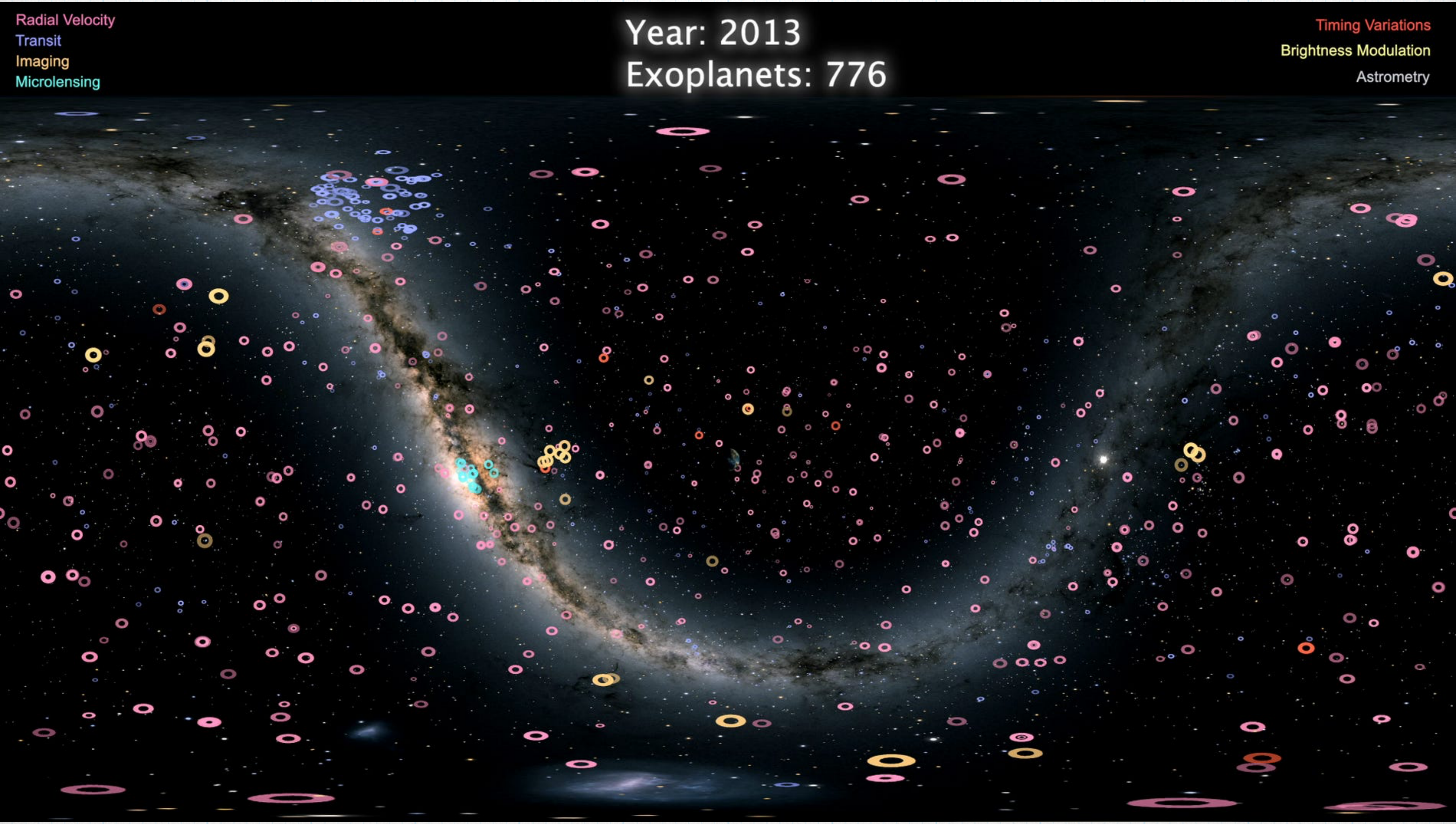
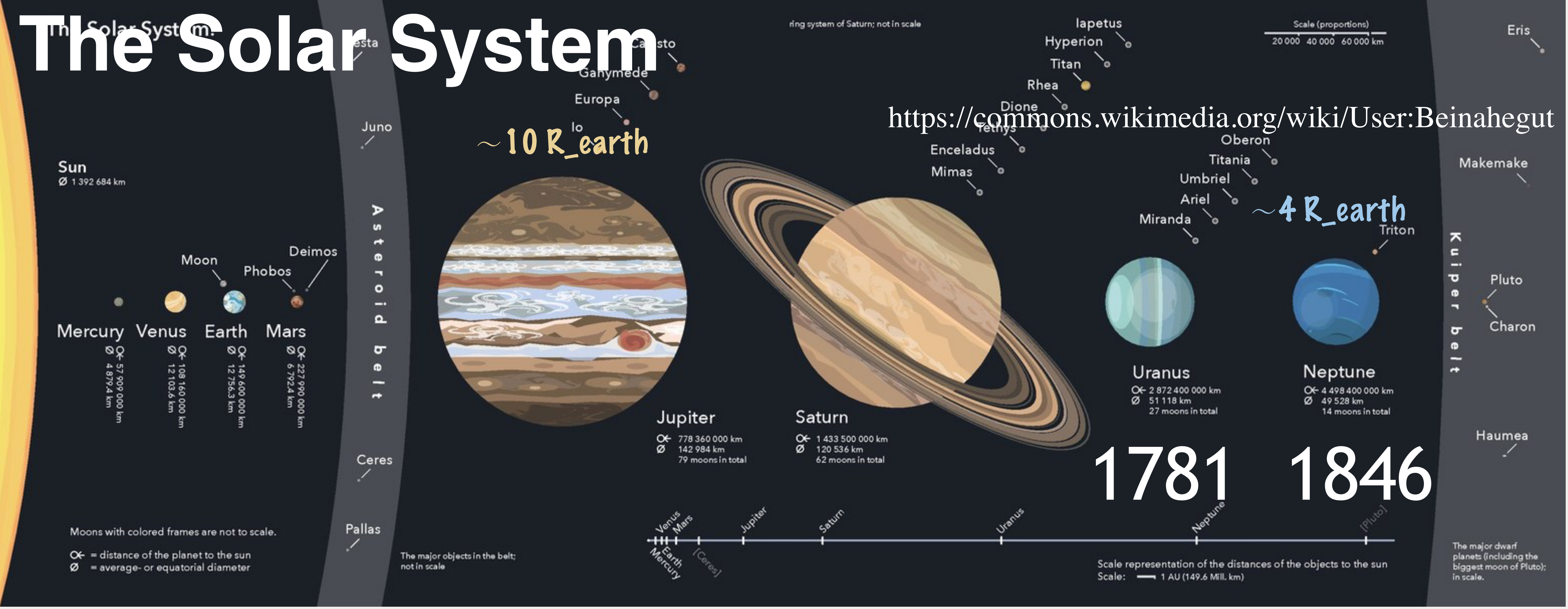
Exoplanet Research

Empirical Predictions for the Period Distribution of Planets to be Discovered by TESS


Radial Velocity
Transit
Imaging
Microlensing
Year: 2013
Exoplanets: 776
Timing Variations
Brightness Modulation
Astrometry

The Solar System



https://commons.wikimedia.org/wiki/User:Beinahegut

~10 R_earth

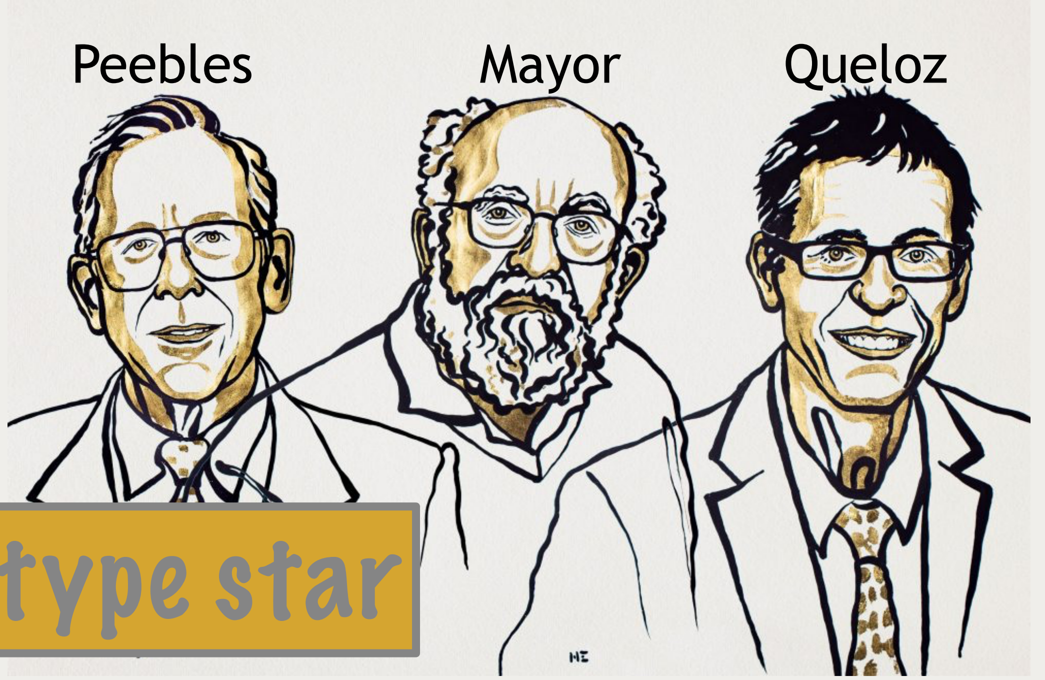
~4 R_earth

1781 1846

The Nobel Prize in Physics 2019

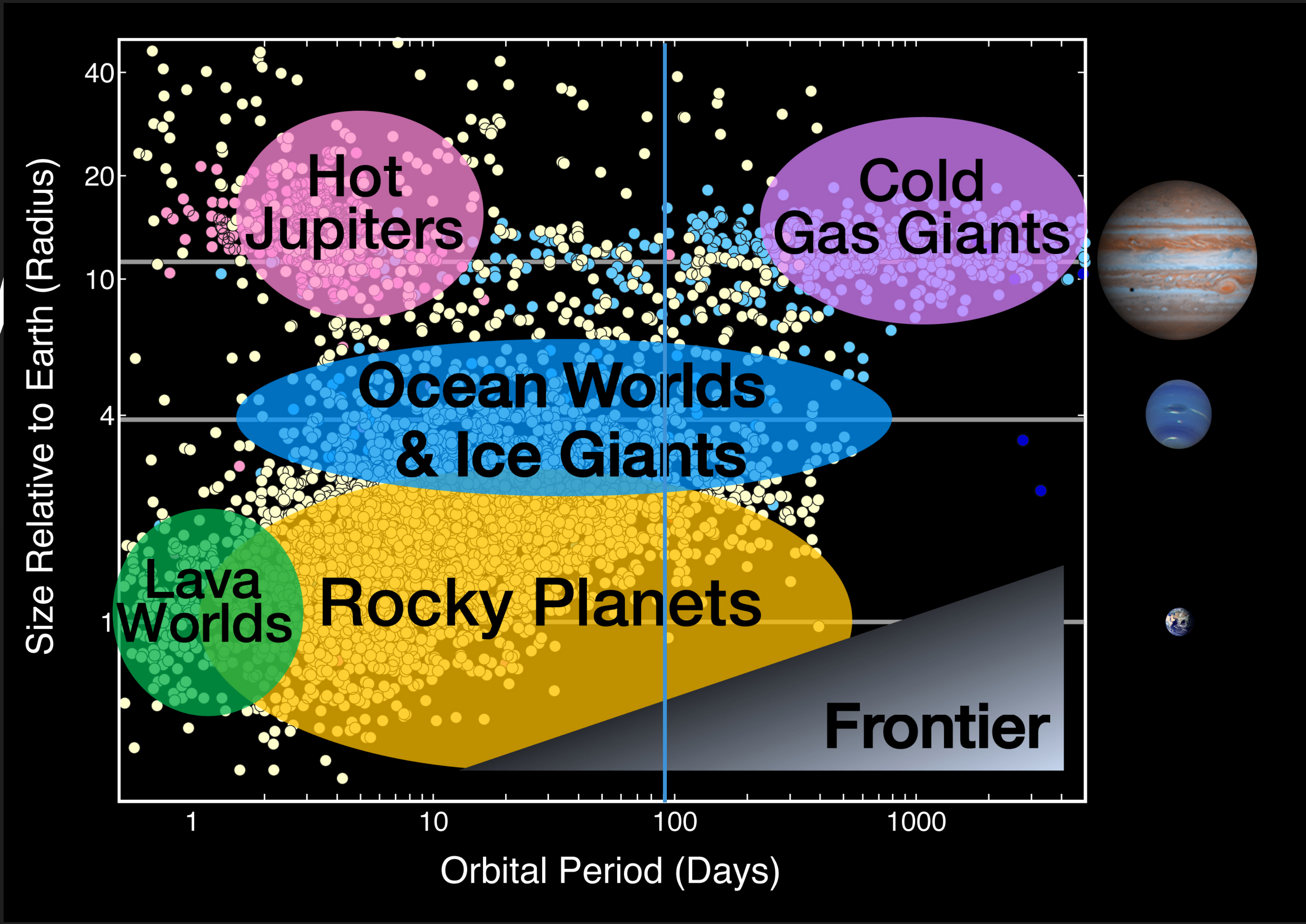
New perspectives on our place in the universe

October 1995,
Michel Mayor and Didier Queloz
Haute-Provence Observatory in France

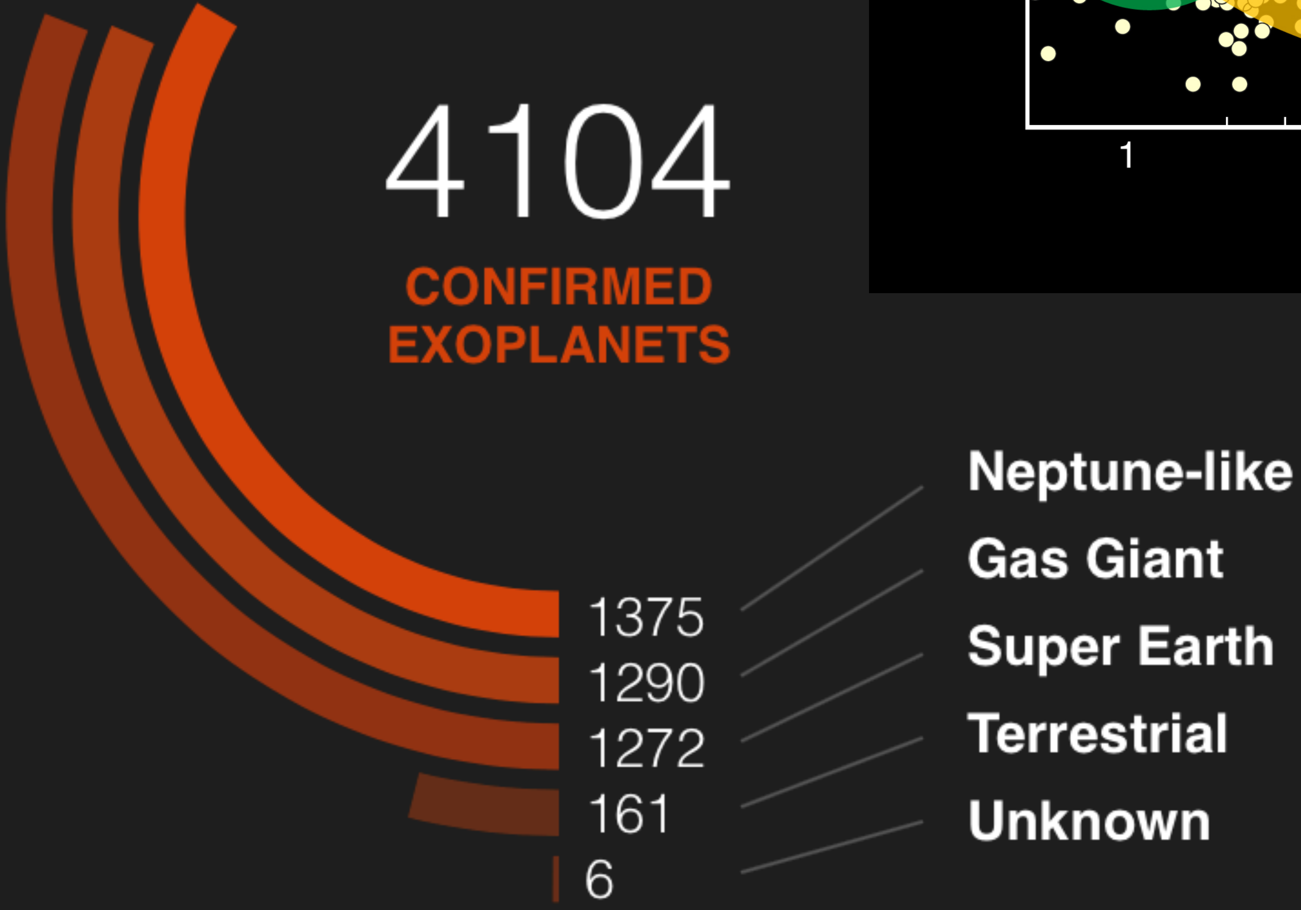


51 Pegasi b: Exoplanet Orbiting Solar-type star

Exoplanets Demography



NASA/Ames Research Center/Natalie Batalha/Wendy Stenzel

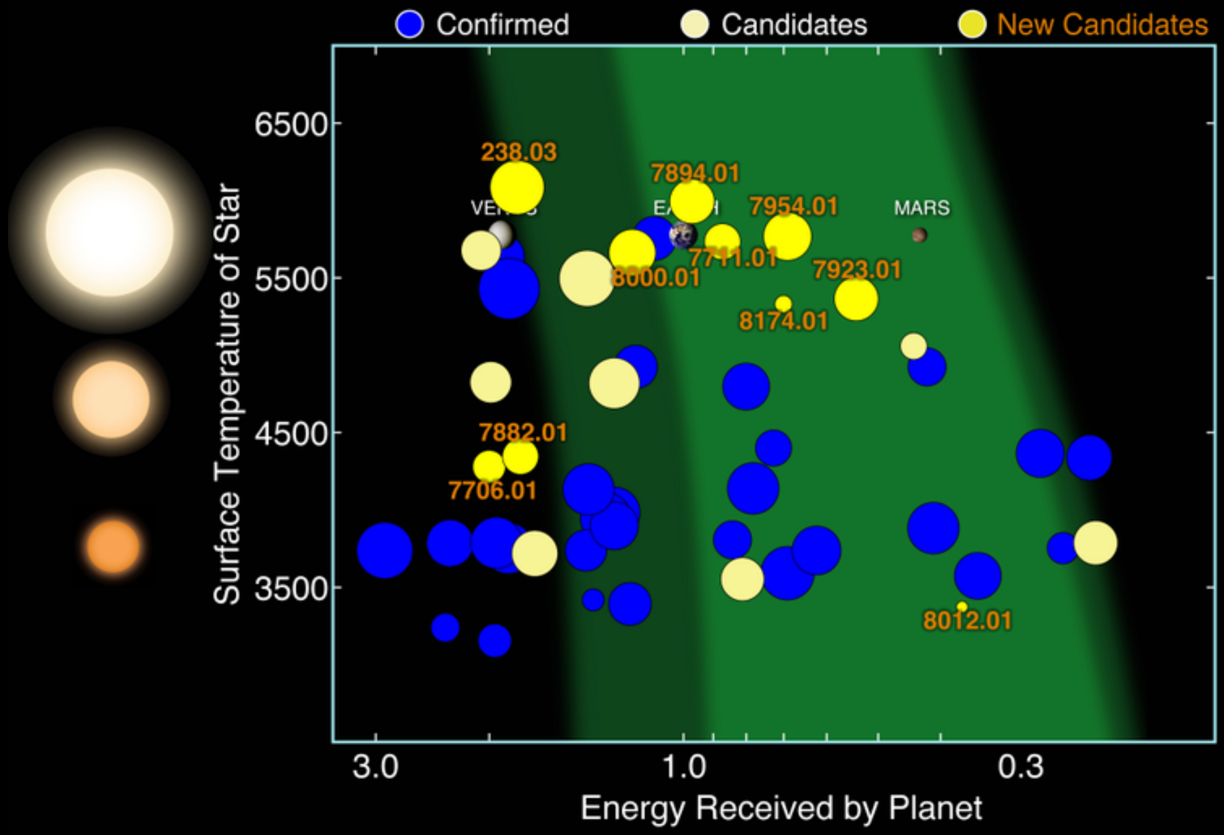


12/16 2019 https://exoplanets.nasa.gov/

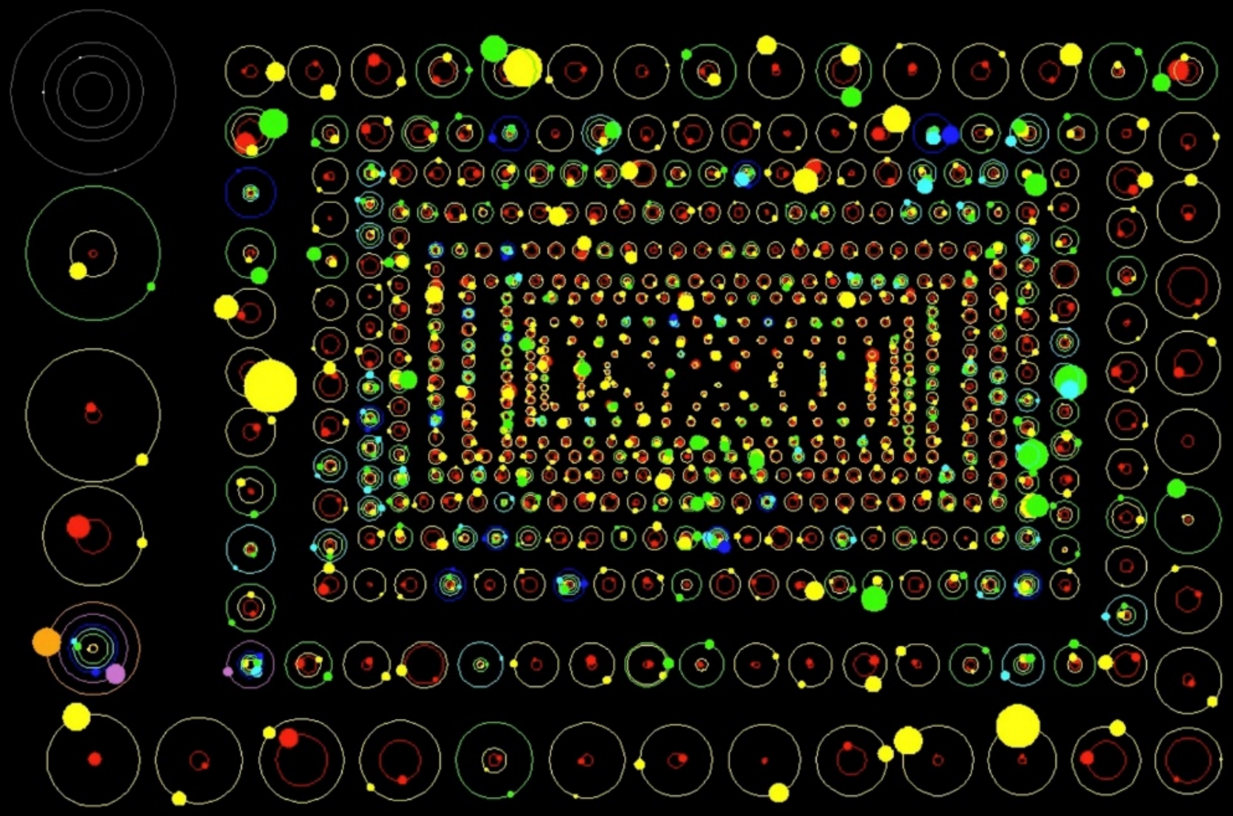
What can we learn from exoplanets?

