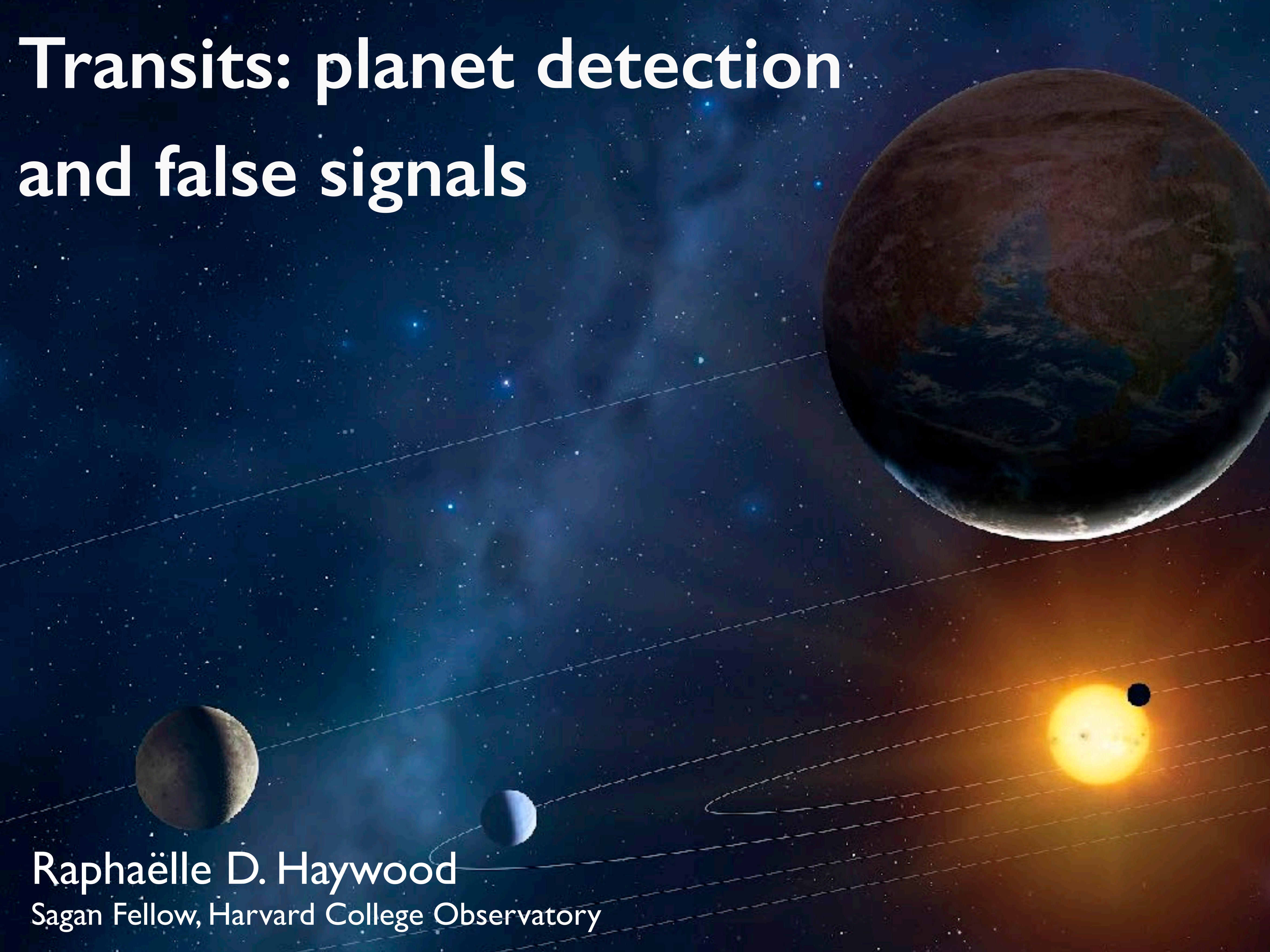
Transits: planet detection and false signals

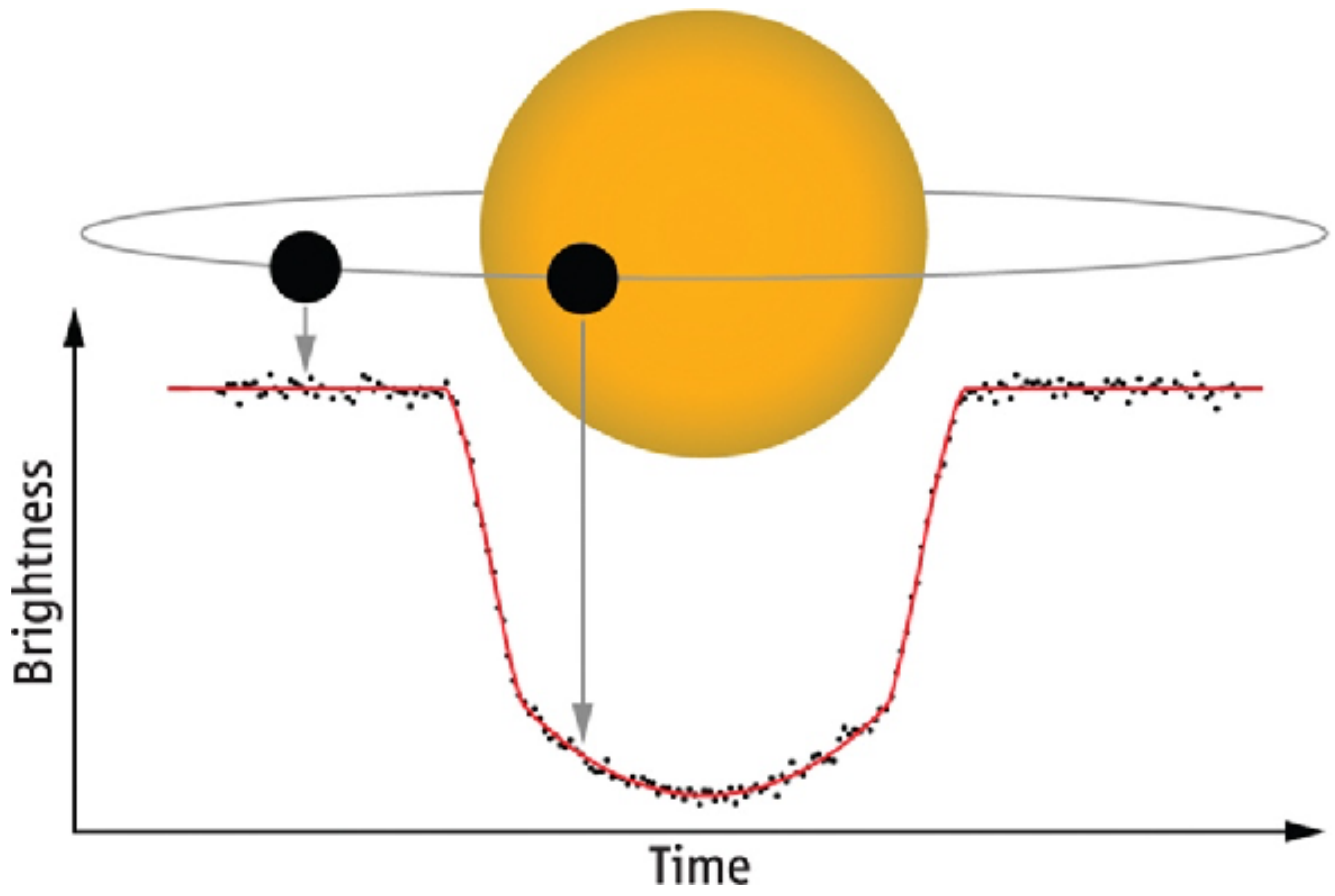


Raphaëlle D. Haywood
Sagan Fellow, Harvard College Observatory

Outline

- Transit method basics
- Transit discoveries so far
- From transit detection to planet confirmation
- Astrophysical false positives
- Factors that can affect derived planet parameters:
    - stellar activity
    - stellar parameter estimations

What is the transit method?



Collier Cameron, A., 2016. *Methods of Detecting Exoplanets*
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Image credits: NASA

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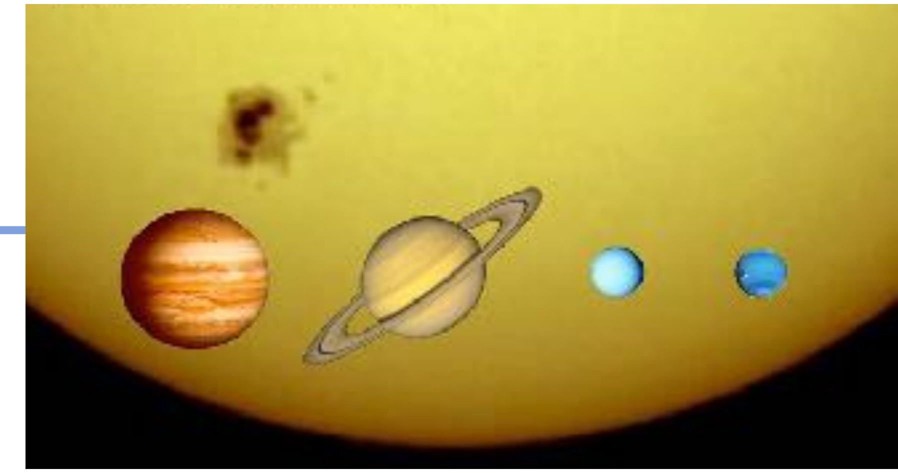

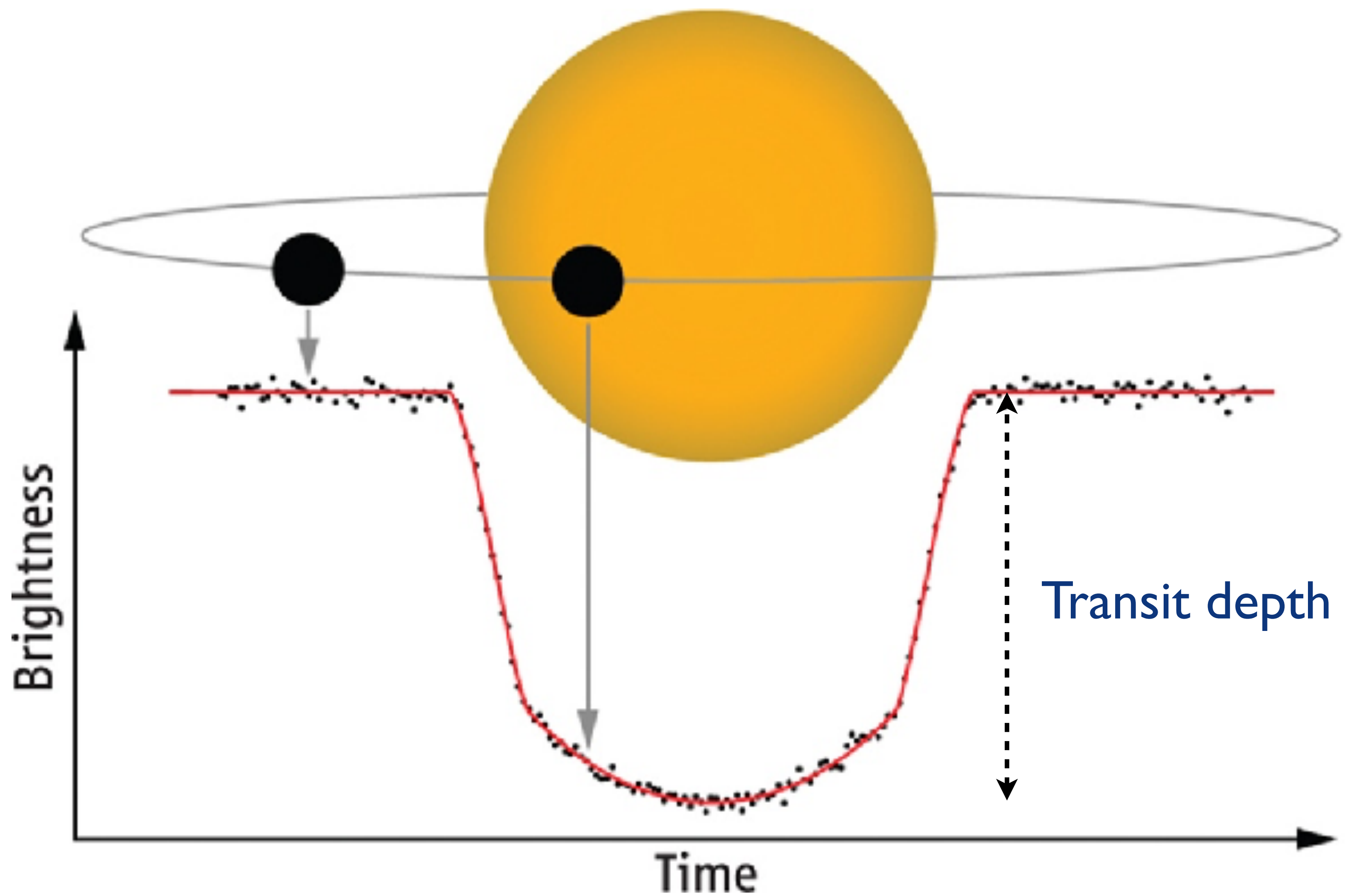

Transit depth $\delta \approx \left(\frac{R_p}{R_*}\right)^2$

Image credits: NASA

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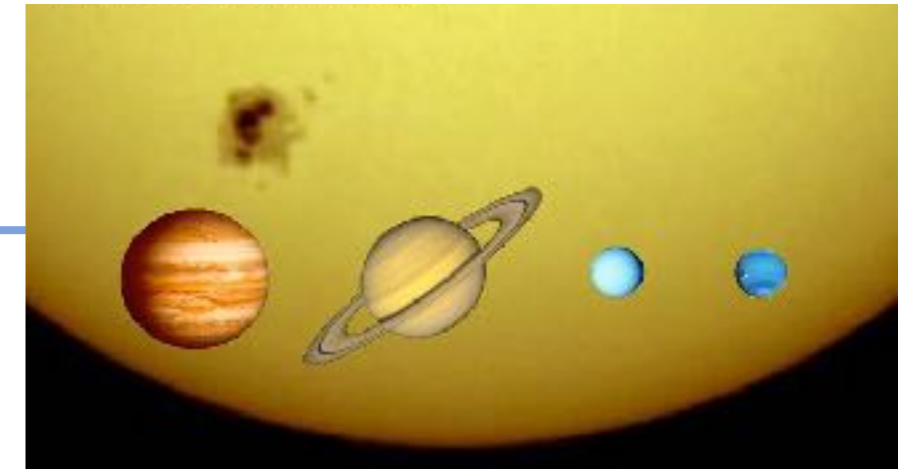
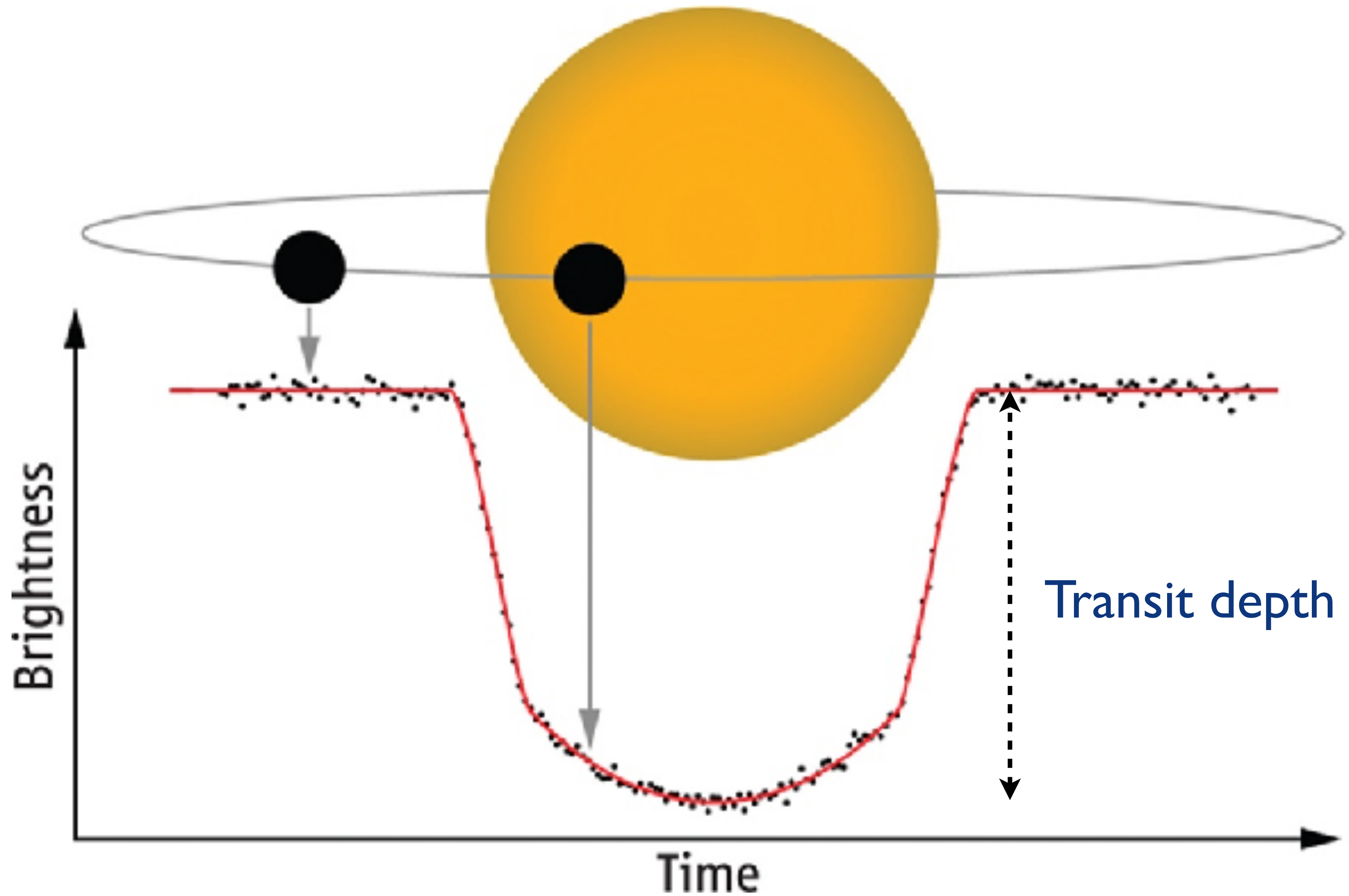


Assuming circular orbit and i = 90°:

Jupiter

δ = 1%



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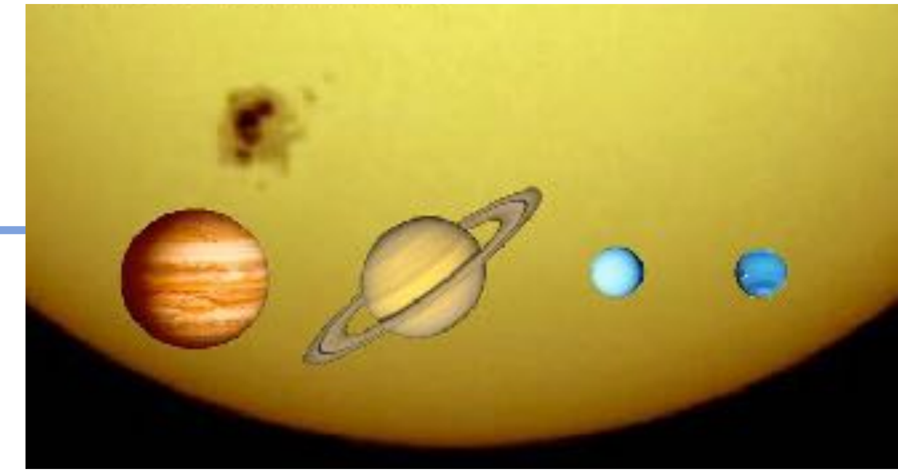
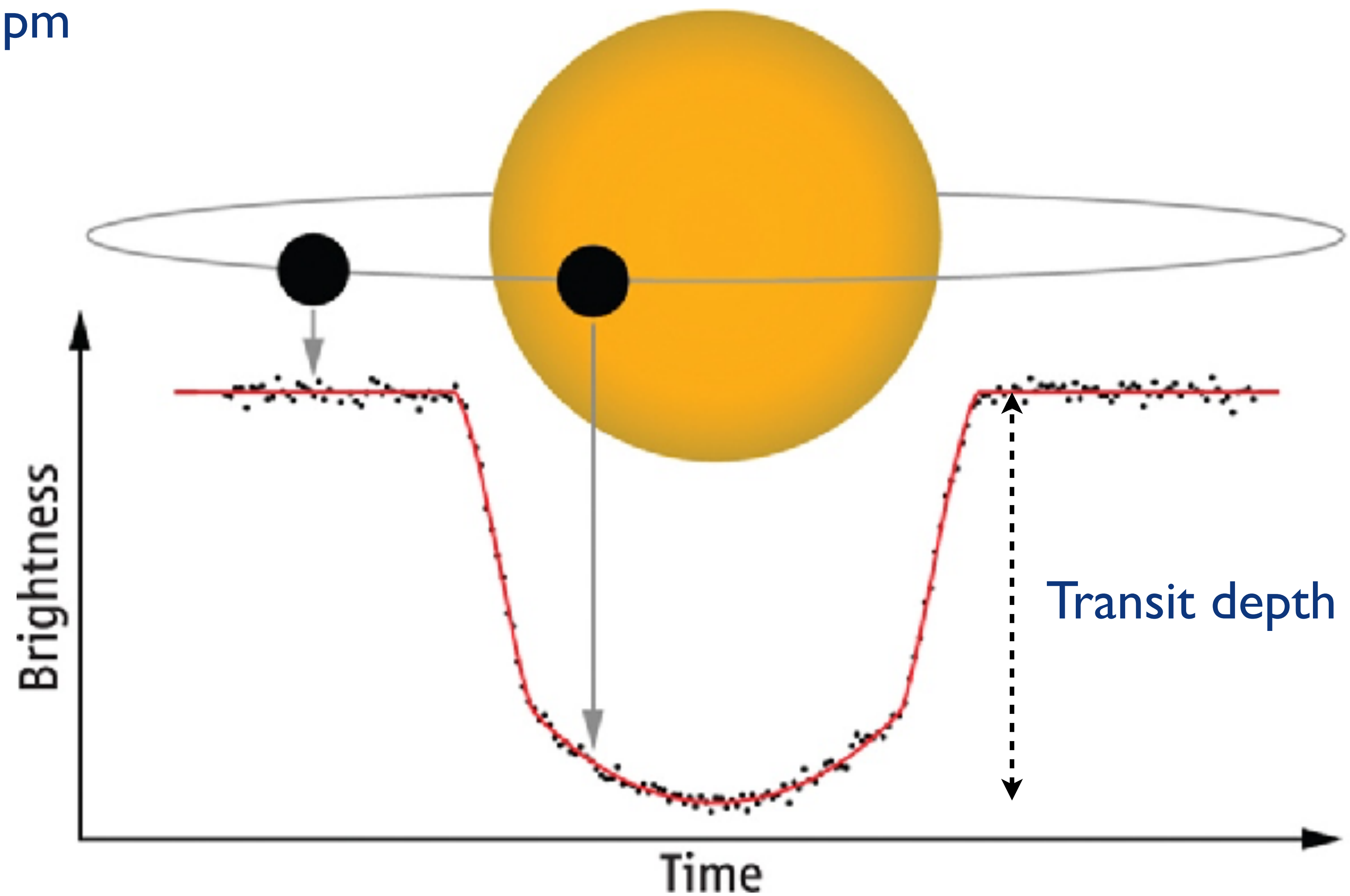


Assuming circular orbit and i = 90°:

Jupiter	**Earth**
δ = 1%	δ = 84 ppm



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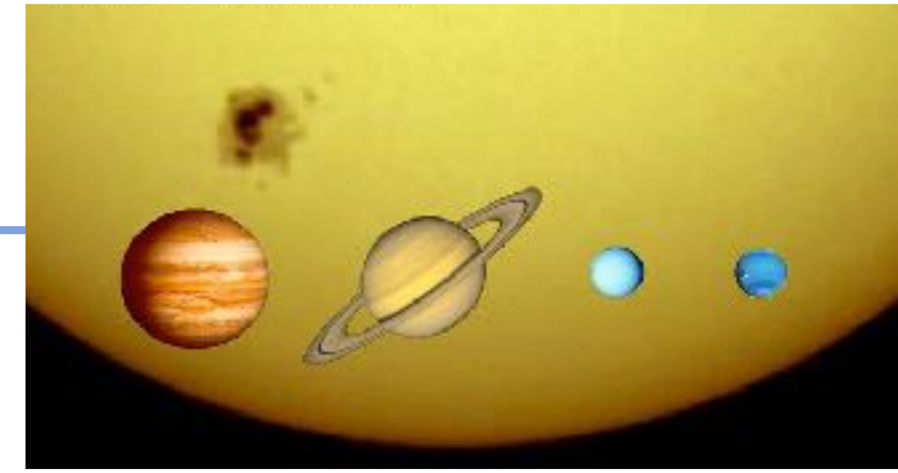

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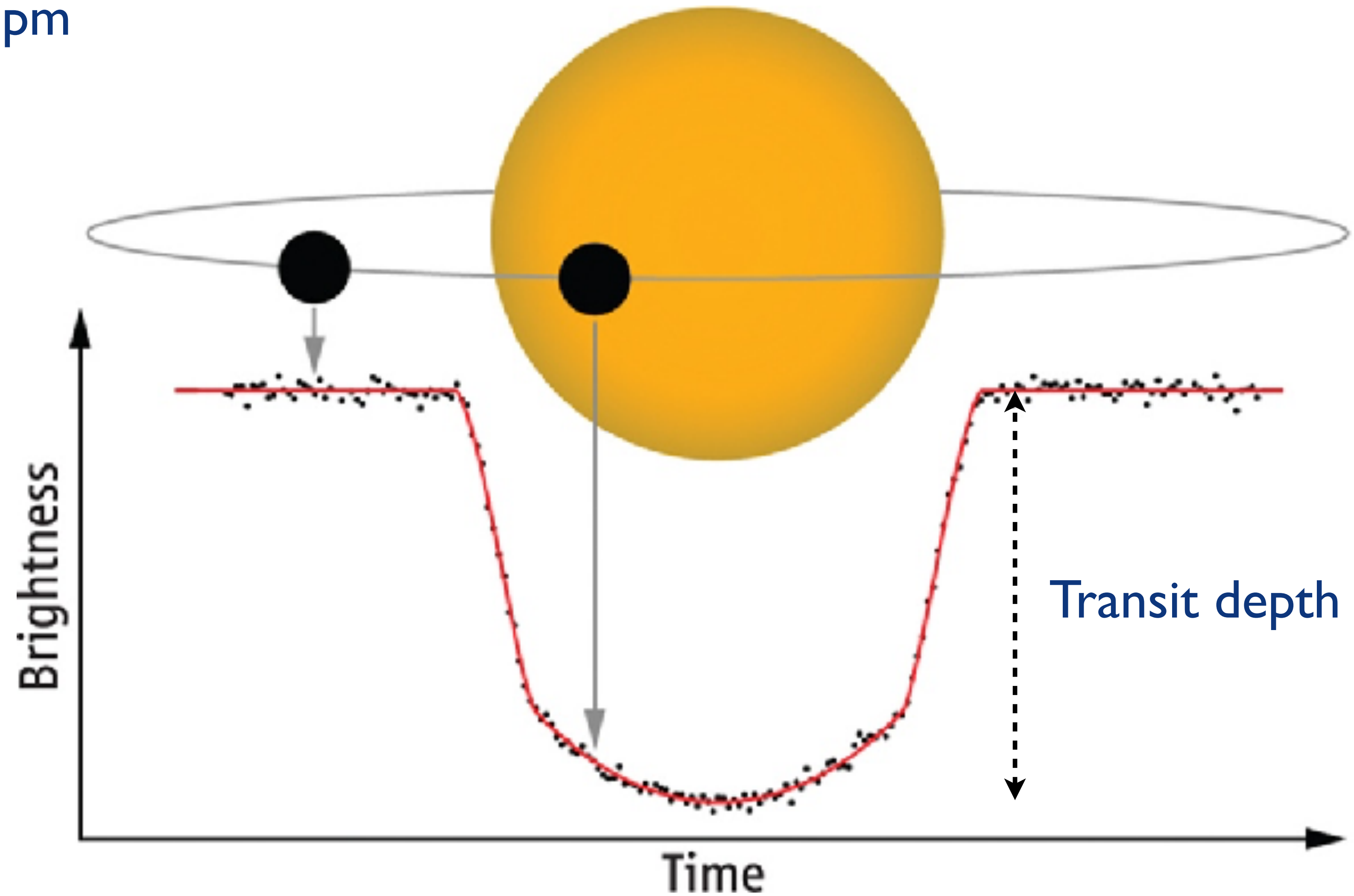

Transit depth $\delta \approx \left(\frac{R_p}{R_*}\right)^2$

⇒ It is easier to find small planets around small stars.

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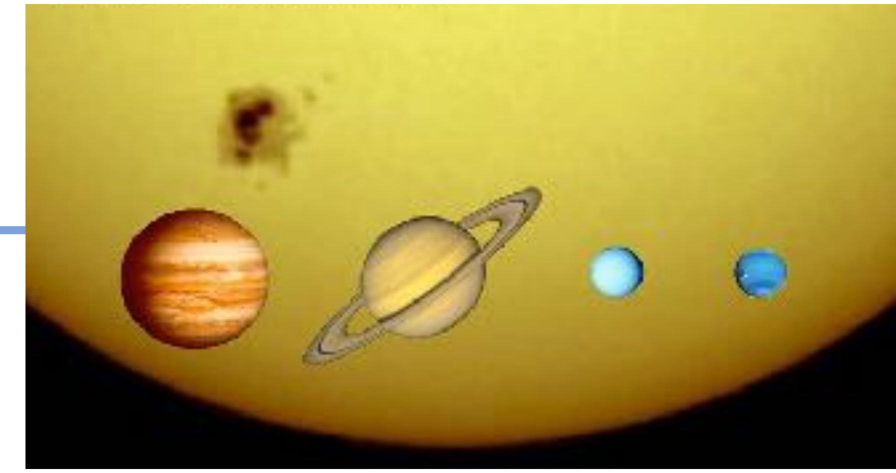

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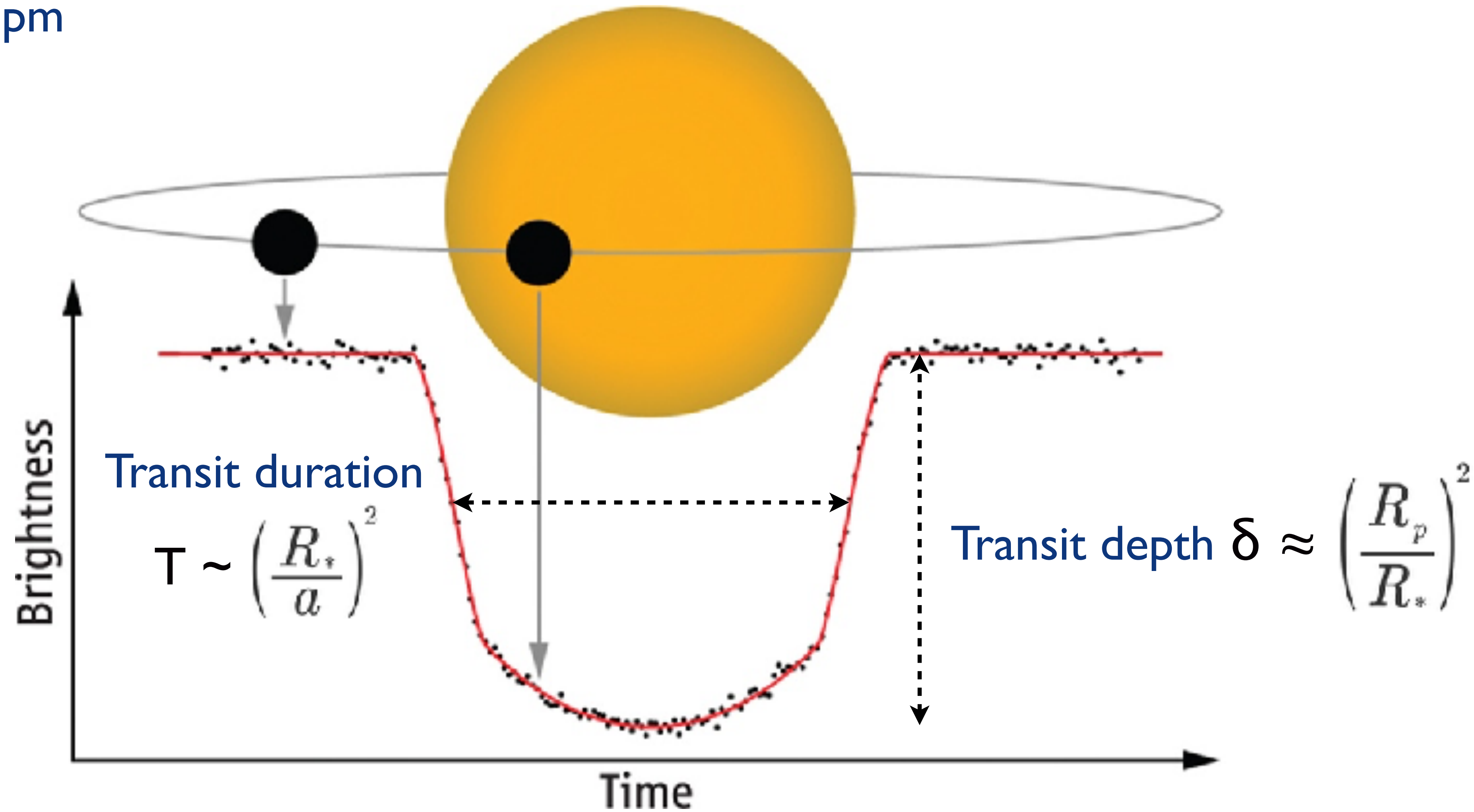

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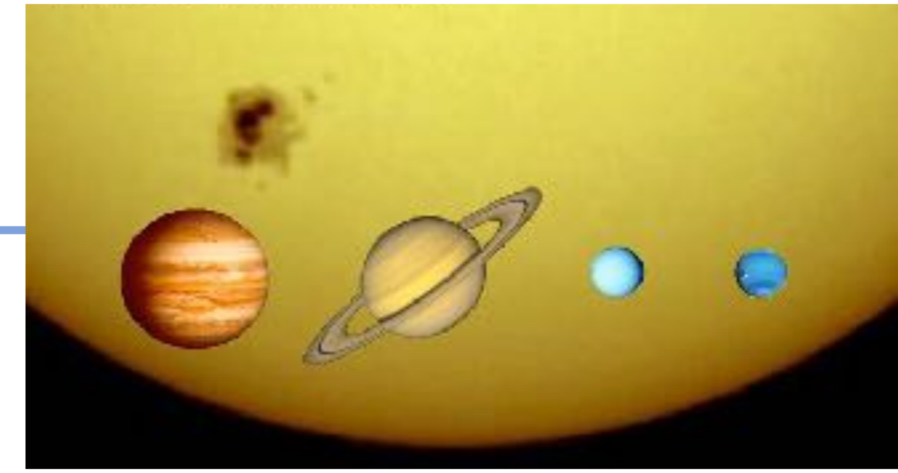
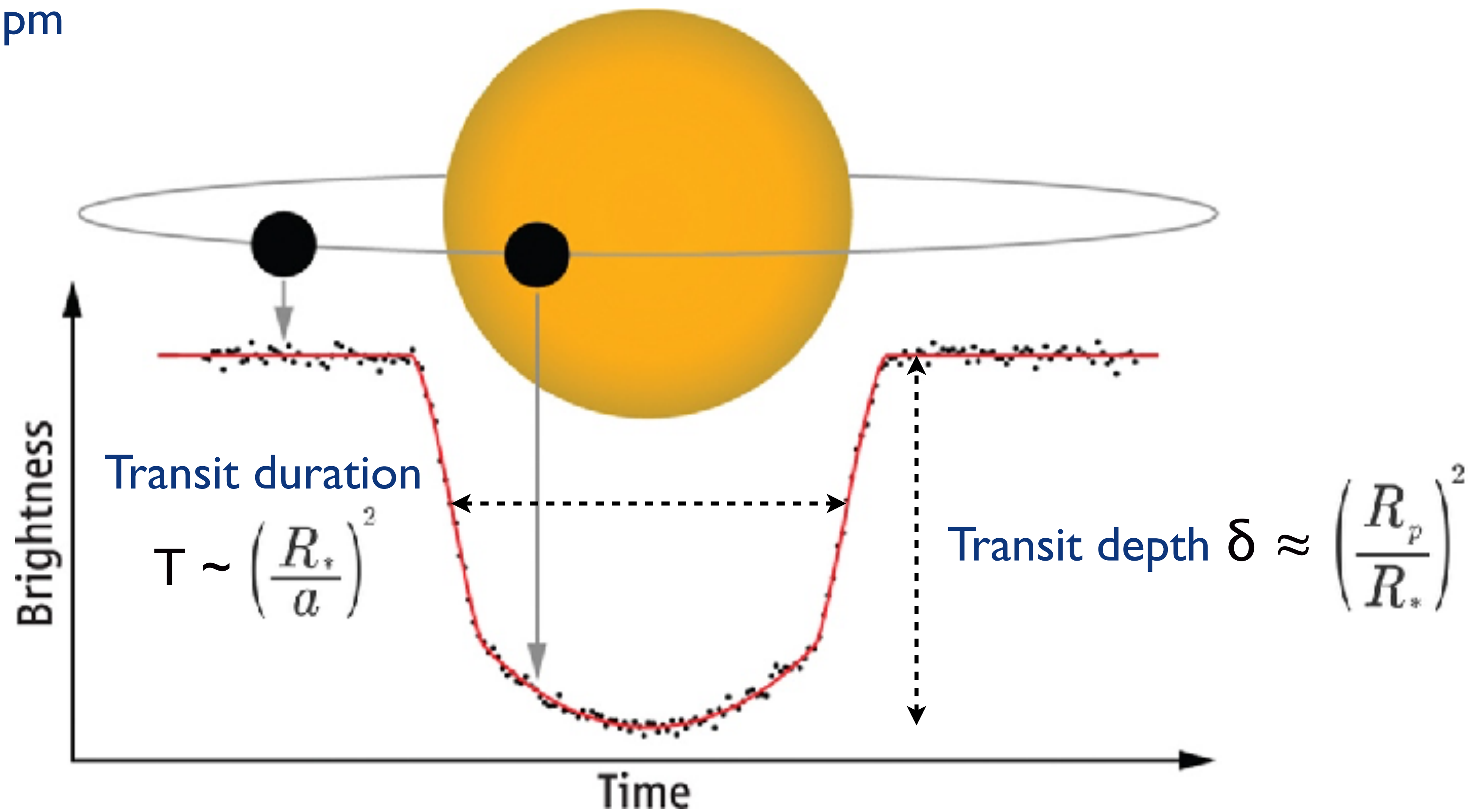


Assuming circular orbit and $i = 90°$:

Jupiter	Earth
$\delta = 1\%$	$\delta = 84$ ppm
$T \approx 30$h	



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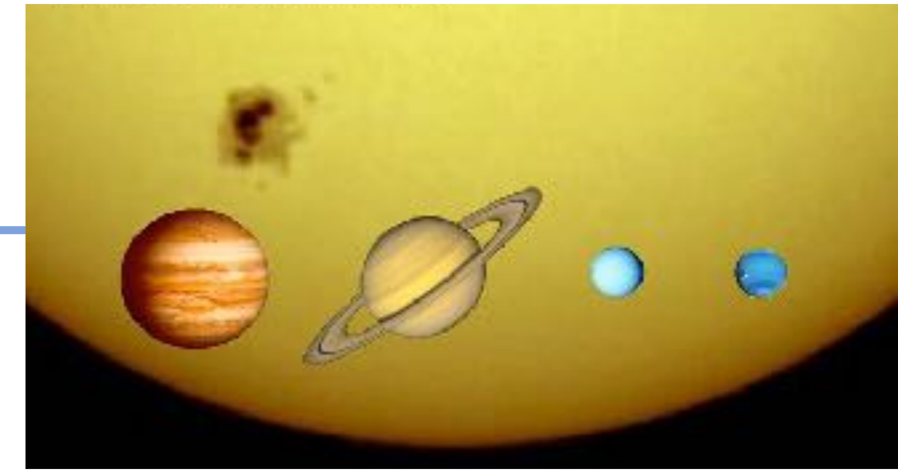
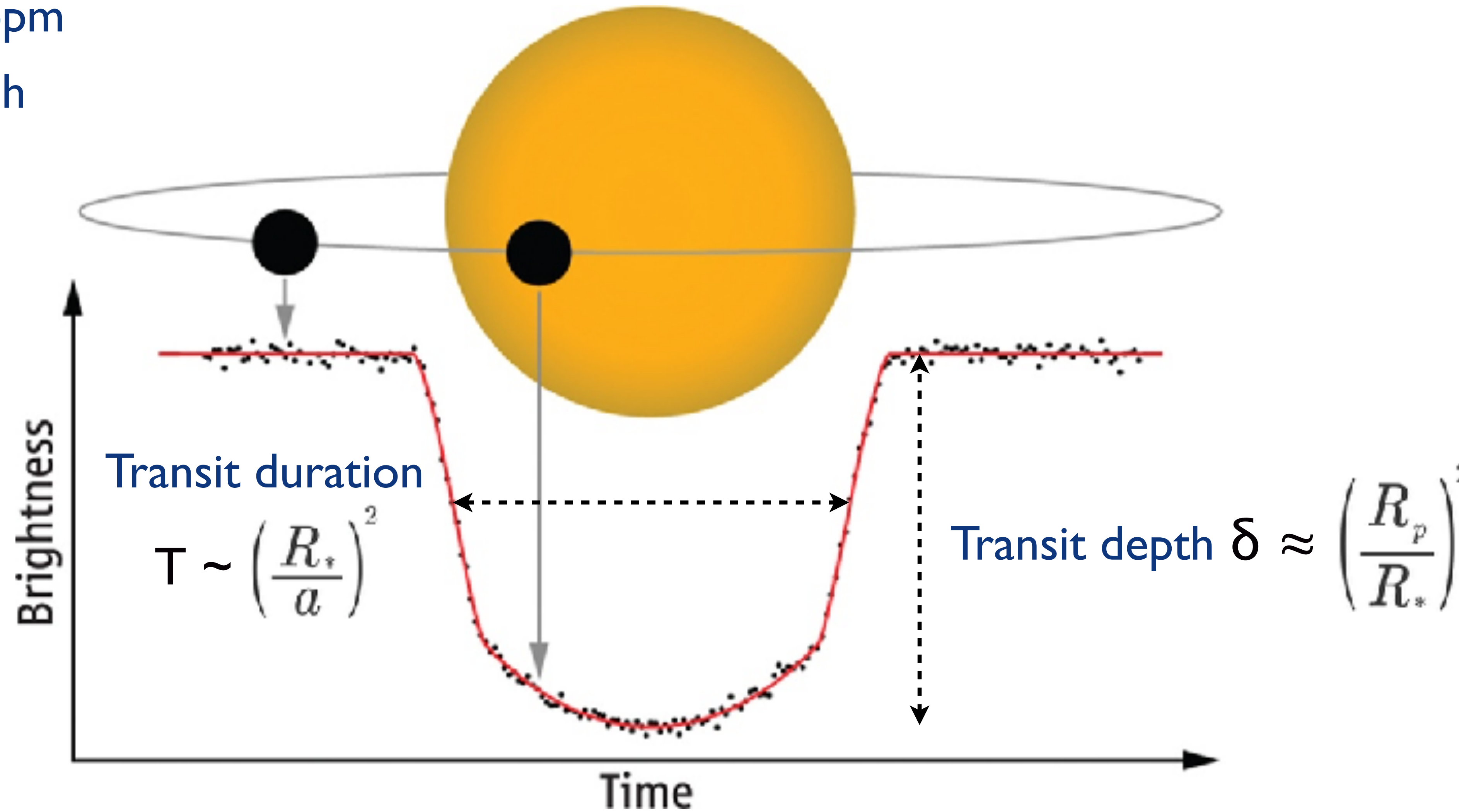


Assuming circular orbit and i = 90°:

Jupiter	**Earth**
δ = 1%	δ = 84 ppm
T ≈ 30h	T ≈ 3h



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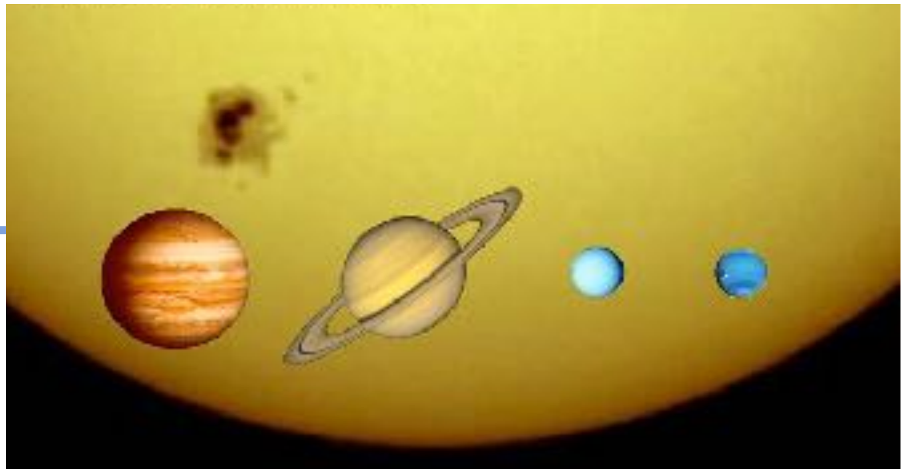

Assuming circular orbit and $i = 90°$:

Jupiter	Earth
$\delta = 1\%$	$\delta = 84$ ppm
$T \approx 30$h	$T \approx 3$h

Hot Jupiter

$T \approx 2.5$h

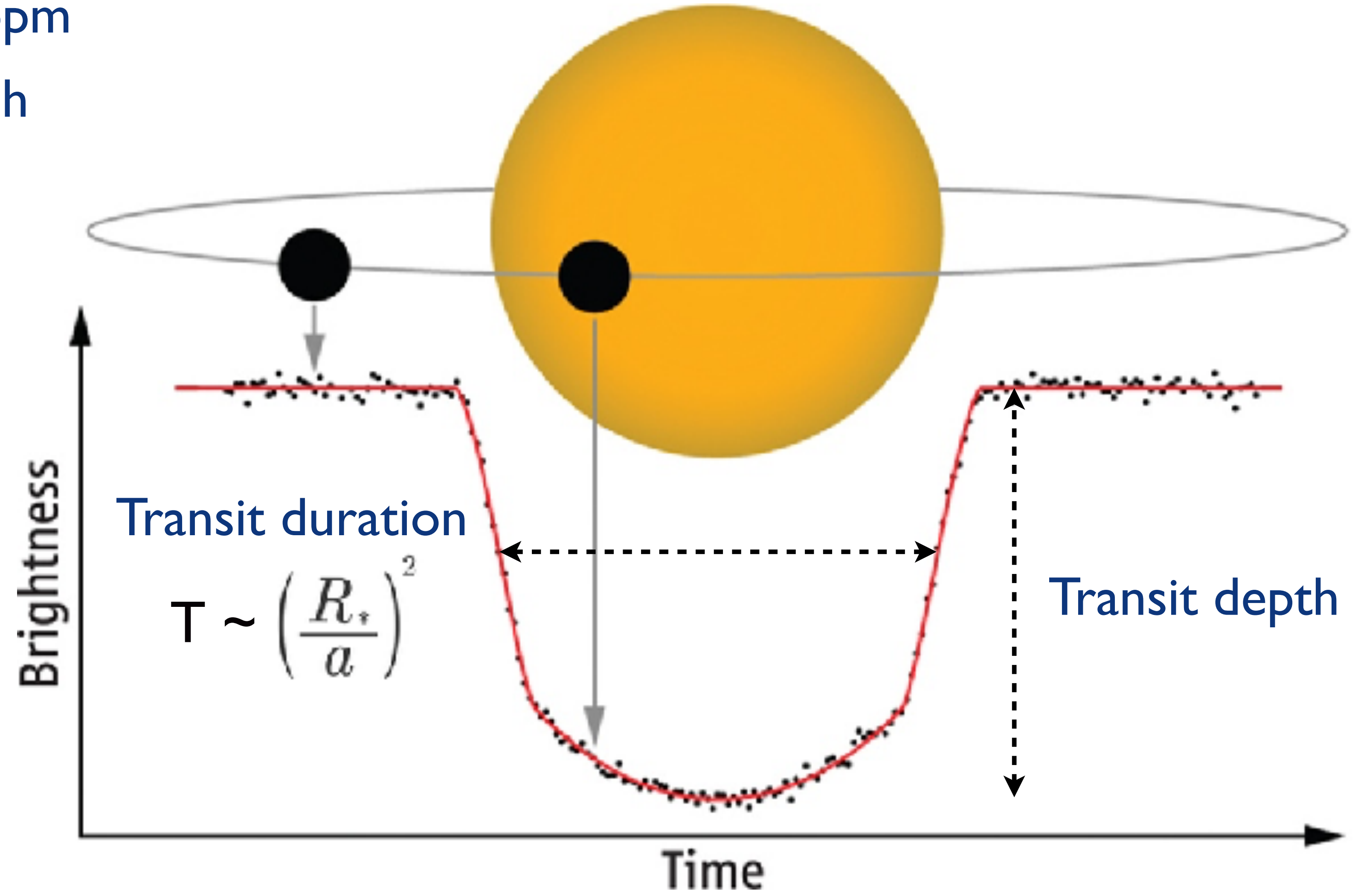

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Image credits: NASA

What is the probability of a planet transiting its star?

