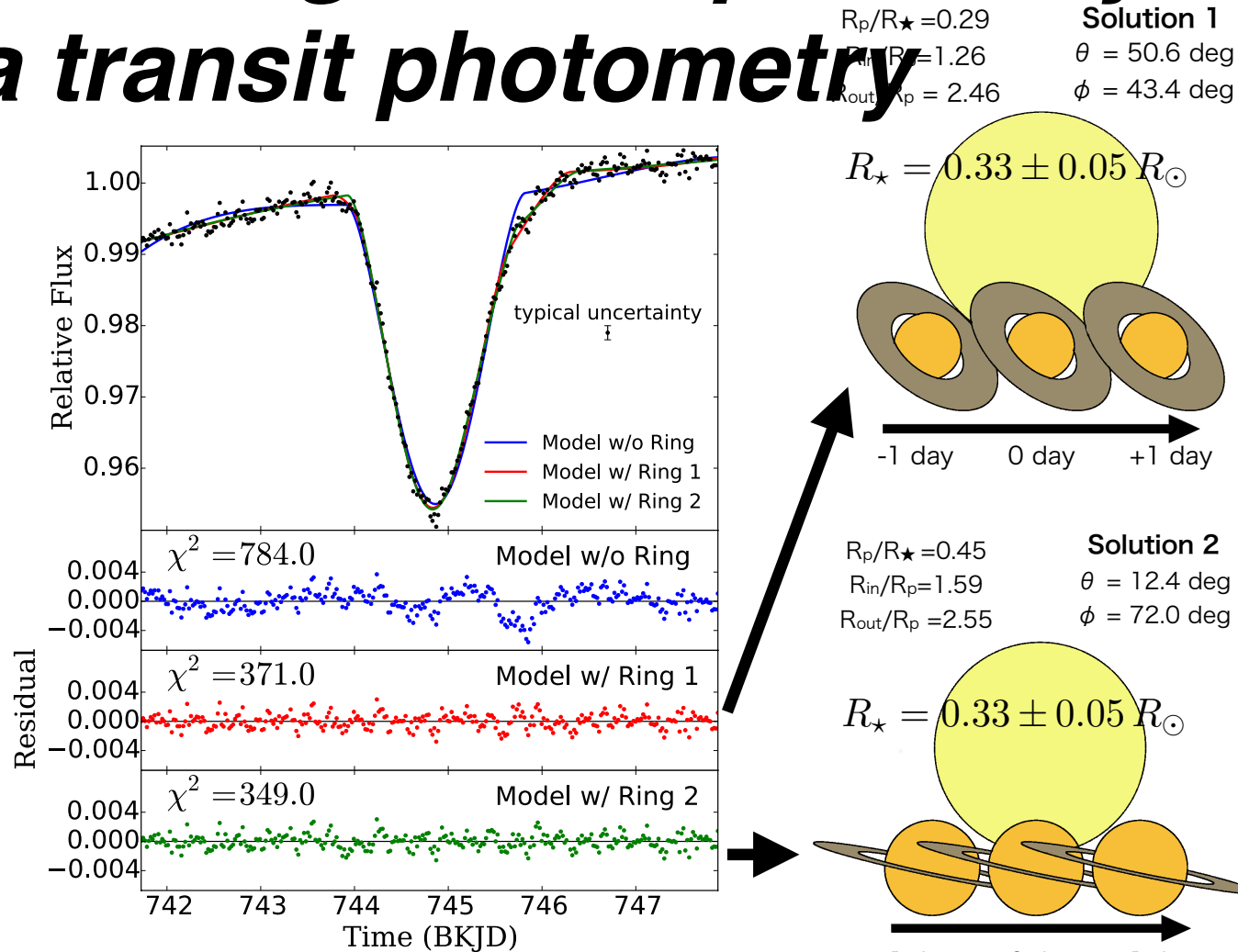


Searching for exoplanetary rings via transit photometry



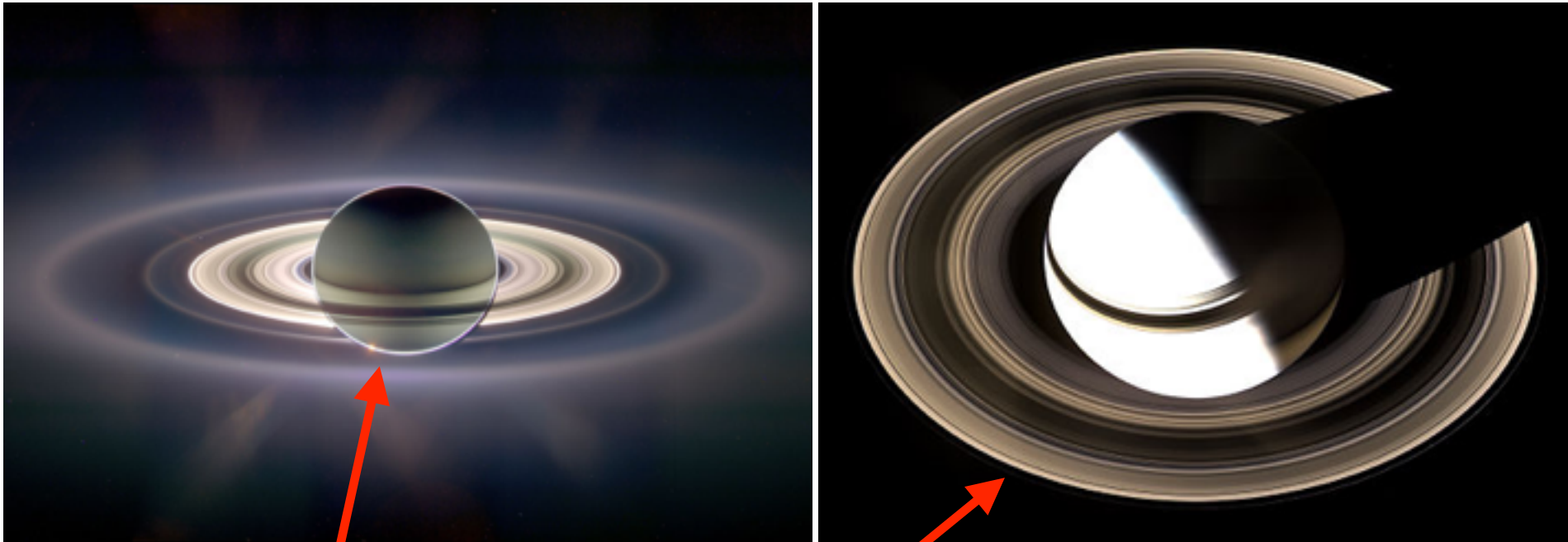
Masataka Aizawa (Univ. of Tokyo)

-----Collaborators-----

Sho Uehara (Tokyo Metropolitan University)

Kento Masuda, Hajime Kawahara, and Yasushi Suto (U.T)¹

No signature of exoplanetary rings until now!

