

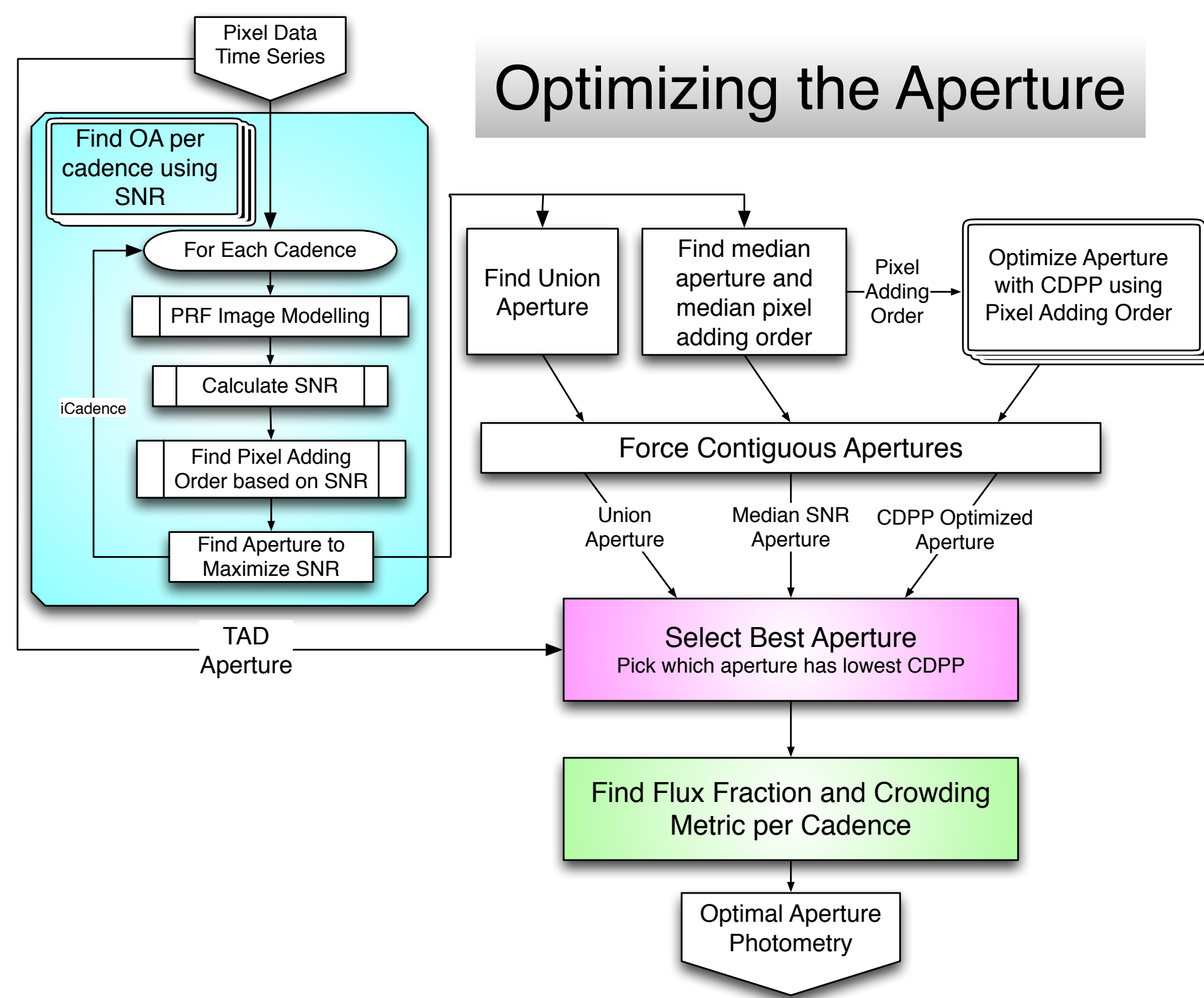
# Finding Every Planet We Can -- Improving the Optimal Apertures in Kepler Data

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With the loss of two spacecraft reaction wheels precluding further data collection in the primary mission, even greater pressure is placed on the processing pipeline to eke out every last transit signal in the data. To that end, we have developed a new method to optimize the Kepler Simple Aperture Photometry photometric apertures for both planet detection and minimization of systematic effects. The approach uses a per cadence modeling of the raw pixel data and then performs an aperture optimization based on the Kepler Combined Differential Photometric Precision (CDPP), which is a measure of the noise over the duration of a reference transit signal. We have found the new apertures to be superior to the standard Kepler apertures. We can now also find a per cadence Flux Fraction in Aperture and Crowding Metric. A modification of this new approach has also been proven robust at finding apertures in K2 data that mitigate the larger motion-induced systematics in the photometry.

