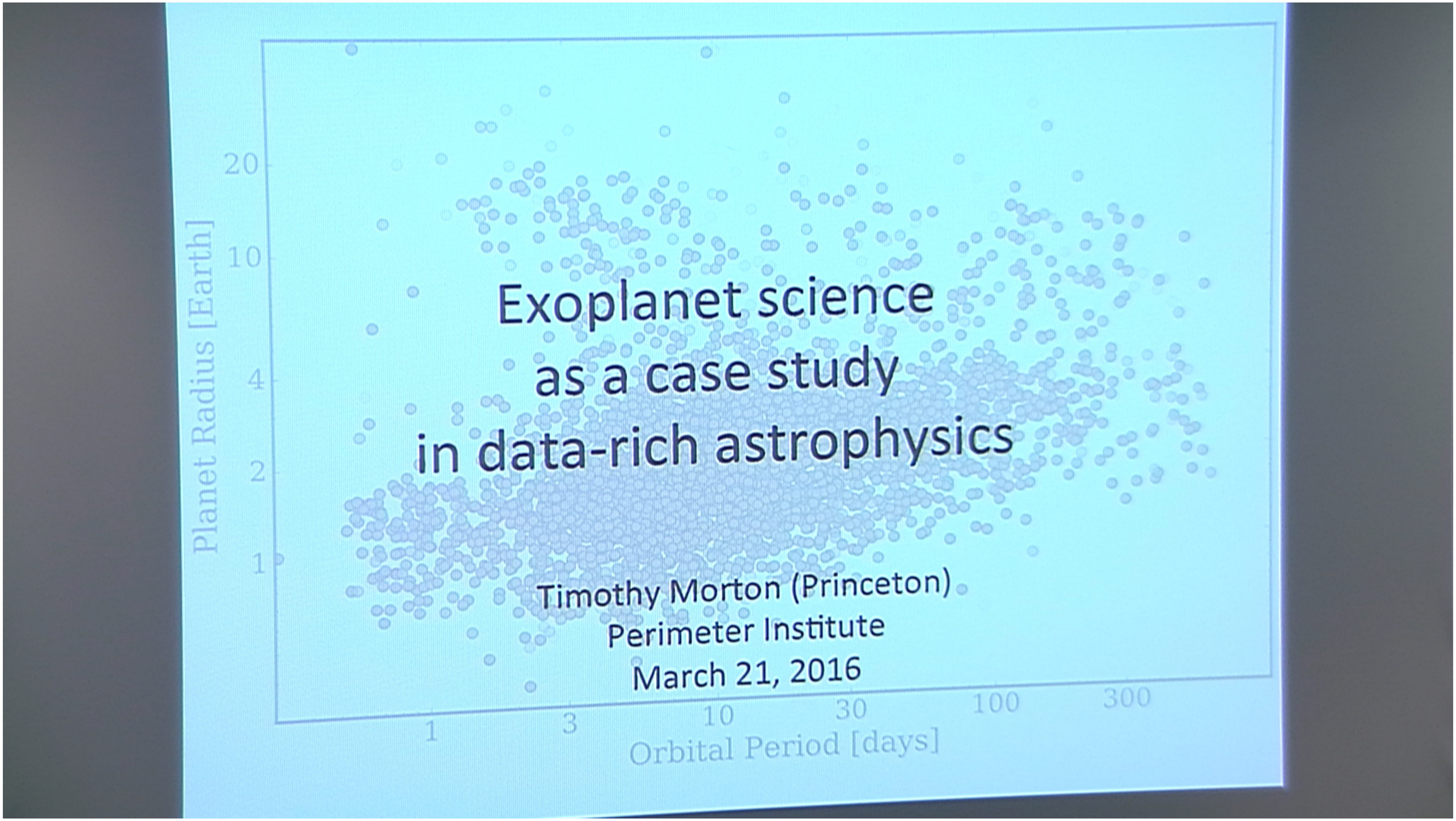
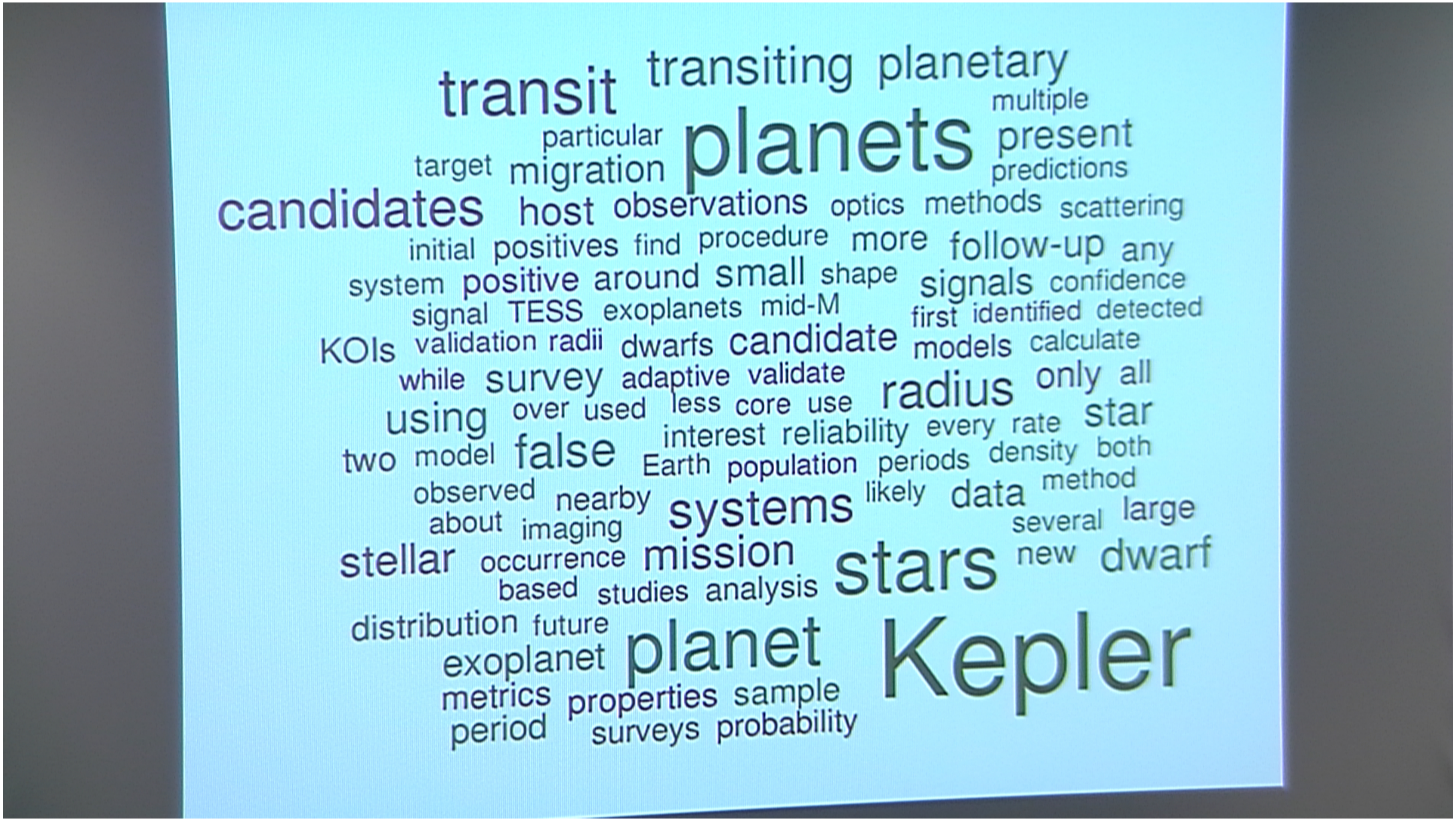
Title: Exoplanet science as a case study in data-rich astrophysics

Date: Mar 21, 2016 11:00 AM

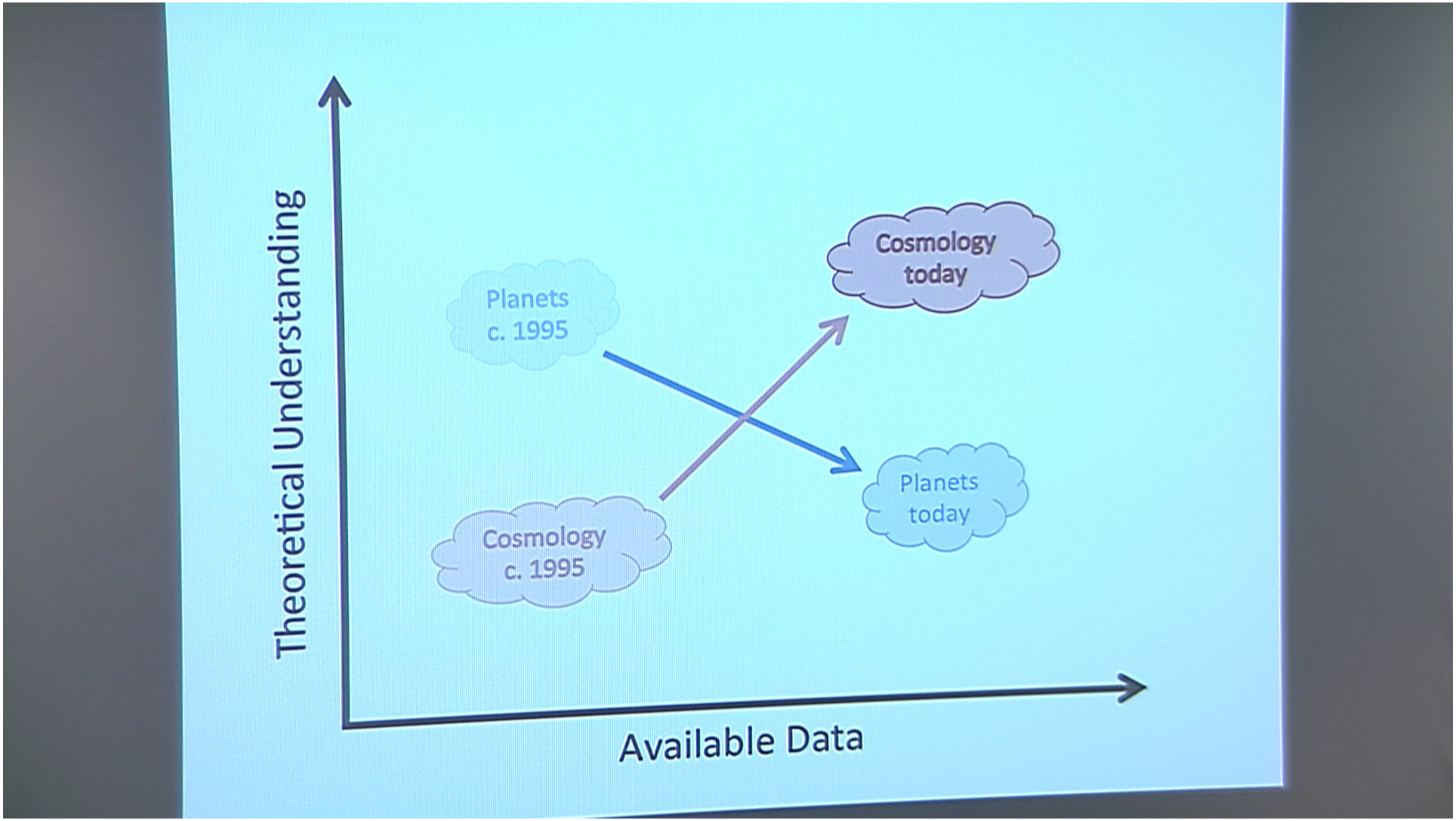
URL: http://pirsa.org/16030129

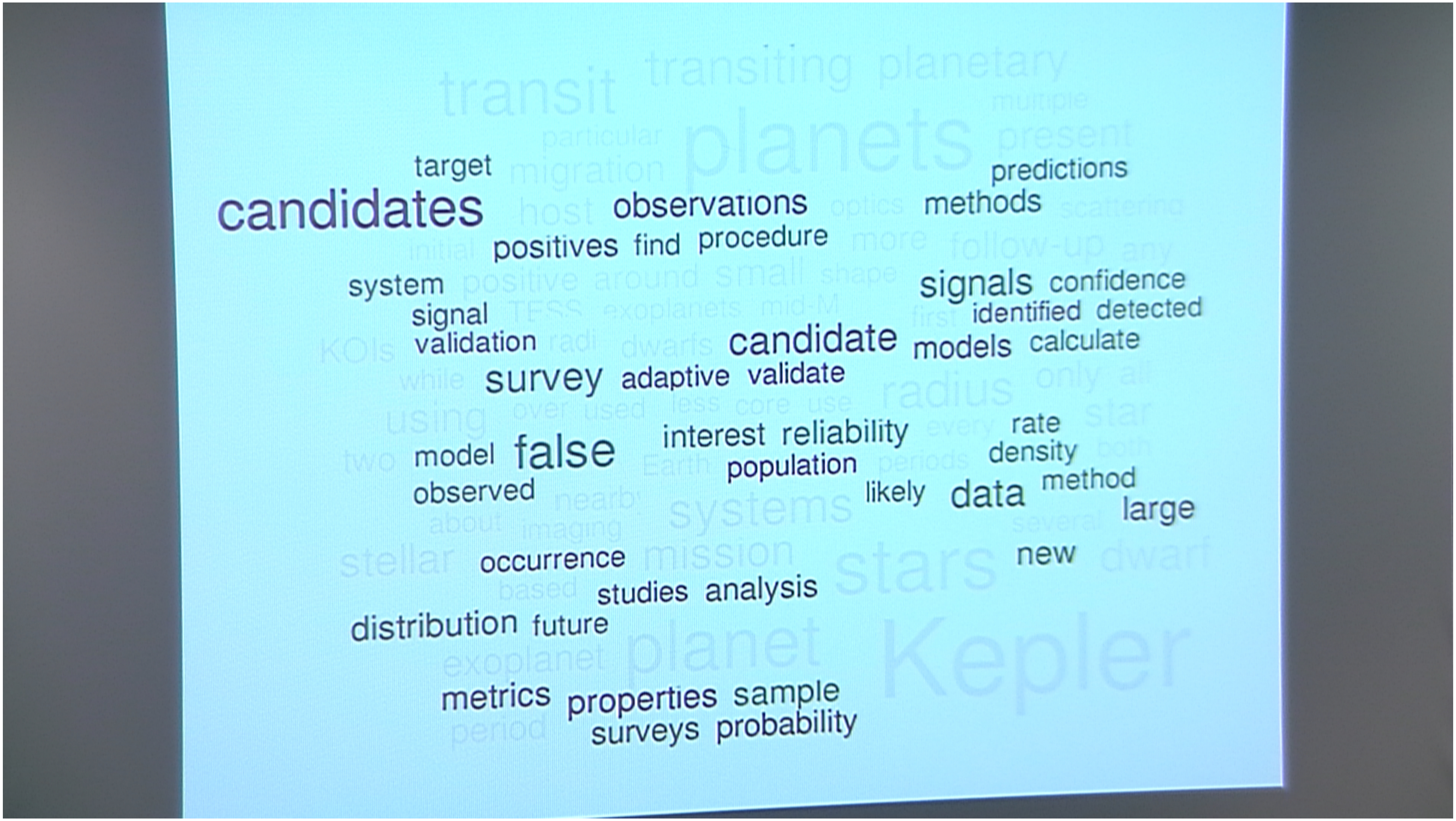
Abstract: <p>I will begin by giving an overview of the current state of exoplanet
science, a field that has advanced tremendously in just the last few
years. While specialized instrumentation and observational facilities
have provided the data driving this advance, the development and
application of statistical techniques to interpret this data have been
of critical importance. These same tools are also at the core of all
data-driven science, and are thus applicable to many other fields of
astrophysics that will be acquiring increasingly large and rich
datasets in the coming years. I will highlight a few examples of
particular interest to fundamental physics, including gravitational
wave observations, fast radio bursts, and cosmological surveys.</p>


Exoplanet science
as a case study
in data-rich astrophysics
Timothy Morton (Princeton)
Perimeter Institute
March 21, 2016
Planet Radius [Earth]
20
10
4
2
1
Orbital Period [days]
1
3
10
30
100
300


transit transiting planetary
multiple
particular planets present
target migration predictions
candidates host observations optics methods scattering
initial positives find procedure more follow-up any
system positive around small shape signals confidence
signal TESS exoplanets mid-M first identified detected
KOIs validation radii dwarfs candidate models calculate
while survey adaptive validate only all
using over used less core use radius star
interest reliability every rate
two model false Earth population periods density both
observed nearby likely data method
about imaging systems several large
stellar occurrence mission stars new dwarf
based studies analysis
distribution future
exoplanet planet Kepler
metrics properties sample
period surveys probability


Theoretical Understanding
Available Data


Theoretical Understanding
Cosmology
today
Planets
c. 1995
Planets
today
Cosmology
c. 1995
Available Data


transiting planetary
transit
planets
present
particular
target
migration
predictions
candidates
host
observations
optics
methods
scattering
initial
positives
find
procedure
more
follow-up
any
system
positive
around
small
shape
signals
confidence
signal
TESS
exoplanets
mid-M
first
identified
detected
KOIs
validation
radi
dwarfs
candidate
models
calculate
while
survey
adaptive
validate
radius
only
all
using
over
used
less
core
use
star
interest
reliability
every
rate
two
model
false
Earth
population
periods
density
both
observed
nearby
likely
data
method
systems
about
imaging
large
several
stellar
occurrence
mission
stars
new
dwarf
based
studies
analysis
distribution
future
exoplanet
planet
Kepler
metrics
properties
sample
period
surveys
probability

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The Planet at 51 Peg

by Jeffrey Winters

From the January 1996 issue; published online January 1, 1996

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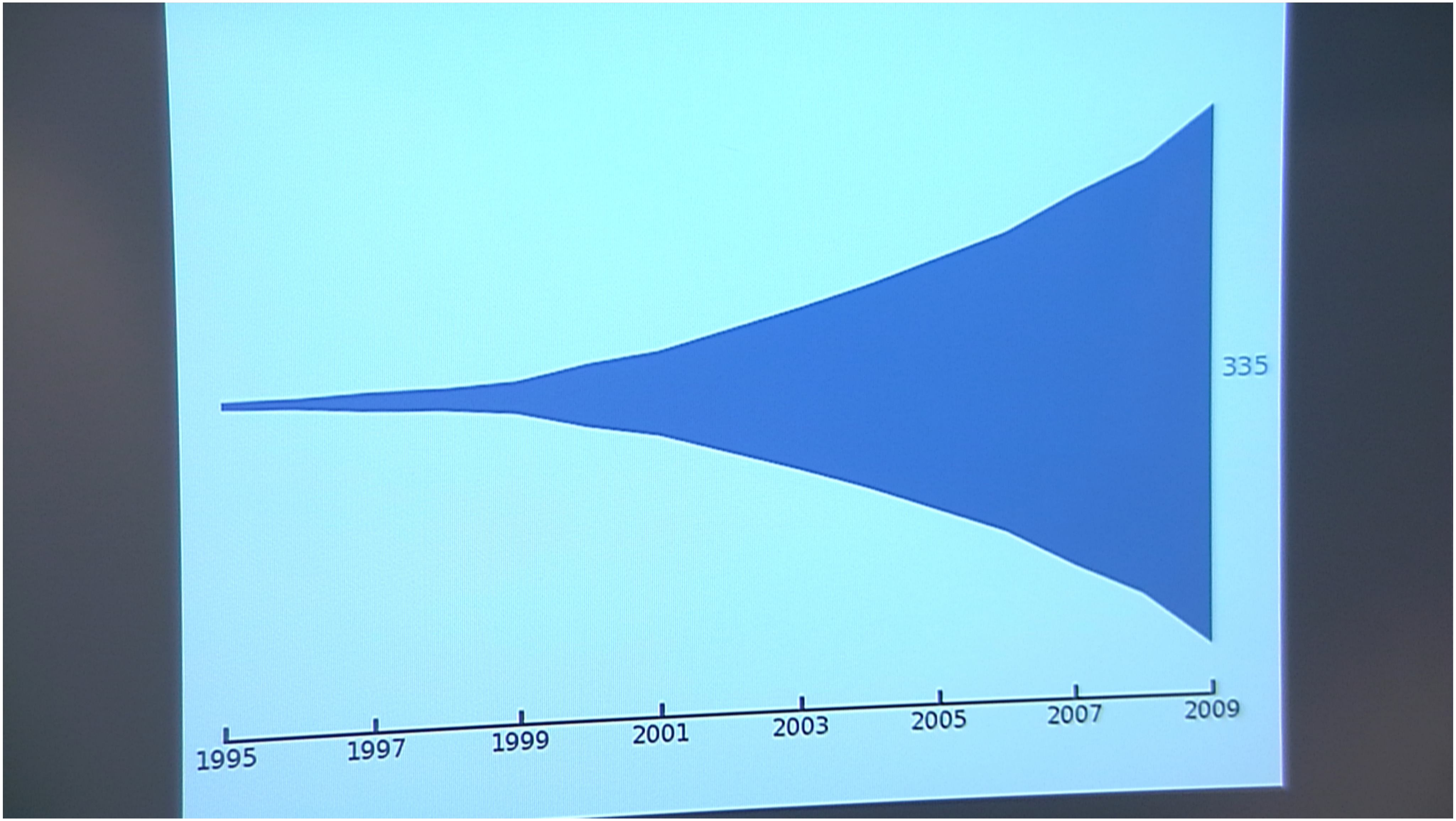
Ever since astronomers realized that stars were like the sun, just farther removed, they have wondered whether these other suns might have their own planets–perhaps inhabited ones. So when astronomers Michel Mayor and Didier Queloz of the University of Geneva quietly reported in October that they had detected a Jupiter-size planet circling a fairly mediocre star 57 light-years away, the news did not stay quiet long. It spread through the astronomical community like a tidal wave–one that spilled right onto the likes of Nightline and the Today show. The enthusiasm was more than justified, says astronomer Geoff Marcy of San Francisco State University, who has himself spent much of the past decade trying to locate extrasolar planets–and who quickly confirmed the Swiss find. This is a discovery that any human being who is curious about the universe should rejoice in, Marcy says. Everyone can now look up in the night sky and look at the stars and say, 'There are planets out there.'

