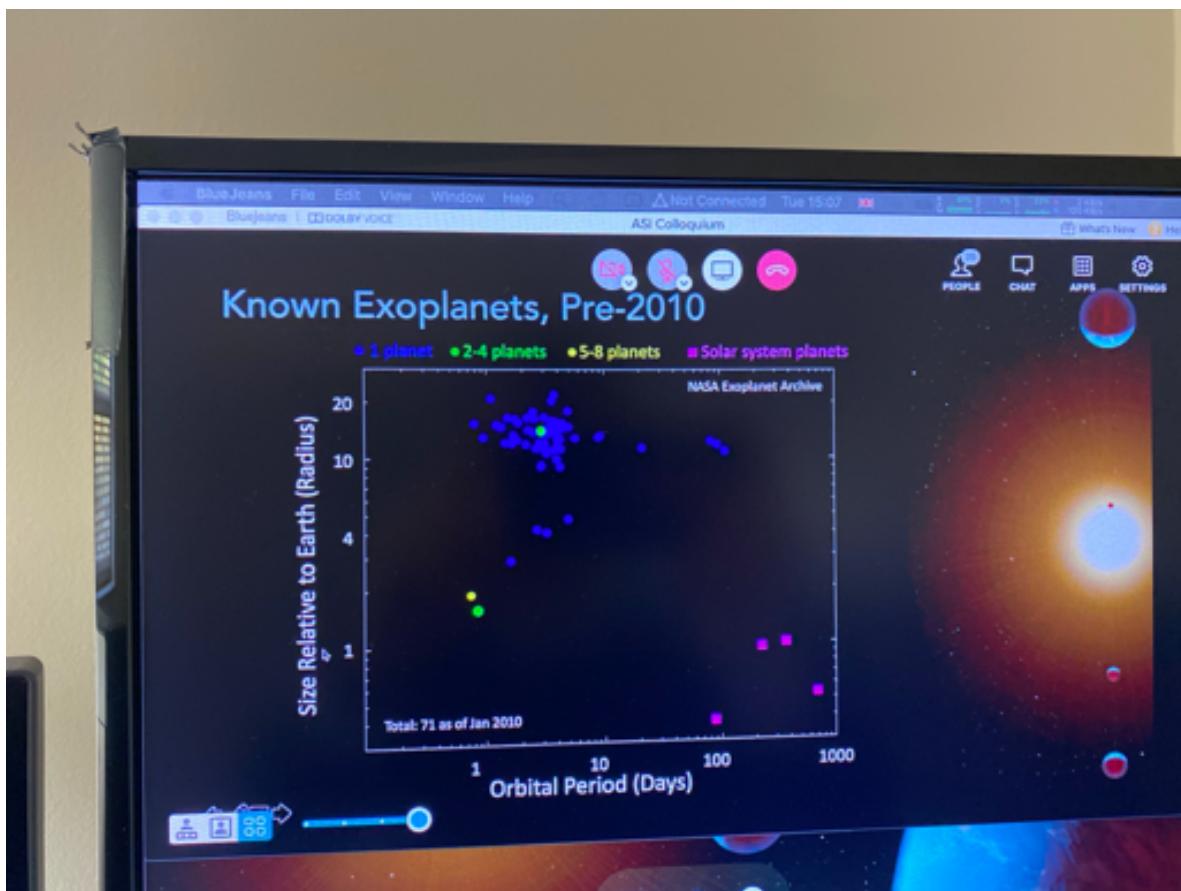


Jessie Christensen

Exoplanet Demographics Towards an Exoplanet Demographics Ladder

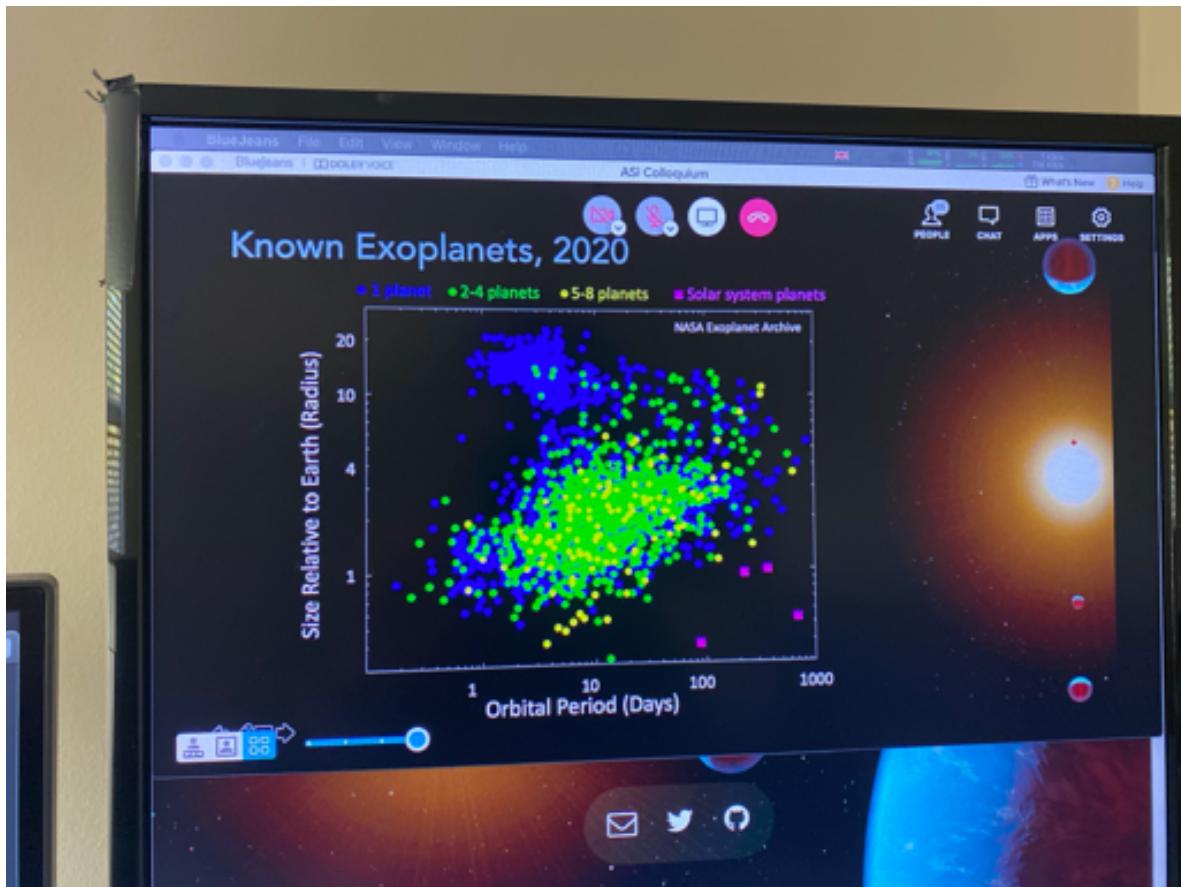
IPAC at Caltech - advances exploration of universe through science ops, data archiving and community support - focus on cosmology and galaxy evolution, exoplanets, asteroid, solar system and infrared sub mm astrophysics. Data processing and archiving for major projects ands all sky surveys, and smaller nasa NSF and privately funded projects

Known exoplanets pre 2010



Pre 2010, exoplanets looked very different to the solar system- all hot

Jupiters, short periods and large



Post 2020 - most of these found in Kepler

Moving away from stamp collecting of 'coldest, hottest etc' into proper population statistics

How do we correct our observations (due to their bias,) to account for true population

What are formation and migration mechanism, how do planet occurrence rates change with stellar properties?

Overview - 4 topics

Kepler (Statistics of occurrence rate calc)