- 1) Life outside the Solar System

2) planetary formation and evolution



NASA/Ames Research Center/Wendy Stenzel



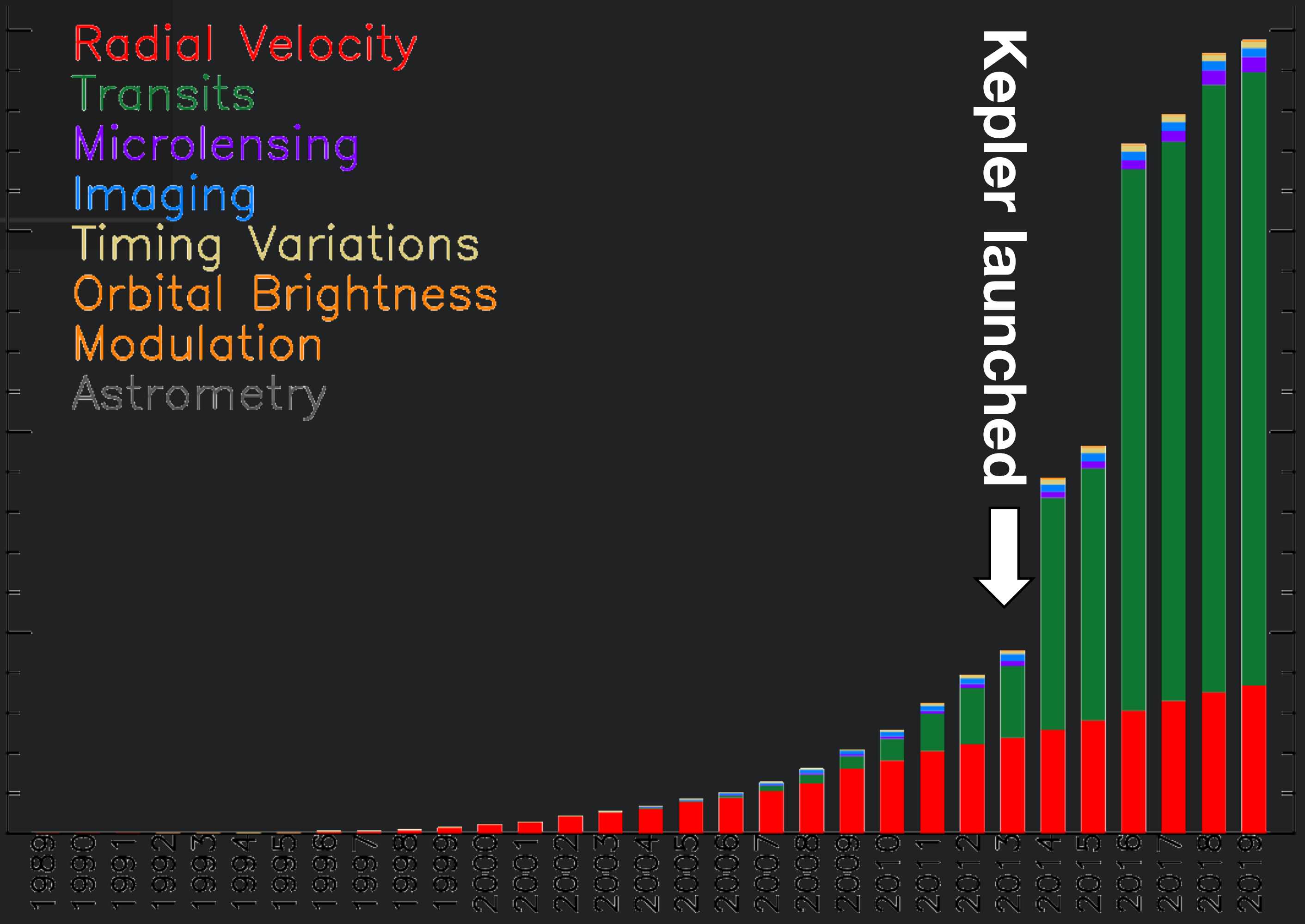
NASA/Kepler/Dan Fabricky

76.4%	Transit
19.1%	Radial Velocity
2.1%	Microlensing
1.1%	Imaging

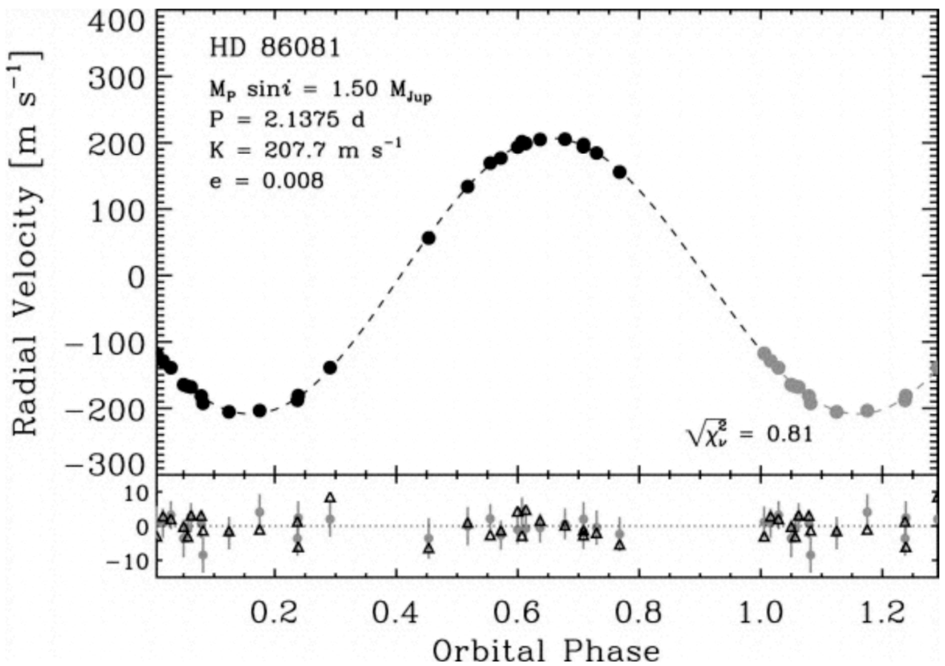
0.51% Transit Timing Variations,
0.39% Eclipse Timing Variations,
0.17% Pulsar Timing,
0.15% Orbital Brightness Modulation,
0.05% Pulsation Timing Variations,
0.02% Disk Kinematics,
0.02% Astrometry

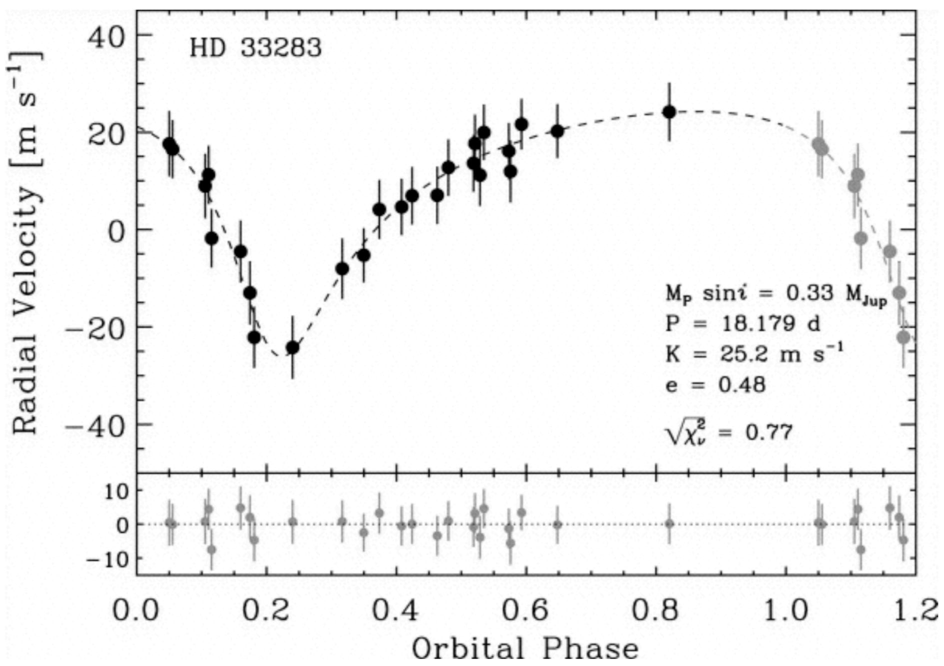
→

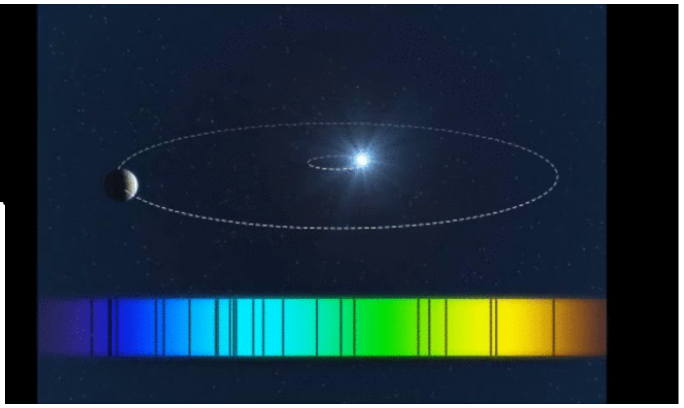
In 1995, Mayor and Queloz discovered the 1st exoplanet orbiting a sun-like star. Haute-Provence Observatory, France



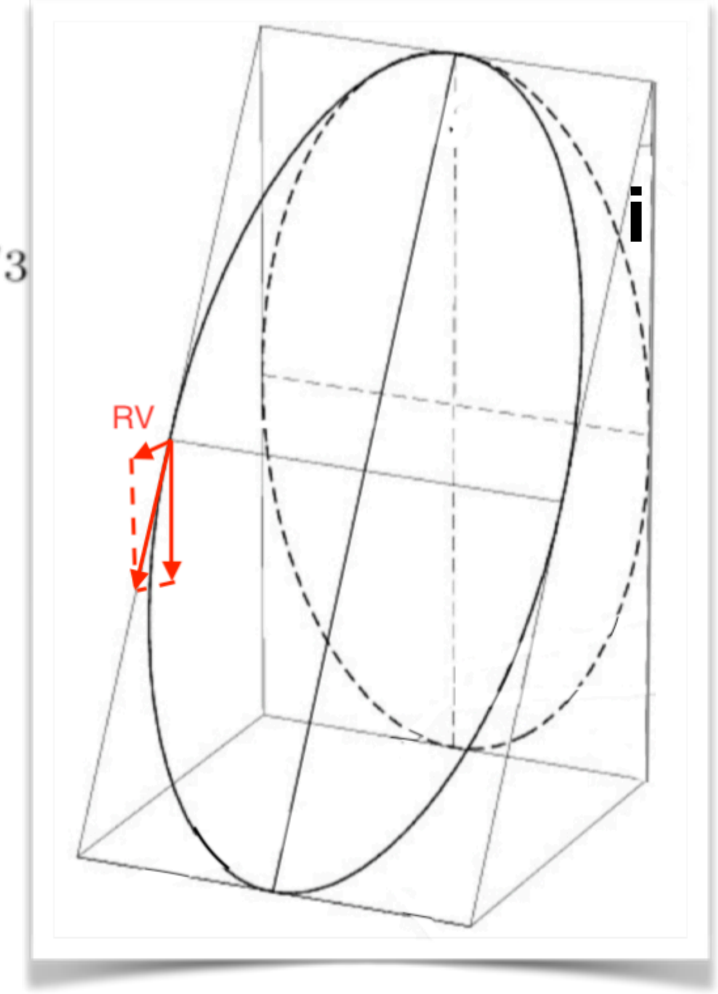
Radial Velocity





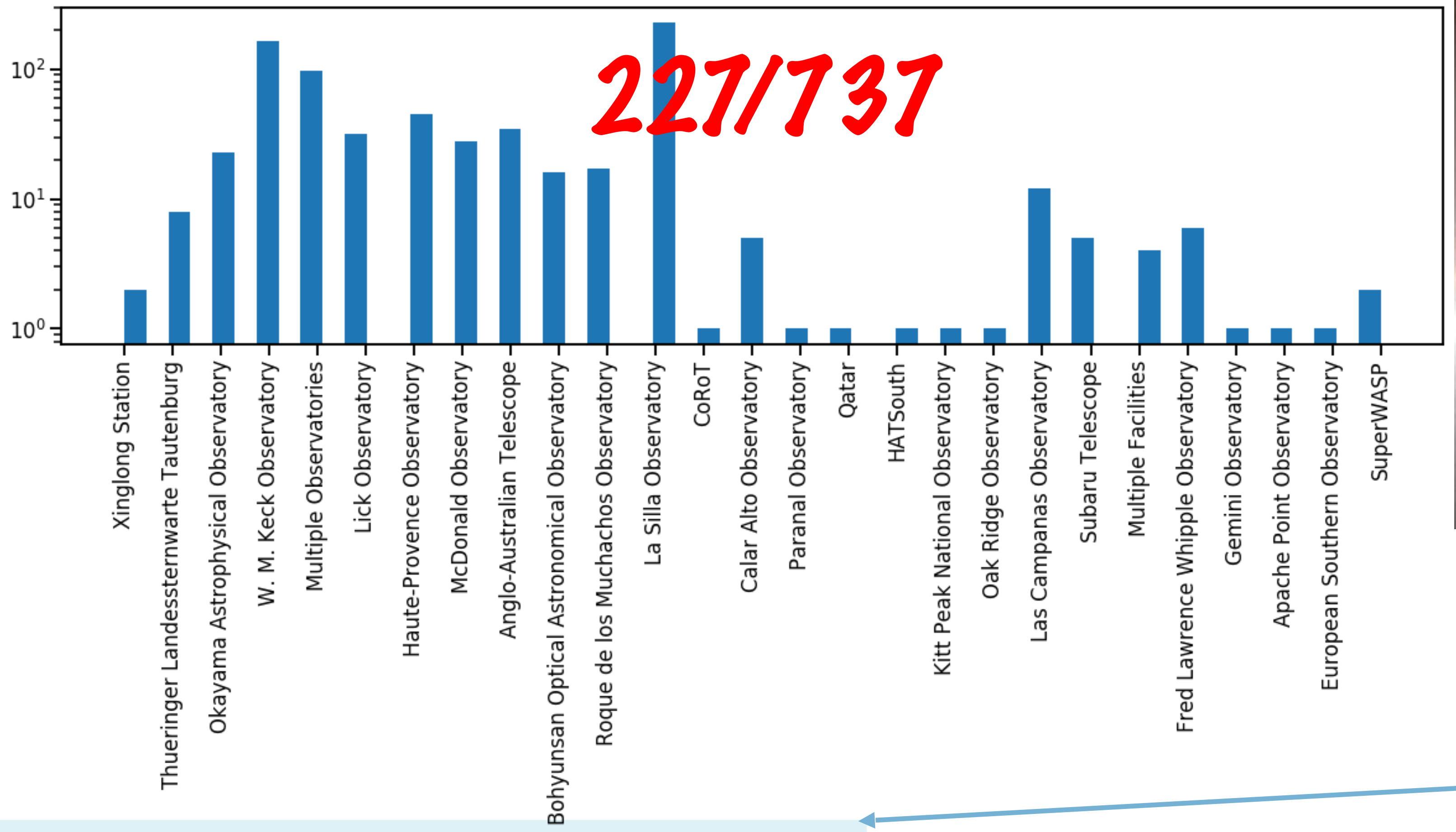


$$
\begin{aligned}
\Delta V_{\max} &= \left(\frac{2\pi G}{P}\right)^{1/3} \frac{\boxed{M_P \sin I}}{(M_P+M_S)^{2/3}} \\
&\approx (12\ \mathrm{m\ s^{-1}}) \left(\frac{P}{12\ \mathrm{yr}}\right)^{-1/3} \left(\frac{M_P \sin I}{M_{\mathrm{Jup}}}\right) \left(\frac{M_S}{M_{\mathrm{Sun}}}\right)^{-2/3}
\end{aligned}
$$

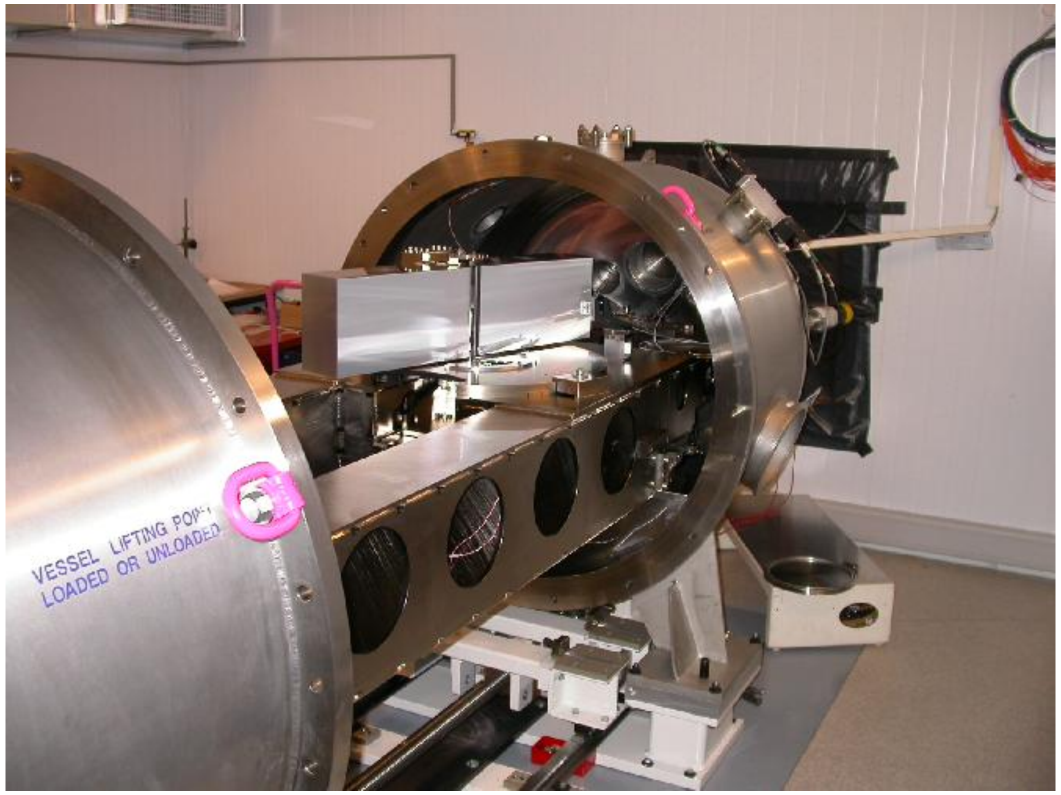


- 限制
  - sin i ambiguity
  - 半径未知
- 假信号，恒星脉动

Radial Velocity



227/737



- 精度
  - 1 m/s **HARPS**, 3.6m, ESO, 智利La Silla天文台
  - 13 m/s 太阳 – 木星
  - 0.09 m/s 太阳 – 地球
- 稳定性
  - 真空 压力 < 0.01 mb
  - 温度 保持17°C, 0.01°C
- 空间劣势

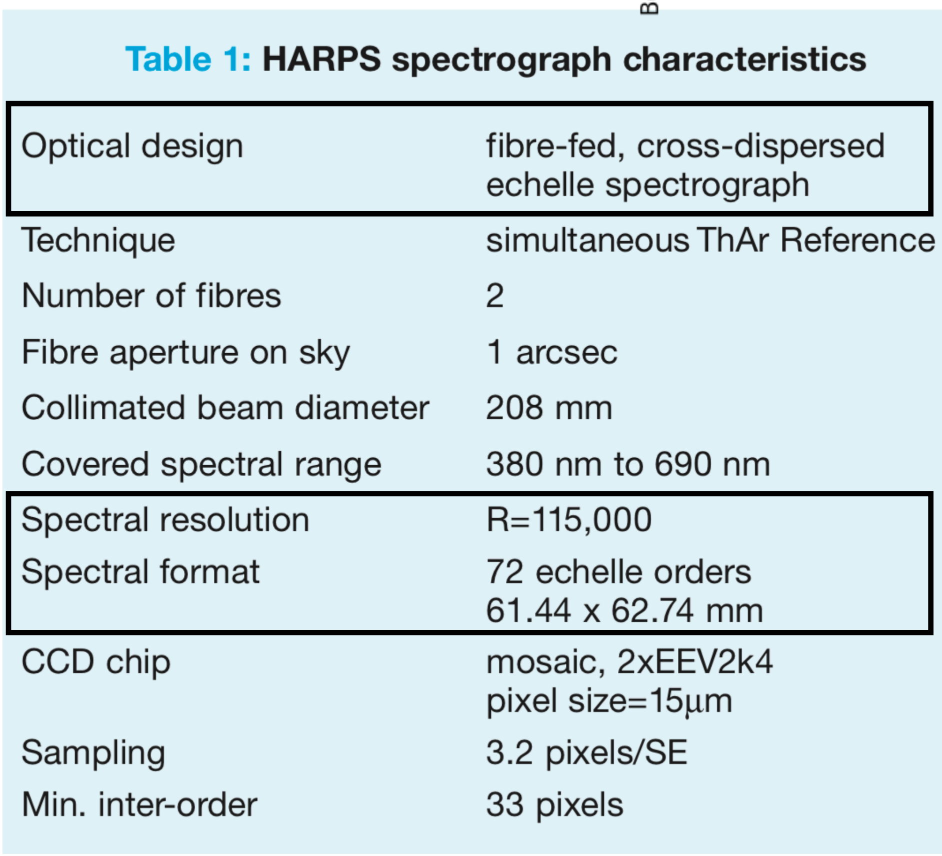
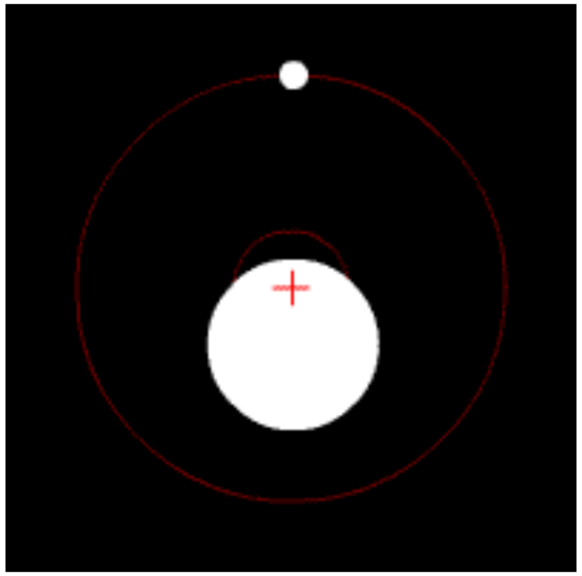


Table 1: HARPS spectrograph characteristics

Optical design	fibre-fed, cross-dispersed echelle spectrograph
Technique	simultaneous ThAr Reference
Number of fibres	2
Fibre aperture on sky	1 arcsec
Collimated beam diameter	208 mm
Covered spectral range	380 nm to 690 nm
Spectral resolution	R=115,000
Spectral format	72 echelle orders 61.44 x 62.74 mm
CCD chip	mosaic, 2xEEV2k4 pixel size=15µm
Sampling	3.2 pixels/SE
Min. inter-order	33 pixels

Astrometry
——古老的方法



- 18世纪~2009年：0颗
- 2010年10月：HD_176051 b Jovian planet
- ——Palomar Testbed Interferometer

- 精度要求：~0.05 mas precision

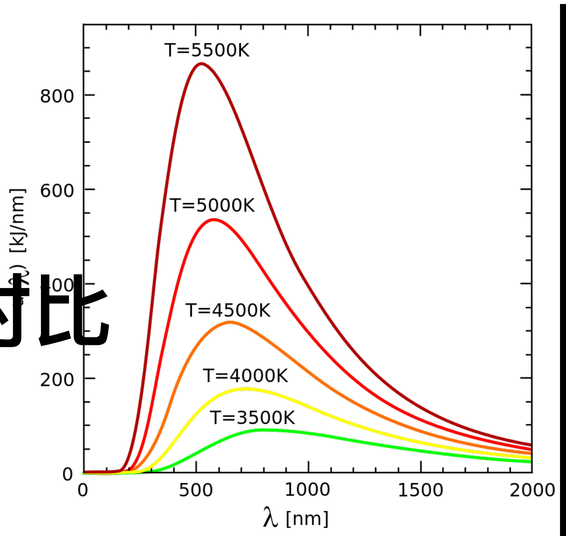
$$\begin{aligned}\Delta\theta_{\max} &= \left(\frac{M_P/M_S}{d}\right)\left(\frac{G(M_P+M_S)P^2}{4\pi^2}\right)^{1/3}\\ &\approx 0.5\ \mathrm{mas}\left(\frac{P}{12\ \mathrm{yr}}\right)^{2/3}\left(\frac{M_P}{M_{\mathrm{Jup}}}\right)\left(\frac{M_S}{M_{\mathrm{Sun}}}\right)^{-2/3}\left(\frac{d}{10\ \mathrm{pc}}\right)^{-1}\end{aligned}$$

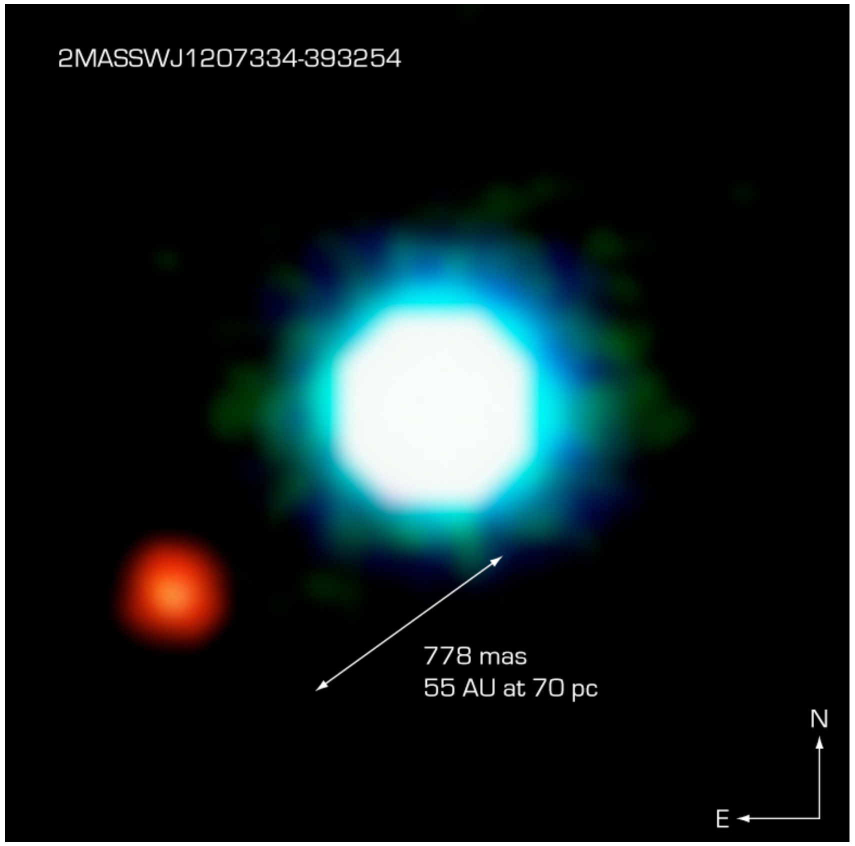
GAIA?

