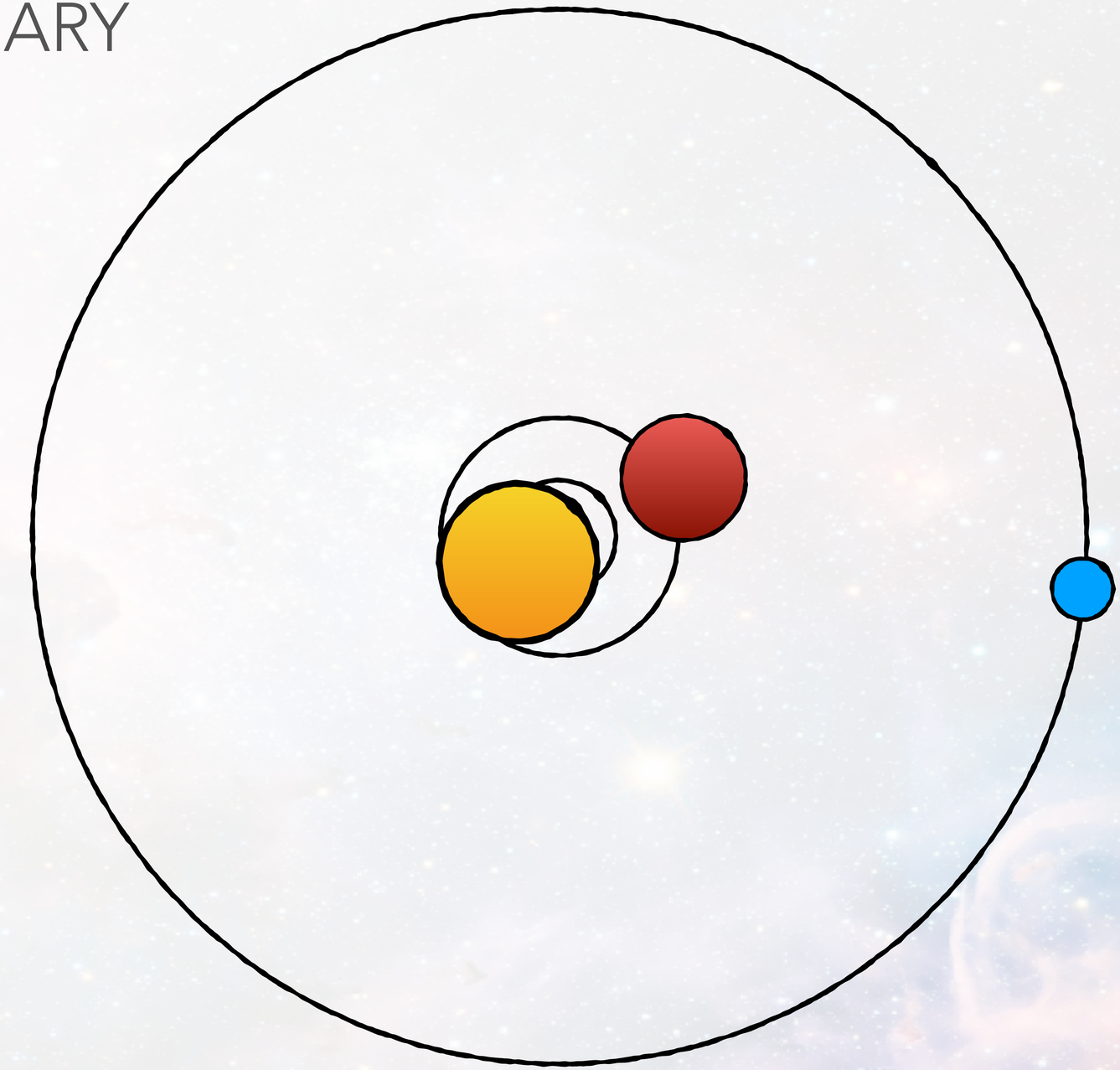
CIRCUMBINARY PLANETS



“Bonjour David,

…

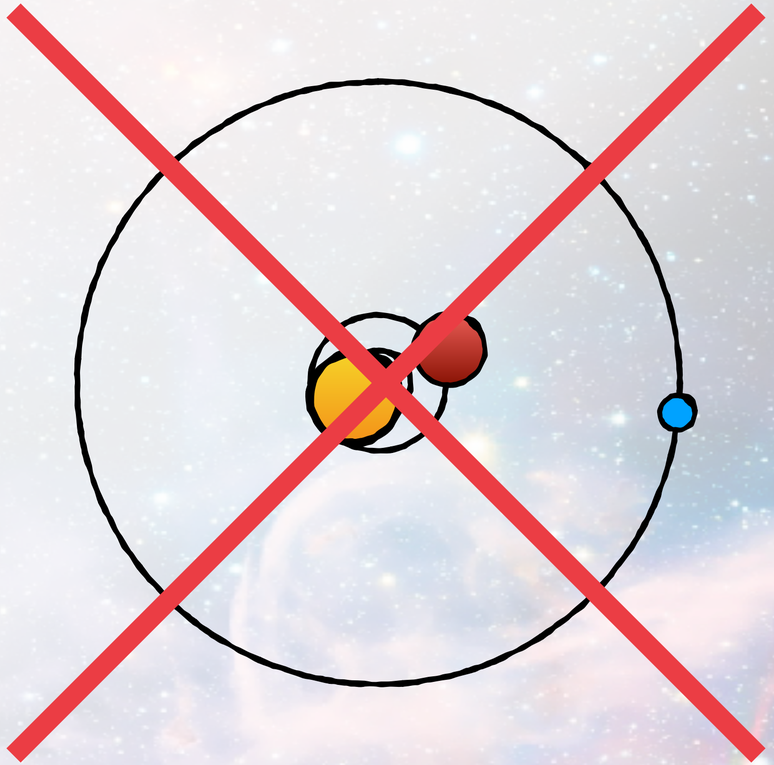
Pour la petite histoire, quand en 1990-92 j’avais demandé des crédits pour chercher des transits autour de CM Dra, ***les “autorités scientifiques” avaient répondu*** *qu’il est bien connu que les orbits circumbinaires sont instables et que* ***ces planètes ne peuvent exister.***

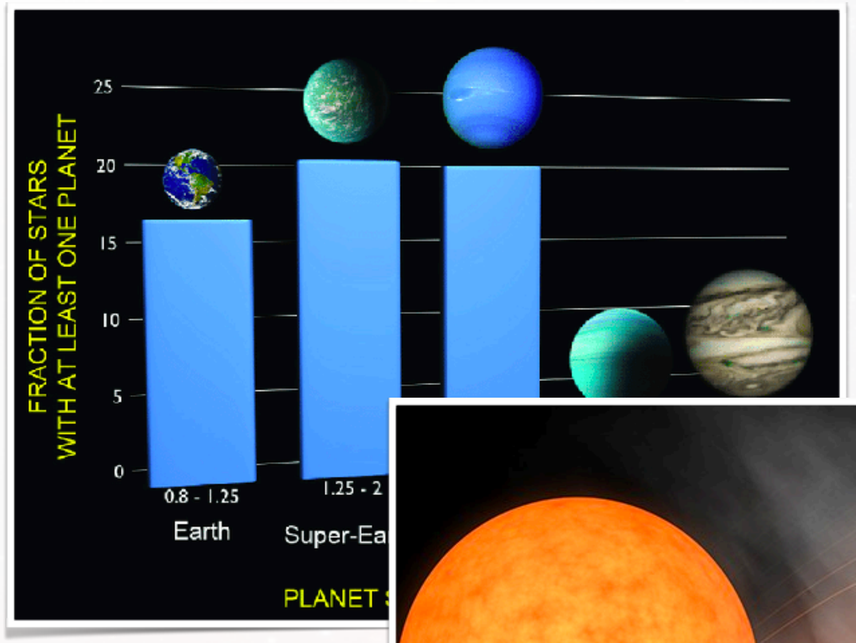
the “scientific authorities” told me

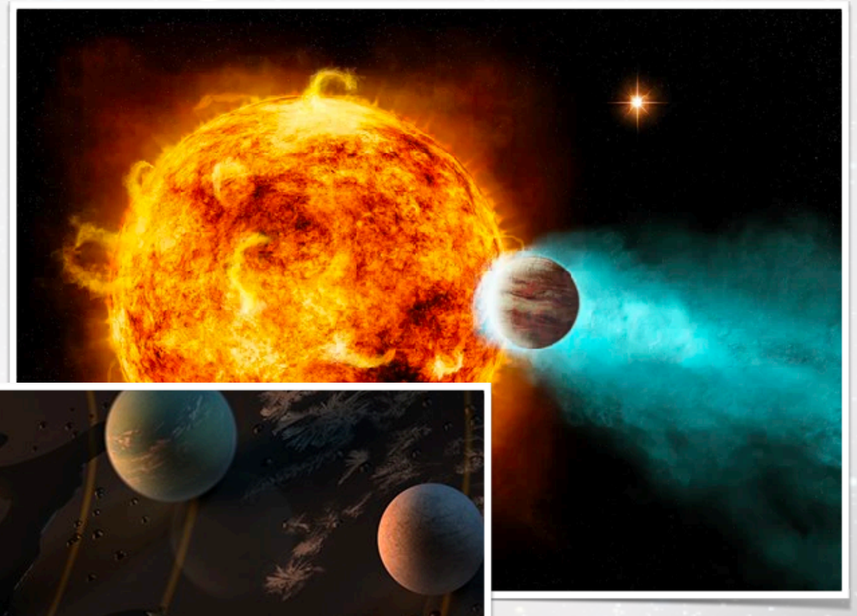
these planets cannot exist

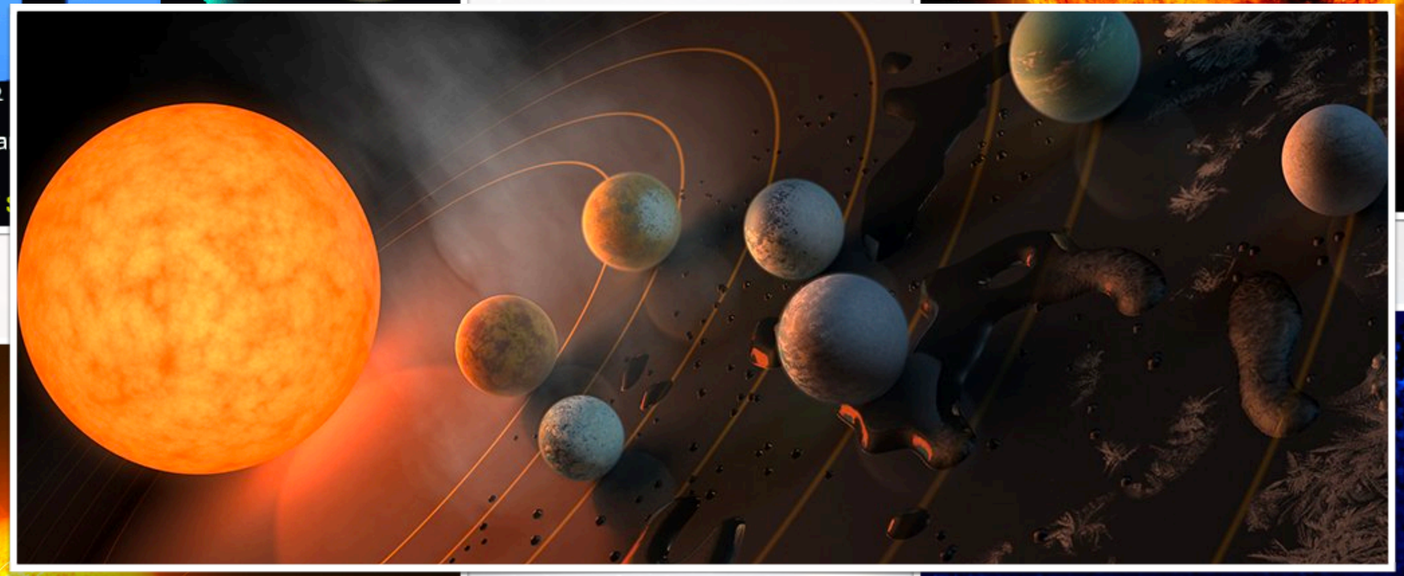
Cordialement,

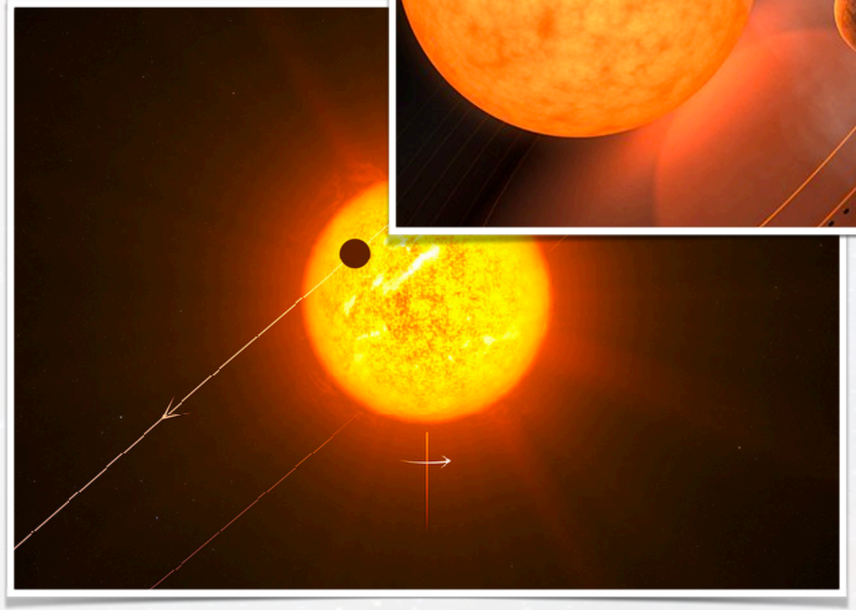
Jean Schneider”

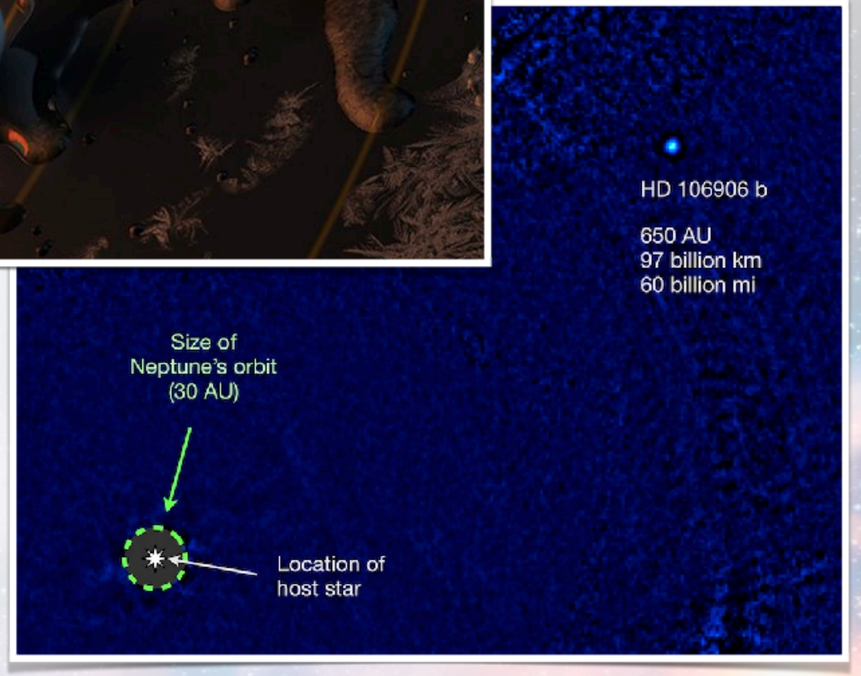


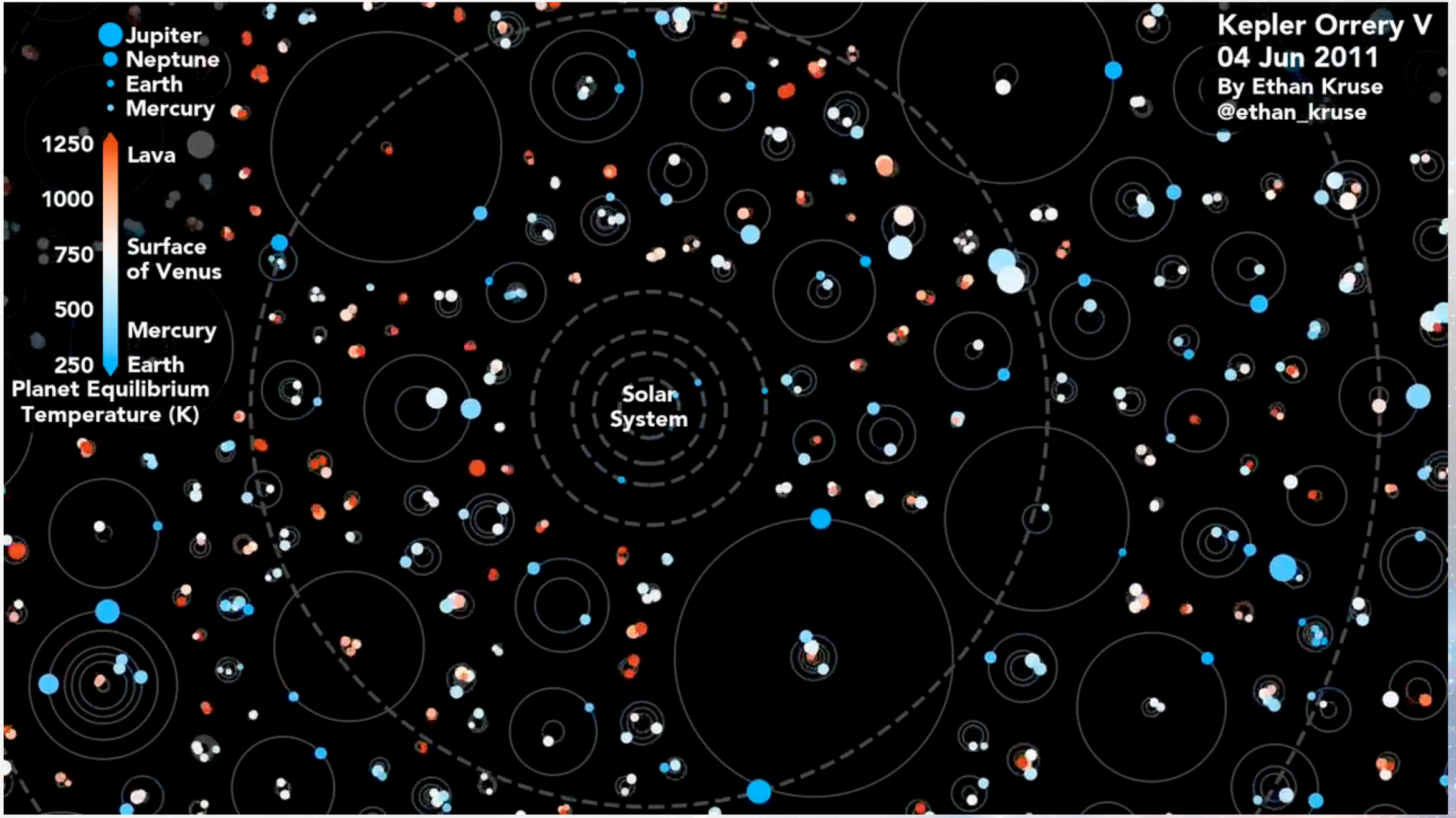

FRACTION OF STARS
WITH AT LEAST ONE PLANET
25
20
15
10
5
0
0.8 - 1.25
Earth
1.25 - 2
Super-Ea
PLANET








HD 106906 b
650 AU
97 billion km
60 billion mi
Size of
Neptune's orbit
(30 AU)
Location of
host star


Jupiter
Neptune
Earth
Mercury
1250
Lava
1000
750
Surface of Venus
500
Mercury
250
Earth
Planet Equilibrium Temperature (K)
Solar System
Kepler Orrery V
04 Jun 2011
By Ethan Kruse
@ethan_kruse