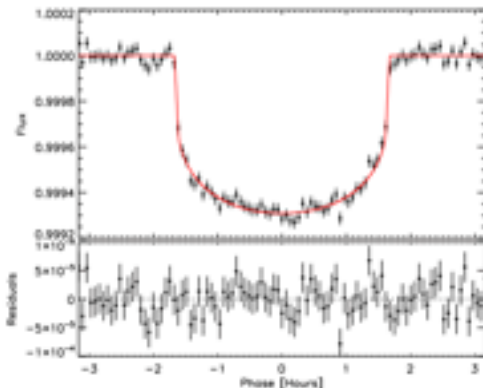
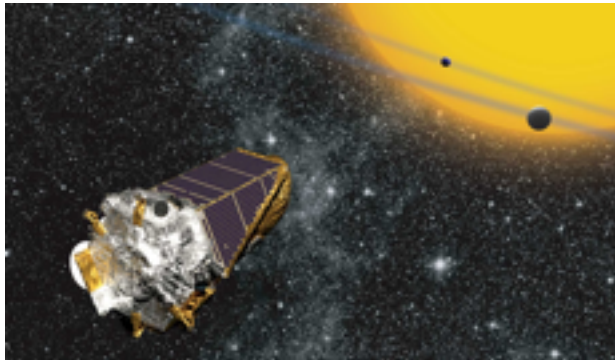


Noteworthy physical property for observation

- ✓ Photometric effect of rings is very large.
- ✓ Mass of Rings is small $M_{\text{ring}}/M_p \doteq 10^{-8}$
(Saturn)
- ✓ Orbital speed of rings is very fast (20~30

Possible probes to detect rings

- ✓ Reflection of Light (e.g. Dyudina et al. 2005)
- ✓ Line broadening due to rings (e.g. Santos et al 2015)
- ✓ Transit signature of rings (e.g. Schneider 2001)



• ***Kepler*** has detected over **8000 KOIs**(***Kepler Of Interests***)!!

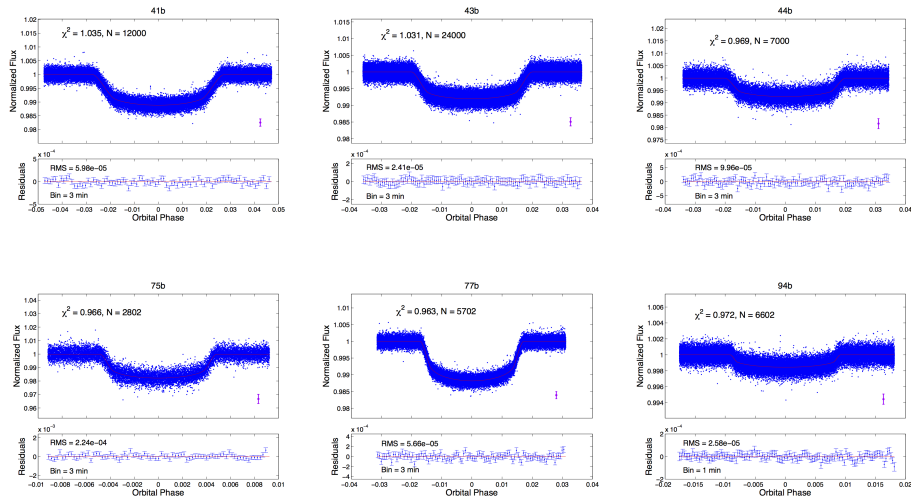
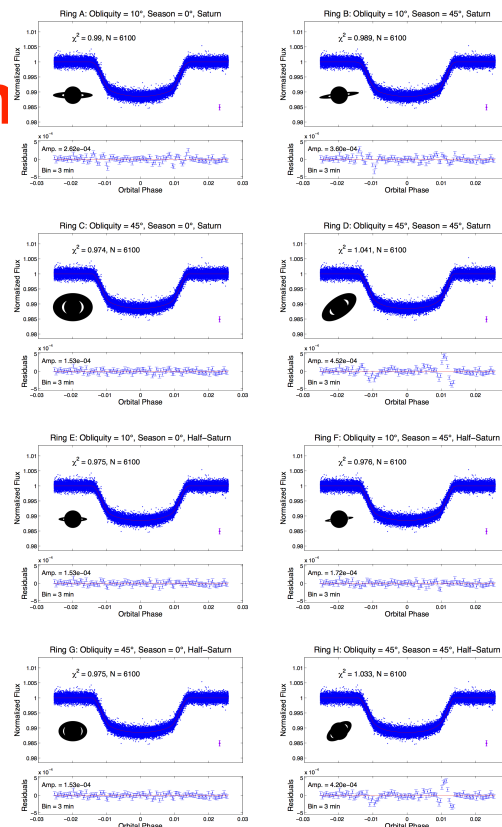
• Great precision light-curve data

Previous attempt to find rings via transit photometry

Heising et al. (2015) searched rings around **21 short-period**

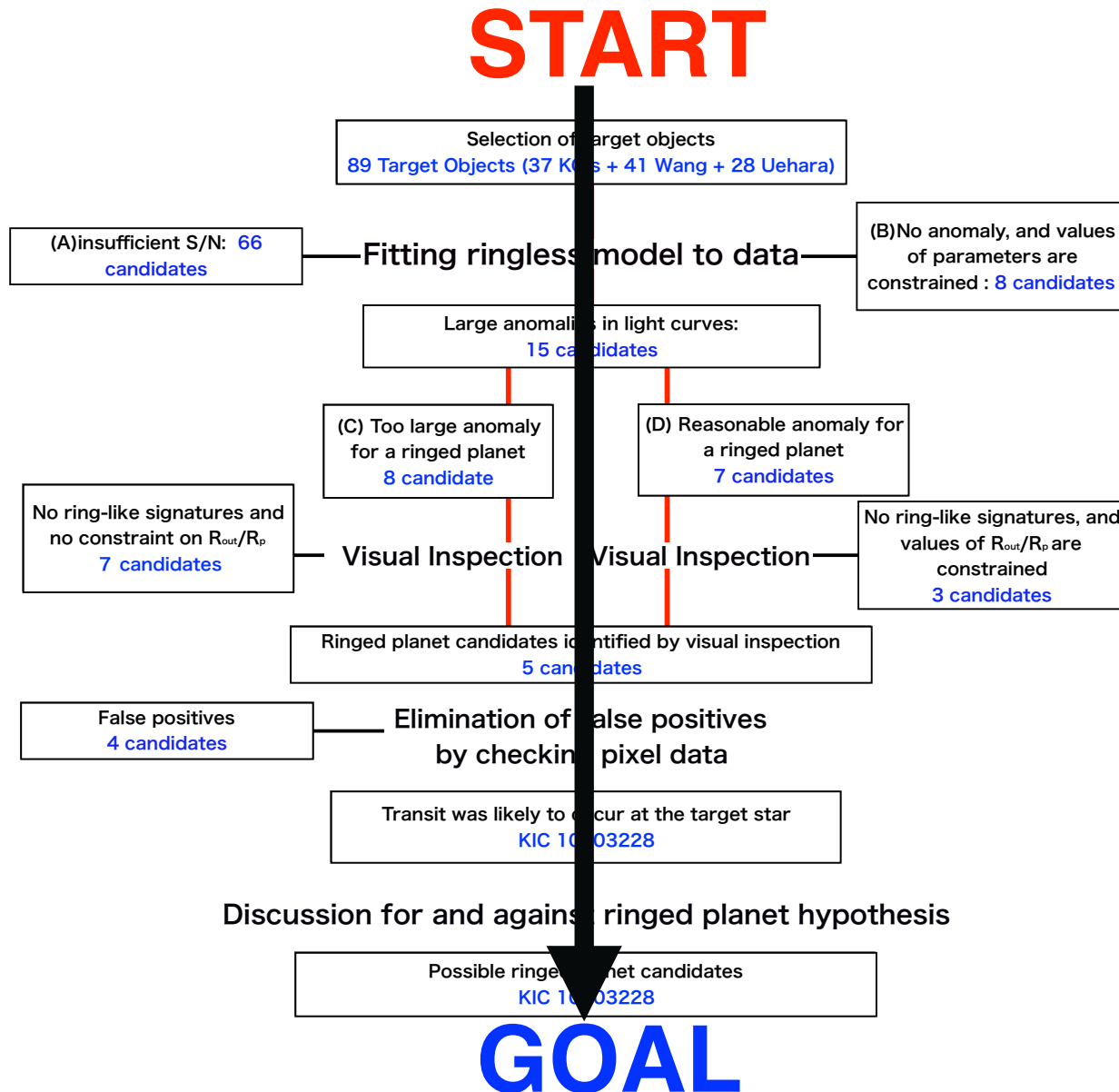
KOIs

No Sign Found



Instead, we searched for rings around **long-period planets** where ring particles are **stable** (Schlichting & Chang 2014)

Systematic search for rings



Selection of target objects
89 Target Objects (37 KOIs + 41 Wang + 28 Uehara)

We are Here!!