干涉?

- 优势：对长轨道行星敏感、精确的轨道参数、质量可知
- 劣势：大气未知、行星半径未知

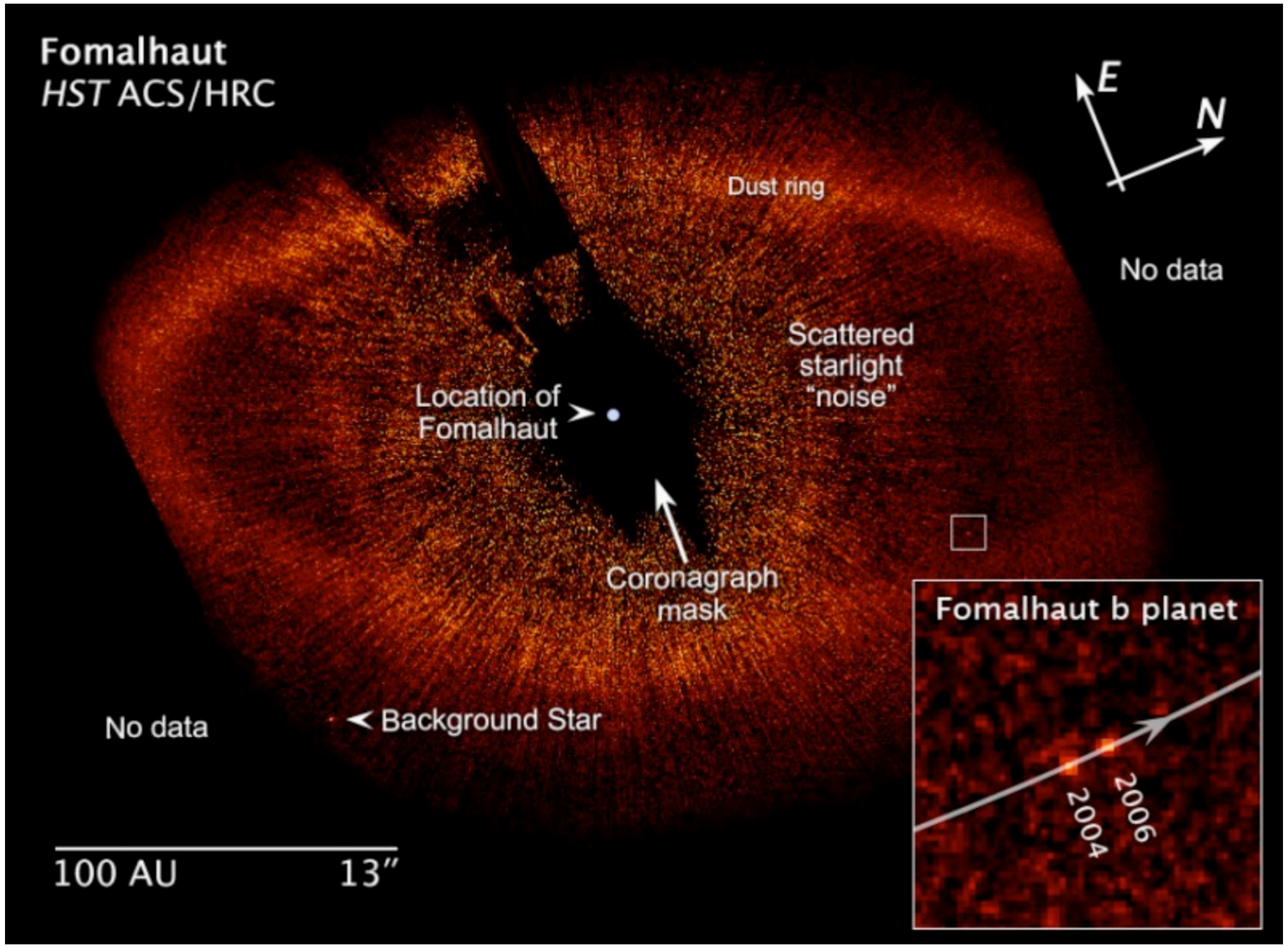
Imaging



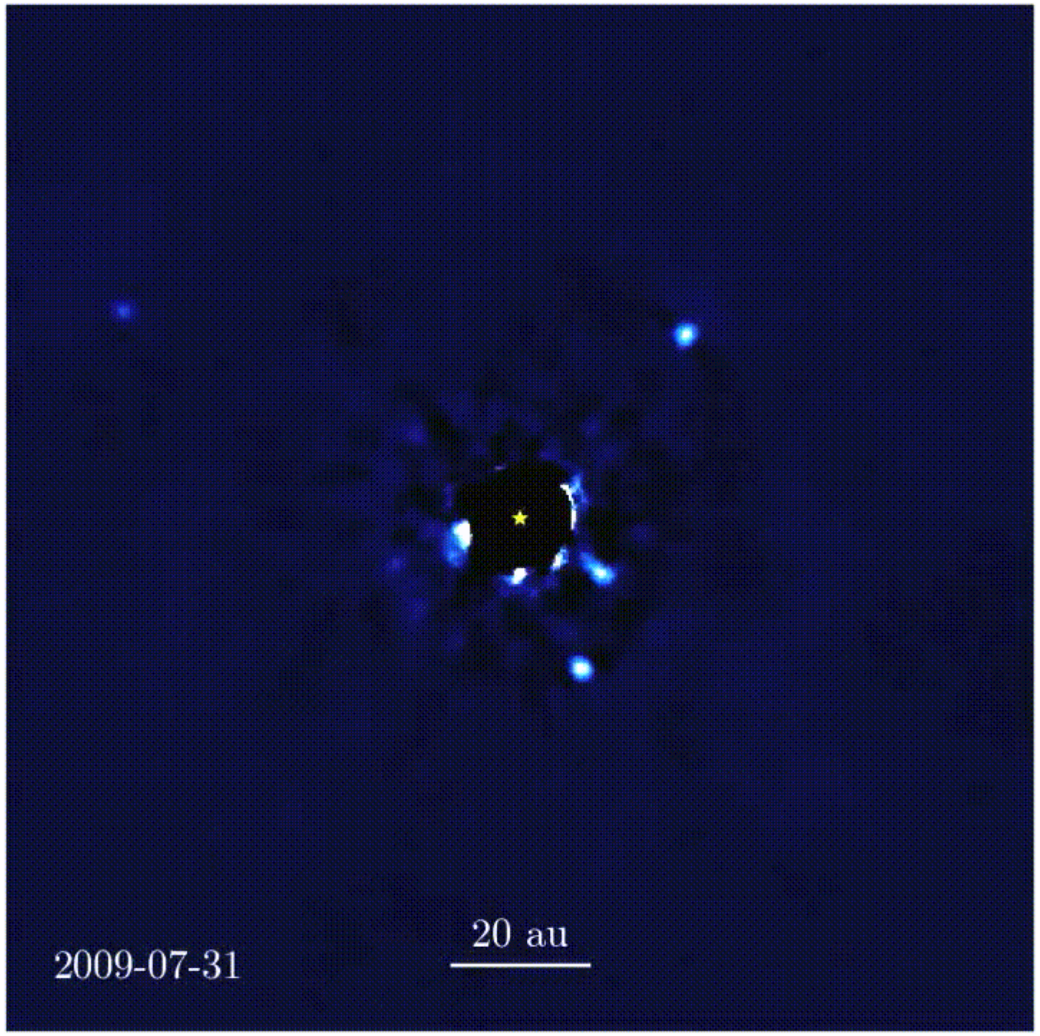


- 难点1：恒星和行星光度的极端对比
- 解决方法
  - 可见光、近红外 $L_{sun}/L_{Jupiter} = 10^8$
  - 中红外，空间！ $L_{sun}/L_{Jupiter} = 10^4$
  - 遮挡恒星，日冕仪