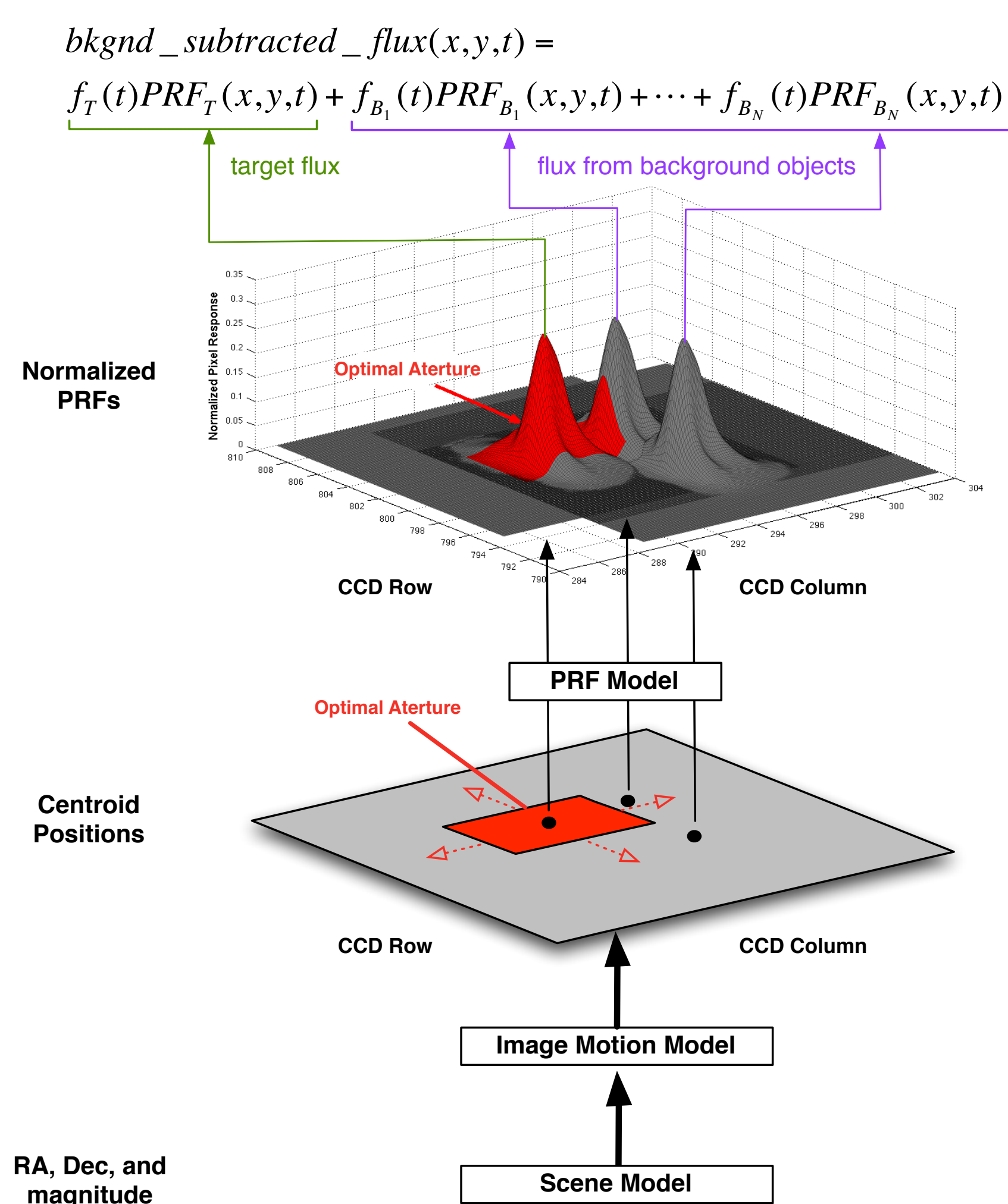


**CDPP:**  $\text{Detection Statistic} = \frac{\text{Transit Depth}}{\text{CDPP}} \sqrt{N_{\text{transits}}}$

- Simply speaking, CDPP is a whitened estimate of how well a transit-like signal can be detected in a stellar light curve.
- A CDPP of 100 ppm means given a pure white Gaussian signal, a 100 ppm transit signal has a detection statistic of 1 sigma.
- Detection probability is therefore inversely proportional to CDPP
  - A 10% improvement in CDPP results in a 10% improvement in detection (i.e. a 1.0 sigma detection becomes 1.1 sigma).
- The best aperture for planet detection is the aperture with the lowest CDPP and lowest crowding.**

