INSTITUT DE RECHERCHE
SUR LES EXOPLANÈTES

INSTITUTE FOR RESEARCH
ON EXOPLANETS

iREx

Université de Montréal

Survey of Transit Photometry: Technique and Results

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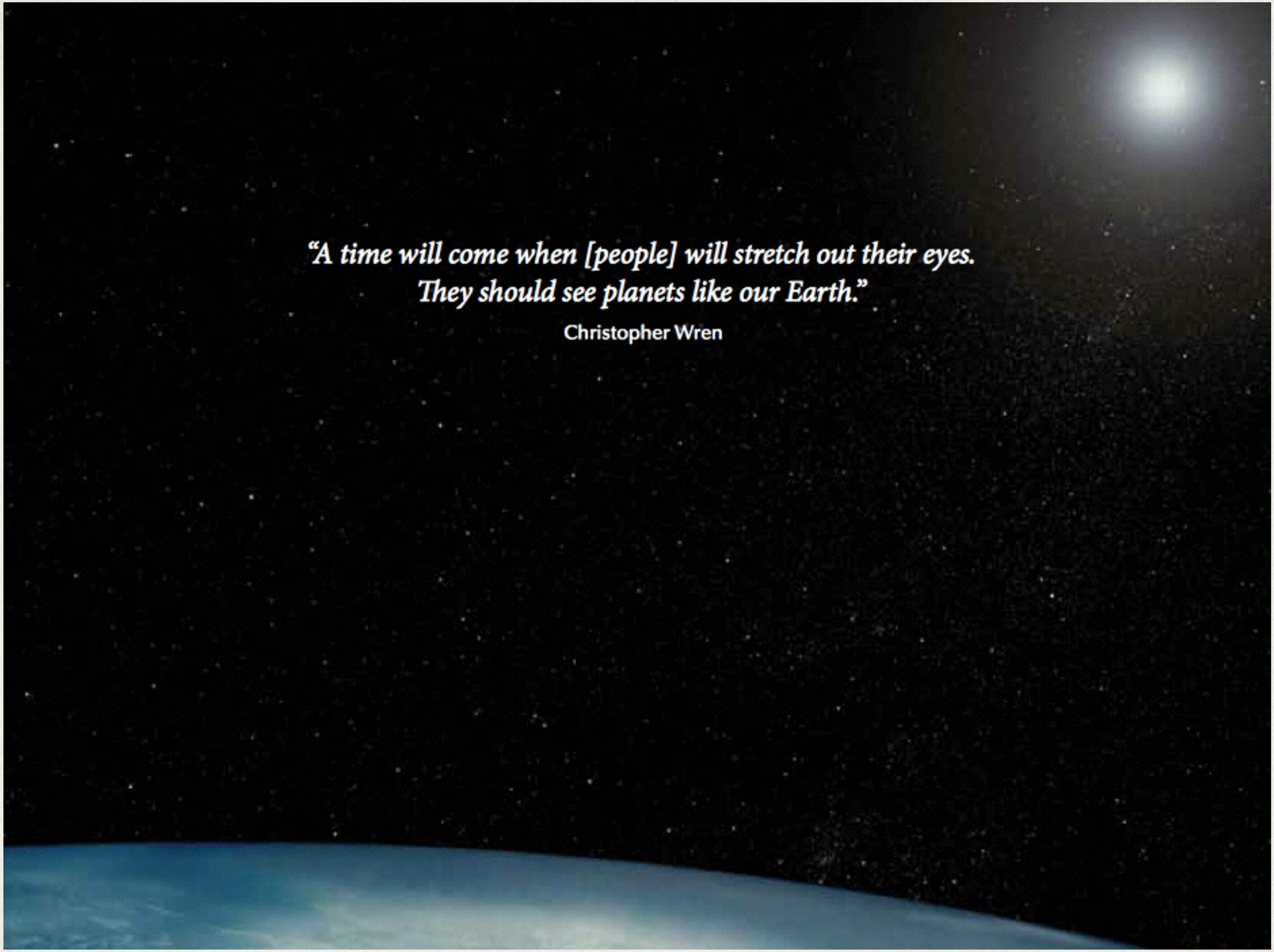
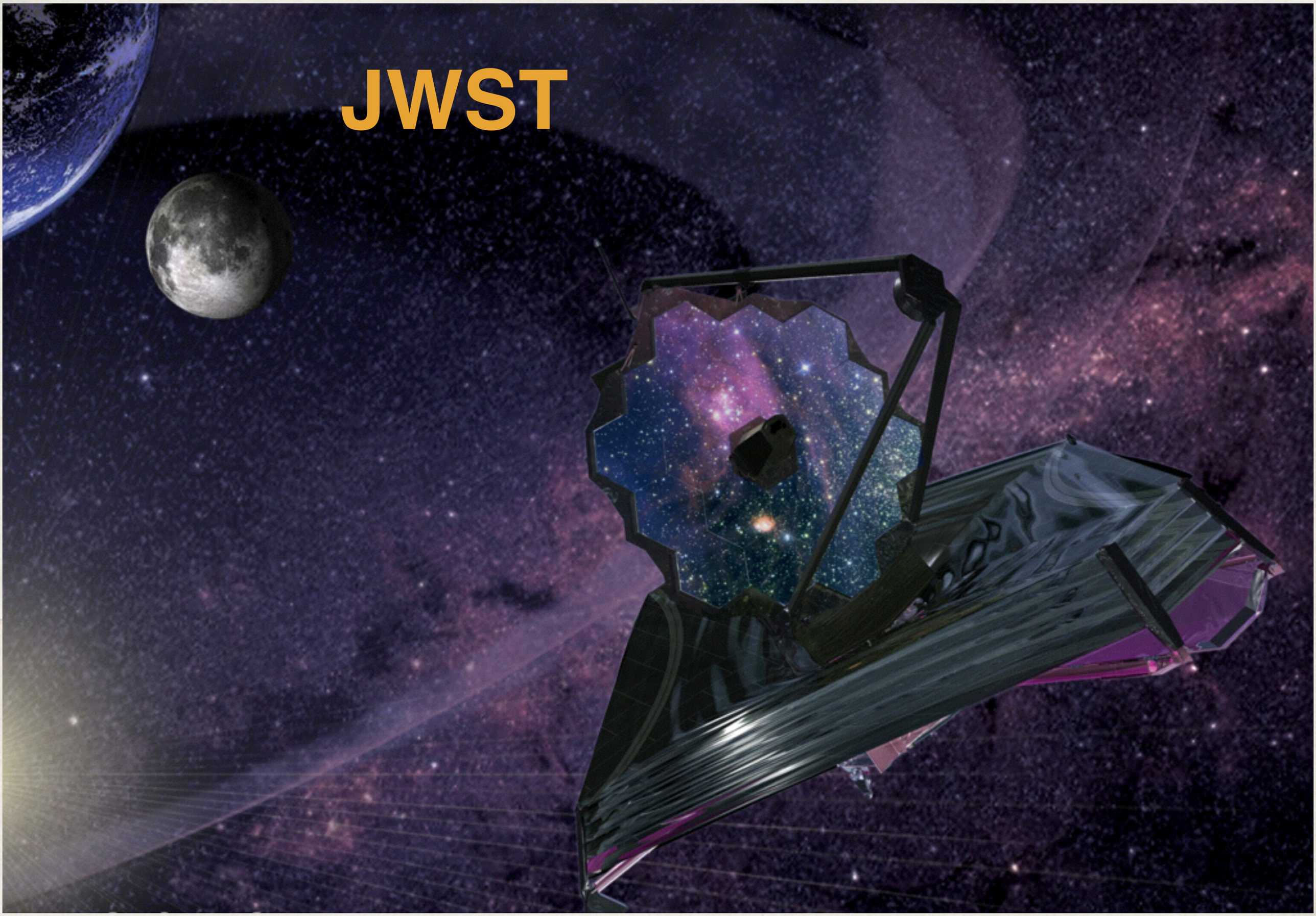
jason@astro.umontreal.ca

June 17, 2016



Canadian Astronomy 2010 LRP

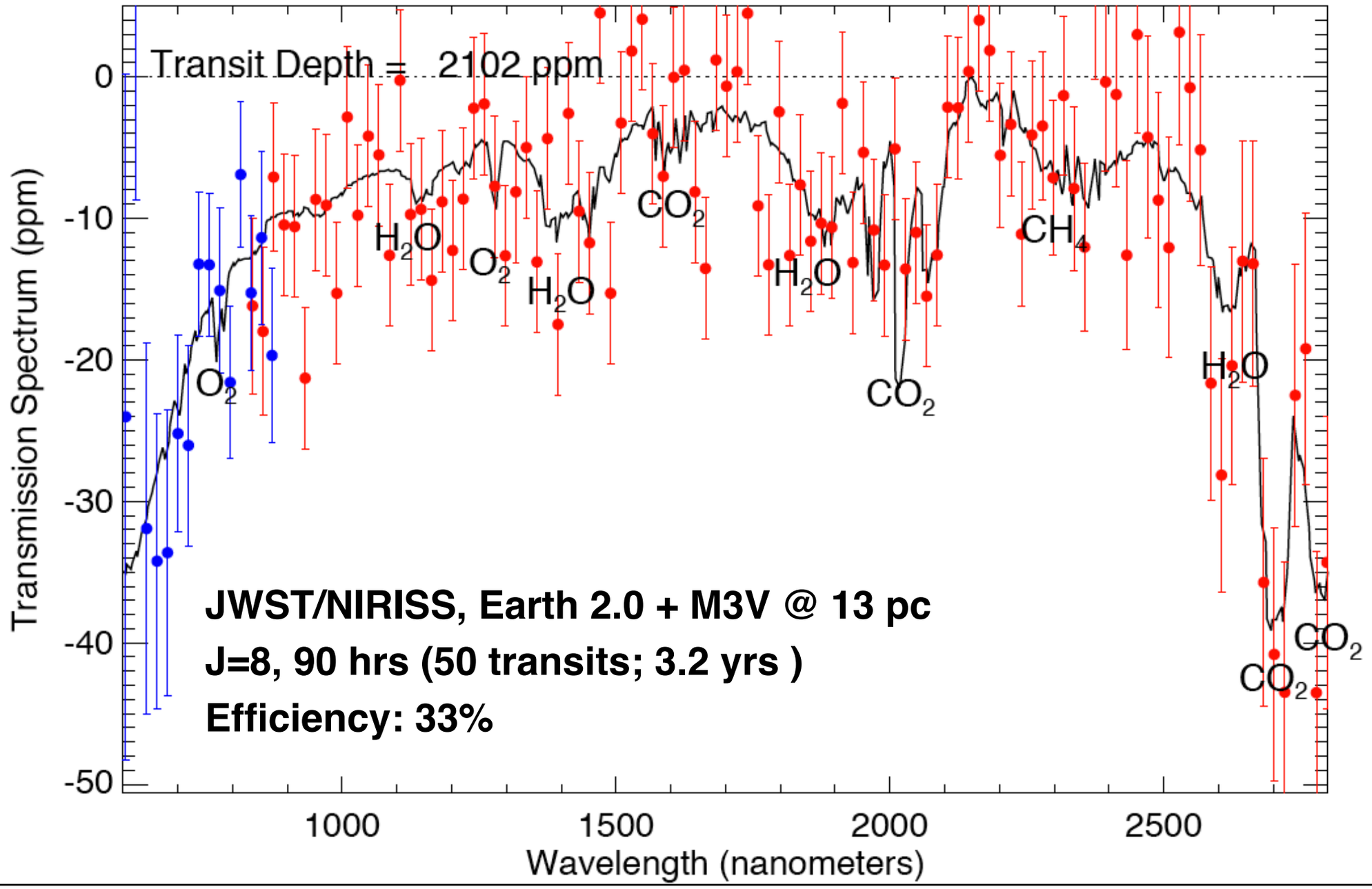
JWST



NIRISS - Slitless Spectrometer

Earth 2.0 + M3V @ 13 pc (likely TESS HZ planet)

$$1\,R_\oplus, \rho = \rho_\oplus/2$$

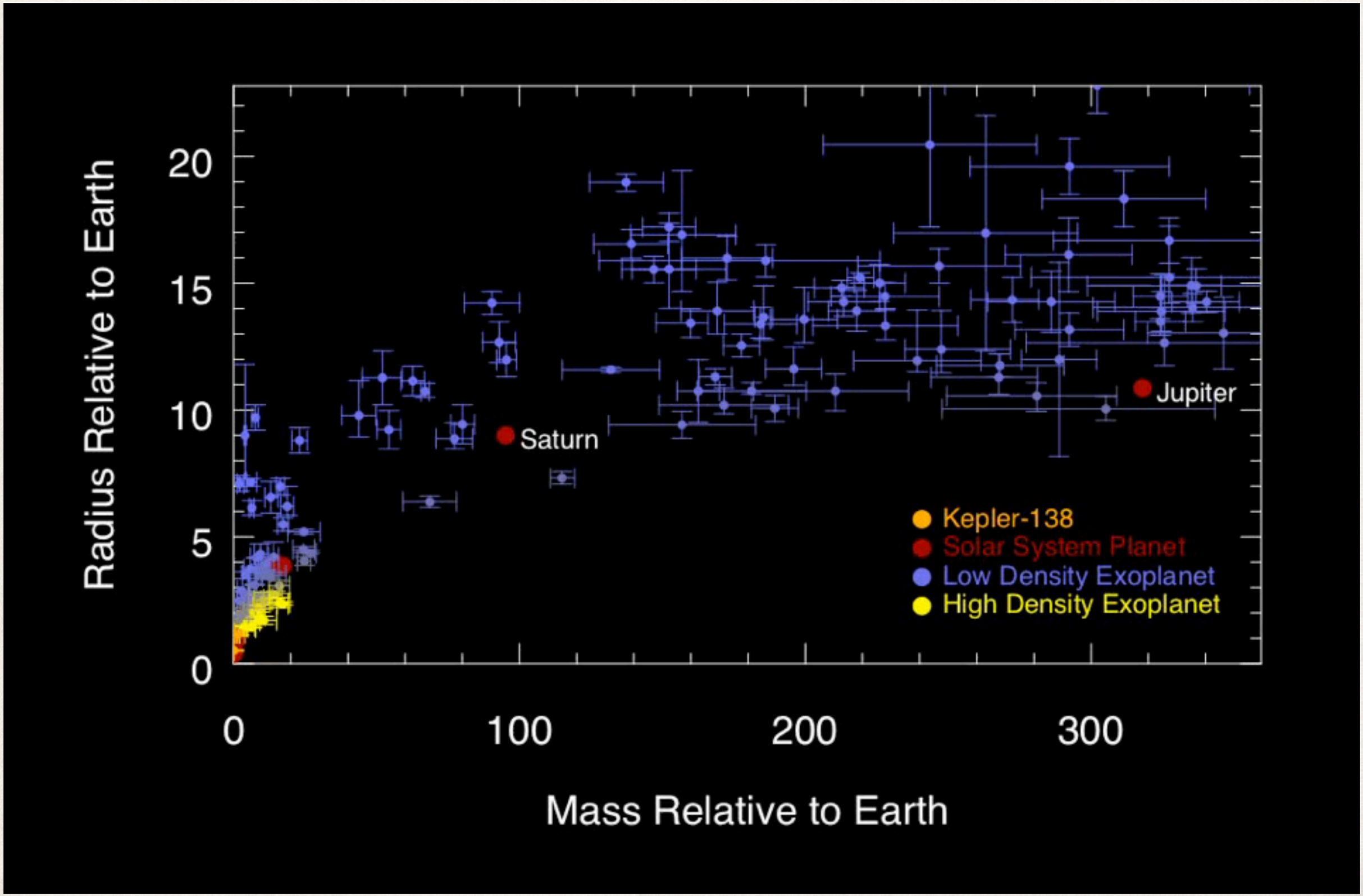


Characterization of habitable Earths possible with a noise floor of 5-10 ppm.

Current Status

- Exoplanets has gone from a field focused on discoveries to characterization
  - mass, radius, bulk density, albedo, brightness temperature, atmosphere composition
  - Driven by transiting exoplanets

Mass-Radius Relation



1980s… Gamma Cephei Ab

Lost world: How Canada missed its moment of glory

JACOB BERKOWITZ

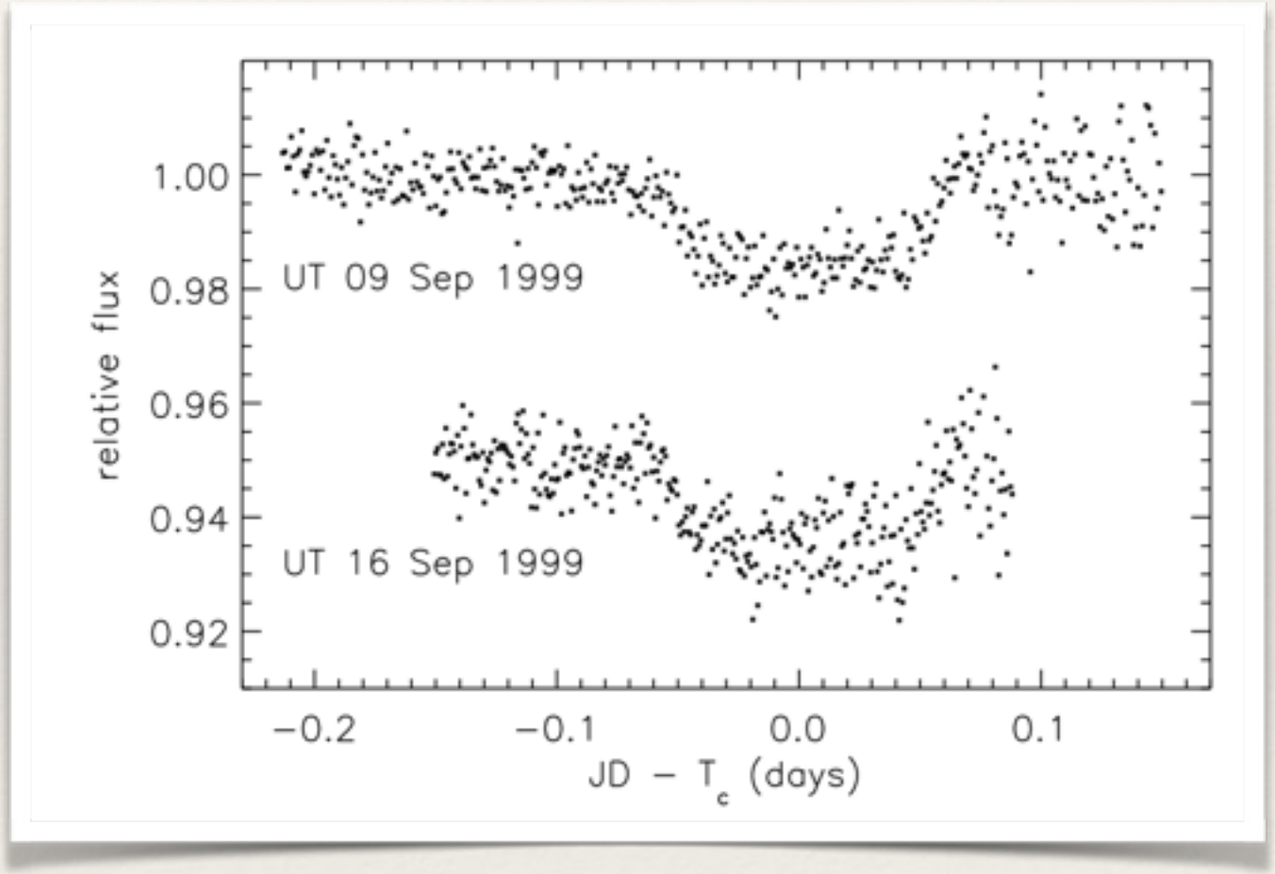
From Saturday's Globe and Mail
Published Friday, Sep. 25, 2009 5:50PM EDT
Last updated Thursday, Aug. 23, 2012 12:32PM EDT

In June, 2007, the Nobel Foundation sponsored a special symposium in Stockholm, inviting top researchers to discuss the physics of "exoplanets" - planets that orbit stars other than the sun.

The quest for far-off worlds, once dismissed as sheer fantasy, is now considered the "other space race." Such planets may help humanity realize its ancient dream of finding extraterrestrial life, and finding the very first of them has gone down as one of the great accomplishments of 20th-century astrophysics.

