Exoplanets

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Tyler McCracken
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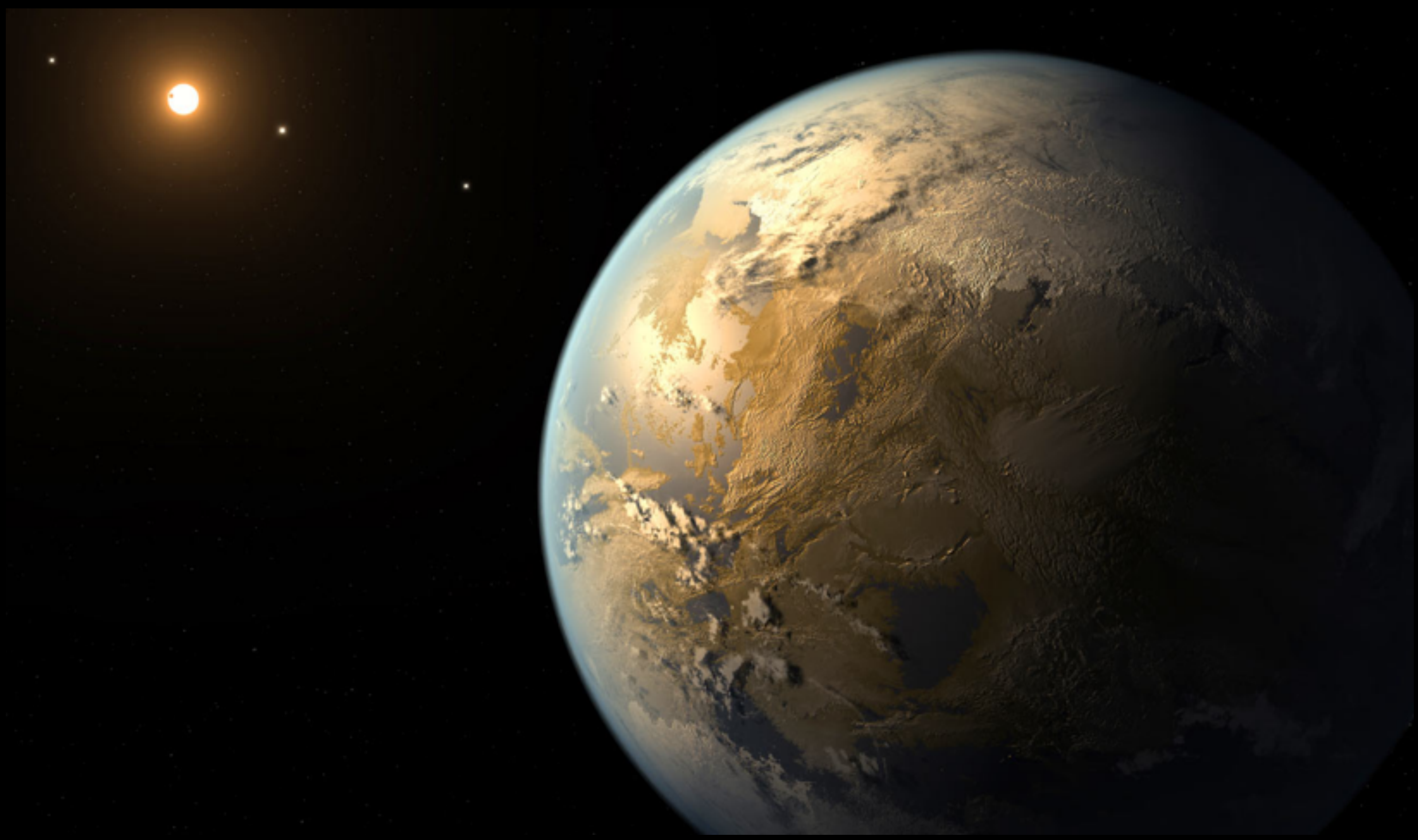
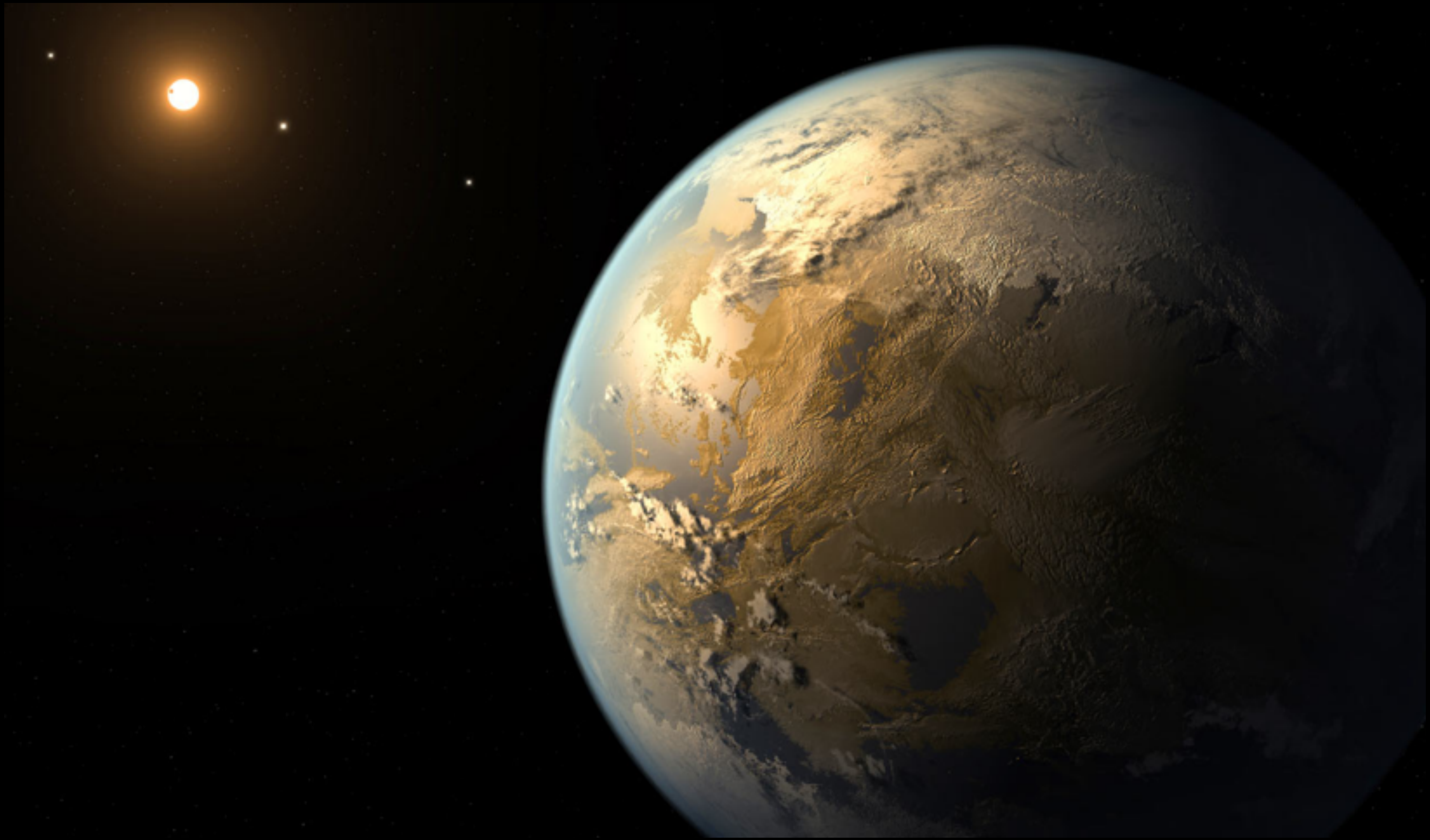
1992: Most stars do not form with planets.