## PRF Image Modelling

At measurement time  $t$ , each background-subtracted pixel  $x, y$  within the aperture is modeled as a linear mixture of responses to each point source in the scene. Let  $f_T$  denote the total flux from the target star and  $f_{B1}, f_{B2}, \dots, f_{BN}$  denote the total fluxes from each background object in the vicinity. Within a measurement interval the flux from each star is distributed among pixels according to the system PSF and spacecraft motion, while the conversion of flux to measurement value is determined by the detector responsivity function. The combined effects of flux distribution and pixel responsivity are captured by the Kepler Pixel Response Function (PRF). In the equation below,  $PRF_T(x, y, t)$  is shorthand for the expected response at pixel  $(x, y)$  and time  $t$  due to the target star.



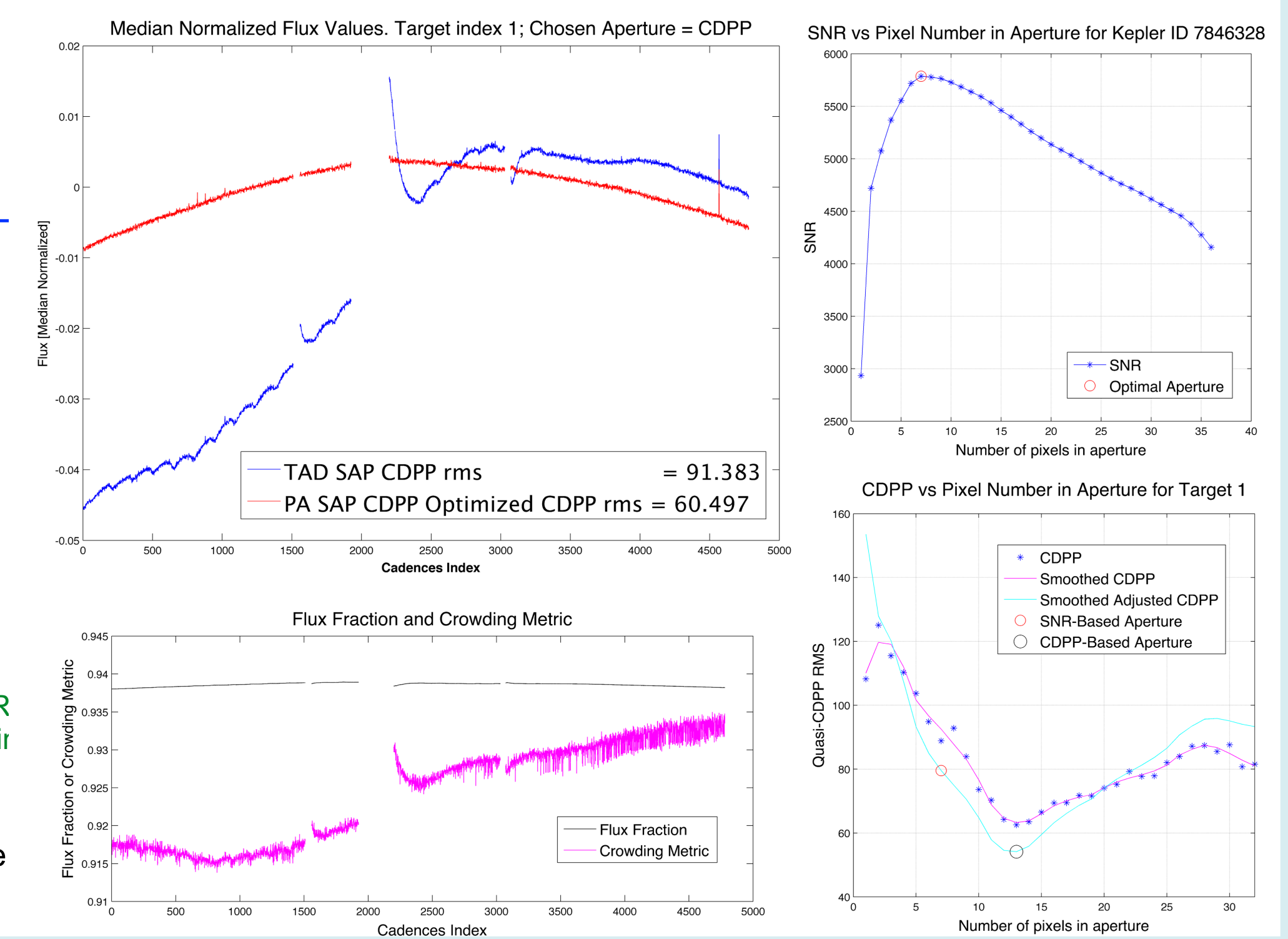
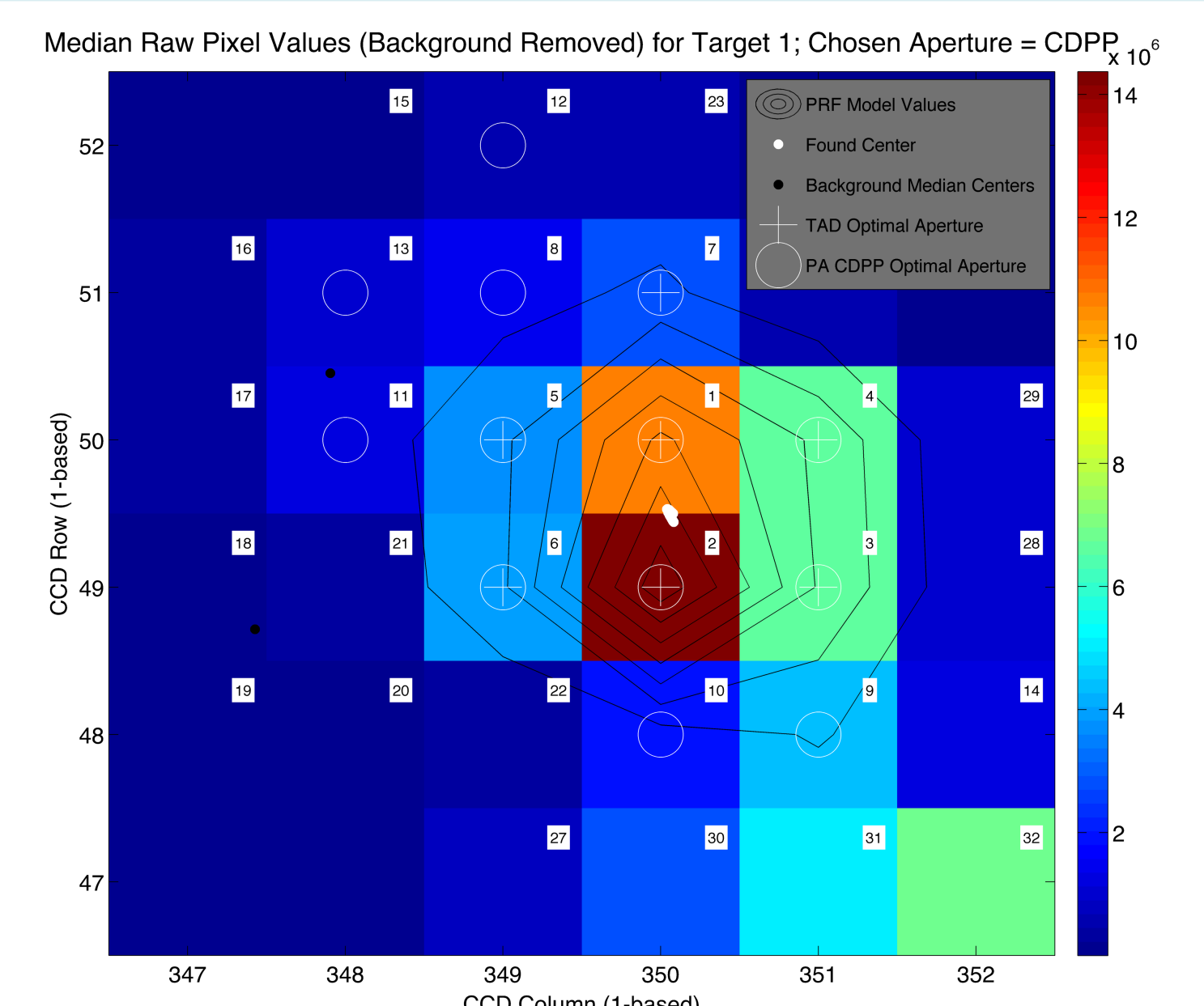
## Finding the Optimal Aperture