Fitting ringless model to data

(A) insufficient S/N: 66 candidates

(B) No anomaly, and values of parameters are constrained : 8 candidates

Large anomalies in light curves:
15 candidates

(C) Too large anomaly for a ringed planet
8 candidate

(D) Reasonable anomaly for a ringed planet
7 candidates

No ring-like signatures and no constraint on R_{out}/R_p
7 candidates

Visual Inspection

Visual Inspection

No ring-like signatures, and values of R_{out}/R_p are constrained
3 candidates

Ringed planet candidates identified by visual inspection
5 candidates

False positives
4 candidates

Elimination of false positives by checking pixel data

Transit was likely to occur at the target star
KIC 10403228

Discussion for and against ringed planet hypothesis

Possible ringed planet candidates
KIC 10403228

Selection of long-period planets

Transit photometry has little sensitivity to long-period planets

- Long-period planet candidates listed in the ***official catalog*** +
- Long-period planet candidates **independently found**

- ✓ Planet Hunters (Wang et al. 2015)
- ✓ Uehara et al. 2016



In total, we have **89 target objects** for searching for rings.

Selection of target objects
89 Target Objects (37 KOIs + 41 Wang + 28 Uehara)

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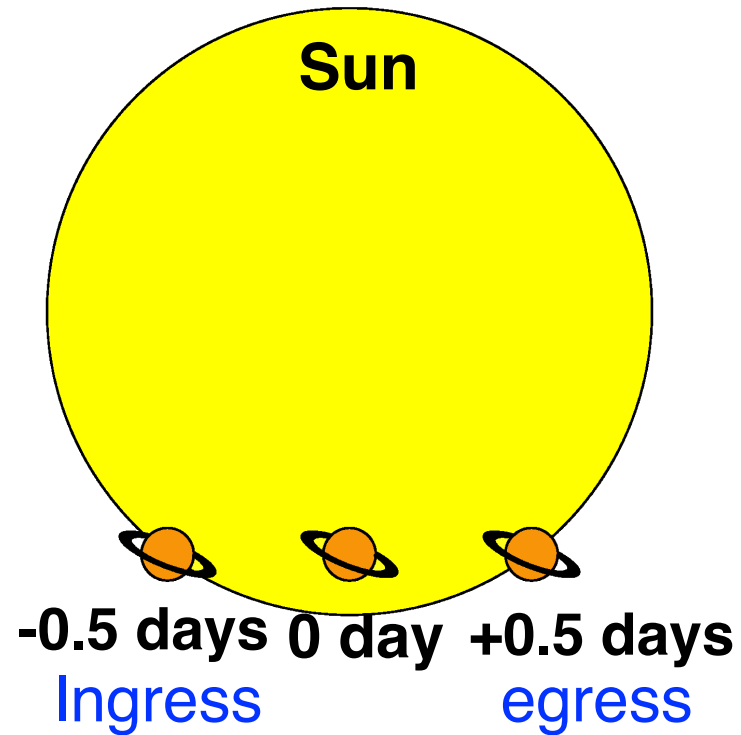
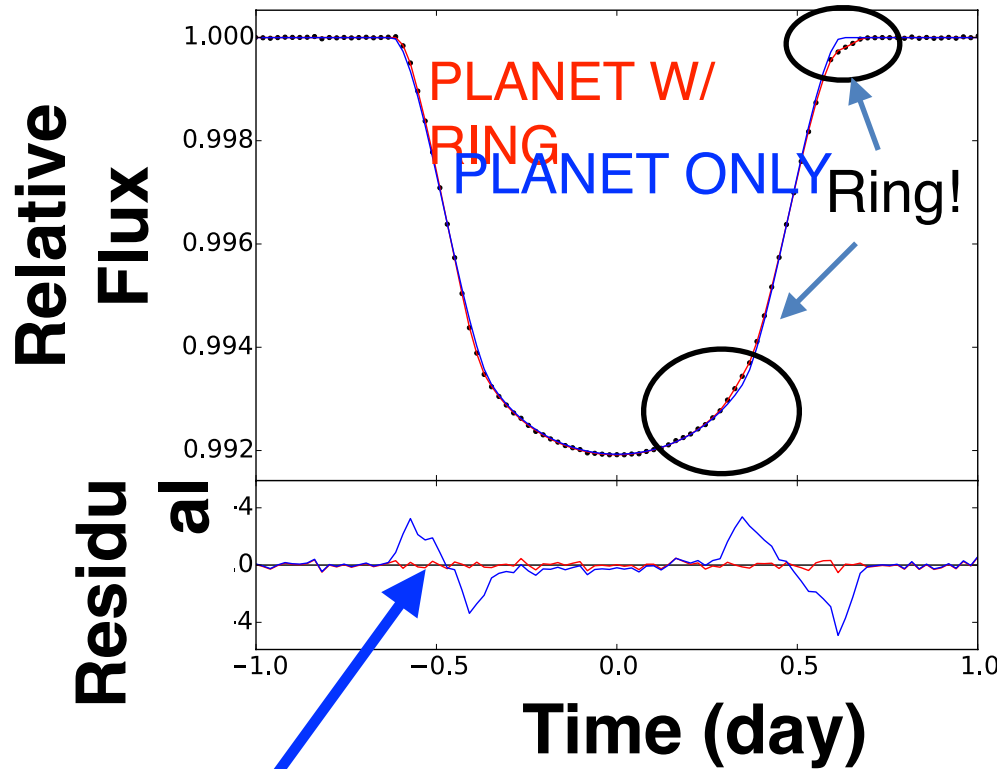
Transit was likely to occur at the target star
KIC 10403228

Discussion for and against ringed planet hypothesis

Possible ringed planet candidates
KIC 10403228

Fitting ringless model to data (simulation)

Suppose that Saturn transits Sun



Signature of rings are possibly left in **residuals** obtained from fitting **single planet model**