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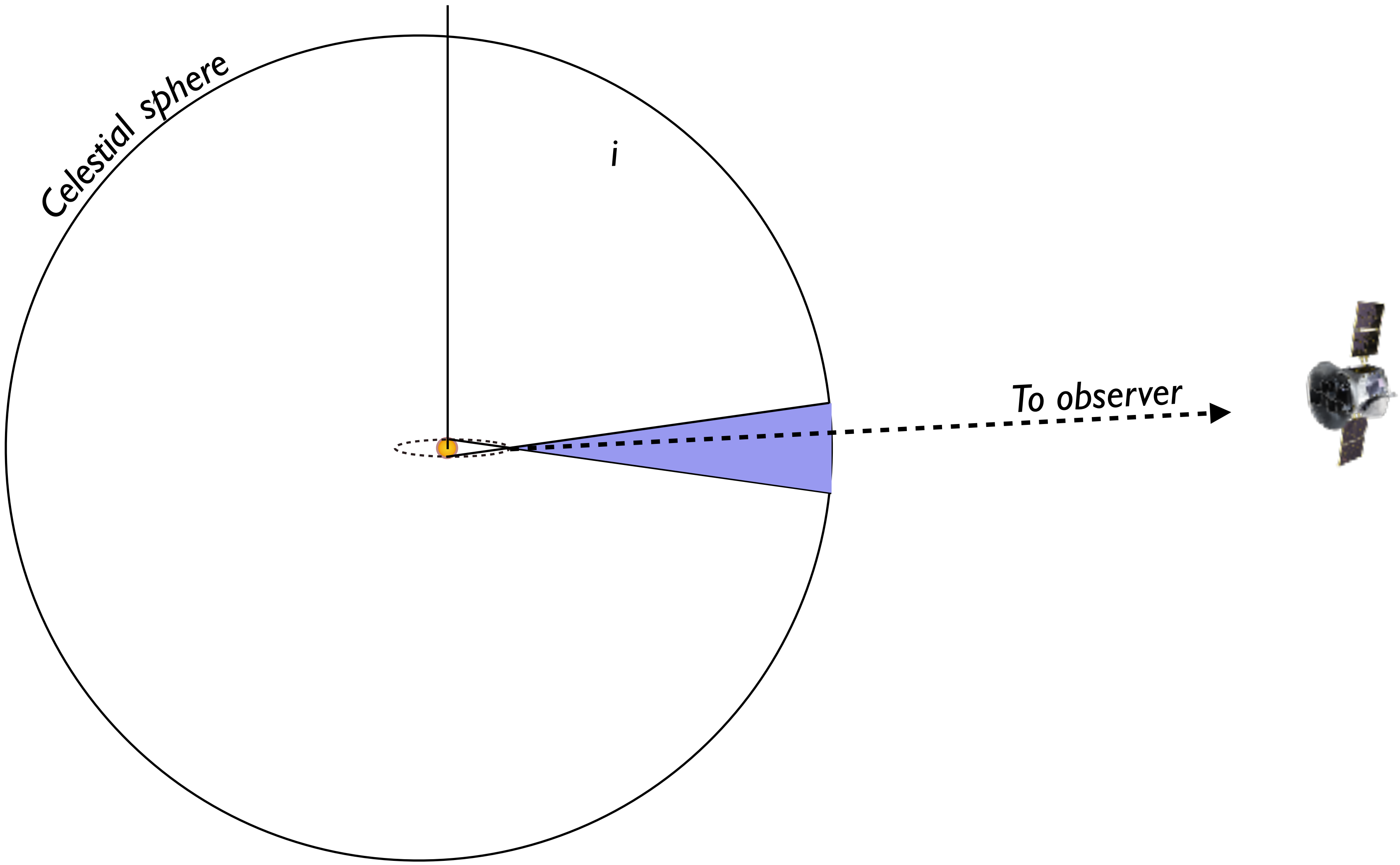

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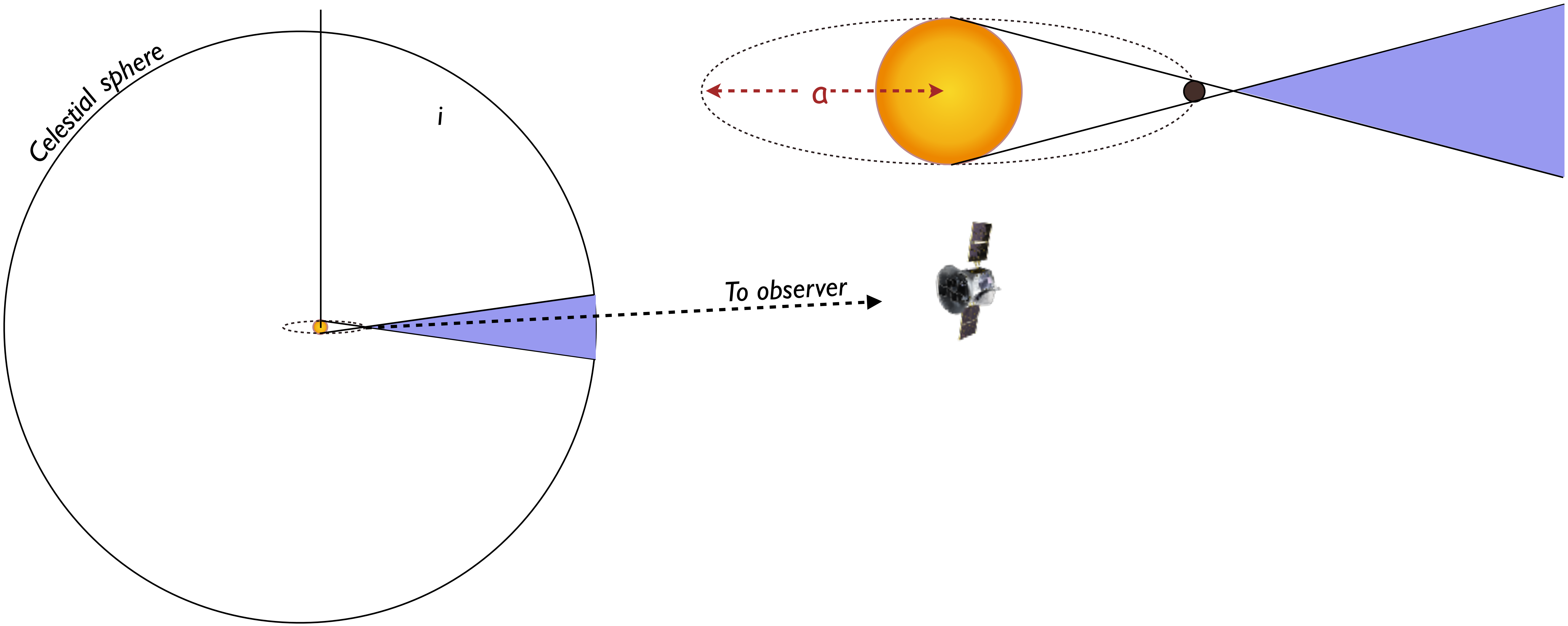

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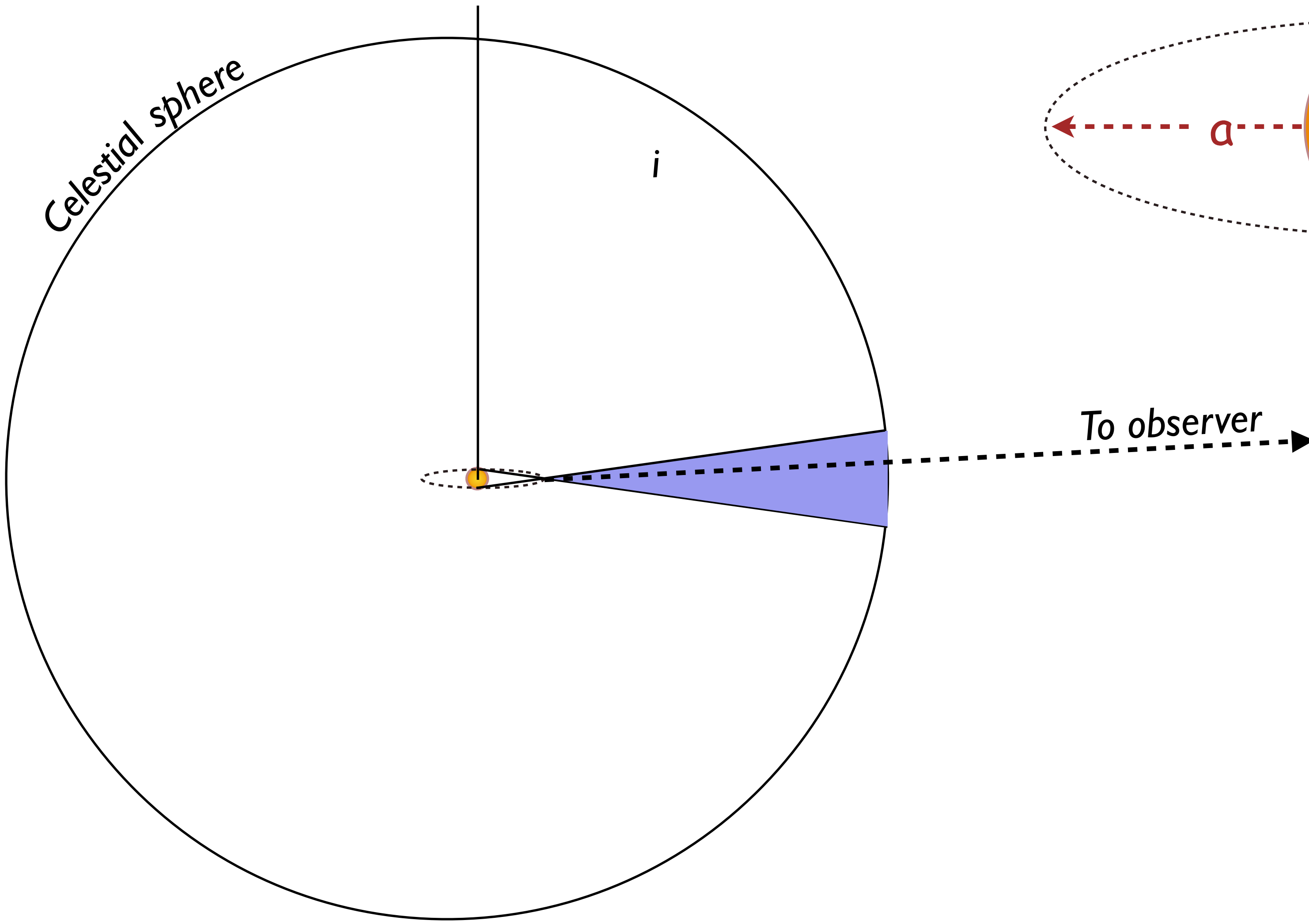

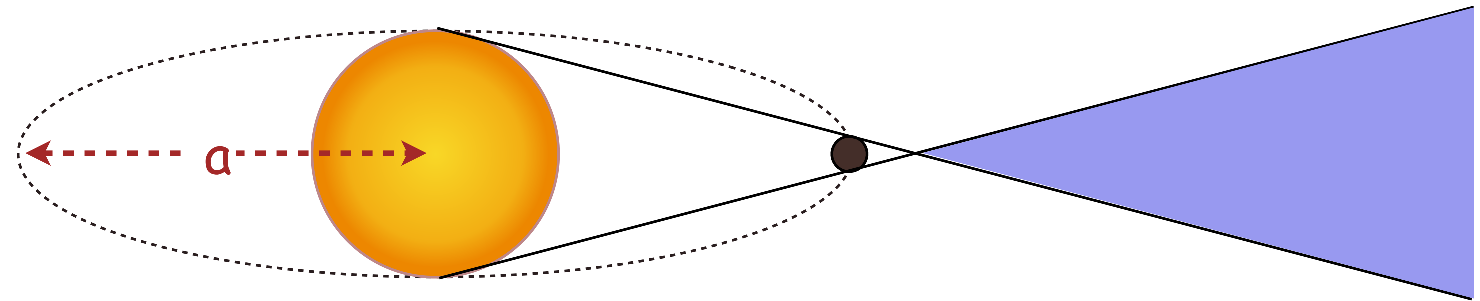

For transits we need:

$$a\cos i \le R_* - R_p$$

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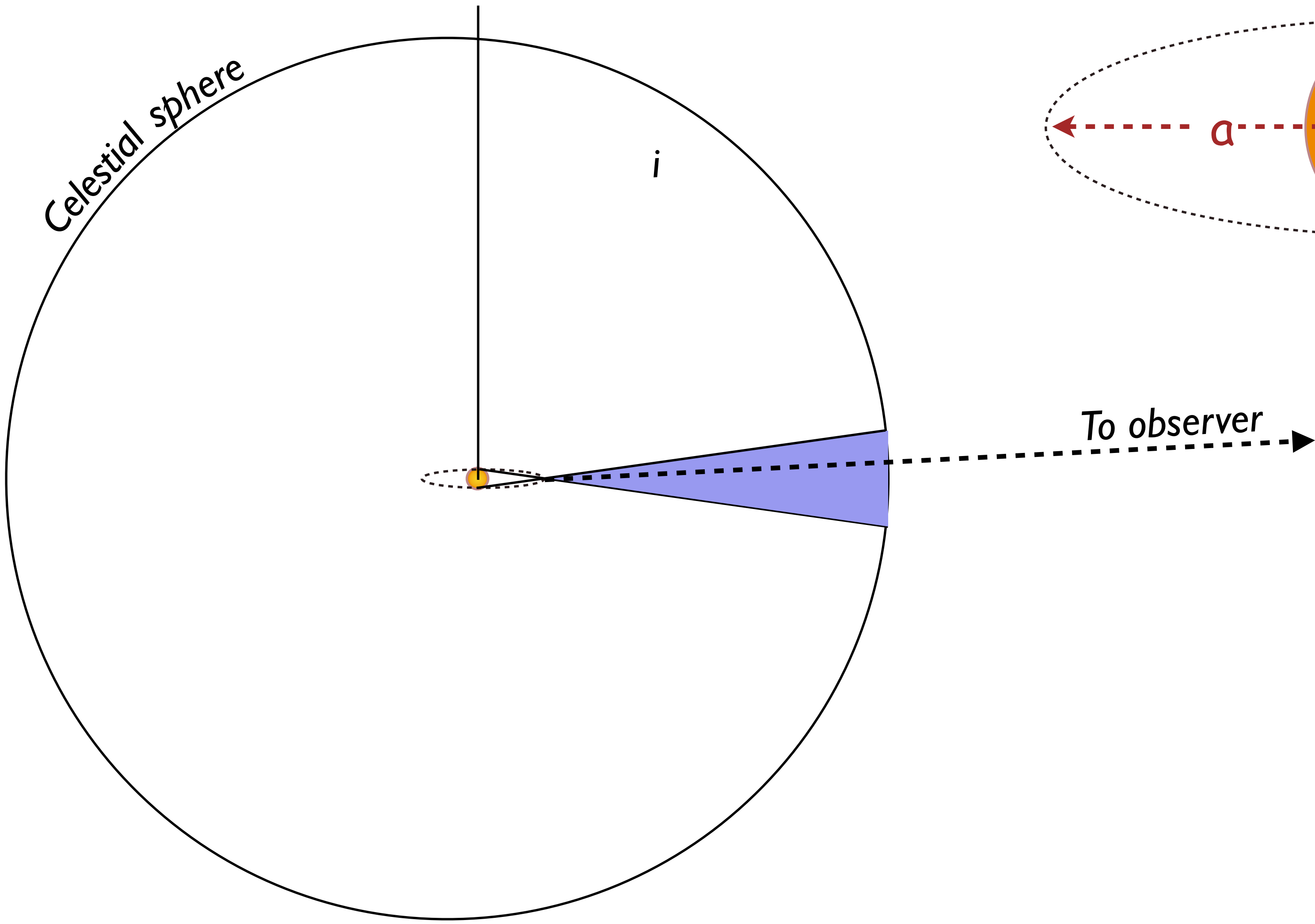

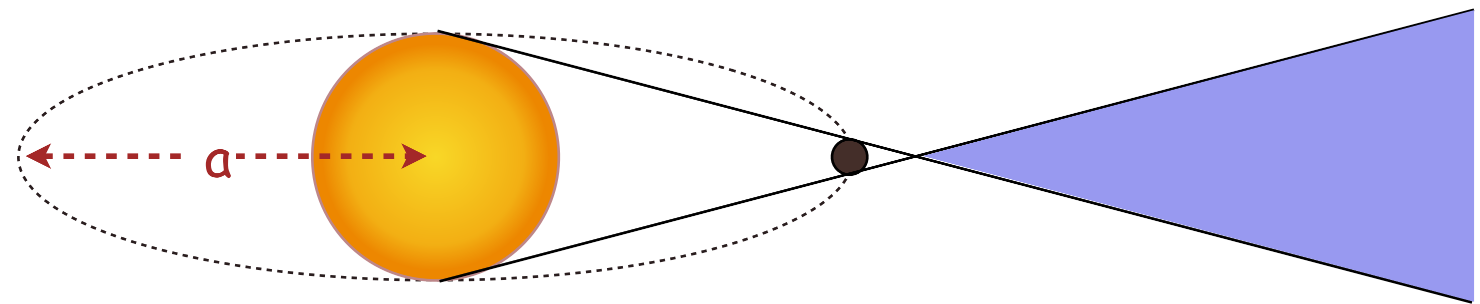

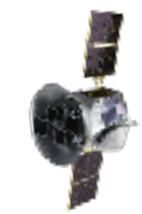

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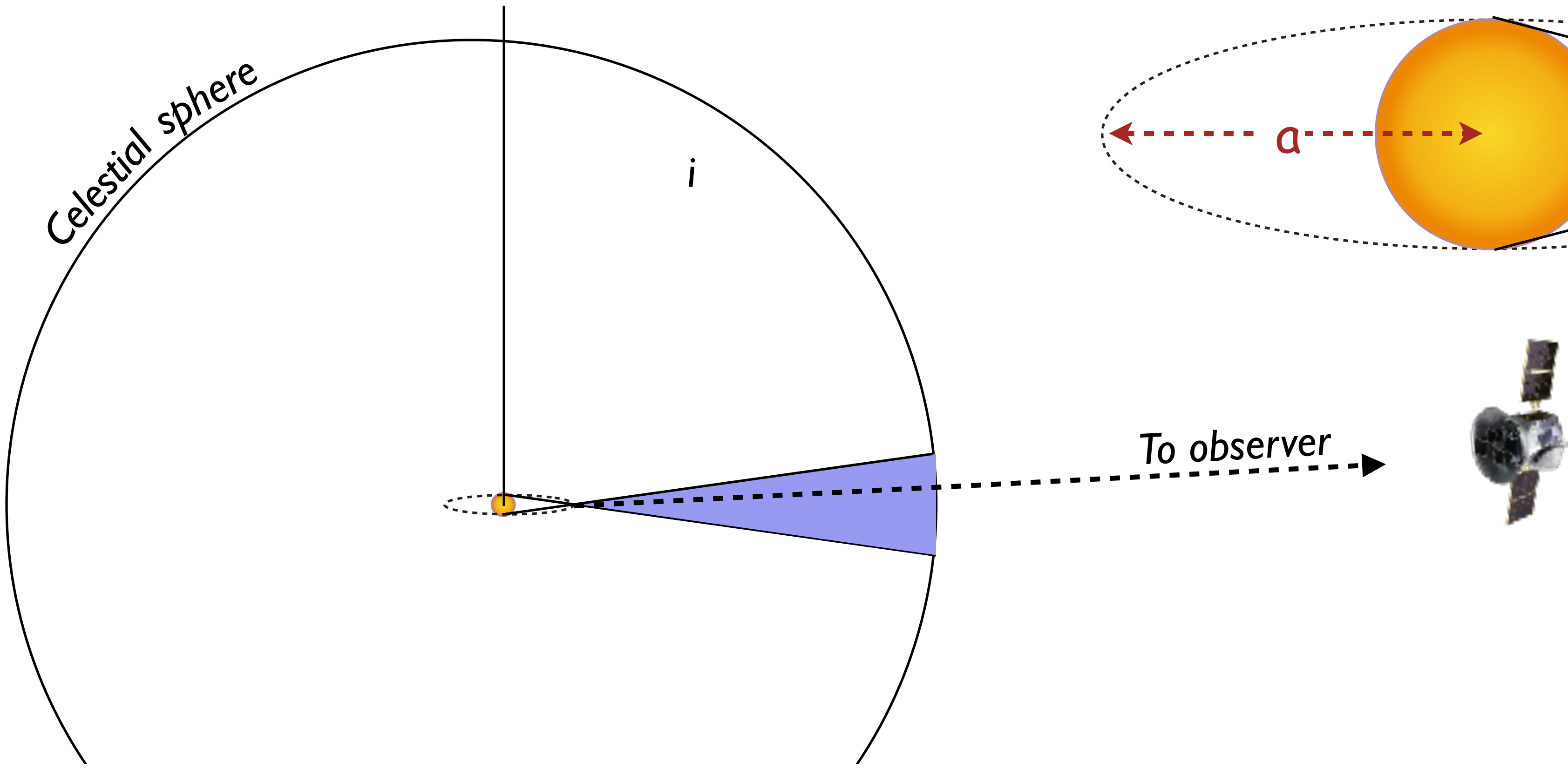

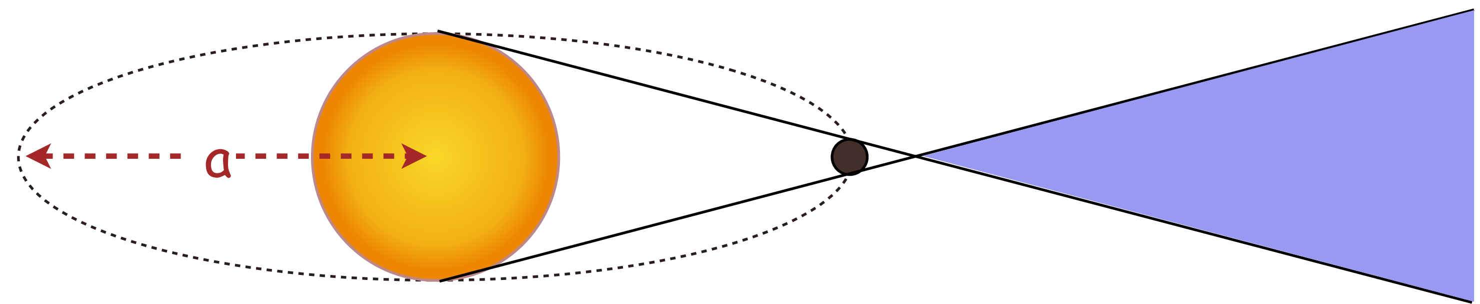

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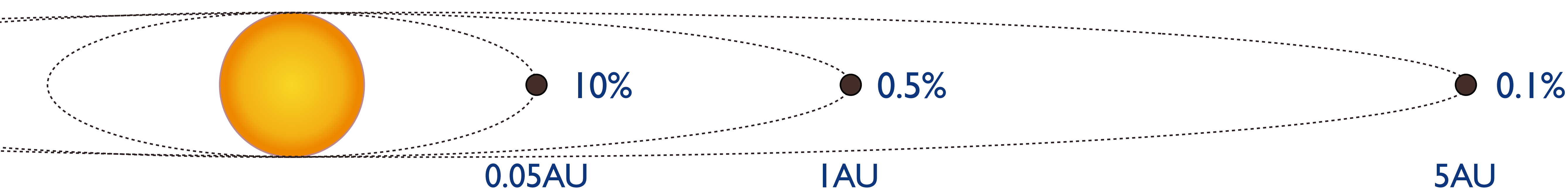

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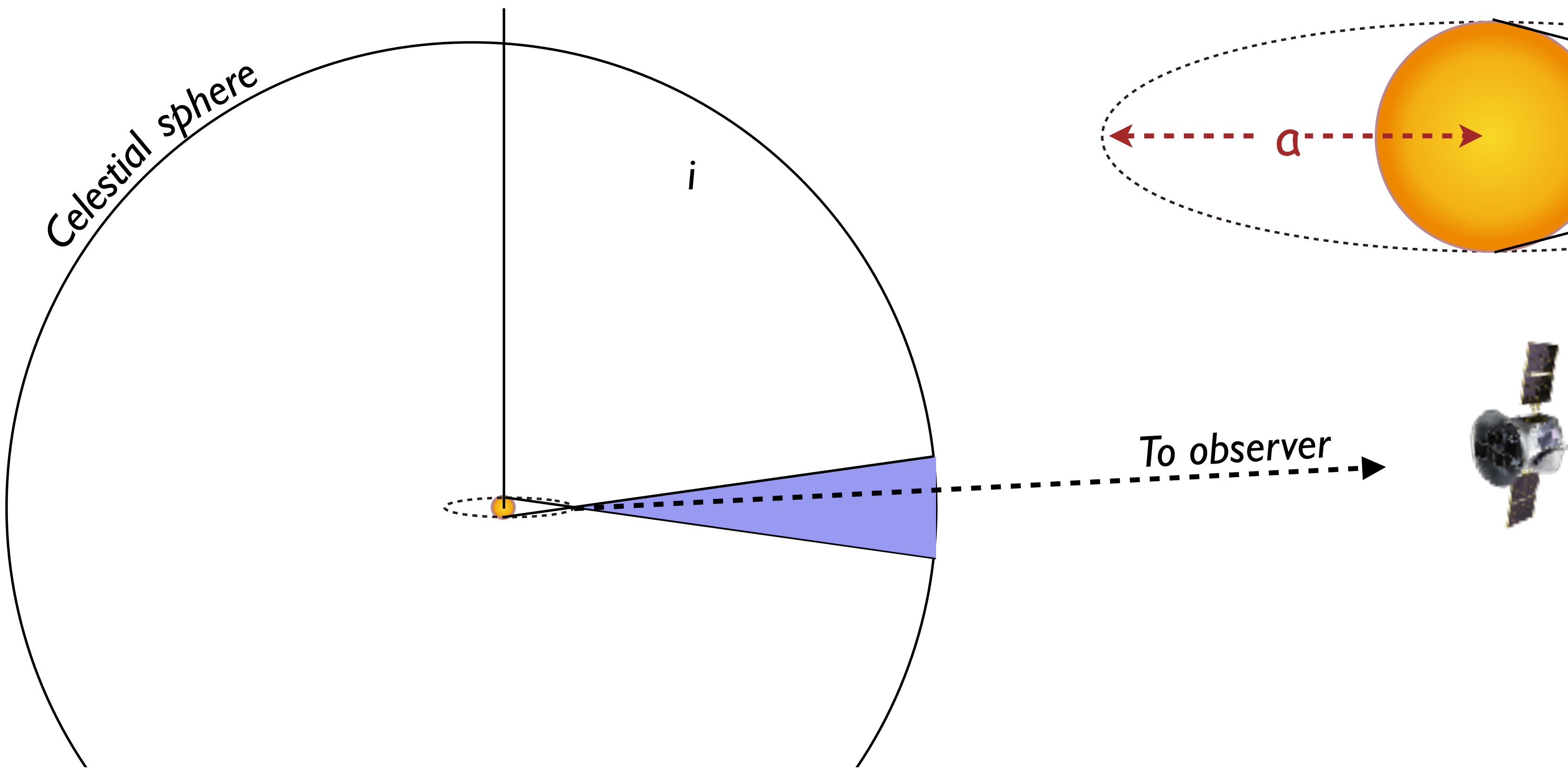

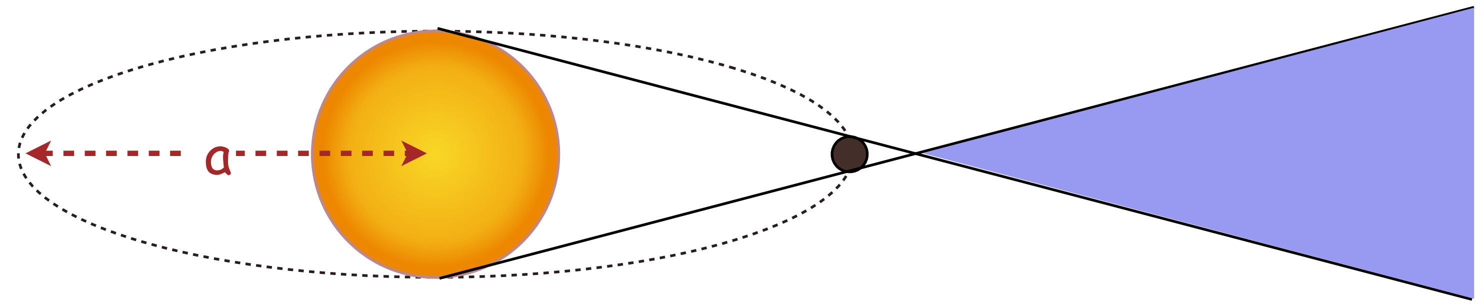

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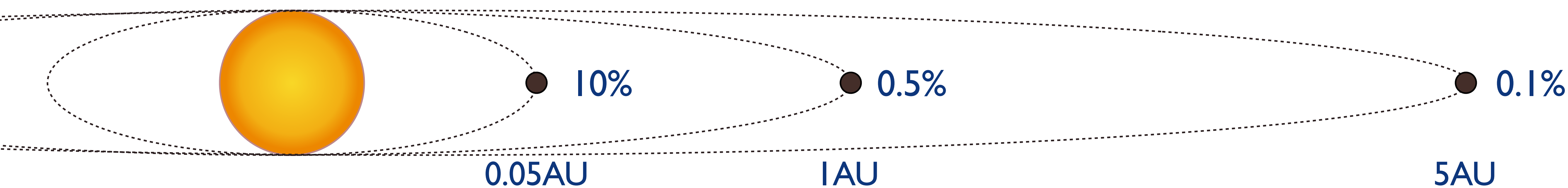

⇒ Transit surveys must monitor thousands of stars at a time.
They find planets in small orbits around large parent stars.

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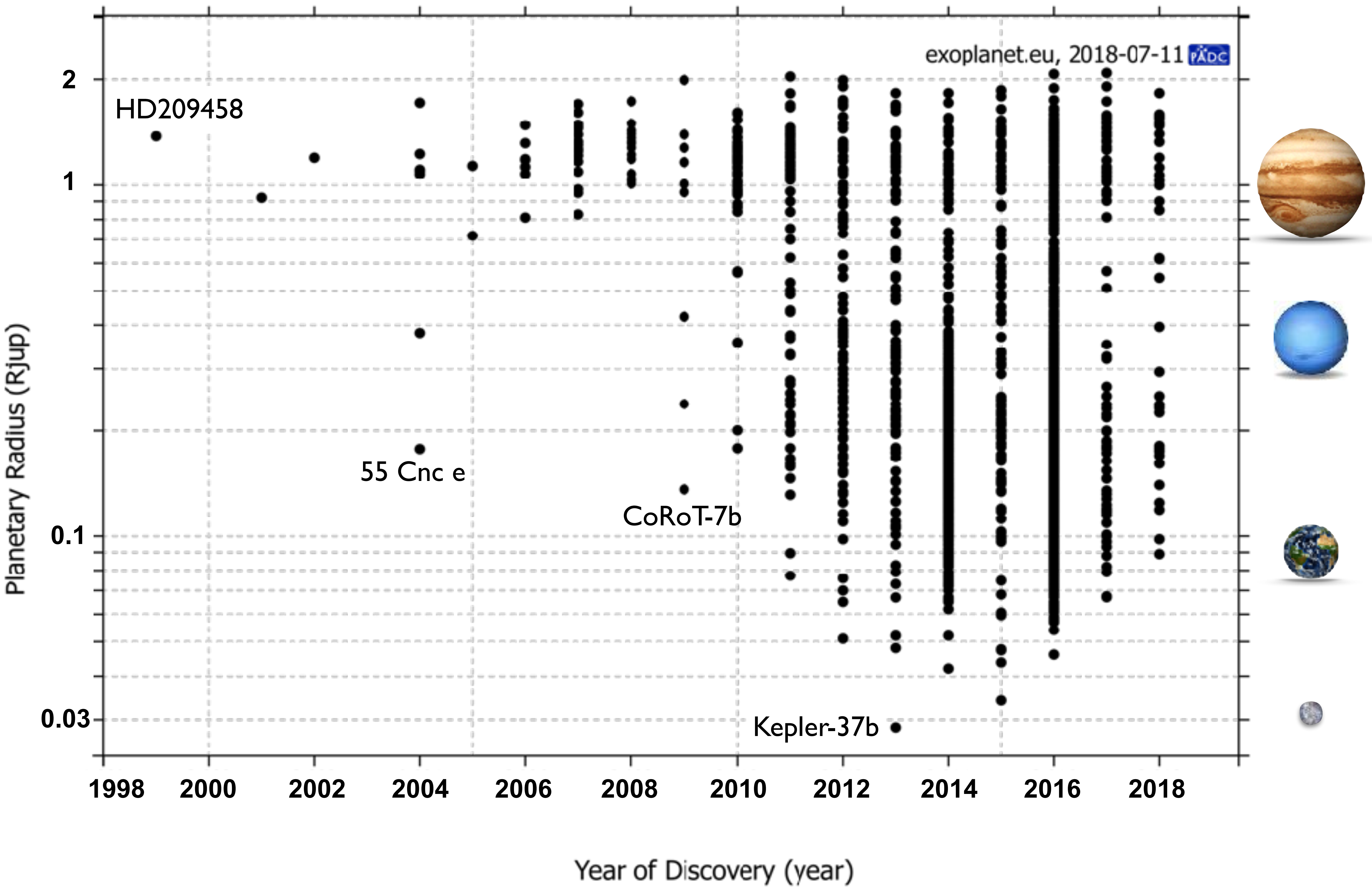
>2920 transiting planets confirmed since 1999



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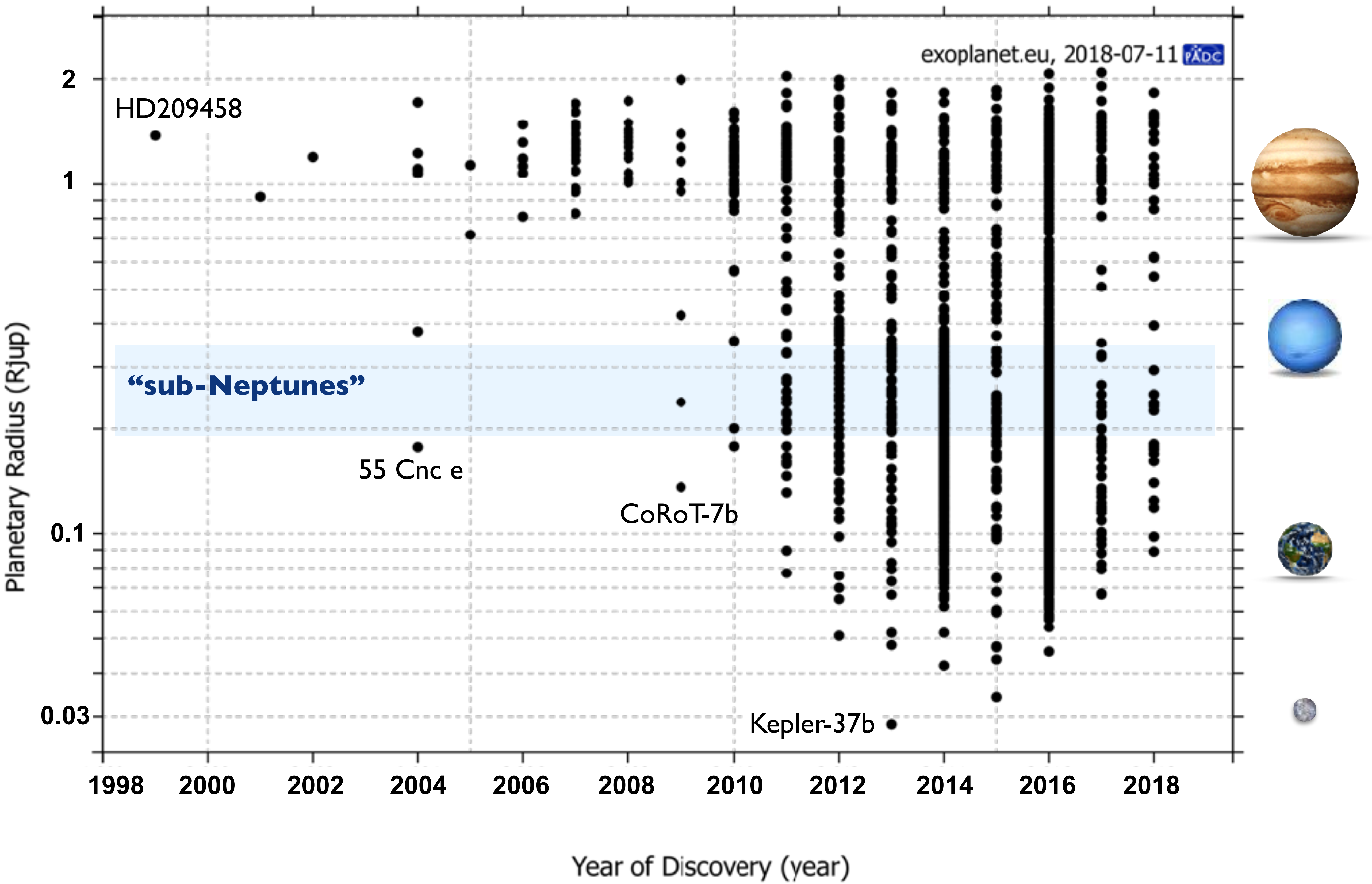

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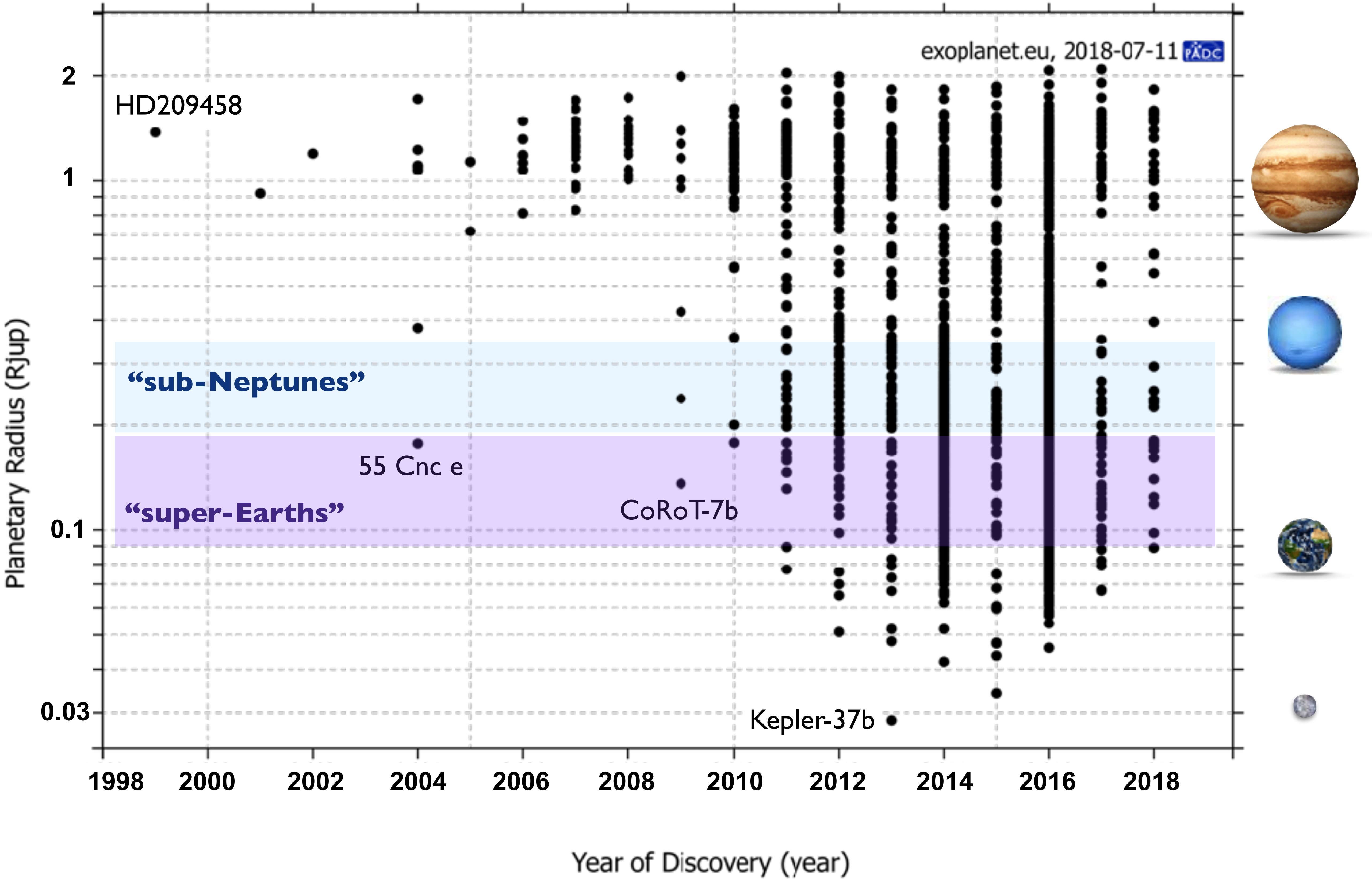
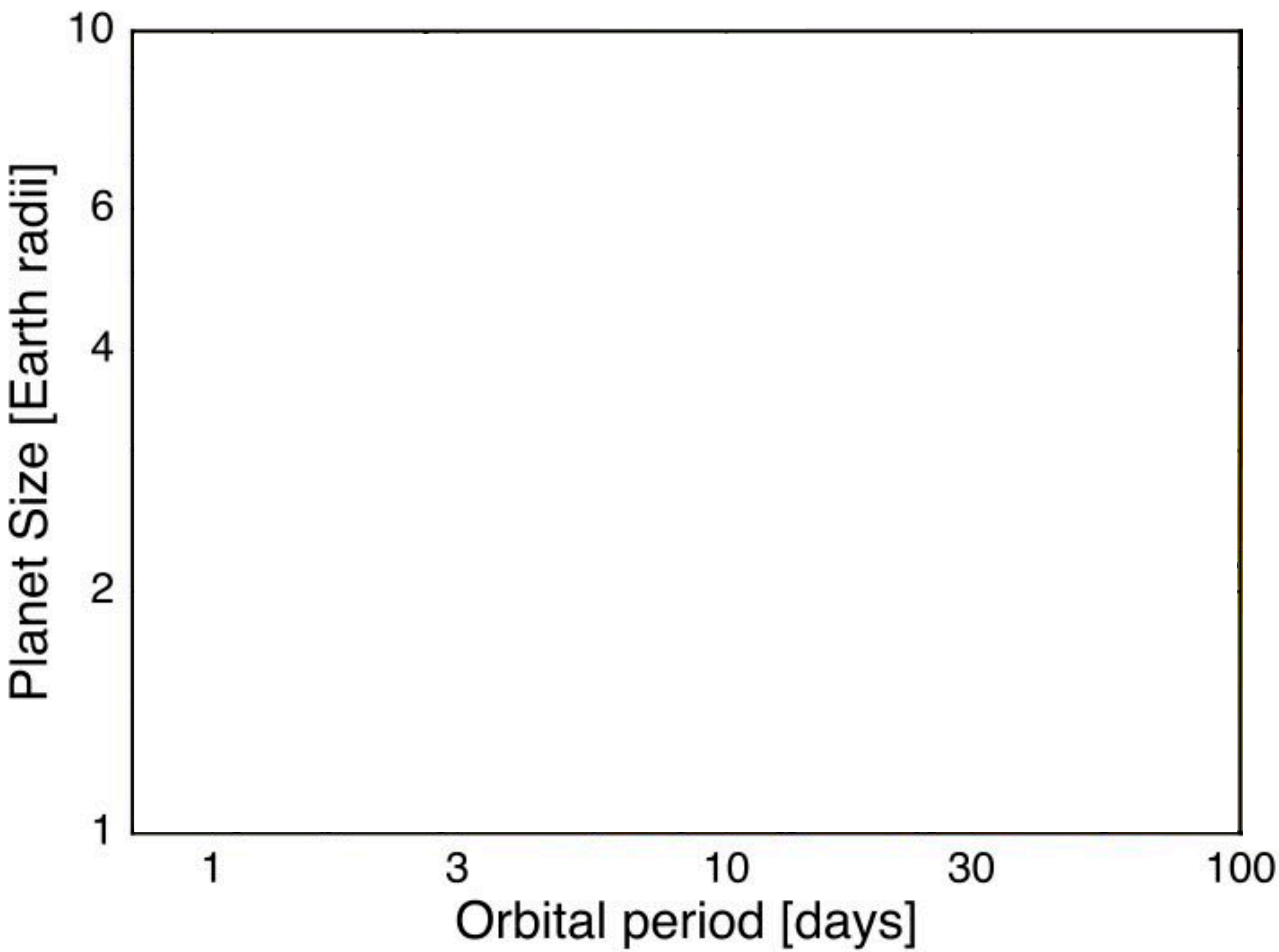


Radius distribution of small planets

Fulton et al. (2017)



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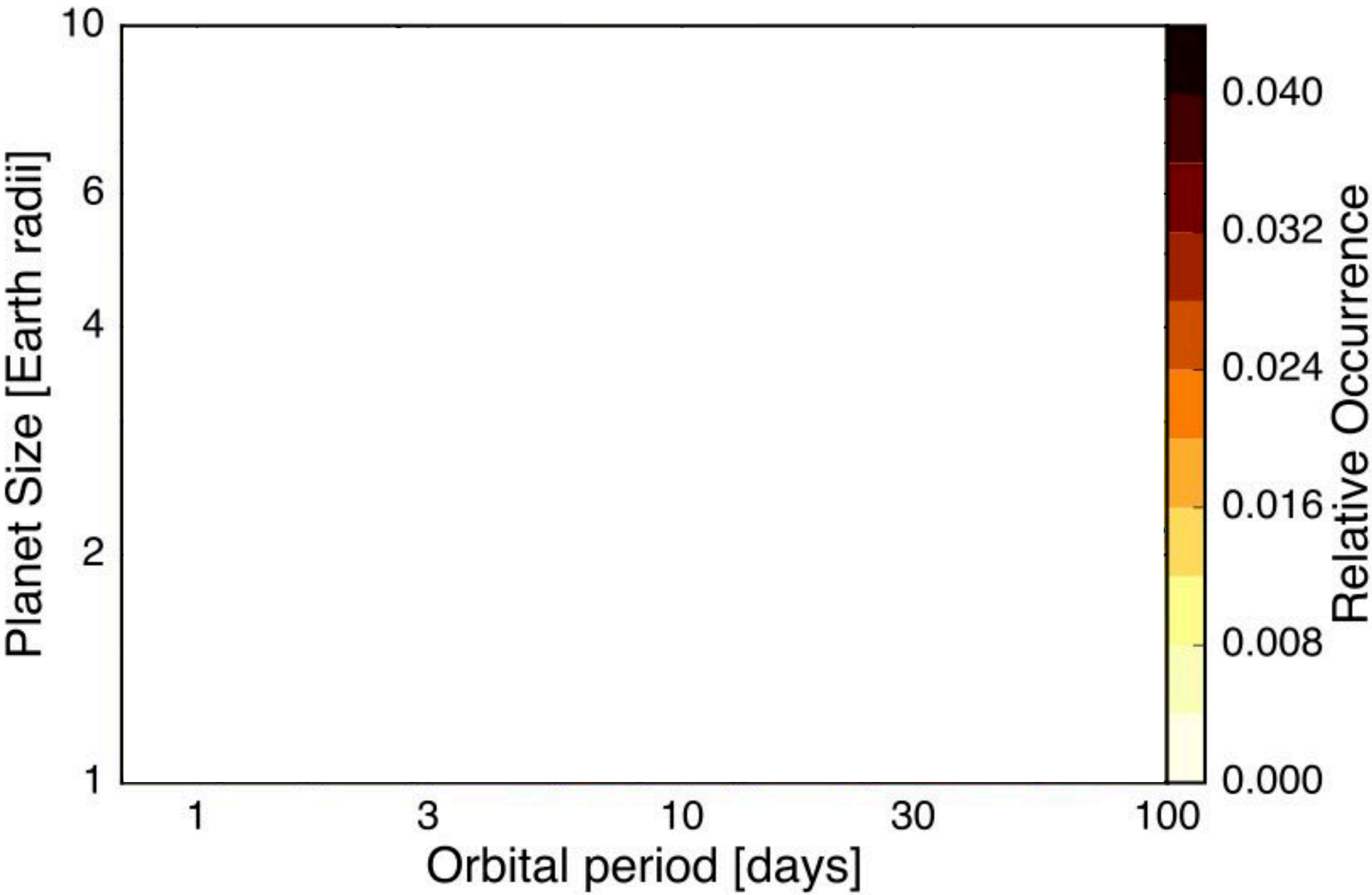

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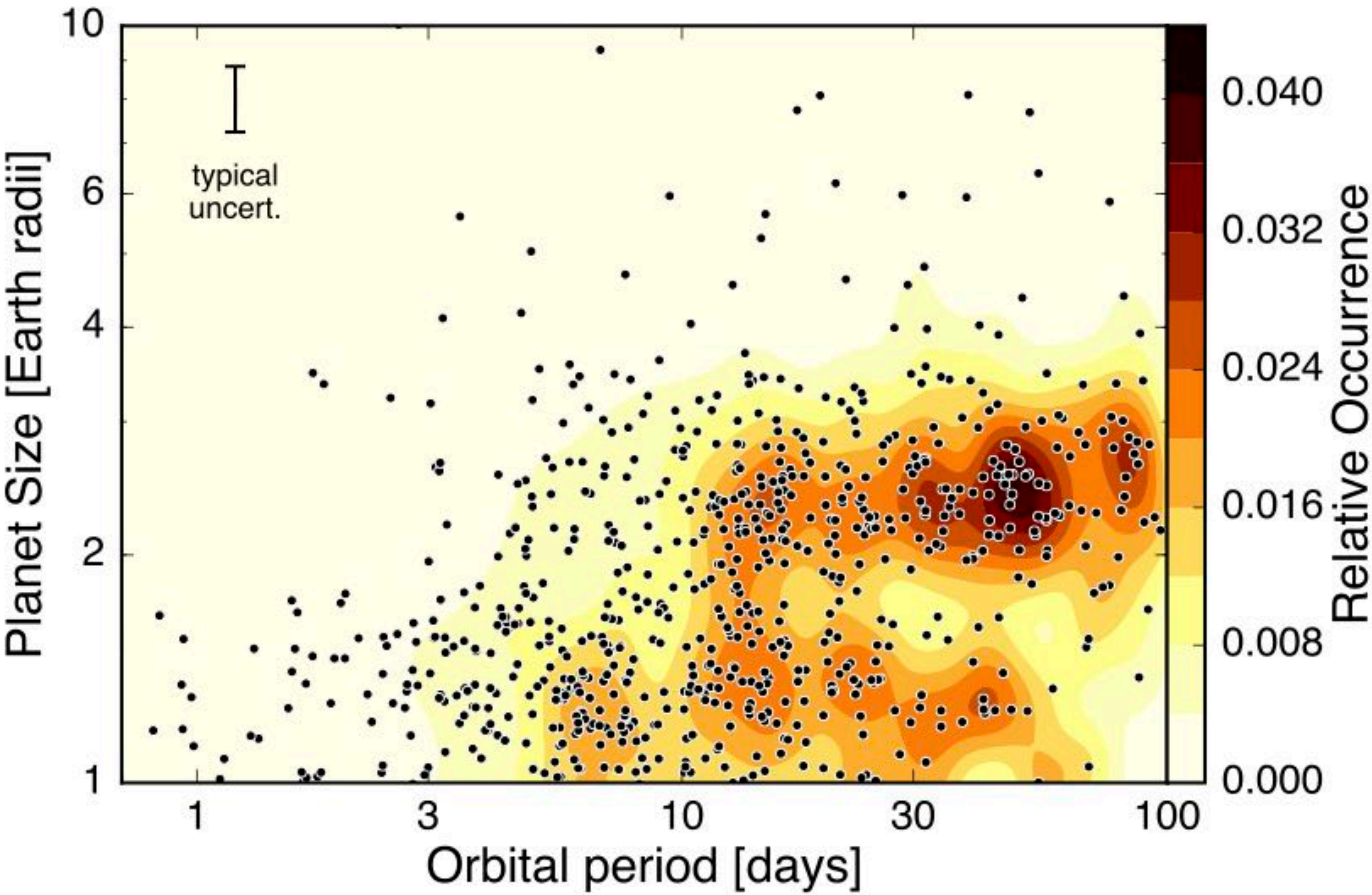