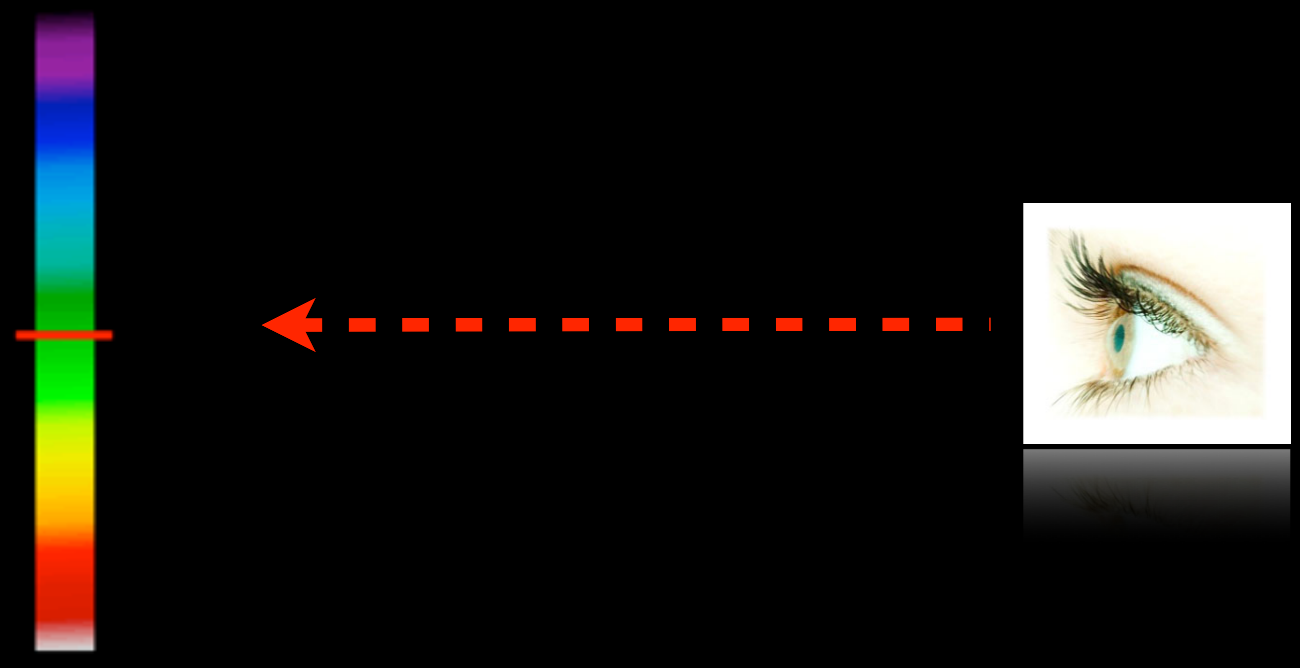
Our Sun is unusual.



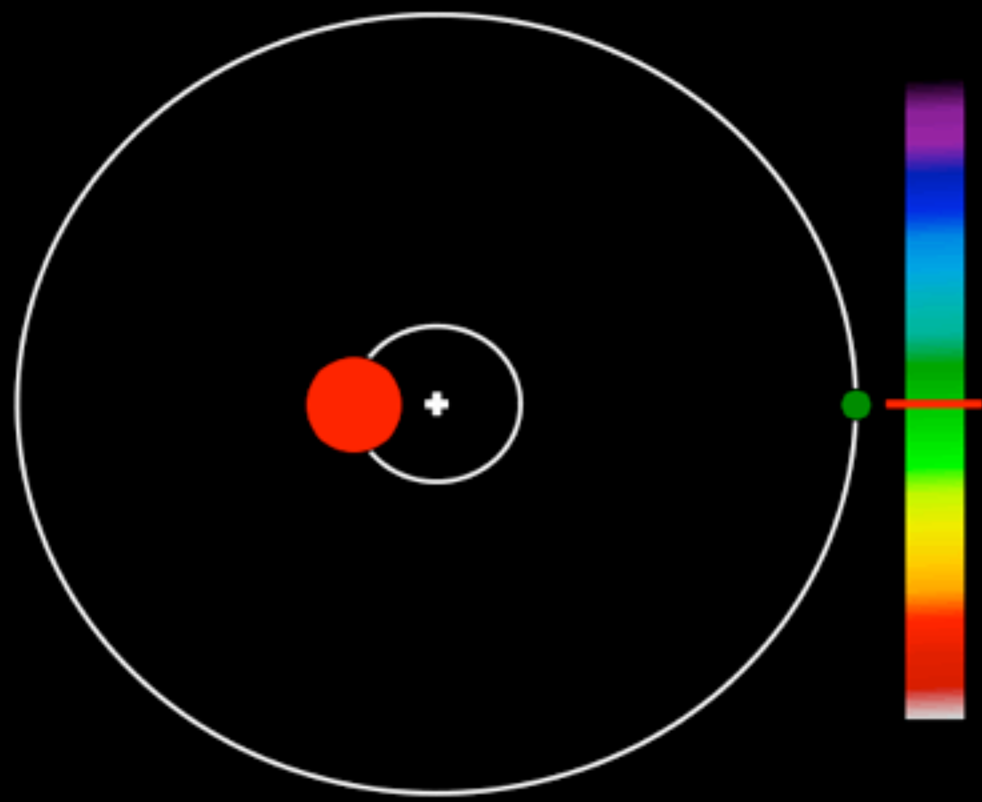
2015: Practically all Sun-like stars have planets

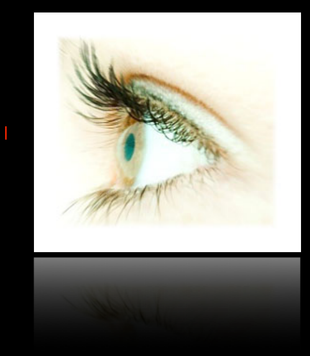
Small rocky planets far out-number gas giants
Rocky planets do not require metal-rich stars (like gas giants)
Gas giants are a more recent addition to planetary architectures
Rocky planets began forming around stars > 11 Gyr