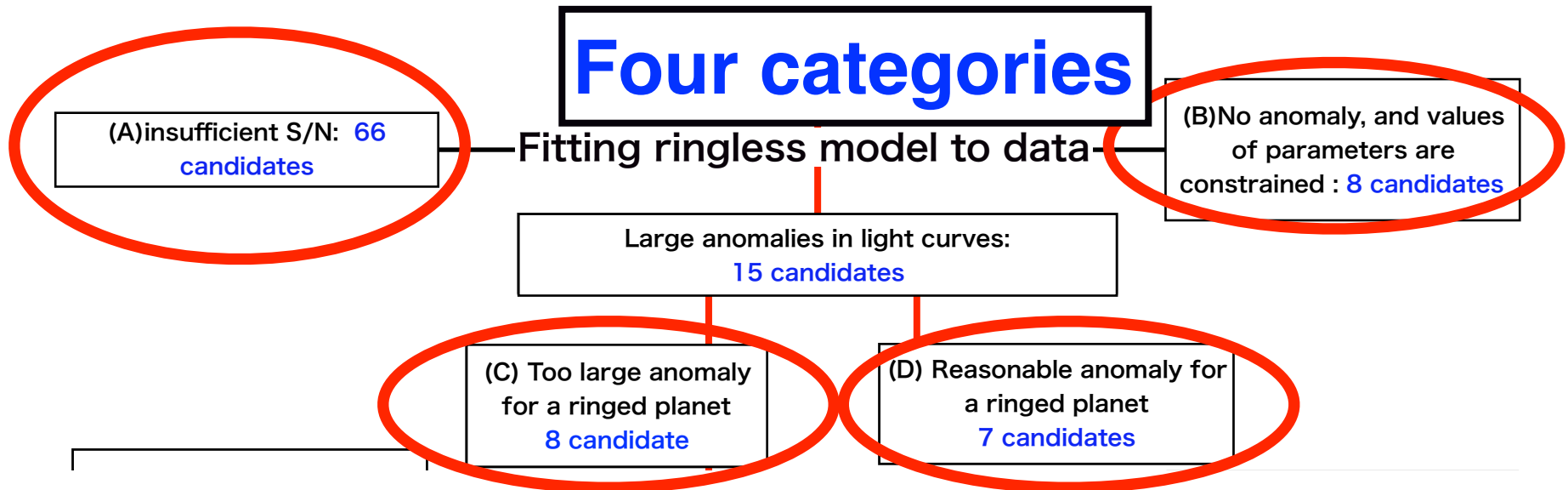
Evaluation of Observed Anomalies

Comparison between

Theoretically expected signals
(We assume some ring configurations)

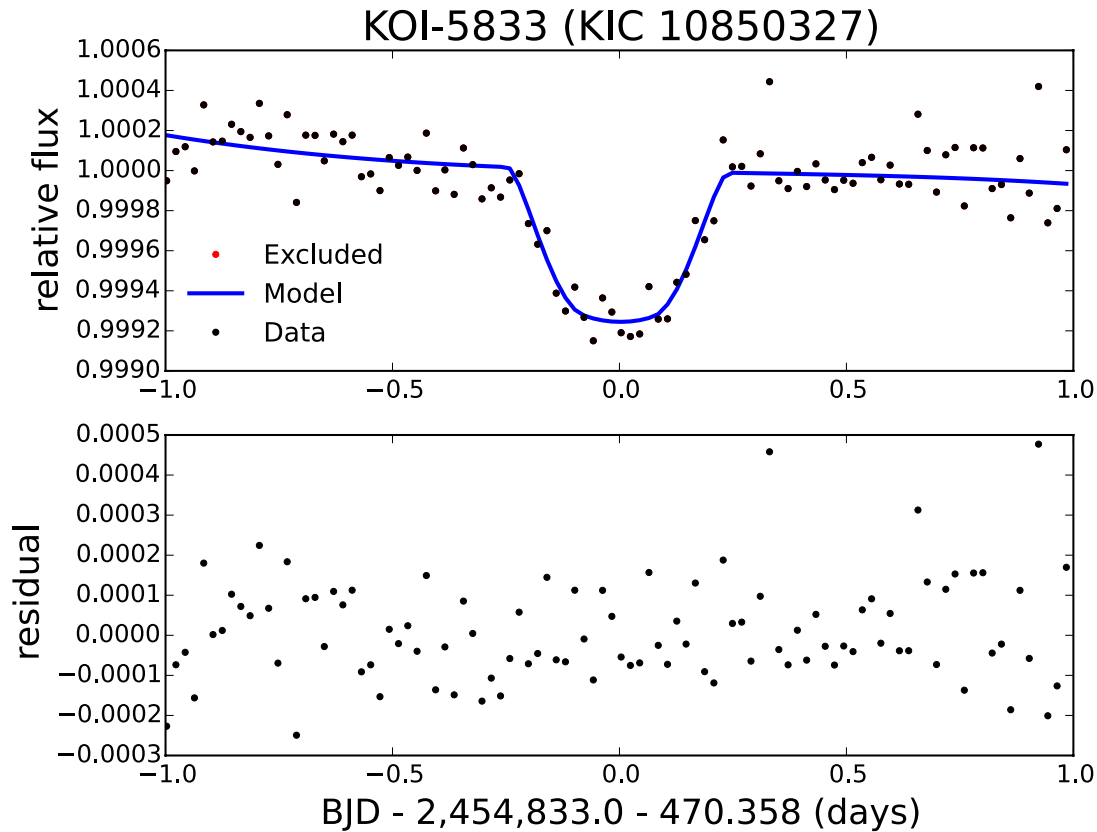
Observed anomalies
obtained
from fitting planet model