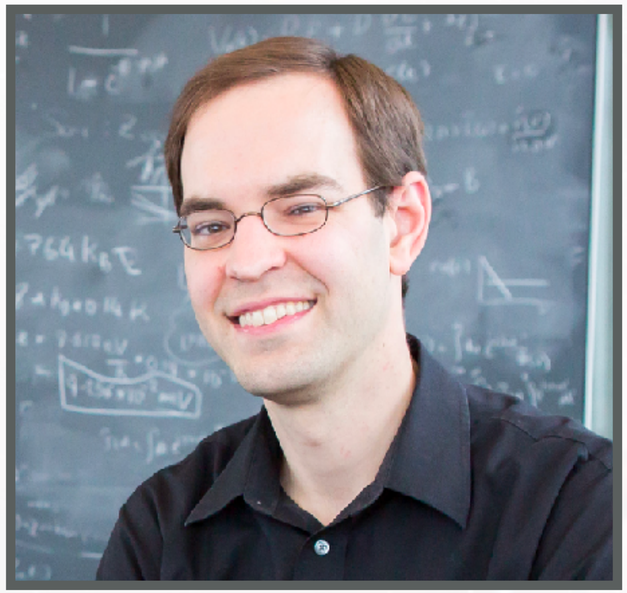
CIRCUMBINARY PLANETS

THE NEXT STEPS

David V. Martin

THE UNIVERSITY OF CHICAGO

FNSNF
SWISS NATIONAL SCIENCE FOUNDATION

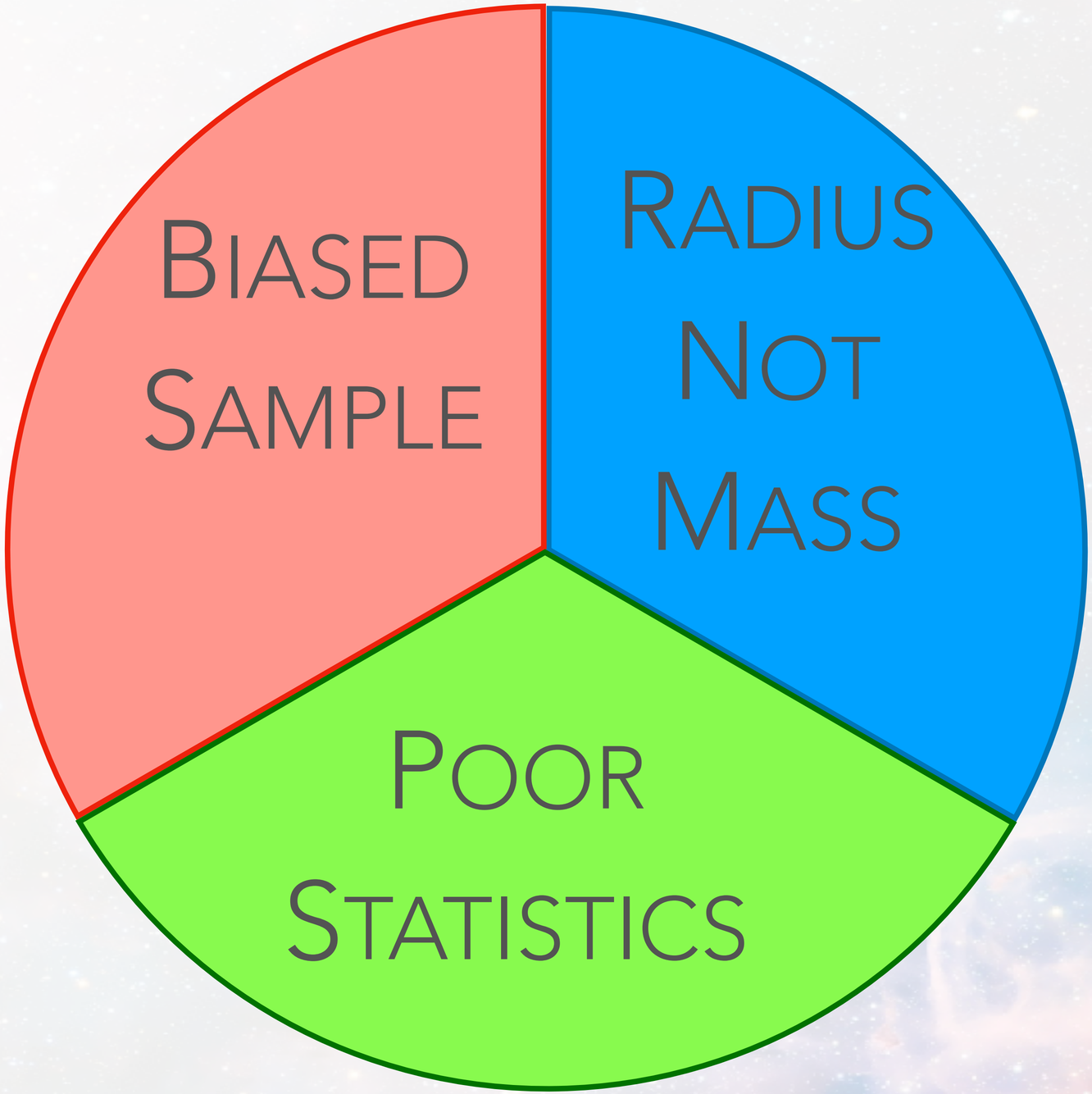


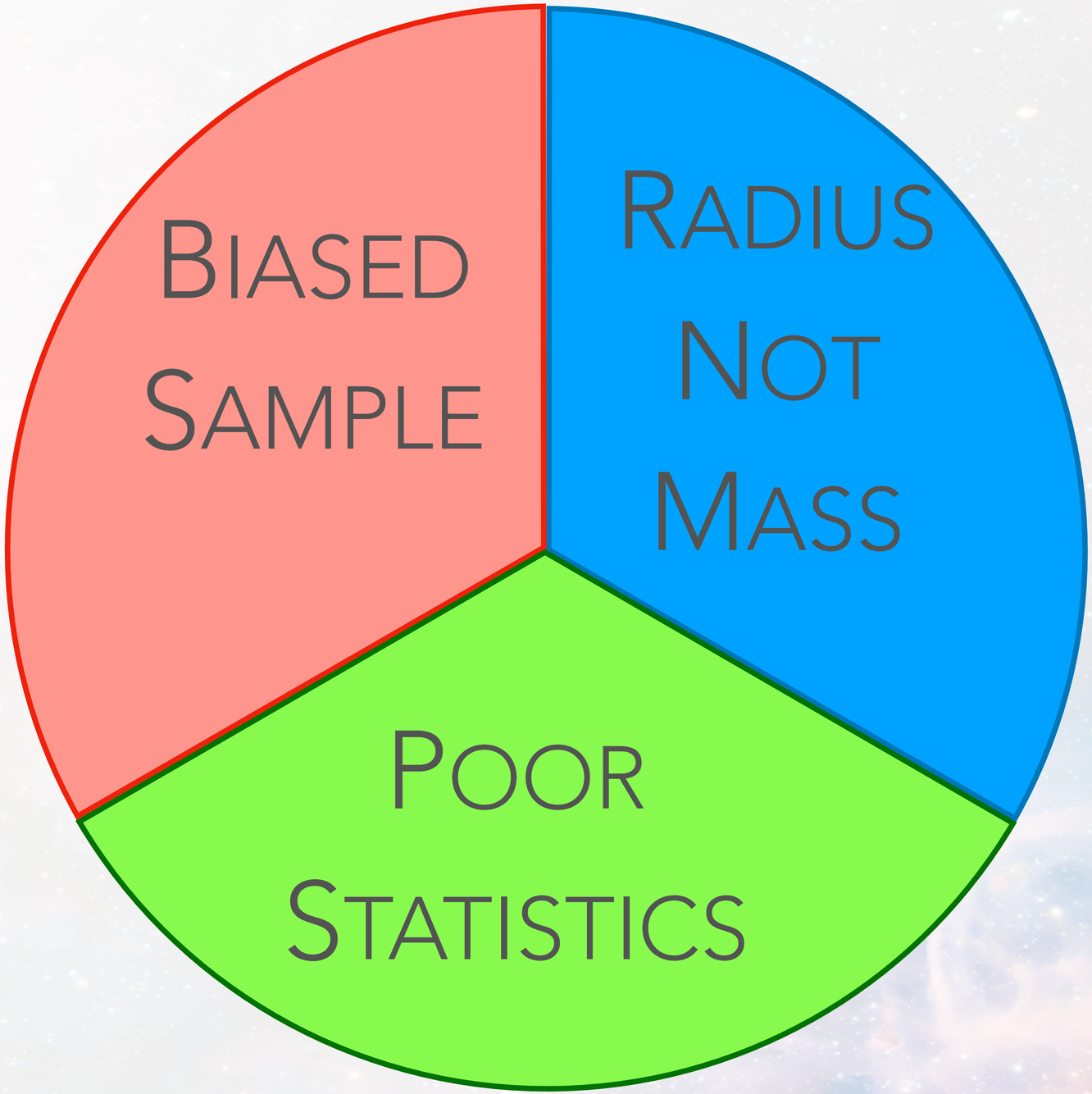
Daniel Fabrycky
University of Chicago

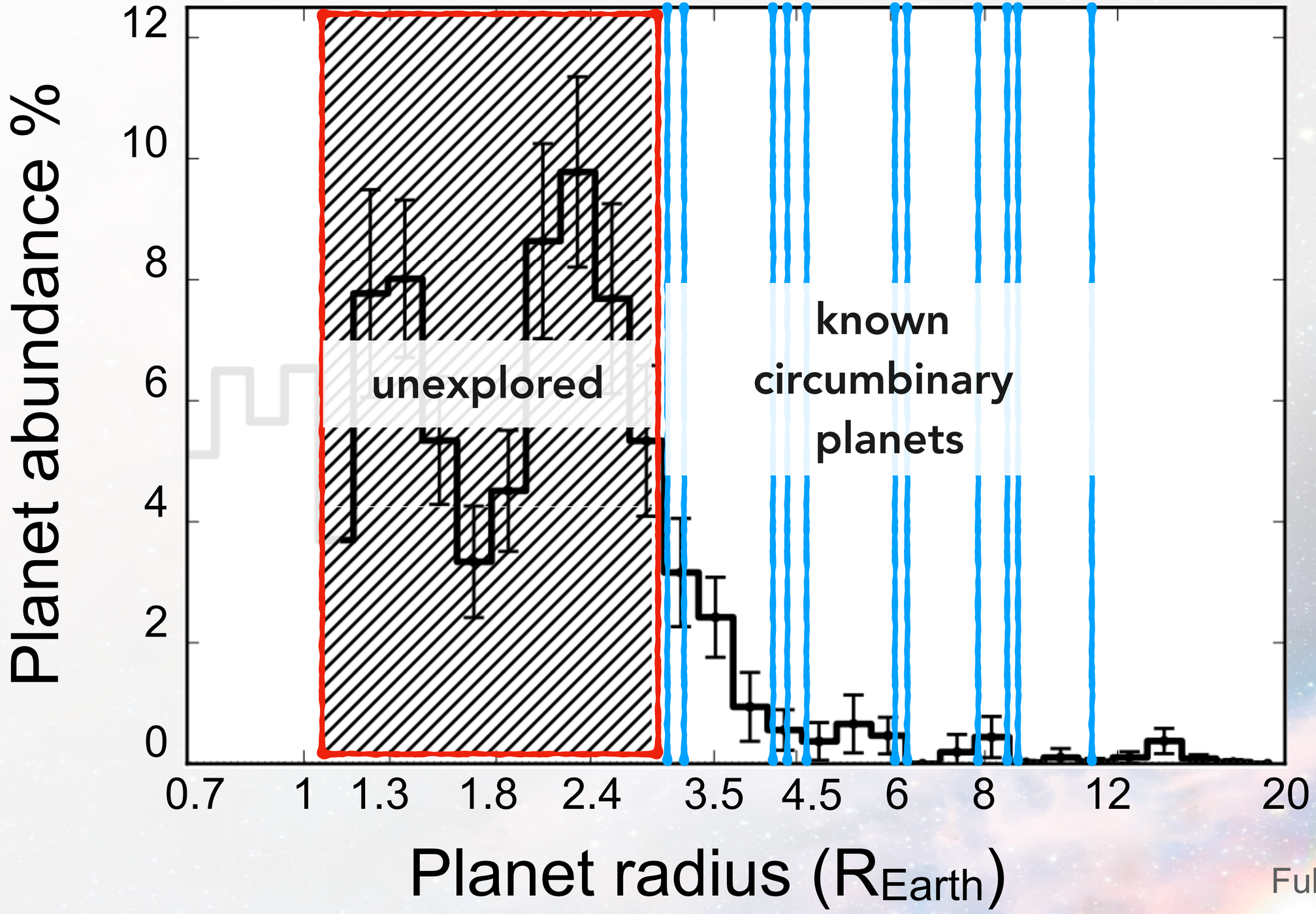
Amaury Triaud
University of Birmingham

Veselin Kostov
NASA Goddard

THREE PROBLEMS


Biased Sample
Radius Not Mass
Poor Statistics

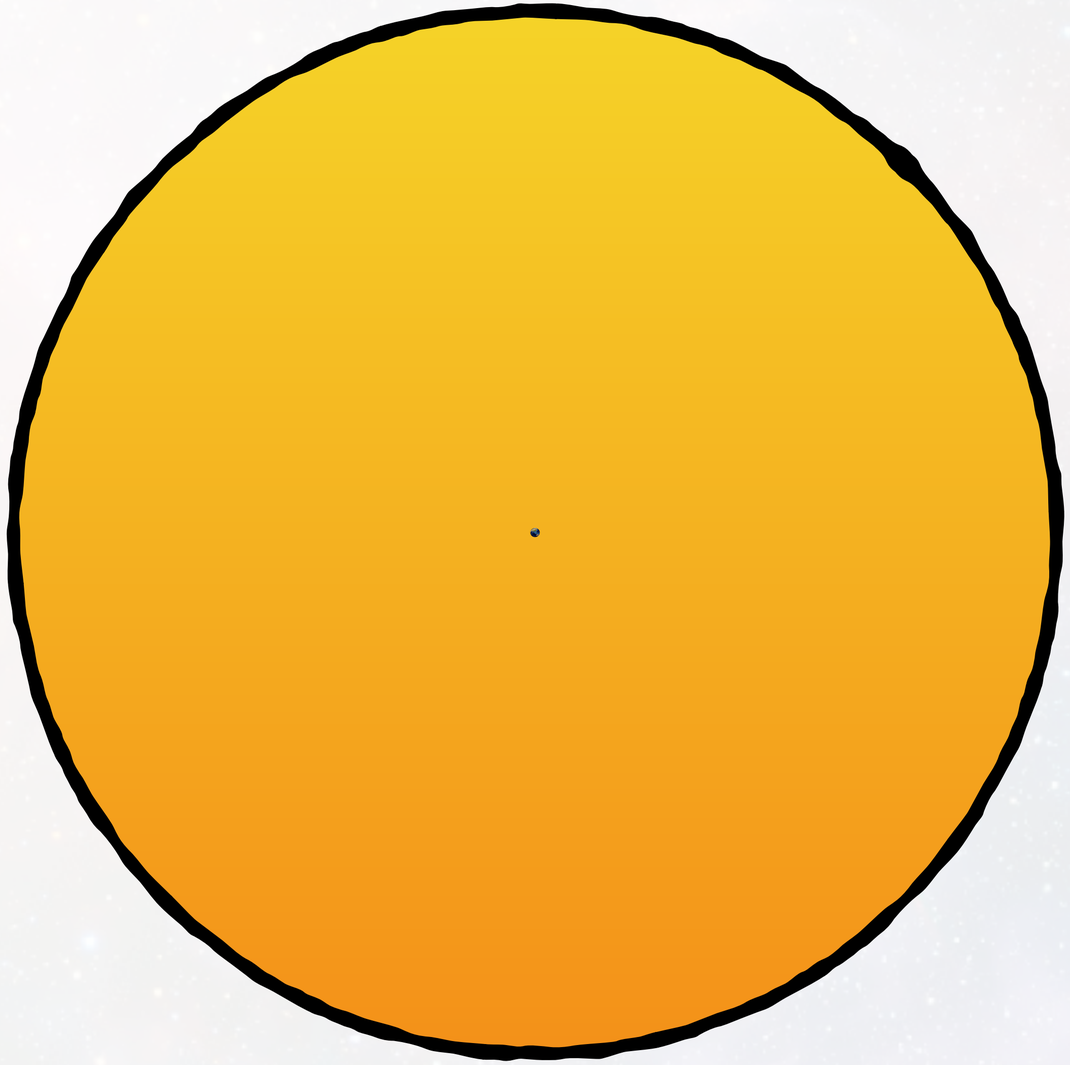

Biased Sample
Radius Not Mass
Poor Statistics


Planet abundance %
12
10
8
6
4
2
0
unexplored
known
circumbinary
planets
0.7
1
1.3
1.8
2.4
3.5
4.5
6
8
12
20
Planet radius (R_{Earth})

Fulton+ (2017)