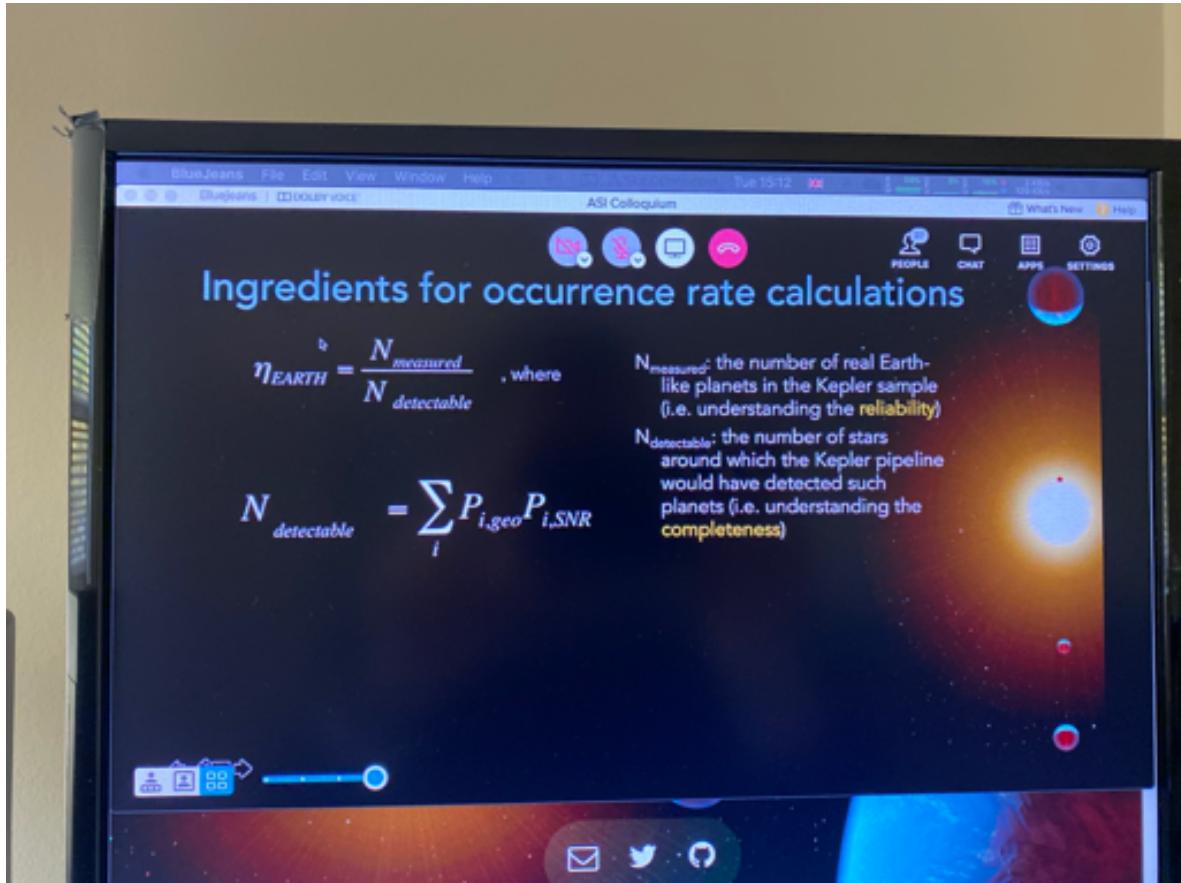
K2 - occurrence rates along new axes

Tess - Occurrence rates of planets

Extending too new orbits -i.e., the future discoveries

Kepler Mission (2009-2013) 1m Opt telescope in space

Uses transit methods of planet discovery
 e.g Trappist 1
 Science goal --- Number of Earth like planets in habitable zones, with a sun like star
 Monitored 200 K stars for 4 years.



Reliability is effectively rate of false positives

The completeness is due to geometric probability (i.e. how probable is a transit due to geometry), and also the SNR of the pipeline, i.e., if its there can we see it

The requirements for calculating gamma Earth (the probability of earth like planets) are

Uniformly Produced stellar parameter set
 Uniformly produced planet candidate catalogue (no humans involved)

Understanding of completeness and reliability -i.e., How many planets could there be, and what is false positive rate

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Tue 15:14 ASI Colloquium PEOPLE CHAT APPS SETTINGS

Ingredients for occurrence rate calculations

$$\eta_{EARTH} = \frac{N_{measured}}{N_{detectable}}, \text{ where}$$

$N_{measured}$: the number of real Earth-like planets in the Kepler sample (i.e. understanding the reliability)

$N_{detectable}$: the number of stars around which the Kepler pipeline would have detected such planets (i.e. understanding the completeness)

$$N_{detectable} = \sum_i P_{i,geo} P_{i,SNR}$$

1. Uniformly produced stellar parameter set
2. Uniformly produced planet candidate catalogue
3. Understanding of completeness and reliability

" T_{\oplus} : Your model population evaluated at $R_p = 1R_{\oplus}$ and $P_{orb} = 1$ year"

New parameter is r_{earth} - Gamma Earth. Evaluate your model at earth conditions, so can compare apples to apples, i.e. these parameters are always set to their own model params, so need a uniform comparison

Major Kepler Updates

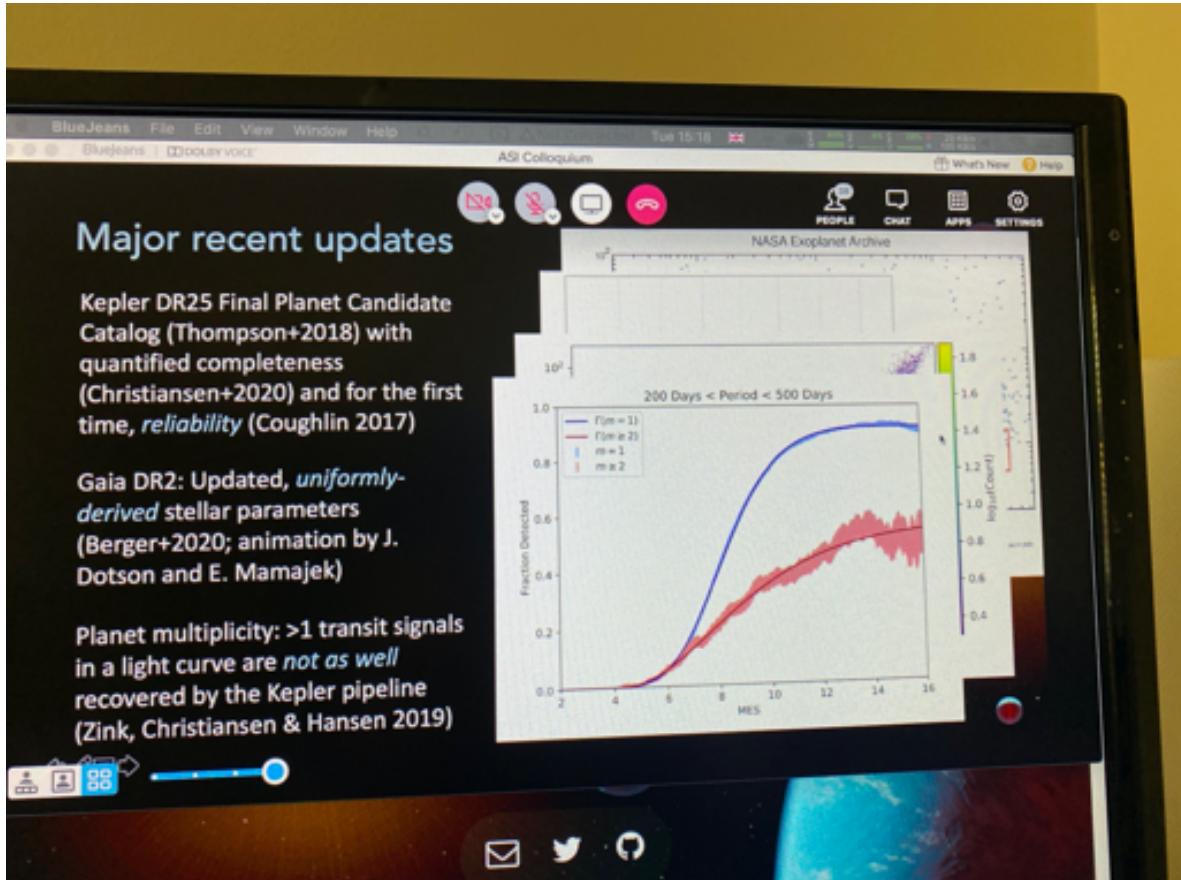
Final; Planet candidate catalogue came out with quantified complement and reliability (Thompson 2018) (Christiansen 2020), (Couhgan 2017)

Not many Earth like candidates - only a handful

Gaia DR2 came out, which has uniformly derived stellar parameters (Berger et al 2020, animation by J Dotson and E Mamajek) -this revealed a bias in stellar parameter in Kepler - the stars were larger

and hotter than expected, so the planets became larger and hotter, therefor habitable planets candidates went down

Planet multiplicity > 1 - can't treat recoverability of planets independently - (Zink, Christiansen and Hansen 2019)