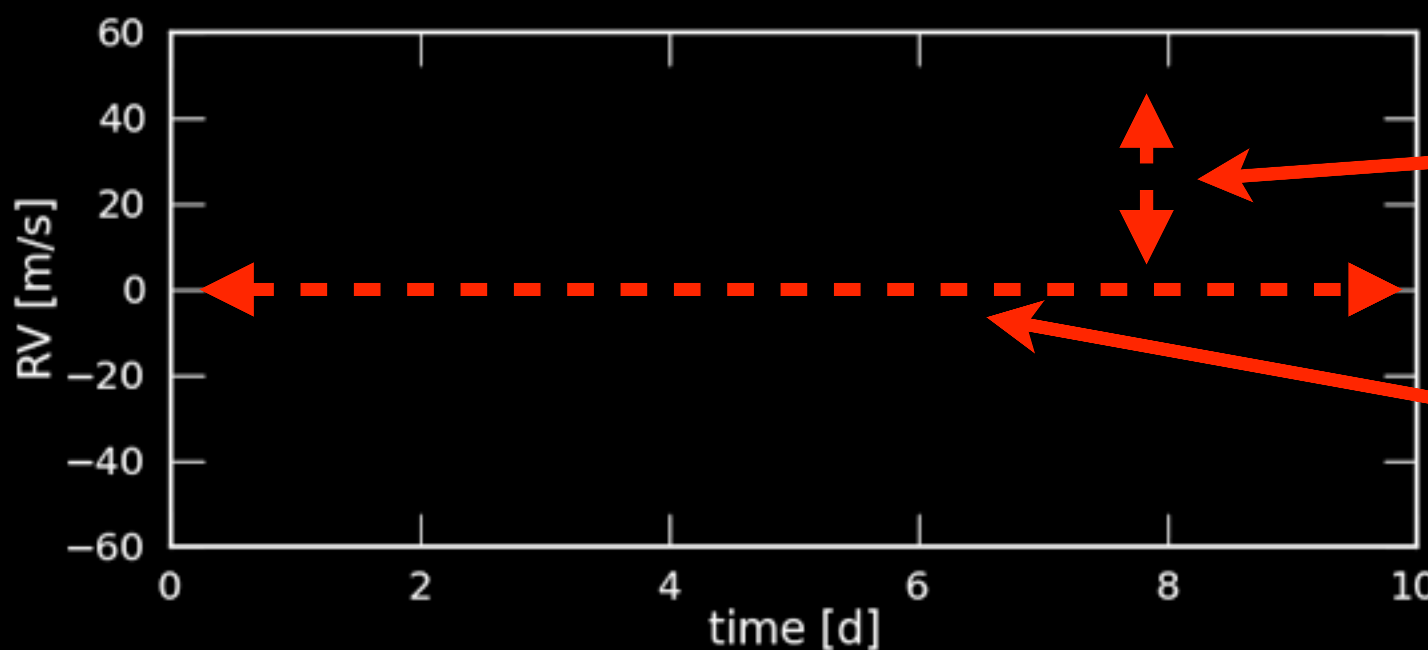




animation credit: Xavier Dumusque





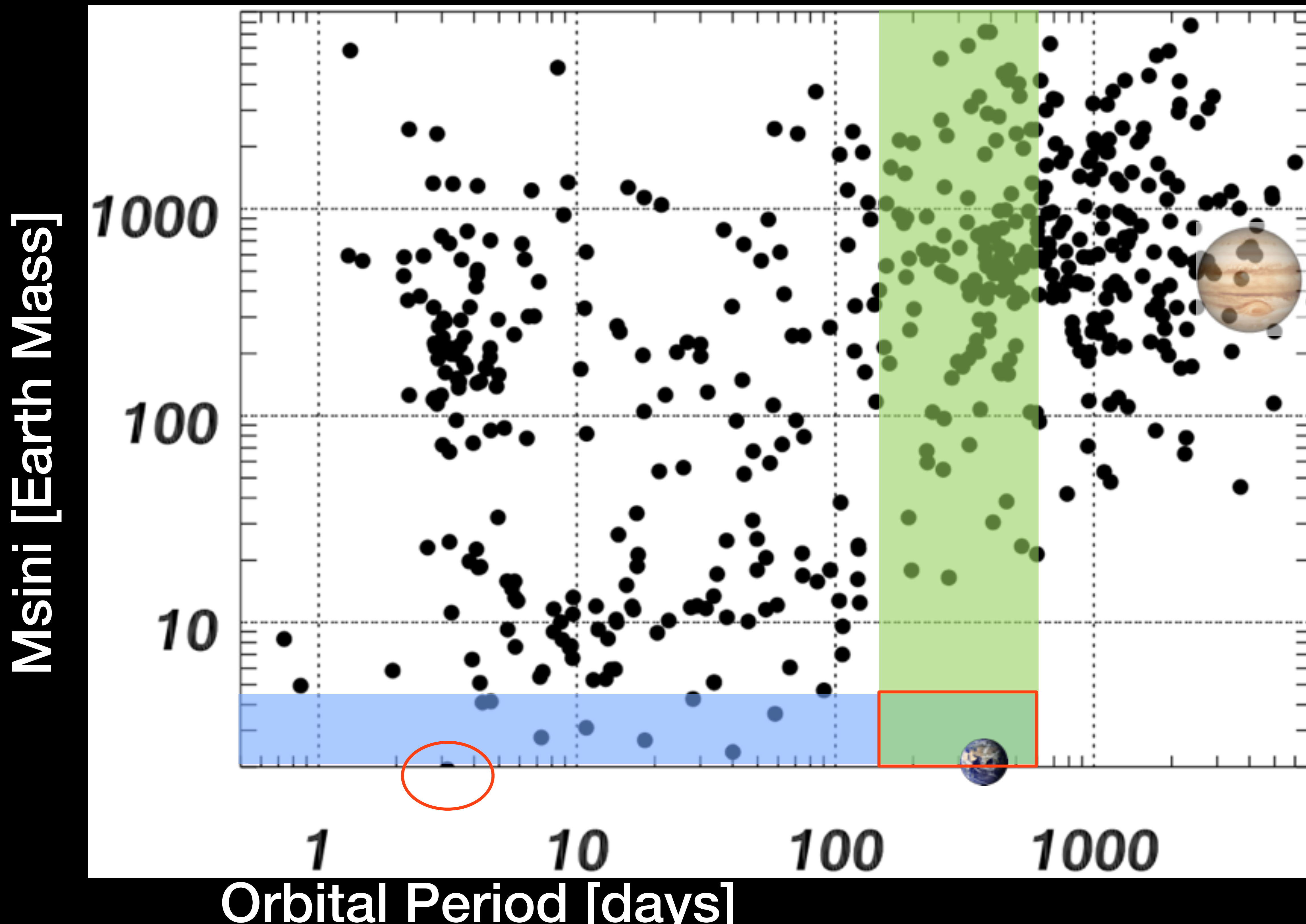


$$\sim \frac{M_{pl} \sin i}{M_\star^{2/3}}$$

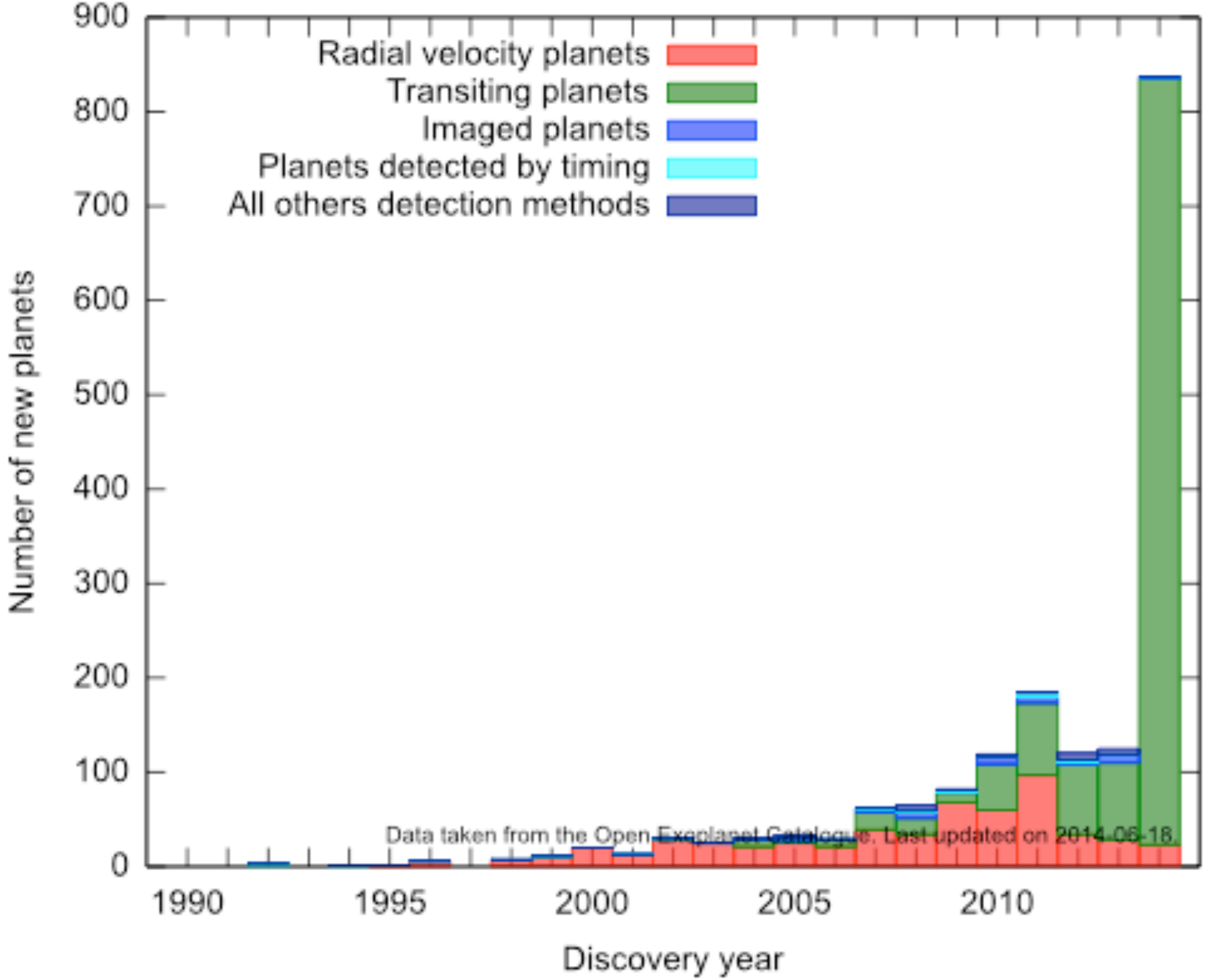
$$P_{pl}$$

animation credit: Xavier Dumusque

2013

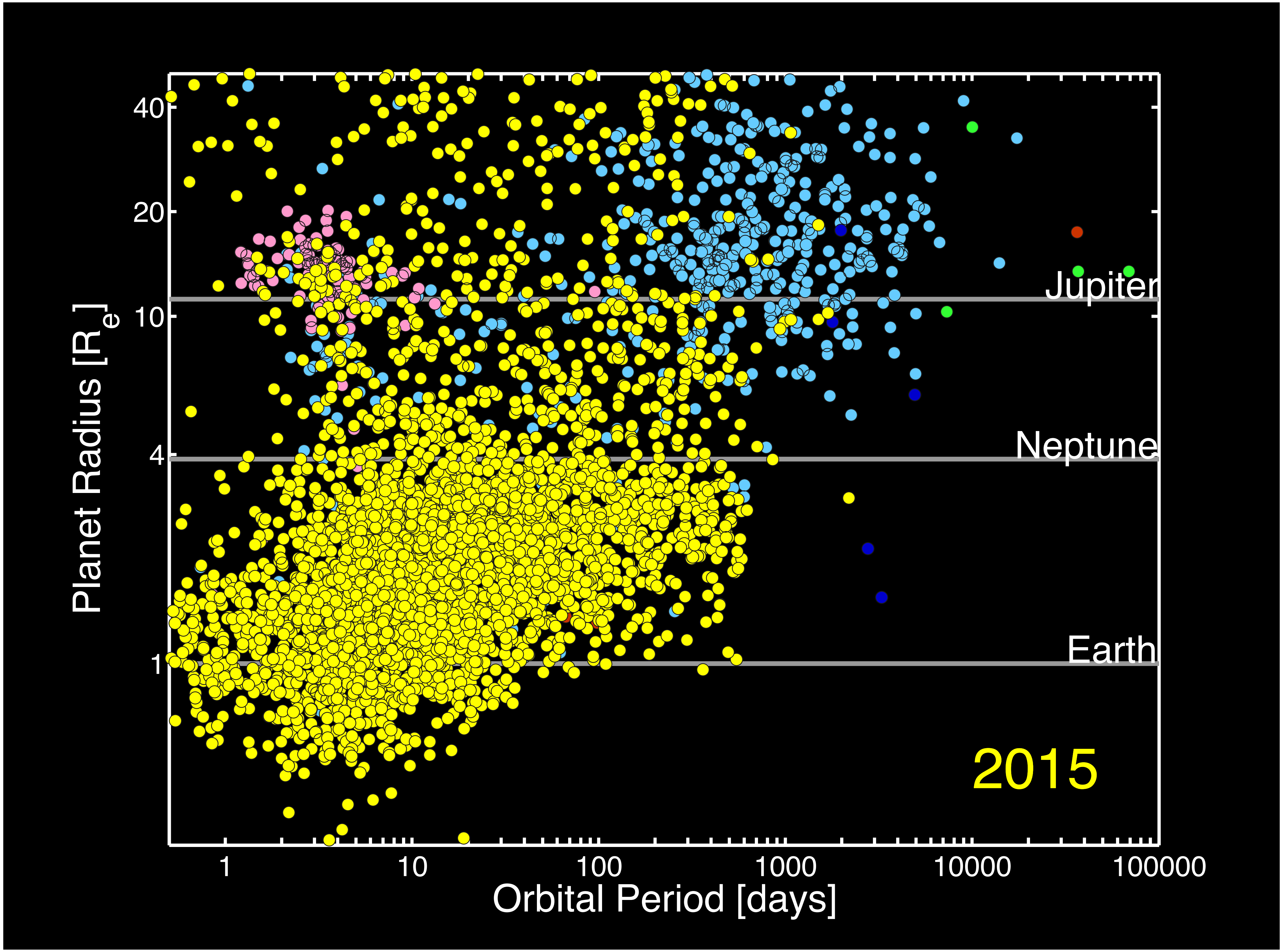


Msini [Earth Mass]
1000
100
10
1
10
100
1000
Orbital Period [days]

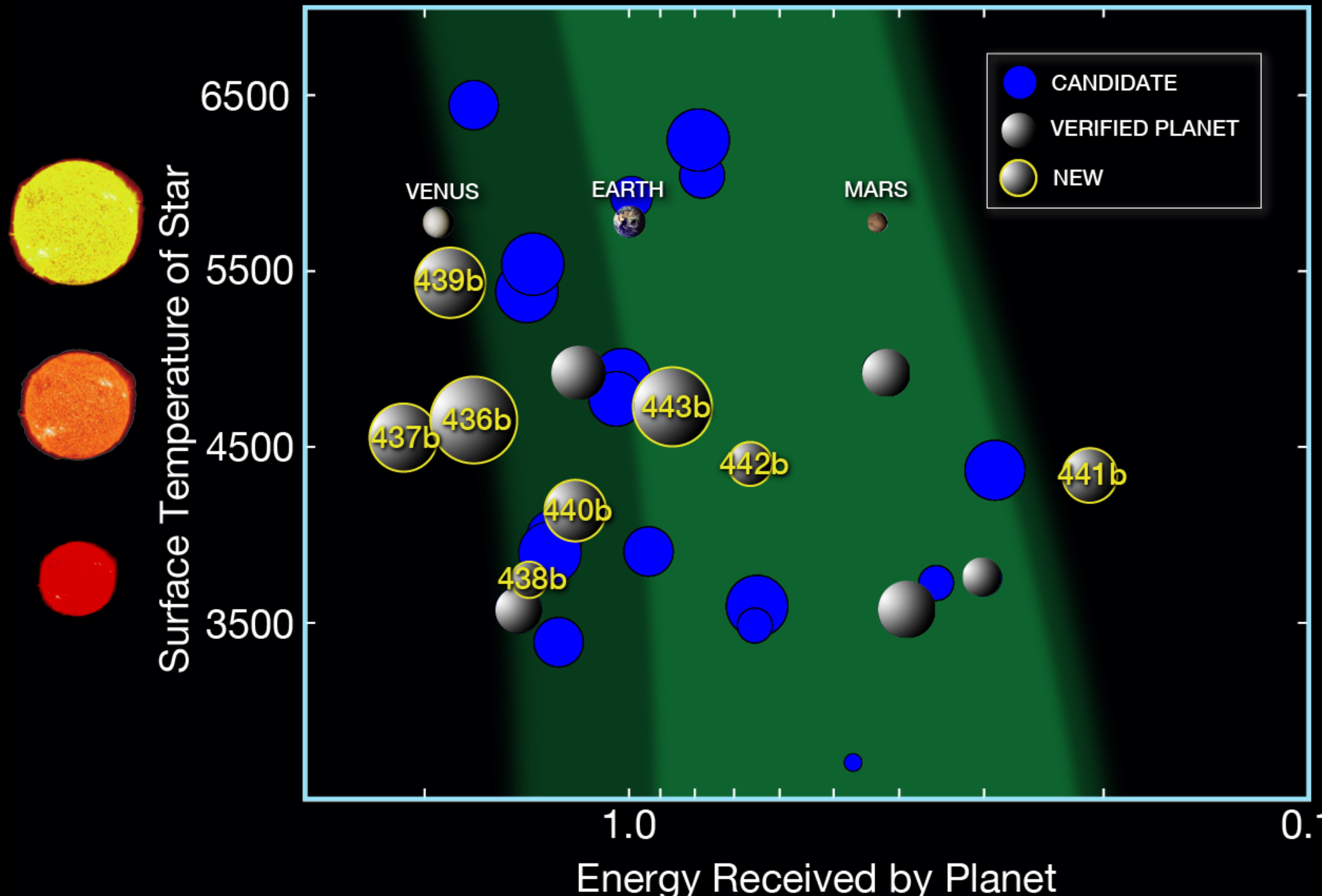


Radial velocity planets
Transiting planets