HD209458b

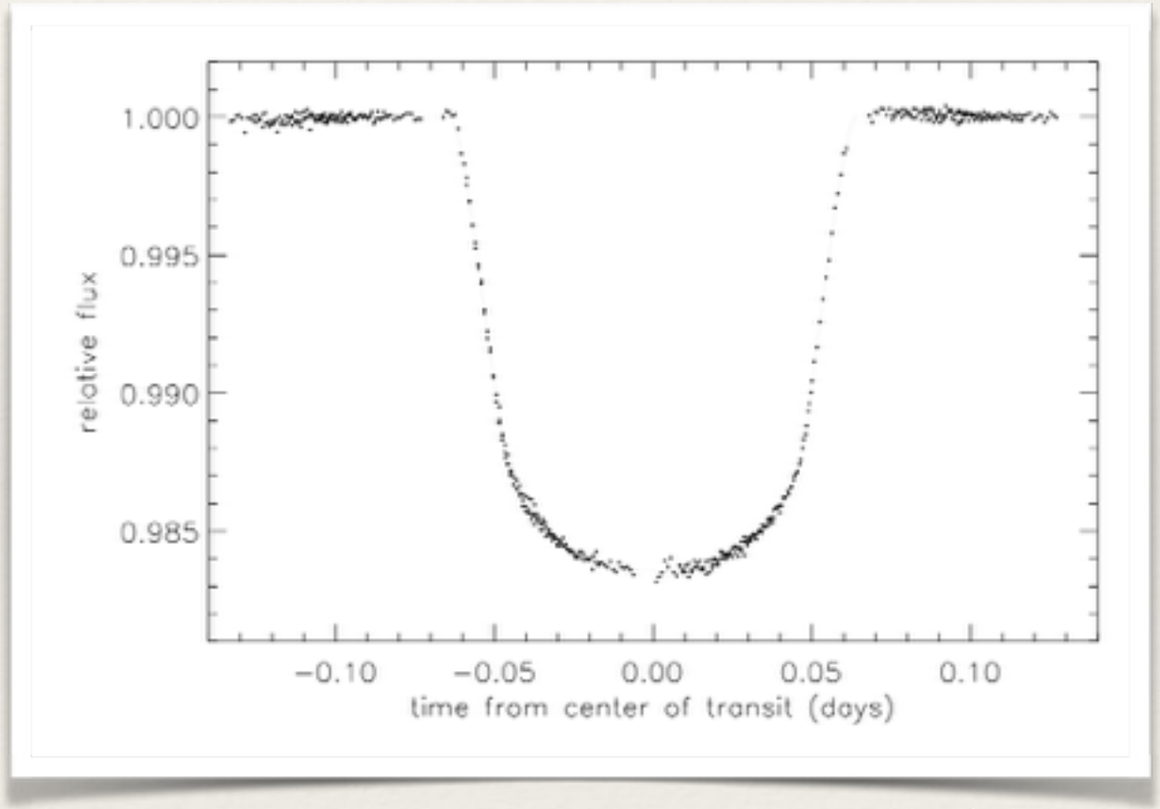
- First transiting extrasolar planet
- no doubt that the companion was planetary
  - RV + transit
- first atmospheric detection
  - Spitzer



Charbonneau, D. et al. 2000

Hubble Space Telescope

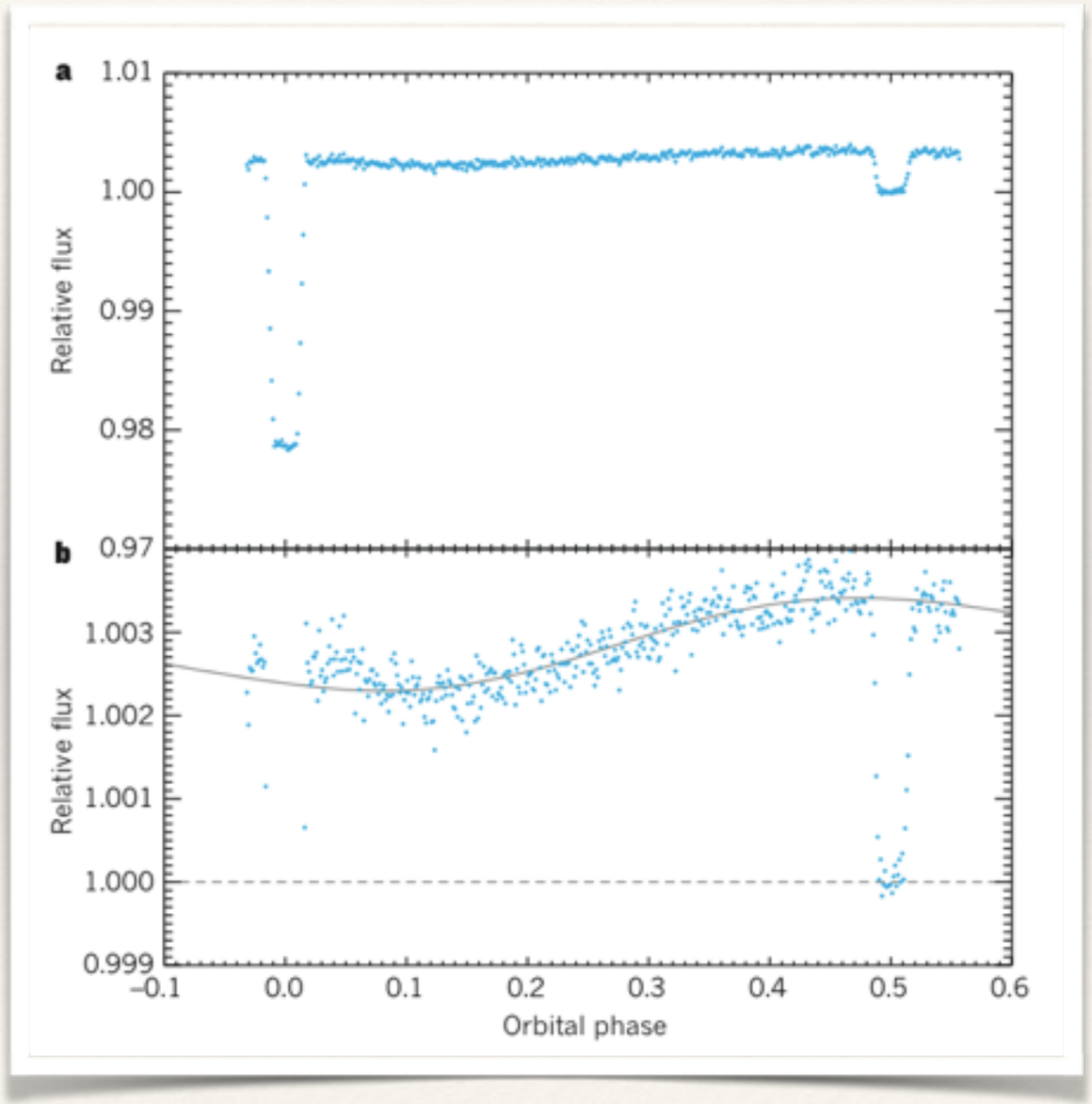
- STIS observations of HD209458
- Detection of sodium, hydrogen, magnesium
  - transit spectroscopy



Brown, T. et al. 2001

Spitzer Space Telescope

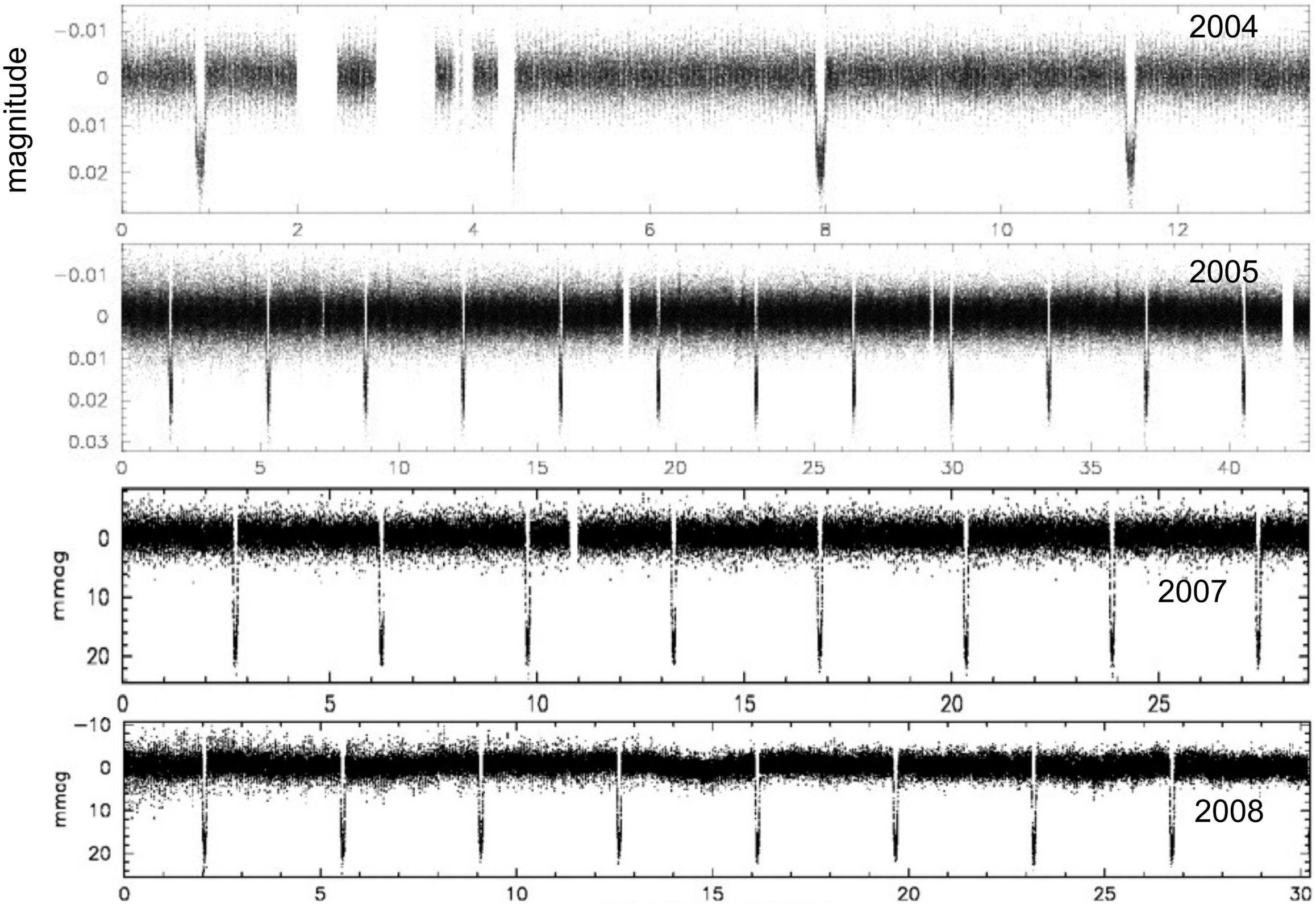
- Occultation of HD209458b
- Phase curve of HD189733
- numerous brightness temperature measurements
- dealing with intrapixel variations



MOST Mission

- launched June 30, 2003
  - 800 km polar orbit
  - 15 cm broadband, optical telescope
- low albedo of HD209458
- transit of 55 Cnc e

MOST Observations



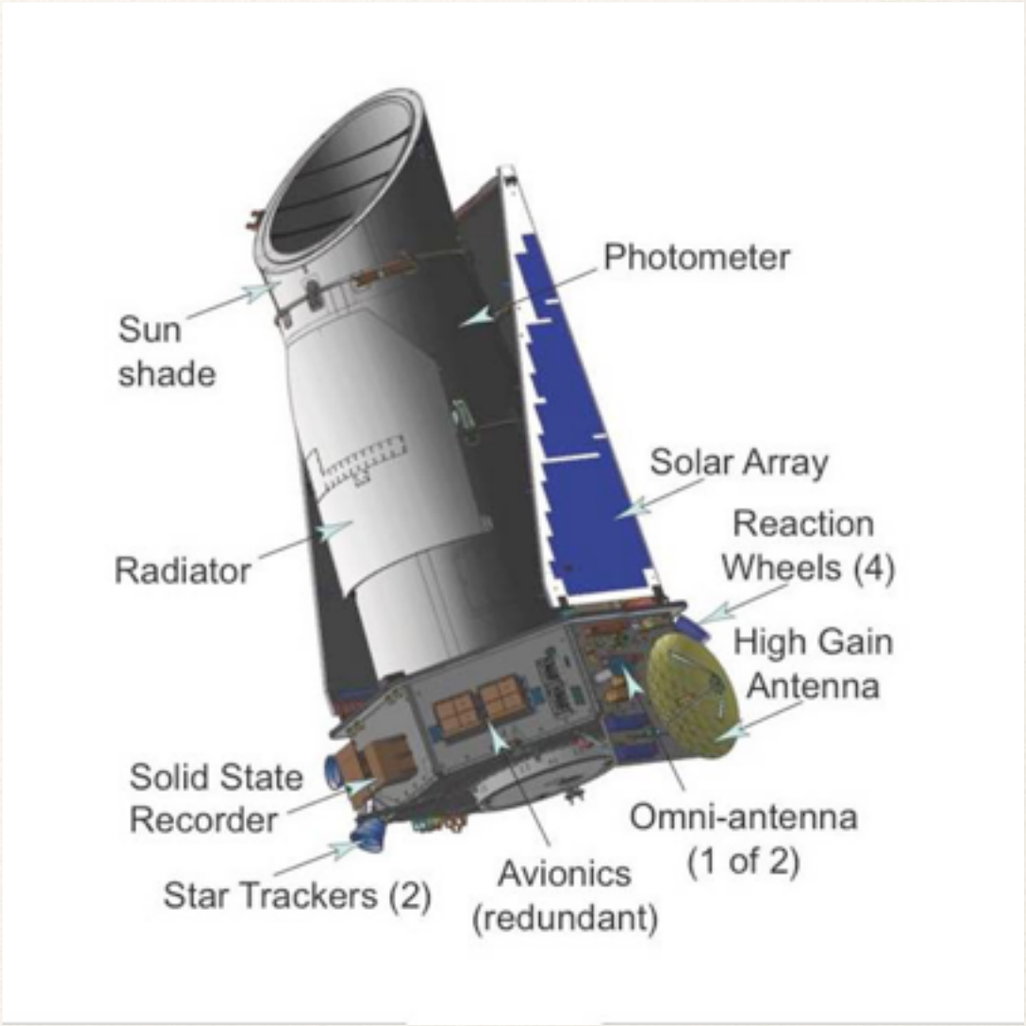
641 692 measurements!

CoRoT Mission

- launched December 2006
  - 27 cm broadband, optical telescope
- CoRoT-2b : planet around an active star
- CoRoT-9b : first moderate temperature giant
- CoRoT-7b : one of the first rocky super-Earths
- Data has been reprocessed and released!
  - http://idoc-corot.ias.u-psud.fr
  - ~160 000 stars

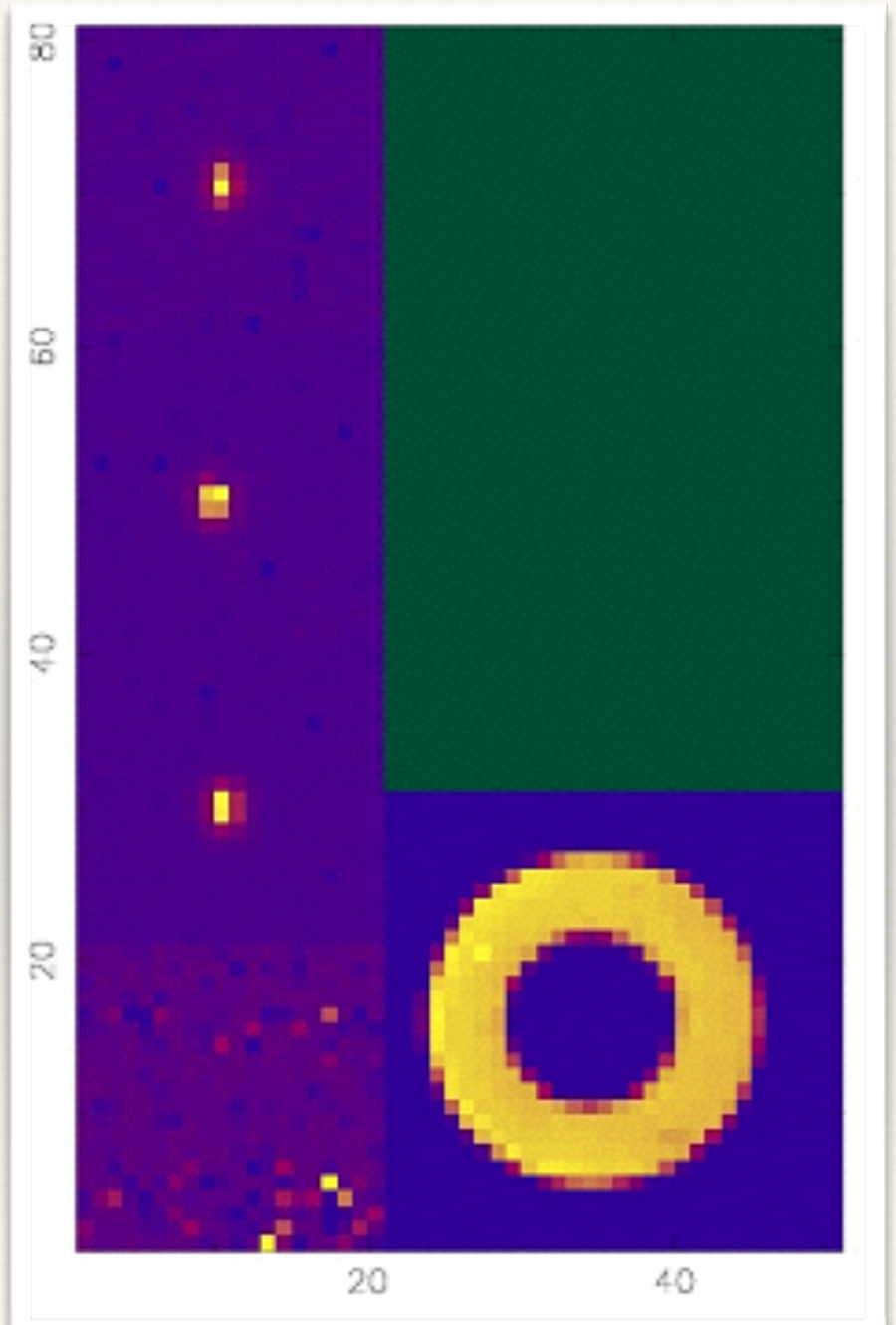
Kepler Mission

- Kepler-9b - TTVs
- Kepler-10b - rocky planet
- Kepler-11 - 6 planet system
- Kepler-16b - cEB planet
- Kepler-20e - smaller than the earth
- Kepler-37b - moon sized
- Kepler-78b - mass/radius of an Earth-sized planet
- Kepler-138b - mass and radius less than the Earth
- Kepler-62f - HZ planet that may be rocky
- Kepler-296f - Earth-sized HZ planet



MOST-CoRoT-Kepler

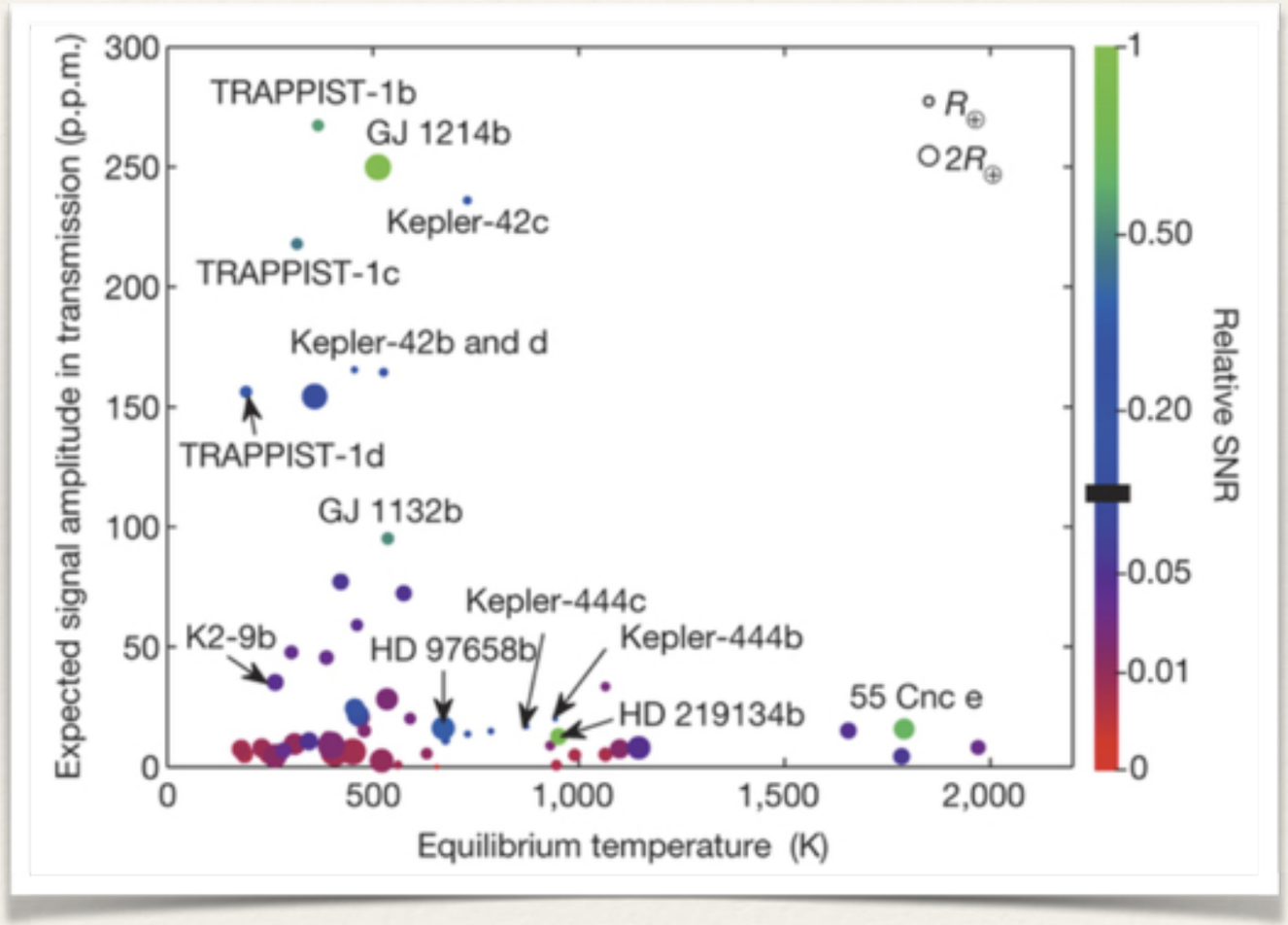
- MOST team provided CoRoT early access to images to test on-board photometry
- CoRoT team provided Kepler early access to photometry to understand impact of stellar variability



