Many planets around mini suns:

Predicting yields of Earth-analogs in the *Kepler* 2-Wheel Mission

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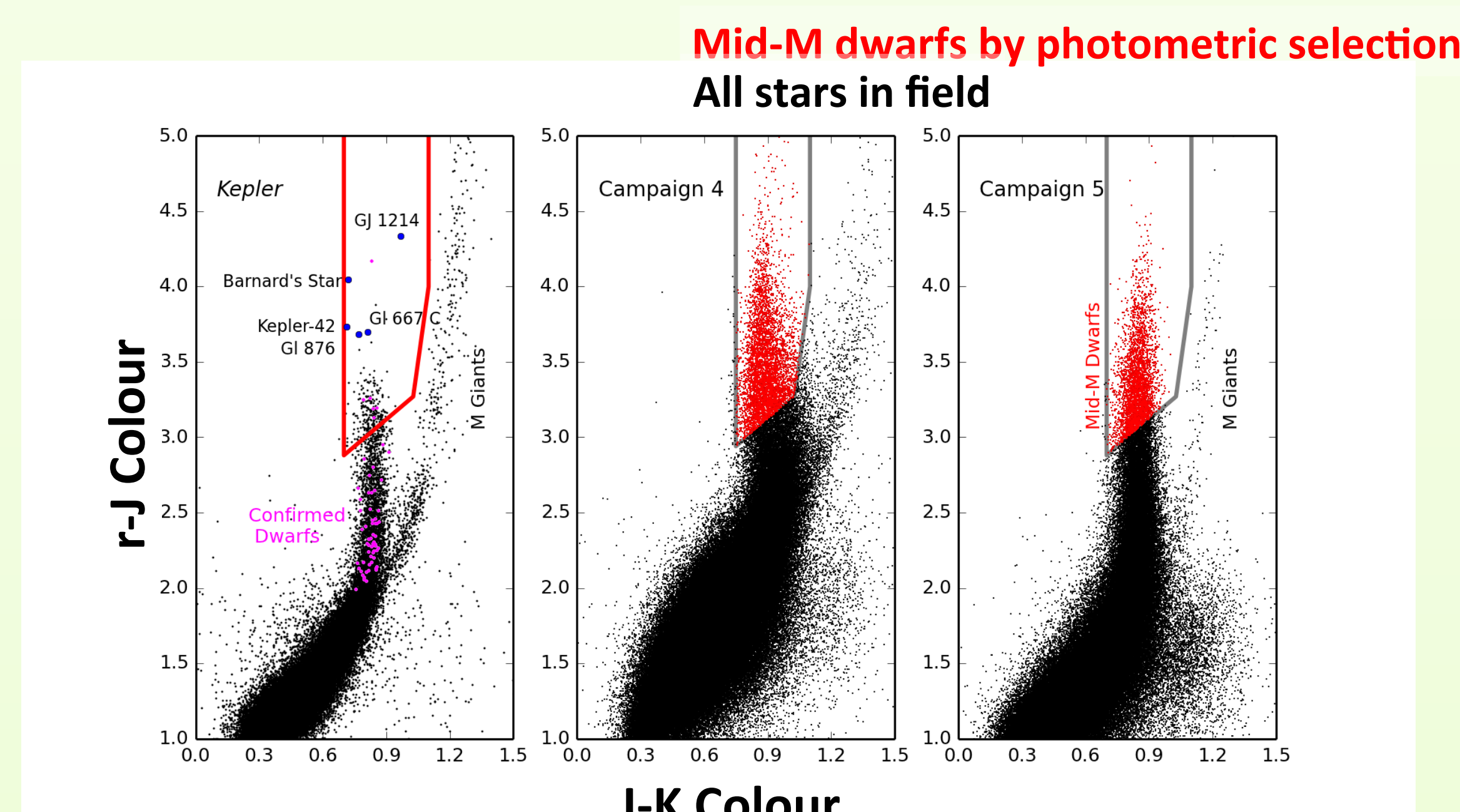
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With the **K2 Mission**—successor of *Kepler*—now underway, **new worlds await to be charted**. The original Kepler mission surveyed mostly sun-like stars, finding planet candidates in the thousands. It also targeted a small