The planet that Mayor and Queloz found orbiting Star 51 in the constellation Pegasus (51 Peg to its friends) is not the first extrasolar planet–just the first one discovered around an ordinary star like the sun. In 1994 astronomers reported convincing evidence of two or three planets orbiting a star in Virgo. But that star was a pulsar–the dense spinning remnant of an exploded star–which meant that it was probably raining lethal radiation on its companions. That put a damper on all dreams of finding extraterrestrial life.

Finding a planet around a homier star, though, is if anything even harder than finding one around a pulsar. In neither case can astronomers actually hope to see the thing. It would be too far away, too faint, and in the case of a sunlike star, too swamped by the visible glare of the star itself. The only way to detect an extrasolar planet is from the way its gravity pulls the star ever so slightly back and forth. In the case of a pulsar, this induces minute changes in the timing of the star's otherwise regular pulses of radiation. If the star is sunlike, astronomers have to look for the subtle compressing and stretching of its light as it is pulled first toward, then away from Earth.


335
1995
1997
1999
2001
2003
2005
2007
2009

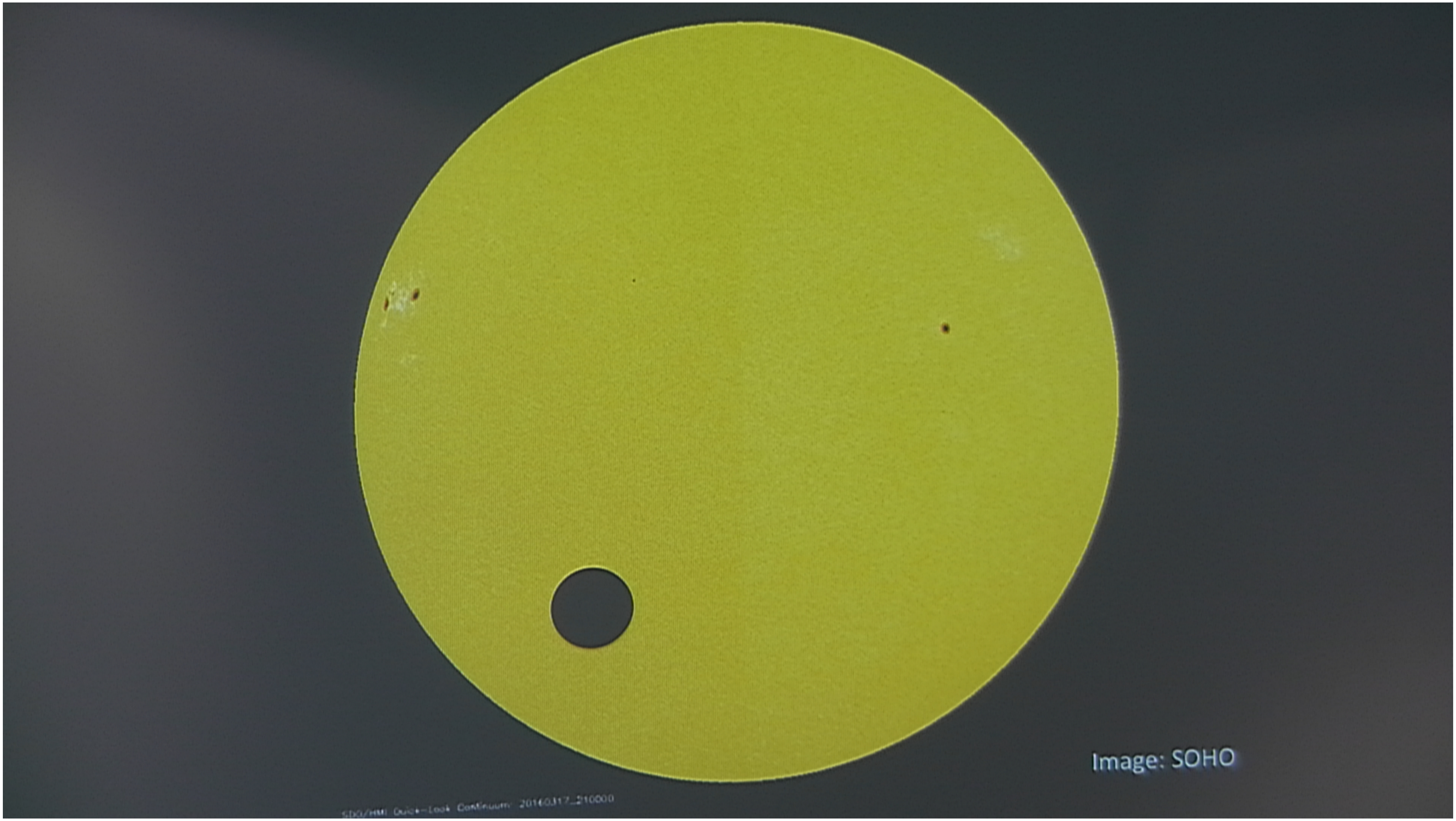
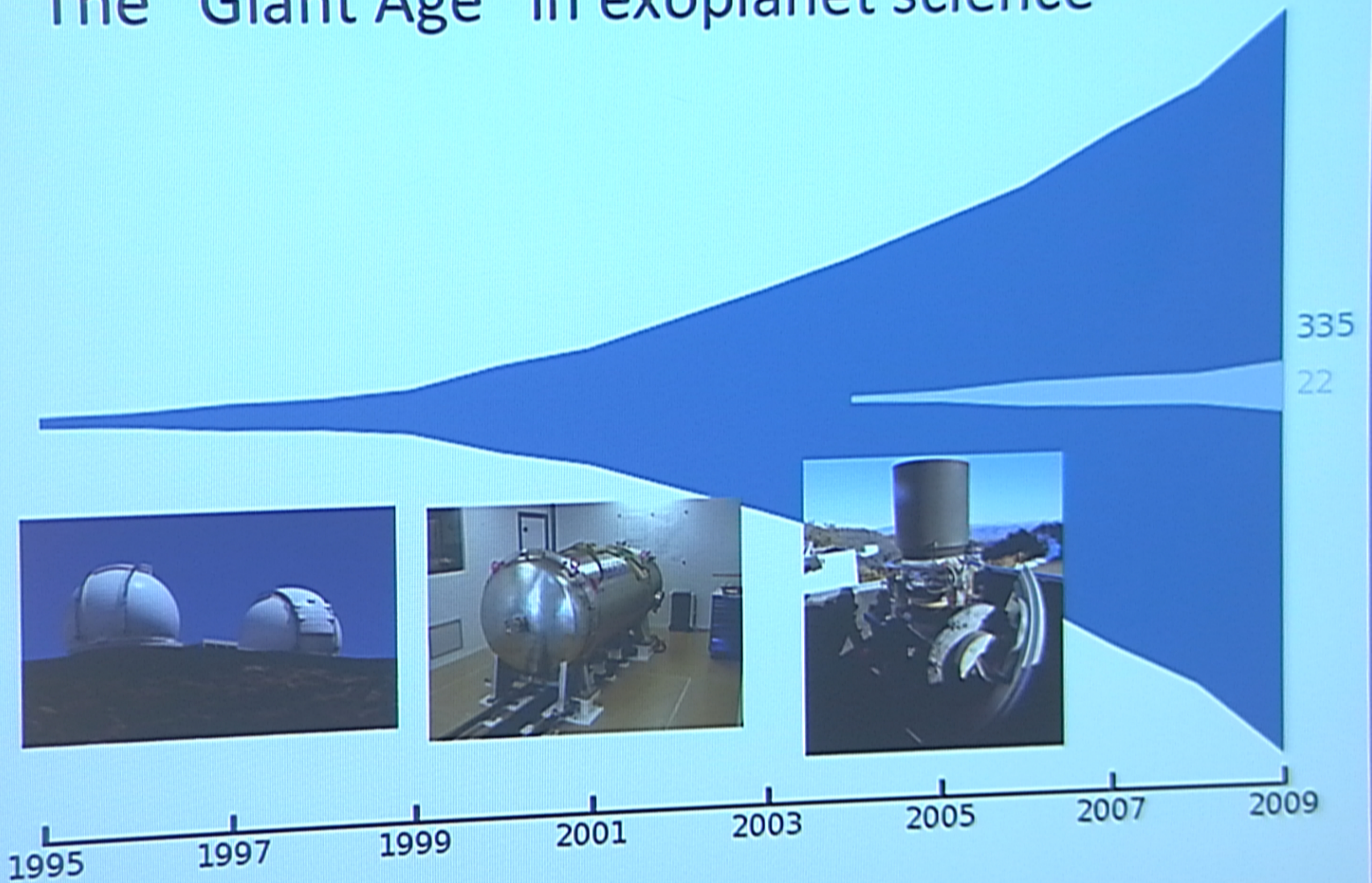


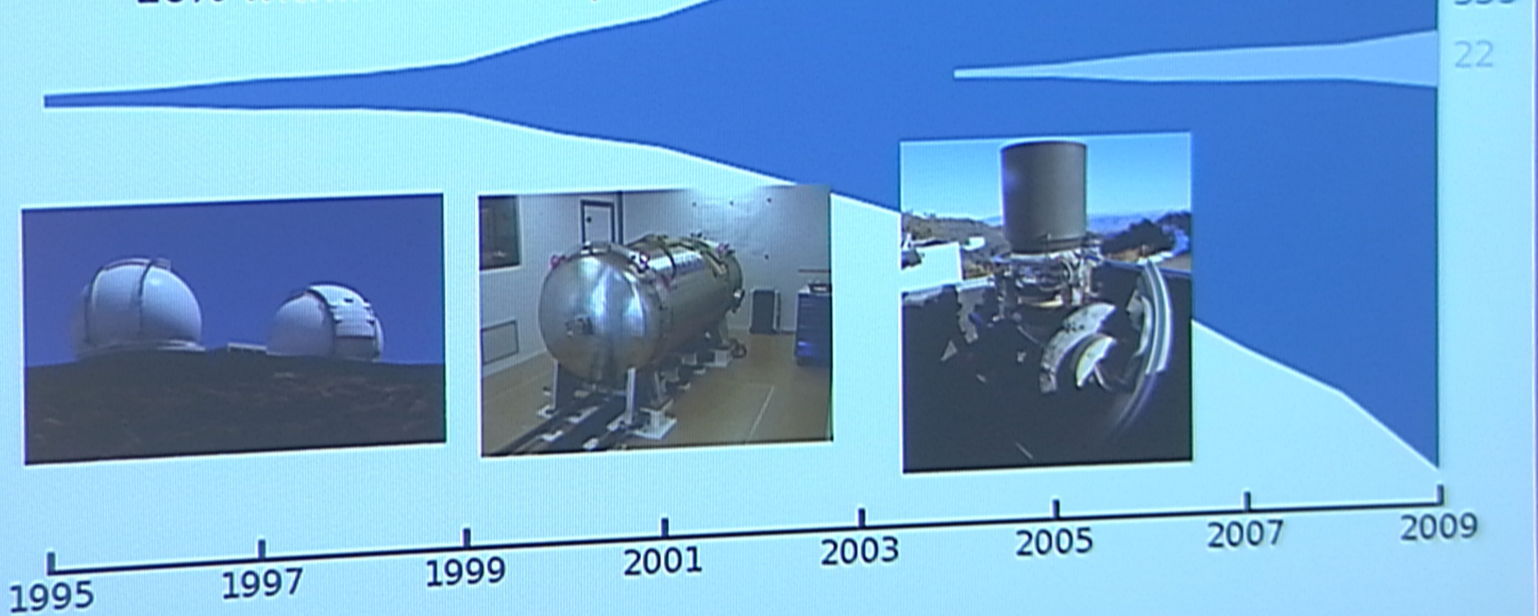
Image: SOHO
SDO/HMI Quick-Look Continuum: 20160317_210000

The "Giant Age" in exoplanet science



The "Giant Age" in exoplanet science

- Existence in short-period orbits (!)
- Significant eccentricities/inclinations (!)
- More common around metal-rich stars
- ~1% of stars host hot Jupiters (<10d)
- ~10% within ~2000 days



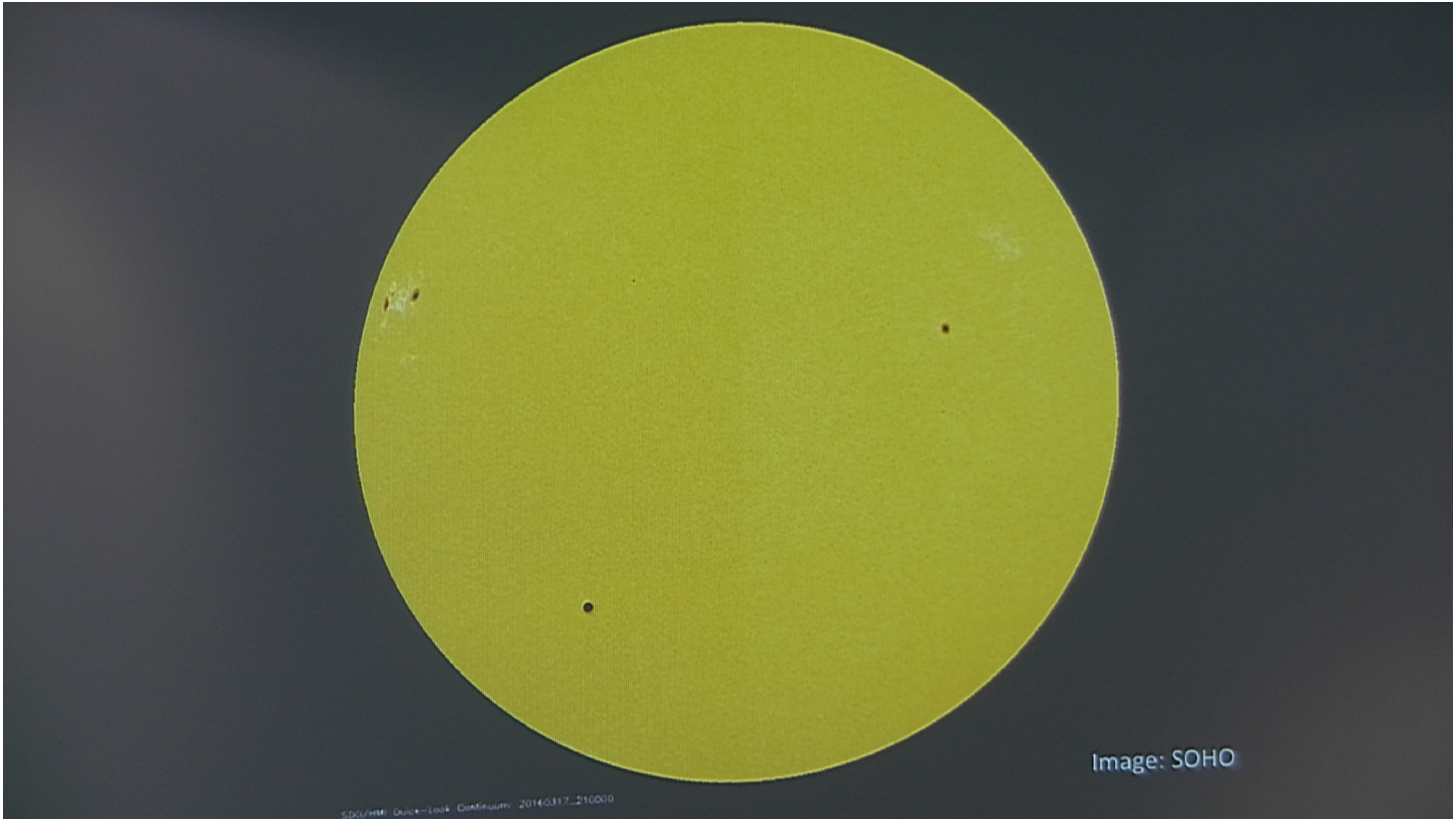
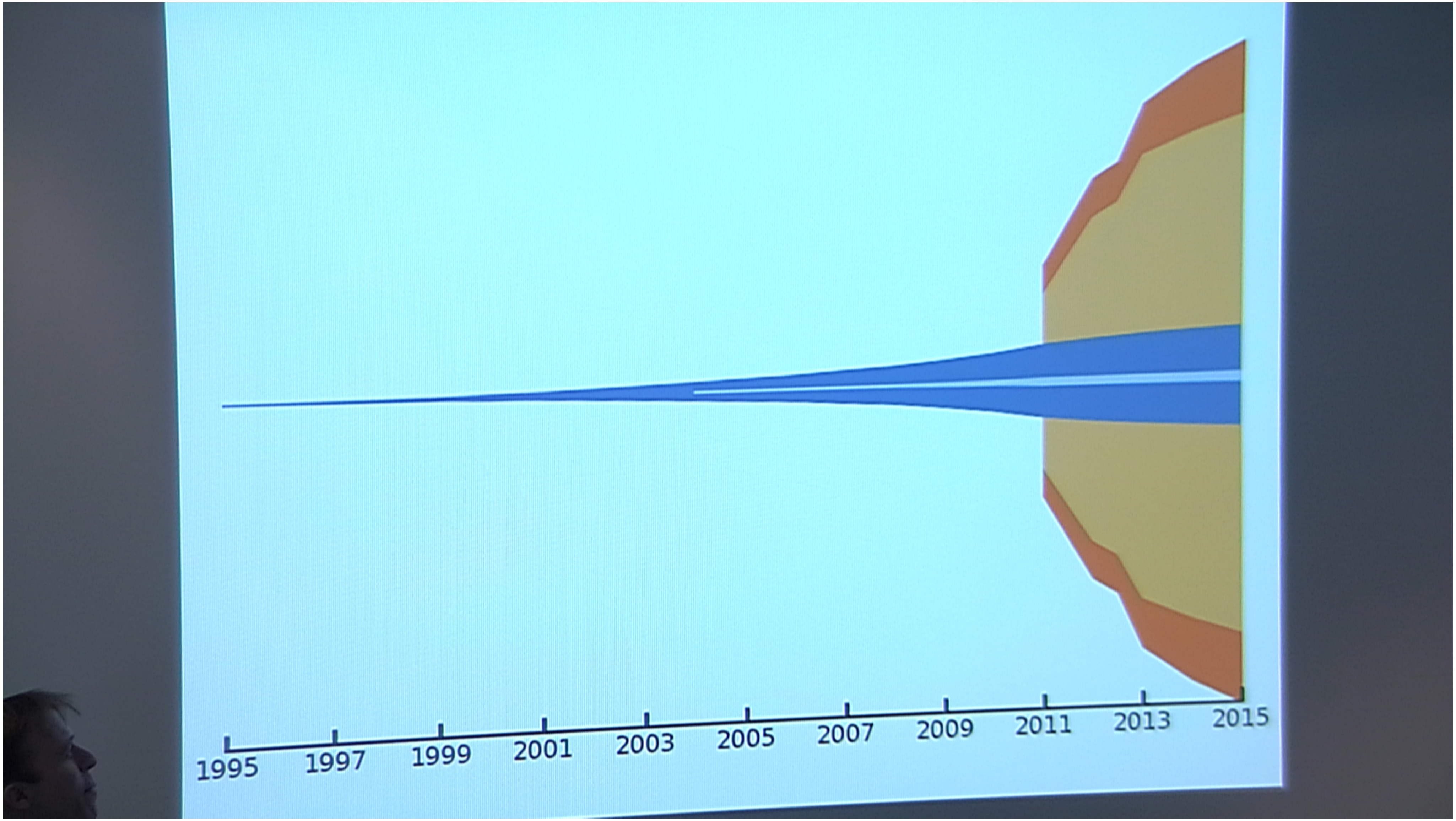
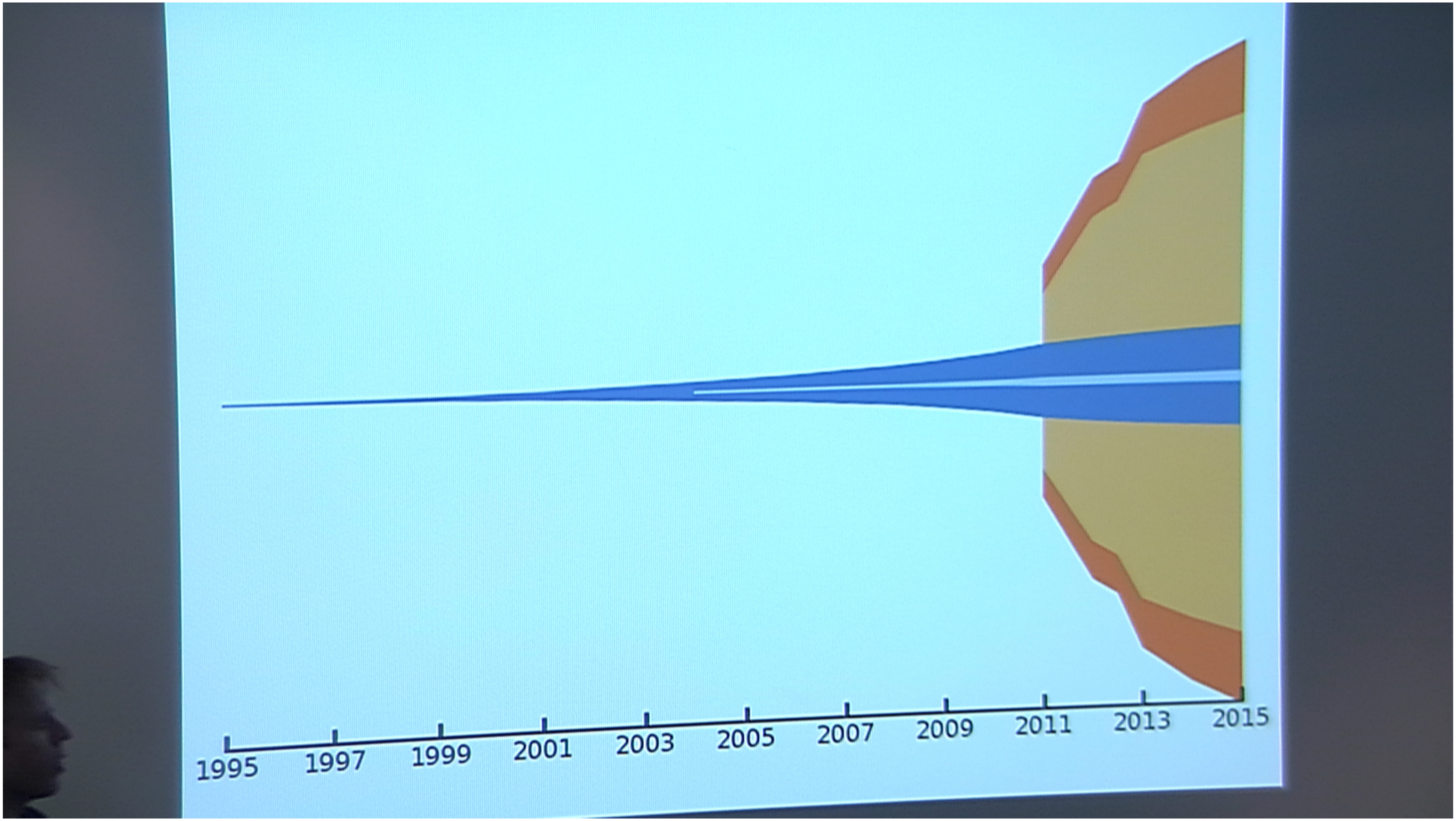