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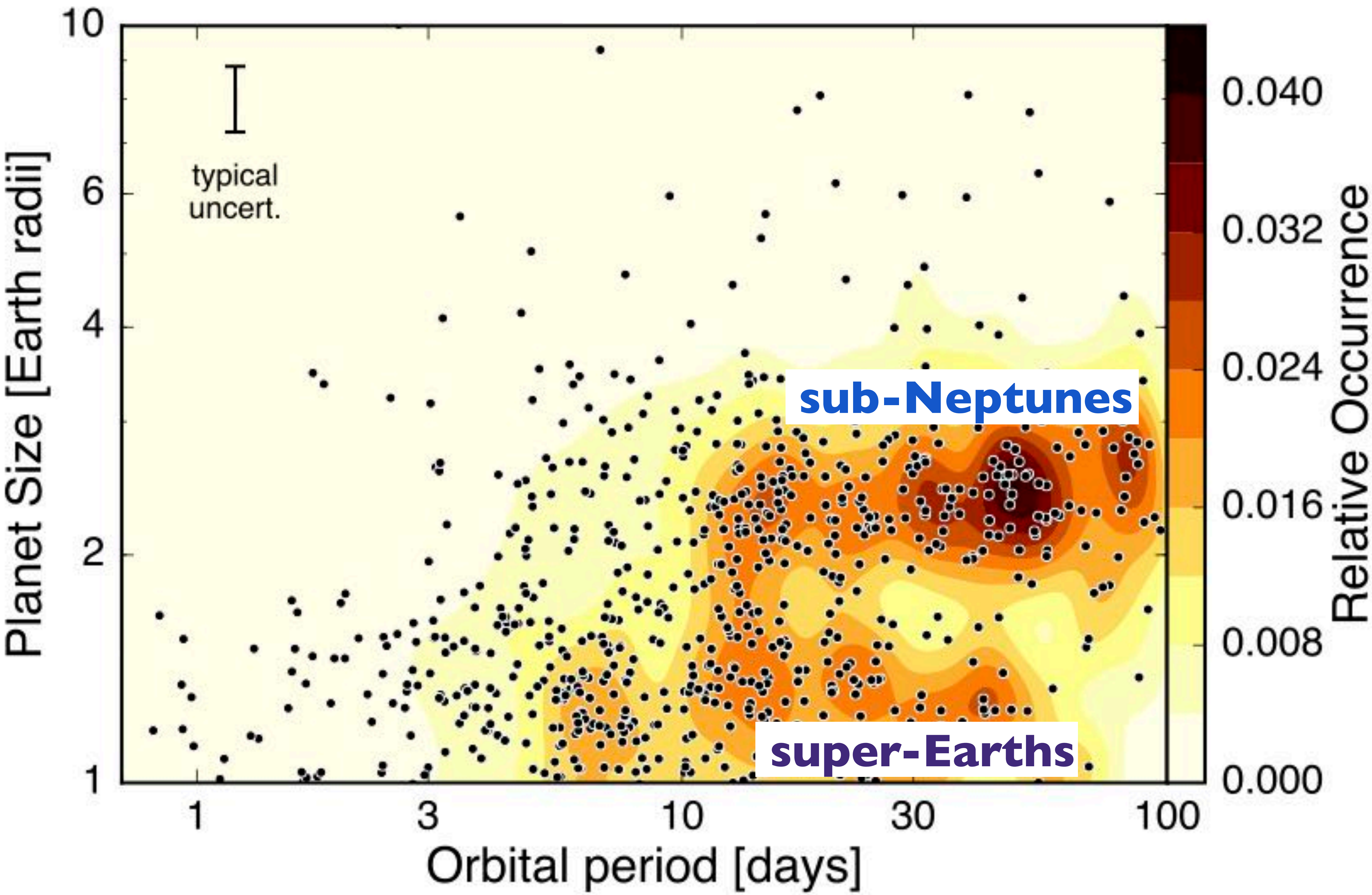

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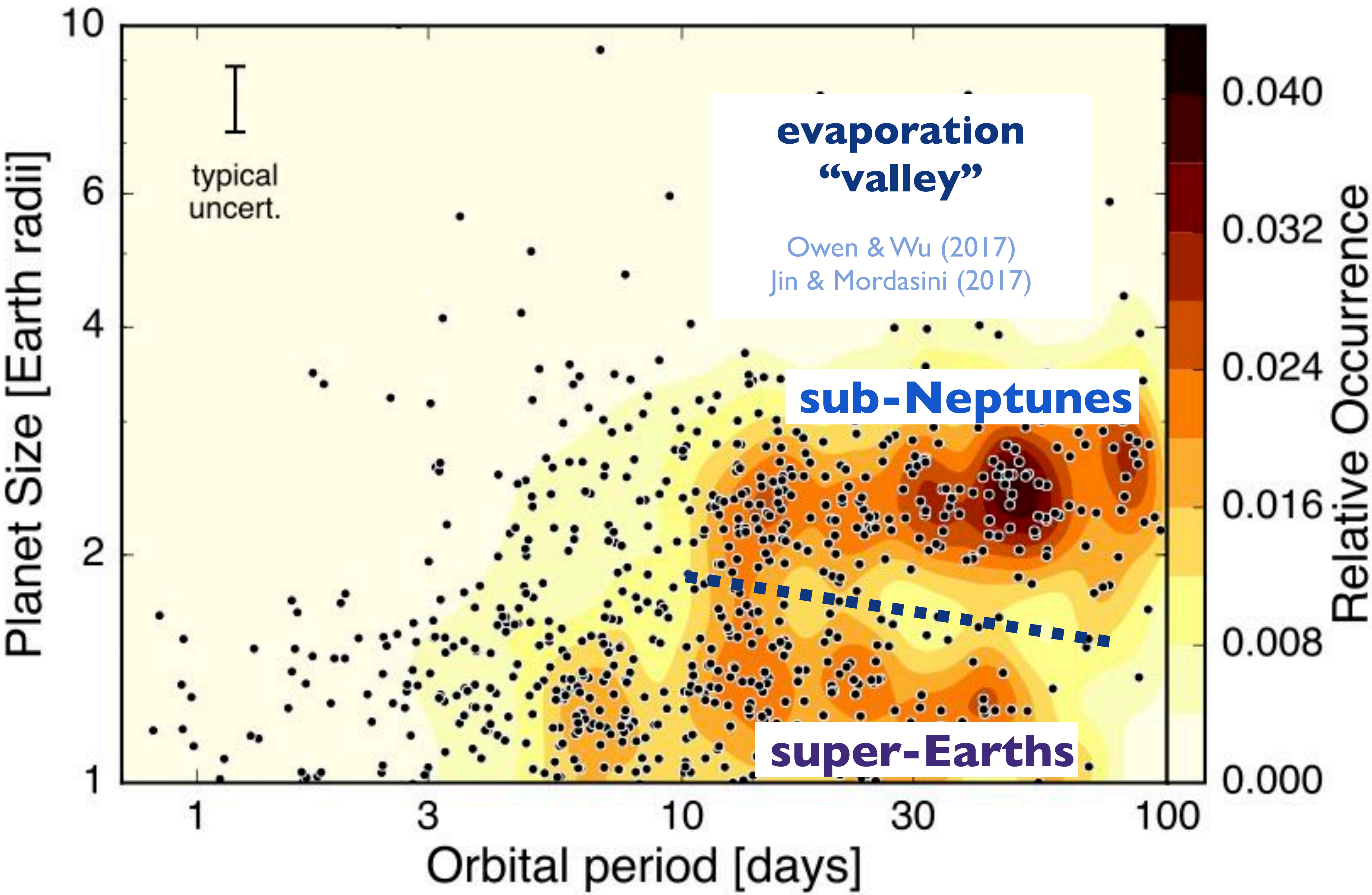

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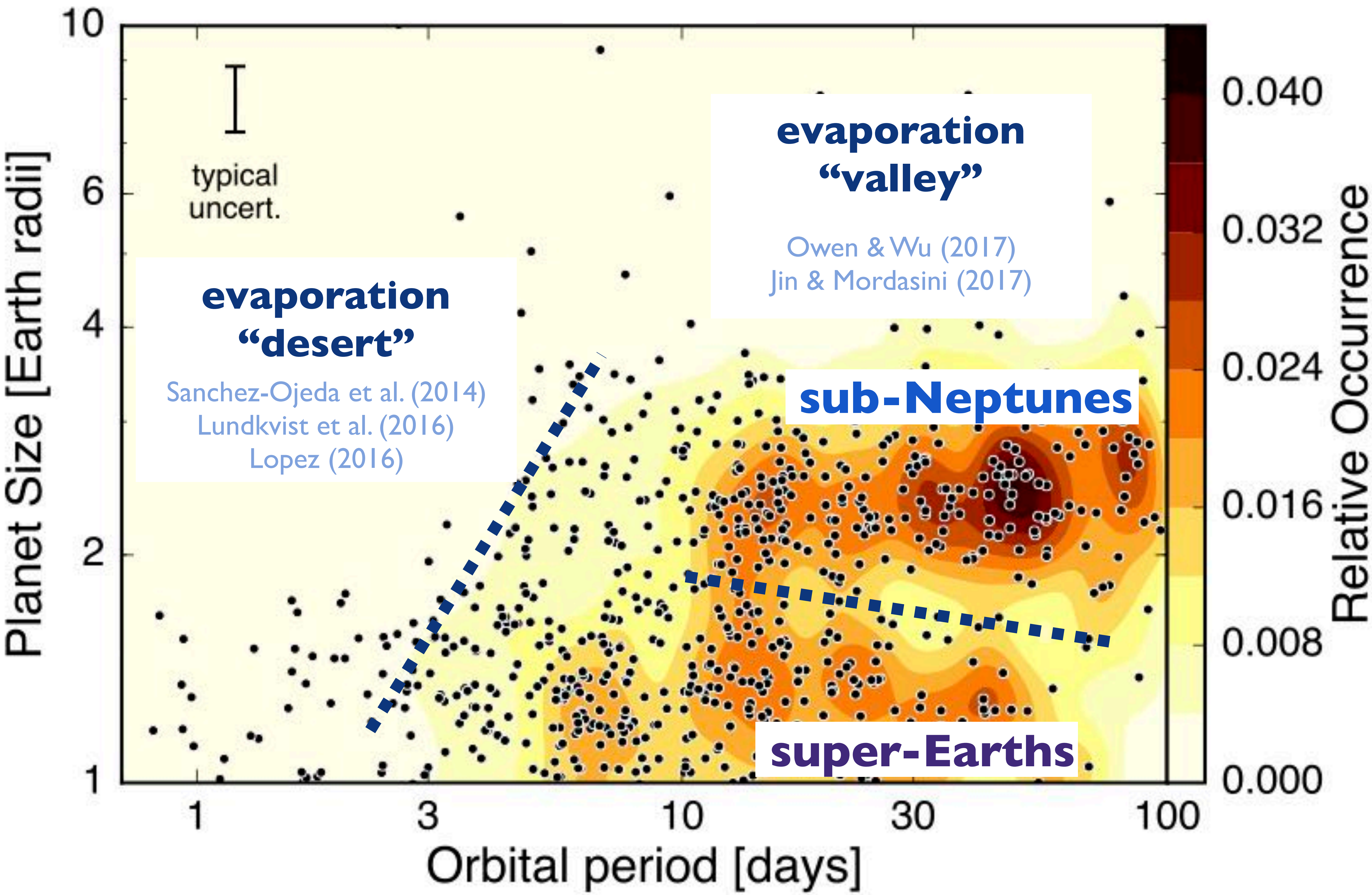

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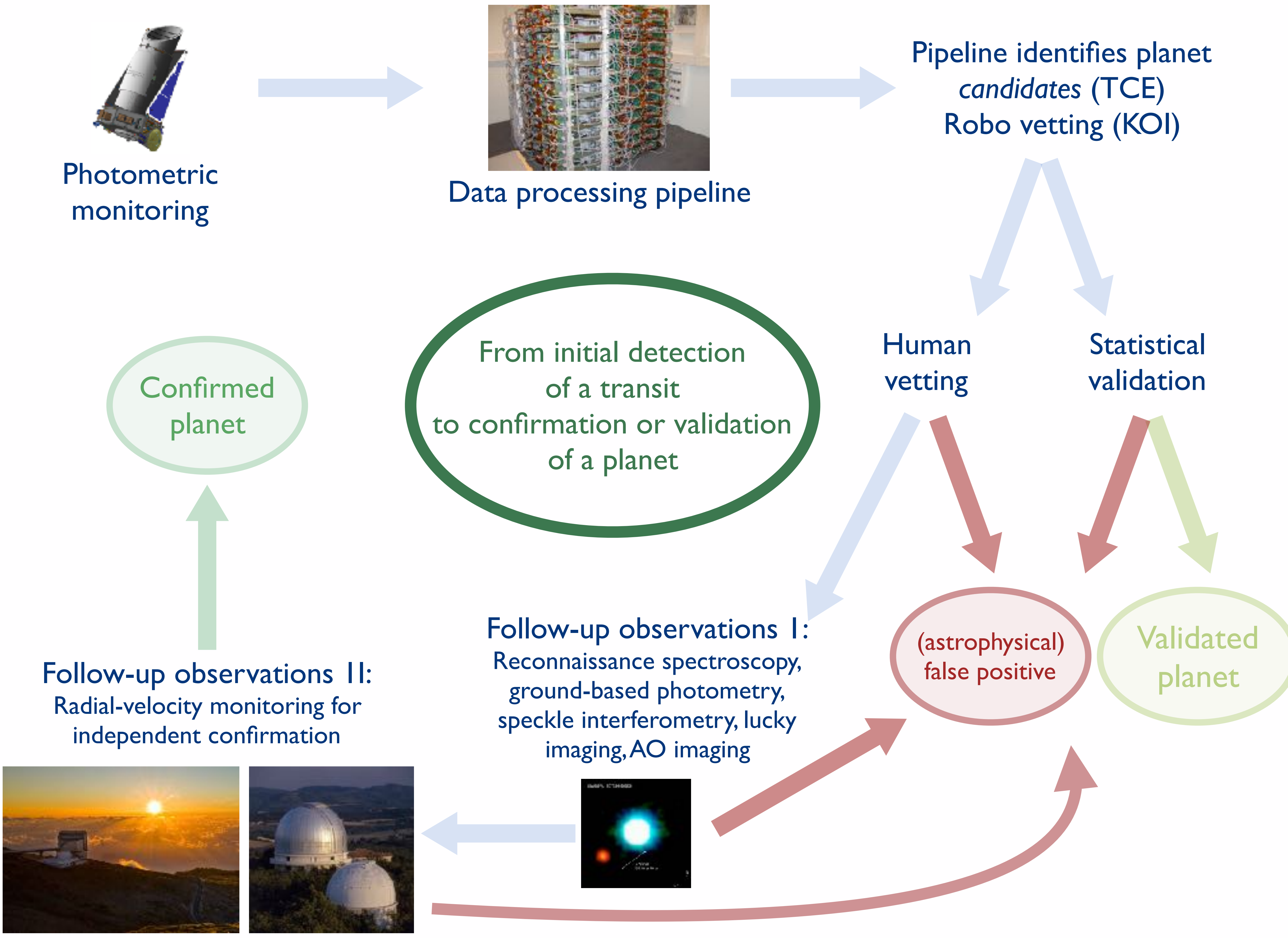
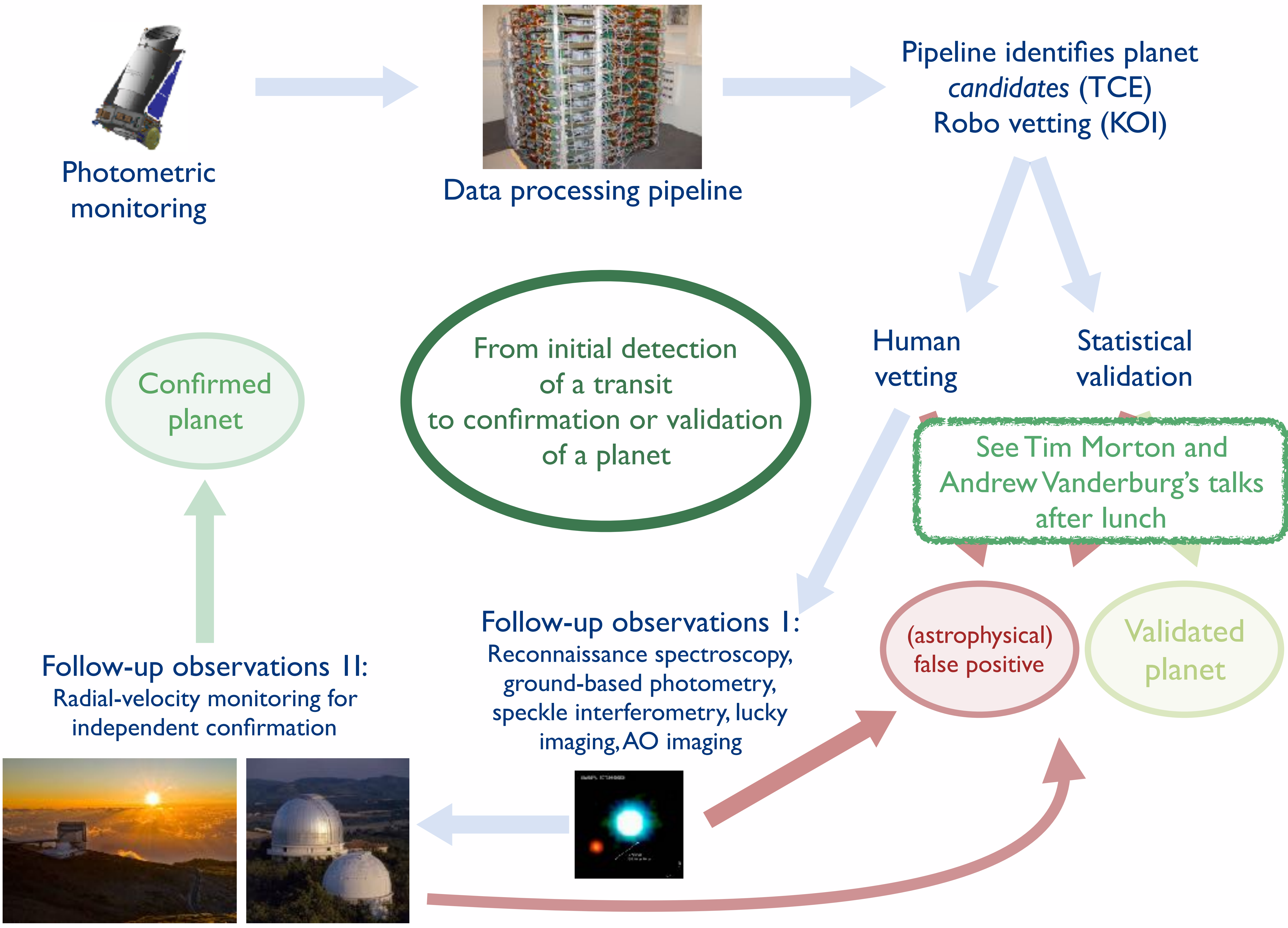
From initial detection
of a transit
to confirmation or validation
of a planet


Photometric monitoring
Data processing pipeline
Pipeline identifies planet candidates (TCE)
Robo vetting (KOI)
Human vetting
Statistical validation
From initial detection of a transit to confirmation or validation of a planet
Confirmed planet
(astrophysical) false positive
Validated planet
Follow-up observations I:
Reconnaissance spectroscopy, ground-based photometry, speckle interferometry, lucky imaging, AO imaging
Follow-up observations II:
Radial-velocity monitoring for independent confirmation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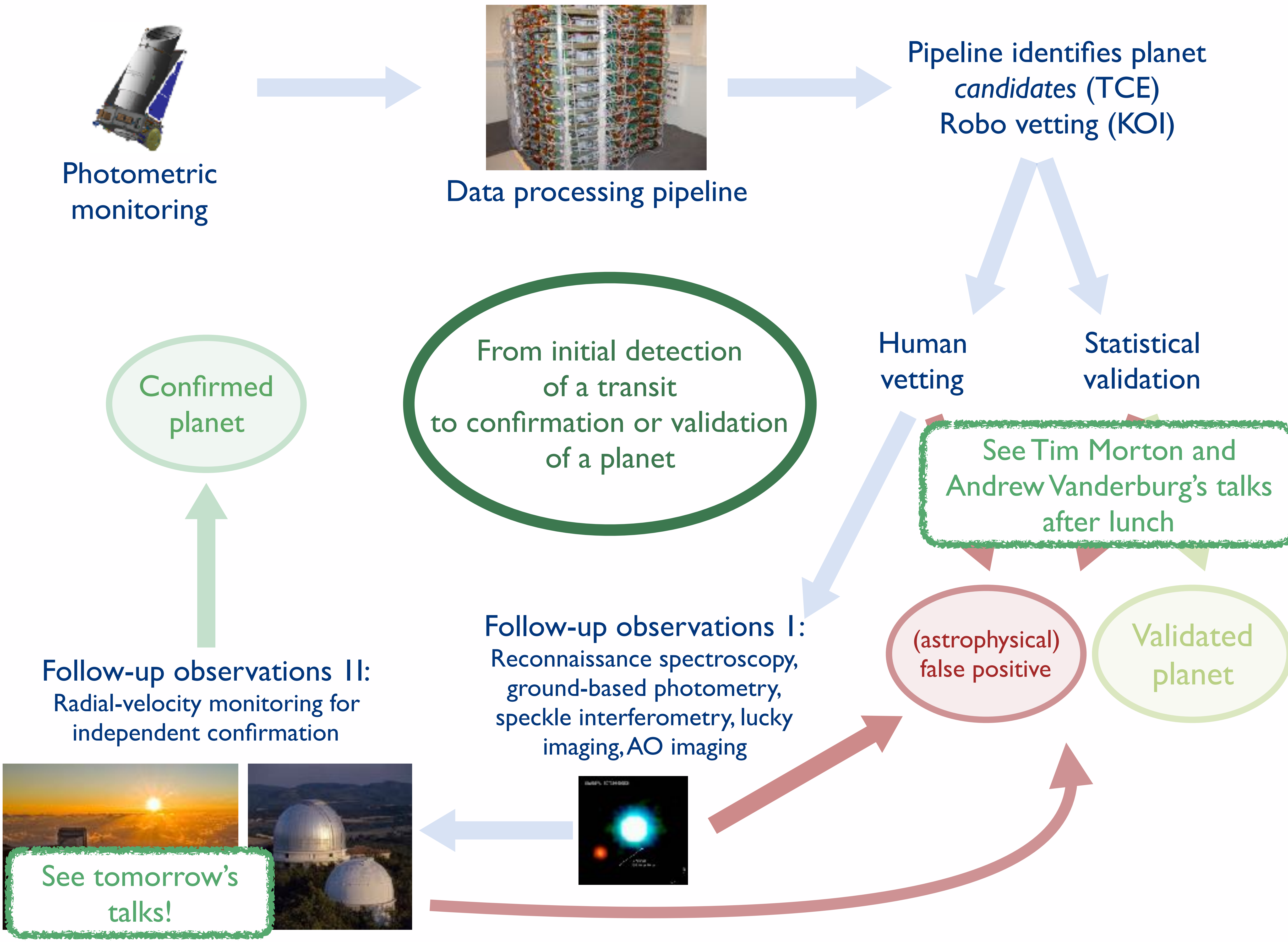
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See tomorrow's talks!

Photometric monitoring

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See Tim Morton and Andrew Vanderburg's talks after lunch

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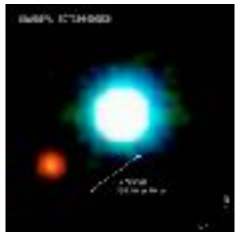

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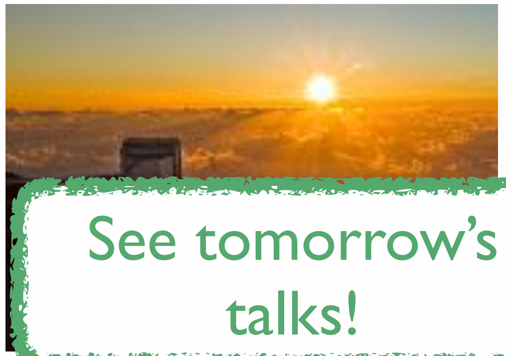

See tomorrow's talks!

Detecting transits: the Box-fitting Least Squares technique (BLS)

Kovács, Zucker & Mazeh (2002)

See also Aigrain & Irwin (2004), Collier Cameron et al. (2006) and others

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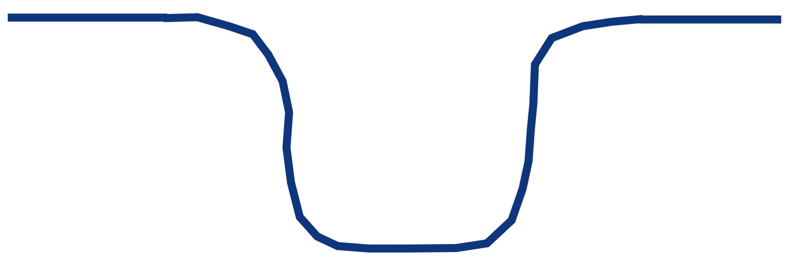
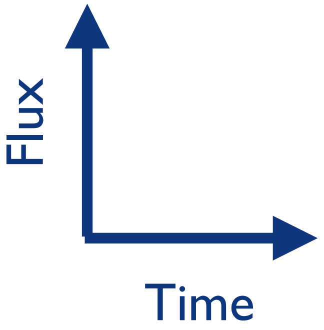


10 parameters: P, t_0, ω, e, i, a/R_*, R_p/R_*, F_0, u_1, u_2



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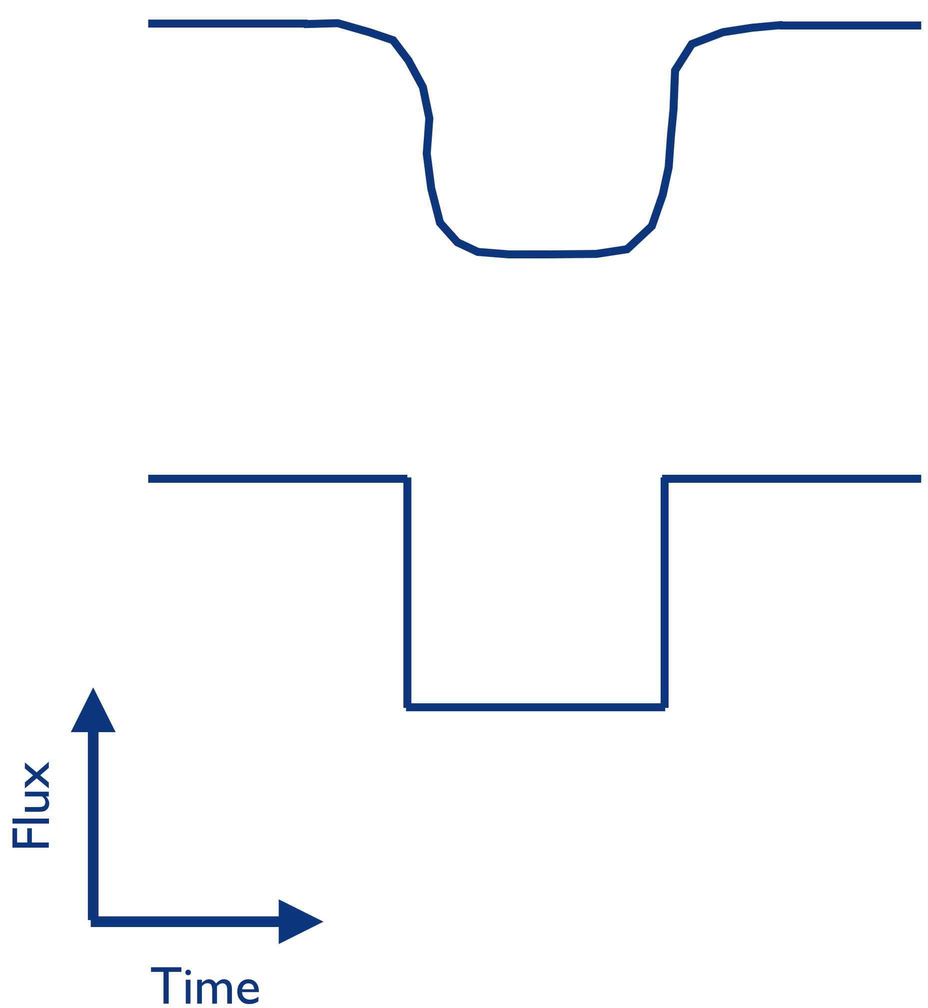


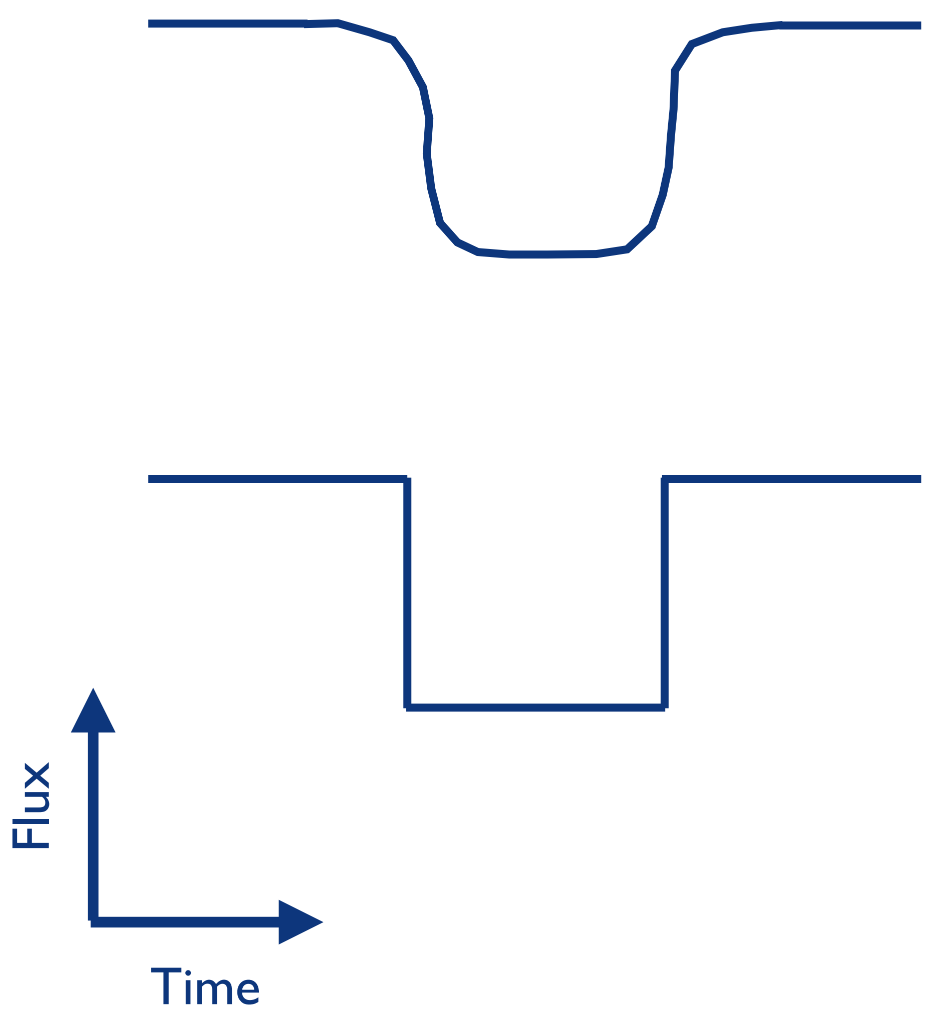
10 parameters: P, t_0, ω, e, i, a/R_*, R_p/R_*, F_0, u_1, u_2

3 non-linear parameters: P, t_0, *width*
and 2 linear parameters: F_0, *depth*

See also Aigrain & Irwin (2004), Collier Cameron et al. (2006) and others

Detecting transits: the Box-fitting Least Squares technique (BLS)

Kovács, Zucker & Mazeh (2002)



10 parameters: P, t_0, ω, e, i, a/R_*, R_p/R_*, F_0, u_1, u_2

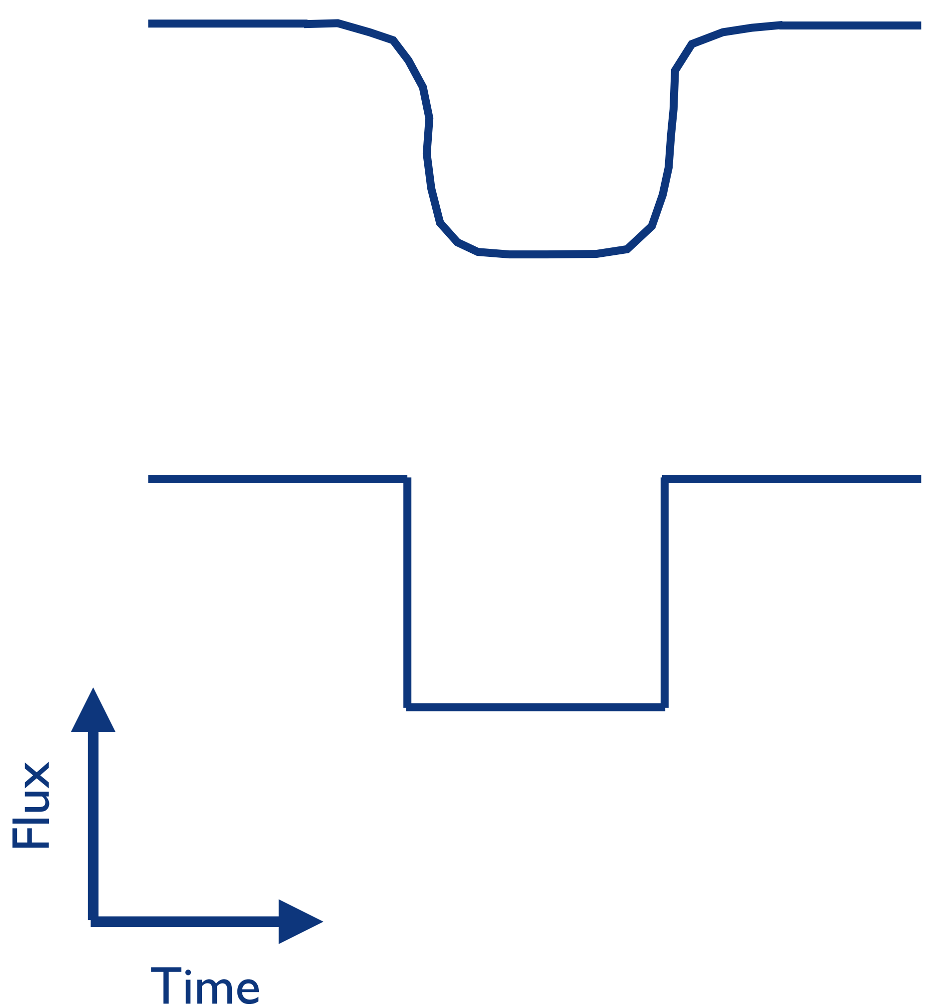
3 non-linear parameters: P, t_0, *width*
and 2 linear parameters: F_0, *depth*

Step through a grid of P, t_0, *width*.

See also Aigrain & Irwin (2004), Collier Cameron et al. (2006) and others

Detecting transits: the Box-fitting Least Squares technique (BLS)

Kovács, Zucker & Mazeh (2002)



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At each step, fit for
F_0, *depth* and
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See also Aigrain & Irwin (2004), Collier Cameron et al. (2006) and others

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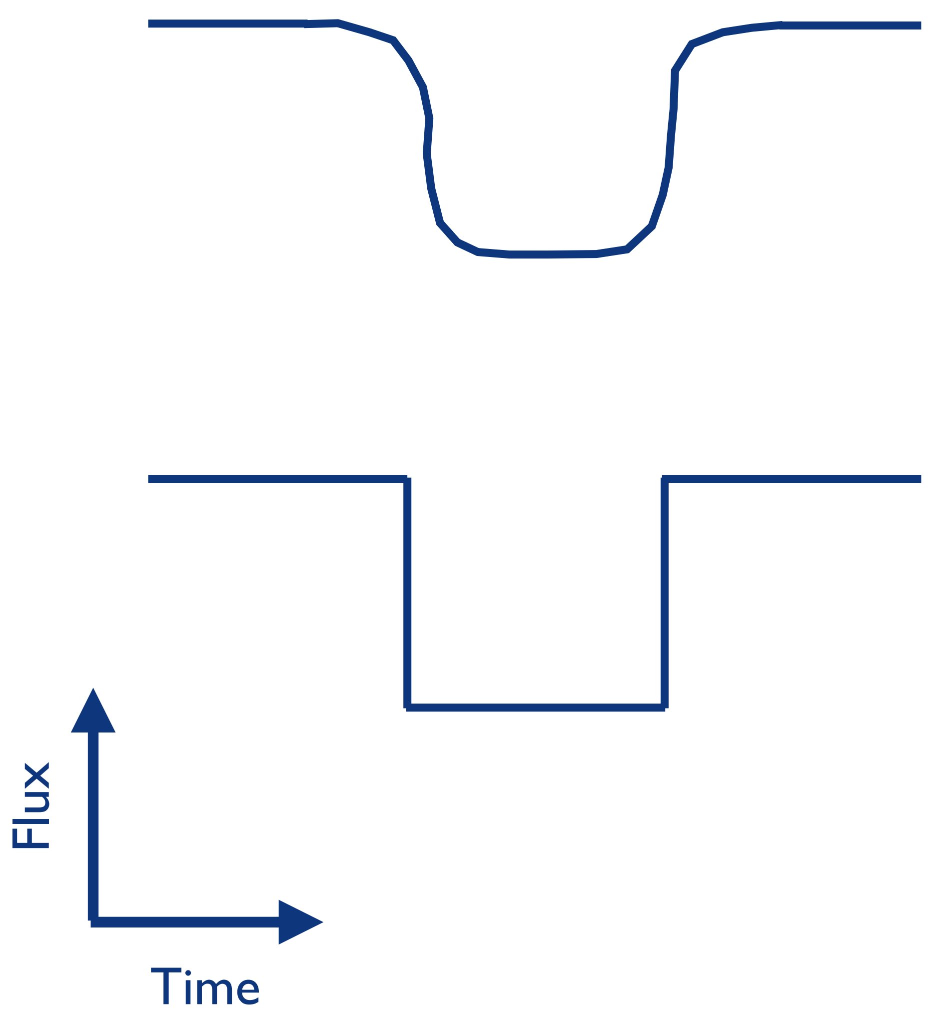

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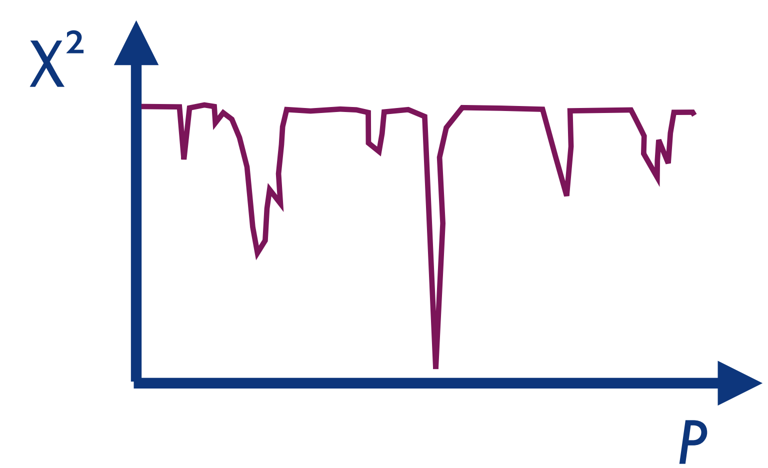


See also Aigrain & Irwin (2004), Collier Cameron et al. (2006) and others

Example of a BLS: SuperWASP candidate

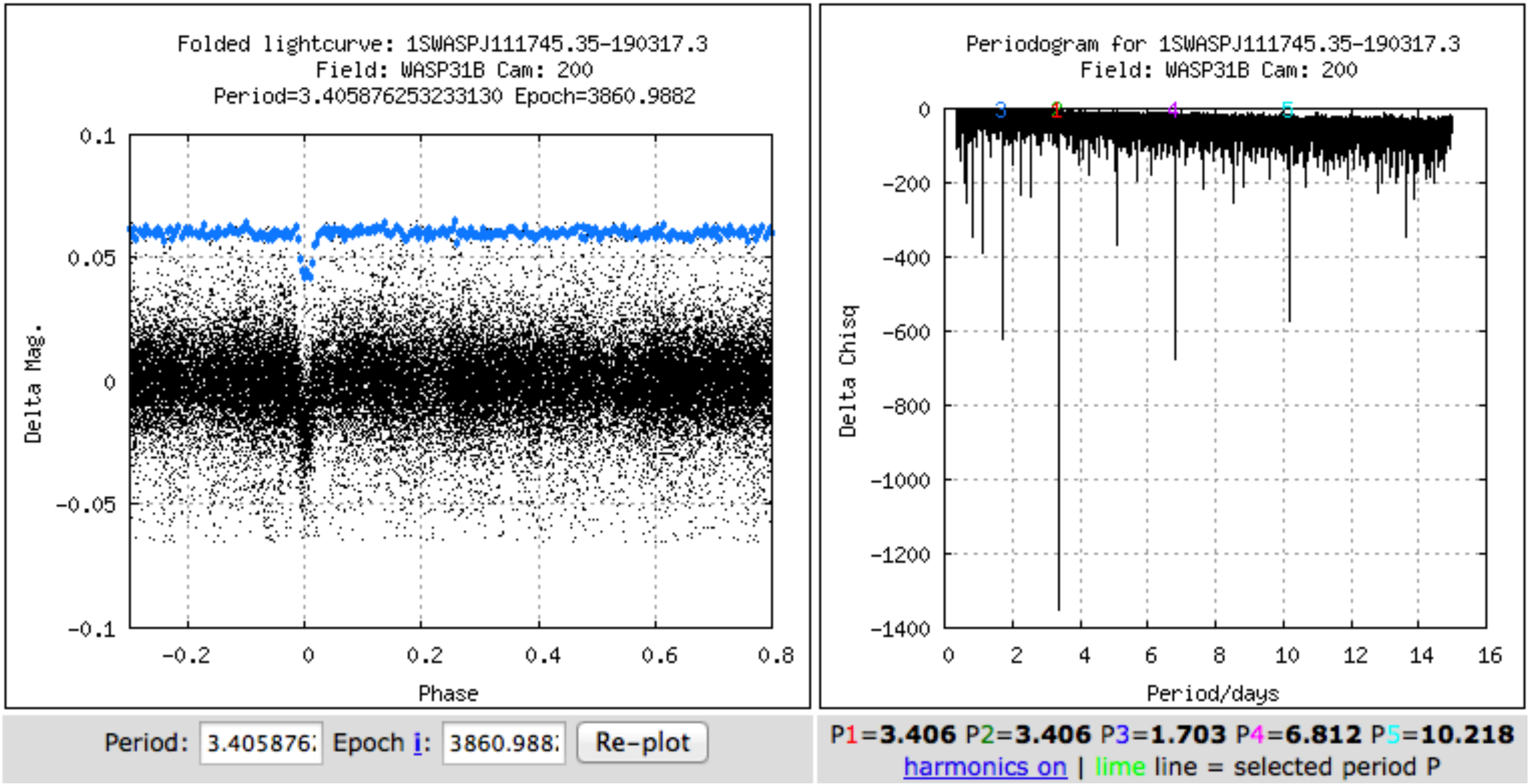
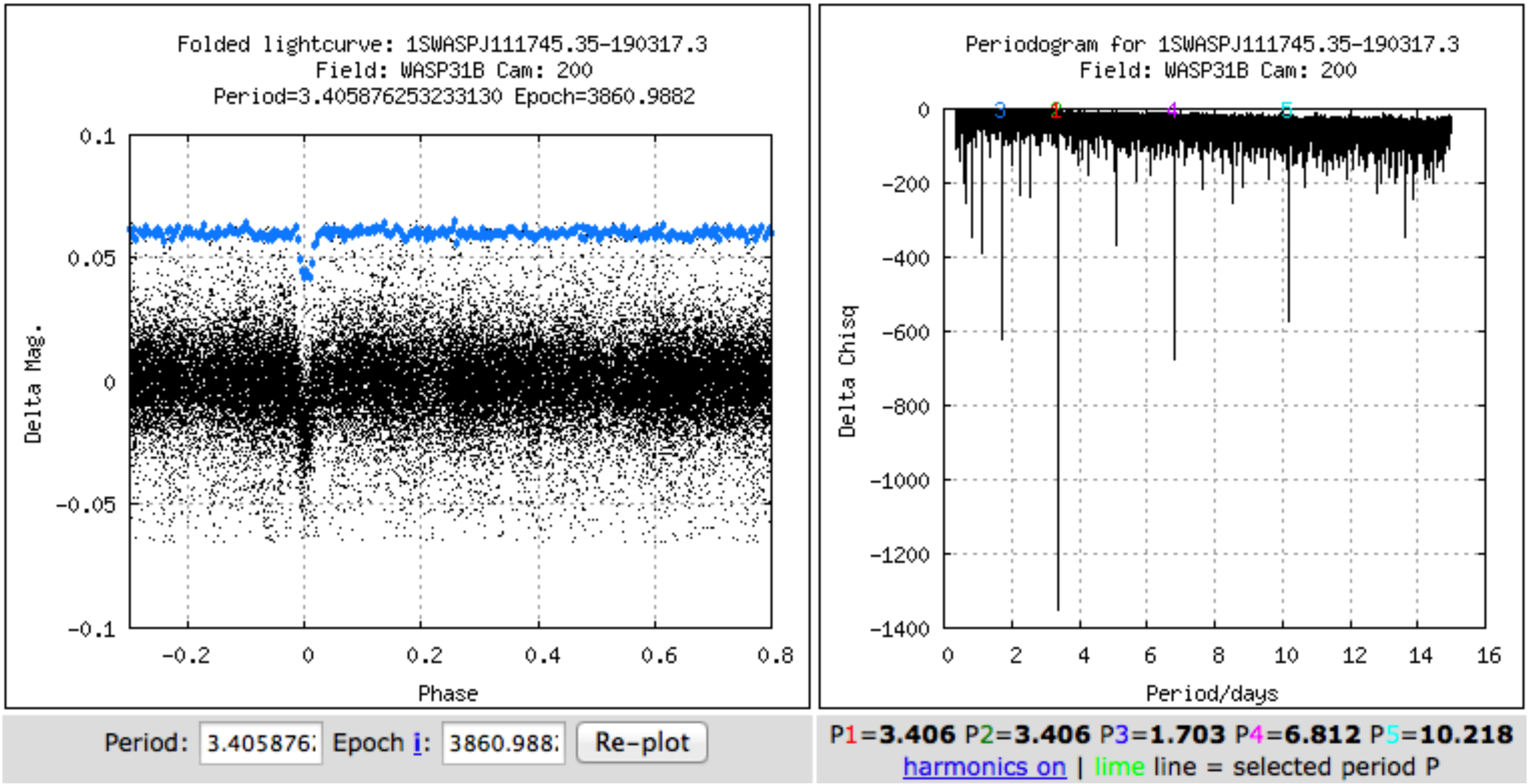


Figure credit: A. Collier Cameron

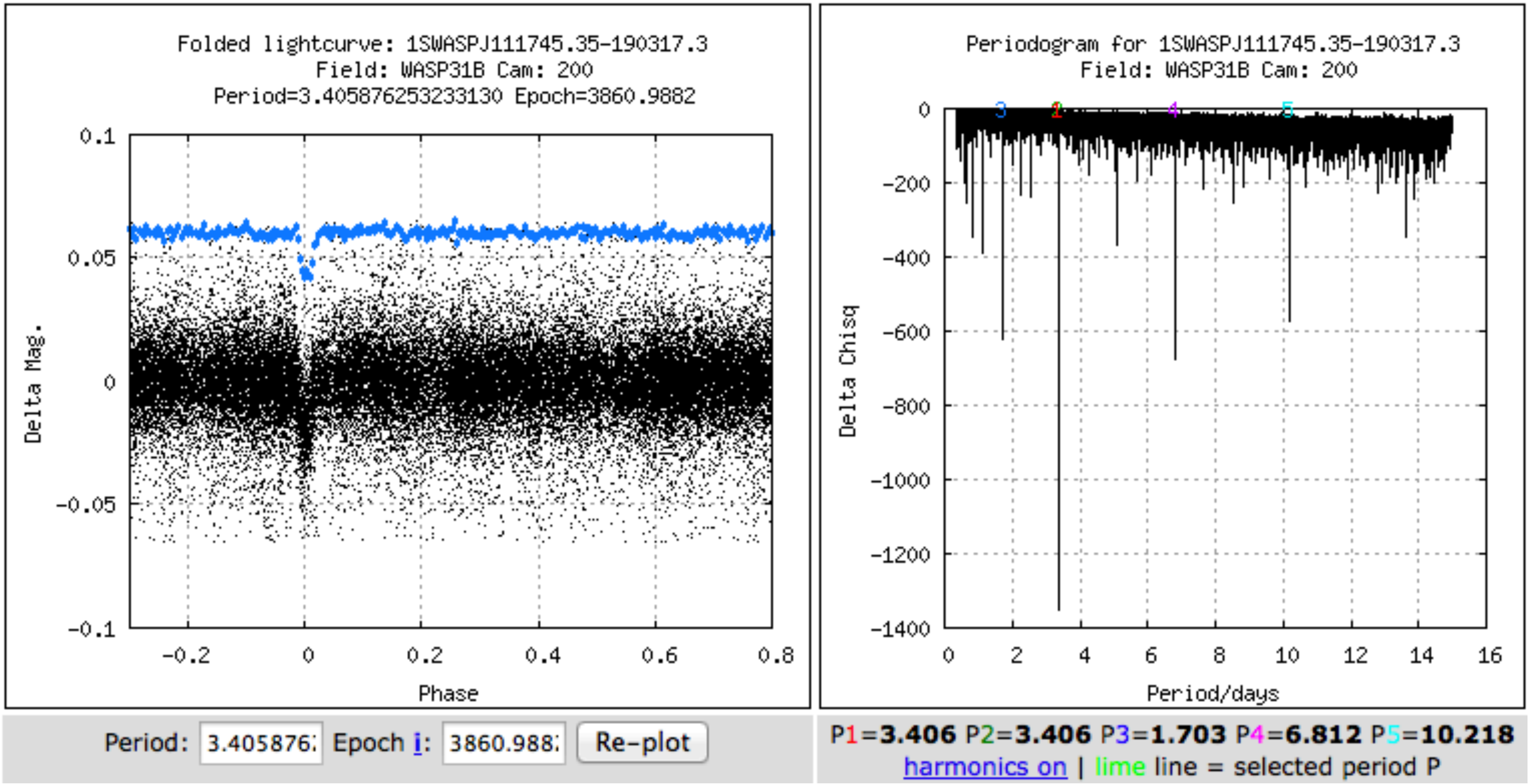
Example of a BLS: SuperWASP candidate



BLS works on sparse and unevenly sampled data.