Imaged planets
Planets detected by timing
All others detection methods
Number of new planets
900
800
700
600
500
400
300
200
100
0
1990
1995
2000
2005
2010
Discovery year
Data taken from the Open Exoplanet Catalogue. Last updated on 2014-06-18.

Kepler-detected exoplanets



Got densities??

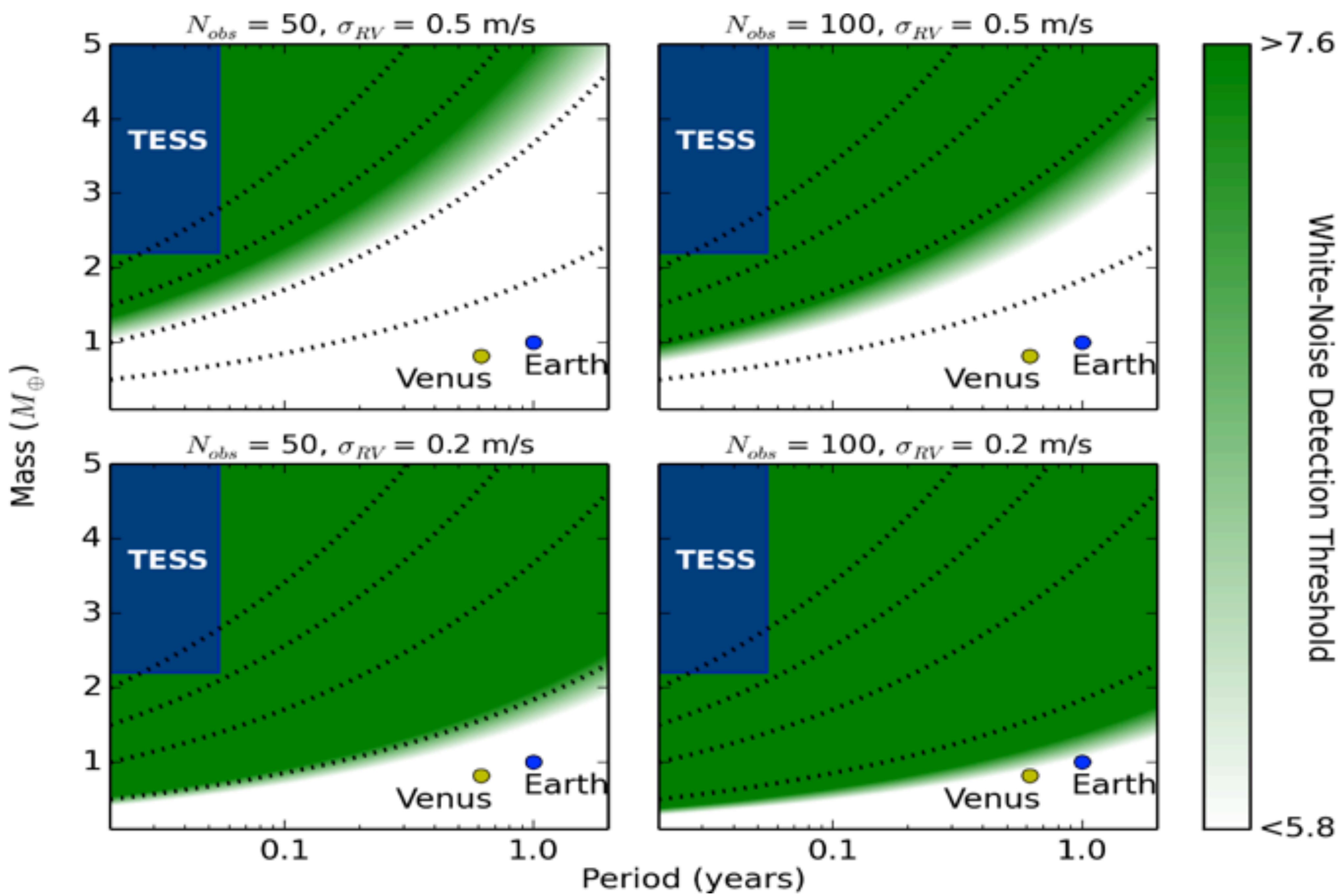


Kepler showed us that if we can reach a detection precision of 1 - 10 cm/s, a bounty of exoplanets exists. We are guaranteed of success.