- The former optimal apertures in Kepler were found using a pure PRF model based on the catalog
  - Errors in the catalog result in errors in the aperture.
  - Unknown background noise/targets are also not included.
- The new apertures proposed here are found using the real data.
  - First, Maximize the Signal-To-Noise ratio:
    - The numerator is from a model fit to the PRF to the background removed pixel data (See box at left)
    - RA, Declination and Magnitude are updated in the fitting
    - The denominator is purely from the data, including background shot, read and quantization noise.
    - This results in all actual sources of noise to be included
  - Then, optimize the number of pixels to minimize CDPP

## Signal-To-Noise Calculation Per Cadence

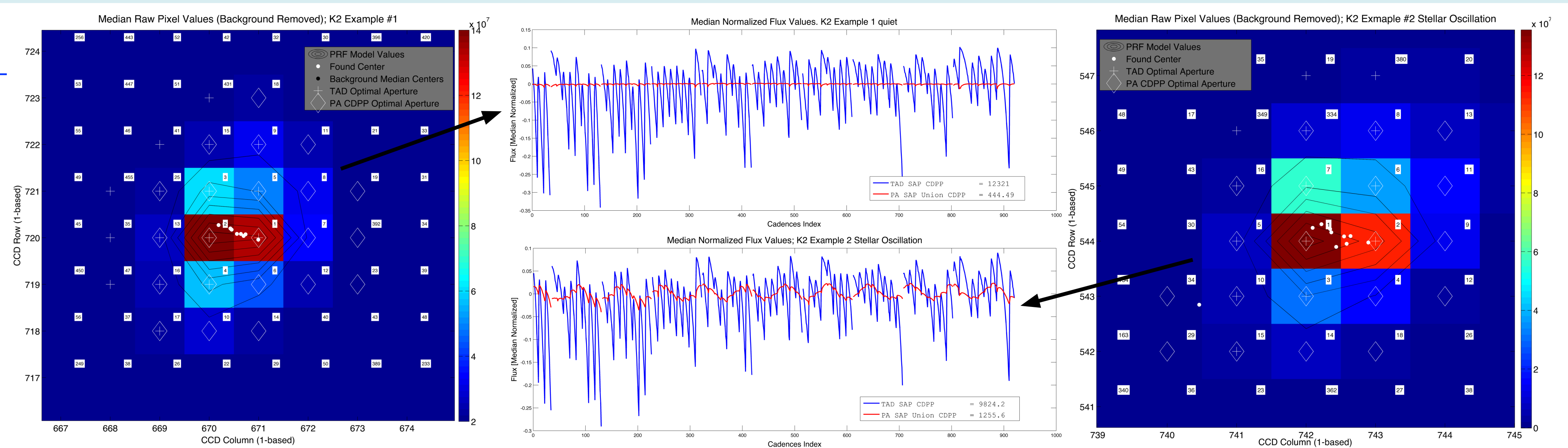
$$\text{SNR}_k = \frac{\sum_i^k \tilde{s}_i}{\sqrt{\sum_i^k y_i + i\sigma^2}}$$

- For each cadence, Where
  - $\tilde{s}$  is the image model fit to the PRF
  - $y$  is the actual pixel data including all background (this is the shot noise term)
  - $\sigma$  is the non-shot noise (read noise + quantization noise)
  - $i$  is over each pixel in the aperture of size  $k$
- Find Pixel Adding Order
  - Rank pixels by descending SNR
  - Begin with first pixel then find the neighboring pixel that increases SNR the most using the above equation... working outwards until all pixels in the mask are included.
- This generates a SNR curve as a function of number of pixels in the aperture. The maximum of the curve gives the optimal SNR aperture