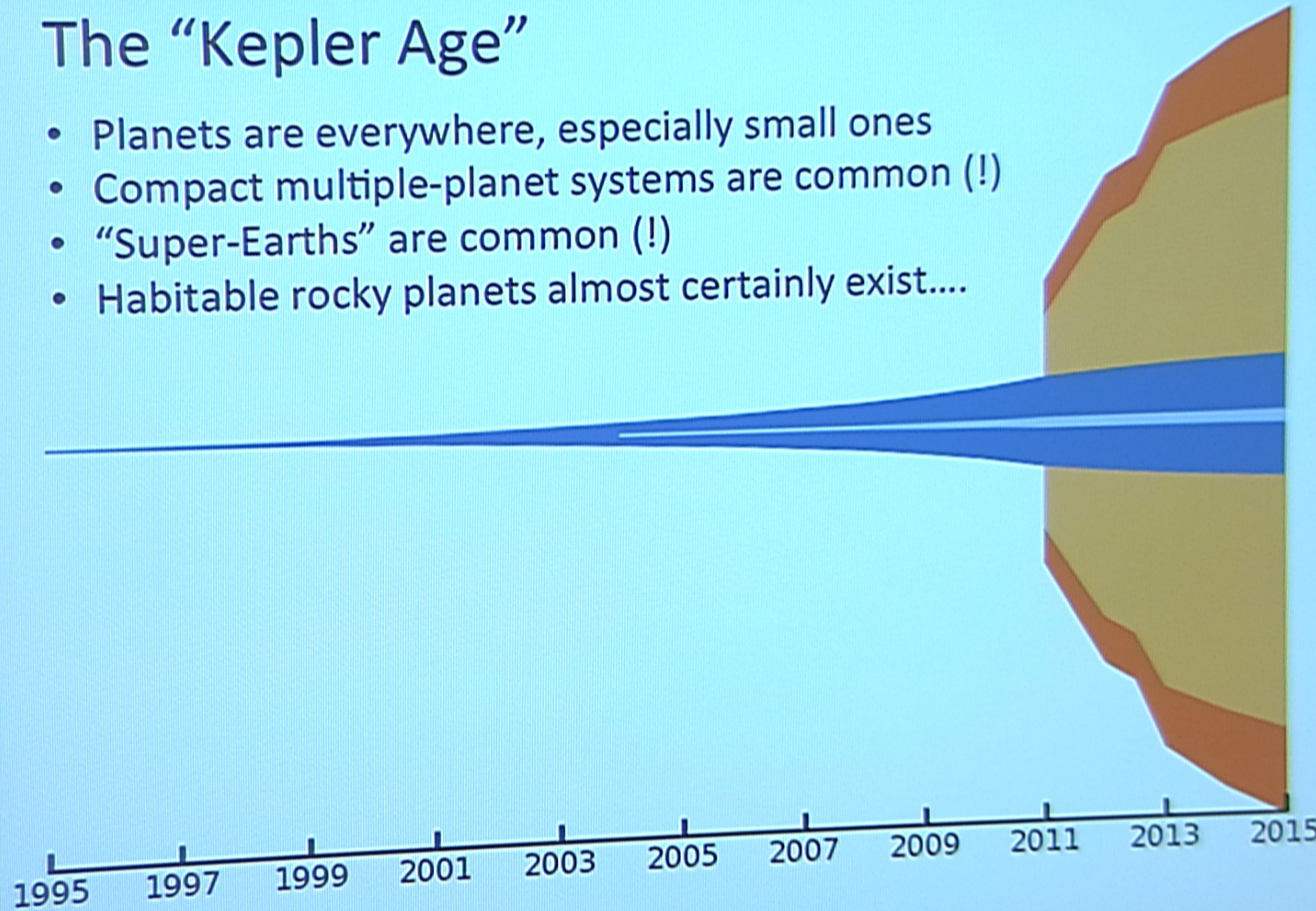
Image: SOHO
SDO/HMI Quick-Look Continuum: 20160317_210000


1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015


1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015

The "Kepler Age"

- Planets are everywhere, especially small ones
- Compact multiple-planet systems are common (!)
- "Super-Earths" are common (!)
- Habitable rocky planets almost certainly exist....



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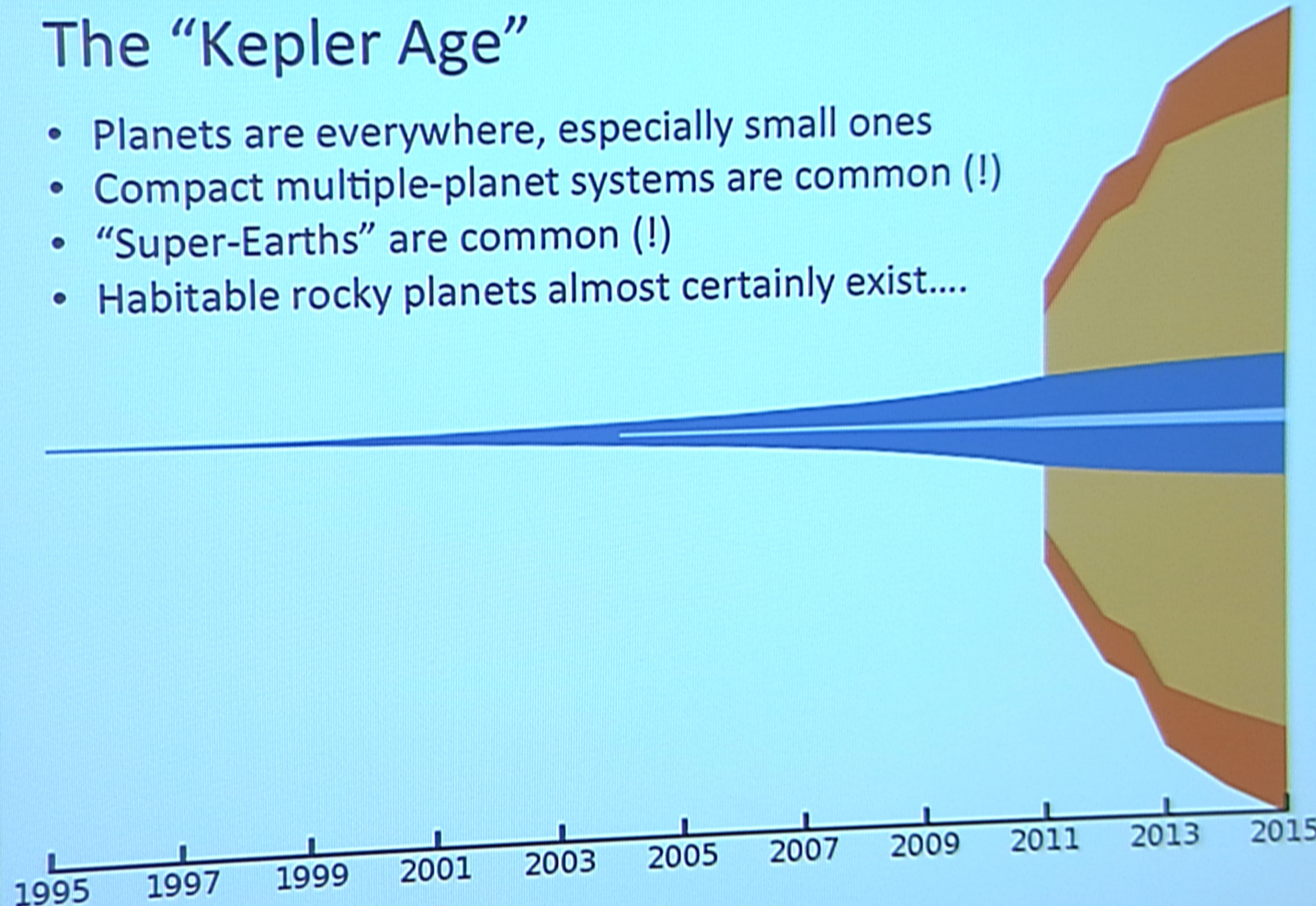
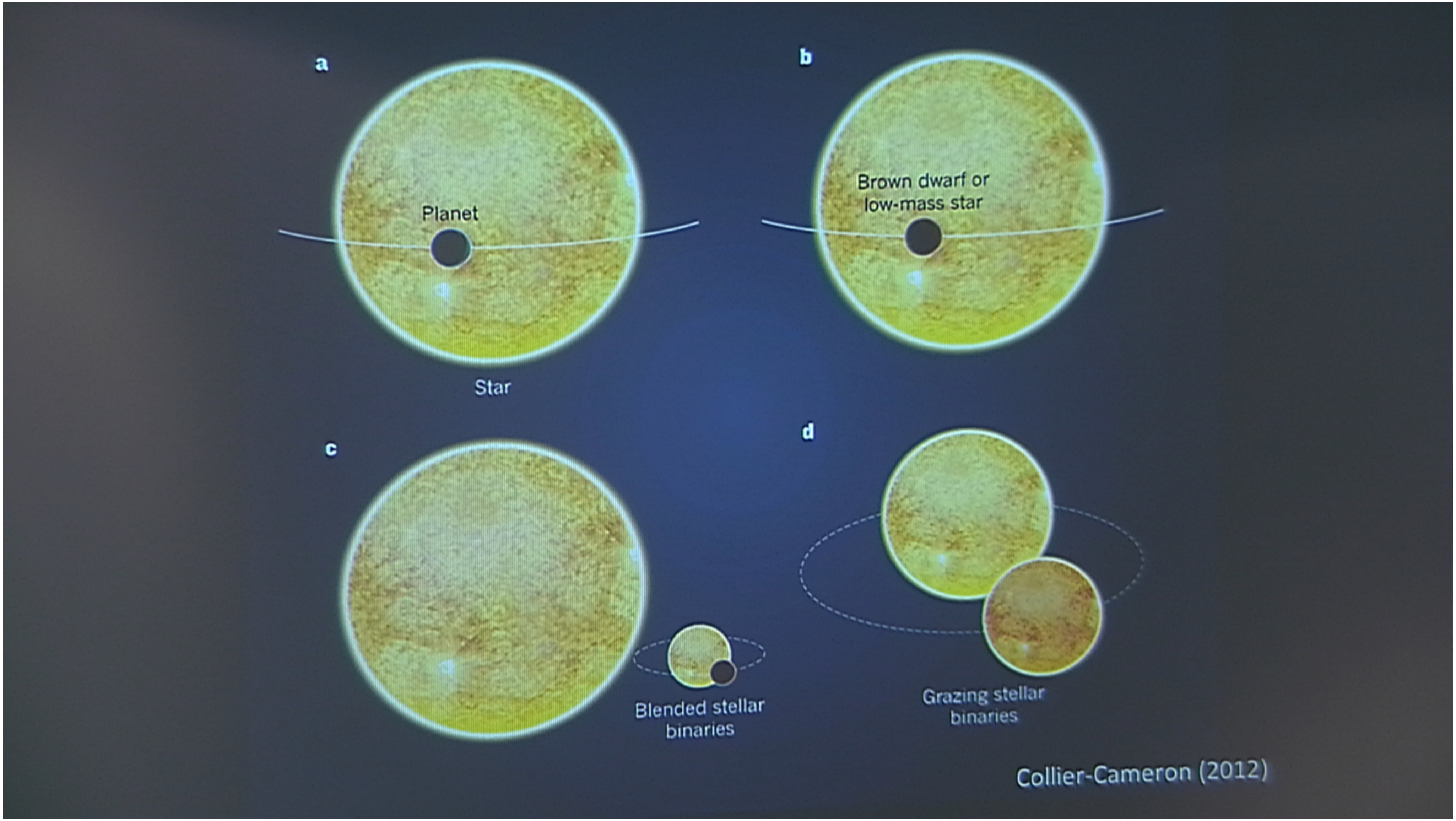
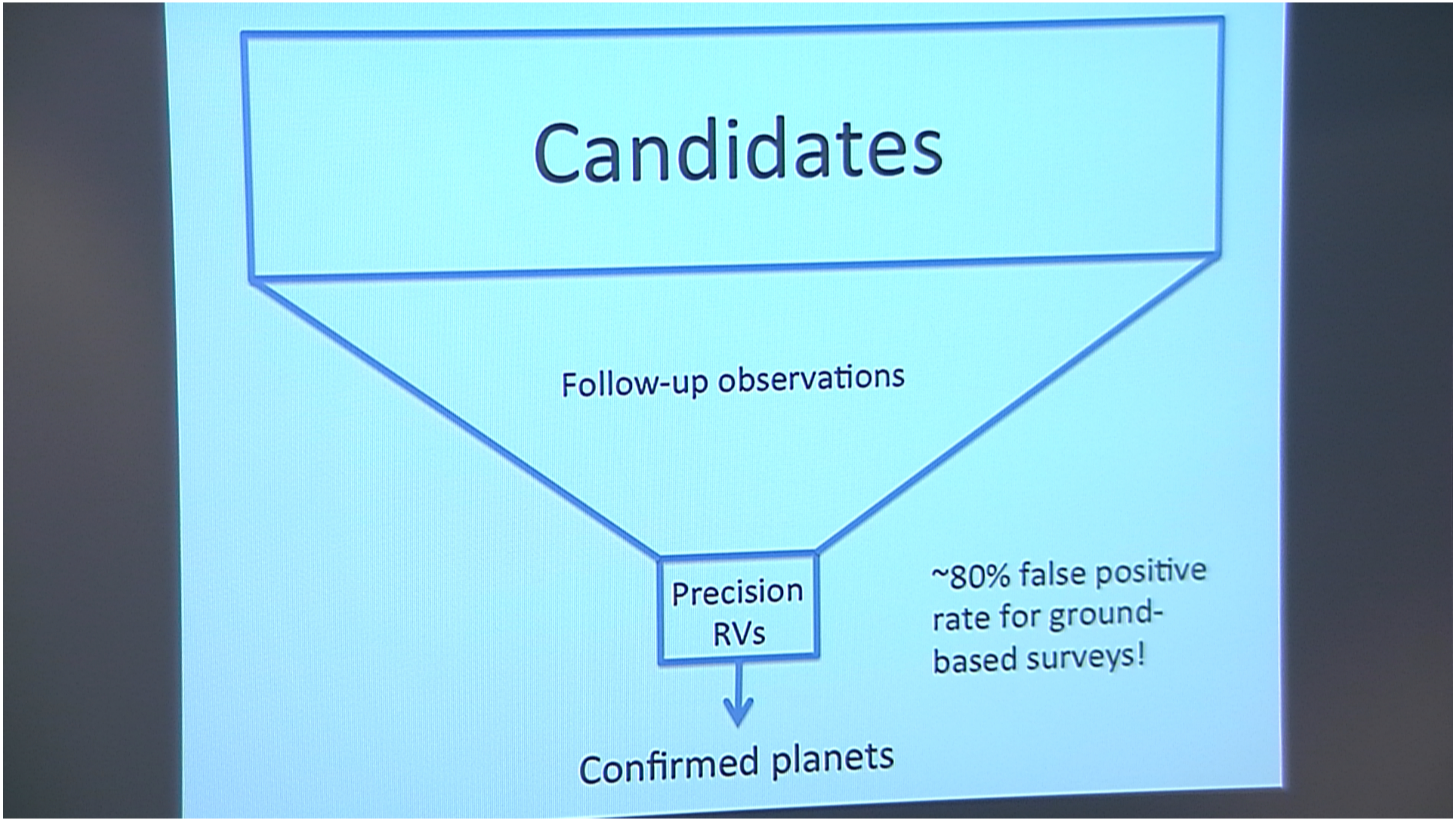
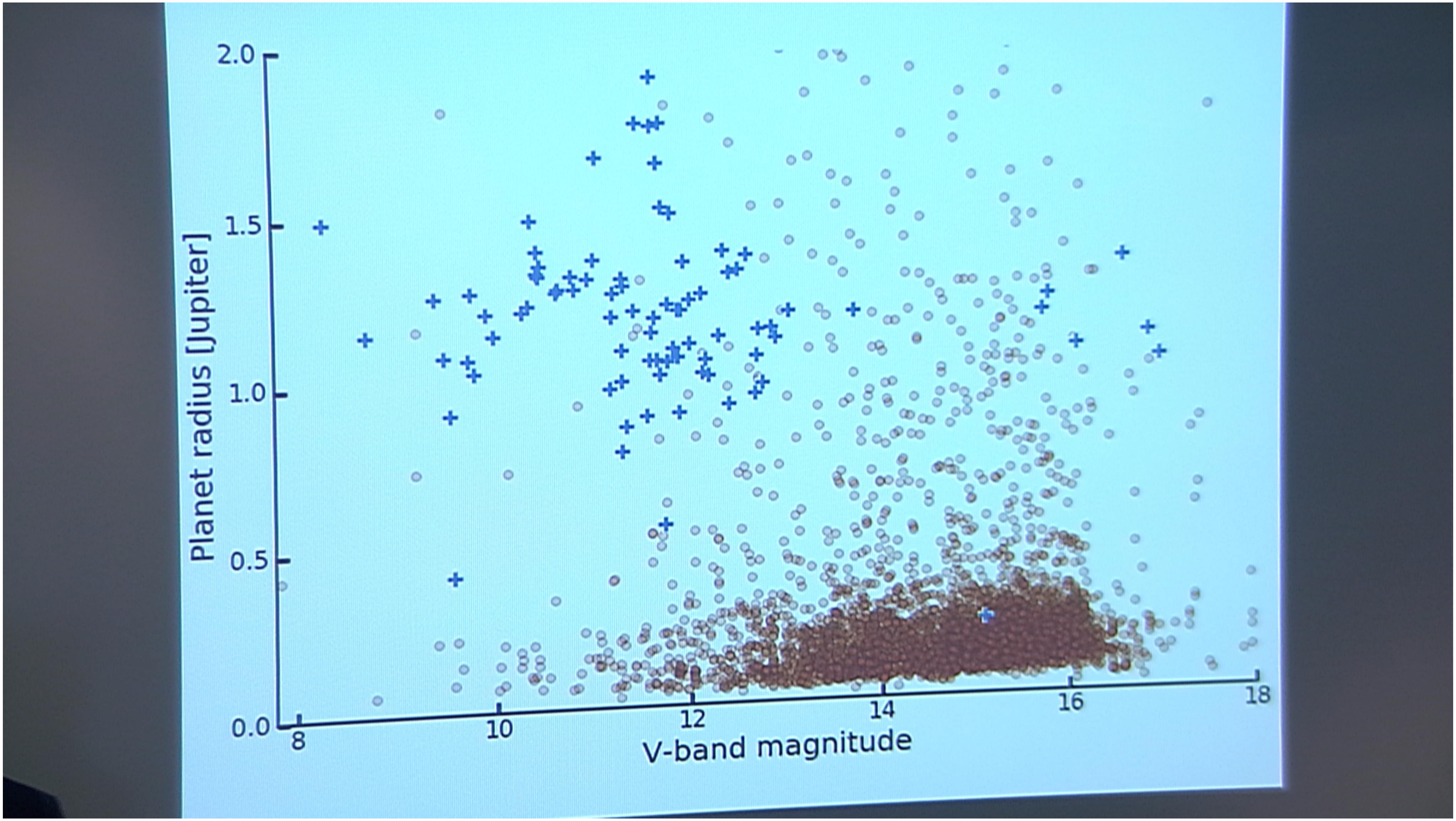
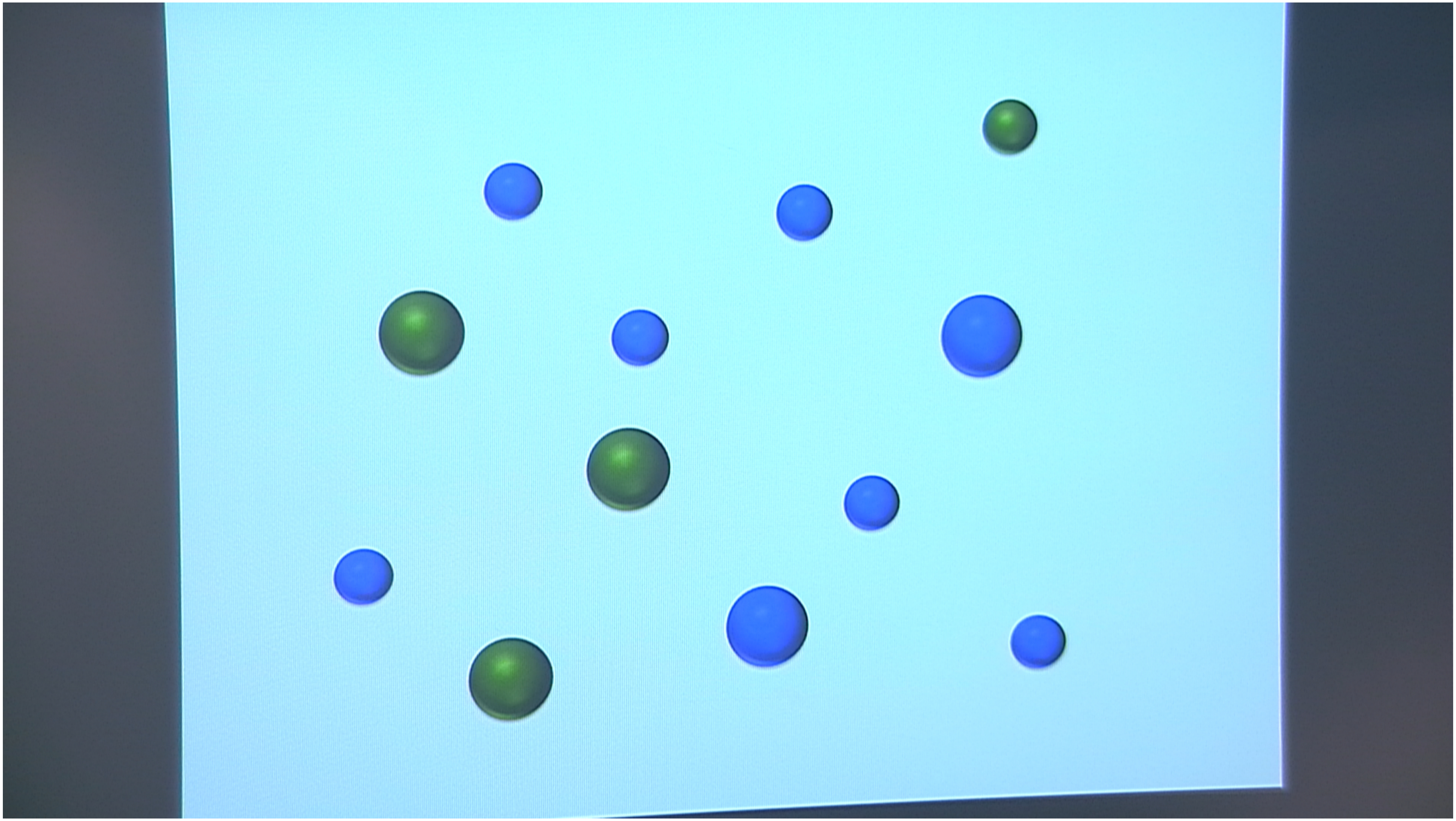



a
Planet
Star
b
Brown dwarf or
low-mass star
c
Blended stellar
binaries
d
Grazing stellar
binaries
Collier-Cameron (2012)