In addition to serving as a primary detection technique, RV measurements support space missions. The measurement of exoplanet masses dramatically improves the efficiency and productivity of space missions.

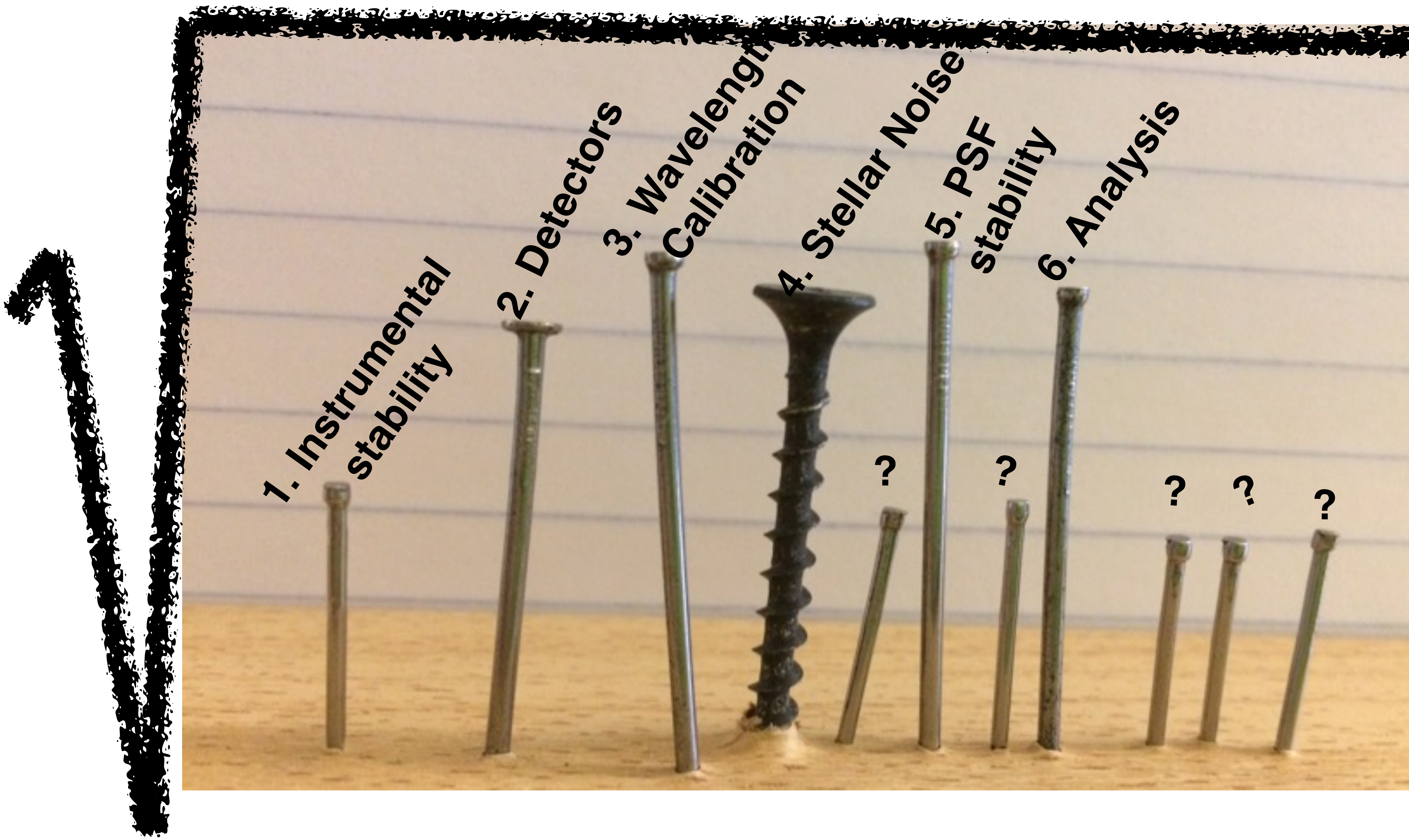
- Business as usual is not very interesting.
- Improving precision is game-changing.

What a difference precision makes!

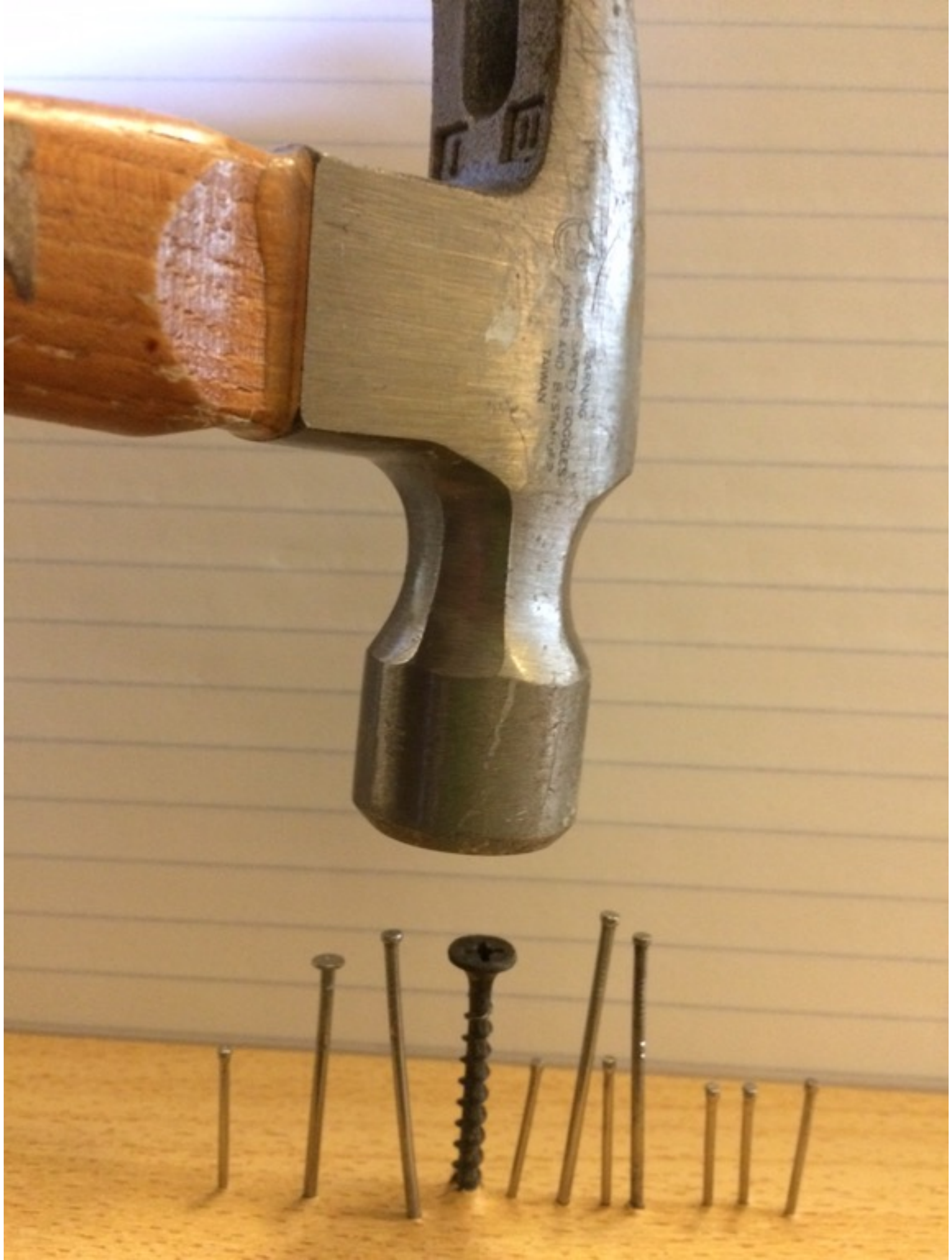


This is not single measurement precision;
this is long term (RMS) precision.

In the next decade, we are trying to achieve another ***factor of ten*** improvement in precision.