MOST Observations

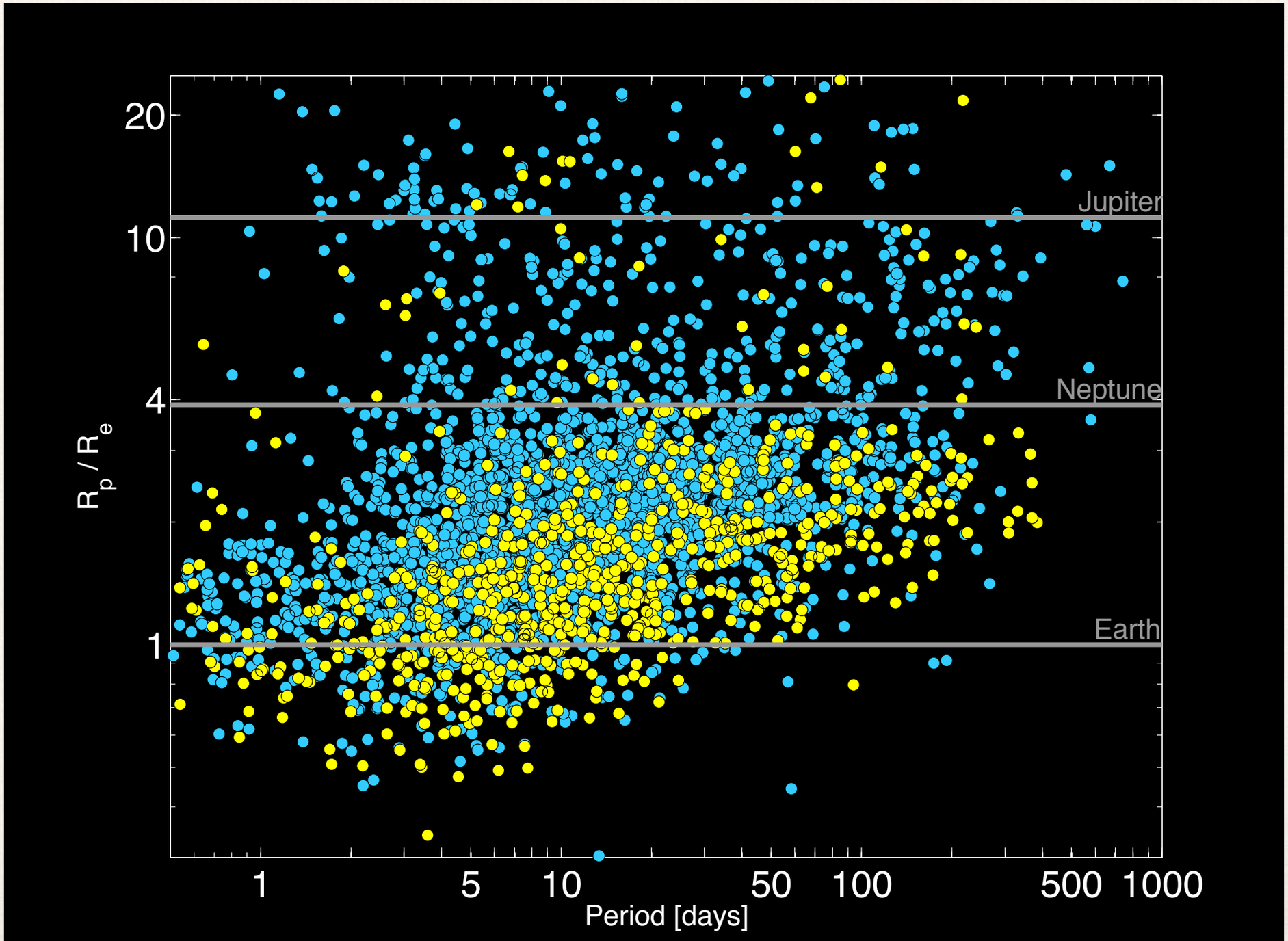
Transit Surveys

- K2 - through GO proposals
- WASP, HATNet, TrES, MEarth, TRAPPIST…
  - TRAPPIST-1 :
    - 2500 K, 0.08 Msun
    - 3 Earth-sized planets



Gillon 2016

Planet Candidates - diversity

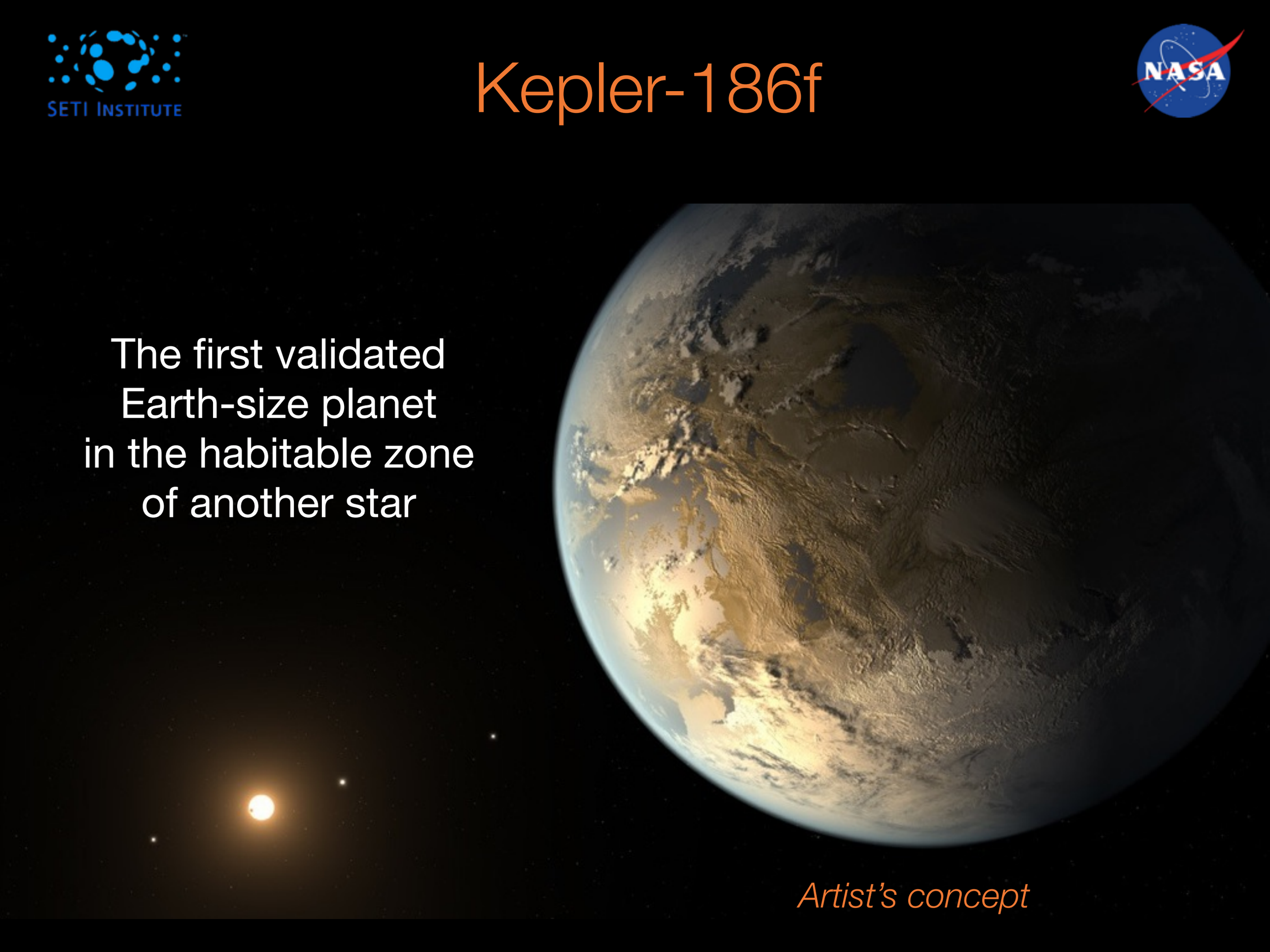


SETI INSTITUTE

Kepler-186f

NASA

The first validated
Earth-size planet
in the habitable zone
of another star



Artist's concept

Apr 17, 2014 12:58AM EDT – Ukrainian, Russian and Western diplomats were in Geneva for emergency talks

Russia says deal reached to 'de-escalate' tensions over Ukraine

- GLOBE EDITORIAL **Kiev must meet provocation with restraint**

Canadian fighter jets to support NATO response to Ukraine crisis

- RELATED **Why 'federalization' is Russia's watchword**

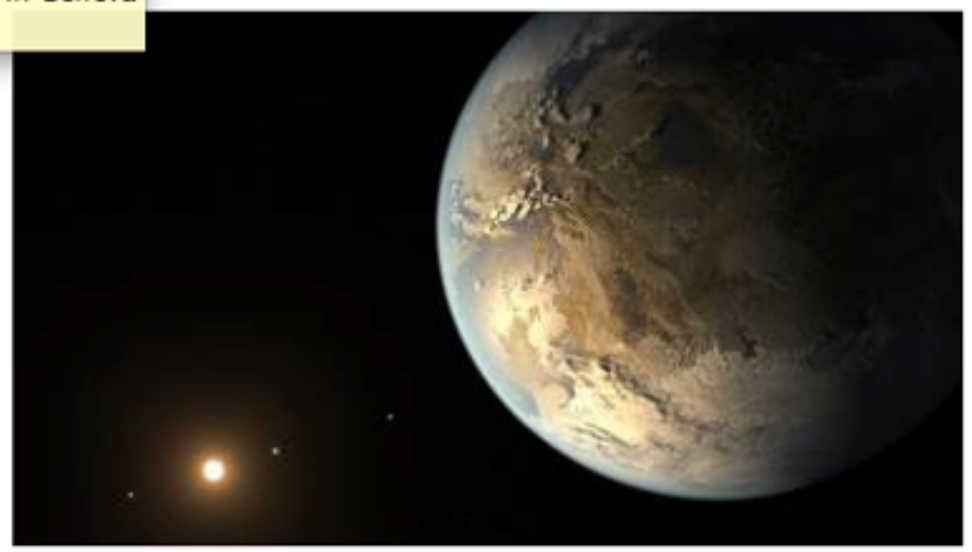
Landmark ruling on rights of Métis upheld

Canadian soldier faces more sex-assault, voyeurism charges

NEW **Toronto's Adam Vaughan wants to run for Liberals in Chow's old seat**

Student accused in CRA case engaged in ethical hacking in high school

UNLIMITED **Nine election changes**



SCIENCE 'This is a big milestone.' For first time, astronomers find 'habitable' Earth-like planet

MARGARET WENTE

Why crime is plunging but police costs are soaring 251

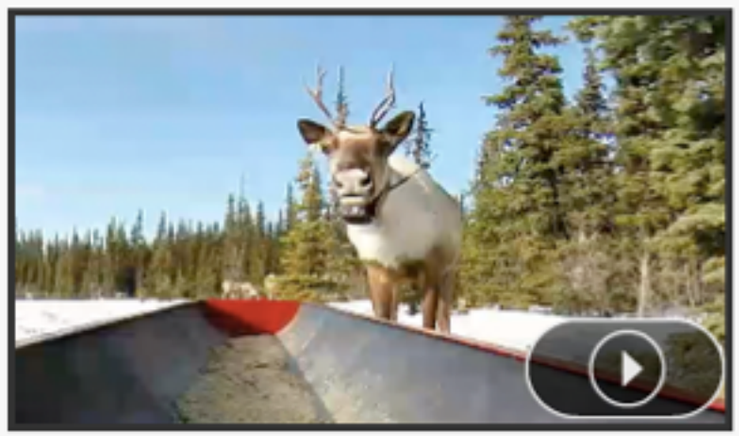
JOANNA SLATER

UNLIMITED **Can Bloomberg outgun the NRA?** 34

CATHAL KELLY

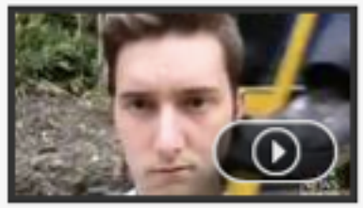
Raptors have a real shot at

MUST WATCH »



NEWS

Watch the unique way endangered caribou are being saved in B.C.



LIFE

Selfie with passing train goes wrong

LIFE

'X-Men' director Singer accused of drugging and raping teenager

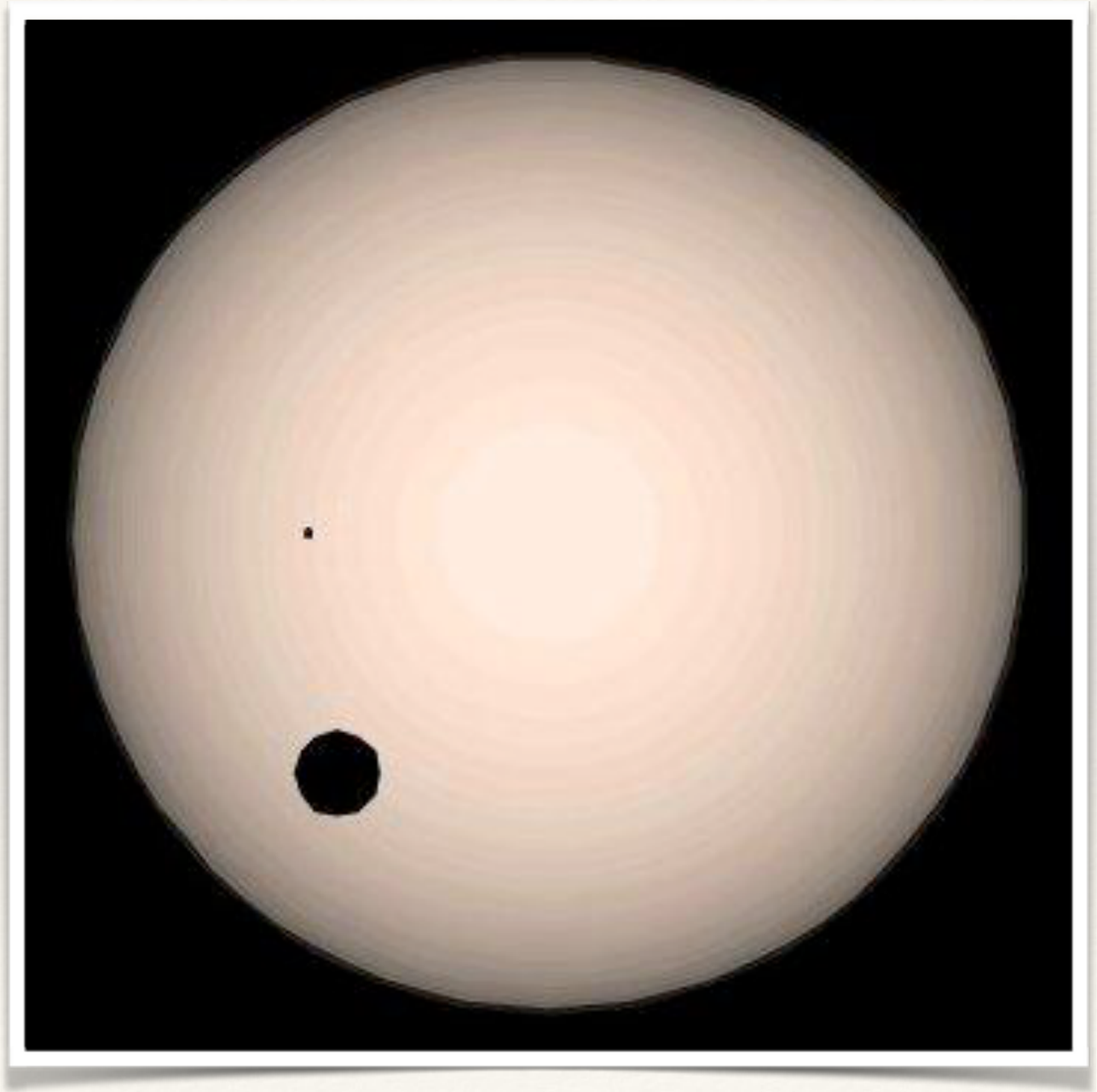
Transit Photometry: Techniques and Results

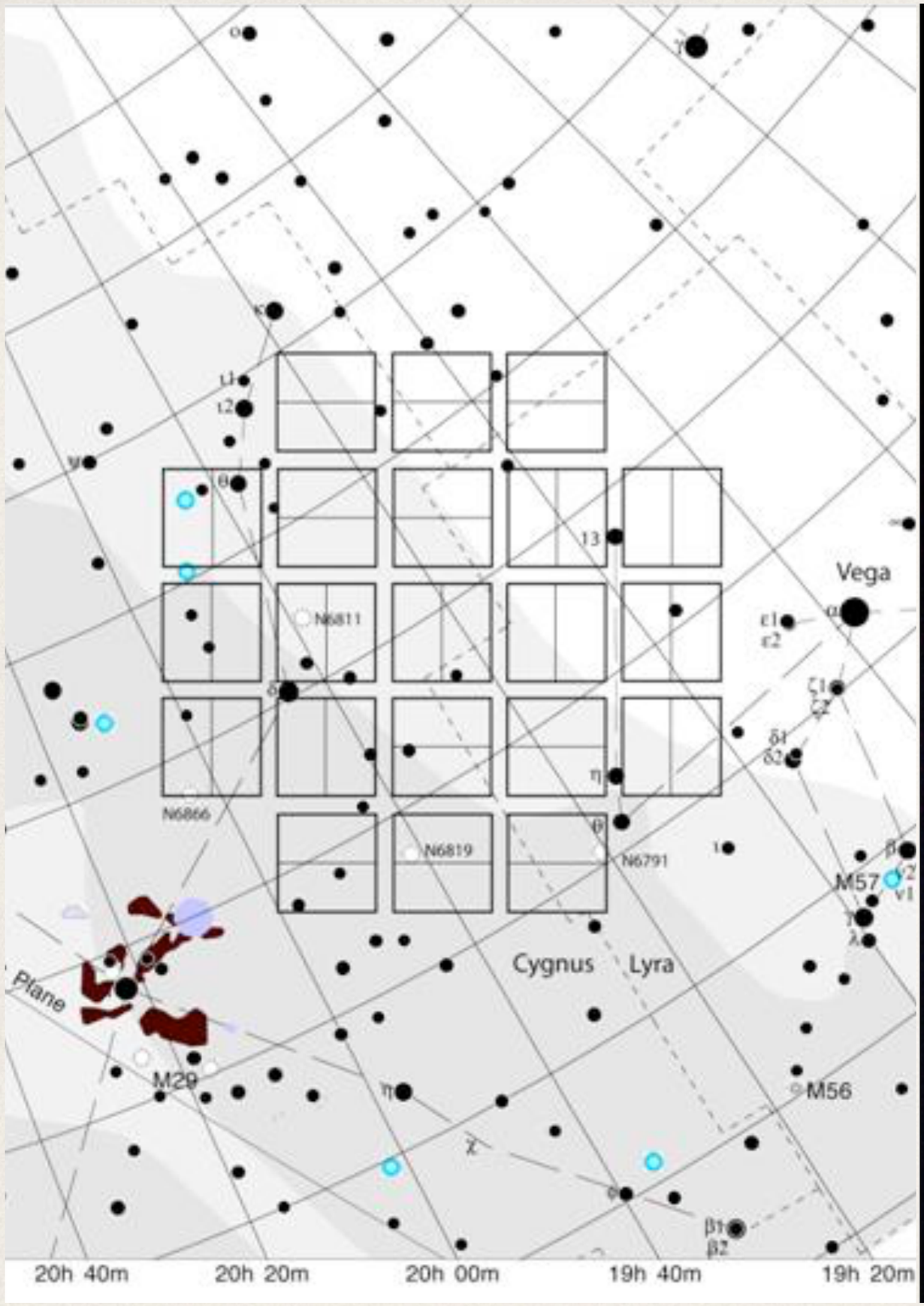
Kepler Mission

- Optimized to find habitable planets around solar-like stars
- continuously & simultaneously monitor over 160 000 stars
- one meter Schmidt telescope
  - > 100 deg^2 FOV
  - 42* CCDs
- 4 year primary mission