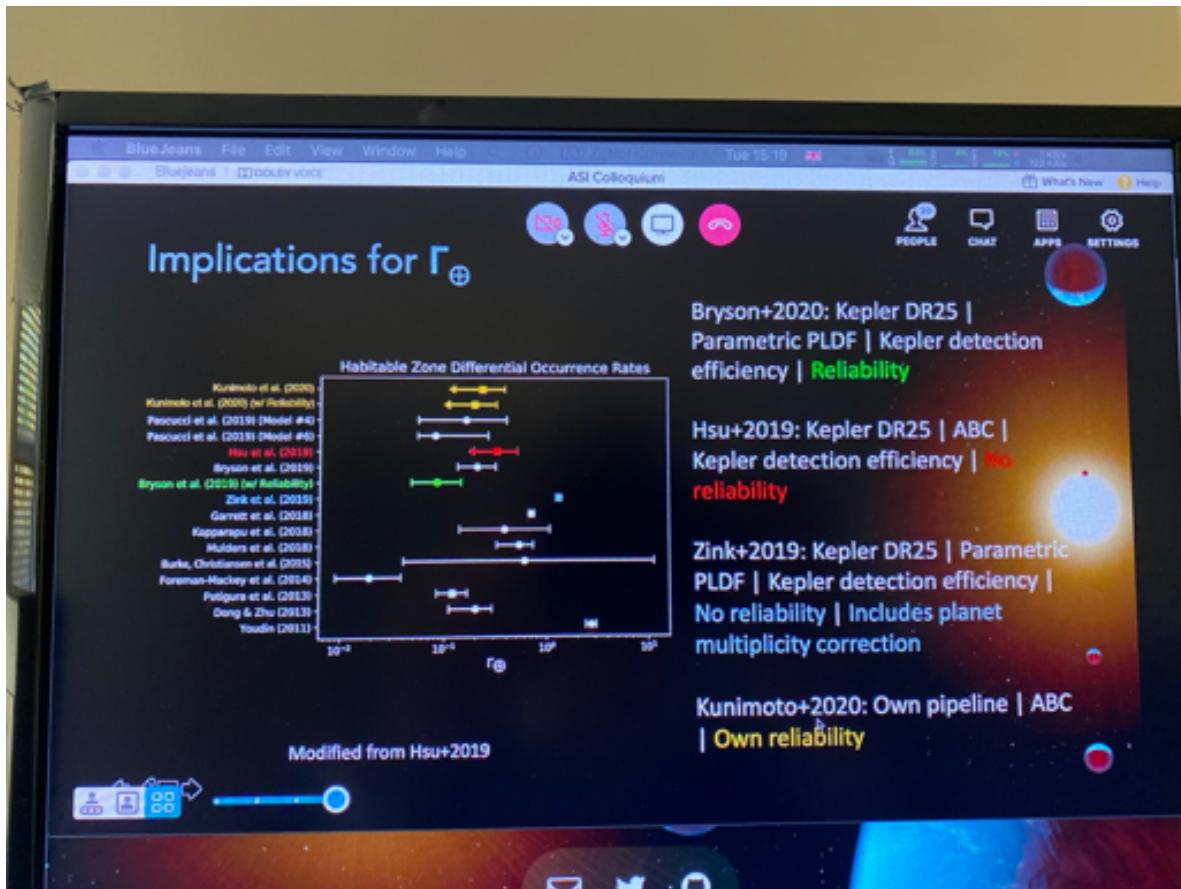


First planet has 90 % chance of recoverability, but this drops to approx 50% as the num of planets go on. This may serve to change final Gamma Earth Level.

Implications for Gamma Earth

Up until 2015, Gamma Earth had a 3 order of mag spread from 1-1000 %.

In last 5 years, lit has converged



But, still have not had multiple studies with same analysis exactly.

10 % is limit we are converging to - **10-50 % of stars like sun have a planet in the habitable zone**

10 billion G stars in the galaxy, so approx 5 billion rocky habitable planets

(This is correcting for detectability, these aren't maybe they should be there)

Still need to address Stellar Multiplicity (2 out of 3 stars are binary)

Kepler input catalogues assumed 1-2 arc sec unresolved sources were single stars. This will be improved by GAIA, but still not there. If we assume kepler stars are singles, we derive incorrect planet parameters for host stars. A second more subtle effect, for the non-host stars we infer the incorrect detectability. i.e., could be off by a factor of 2

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ASL Colloquium TUE 15:23

Still to address: stellar multiplicity

Work with collaborators at Caltech, UC(LA+B)

We randomly select 200 of the 2,135 "single" stars sensitive to Earths

We are completing a survey of the 200 stars with the Palomar/PHARO instrument and the Lick/Shane AO system

First one they looked at turned out to be a triple. Prelim results - multiplicity rates is higher (40 %) for non hosts then non-hosts (30 % for hosts)

Also need to address dangers of extrapolation

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Tue 15:24 ASI Colloquium What's New Help

Still to address: dangers of extrapolation

Pascucci+2019: Many short period (<25d) Earth-sized planets will be stripped cores of larger planets

BUT we are using them to anchor our extrapolations to long periods

" Γ_{\oplus} drops by a factor of 4–8" if you exclude the short period planets

R_p(R_⊕)

period [days]

Reliability

F₁

F₂

Bryson+(JLC)+2020

- There are physical reasons to believe we can fit a power law --- however, this can be misleading, as short period planets might not originally have been short period small planets - could have been larger and had their atmospheres and cores stripped.

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DOLBY VOICE ASI Colloquium What's New Help

ill to address: dangers of extrapolation

ascucci+2019: Many short period (<25d) Earth-sized planets will be stripped cores of larger planets

BUT we are using them to anchor our extrapolations to long periods

" Γ_{\oplus} drops by a factor of 4–8" if you exclude the short period planets

Model #	Fitted P days	Fitted R R_{\oplus}	Function	Γ_{\oplus} %	η_{\oplus} %
1	2–400	0.5–6	2D broken	59.6 ^{+21.8} _{-20.4}	40.6 ^{+54.9} _{-17.3}
2	2–400	0.5–2	P broken	78.7 ^{+13.1} _{-12.2}	53.6 ^{+29.7} _{-22.7}
3	12–400	0.5–6	R broken	17.0 ^{+7.6} _{-5.8}	11.5 ^{+5.2} _{-3.8}
4	12–400	1–6	R broken	16.0 ^{+8.0} _{-5.1}	10.9 ^{+5.4} _{-3.8}
5	25–400	0.5–6	R broken	8.6 ^{+4.9} _{-5.1}	5.9 ^{+3.0} _{-3.8}
6	25–400	1–6	R broken	8.0 ^{+10.3} _{-10.3}	5.4 ^{+7.0} _{-7.0}
7	25–400	1–2	P & R single	7.8 ^{+10.3} _{-3.8}	5.3 ^{+7.0} _{-2.8}

$R_{\oplus} [R_{\oplus}]$

period [days]

Bryson+(JLC)+2020

Reliability

Moving forward

The screenshot shows a BlueJeans video conference interface. The top bar includes menu options like File, Edit, View, Window, Help, and Dolby Voice. The title bar reads "ASI Colloquium". The main content area features a dark background with a stylized sun and planets. A blue banner at the top says "Moving forward with Earth-like occurrence rates...". Below this, under "With Kepler data...", there is a bulleted list:

- Incorporate stellar and planet multiplicity corrections
- Improve treatment of reliability
- Potentially confirm a statistical sample of candidates (e.g. with HST)
- Improve population model to include two-component fit at short periods

Under "New data sets...", there is another bulleted list:

- EarthFinder?
- NASA Roman Telescope?
- PLATO currently plans to overlap partially with the Kepler FOV (precision goal of 34ppm in 1hr)?

At the bottom of the slide, there are icons for printing, saving, and sharing, followed by a progress bar.

New data sets are key - Earth finder still a concept. Roman telescope is microlensing - just marginally sensitive to Earth like planets. Plato plans to go back to kepler FOV - with more robust tools

K2 Mission (2014 to 2018)
Ecliptic plane survey

The K2 Mission (2014—2018)

- 70-80 day 'stares' along the ecliptic, 10-30k stars per field
- Sampling a variety of stellar and Galactic fields
- Target list entirely guest-observer driven
- Many science drivers – many types of stars observed

K2 Campaigns 0 through 19 (2014-2018)

Campaign	Approximate Dec	Approximate RA
1	-10°	270°
2	-10°	250°
3	0°	330°
4	0°	300°
5	-10°	240°
6	-10°	220°
7	-20°	300°
8	-20°	280°
9	-20°	260°
10	-10°	240°
11	-10°	220°
12	0°	330°
13	0°	300°
14	10°	240°
15	10°	220°
16	20°	180°
17	20°	160°
18	20°	140°
19	20°	120°
0	30°	100°
1	30°	80°
2	30°	60°
3	30°	40°
4	30°	20°
5	30°	0°

