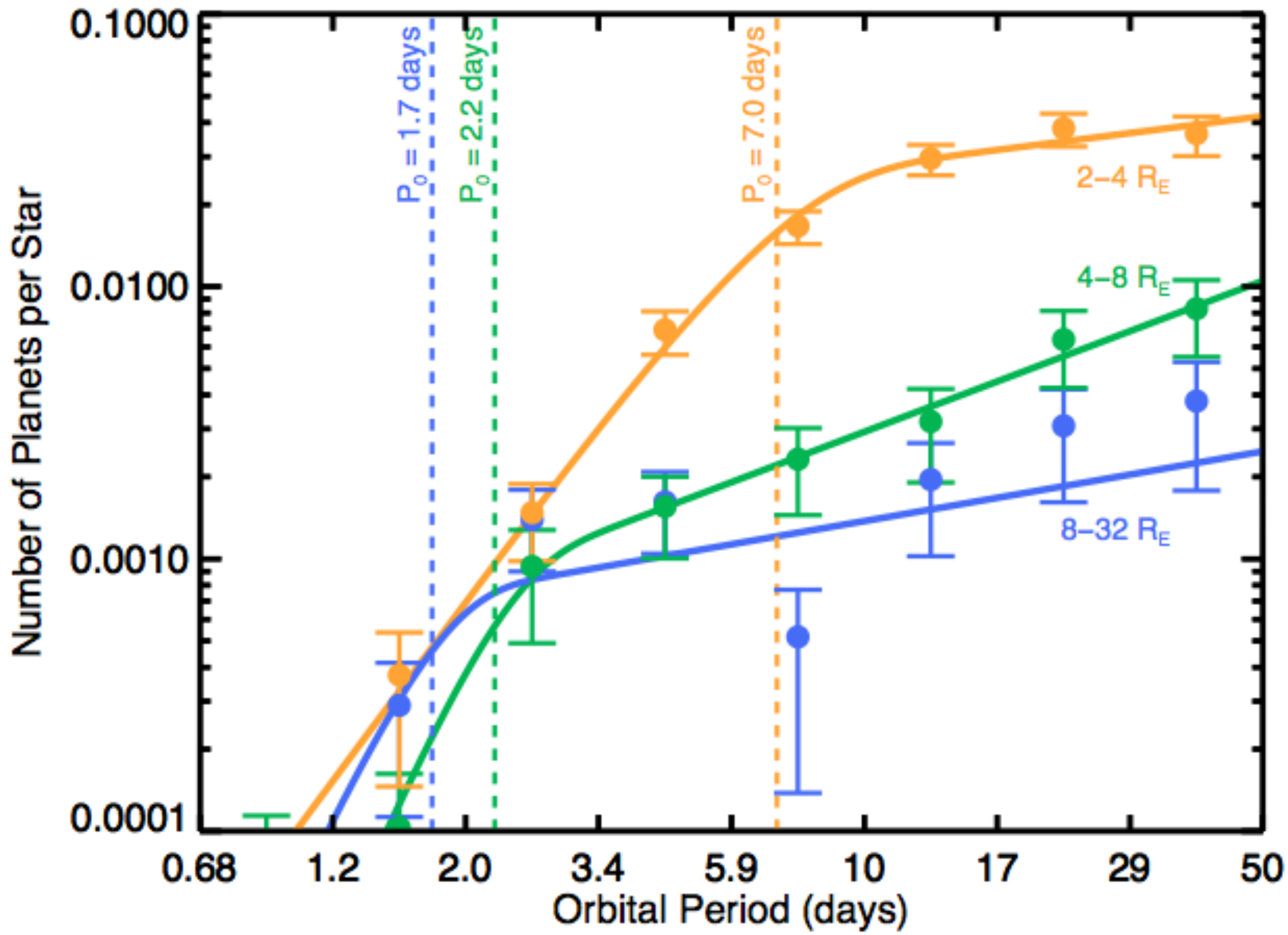

A
B
C.
1.0000
0.9980
0.9960
0.9940
Relative Flux
1.0002
1.0001
1
0.9999
0.9998
Relative Flux
0.0002
0.0000
-0.0002
Fit Residual
-0.5
0
0.5
1
1.5
2
Orbital Phase (Days)

行星半径与周期的分布



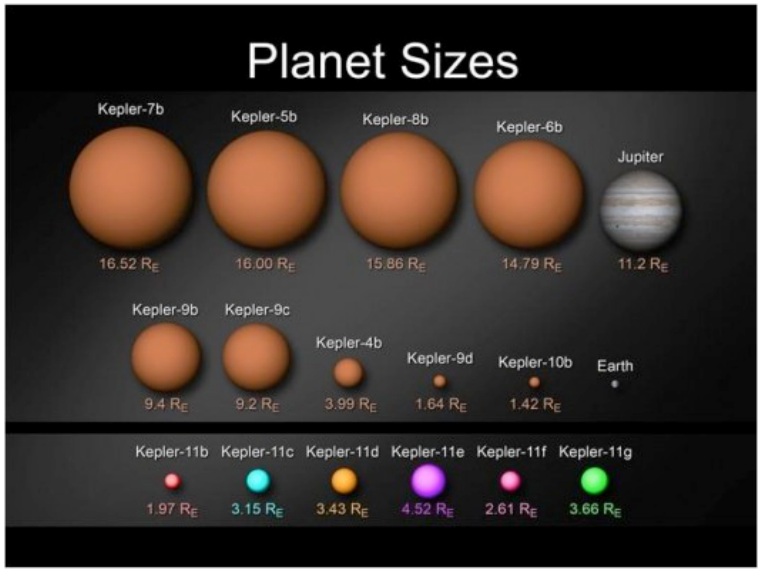
Planet Candidates
As of February 27, 2012
Jun 2010
Feb 2011
Feb 2012
Size Relative to Earth (Radius)
20
10
4
1
Jupiter
Neptune
Earth
1
4
10
40
100
Orbital Period in Days

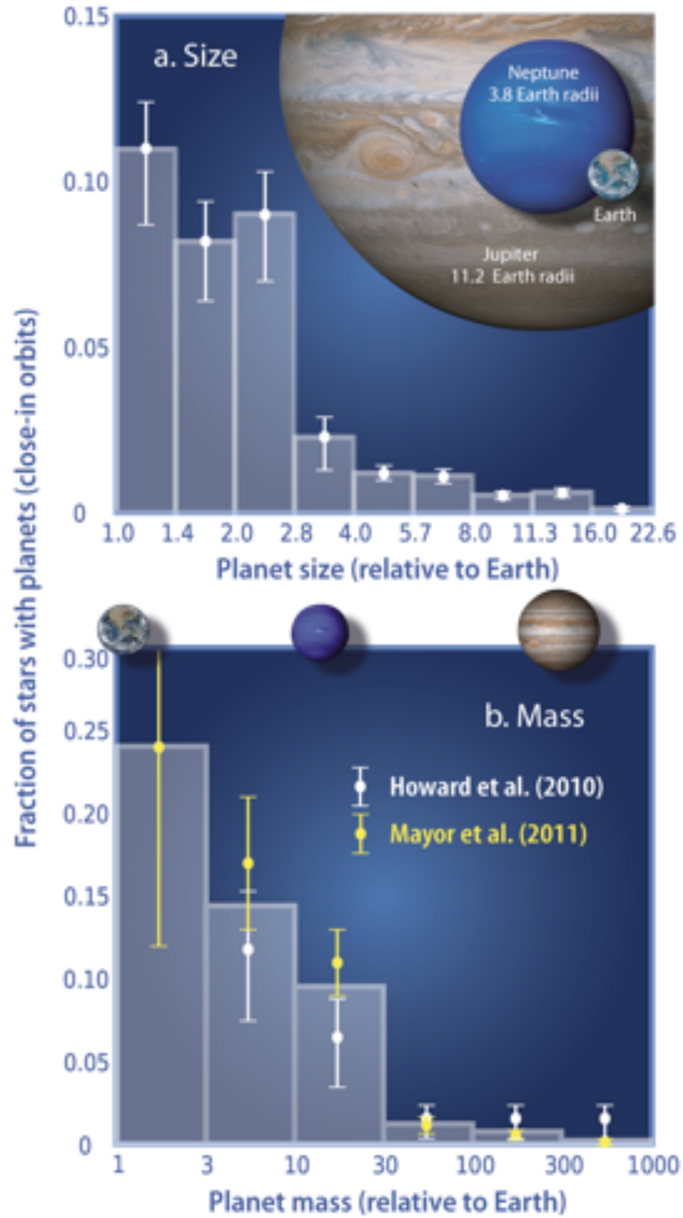
凌星观测（亮点1）：行星半径与周期的分布



类木行星：周期3天处的跳变　超级地球：周期连续分布

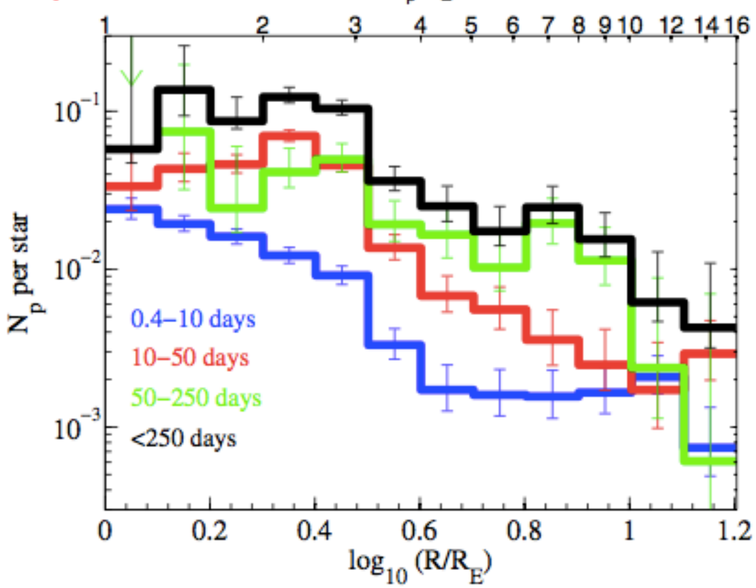
凌星观测（亮点2）：行星半径与质量的分布





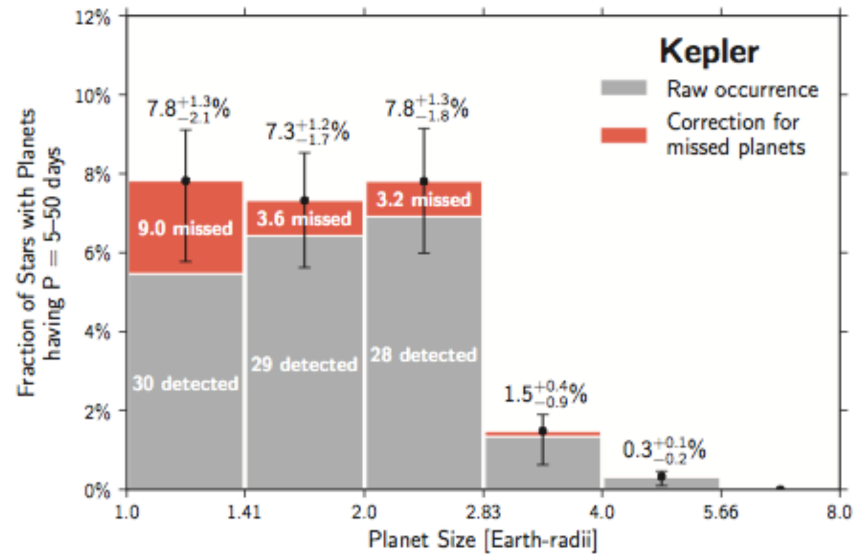
众多的超级地球

Log Scale!

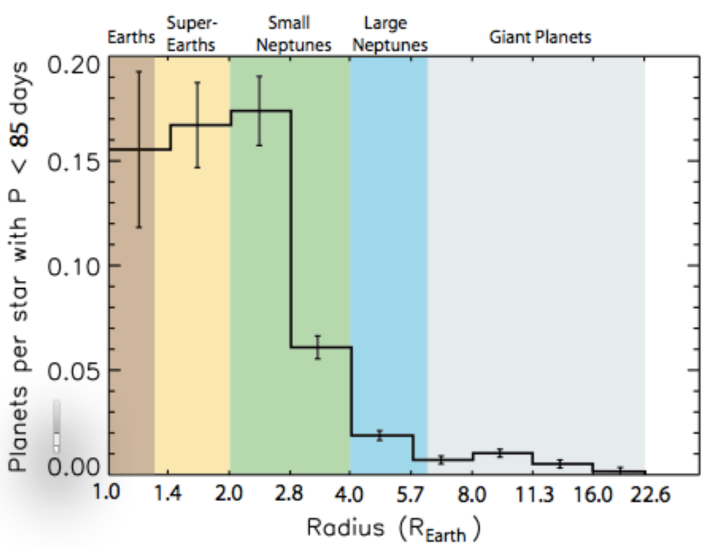


Dong & Zhu (2013)

Comparing Radius Distribution Among three works (Dong)



Petigura et al. 2013a

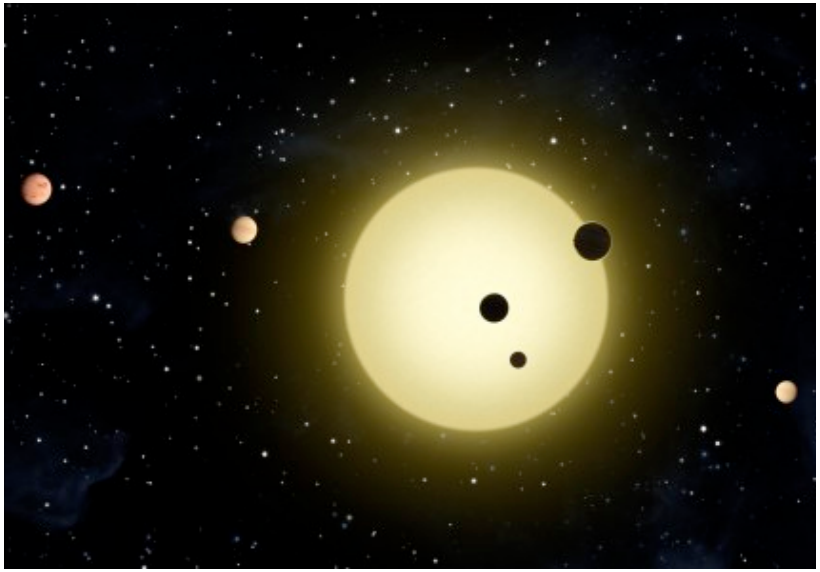


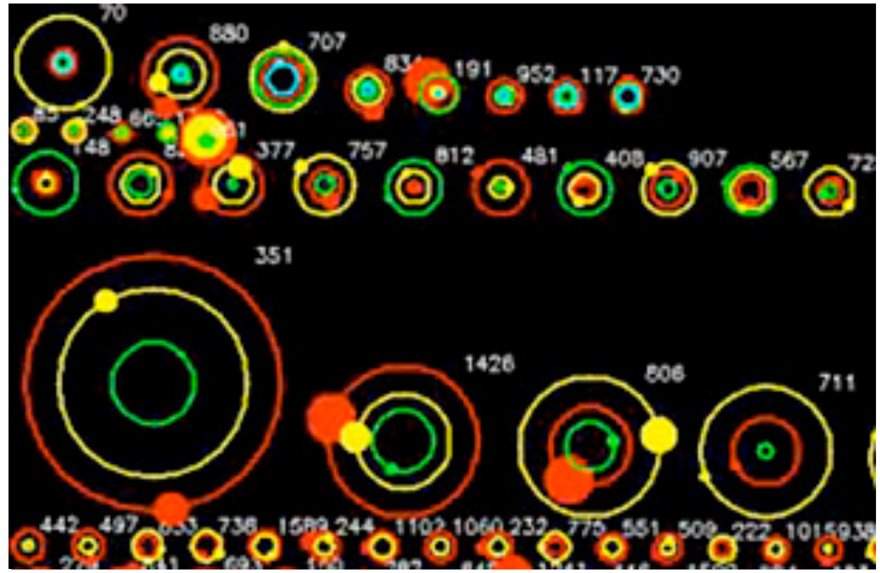
Fressin et al. (2013)

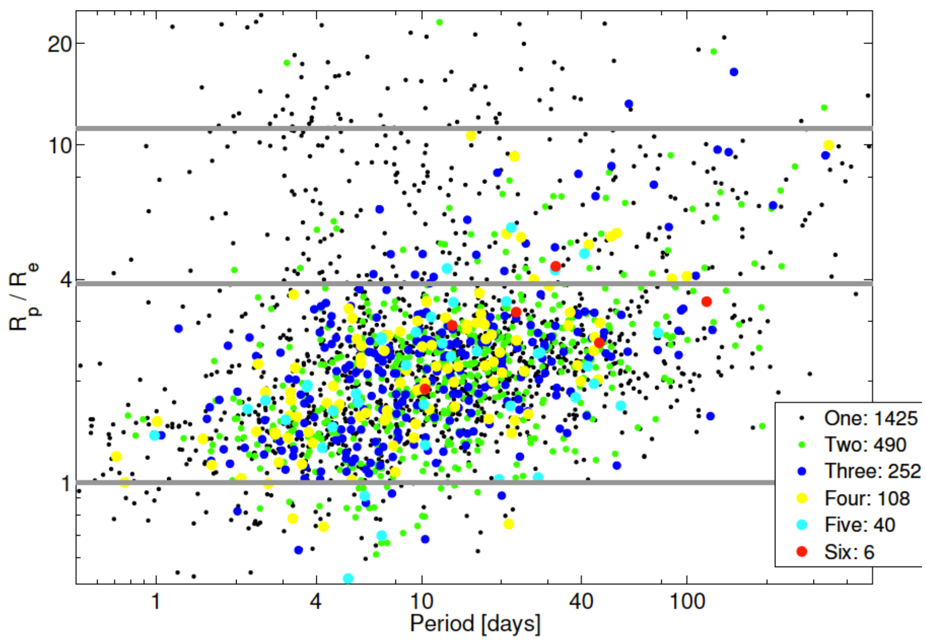
Core accretion model?