2M1207b， 2004年第一个成像法发现的系外行星



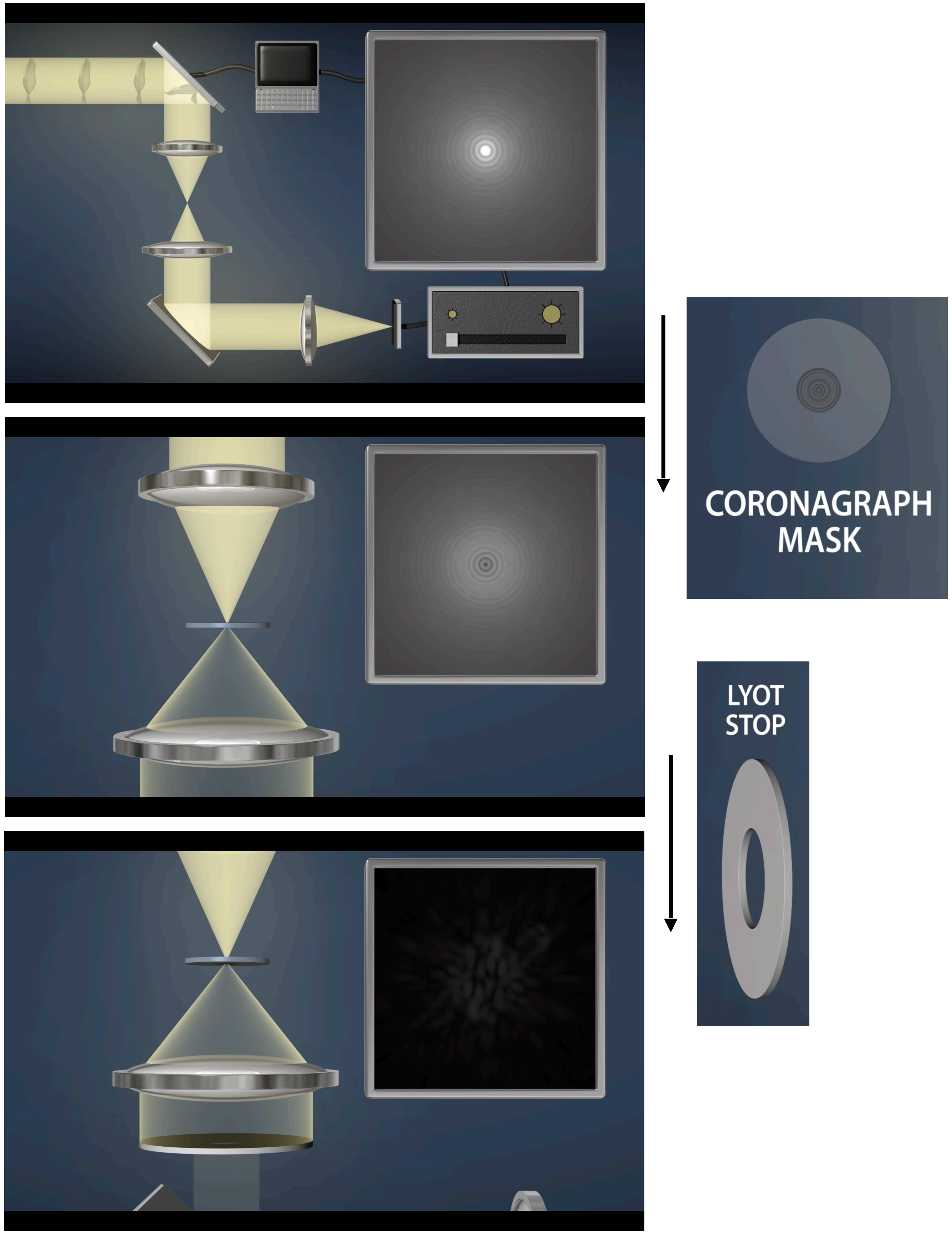
Fomalhautb, HST

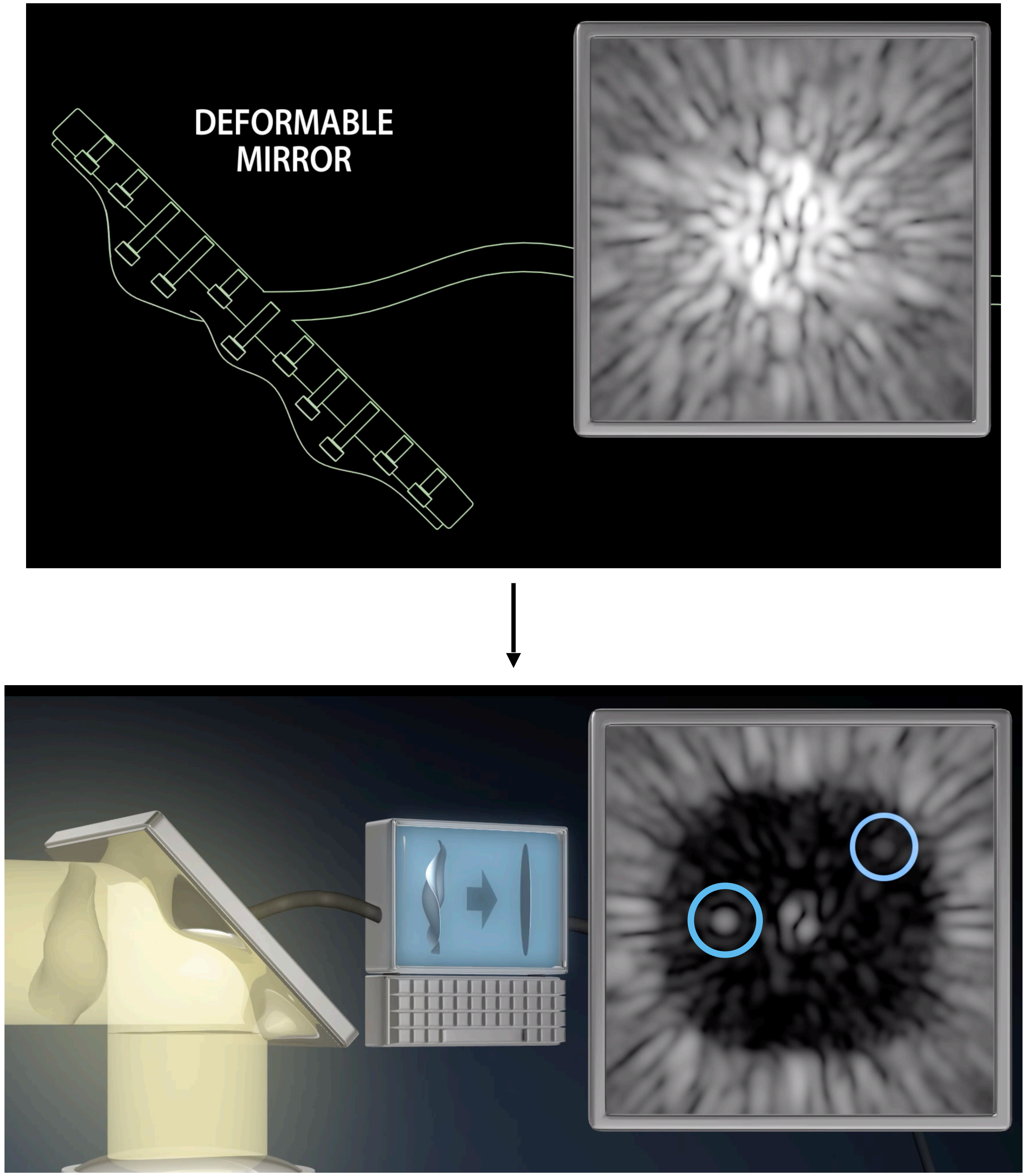


HR8799，Keck 近红外

Imaging

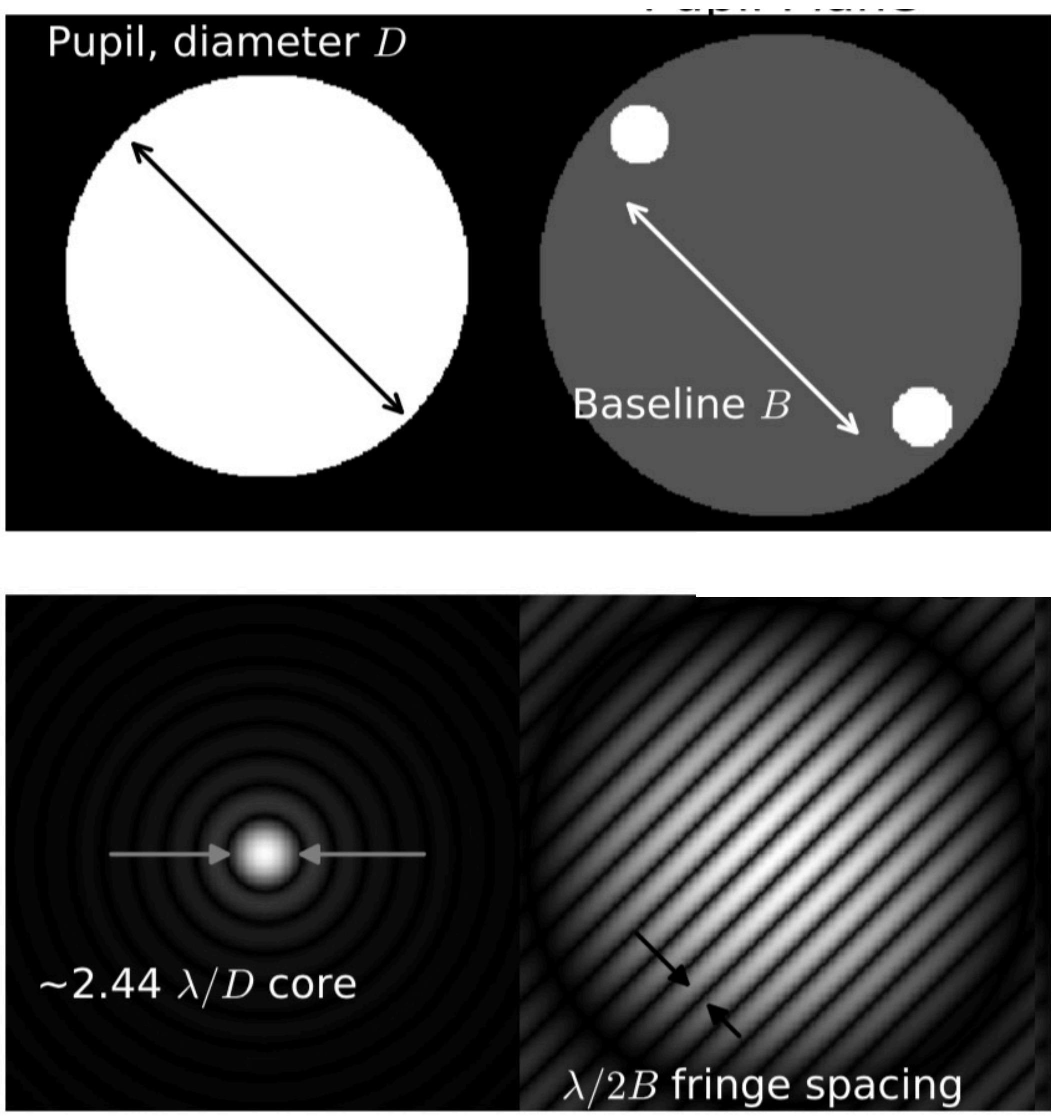
- 下一代空间望远镜 WFIRST 搭载的日冕仪

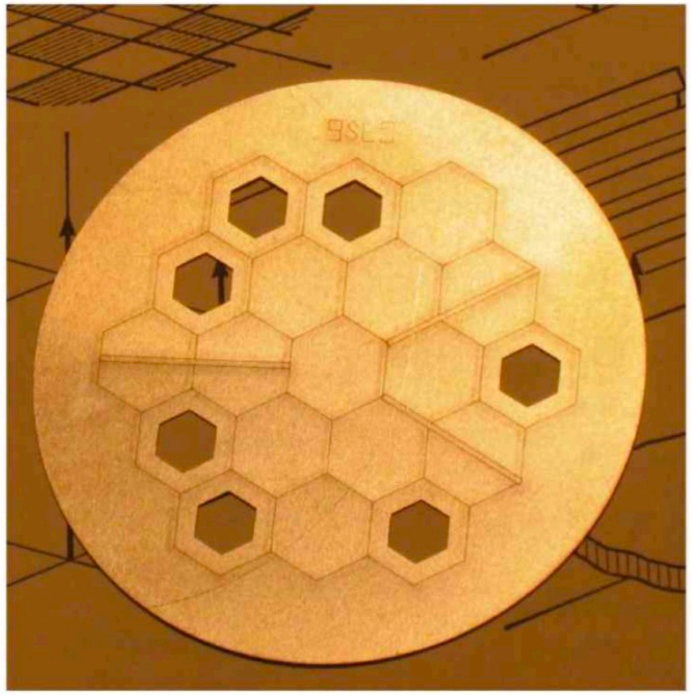




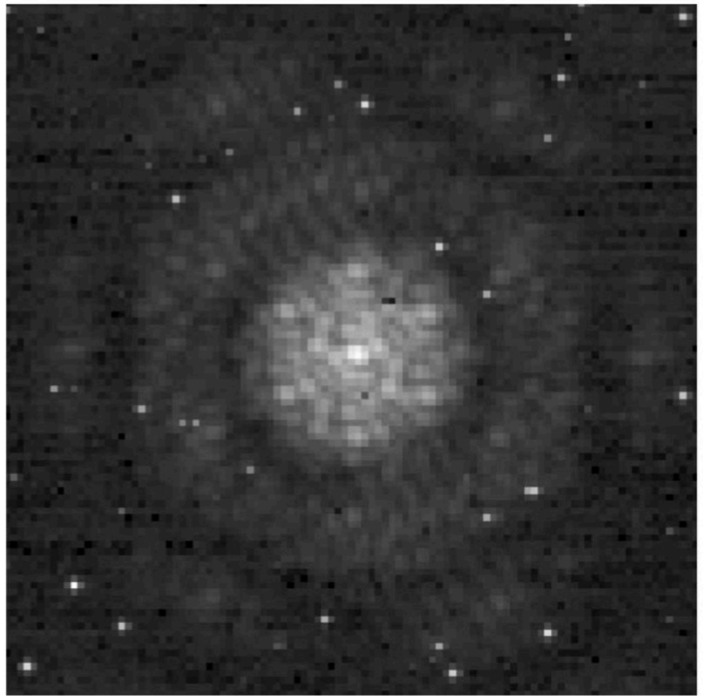
Imaging

- 难点2：分辨率
  - 衍射极限 — 空间X，地面 + 自适应光学
  - 干涉 — Aperture Masking Interferometry





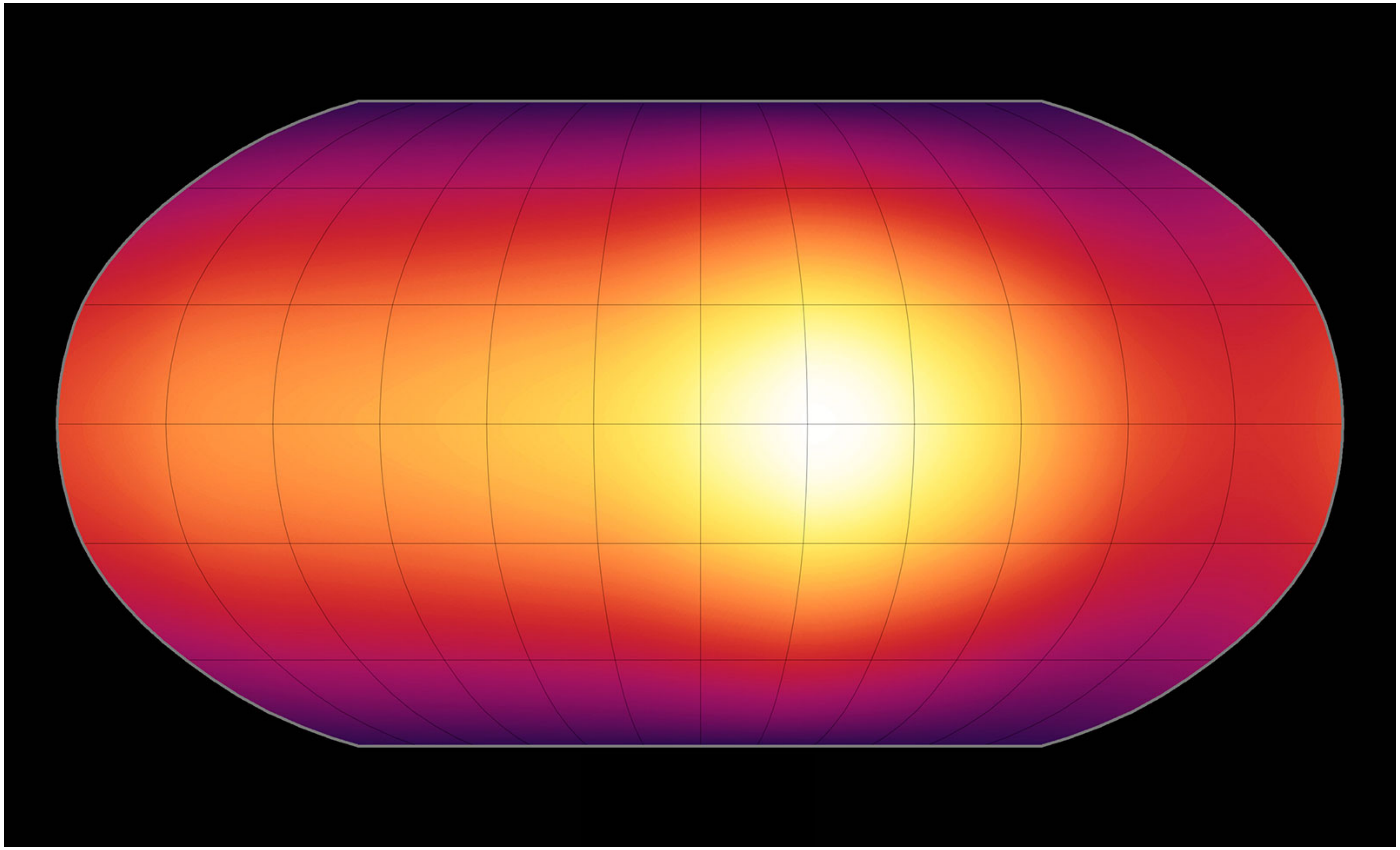
JWST mask



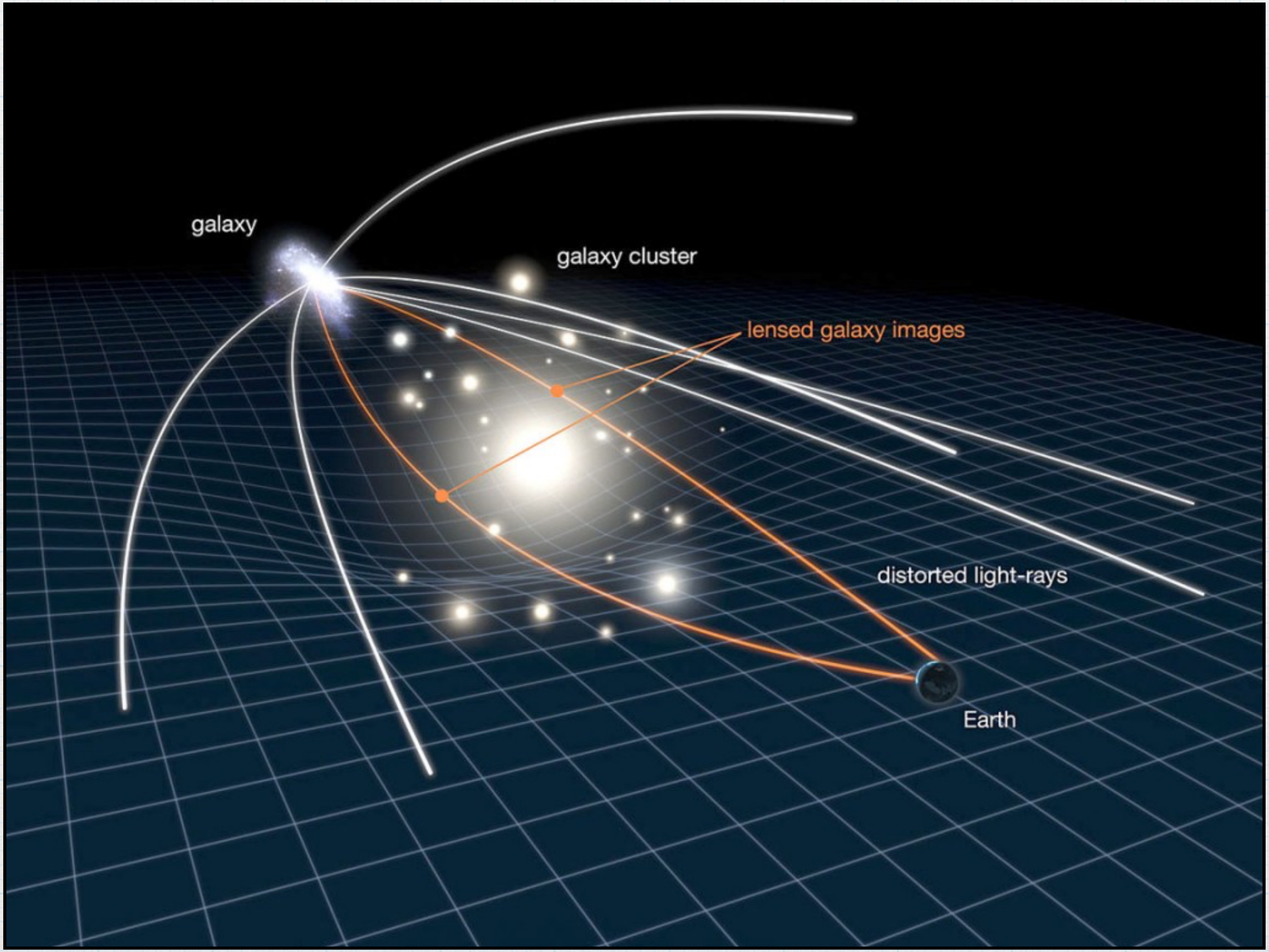
Imaging

望远镜	数量
Imaging 总计	45
Palomar Observatory	12
Gemini Observatory	8
W. M. Keck Observatory	8
Hubble Space Telescope	3
Spitzer Space Telescope	3
Subaru Telescope	3
...	...

- Spitzer　通过行星的红外光 – 测温度
- HD 189733b
  - 潮汐锁定
  - 黑暗/阳光 - 650°C/930°C
  - 强风 - 9600 km/h

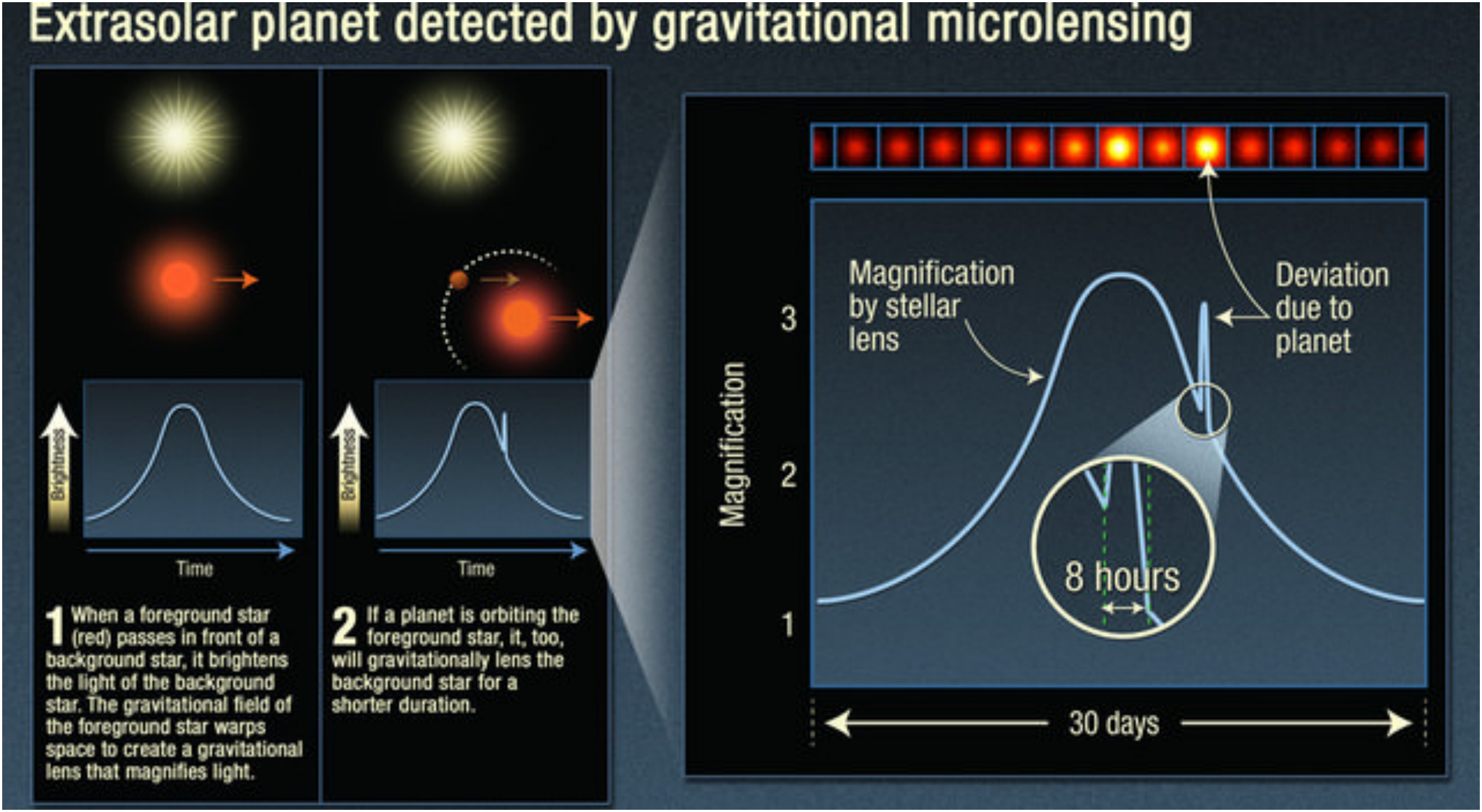


Microlensing



Microlensing

- 原理



Extrasolar planet detected by gravitational microlensing

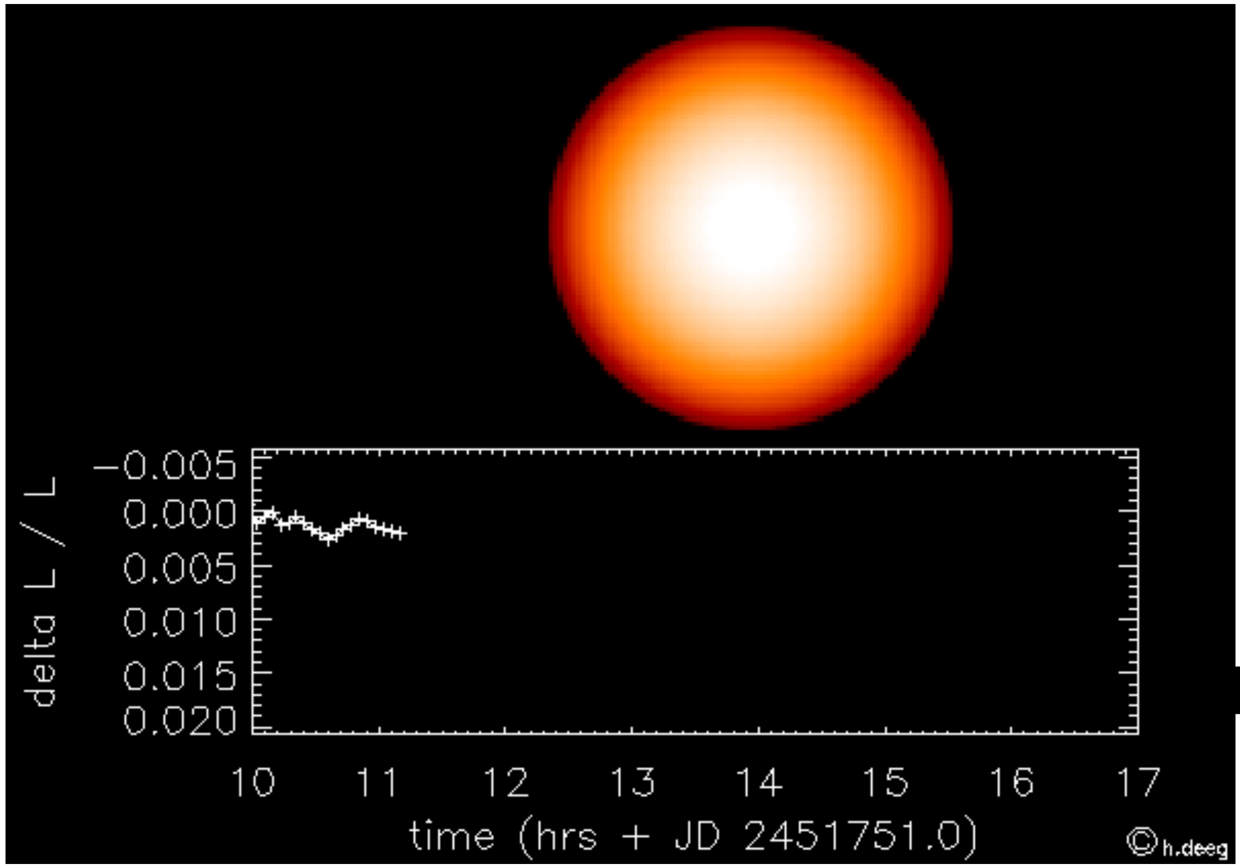
1 When a foreground star (red) passes in front of a background star, it brightens the light of the background star. The gravitational field of the foreground star warps space to create a gravitational lens that magnifies light.

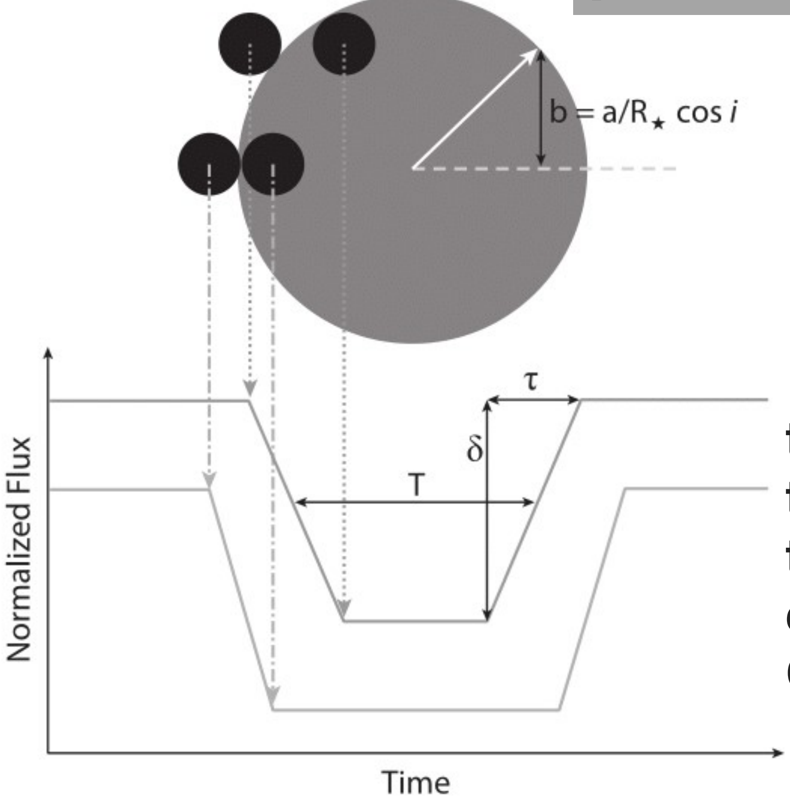
2 If a planet is orbiting the foreground star, it, too, will gravitationally lens the background star for a shorter duration.

A sketch of a microlensing signature with a planet in the lens system. Image Credit: NASA / ESA / K. Sahu / STScI

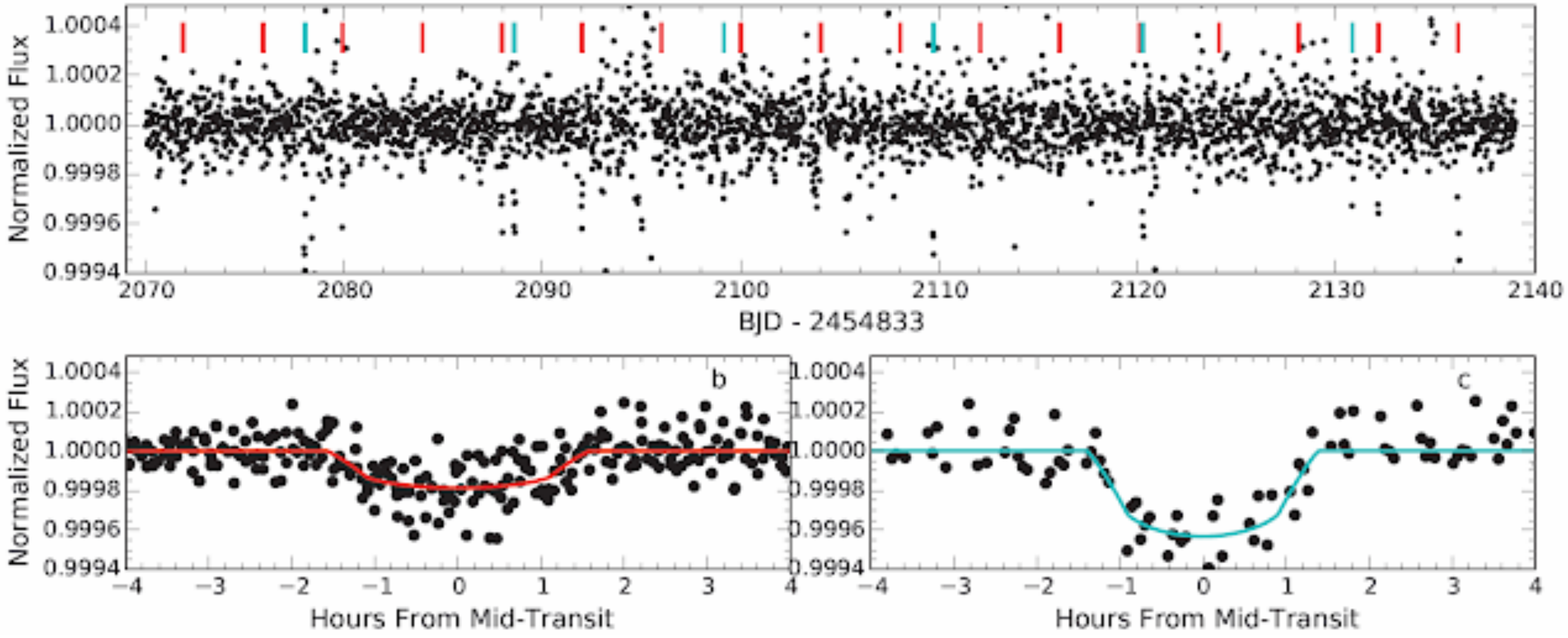
Transit

Assumption：The planets and stars are spherical; The orbit is perfect circle





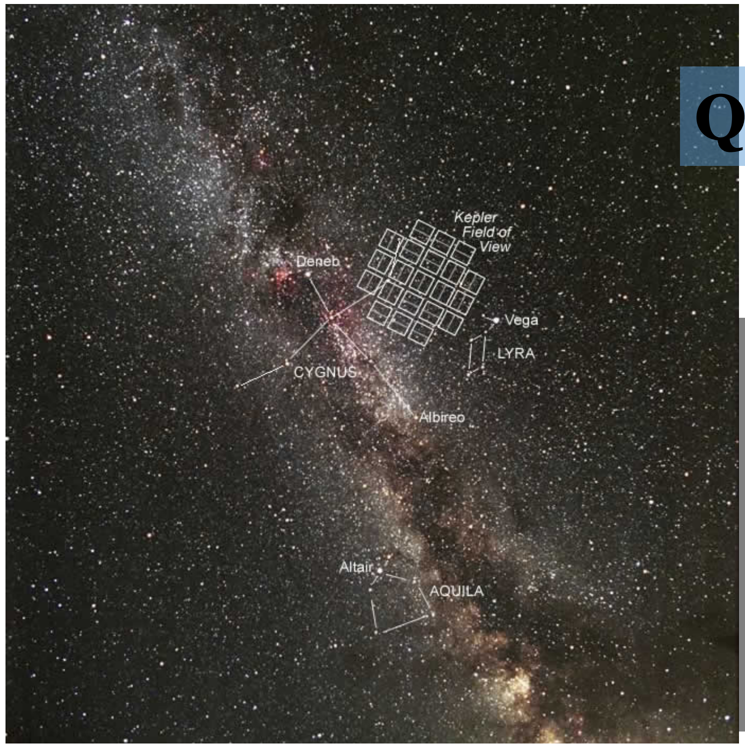
transit depth (δ)
transit duration (T),
the ingress/egress duration (τ),
Orbital period(P)



Semi-major axis, stellar mass, stellar radius, planetary radius, eccentricity, inclination ~~, planetary mass~~

Transit——Kepler

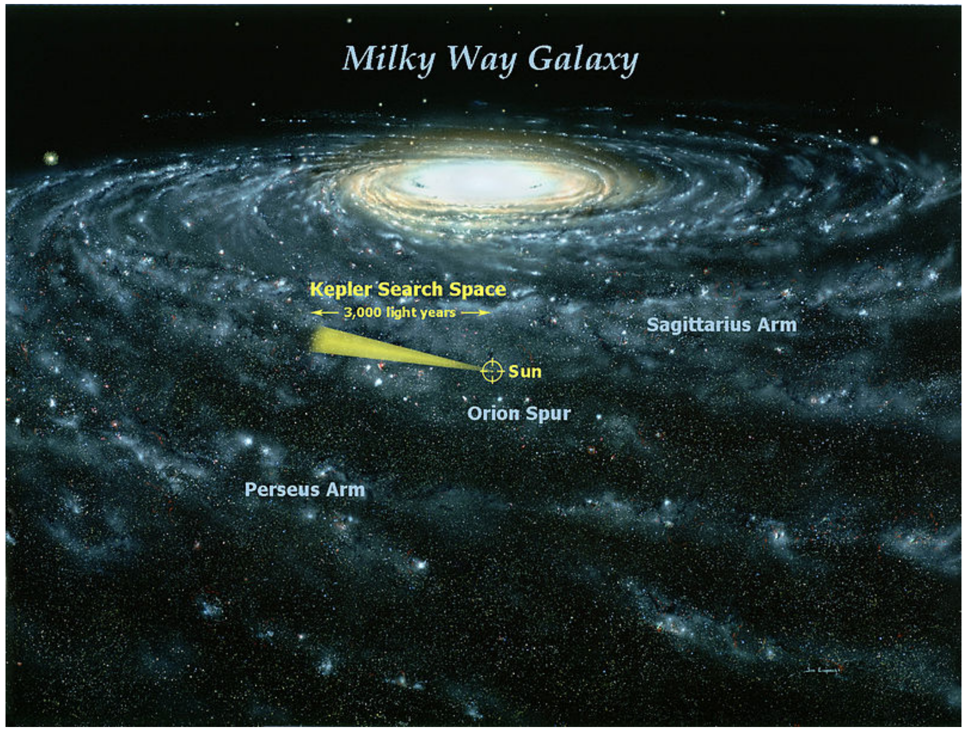
Observing strategy：



Quarterly rolls

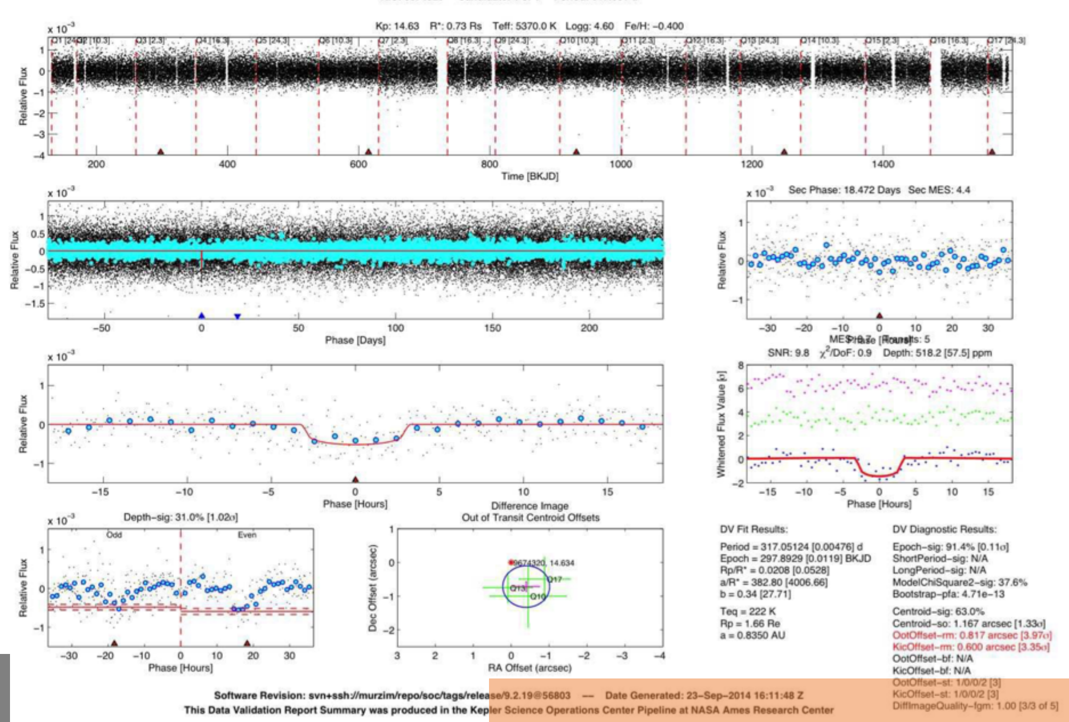
- 115 square degree
- 0.25% full sky
- 400 Kepler can cover the whole sky

https://www.jpl.nasa.gov/news/press_kits/Kepler-presskit-2-19-smfile.pdf



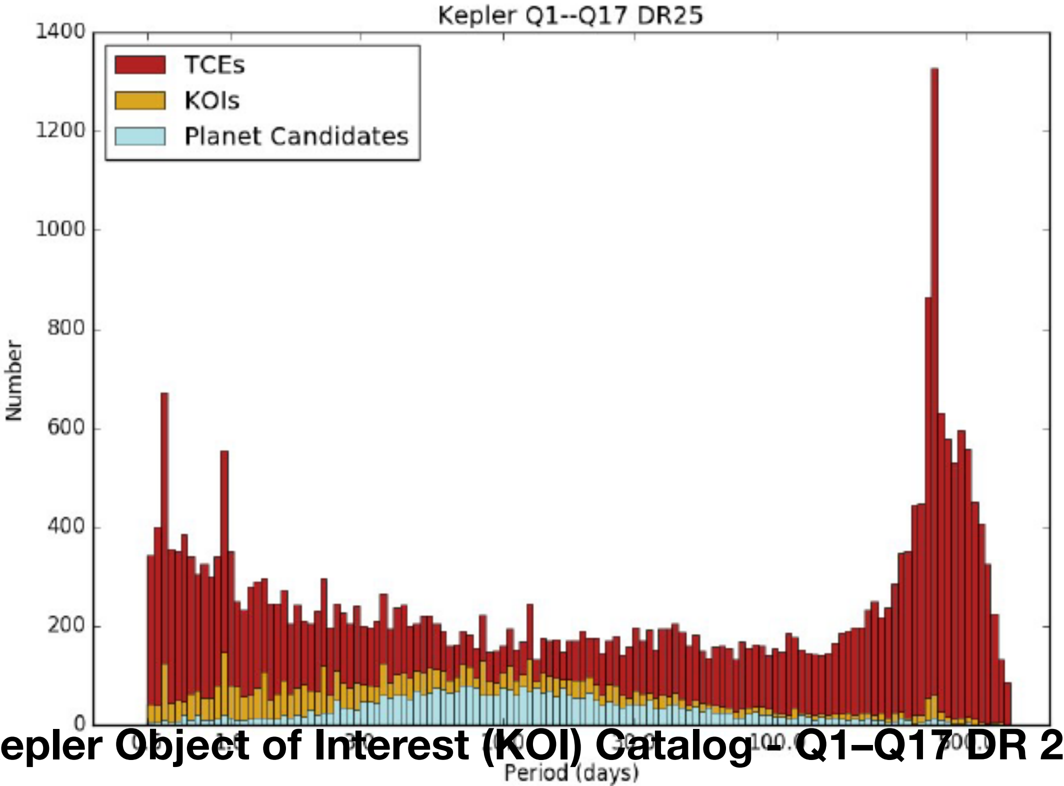
http://kepler.nasa.gov/images/LombergA1600-full.jpeg