K2 looked at a range of stars - a range of age, metallicity, stellar types

Expanding from Gamma Earth -how does stellar type affect this

Only 3000 M dwarfs observed with Kepler

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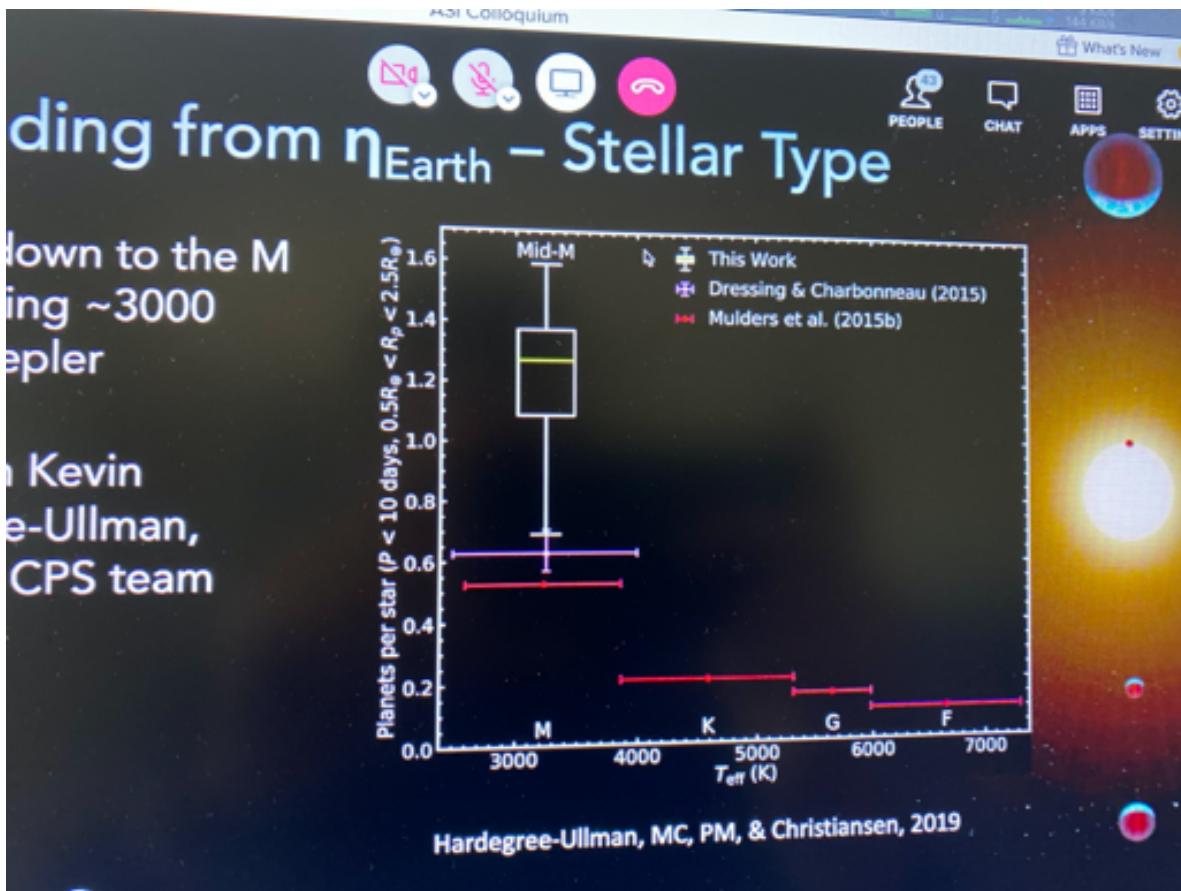
Expanding from η_{Earth} – Stellar Type

Pushing down to the M dwarfs using ~3000 stars in Kepler

Work with Kevin Hardegree-Ullman, Dressing, CPS team

Hardegree-Ullman, MC, PM, & Christiansen, 2019

Increase of occurrence rates at cooler stars. Why were smaller stars better at making super earths at low periods



This trend is increasing

Plan to use the 30,000 cool stars from K2 to better investigate this

Kevin Hardegree Ulman working on this

Expanding from gamma Earth - Effect of Stellar Age

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BlueJeans DOLBY VOICE ASI Colloquium PEOPLE CHAT APPS

Expanding from η_{Earth} – Stellar Age

Pushing to younger stars with K2

Can we constrain the timescales of planet formation and migration?

Working with Josh Schlieder, CPS team

The diagram shows a timeline of stellar ages from 0 to 1000 Myr. It highlights four clusters: Upper Sco (around 100 Myr), Pleiades (around 120 Myr), Hyades (around 600 Myr), and Praesepe (around 800 Myr). The diagram also shows regions for disk-driven migration, growth by gas accretion, and growth by collision, along with arrows indicating formation and migration processes.

Mauro

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Each of these competing theories makes different predictions for the timescales - can we constrain this with observations?

K2 observed 4 clusters, seen on diagram. Look at planet occurrence rate in these 4 clusters, and compare to the Kepler field occurrence rates

This is being done with CPS team

How do we calc. Occ. rates with K2? (Same requirements as Kepler had)

Need a Uniform stellar catalogue

BlueJeans File Edit View Window Help Tue 15:35 ASI Colloquium BlueJeans DOLBY VOICE What's New

Calculating occurrence rates with K2

- 1. Uniform stellar catalogue**
 - Gaia DR2 + LAMOST: updated parameters for 27,060 K2 stars
 - Training set for random forest regression for 157,874 K2 stars
 - Full set of 184,935 A-M stars: T_{eff} , $\log g$, [Fe/H], M_* , R_*

EPIC (Huber+16)

Hardegree-Ullman+2020

Mauro

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Calculating occurrence rates with K2

Reproduce key Kepler result – bimodal planet radius distribution! (Hardegree-Ullman+(JLC)+2020)

Normalized # of Planets ($p < 80$ days)

$R_p (R_E)$

Kepler (Huber+2018)

K2 (This Work)

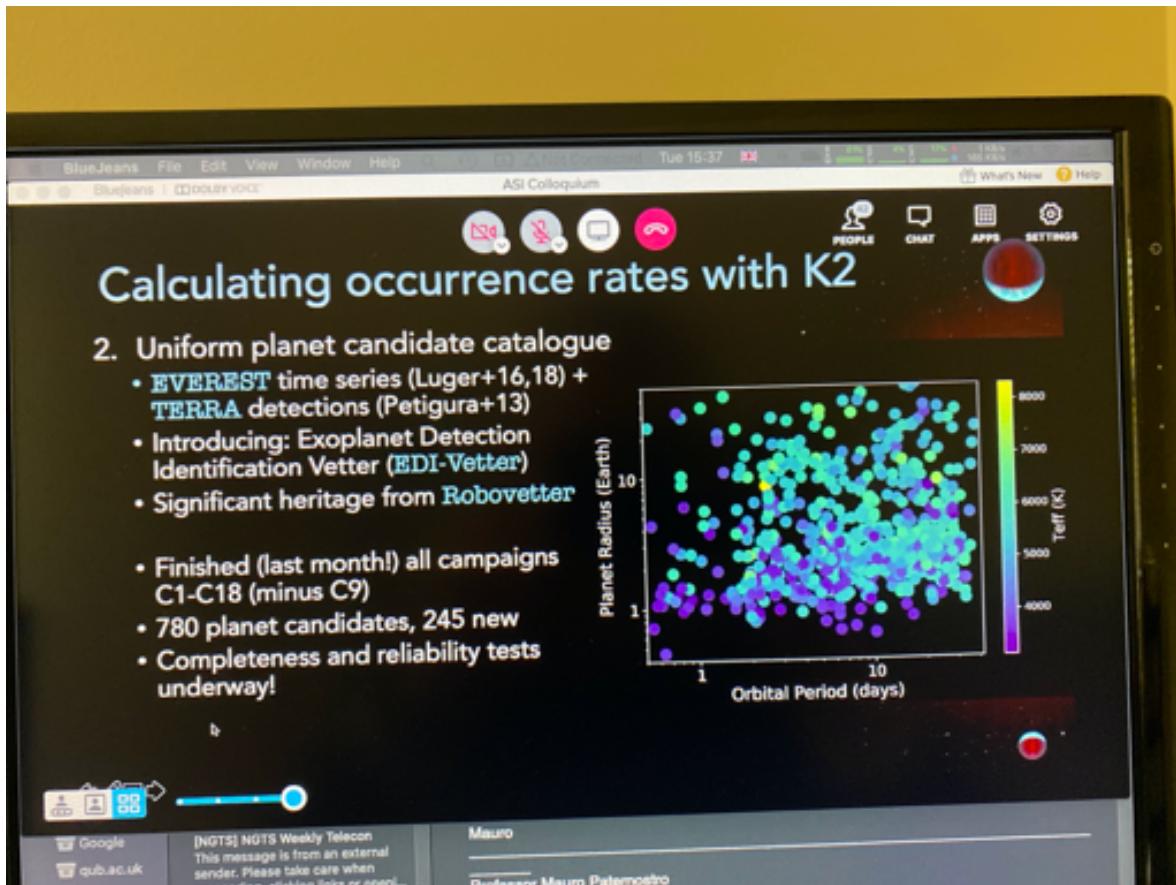
Mauro

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Professor Mauro Paternostro

Bimodal distribution for short period planets - sub Neptune and super earths, valley in between

Explanations are about atmosphere loss, or core powered mass loss
The K2 data reproduced the bimodal dist seen in the Kepler data -
first independent check of this result from Kepler



2. Uniform planet candidate catalogue
 - EVEREST time series (Luger+16,18) + TERRA detections (Petigura+13)
 - Introducing: Exoplanet Detection Identification Vetter (EDI-Vetter)
 - Significant heritage from Robovetter
 - Finished (last month!) all campaigns C1-C18 (minus C9)
 - 780 planet candidates, 245 new
 - Completeness and reliability tests underway!