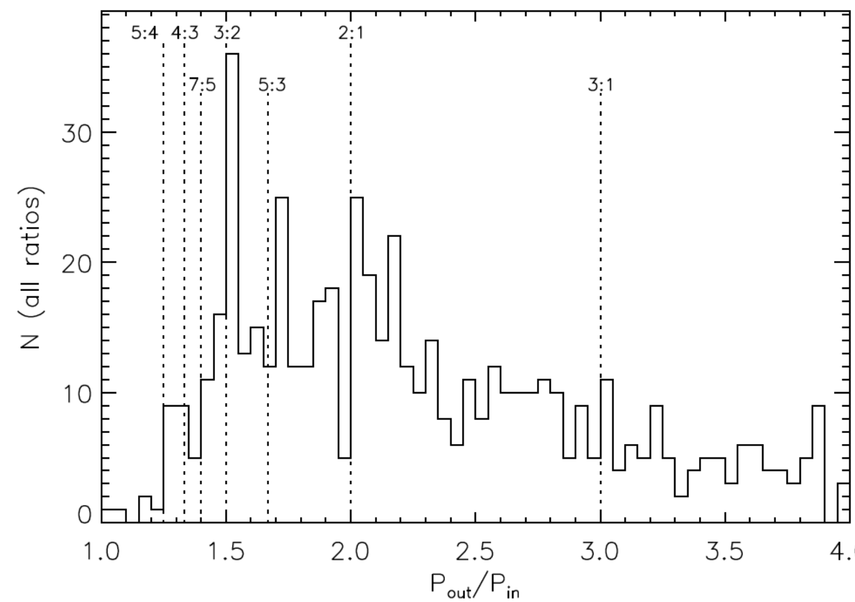
See also Gould et al. (2011); Youdin et al., (2011)

凌星观测（亮点3）：多成员的行星系统









Architectures of Other Planetary Systems

Basic facts:

- Planet number
- Masses
- Radii

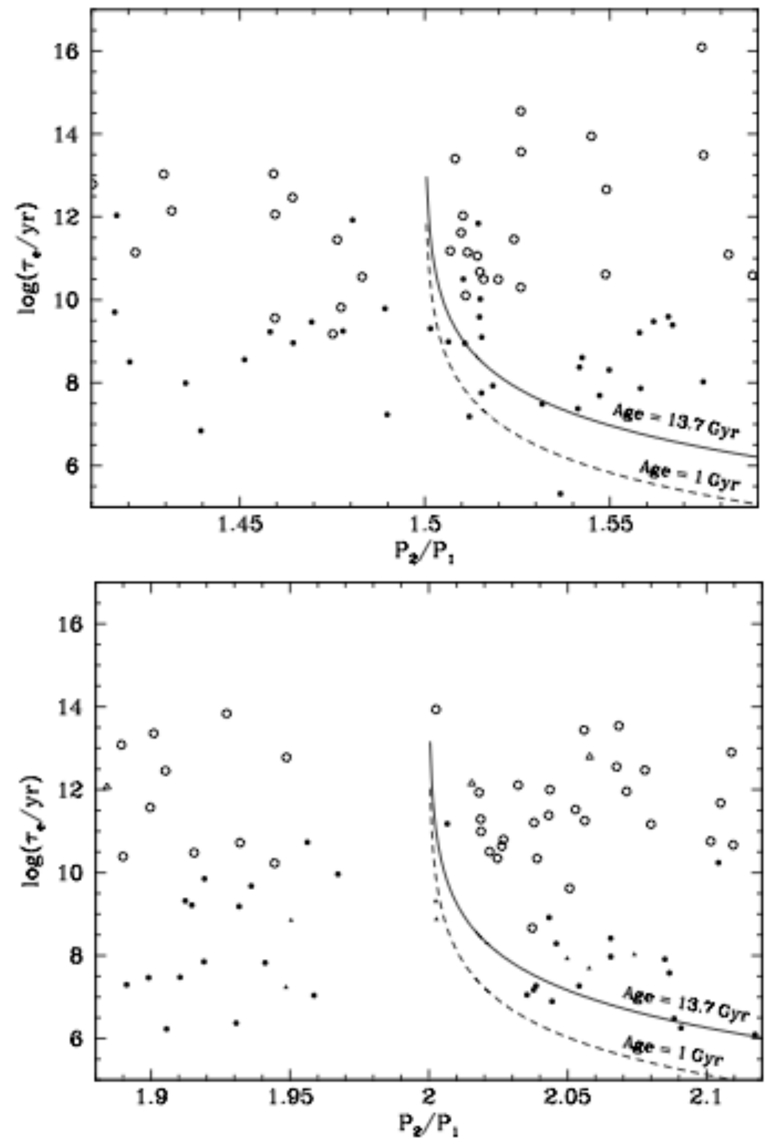
Dynamical properties:

- Periods (n.b.: their ratios)
- Eccentricities
- Mutual Inclinations

Transits	Radial Velocities
w/ TTV	✔
w/ TTV	✔
✔	
✔✔	✔
w/ TTV	✔
w/ TDV	

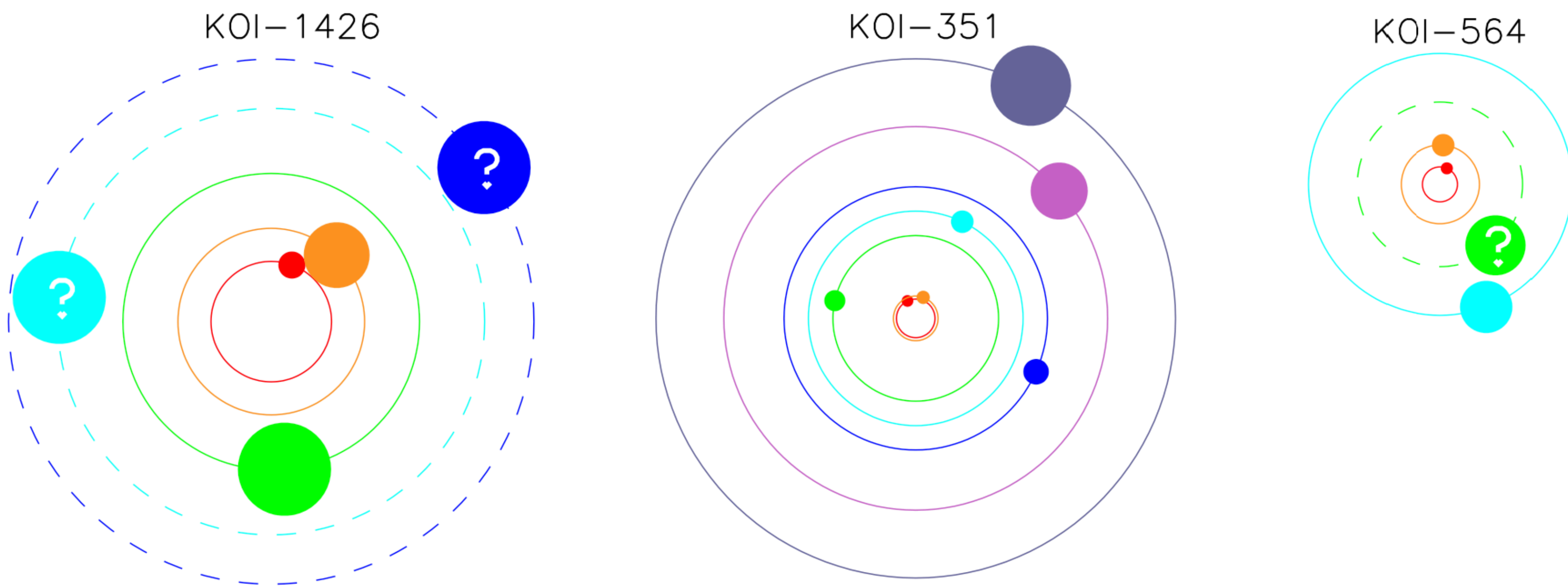
Science Goals:
Mass-Radius measurements (Composition)
Planet Discovery / *Full* Architectures
Resonant dynamics → Migration Constraints

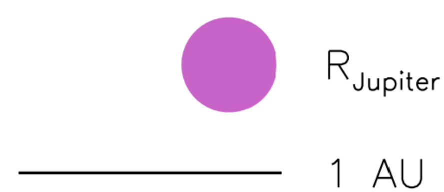
Exiting Resonance through Tides



Lee, Fabrycky

Spitzer TTV program (Fabrycky)

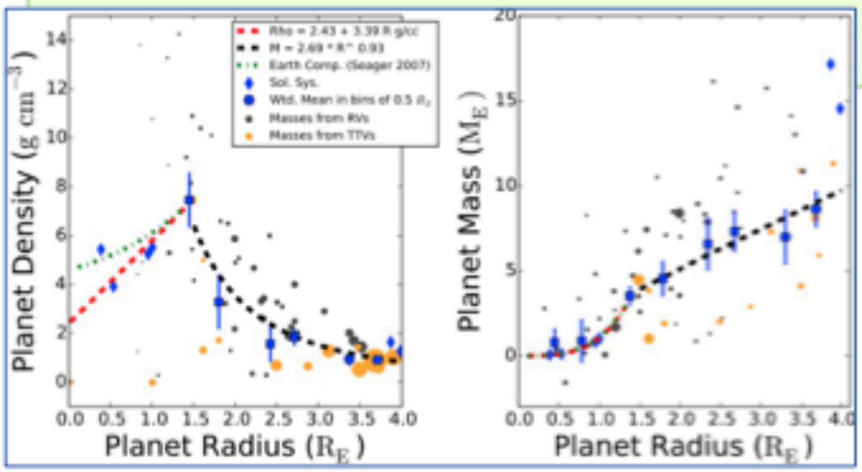




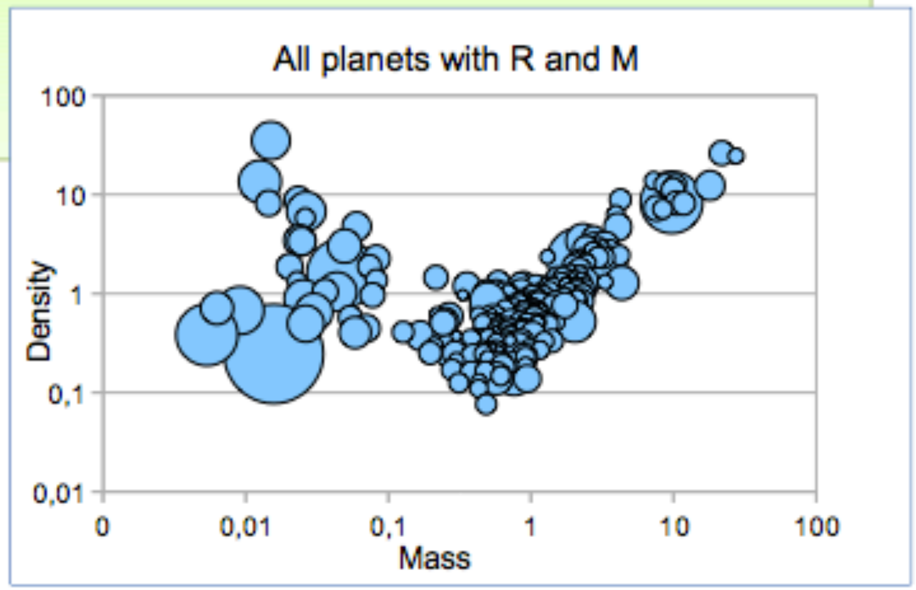
- Spitzer program p10127
- *Not* hot Jupiters
- Deep transits
- Long-period = Long durations

The selected sample

- Despite 1800 exoplanets, still a statistically modest population where density is rather well characterized
- Basis : Exoplanet.eu
- Selection :
  - Radius : only transit (no direct detection)
  - Mass : only radial velocity (TTV progressing but still large uncertainties and bias)
  - Acceptable uncertainties
- 220 planets at the end

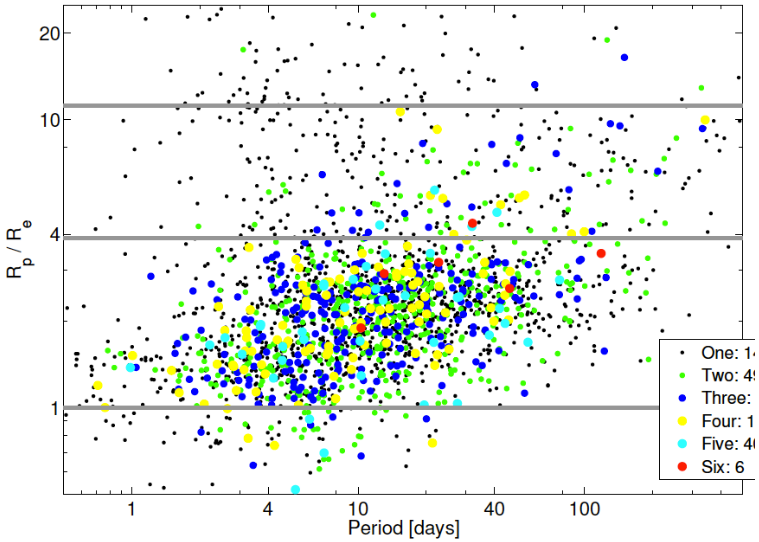


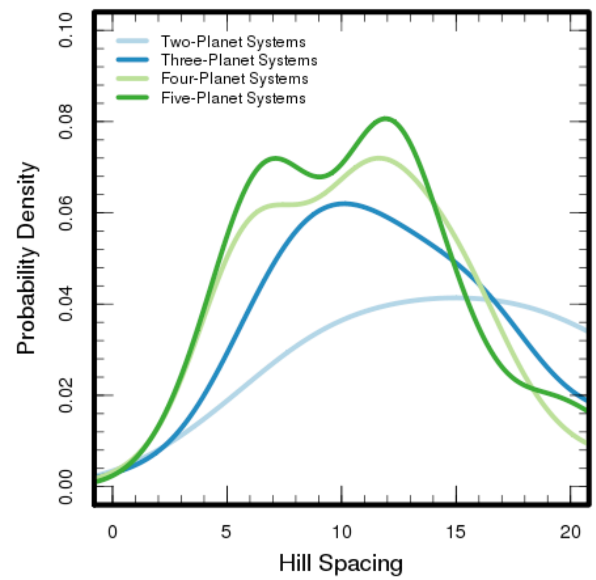
Weiss et al 2014

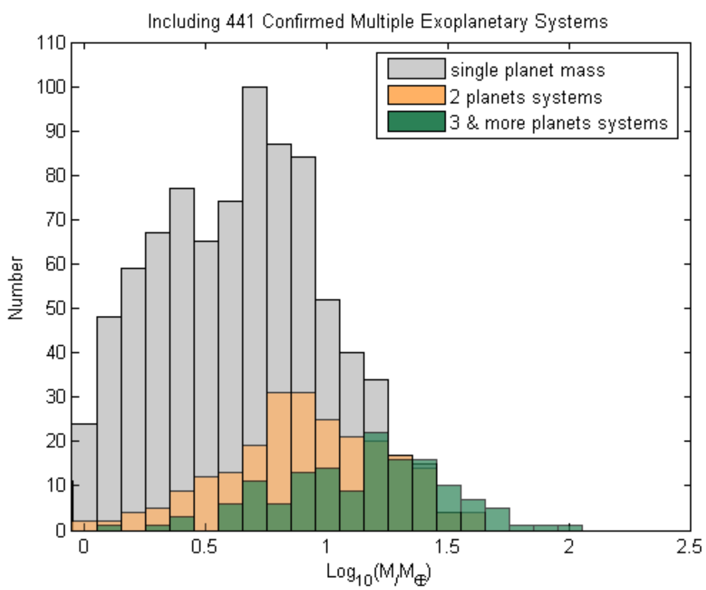


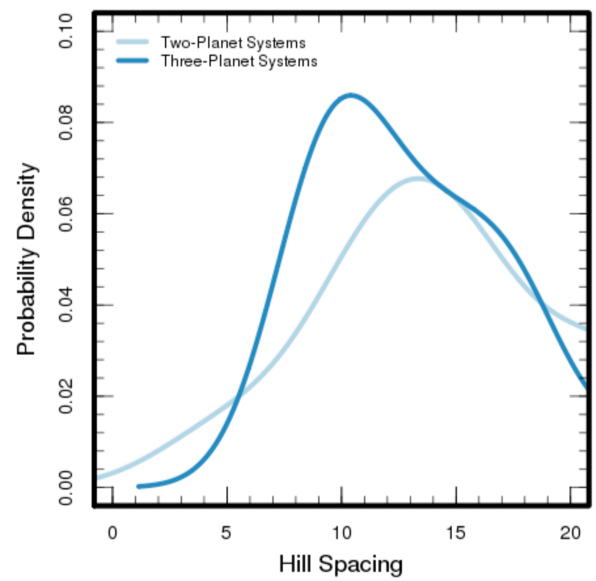
New Candidate Catalog (Batalha et al. 2012)

What can we learn from Multiple systems !!!