sample of **M dwarfs**—stars less than half the size of the sun—returning hints at enticing planetary statistics around these cool, numerous stars. K2 can greatly expand the existing repertoire of mid- to late-M dwarfs monitored for planetary companion searches, promising the **potential to discover many temperate alien territories** (perhaps quite literally) in the near future.
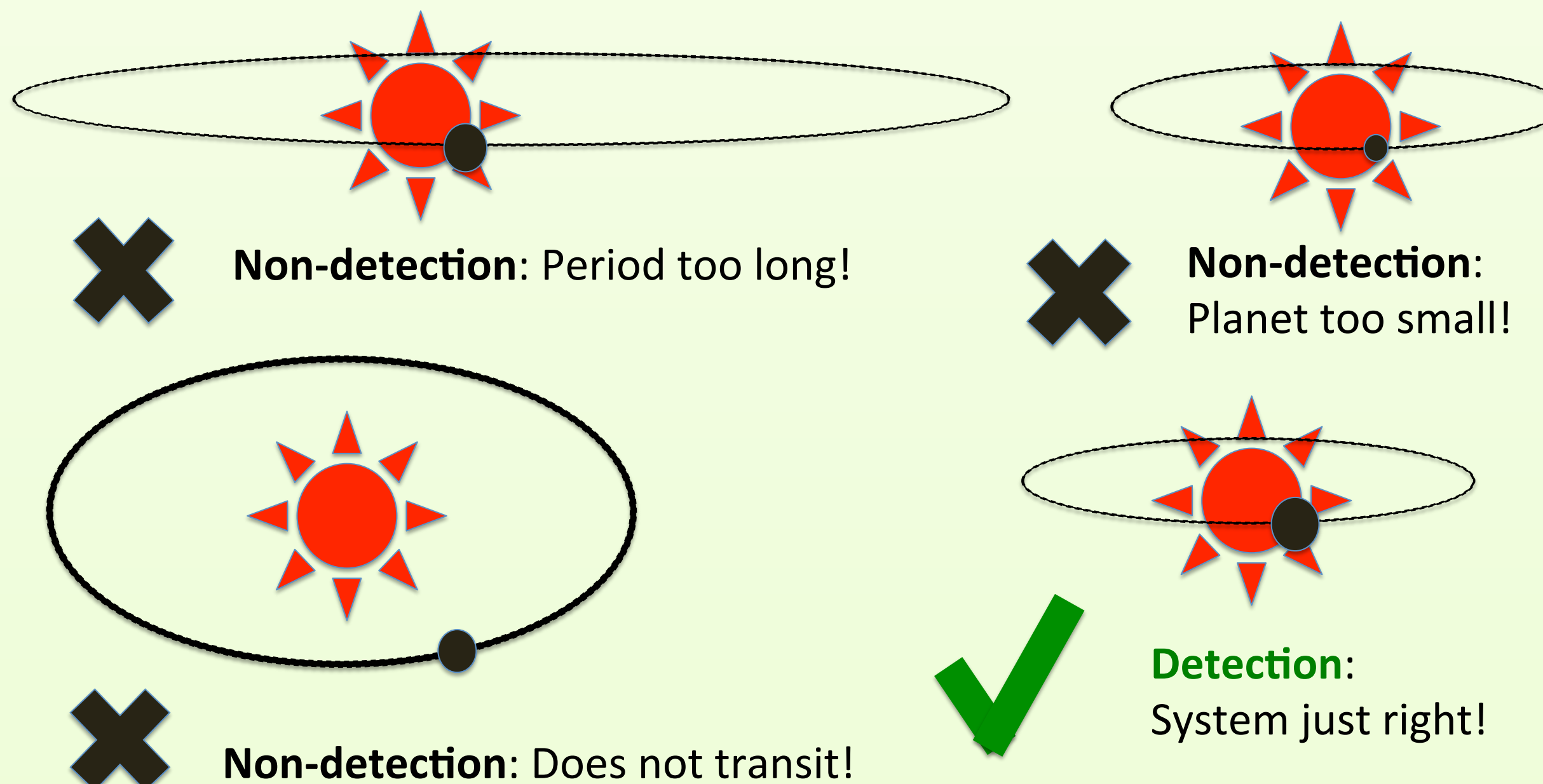
K2: How many planets can we expect to discover?