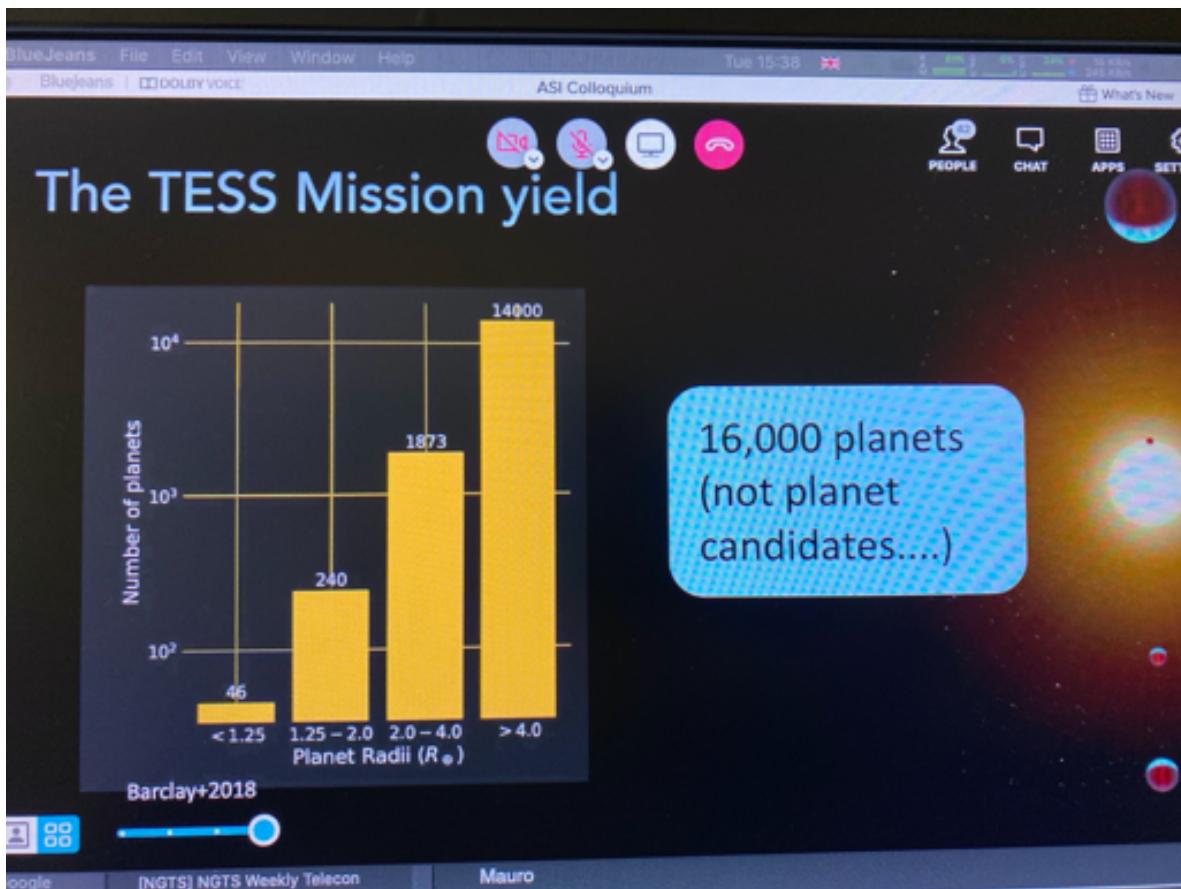
Uniform planet candidate catalogue. Down to earth sized planets at short period (40 days)

They are currently working on completeness and reliability of the K2 survey now

Tess Mission (2018)

Kepler was a narrow deep survey,. Tess is a wide shallow survey
Goal is to cover all bright stars in sky down to 12 mag (maybe 14 for giant planets)

Can do more interesting followup on bright stars



Could quadruple the number of known planets

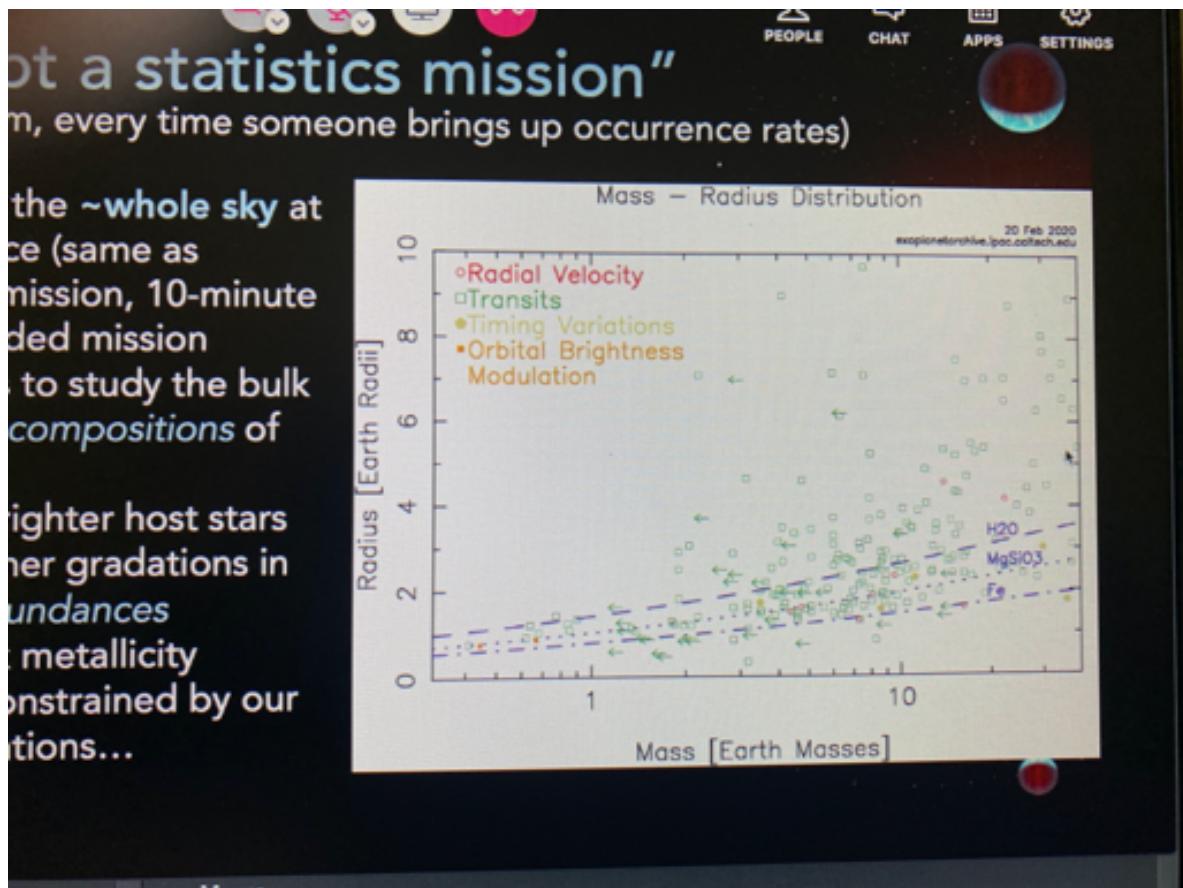
“TESS is not a statistics mission”
(Dave Latham, every time someone brings up occurrence rates)

- TESS is sampling the ~whole sky at 30-minute cadence (same as Kepler) in prime mission, 10-minute cadence in extended mission
- TESS will allow us to study the bulk and atmospheric compositions of these planets
- With more and brighter host stars we can explore finer gradations in trends such as abundances compared to bulk metallicity
- We will only be constrained by our follow-up observations...

Can look at different atmospheres

Bulk metal rich stars make more planets. Do carbon rich stars make more rocky planets, more wet planets, more wet etc. Where do planets form, using these abundance measurements

We will be constrained by follow up, due to how many candidates we have



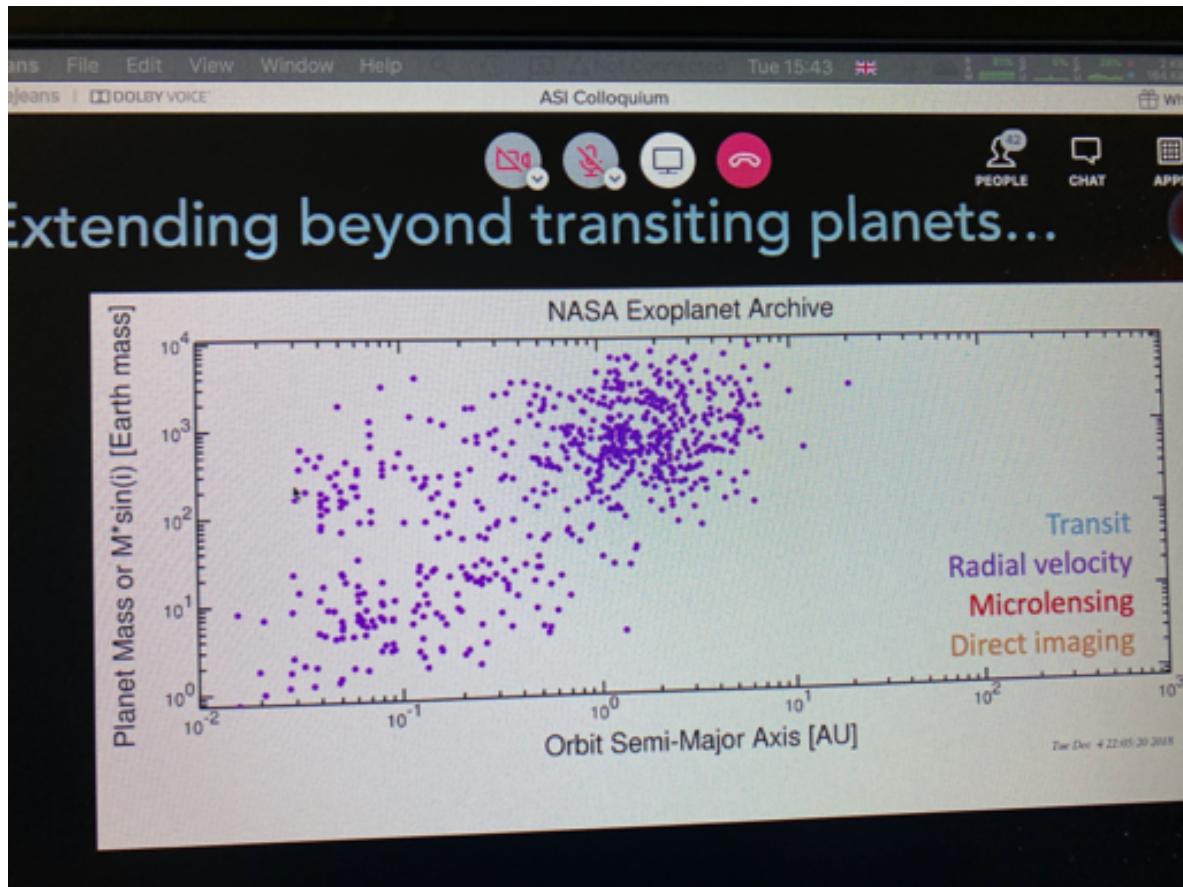
Not a statistics mission
(in, every time someone brings up occurrence rates)