A look back…

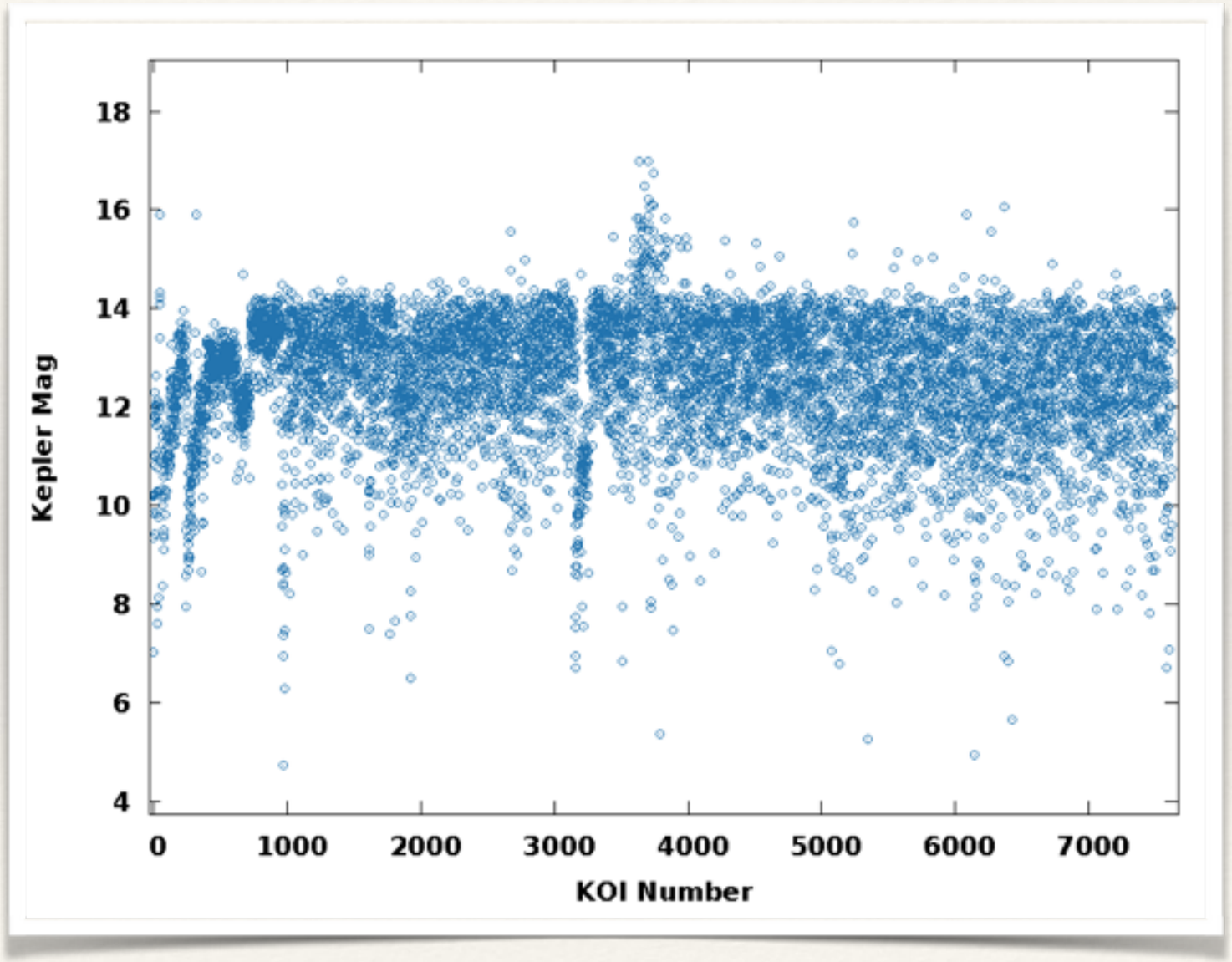
- From pixel to planet
  - searching for planets
  - cataloging planets
  - characterizing planets
- All my source codes and documentation are public
- https://github.com/jasonfrowe/Kepler




Vega
Cygnus
Lyra
Pfane
M29
M56
M57
N6811
N6866
N6819
N6791
20h 40m
20h 20m
20h 00m
19h 40m
19h 20m

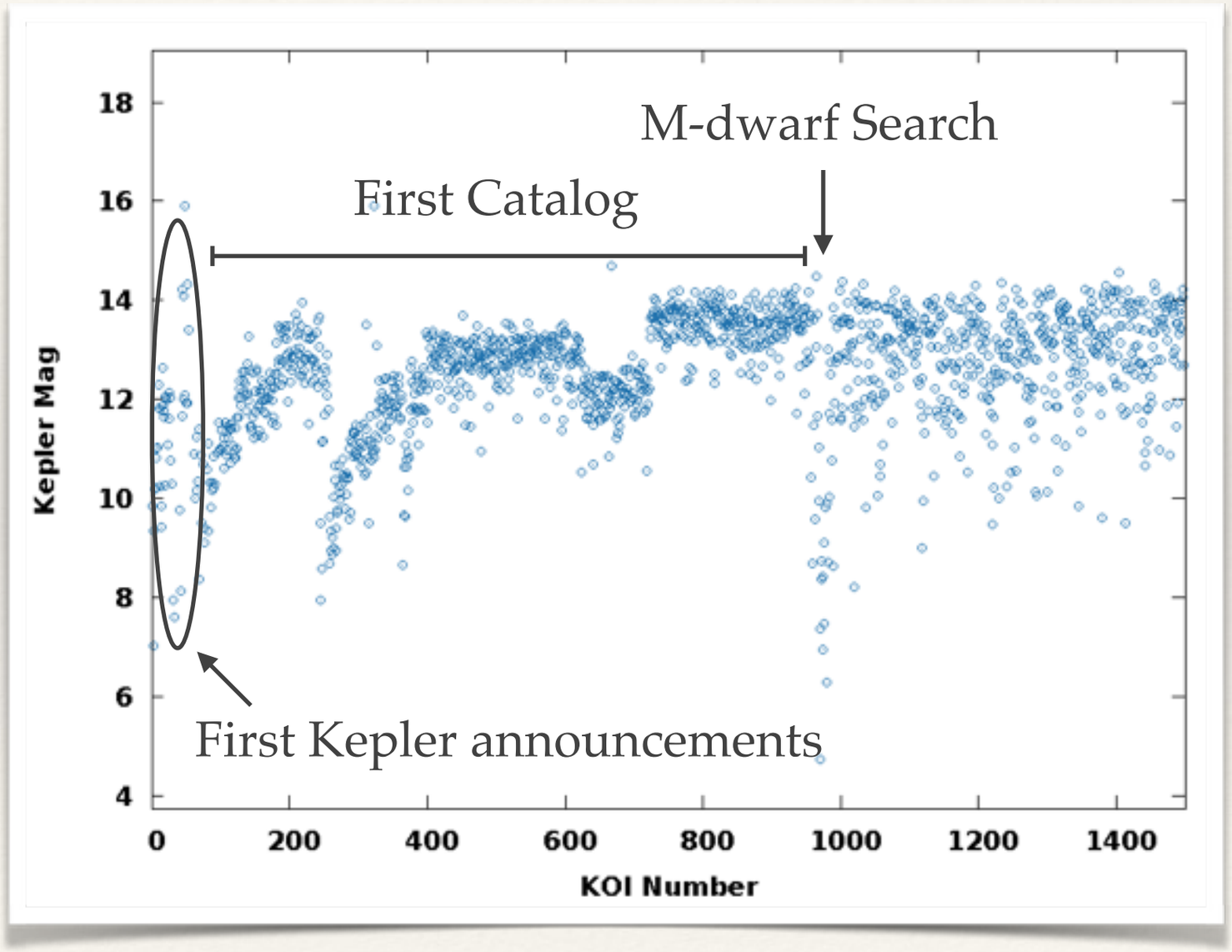
KOIs tell a story

- KOI : Kepler-Object-of-Interest
  - a number invented to track potential planet discoveries
- First KOIs where discovered by eye
  - printing Q0/Q1 lightcurves on paper



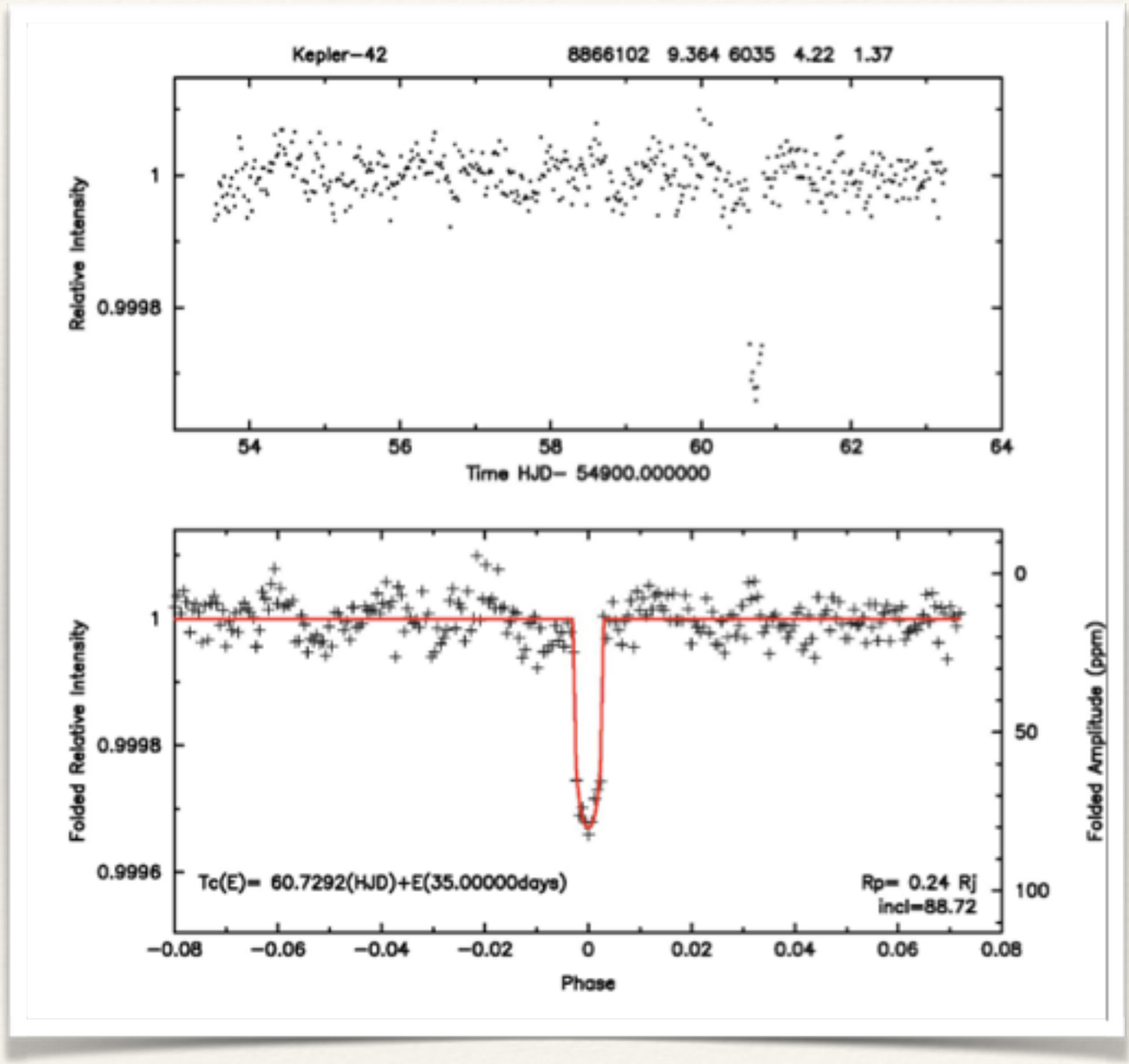
KOIs Searches

- priority was to find planets around bright stars to support ground based followup
  - Imaging + RV
- Candidates were primarily found using median detrending and BLS



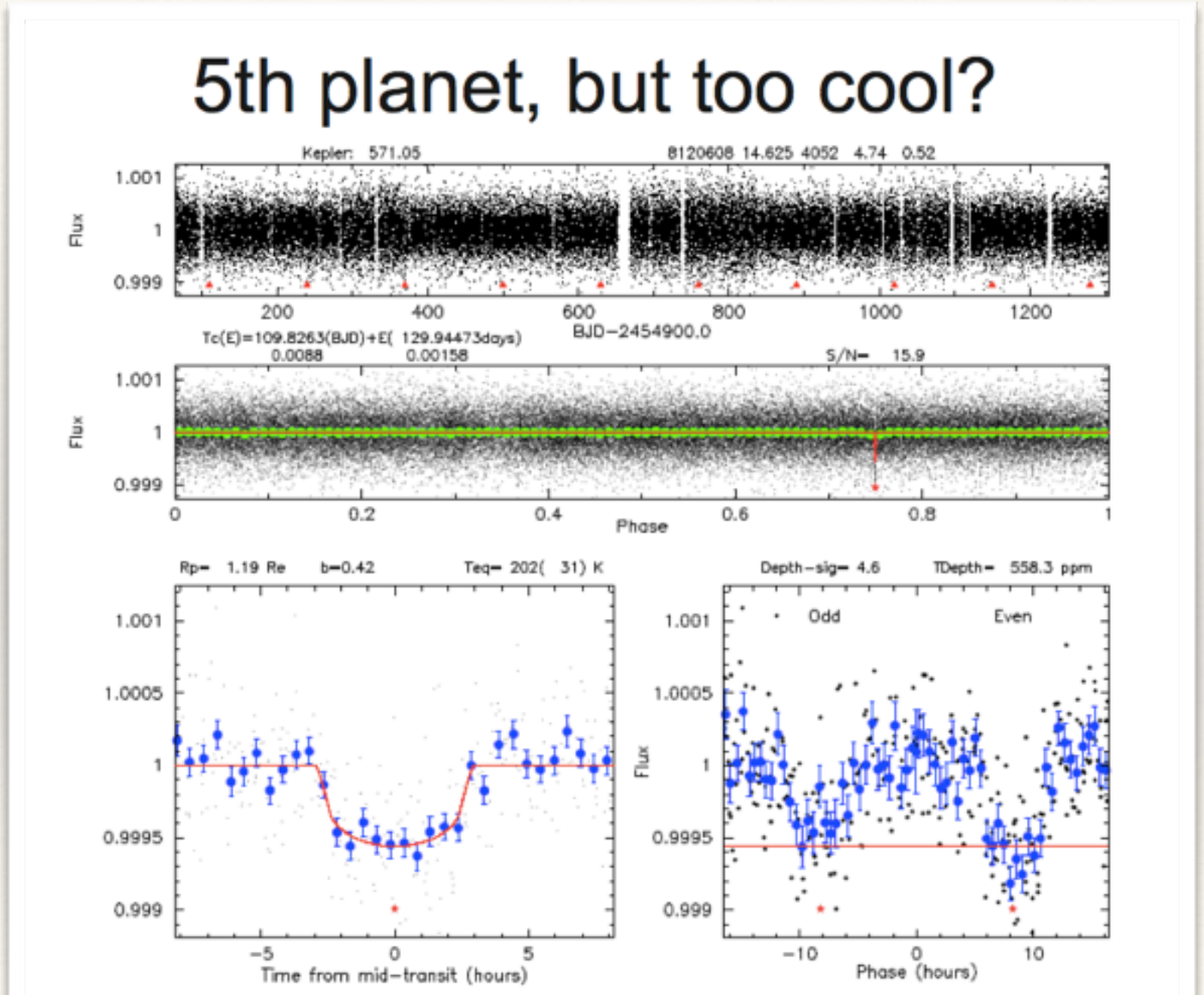
Finding Planets

- The best period/epoch was returned from a transit search
  - no multiple passes
- plots would be generated to show the lightcurve and folded lightcurve
  - chi-by-eye detections
- Diagnostic reports modeled from initial development by Ron Gilliland

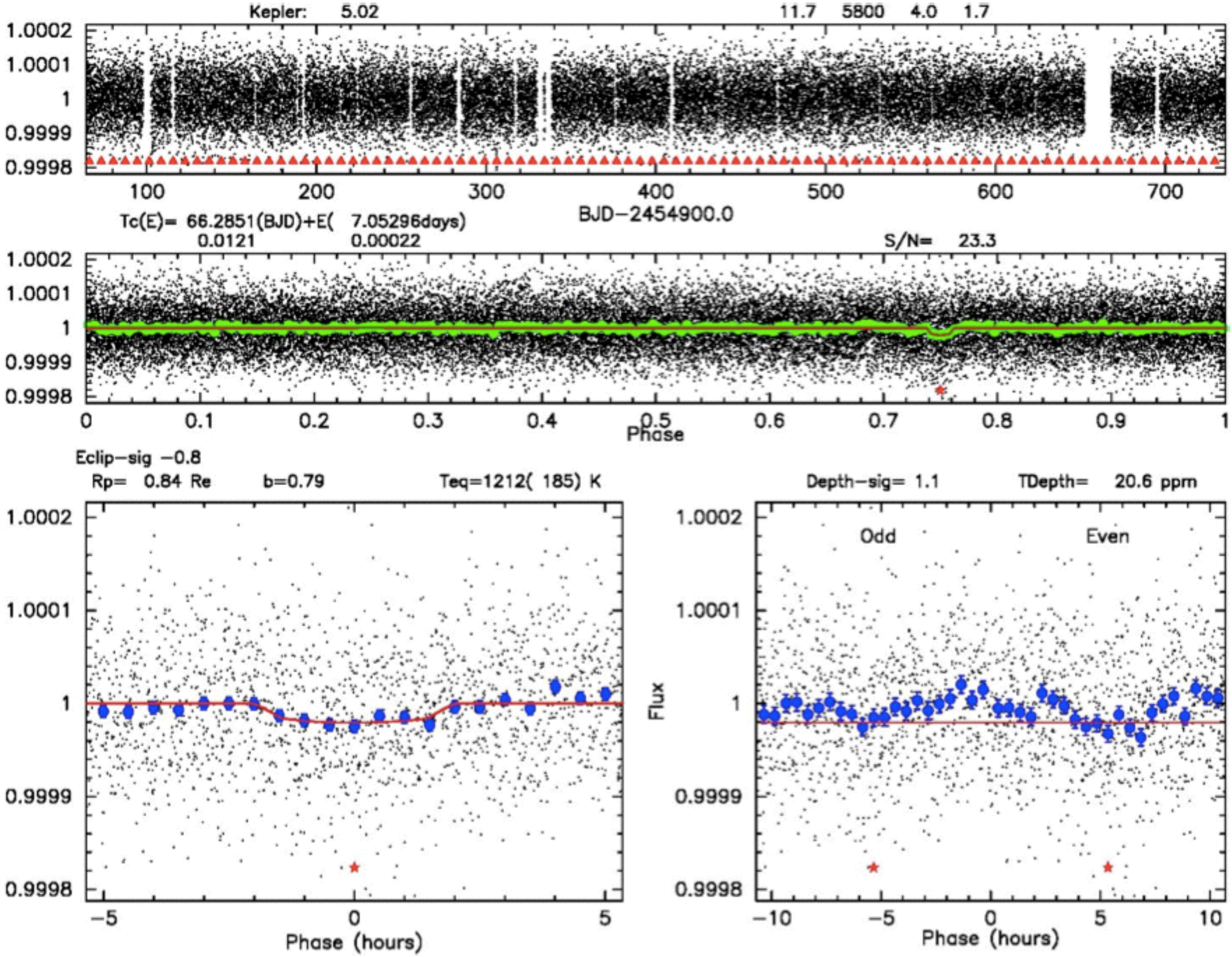


Finding Planets

- Discovery plot for Kepler-296f from a Kepler TCERT meeting
- but for a while, the rule for KOIs was S/N > 7 and validation by visual inspection