Figure credit: A. Collier Cameron

Example of a BLS: SuperWASP candidate



BLS works on sparse and unevenly sampled data.
Beware of window-function effects — often the true signal is the *n*-th strongest peak.

Figure credit: A. Collier Cameron

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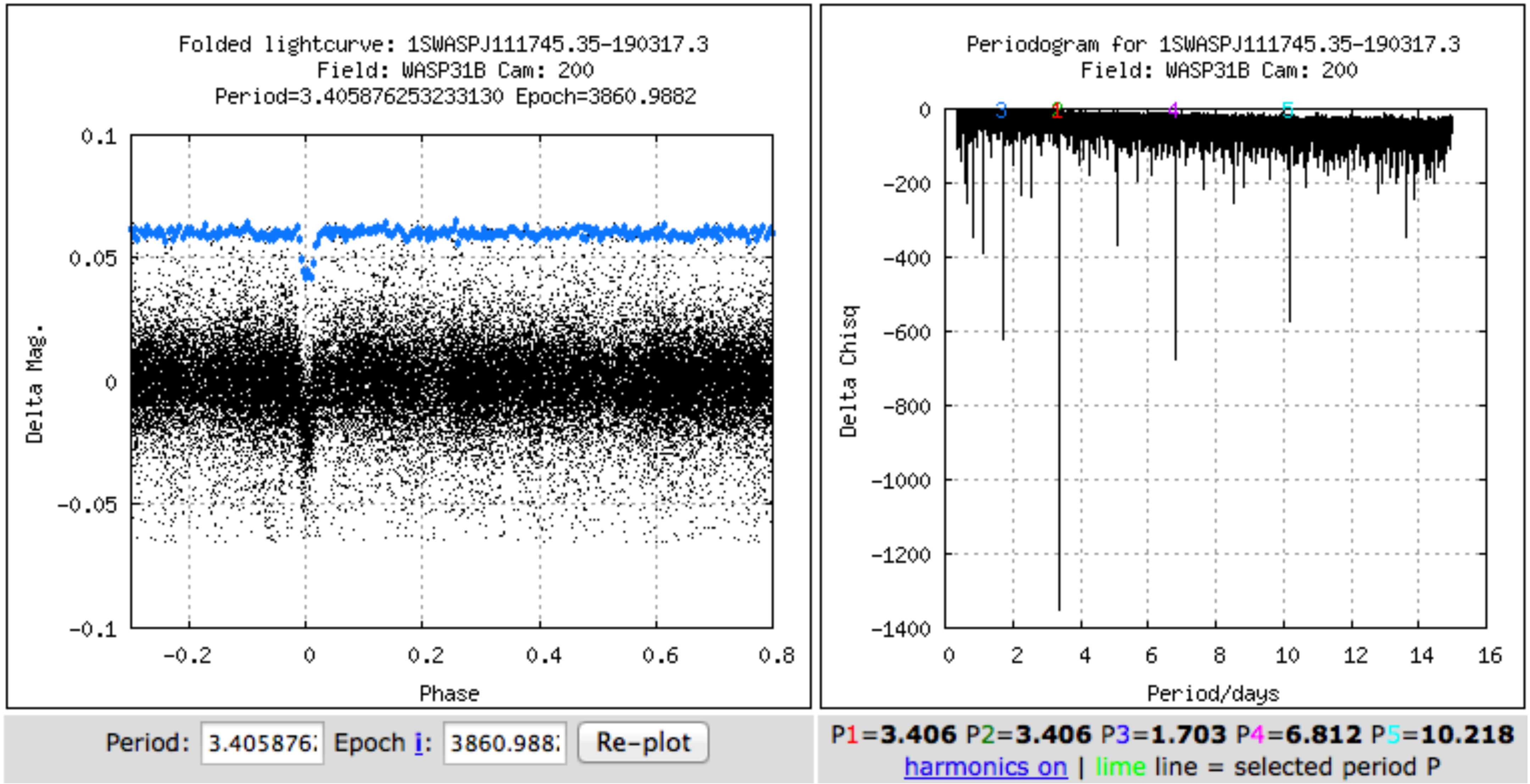


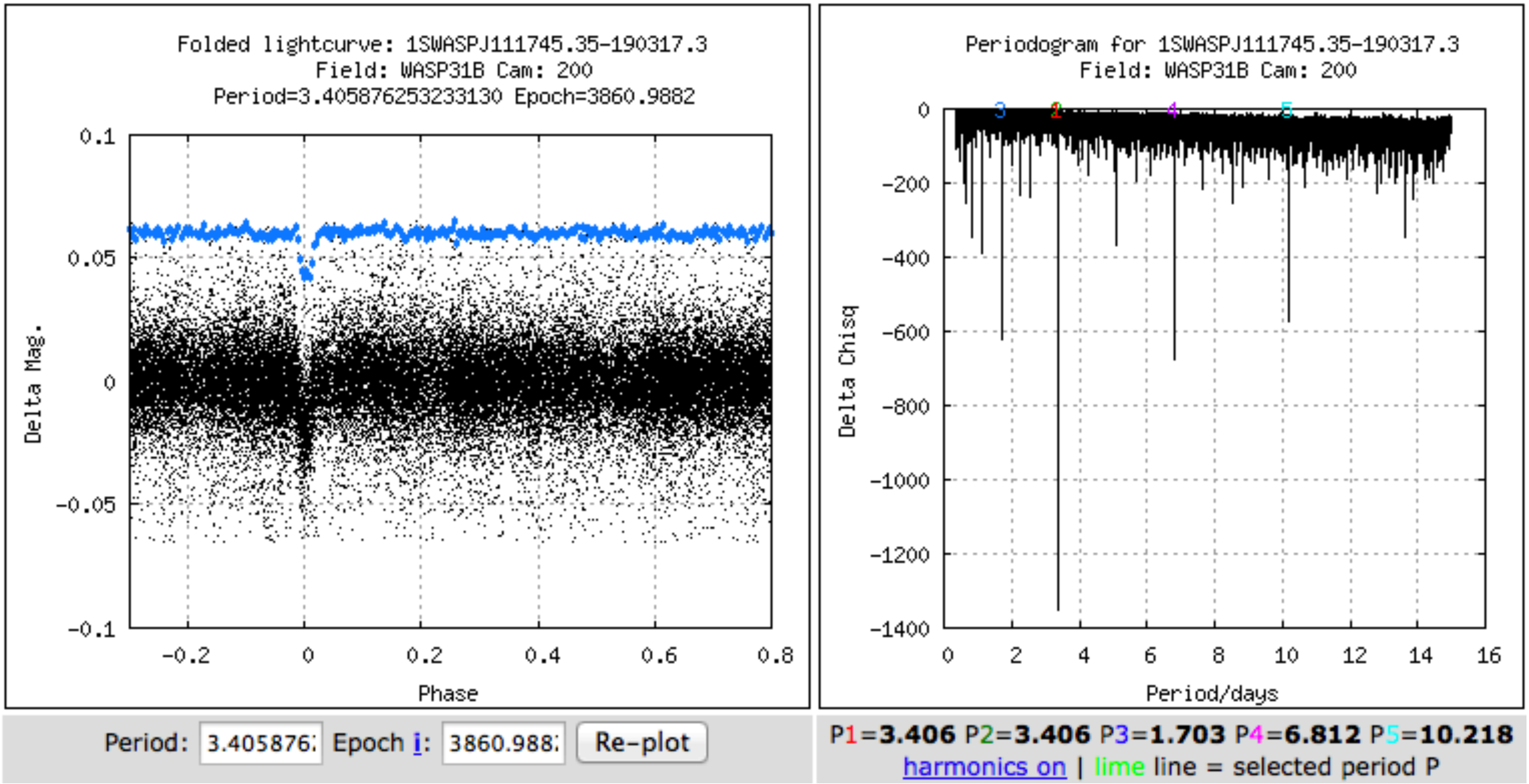
BLS works on sparse and unevenly sampled data.

Beware of window-function effects — often the true signal is the *n*-th strongest peak.

Does not account for correlated noise.

Figure credit: A. Collier Cameron

Example of a BLS: SuperWASP candidate



BLS works on sparse and unevenly sampled data.
Beware of window-function effects — often the true signal is the *n*-th strongest peak.
Does not account for correlated noise.

There are other techniques for transit detection, *eg.* the Transiting Planet Search (TPS, Jenkins 2002), Trend Filtering Analysis (TFA, Kovàcs et al. 2005), Schwarzenberg-Czerny (1989, 1996), *etc.*

Figure credit: A. Collier Cameron

Single transit searches

Single transit searches

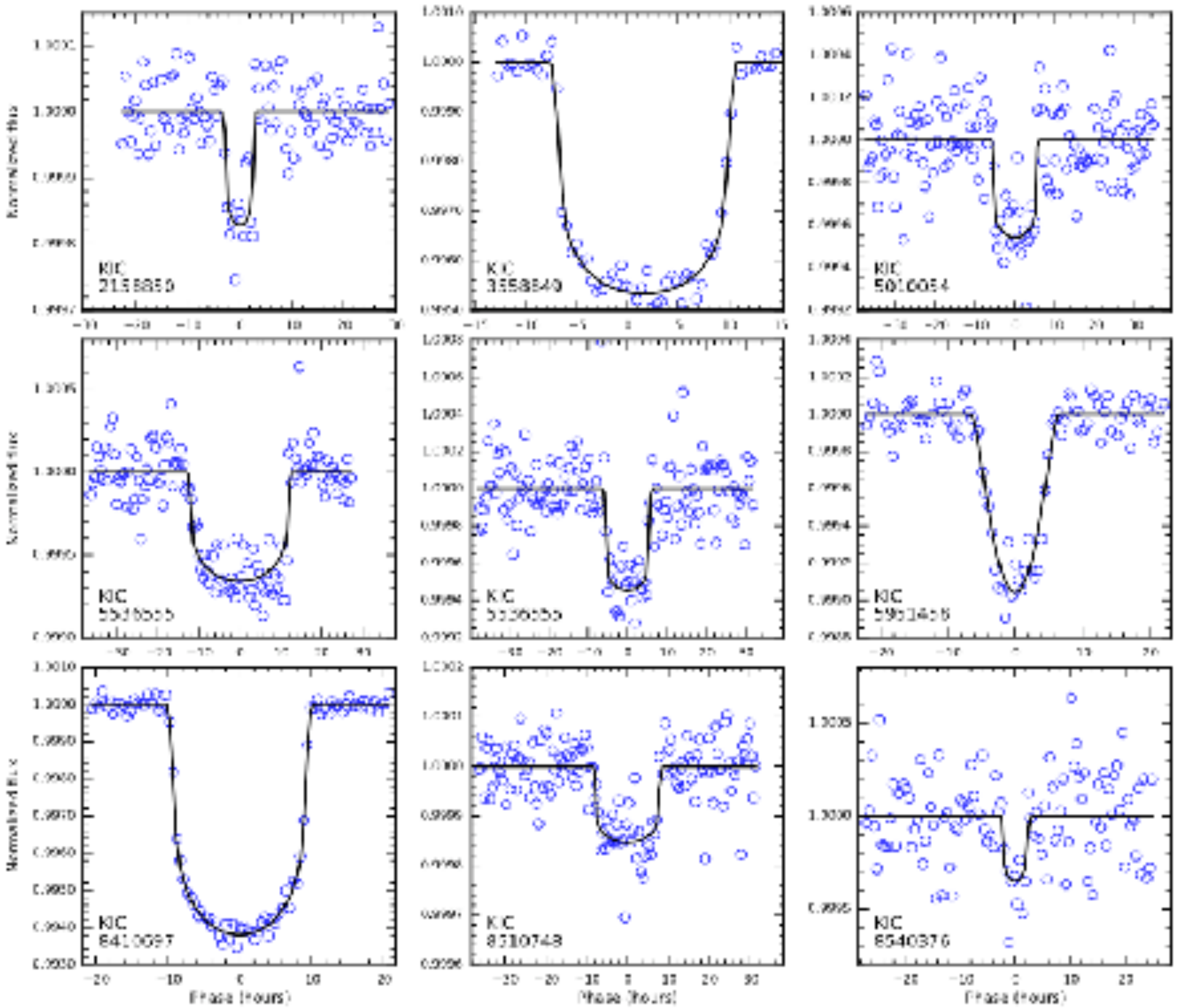
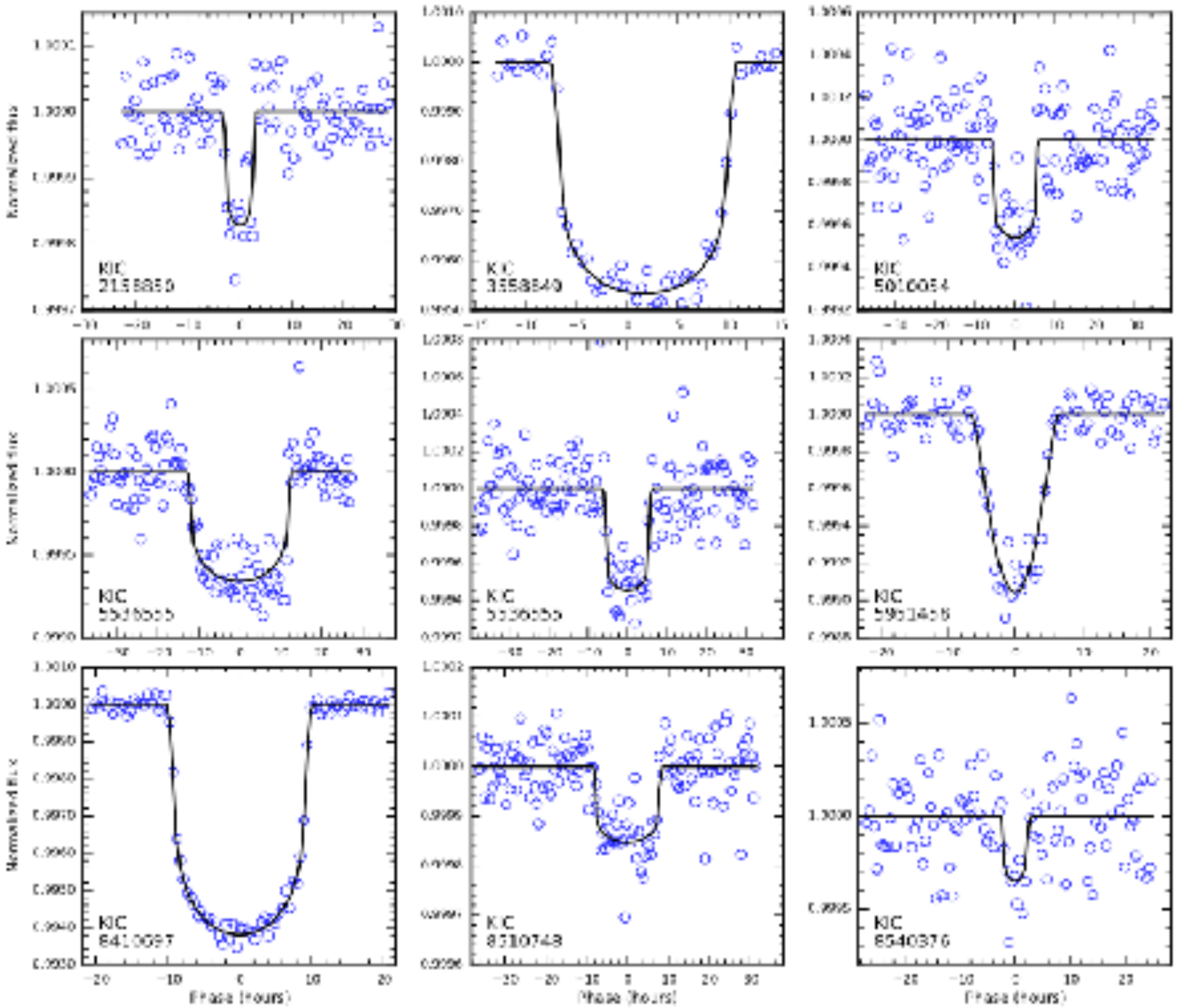


Figure from Wang et al. (2015)

PlanetHunters (Kepler) Wang et al. (2015), **MEarth** Dittmann et al. (2017), **TRAPPIST** Gillon et al. (2017)
See also Yee & Gaudi (2008), Uehara et al. (2016), Foreman-Mackey et al. (2016), Schmitt et al. (2017)

Single transit searches



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Detected by human eyeballing (eg. PlanetHunters), machine learning (see Dittmann et al. 2017, Foreman-Mackey et al. 2016)

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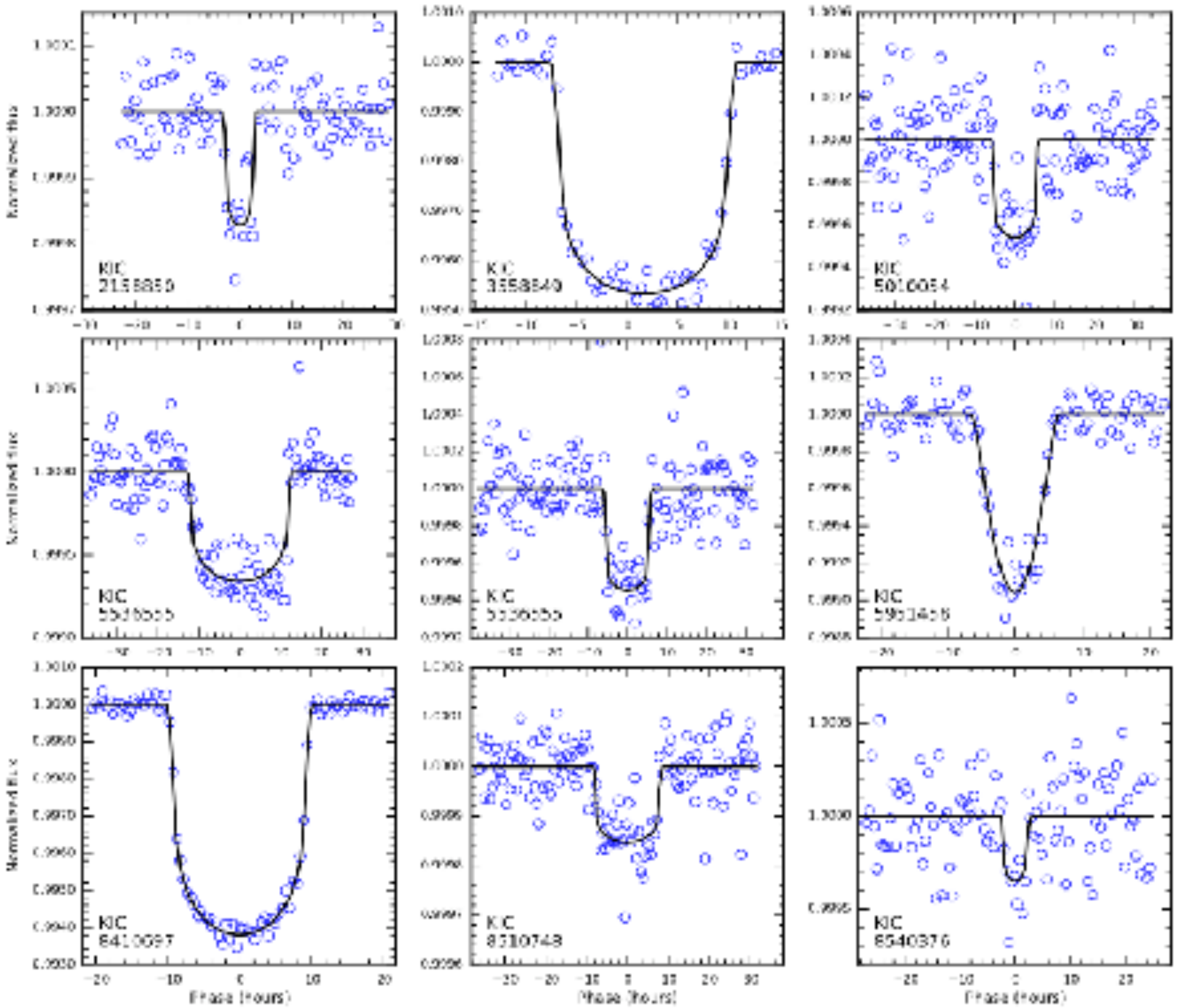

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Detected by human eyeballing (eg. PlanetHunters), machine learning (see Dittmann et al. 2017, Foreman-Mackey et al. 2016)

⇒ **Find the period with RVs or more photometry**

PlanetHunters (Kepler) Wang et al. (2015), MEarth Dittmann et al. (2017), TRAPPIST Gillon et al. (2017)
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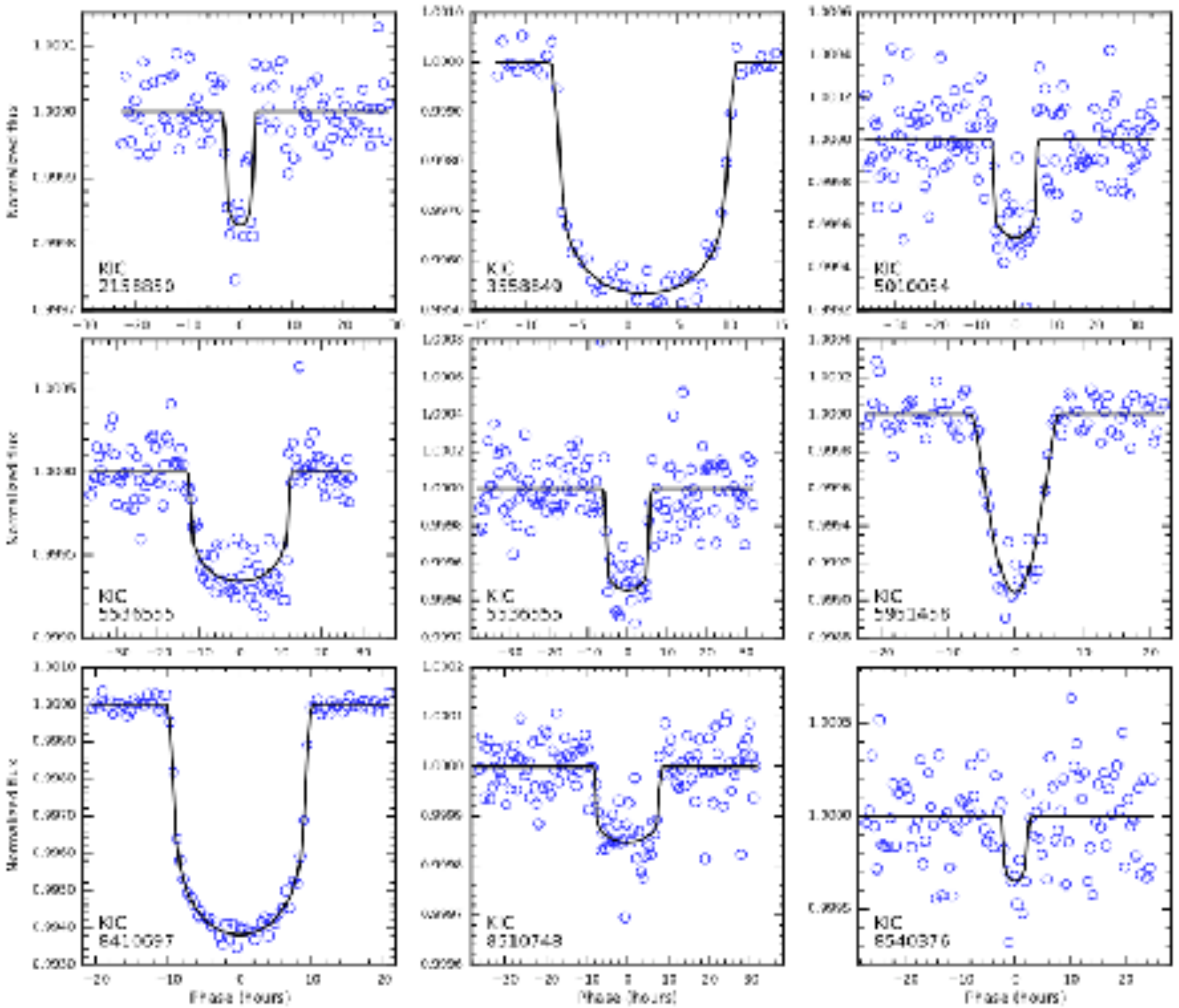
Single transit searches



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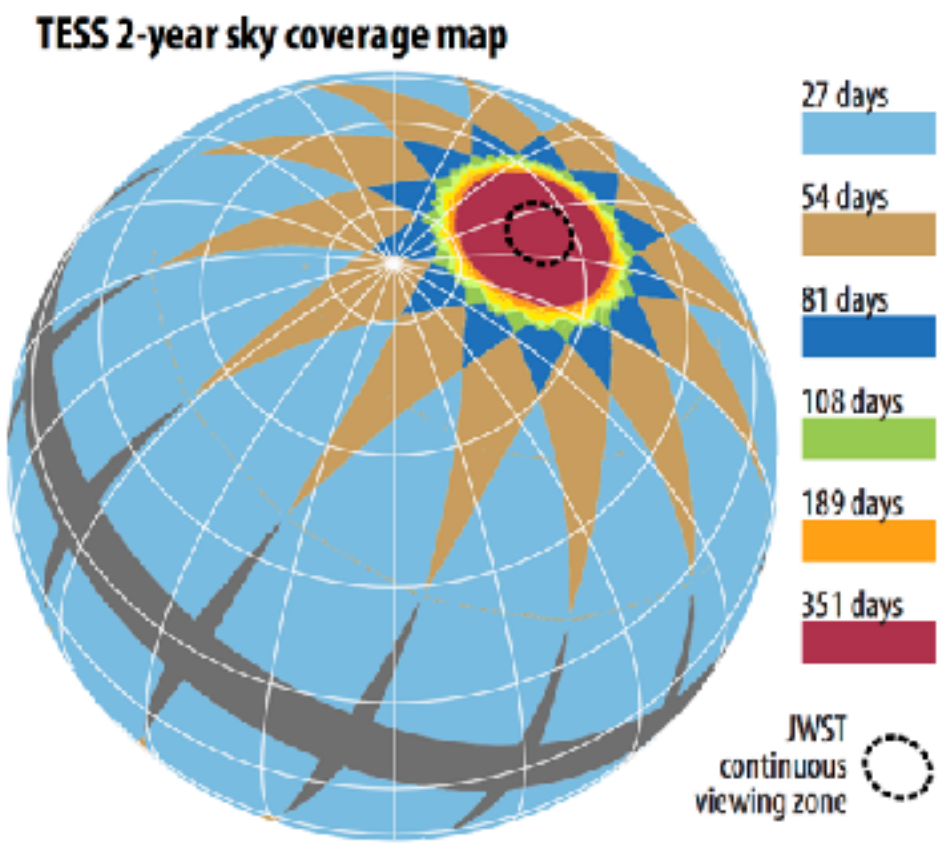

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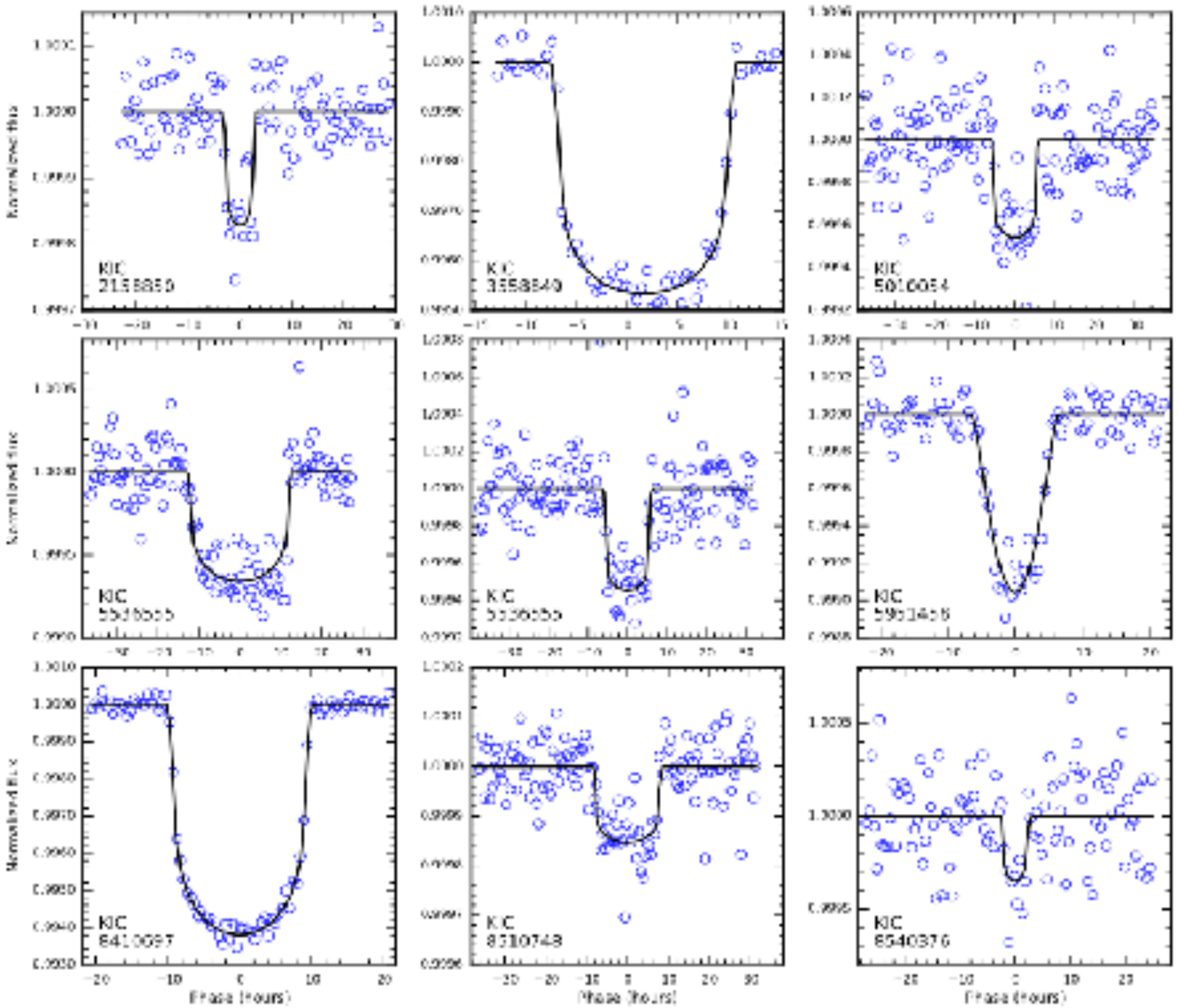
Single transit searches



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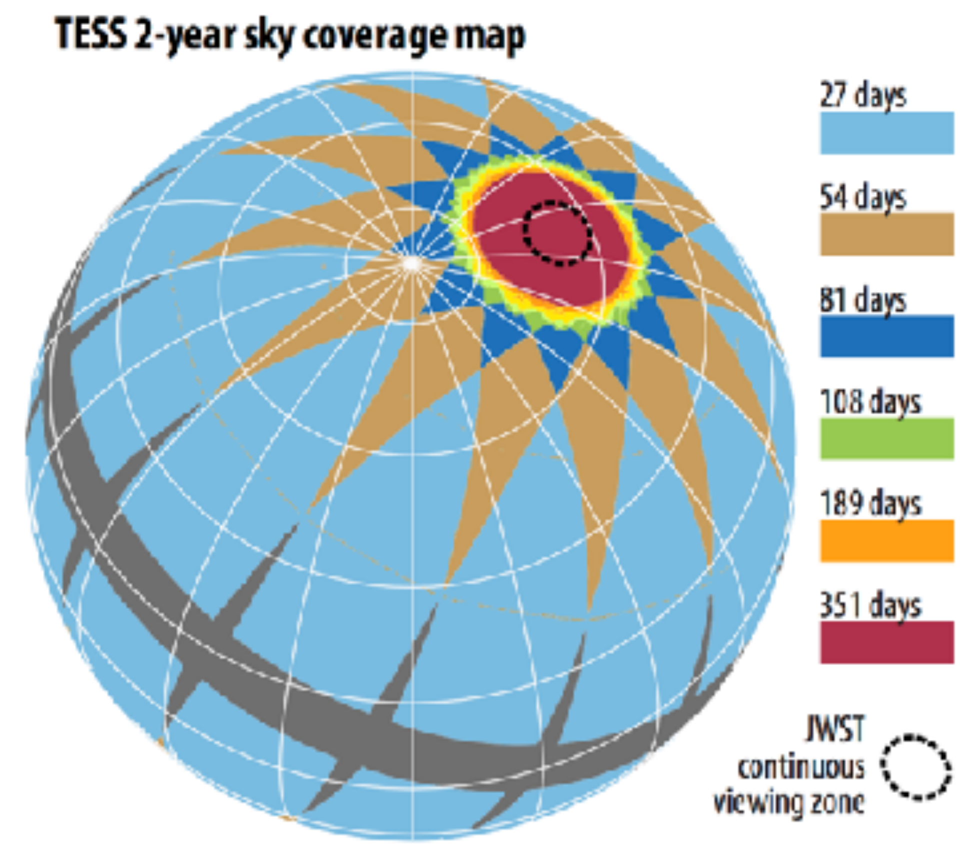

"… the number of planets detected by TESS […]
with P > 25 days will be doubled […]
with P > 250 days will be increased by an order or magnitude"

Villanueva, Dragomir & Gaudi (submitted to AAS Journals)

Detected by human eyeballing (eg. PlanetHunters), machine learning (see Dittmann et al. 2017, Foreman-Mackey et al. 2016)

⇒ **Find the period with RVs or more photometry**

PlanetHunters (Kepler) Wang et al. (2015), MEarth Dittmann et al. (2017), TRAPPIST Gillon et al. (2017)
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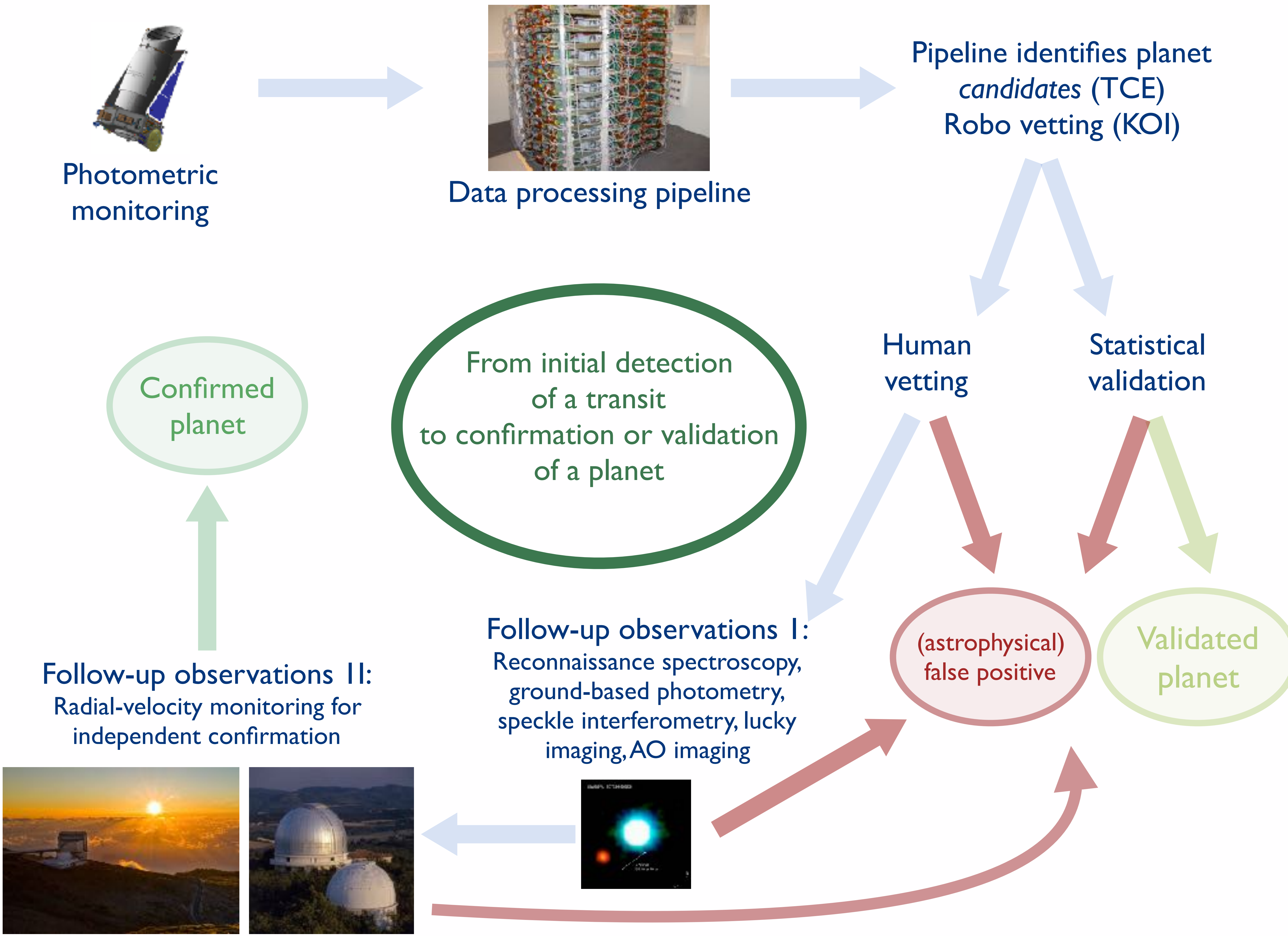
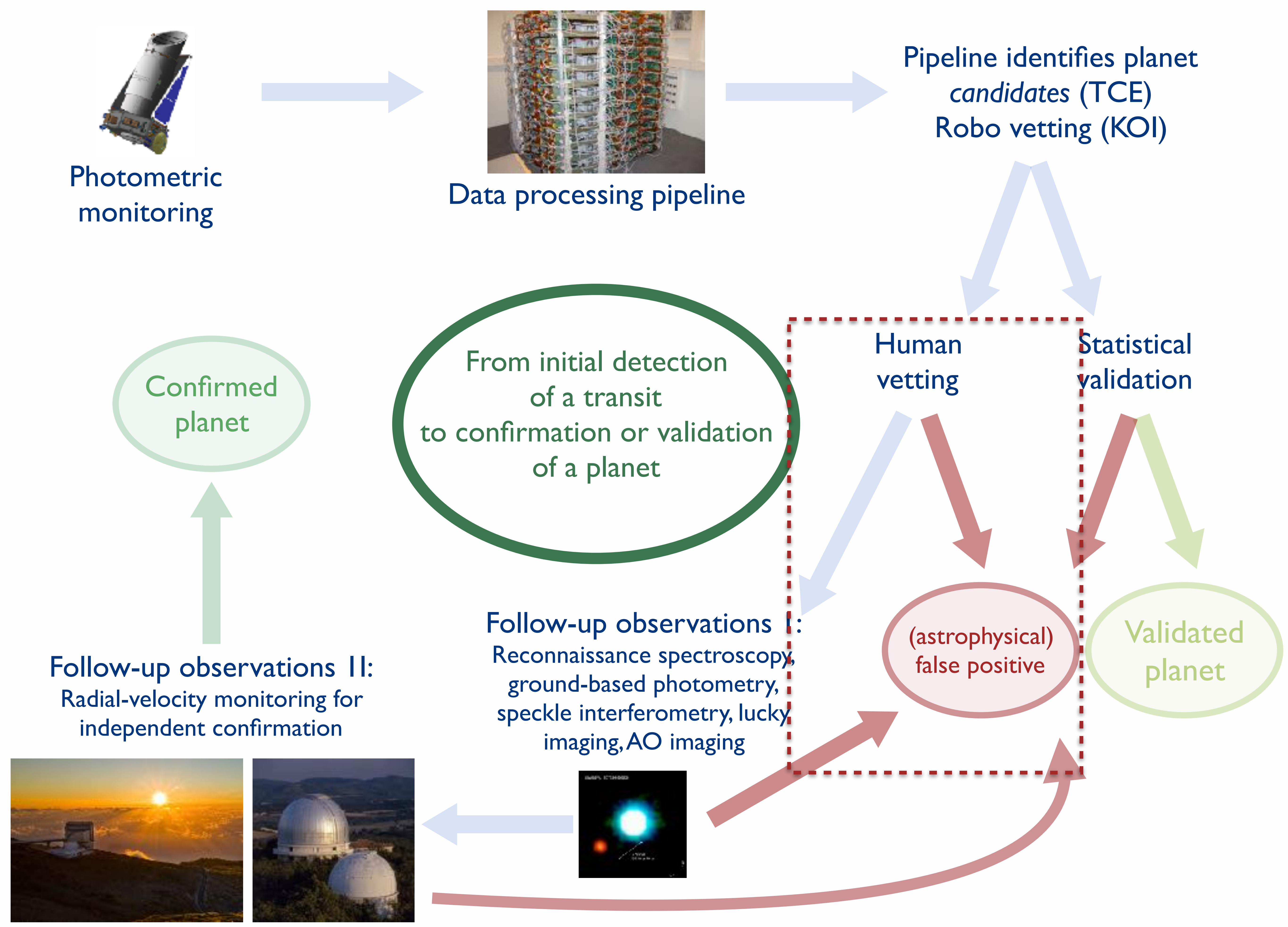

Photometric monitoring
Data processing pipeline
Pipeline identifies planet *candidates* (TCE)
Robo vetting (KOI)
Human vetting
Statistical validation
From initial detection of a transit to confirmation or validation of a planet
Confirmed planet
(astrophysical) false positive
Validated planet
Follow-up observations I:
Reconnaissance spectroscopy, ground-based photometry, speckle interferometry, lucky imaging, AO imaging
Follow-up observations II:
Radial-velocity monitoring for independent confirmation



Photometric monitoring
Data processing pipeline
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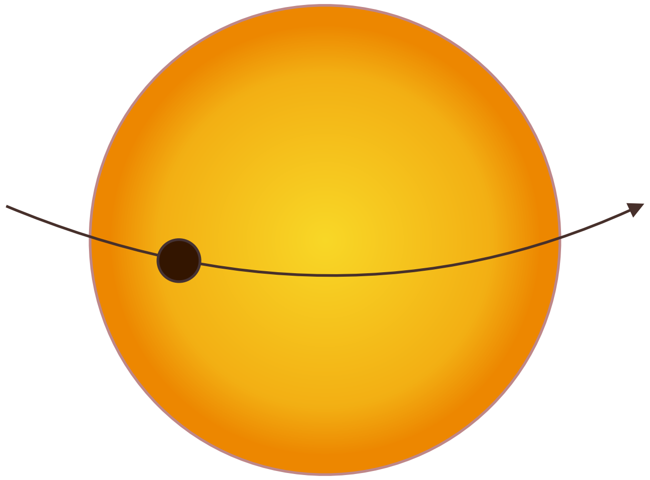
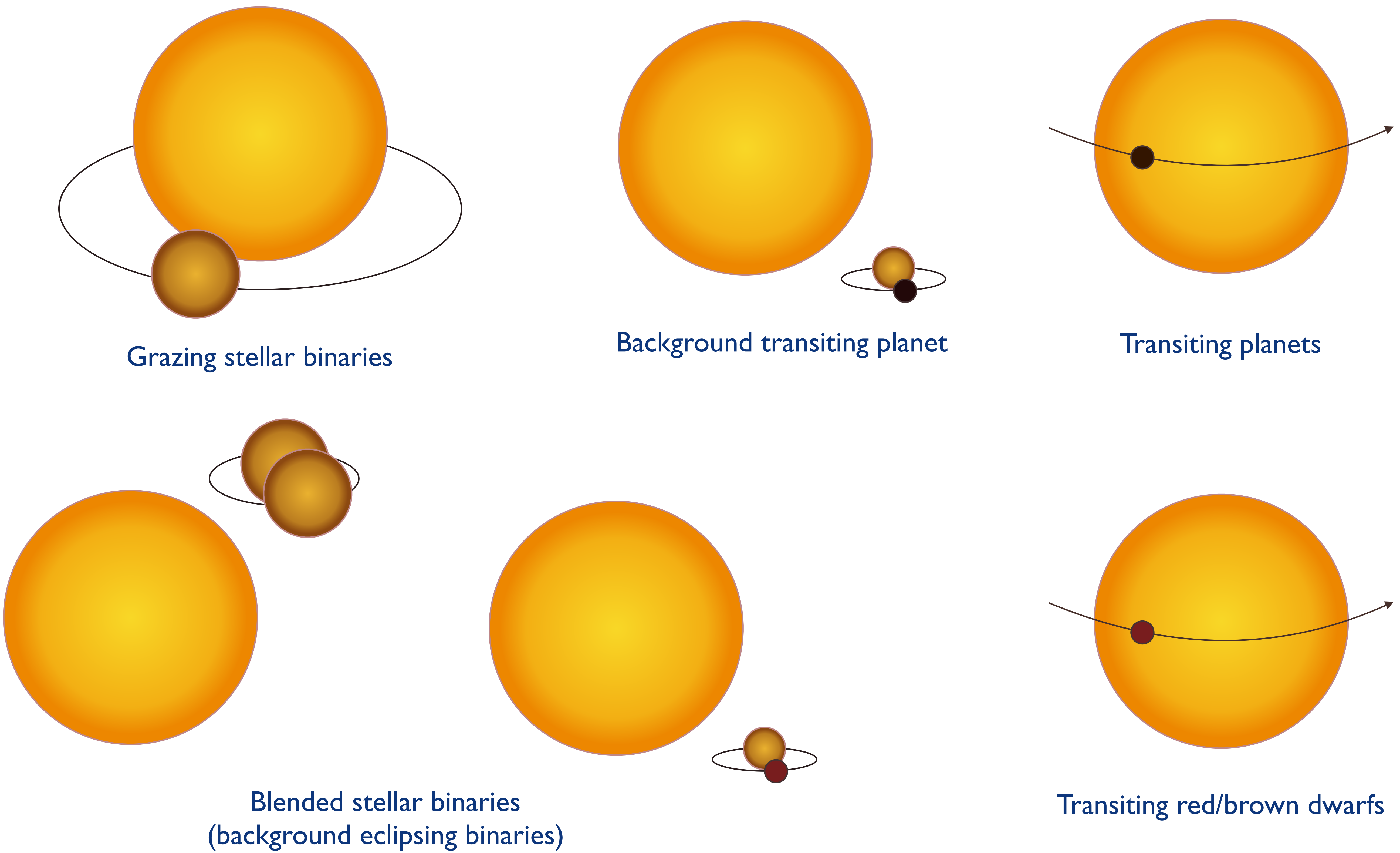
Astrophysical scenarios that create transits



Transiting planets

Morton et al. 2011, 2012; Santerne et al., 2012,2013; Latham et al. 2009;
Collier Cameron et al. 2007; Pont et al. 2005 and others

Astrophysical scenarios that create transits (astrophysical false positives)