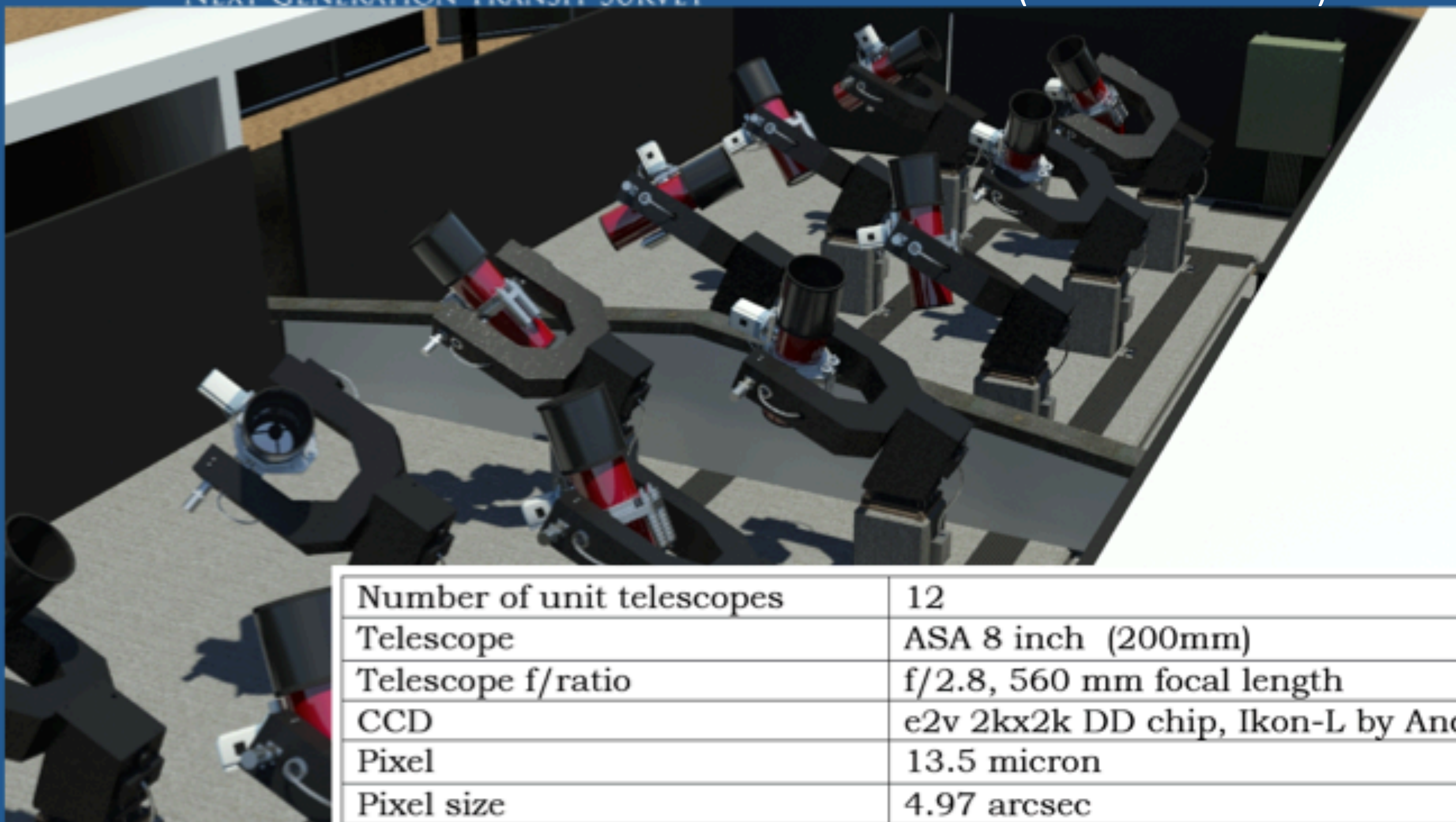
Kevin Schla
Xiaojia Zhe

NGTS

NEXT-GENERATION TRANSIT SURVEY

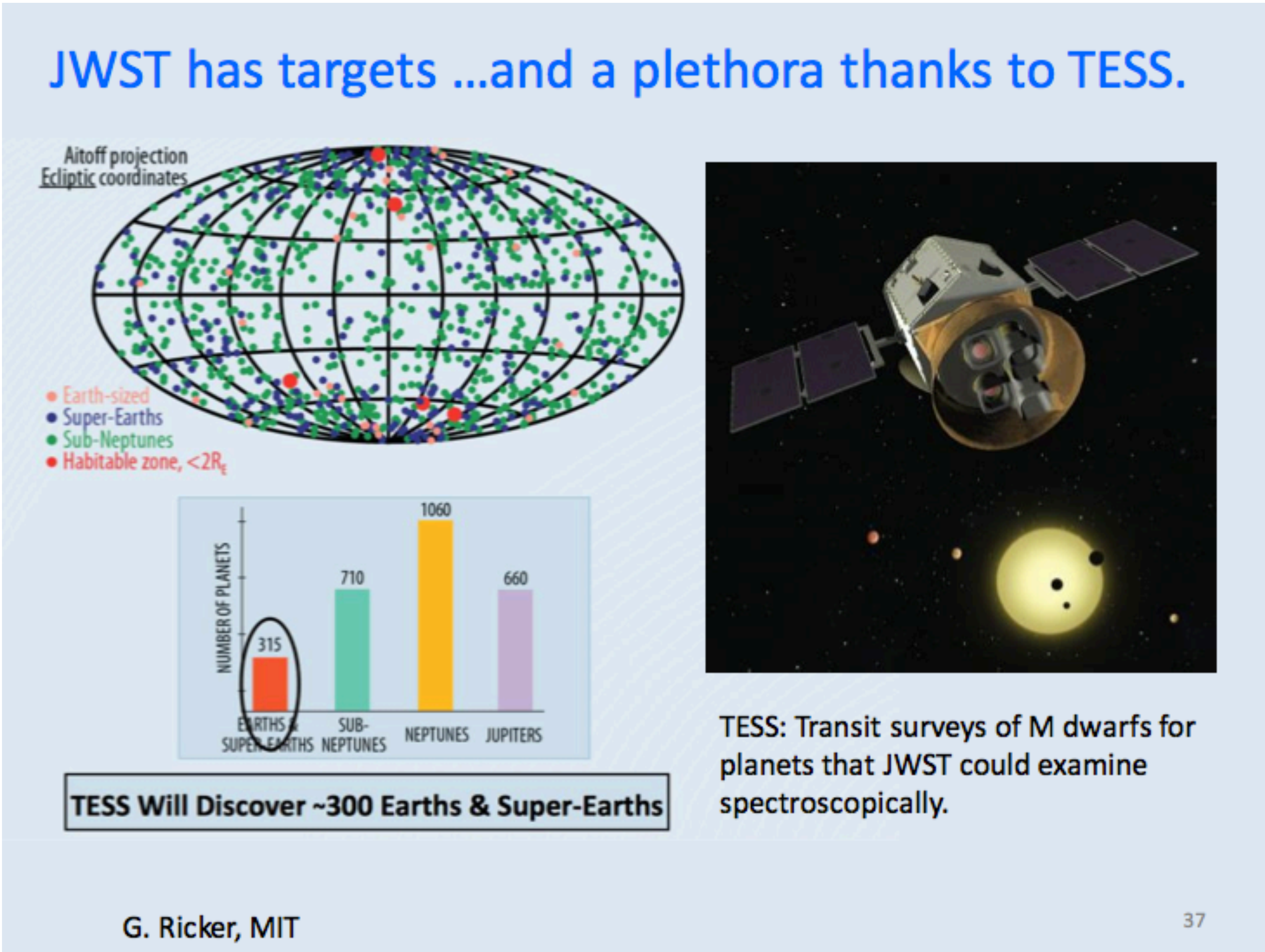
www.ngtransits.org

(Neveu-van Malle)



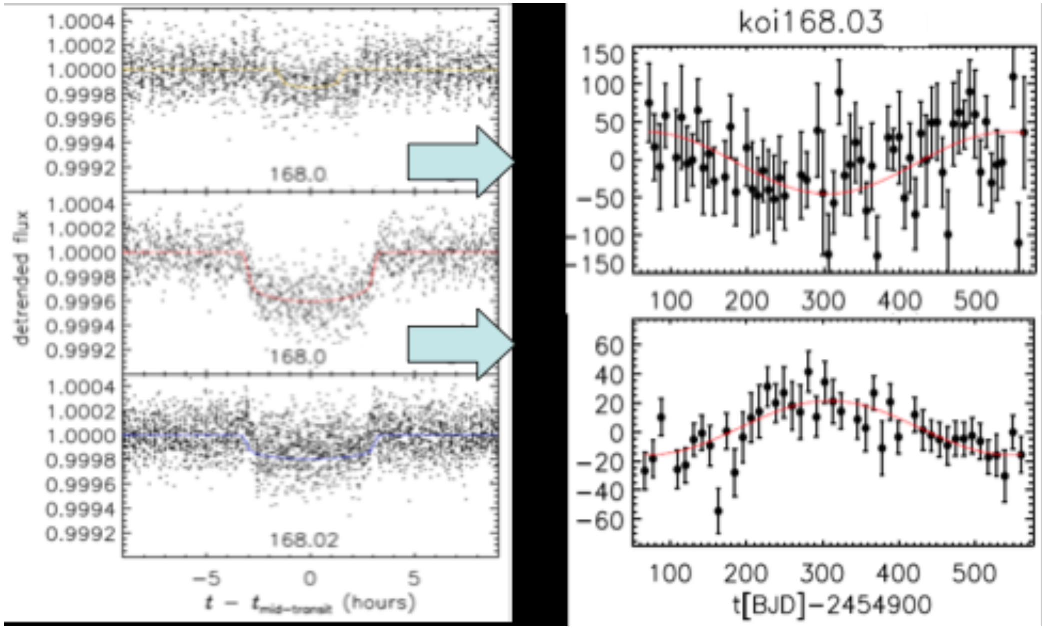
Number of unit telescopes	12
Telescope	ASA 8 inch (200mm)
Telescope f/ratio	f/2.8, 560 mm focal length
CCD	e2v 2kx2k DD chip, Ikon-L by Andor
Pixel	13.5 micron
Pixel size	4.97 arcsec
Telescope FOV	8.00 square degrees
Mount type	OMI equatorial fork, 1 per telescope
Building dimension	12m x 15m (including a 3m wide parking)
Pointing limit	Airmass < 2
Total FoV	96 square degrees

TESS (Lunine)



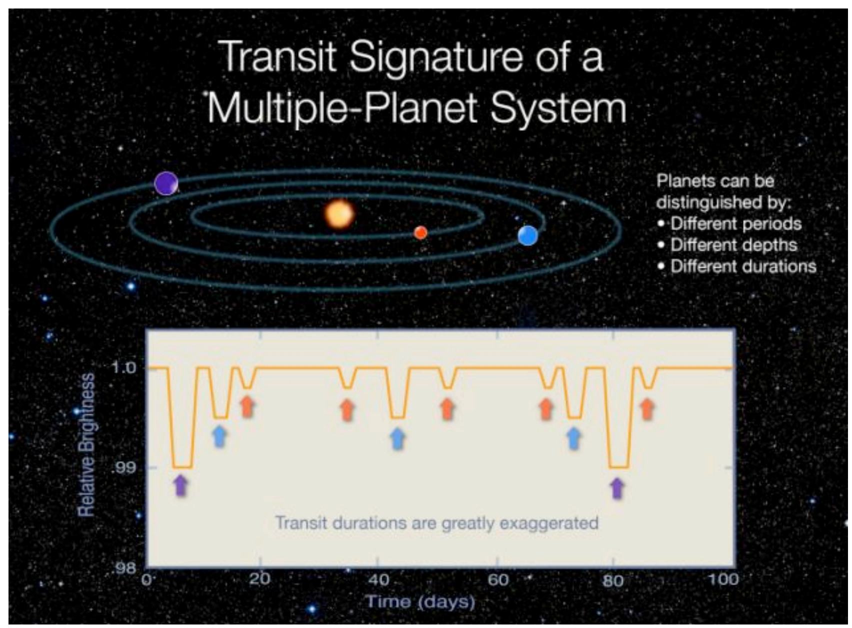
JWST has targets ...and a plethora thanks to TESS.
Aitoff projection
Ecliptic coordinates
Earth-sized
Super-Earths
Sub-Neptunes
Habitable zone, <2R$_E$
NUMBER OF PLANETS
315
710
1060
660
EARTHS & SUPER-EARTHS
SUB-NEPTUNES
NEPTUNES
JUPITERS
TESS Will Discover ~300 Earths & Super-Earths
TESS: Transit surveys of M dwarfs for planets that JWST could examine spectroscopically.
G. Ricker, MIT