1. Get a population of mid-M stars and their approximate properties in photometric survey field (M*, R*, brightness, noise)

Mid-M dwarfs by photometric selection
All stars in field

Our proposed targets in K2 fields 4 & 5 (see K2 box below): mid-M dwarf selection in colour-colour space (3544 stars)

Mean: 0.357 R_{Sun}

Mean: 0.366 M_{Sun}

← Solar Units →

Our K2 mid-M dwarf targets in fields 4 & 5 : radius and mass distribution

2. Get reasonable prior distributions on planetary system properties (NPPS, Rp, orbital period, orbital inclination)

Assumed **planet radius (Rp = 1 → 4 R_E) & orbital period (P = 0 → 150 days)** distributions [4]:

2.00 ± 0.45 planets per star (P < 150 days)

Implied all-planet period distribution (corrected for transit probability)
Observed planets

3. Simulate planetary systems around each field star as drawn from the priors in step (2) above

4. Try to 'detect' the planets that transit, accounting for K2 sensitivity [4,5] (P_{orb} vs. baseline time duration of operation, SNR)

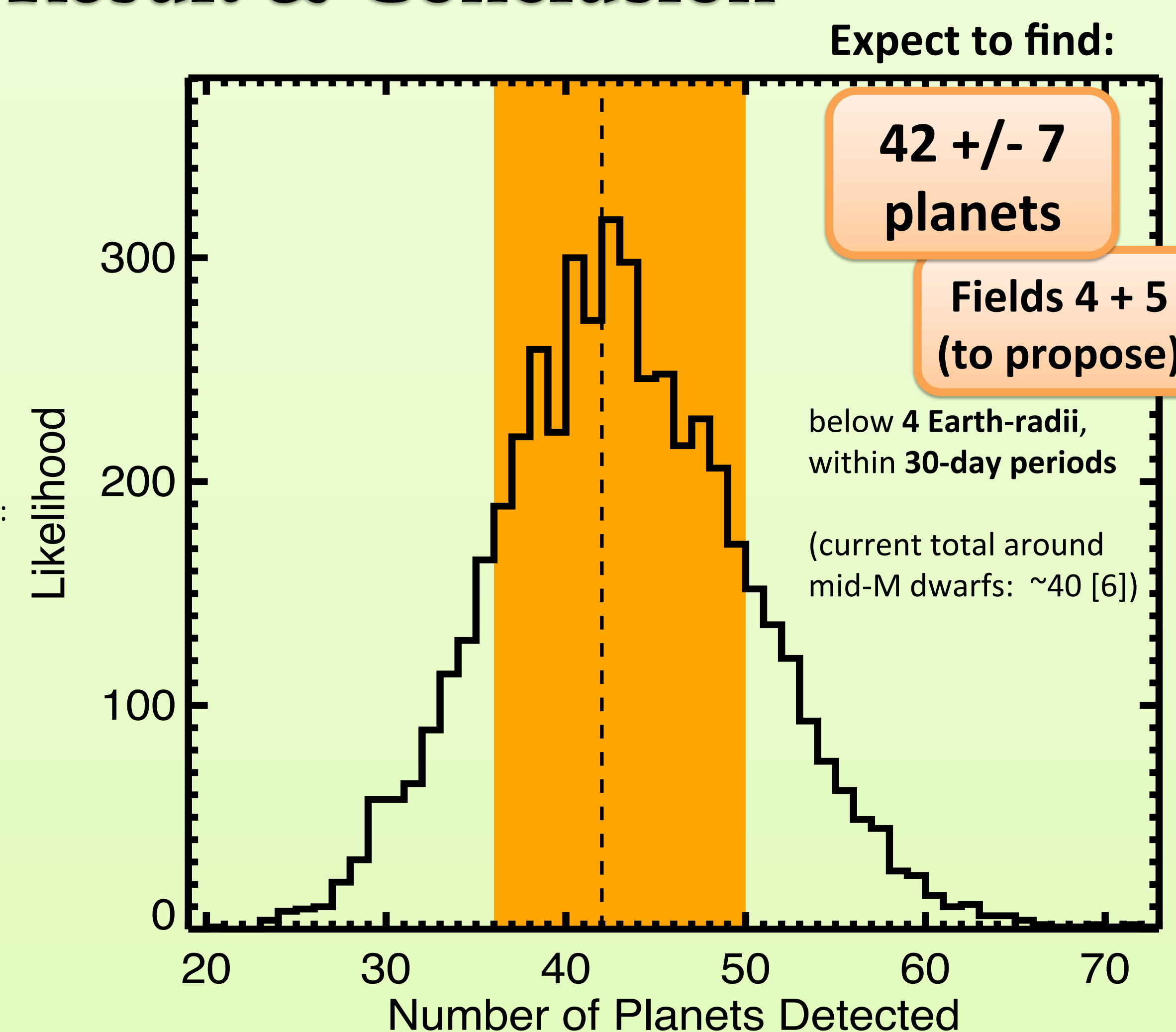**See Andrew Vanderburg's Poster on K2 Photometry Extraction!**

❌ **Non-detection**: Period too long!