Candidates
Follow-up observations
Precision
RVs
~80% false positive
rate for ground-
based surveys!
Confirmed planets



Planet radius [Jupiter]
2.0
1.5
1.0
0.5
0.0
8
10
12
14
16
18
V-band magnitude



$$\{H_i\} = \{\text{planet}, \text{FP}_1, \text{FP}_2, ...\}$$

$$p(H_i \,|\, \text{data}) = \frac{\mathcal{L}_i(\text{data} \,|\, H_i)\pi(H_i)}{\sum_j \mathcal{L}_j(\text{data} \,|\, H_j)\pi(H_j)}$$

Kepler False Positive Probabilities (FPPs)

- Morton & Johnson (2011; 165 citations)
  - First *Kepler* candidate FPP estimate: 5-10%
  - Independently confirmed (theoretically & observationally)
- Morton (2012; 55 citations)
  - Extended analysis framework to include signal shape, observational constraints
  - Applied to validate many *Kepler* planets
- Open-source python software packages (2015)
  - `vespa`: FPP calculation, population synthesis
  - `isochrones`: stellar parameter fitting
  - Used by several independent groups

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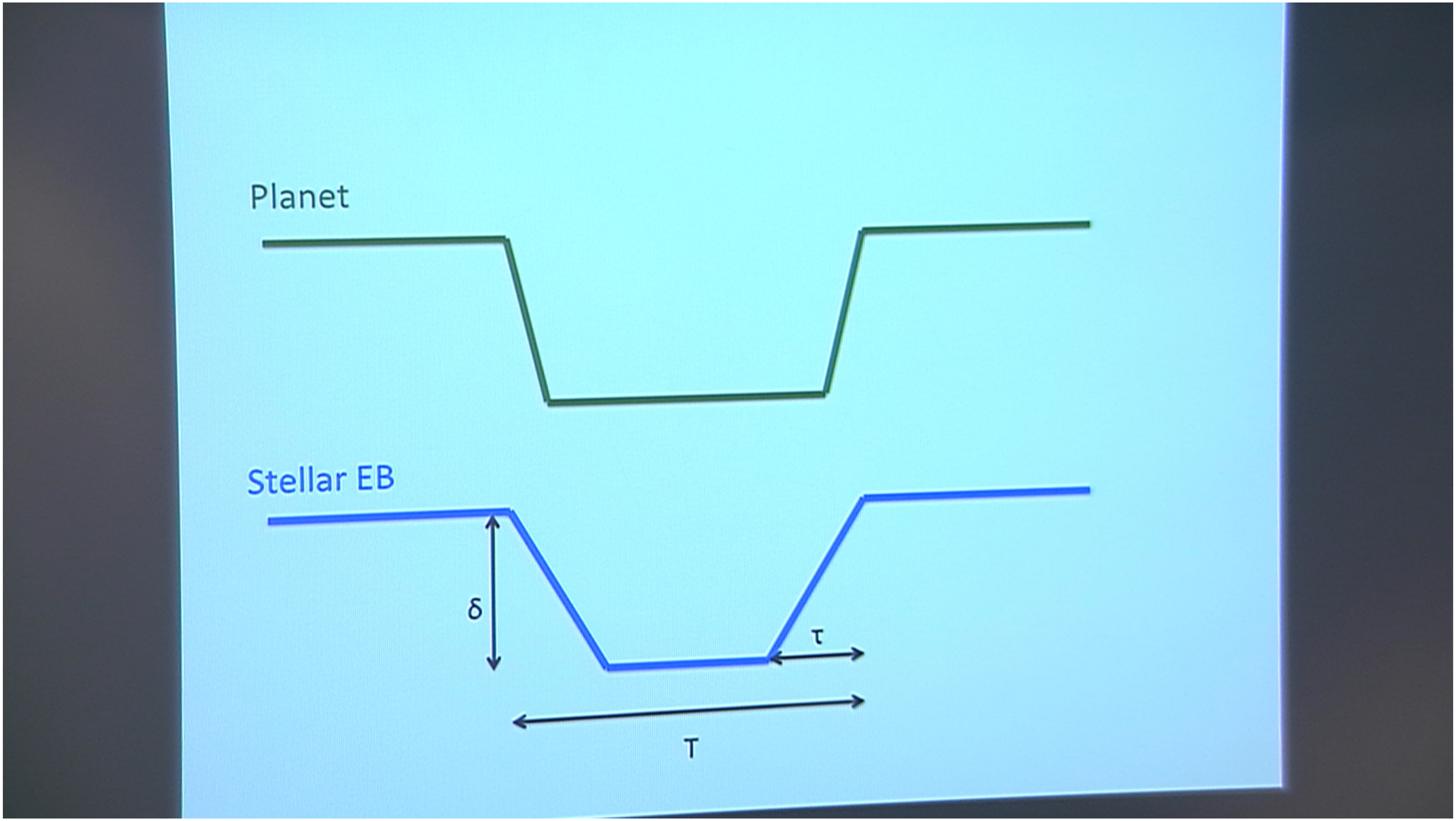
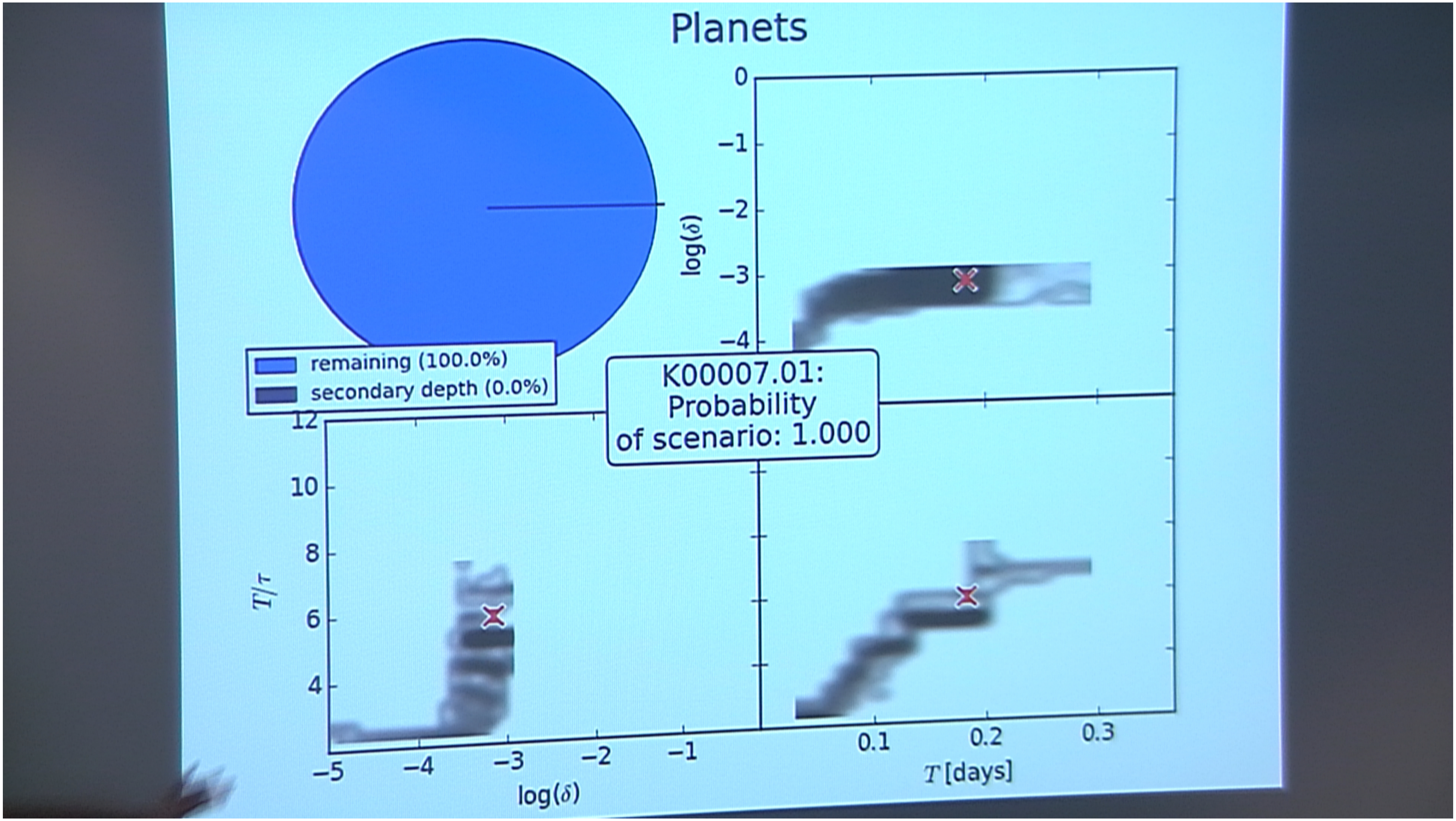
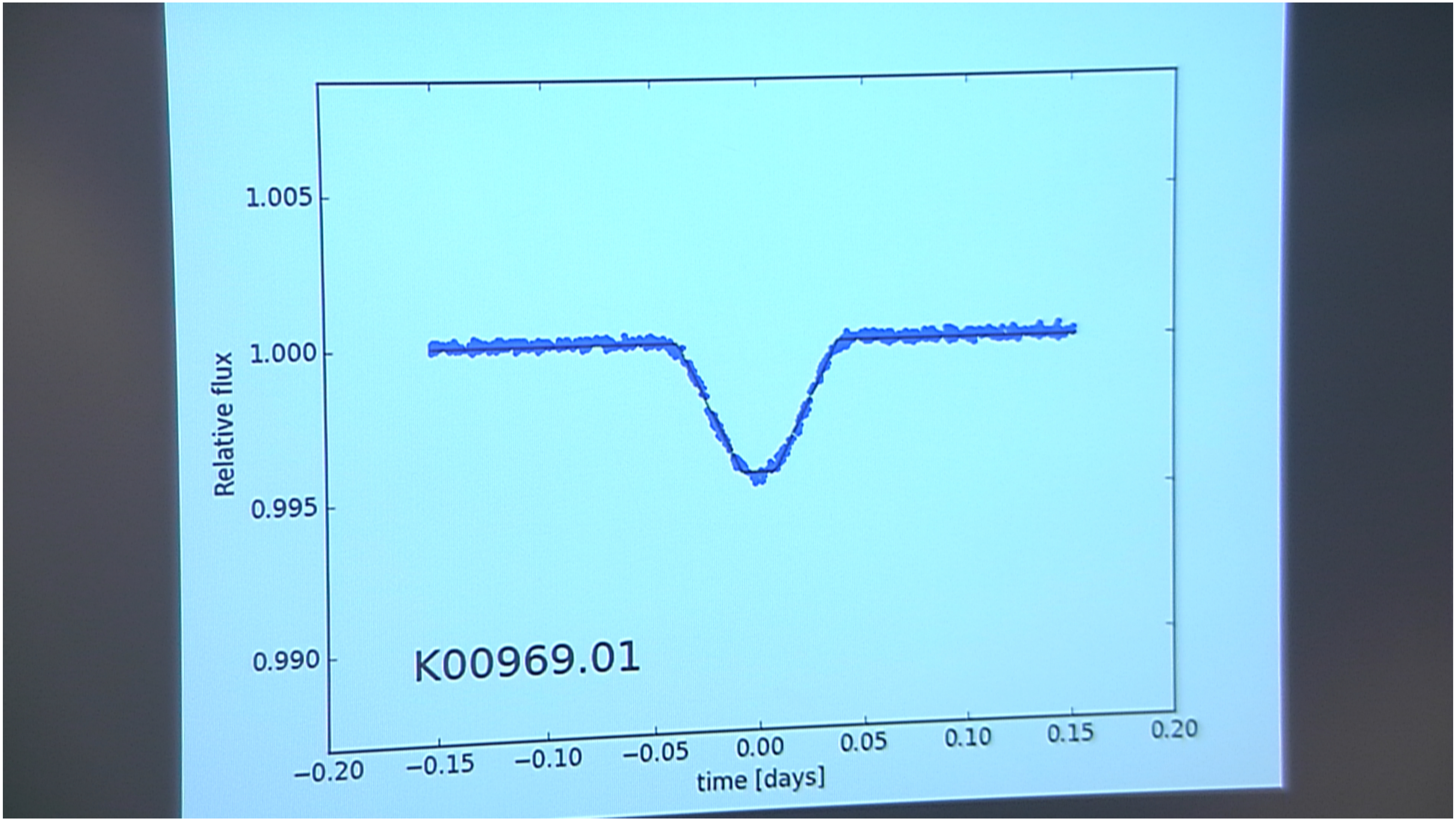
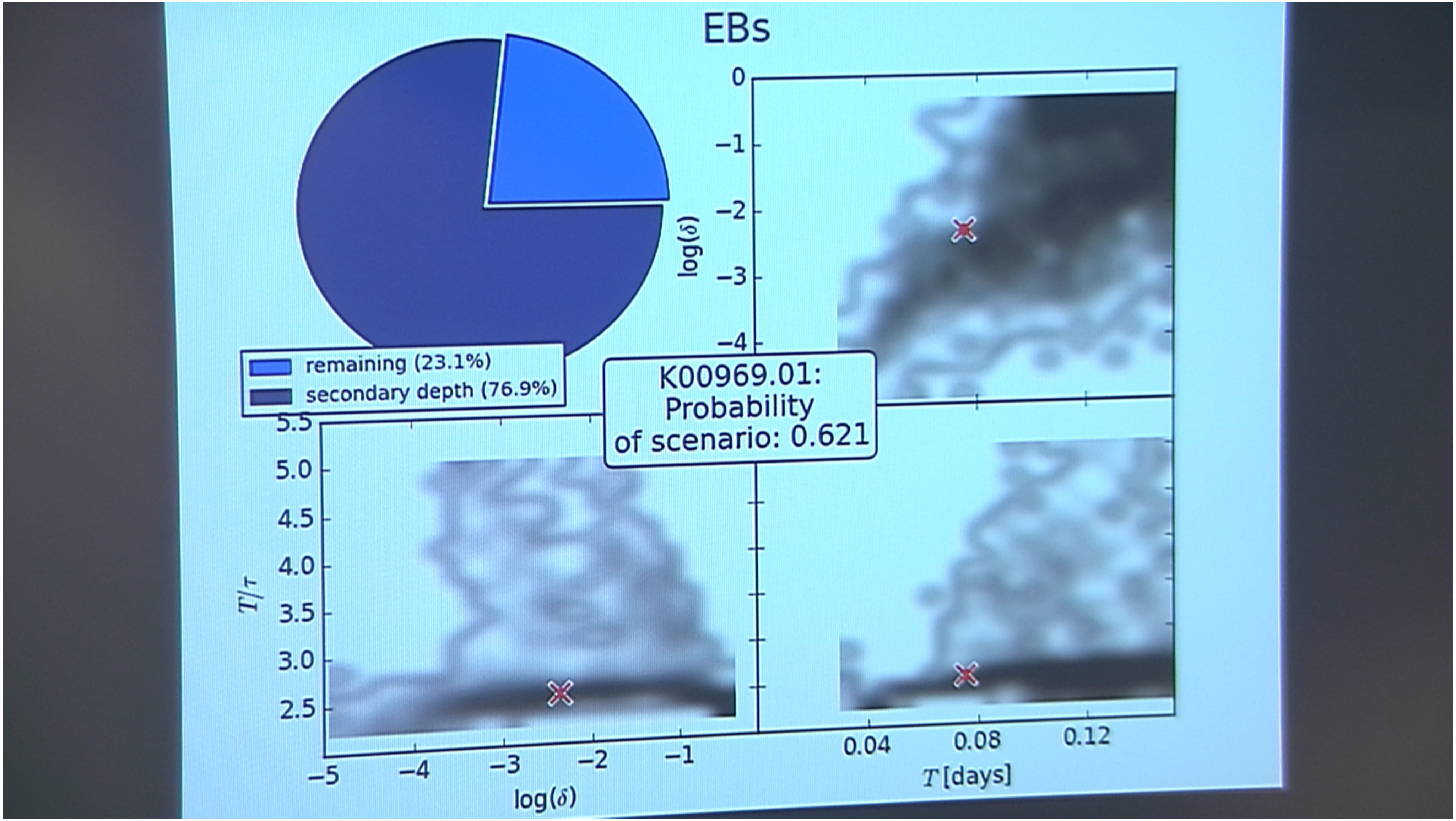