综合观测（方法）：质量与半径

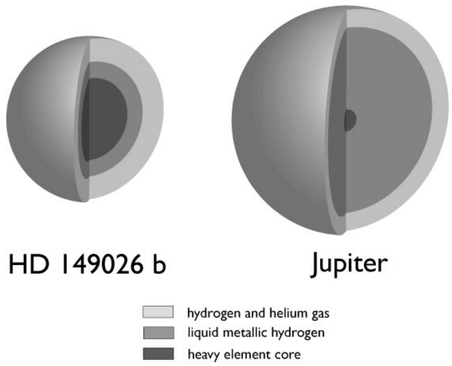


凌星法选出的目标需要通过昂贵的视向速度测量确认

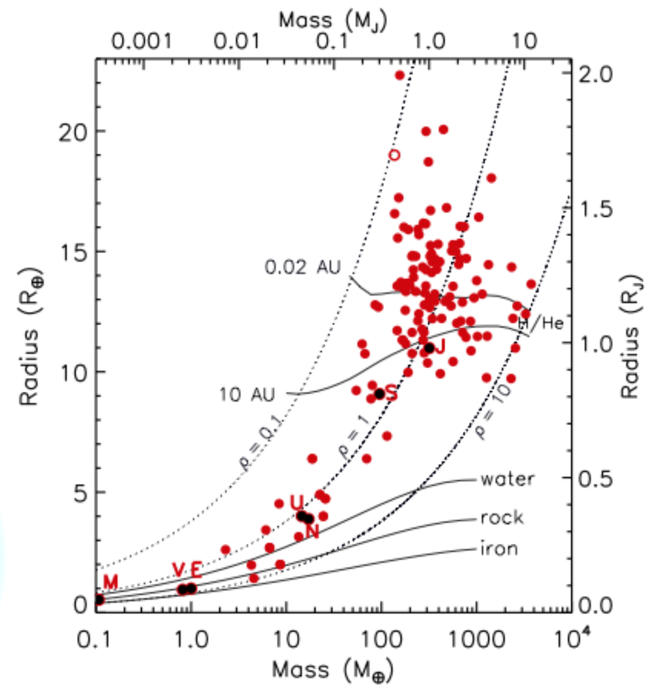
在多成员系统中行星的质量可通过测量凌星时标演化 (TTV)而得到

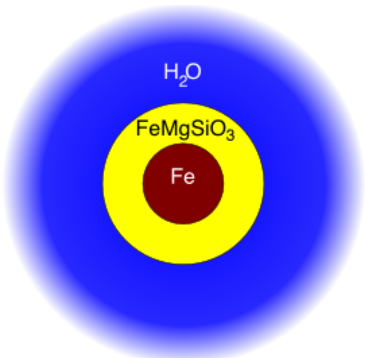


综合观测（亮点1）：密度差异较大

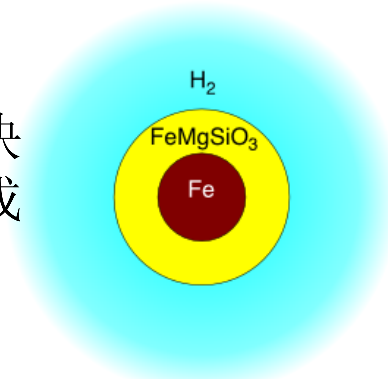


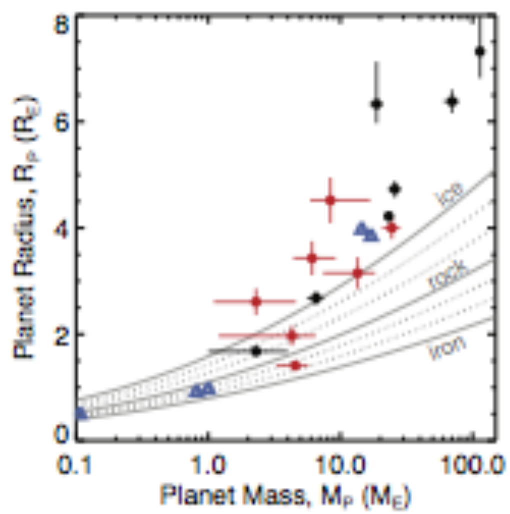
类木行星的半径取决于其核结构与热量损失

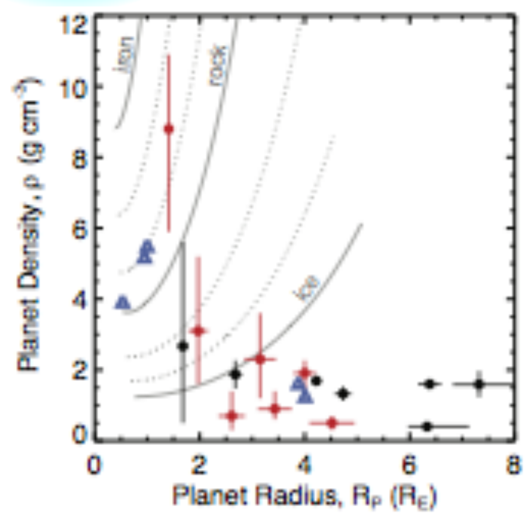




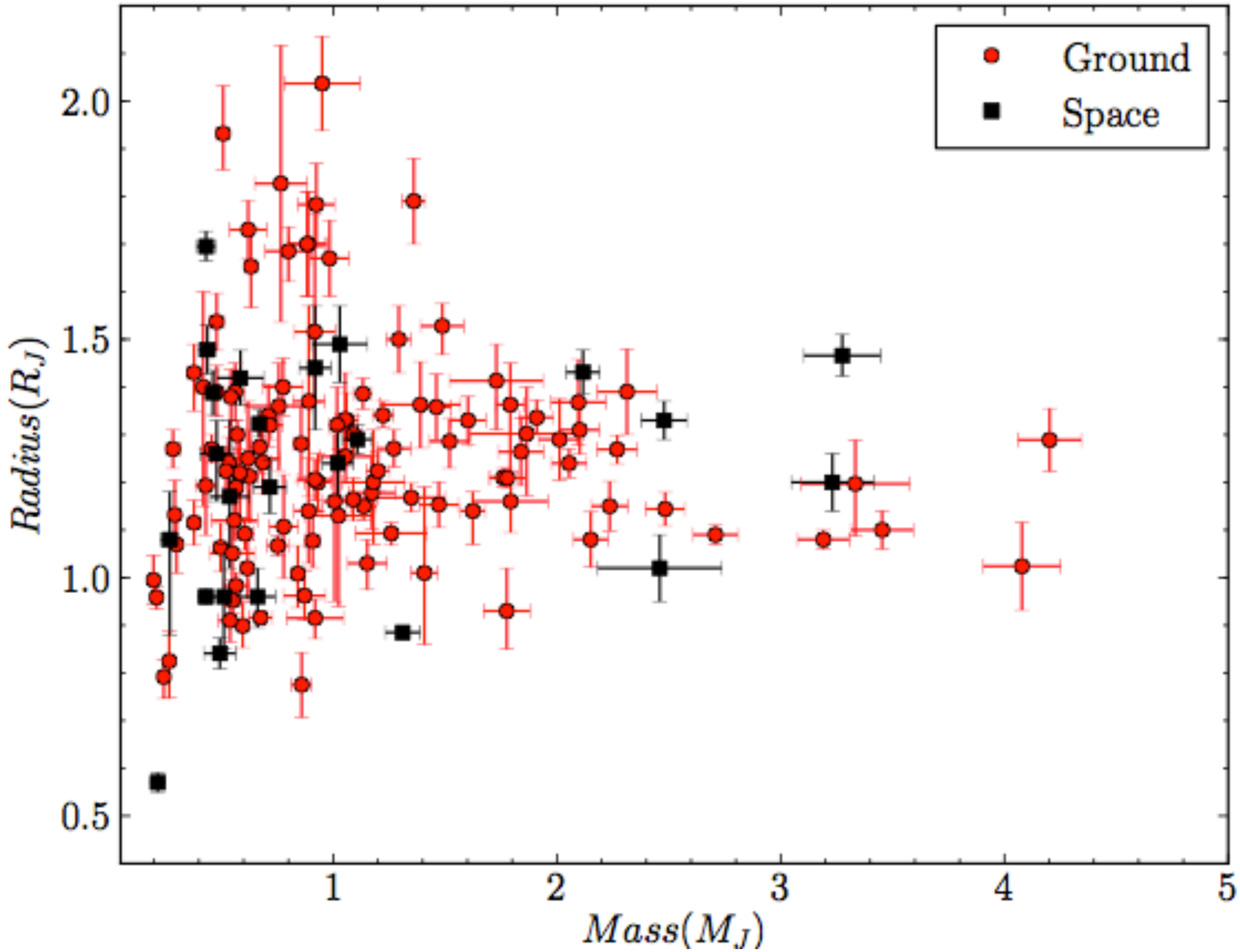
类地行星的半径取决于内部铁硅水相对成分与大气层的结构



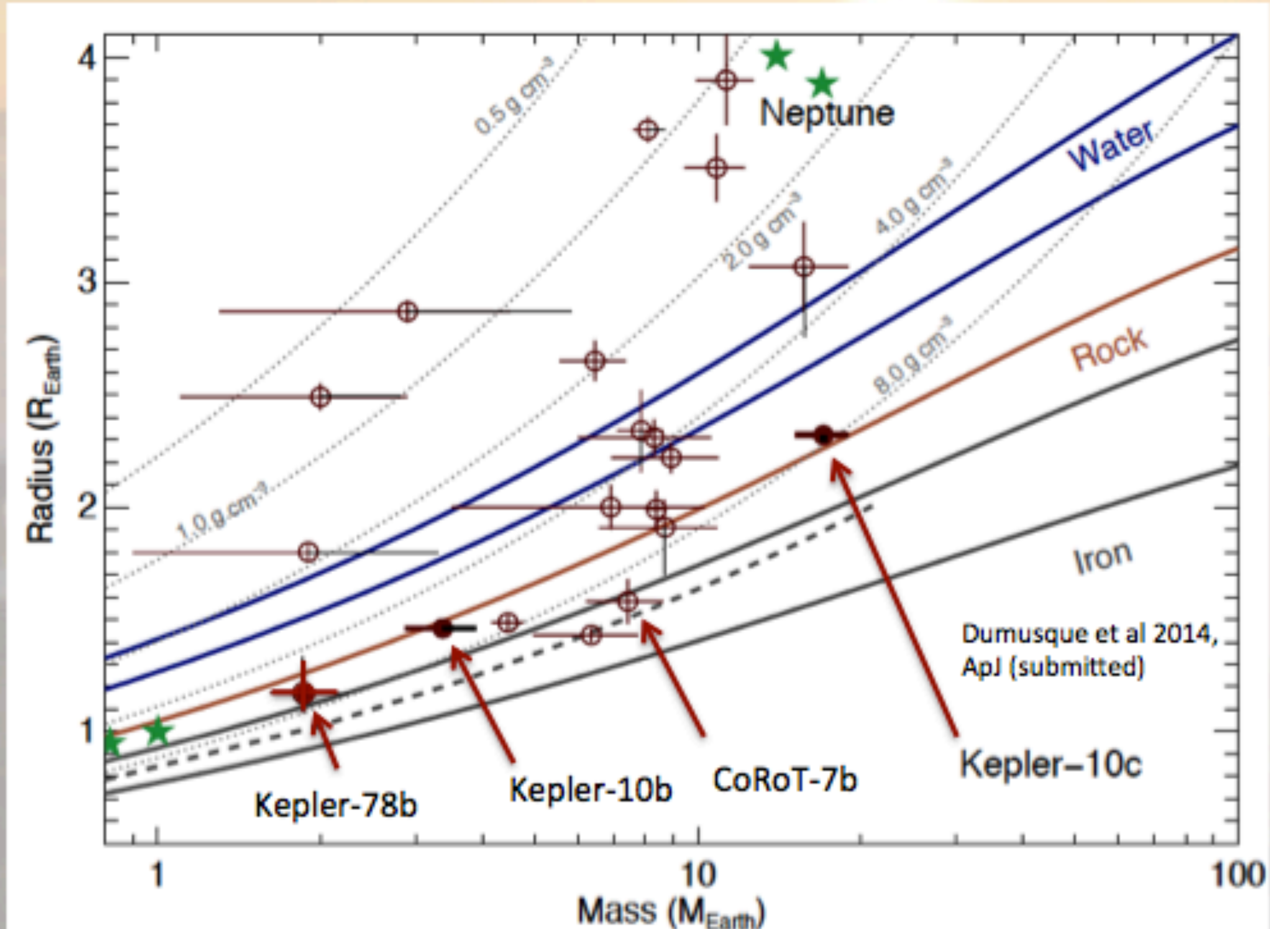




Highlight 1 - Densities (Bayliss)