❌ **Non-detection**: Planet too small!

✔ **Detection**: System just right!

❌ **Non-detection**: Does not transit!

5. Iterate for many realizations of the stellar / planet parameters, then harvest:

Result & Conclusion

Expect to find:

42 +/- 7 planets

Fields 4 + 5 (to propose)

below **4 Earth-radii**, within **30-day periods**

(current total around mid-M dwarfs: ~40 [6])

Devoting K2 resources to mid-M dwarf planet searches promises to grow the inventory of Earth-analogs in scaled-down solar systems!
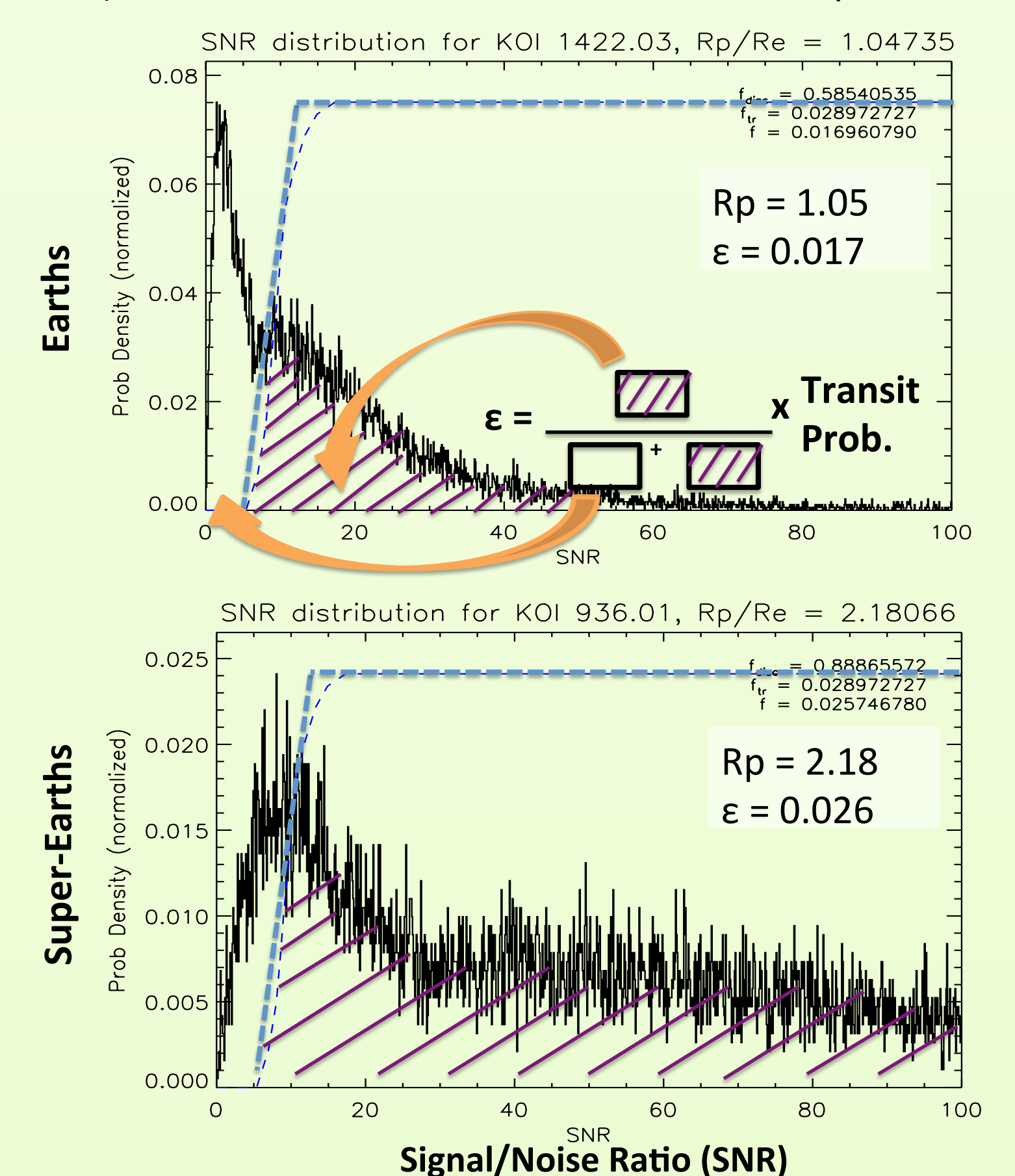
Planet occurrence

How many planets per star?