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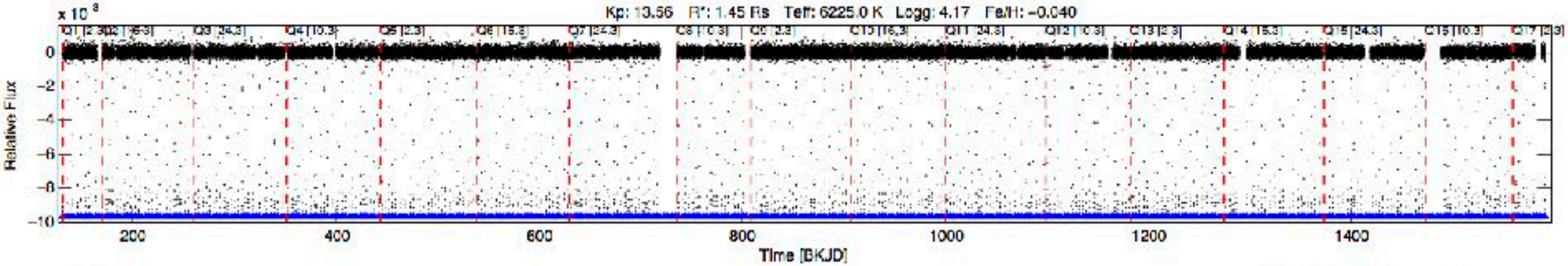
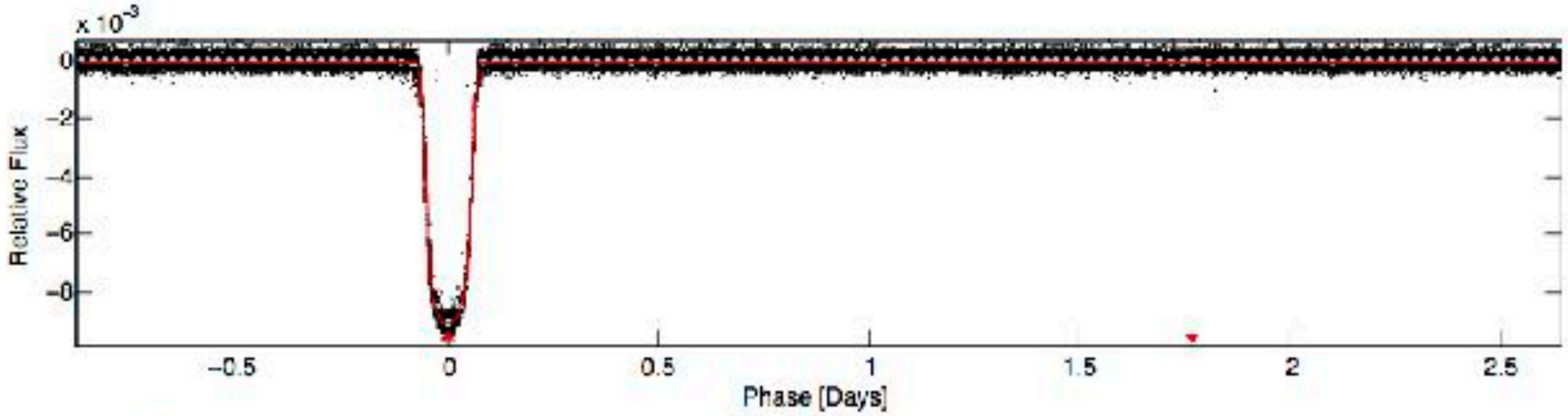
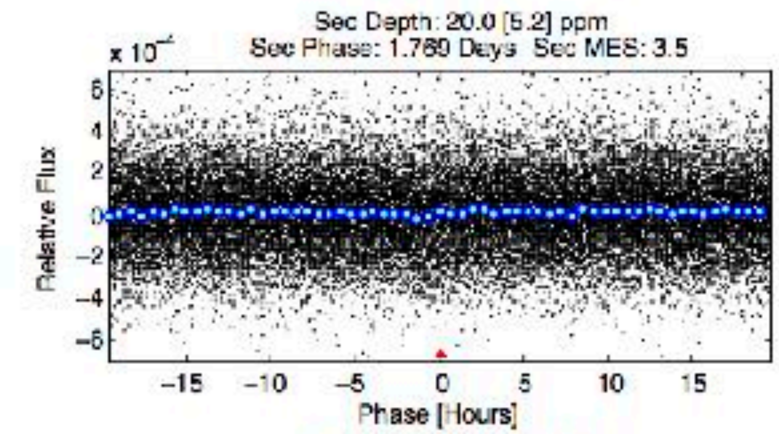
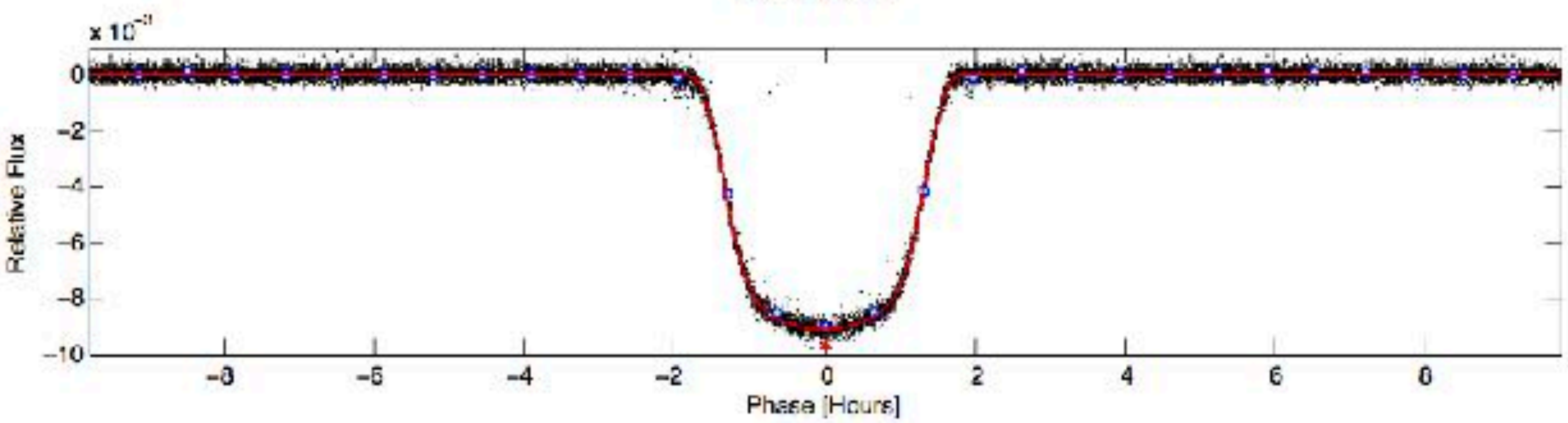
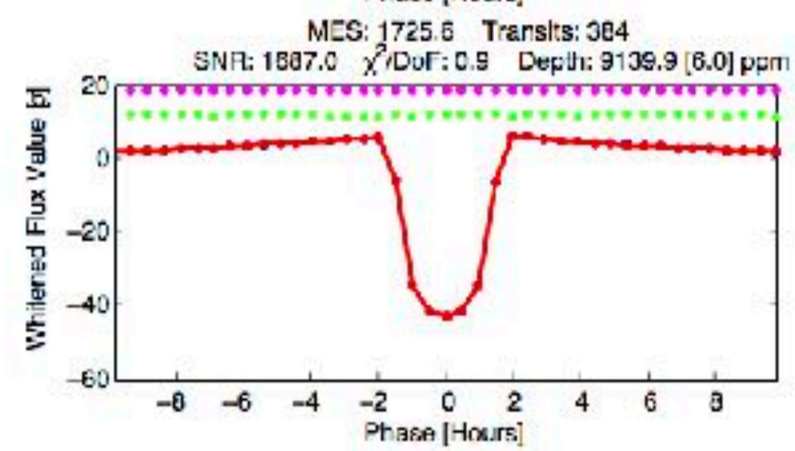
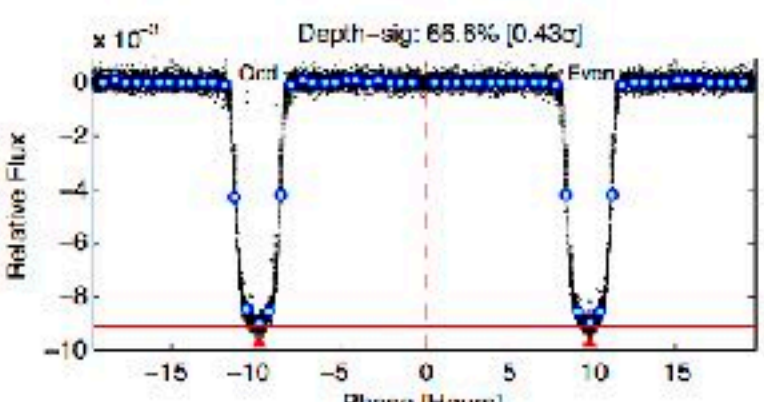


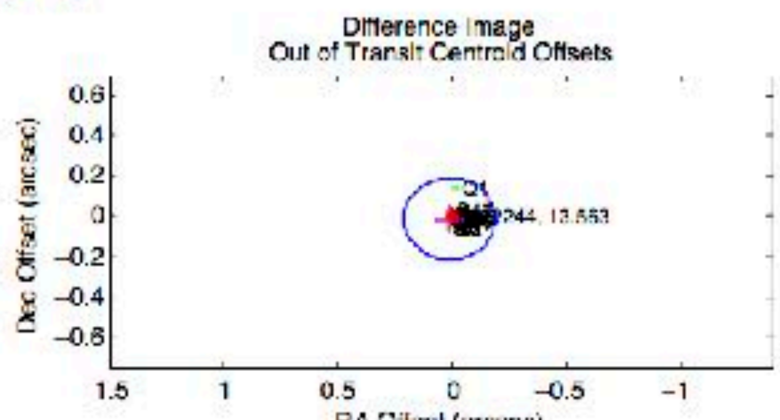












DV Fit Results:

Period = 3.52250 [0.00000] d
Epoch = 131.6870 [0.0000] BKJD
Rp/R* = 0.0941 [0.0001]
a/R* = 6.93 [0.03]
b = 0.71 [0.00]

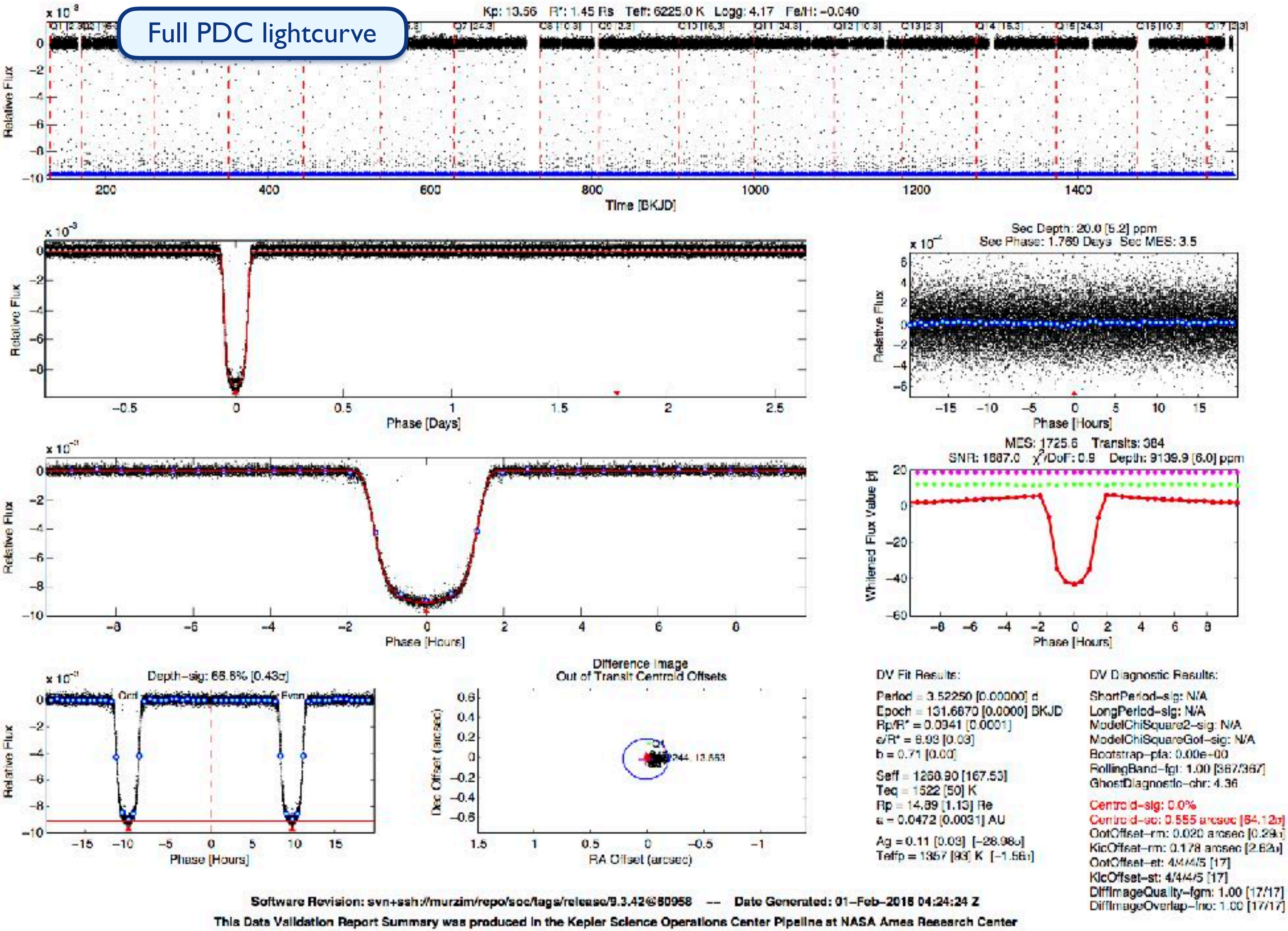
Seff = 1260.90 [167.53]
Teq = 1522 [50] K
Rp = 14.89 [1.13] Re
a = 0.0472 [0.0031] AU

Ag = 0.11 [0.03] [-28.98σ]
Teffp = 1357 [93] K [-1.56σ]

DV Diagnostic Results:

ShortPeriod-sig: N/A
LongPeriod-sig: N/A
ModelChiSquare2-sig: N/A
ModelChiSquareGof-sig: N/A
Bootstrap-pfa: 0.00e+00
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36

Centroid-sig: 0.0%
Centroid-so: 0.555 arcsec [64.12σ]
OotOffset-rm: 0.020 arcsec [0.29σ]
KicOffset-rm: 0.178 arcsec [2.62σ]
OotOffset-st: 4/4/4/5 [17]
KicOffset-st: 4/4/4/5 [17]
DiffImageQuality-fgm: 1.00 [17/17]
DiffImageOverlap-fno: 1.00 [17/17]


Full PDC lightcurve
Kp: 13.56   R*: 1.45 Rs   Teff: 6225.0 K   Logg: 4.17   Fe/H: -0.040
Relative Flux
Time [BKJD]
Phase [Days]
Phase [Hours]
Sec Depth: 20.0 [5.2] ppm
Sec Phase: 1.769 Days   Sec MES: 3.5
MES: 1725.6   Transits: 384
SNR: 1887.0 χ^2/DoF: 0.9   Depth: 9139.9 [6.0] ppm
Whitened Flux Value [σ]
Depth-sig: 66.6% [0.43σ]
Odd
Even
Difference Image
Out of Transit Centroid Offsets
Dec Offset (arcsec)
RA Offset (arcsec)
DV Fit Results:
Period = 3.52250 [0.00000] d
Epoch = 131.6870 [0.0000] BKJD
Rp/R* = 0.0941 [0.0001]
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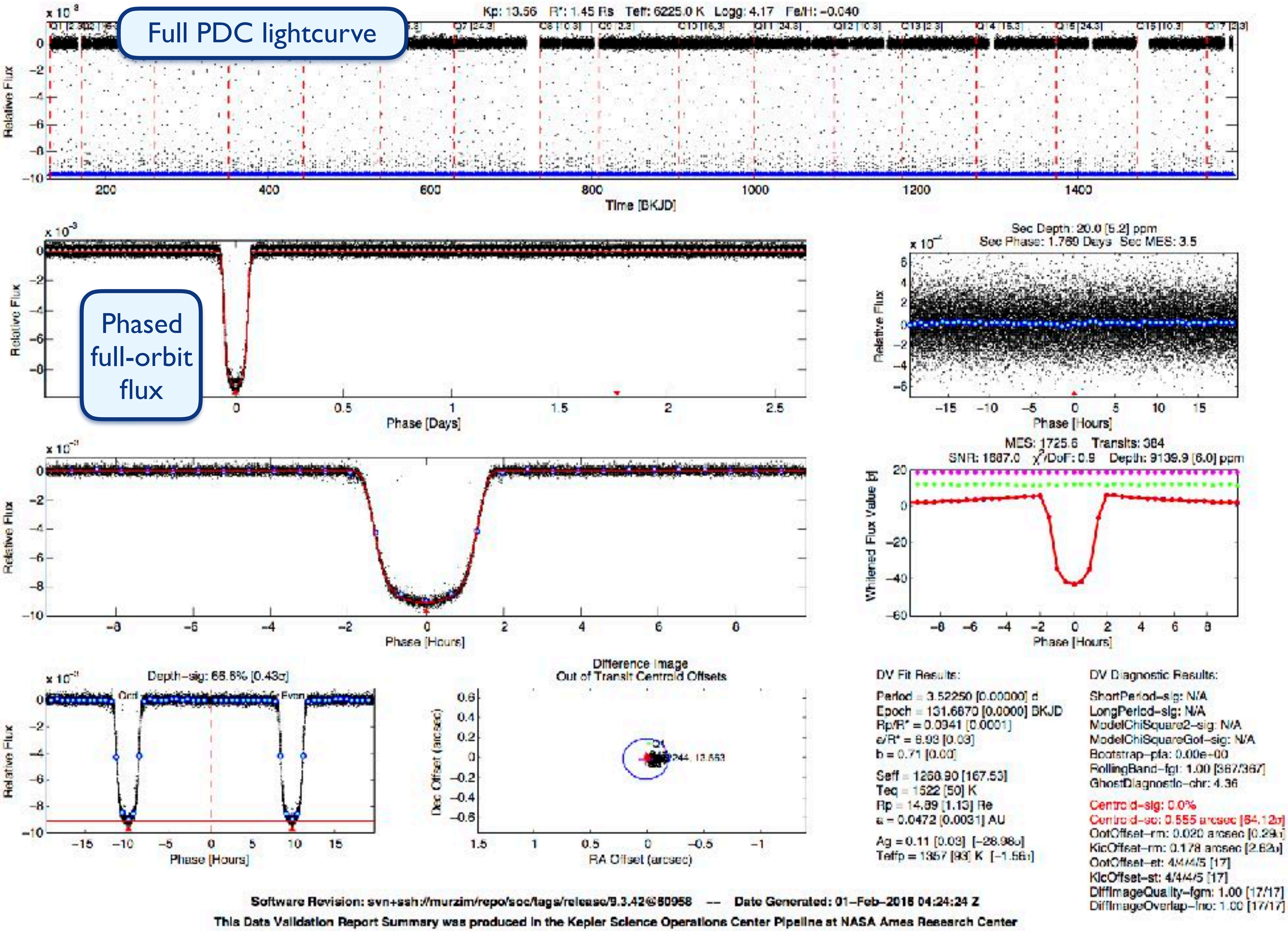
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36
Centroid-sig: 0.0%
Centroid-so: 0.555 arcsec [64.12σ]
OotOffset-rm: 0.020 arcsec [0.29σ]
KicOffset-rm: 0.178 arcsec [2.62σ]
OotOffset-st: 4/4/4/5 [17]
KicOffset-st: 4/4/4/5 [17]
DiffImageQuality-fgm: 1.00 [17/17]
DiffImageOverlap-fno: 1.00 [17/17]
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 01-Feb-2016 04:24:24 Z
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center


Full PDC lightcurve
Phased full-orbit flux
Kp: 13.56 R*: 1.45 Rs Teff: 6225.0 K Logg: 4.17 Fe/H: -0.040
Relative Flux
Time [BKJD]
Phase [Days]
Sec Depth: 20.0 [5.2] ppm
Sec Phase: 1.769 Days Sec MES: 3.5
Phase [Hours]
MES: 1725.6 Transits: 384
SNR: 1867.0 χ²/DoF: 0.9 Depth: 9139.9 [6.0] ppm
Whitened Flux Value [σ]
Depth-sig: 66.6% [0.43σ]
Odd
Even
Difference Image
Out of Transit Centroid Offsets
Dec Offset (arcsec)
RA Offset (arcsec)
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Bootstrap-pfa: 0.00e-00
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36
Centroid-sig: 0.0%
Centroid-so: 0.555 arcsec [54.12σ]
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KicOffset-rm: 0.178 arcsec [2.62σ]
OotOffset-st: 4/4/4/5 [17]
KicOffset-st: 4/4/4/5 [17]
DiffImageQuality-fgm: 1.00 [17/17]
DiffImageOverlap-lno: 1.00 [17/17]
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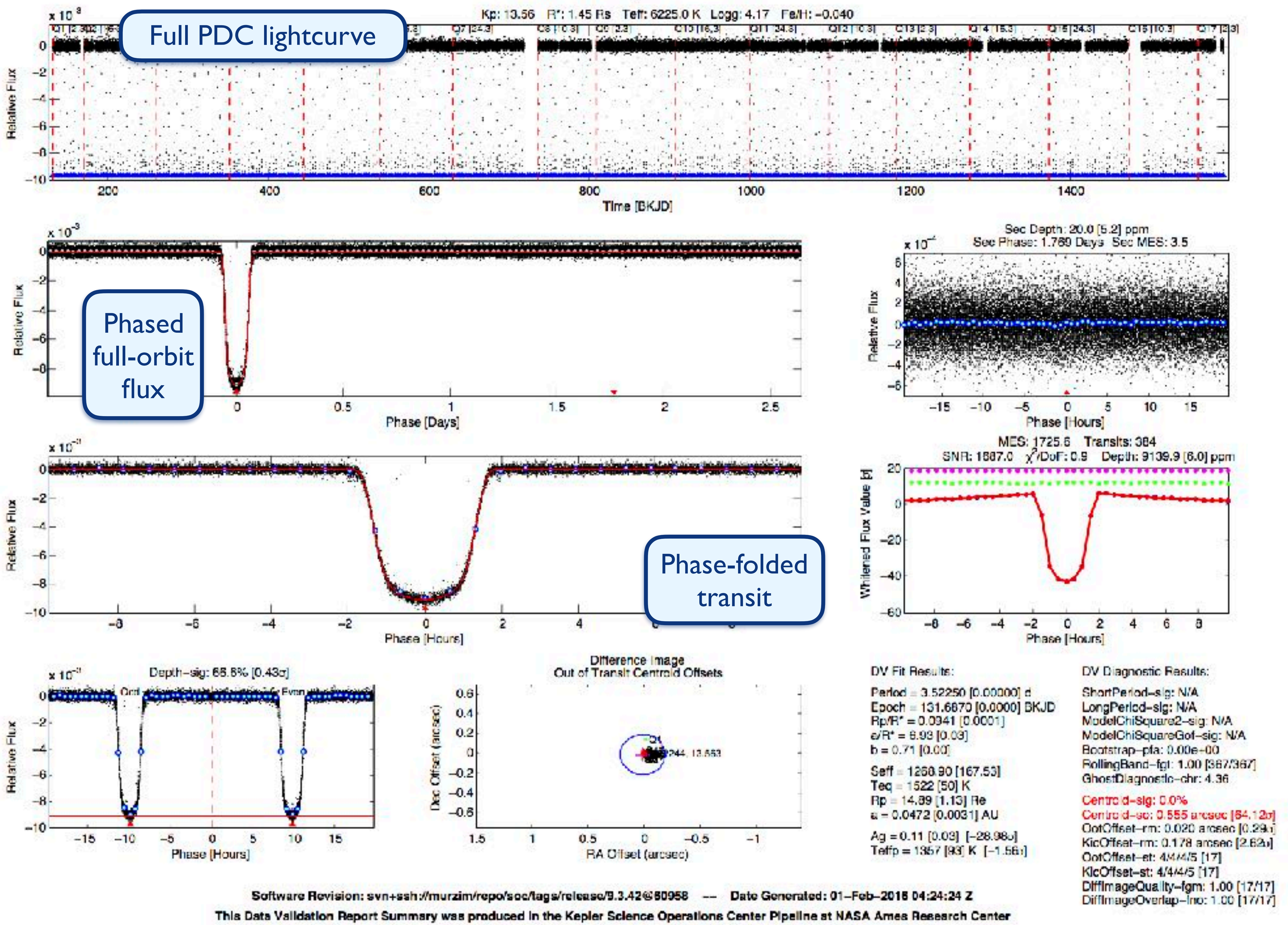

Full PDC lightcurve
Phased full-orbit flux
Phase-folded transit
Kp: 13.56 R*: 1.45 Rs Teff: 6225.0 K Logg: 4.17 Fe/H: -0.040
Relative Flux
Time [BKJD]
Phase [Days]
Sec Depth: 20.0 [5.2] ppm
Sec Phase: 1.769 Days Sec MES: 3.5
Phase [Hours]
MES: 1725.6 Transits: 384
SNR: 1887.0 χ²/DoF: 0.9 Depth: 9139.9 [6.0] ppm
Whitened Flux Value [σ]
Depth-sig: 66.6% [0.43σ]
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Dec Offset (arcsec)
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ShortPeriod-sig: N/A
LongPeriod-sig: N/A
ModelChiSquare2-sig: N/A
ModelChiSquareGof-sig: N/A
Bootstrap-pfa: 0.00e-00
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36
Centroid-sig: 0.0%
Centroid-so: 0.555 arcsec [84.12σ]
OotOffset-rm: 0.020 arcsec [0.29σ]
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OotOffset-st: 4/4/4/5 [17]
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DiffImageQuality-fgm: 1.00 [17/17]
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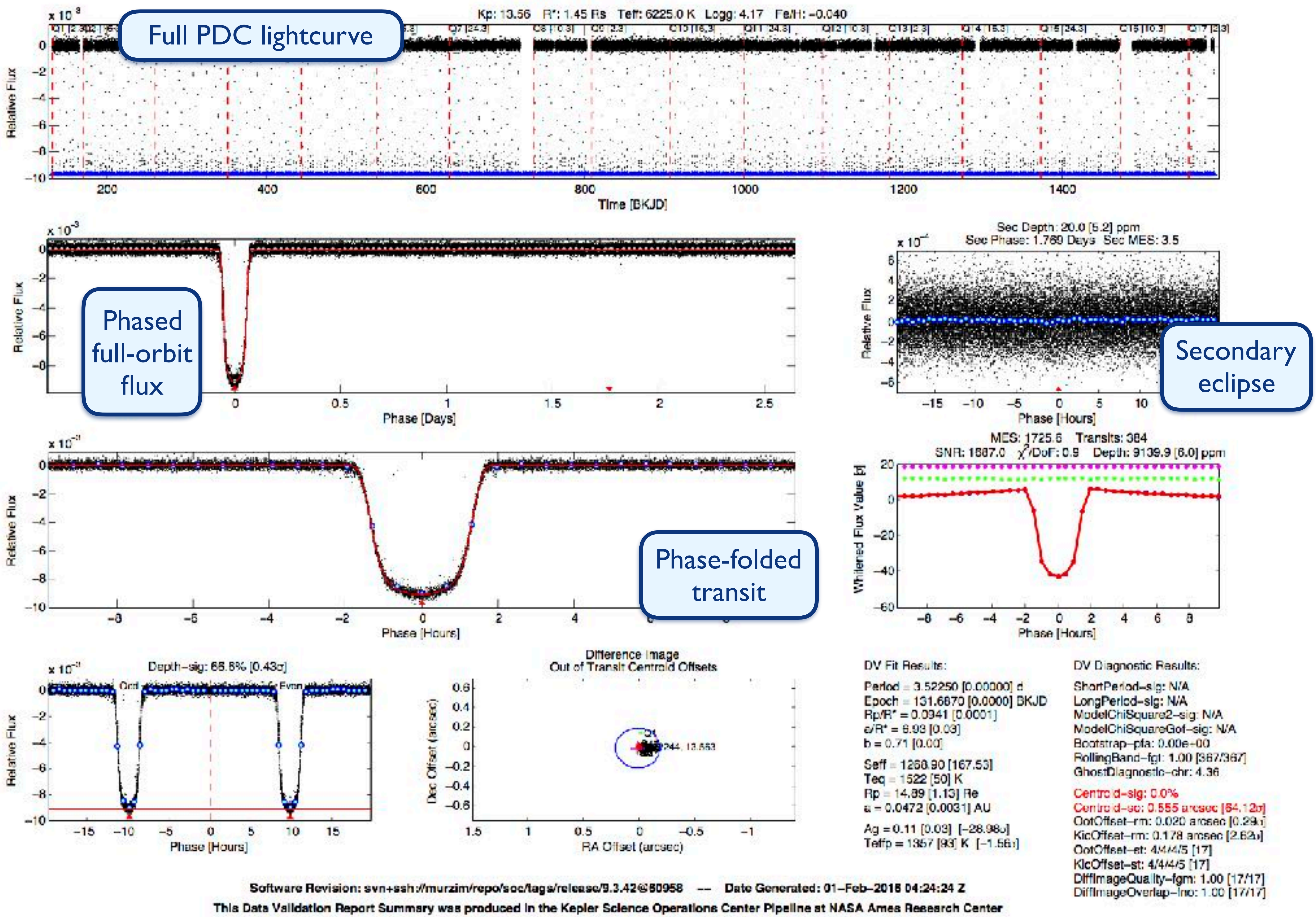

Full PDC lightcurve
Phased full-orbit flux
Secondary eclipse
Phase-folded transit
Kp: 13.56 R*: 1.45 Rs Teff: 6225.0 K Logg: 4.17 Fe/H: -0.040
Relative Flux
Time [BKJD]
Phase [Days]
Sec Depth: 20.0 [5.2] ppm
Sec Phase: 1.769 Days Sec MES: 3.5
Phase [Hours]
MES: 1725.6 Transits: 384
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ShortPeriod-sig: N/A
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Bootstrap-pfa: 0.00e+00
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36
Centroid-sig: 0.0%
Centroid-so: 0.555 arcsec [64.12σ]
OotOffset-rm: 0.020 arcsec [0.29σ]
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Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 01-Feb-2016 04:24:24 Z
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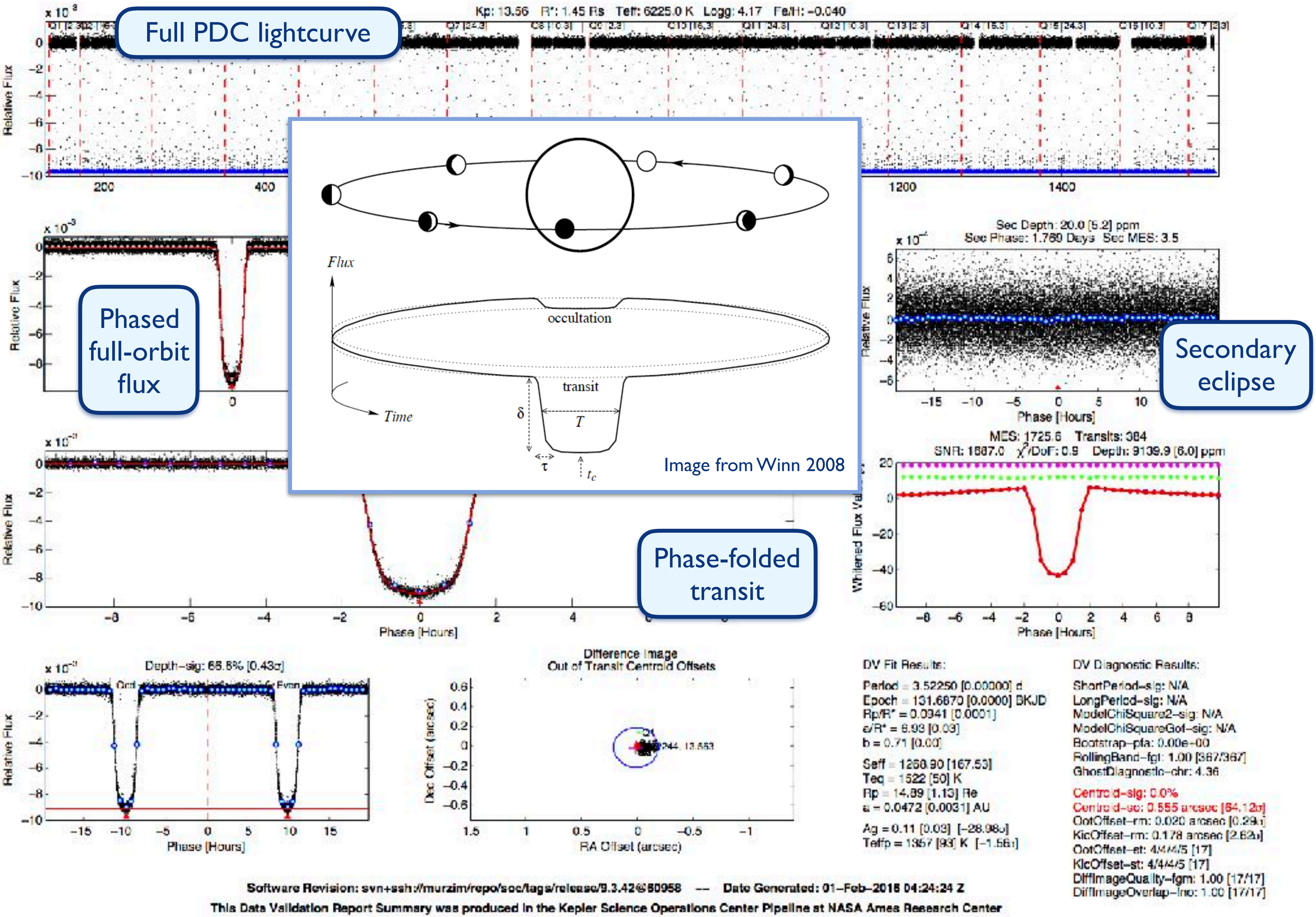
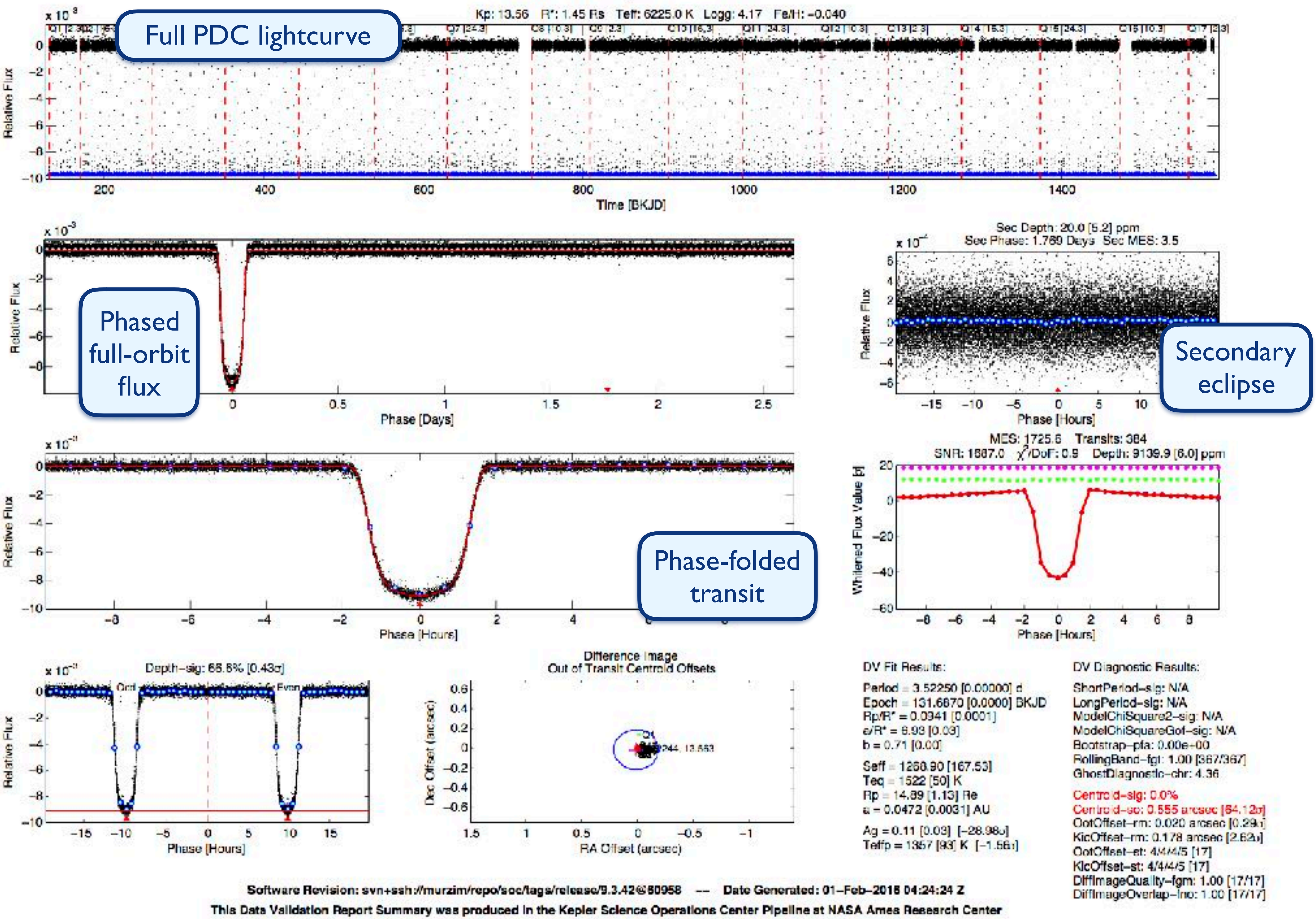
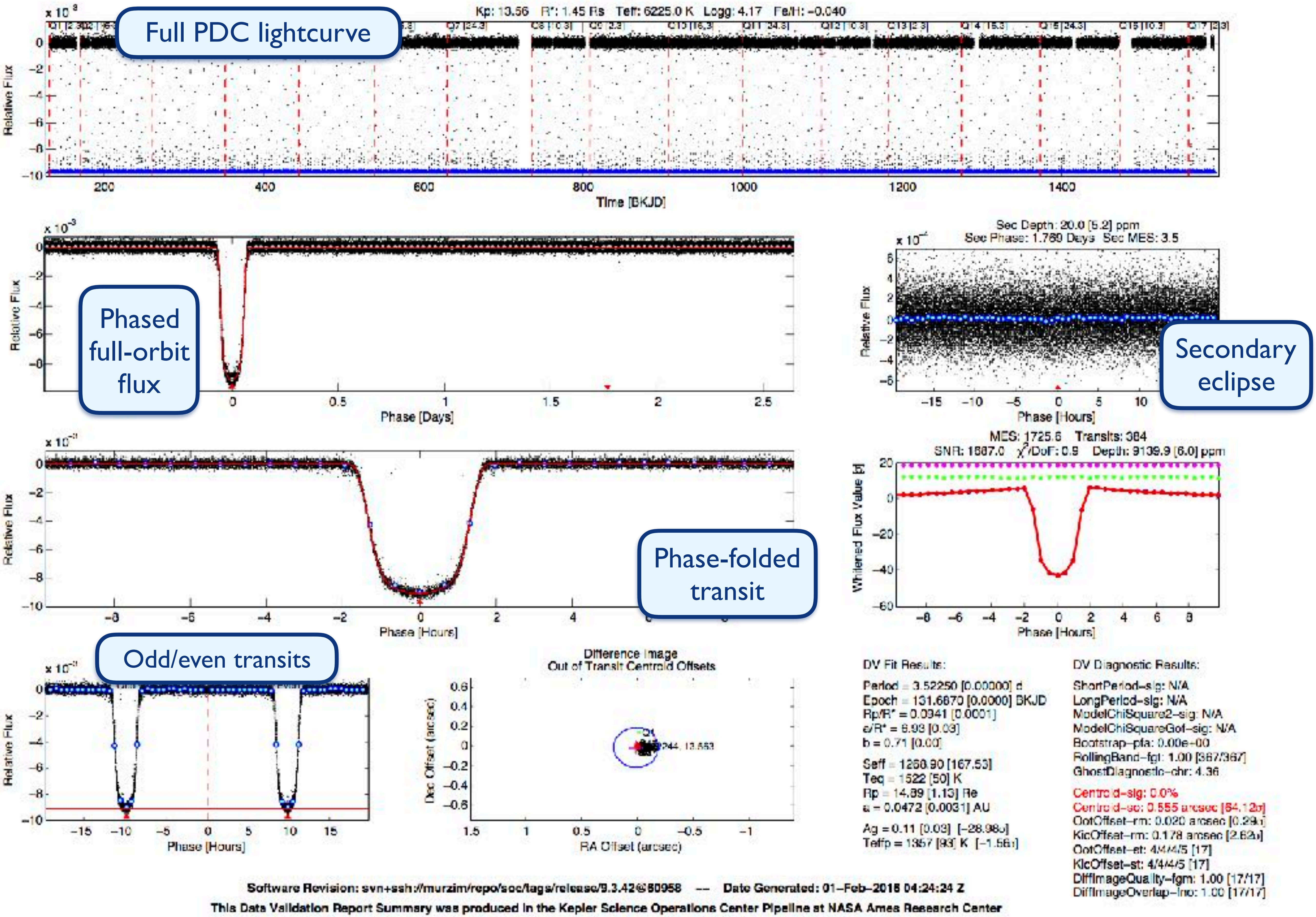
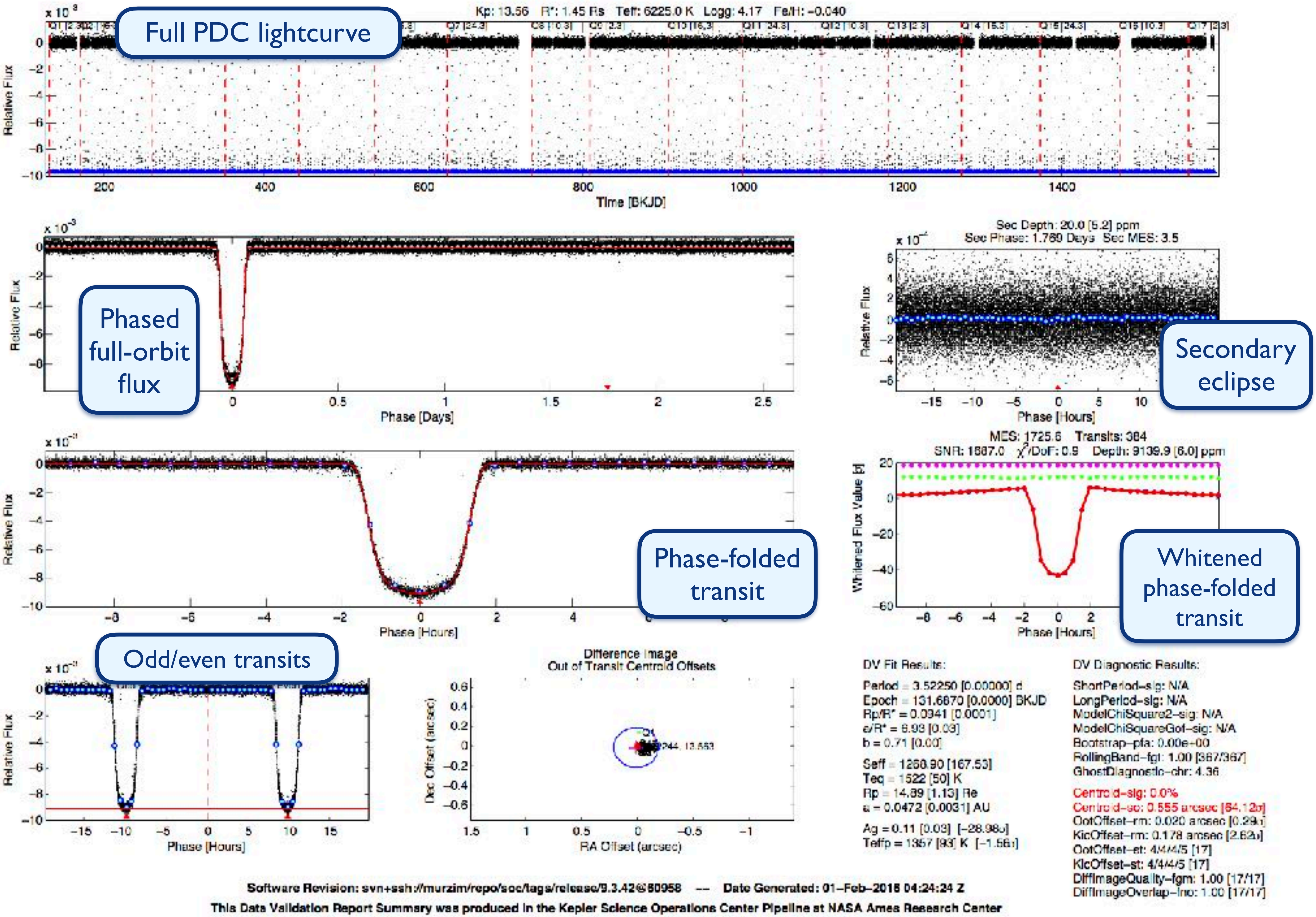


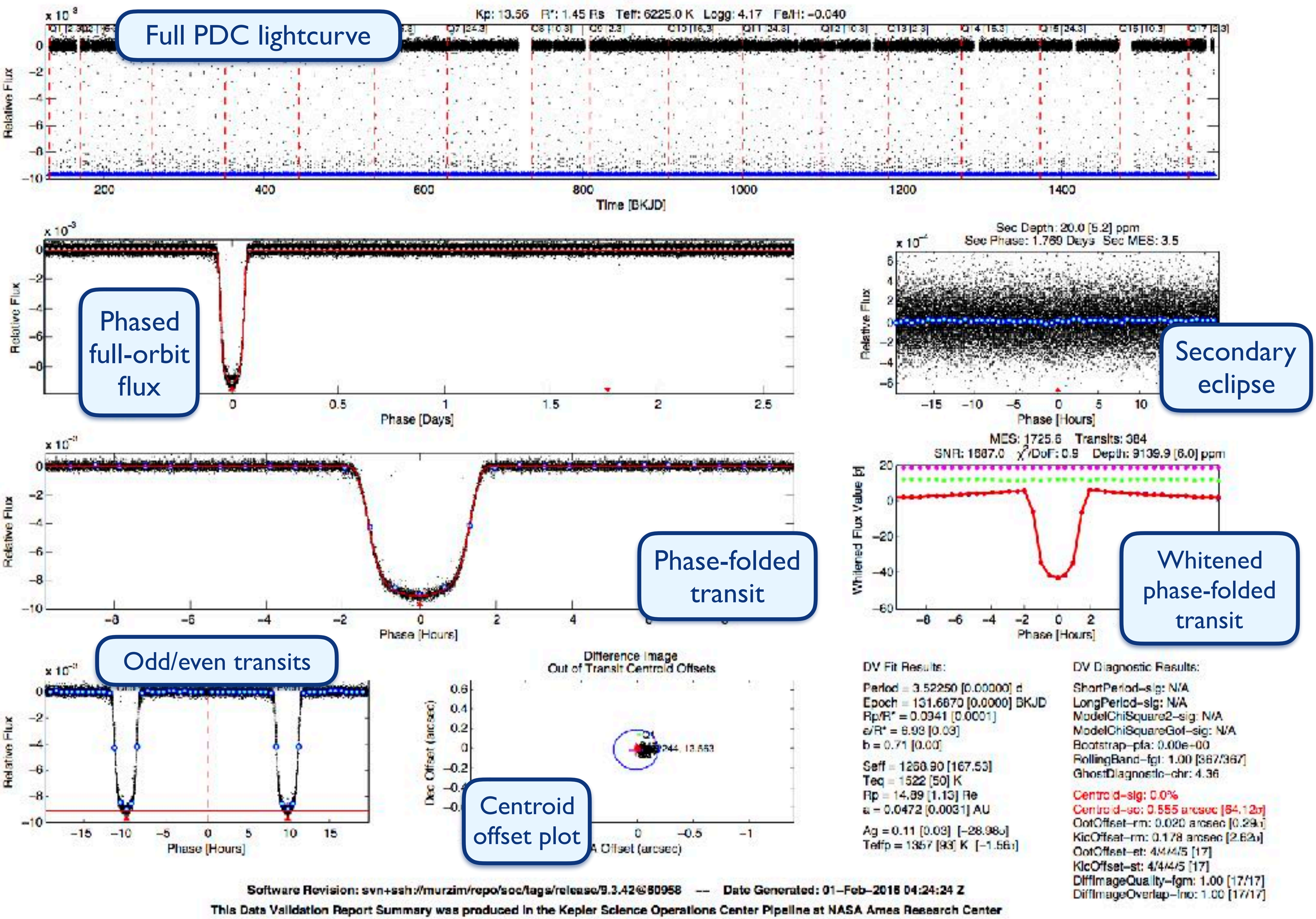
Full PDC lightcurve
Kp: 13.56 R*: 1.45 Rs Teff: 6225.0 K Logg: 4.17 Fe/H: -0.040
Relative Flux
Phased full-orbit flux
Flux
occultation
transit
Time
Image from Winn 2008
Secondary eclipse
Sec Depth: 20.0 [5.2] ppm
Sec Phase: 1.760 Days Sec MES: 3.5
Phase [Hours]
MES: 1725.6 Transits: 384
SNR: 1887.0 χ²/DoF: 0.9 Depth: 9139.9 [6.0] ppm
Phase-folded transit
Whitened Flux Value
Depth-sig: 66.6% [0.43σ]
Odd
Even
Difference Image
Out of Transit Centroid Offsets
Dec Offset (arcsec)
RA Offset (arcsec)
DV Fit Results:
Period = 3.52250 [0.00000] d
Epoch = 131.6870 [0.0000] BKJD
Rp/R* = 0.0941 [0.0001]
a/R* = 6.93 [0.03]
b = 0.71 [0.00]
Seff = 1250.90 [167.53]
Teq = 1522 [50] K
Rp = 14.89 [1.13] Re
a = 0.0472 [0.0031] AU
Ag = 0.11 [0.03] [-28.98σ]
Teffp = 1357 [93] K [-1.56σ]
DV Diagnostic Results:
ShortPeriod-sig: N/A
LongPeriod-sig: N/A
ModelChiSquare2-sig: N/A
ModelChiSquareGof-sig: N/A
Bootstrap-pfa: 0.00e-00
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36
Centroid-sig: 0.0%
Centroid-so: 0.555 arcsec [64.12σ]
OotOffset-rm: 0.020 arcsec [0.29σ]
KicOffset-rm: 0.178 arcsec [2.62σ]
OotOffset-st: 4/4/4/5 [17]
KicOffset-st: 4/4/4/5 [17]
DiffImageQuality-fgm: 1.00 [17/17]
DiffImageOverlap-fno: 1.00 [17/17]
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 01-Feb-2016 04:24:24 Z
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center


Full PDC lightcurve
Phased full-orbit flux
Secondary eclipse
Phase-folded transit
Kp: 13.56 R*: 1.45 Rs Teff: 6225.0 K Logg: 4.17 Fe/H: -0.040
Relative Flux
Time [BKJD]
Phase [Days]
Sec Depth: 20.0 [5.2] ppm
Sec Phase: 1.760 Days Sec MES: 3.5
Phase [Hours]
MES: 1725.6 Transits: 384
SNR: 1887.0 χ²/DoF: 0.9 Depth: 9139.9 [6.0] ppm
Whitened Flux Value [σ]
Depth-sig: 68.6% [0.43σ]
Odd
Even
Difference Image
Out of Transit Centroid Offsets
Dec Offset (arcsec)
RA Offset (arcsec)
DV Fit Results:
Period = 3.52250 [0.00000] d
Epoch = 131.6870 [0.0000] BKJD
Rp/R* = 0.0941 [0.0001]
a/R* = 6.93 [0.03]
b = 0.71 [0.00]
Seff = 1260.90 [167.53]
Teq = 1522 [50] K
Rp = 14.89 [1.13] Re
a = 0.0472 [0.0031] AU
Ag = 0.11 [0.03] [-28.98σ]
Teffp = 1357 [93] K [-1.56σ]
DV Diagnostic Results:
ShortPeriod-sig: N/A
LongPeriod-sig: N/A
ModelChiSquare2-sig: N/A
ModelChiSquareGof-sig: N/A
Bootstrap-pfa: 0.00e-00
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36
Centroid-sig: 0.0%
Centroid-so: 0.555 arcsec [54.12σ]
OotOffset-rm: 0.020 arcsec [0.29σ]
KicOffset-rm: 0.178 arcsec [2.62σ]
OotOffset-st: 4/4/4/5 [17]
KicOffset-st: 4/4/4/5 [17]
DiffImageQuality-fgm: 1.00 [17/17]
DiffImageOverlap-fno: 1.00 [17/17]
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 01-Feb-2016 04:24:24 Z
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center