the ~whole sky at once (same as our mission, 10-minute dedicated mission)
to study the bulk compositions of brighter host stars
other gradations in abundances
metallicity constrained by our detections...

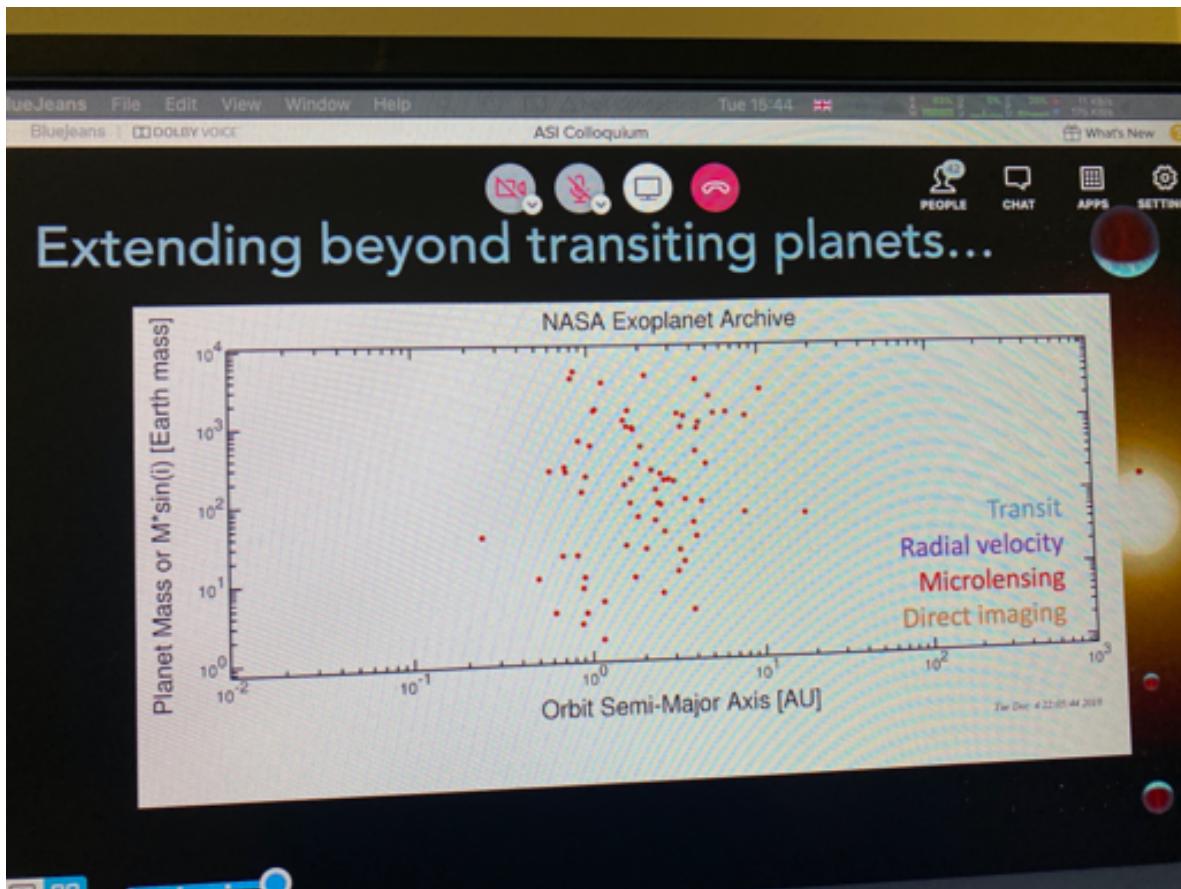
Our solar system has a nice neat trend of metallicity, but do exoplanets have the same trend?? TESS can help us with this, as it will look at atmospheres

Extending beyond Transiting Planets

They are biased by detection technique to short periods
Excess of Super earths etc is real, compared to Neptune desert which might not be (I don't know If I heard this correctly not gonna lie)