Pipeline：



≥3 transits！

Pixels → TCEs → KOIs
→planet candidates
→confirmed planets

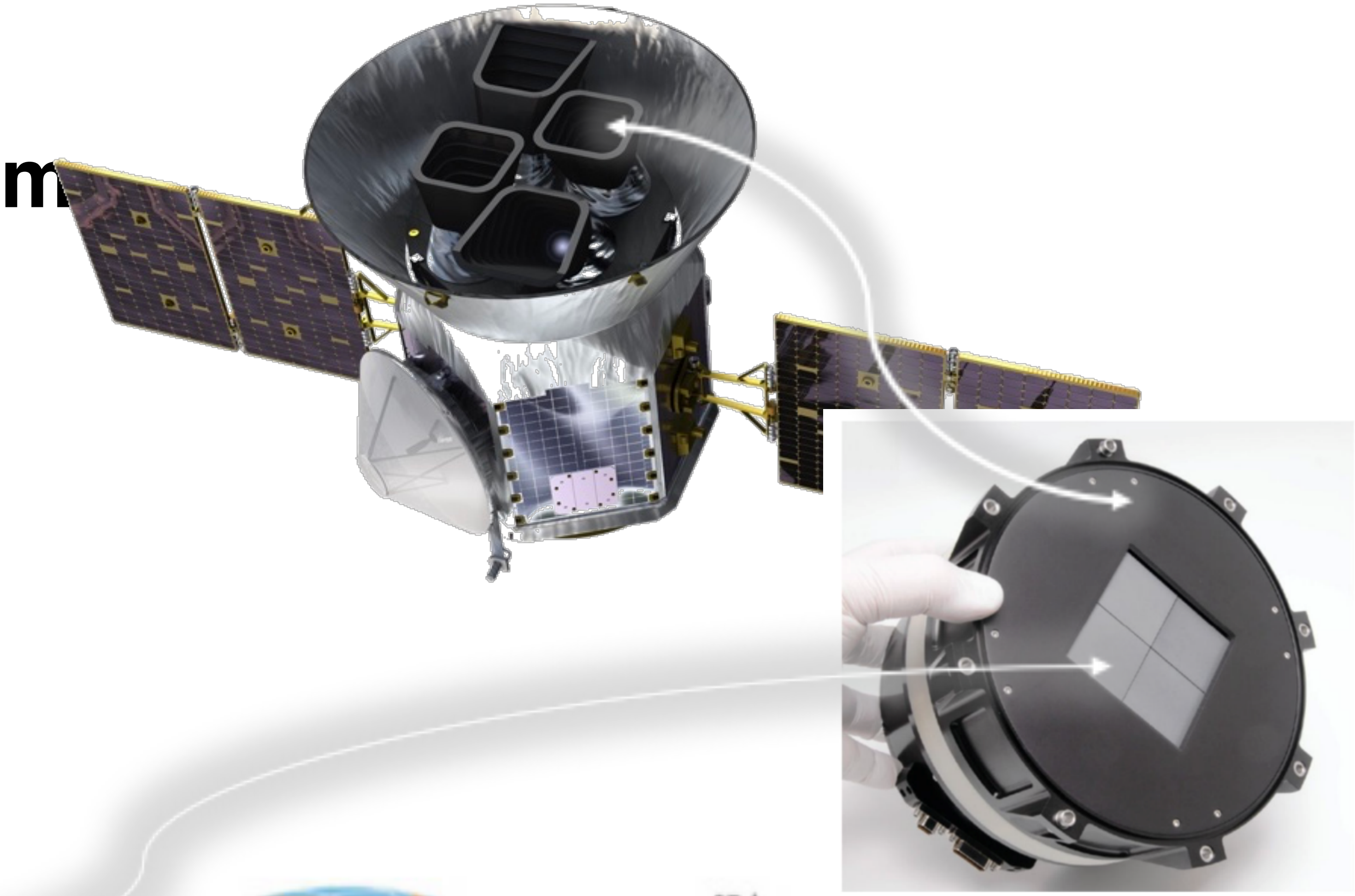


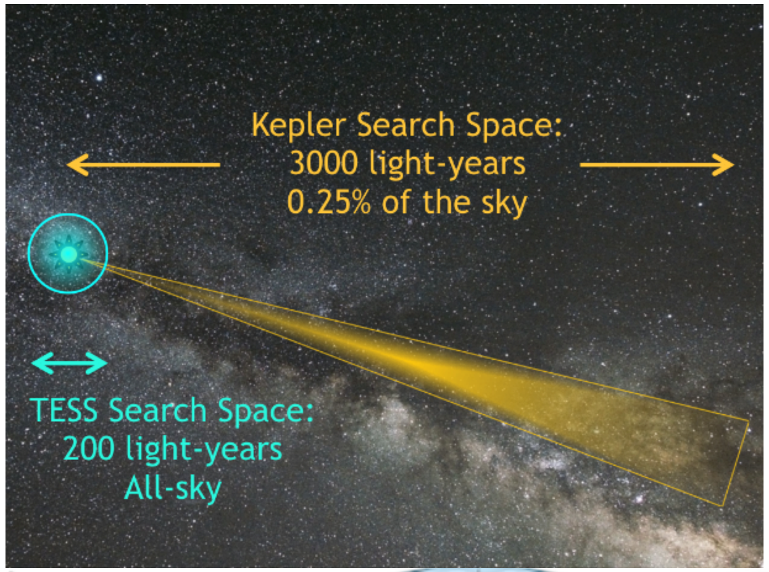
Kepler Object of Interest (KOI) Catalog - Q1–Q17 DR 25

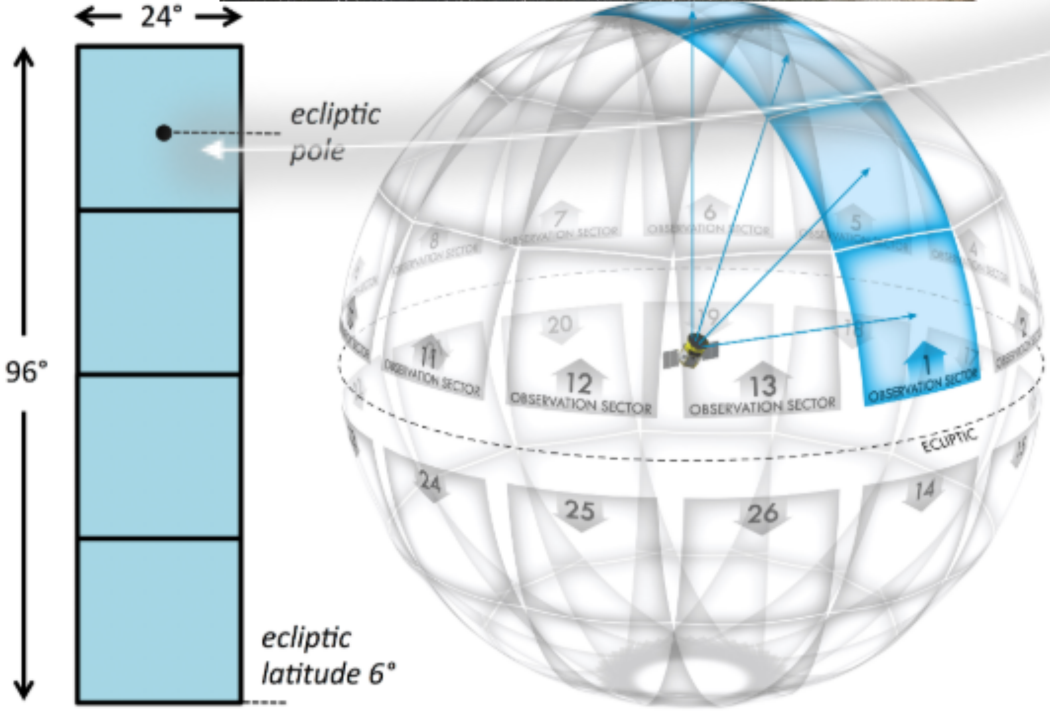
Transit——TESS

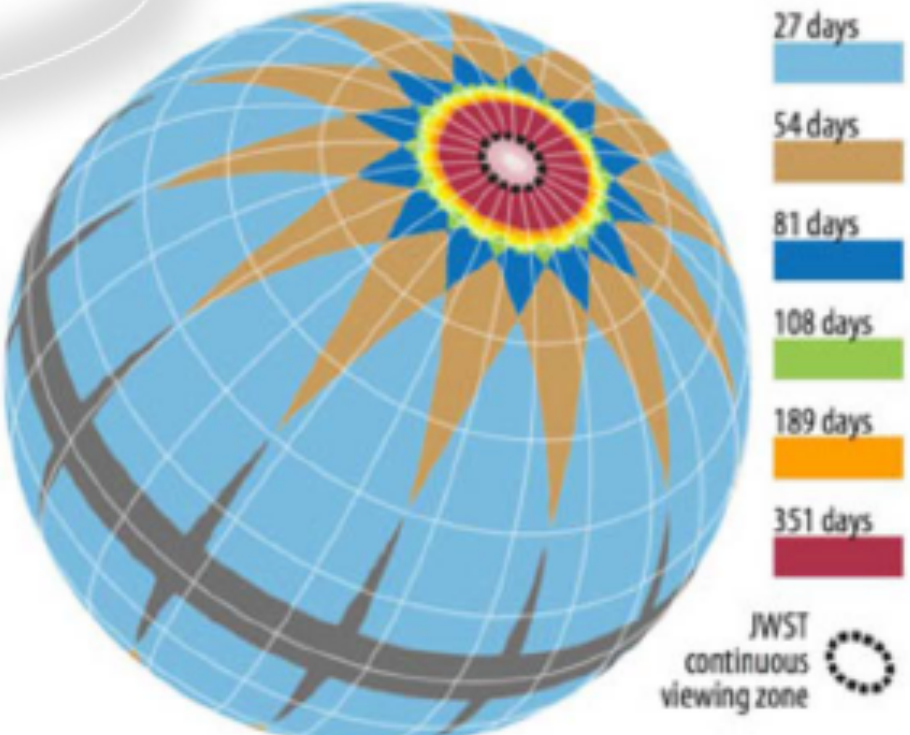
Launched April 18, 2018
Started science operations July 25, 2018

- **10 cm aperture**
- **Bandpass: 600 - 1100 nm**
- **13.7-day elliptical orbit**









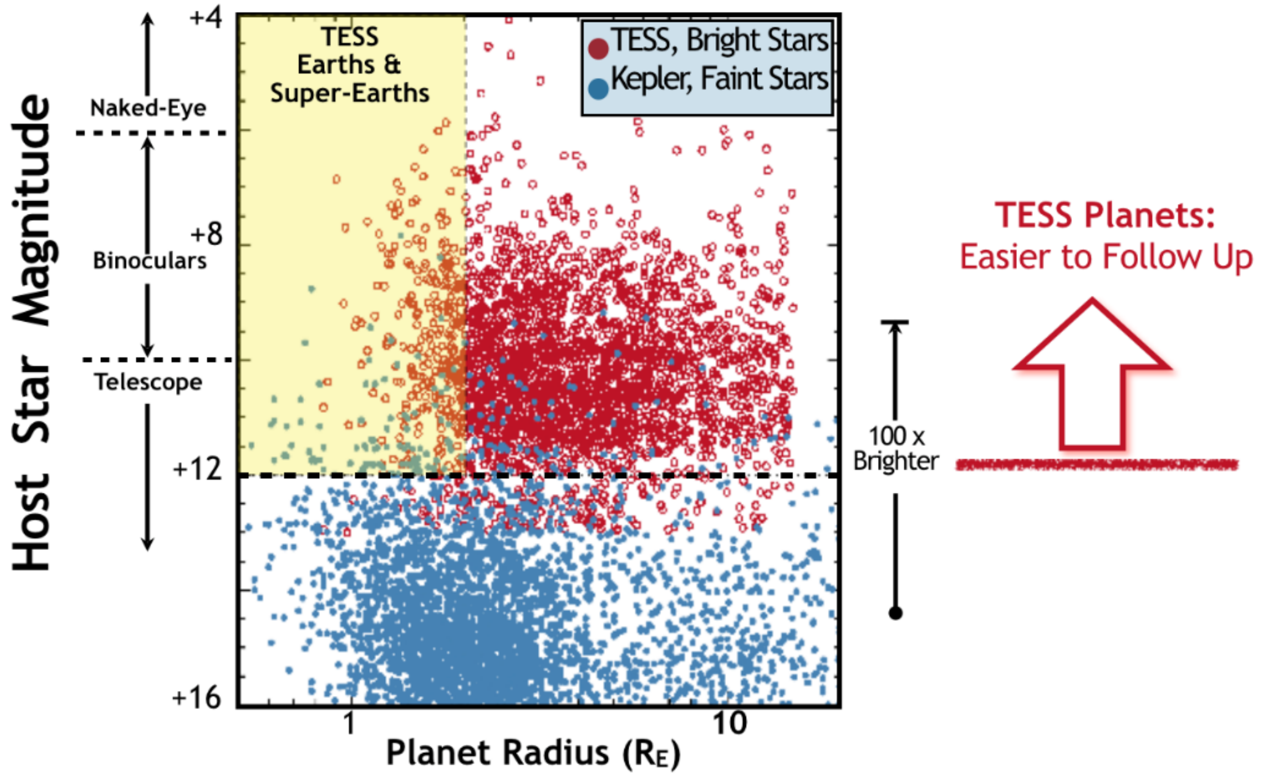
短周期、
近轨道行星

https://heasarc.gsfc.nasa.gov/docs/tess/primary-science.html

Transit——TESS

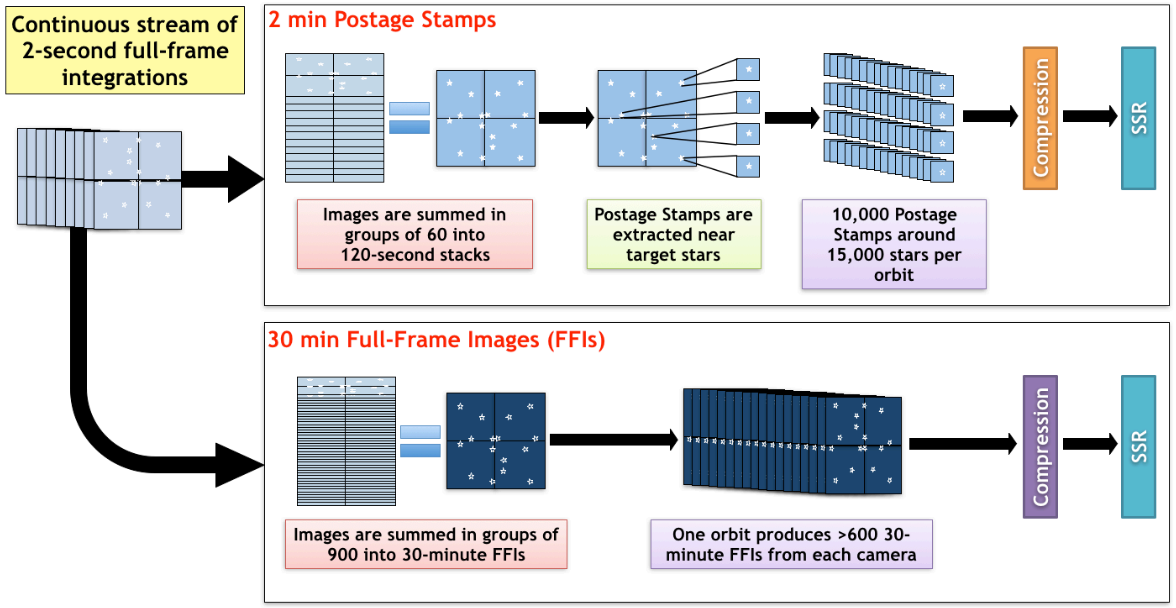
Science Goal： Bright!

- Improve statistics for studies of the mass-radius relation of small planets as a function of distance from host stars.
- More temperate planets among which to select the best for atmospheric characterization with the JWST/ELTs
- ……



TESS Will Discover Earths & Super-Earths Orbiting Bright Stars

Image Credit: MIT



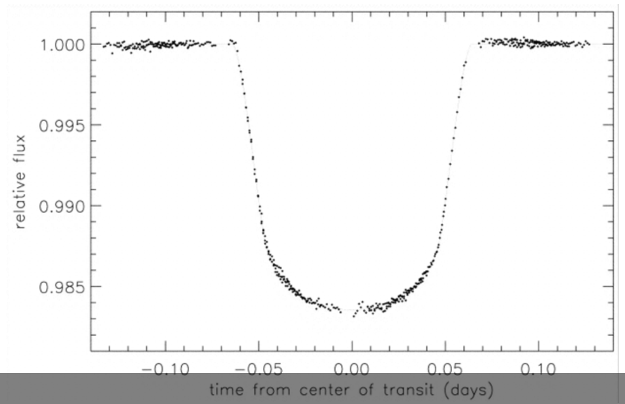
Villanueva, Dragomir & Gaudi (2019)

Transit——TESS

Single Transit

Stellar density
Eccentric

+



=

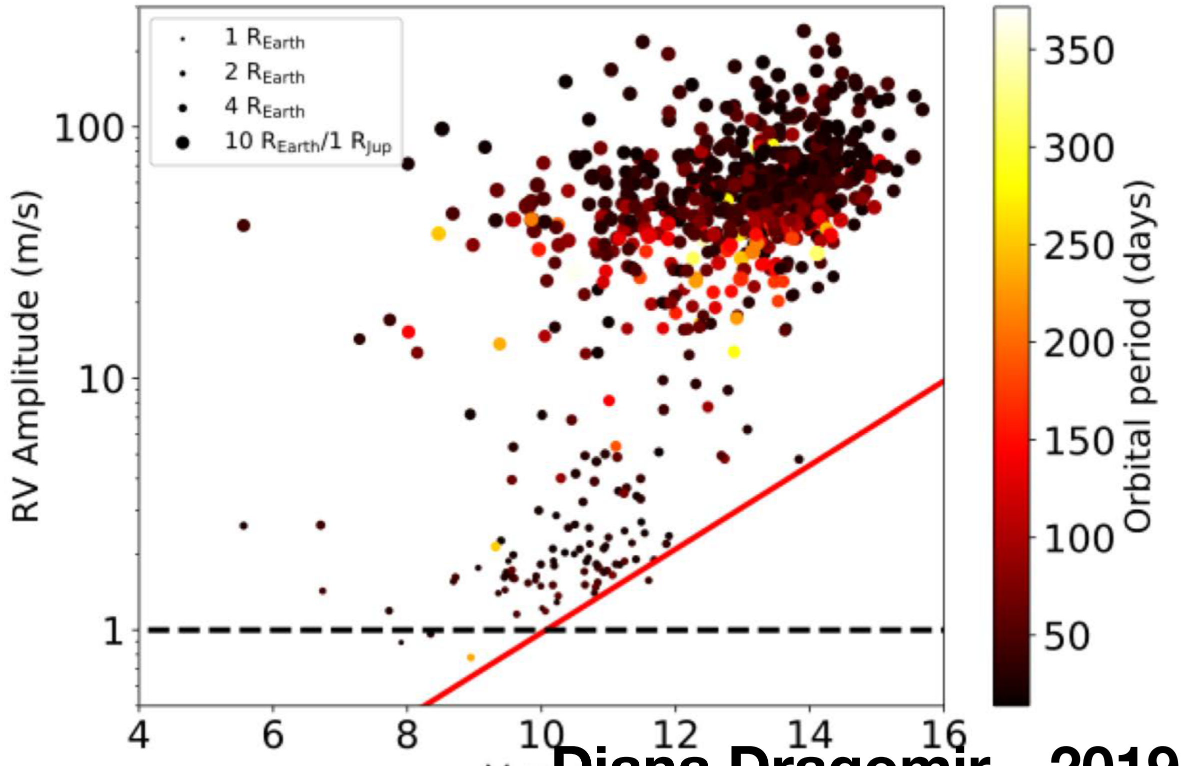
Orbital Period

Density: Gaia (Raidus) and spectroscopy/ asteroseismology (spectroscopy).
Eccentricity： prior from known distribution).