1. Instrumental stability
2. Detectors
3. Wavelengt Calibration
4. Stellar Noise
5. PSF stability
6. Analysis
?
?
?
?
?




4V
10
8

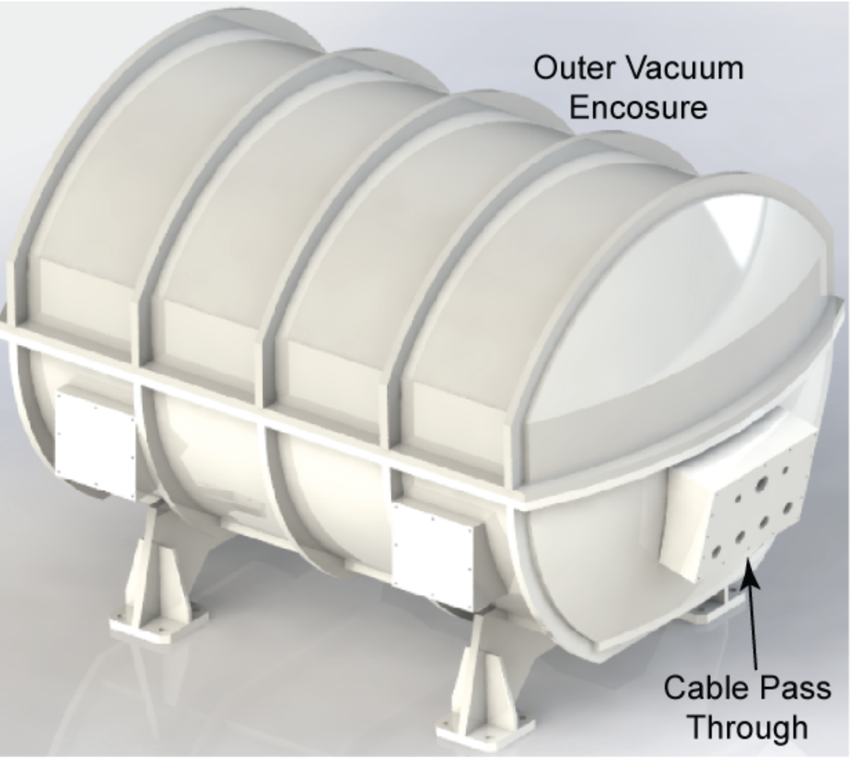
The Future of the Doppler Technique

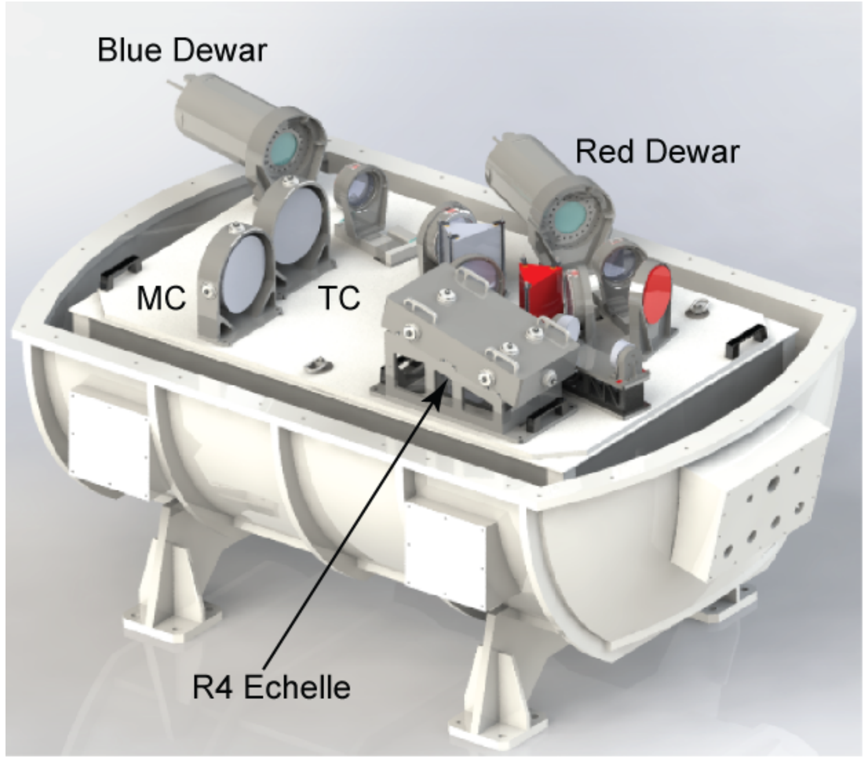
Yale Exoplanet Instrumentation Group

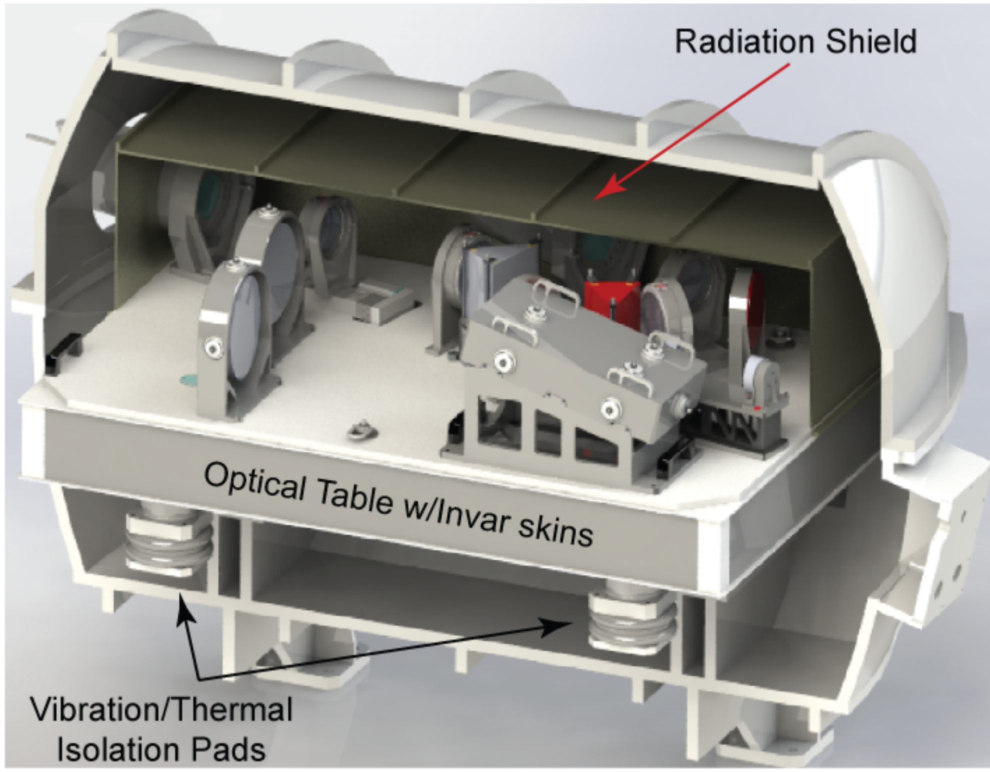
- Fiber-coupling of light to the spectrometer
- Wavelength calibration
- Distinguishing stellar noise from Doppler shifts
- Stable instrument design