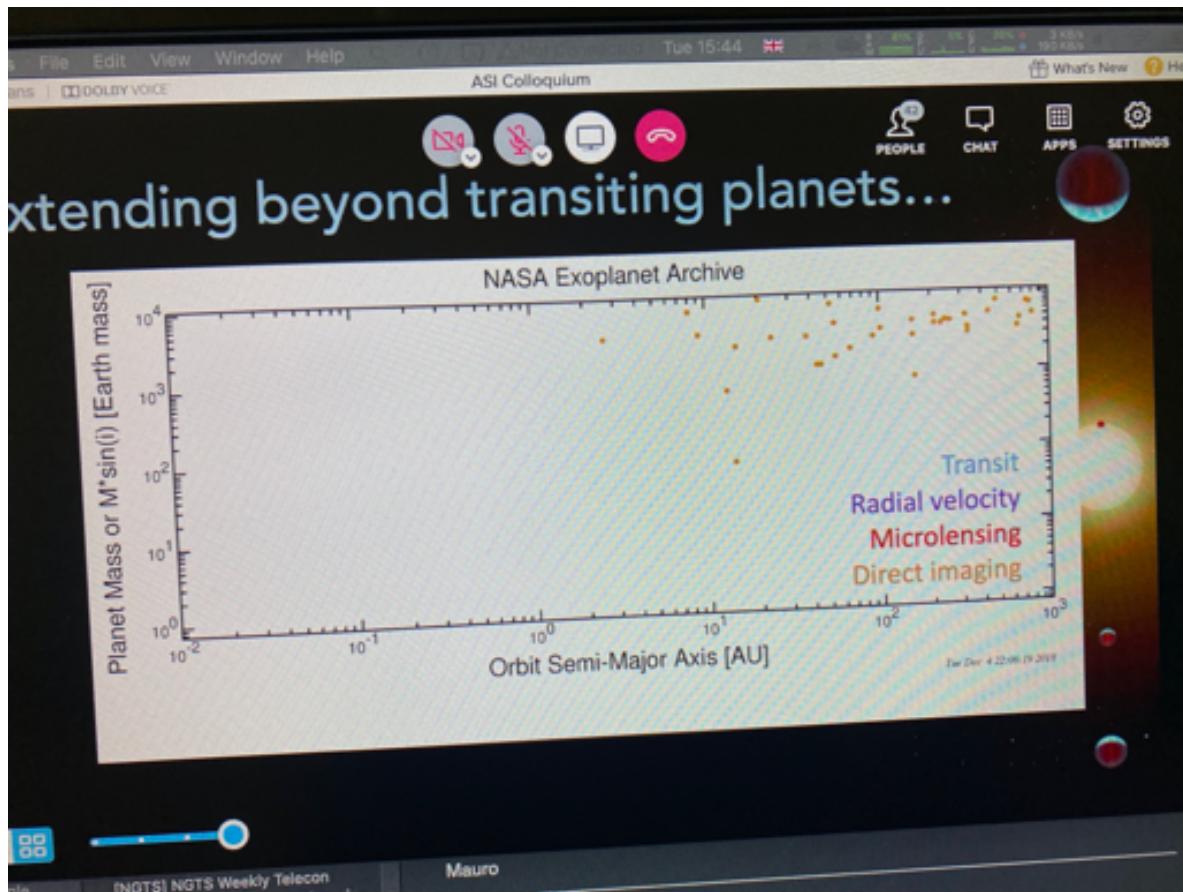


RV method Biased to heavier planets

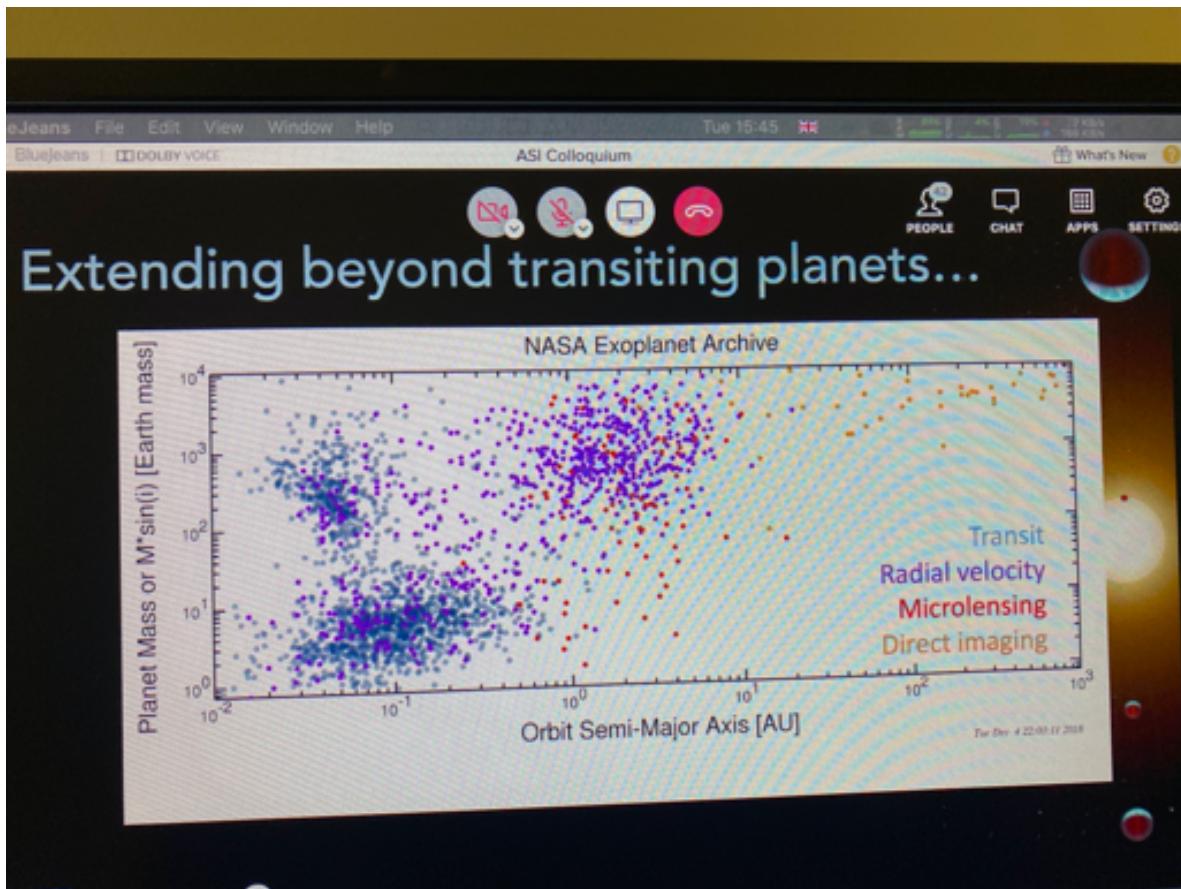


Microlensing planets

Don't see the same trend of mass drop-off. Only sensitive to mass ratio, not to mass itself. Can remove some of mass dependence. Most sensitive to planets around the snow line

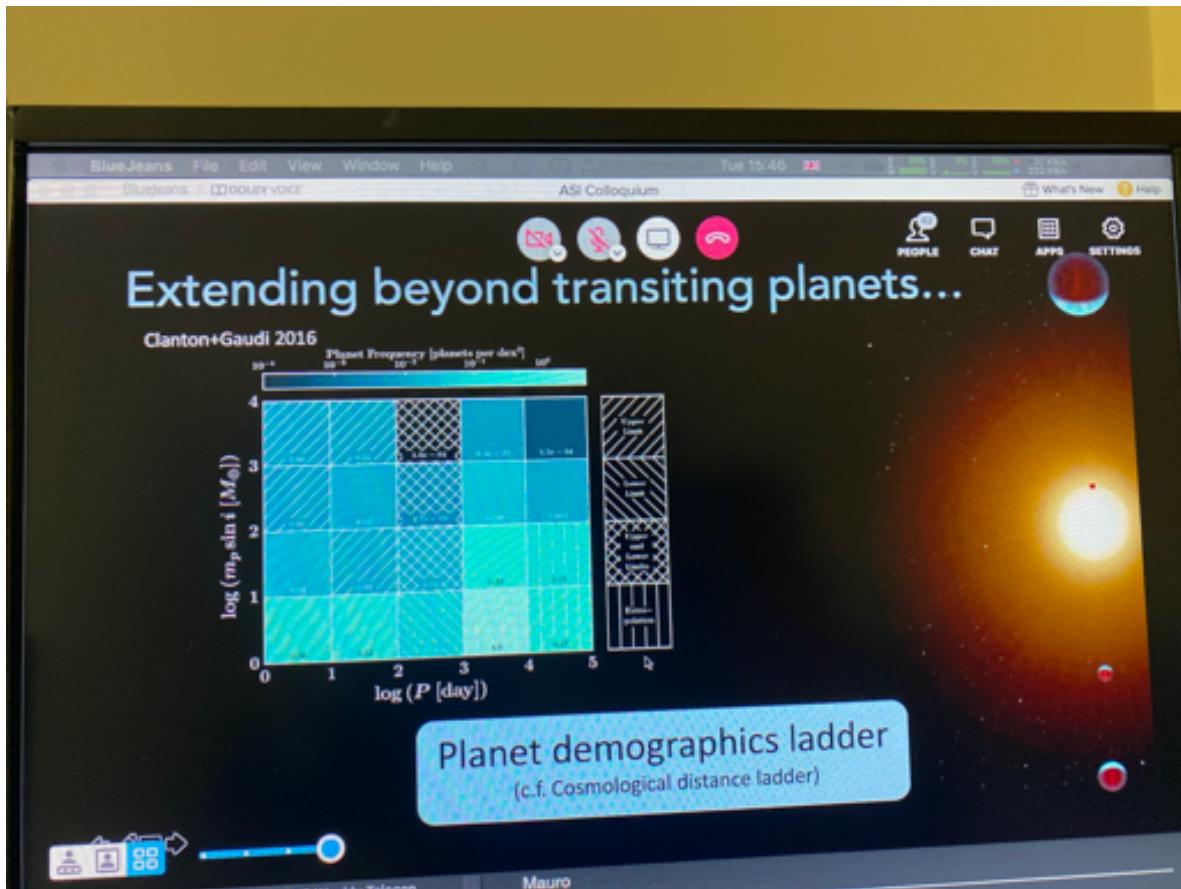


Only works for big planets far away from the star. Don't measure mass directly, have to use their luminosity, and modelling to determine this