enables us to evaluate the magnitude of observed anomalies



(A) Expected S/N is insufficient

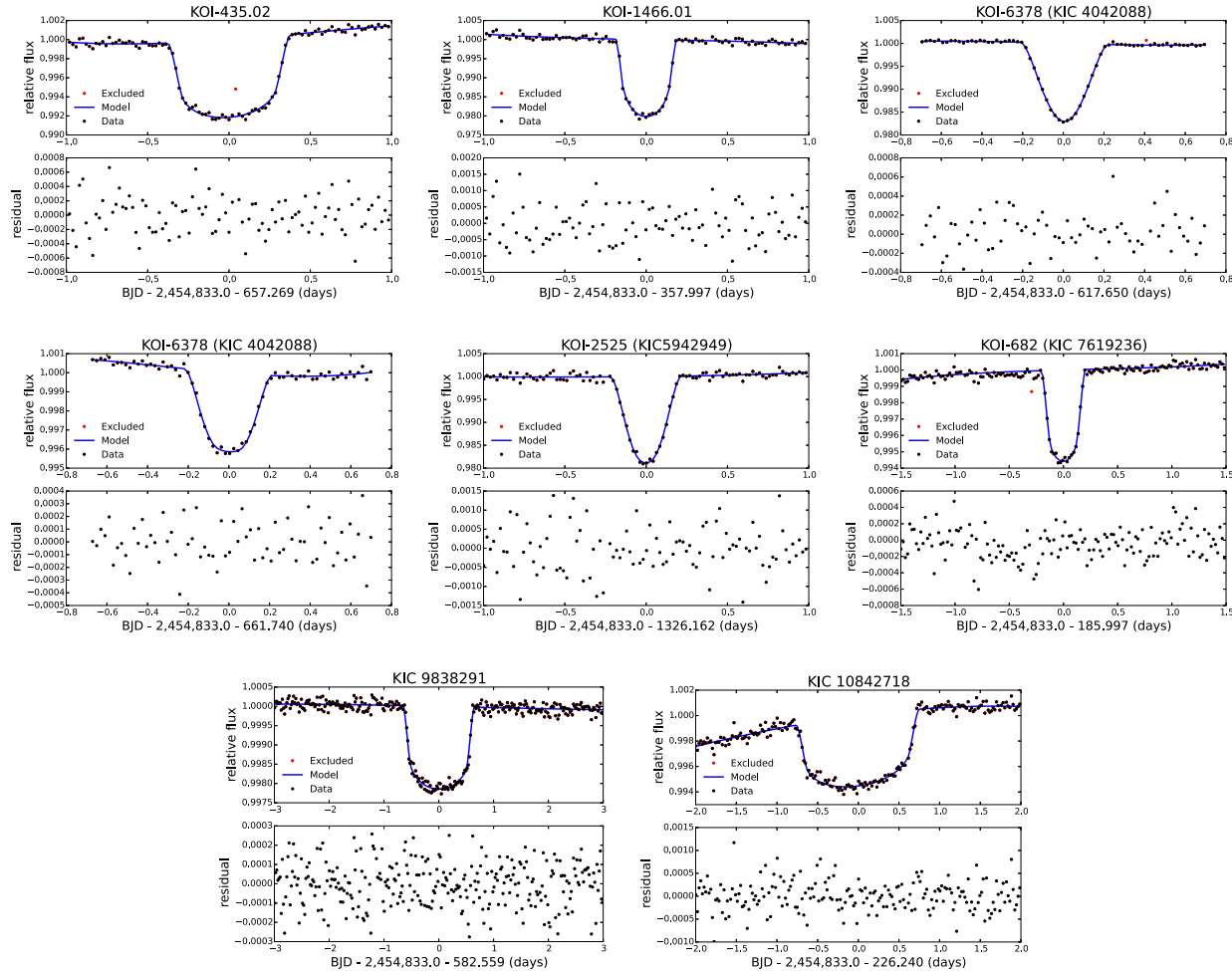
66 candidates



Noise is large, and we cannot discern rings if they e

(B) Sufficient S/N, but no anomaly found

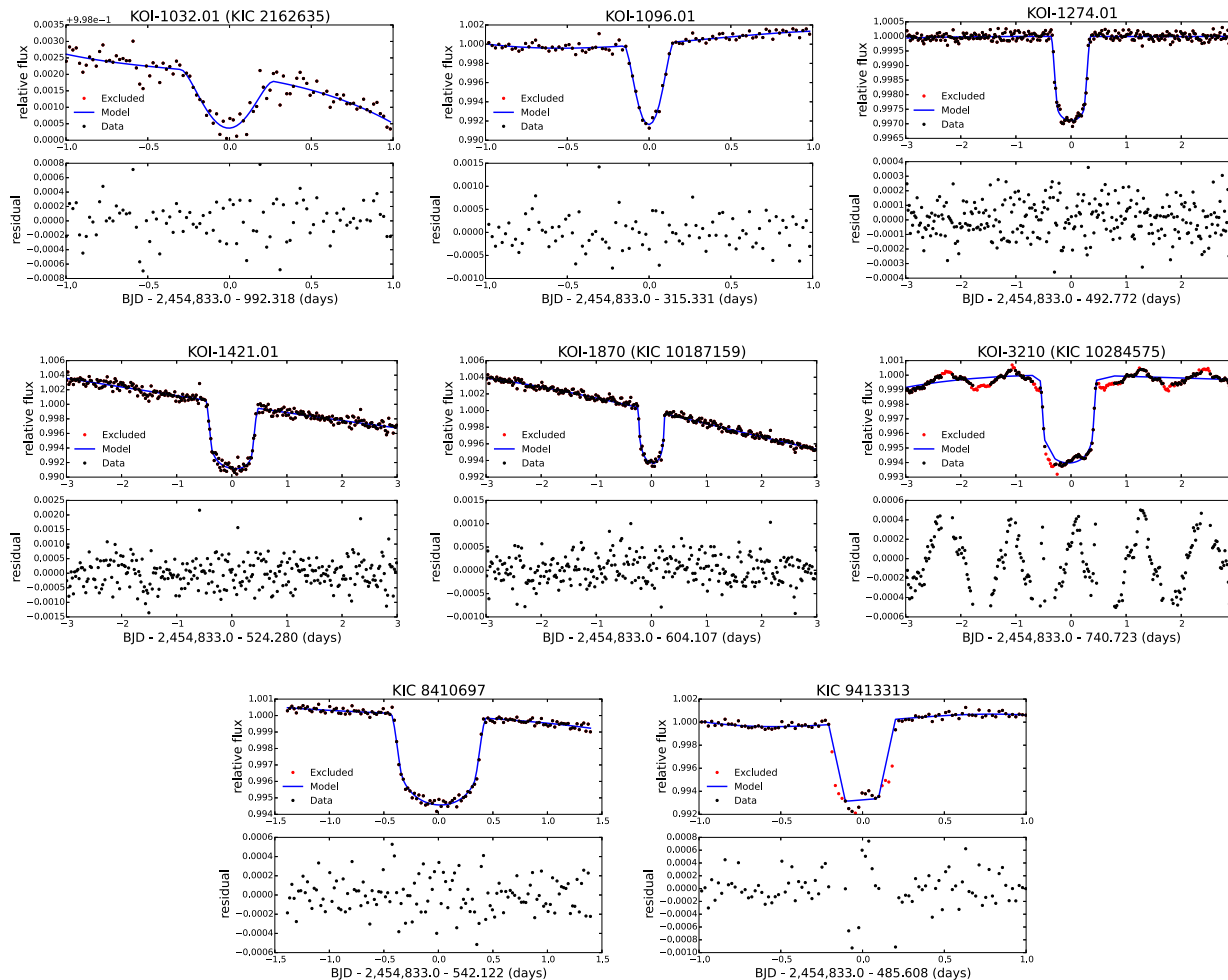
8 candidates



We can detect some rings if they exist, but there are no feature.

(C) Too large anomaly for ringed planets

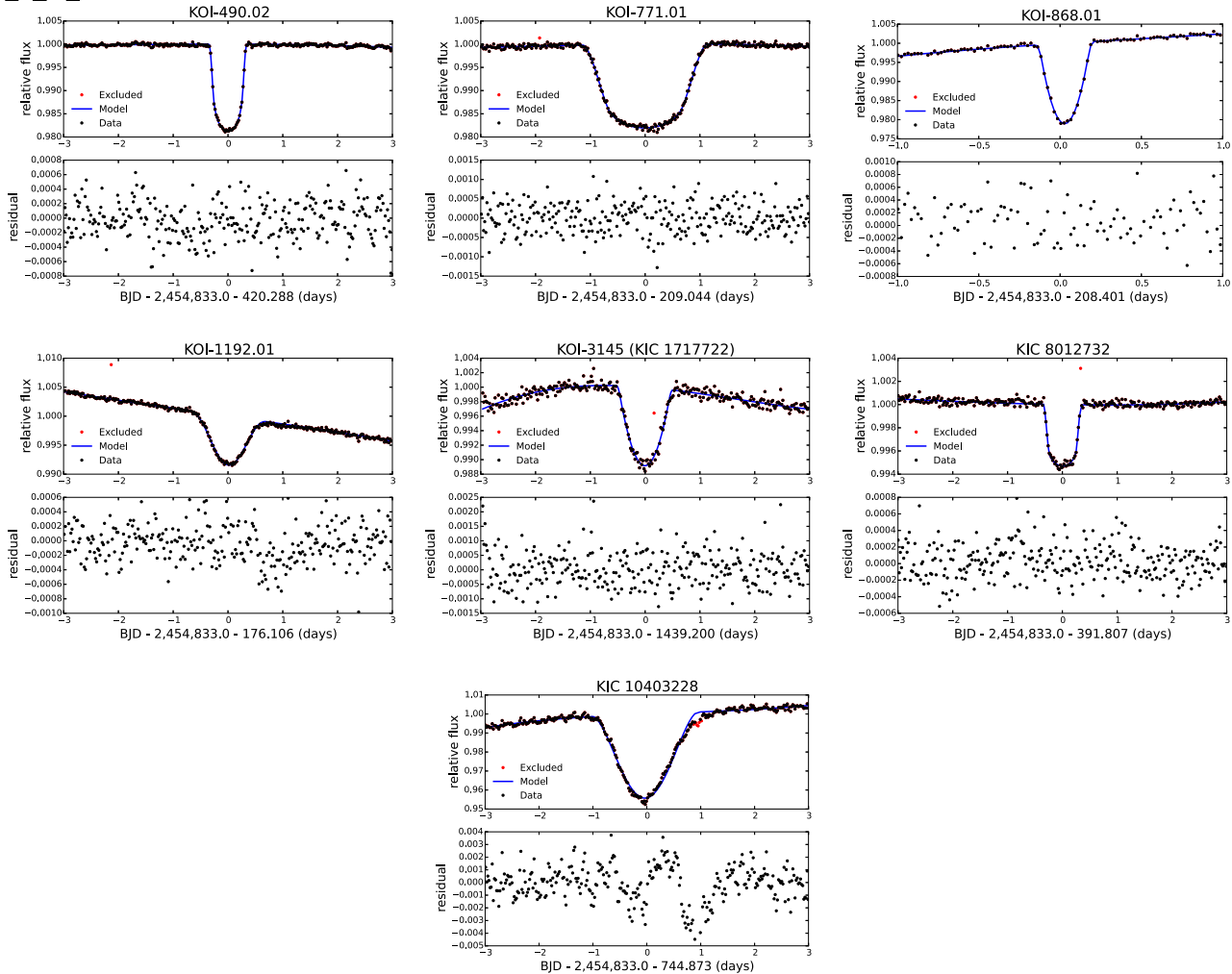
8 candidates



Anomalies are too large to be explained by assumed models.