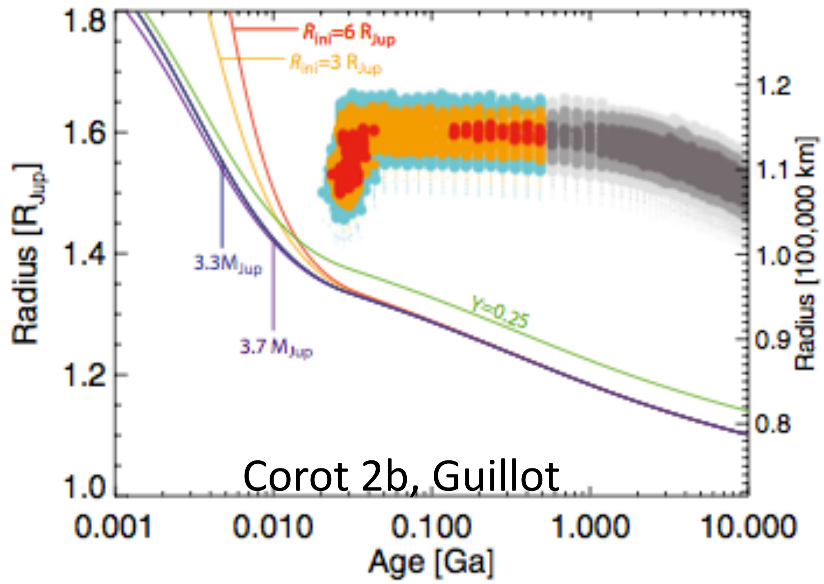


Mass-radius diagram

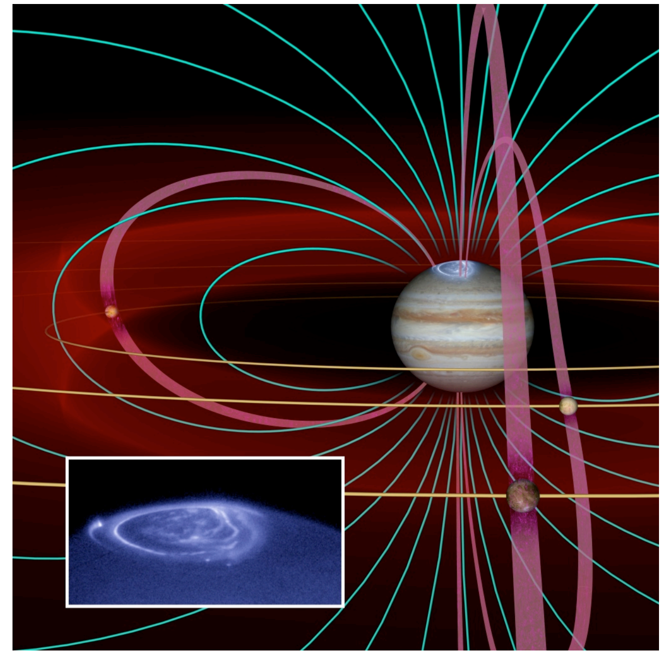


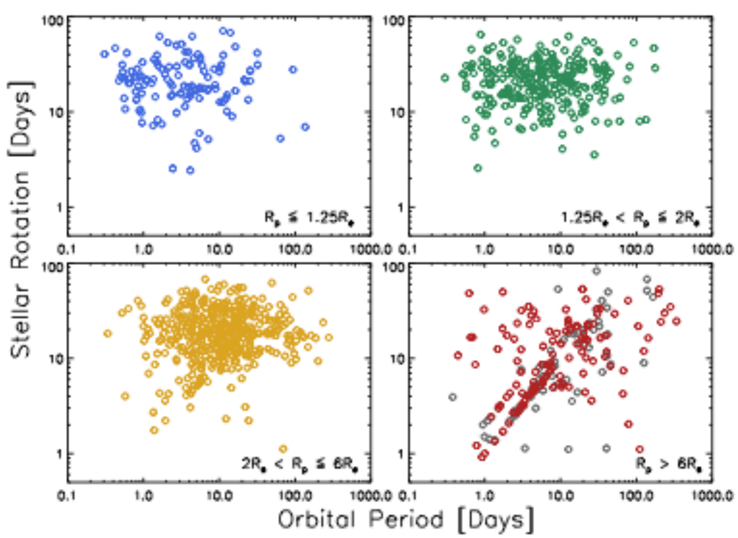
Cameron

Oversized planets and stellar hot spots

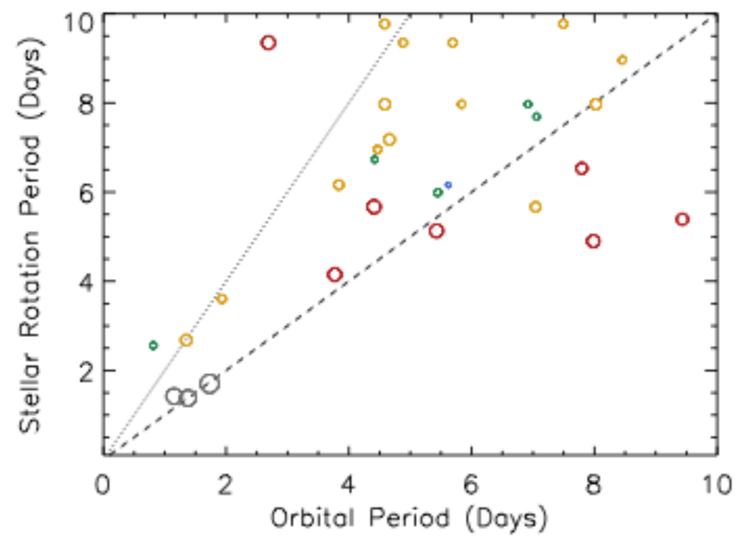


Corot 2b, Guillot

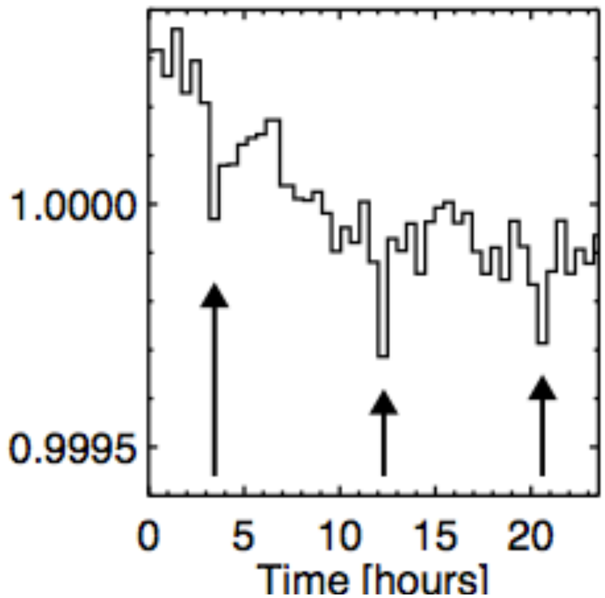


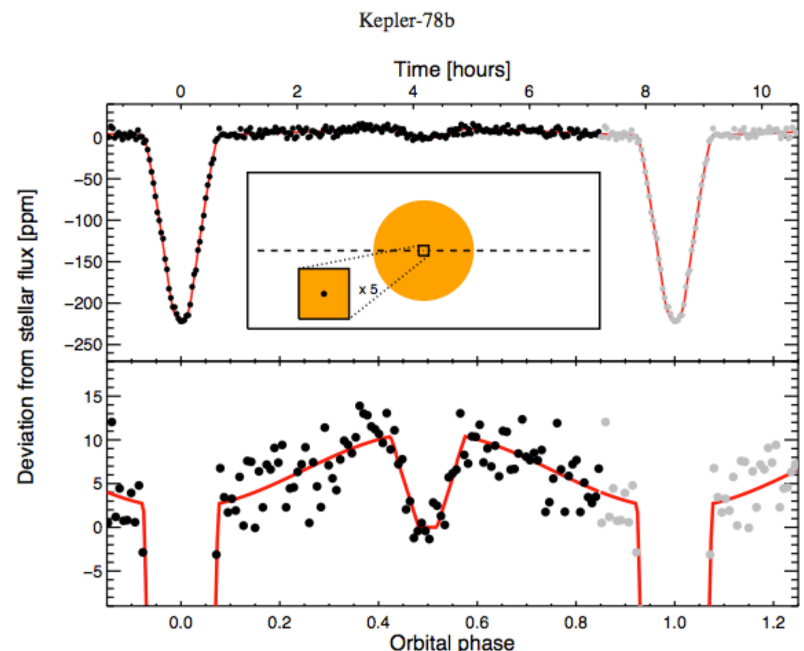


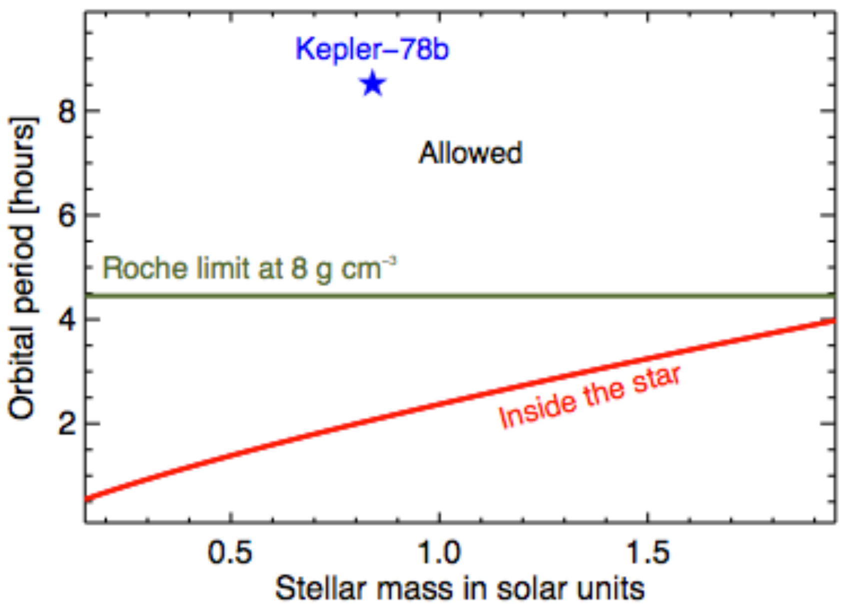
Walkowicz & Basri

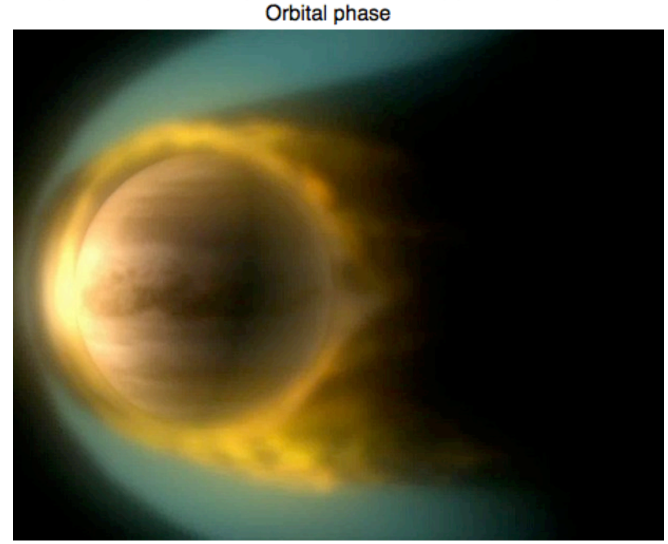


How to identify differentiation

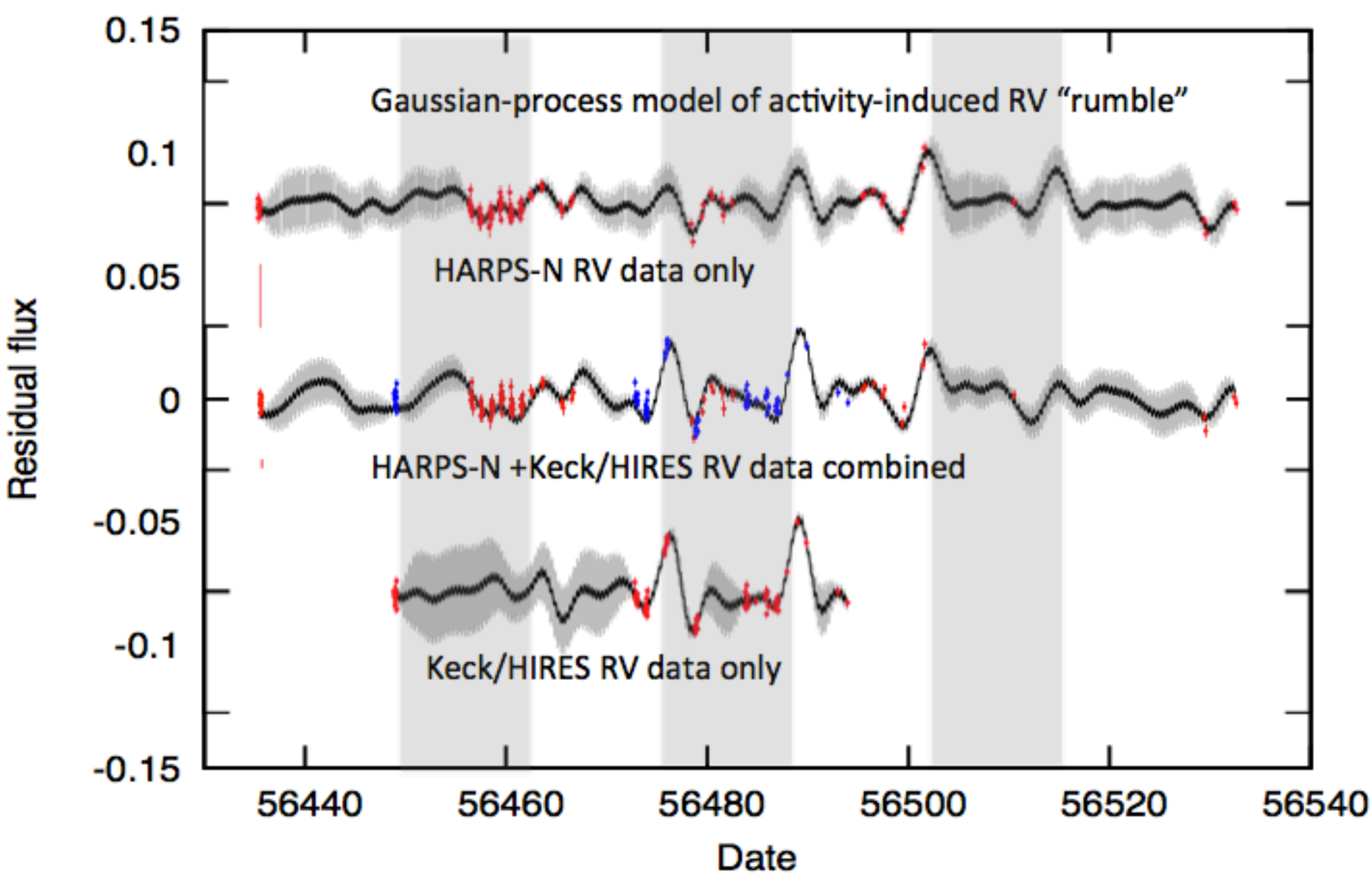






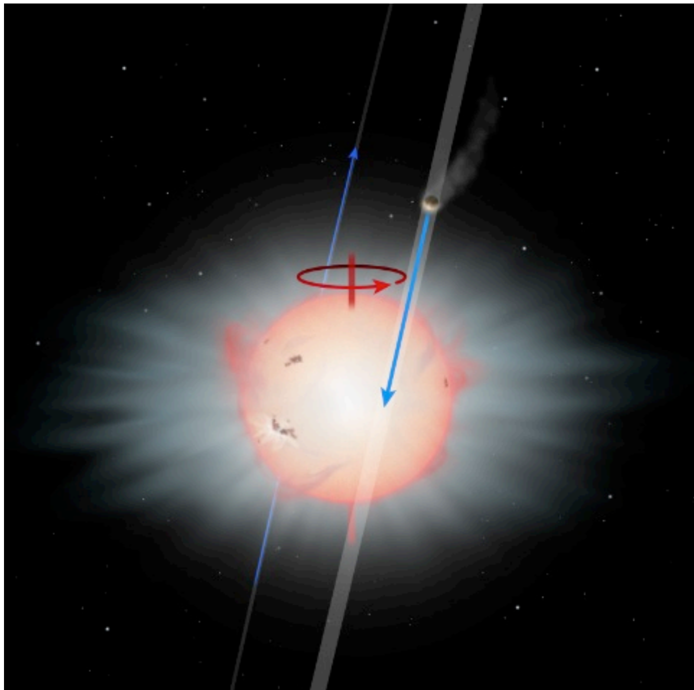


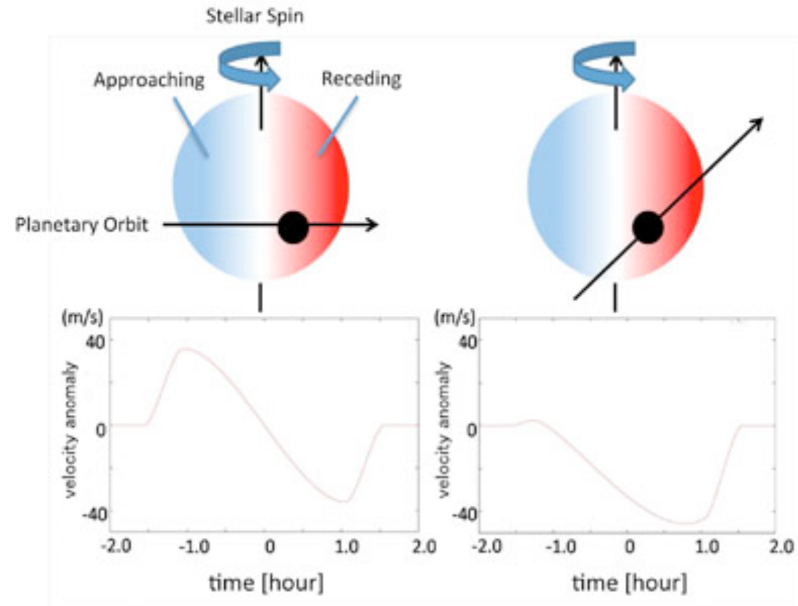
Activity modelling: Kepler-78

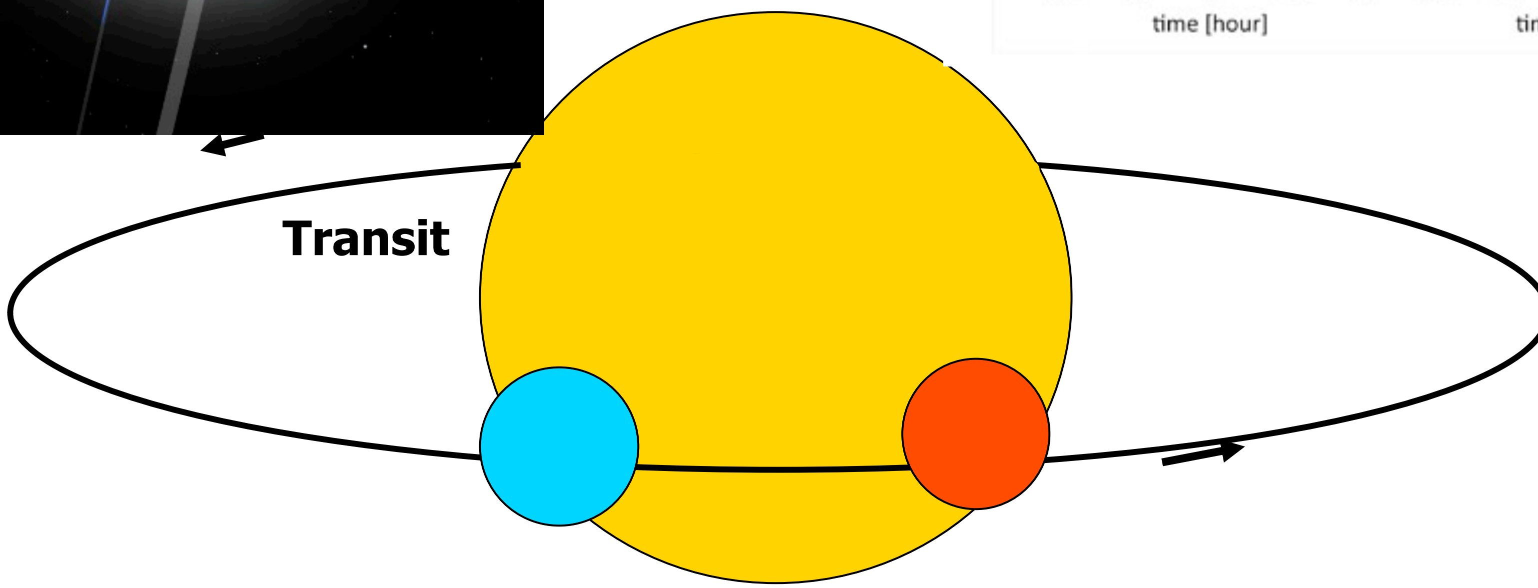


Disk migration challenge: obliquity

What about spin-orbit misalignment?

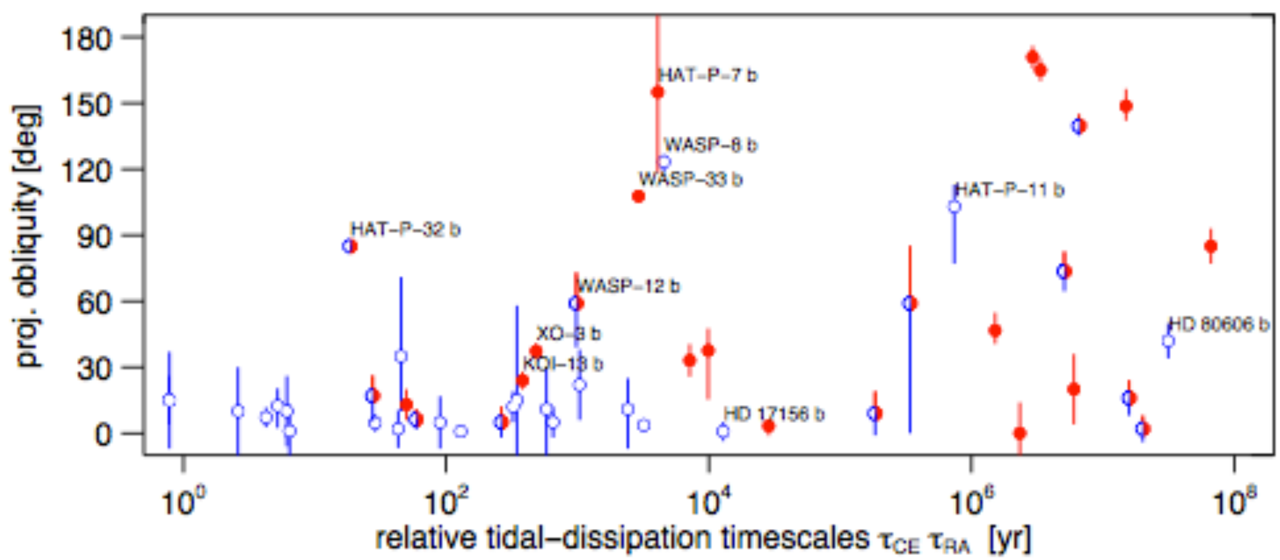




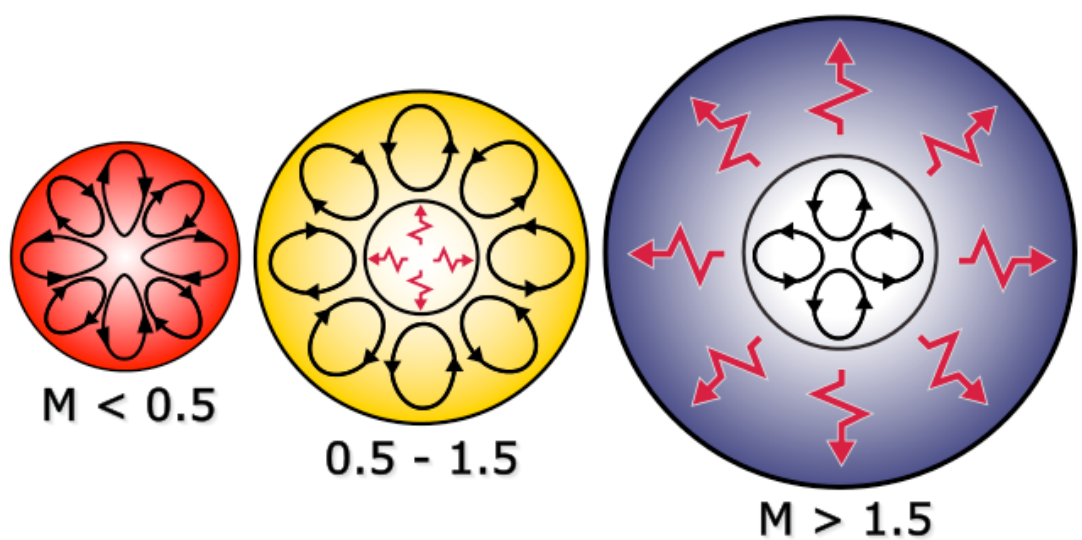


Gas giants: some key issues

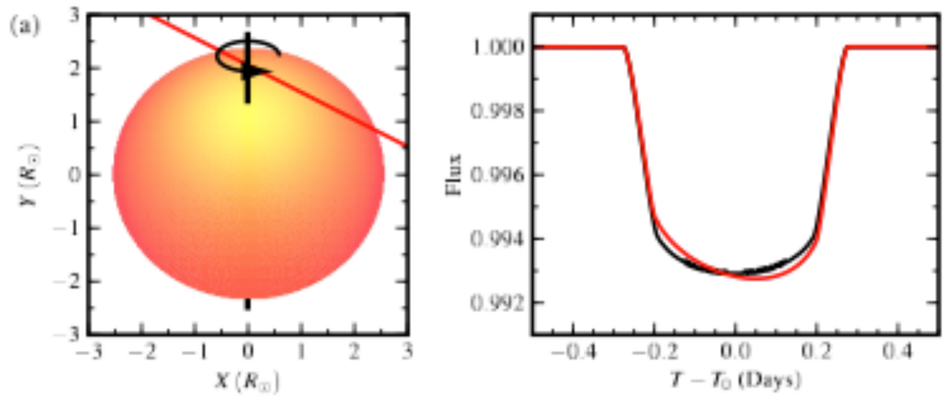
- Is there evidence for M_*-dependent tidal dissipation?

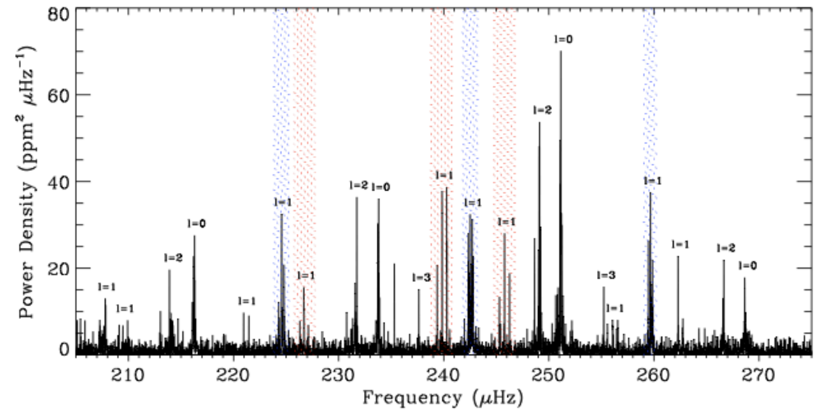


Winn



Alternative obliquity determination

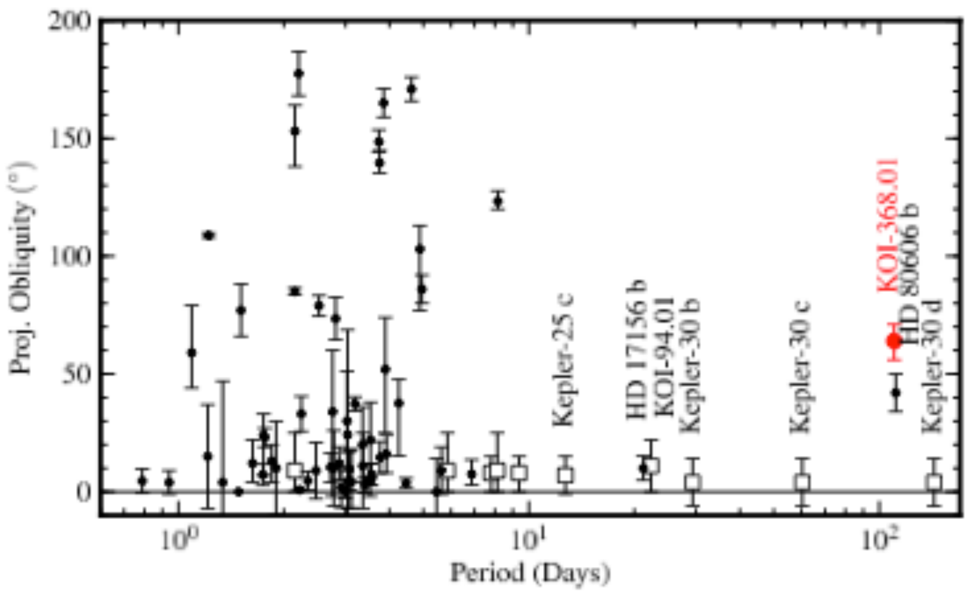




Zhou & Huang

Huber et al

KOI 368-01



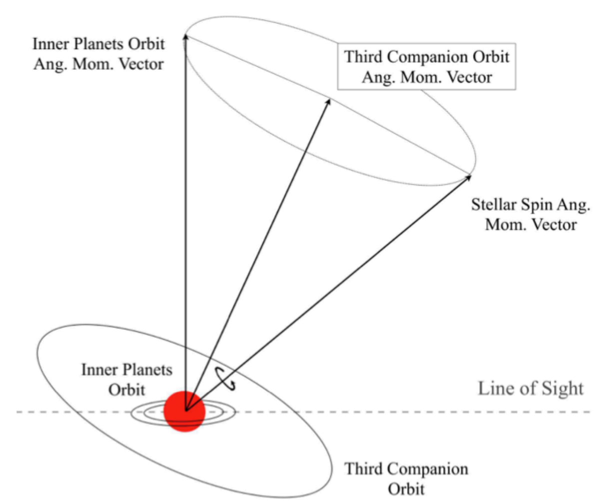
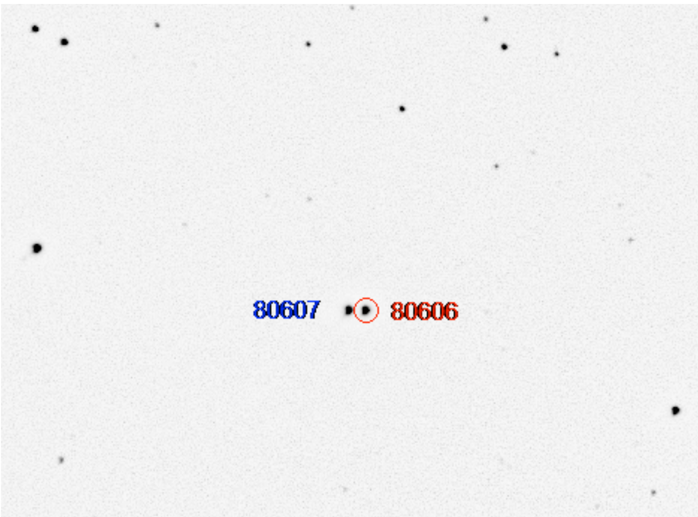
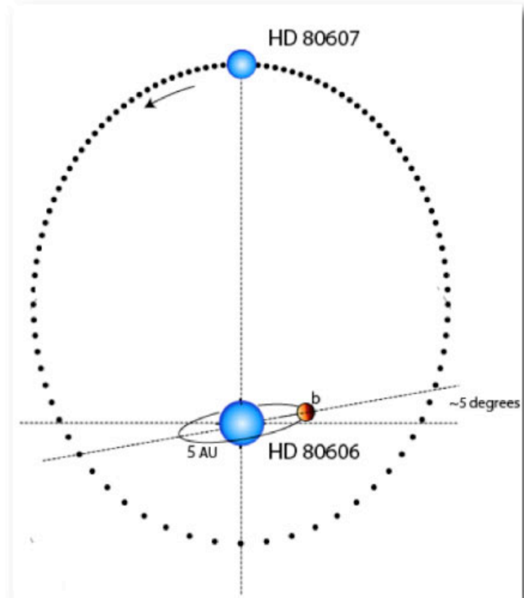


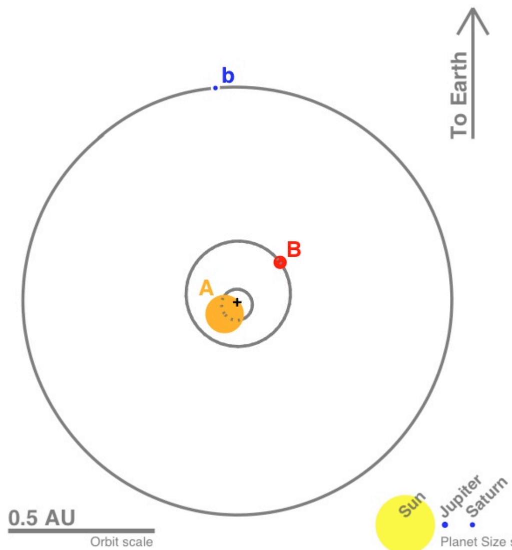
Figure S23: Graphical illustration of the dynamical tilting hypothesis for the Kepler-56 system. Note that the sizes are not to scale.