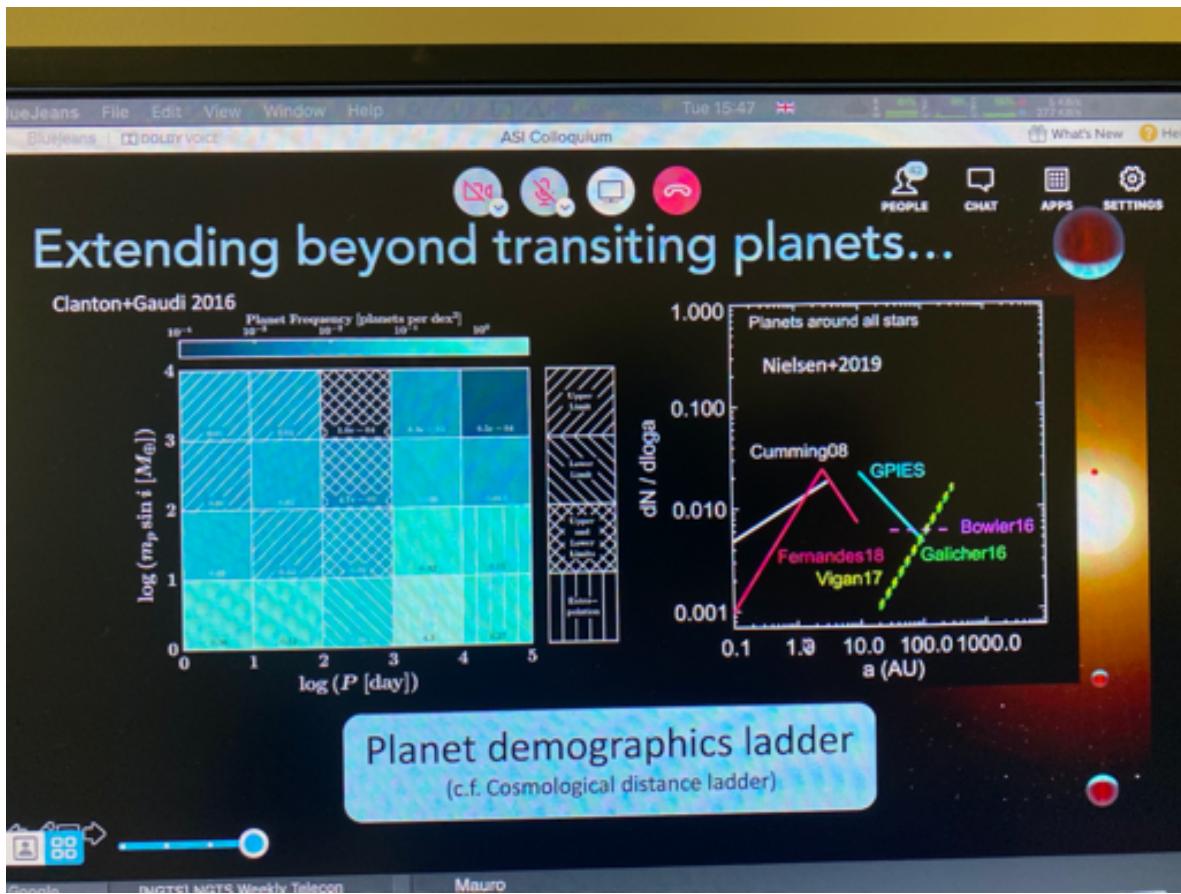


On the same plot -not trivial to get them all on same plot. Each technique overlaps. This means there is possibility for a planet demographics ladder (analogous to cosmological distance ladder) allowing for a diagnostic / calibration between these distinct techniques.

Has been tried before

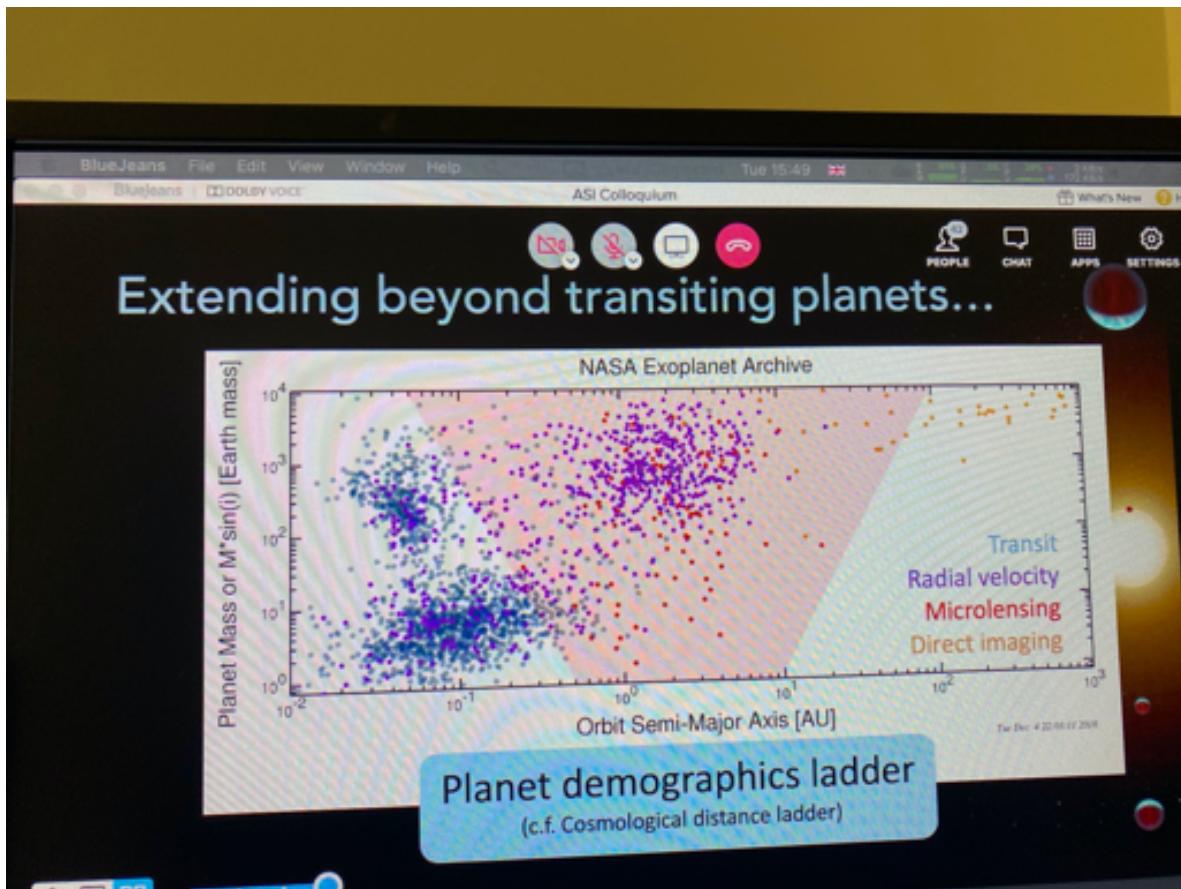


If you squint, the peak is between 1000 and 10000 days

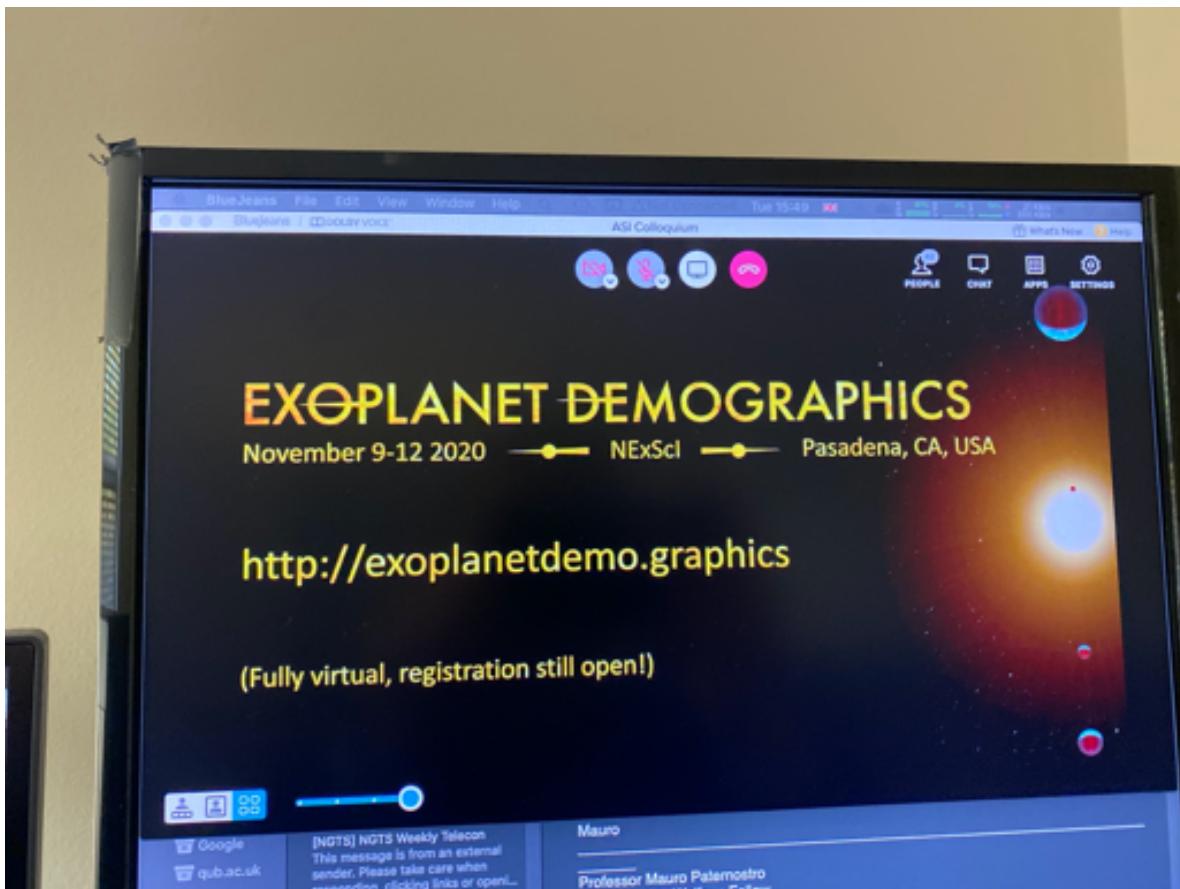


These 2 results agree - by 10 Au there is a 'turnover' in planet rates
 Need to make self consistent planet population we can look at
 different catalogues, and see if they agree

With all the overlaps in these types of detection, we can look at so many things



Pink cone is the detection range of ROMAN telescope (if it gets made) which looks at a range of these, so could be a great calibration tool



**Virtual conference in 2 weeks - Free as its a NASA conference,
please apply! :)**

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Summary

- Kepler
 - Status of occurrence rate calculations – converging (?)
 - Final pieces of the puzzle – in progress
- K2
 - Exploring occurrence rates along new axes
 - First results – methodology established, C5 pilot study complete
- TESS
 - Occurrence rates for classes of planets – parallel efforts underway
- Extending to wider orbits
 - The challenge of producing a consistent picture of planet formation and evolution – problems remain, very fruitful

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