1. Instrumental stability

Vacuum chamber: control pressure and temperature

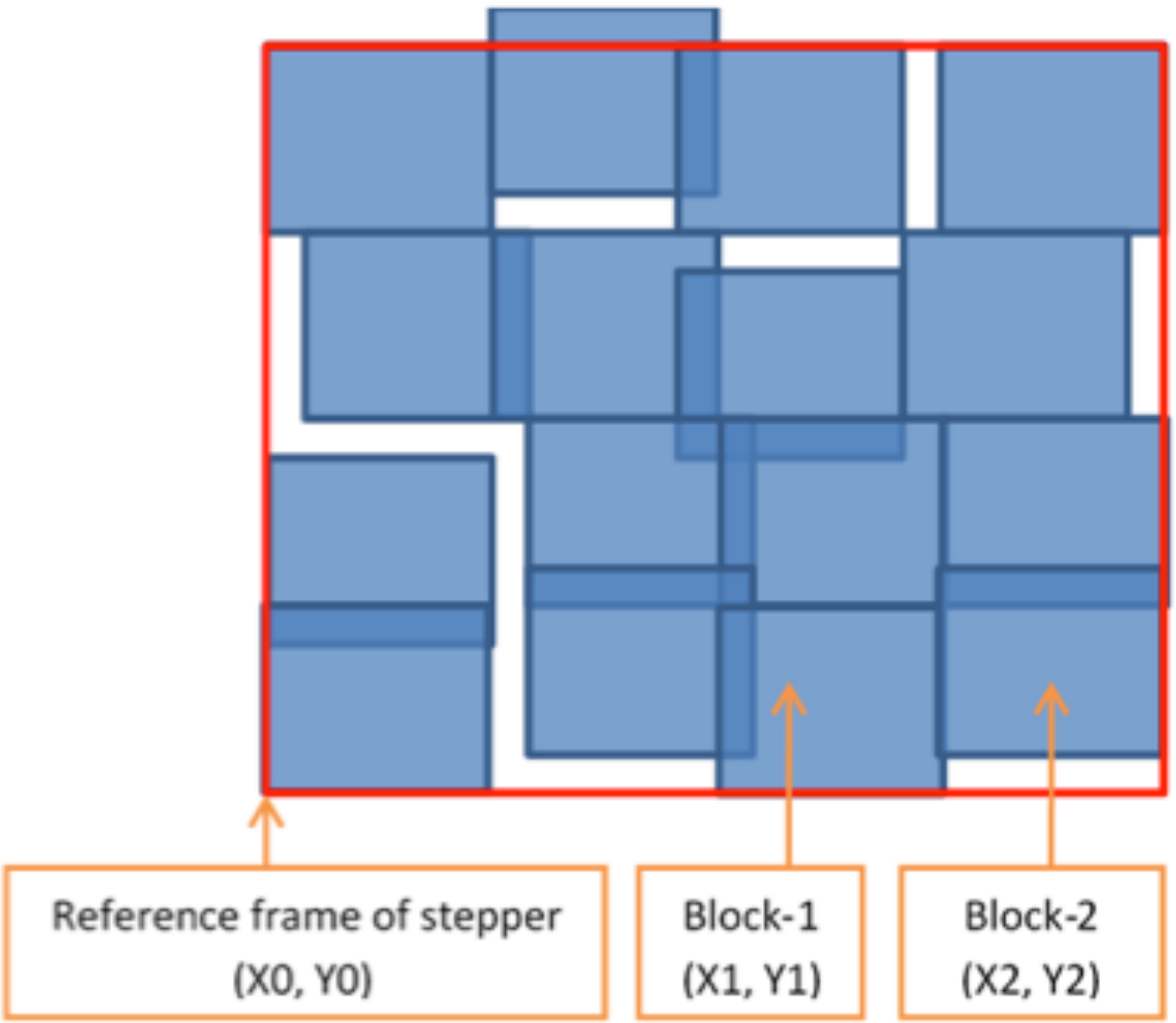






2. Detectors

e2V Detectors



Example of the pixel image blocks required to create a 2k x 2k pixel CCD with exaggerated random position errors relative to the reference frame.

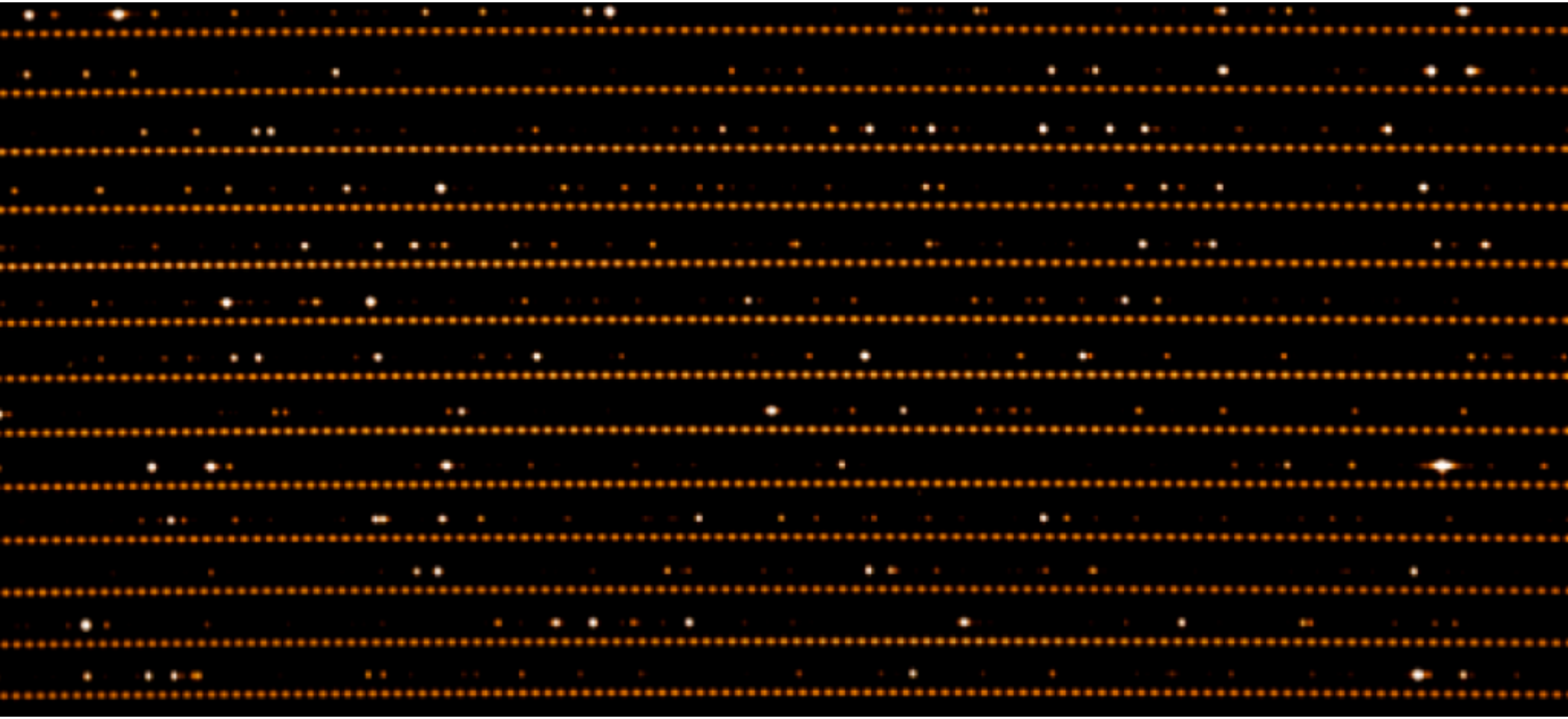
STA detectors:

- 10K devices are built with single photolithography block.
- Also get an extra “9” in the CTE

3. Wavelength Calibration

Thermally stabilized etalon

- regularly spaced emission lines
- quasi-constant amplitude
- covers all orders of the spectrum