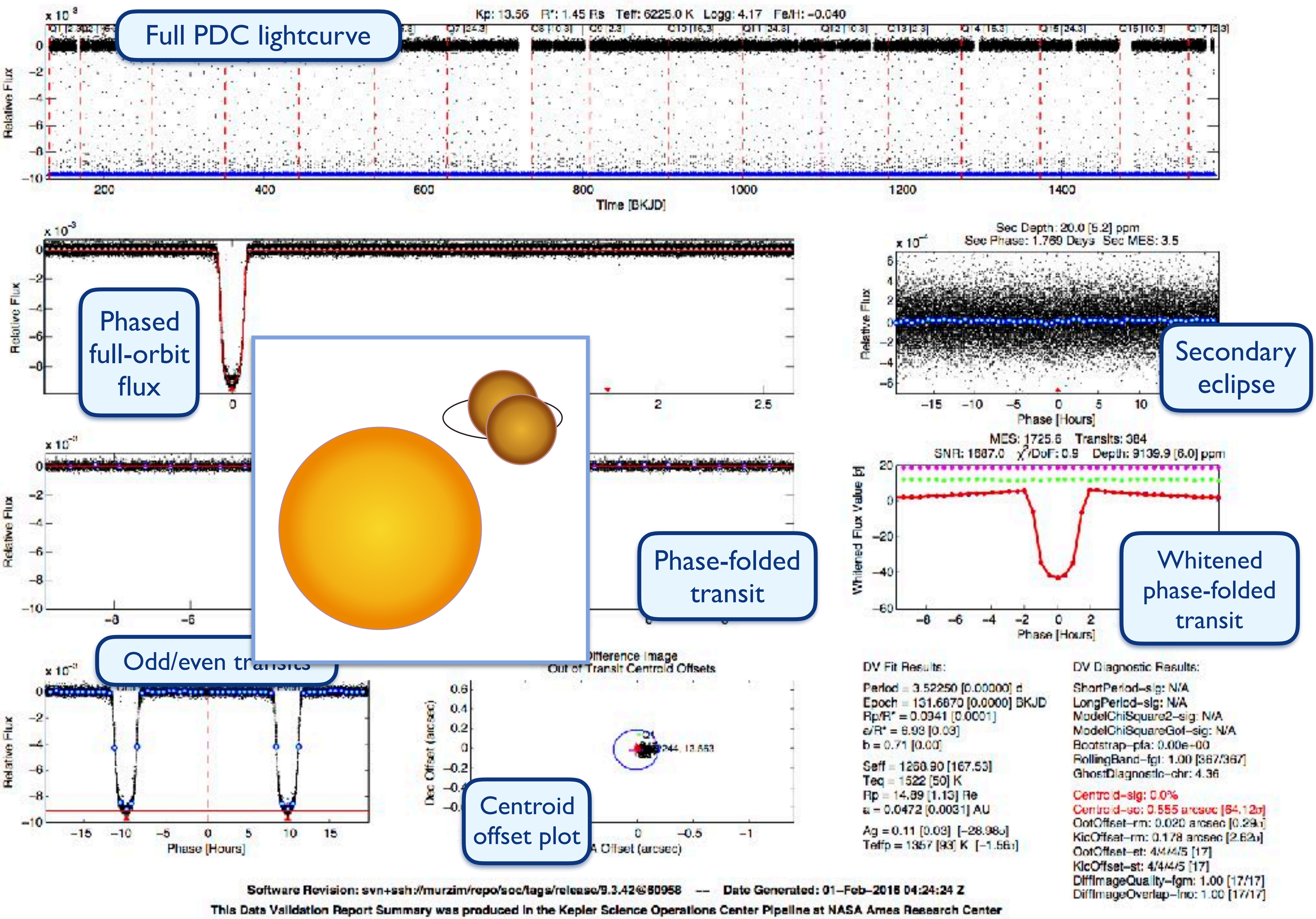

Full PDC lightcurve
Kp: 13.56 R*: 1.45 Rs Teff: 6225.0 K Logg: 4.17 Fe/H: -0.040
Relative Flux
Time [BKJD]
Phased full-orbit flux
Phase [Days]
Sec Depth: 20.0 [5.2] ppm
Sec Phase: 1.769 Days Sec MES: 3.5
Secondary eclipse
Phase [Hours]
Phase-folded transit
MES: 1725.6 Transits: 384
SNR: 1687.0 χ²/DoF: 0.9 Depth: 9139.9 [6.0] ppm
Whitened Flux Value [σ]
Odd/even transits
Difference Image
Out of Transit Centroid Offsets
Dec Offset (arcsec)
RA Offset (arcsec)
DV Fit Results:
Period = 3.52250 [0.00000] d
Epoch = 131.6870 [0.0000] BKJD
Rp/R* = 0.0941 [0.0001]
a/R* = 6.93 [0.03]
b = 0.71 [0.00]
Seff = 1260.90 [167.53]
Teq = 1522 [50] K
Rp = 14.89 [1.13] Re
a = 0.0472 [0.0031] AU
Ag = 0.11 [0.03] [-28.98σ]
Teffp = 1357 [93] K [-1.56σ]
DV Diagnostic Results:
ShortPeriod-sig: N/A
LongPeriod-sig: N/A
ModelChiSquare2-sig: N/A
ModelChiSquareGof-sig: N/A
Bootstrap-pfa: 0.00e-00
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36
Centroid-sig: 0.0%
Centroid-so: 0.555 arcsec [64.12σ]
OotOffset-rm: 0.020 arcsec [0.29σ]
KicOffset-rm: 0.178 arcsec [2.62σ]
OotOffset-st: 4/4/4/5 [17]
KicOffset-st: 4/4/4/5 [17]
DiffImageQuality-fgm: 1.00 [17/17]
DiffImageOverlap-lno: 1.00 [17/17]
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 01-Feb-2016 04:24:24 Z
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center

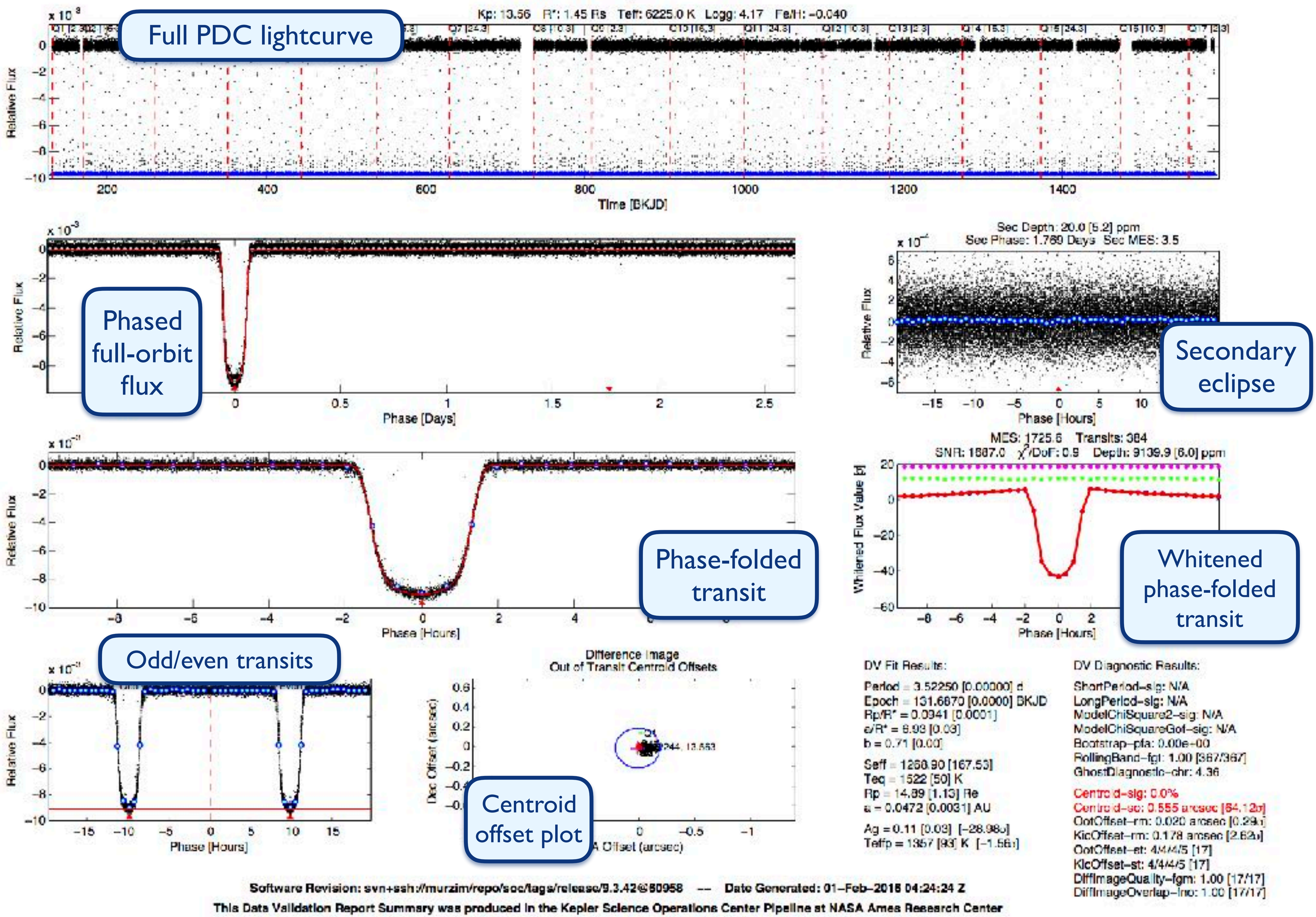


Full PDC lightcurve
Kp: 13.56 R*: 1.45 Rs Teff: 6225.0 K Logg: 4.17 Fe/H: -0.040
Relative Flux
Time [BKJD]
Phased full-orbit flux
Phase [Days]
Sec Depth: 20.0 [5.2] ppm
Sec Phase: 1.769 Days Sec MES: 3.5
Secondary eclipse
Phase [Hours]
MES: 1725.6 Transits: 384
SNR: 1887.0 χ²/DoF: 0.9 Depth: 9139.9 [6.0] ppm
Phase-folded transit
Whitened Flux Value [σ]
Whitened phase-folded transit
Odd/even transits
Difference Image
Out of Transit Centroid Offsets
Dec Offset (arcsec)
RA Offset (arcsec)
DV Fit Results:
Period = 3.52250 [0.00000] d
Epoch = 131.6870 [0.0000] BKJD
Rp/R* = 0.0941 [0.0001]
a/R* = 6.93 [0.03]
b = 0.71 [0.00]
Seff = 1250.90 [167.53]
Teq = 1522 [50] K
Rp = 14.89 [1.13] Re
a = 0.0472 [0.0031] AU
DV Diagnostic Results:
ShortPeriod-sig: N/A
LongPeriod-sig: N/A
ModelChiSquare2-sig: N/A
ModelChiSquareGof-sig: N/A
Bootstrap-pfa: 0.00e-00
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36
Centroid-sig: 0.0%
Centroid-so: 0.555 arcsec [54.12σ]
OotOffset-rm: 0.020 arcsec [0.29σ]
KicOffset-rm: 0.178 arcsec [2.62σ]
OotOffset-st: 4/4/4/5 [17]
KicOffset-st: 4/4/4/5 [17]
DiffImageQuality-fgm: 1.00 [17/17]
DiffImageOverlap-fno: 1.00 [17/17]
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 01-Feb-2016 04:24:24 Z
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center

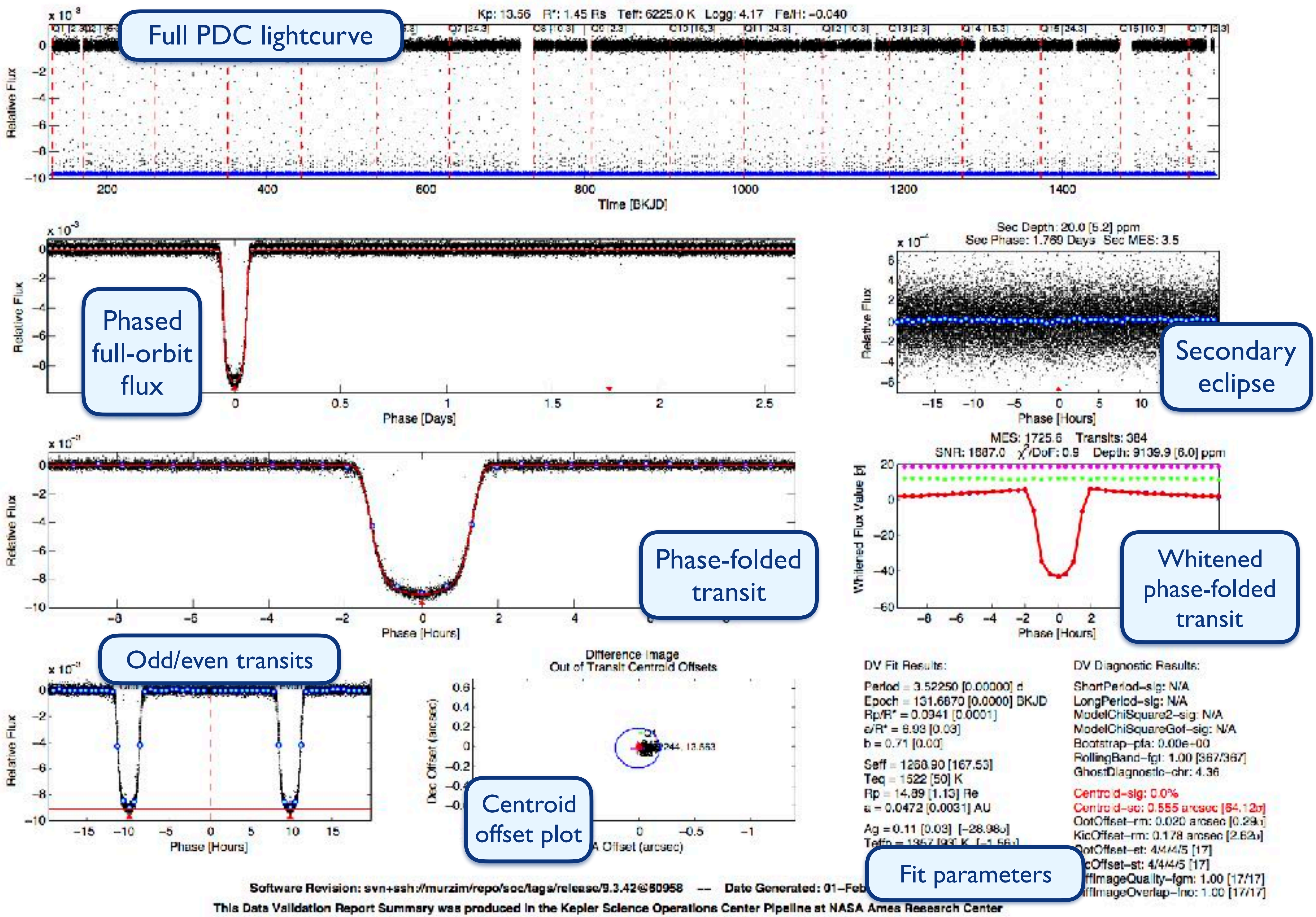


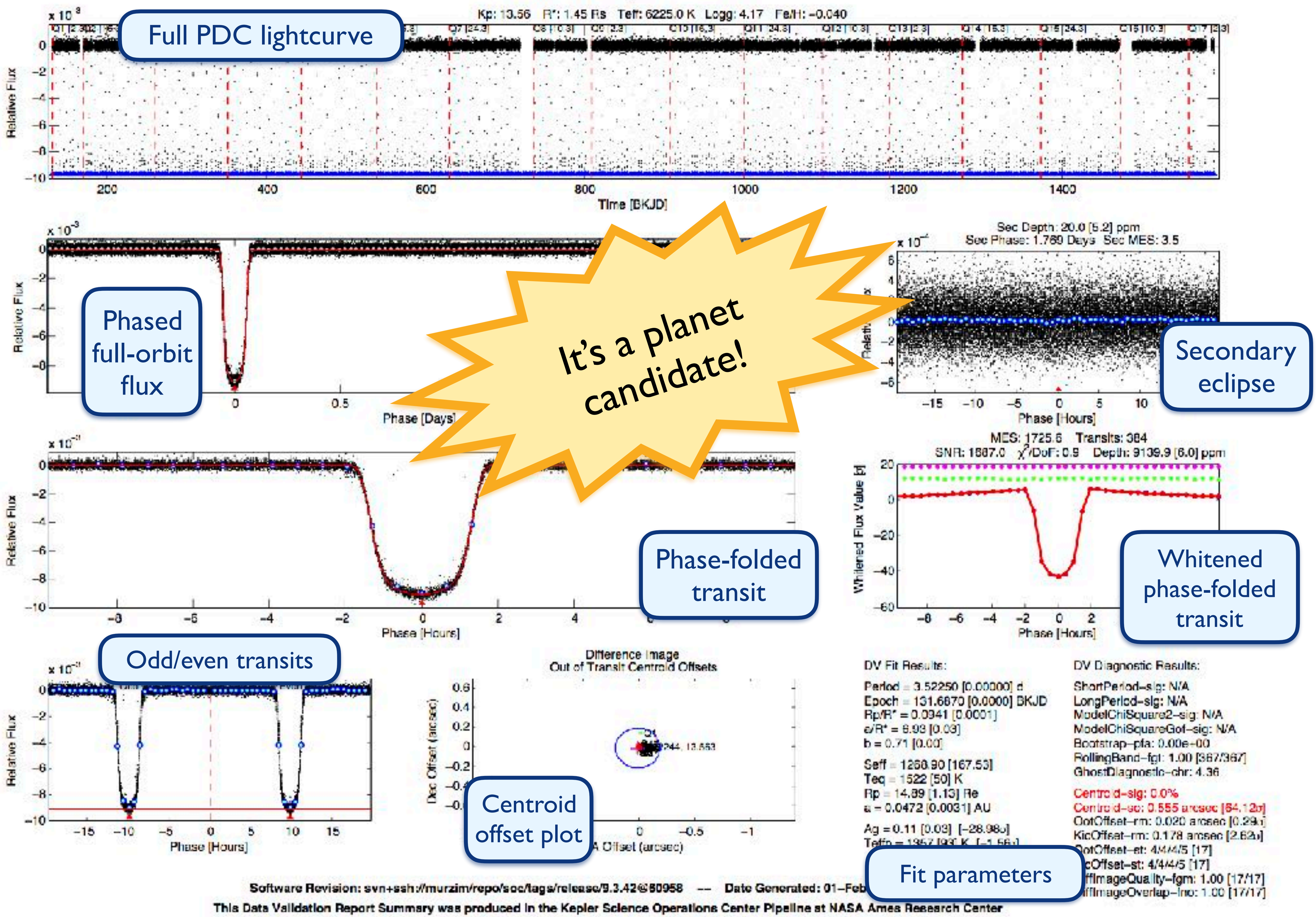
Full PDC lightcurve
Kp: 13.56 R*: 1.45 Rs Teff: 6225.0 K Logg: 4.17 Fe/H: -0.040
Relative Flux
Time [BKJD]
Phased full-orbit flux
Phase [Days]
Sec Depth: 20.0 [5.2] ppm
Sec Phase: 1.769 Days Sec MES: 3.5
Secondary eclipse
Phase [Hours]
MES: 1725.6 Transits: 384
SNR: 1887.0 χ²/DoF: 0.9 Depth: 9139.9 [6.0] ppm
Phase-folded transit
Whitened Flux Value [σ]
Whitened phase-folded transit
Odd/even transits
Difference Image
Out of Transit Centroid Offsets
Dec Offset (arcsec)
Centroid offset plot
DV Fit Results:
Period = 3.52250 [0.00000] d
Epoch = 131.6870 [0.0000] BKJD
Rp/R* = 0.0941 [0.0001]
a/R* = 6.93 [0.03]
b = 0.71 [0.00]
Seff = 1260.90 [167.53]
Teq = 1522 [50] K
Rp = 14.89 [1.13] Re
a = 0.0472 [0.0031] AU
Ag = 0.11 [0.03] [-28.98σ]
Teffp = 1357 [93] K [-1.56σ]
DV Diagnostic Results:
ShortPeriod-sig: N/A
LongPeriod-sig: N/A
ModelChiSquare2-sig: N/A
ModelChiSquareGof-sig: N/A
Bootstrap-pfa: 0.00e-00
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36
Centroid-sig: 0.0%
Centroid-so: 0.555 arcsec [54.12σ]
OotOffset-rm: 0.020 arcsec [0.29σ]
KicOffset-rm: 0.178 arcsec [2.62σ]
OotOffset-st: 4/4/4/5 [17]
KicOffset-st: 4/4/4/5 [17]
DiffImageQuality-fgm: 1.00 [17/17]
DiffImageOverlap-ino: 1.00 [17/17]
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 01-Feb-2016 04:24:24 Z
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center

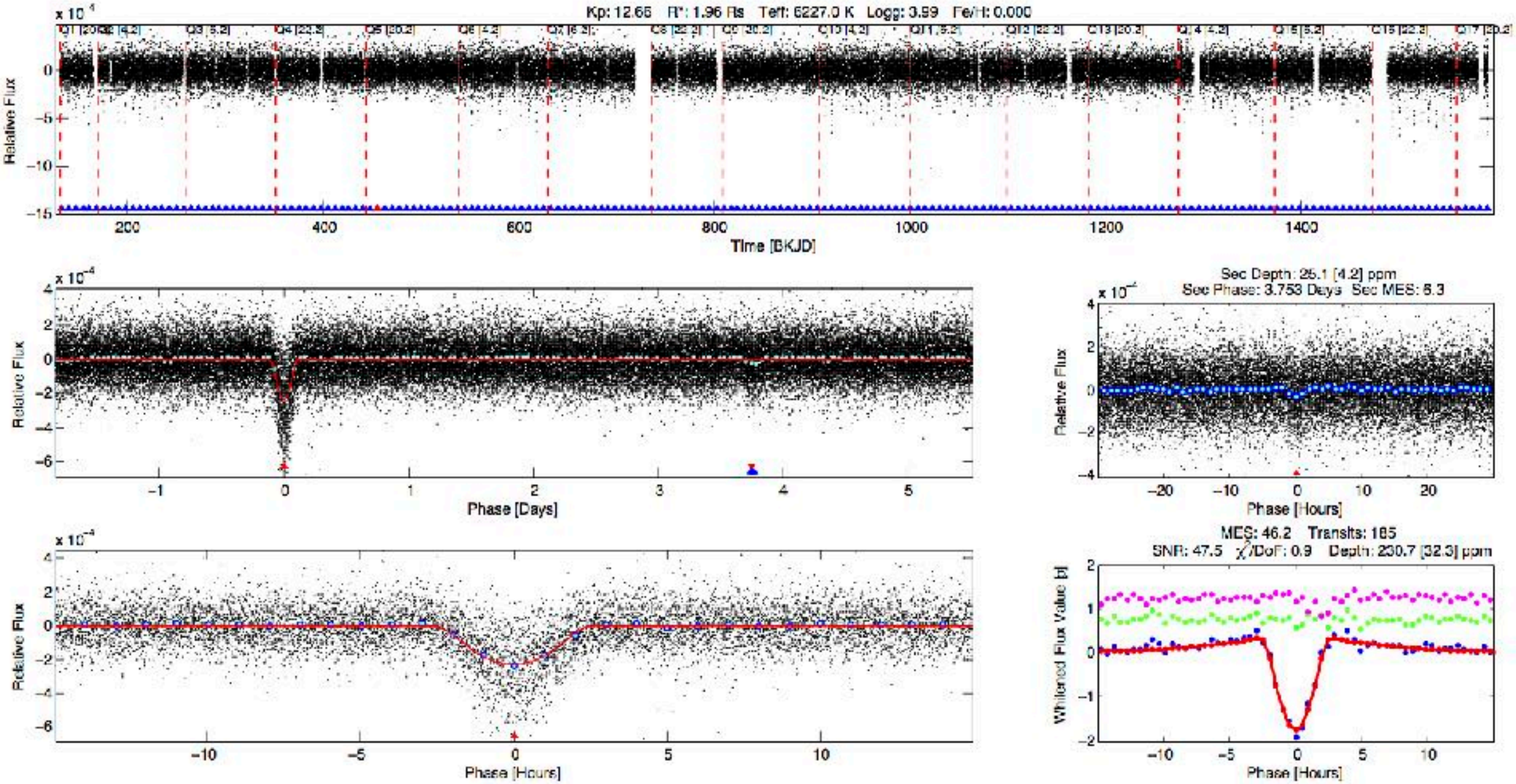

Full PDC lightcurve
Kp: 13.56 R*: 1.45 Rs Teff: 6225.0 K Logg: 4.17 Fe/H: -0.040
Relative Flux
Time [BKJD]
Phased full-orbit flux
Sec Depth: 20.0 [5.2] ppm
Sec Phase: 1.769 Days Sec MES: 3.5
Phase [Hours]
Secondary eclipse
MES: 1725.6 Transits: 384
SNR: 1867.0 χ²/DoF: 0.9 Depth: 9139.9 [6.0] ppm
Whitened Flux Value [σ]
Phase-folded transit
Whitened phase-folded transit
Odd/even transits
Difference Image
Out of Transit Centroid Offsets
Dec Offset (arcsec)
Centroid offset plot
DV Fit Results:
Period = 3.52250 [0.00000] d
Epoch = 131.6870 [0.0000] BKJD
Rp/R* = 0.0941 [0.0001]
a/R* = 6.93 [0.03]
b = 0.71 [0.00]
Seff = 1260.90 [167.53]
Teq = 1522 [50] K
Rp = 14.89 [1.13] Re
a = 0.0472 [0.0031] AU
Ag = 0.11 [0.03] [-28.98σ]
Teffp = 1357 [93] K [-1.56σ]
DV Diagnostic Results:
ShortPeriod-sig: N/A
LongPeriod-sig: N/A
ModelChiSquare2-sig: N/A
ModelChiSquareGof-sig: N/A
Bootstrap-pfa: 0.00e-00
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36
Centroid-sig: 0.0%
Centroid-so: 0.555 arcsec [54.12σ]
OotOffset-rm: 0.020 arcsec [0.29σ]
KicOffset-rm: 0.178 arcsec [2.62σ]
OotOffset-st: 4/4/4/5 [17]
KicOffset-st: 4/4/4/5 [17]
DiffImageQuality-fgm: 1.00 [17/17]
DiffImageOverlap-ino: 1.00 [17/17]
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 01-Feb-2016 04:24:24 Z
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center

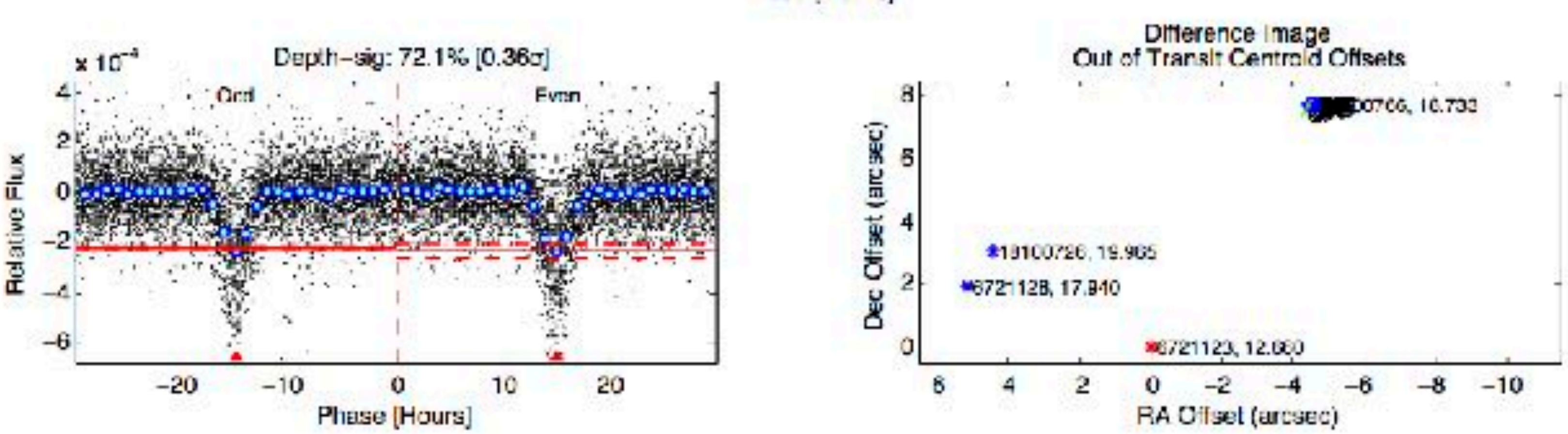


Full PDC lightcurve
Kp: 13.56 R*: 1.45 Rs Teff: 6225.0 K Logg: 4.17 Fe/H: -0.040
Relative Flux
Time [BKJD]
Phased full-orbit flux
Phase [Days]
Sec Depth: 20.0 [5.2] ppm
Sec Phase: 1.769 Days Sec MES: 3.5
Secondary eclipse
Phase [Hours]
MES: 1725.6 Transits: 384
SNR: 1667.0 χ²/DoF: 0.9 Depth: 9139.9 [6.0] ppm
Phase-folded transit
Whitened Flux Value [σ]
Whitened phase-folded transit
Odd/even transits
Difference Image
Out of Transit Centroid Offsets
Dec Offset (arcsec)
Centroid offset plot
DV Fit Results:
Period = 3.52250 [0.00000] d
Epoch = 131.6870 [0.0000] BKJD
Rp/R* = 0.0941 [0.0001]
a/R* = 6.93 [0.03]
b = 0.71 [0.00]
Seff = 1260.90 [167.53]
Teq = 1522 [50] K
Rp = 14.89 [1.13] Re
a = 0.0472 [0.0031] AU
Ag = 0.11 [0.03] [-28.98σ]
Teffp = 1357 [93] K [-1.56σ]
DV Diagnostic Results:
ShortPeriod-sig: N/A
LongPeriod-sig: N/A
ModelChiSquare2-sig: N/A
ModelChiSquareGof-sig: N/A
Bootstrap-pfa: 0.00e+00
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36
Centroid-sig: 0.0%
Centroid-so: 0.555 arcsec [64.12σ]
OotOffset-rm: 0.020 arcsec [0.29σ]
KicOffset-rm: 0.178 arcsec [2.62σ]
OotOffset-st: 4/4/4/5 [17]
KicOffset-st: 4/4/4/5 [17]
DiffImageQuality-fgm: 1.00 [17/17]
DiffImageOverlap-fno: 1.00 [17/17]
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 01-Feb-2016 04:24:24 Z
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center


Full PDC lightcurve
Kp: 13.56 R*: 1.45 Rs Teff: 6225.0 K Logg: 4.17 Fe/H: -0.040
Relative Flux
Time [BKJD]
Phased full-orbit flux
Phase [Days]
Secondary eclipse
Sec Depth: 20.0 [5.2] ppm
Sec Phase: 1.769 Days Sec MES: 3.5
Phase [Hours]
Phase-folded transit
Whitened phase-folded transit
MES: 1725.6 Transits: 384
SNR: 1687.0 χ²/DoF: 0.9 Depth: 9139.9 [6.0] ppm
Whitened Flux Value [σ]
Odd/even transits
Difference Image
Out of Transit Centroid Offsets
Dec Offset (arcsec)
Centroid offset plot
DV Fit Results:
Period = 3.52250 [0.00000] d
Epoch = 131.6870 [0.0000] BKJD
Rp/R* = 0.0941 [0.0001]
a/R* = 6.93 [0.03]
b = 0.71 [0.00]
Seff = 1260.90 [167.53]
Teq = 1522 [50] K
Rp = 14.89 [1.13] Re
a = 0.0472 [0.0031] AU
DV Diagnostic Results:
ShortPeriod-sig: N/A
LongPeriod-sig: N/A
ModelChiSquare2-sig: N/A
ModelChiSquareGof-sig: N/A
Bootstrap-pfa: 0.00e-00
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36
Centroid-sig: 0.0%
Fit parameters
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 01-Feb
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center


Full PDC lightcurve
Kp: 13.56 R*: 1.45 Rs Teff: 6225.0 K Logg: 4.17 Fe/H: -0.040
Relative Flux
Time [BKJD]
Phased full-orbit flux
Phase [Days]
It's a planet candidate!
Sec Depth: 20.0 [5.2] ppm
Sec Phase: 1.760 Days Sec MES: 3.5
Secondary eclipse
Phase [Hours]
MES: 1725.6 Transits: 384
SNR: 1867.0 χ²/DoF: 0.9 Depth: 9139.9 [6.0] ppm
Whitened Flux Value [σ]
Phase-folded transit
Whitened phase-folded transit
Odd/even transits
Difference Image
Out of Transit Centroid Offsets
Dec Offset (arcsec)
Centroid offset plot
DV Fit Results:
Period = 3.52250 [0.00000] d
Epoch = 131.6870 [0.0000] BKJD
Rp/R* = 0.0941 [0.0001]
a/R* = 6.93 [0.03]
b = 0.71 [0.00]
Seff = 1260.90 [167.53]
Teq = 1522 [50] K
Rp = 14.89 [1.13] Re
a = 0.0472 [0.0031] AU
DV Diagnostic Results:
ShortPeriod-sig: N/A
LongPeriod-sig: N/A
ModelChiSquare2-sig: N/A
ModelChiSquareGof-sig: N/A
Bootstrap-pfa: 0.00e-00
RollingBand-fgt: 1.00 [367/367]
GhostDiagnostic-chr: 4.36
Centroid-sig: 0.0%
Fit parameters
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 01-Feb
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center





DV Fit Results:

Period = 7.36179 [0.00002] d
Epoch = 132.2494 [0.0022] BKJD
Rp/R* = 0.0278 [0.0195]
a/R* = 2.86 [0.46]
b = 1.00 [0.03]

Seff = 768.97 [256.70]
Teq = 1343 [112] K
Rp = 5.94 [4.41] Re
a = 0.0820 [0.0177] AU

Ag = 2.68 [3.80] [0.48σ]
Teffp = 2643 [933] K [1.38σ]

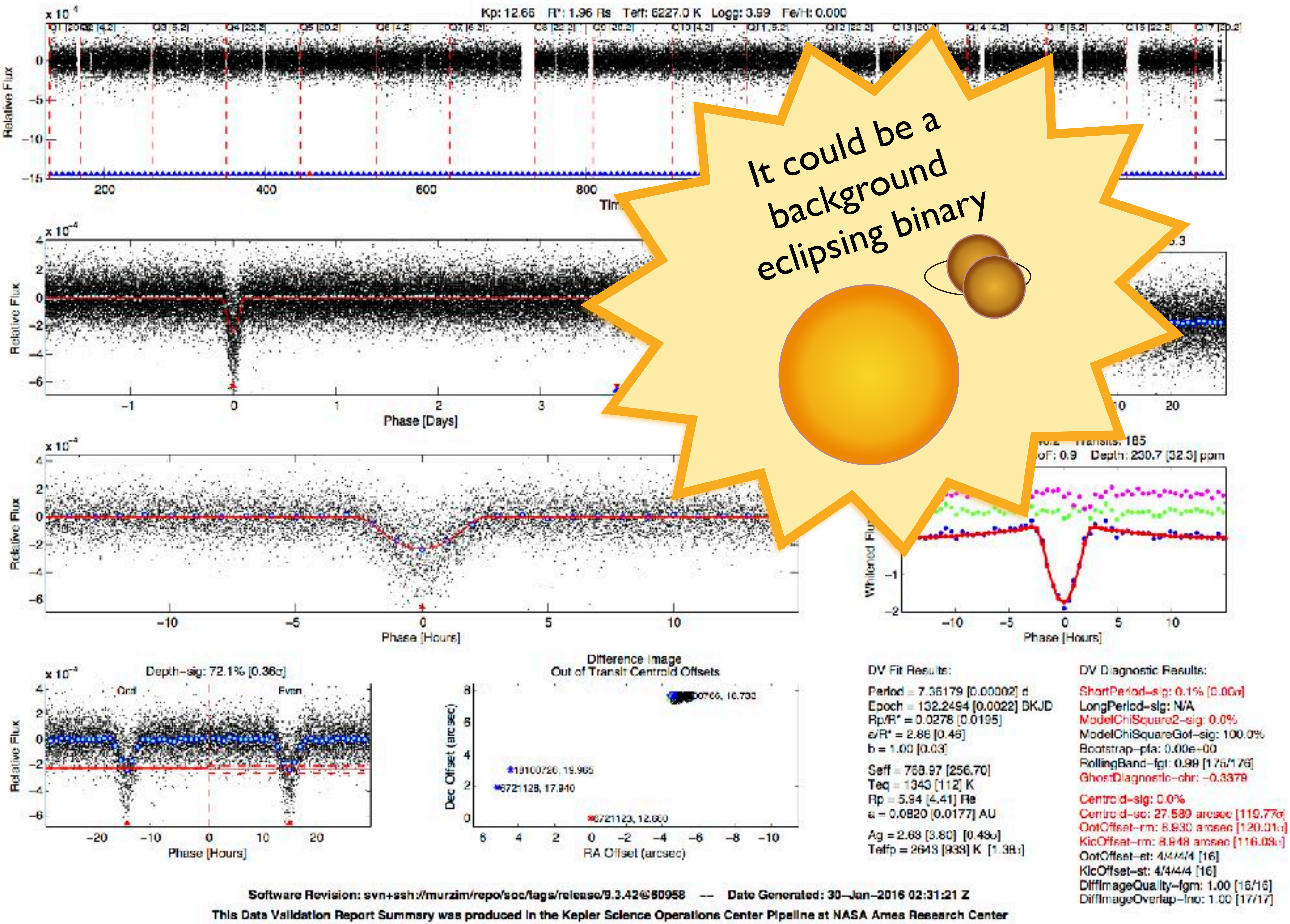
DV Diagnostic Results:

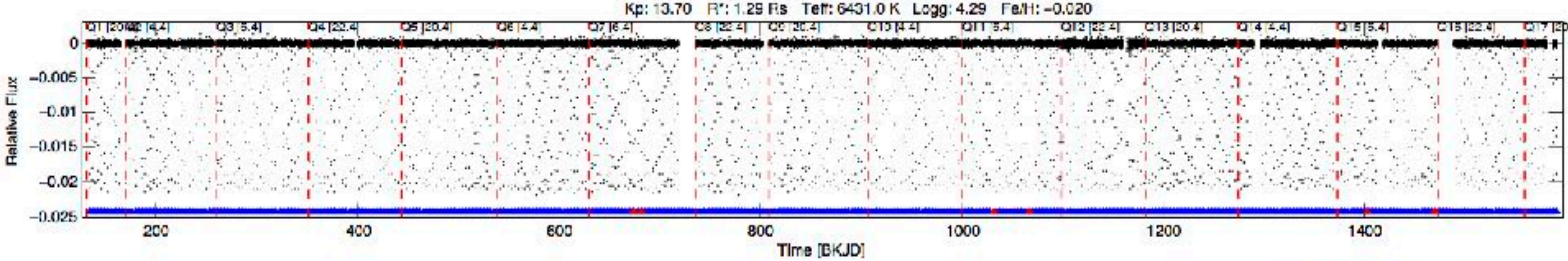
ShortPeriod–sig: 0.1% [0.00σ]
LongPeriod–sig: N/A
ModelChiSquare2–sig: 0.0%
ModelChiSquareGof–sig: 100.0%
Bootstrap–pfa: 0.00e+00
RollingBand–fgt: 0.99 [175/176]
GhostDiagnostic–chr: −0.3379

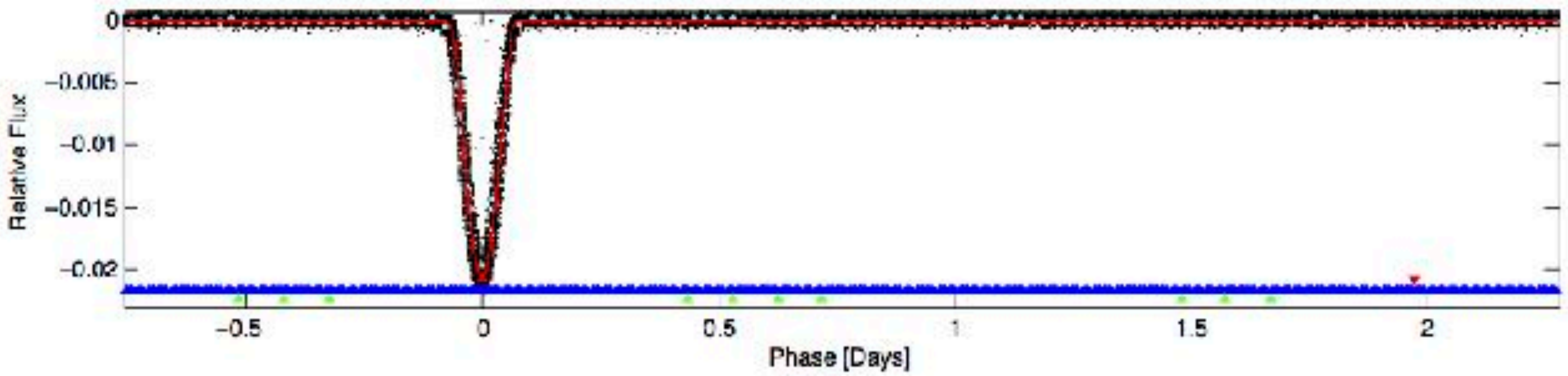
Centroid–sig: 0.0%
Centroid–so: 27.589 arcsec [119.77σ]
OotOffset–rm: 8.930 arcsec [120.01σ]
KicOffset–rm: 8.848 arcsec [116.08σ]
OotOffset–st: 4/4/4/4 [16]
KicOffset–st: 4/4/4/4 [16]
DiffImageQuality–fgm: 1.00 [16/16]
DiffImageOverlap–ino: 1.00 [17/17]

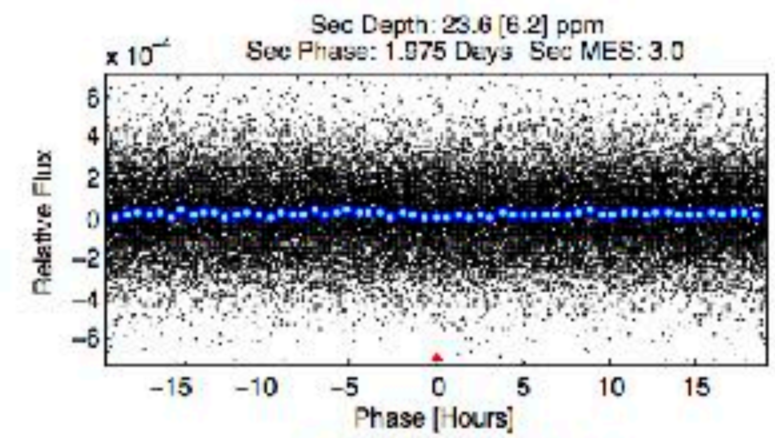
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 30–Jan–2016 02:31:21 Z

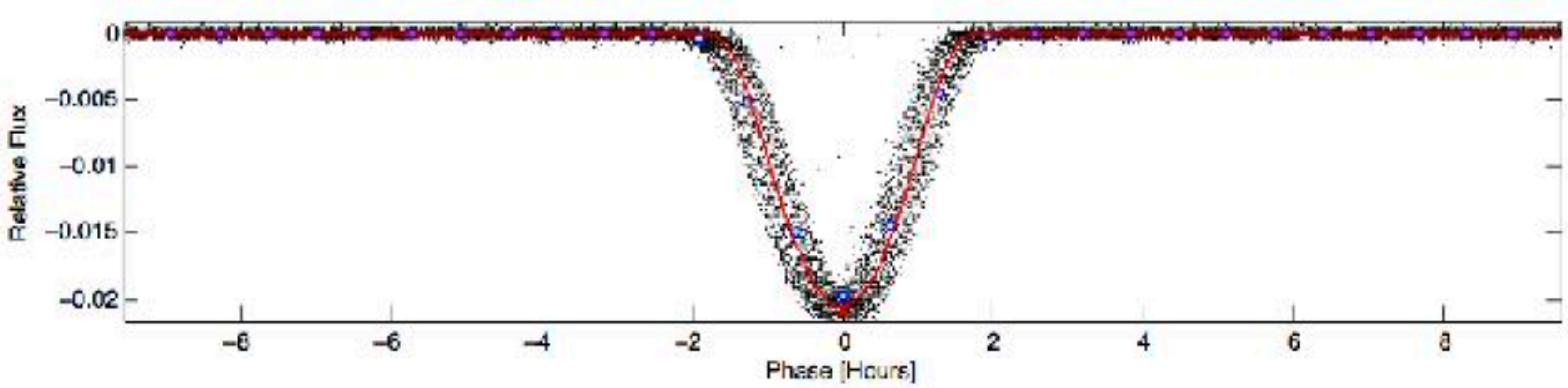
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center

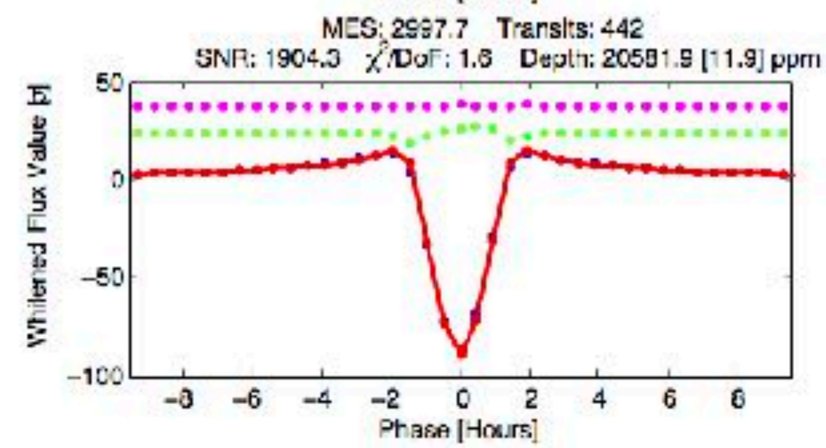

It could be a background eclipsing binary
Kp: 12.66 R*: 1.96 Rs Teff: 6227.0 K Logg: 3.99 Fe/H: 0.000
Relative Flux
Phase [Days]
Phase [Hours]
Whitened Flux
Transits: 185
Depth: 230.7 [32.3] ppm
Depth-sig: 72.1% [0.36σ]
Odd
Even
Difference Image
Out of Transit Centroid Offsets
Dec Offset (arcsec)
RA Offset (arcsec)
DV Fit Results:
Period = 7.36179 [0.00002] d
Epoch = 132.2494 [0.0022] BKJD
Rp/R* = 0.0278 [0.0195]
a/R* = 2.86 [0.46]
b = 1.00 [0.03]
Seff = 768.97 [256.70]
Teq = 1343 [112] K
Rp = 5.94 [4.41] Re
a = 0.0820 [0.0177] AU
Ag = 2.68 [3.80] [0.43σ]
Teffp = 2643 [933] K [1.38σ]
DV Diagnostic Results:
ShortPeriod-sig: 0.1% [0.00σ]
LongPeriod-sig: N/A
ModelChiSquare2-sig: 0.0%
ModelChiSquareGof-sig: 100.0%
Bootstrap-pfa: 0.00e-00
RollingBand-fgt: 0.99 [175/176]
GhostDiagnostic-chr: -0.3379
Centroid-sig: 0.0%
Centroid-so: 27.580 arcsec [119.77σ]
OotOffset-rm: 8.930 arcsec [120.01σ]
KicOffset-rm: 8.948 arcsec [116.03σ]
OotOffset-st: 4/4/4/4 [16]
KicOffset-st: 4/4/4/4 [16]
DiffImageQuality-fgm: 1.00 [16/16]
DiffImageOverlap-fno: 1.00 [17/17]
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 30-Jan-2016 02:31:21 Z
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center

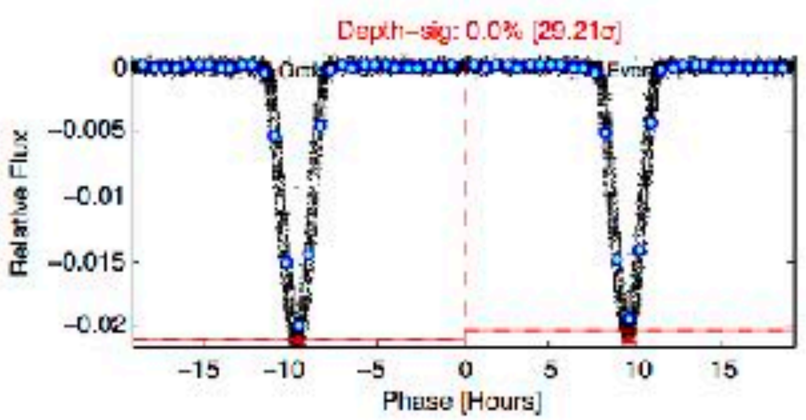


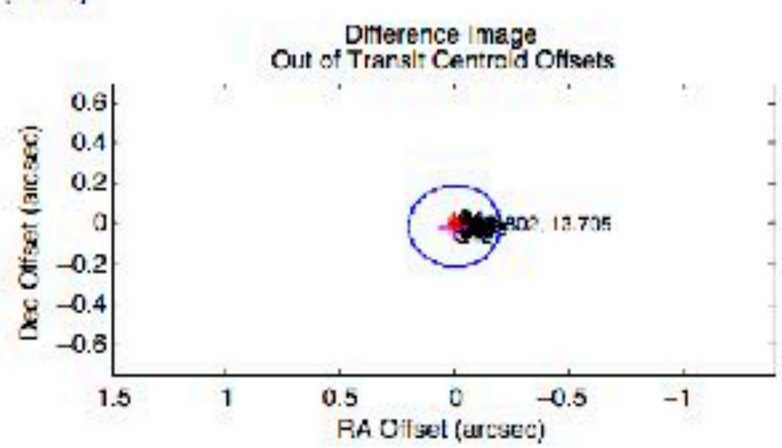












DV Fit Results:

Period = 3.04156 [0.00000] d
Epoch = 133.9874 [0.0000] BKJD
Rp/R* = 0.1992 [0.0031]
a/R* = 5.40 [0.01]
b = 0.95 [0.00]

Seff = 1347.08 [304.29]
Teq = 1545 [87] K
Rp = 28.15 [4.76] Re
a = 0.0437 [0.0062] AU

Ag = 0.03 [0.01] [-91.86σ]
Teffp = 1004 [70] K [-4.83σ]