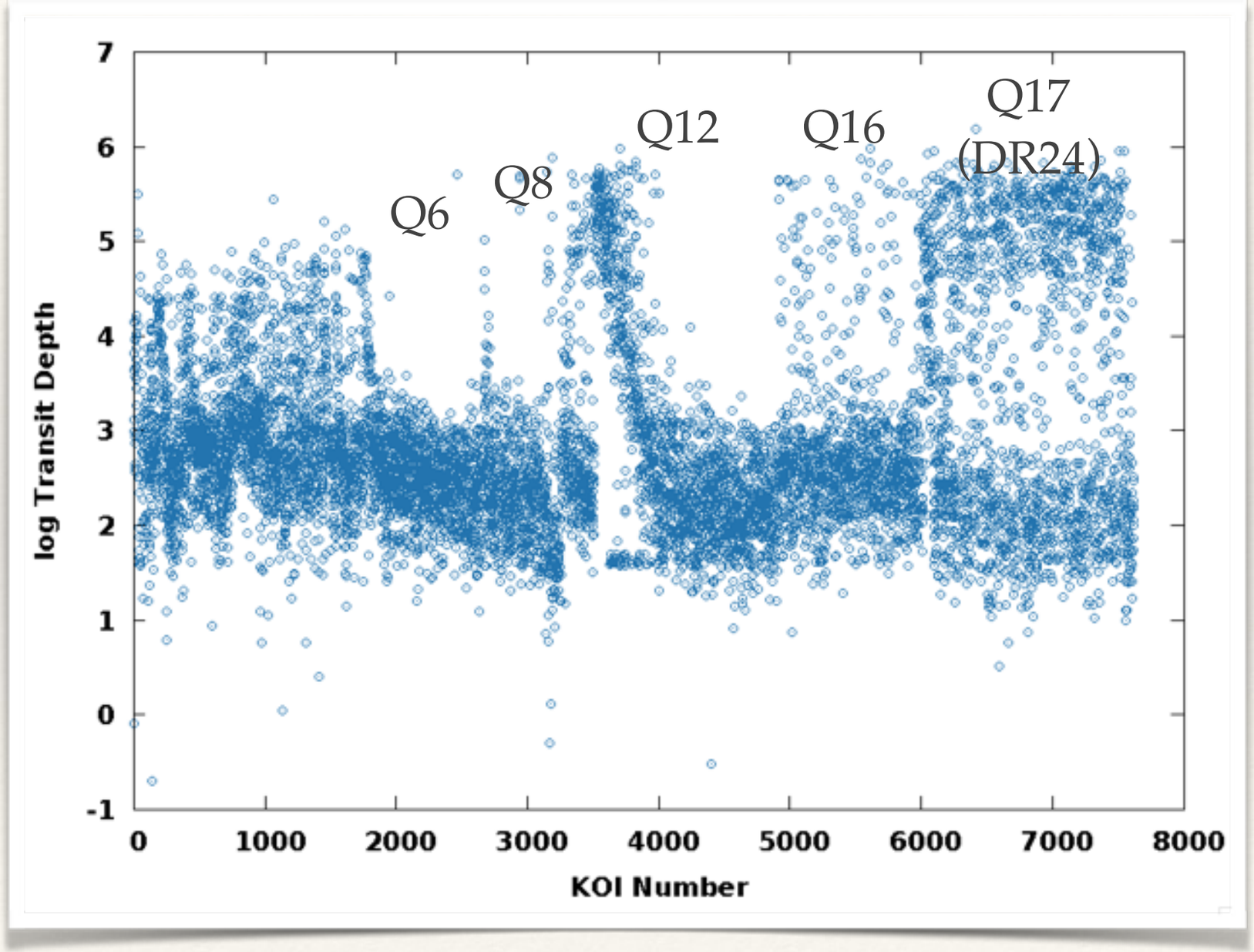


NEW


Kepler: 5.02
11.7 5800 4.0 1.7
Flux
1.0002
1.0001
1
0.9999
0.9998
100
200
300
400
500
600
700
BJD−2454900.0
Tc(E)= 66.2851(BJD)+E(7.05296days)
0.0121 0.00022
S/N= 23.3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Phase
Eclip−sig −0.8
Rp= 0.84 Re b=0.79 Teq=1212(185) K
Depth−sig= 1.1 TDepth= 20.6 ppm
Odd
Even
−5
0
5
−10
Phase (hours)

KOI History

- Q6 - pipeline method used for single pass detection
  - multi's from BLS
- Q8 - multiple-pass wavelet
- Q12 - community dispositions
- Q16 - automating dispositions
- Q17 - robovetting + deep EBs



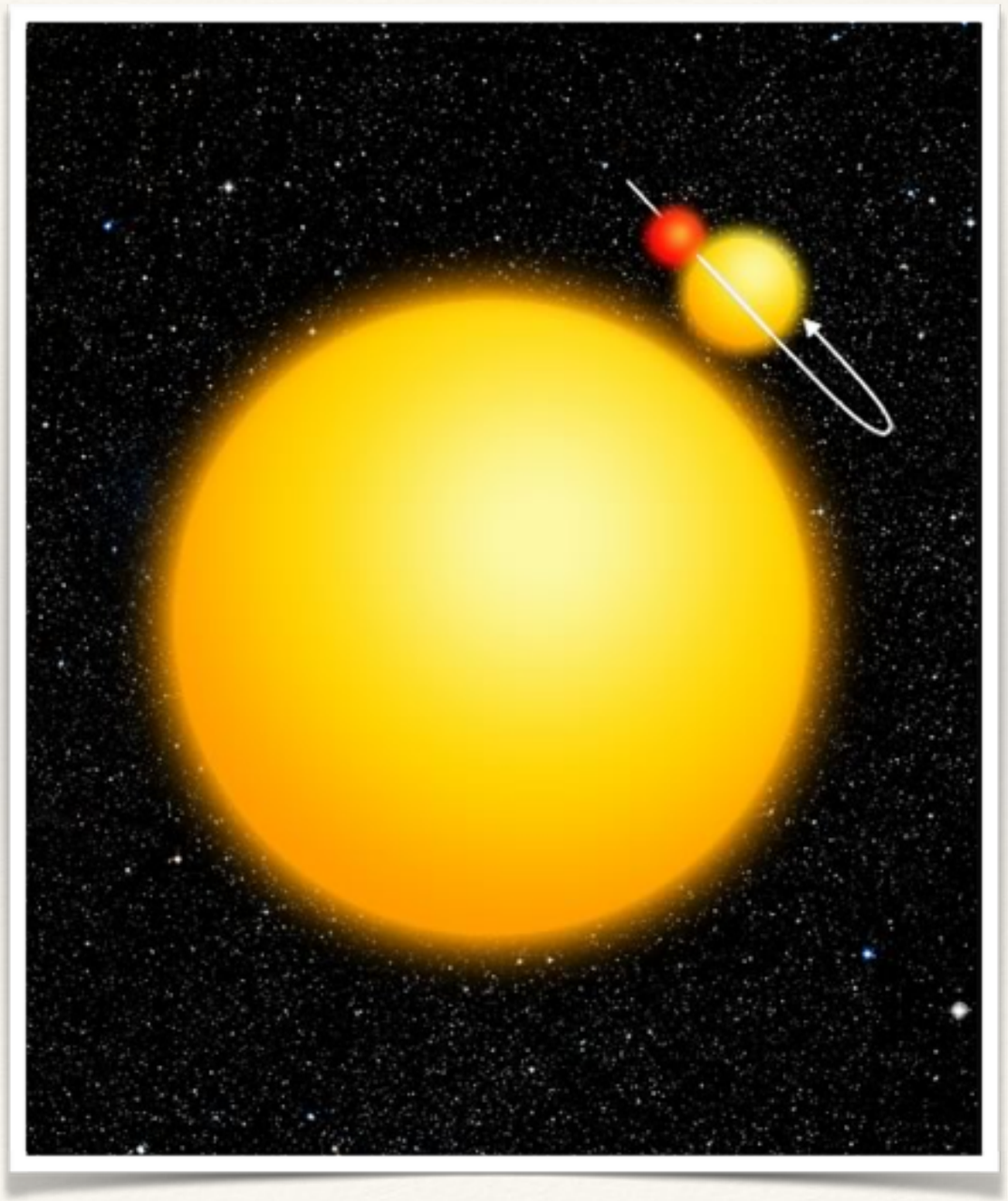
Transit Detection Reliability

- **False-alarms**
- Transit Injection
  - insert signals into you data and go find them.
- Transit Inversion
  - mirror the light curves about zero.
  - estimate your false detection rate

Ford Transit Fuel Pump

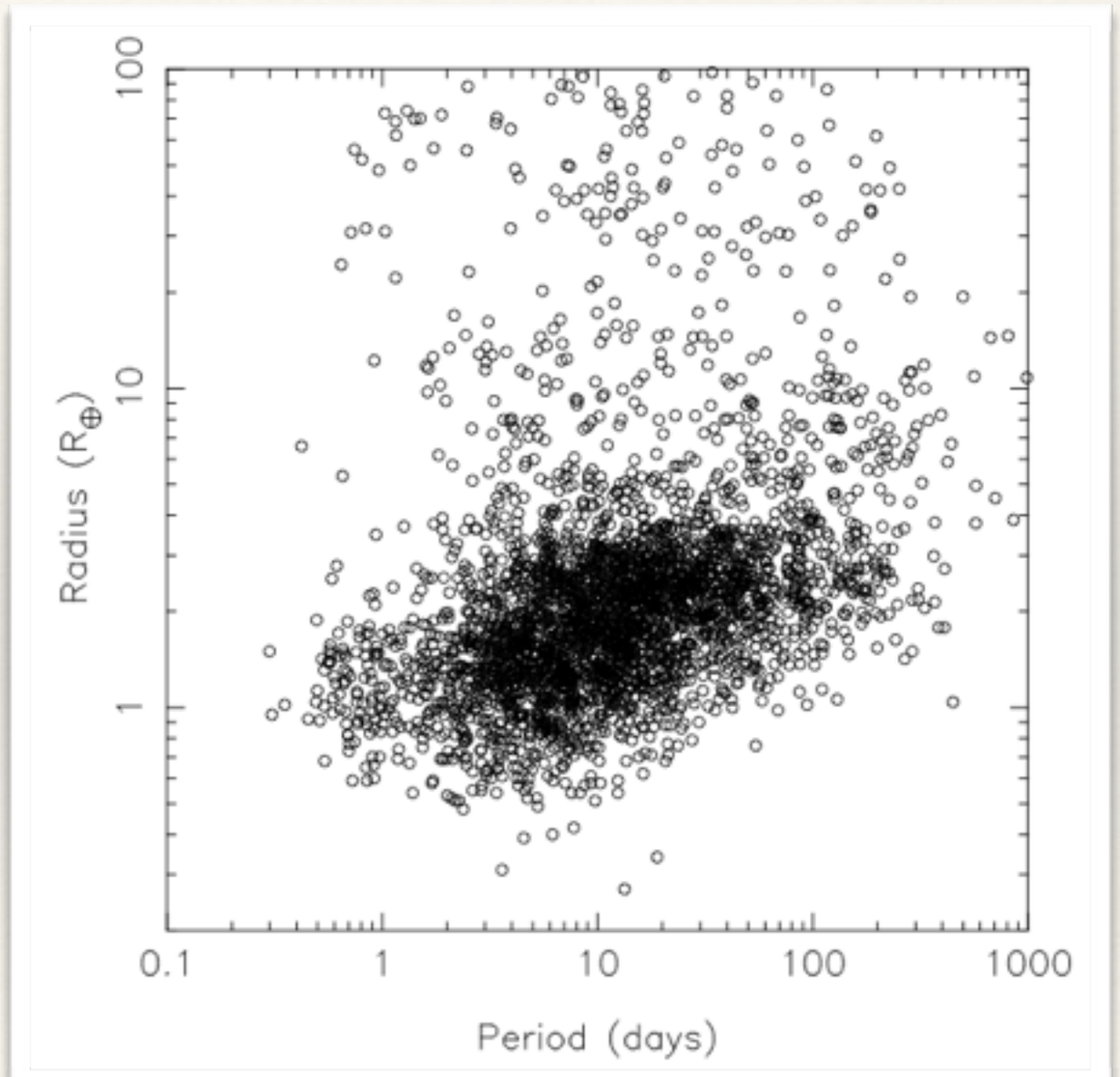
False-positives

- **False-alarms and false-positives are two different classes**
  - currently merged.
- False-positive tests
  - odd-even, uniqueness test, S/N, centroids
  - important efforts towards automating and assigning a false-positive probability



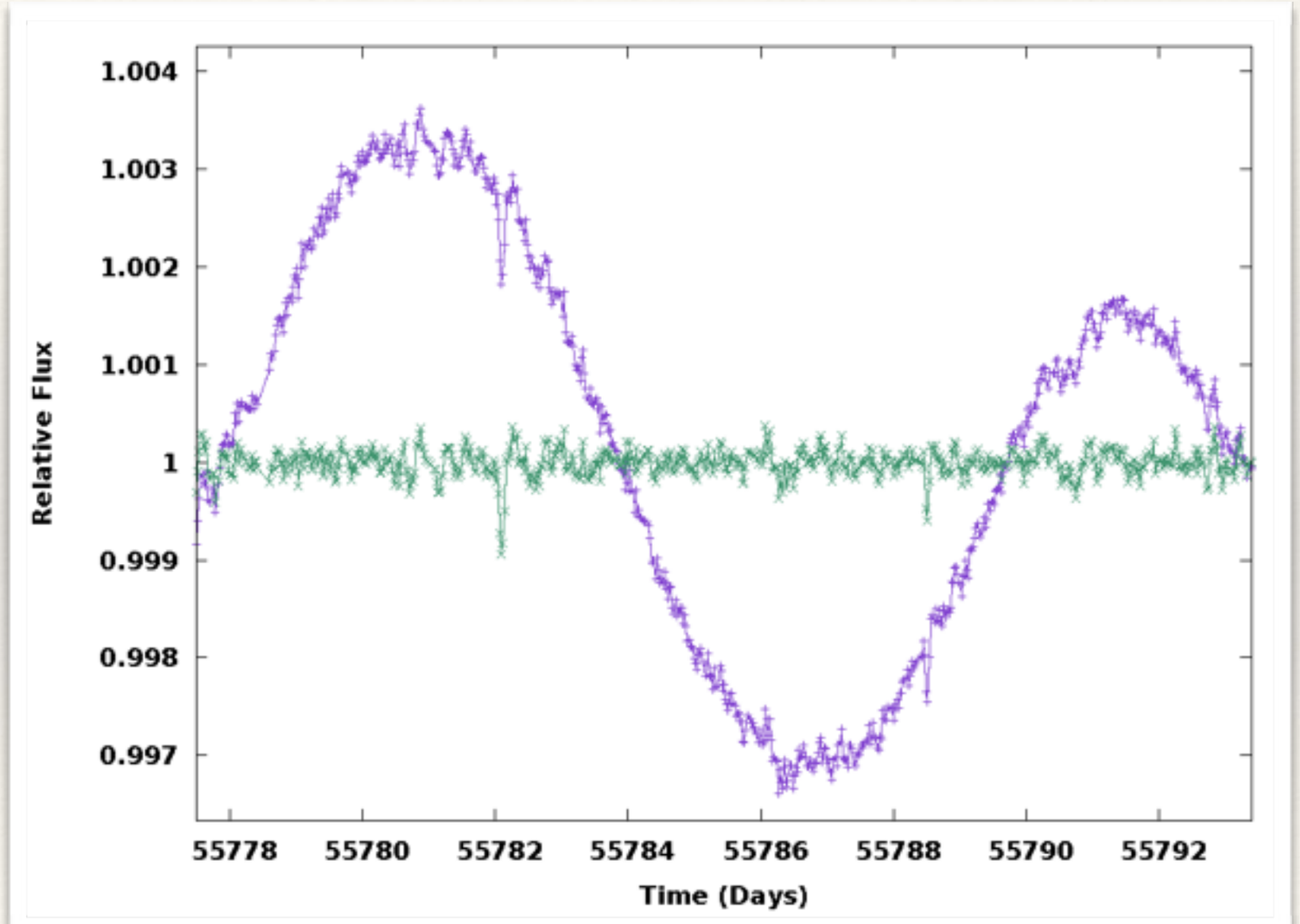
Planet Characterization

- lightcurve model
  - detrending/GPs
  - stellar parameters
  - transit-model
    - Mandel+Agol
  - limb-darkening
  - TTVs
  - posterior distributions



Detrending

- polynomial (cubic) filter
  - 2, 5 or 10 days
  - dependent on transit duration
  - transits are masked
- **Better** method is to fit transits and filter simultaneously



Papers and Resources

- **Gaussian Processes for Machine Learning**
  - Rasmussen & Williams MIT Press, 2006
  - http://www.gaussianprocess.org/gpml/chapters/
- **George : Python library for Gaussian Process Regression**
  - Dan Foreman-Mackey
  - http://dan.iel.fm/george/current/

Inverting a Matrix

- calculating likelihoods requires inverting the covariance matrix

$$log\ p(y|x,\sigma,\theta) = -\frac{1}{2}r^T K^{-1} r - \frac{1}{2} log\ det\ K - \frac{N}{2} log 2\pi$$

- we have a Hermitian, positive-definite matrix
  - common to use Cholesky decomposition

$$K = LL^{\mathrm{T}}$$

  - decomposes K into a product of a lower triangular matrix L and its transpose

LAPACK – Linear Algebra PACKage

- the hidden magic in most online Gaussian Process Packages
- dpotrf -> decomposes your matrix, A, and returns Cholesky factor **L**
- dpotrs -> solves $A\ x = b\ ;\ x = A^{-1}b$
  - dpotrf - slow, dpotrs - fast
  - If Kernel is constant, only need to call dpotrs when calculating likelihoods.

Bestfit Model Parameters

- maximize

$$log\ p(y|x,\sigma,\theta) = -\frac{1}{2}r^T K^{-1} r - \frac{1}{2} log\ det\ K - \frac{N}{2} log 2\pi$$

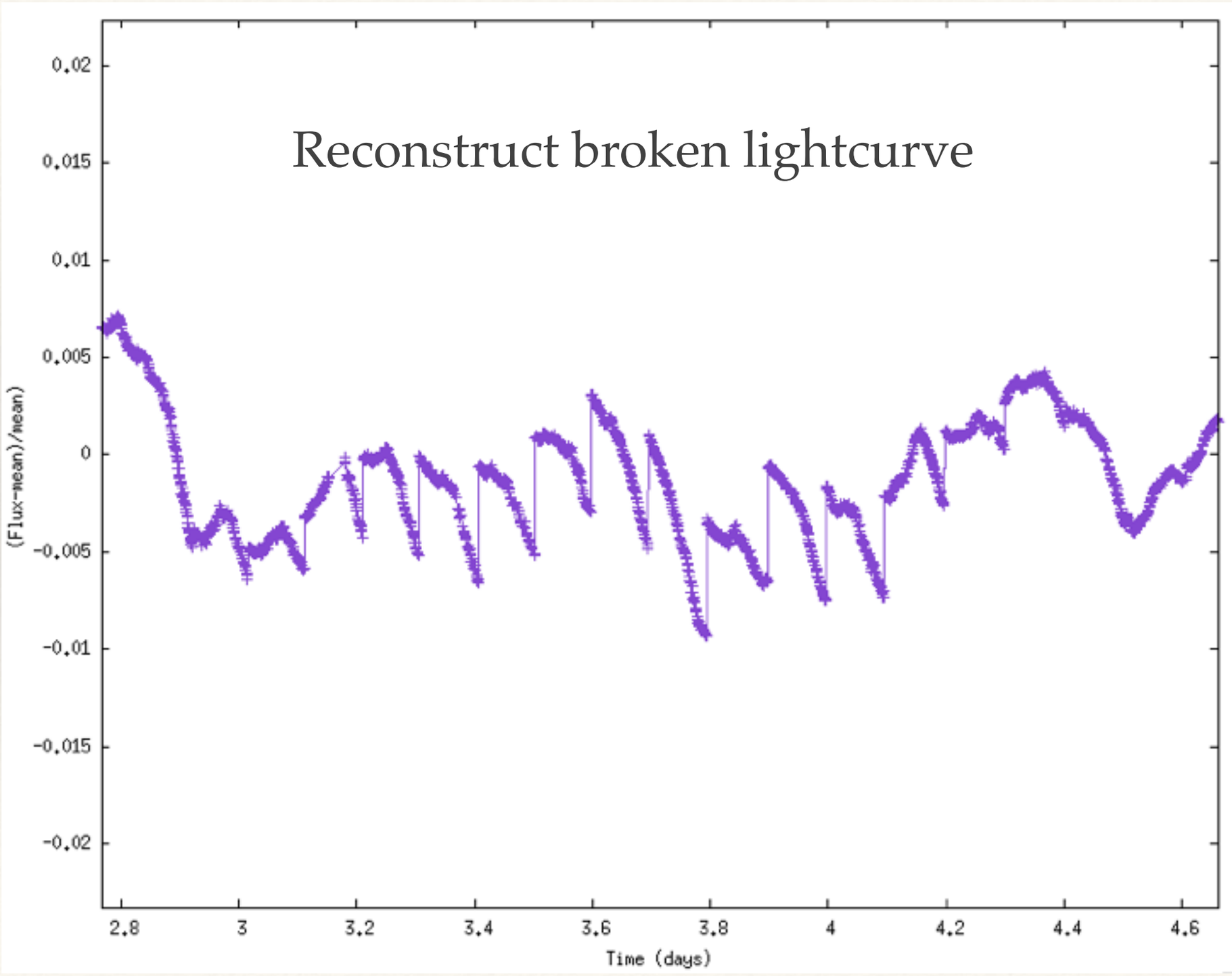
  - (don't forget your priors)