综合观测（亮点2）：双星系统



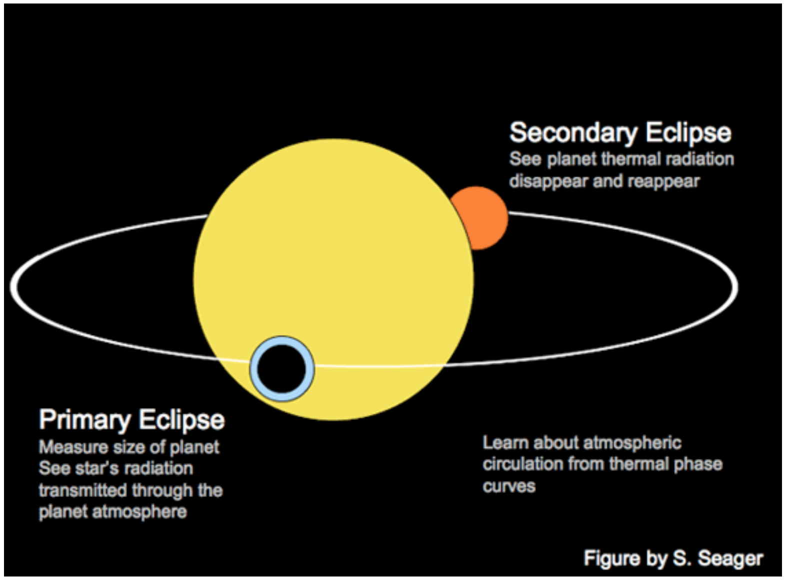
行星与伴星
轨道的倾角：
Kozai 共振

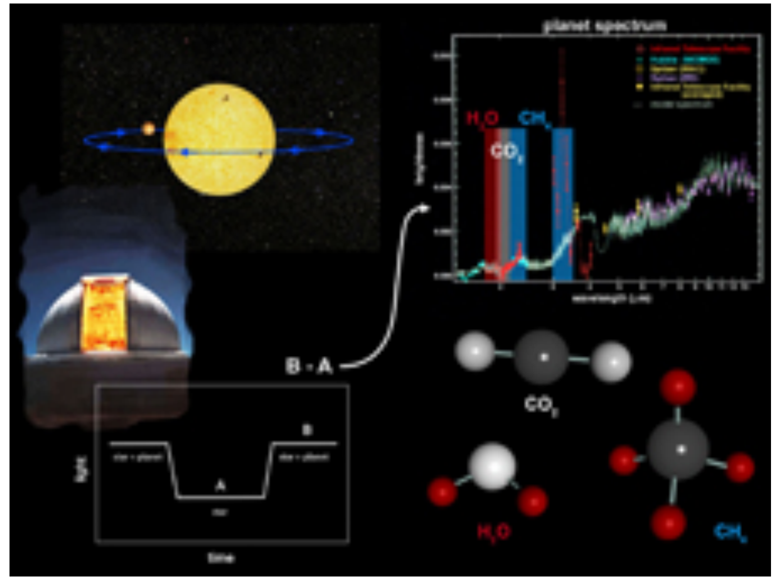


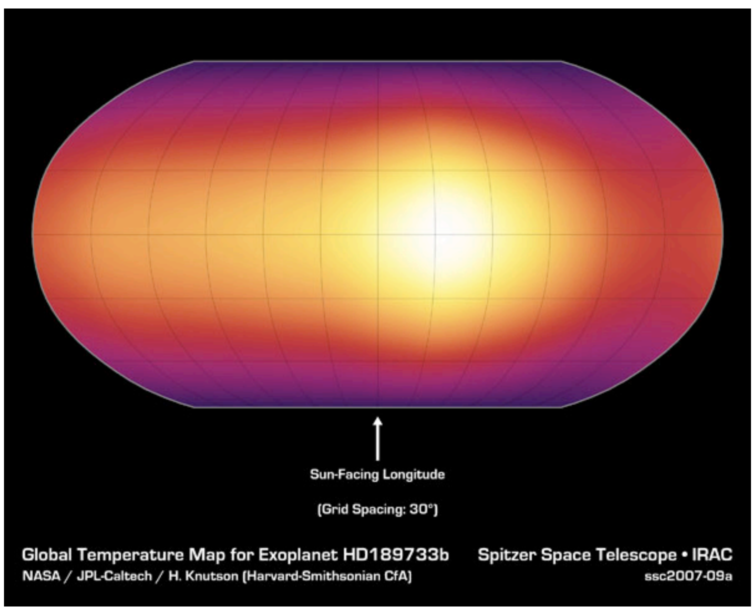


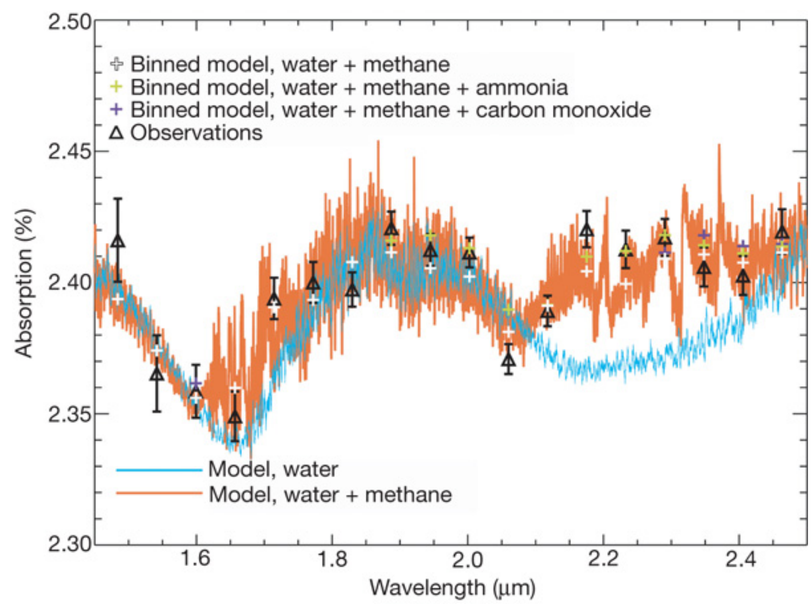
双星周围的行星

行星大气的红外凌星观测（亮点1）行星大气



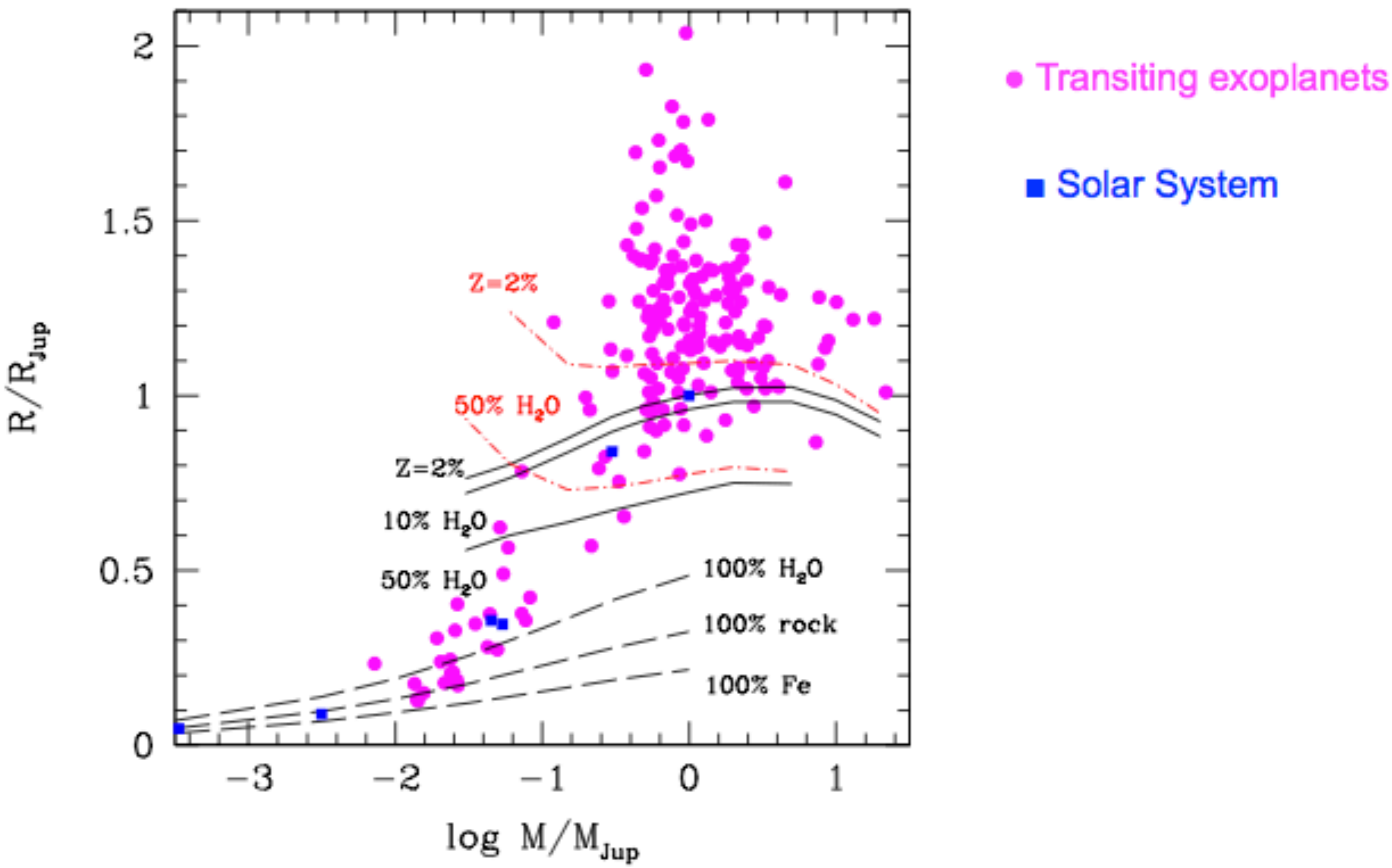






Knowledge of Solar System necessary to understand the huge diversity of planetary structures from the mass-radius relationship of exoplanets

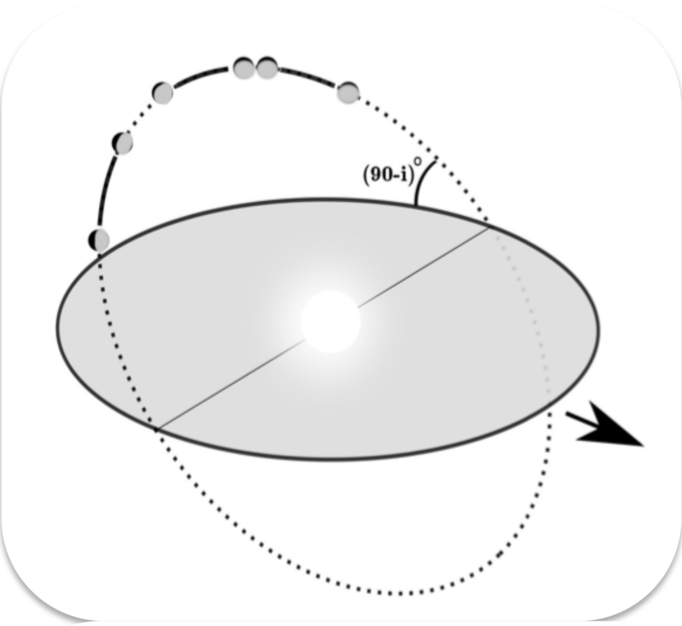
(Baraffe)

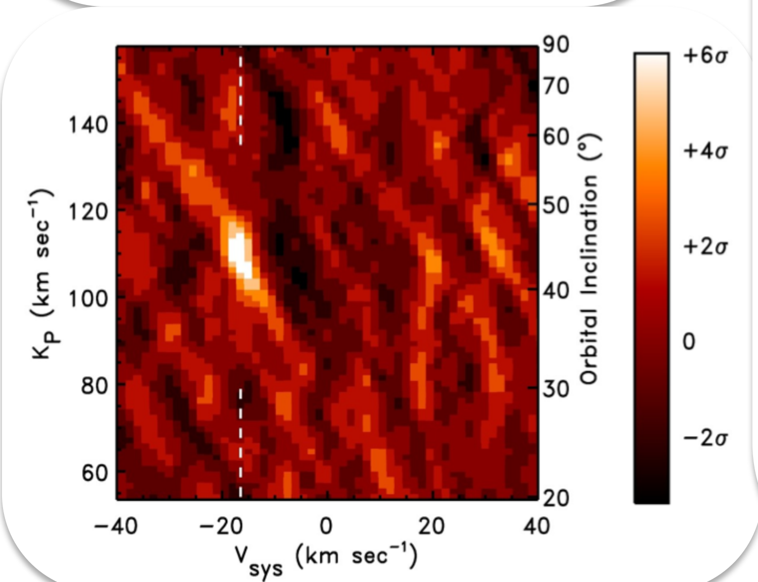


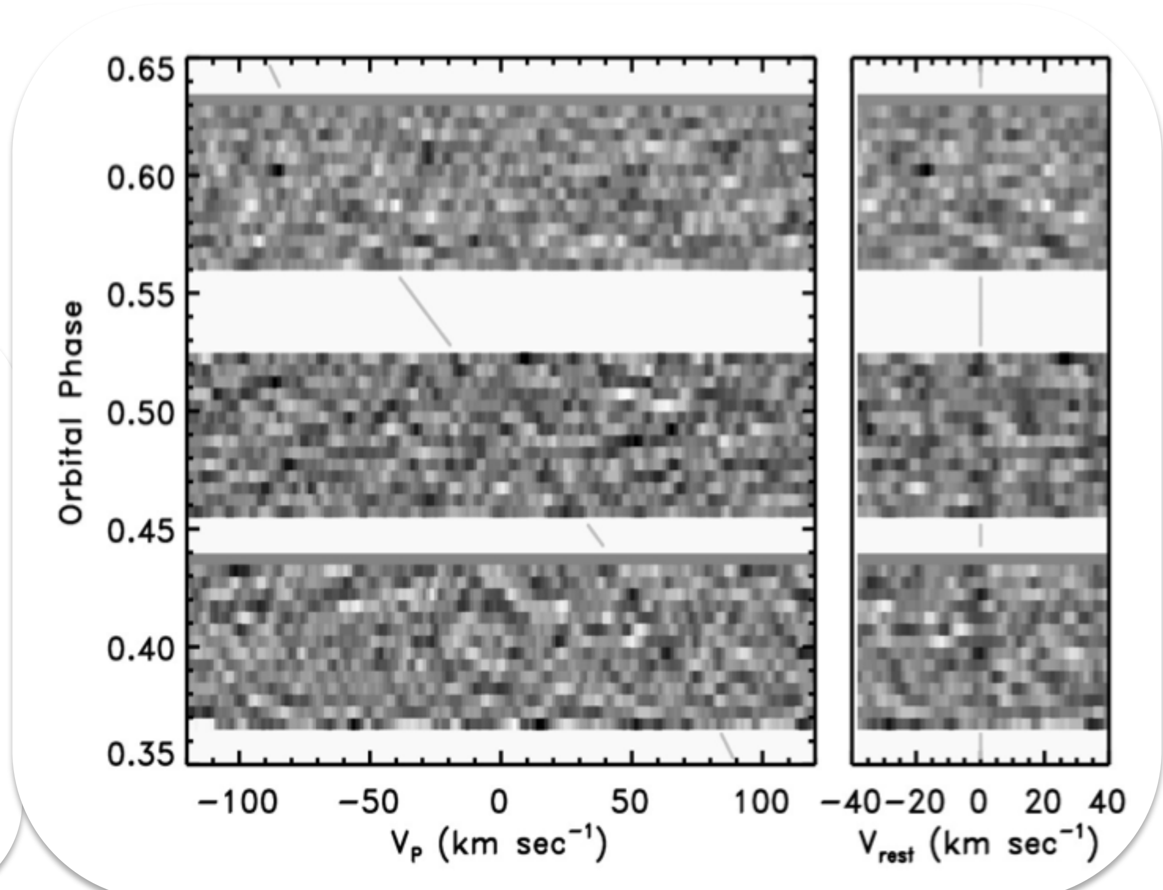
CO in dayside spectrum of tau Bootis b (CRIRES@VLT)

(**Brogi et al.** ***Nature*** **2012 – see also Rodler et al. 2012**)