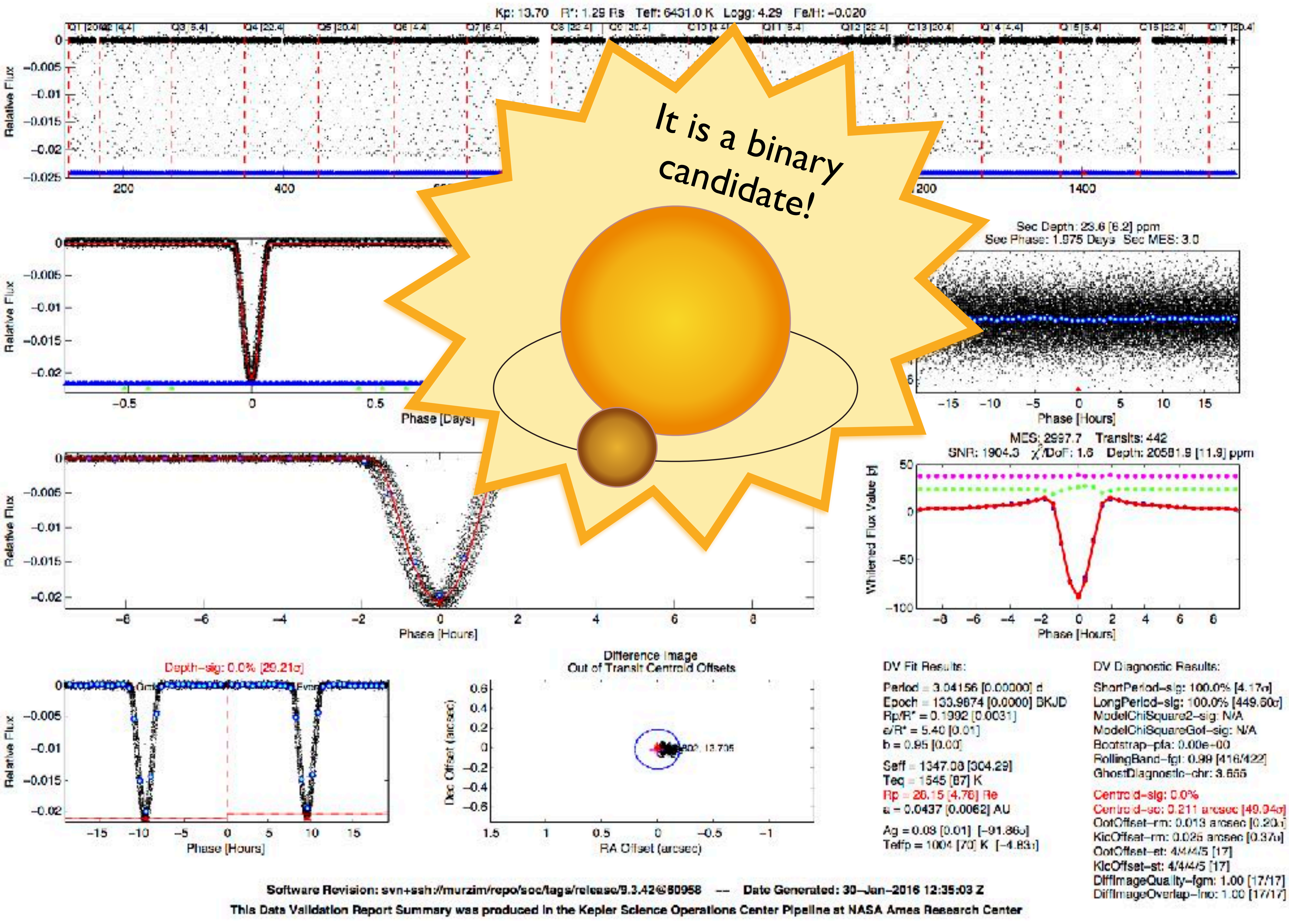
DV Diagnostic Results:

ShortPeriod-sig: 100.0% [4.17σ]
LongPeriod-sig: 100.0% [449.60σ]
ModelChiSquare2-sig: N/A
ModelChiSquareGof-sig: N/A
Bootstrap-pfa: 0.00e-00
RollingBand-fgt: 0.99 [416/422]
GhostDiagnostic-chr: 3.655

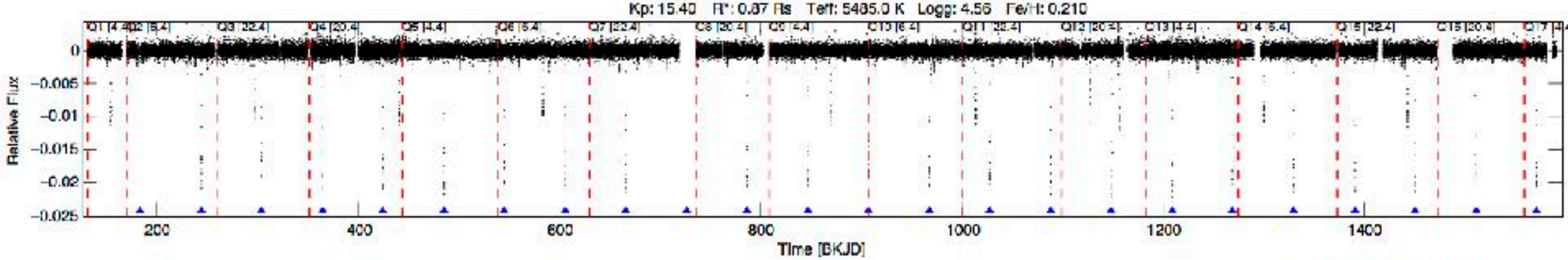
Centroid-sig: 0.0%
Centroid-so: 0.211 arcsec [49.04σ]
OotOffset-rm: 0.013 arcsec [0.20σ]
KicOffset-rm: 0.026 arcsec [0.37σ]
OotOffset-st: 4/4/4/5 [17]
KicOffset-st: 4/4/4/5 [17]
DiffImageQuality-fgm: 1.00 [17/17]
DiffImageOverlap-fno: 1.00 [17/17]

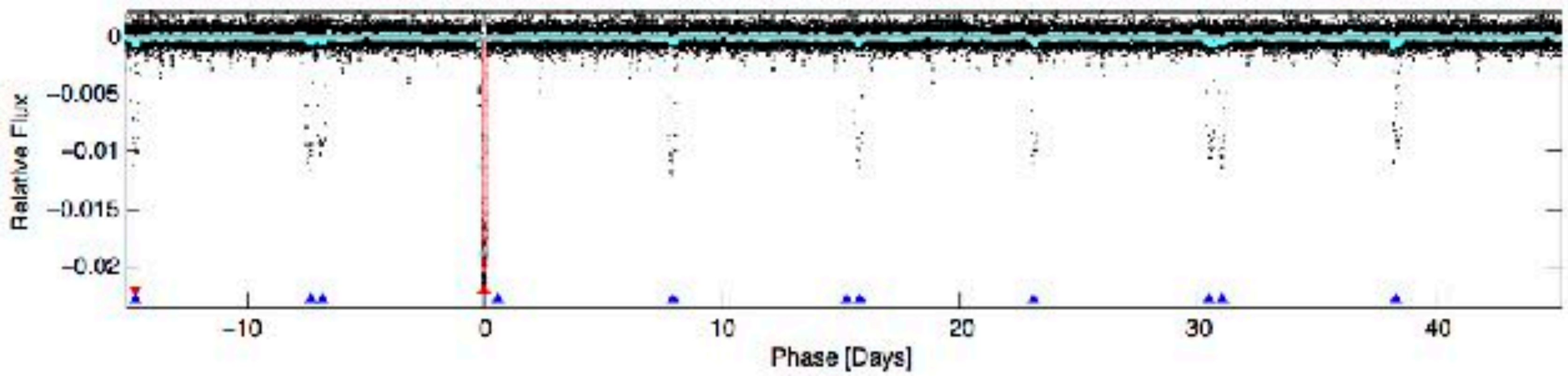
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 30-Jan-2016 12:35:03 Z

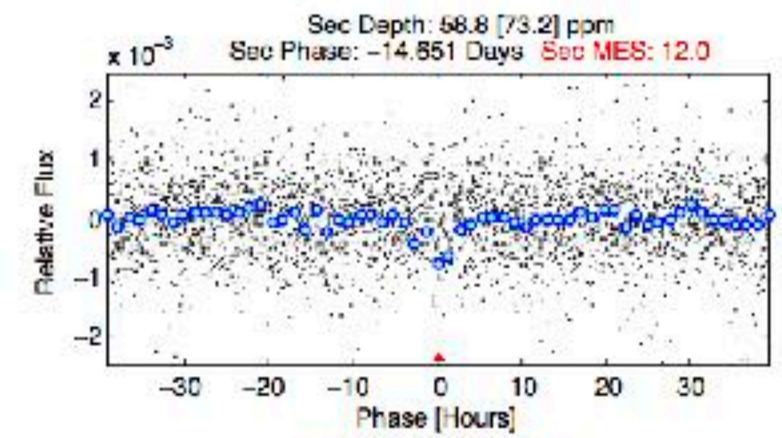
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center

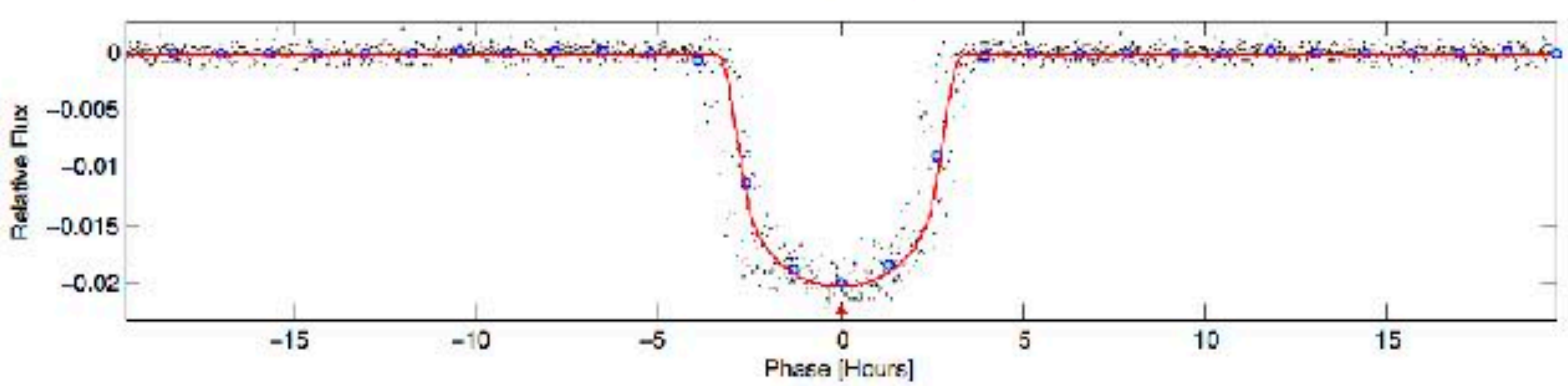


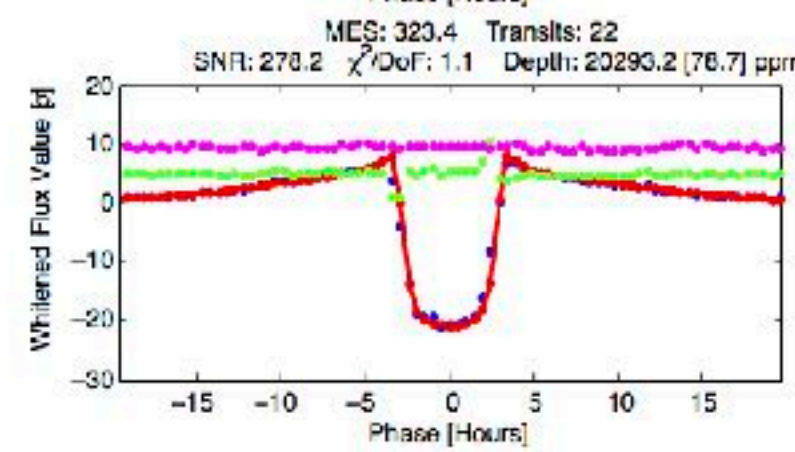
It is a binary candidate!
Kp: 13.70 R*: 1.29 Rs Teff: 6431.0 K Logg: 4.29 Fe/H: -0.020
Relative Flux
Phase [Days]
Sec Depth: 23.6 [6.2] ppm
Sec Phase: 1.875 Days Sec MES: 3.0
Phase [Hours]
MES: 2997.7 Transits: 442
SNR: 1904.3 χ²/DoF: 1.6 Depth: 20581.9 [11.9] ppm
Whitened Flux Value [σ]
Depth-sig: 0.0% [29.21σ]
Difference Image
Out of Transit Centroid Offsets
Dec Offset (arcsec)
RA Offset (arcsec)
DV Fit Results:
Period = 3.04156 [0.00000] d
Epoch = 133.9874 [0.0000] BKJD
Rp/R* = 0.1992 [0.0031]
a/R* = 5.40 [0.01]
b = 0.95 [0.00]
Seff = 1347.08 [304.29]
Teq = 1545 [87] K
Rp = 28.15 [4.76] Re
a = 0.0437 [0.0062] AU
DV Diagnostic Results:
ShortPeriod-sig: 100.0% [4.17σ]
LongPeriod-sig: 100.0% [449.60σ]
ModelChiSquare2-sig: N/A
ModelChiSquareGof-sig: N/A
Centroid-sig: 0.0%
DiffImageQuality-fgm: 1.00 [17/17]
DiffImageOverlap-ino: 1.00 [17/17]
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 30-Jan-2016 12:35:03 Z
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center

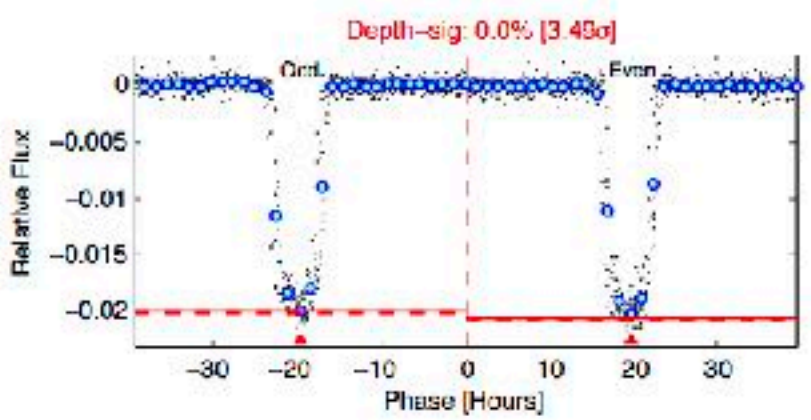


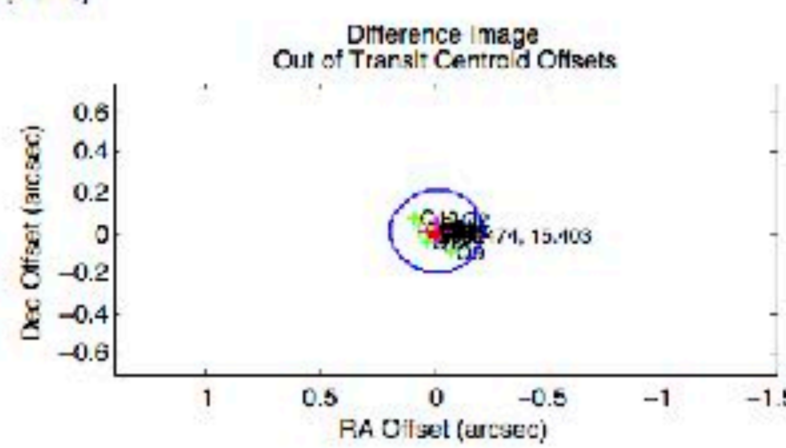












DV Fit Results:

Period = 60.32524 [0.00003] d
Epoch = 163.5691 [0.0004] BKJD
Rp/R* = 0.1279 [0.0008]
a/R* = 79.28 [1.75]
b = 0.01 [4.40]

Seff = 6.79 [1.11]
Teq = 412 [17] K
Rp = 12.10 [1.11] Re
a = 0.2997 [0.0261] AU

Ag = 19.86 [24.86] [0.76σ]
Teffp = 1343 [419] K [2.22σ]

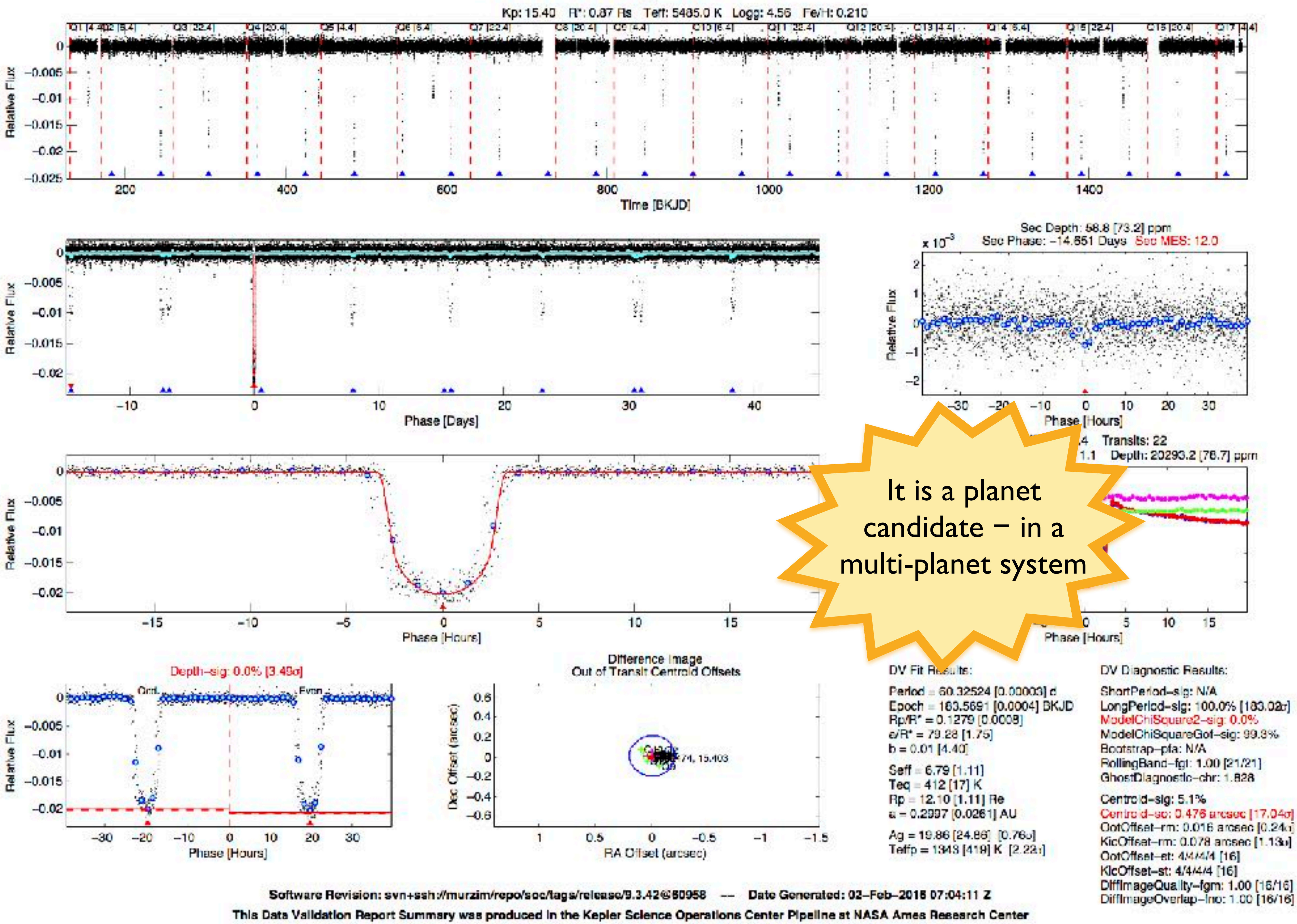
DV Diagnostic Results:

ShortPeriod-sig: N/A
LongPeriod-sig: 100.0% [183.02σ]
ModelChiSquare2-sig: 0.0%
ModelChiSquareGof-sig: 99.3%
Bootstrap-pfa: N/A
RollingBand-fgt: 1.00 [21/21]
GhostDiagnostic-chr: 1.828

Centroid-sig: 5.1%
Centroid-so: 0.476 arcsec [17.04σ]
OotOffset-rm: 0.016 arcsec [0.24σ]
KicOffset-rm: 0.078 arcsec [1.13σ]
OotOffset-st: 4/4/4/4 [16]
KicOffset-st: 4/4/4/4 [16]
DiffImageQuality-fgm: 1.00 [16/16]
DiffImageOverlap-fno: 1.00 [16/16]

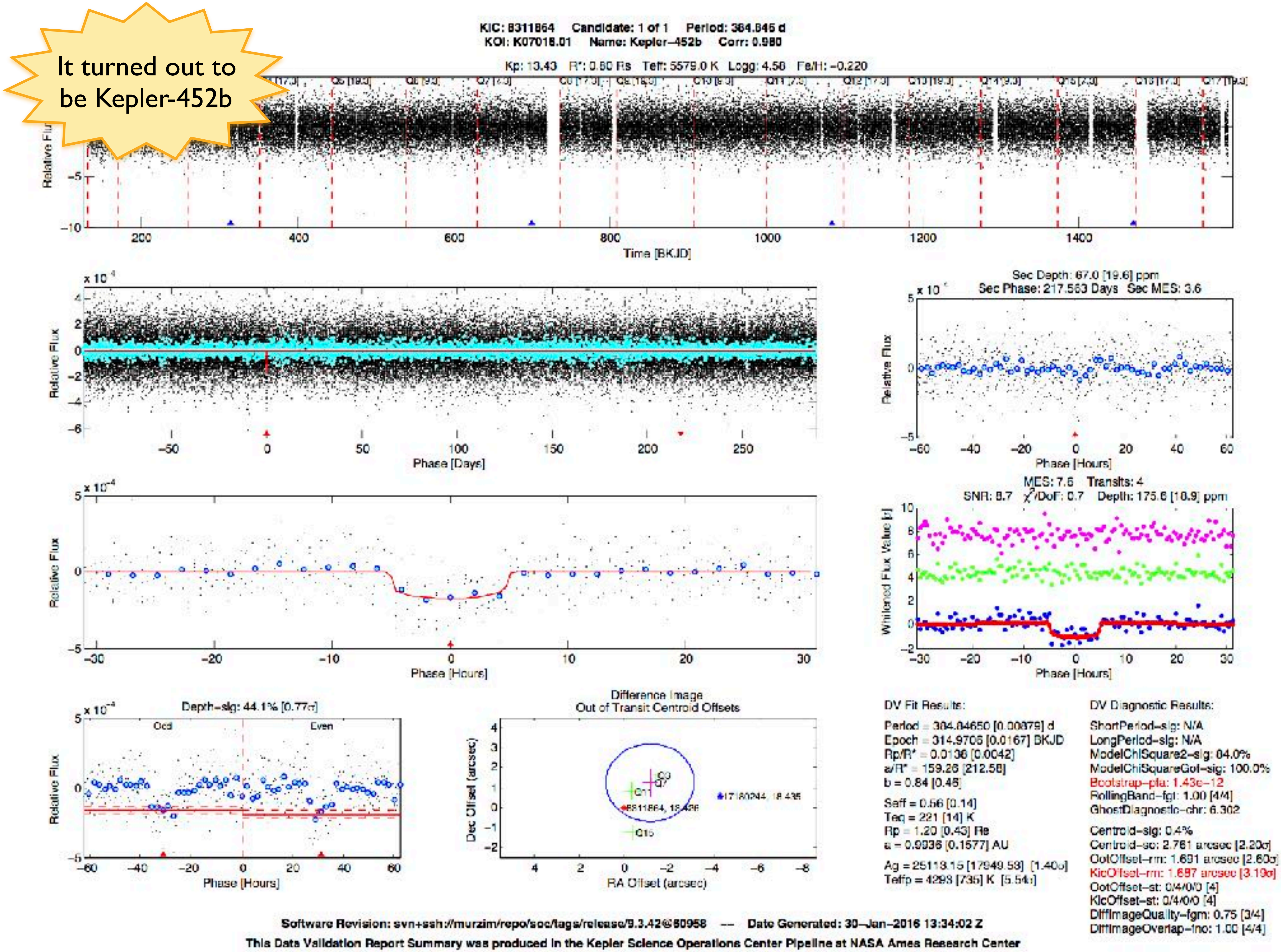
Software Revision: svn+ssh://murzim/repo/soc/tags/release/9.3.42@60958 -- Date Generated: 02-Feb-2016 07:04:11 Z

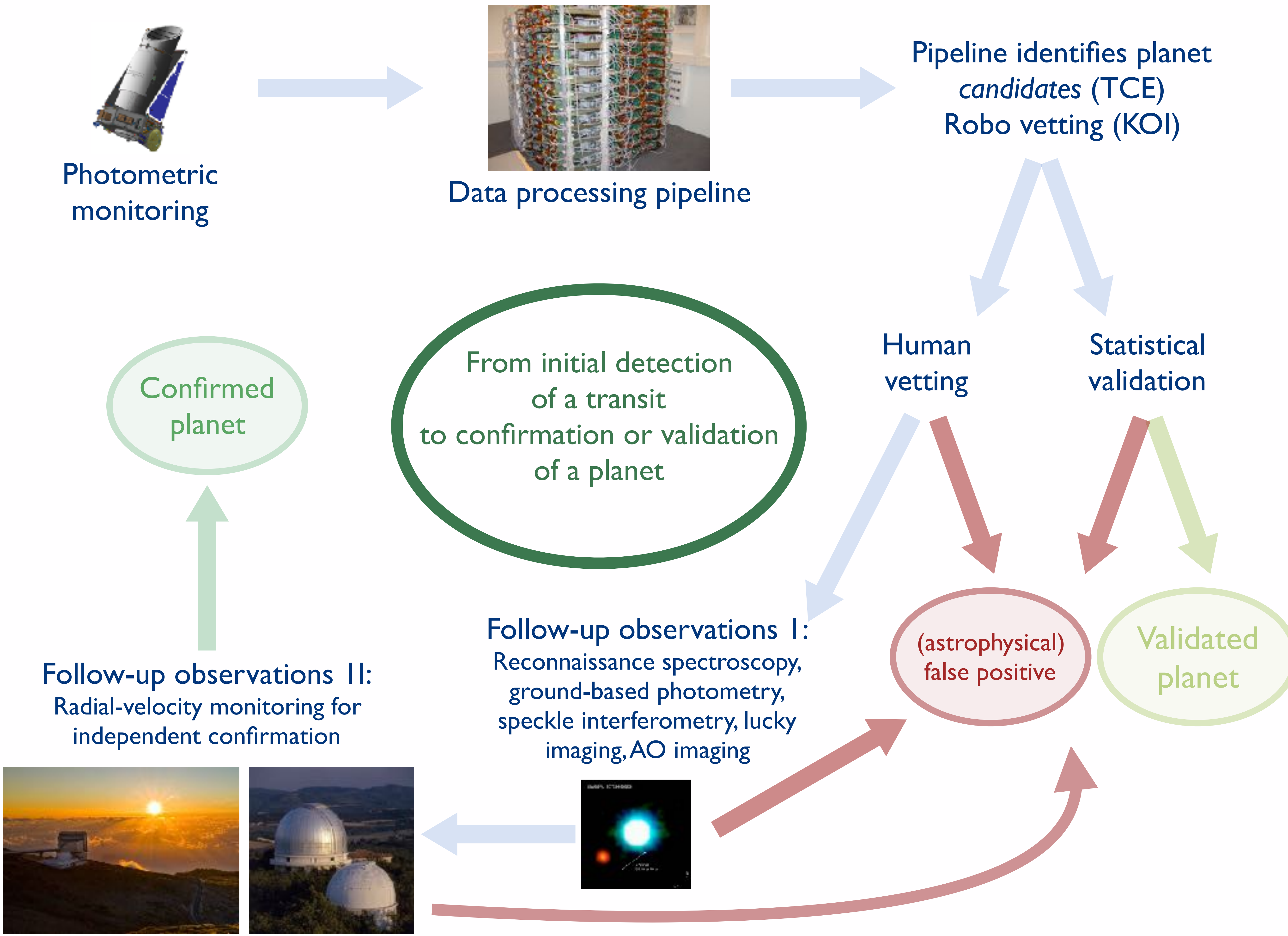
This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center



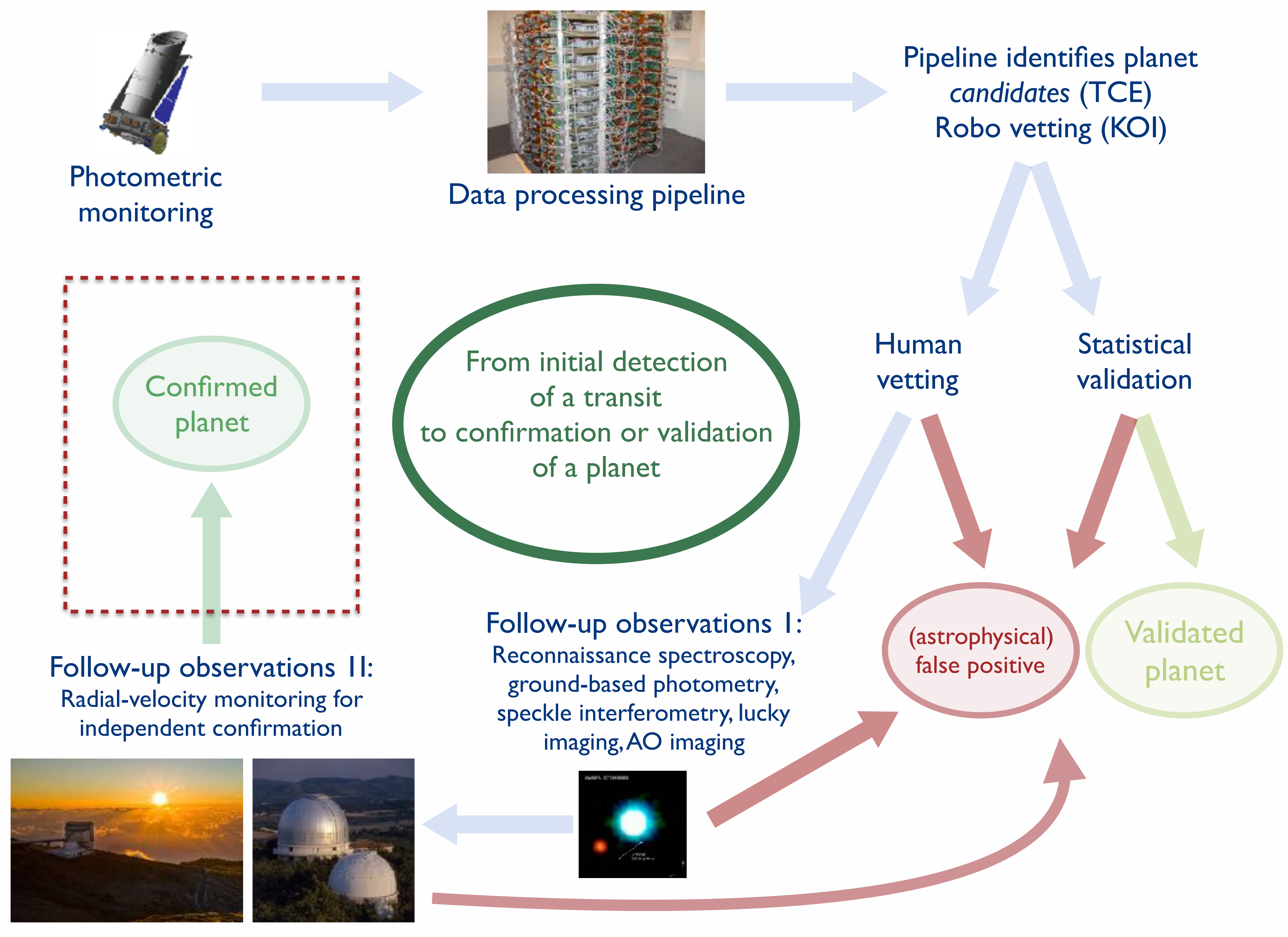
It is a planet candidate – in a multi-planet system

It turned out to be Kepler-452b





Photometric monitoring
Data processing pipeline
Pipeline identifies planet *candidates* (TCE)
Robo vetting (KOI)
Human vetting
Statistical validation
From initial detection of a transit to confirmation or validation of a planet
Confirmed planet
(astrophysical) false positive
Validated planet
Follow-up observations I:
Reconnaissance spectroscopy, ground-based photometry, speckle interferometry, lucky imaging, AO imaging
Follow-up observations II:
Radial-velocity monitoring for independent confirmation


Photometric monitoring
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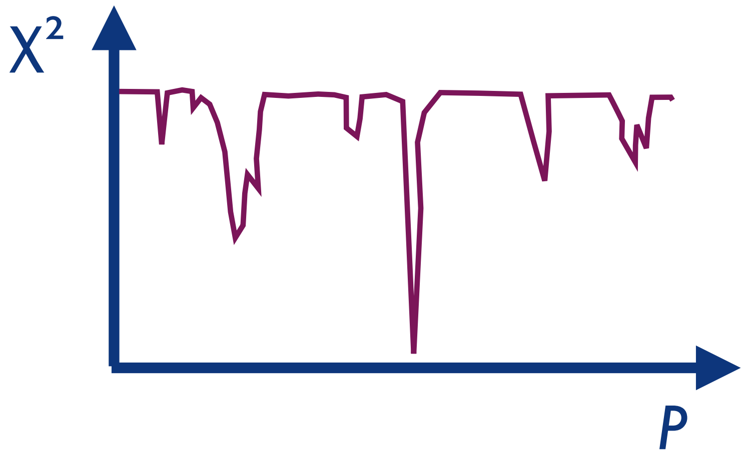
From transit detection to planet characterisation

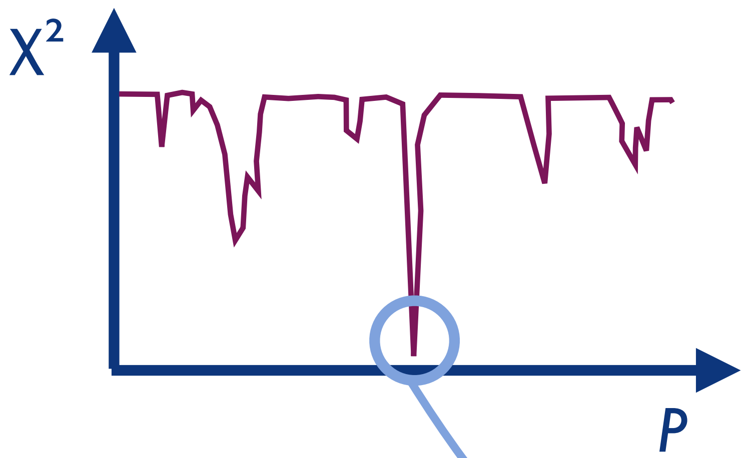
From transit detection to planet characterisation

Step 1: Find the **global** χ^2 minimum using BLS, TPS, TFA, etc.

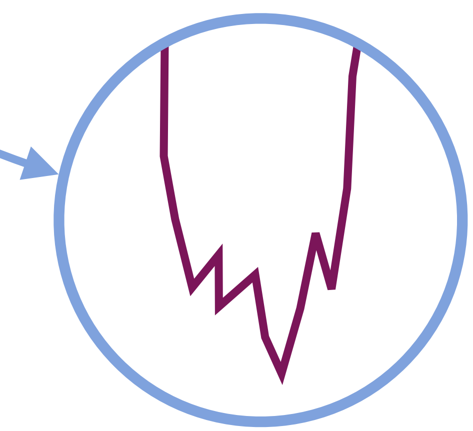


From transit detection to planet characterisation

<u>Step 1</u>: Find the **global** χ^2 minimum
using BLS, TPS, TFA, etc.

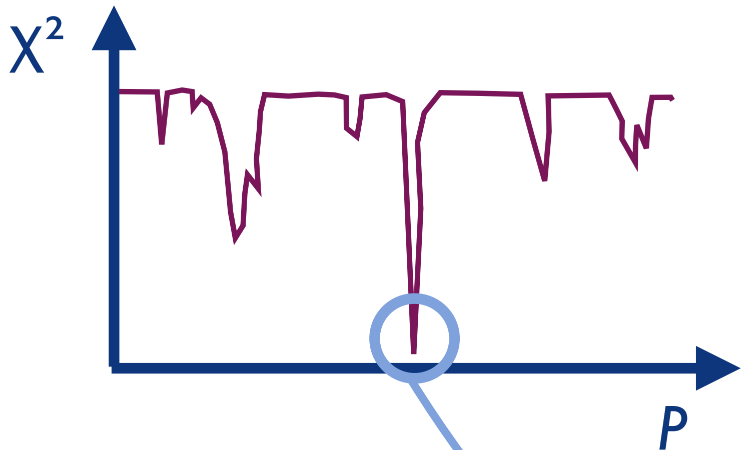


<u>Step 2</u>: Find the **local** χ^2 minimum
using Ameoba method or equivalent



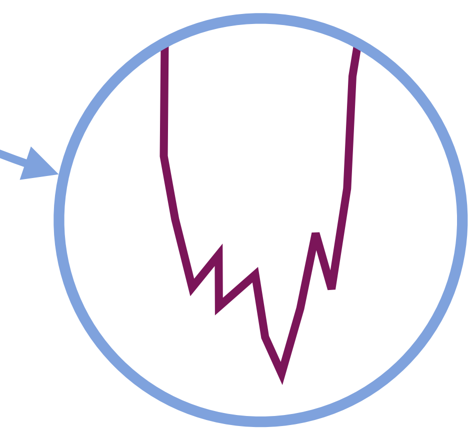
From transit detection to planet characterisation

Step 1: Find the **global** χ^2 minimum using BLS, TPS, TFA, etc.



See Jason Eastman's talk on EXOFAST this afternoon

Step 2: Find the **local** χ^2 minimum using Ameoba method or equivalent



From transit detection to planet characterisation

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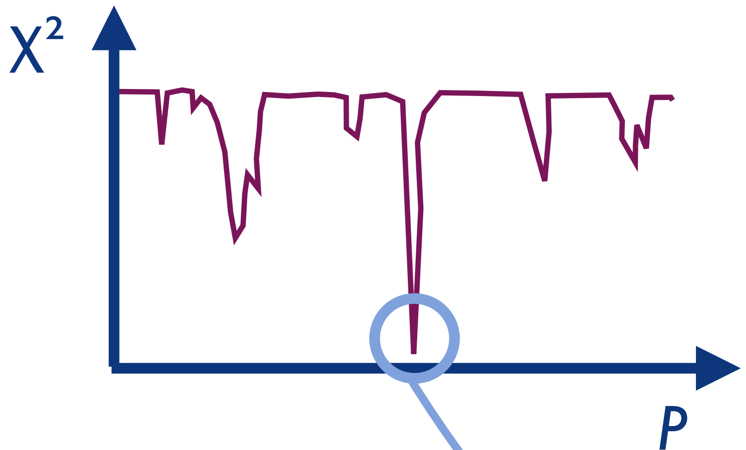
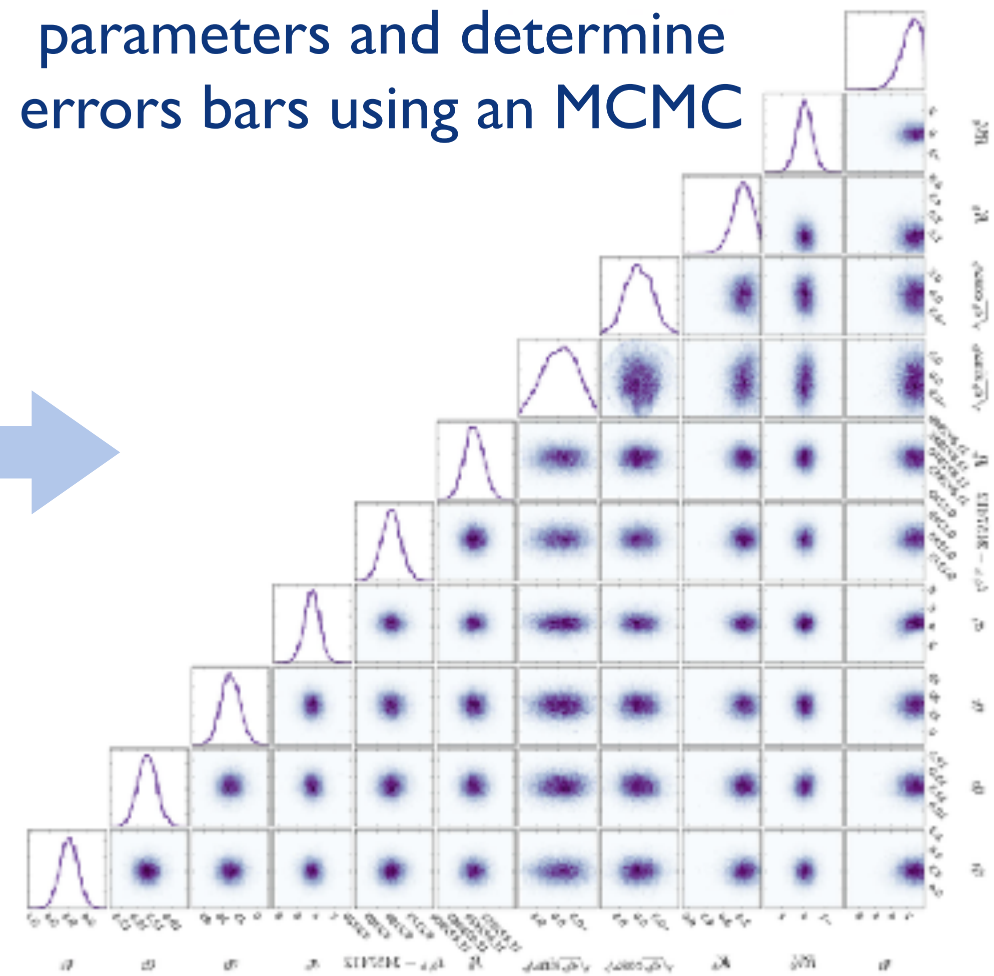


See Jason Eastman's talk on EXOFAST this afternoon

Step 2: Find the **local** χ^2 minimum using Ameoba method or equivalent

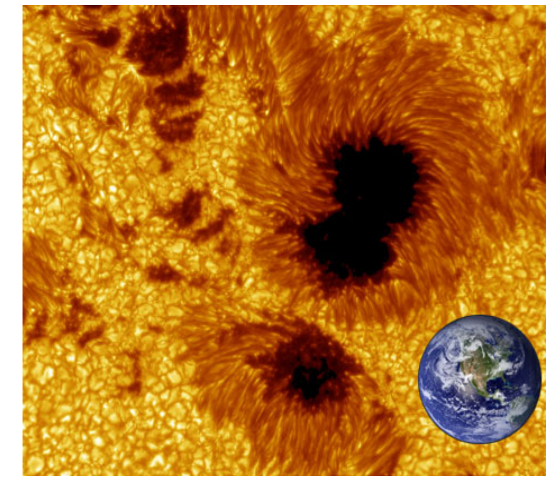
Step 3: Estimate transit parameters and determine errors bars using an MCMC



Stellar activity can affect transit-measured planet parameters

Stars vary on timescales from minutes to years:

Full Sun: SDO/HMI continuum



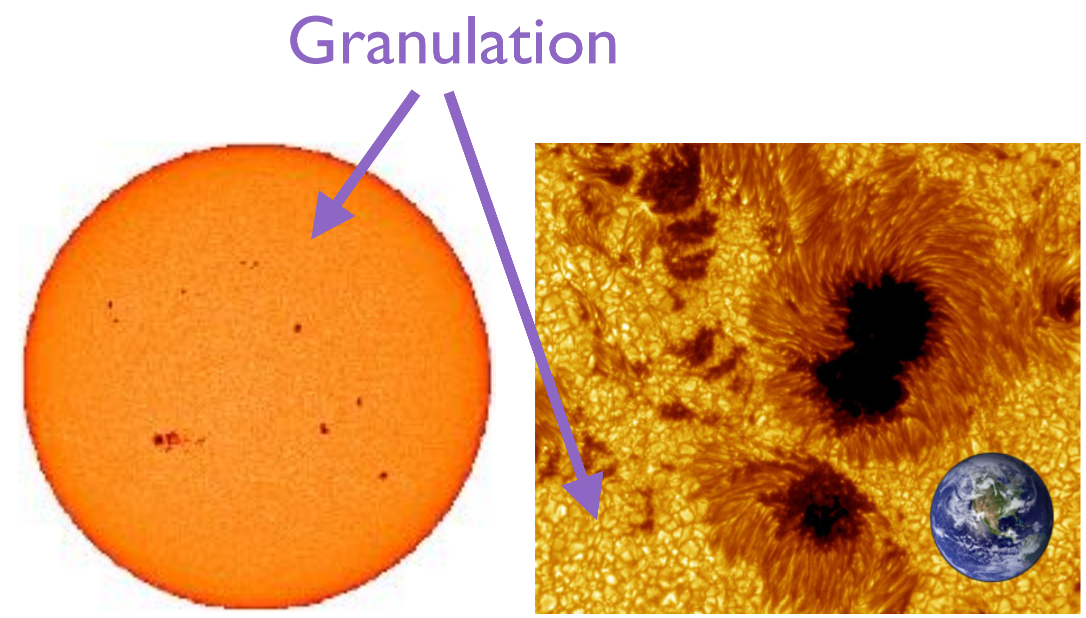
Swedish Telescope, V. Henriques

See Schrijver & Zwaan (2000),
Hall (2008), Reiners (2012),
Haywood (2015, Chap. 1) and others

Stellar activity can affect transit-measured planet parameters

Stars vary on timescales from minutes to years:

- Oscillations and granulation *min-hours*



Full Sun: SDO/HMI continuum

Swedish Telescope, V. Henriques

See Schrijver & Zwaan (2000), Hall (2008), Reiners (2012), Haywood (2015, Chap. 1) and others

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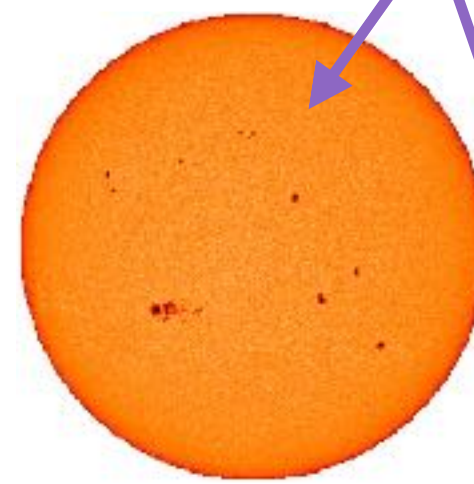
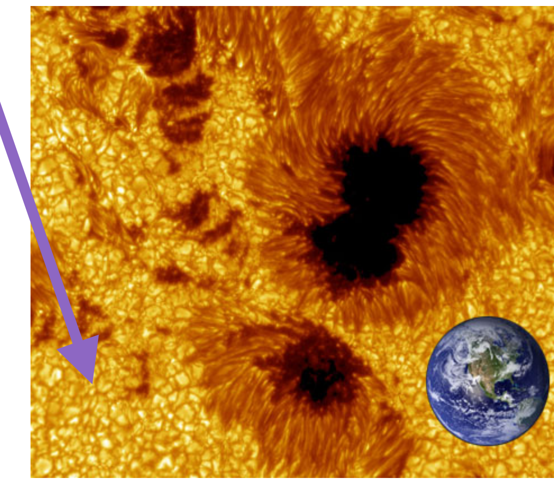
Stars vary on timescales from minutes to years:

- Oscillations and granulation *min-hours*
- Flares/coronal mass ejections *min-hours (esp. M dwarfs)*

Granulation



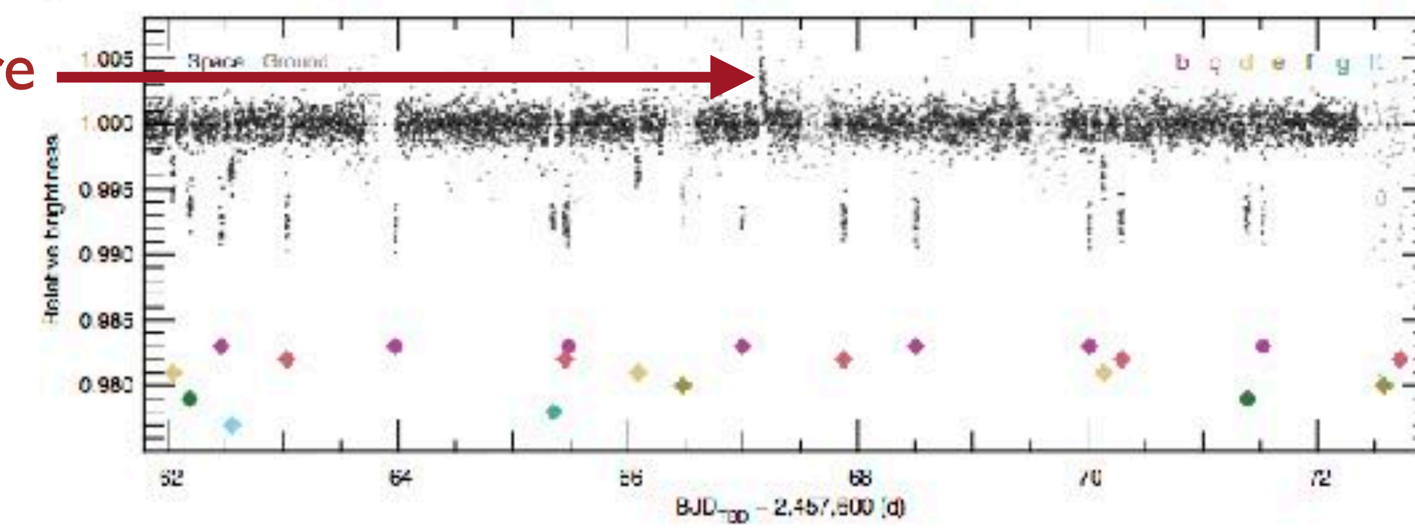
Full Sun: SDO/HMI continuum



Swedish Telescope, V. Henriques

Spitzer lightcurve, TRAPPIST-1 Gillon et al. (2017)