Several recent studies (e.g. [2,3,4]) in planet occurrence rates and distributions around various stellar types use *Kepler* data to show **Number of Planets Per Star (NPPS) = 1 – 2**.

Given a sample of detected planets, the challenge is to **account for incompleteness–to infer from the visible population what is there but could not be seen**. We must understand the **selectivity in our detection sensitivity** to different types of planets around different types of stars. Ex. *Kepler* is more likely to detect shorter-period and larger planets around brighter and less variable stars.

Strategy: use a **correction factor—w=1/ε—to represent the effective number of analogous planets, whose existences are hinted at by each actual *Kepler* planet detection. Examples:

Sample ε calculations around mid-M dwarfs in *Kepler*:

SNR distribution for KOI 1422.03, Rp/Re = 1.04735

Rp = 1.05
ε = 0.017

$\varepsilon = $ ▭ × Transit Prob.

SNR distribution for KOI 936.01, Rp/Re = 2.18066

Rp = 2.18
ε = 0.026

Signal/Noise Ratio (SNR)

- - - S/N detection sensitivity threshold (of Kepler pipeline)
▨ S/N probability distribution (transiting configurations only)
Successful detection 'area'

A generic method (following [4]):
1. Define group of **stars** of interest (e.g. by stellar type)
2. Gather all such **stars** in a given survey field, and all existing **planet** detections around them
3. For a given **planet**, put on hypothetical orbits around every survey field **star** according to a prior
4. Try to detect this **planet** in each configuration. Successful detection means meeting a **signal-to-noise threshold**
5. Record **fraction** of all simulated **planet** orbits that actually lead to detection–this is the **detection efficiency, ε**
6. Invert the efficiency: **w = weight = 1/ε** . For every 1 such **planet** detected in this field, w such planets actually exist
7. Repeat 3 - 6, compute **w** for every **planet**, then sum w. This is the total number of **planets** expected to exist in the field
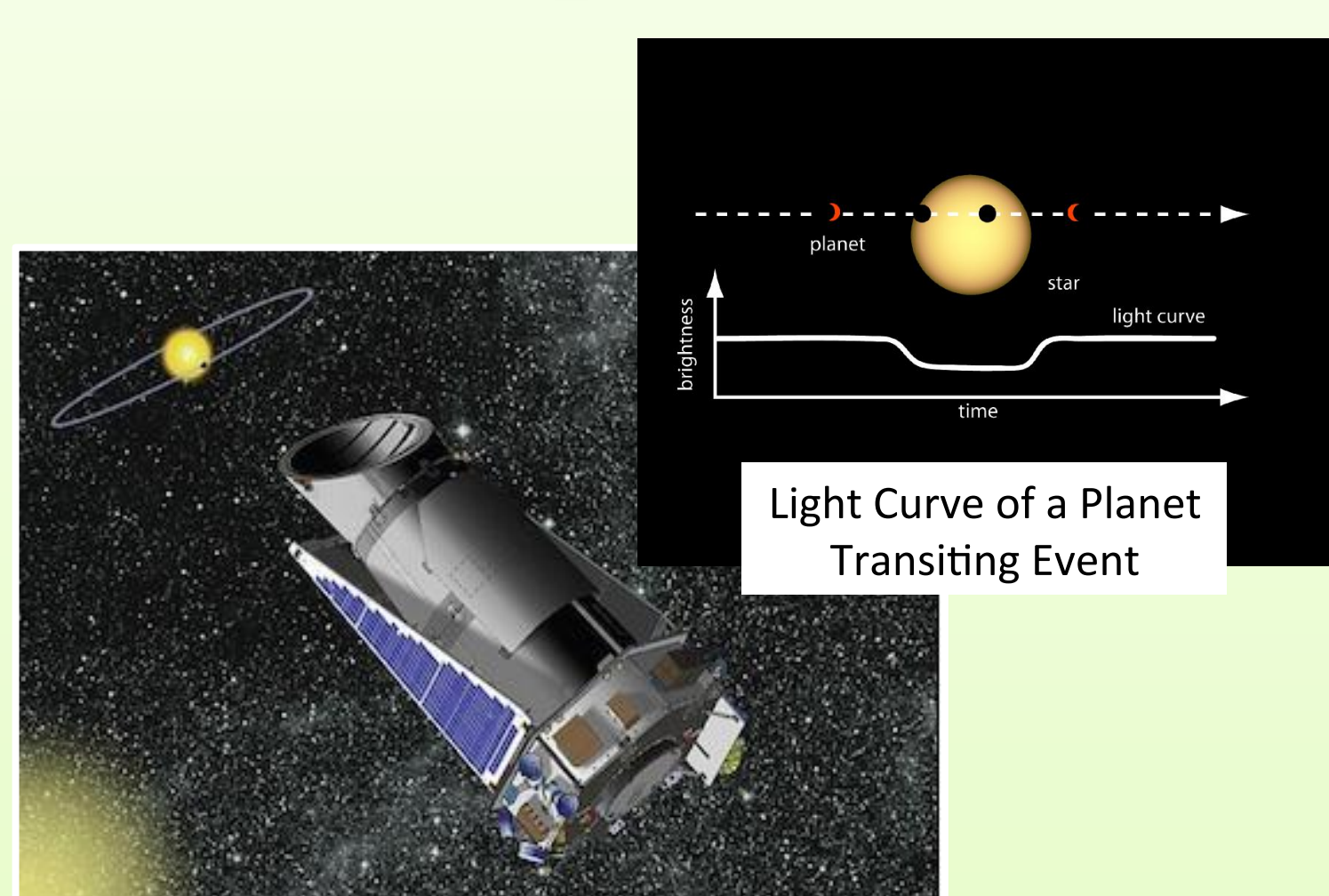8. Divide by total number of field **stars** to get **number of planets per star (NPPS)**