(D) Reasonable anomaly for ringed planets

7 candidates



Anomalies are comparable to expected signals from assumed ringed planet model

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We are Here!!

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KIC 10403228

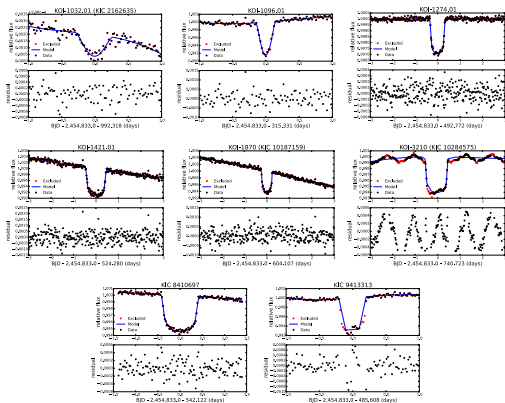
Discussion for and against ringed planet hypothesis

Possible ringed planet candidates
KIC 10403228

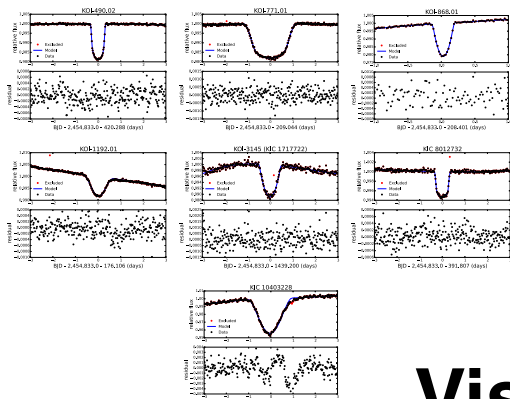
Visual searching for ring-like anomalies

15 anomalous transits

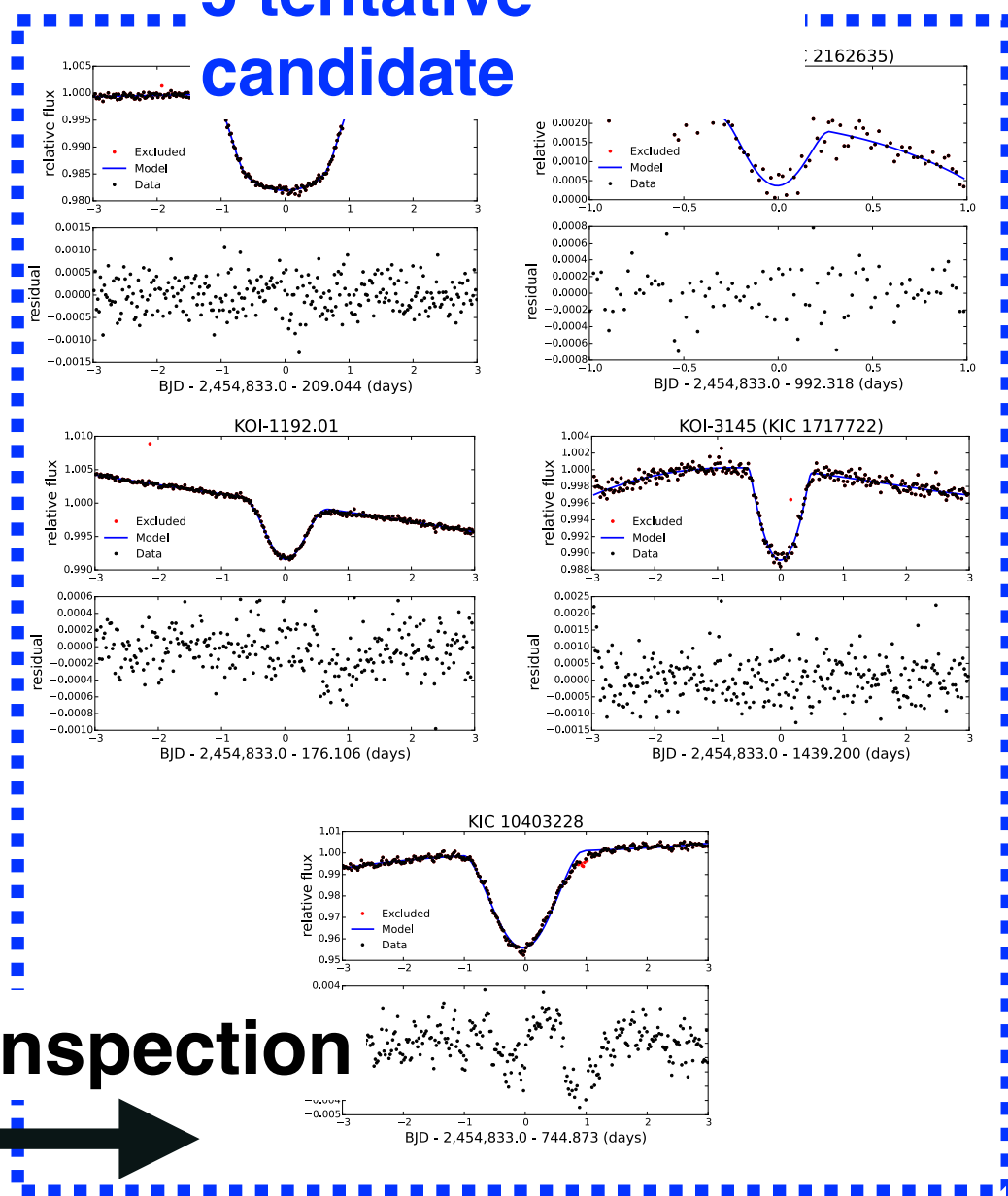
(C)



(D)



5 tentative candidate



Visual inspection



Selection of target objects
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4 candidates