TRANSITING EARTHS

TRANSITING EARTHS

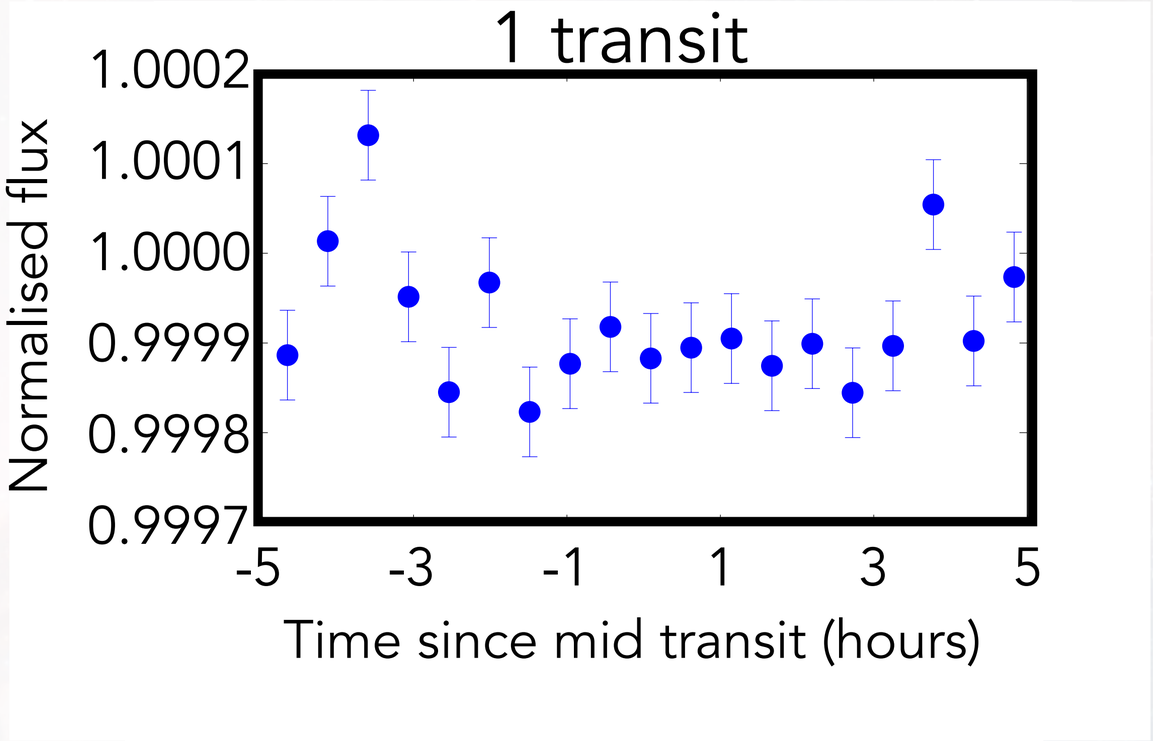


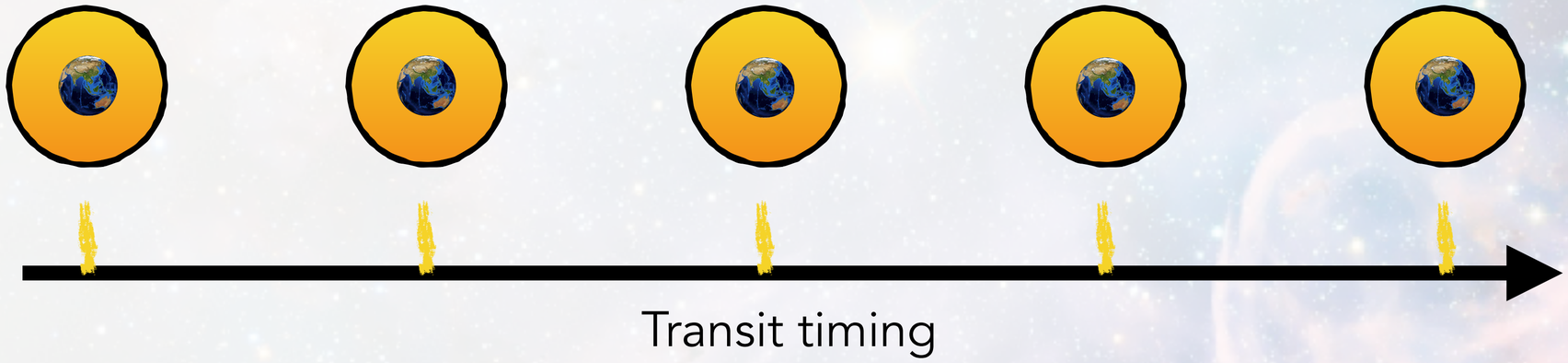
Radius ratio:
~ 1/100

Area ratio:
~ 1/10,000

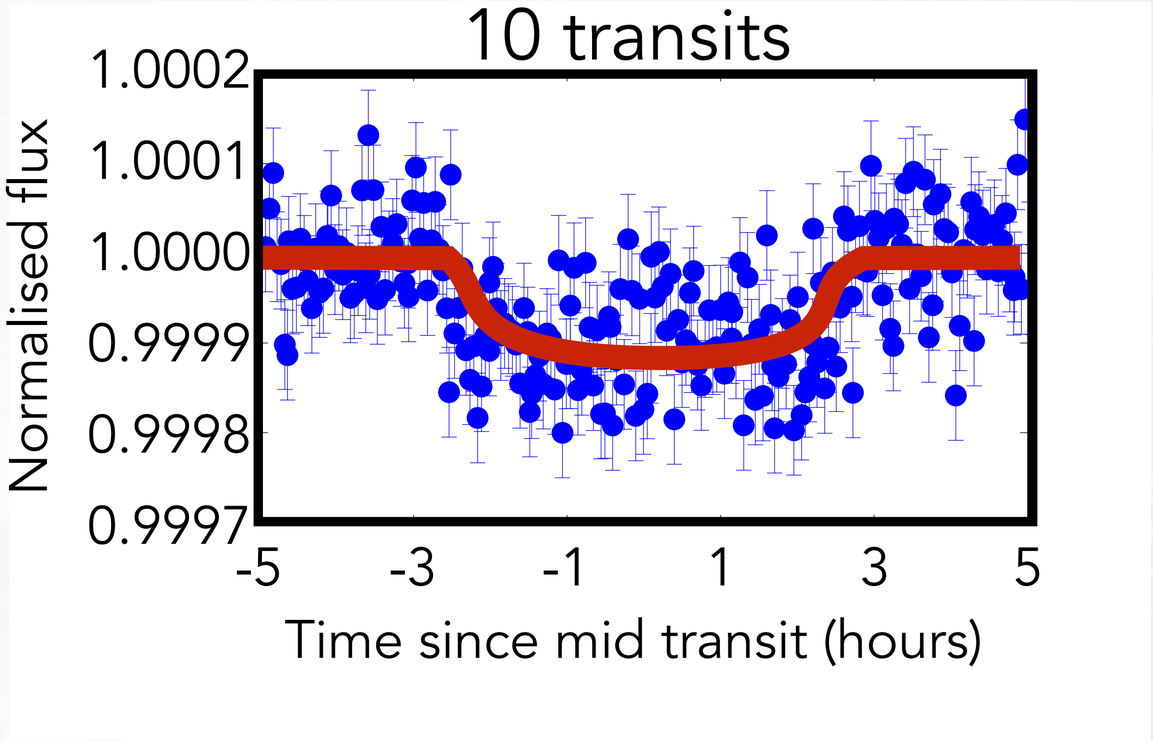
Transit depth
~ 0.01%

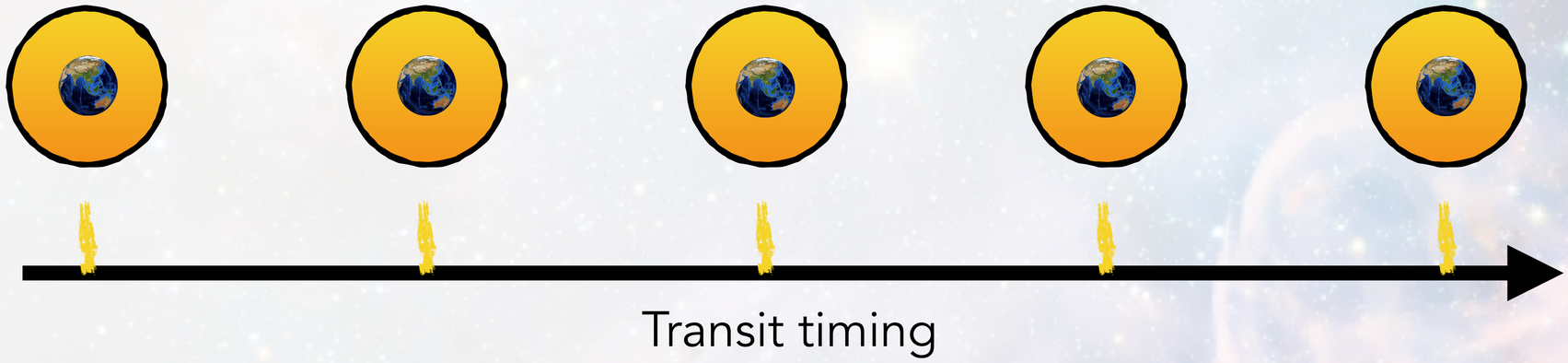
PHASE-FOLDING

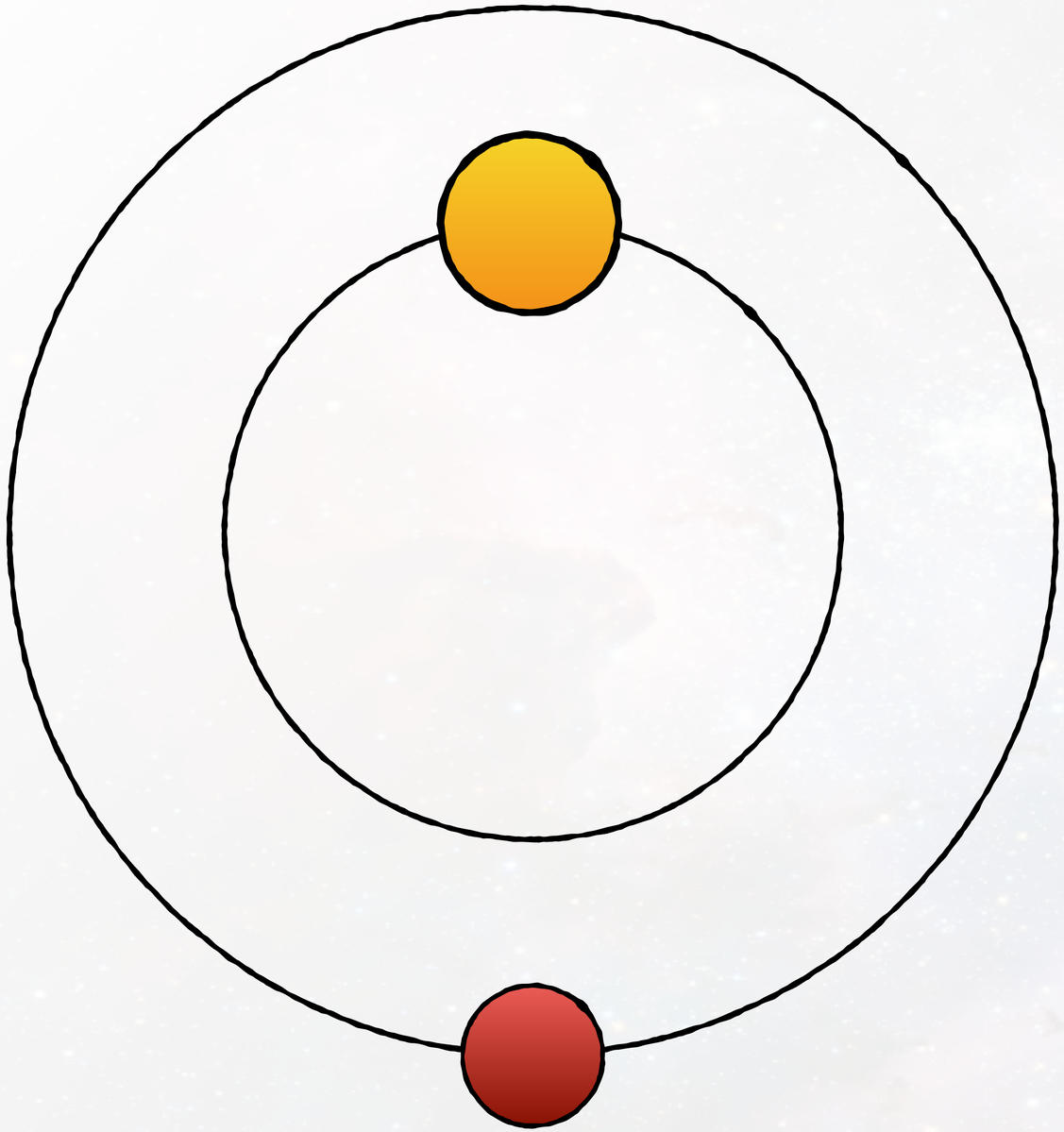


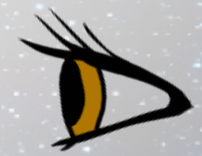


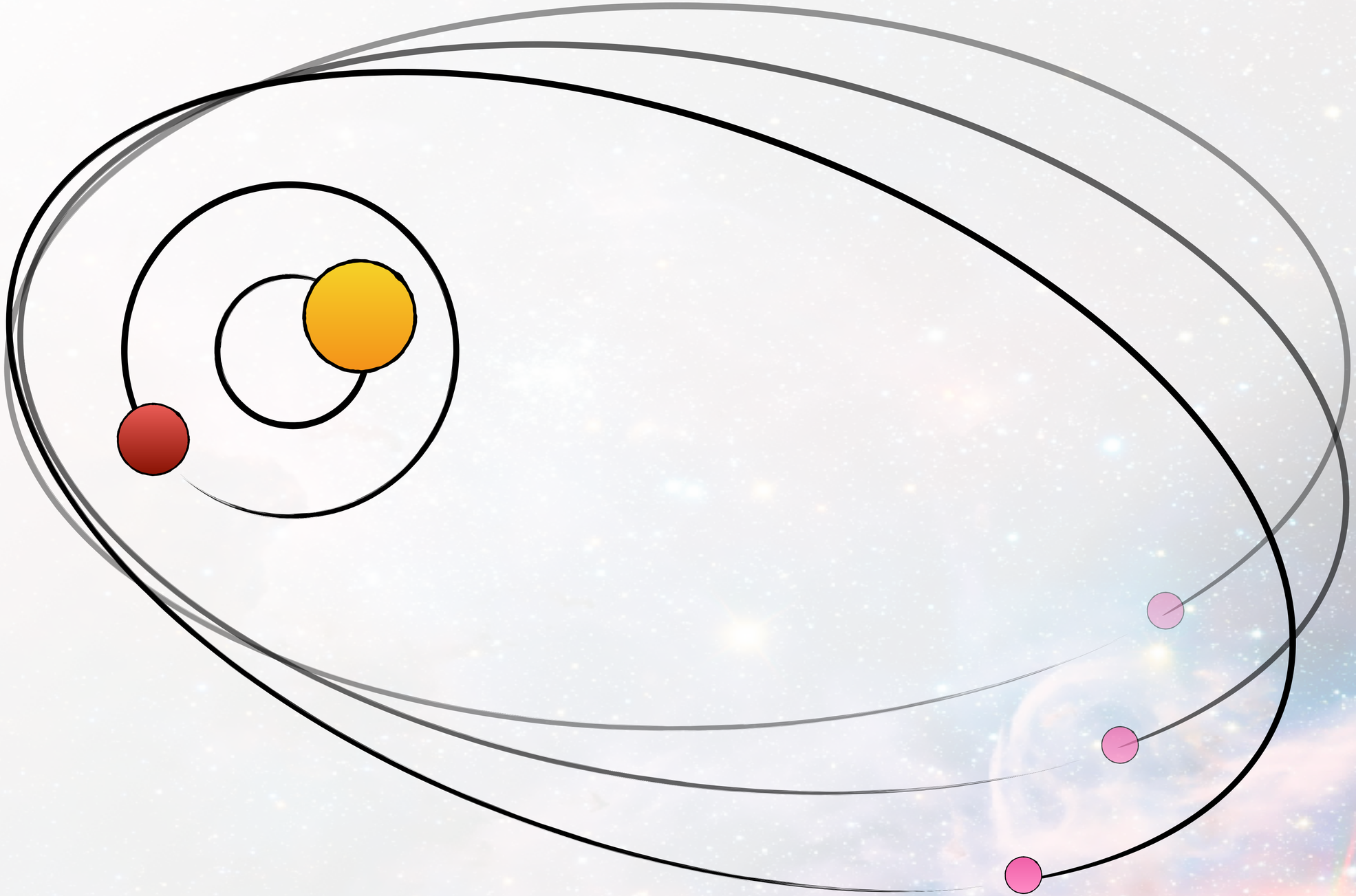
PHASE-FOLDING

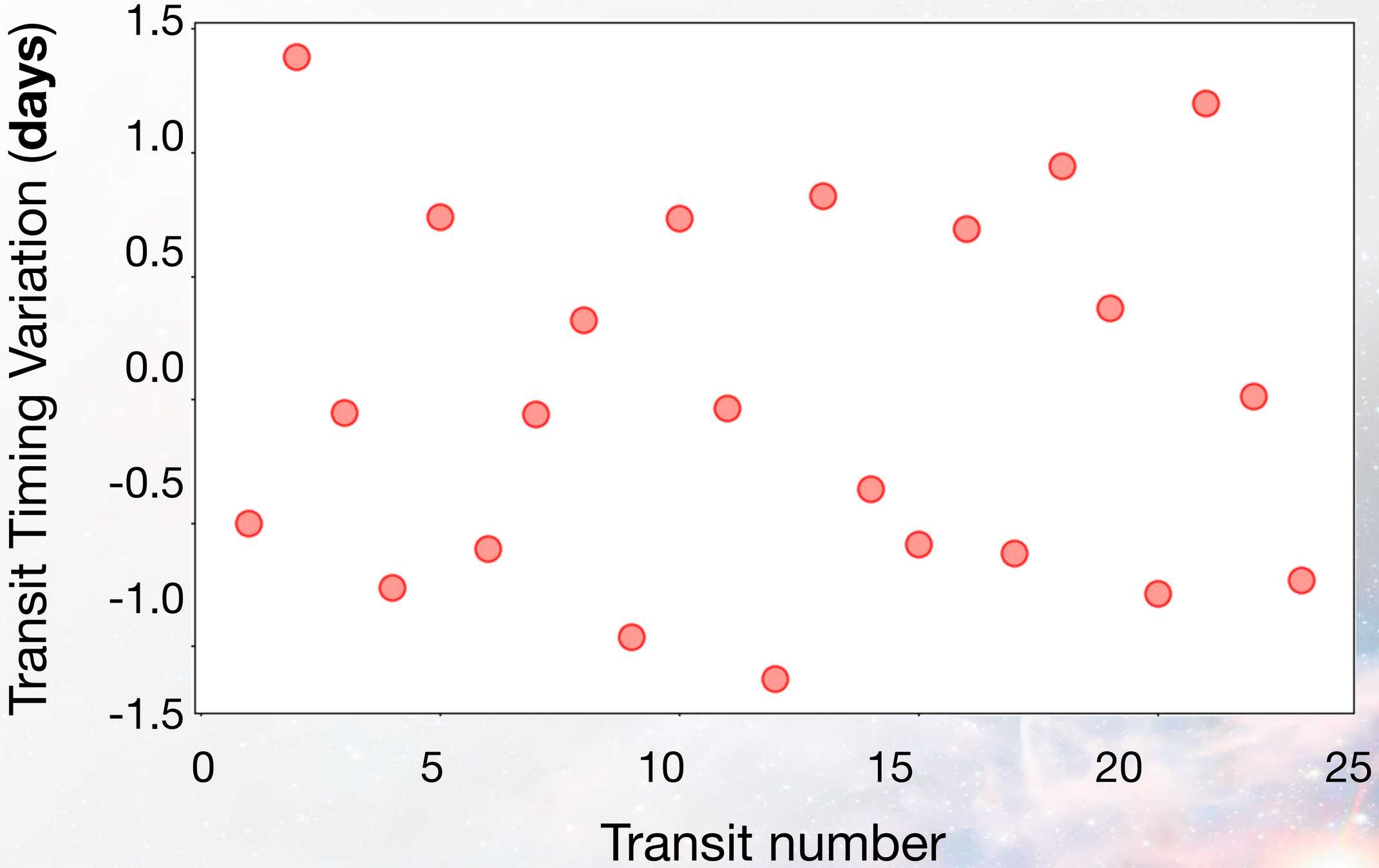


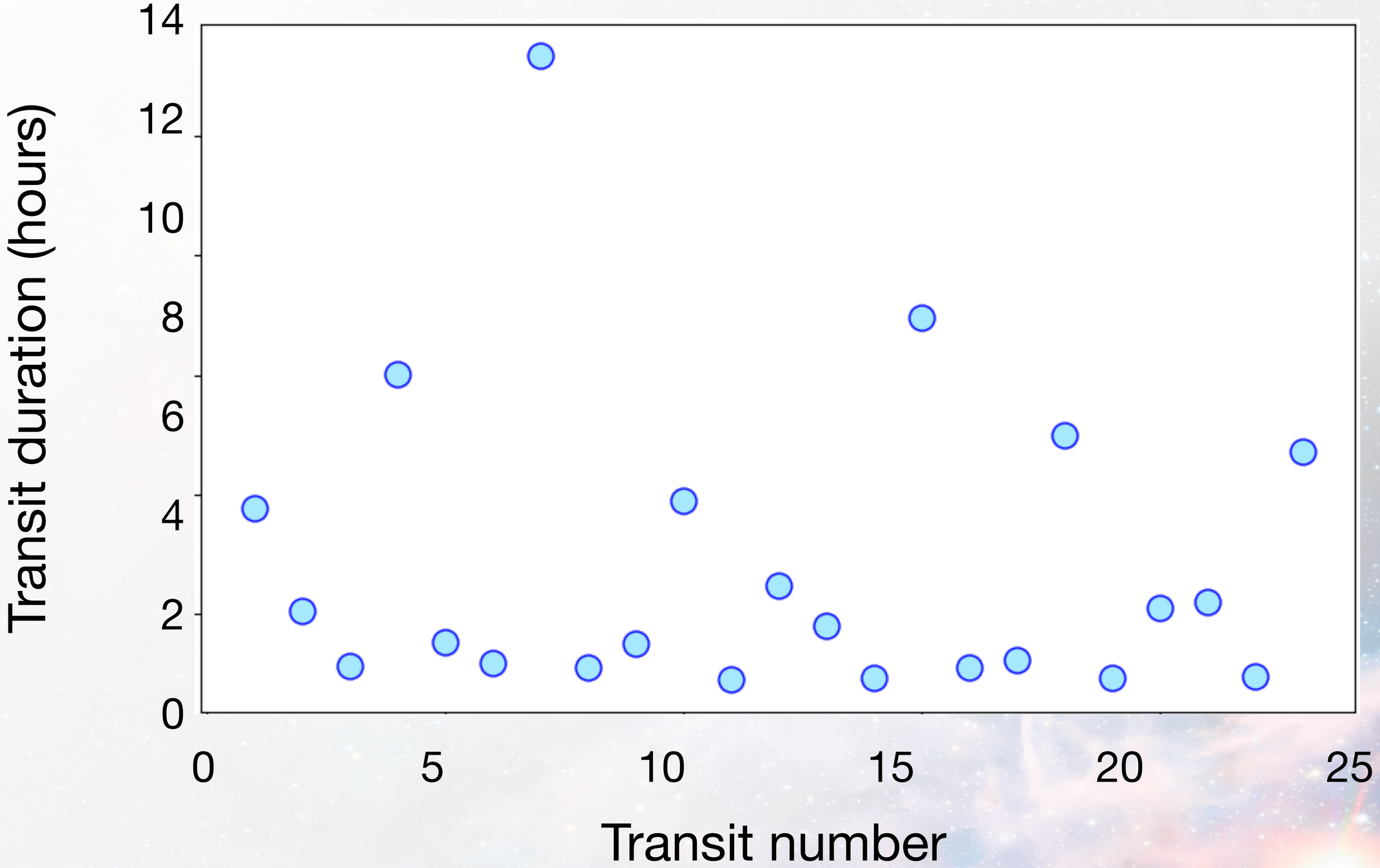




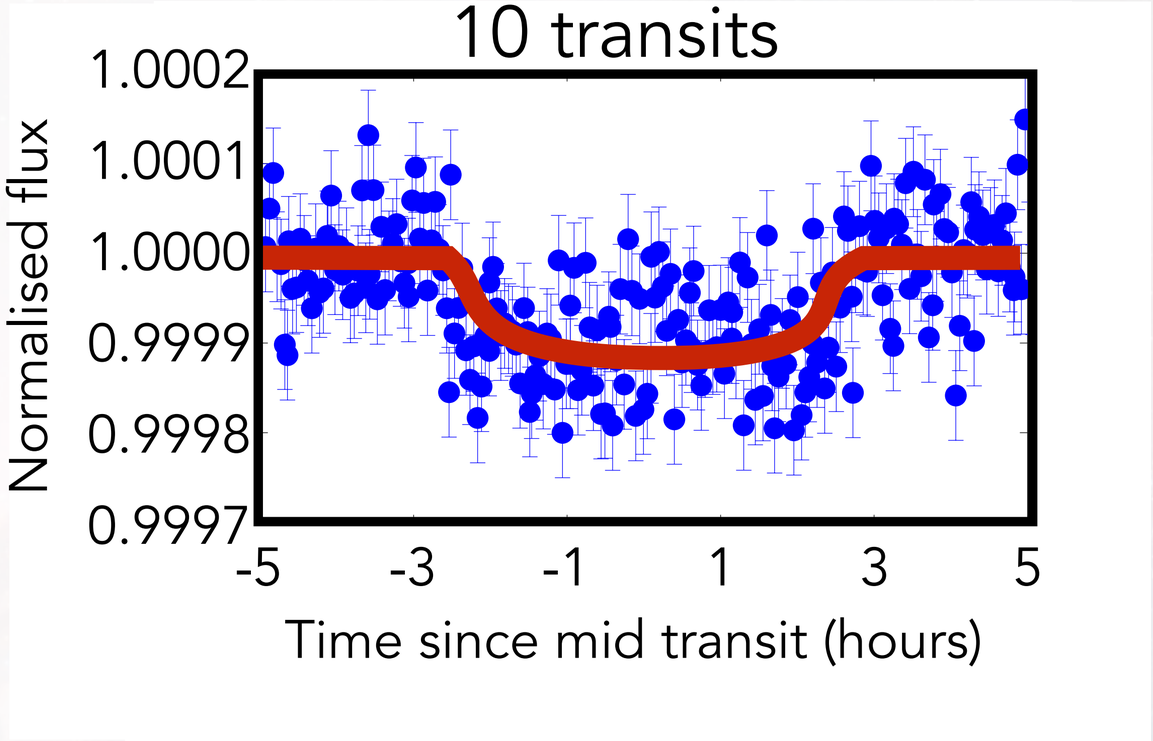


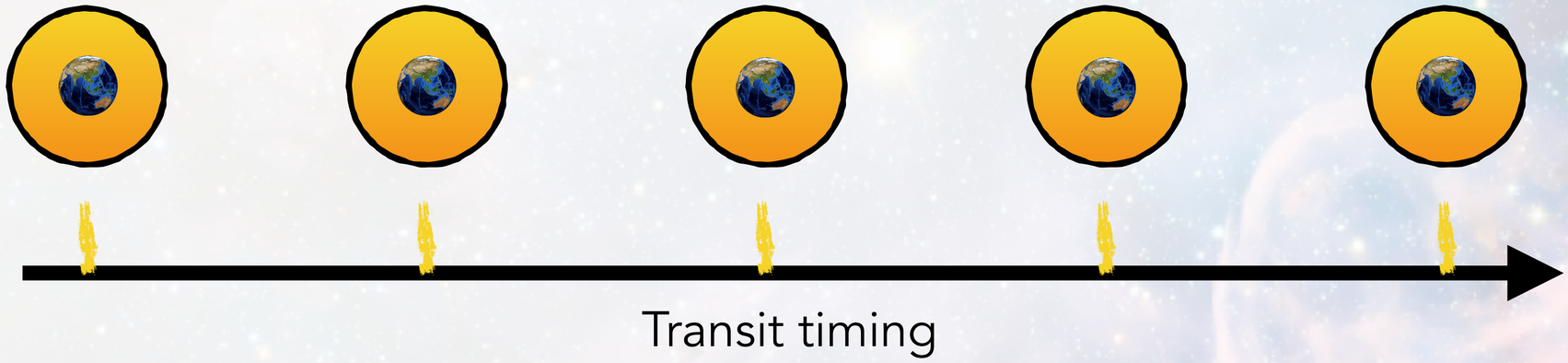



Transit Timing Variation (days)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0
5
10
15
20
25
Transit number

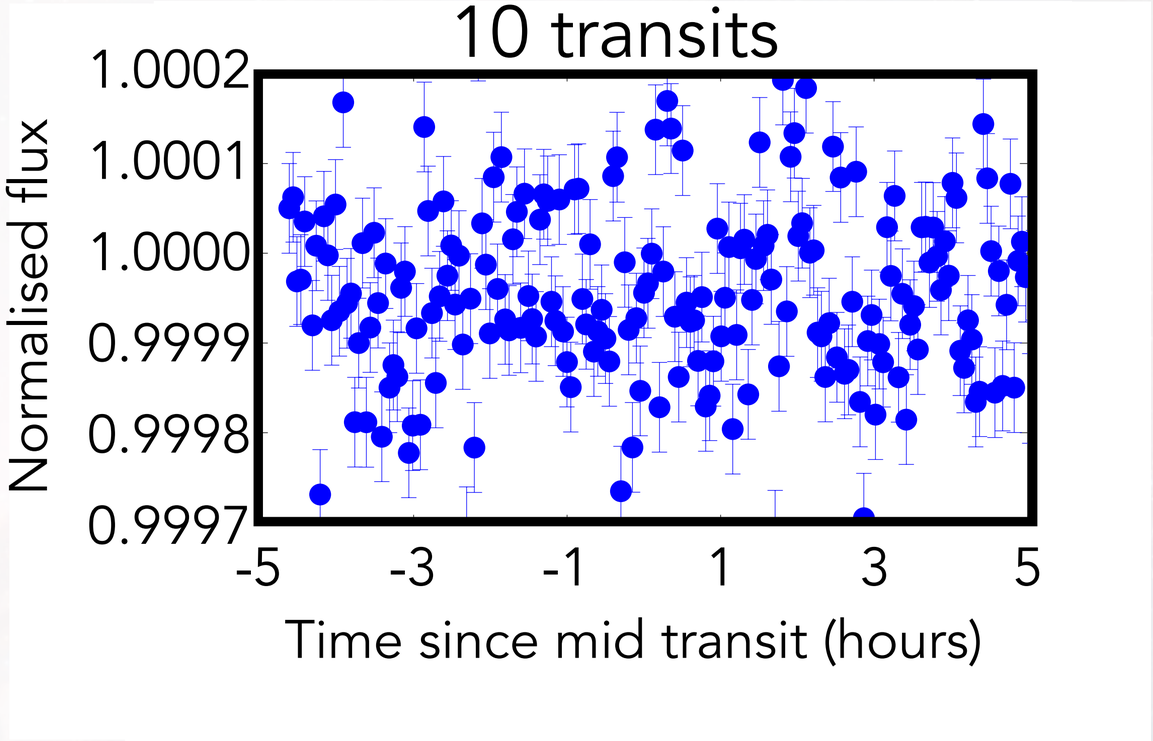

Transit duration (hours)
14
12
10
8
6
4
2
0
0
5
10
15
20
25
Transit number

PHASE-FOLDING





PHASE-FOLDING

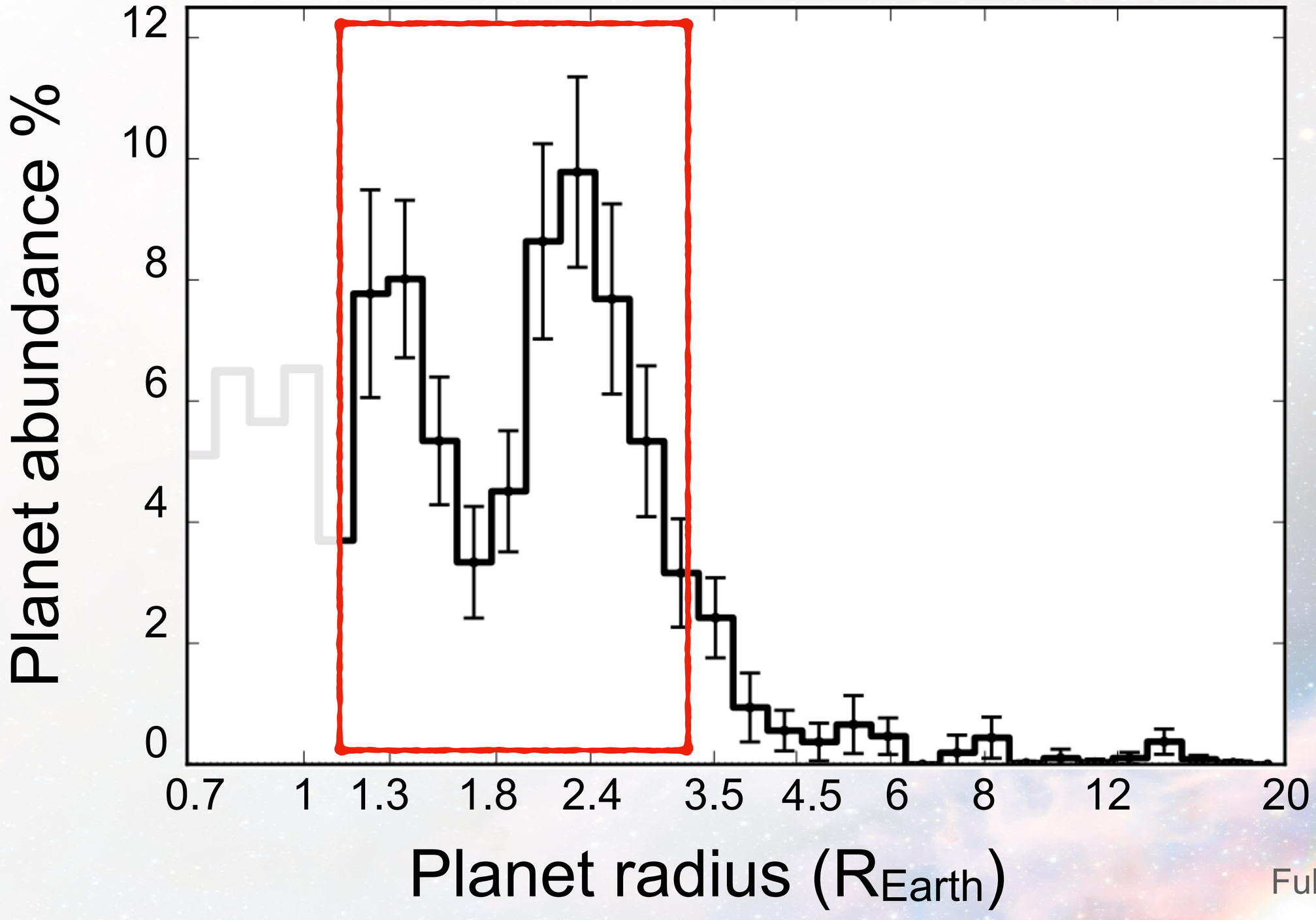


Old Method

INDIVIDUALLY SIGNIFICANT TRANSITS

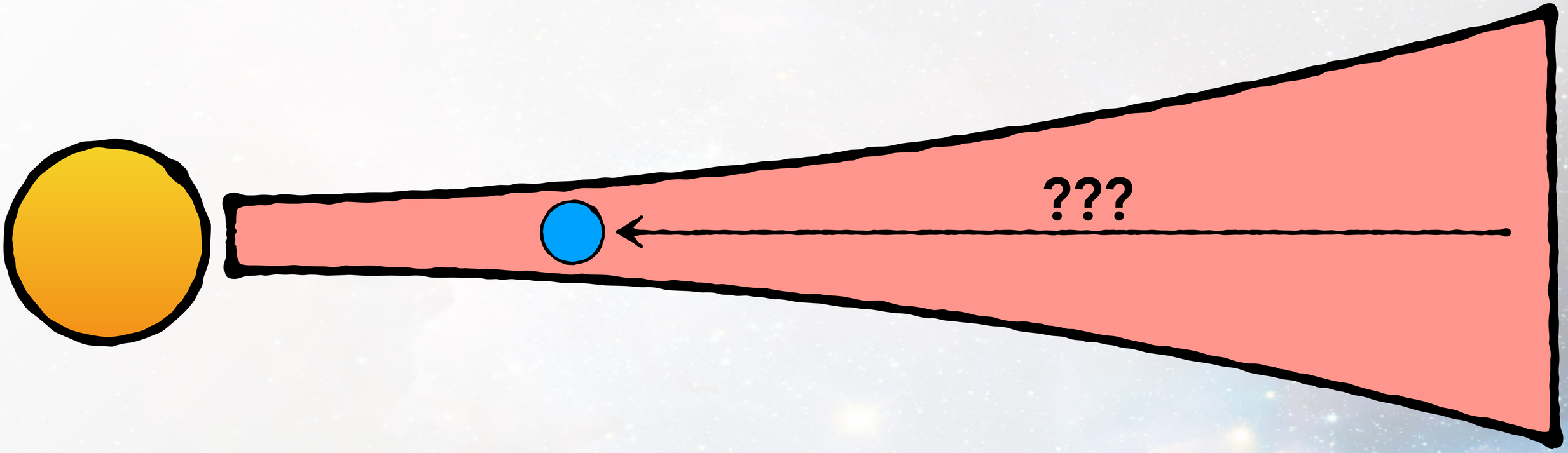
↓

GIANT PLANETS


Planet abundance %
0
2
4
6
8
10
12
0.7
1
1.3
1.8
2.4
3.5
4.5
6
8
12
20
Planet radius (R_{Earth})

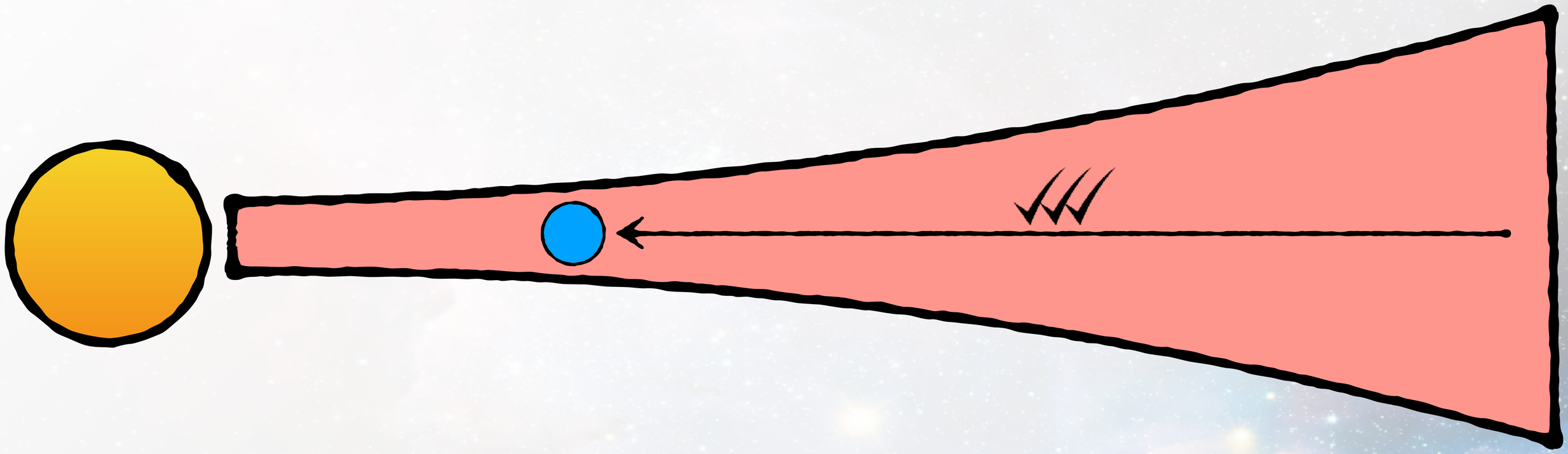
Fulton+ (2017)

In -Situ vs Migration

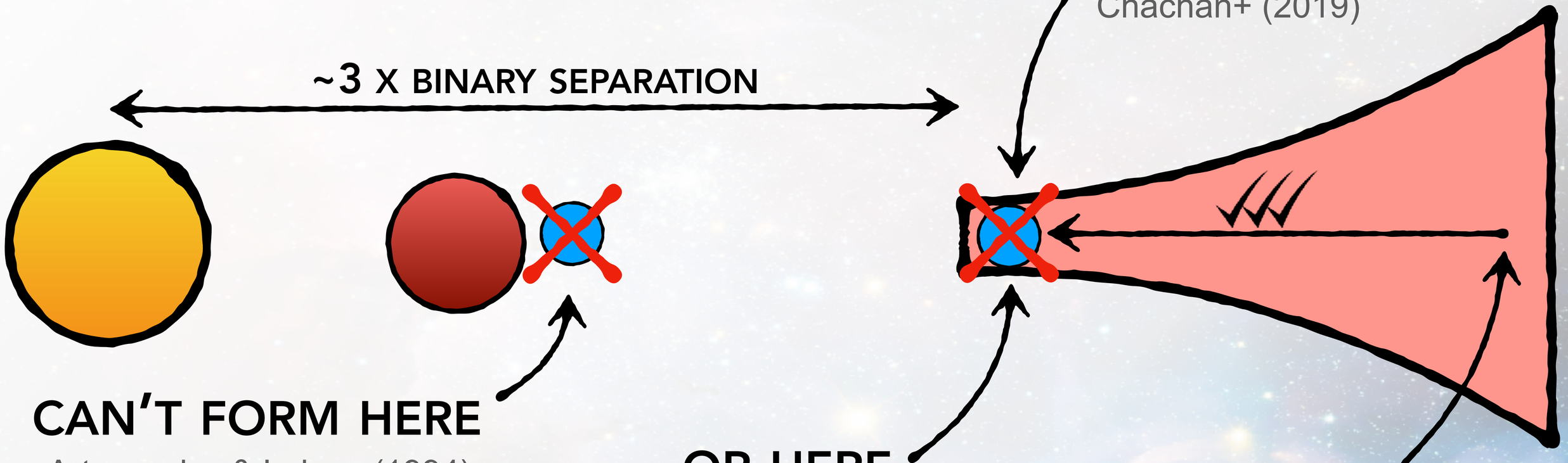


Hansen & Murray (2012)
Cossou+ (2014)
Martin & Livio (2016)
Lee & Chiang (2016)

~~In-Situ~~ vs Migration



~~In-Situ~~ vs Migration



Can't form here

Artymowicz & Lubow (1994)

But...

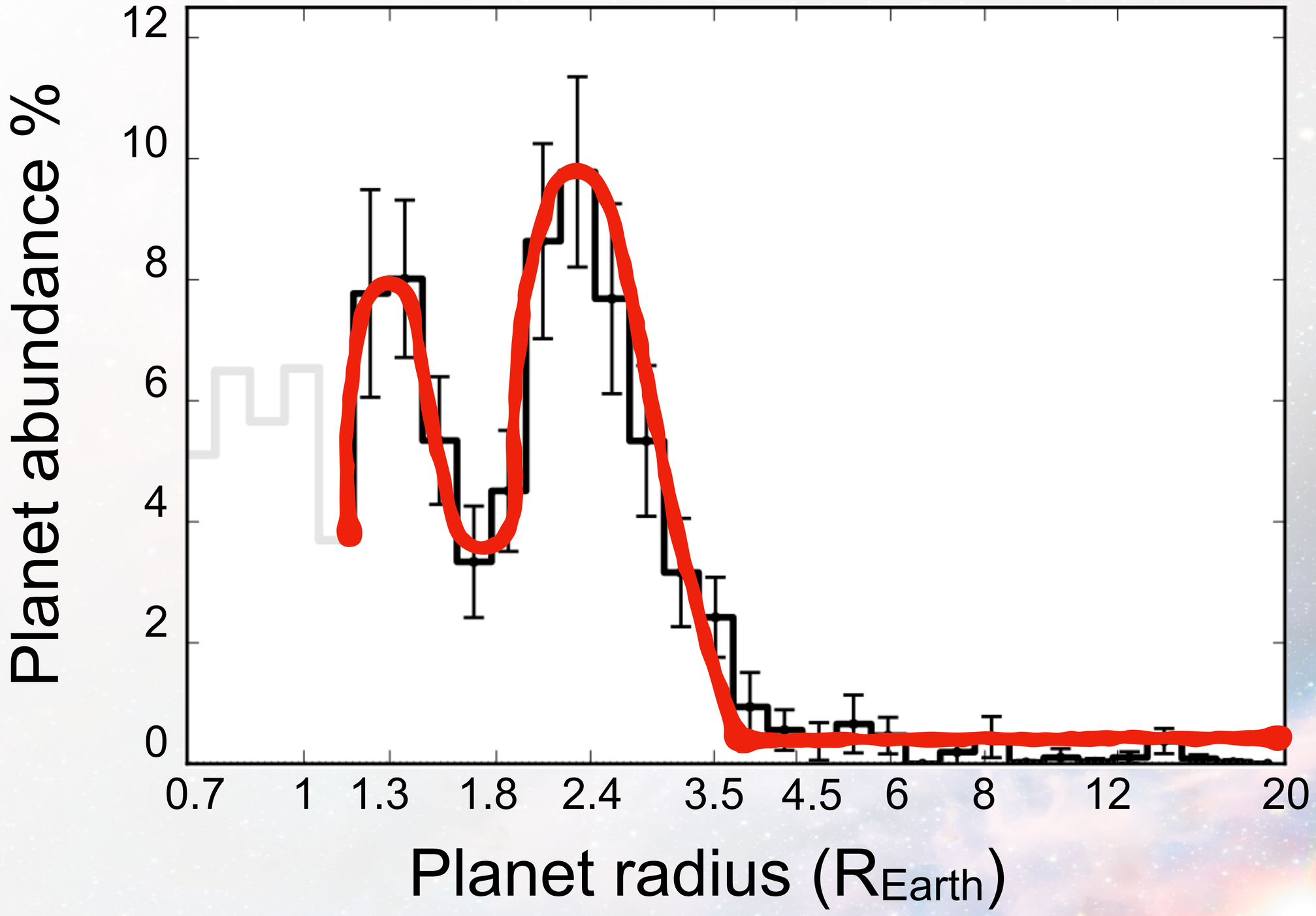
Chachan+ (2019)

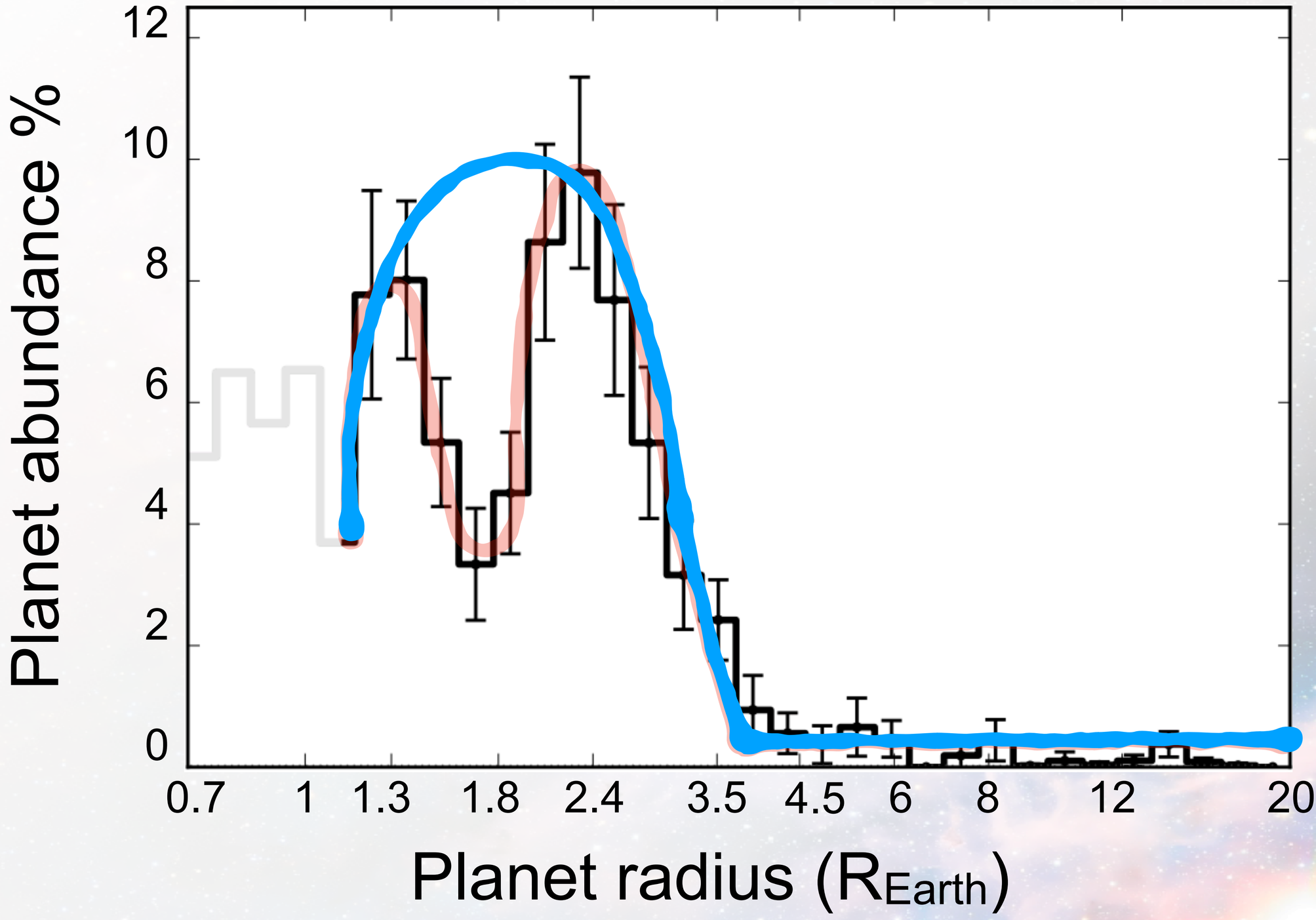
Or here

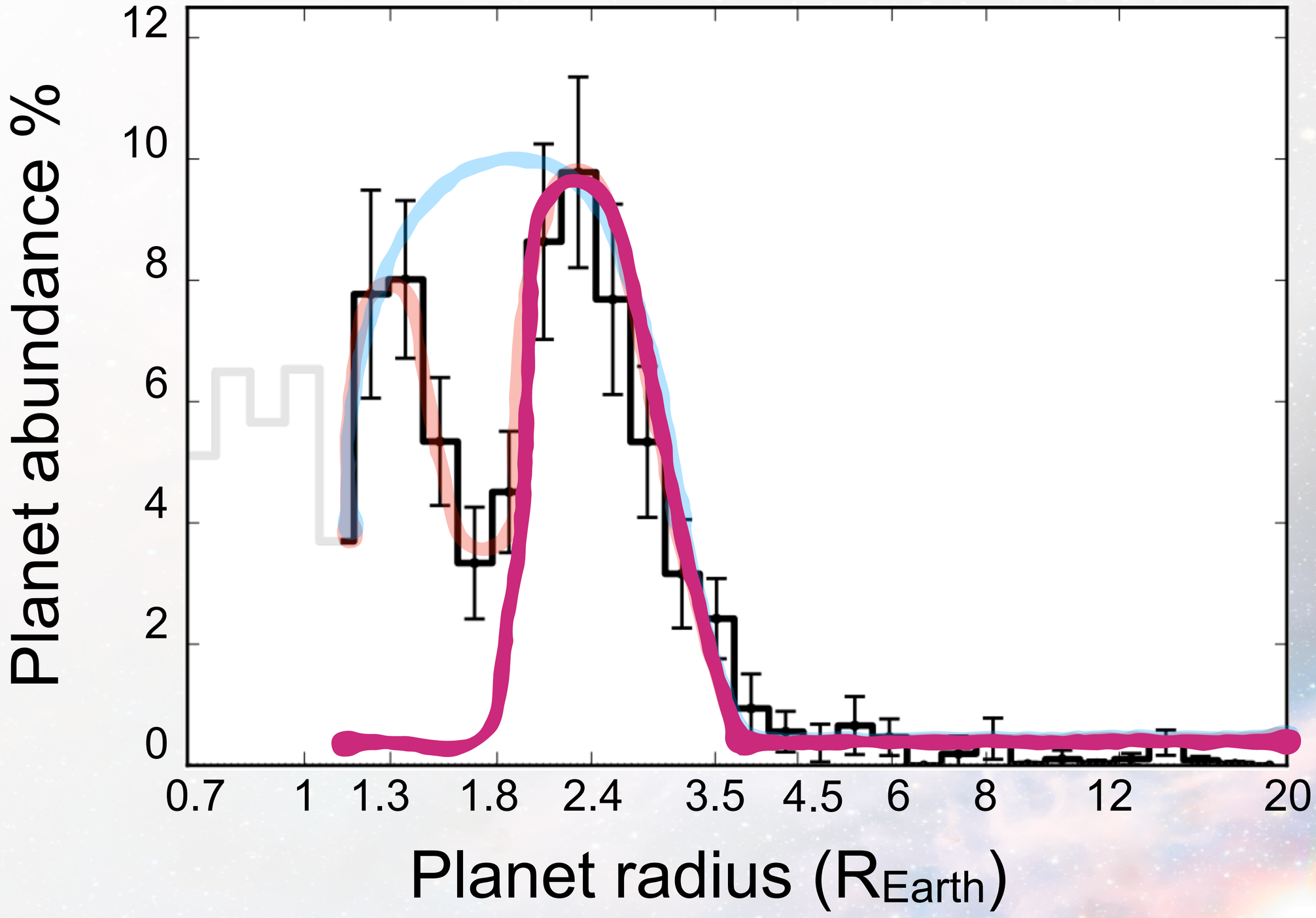
Pelupessy (2012)
Meschiari (2013)
Lines (2016)