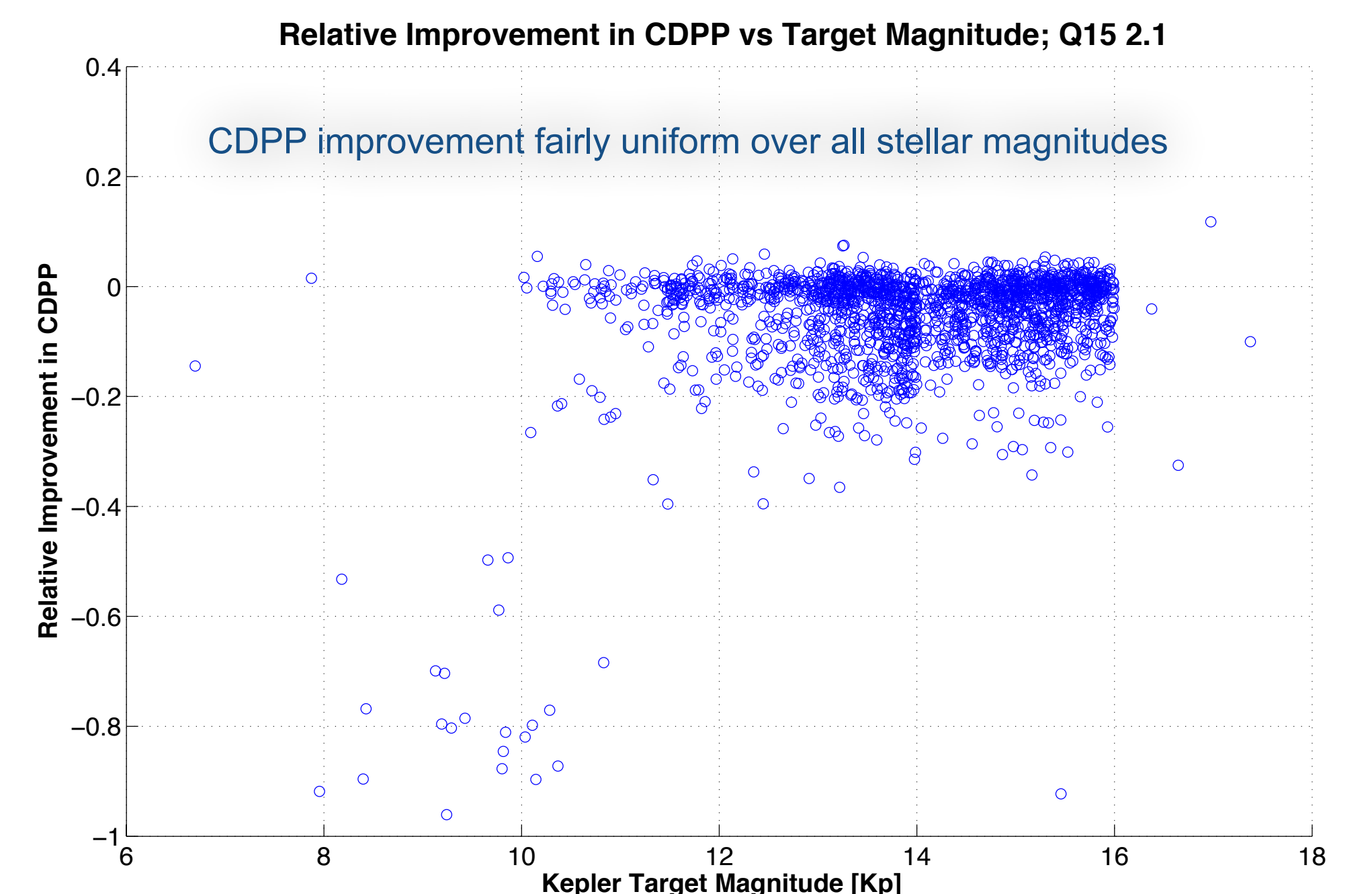
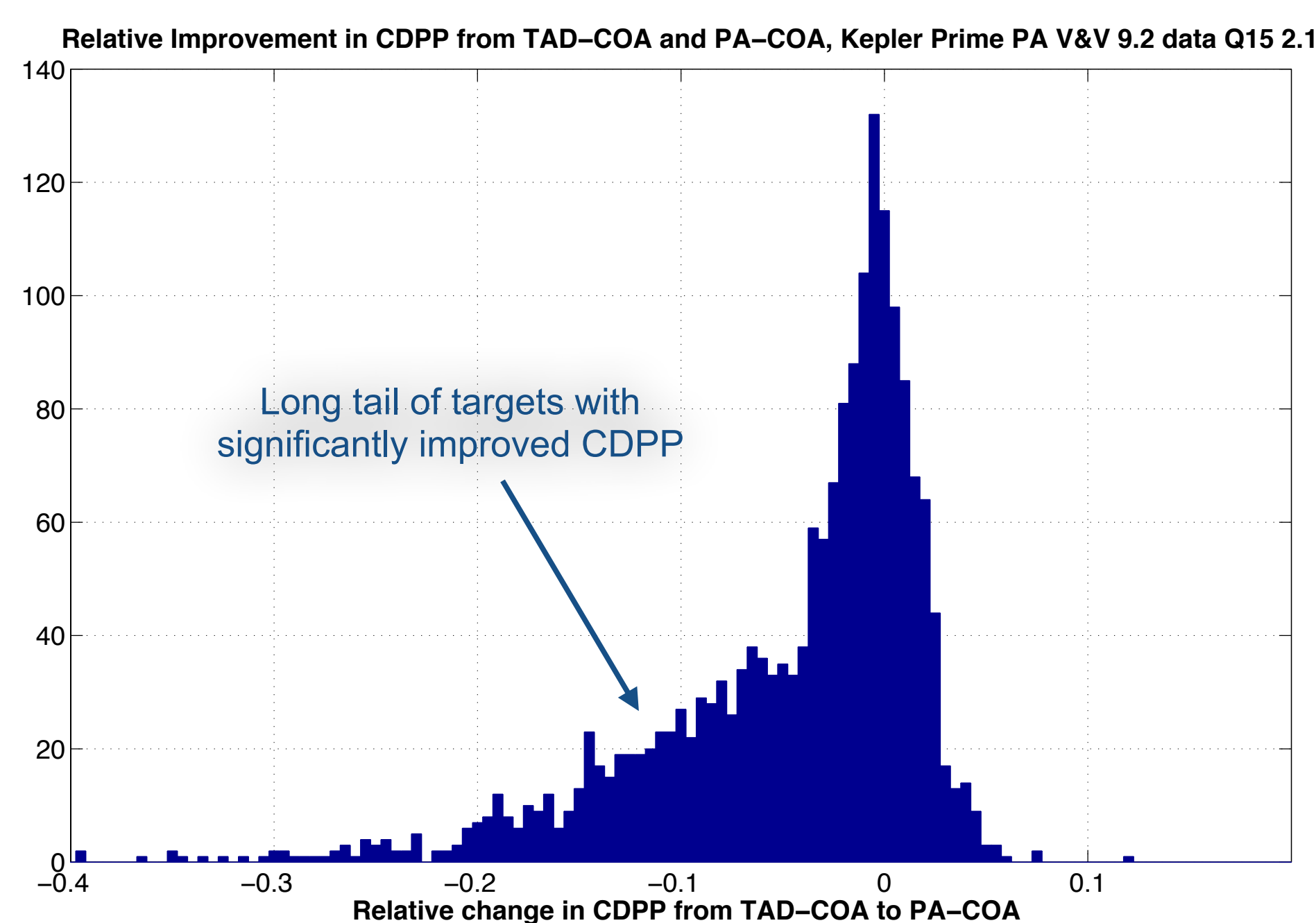
## Application to K2 data (2-Wheel Kepler)

- K2 data has dramatically more motion due to the roll drift
- The optimal aperture consequently drifts over time
  - Ideally, we would allow the aperture to drift or use a weighted aperture
  - But the Kepler mission is committed to simple apertures
- Therefore the apertures need to be opened up to account for the drift.
  - This is performed by taking the union of each aperture found from the SNR test on each cadence.
  - ... actually, four apertures are calculated and the one with the lowest CDPP is chosen (see flow chart above). Most of the time, for K2 data, the union aperture is chosen



## Results

- Preliminary results show a mean reduction in CDPP of 5.5% versus old Kepler apertures
  - With some targets showing greater than 20% reduction in CDPP.
- Also consistently showing a reduction in focus and motion - based systematics.
  - Better apertures means less work removing systematics.
- Also generates a per cadence Flux Fraction in aperture and Crowding Metric in aperture.
- Additionally provides updated magnitudes, RAs and Declinations for the catalog.
- Will be utilized in the next Kepler Pipeline release for both 4-wheel Kepler and K2 (2-wheel).



Discovery Mission 10 - Launched 2009 - <http://Kepler.NASA.gov>