Planet
Stellar EB
δ
τ
T

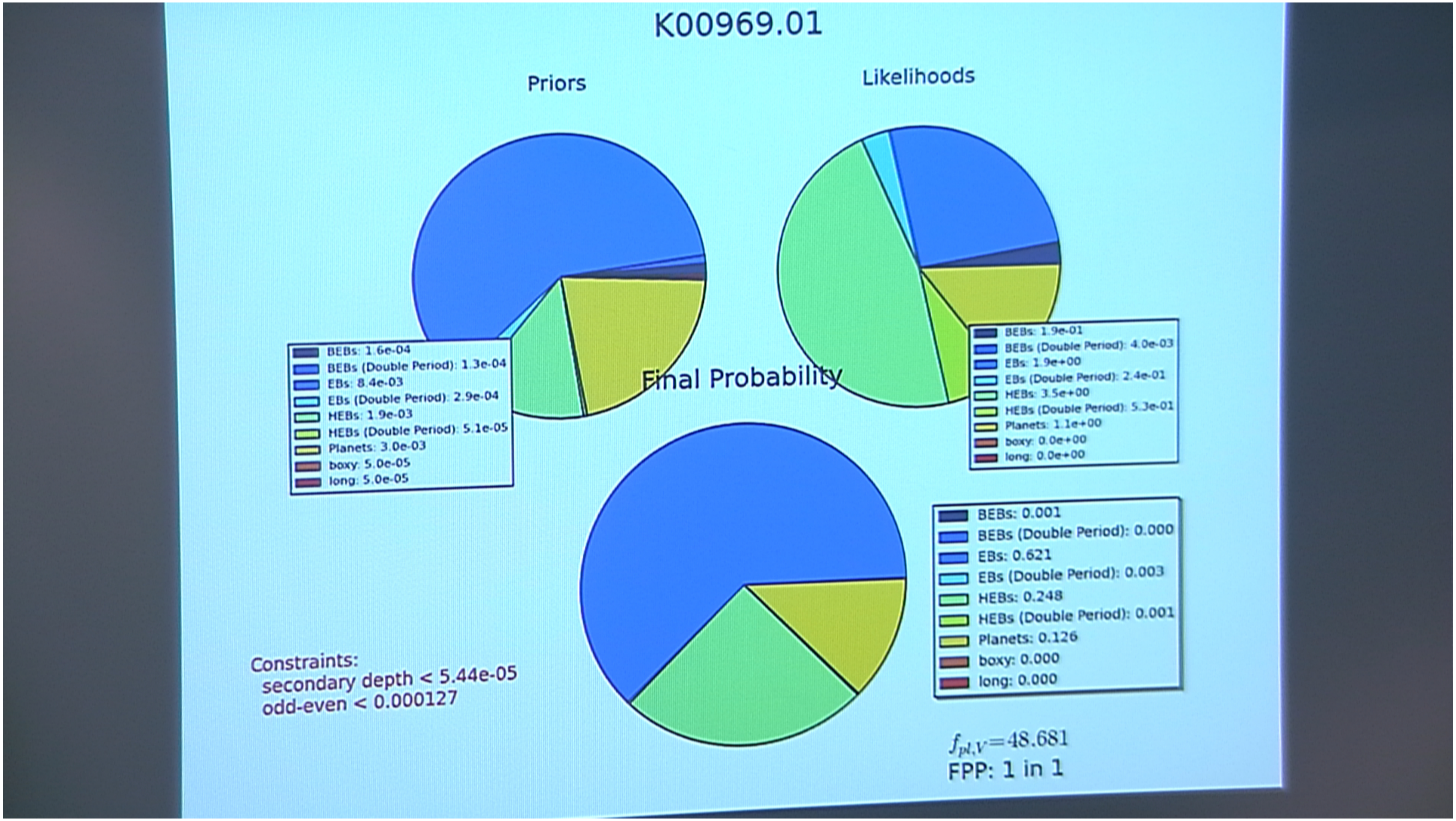


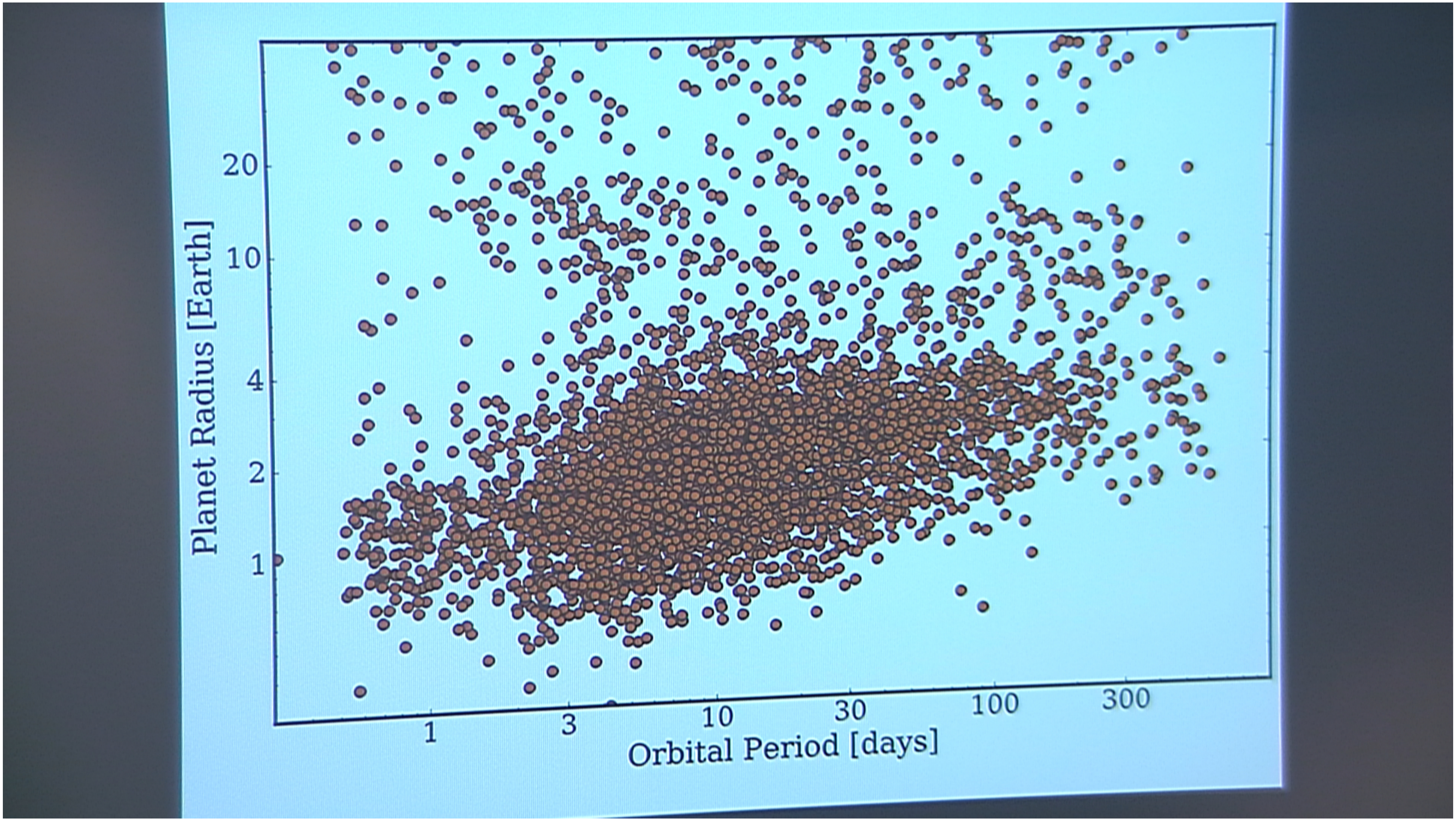
Planets
remaining (100.0%)
secondary depth (0.0%)
K00007.01:
Probability
of scenario: 1.000
log(δ)
T/τ
T [days]
0
−1
−2
−3
−4
12
10
8
6
4
−5
−4
−3
−2
−1
0.1
0.2
0.3

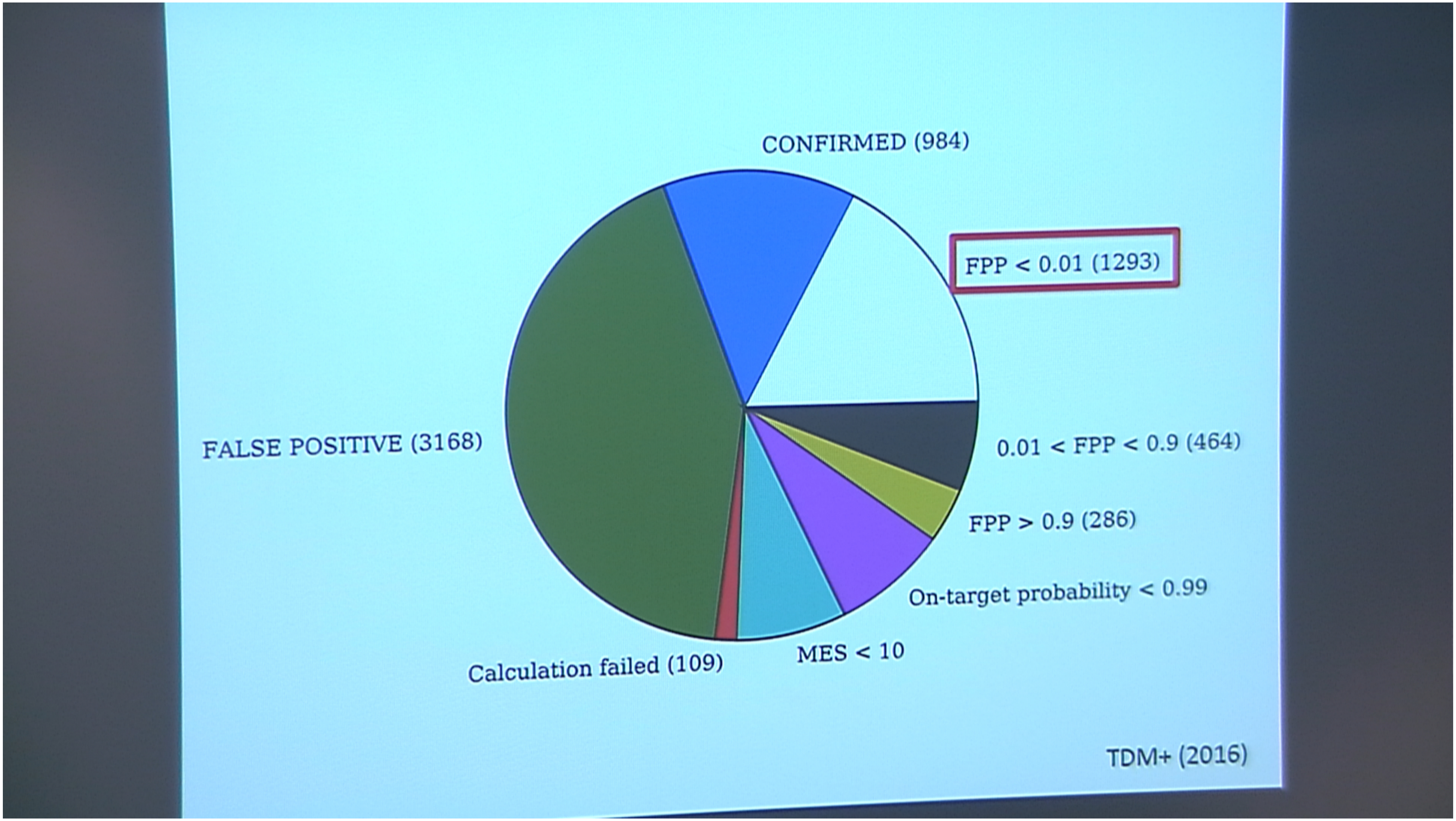


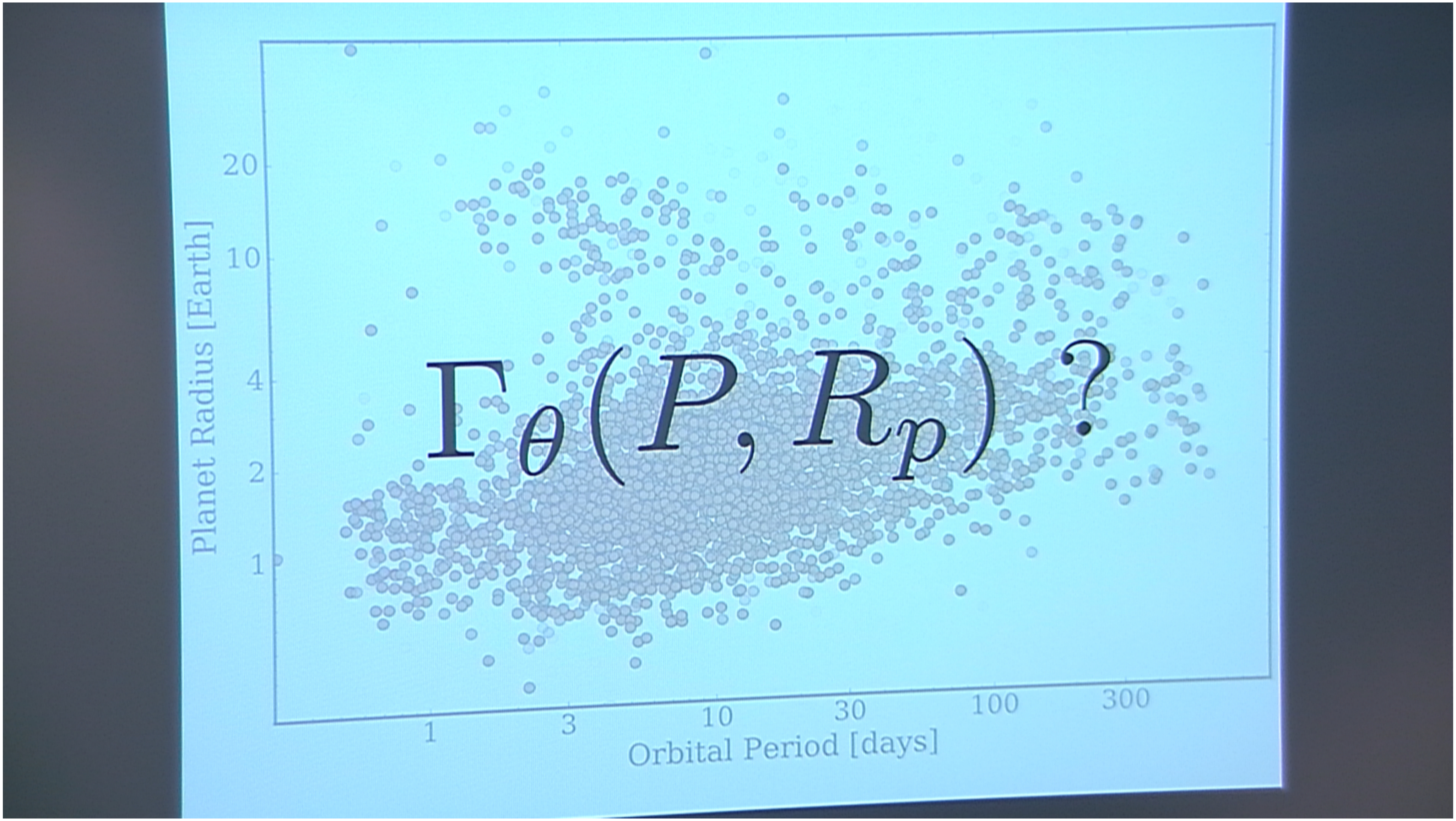
Relative flux
1.005
1.000
0.995
0.990
K00969.01
−0.20
−0.15
−0.10
−0.05
0.00
0.05
0.10
0.15
0.20
time [days]


EBs
remaining (23.1%)
secondary depth (76.9%)
K00969.01:
Probability
of scenario: 0.621
log(δ)
T/τ
T [days]
0
−1
−2
−3
−4
5.5
5.0
4.5
4.0
3.5
3.0
2.5
−5
−4
−3
−2
−1
0.04
0.08
0.12

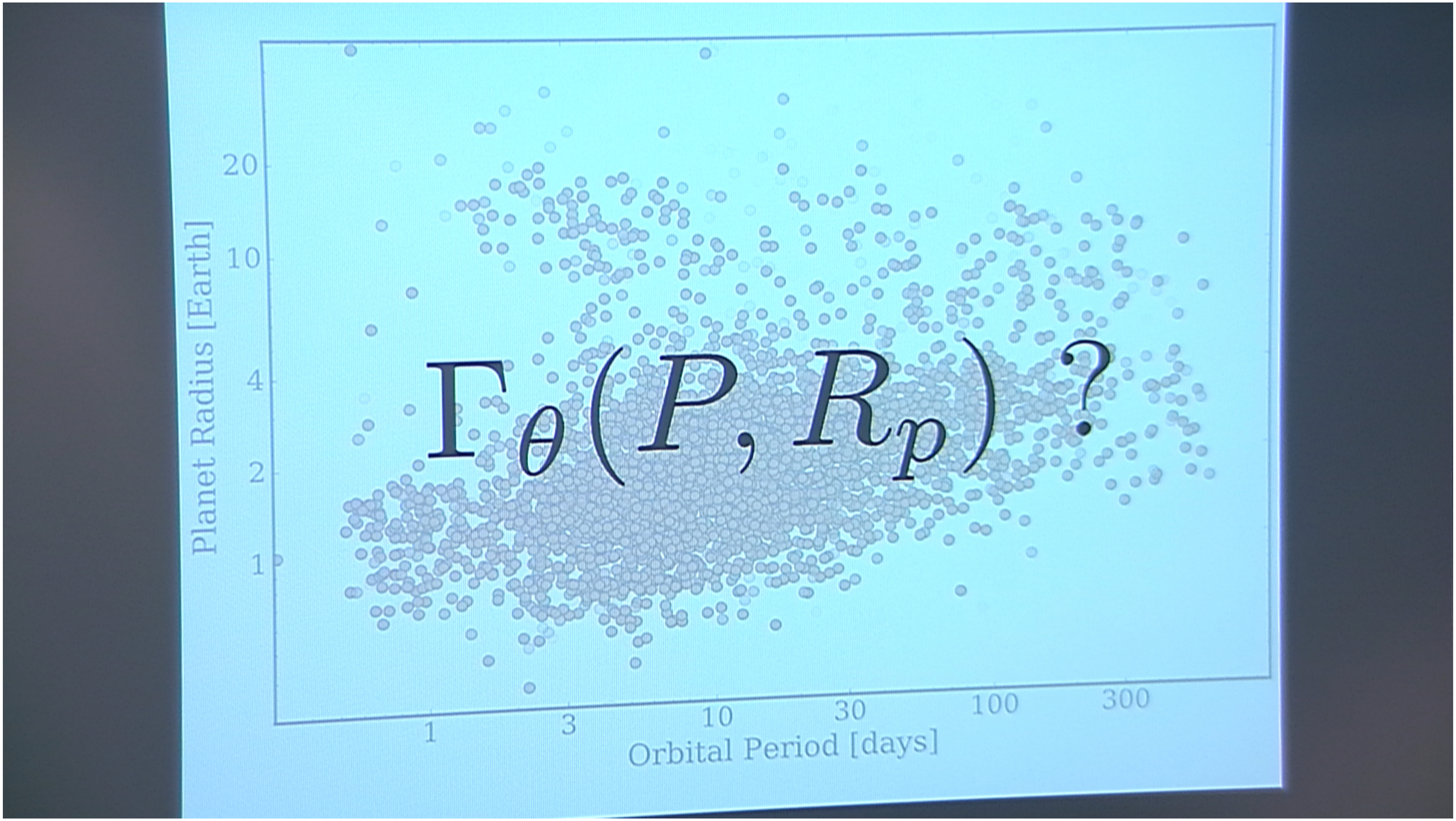

K00969.01
Priors
Likelihoods
Final Probability
BEBs: 1.6e-04
BEBs (Double Period): 1.3e-04
EBs: 8.4e-03
EBs (Double Period): 2.9e-04
HEBs: 1.9e-03
HEBs (Double Period): 5.1e-05
Planets: 3.0e-03
boxy: 5.0e-05
long: 5.0e-05
BEBs: 1.9e-01
BEBs (Double Period): 4.0e-03
EBs: 1.9e+00
EBs (Double Period): 2.4e-01
HEBs: 3.5e+00
HEBs (Double Period): 5.3e-01
Planets: 1.1e+00
boxy: 0.0e+00
long: 0.0e+00
BEBs: 0.001
BEBs (Double Period): 0.000
EBs: 0.621
EBs (Double Period): 0.003
HEBs: 0.248
HEBs (Double Period): 0.001
Planets: 0.126
boxy: 0.000
long: 0.000
Constraints:
secondary depth < 5.44e-05
odd-even < 0.000127
$f_{pl,V}$=48.681
FPP: 1 in 1

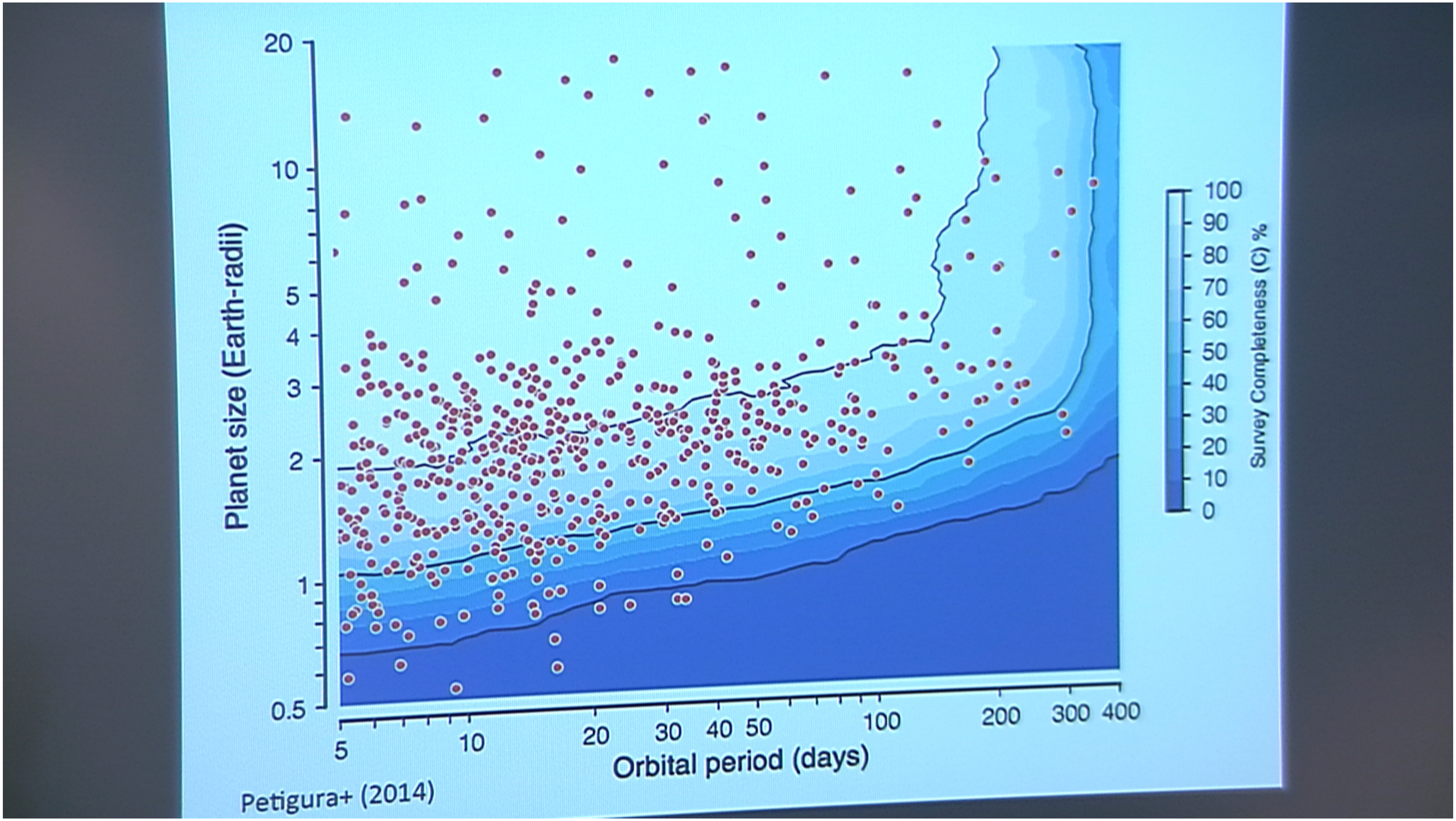

Planet Radius [Earth]
20
10
4
2
1
1
3
10
30
100
300
Orbital Period [days]


CONFIRMED (984)
FPP < 0.01 (1293)
0.01 < FPP < 0.9 (464)
FPP > 0.9 (286)
On-target probability < 0.99
MES < 10
Calculation failed (109)
FALSE POSITIVE (3168)
TDM+ (2016)