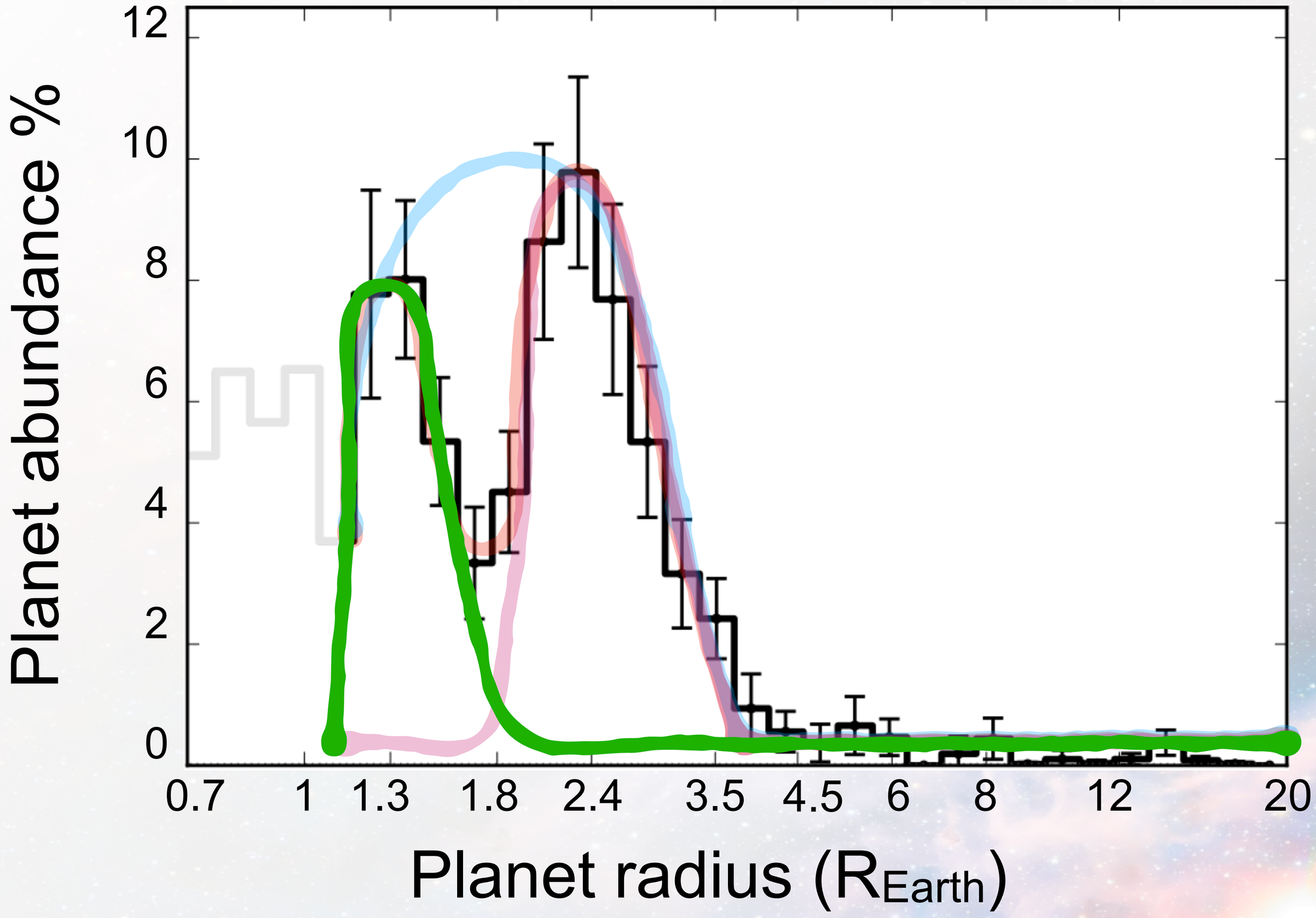
But far away is fine

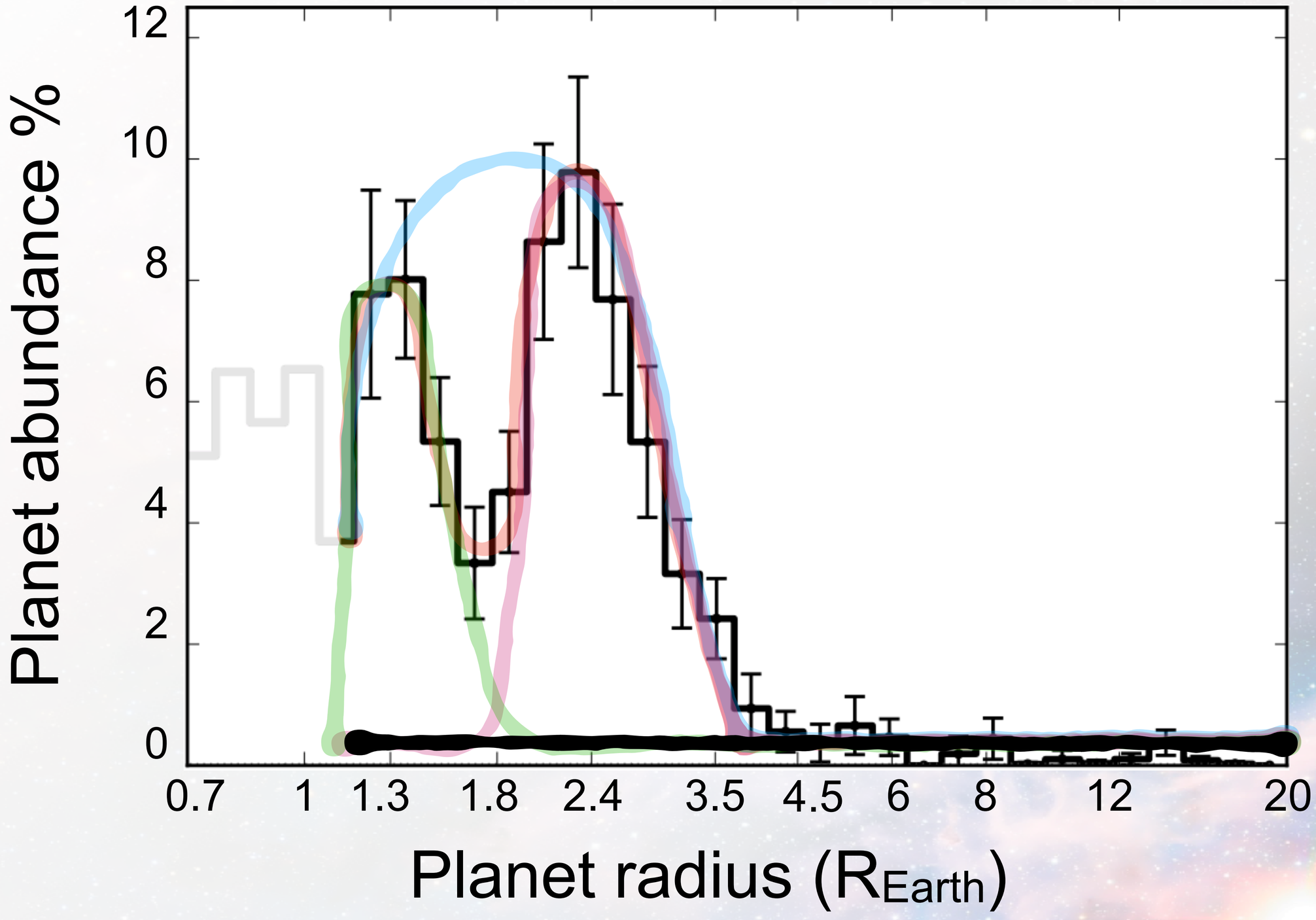
Pierens & Nelson (2013,18)
Kley & Haghighipour (2014,15)
Sutherland & Kratter (2019)


Planet abundance %
12
10
8
6
4
2
0
0.7
1
1.3
1.8
2.4
3.5
4.5
6
8
12
20
Planet radius (R_{Earth})


Planet abundance %
12
10
8
6
4
2
0
0.7
1
1.3
1.8
2.4
3.5
4.5
6
8
12
20
Planet radius (R_{Earth})


Planet abundance %
12
10
8
6
4
2
0
0.7
1
1.3
1.8
2.4
3.5
4.5
6
8
12
20
Planet radius (R_{Earth})


Planet abundance %
12
10
8
6
4
2
0
0.7
1
1.3
1.8
2.4
3.5
4.5
6
8
12
20
Planet radius (R_{Earth})


Planet abundance %
12
10
8
6
4
2
0
0.7
1
1.3
1.8
2.4
3.5
4.5
6
8
12
20
Planet radius (R_{Earth})

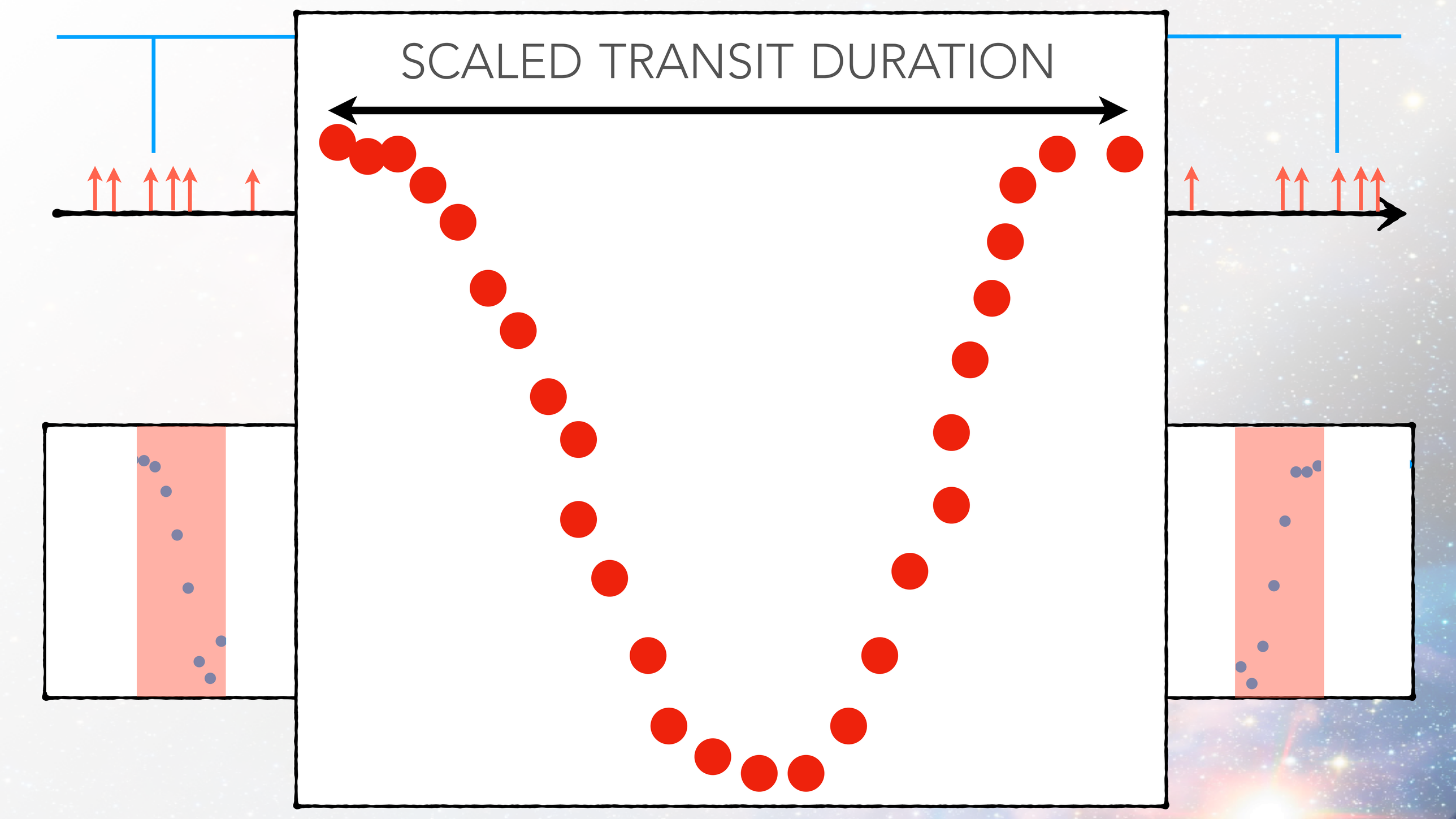
New Method

FOLD ON VARIABLE TRANSIT TIMES AND DURATIONS

↓

SMALL PLANETS

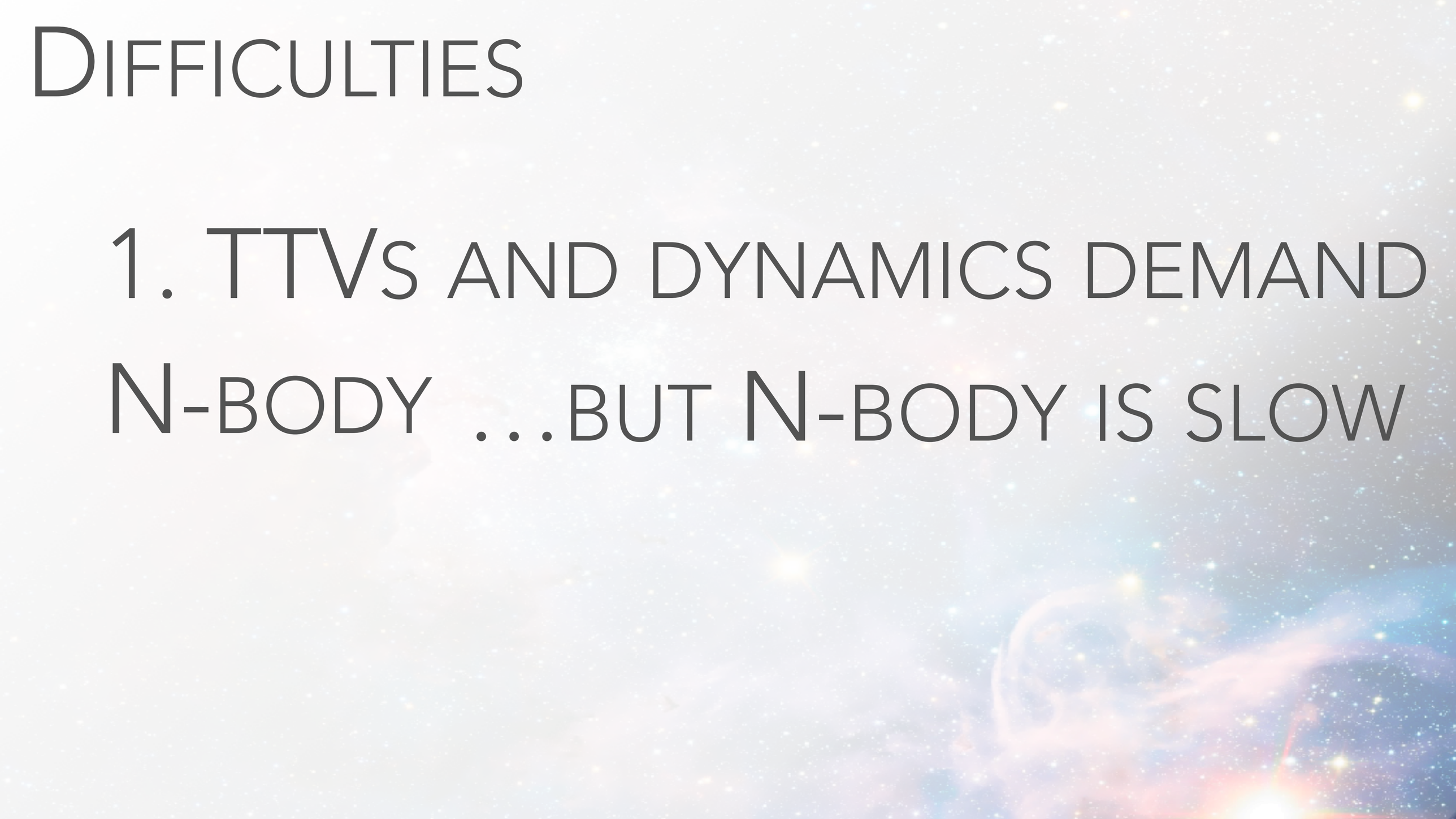

time


SCALED TRANSIT DURATION

Difficulties

Difficulties

1. TTVs and dynamics demand N-body …but N-body is slow



PARAMETER LIST

Binary

Period, P

Eccentricity, e

Argument periapse, ω

Orbital phase, ϑ

Inclination, I

Long. Ascending Node, Ω

Planet

Period, P

Eccentricity, e

Argument periapse, ω

Orbital phase, ϑ

Inclination, I

Long. Ascending Node, Ω

Bodies

M_A

M_B

M_p

R_A

R_B

R_p

18 parameters

PARAMETER LIST

Binary

Period, P

Eccentricity, e

Argument periapse, ω

Orbital phase, ϑ

Inclination, I

Long. Ascending Node, Ω

Planet

Period, P

Eccentricity, e

Argument periapse, ω

Orbital phase, ϑ

Inclination, I

Long. Ascending Node, Ω

Bodies

M_A

M_B

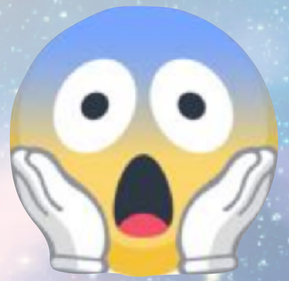
~~M_p~~

~~R_A~~

~~R_B~~

~~R_p~~

14 parameters



PARAMETER LIST

Binary

Period, P

Eccentricity, e

Argument periapse, ω

Orbital phase, ϑ

~~Inclination, I~~

~~Long. Ascending Node, Ω~~

Planet

Period, P

Eccentricity, e

Argument periapse, ω

Orbital phase, ϑ

~~Inclination, I~~

~~Long. Ascending Node, Ω~~

Bodies

M_A

M_B

~~M_p~~

~~R_A~~

~~R_B~~

~~R_p~~

10 parameters

PARAMETER LIST

Binary

Period, P

Eccentricity, e

Argument periapse, ω

Orbital phase, ϑ

~~Inclination, I~~

~~Long. Ascending Node, Ω~~

Planet

Period, P

Eccentricity, e

Argument periapse, ω

Orbital phase, ϑ

~~Inclination, I~~

~~Long. Ascending Node, Ω~~

Bodies

M_A

M_B

~~M_p~~

~~R_A~~

~~R_B~~

~~R_p~~

Villanova EB catalog

(e.g. Prsa+ 11, Kirk+ 16)

6 parameters

PARAMETER LIST

Windemuth & Agol+ 19
Moe & Di Stefano 15a,b
Future Villanova RVs

Binary

Period, P
Eccentricity, e
Argument periapse, ω
Orbital phase, ϑ
~~Inclination, I~~
~~Long. Ascending Node, Ω~~

Planet

Period, P
Eccentricity, e
Argument periapse, ω
Orbital phase, ϑ
~~Inclination, I~~
~~Long. Ascending Node, Ω~~

Bodies

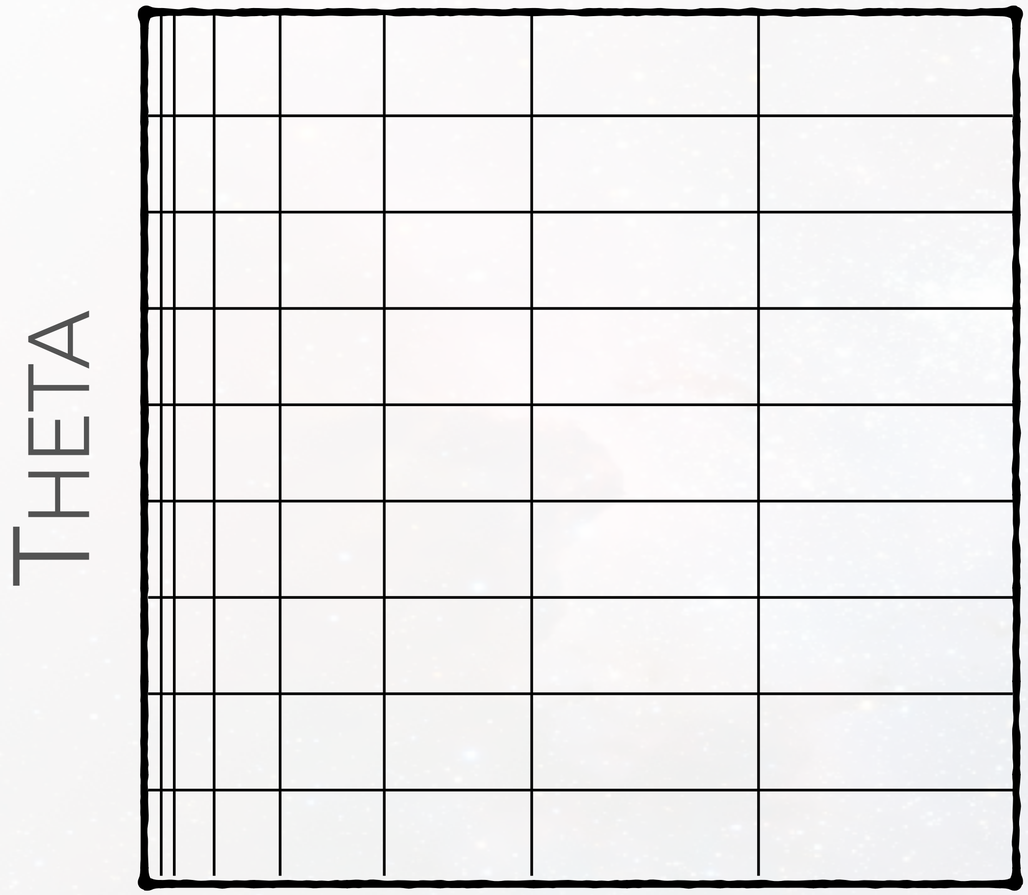
M_A
M_B
~~M_p~~
~~R_A~~
~~R_B~~
~~R_p~~

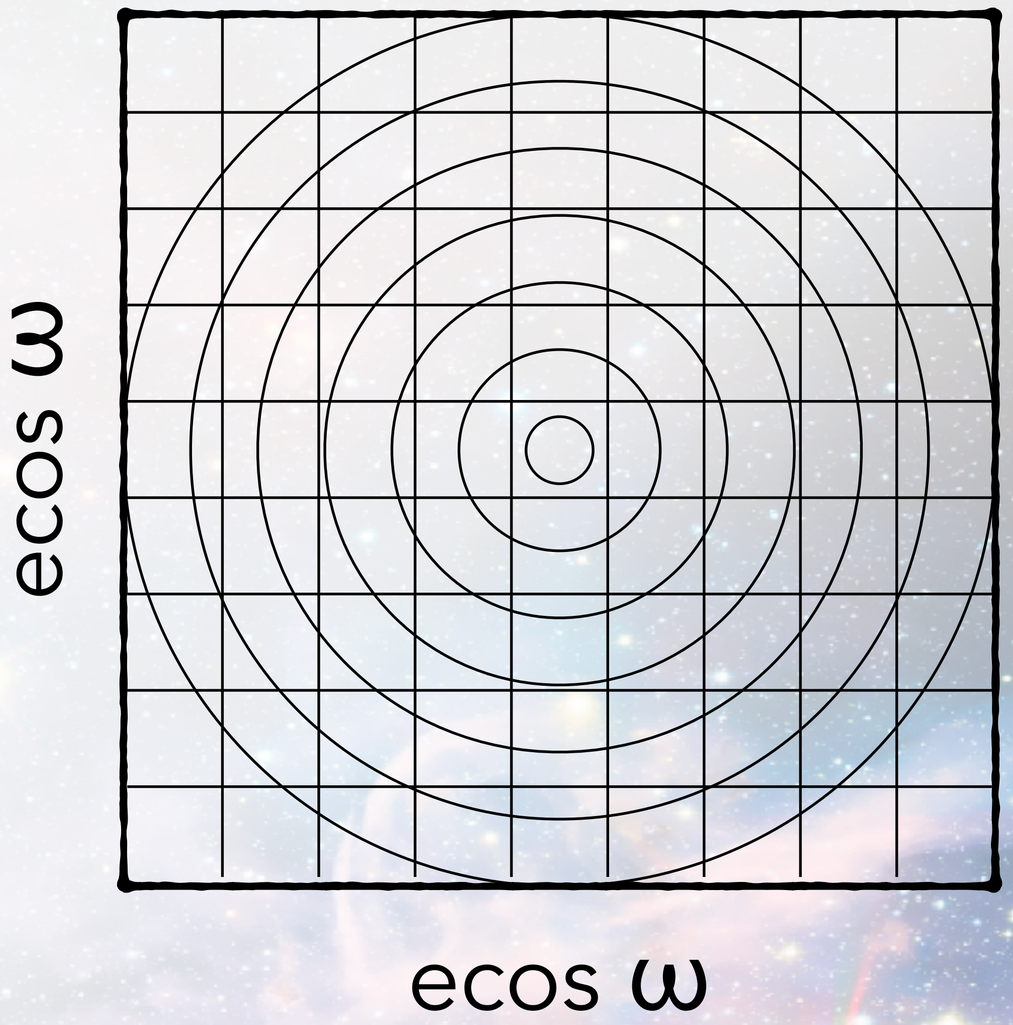
Villanova EB catalog

(e.g. Prsa+ 11, Kirk+ 16)