Flare

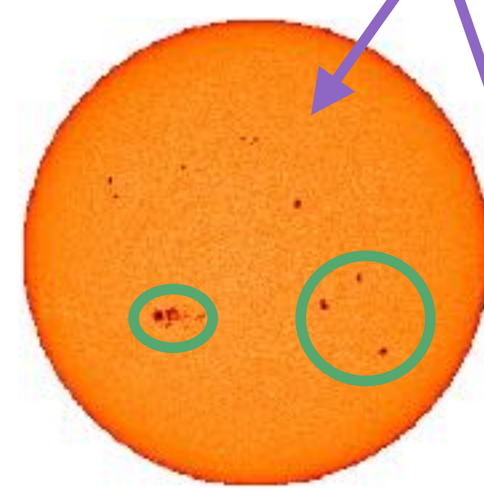


See Schrijver & Zwaan (2000), Hall (2008), Reiners (2012), Haywood (2015, Chap. 1) and others

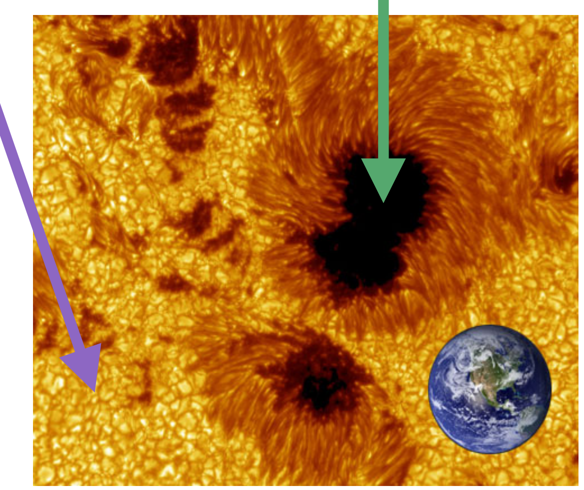
Stellar activity can affect transit-measured planet parameters

Stars vary on timescales from minutes to years:

- Oscillations and granulation *min-hours*
- Flares/coronal mass ejections *min-hours (esp. M dwarfs)*
- Magnetic surface features (spots, faculae) *stellar rotation period*

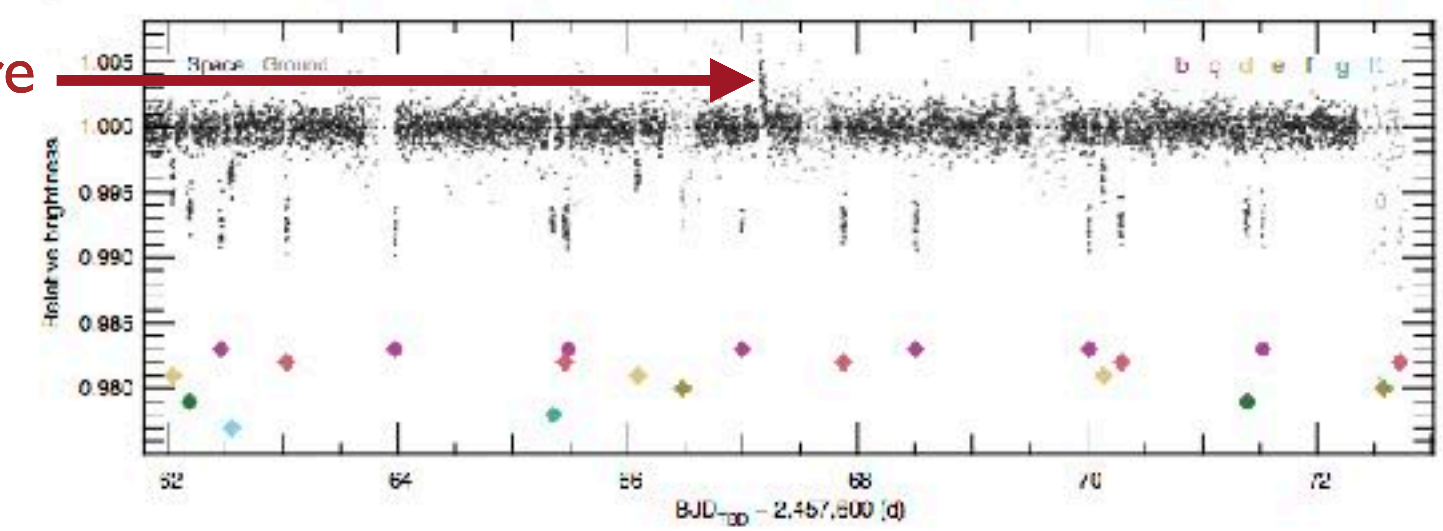


Full Sun: SDO/HMI continuum



Swedish Telescope, V. Henriques

Spitzer lightcurve, TRAPPIST-1 Gillon et al. (2017)



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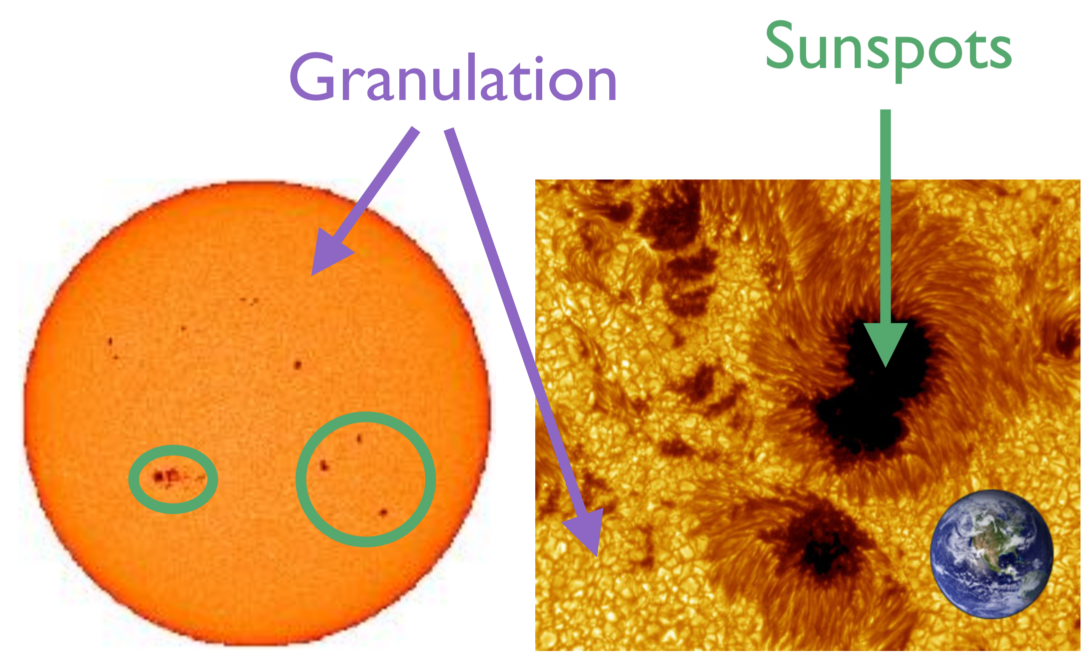
Stellar activity can affect transit-measured planet parameters

Stars vary on timescales from minutes to years:

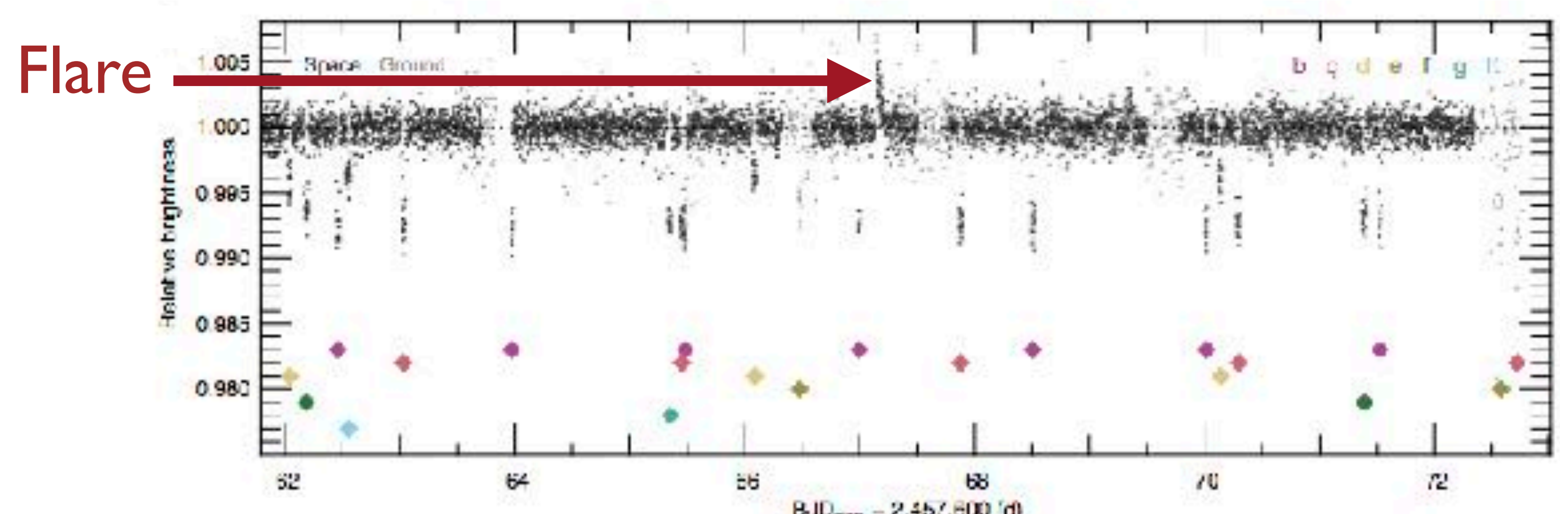
- Oscillations and granulation *min-hours*
- Flares/coronal mass ejections *min-hours (esp. M dwarfs)*
- Magnetic surface features (spots, faculae) *stellar rotation period*
- Magnetic cycles *years*



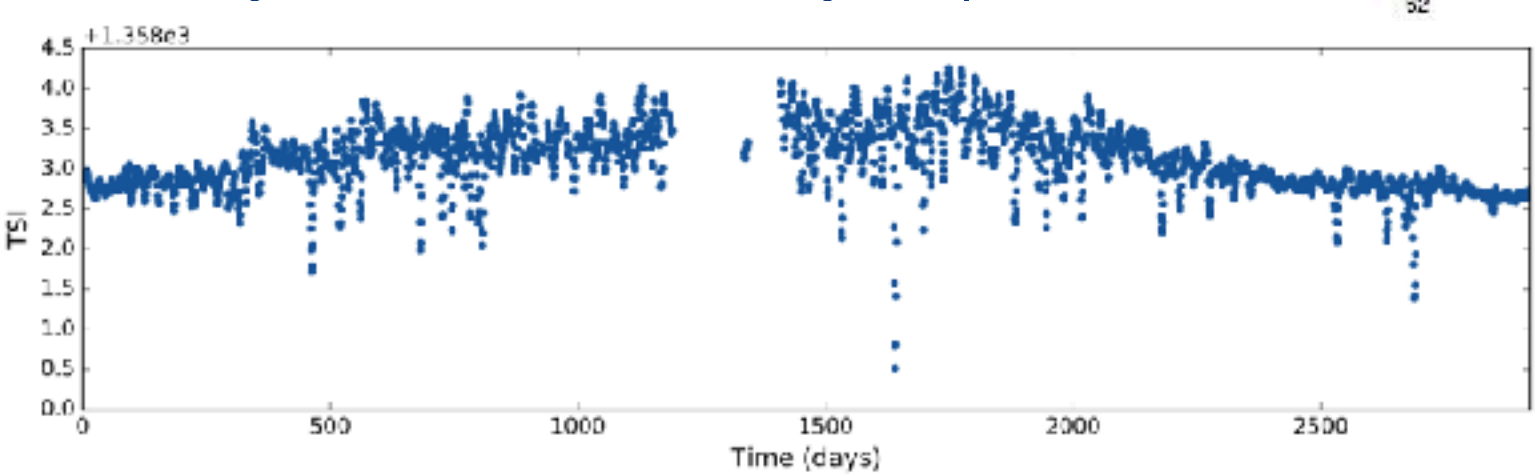
Full Sun: SDO/HMI continuum

Swedish Telescope, V. Henriques

Spitzer lightcurve, TRAPPIST-1 Gillon et al. (2017)



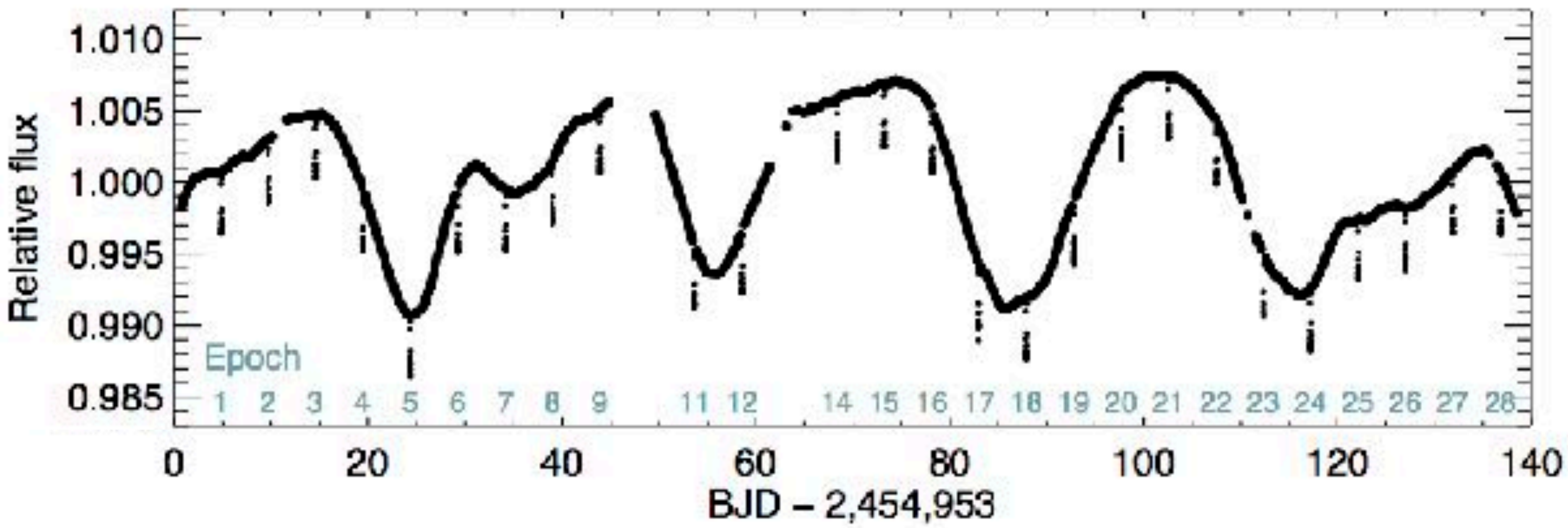
SORCE lightcurve of the Sun over a magnetic cycle



See Schrijver & Zwaan (2000), Hall (2008), Reiners (2012), Haywood (2015, Chap. 1) and others

Example: starspots (occulted AND unocculted) can affect estimate of planet radius

Kepler photometry of HAT-P-11 Sanchis-Ojeda et al. (2011)



See also Oshagh et al. (2014), Llama & Shkolnik (2015), Rackham et al. (2017a,b, 2018), Mallonn et al. (2018), and Apai et al. (2018) and references therein.

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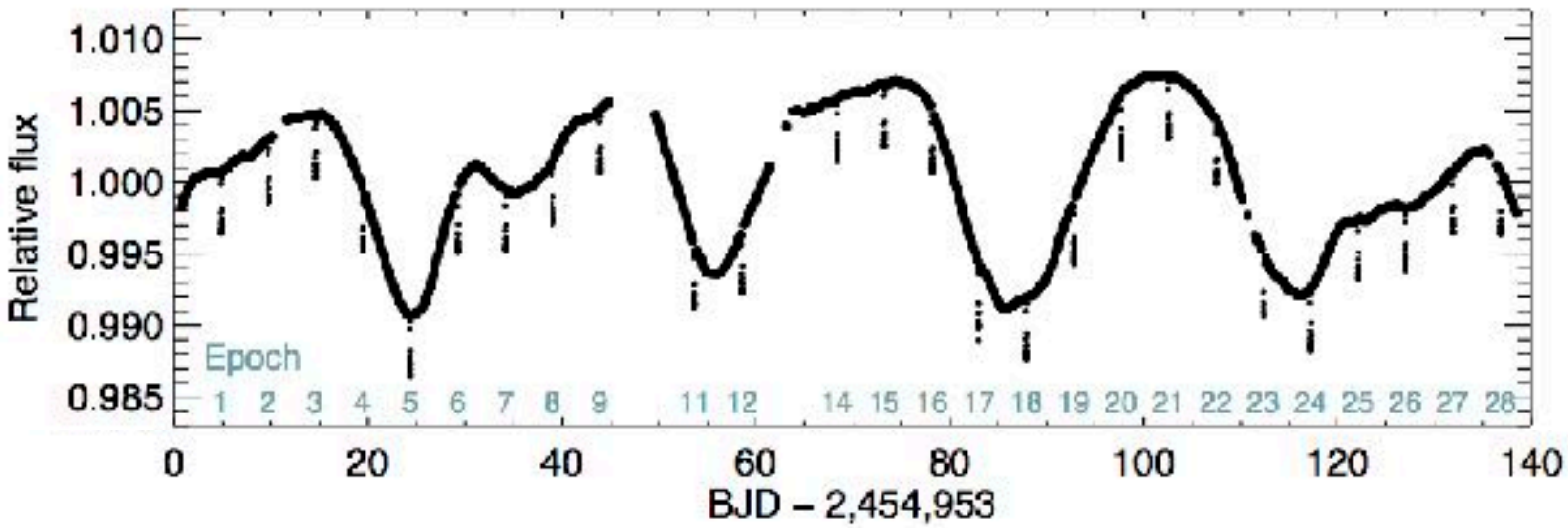
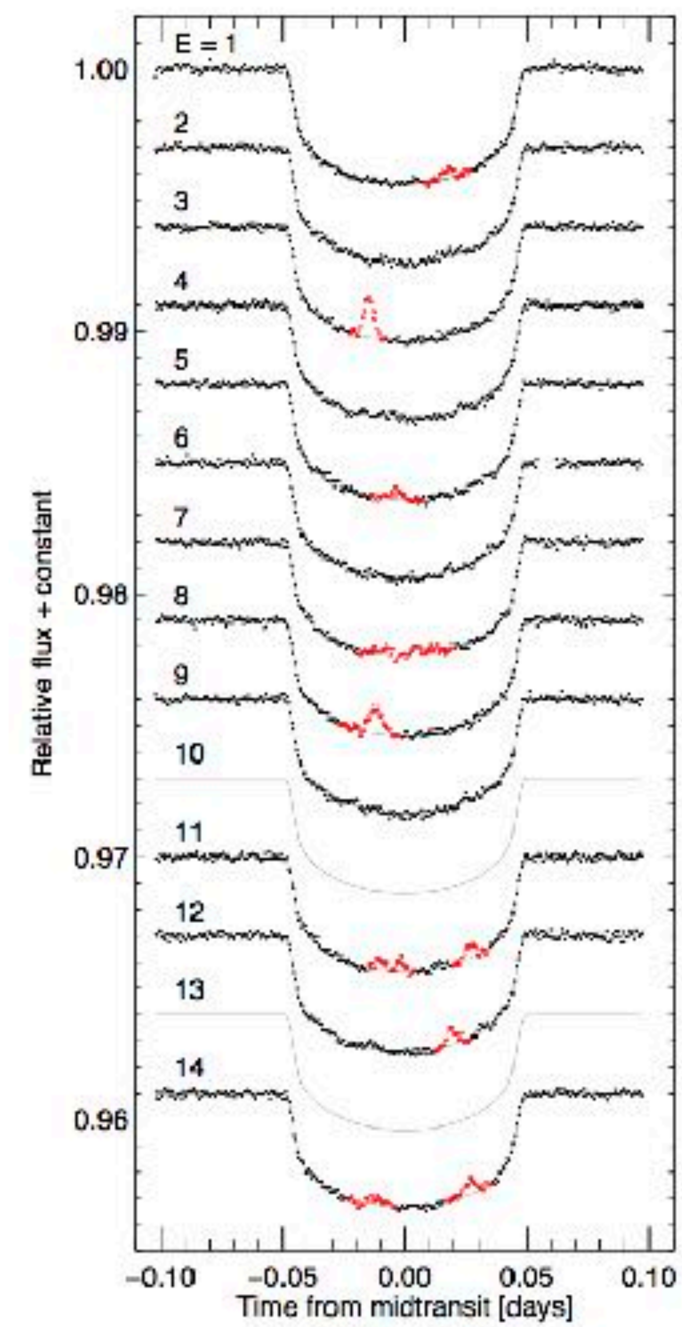


Individual transits of HAT-P-11b

Sanchis-Ojeda et al. (2011)



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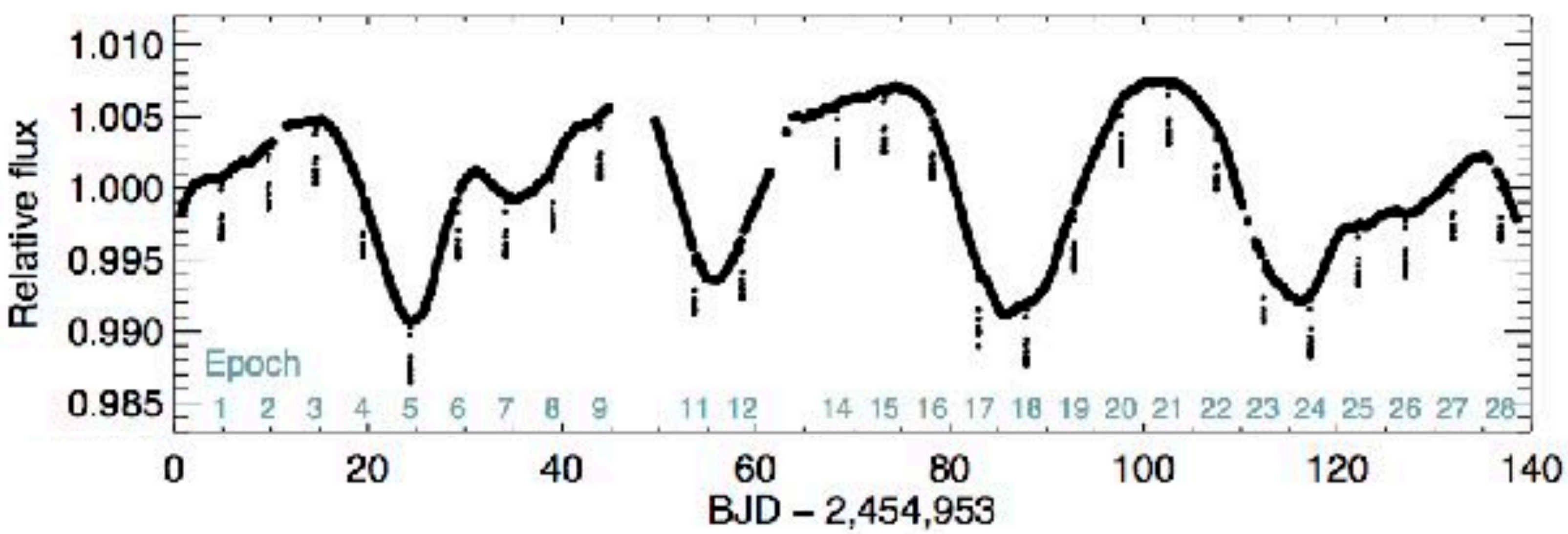
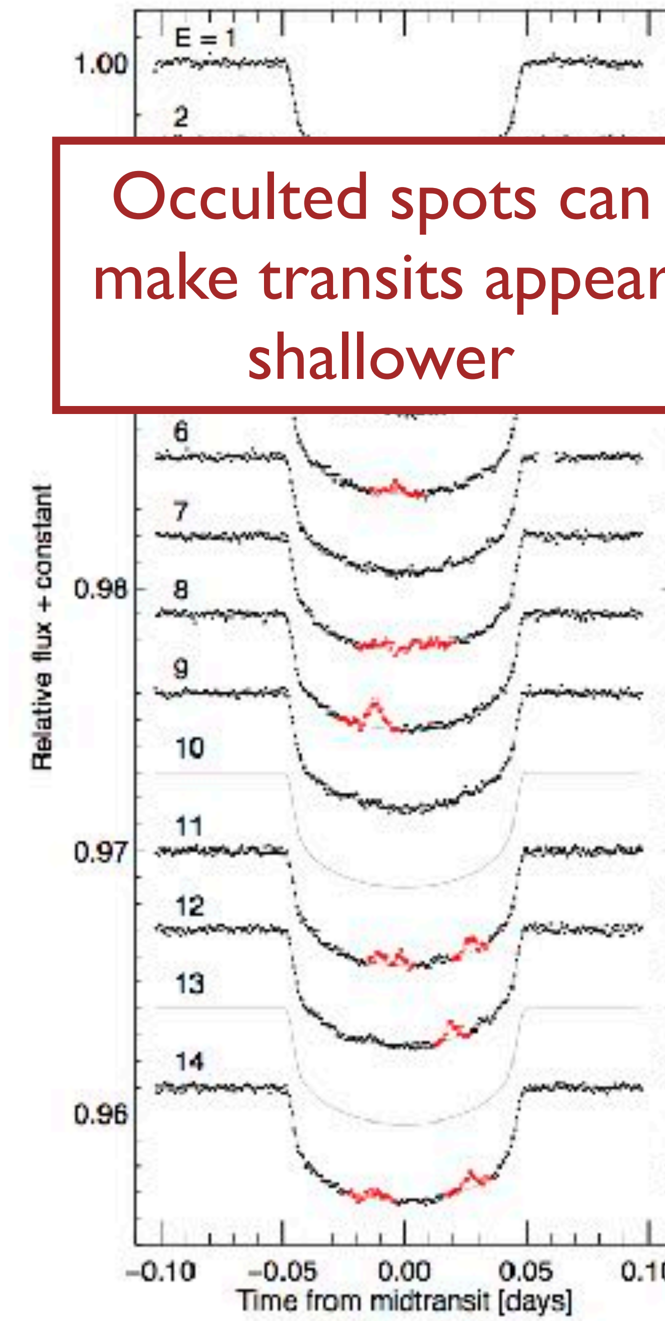


Individual transits of HAT-P-11b

Sanchis-Ojeda et al. (2011)

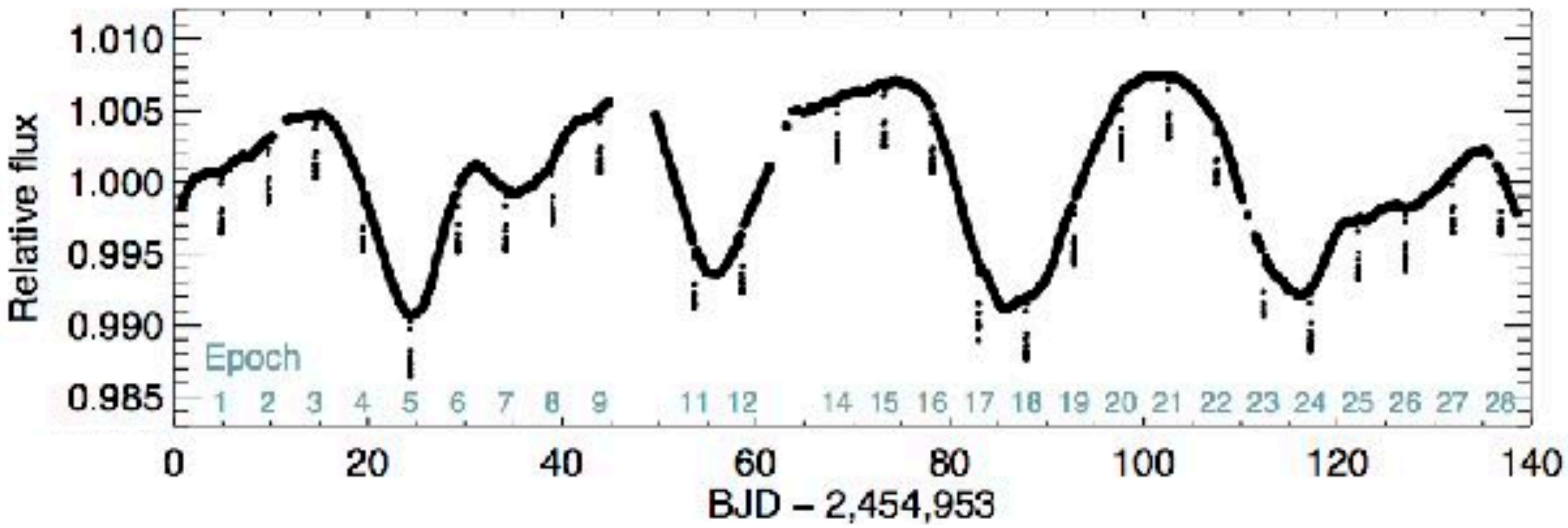


Occulted spots can make transits appear shallower

See also Oshagh et al. (2014), Llama & Shkolnik (2015), Rackham et al. (2017a,b, 2018), Mallonn et al. (2018), and Apai et al. (2018) and references therein.

Example: starspots (occulted AND unocculted) can affect estimate of planet radius

Kepler photometry of HAT-P-11 Sanchis-Ojeda et al. (2011)



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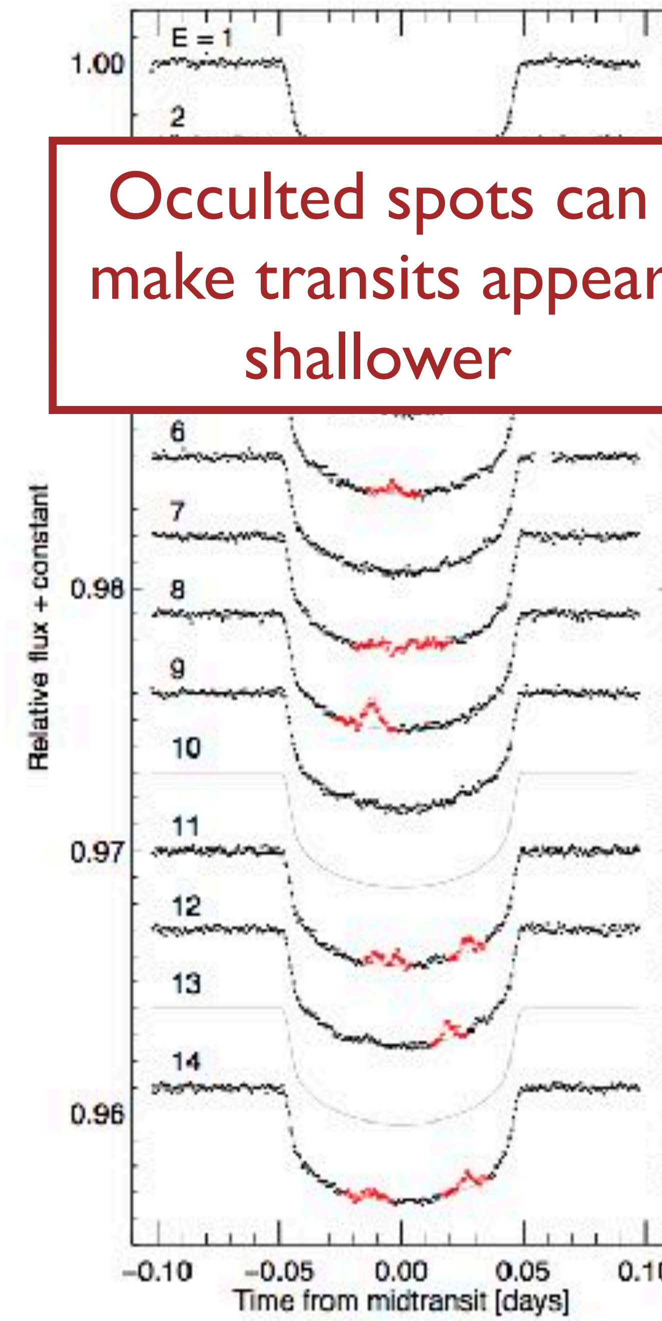

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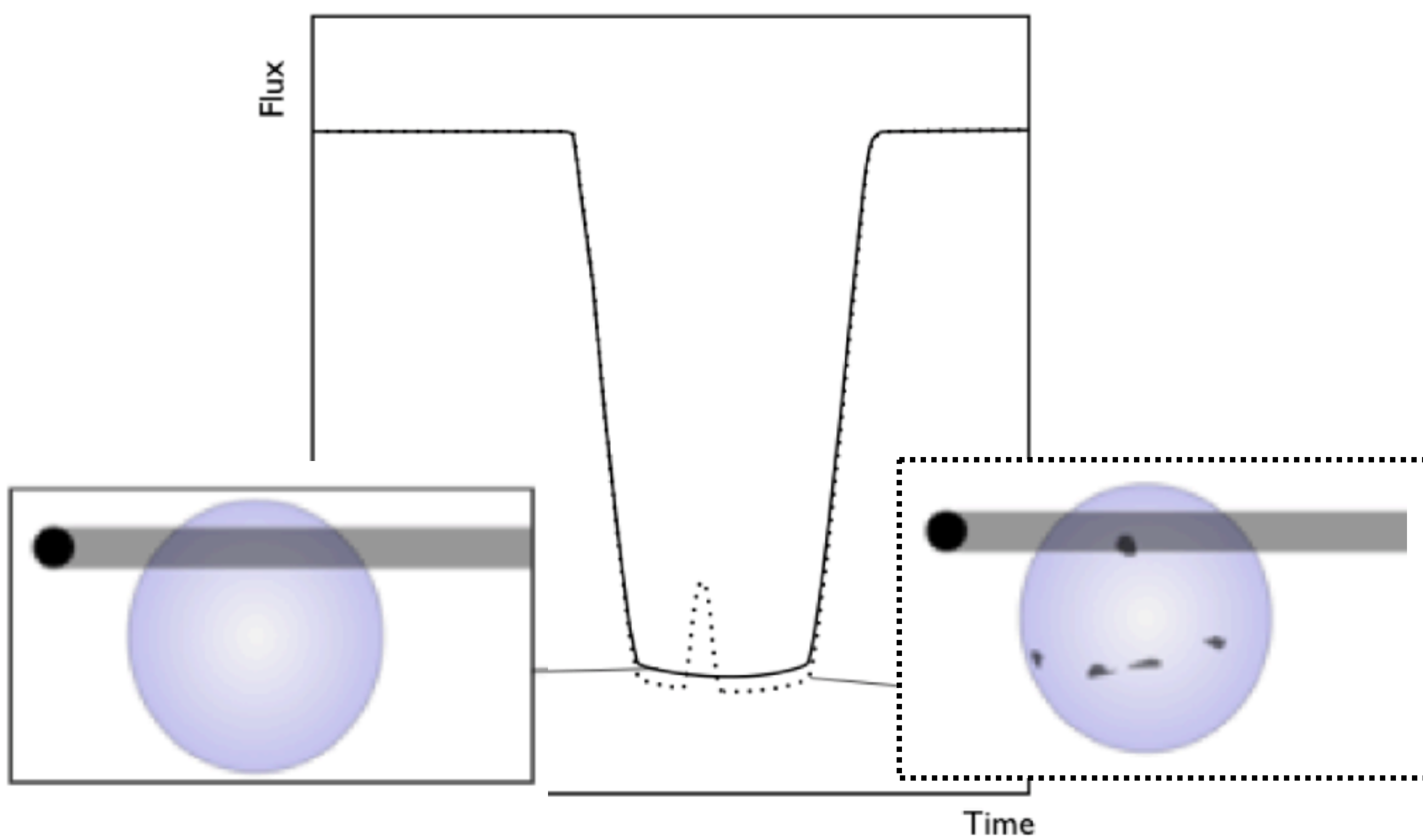
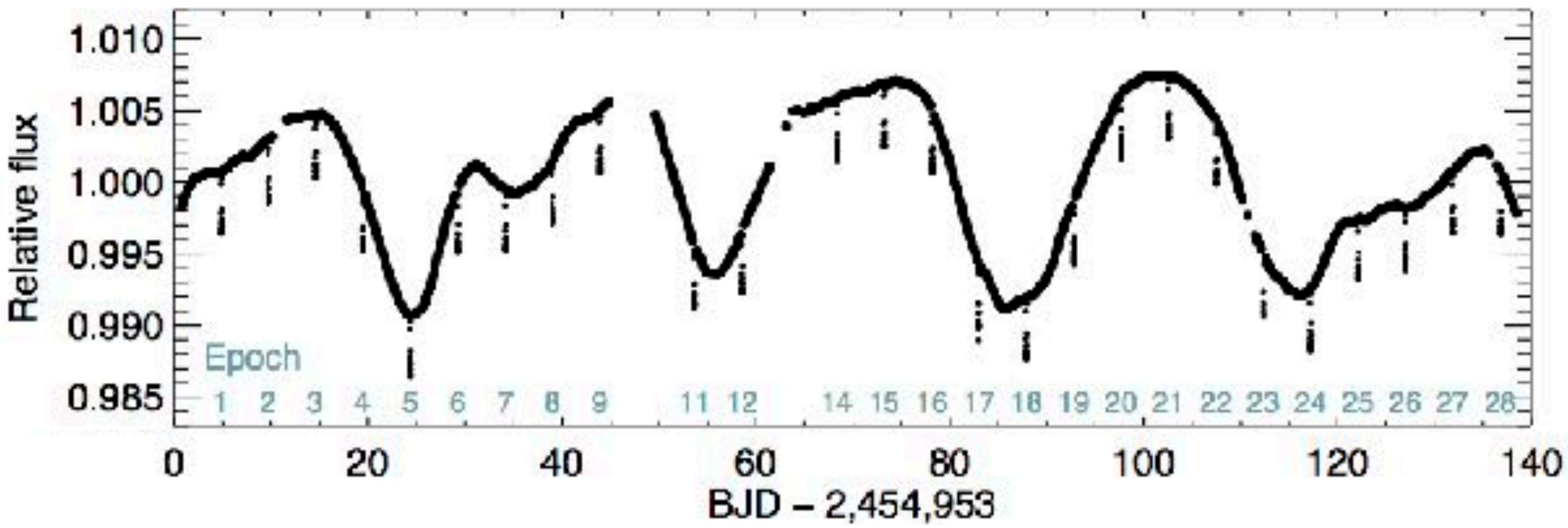


Pont et al. (2008), Pont et al. (2013)

See also Oshagh et al. (2014), Llama & Shkolnik (2015), Rackham et al. (2017a,b, 2018), Mallonn et al. (2018), and Apai et al. (2018) and references therein.

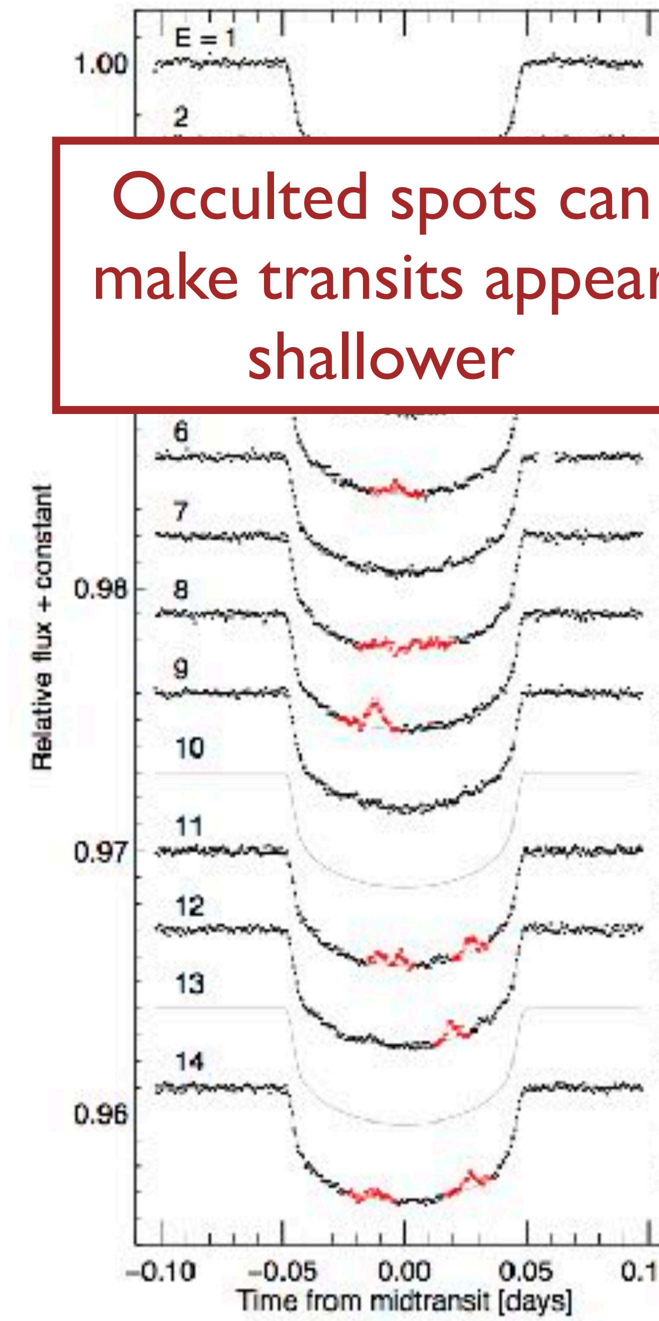
Example: starspots (occulted AND unocculted) can affect estimate of planet radius

Kepler photometry of HAT-P-11 Sanchis-Ojeda et al. (2011)

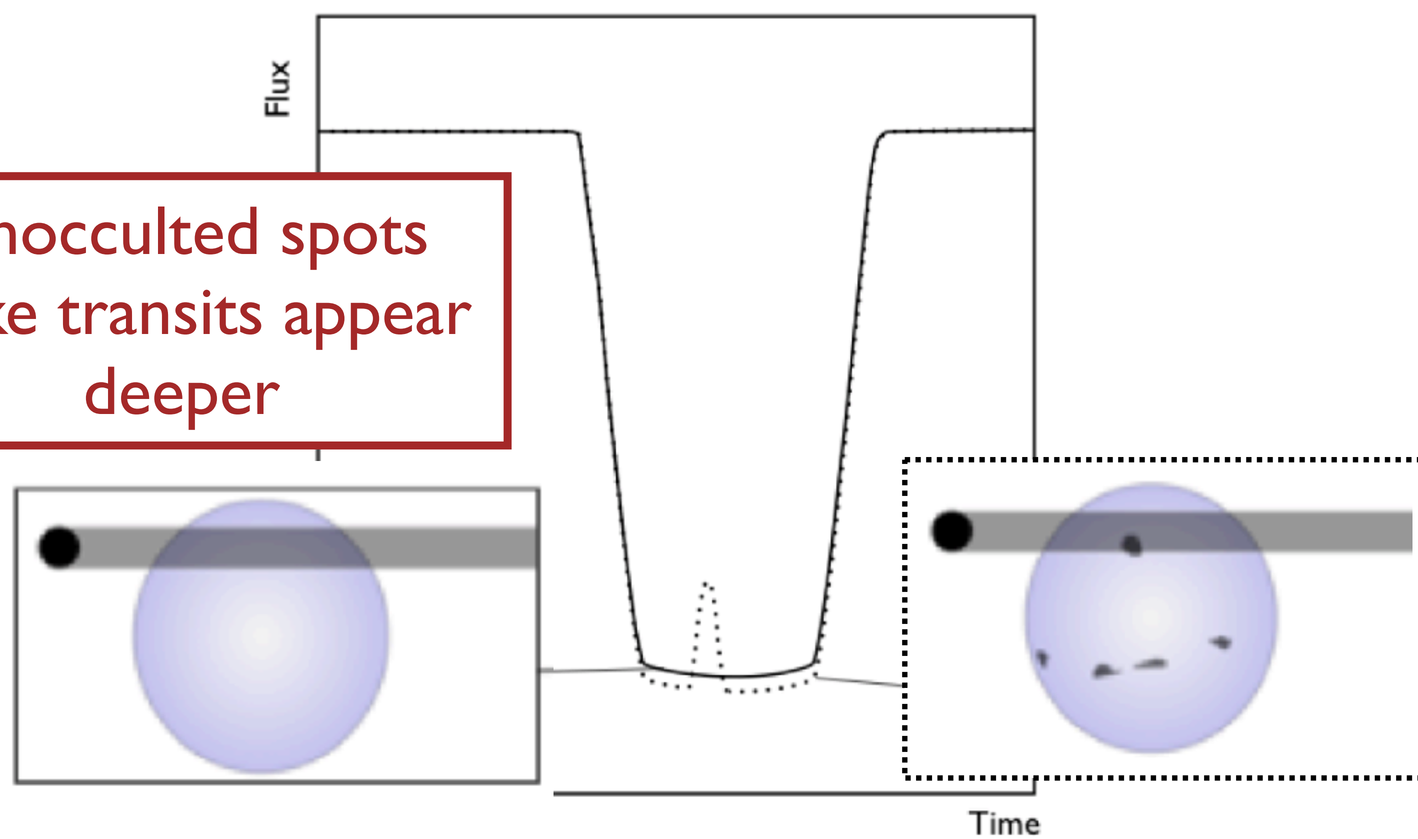


Individual transits of HAT-P-11b

Sanchis-Ojeda et al. (2011)



Occulted spots can make transits appear shallower



Unocculted spots make transits appear deeper

Pont et al. (2008), Pont et al. (2013)

See also Oshagh et al. (2014), Llama & Shkolnik (2015), Rackham et al. (2017a,b, 2018), Mallonn et al. (2018), and Apai et al. (2018) and references therein.

Inaccurate stellar radii bias planet radii

See Huber et al. (2016, 2014, 2013), Petigura et al. (2017), Bastien et al. (2014),
Dressing & Charbonneau (2013) and others

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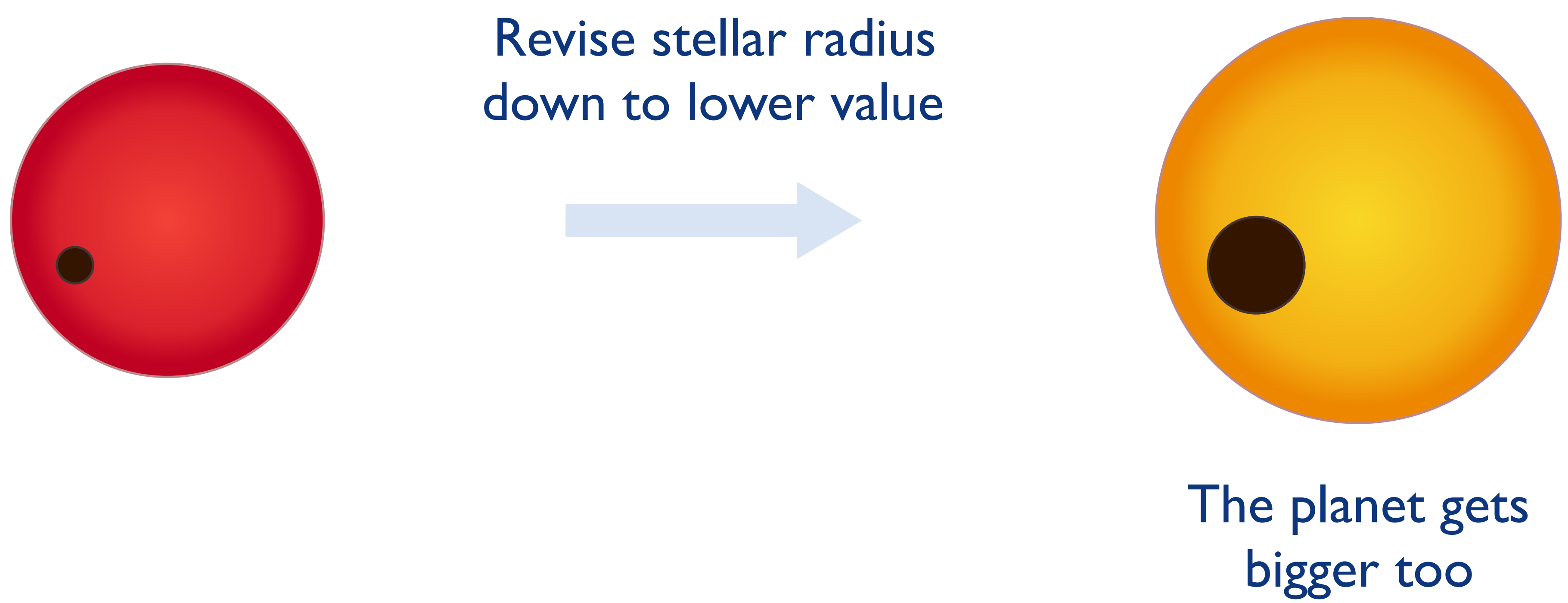

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Revise stellar radius
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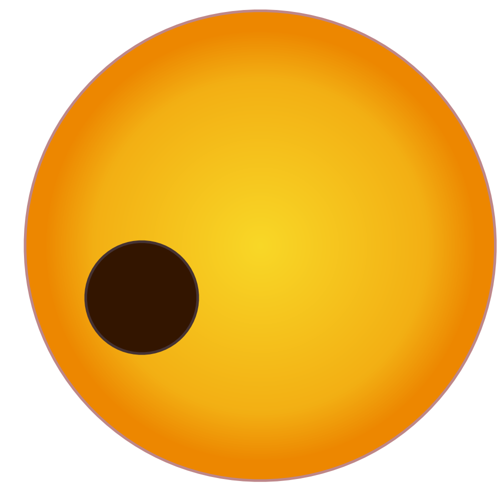

The planet gets
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An accurate and precise
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See Alessandro Sozzetti's talk about Gaia on Thursday

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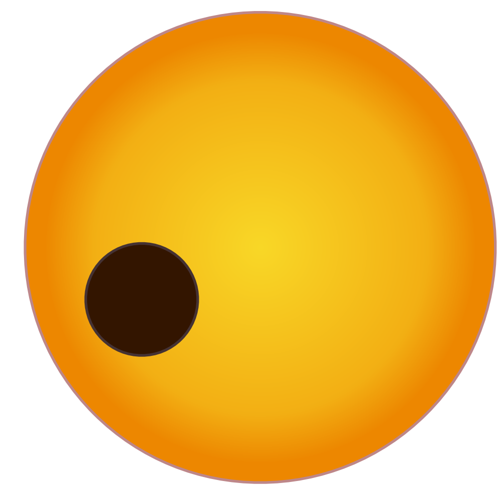

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- For accurate and precise planet parameters, we need accurate and precise stellar parameters!!!

References for further reading

The basics of exoplanet detection and characterisation:

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Reviews on stellar activity:

Haywood, R. D. (2015). *Hide and Seek: Radial-Velocity Searches for Planets around Active Stars*. Chapter 1, PhD thesis, University of St Andrews.

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Hall, J. C. 2008, Living Reviews in Solar Physics, 5, 2.

Reiners, A. 2012, Living Rev. Solar Phys., 9.

(The talk slides contain many more references about specific topics not listed on this slide.)