- my favourite is Broyden–Fletcher–Goldfarb–Shanno algorithm

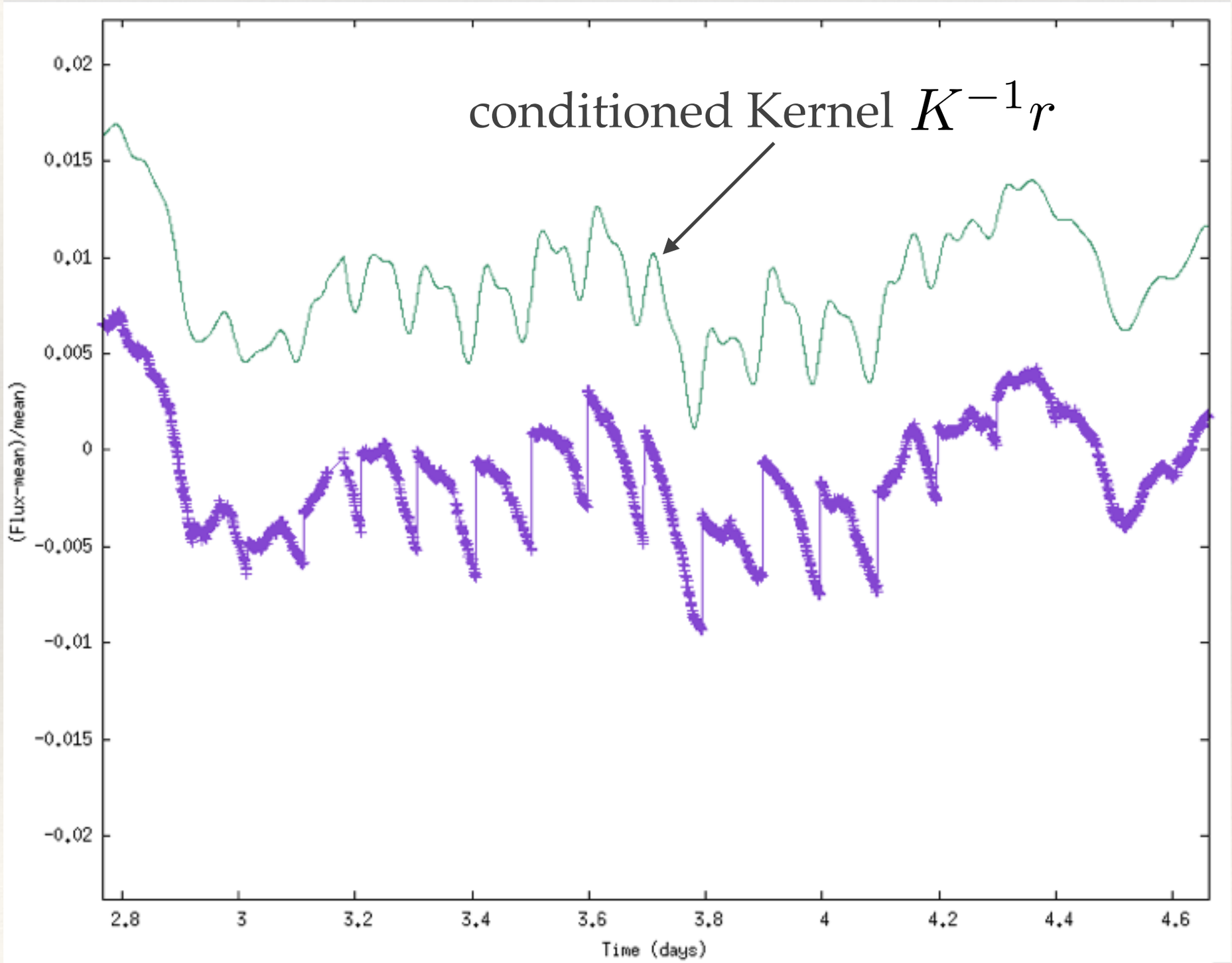
  - python, IDL, C/C++, Matlab, Octave, FORTRAN,…

  - you can fit both model parameters and Kernel hyper-parameters

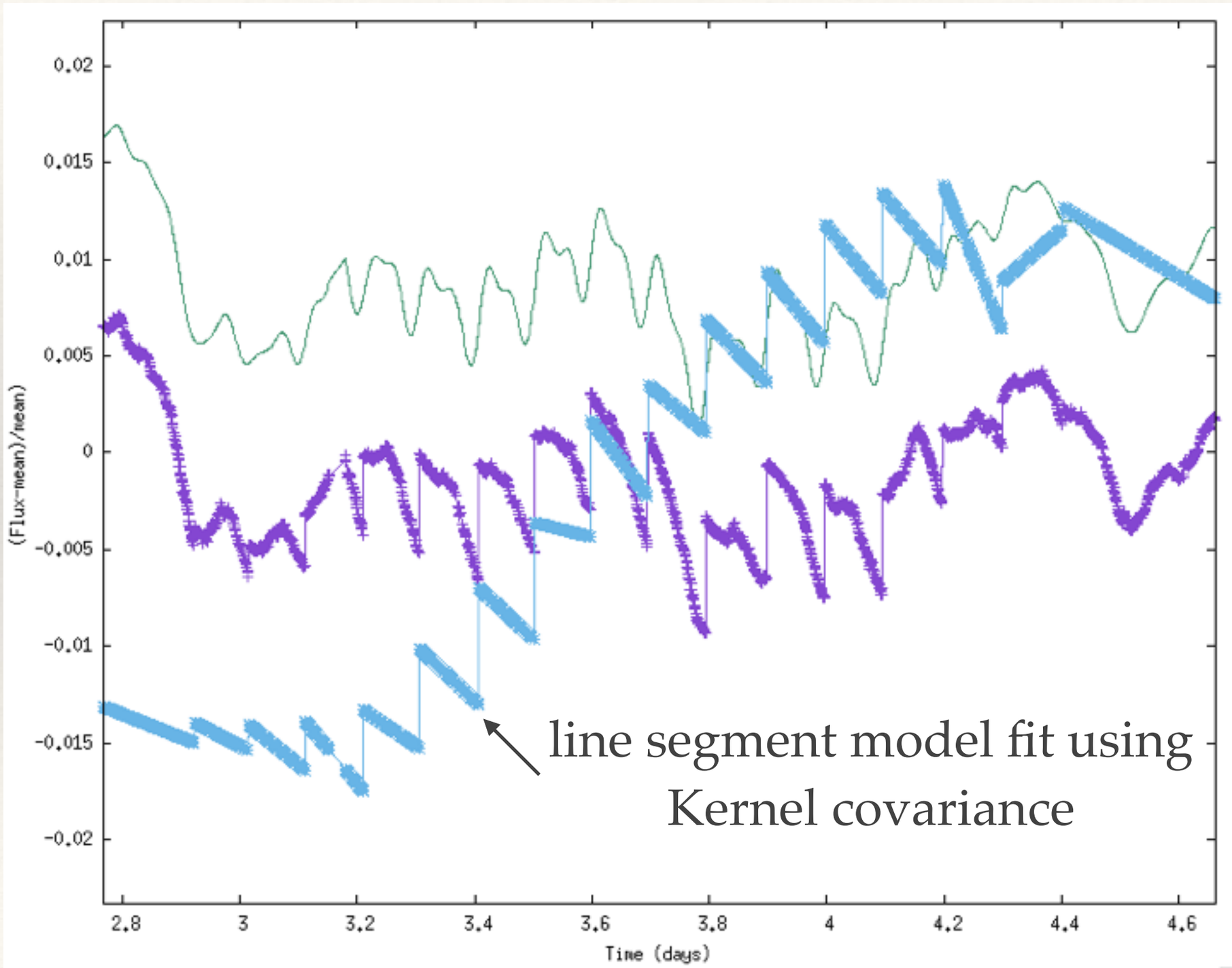
Example


Reconstruct broken lightcurve
(Flux-mean)/mean)
Time (days)
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
2.8
3
3.2
3.4
3.6
3.8
4
4.2
4.4
4.6

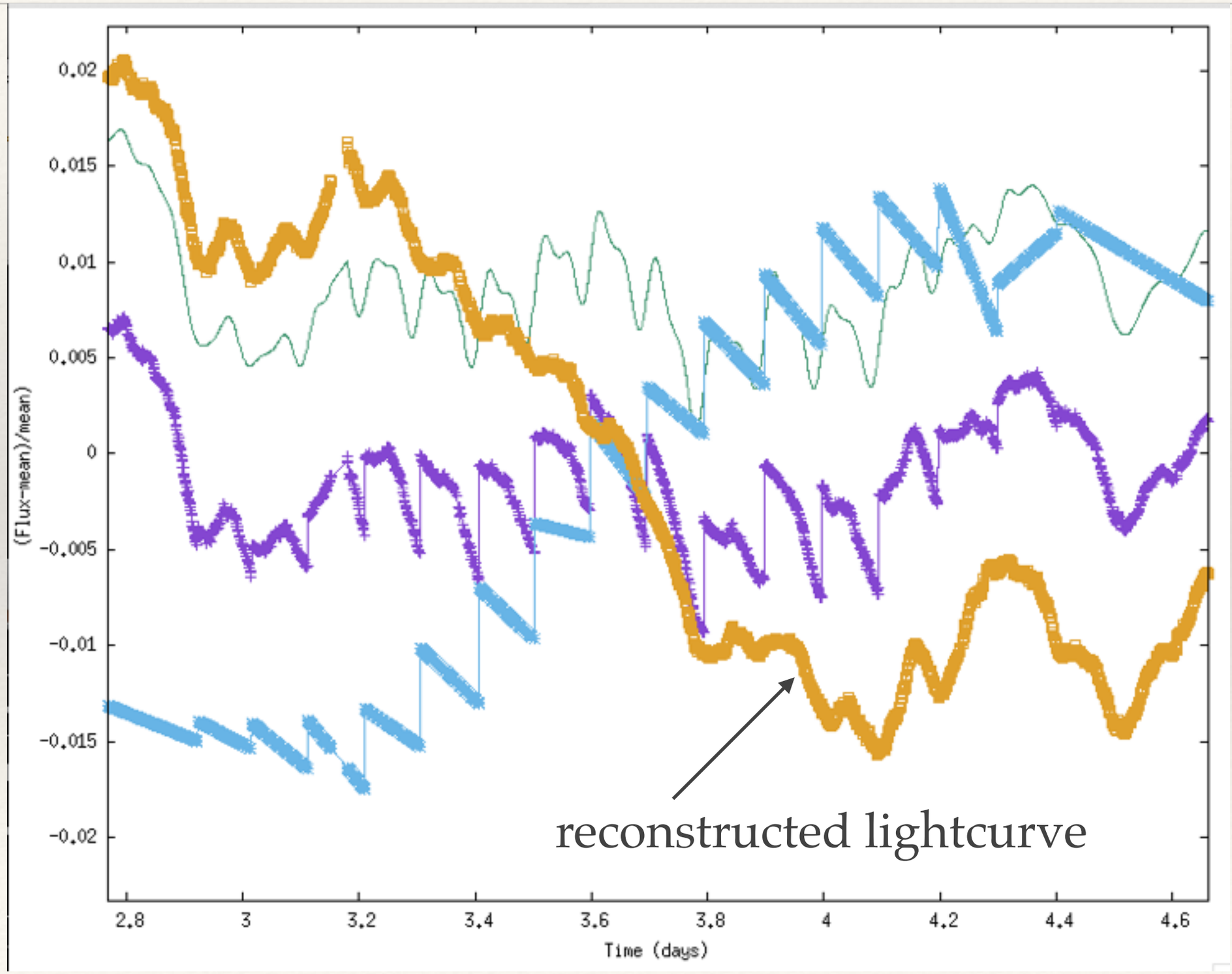
Example


conditioned Kernel $K^{-1}r$
offset for display only
(Flux-mean)/mean)
Time (days)
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
2.8
3
3.2
3.4
3.6
3.8
4
4.2
4.4
4.6

Example

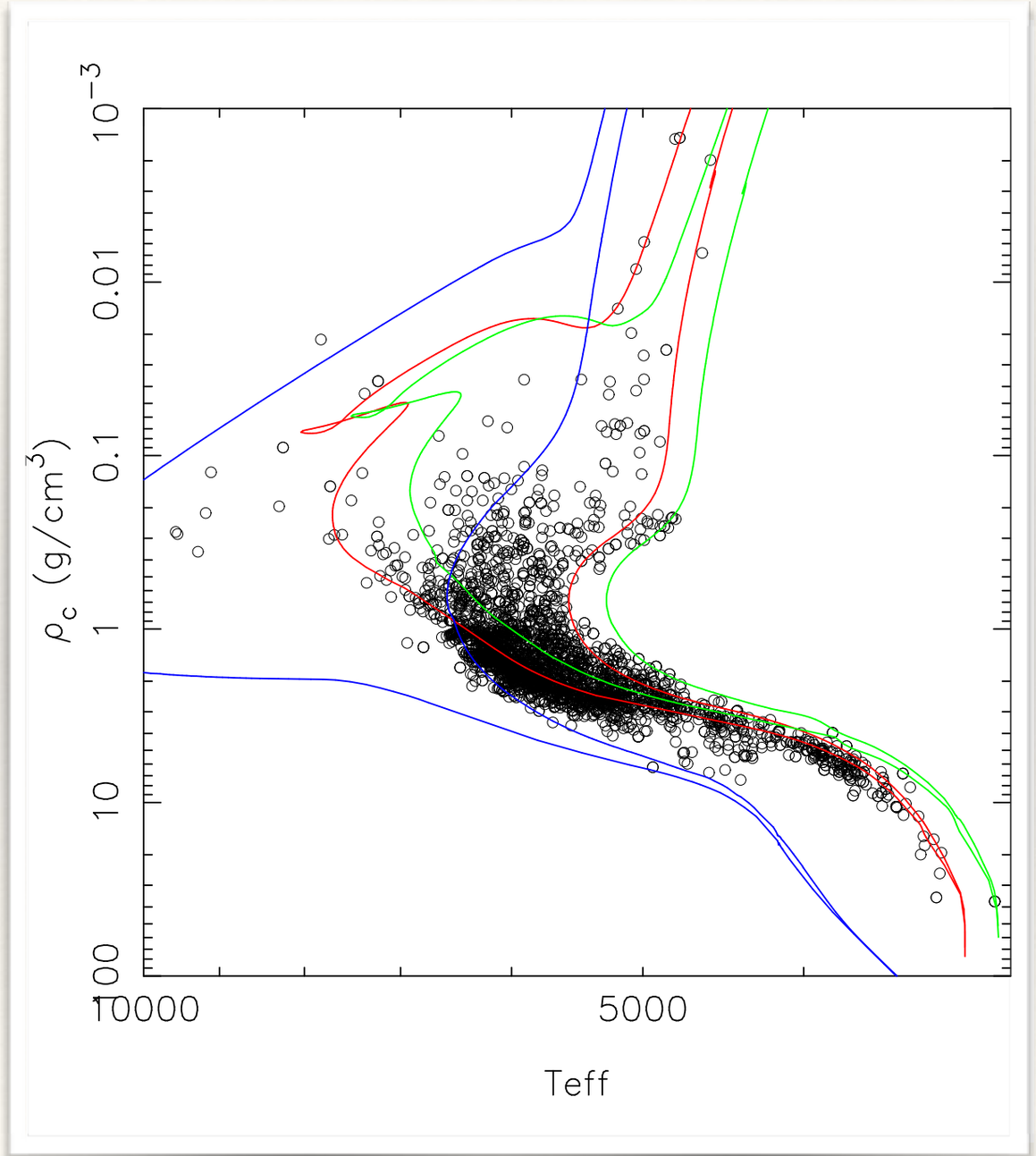

0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
(Flux-mean)/mean)
2.8
3
3.2
3.4
3.6
3.8
4
4.2
4.4
4.6
Time (days)
line segment model fit using
Kernel covariance

Example


0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
(Flux-mean)/mean)
2.8
3
3.2
3.4
3.6
3.8
4
4.2
4.4
4.6
Time (days)
reconstructed lightcurve

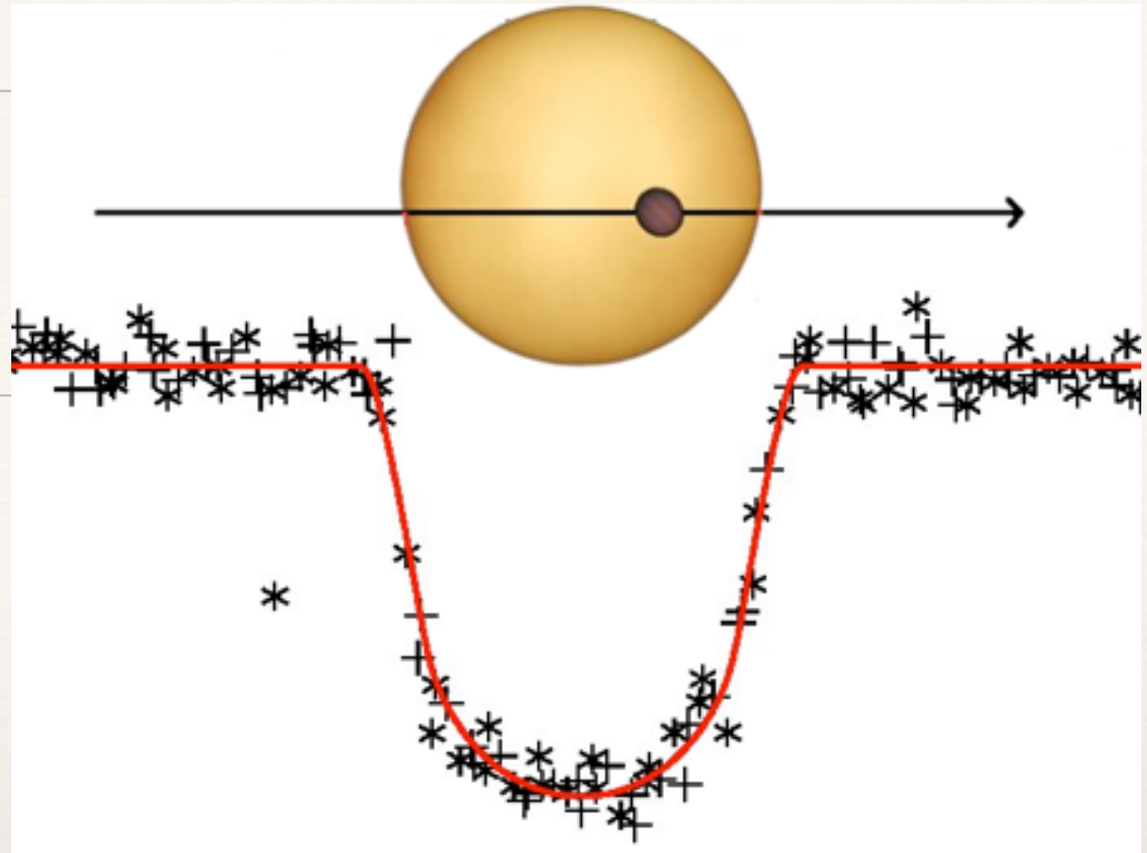
Stellar Parameters

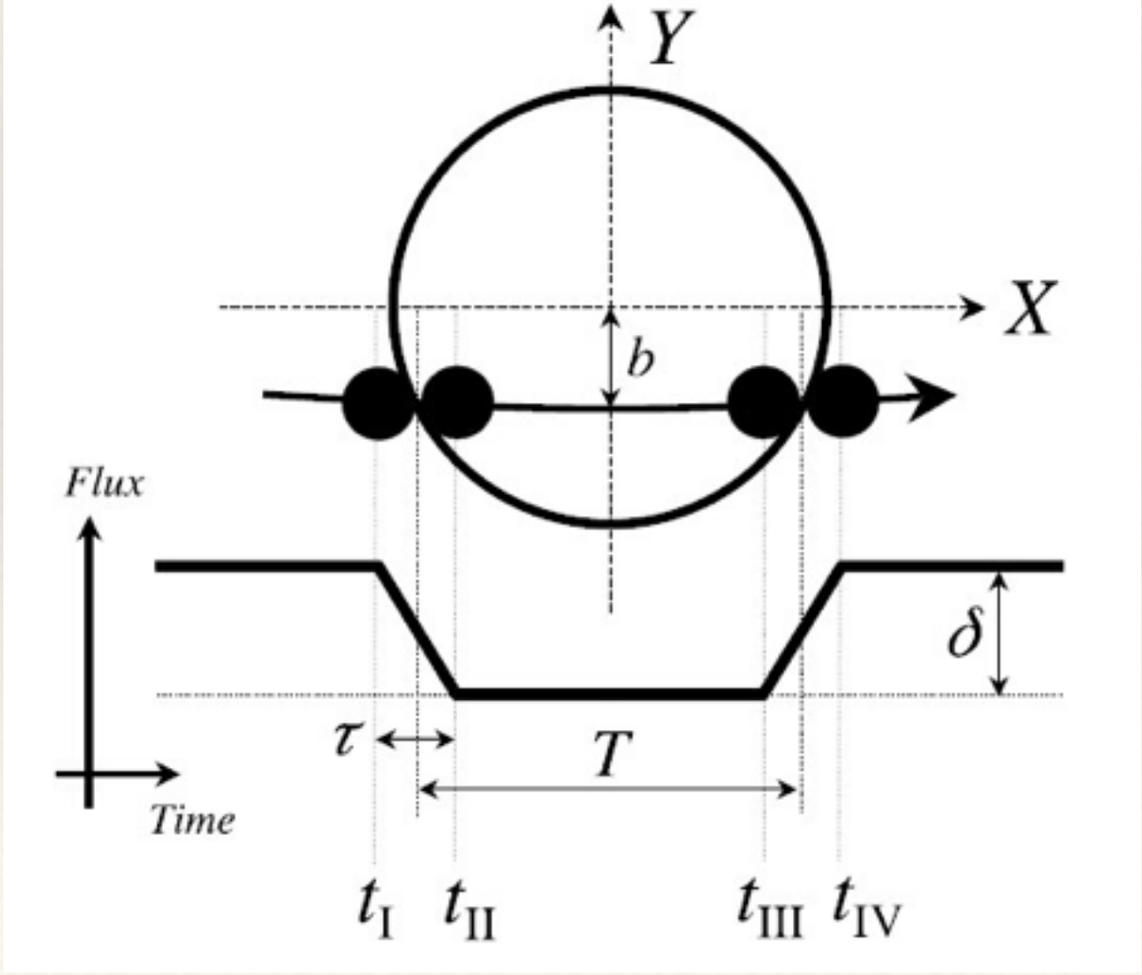
- Kepler Input Catalog
  - broadband photometry
    - log(g) was hard
    - [Fe/H] was a product of the prior
- Spectroscopy
  - Teff, log(g), [Fe/H]
- asteroseismology
  - scaling relations (numax, dnu)
- matched to stellar evolution models
  - Yale-Yonsei, Dartmouth, Baraffe