4 parameters

Optimized search grids





Difficulties

1. Slow N-body

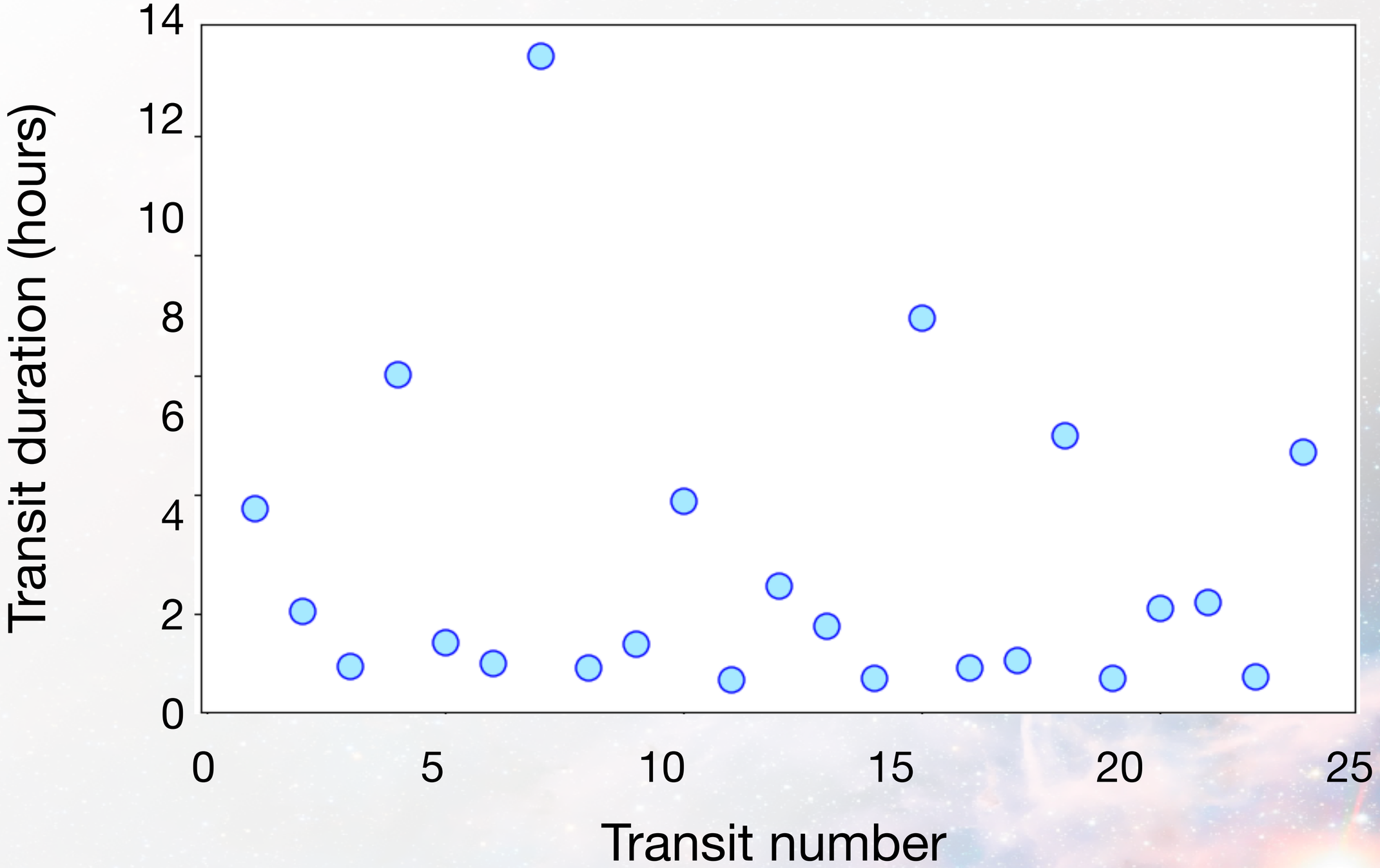
2. Detrending EBs is tricky

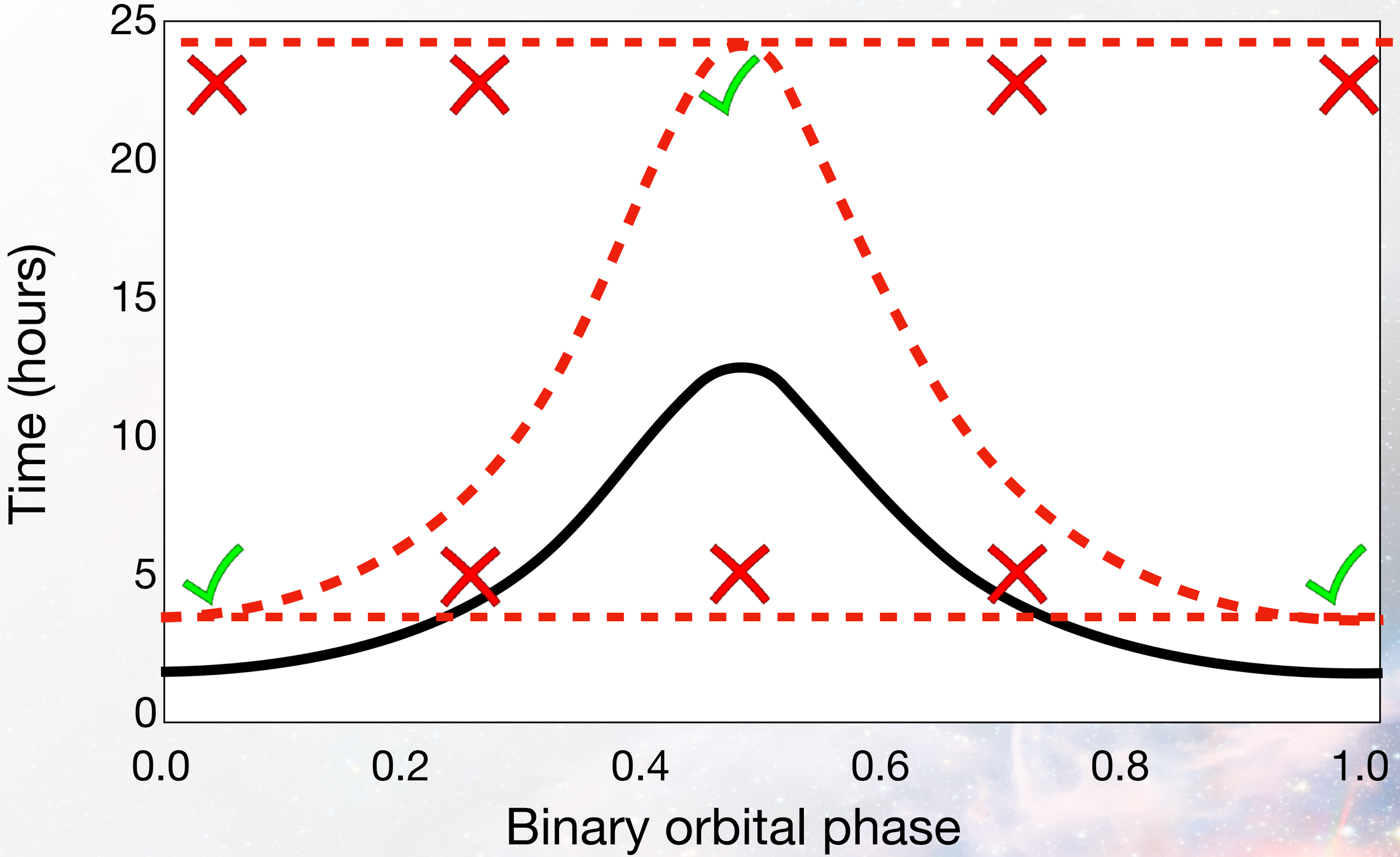
Effects in light curve

- Eclipses (can be few % duty cycle)
- Stellar variability/rotation x2
- Doppler beaming/boosting
- Ellipsoidal variation
- Reflection
- Variable transit duration

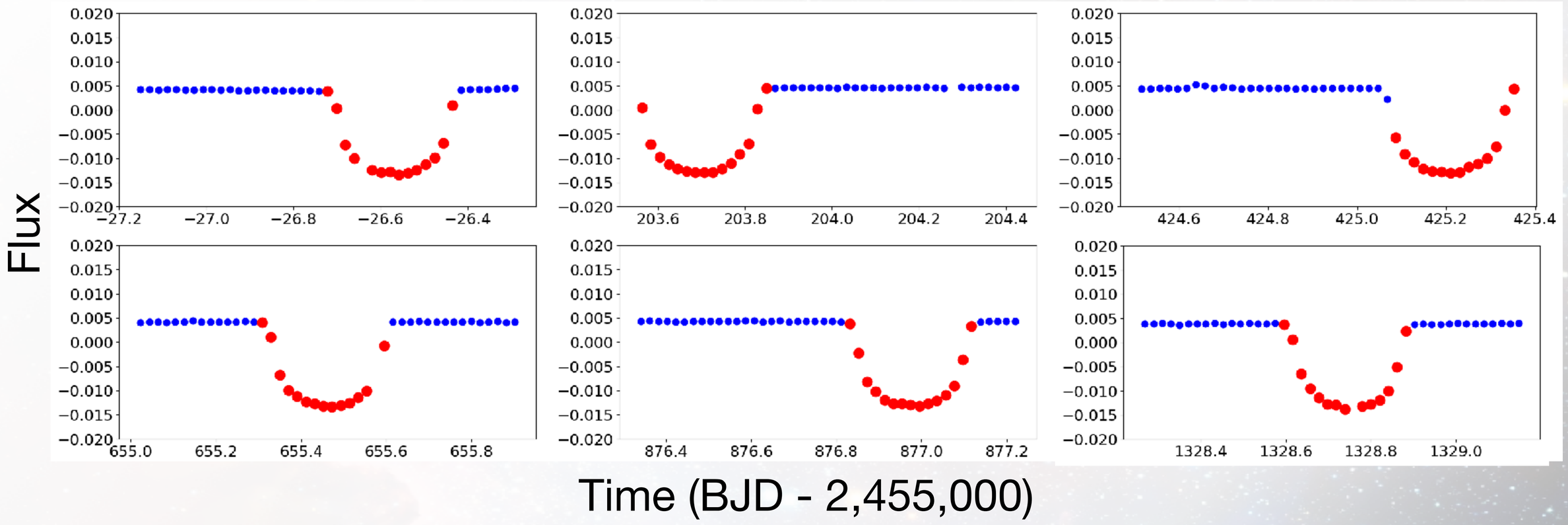
Effects in light curve

- Eclipses (can be few % duty cycle)
- Stellar variability/rotation x2
- Doppler beaming/boosting
- Ellipsoidal variation
- Reflection
- **Variable transit duration**


Transit duration (hours)
14
12
10
8
6
4
2
0
0
5
10
15
20
25
Transit number

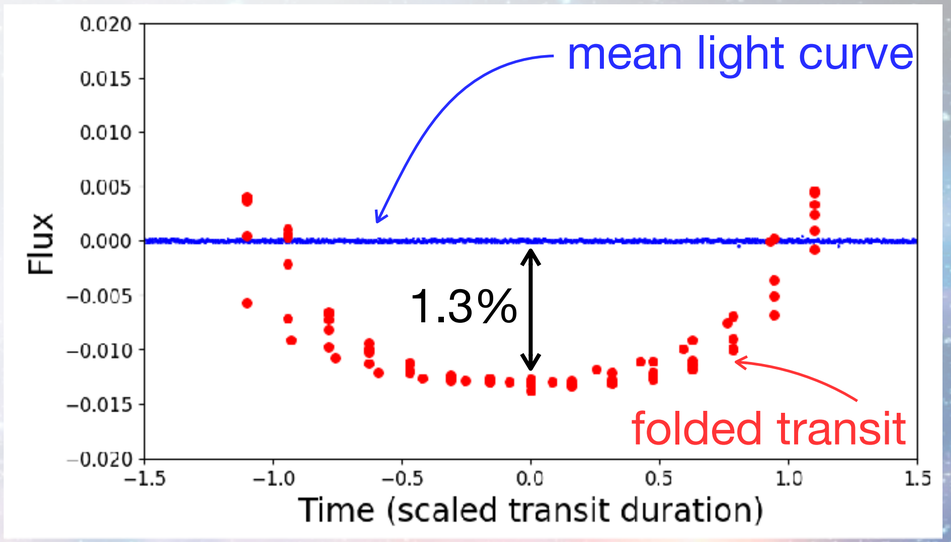

25
20
15
10
5
0
Time (hours)
0.0
0.2
0.4
0.6
0.8
1.0
Binary orbital phase

But in the end…

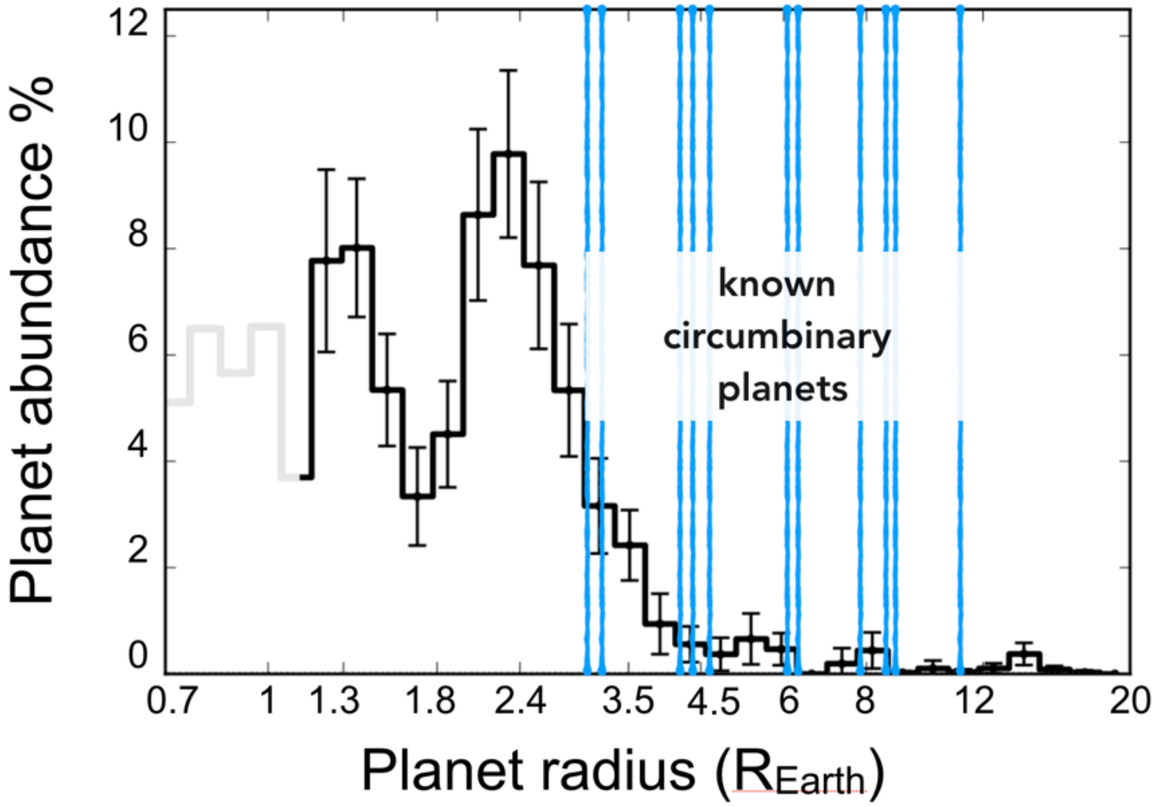


KEPLER 16

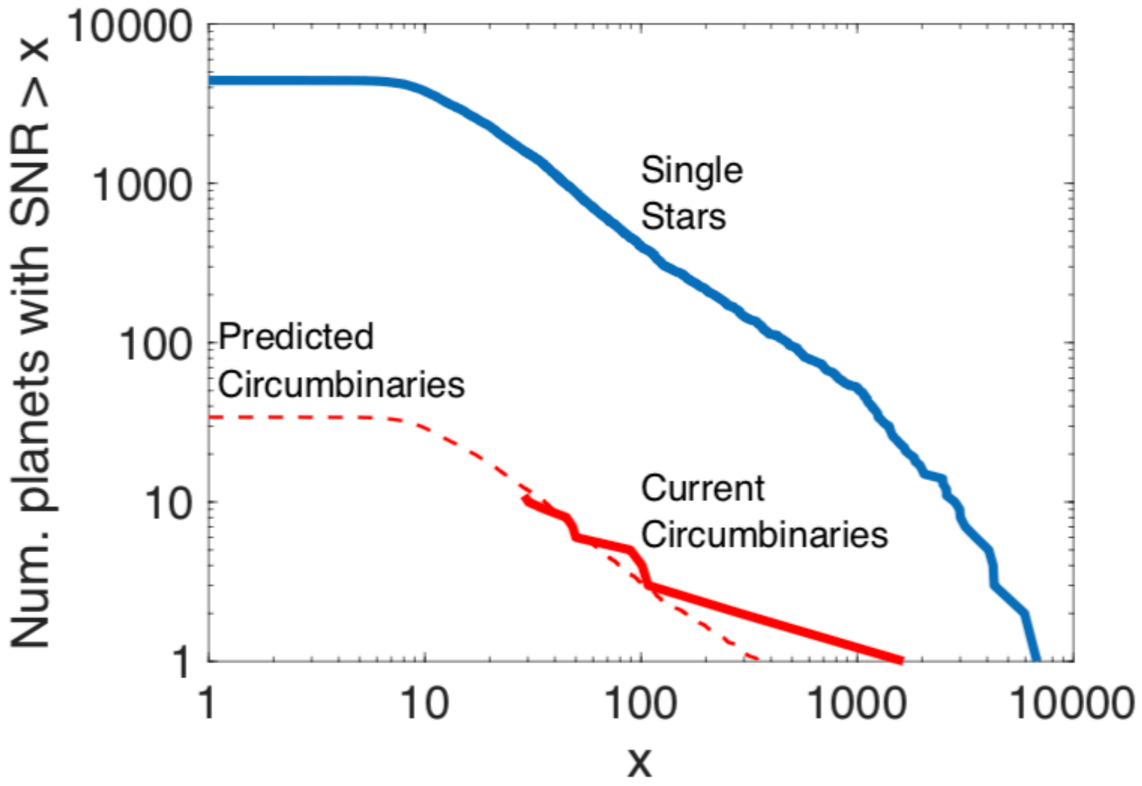
8.3 R_{EARTH} @ ~228 DAYS

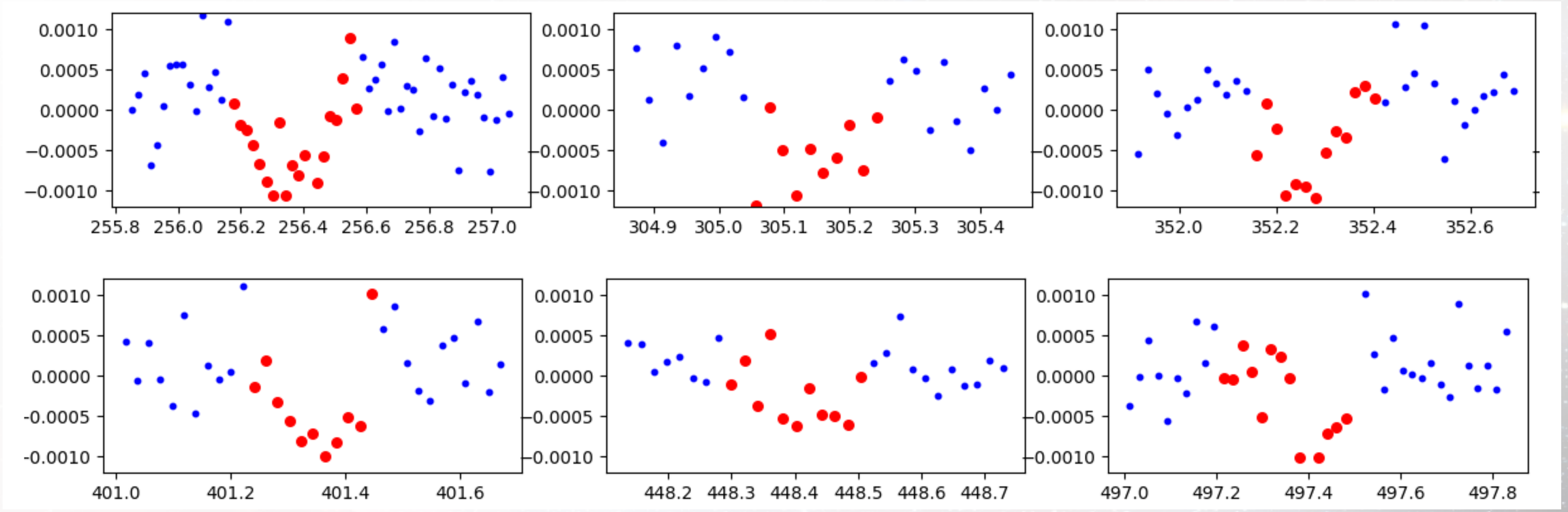


(a)


Planet abundance %
12
10
8
6
4
2
0
0.7
1
1.3
1.8
2.4
3.5
4.5
6
8
12
20
known
circumbinary
planets
Planet radius (R_Earth)

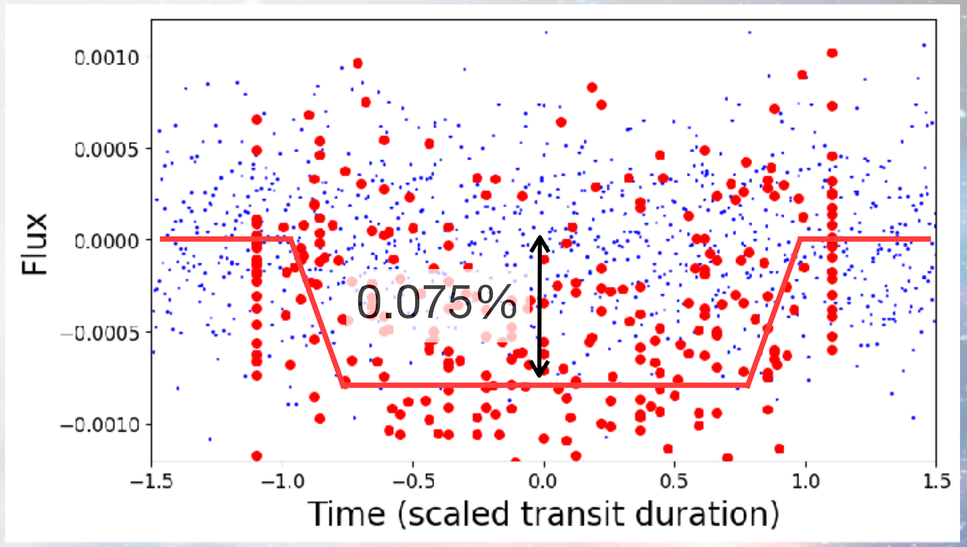
(b)

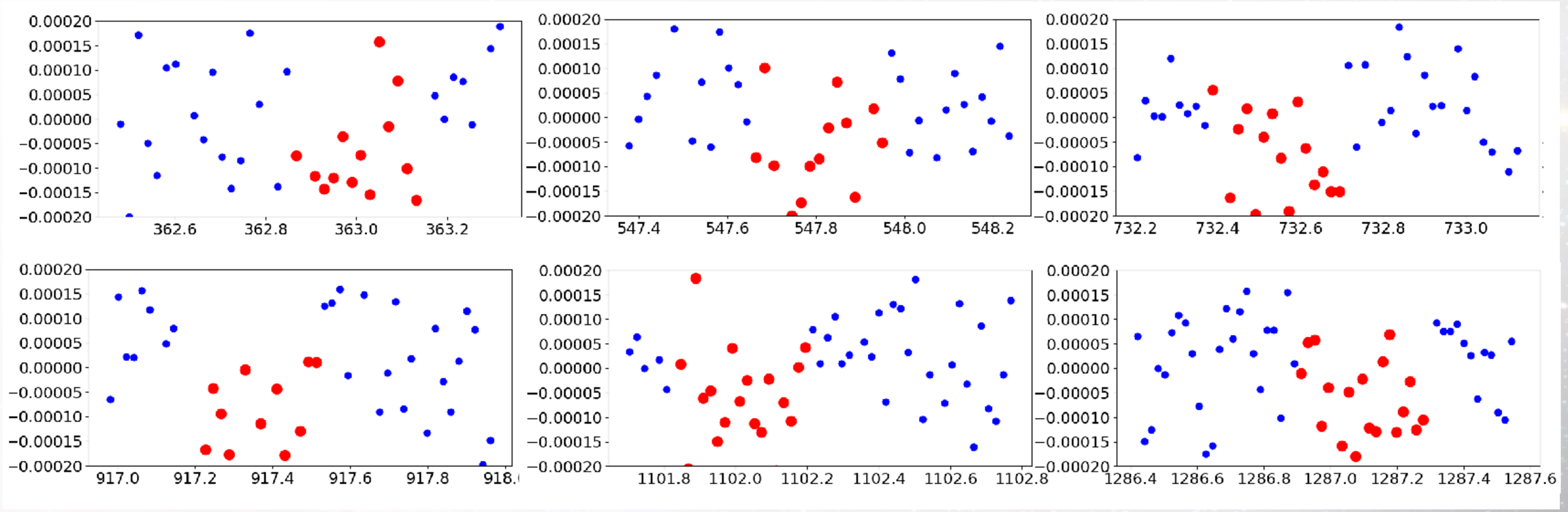

Num. planets with SNR > x
10000
1000
100
10
1
1
10
100
1000
10000
x
Single
Stars
Predicted
Circumbinaries
Current
Circumbinaries



KEPLER 47

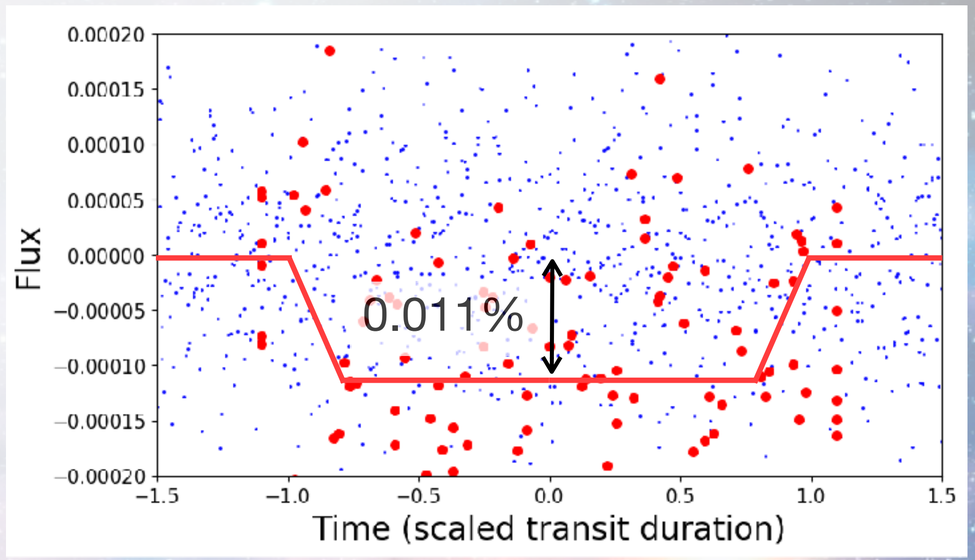
3 R_{EARTH} @ ~49 DAYS

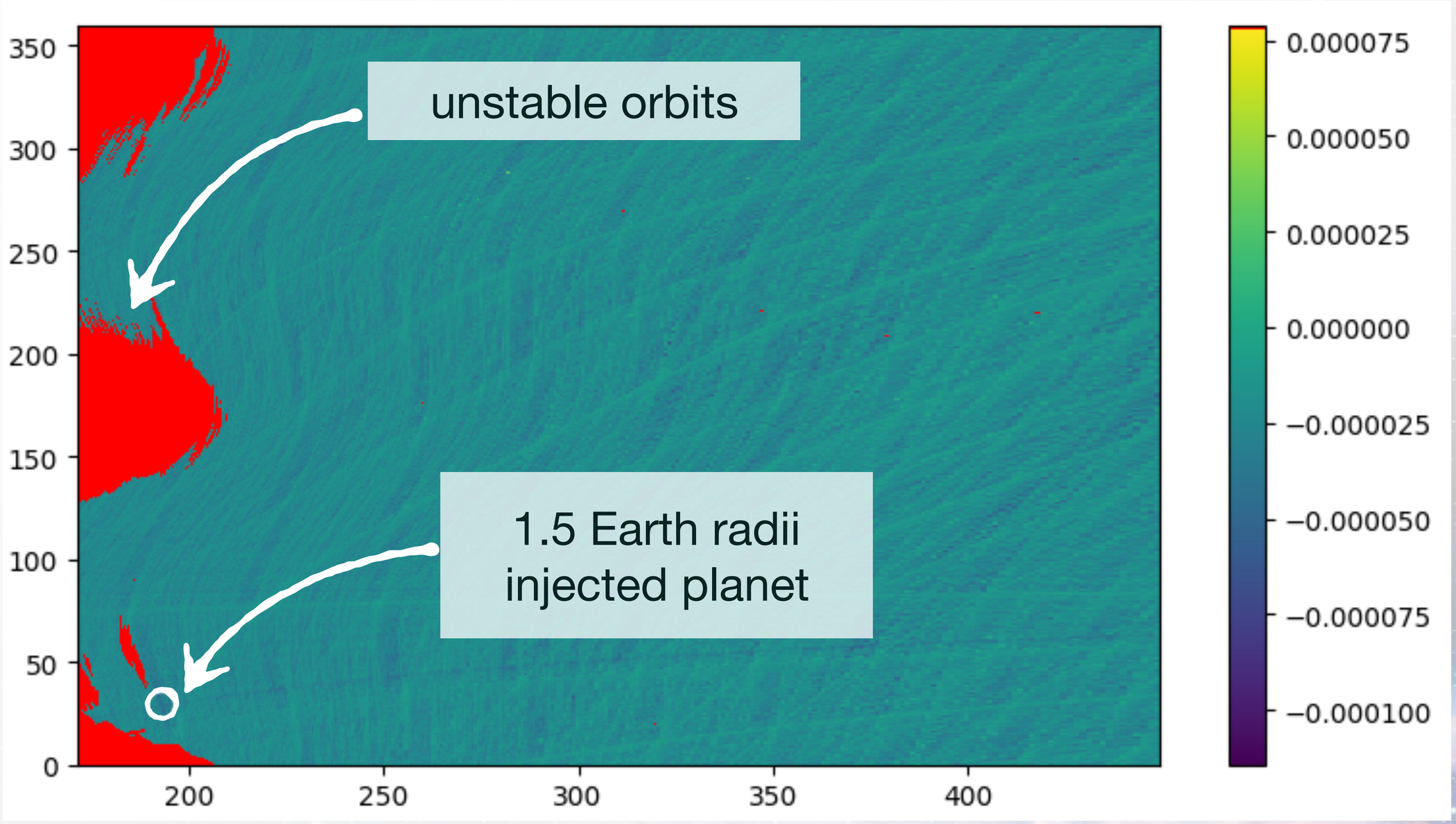




INJECTION

1.5 R_{EARTH} @ ~193 DAYS

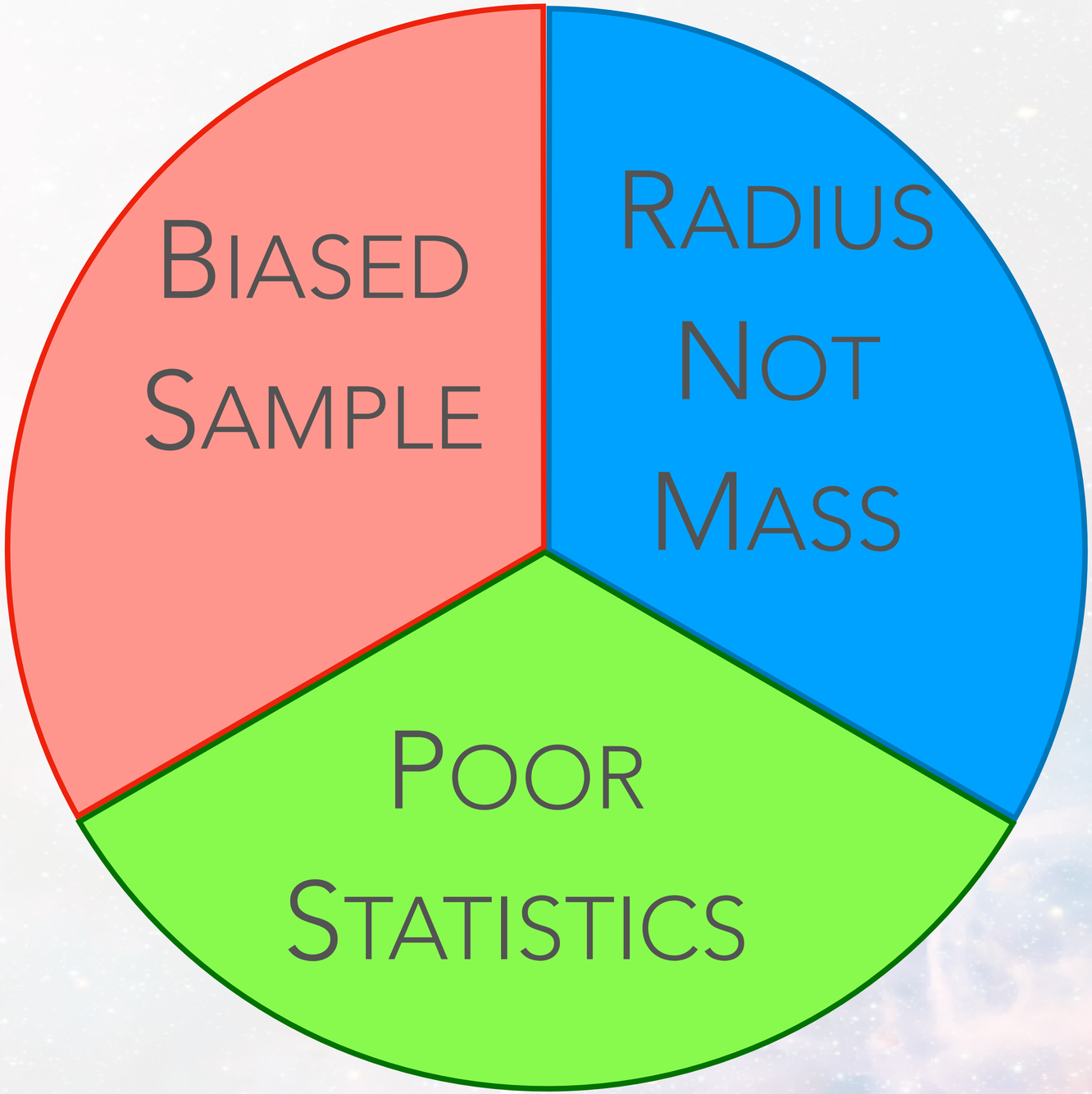



unstable orbits
1.5 Earth radii
injected planet
Planet phase (deg)
Planet period (days)
In-transit mean flux
350
300
250
200
150
100
50
0
200
250
300
350
400
0.000075
0.000050
0.000025
0.000000
−0.000025
−0.000050
−0.000075
−0.000100