Seager & Mallén-Ornelas (2003)
Yee & Gaudi (2008)

Radial Velocity Prospects for Single-Transit Planets

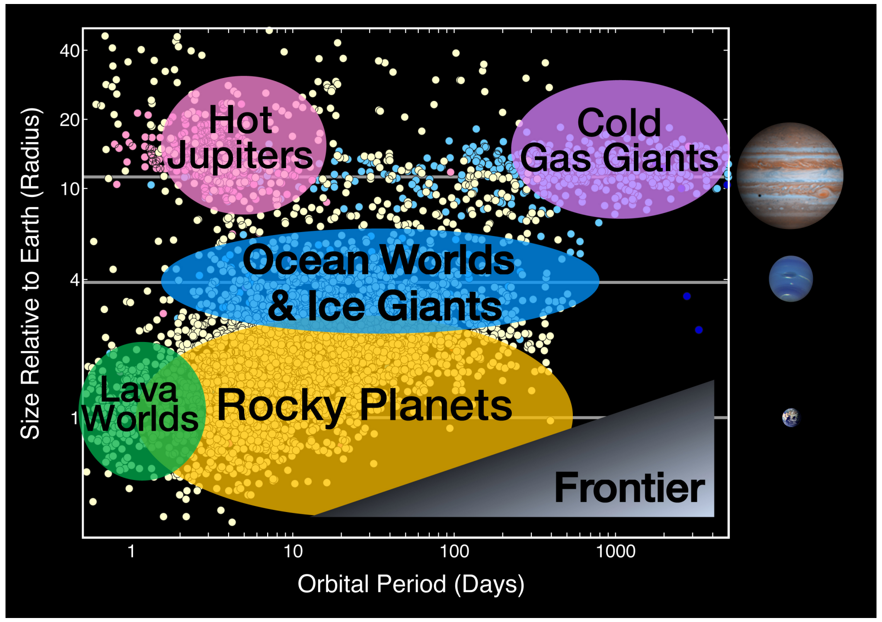
- If period constrained well enough
  → get photometry to catch next transit
- Not well enough
  → use RV measurements to improve constraint

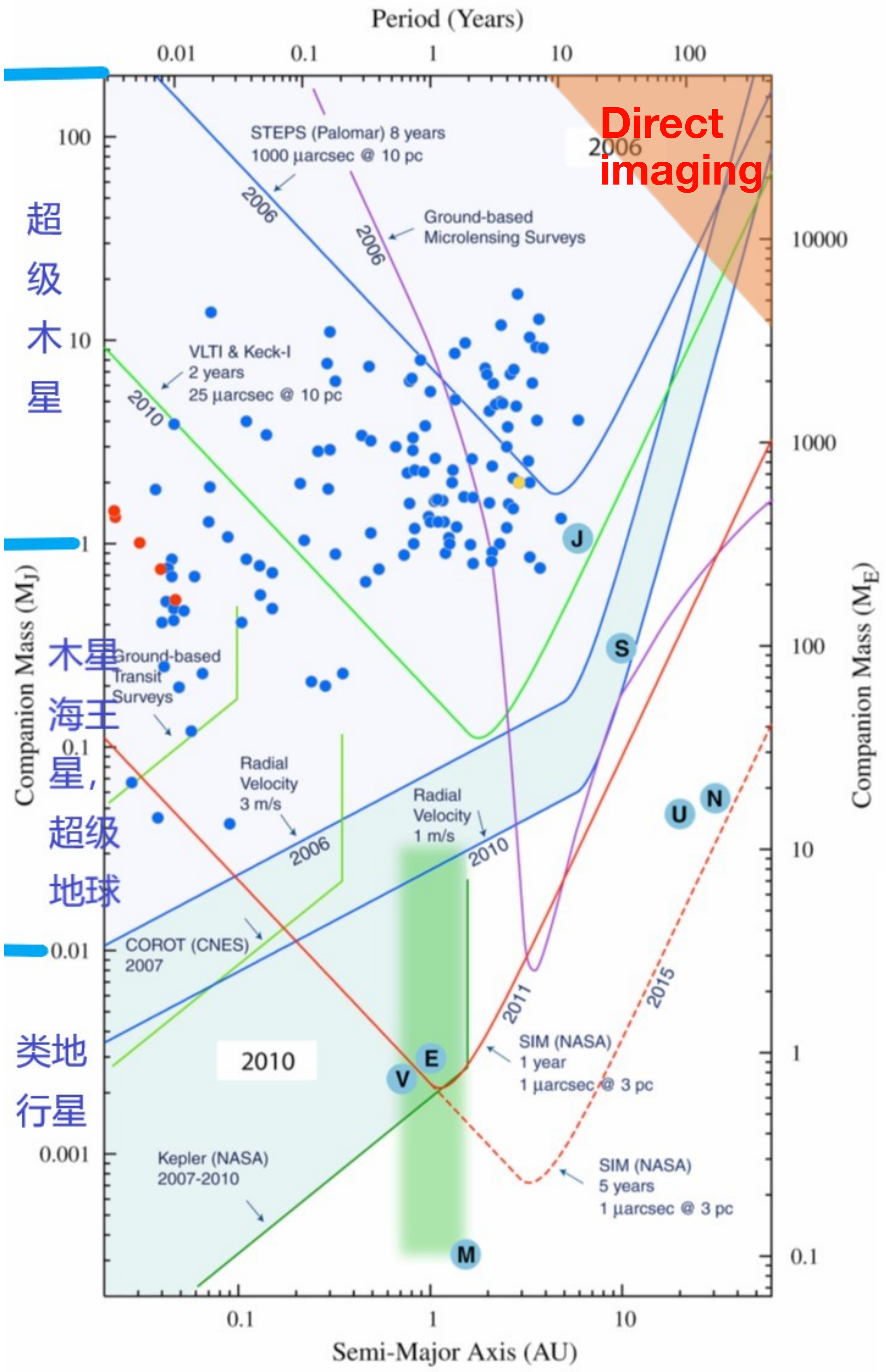


Diana Dragomir, 2019

Detection Method and Statistic

- habitable zone(green area)
- ~150 exoplanets detected in 2004
- – r.v. (blue)
  – transits (red)
  – microlensing (yellow)
  – pulsar timing (purple)
  – Imaging(magenta)





Our Project

- **Empirical Predictions for the Period Distribution of Planets to be Discovered by TESS**

Previous work：

Incomplete data

Data Recovery

Occurrence rate of exoplanets

Simulation considering the selection effect

Distribution for TESS

My work：

Data of Kepler

Comparing the selection effect between two missions

Data of TESS

Methodology

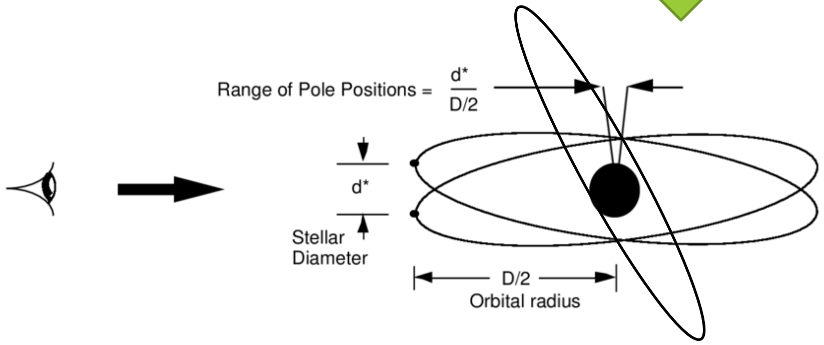
The probability that an exoplanet of which orbital period is P days is detected by TESS

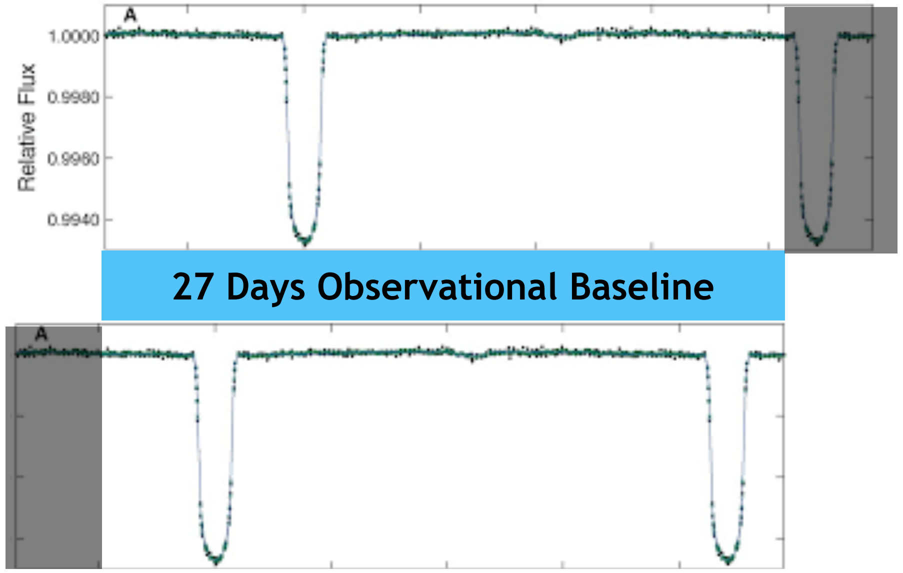
The occurrence rate of an exoplanet of which orbital period is P days

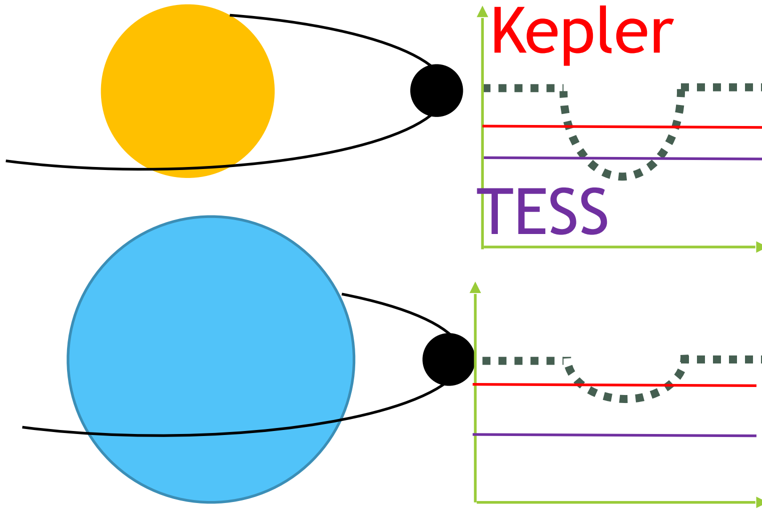
$$Prob\left(P, R_p \middle| TESS\right) = \frac{Prob\left(TESS \middle| P, R_p\right) * Prob\left(P, R_p\right)}{Prob(TESS)}$$

constant

$$\boxed{\Pr ob(TESS \mid P, R_p) = \Pr ob(Tr \mid P, R_p) \times \Pr ob(NTr(\tau_1) \mid Tr, P, R_p) \times \Pr ob(SNR\_T \mid NTr(\tau_1), Tr, P, R_p)}$$







Methodology

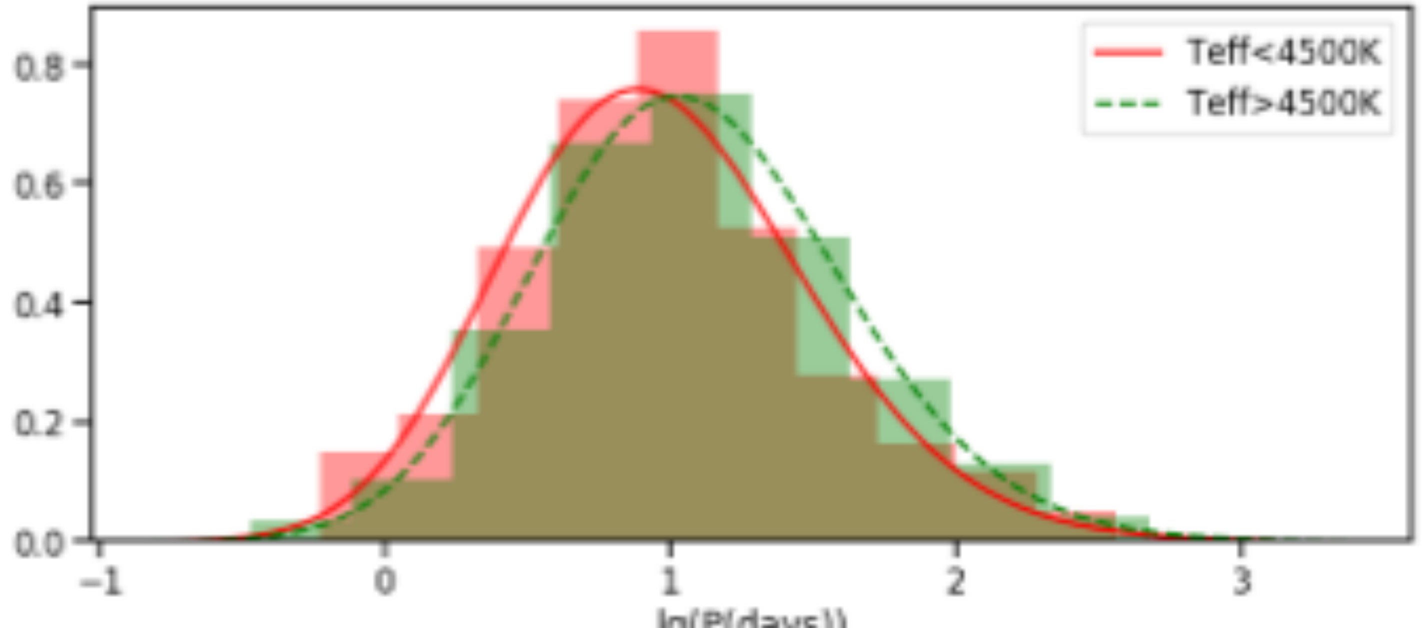
TESS : CTL
(dwarfs and subgiants)

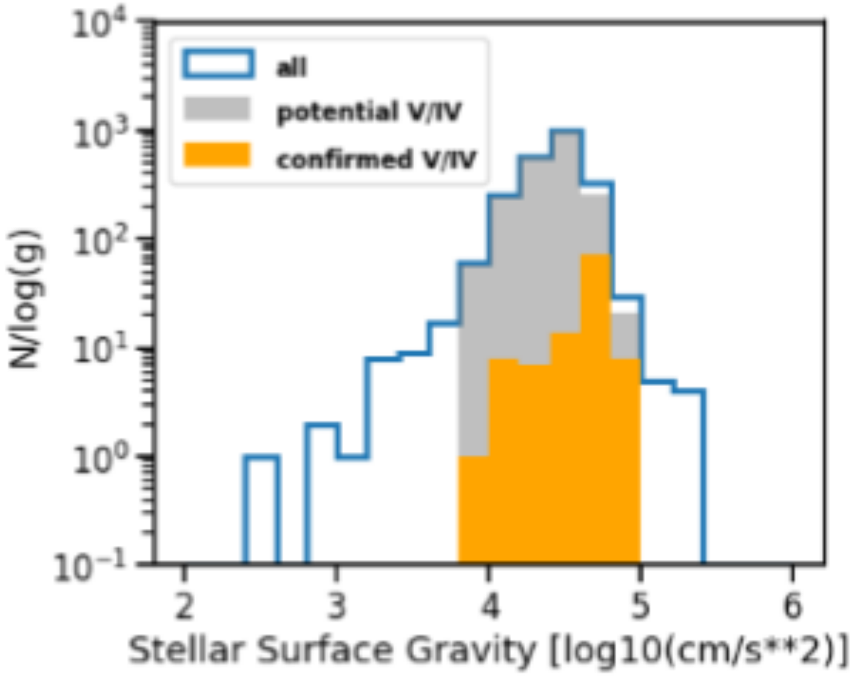
Input Catalogue

$$\mathrm{Prob}(P|TESS) = \frac{\mathrm{Prob}(tr|P) \cdot \mathrm{Prob}(Ntrs_T|P,tr) \cdot \mathrm{Prob}(\mathrm{SNR}_T > \mathrm{SNRT}_{min}|P,tr,Ntrs_T) \boxed{\cdot \mathrm{Prob}(P)}}{\mathrm{Prob}(TESS)}$$

Likewise, repeat the above analysis but for Kepler:

$$\mathrm{Prob}(P|Kepler) = \frac{\mathrm{Prob}(tr|P) \cdot \mathrm{Prob}(Ntrs_K|P,tr) \cdot \mathrm{Prob}(\mathrm{SNR}_K > \mathrm{SNR}K_{min}|P,tr,Ntrs_K) \boxed{\cdot \mathrm{Prob}(P)}}{\mathrm{Prob}(Kepler)}$$





Methodology

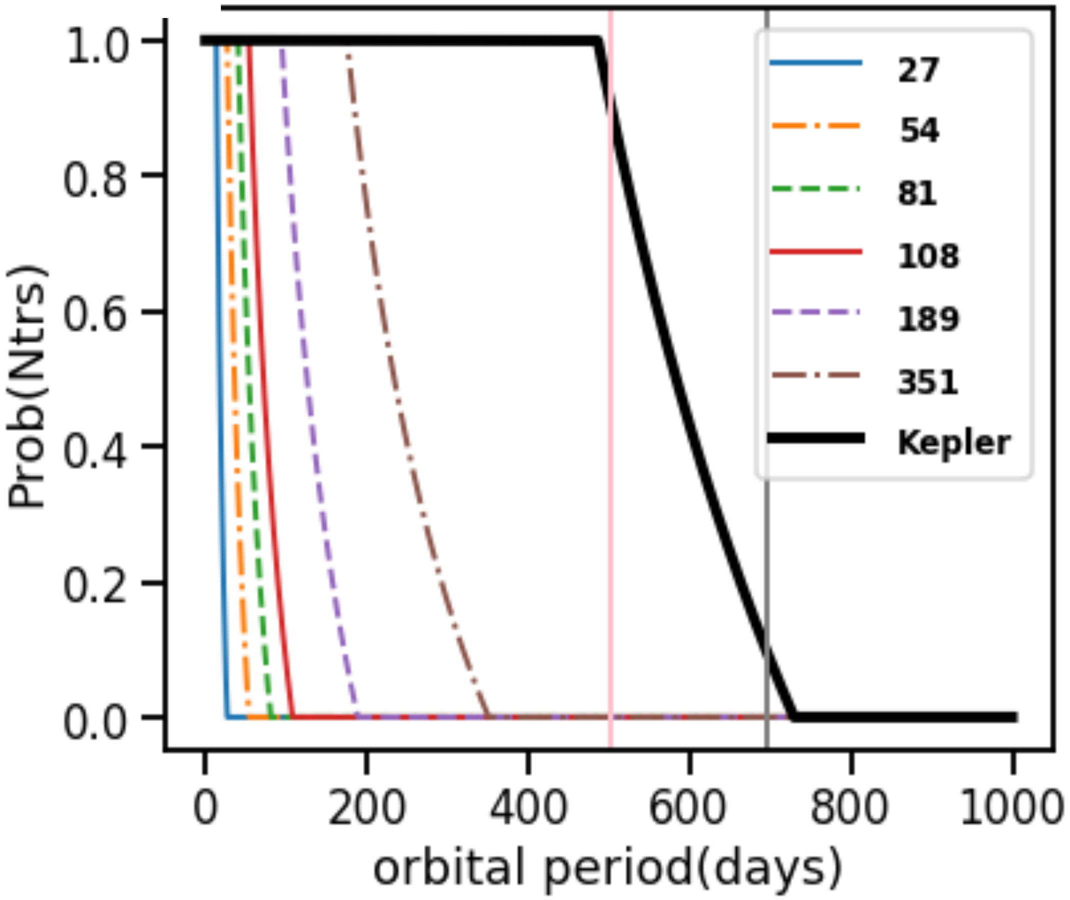
The gray vertical line is 694.76 days beyond which the probability that it can be detected by Kepler is less than 10% and the pink vertical line is 503.10 days within which the probability is higher than 90%

1. Prob (tr|P)

$$\text{Prob}\,(tr|P) = \int \frac{R_*}{a} f_{R_*,a|P}(R_*, a)\, dR_*\, da = \int \left(\frac{4\pi^2}{G}\right)^{\frac{1}{3}} R_* M_*^{-\frac{1}{3}} P^{-\frac{2}{3}} f_{R_*,M_*,|P}(R_*, M_*)\, dR_*\, dM_*$$

2. $\mathrm{Prob}(2Tr(\tau_1)\,|\,Tr, P)$

$$\text{Prob}\,(Ntrs_T|P, tr) = \begin{cases} 0, & t \le (N-1)P \\ \frac{t-(N-1)\cdot P}{P}, & (N-1)P < t < NP \\ 1, & t \ge N \cdot P \end{cases}$$



↓

$$\mathbf{Prob}_i\left(P\middle|TESS\right) = c_i\mathbf{Prob}_i(P|\,Kepler)\frac{\mathbf{Prob}_i\left(Ntrs_T\middle|P, tr\right) \bullet \mathbf{Prob}_i\left(\mathbf{SNR}_T > \mathbf{SNRT}_{min}\middle|P, tr, Ntrs_T\right)}{\mathbf{Prob}_i\left(Ntrs_K\middle|P, tr\right) \bullet \mathbf{Prob}_i\left(\mathbf{SNR}_K > \mathbf{SNRK}_{min}\middle|P, tr, Ntrs_K\right)}$$

Methodology

3. $\mathbf{Prob}(\boldsymbol{SNR\_T} | \boldsymbol{2Tr(\tau_1), Tr, P})$

$$\mathrm{SNR} = R_p^2 P^{-\frac{1}{3}} \left(\frac{4\pi^2}{GM_*} \right)^{\frac{1}{6}} \sqrt{\frac{At_m}{4R_* r^2} \int_{\lambda_1}^{\lambda_2} \tau\pi B\left(\lambda, T_*\right) \left(\frac{\lambda}{hc} \right) d\lambda},$$

$$\mathrm{SNR} = \mathrm{f}(\mathbb{P})\mathrm{g}(\mathbb{S})\mathrm{h}\left(\mathbb{M},\ \mathbf{T}_*\right)$$

$$\mathrm{f}(\mathbb{P}) = R_p^2 P^{-\frac{1}{3}}$$

$$\mathrm{g}(\mathbb{S}) = \left(\frac{4\pi^2}{GM_*} \right)^{\frac{1}{6}} \sqrt{\frac{1}{4R_*}}$$

$$\mathrm{h}\left(\mathbb{M},\ \mathbf{T}_*\right) = \sqrt{\frac{At_m}{r^2} \int_{\lambda_1}^{\lambda_2} \tau\pi B\left(\lambda, T_*\right) \left(\frac{\lambda}{hc} \right) d\lambda}$$

$$\mathrm{SNR}_K = \mathrm{f}(\mathbb{P})\mathrm{g}(\mathbb{S})\mathrm{h}\left(\mathbb{M}_K, T_*\right);$$

$$\mathrm{SNR}_T = \mathrm{f}(\mathbb{P})\mathrm{g}(\mathbb{S})\mathrm{h}\left(\mathbb{M}_T, T_*\right)$$

↓

$$\mathrm{SNR}_T = \mathrm{SNR}_K \frac{\mathrm{h}\left(\mathbb{M}_\mathrm{T}, T_*\right)}{\mathrm{h}\left(\mathbb{M}_\mathrm{K}, T_*\right)} = k(\mathbb{M}_T, \mathbb{M}_K, T_*) \bullet \mathrm{SNR}_K$$

SubSample		k (27 days)	k (54 days)	k (81 days)	k (108 days)	k (189 days)	k (351 days)
< 4500K	3974.41	0.0327	0.0463	0.0567	0.0655	0.0866	0.1180
> 4500K	5653.53	0.0621	0.0878	0.1075	0.1242	0.1643	0.2239

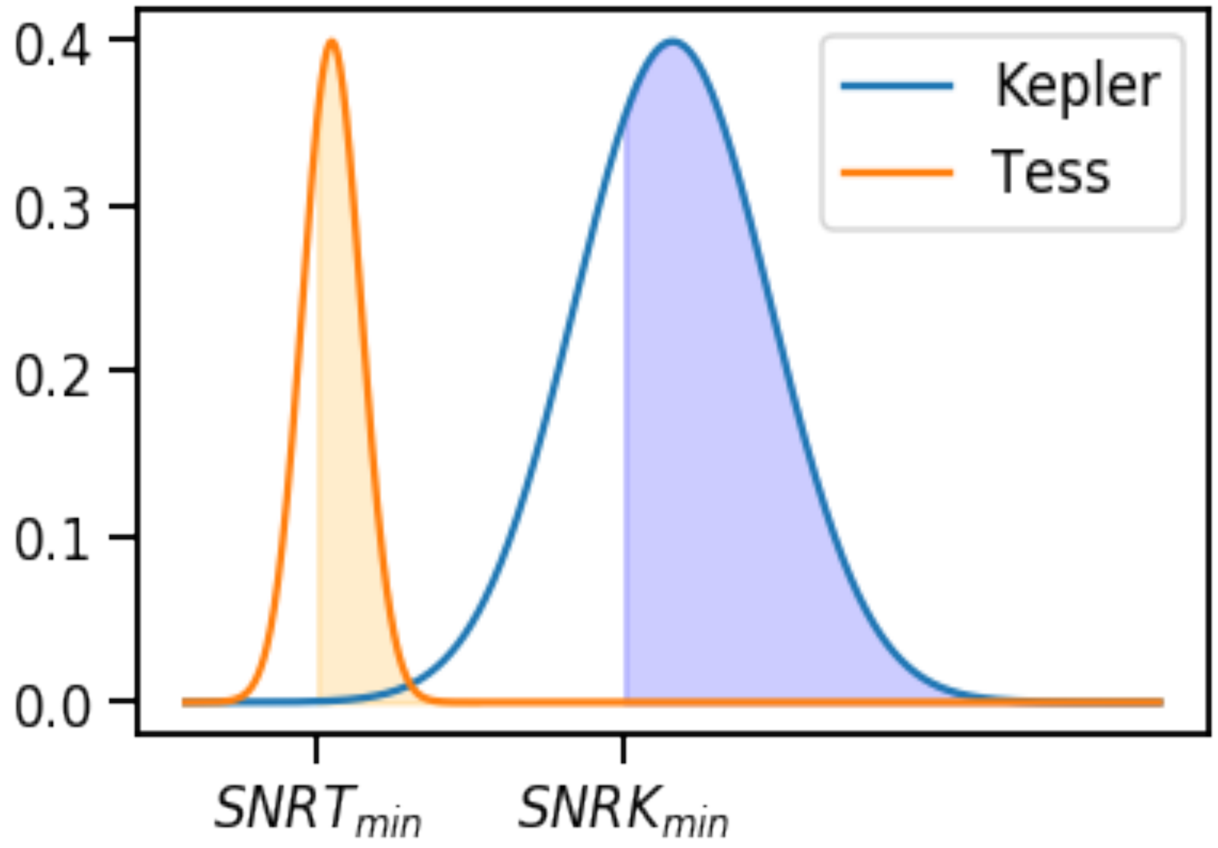
Methodology

$3.\ \mathrm{Prob}(SNR\_T\,|\,2Tr(\tau_1), Tr, P)$

$$f_{\mathrm{SNRT}i}(\mathrm{SNR}_T|P,tr) = f_{SNRTi}(k\cdot\mathrm{SNR}_K|P,tr) = f_{SNRKi}(\mathrm{SNR}_K|P,tr)$$

$$f_{\mathrm{SNRT}i}(\mathrm{SNR}|P,tr) = f_{\mathrm{SNRK}i}(\mathrm{SNR}/k|P,tr)$$

$$\begin{aligned}
&\mathrm{Prob}_i(\mathrm{SNR}_T > \mathrm{SNRT}_{min}\ |P,tr)\\
&= \int_{\mathrm{SNRT}_{min}}^{\infty} f_{\mathrm{SNRT}i}\ (SNR'|P,tr)dSNR'\\
&= \int_{\mathrm{SNRT}_{min}}^{\infty} f_{\mathrm{SNRK}i}\left(\frac{SNR'}{k}|P,tr\right)dSNR'\\
&= \int_{\frac{\mathrm{SNRT}_{\mathrm{min}}}{k}}^{\infty} k\cdot f_{\mathrm{SNRK}i}\ (SNR''|P,tr)dSNR''\\
&= k\cdot\mathrm{Prob}_i\left(\mathrm{SNR}_K > \frac{\mathrm{SNRT}_{min}}{k}\middle|P,tr\right)
\end{aligned}$$



↓

$$\frac{\mathrm{Prob}_i(\mathrm{SNR}_T > \mathrm{SNRT}_{min}\ |P,tr)}{\mathrm{Prob}_i(\mathrm{SNR}_K > \mathrm{SNRK}_{min}\ |P,tr)} = k\cdot\frac{\mathrm{Prob}_i\left(\mathrm{SNR}_K > \frac{\mathrm{SNRT}_{min}}{k}\middle|P,tr\right)}{\mathrm{Prob}_i(\mathrm{SNR}_K > \mathrm{SNRK}_{min}\ |P,tr)}$$

?