First detection of non-transiting planet→ inclination, mass



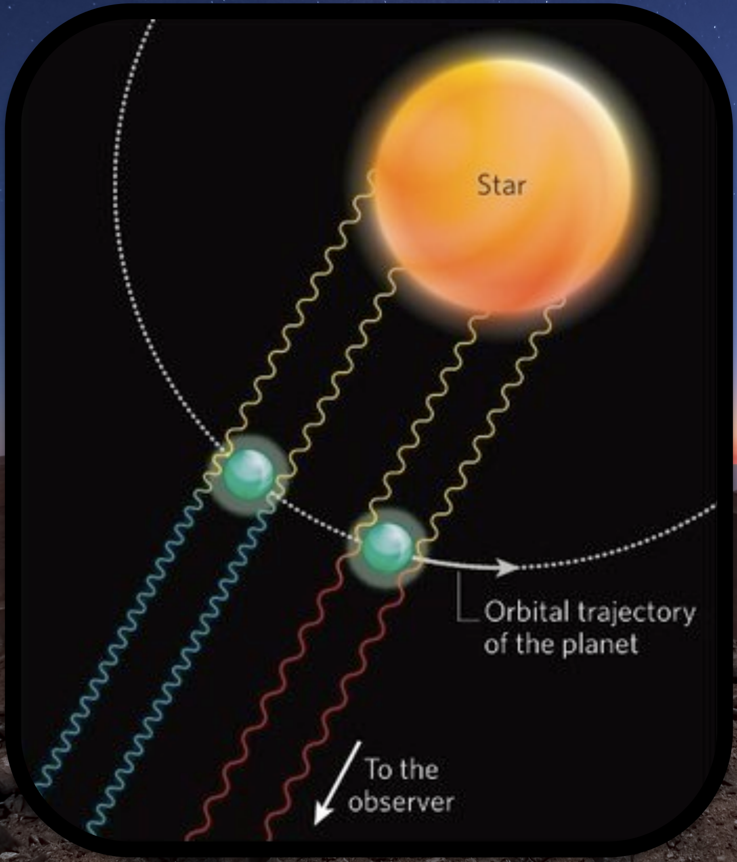


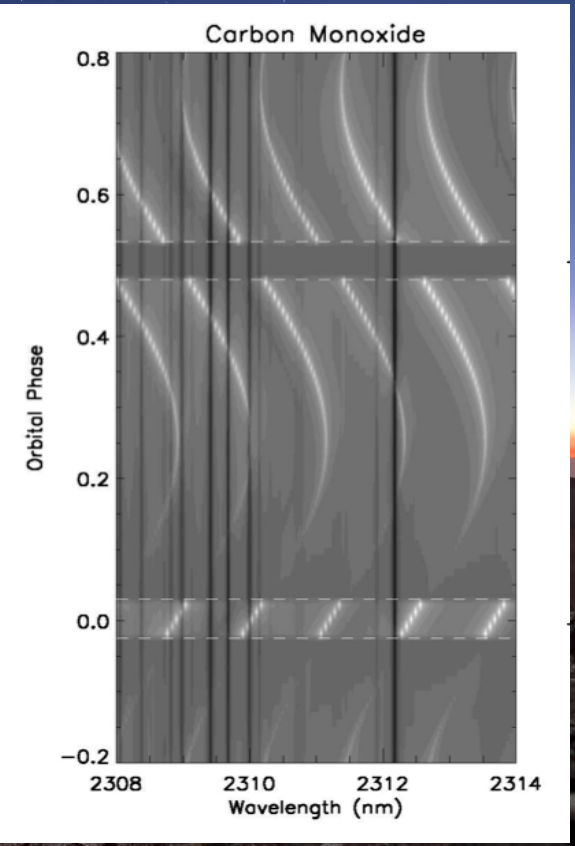


Solutions for Ground-based Observations

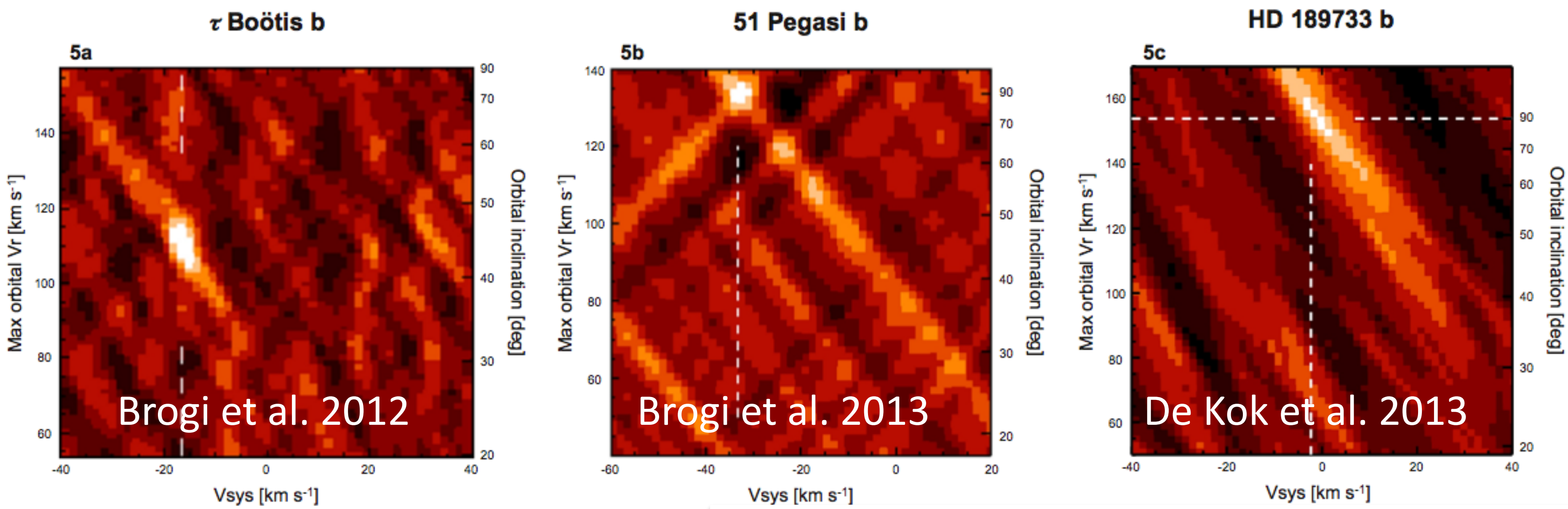
High-Dispersion Spectroscopy ($\lambda/\Delta\lambda$=100,000)

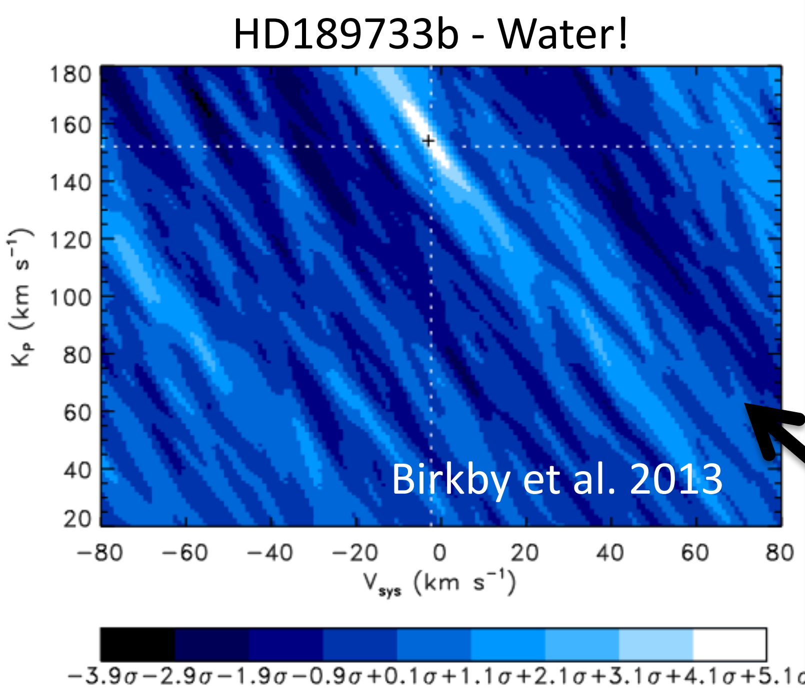
- Molecular Bands are resolved in tens of individual lines
- Strong Doppler effects due to orbital motion of the planet (upto >150 km/sec)
- moving planet lines can be distinguished from stationary telluric & stellar lines





CO in dayside spectra of hot Jupiters





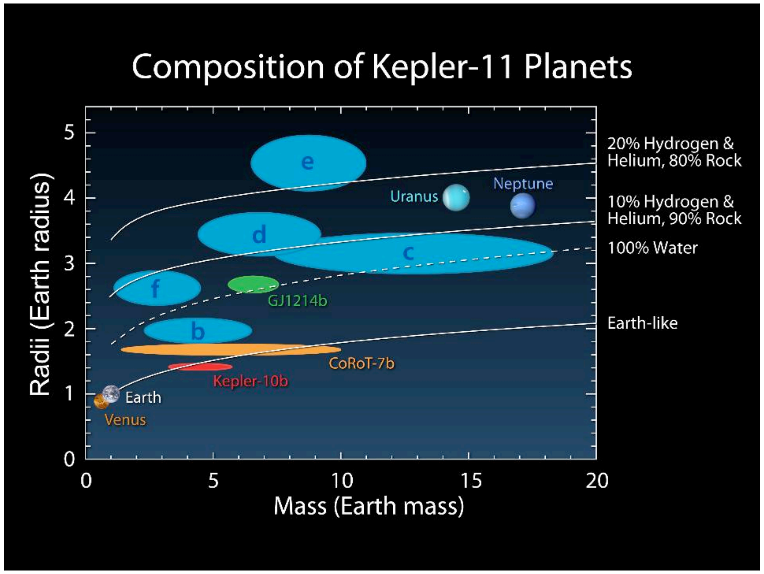
CRIRES@VLT Upgrade (2015) →
6x larger wavelength coverage
CO, H2O, CH4, NH3, H3+,.....

VLT ESPRESSO (Optical → TiO, VO, FeH...)

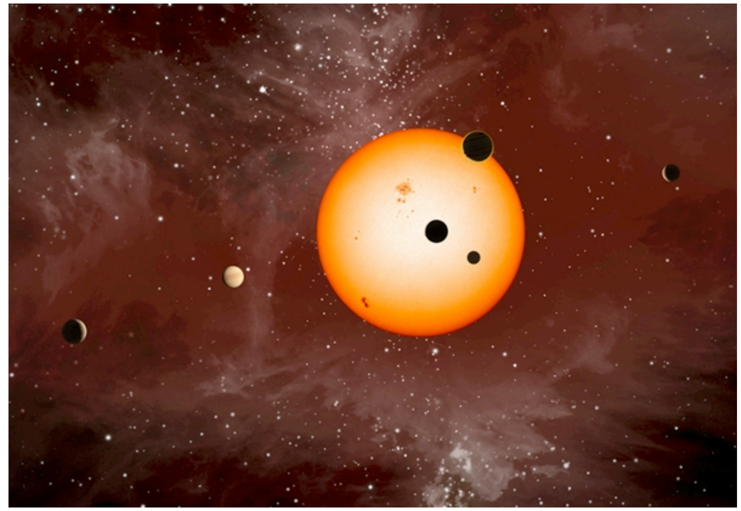
Now also with Keck!
Lockwood et al. 2014

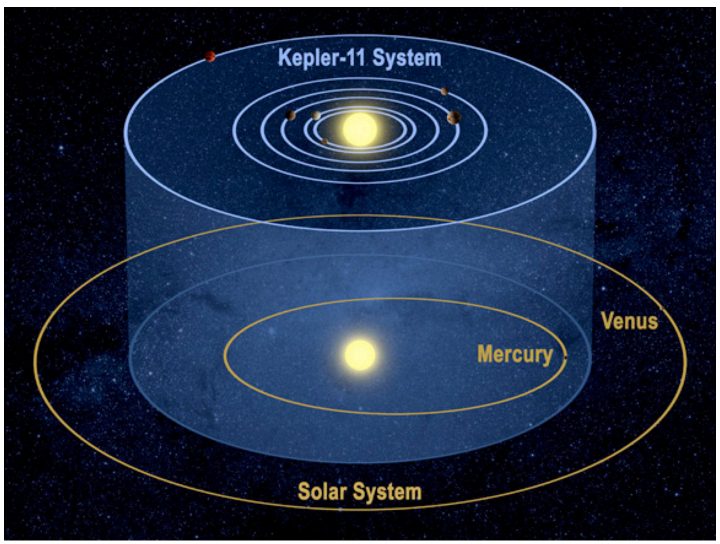
Stepping-stone for the ELTs

超级地球的大气成分

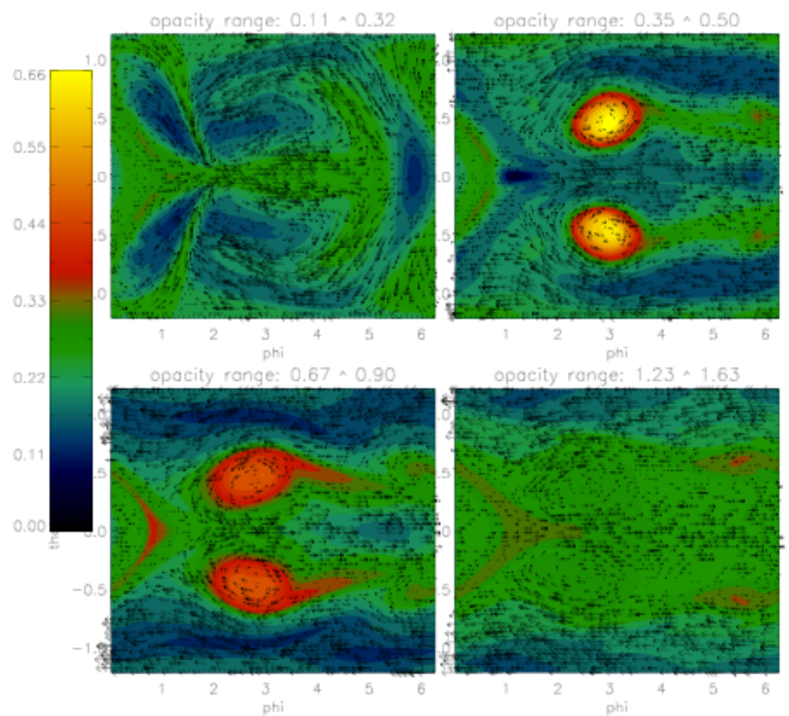


Composition of Kepler-11 Planets
Radii (Earth radius)
Mass (Earth mass)
20% Hydrogen & Helium, 80% Rock
10% Hydrogen & Helium, 90% Rock
100% Water
Earth-like
Uranus
Neptune
GJ1214b
CoRoT-7b
Kepler-10b
Earth
Venus

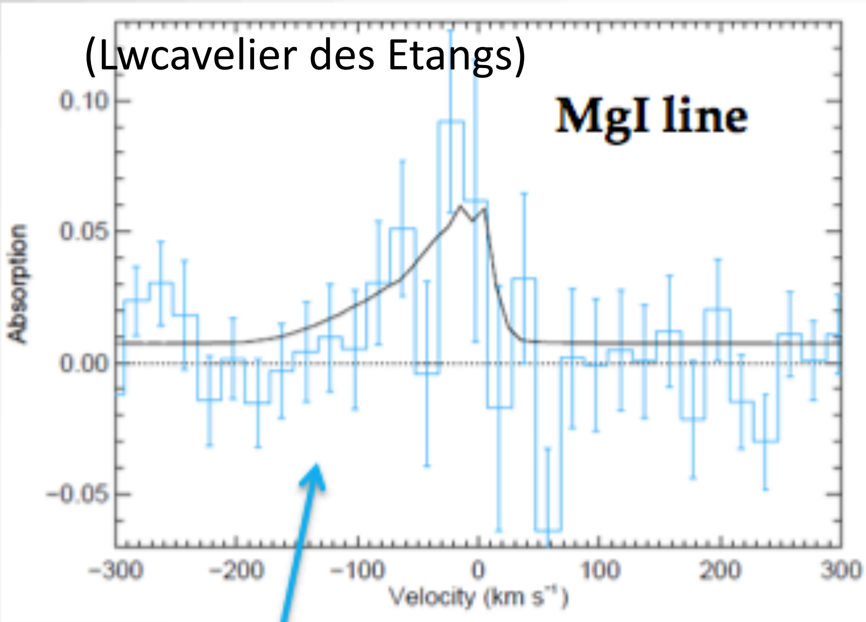




Kepler-11 System
Venus
Mercury
Solar System



opacity range: 0.11 ^ 0.32
opacity range: 0.35 ^ 0.50
opacity range: 0.67 ^ 0.90
opacity range: 1.23 ^ 1.63
phi