Status

1. Can find all Kepler planets
2. Windemuth+ 19 masses work
3. injection/recovery tests
4. Finalise grid optimisation
5. Run on Kepler EBs
6. Public release
7. Run on TESS

TESS

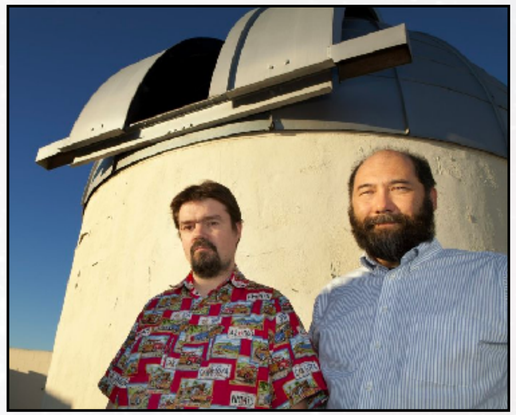

Biased Sample
Radius Not Mass
Poor Statistics

CIRCUMBINARY WORKING GROUP

Veselin Kostov

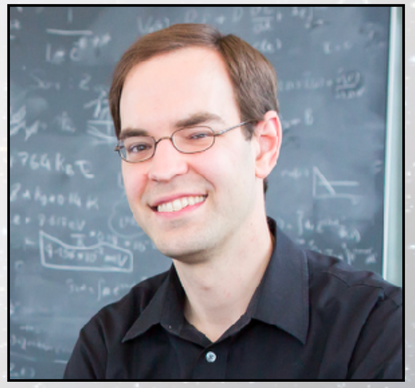
Nader Haghighipour

Jerry Orosz



Bill Welsh

Laurence Doyle



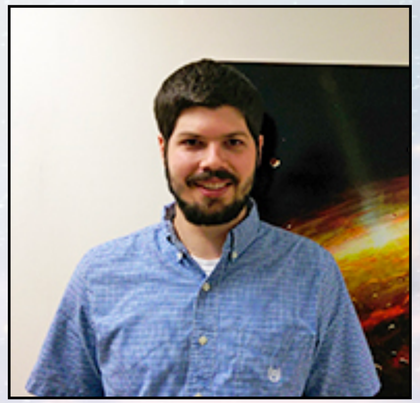
Dan Fabrycky

Gongjie Li

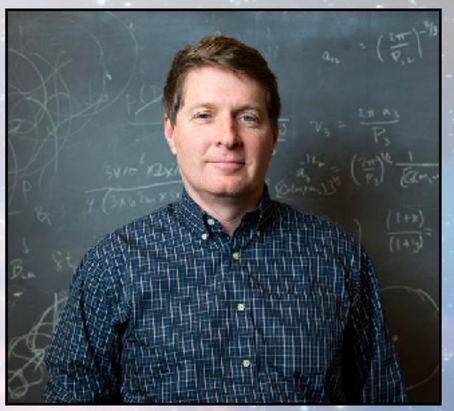
David Martin

Stanley
(not a member)

Tsevi Mazeh

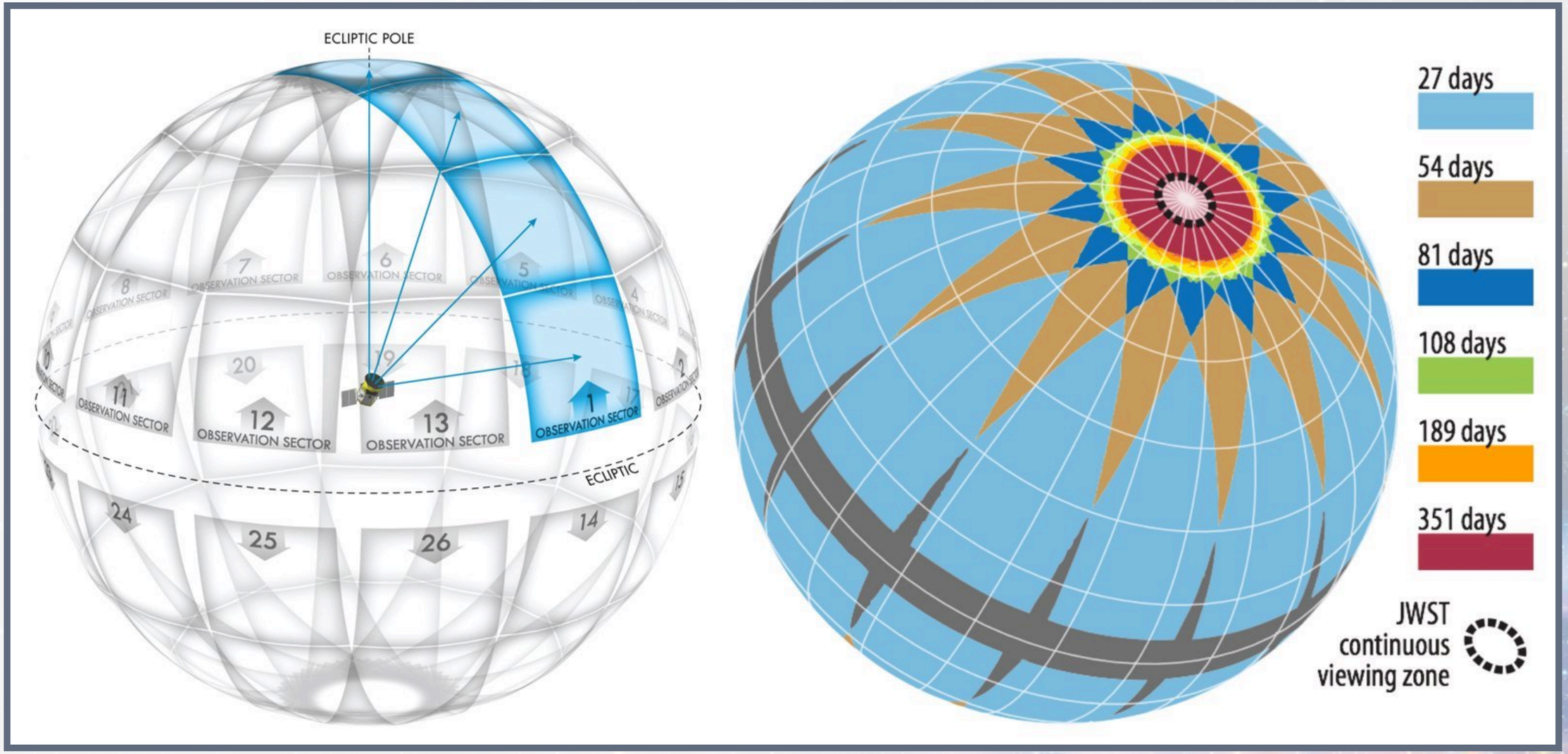


Billy Quarles



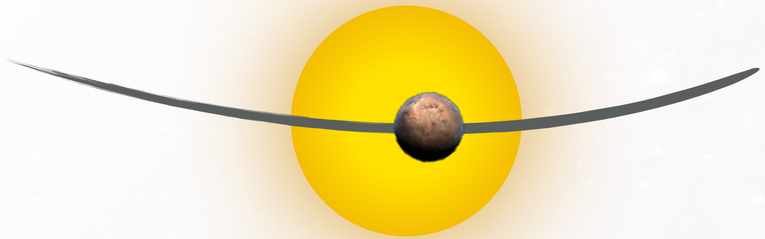
Eric Agol

ALL SKY, NOT ALL TIME

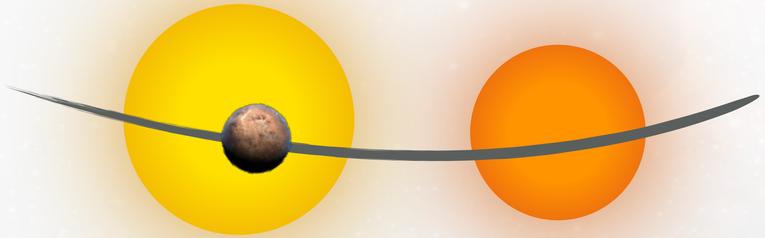


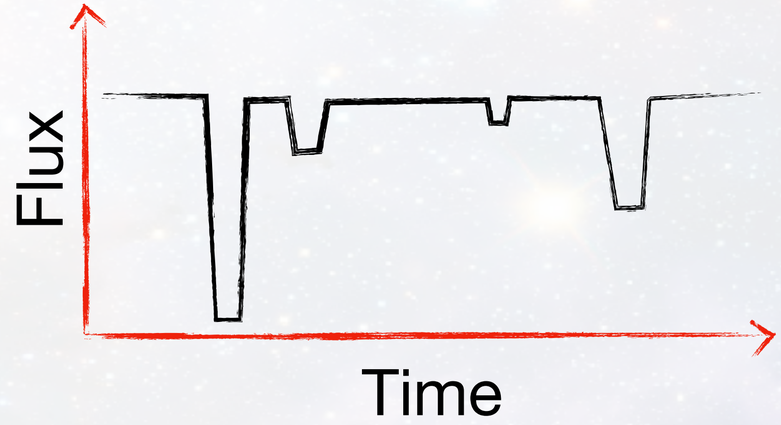
"1-2 PUNCH"

Single star



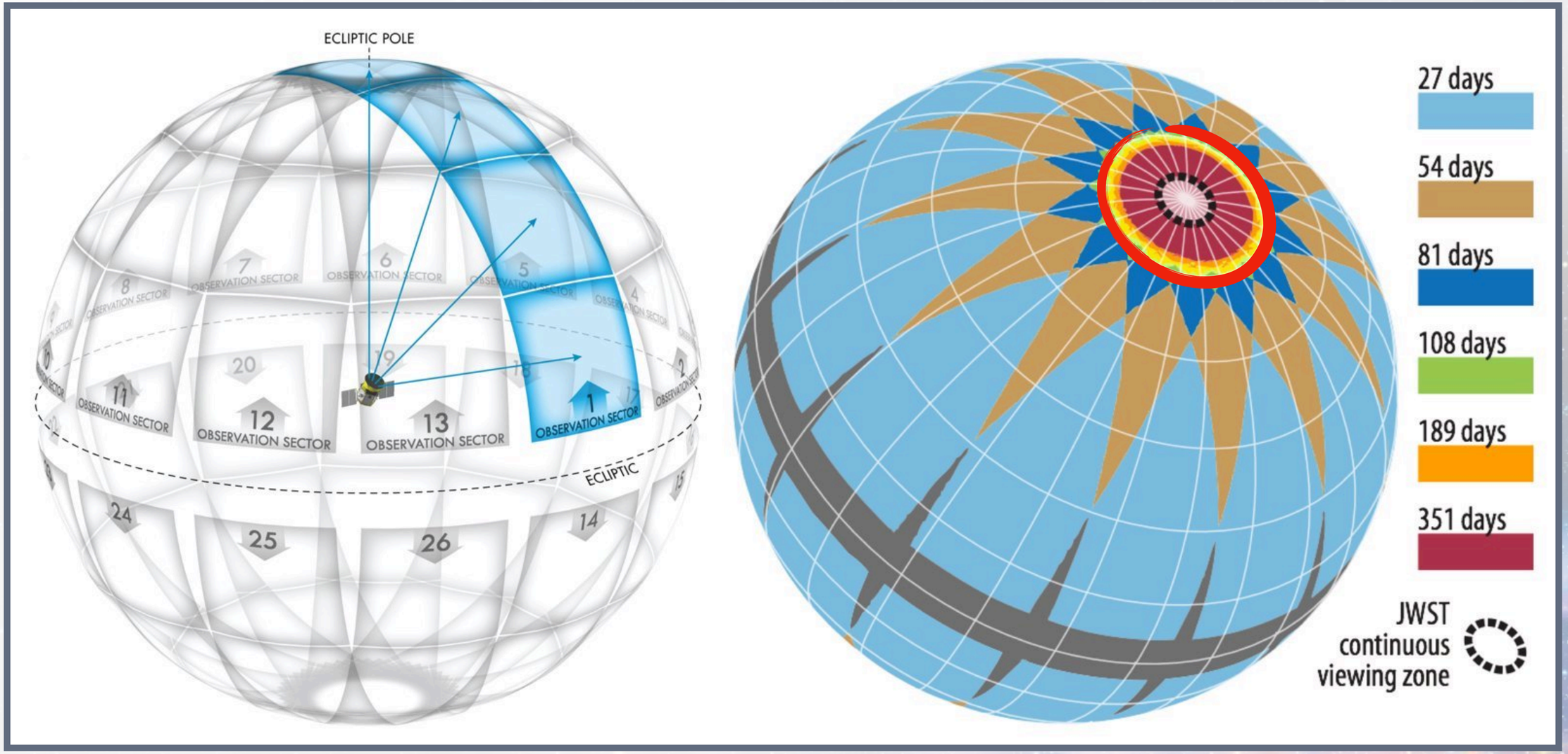
Circumbinary





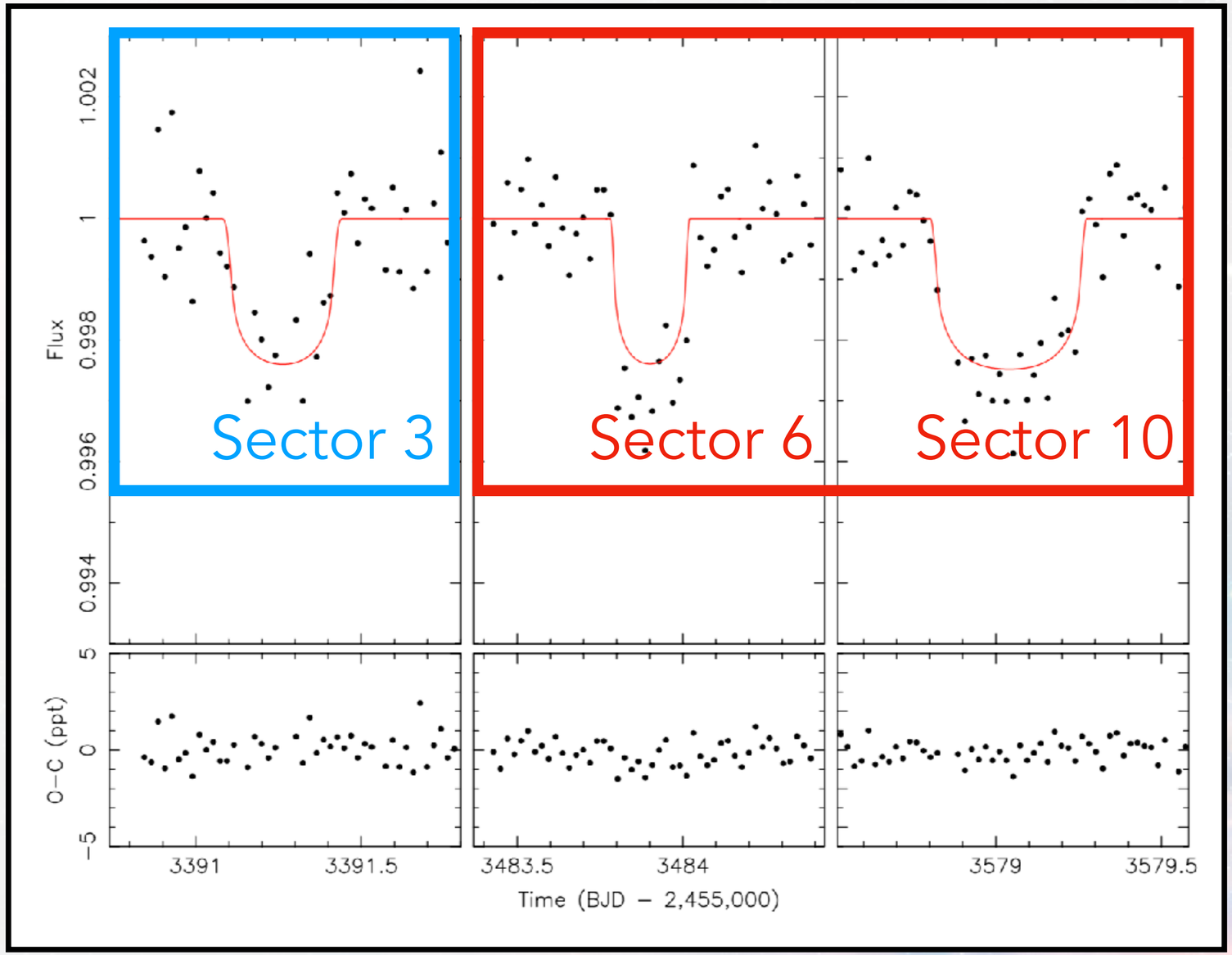
- 400,000 EBs (Sullivan+ 15)
- 140 CBPs (Kostov+ rev.)
- Bright stars!

CONTINUOUS VIEWING ZONE



First TESS CBP candidate!

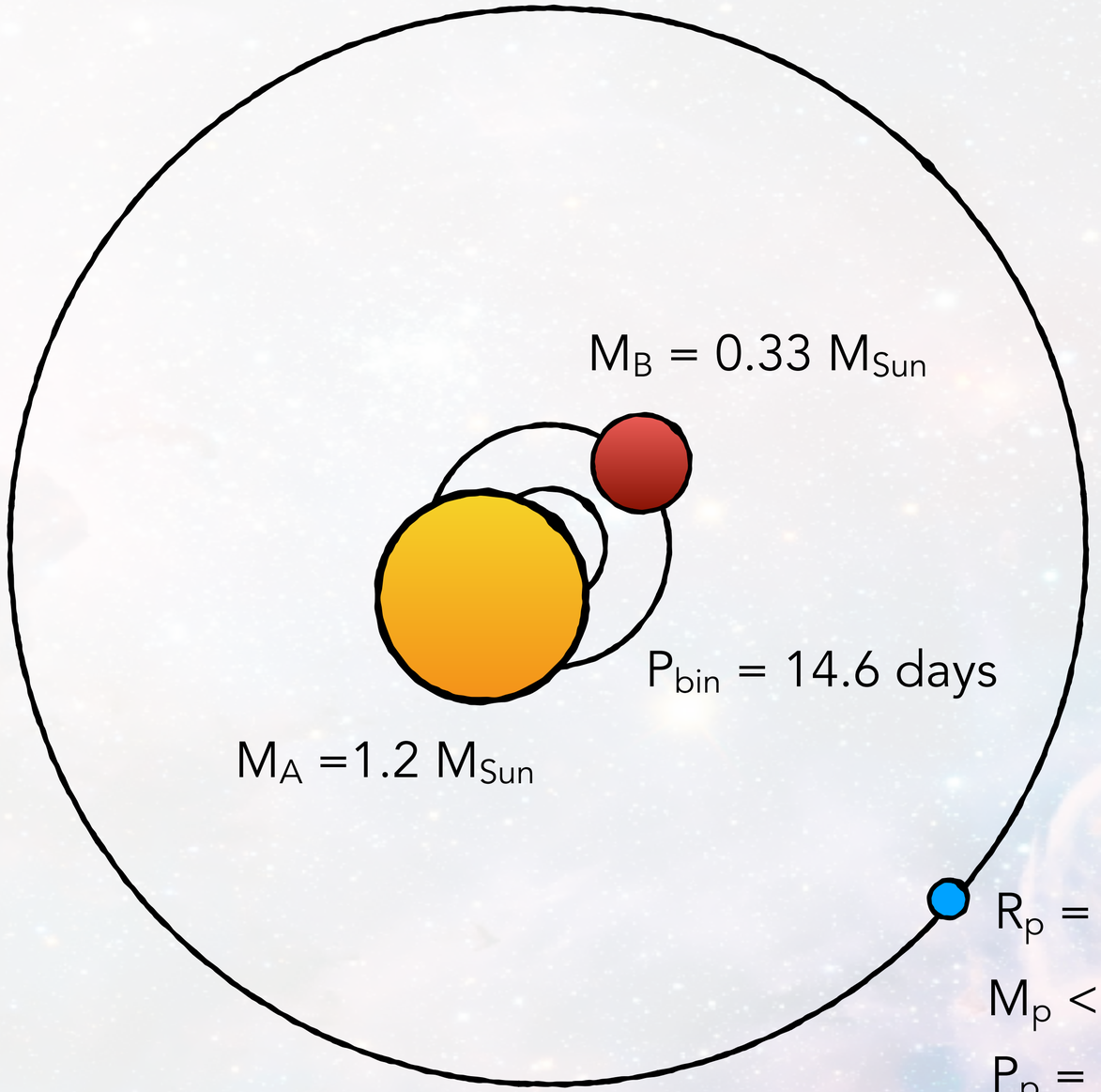
Long cadence data with Eleanor (Feinstein+ 19)



Short cadence data

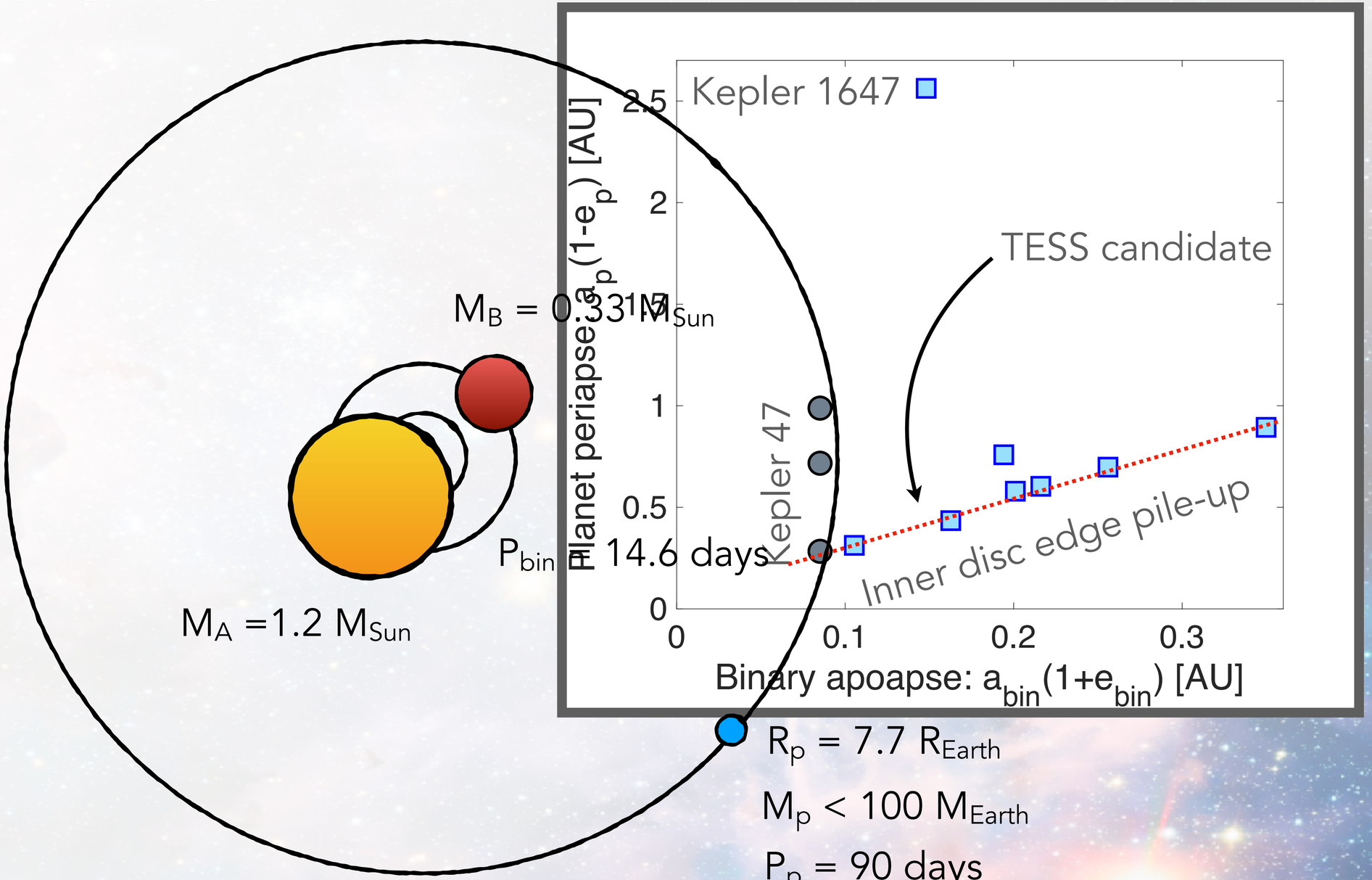
Kostov+ (in prep)

First TESS CBP candidate!