Methodology

$3.\ \mathrm{Prob}(\boldsymbol{SNR\_T} \mid \boldsymbol{2Tr(\tau_1)}, \boldsymbol{Tr}, \boldsymbol{P})$

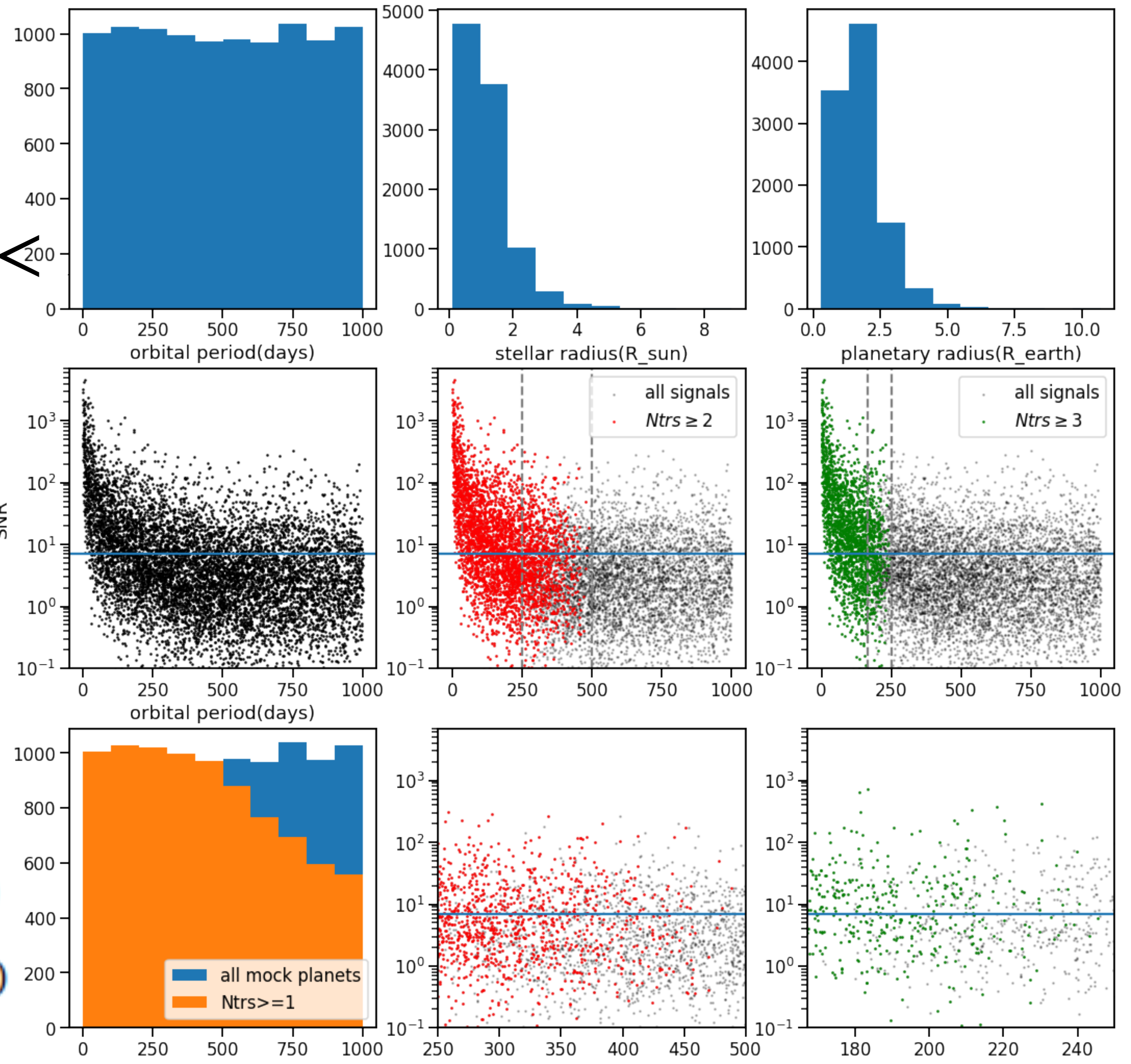
$$\boxed{\mathrm{Prob}(TESS \mid P) = \mathrm{Prob}(Tr \mid P) \times \mathrm{Prob}(NTr(\tau_1) \mid Tr, P) \times \mathrm{Prob}(SNR\_T \mid NTr(\tau_1)\ Tr, P)}$$

3 scenarios:

$$(Ntrs_T \mid P, tr) = \begin{cases} 0, & t \le (N-1)P \\ \dfrac{t - N \cdot P}{P}, & (N-1)P < t < \\ 1, & t \ge N \cdot P \end{cases}$$

$$\mathrm{Prob}_i\left(\mathrm{SNR}_K > \frac{\mathrm{SNRT}_{min}}{k} \middle| P, tr\right) \rightarrow \mathrm{Prob}_i\left(\mathrm{SNR}_K > \frac{\mathrm{SNRT}_{min}}{k} \middle| P, tr, 3trs_K\right)$$

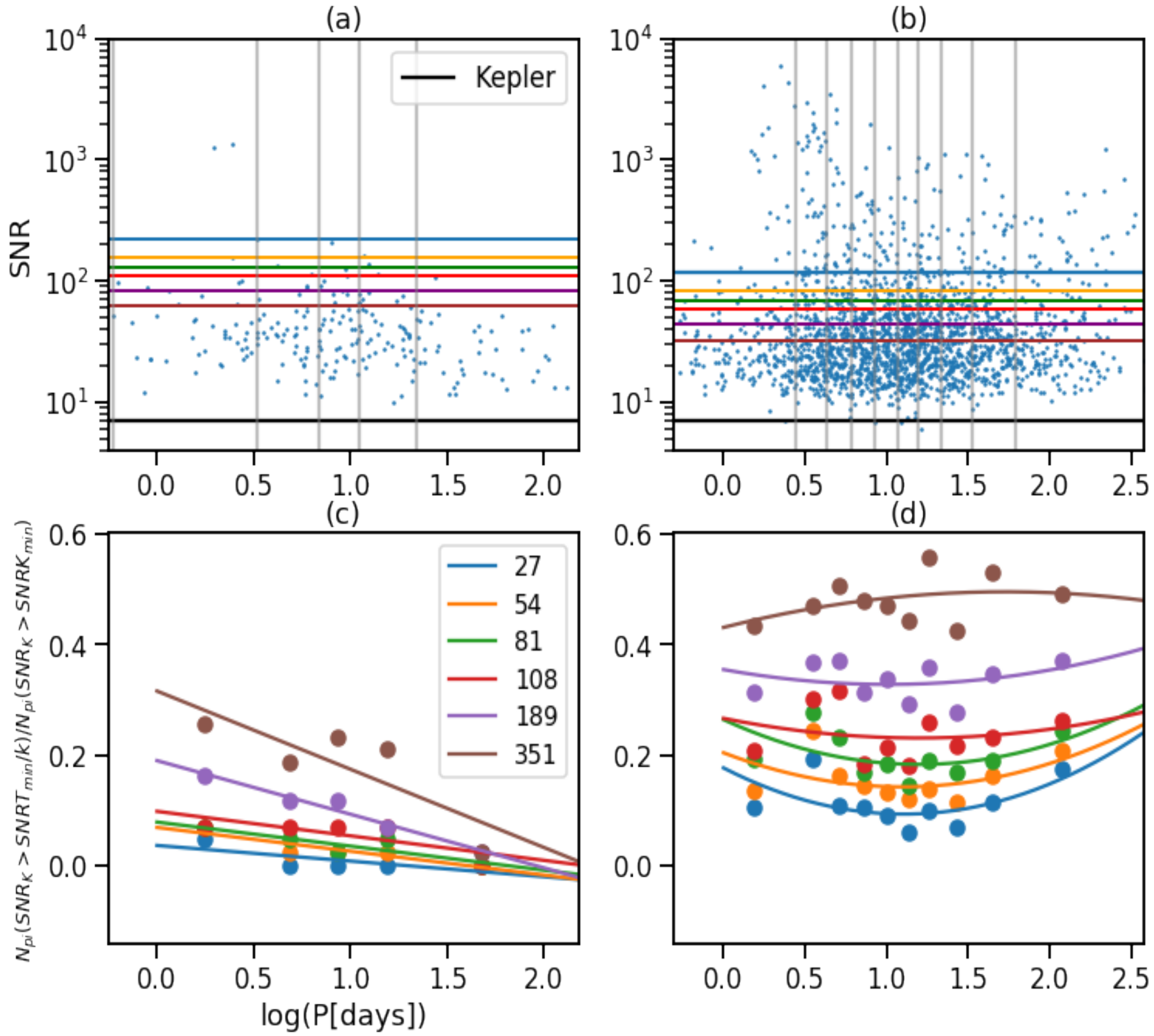
$$\mathrm{Prob}_i\,(\mathrm{SNR}_K > \mathrm{SNRK}_{min}\,|P, tr) \rightarrow \mathrm{Prob}_i\,(\mathrm{SNR}_K > \mathrm{SNRK}_{min}\,|P, tr, 3trs_K)$$



Methodology

$$\frac{\mathrm{Prob}_i\left(\mathrm{SNR}_K > \frac{\mathrm{SNRT}_{min}}{k}\,\middle|\,P, tr, 3trs_K\right)}{\mathrm{Prob}_i(\mathrm{SNR}_K > \mathrm{SNRK}_{min}\,|P, tr, 3trs_K)} = \frac{N_{Pi}\left(\mathrm{SNR}_K > \frac{\mathrm{SNRT}_{min}}{k}\right)/N_{Pi}}{N_{Pi}(\mathrm{SNR}_K > \mathrm{SNRK}_{min})/N_{Pi}}$$

$$= \frac{N_{Pi}\left(\mathrm{SNR}_K > \frac{\mathrm{SNRT}_{min}}{k}\right)}{N_{Pi}(\mathrm{SNR}_K > \mathrm{SNRK}_{min})}$$



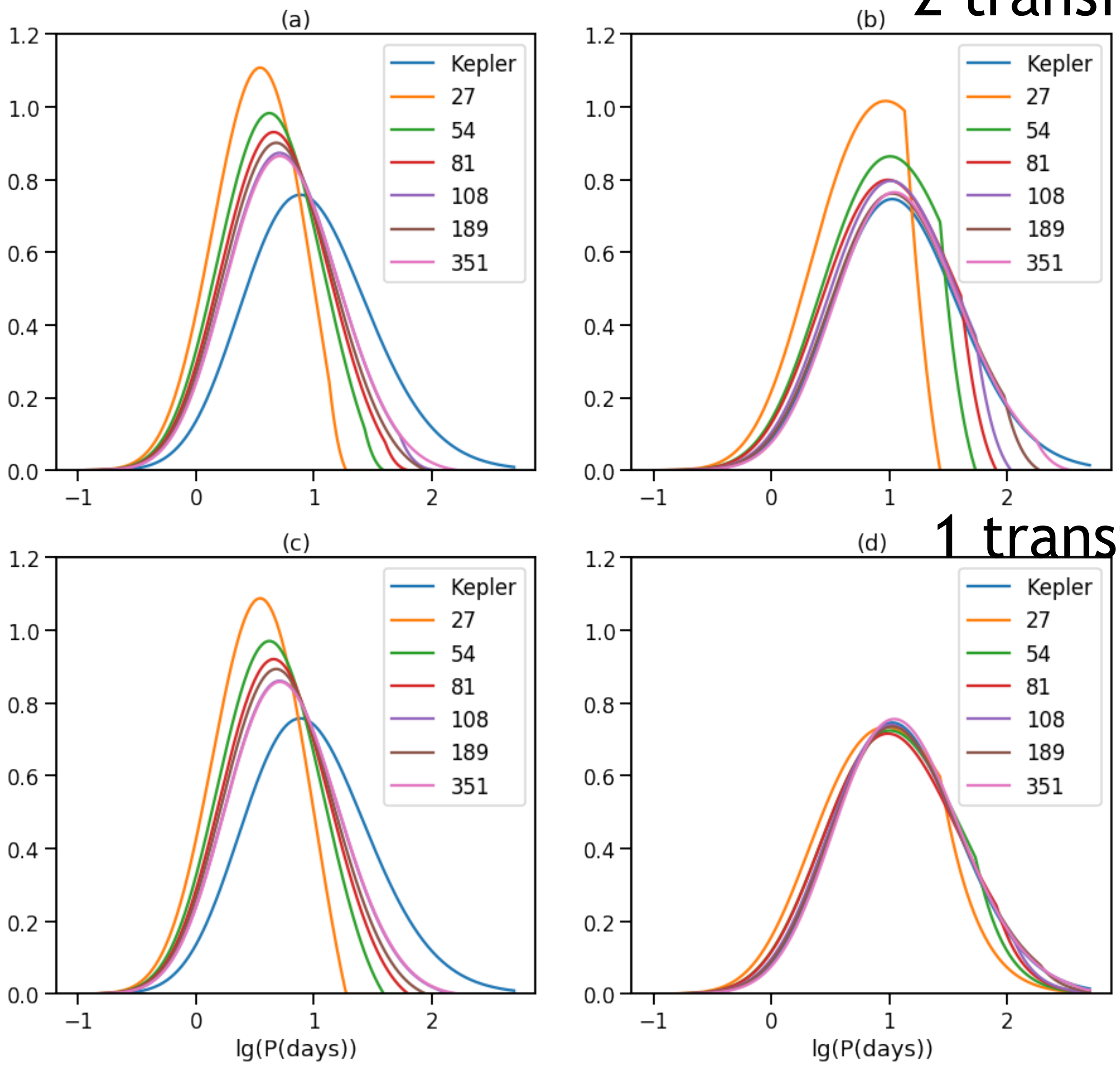
$$\mathrm{Prob}_i\left(P\middle|TESS\right) = c_i\mathrm{Prob}_i(P|\,Kepler)\frac{\mathrm{Prob}_i\left(Ntrs_T\middle|P, tr\right)\bullet\mathrm{Prob}_i\left(\mathrm{SNR}_T > \mathrm{SNRT}_{min}\middle|P, tr, Ntrs_T\right)}{\mathrm{Prob}_i\left(Ntrs_K\middle|P, tr\right)\bullet\mathrm{Prob}_i\left(\mathrm{SNR}_K > \mathrm{SNRK}_{min}\middle|P, tr, Ntrs_K\right)}$$

Results

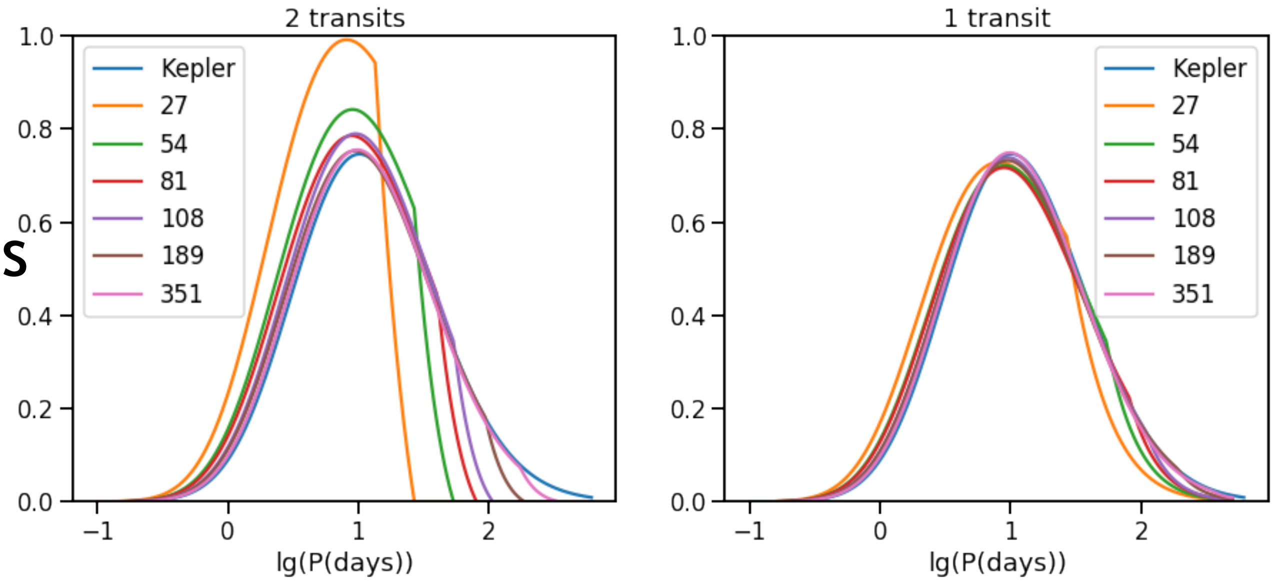
1. Results of two subsamples for different observation baseline

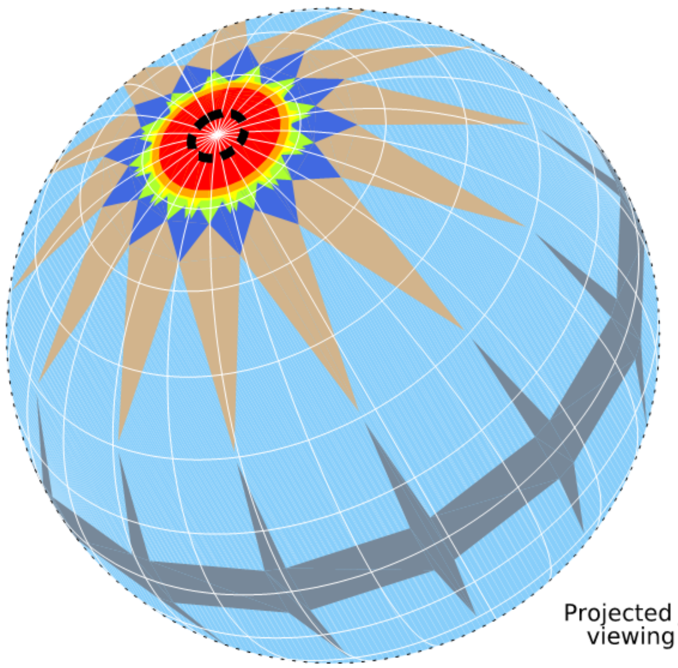
2 transits

1 transit



2. Results of different observation baseline

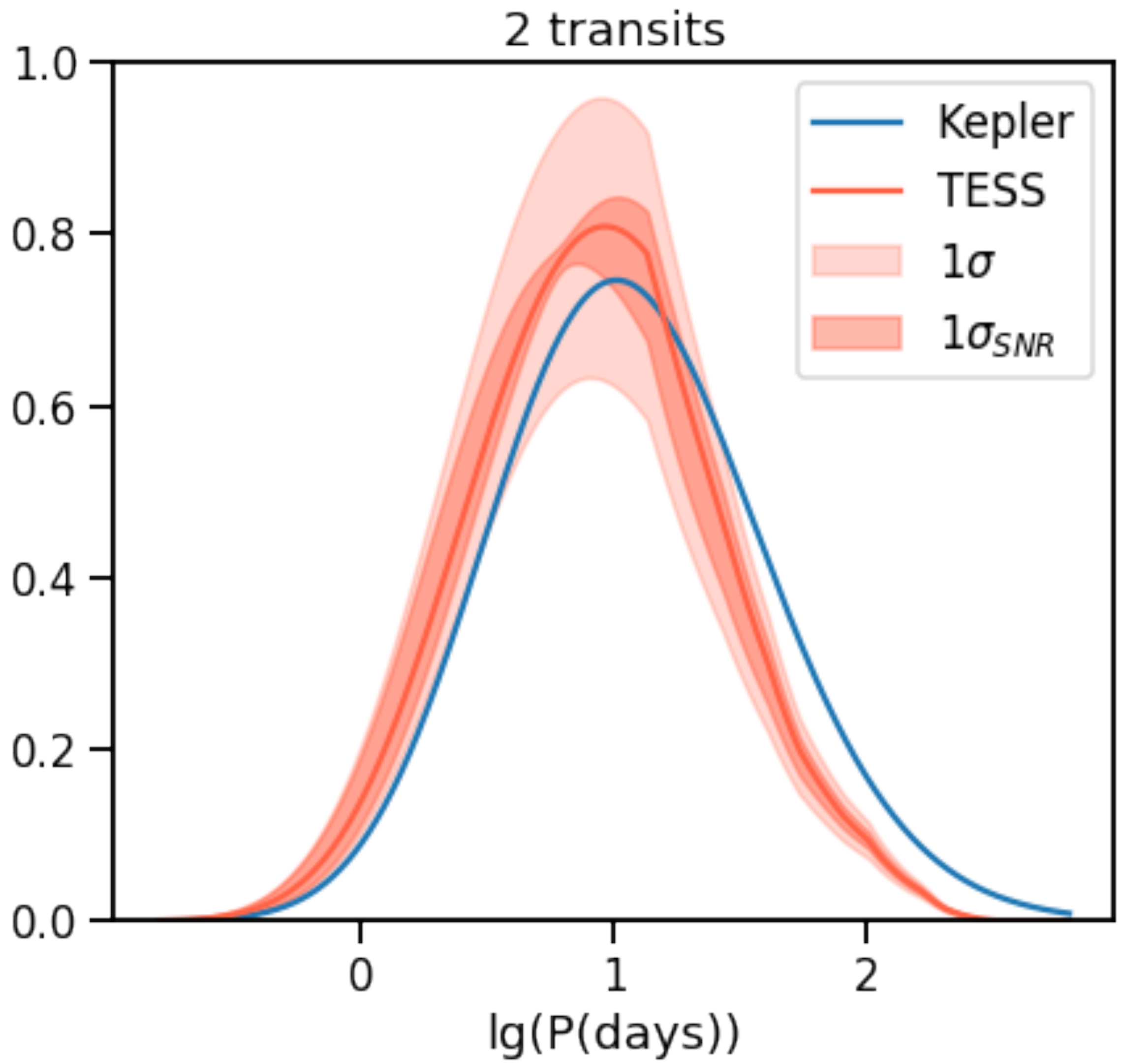


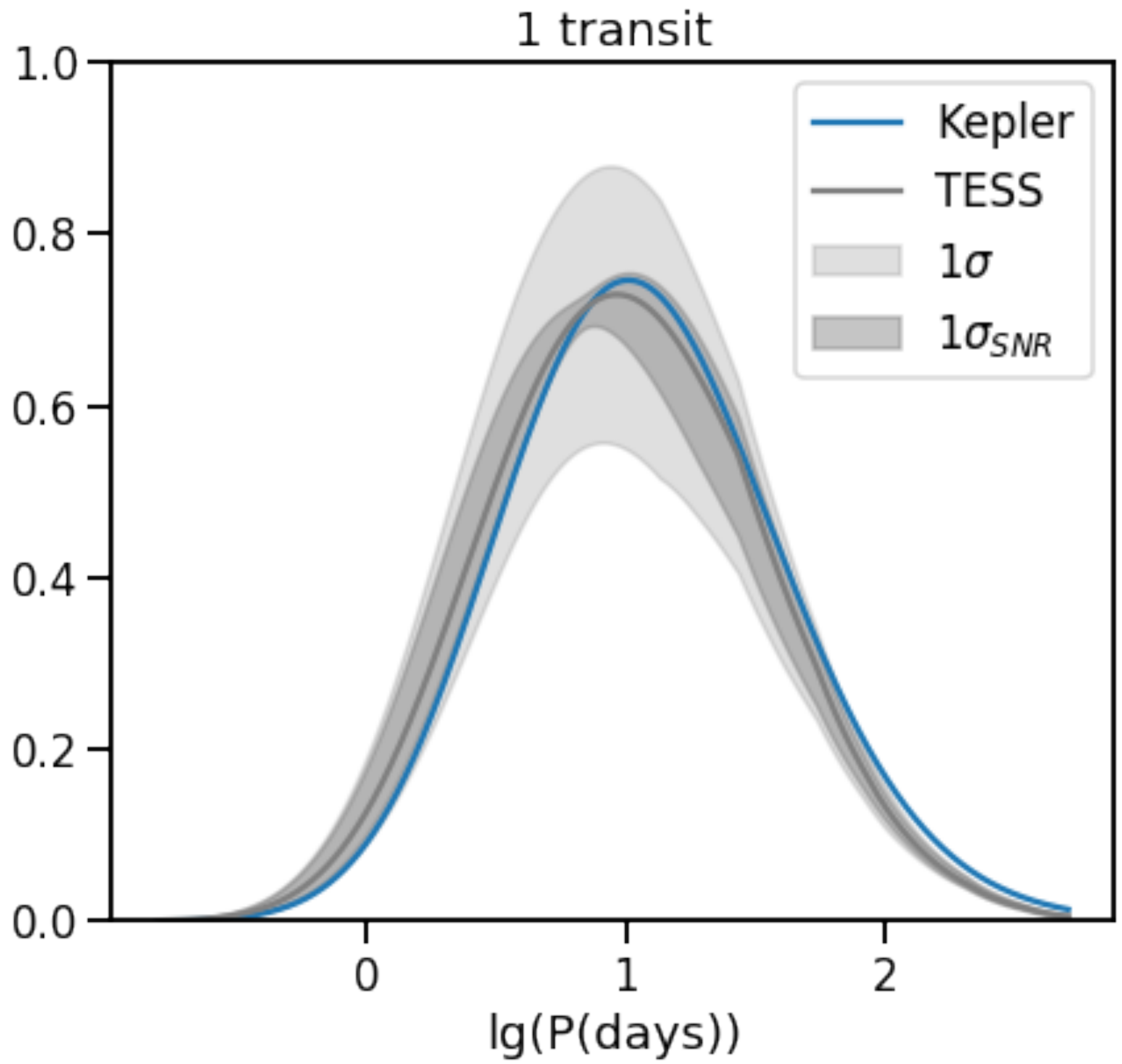


	Two-Transit	One-Transit
27 days	5.0 [2.1-12]	8.2 [2.6-26]
54 days	7.1 [2.6-19]	9.7 [3.0-32]
81 days	8.0 [2.8-23]	10 [3.0-34]
108 days	9.2 [3.2-27]	11 [3.2-36]
189 days	10 [3.2-32]	11 [3.2-38]
351 days	11 [3.4-36]	11 [3.3-38]