Transit Model

- parameters: rhostar, T0, P, b, r/R*, esinw, ecosw, secondary eclipse
  - choice of rhostar allows for multiple transiting planets
    - assume all planets transit the same star.
- lightcurve models: Doppler, ellipsoidal, planet phases, occultation, gravity darkening



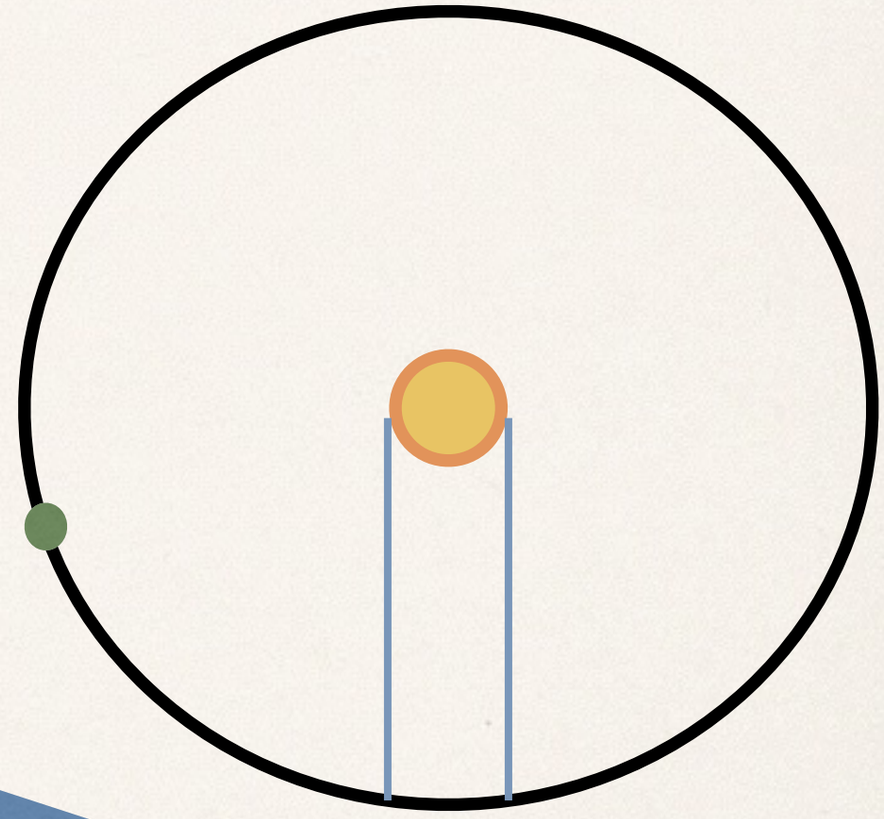


Kepler's 3rd Law

$$P^2 = \frac{4\pi^2 a^3}{G(M_* + M_p)}$$

$$\frac{M_* + M_p}{R_*^3} = \frac{4\pi^2 a^3 P}{G R_*^3 P^3}$$

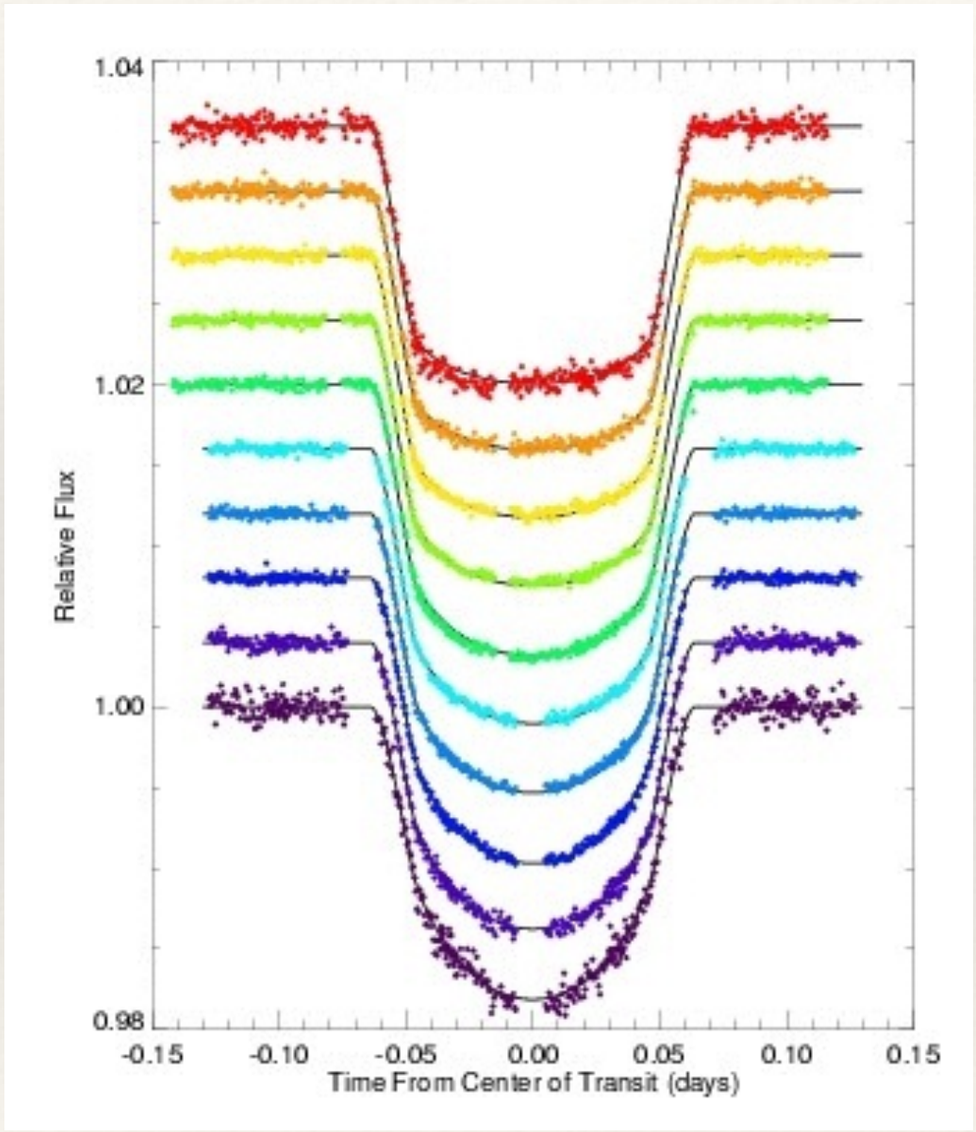
$$\rho_* \sim \frac{M_* + M_p}{R_*^3} \sim \frac{T_{dur} P}{G}$$



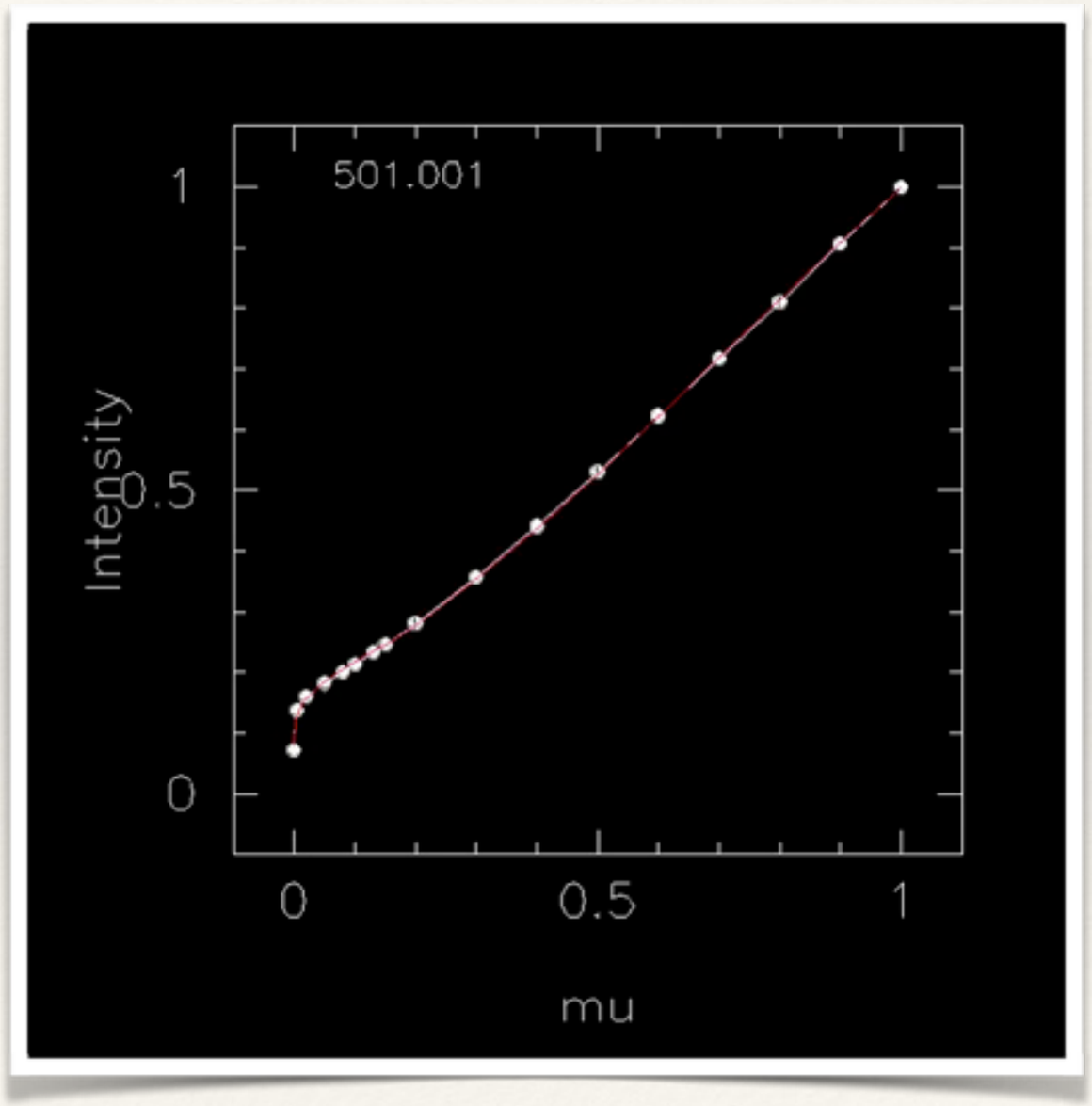
$$T_{dur} \sim P \frac{R_*}{2\pi a}$$

Assumes mass of the star is much greater than mass of the planet

Limb-darkening

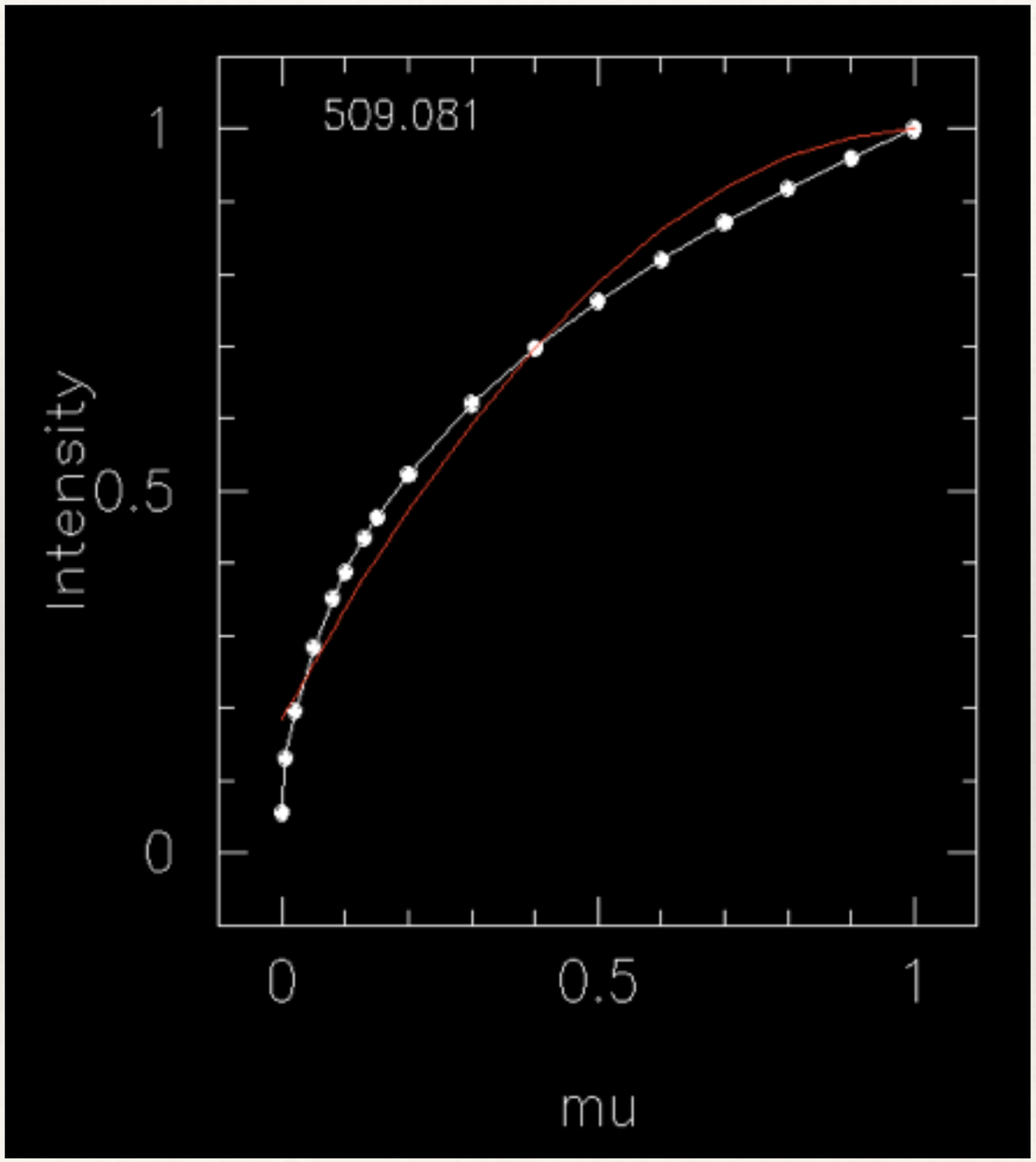


Knutson, H. 2007

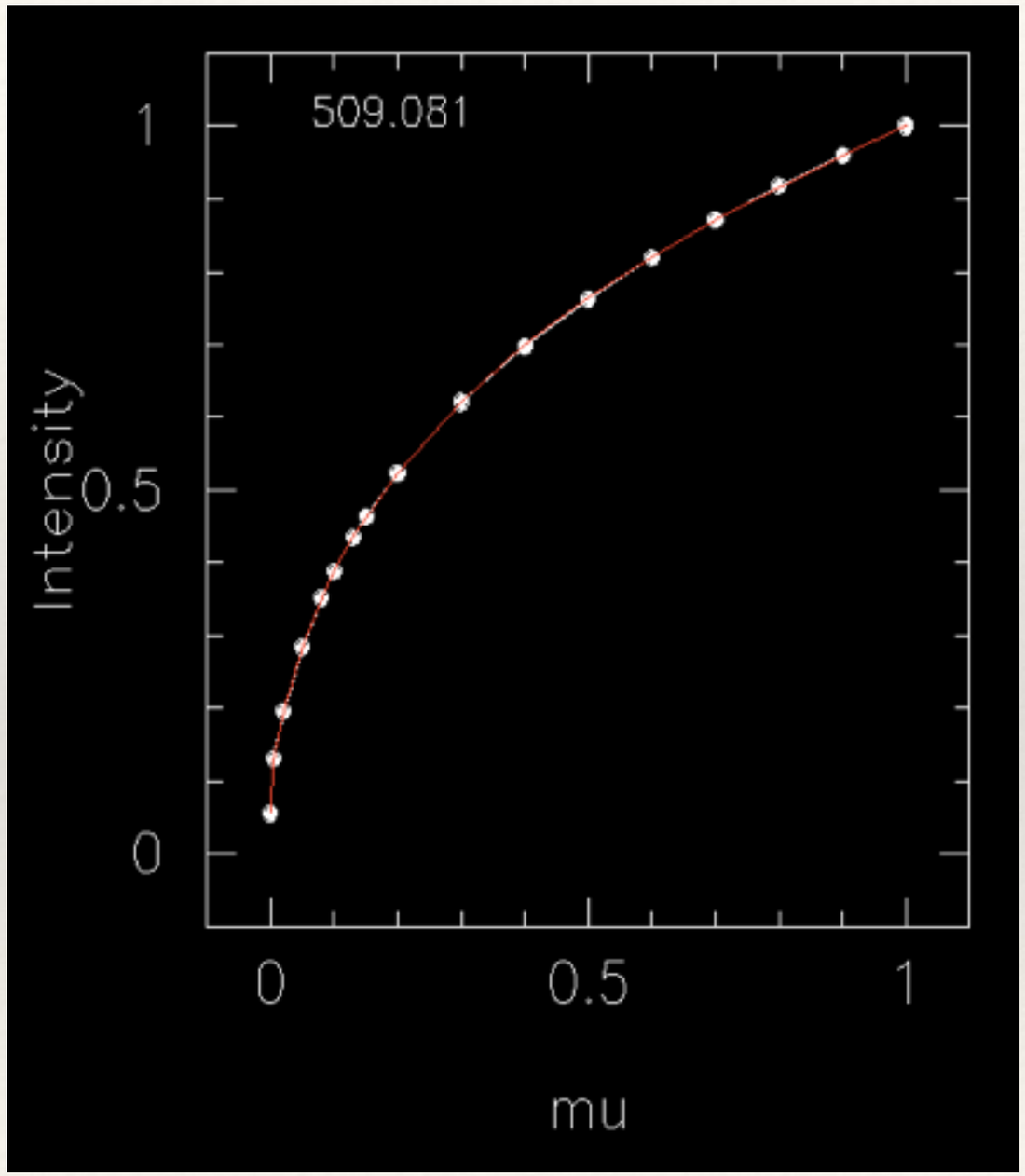


- 3500 K, log(g)=5, [m/H]=0

Limb Darkening



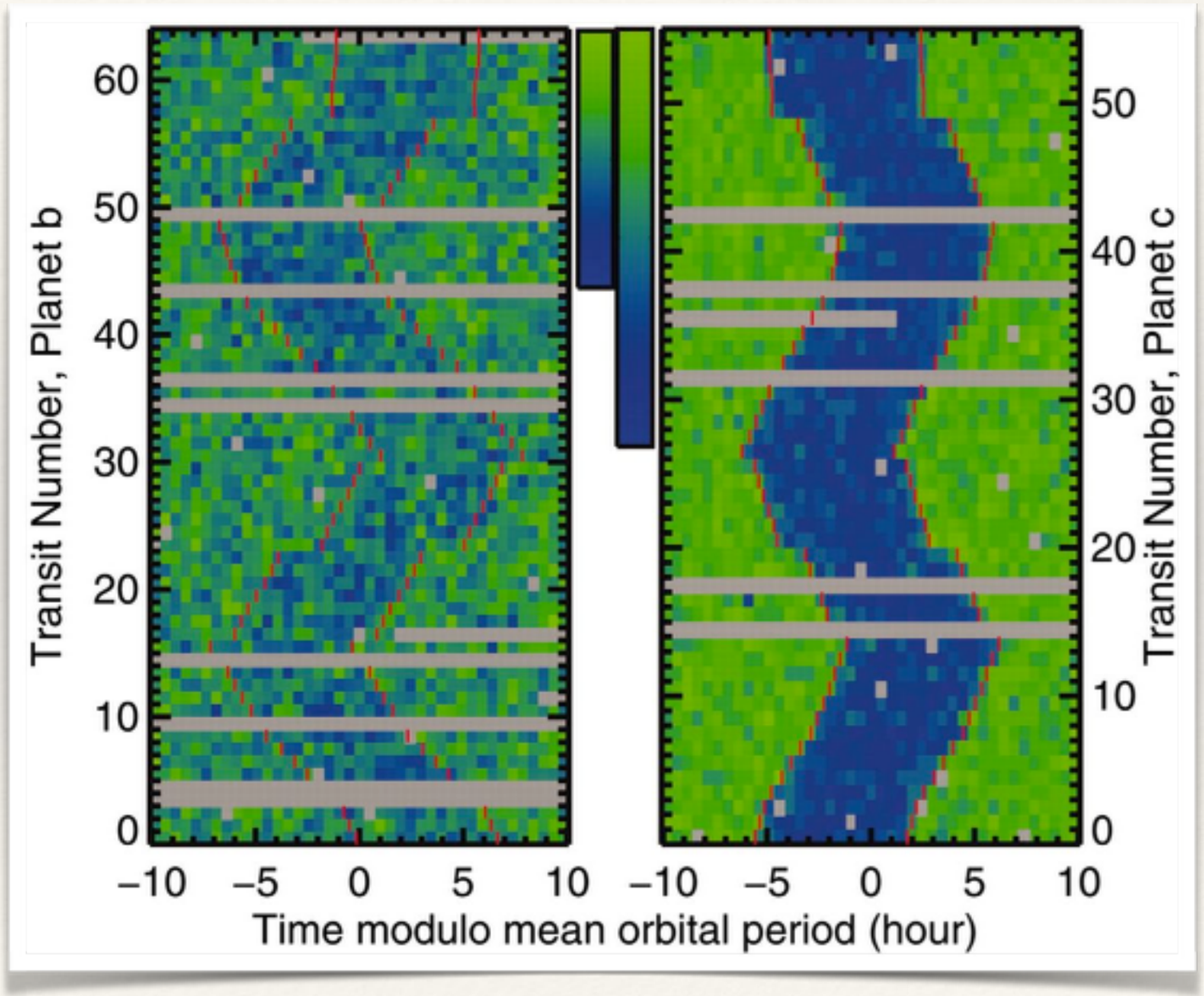
Quadratic Law
(2 Parameters)