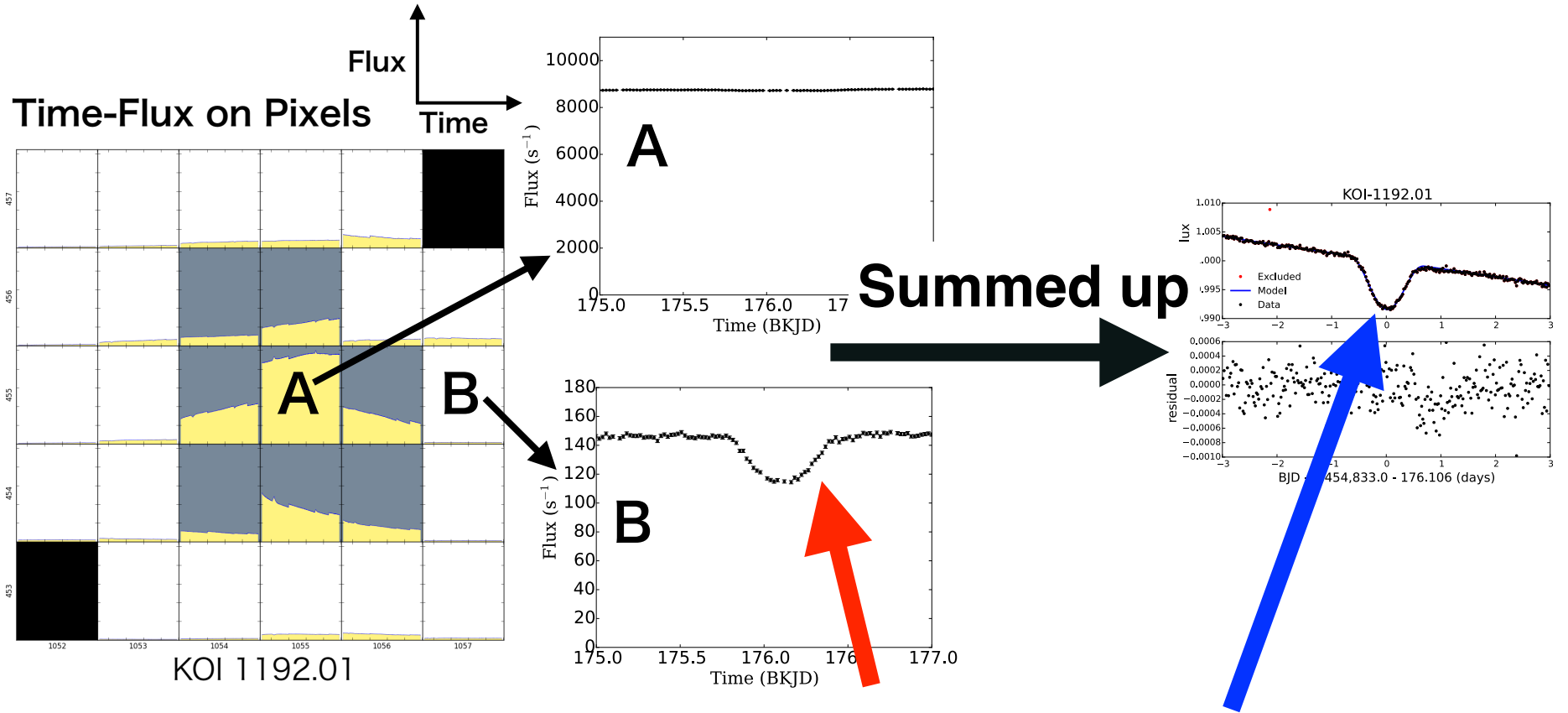
Elimination of false positives by checking pixel data

Transit was likely to occur at the target star
KIC 10403228

Discussion for and against ringed planet hypothesis

Possible ringed planet candidates
KIC 10403228

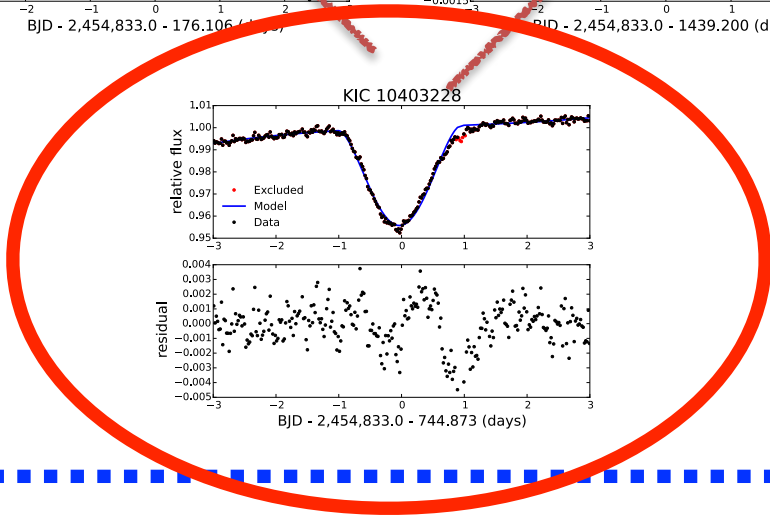
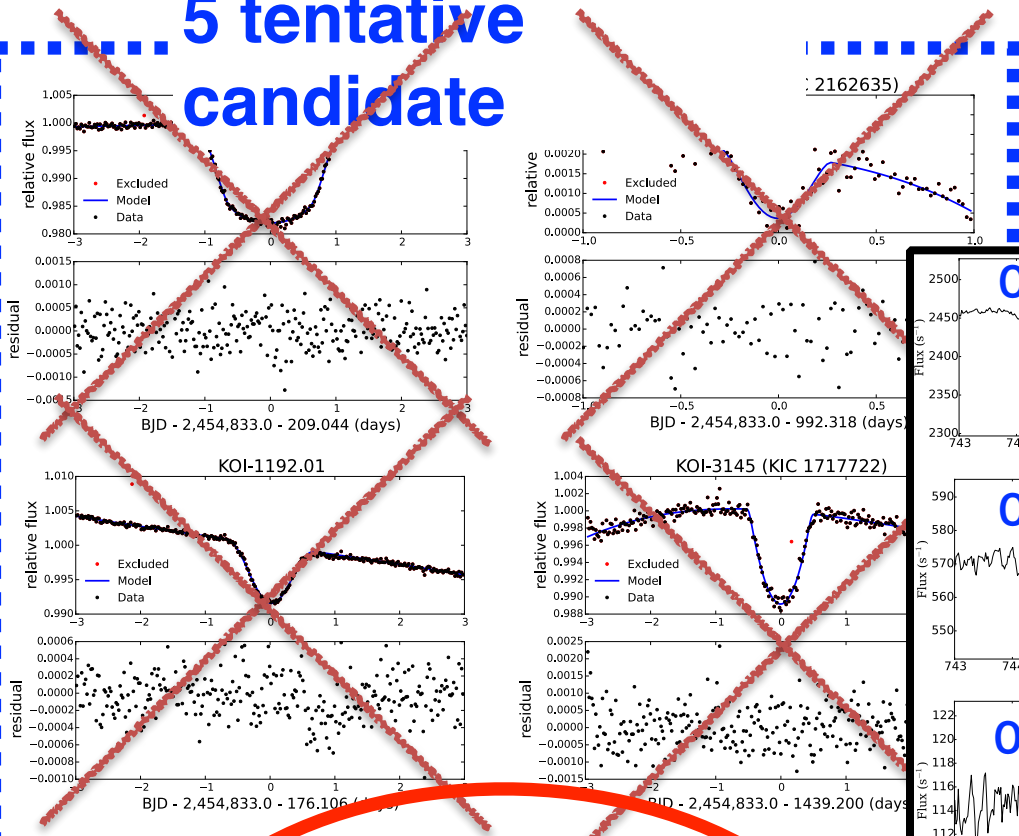
Elimination of false positives through pixel-based ana



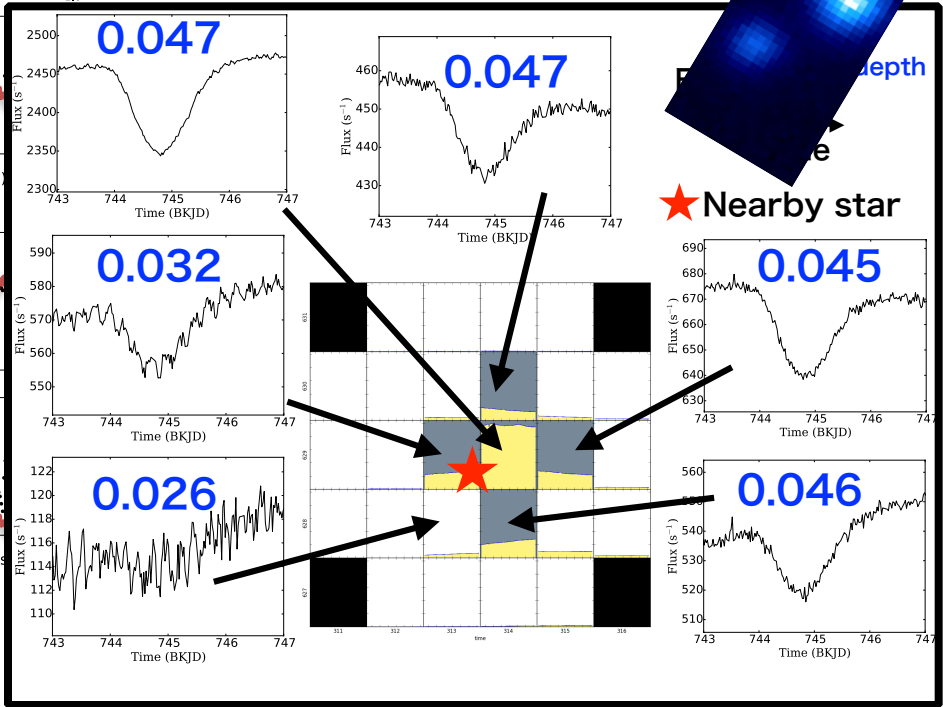
Other originated signals contaminate light cur