4: Number of detected planets in mass bin

Mid-M

4   5   4   2   13   18

Later M ← Mstar → Earlier M
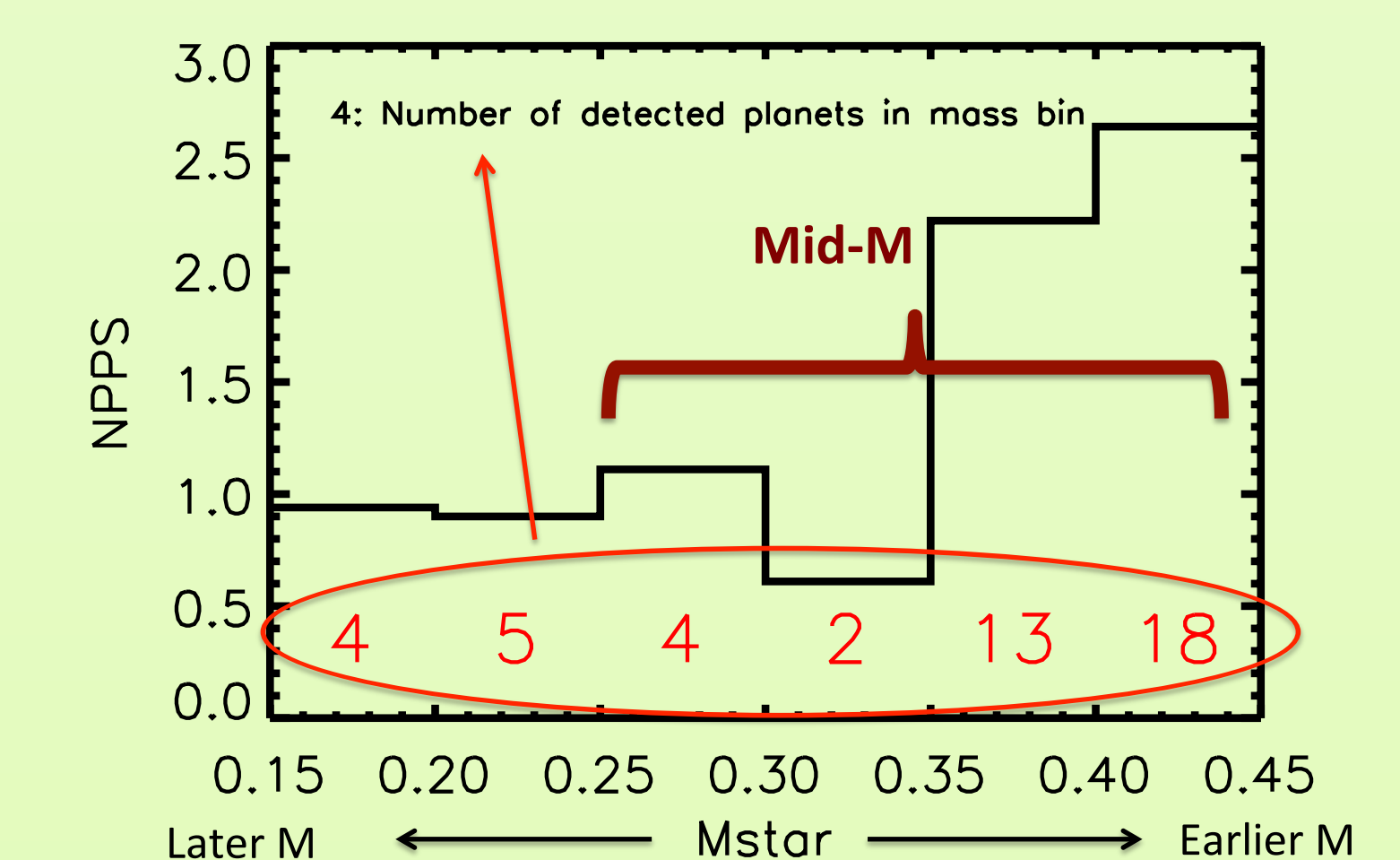
Number of planets per star (NPPS) implicated for various M dwarf stellar mass bins using the latest Kepler KOI catalogs. Many are **poorly constrained** due to small number statistics–**the original *Kepler* did not observe enough M dwarfs**.