Non Linear Law
(4 parameters)

Transiting Timing Variations

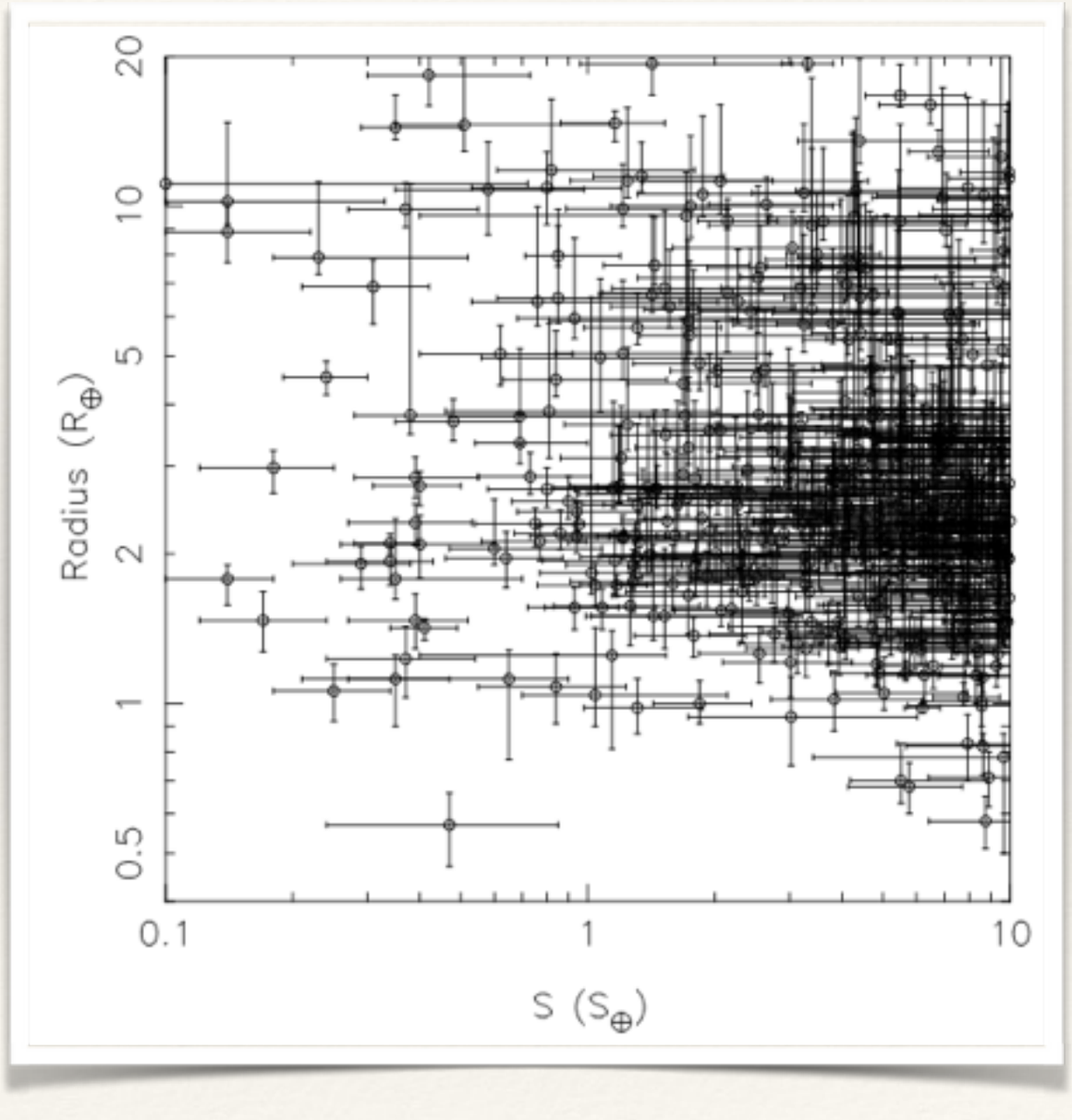
- gravitational interactions between planets
- Transits will not phase up with strictly periodic ephemeris
- measure shift in center of transit time using a transit-template
- "de-TTV" lightcurve
  - resampling/interpolation
- **photodynamics** for in-depth studies



Carter, J. et al. 2012

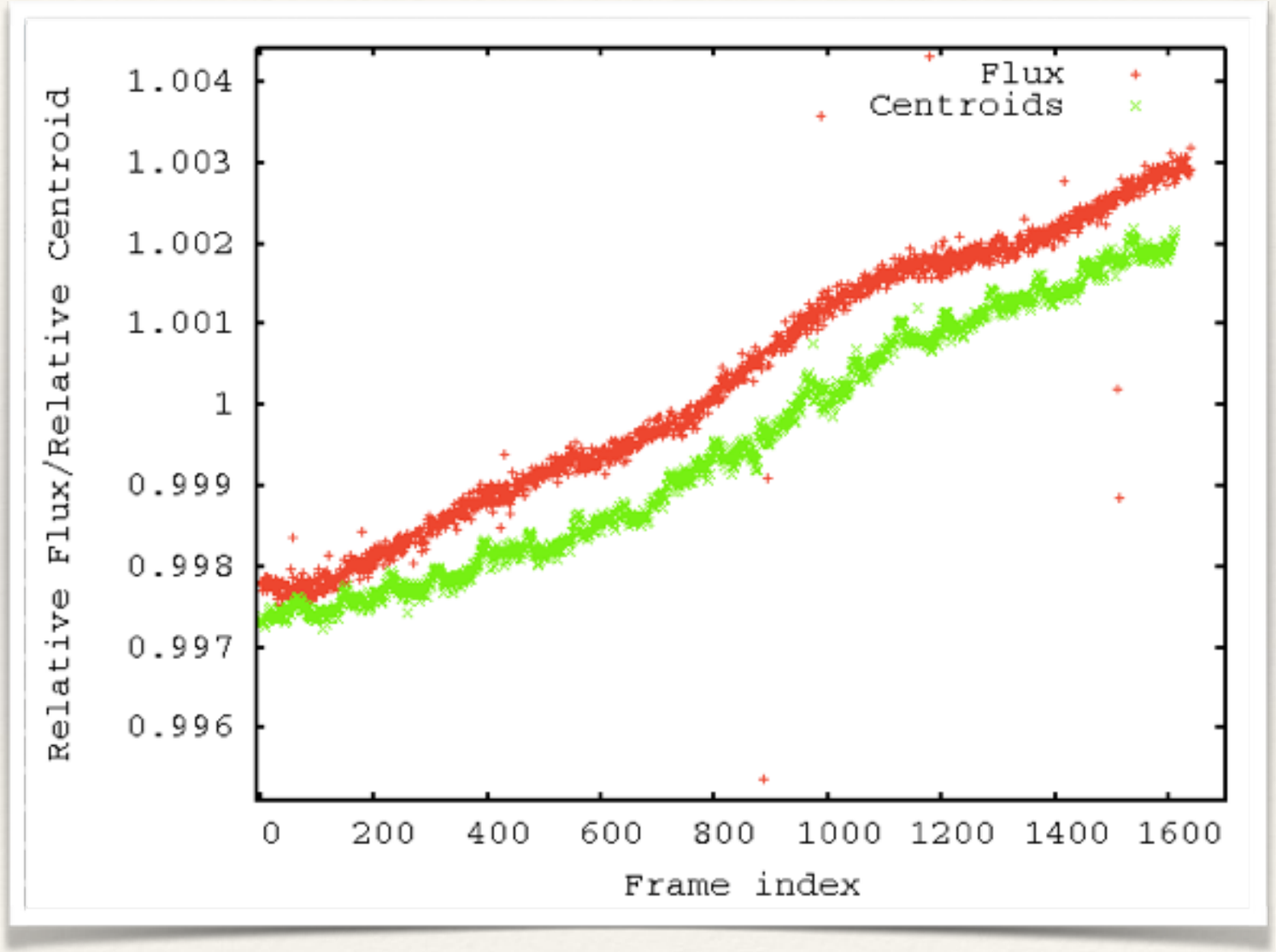
Posterior Distributions

- initially the bootstrap method was used
  - data resampling with replacement
    - can be very slow
- switched to MCMC
  - deMCMC implemented to handle heavily correlated variables
- chains are available through NExScI

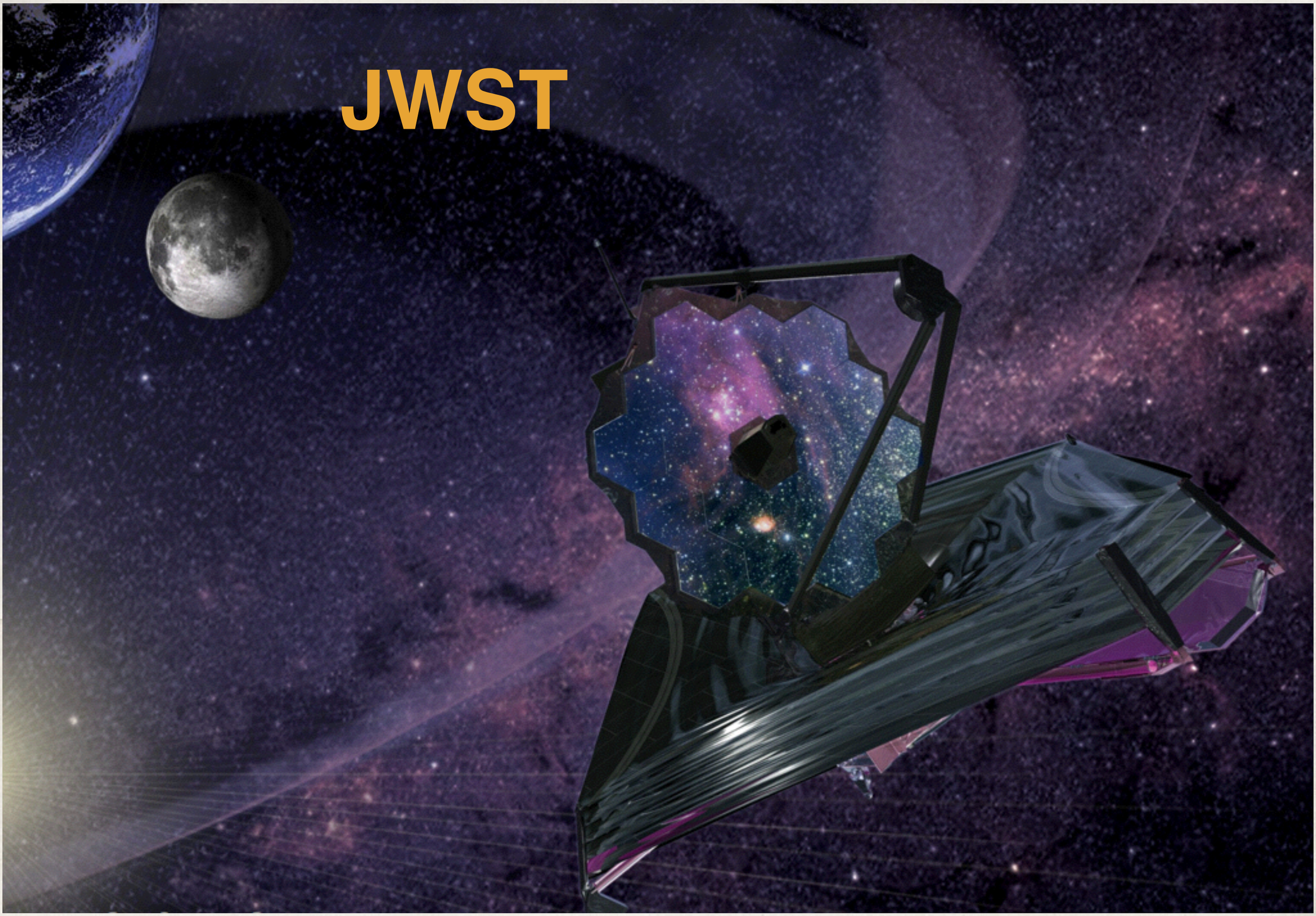


What's next..

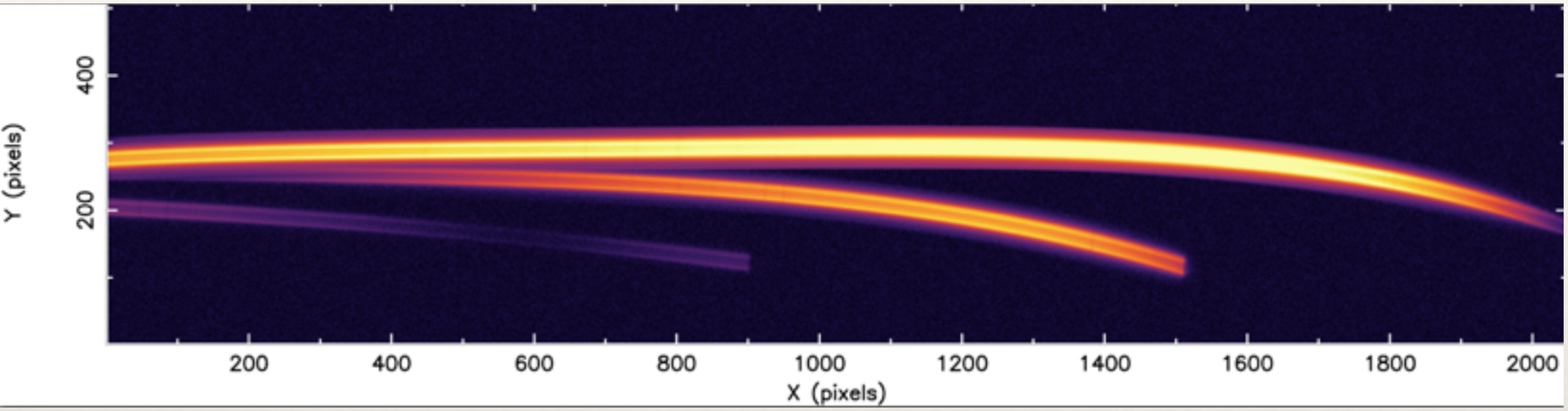
- Understanding data systematics
  - seems to be related to centroids and intrapixel variations
  - drastically improve long-time scale astrophysical variability

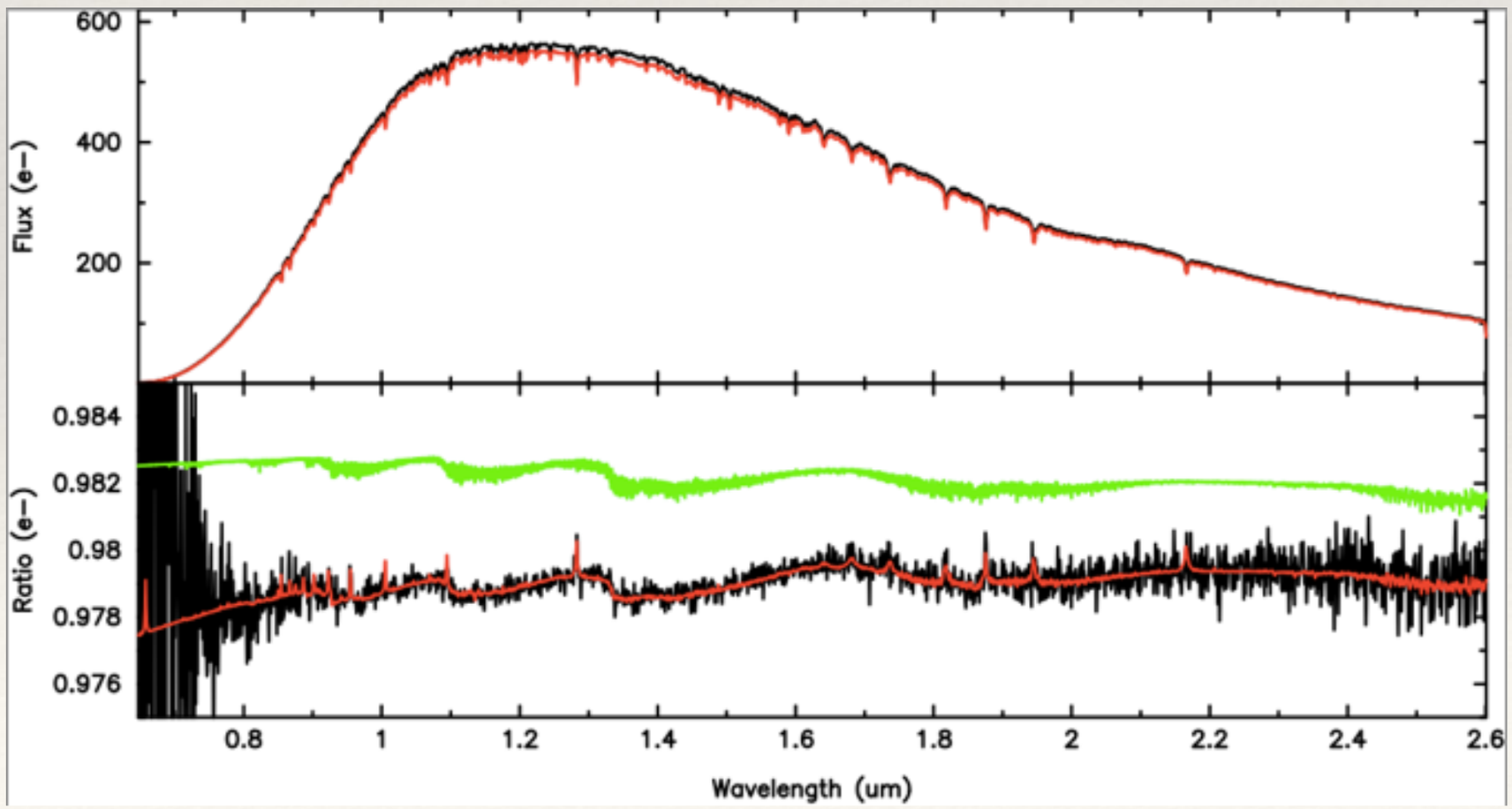


JWST



Transit Spectroscopy





Summary

- The field of transiting exoplanet has drastically changed.
  - first discovery: 1999
  - now planets are in the thousands
- TESS/JWST/WFIRST/Plato/Cheops/BRITE

The smell-o-scope