Four objects are excluded, and one remains

5 tentative candidate



KIC 10403228



Transit comes from the target star

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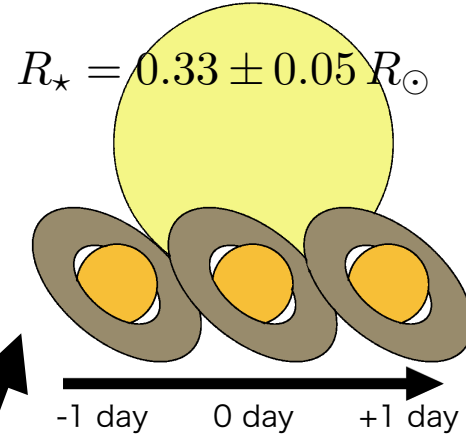
We are Here!!

Discussion for and against ringed planet hypothesis

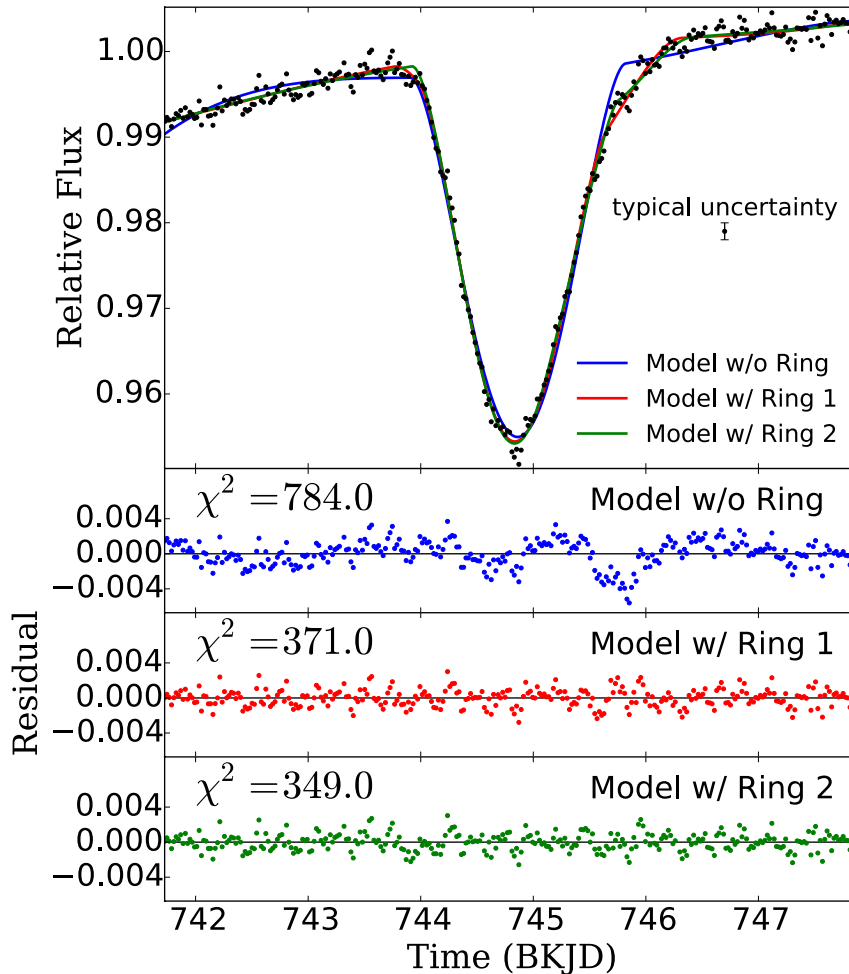
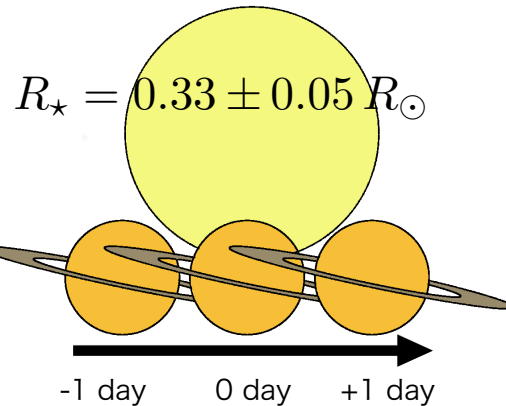
Possible ringed planet candidates
KIC 10403228

Possible ringed planet "KIC 10403228"

$R_p/R_\star = 0.29$ **Solution 1**
 $R_{in}/R_p = 1.26$ $\theta = 50.6$ deg
 $R_{out}/R_p = 2.46$ $\phi = 43.4$ deg



$R_p/R_\star = 0.45$ **Solution 2**
 $R_{in}/R_p = 1.59$ $\theta = 12.4$ deg
 $R_{out}/R_p = 2.55$ $\phi = 72.0$ deg



Ringed planet model explains the data well

Implication of the fitted model for KIC

10403228

- Expected number of transits (if all *Kepler stars have KIC 10403228*)

$$n_{\text{tra}} = 0.037 \left(\frac{N_{\text{target}}}{150,000} \right) \left(\frac{t_{\text{obs,dur}}/P}{4 \times 365 \text{ days}/200,000 \text{ days}} \right) \left(\frac{R_{\star}/a}{1/300,00} \right)$$

Not big, but not unlikely

- Estimated equilibrium temperature

$$T_{\text{eq}} \simeq 16.4 \text{ K} \left(\frac{30000}{a/R_{\star}} \right)^{0.5} \left(\frac{T_{\star}}{3386 \text{ K}} \right) \left(\frac{1 - A}{1 - 0.5} \right)^{0.25}$$

Sufficiently cold for ice particles to survive

- Tidal damping time of planetary spin

$$\tau_{\text{tidal}} = 1.25 \times 10^{17} \text{ yr} \left(\frac{P_{\text{orb}}}{2.0 \times 10^5 \text{ day}} \right)^3 \left(\frac{2.3 \times 10^{-4}}{k_2/Q} \right) \left(\frac{\rho_p}{0.70 \text{ g cm}^{-3}} \right)$$

Sufficiently long for obliquity not to damp

Other possible models without ringed planet

Possible Models		Comment
Oblate planet	unlikely	Bad fitting + best-fit oblateness is unphysical
Planet + noise out of transit	unlikely	Statistically detailed analysis excluded this possibility
Gravity darkening	unlikely	Rotational period is too long for GD to make signals
Spot crossing	unlikely	Anomaly is inconsistent with expected signals

Every possible models other than ringed planet model are unlikely

Conclusion

- We searched long-period planetary candidates for rings
- We found a possible candidate of a ringed planet