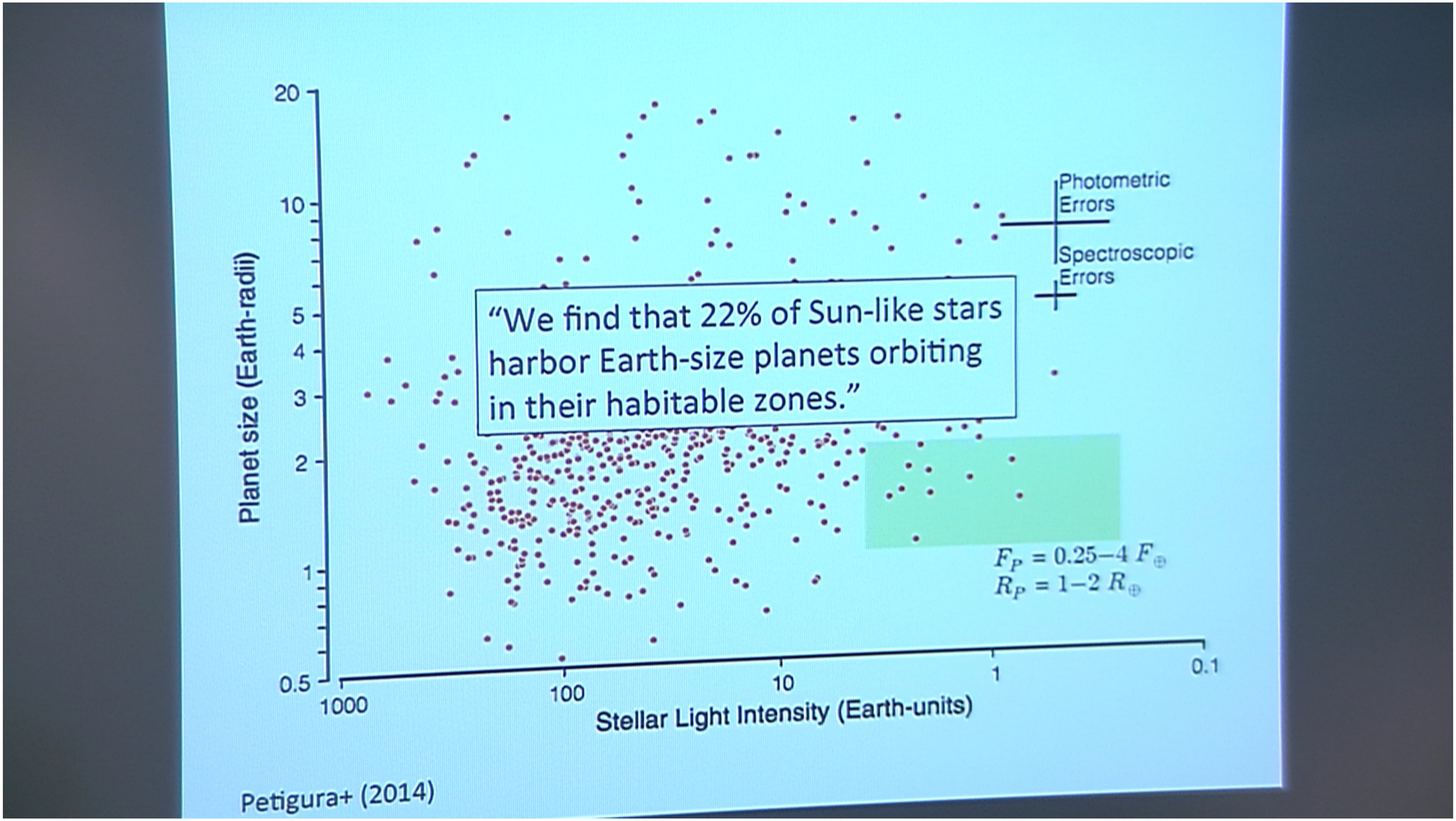


$\Gamma_\theta(P, R_p)$?
Planet Radius [Earth]
20
10
4
2
1
1
3
10
30
100
300
Orbital Period [days]

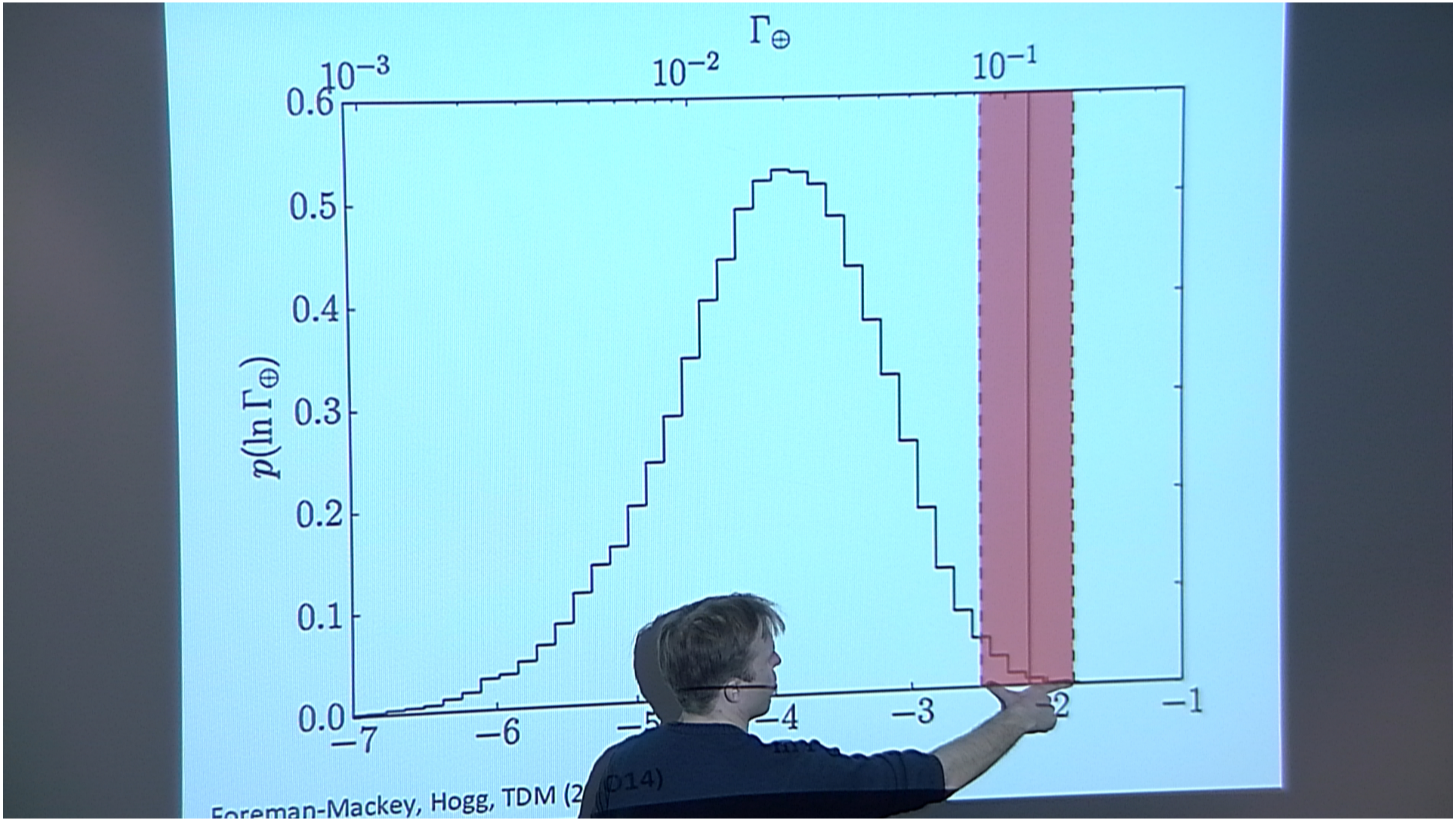

$\Gamma_\theta(P, R_p)$?
Planet Radius [Earth]
20
10
4
2
1
Orbital Period [days]
1
3
10
30
100
300

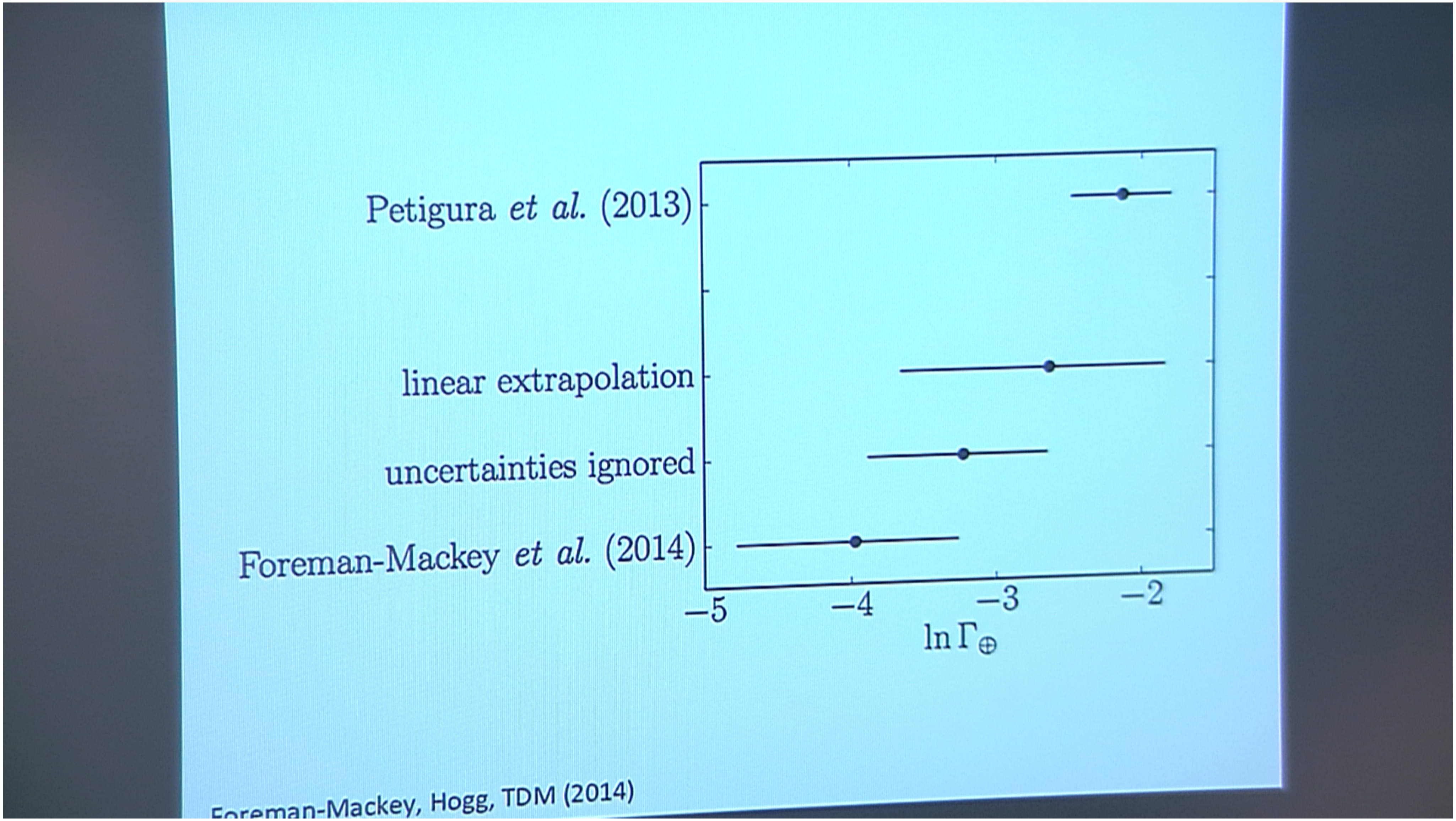


Planet size (Earth-radii)
20
10
5
4
3
2
1
0.5
5
10
20
30
40
50
100
200
300
400
Orbital period (days)
Survey Completeness (C) %
100
90
80
70
60
50
40
30
20
10
0
Petigura+ (2014)

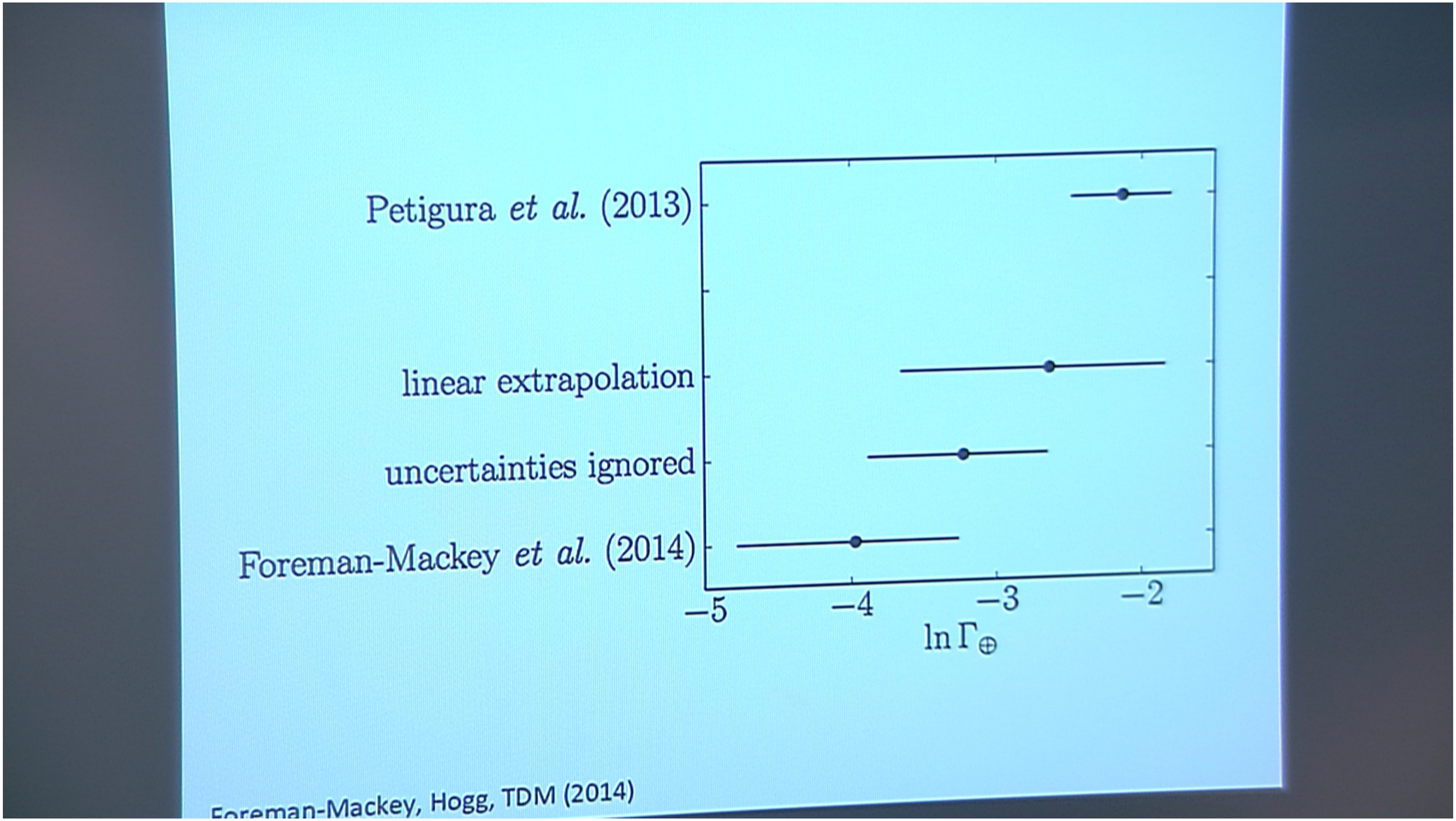


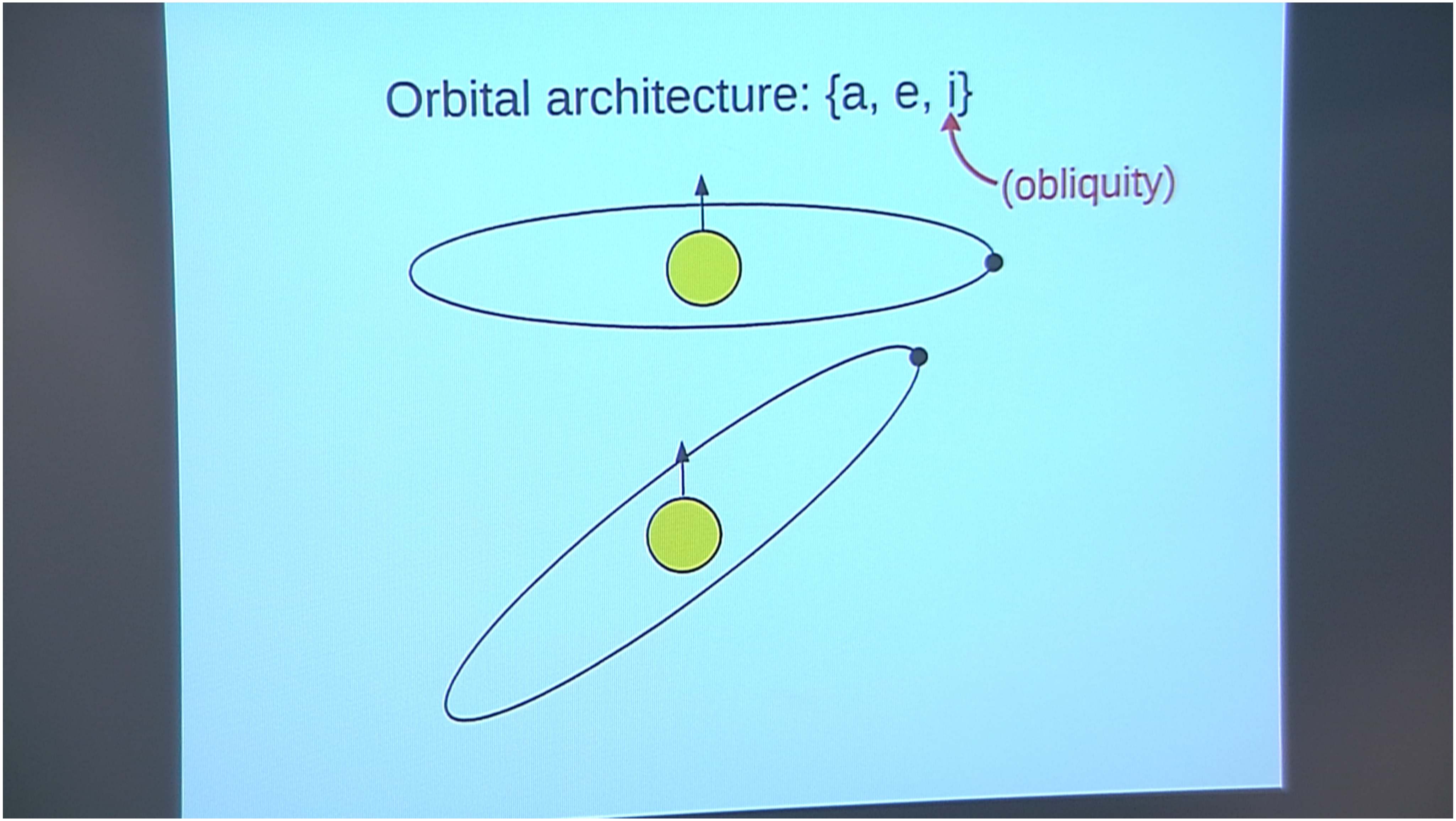
Planet size (Earth-radii)
20
10
5
4
3
2
1
0.5
1000
100
10
1
0.1
Stellar Light Intensity (Earth-units)
Photometric Errors
Spectroscopic Errors
"We find that 22% of Sun-like stars harbor Earth-size planets orbiting in their habitable zones."
$F_P = 0.25–4\ F_\oplus$
$R_P = 1–2\ R_\oplus$
Petigura+ (2014)

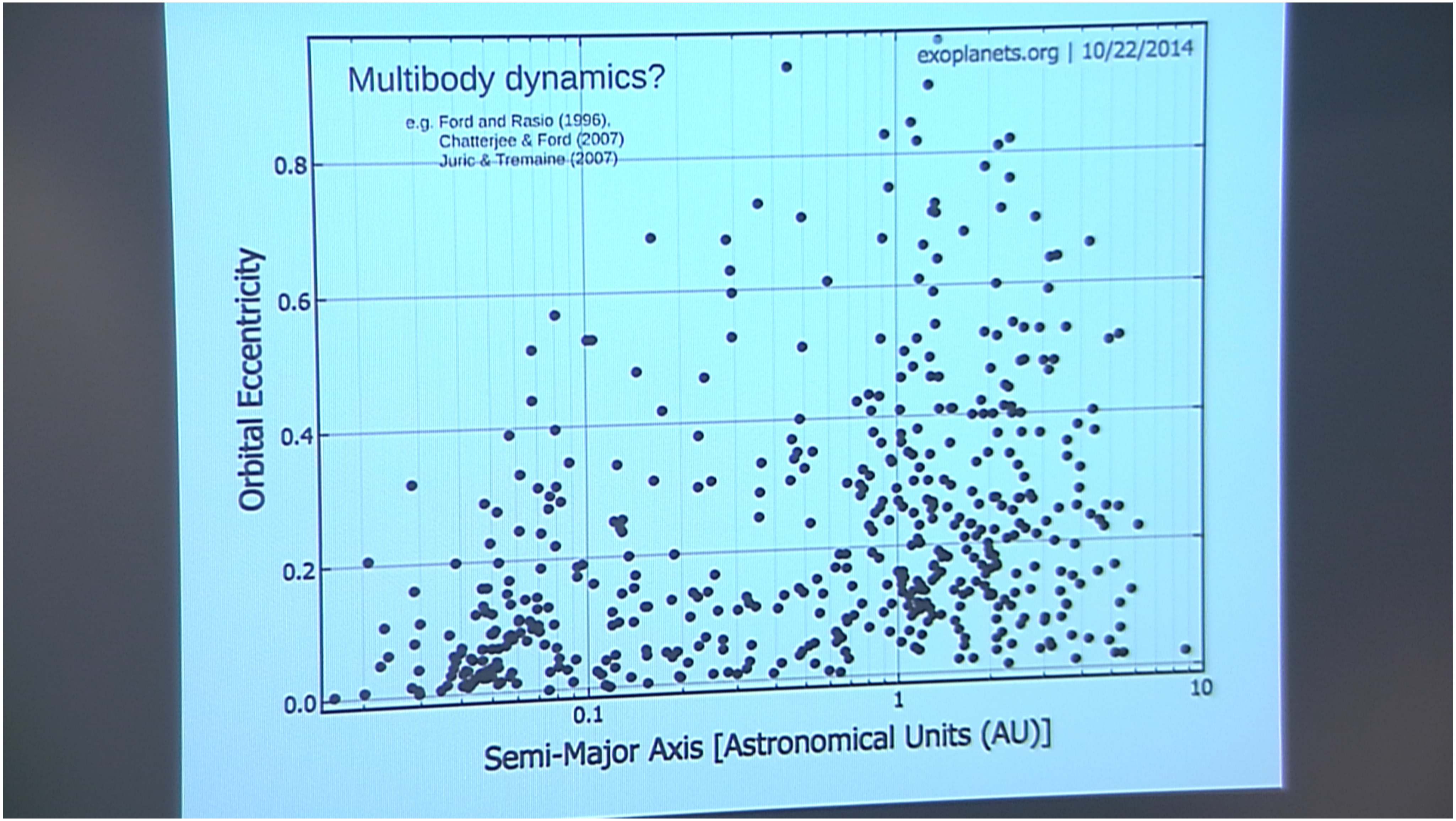

$\Gamma_\oplus$
10^{-3}
10^{-2}
10^{-1}
$p(\ln \Gamma_\oplus)$
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−7
−6
−4
−3
−1
Foreman-Mackey, Hogg, TDM (2