Our unique goal to capitalize on K2 prompts interest in **planets around mid-M dwarfs,** whose occurrence needs better constraint and offer great prospects to the near-term search for habitable worlds.
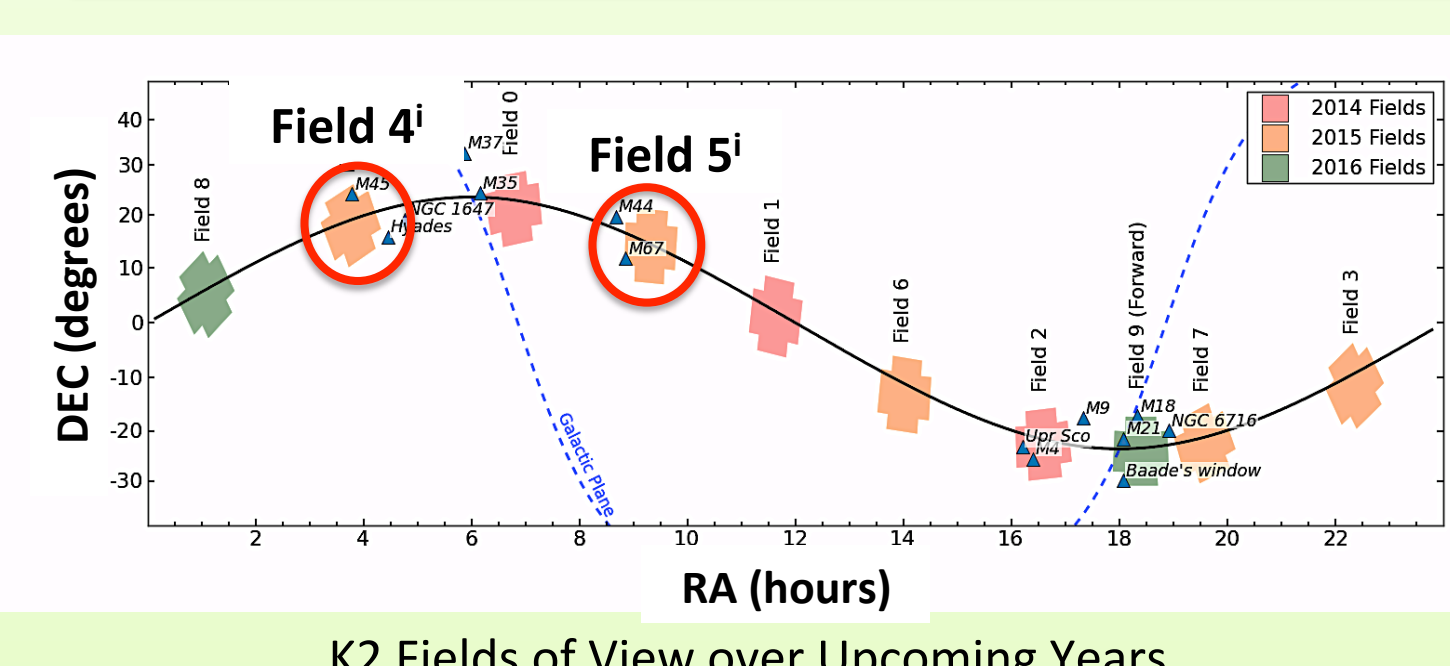
Kepler

Light Curve of a Planet Transiting Event

From 2009 to 2013, the **NASA *Kepler* Mission** continuously stared at a small patch of the sky to search for **transiting exoplanets** around various preselected stars (mostly sun-like + ~4000 M dwarfs). It discovered **> 4000 diverse planet candidates**.