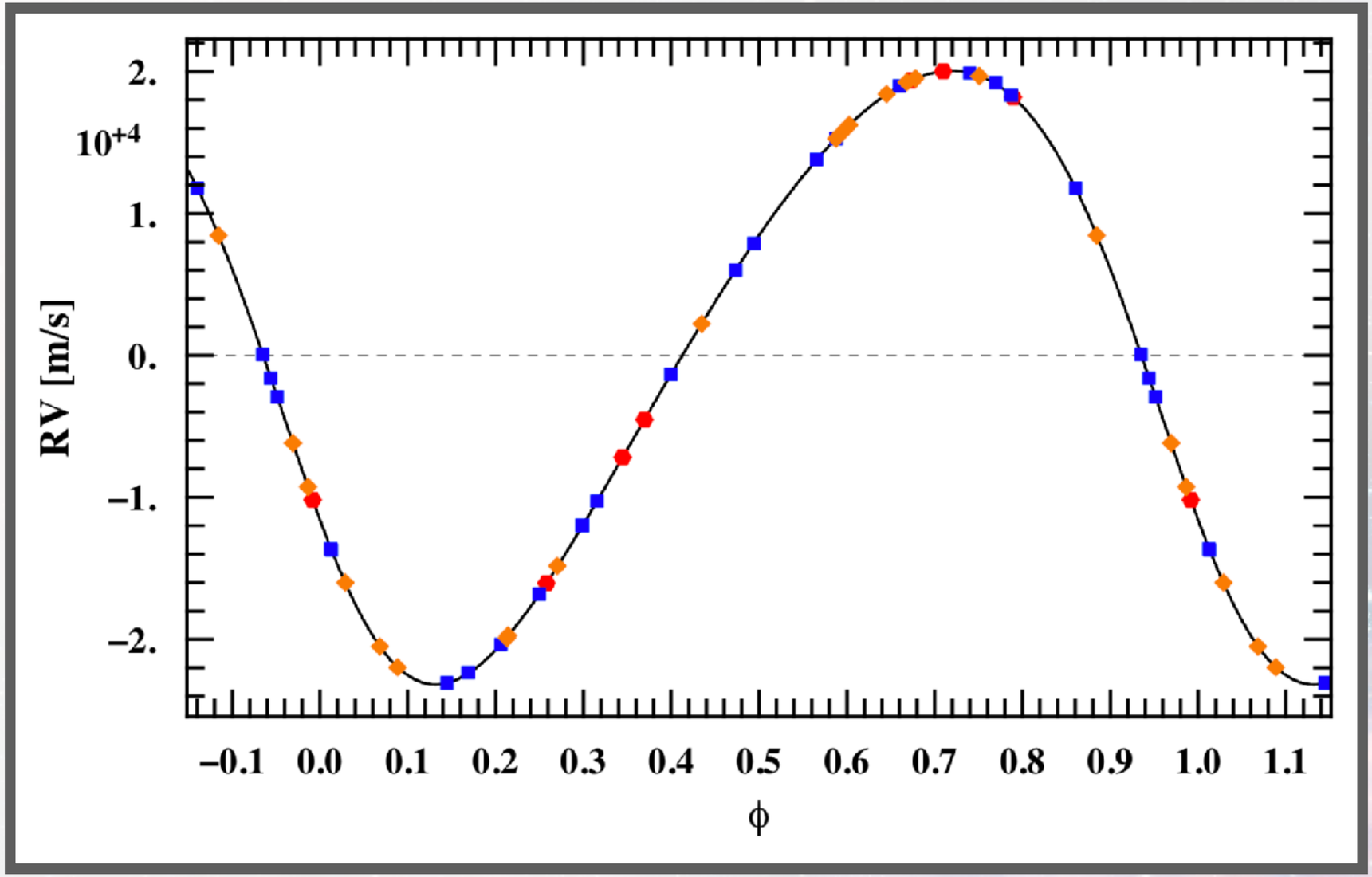
Kostov+
(in prep)

First TESS CBP candidate!

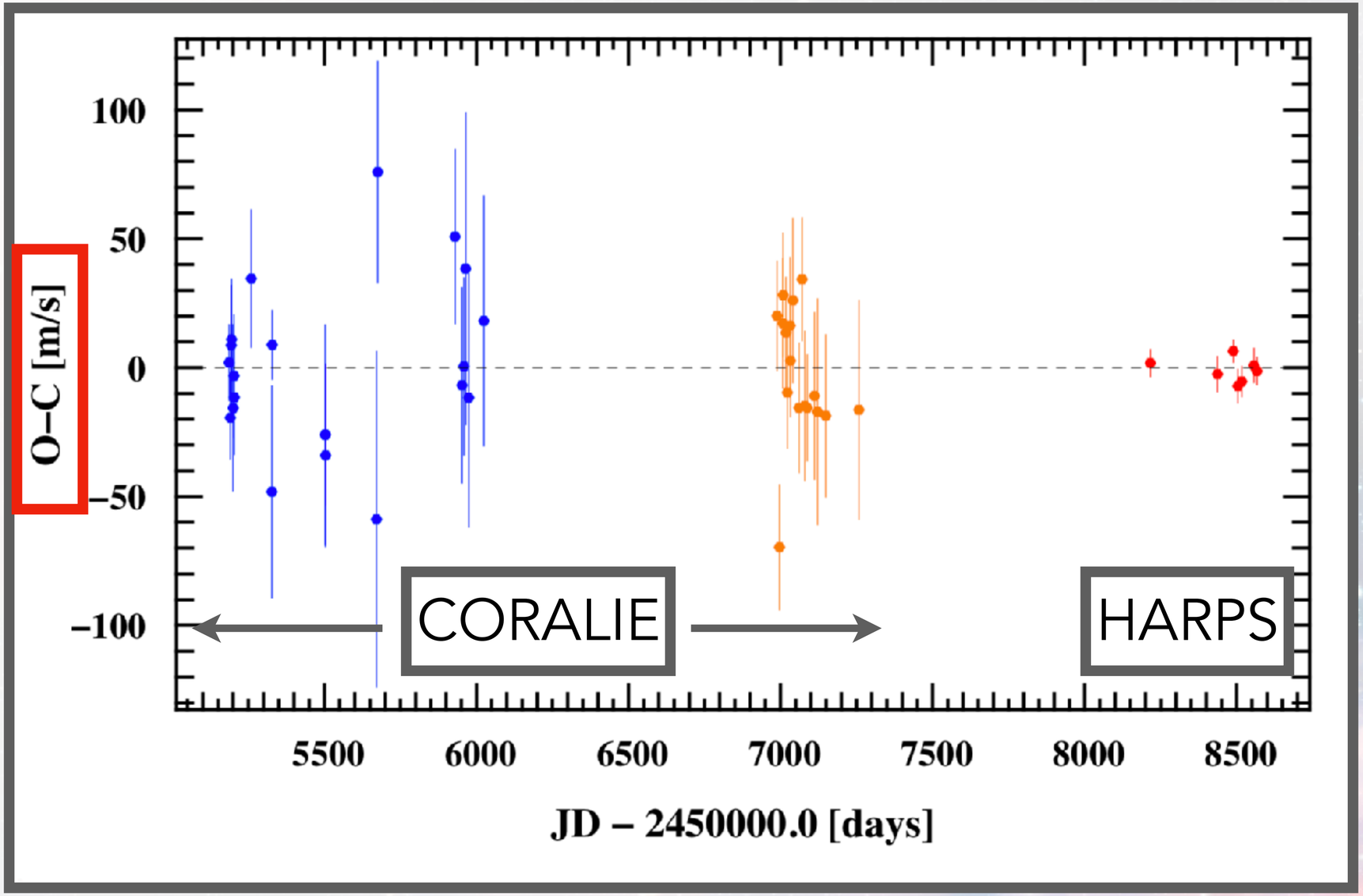


Kostov+
(in prep)

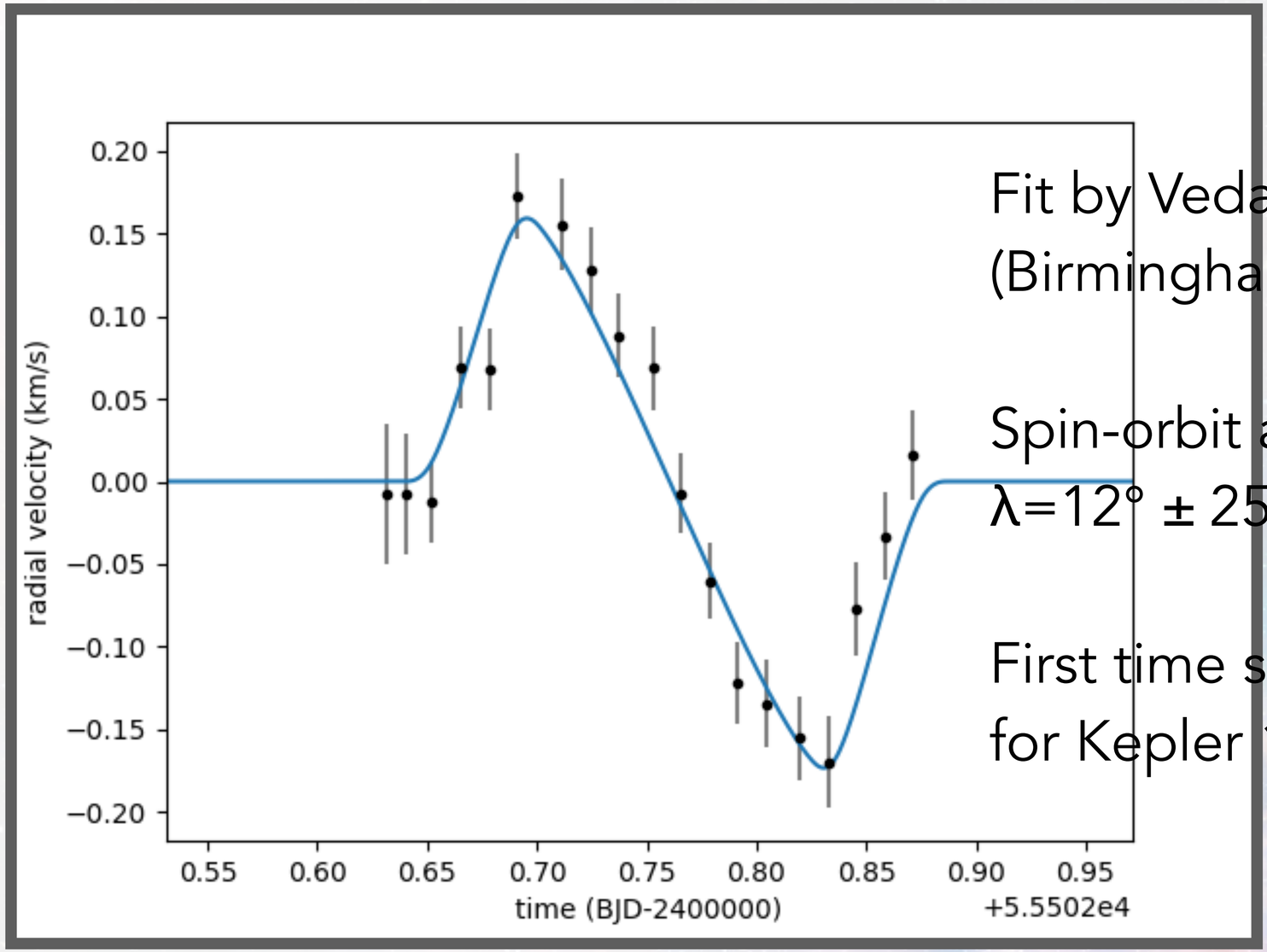
COMPLEMENTARY RADIAL VELOCITIES



Down to 2 m/s precision



ROSSITER-MCLAUGHLIN



Fit by Vedad Hodzic
(Birmingham PhD student)

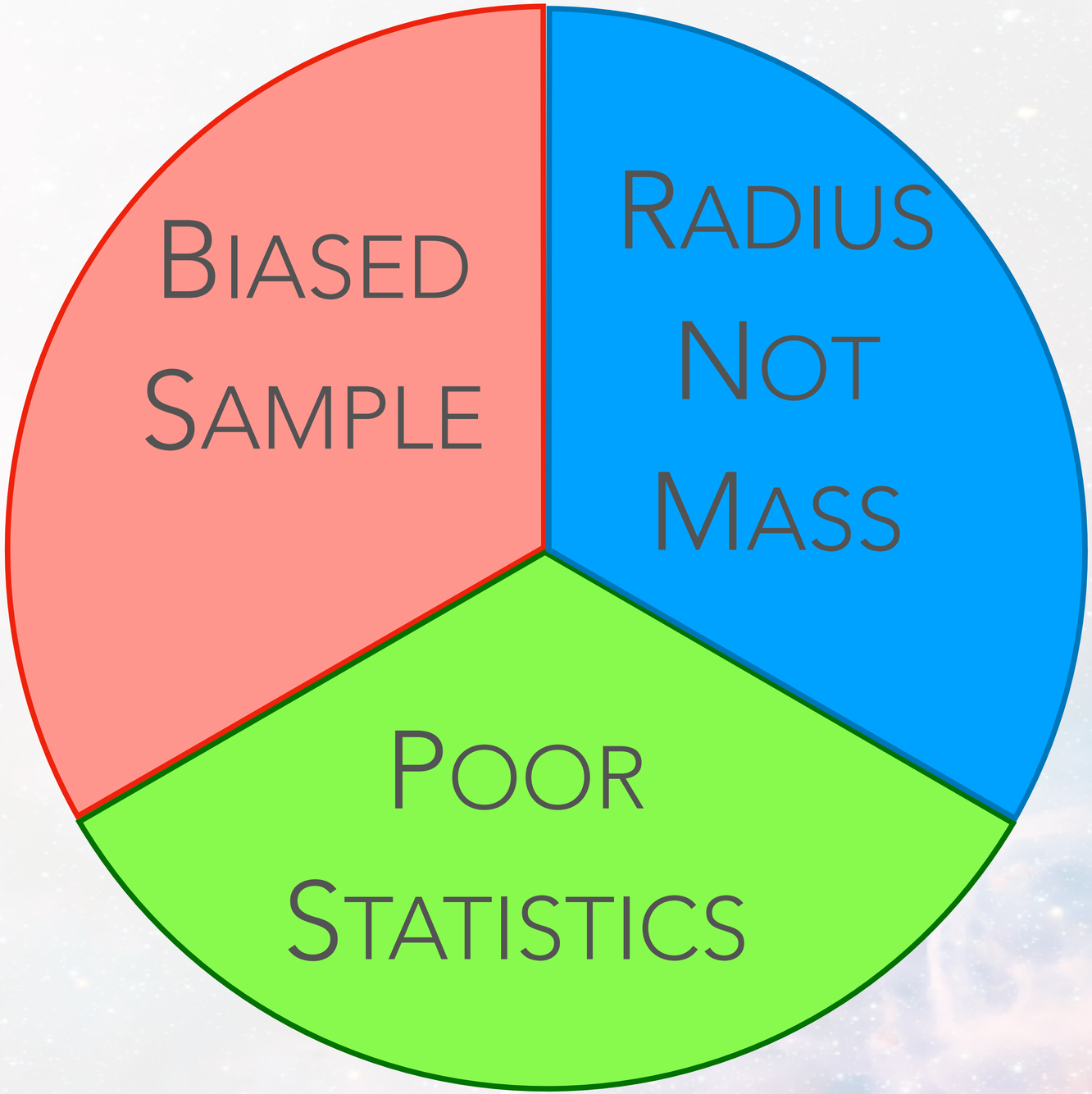
Spin-orbit aligned
$\lambda = 12° \pm 25°$

First time since Winn+ 12
for Kepler 16 (also aligned)

How come so many RVs?
TIC 260128333 = EBLM J0609-59
= BEBOP target

BEBOP

Binaries Escorted By Orbiting Planets


Biased Sample
Radius Not Mass
Poor Statistics

Radial velocities

$$K_{RV} \propto \frac{m_p \sin I_p}{P_p^{1/3}}$$

PAST EFFORTS: TATOOINE

THE ASTROPHYSICAL JOURNAL, 626:431–438, 2005 June 10

PRECISION RADIAL VELOCITIES OF DOUBLE-LINED SPECTROSCOPIC BINARIES WITH AN IODINE ABSORPTION CELL

MACIEJ KONACKI
Department of Geological and Planetary Sciences, California Institute of Technology, MS 150-21, 1201 East California Boulevard, Pasadena, CA 91125; maciej@gps.caltech.edu
Received 2004 October 15; accepted 2005 February 25

THE ASTROPHYSICAL JOURNAL, 704:513–521, 2009 October 10 doi:10.1088/0004-637X/704/1/513

THE RADIAL VELOCITY TATOOINE SEARCH FOR CIRCUMBINARY PLANETS: PLANET DETECTION LIMITS FOR A SAMPLE OF DOUBLE-LINED BINARY STARS—INITIAL RESULTS FROM KECK I/HIRES, SHANE/CAT/HAMSPEC, AND TNG/SARG OBSERVATIONS

MACIEJ KONACKI[1,2], MATTHEW W. MUTERSPAUGH[3,4], SHRINIVAS R. KULKARNI[5], AND KRZYSZTOF G. HEŁMINIAK[1]

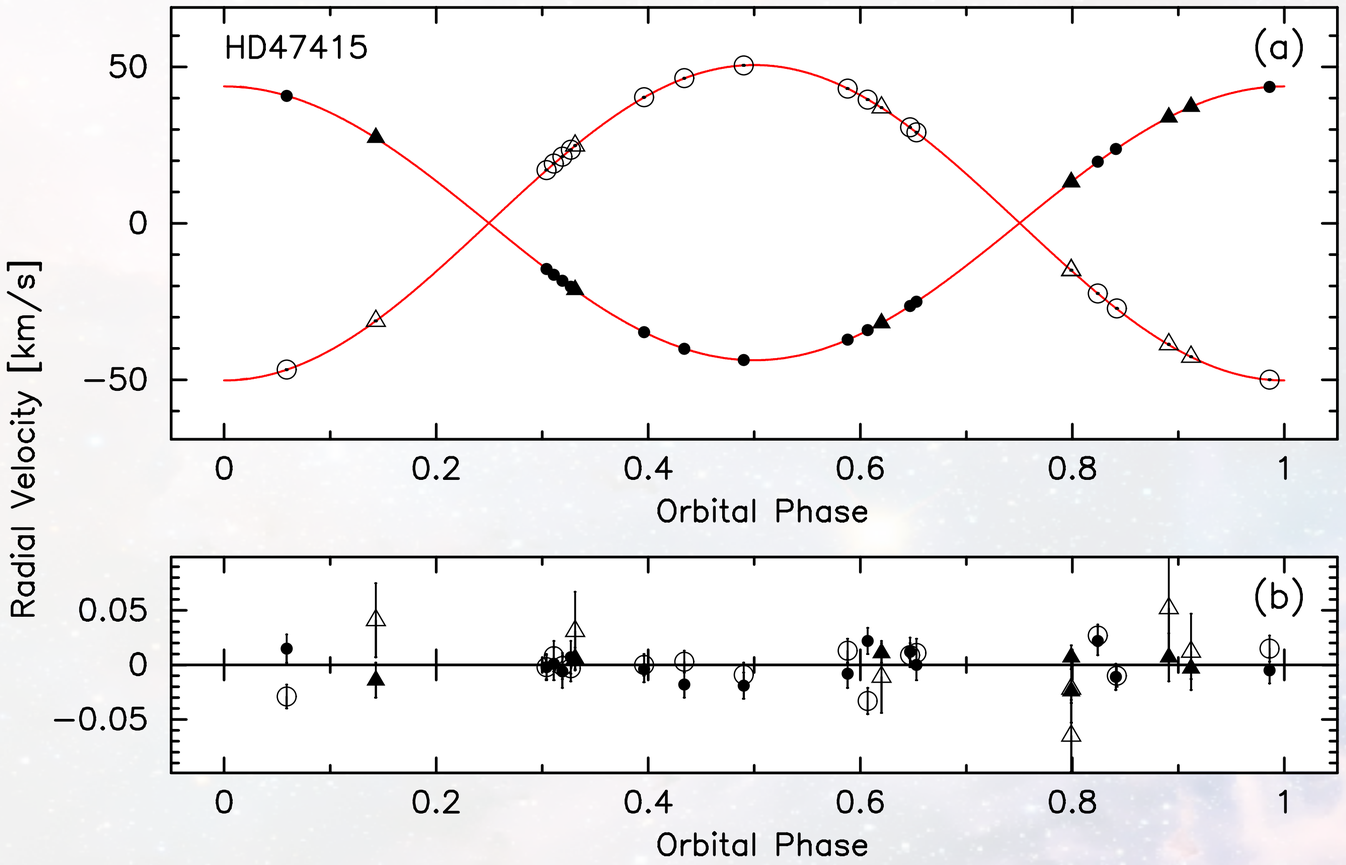
THE ASTROPHYSICAL JOURNAL, 719:1293–1314, 2010 August 20 doi:10.1088/0004-637X/719/2/1293

HIGH-PRECISION ORBITAL AND PHYSICAL PARAMETERS OF DOUBLE-LINED SPECTROSCOPIC BINARY STARS—HD78418, HD123999, HD160922, HD200077, AND HD210027

MACIEJ KONACKI[1,2], MATTHEW W. MUTERSPAUGH[3,4], SHRINIVAS R. KULKARNI[5], AND KRZYSZTOF G. HEŁMINIAK[1]

PAST EFFORTS: TATOOINE

Double-lined spectroscopic binaries:



Past efforts: Tatooine

Tatooine: double-lined spectroscopic binaries:

From Konacki et al. 2010:

> Current state-of-the-art precision is at the level of $\sim$1 m s^{-1}. It is however important to note that such a precision refers to single stars or at best single-lined spectroscopic binaries where the influence of the secondary spectrum can be neglected. In

New approach: use single line binaries.

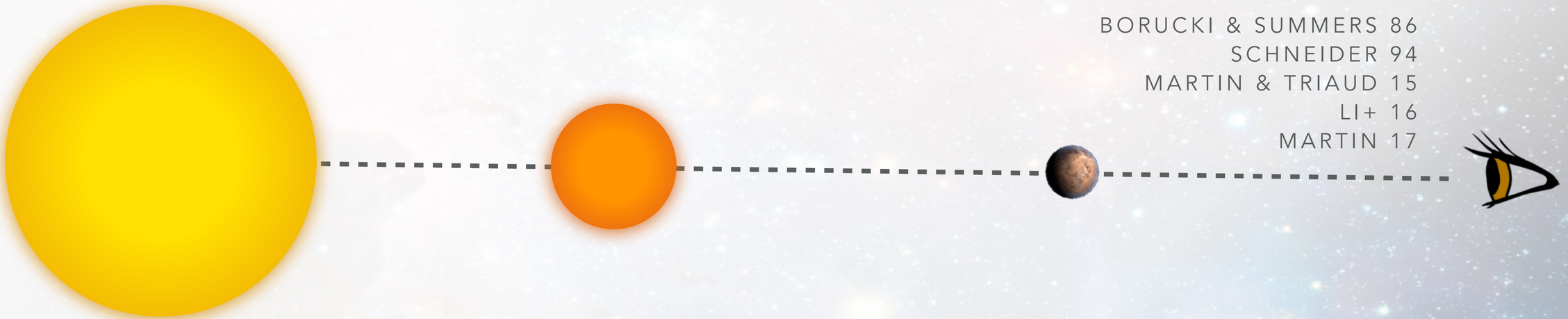
Take the best EBLM targets to form BEBOP

ECLIPSING BINARY ADVANTAGES

Maximised radial velocity amplitude

Maximised, almost guaranteed transit probability

BORUCKI & SUMMERS 86
SCHNEIDER 94
MARTIN & TRIAUD 15
LI+ 16
MARTIN 17



Secondary mass, radius known

Predict secondary magnitude to avoid contamination

CORALIE

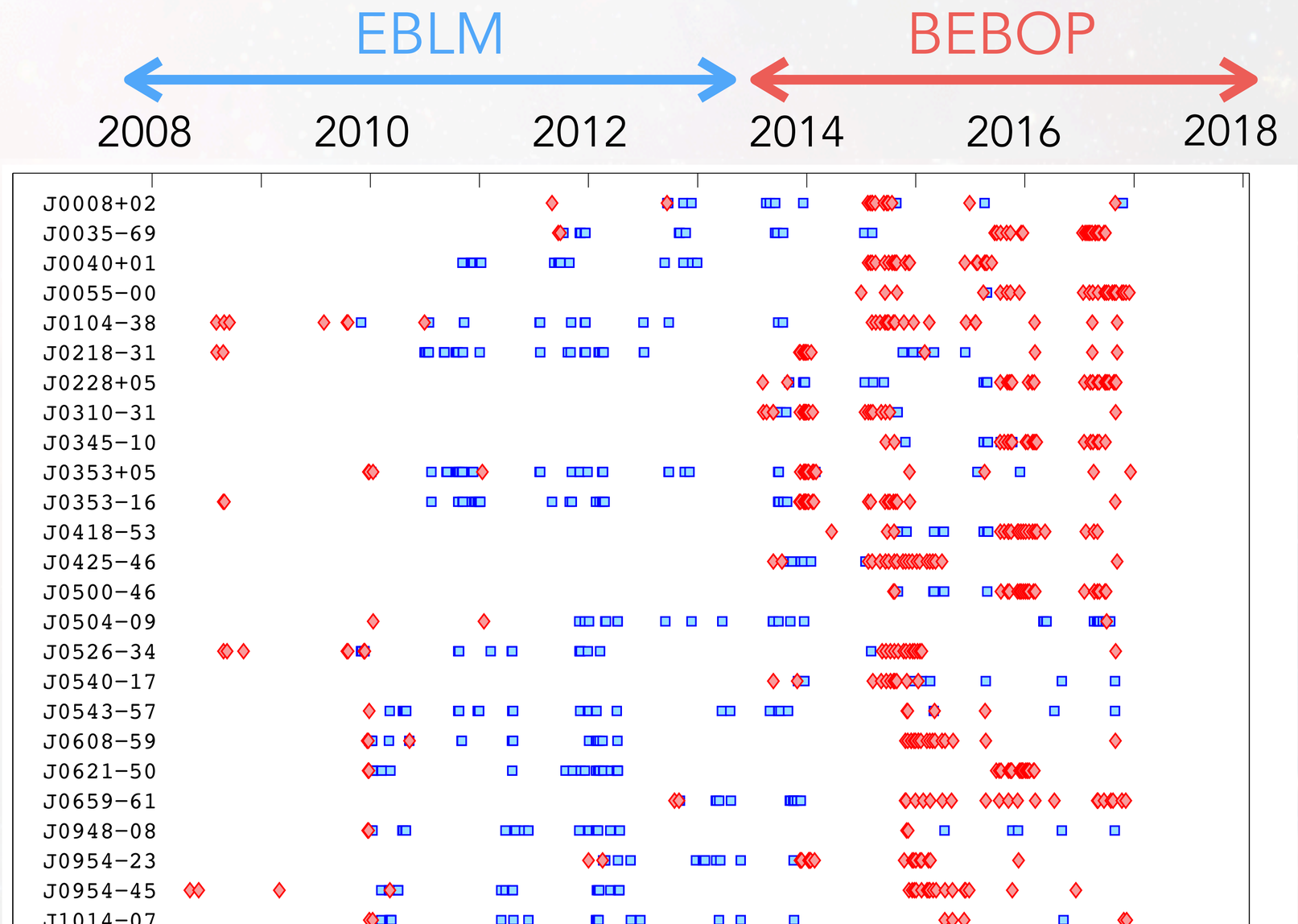
2008 - 2017 59 nights

Martin, Triaud+ (2019)