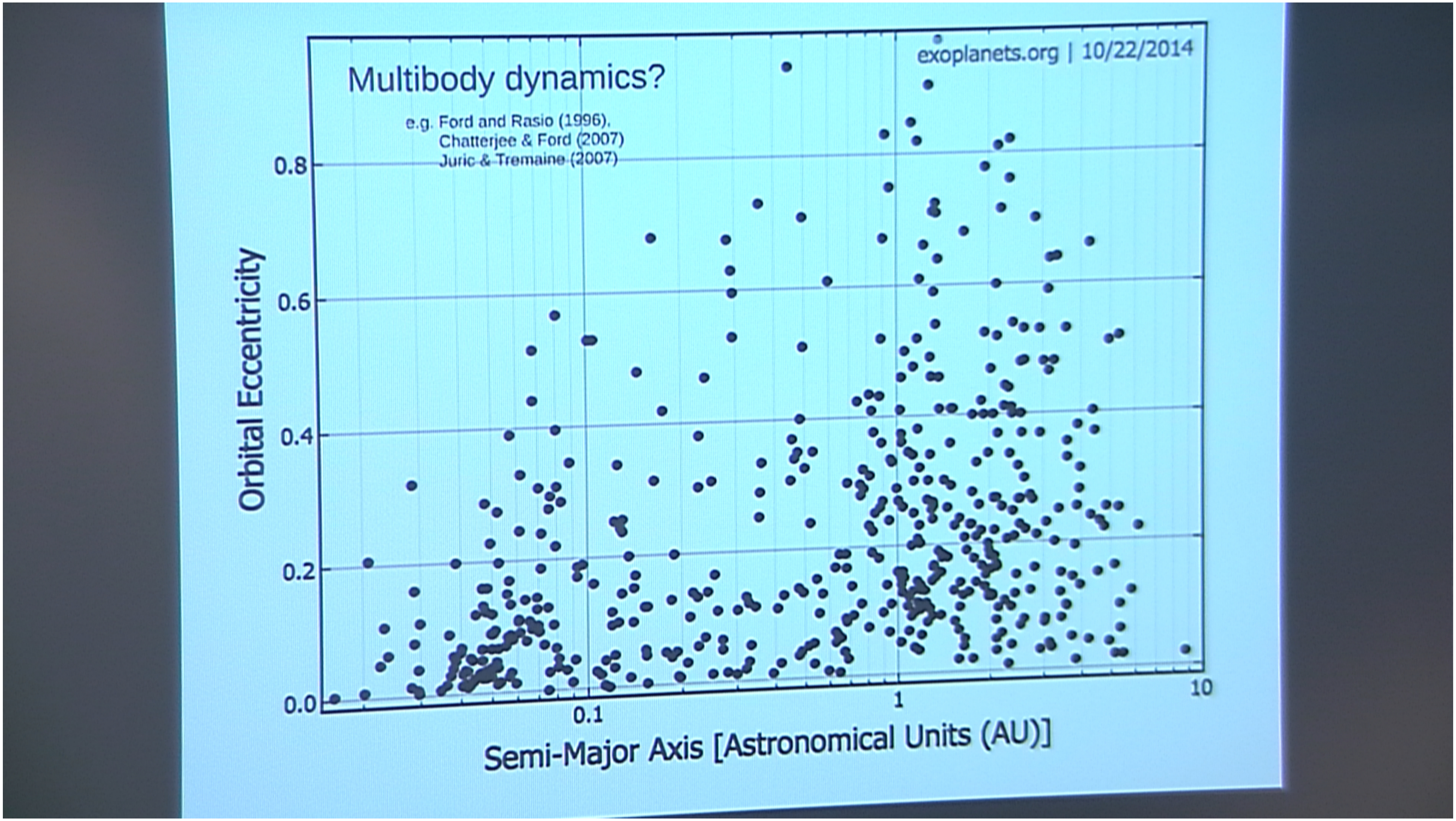


Petigura et al. (2013)
linear extrapolation
uncertainties ignored
Foreman-Mackey et al. (2014)
−5
−4
−3
−2
$\ln \Gamma_\oplus$
Foreman-Mackey, Hogg, TDM (2014)


Petigura et al. (2013)
linear extrapolation
uncertainties ignored
Foreman-Mackey et al. (2014)
−5
−4
−3
−2
ln Γ⊕
Foreman-Mackey, Hogg, TDM (2014)


Orbital architecture: {a, e, i}
(obliquity)


Multibody dynamics?
e.g. Ford and Rasio (1996),
Chatterjee & Ford (2007)
Juric & Tremaine (2007)
exoplanets.org | 10/22/2014
Orbital Eccentricity
0.0
0.2
0.4
0.6
0.8
0.1
1
10
Semi-Major Axis [Astronomical Units (AU)]


Multibody dynamics?
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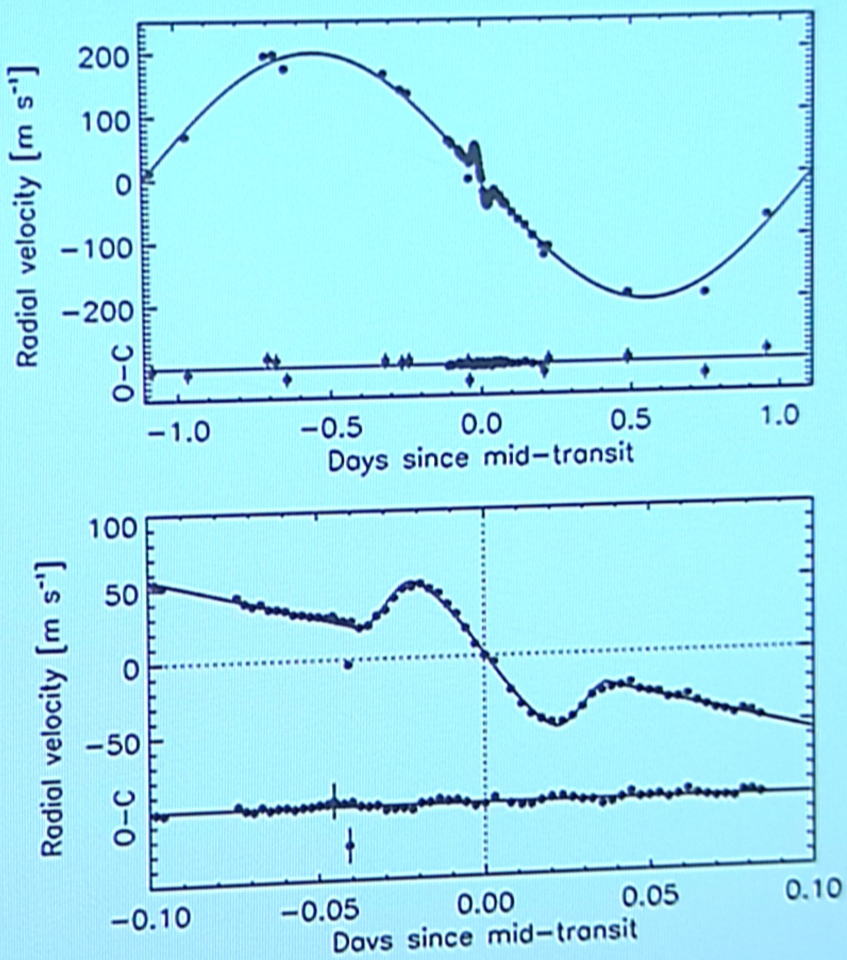
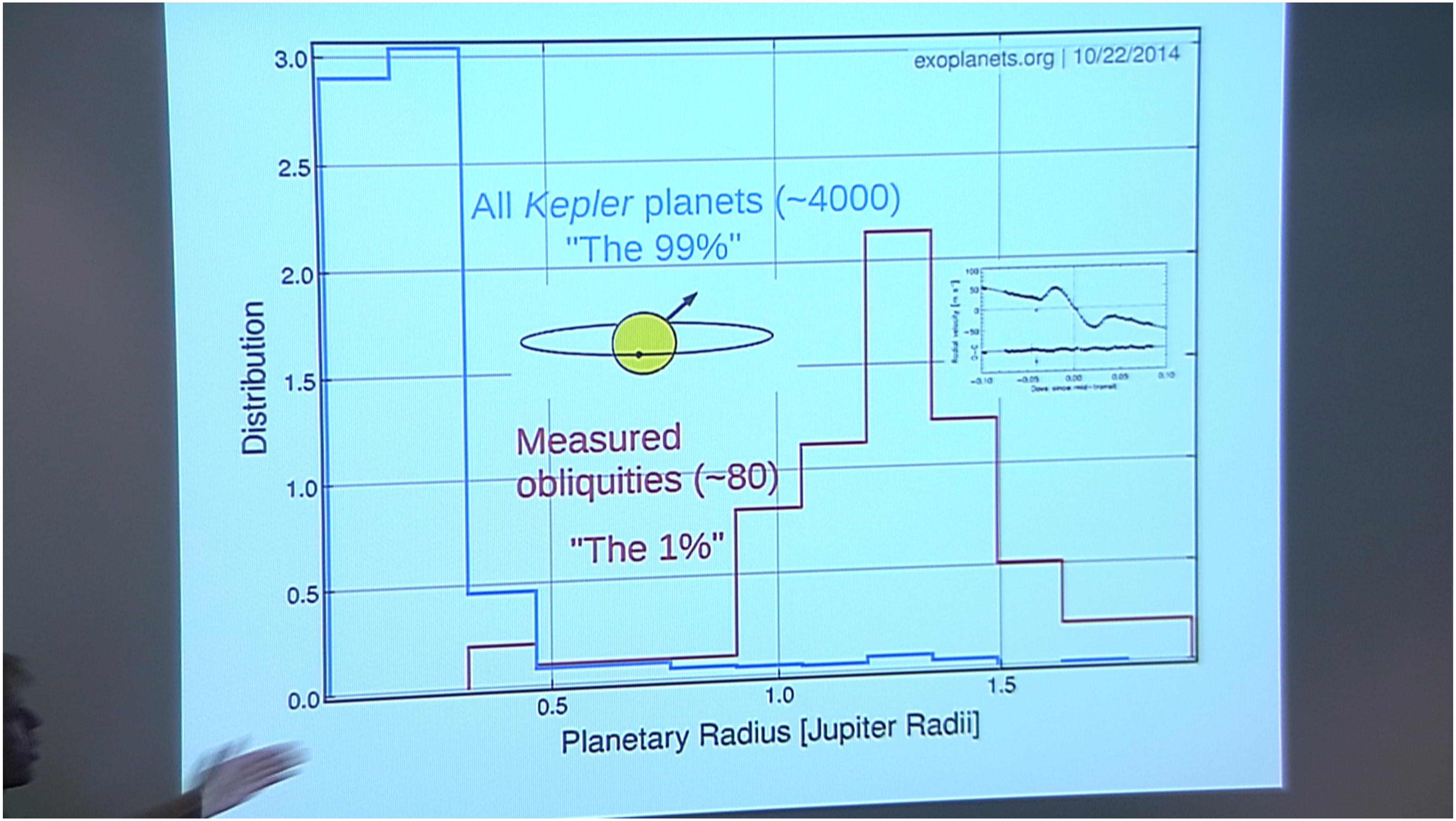
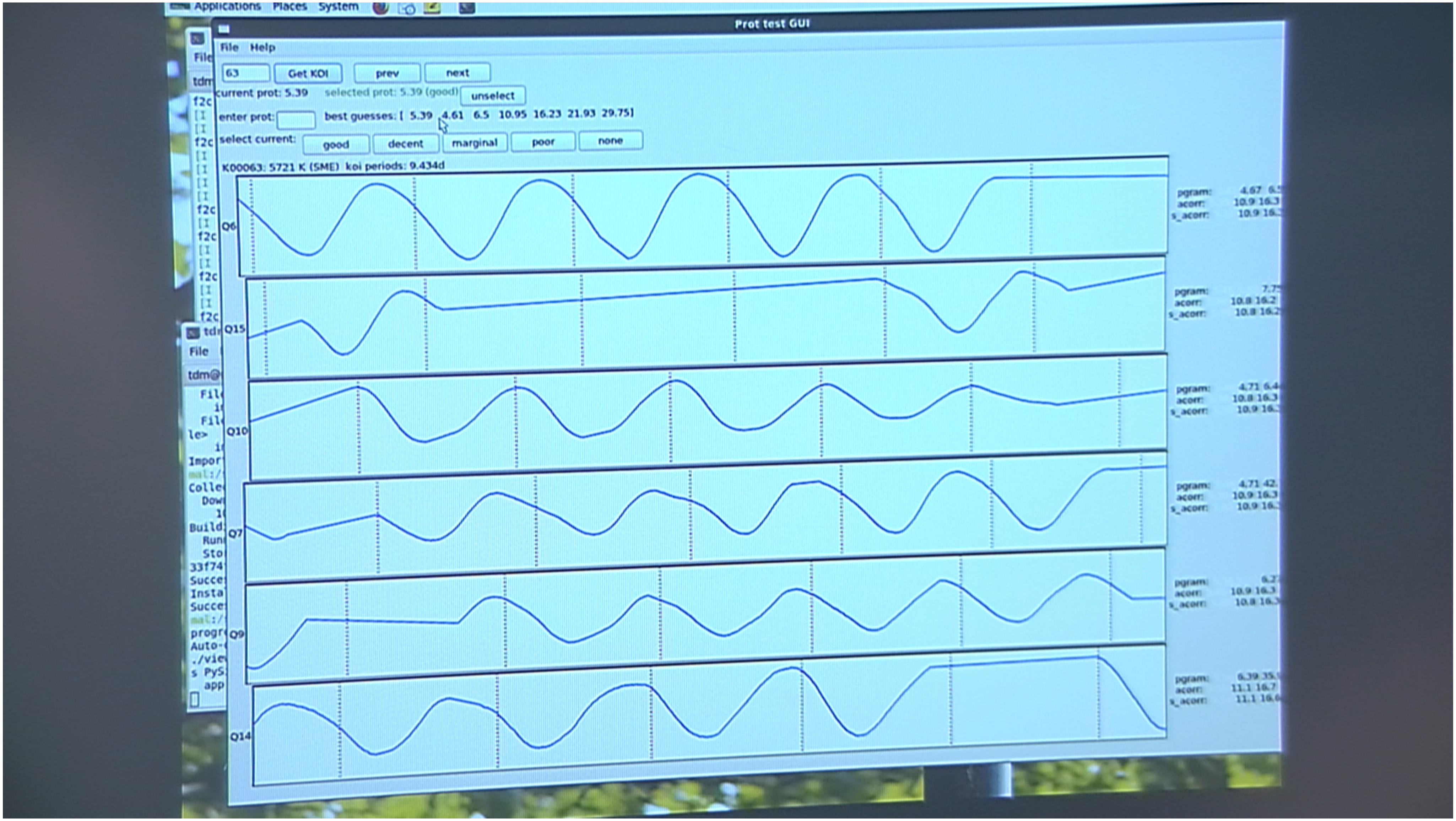
exoplanets.org | 10/22/2014
Orbital Eccentricity
0.0
0.2
0.4
0.6
0.8
0.1
1
10
Semi-Major Axis [Astronomical Units (AU)]

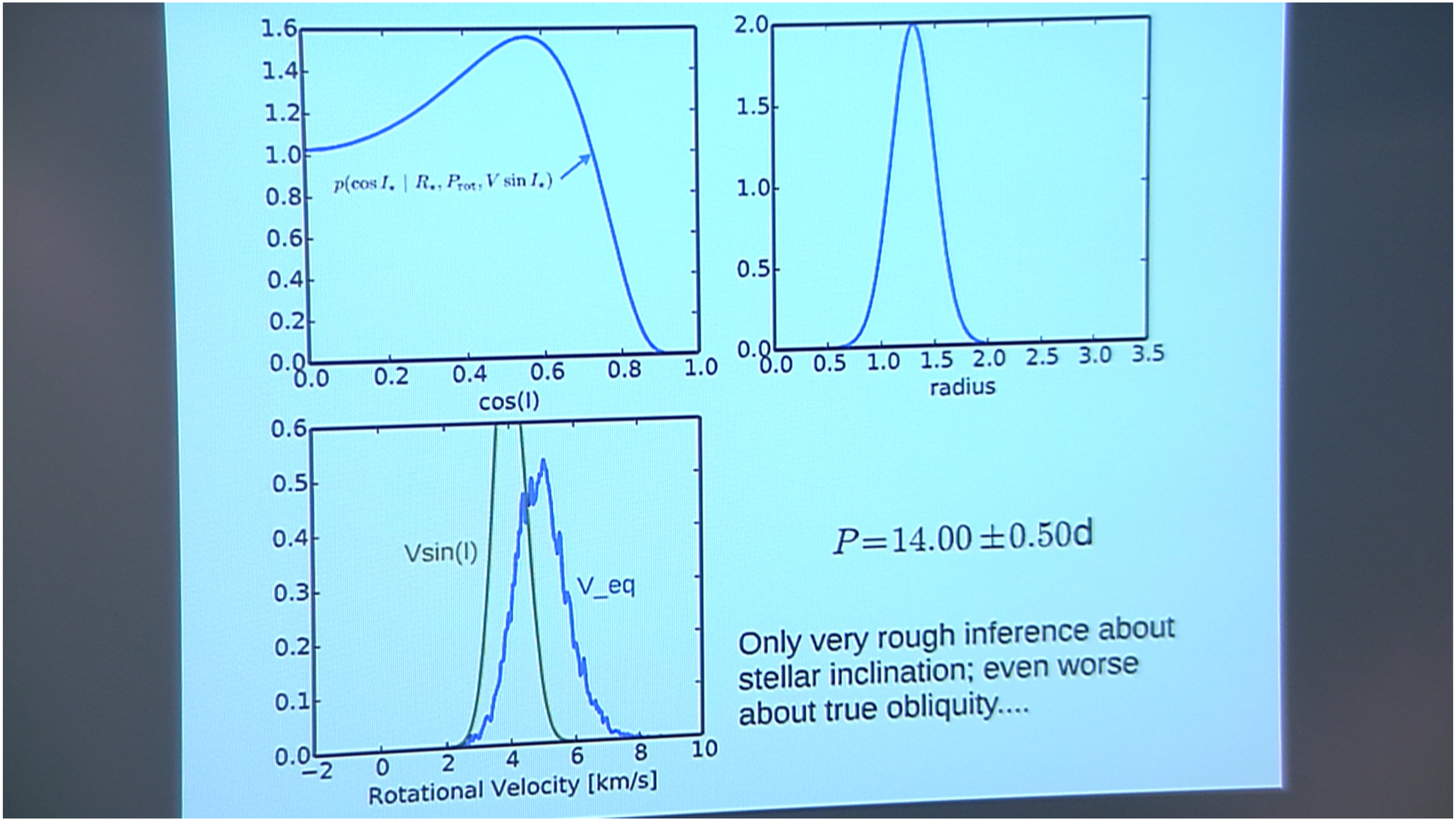


Rossiter-McLaughlin effect



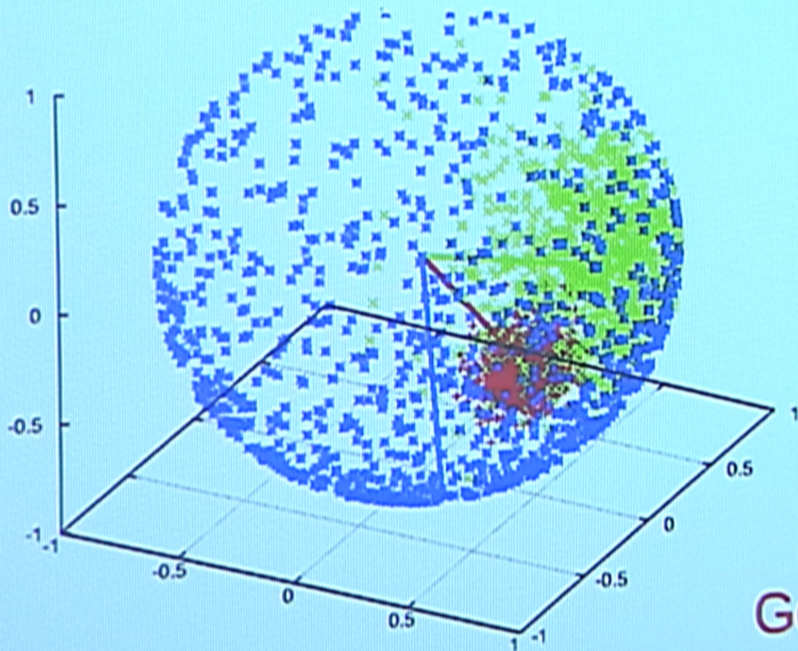
exoplanets.org | 10/22/2014
All Kepler planets (~4000)
"The 99%"
Measured obliquities (~80)
"The 1%"
Distribution
Planetary Radius [Jupiter Radii]
0.0
0.5
1.0
1.5
2.0
2.5
3.0


Applications Places System
Prot test GUI
File Help
63
Get KOI
prev
next
current prot: 5.39
selected prot: 5.39 (good)
unselect
enter prot:
best guesses: [5.39 4.61 6.5 10.95 16.23 21.93 29.75]
select current:
good
decent
marginal
poor
none
K00063: 5721 K (SME) koi periods: 9.434d
Q6
Q15
Q10
Q7
Q9
Q14
pgram:
acorr:
s_acorr:


$p(\cos I_\star \mid R_\star, P_{rot}, V \sin I_\star)$
cos(I)
radius
Vsin(I)
V_eq
Rotational Velocity [km/s]
$P = 14.00 \pm 0.50$d
Only very rough inference about
stellar inclination; even worse
about true obliquity....