K2: *Kepler* Reborn

Two of *Kepler*'s 4 **reaction wheels failed** by 2013, compromising its pointing precision. Luckily, good precision could still be attained when pointing along the **ecliptic plane**, inviting **new science**.

Field 4[i]   Field 5[i]

2014 Fields
2015 Fields
2016 Fields

K2 Fields of View over Upcoming Years

Each field can only be monitored for 75 days [1]. This means **only short-period planets (P < 30 days) with large transit depths** can be detected. Nonetheless, **new interesting targets** are up for **community proposal**.

[i] Fields 4 and 5 observations run February -- July 2015.

Why target M dwarfs

Advantage M Dwarf!
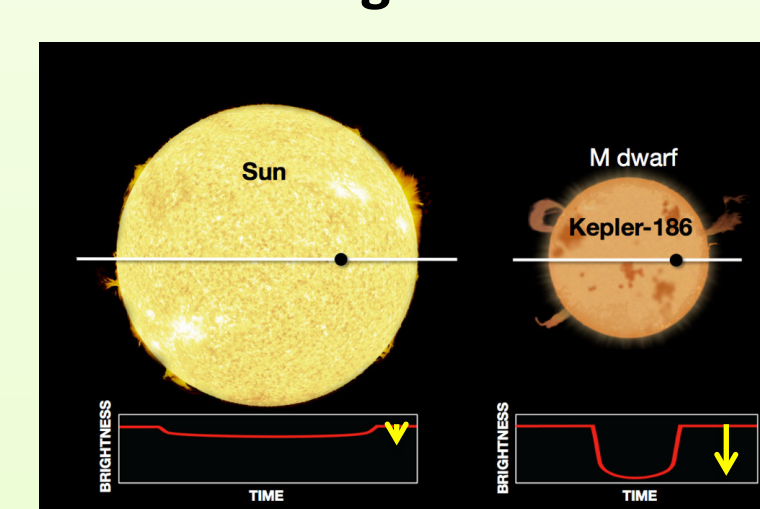
M dwarfs are ideal targets for astrobiology-oriented investigations and **Earth-analog** searches with K2:
- **Deeper transits** for small (e.g. Earth-sized) planets
- **Closer Habitable Zone** = shorter-period HZ planets

Transit Depth

M dwarf

Solar System

Habitable Zone Orbital Radius / Period
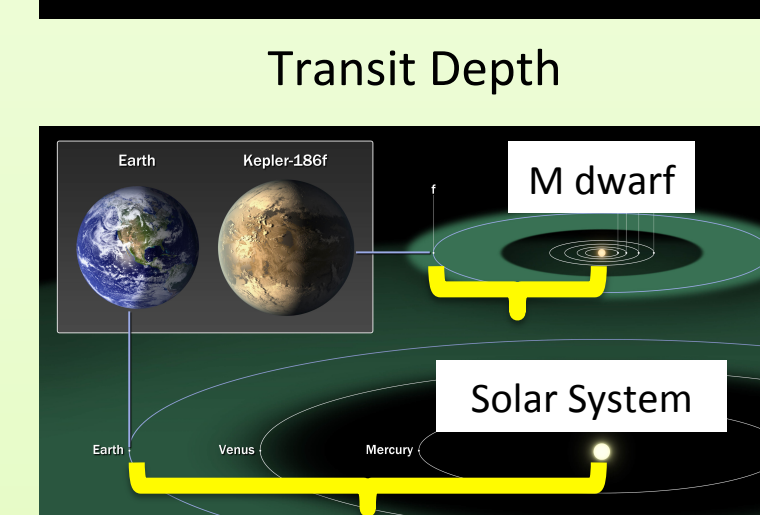
Star Type	R*,M* (solar)	Teff (K)	P_{orb} (HZ)
G2V (sun)	1	5700	1 yr
M0V (early-M)	0.6	4000	70 d
M3V (mid-M)	0.35	3200	30 d

Crudely: $\frac{P_1}{P_2} \approx \frac{R_1}{R_2}\left(\frac{T_1}{T_2}\right)^3$

References
[1] Howell et al. 2014, PASP, 126, 398
[2] Dressing & Charbonneau 2013, ApJ, 767, 95
[3] Petigura, Howard, & Marcy 2013, PNAS, 110, 19273
[4] Morton & Swift 2014, ApJ, 791, 10
[5] Muirhead et al. 2014, ApJS, 213, 5
[6] Vanderburg & Johnson 2014, PASP, arXiv: 1408:3853