Projected JWST viewing zone

Results



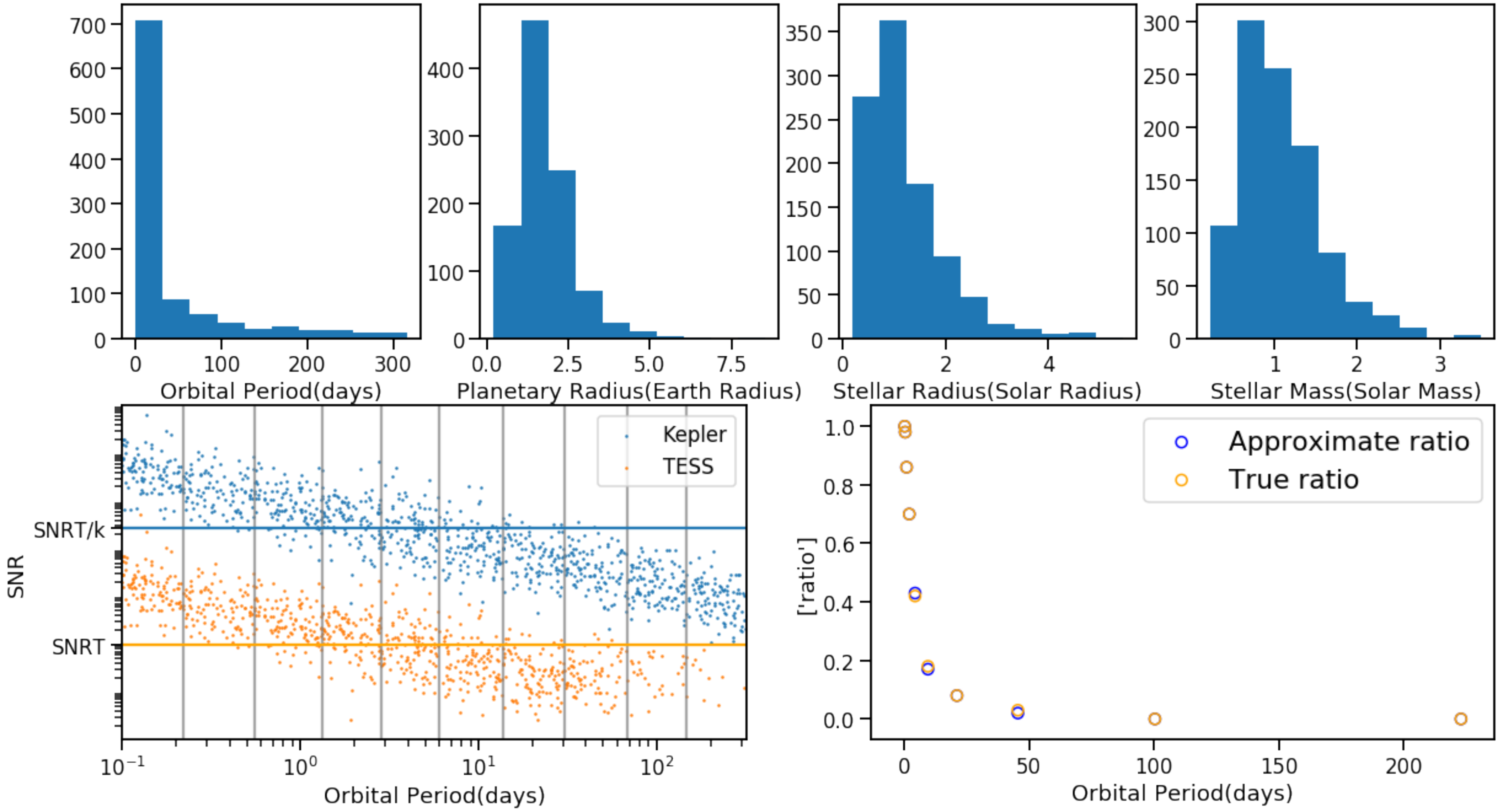


Duration of Observation (days)	TESS	Kepler
MP(days) -2 transits	8.47	11.89
1sigma(days) -2 transits	2.75-26.12	3.45-41.04
MP(days) -1 transit	10.09	-
1sigma(days) -1 transit	2.99-34.08	-

Uncertainty

- Uncertainty of approximating $\boldsymbol{Ntrs}$

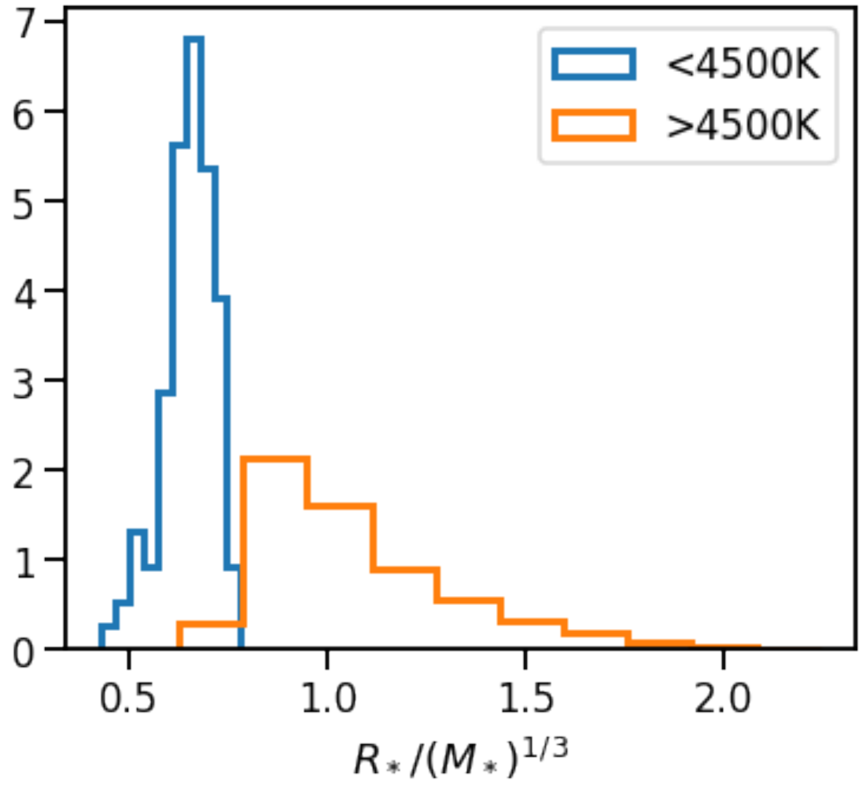
$$\mathbf{SNR} = R_p^2\left(\frac{4\pi^2 P}{GM_*}\right)^{\frac{1}{6}}\sqrt{\frac{N_{trs}A}{4R_*r^2}\int_{\lambda_1}^{\lambda_2}\tau\pi B(\lambda,T_*)\left(\frac{\lambda}{hc}\right)d\lambda}$$



Uncertainty

Uncertainty of Stellar Parameters

$$\text{Prob}_i\left(P\middle|TESS\right) = c_i\text{Prob}_i\left(P\middle|Kepler\right)\cdot\frac{\text{Prob}(\boldsymbol{tr}|\boldsymbol{P})}{\text{Prob}(\boldsymbol{tr}|\boldsymbol{P})}\cdot\frac{\text{Prob}_i\left(Ntrs_T\middle|P,tr\right)}{\text{Prob}_i\left(Ntrs_K\middle|P,tr\right)}\cdot\cdot\frac{\text{Prob}_i\left(\text{SNR}_T > \text{SNRT}_{min}\middle|P,tr\right)}{\text{Prob}_i\left(\text{SNR}_K > \text{SNRK}_{min}\middle|P,tr\right)}$$



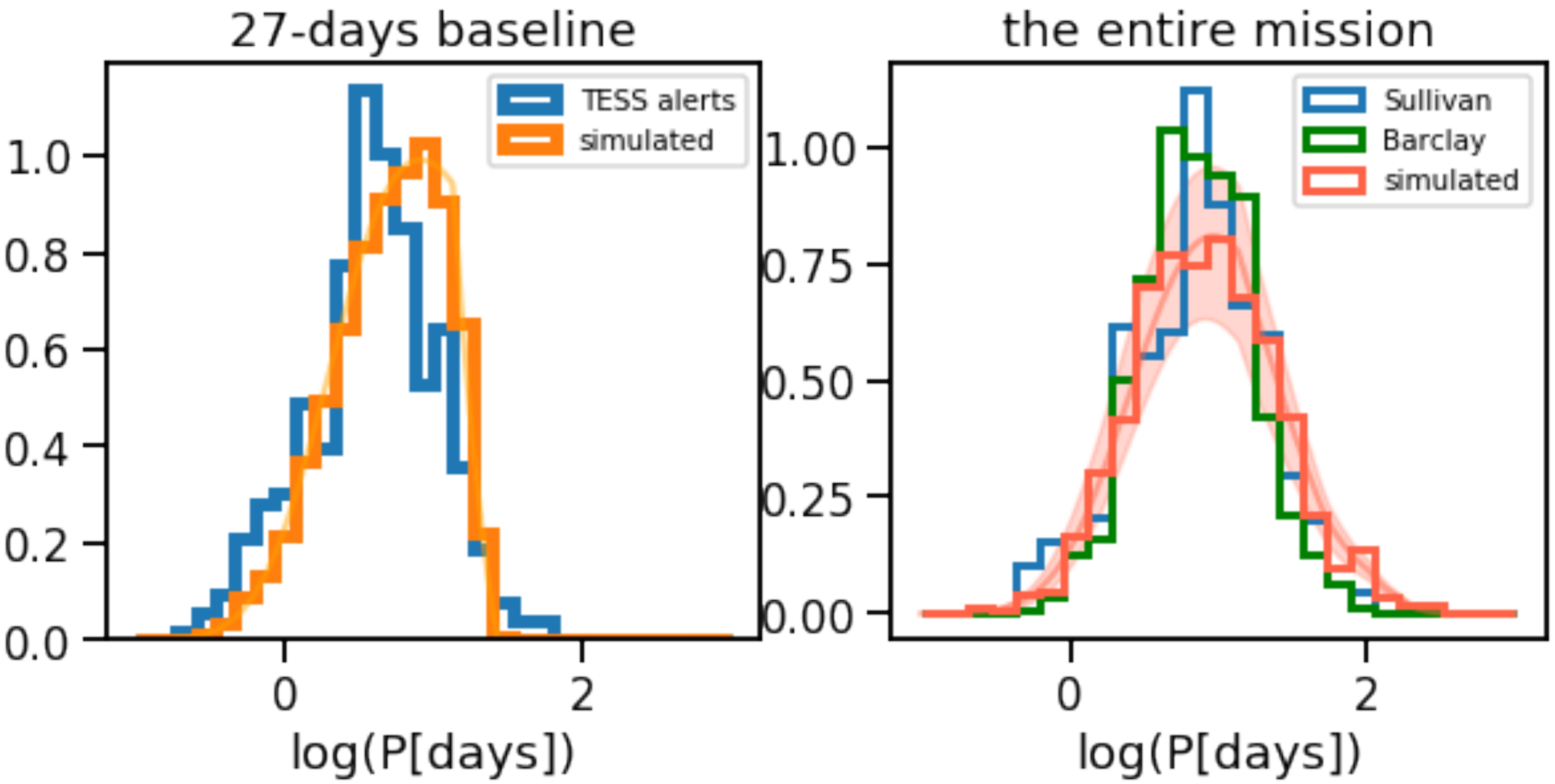
- Uncertainty of SNR model

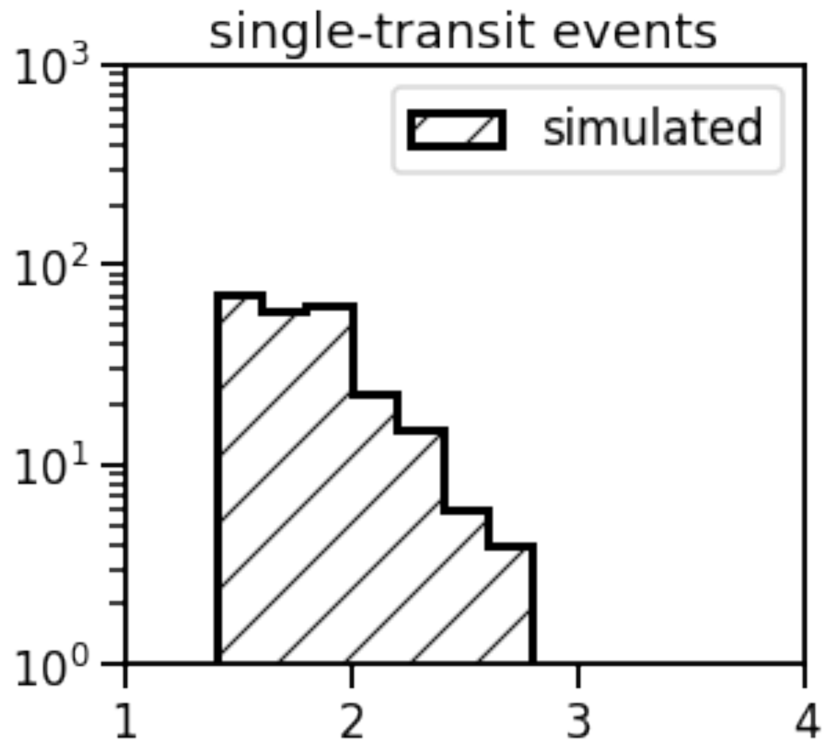
$$\text{SNR} = R_p^2 P^{-\frac{1}{3}}\left(\frac{4\pi^2}{GM_*}\right)^{\frac{1}{6}}\sqrt{\frac{At_m}{4R_* r^2}\int_{\lambda_1}^{\lambda_2}\tau\pi B(\lambda,T_*)\left(\frac{\lambda}{hc}\right)d\lambda},$$

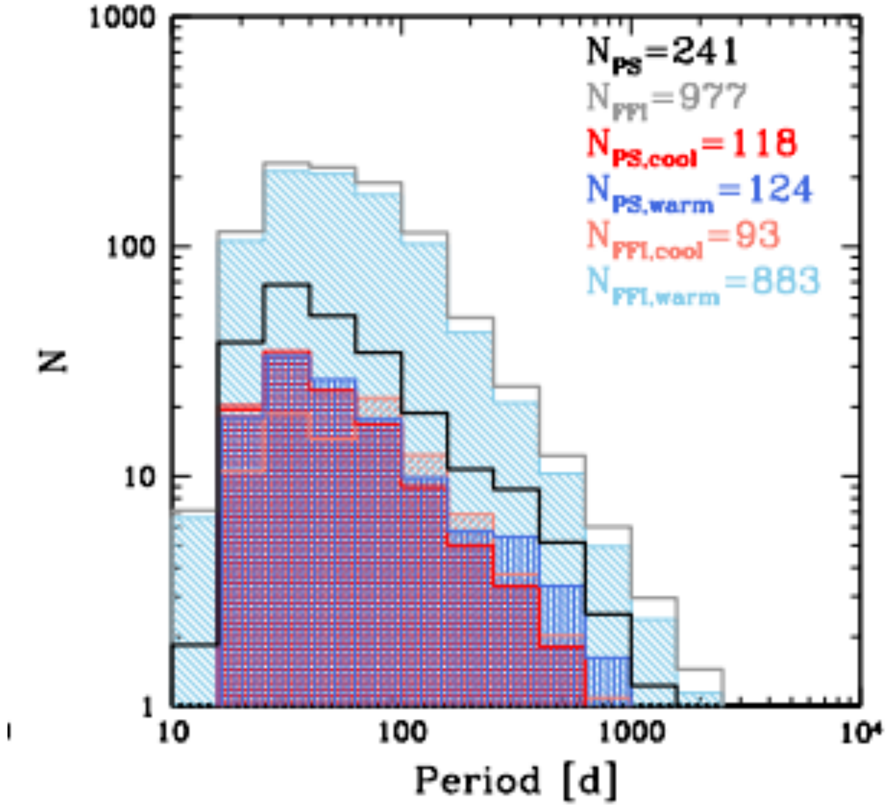
$$\text{h}(\mathbb{M},\ \mathbf{T}_*) = \sqrt{\frac{At_m}{r^2}\int_{\lambda_1}^{\lambda_2}\tau\pi B(\lambda,T_*)\left(\frac{\lambda}{hc}\right)d\lambda}$$

1000 times

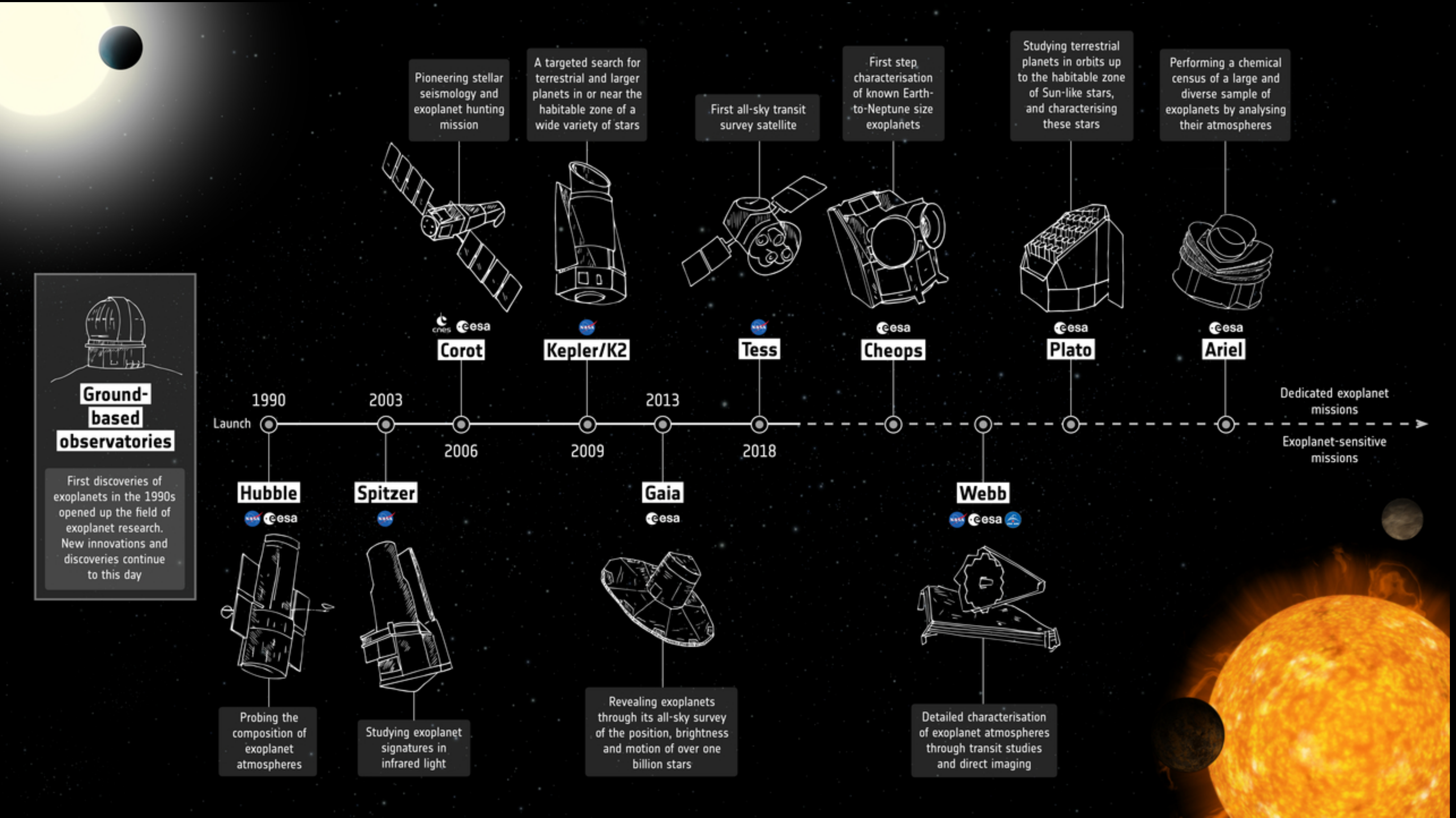
Comparison


27-days baseline
TESS alerts
simulated
1.0
0.8
0.6
0.4
0.2
0.0
0
2
log(P[days])
the entire mission
Sullivan
Barclay
simulated
1.00
0.75
0.50
0.25
0.00
0
2
log(P[days])


single-transit events
simulated
10^3
10^2
10^1
10^0
1
2
3
4


$N_{PS}=241$
$N_{FFI}=977$
$N_{PS,cool}=118$
$N_{PS,warm}=124$
$N_{FFI,cool}=93$
$N_{FFI,warm}=883$
1000
100
10
1
N
10
100
1000
10^4
Period [d]

Bright Future!



Ground-based observatories

First discoveries of exoplanets in the 1990s opened up the field of exoplanet research. New innovations and discoveries continue to this day

Hubble (1990): Probing the composition of exoplanet atmospheres

Spitzer (2003): Studying exoplanet signatures in infrared light

Corot (2006): Pioneering stellar seismology and exoplanet hunting mission

Kepler/K2 (2009): A targeted search for terrestrial and larger planets in or near the habitable zone of a wide variety of stars

Gaia (2013): Revealing exoplanets through its all-sky survey of the position, brightness and motion of over one billion stars

Tess (2018): First all-sky transit survey satellite

Cheops: First step characterisation of known Earth-to-Neptune size exoplanets

Webb: Detailed characterisation of exoplanet atmospheres through transit studies and direct imaging

Plato: Studying terrestrial planets in orbits up to the habitable zone of Sun-like stars, and characterising these stars

Ariel: Performing a chemical census of a large and diverse sample of exoplanets by analysing their atmospheres

Any Questions?