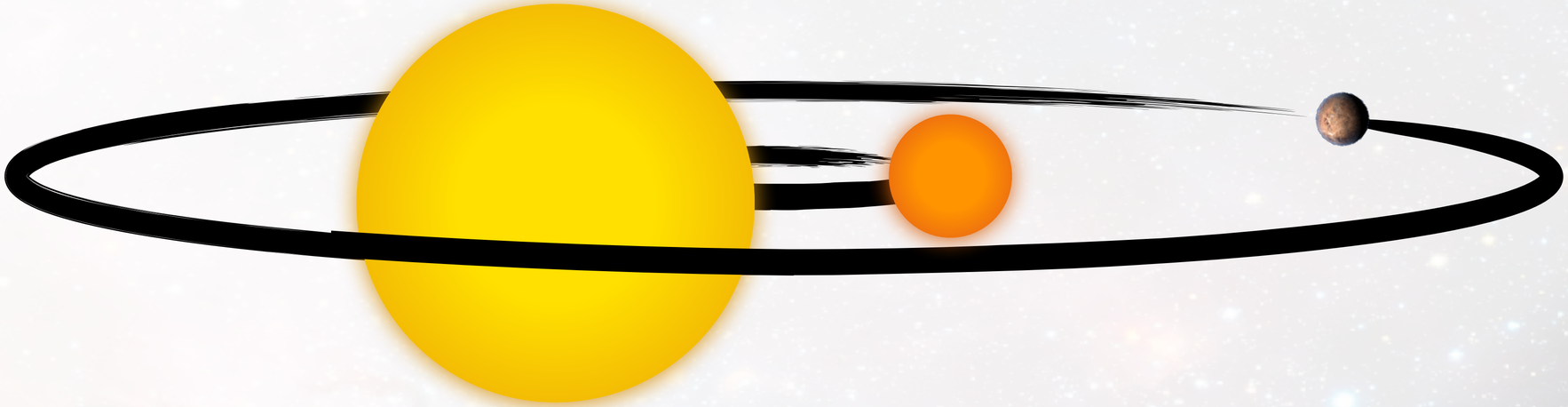
LONG-TERM

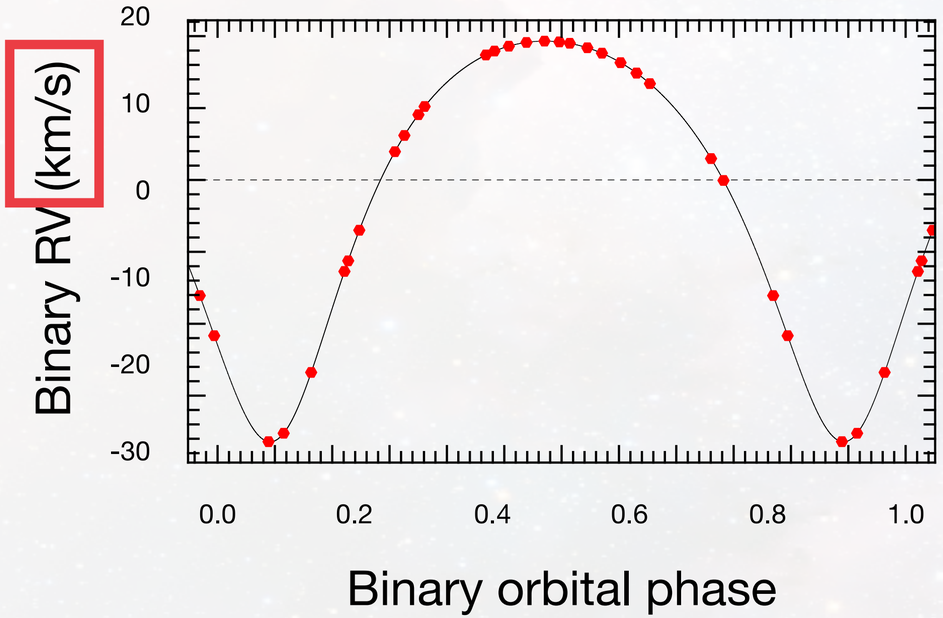
10/15 minute observation

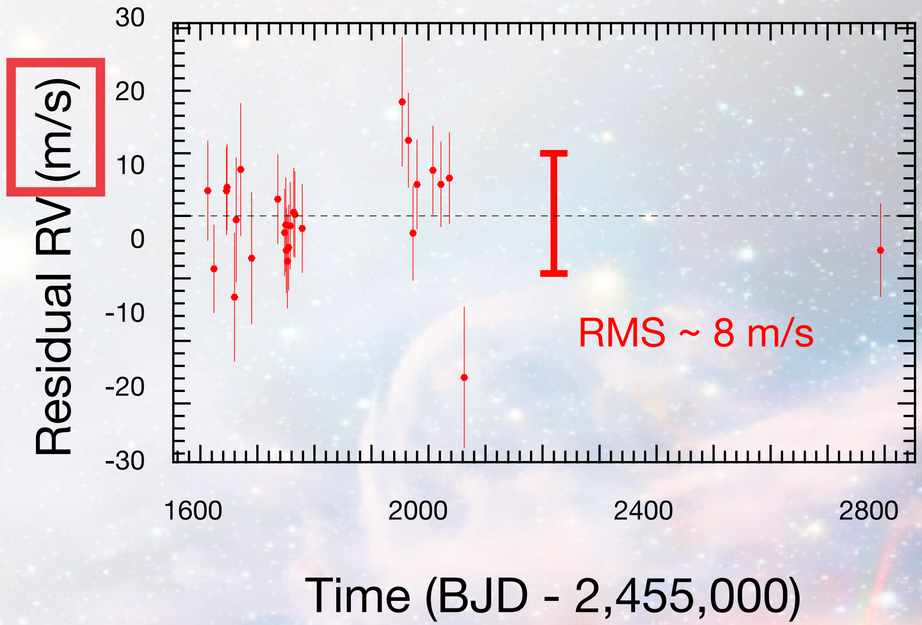
30 minute observation



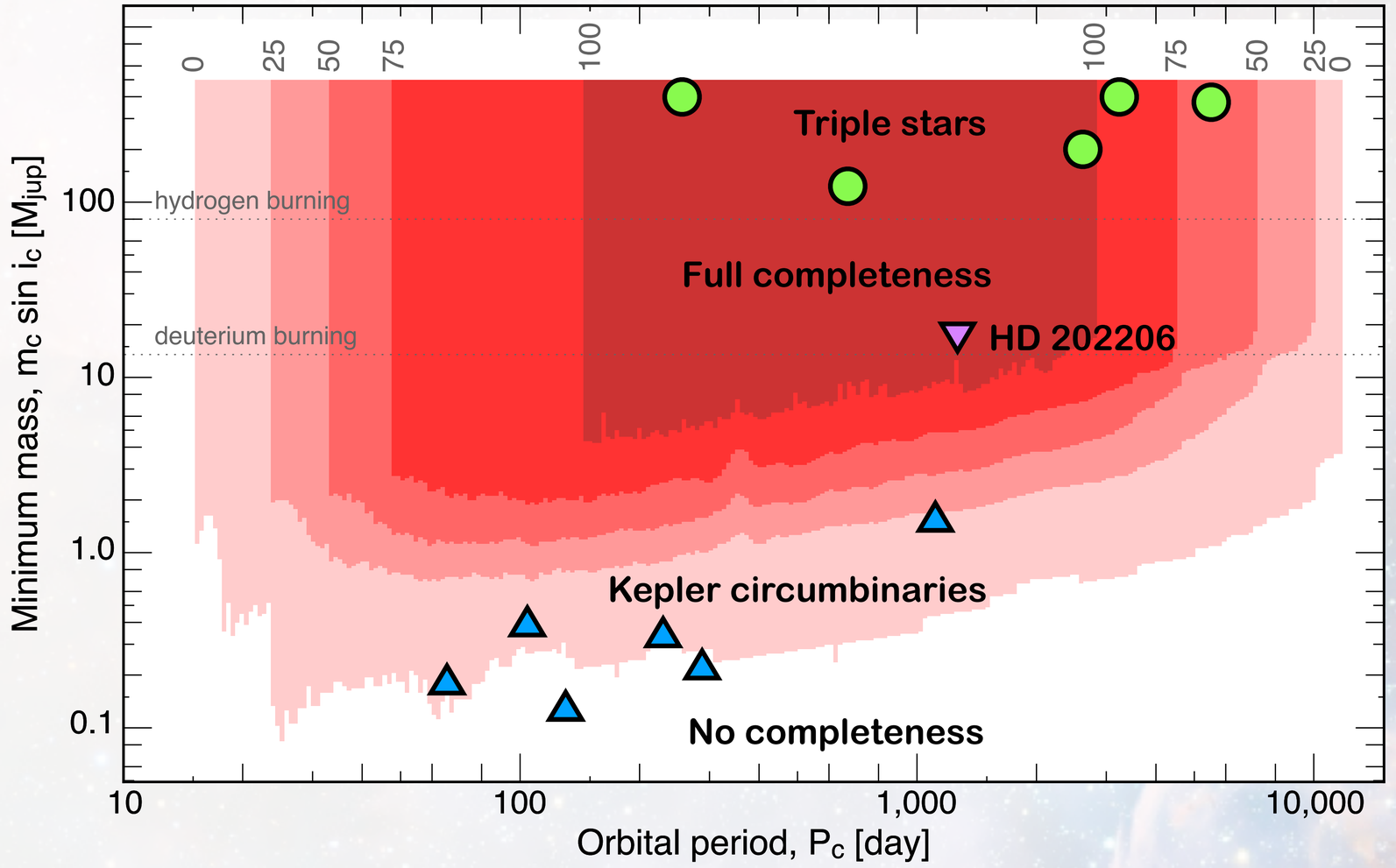
Two RV signals





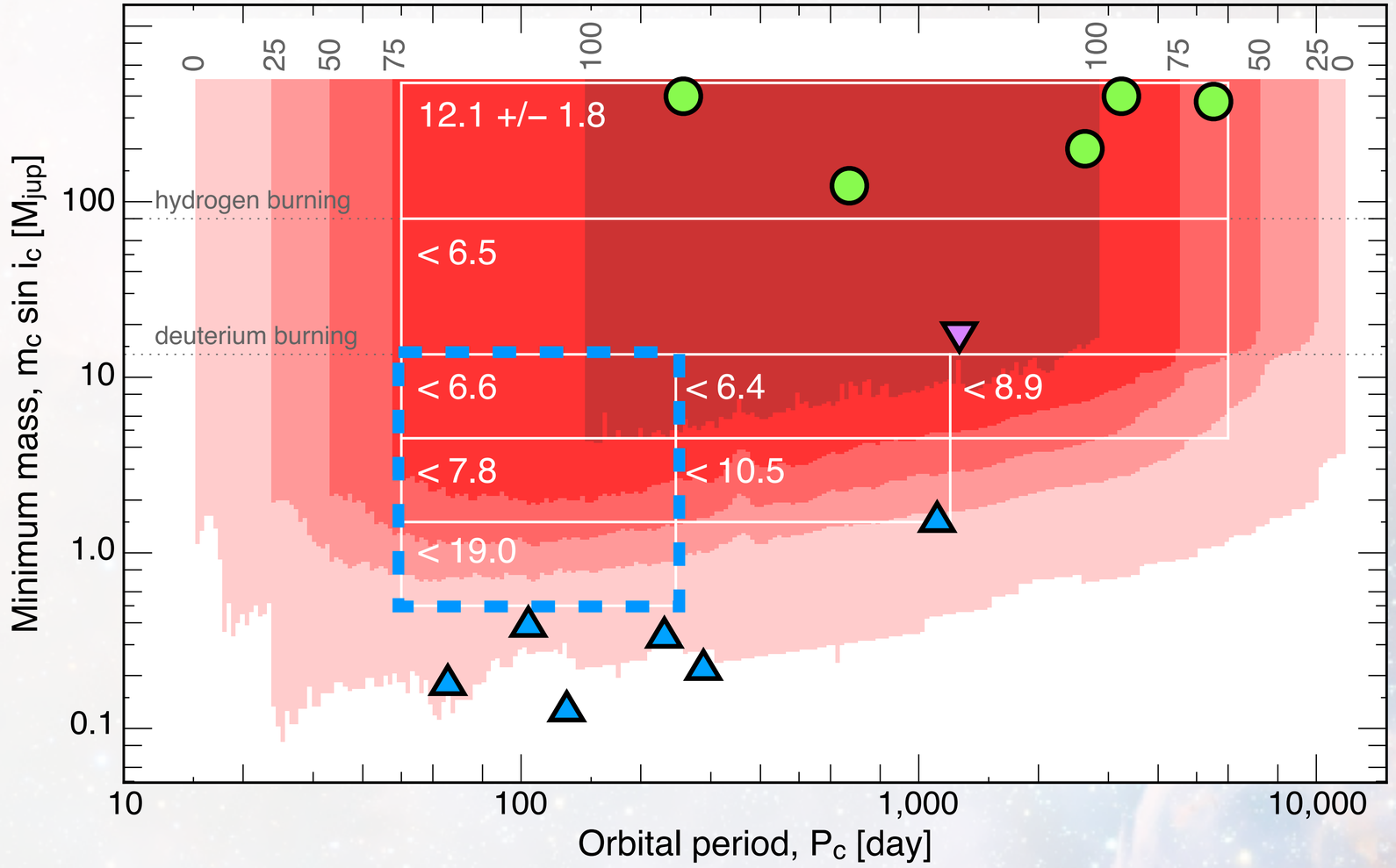


CORALIE RESULTS

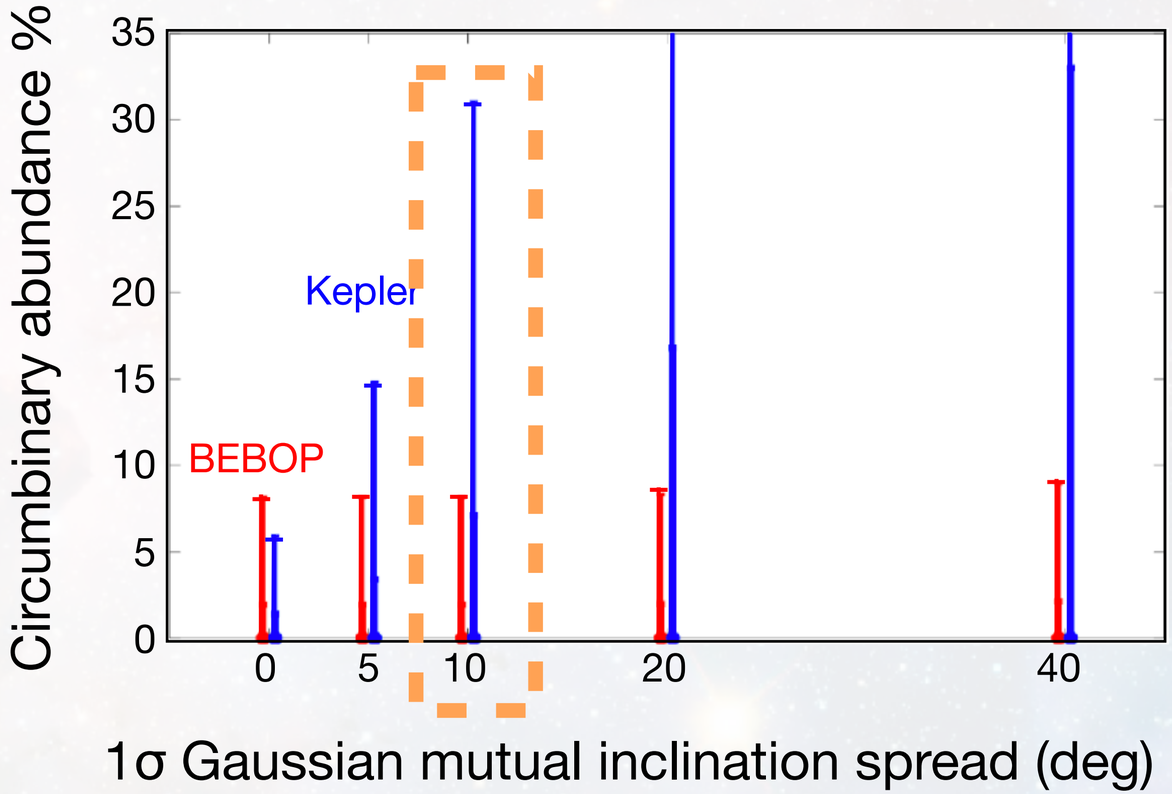


MARTIN, TRIAUD+ 19

CORALIE RESULTS



INCLINATION DISTRIBUTION



ARMSTRONG+ 14
MARTIN, TRIAUD + 19

MOVING FORWARD…

HARPS @ LA SILLA

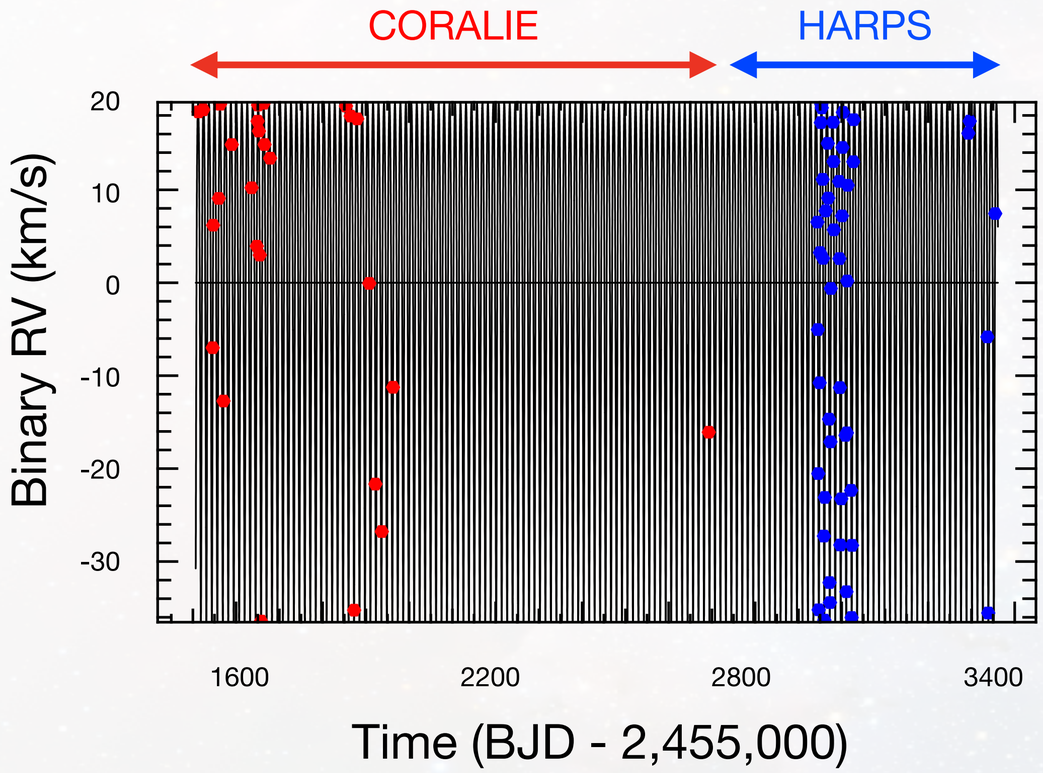
2017 7 nights

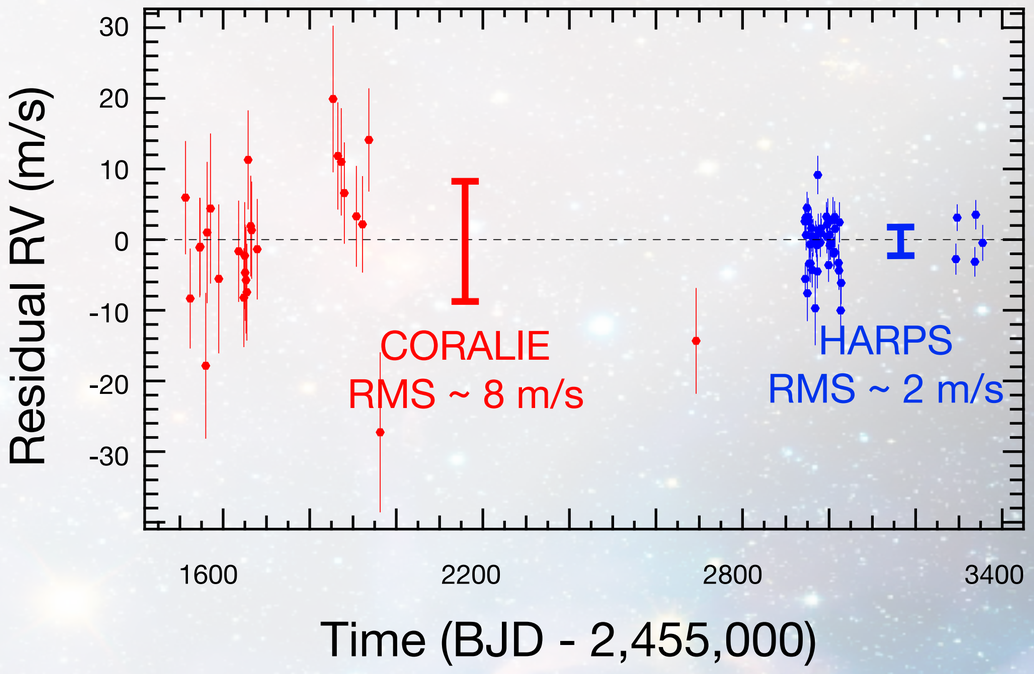
2018 - 2020 80 nights

SOPHIE @ OHP

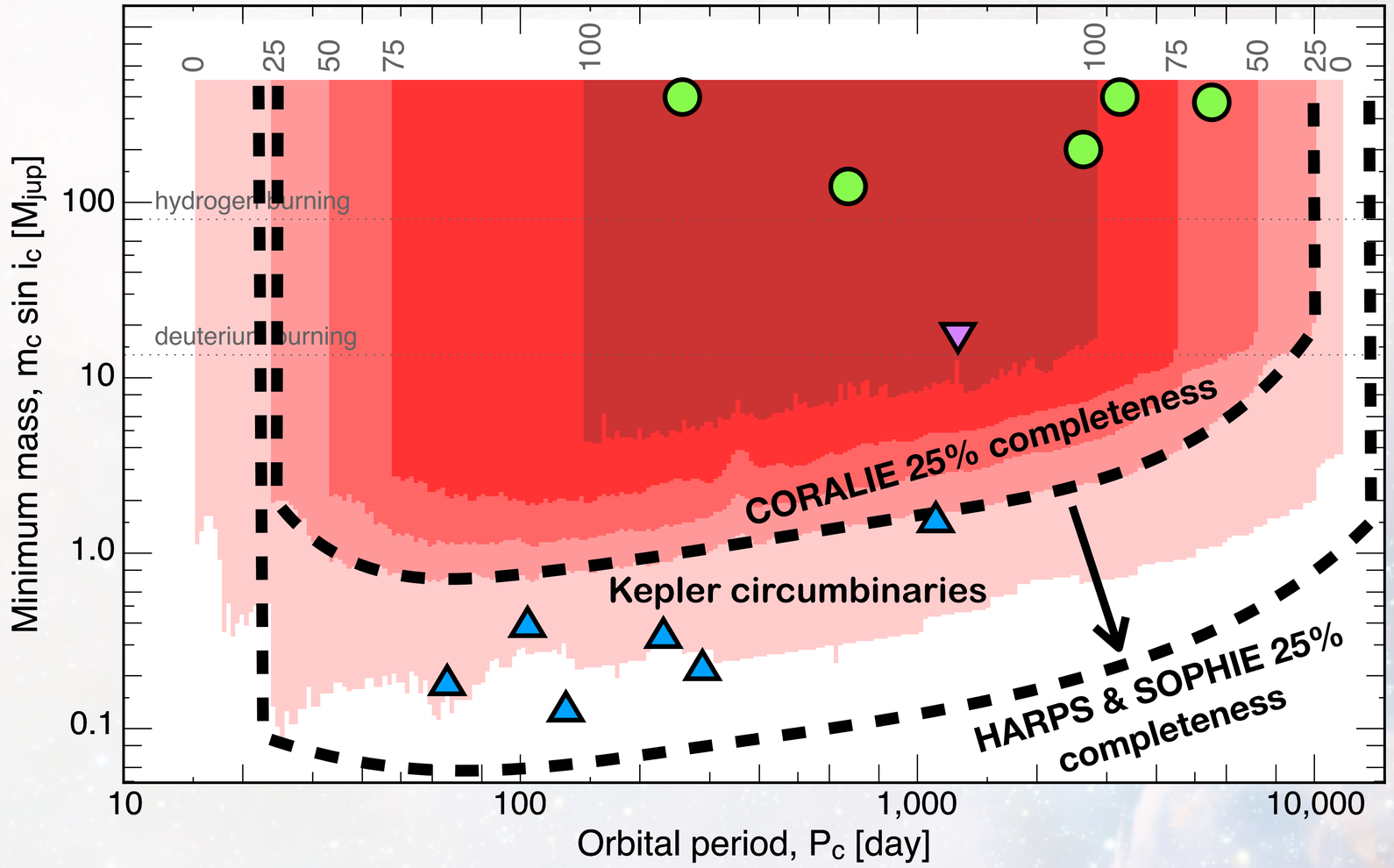
2018 - 2021 257 nights

BASELINE & PRECISION

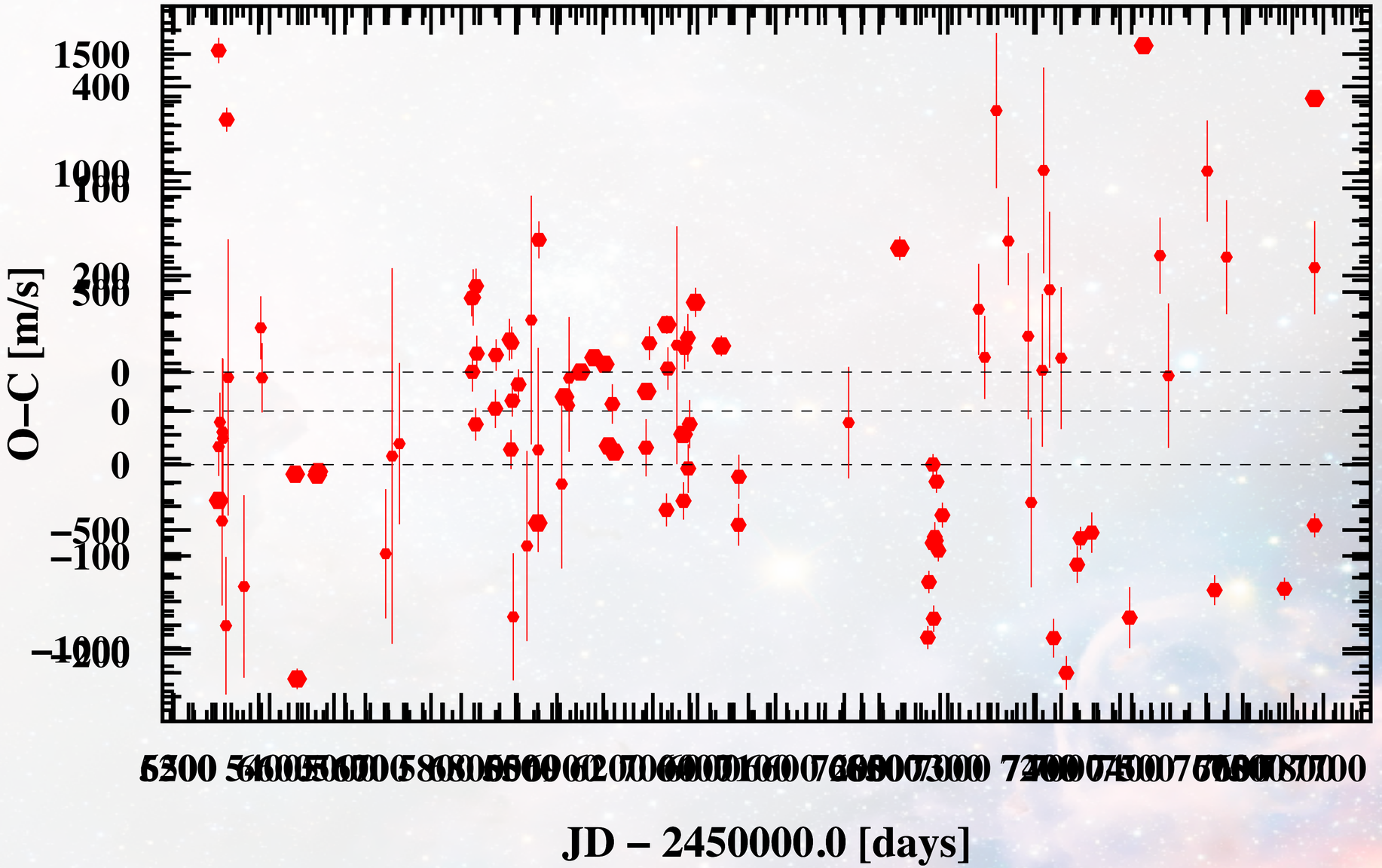




HARPS & SOPHIE EXTENSION



RV TRENDS


O–C [m/s]
1500
400
1000
100
200
500
0
0
0
–500
–100
–1000
–200
JD – 2450000.0 [days]

IMAGING FOLLOW-UP

Keck

LBT

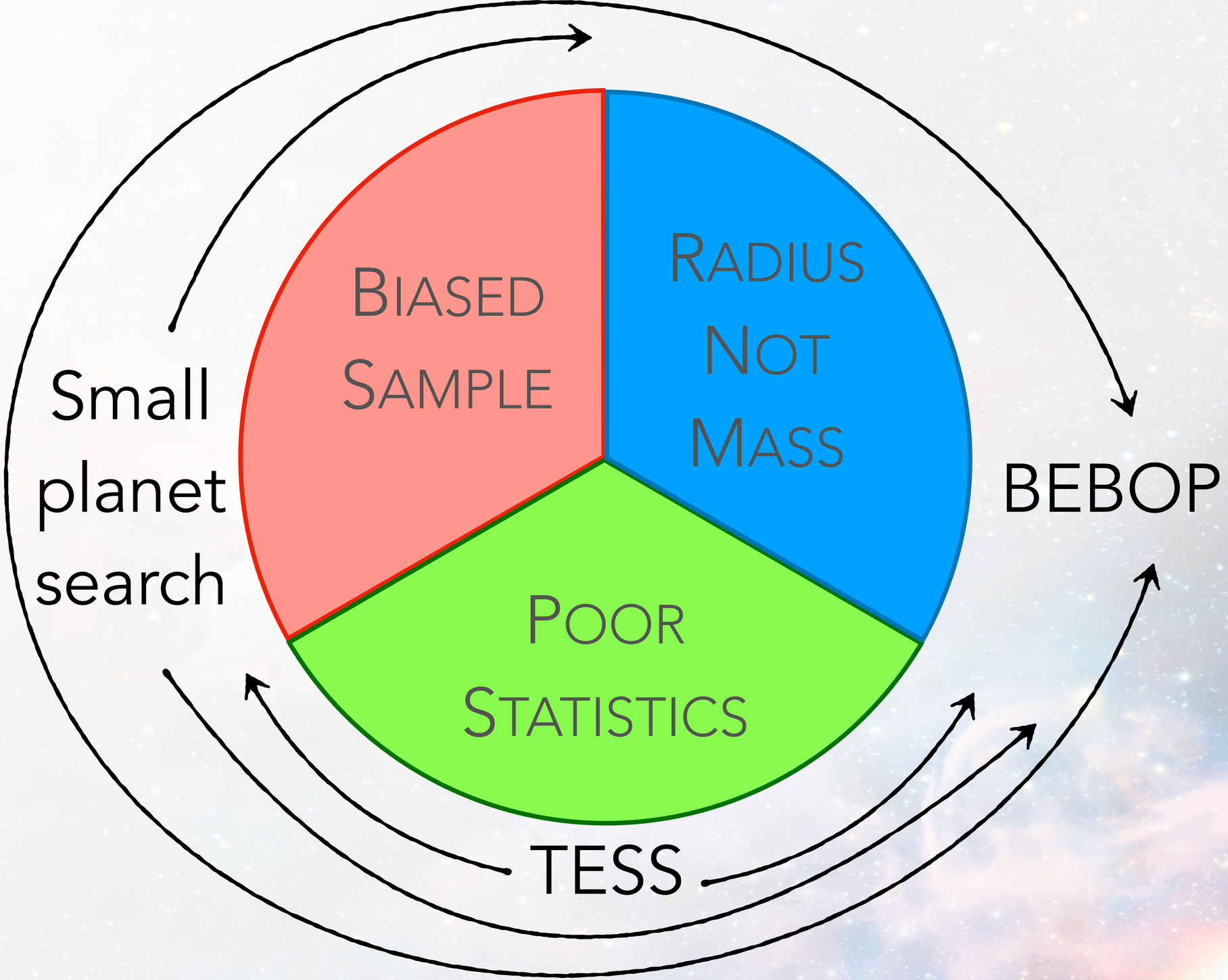
SOAR

Ji Wang

(THE Ohio State University)

Andrei Tokovinin

(CTIO, Chile)


Small planet search
Biased Sample
Radius Not Mass
Poor Statistics
BEBOP
TESS

CIRCUMBINARY PLANETS

THE NEXT STEPS

David V. Martin

THE UNIVERSITY OF CHICAGO

FNSNF
SWISS NATIONAL SCIENCE FOUNDATION