To quantify the obliquity population distribution, parametrize by a Fisher distribution, with a single parameter κ:

$$f_\theta(\theta|\kappa) = \frac{\kappa}{2\sinh\kappa} \exp(\kappa\cos\theta)\sin\theta.$$



$\kappa \to 0$

isotropic

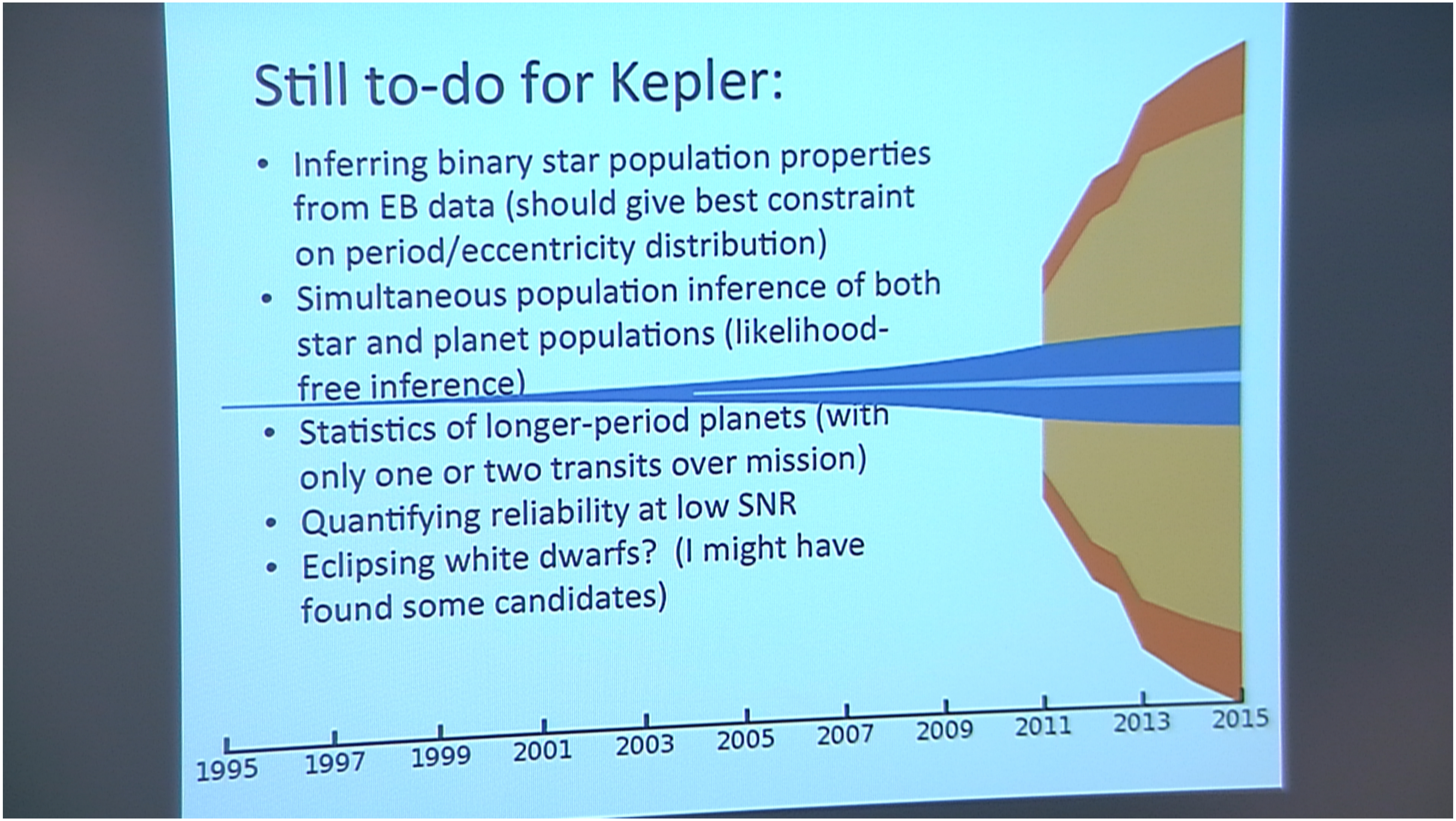
$\kappa \to \infty$

Rayleigh $\sigma = \kappa^{-1/2}$

$$\{\boldsymbol{x}_i\} = \{R_i, P_i, V\sin I_i\}$$

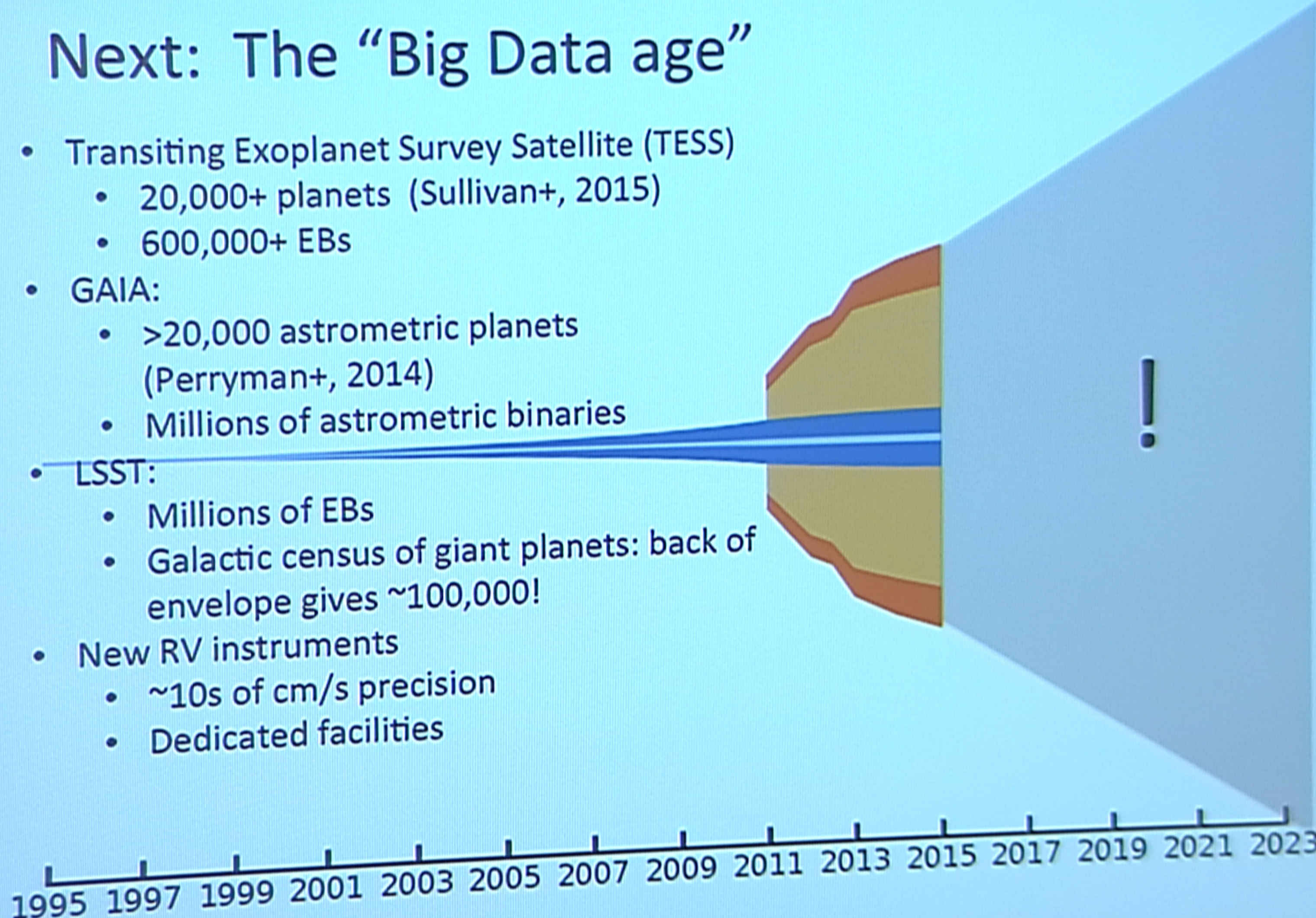
$$\{\boldsymbol{w}_i\} = \{\cos I_i\}$$

Goal: $p(\kappa \mid \{\boldsymbol{x}_i\})$


Still to-do for Kepler:
• Inferring binary star population properties from EB data (should give best constraint on period/eccentricity distribution)
• Simultaneous population inference of both star and planet populations (likelihood-free inference)
• Statistics of longer-period planets (with only one or two transits over mission)
• Quantifying reliability at low SNR
• Eclipsing white dwarfs? (I might have found some candidates)
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015

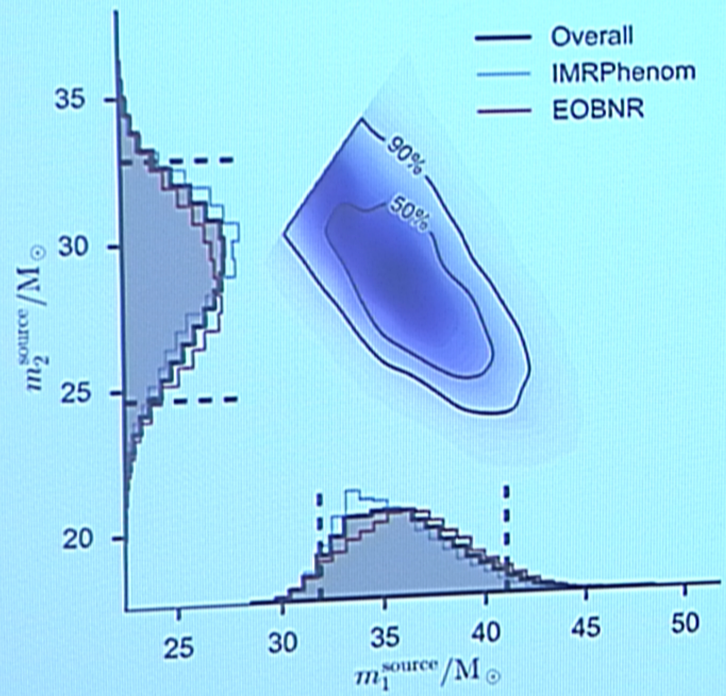
Next: The "Big Data age"

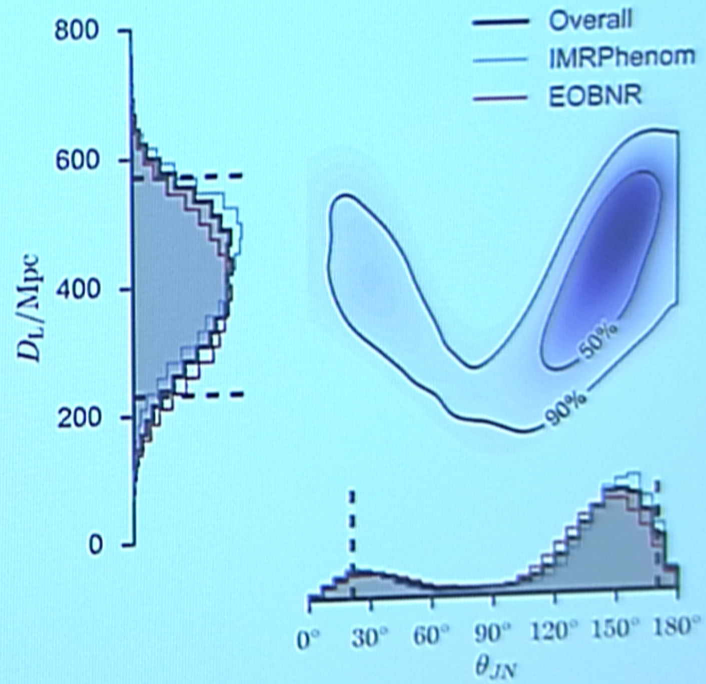
- Transiting Exoplanet Survey Satellite (TESS)
  - 20,000+ planets (Sullivan+, 2015)
  - 600,000+ EBs
- GAIA:
  - >20,000 astrometric planets (Perryman+, 2014)
  - Millions of astrometric binaries
- LSST:
  - Millions of EBs
  - Galactic census of giant planets: back of envelope gives ~100,000!
- New RV instruments
  - ~10s of cm/s precision
  - Dedicated facilities



Gravitational Wave Astrophysics

Fast Radio Bursts Cosmology





- Population inference
- Binary star progenitor populations

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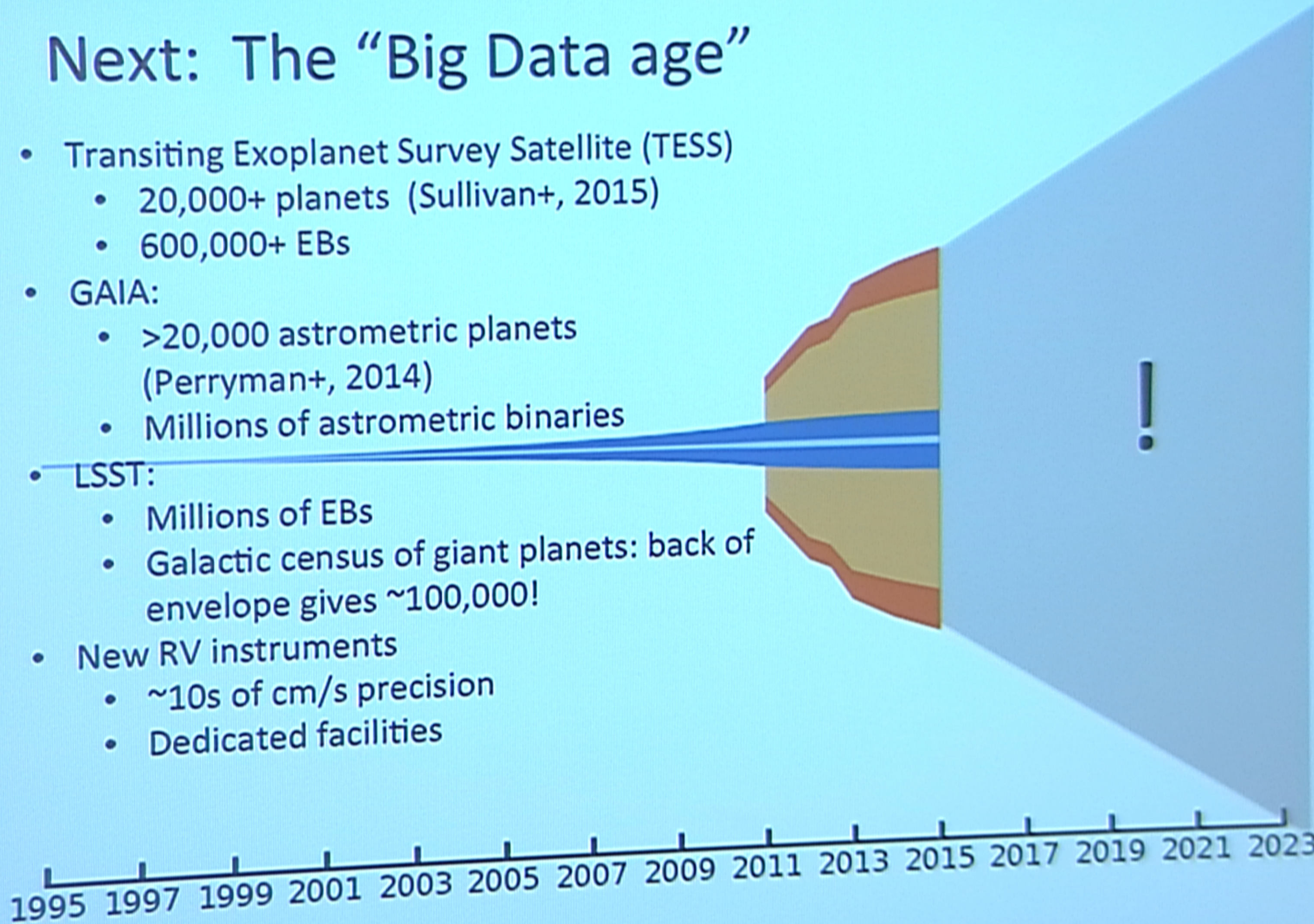
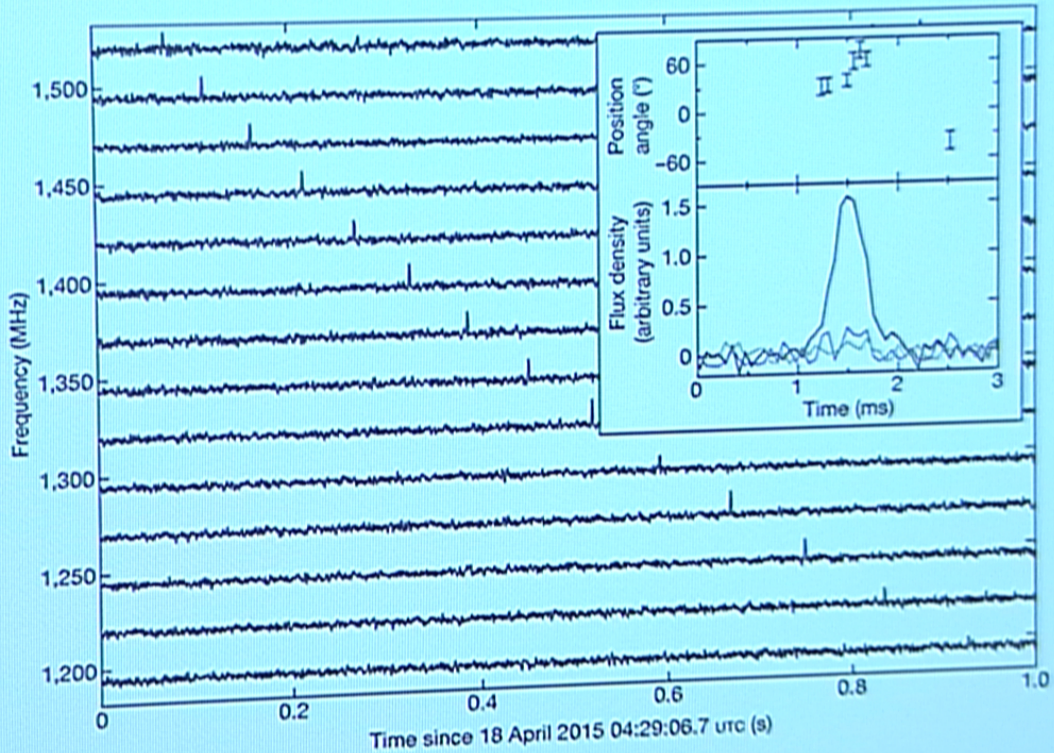


Gravitational Wave Astrophysics

Fast Radio Bursts

Cosmology



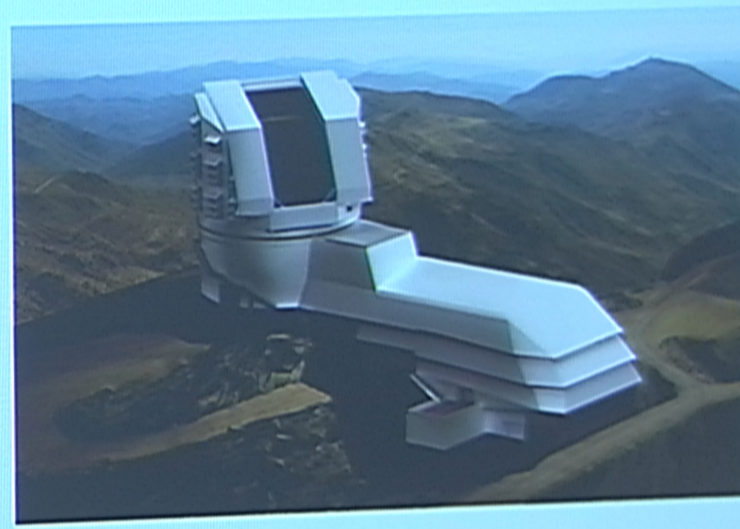
- Surveys/detection sensitivity
- Origin? Luminosity function? Multiple populations?

Gravitational Wave Astrophysics

Fast Radio Bursts

Cosmology

CMB Galactic foregrounds?



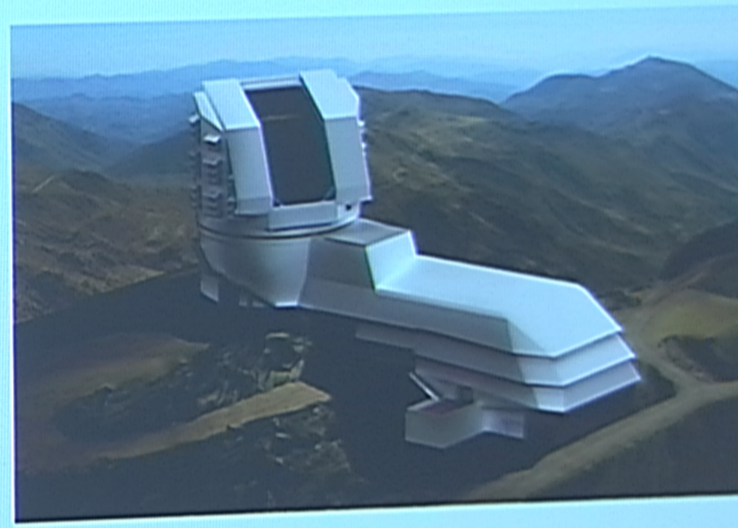
Modeling non-linear structure?

Gravitational Wave Astrophysics

Fast Radio Bursts

Cosmology

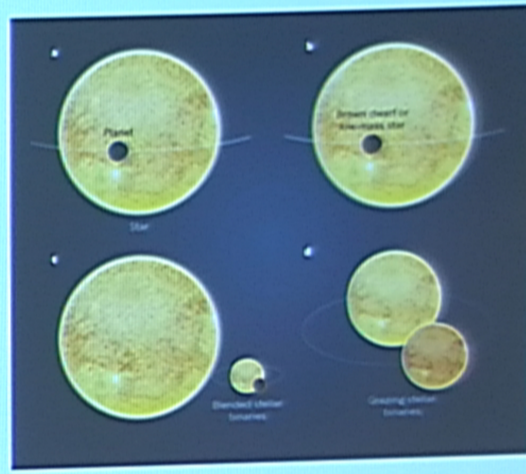
CMB Galactic foregrounds?



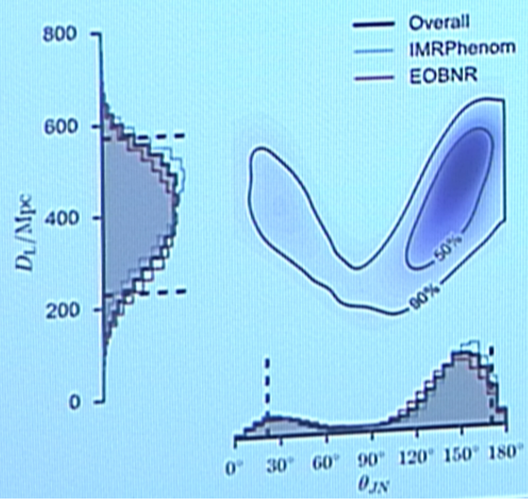
Modeling non-linear structure?

Dataset Challenges

- Data volume
- Signal detection
- Individual detections requiring detailed inference
- Complexity of the nuisance sector
- Picking the right battles



$$p(\text{theory} \,|\, \text{data})$$



Data Science Tools

- Parameter estimation
- Model selection
- Hierarchical inference
- Likelihood-free inference
- Software design
- ...