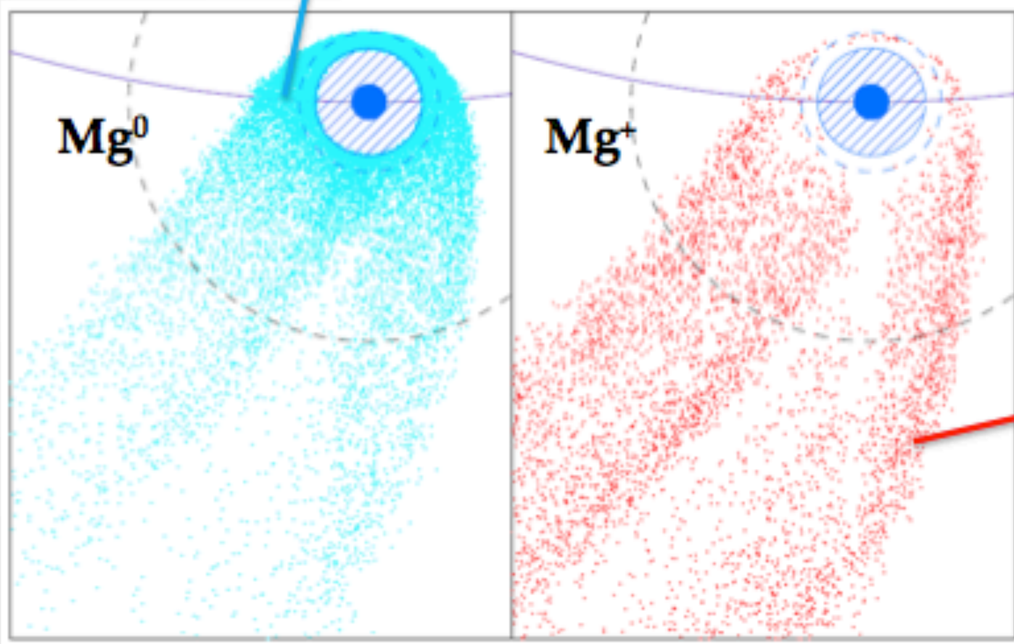


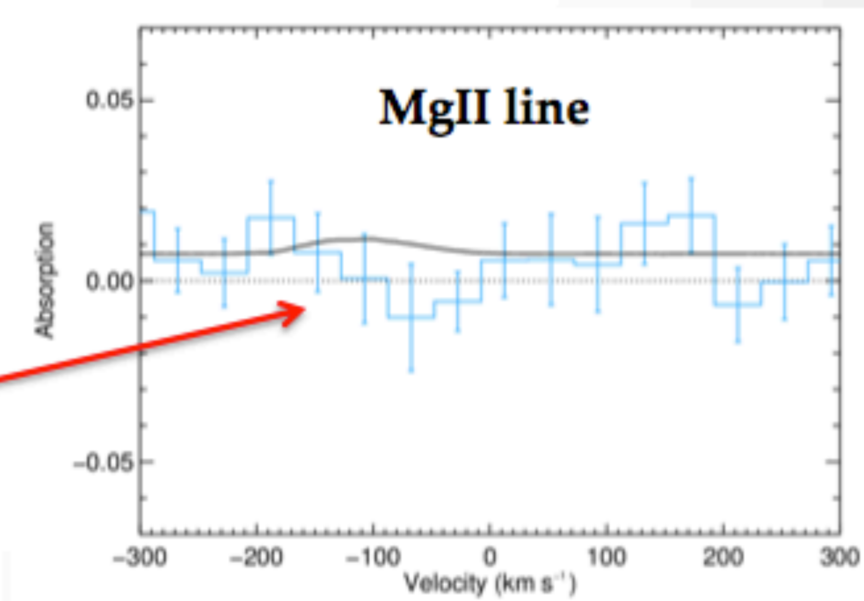
- Radial velocities of MgI : **[-60 ; - 19] km/s** explained by **radiation pressure**
- Neutral magnesium escape rate

$$\dot{M}_{Mg} = 2.9 \times 10^{7}\ \mathrm{g\ s^{-1}}$$

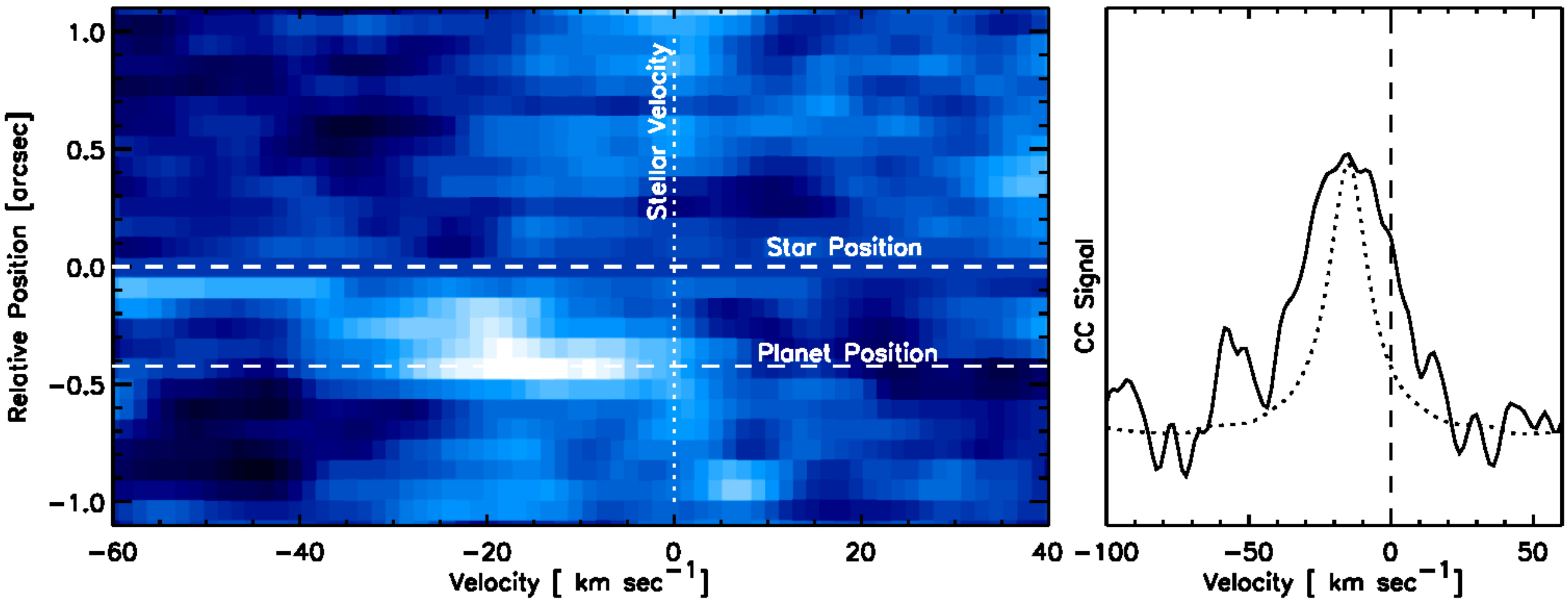
$$\Downarrow$$

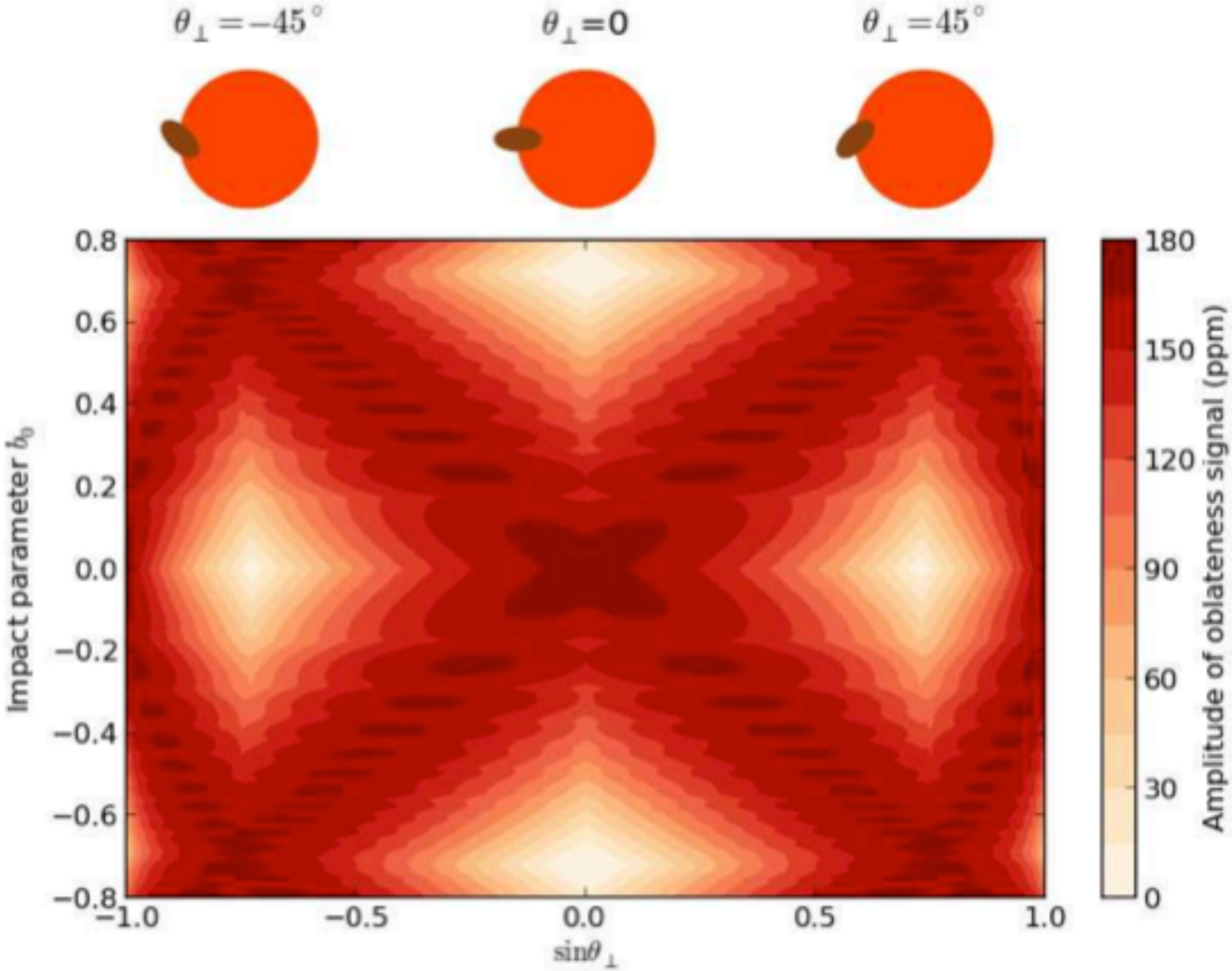
$$\dot{M}_{H} = 3 \times 10^{10}\ \mathrm{g\ s^{-1}}$$



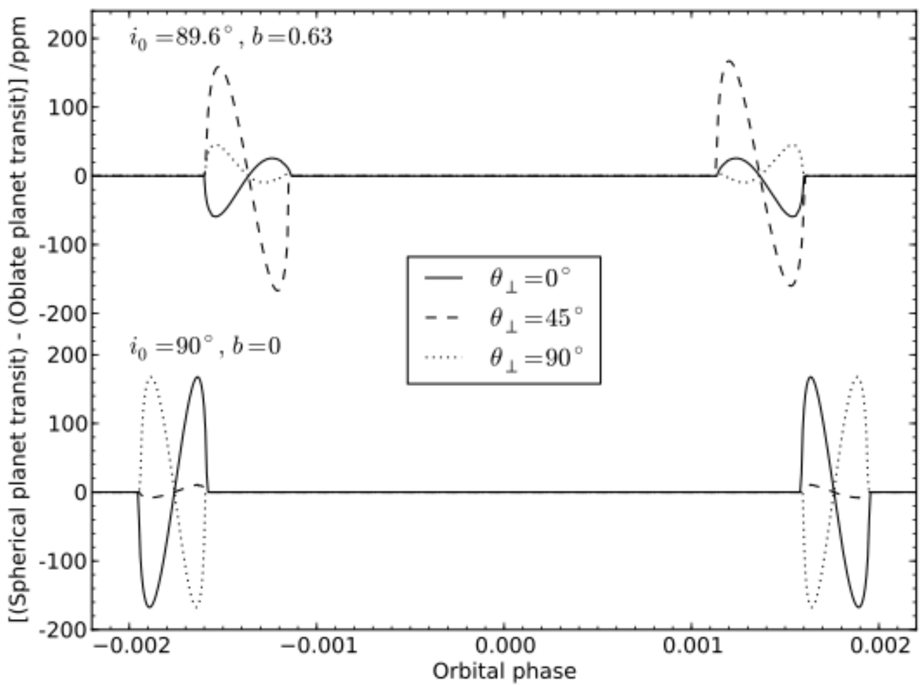


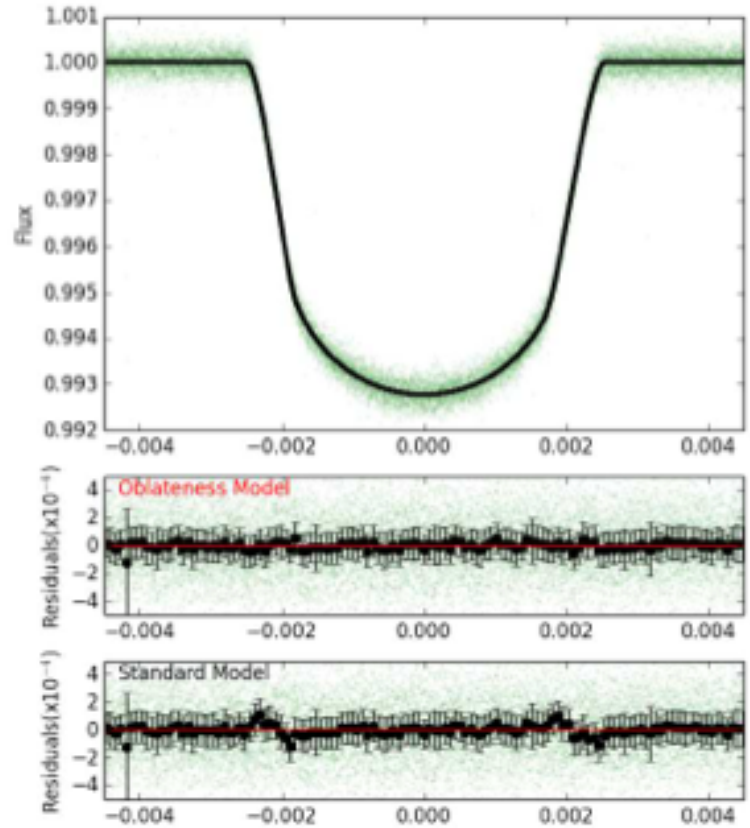
Fast spin of a young extrasolar planet *Snellen et al. - embargoed*



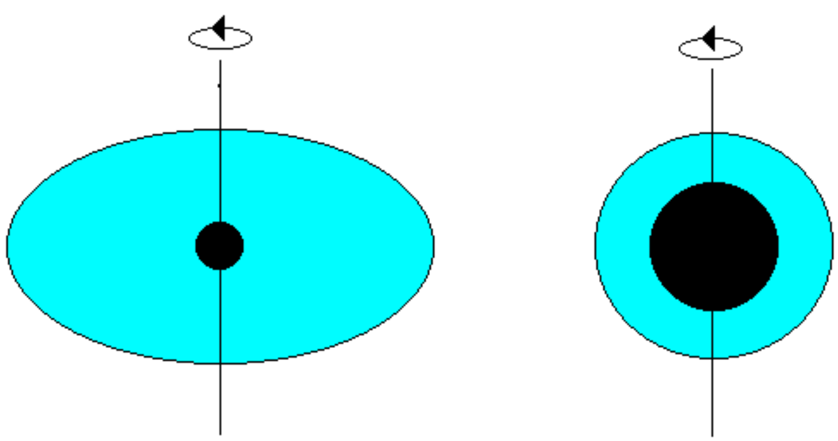


$\theta_\perp = -45^\circ$
$\theta_\perp = 0$
$\theta_\perp = 45^\circ$
Impact parameter b_0
$\sin\theta_\perp$
Amplitude of oblateness signal (ppm)
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−0.5
0.0
0.5
1.0
180
150
120
90
60
30
0

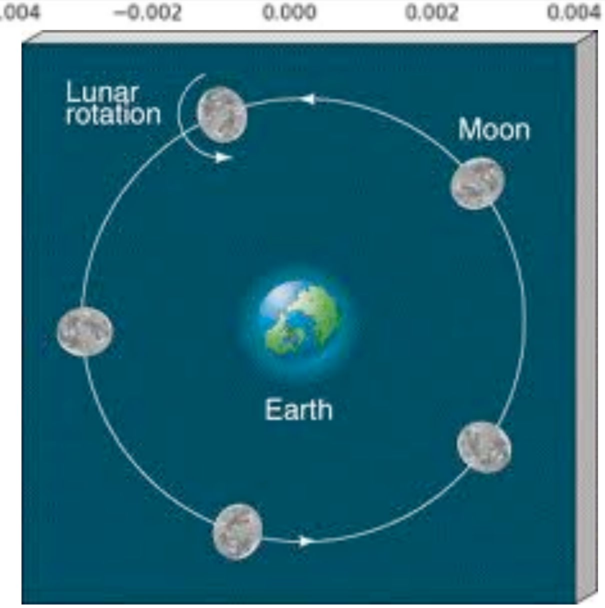




high rotation rate + fluid planetary structure = oblateness



the smaller the core of a Jovian world, the more oblate its shape



Precision COSMOGONY 精确起源理论

- Ubiquity of planets:

case study vs **Science**

- Diversity of systems:

realm of possibilities

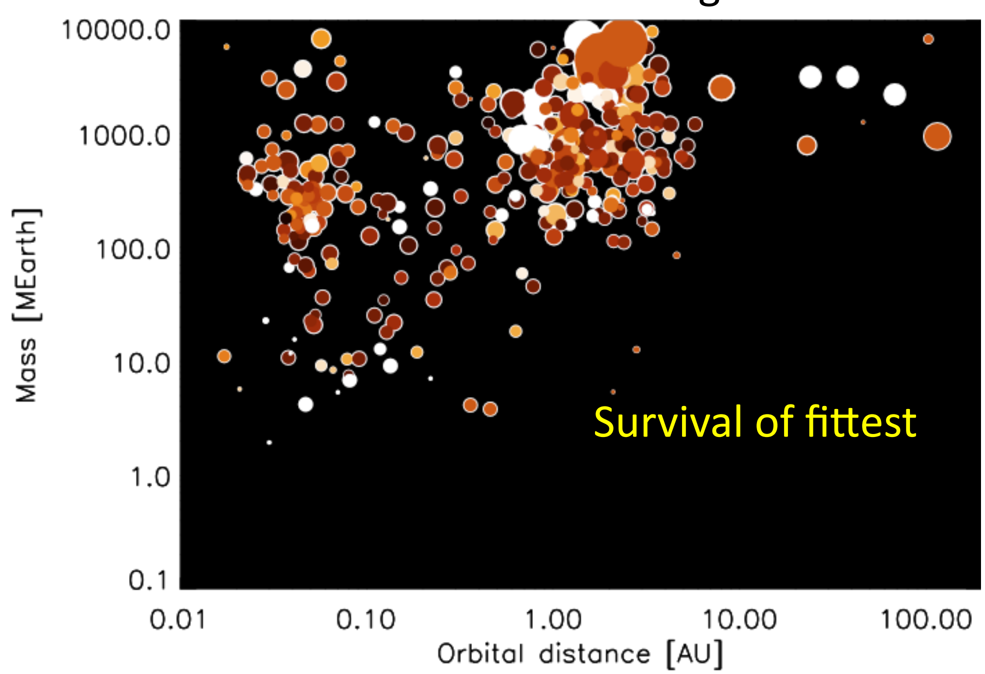
- Population census

missing info & big picture

- Solar system connection

Anthropic principle

Integral of details



总结：

- 寻找与分析系外行星已是二十一世纪最活跃的天文领域
- 系外数个类地行星的系统普遍存在
- 类木行星偏于在富金属高质量恒星周围
- 行星起源是通过核碰撞、气体吸积、迁移等过程
- 互相作用导致行星系统轨道分布的长期混沌演化
- 各种互相竞争的物理过程造成了系外行星的多元化
- 恒星周围普遍存在可居住的类地行星
- 很有可能十年内找到生命痕迹、导致天文生物学的突破
- 今后十年中行星天文与天体物理还将会有更大的所为
- **祝中国在行星天文学研究上迎头赶上、生根结果**