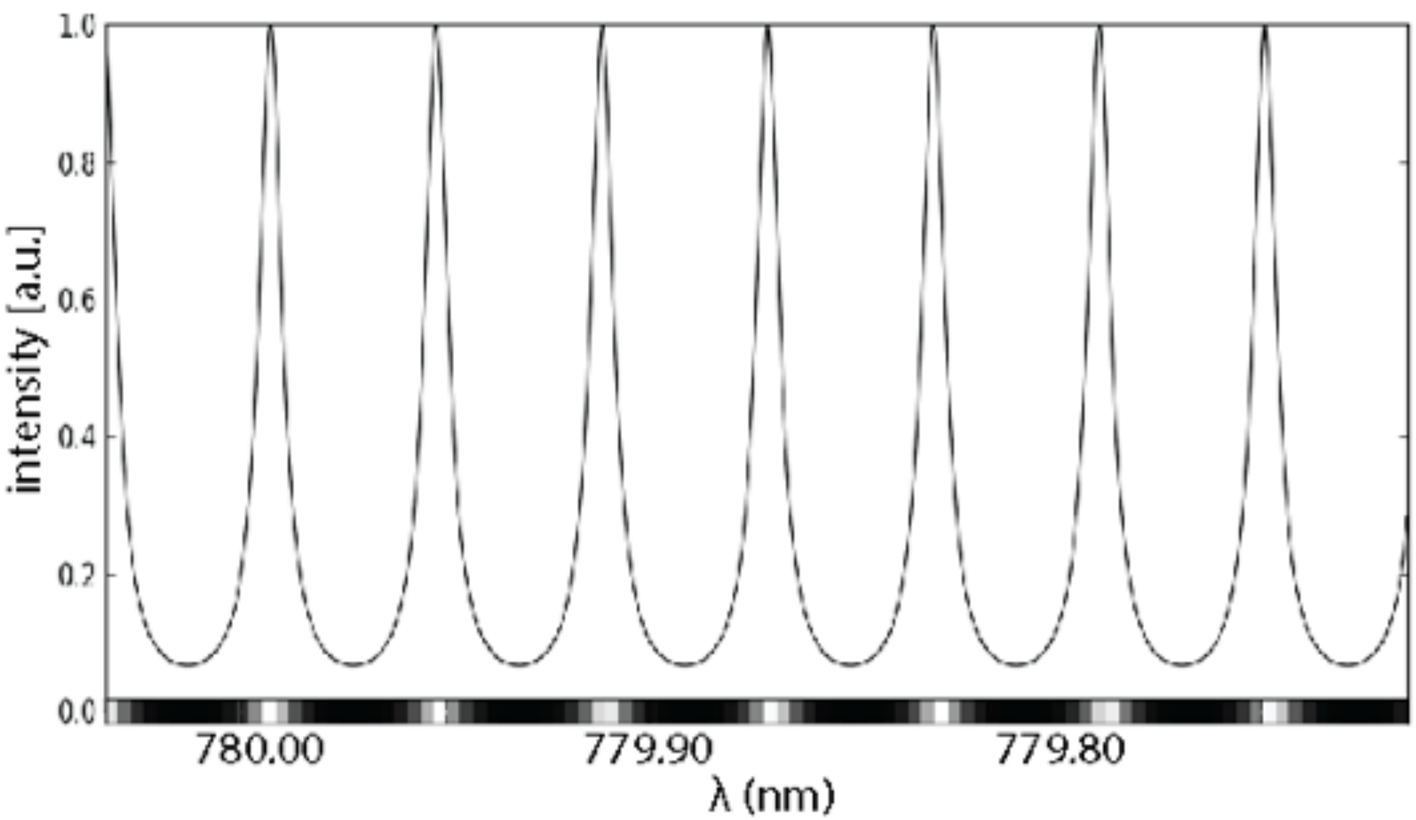


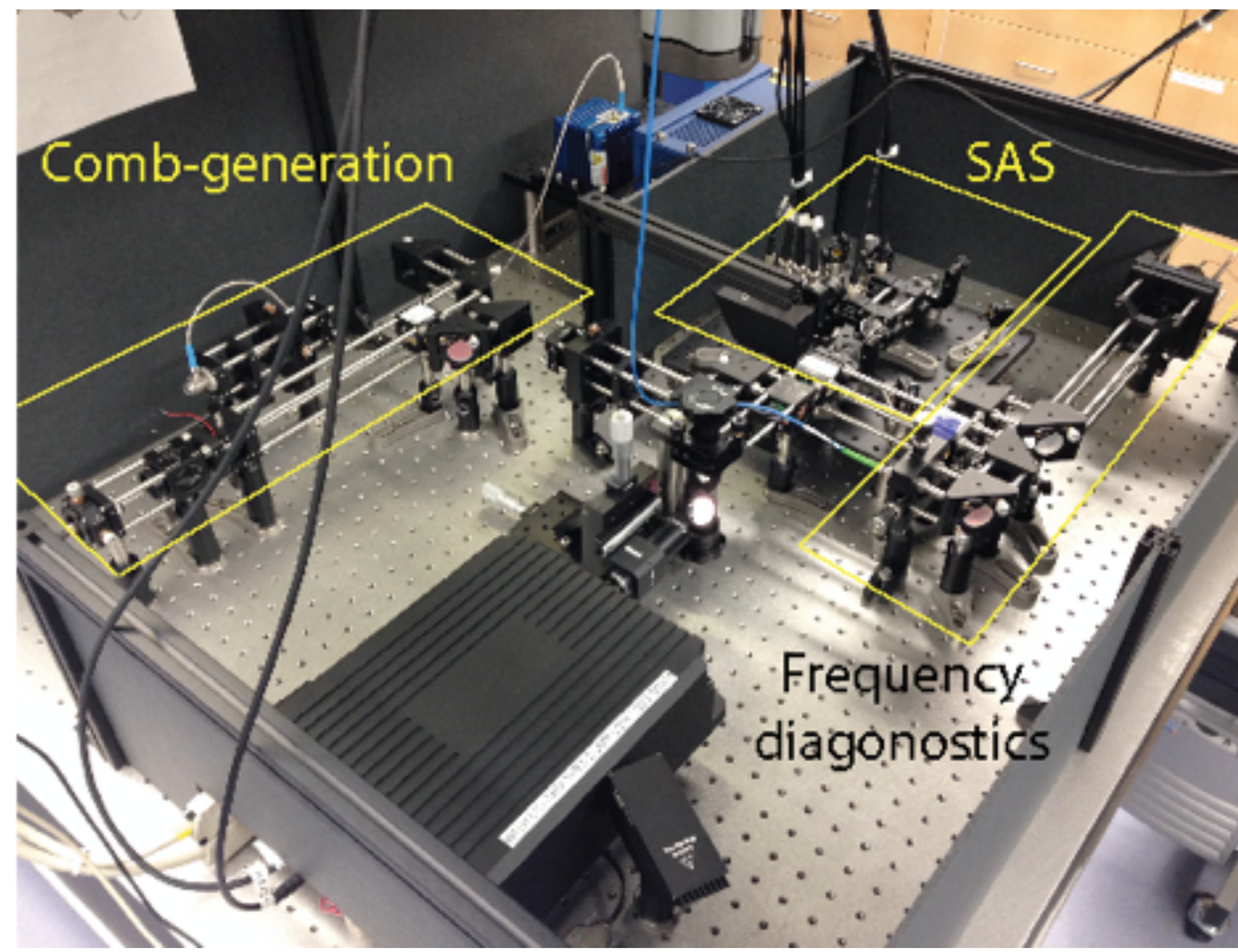
Wildi, Chazelas, Pepe
2012 Proc. SPIE 8446

3. Wavelength Calibration

Actively stabilized F-P etalon

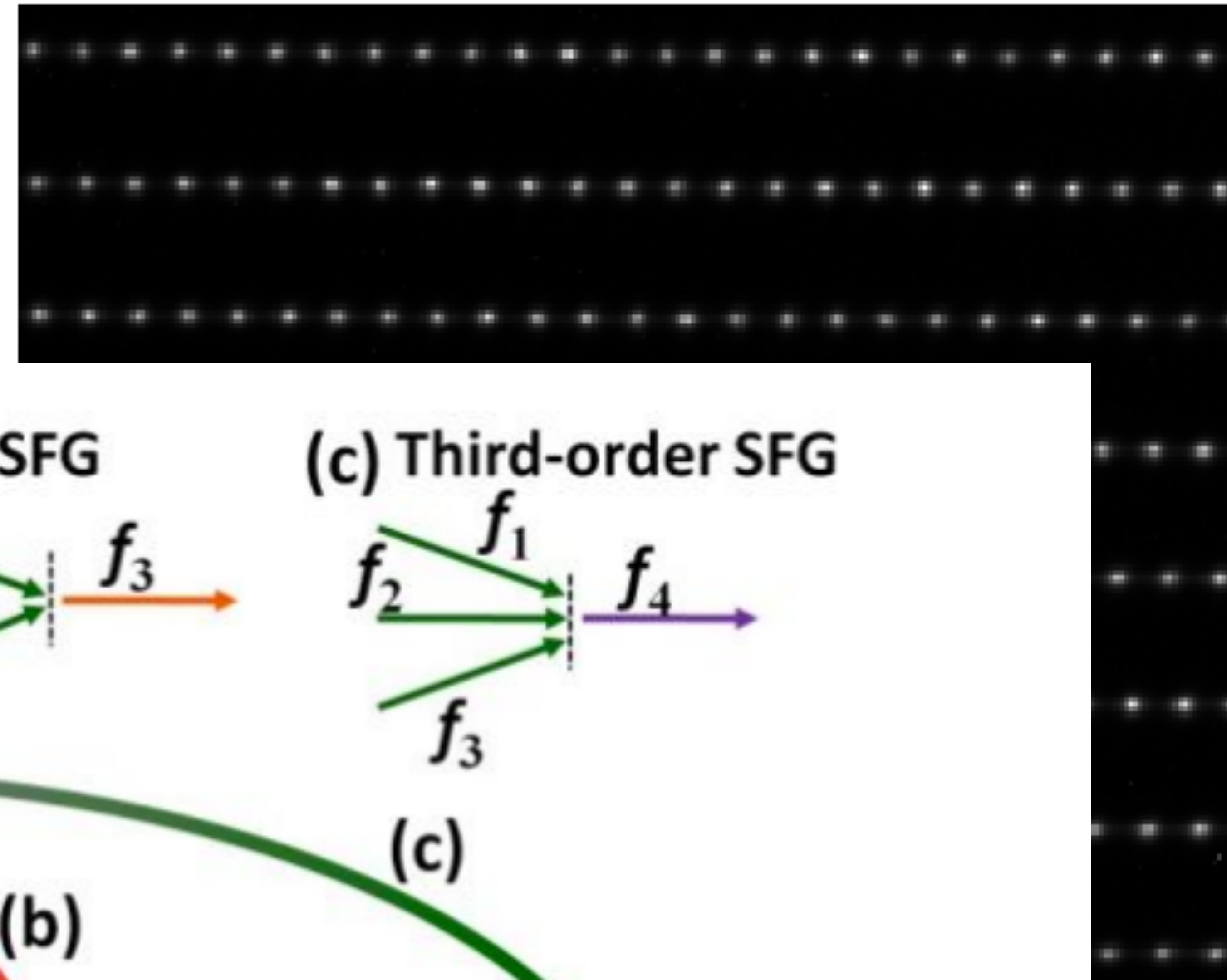
- regularly spaced calibration lines
  - quasi-constant amplitude
  - 20 GHz mode spacing
  - covers all orders of the spectrum

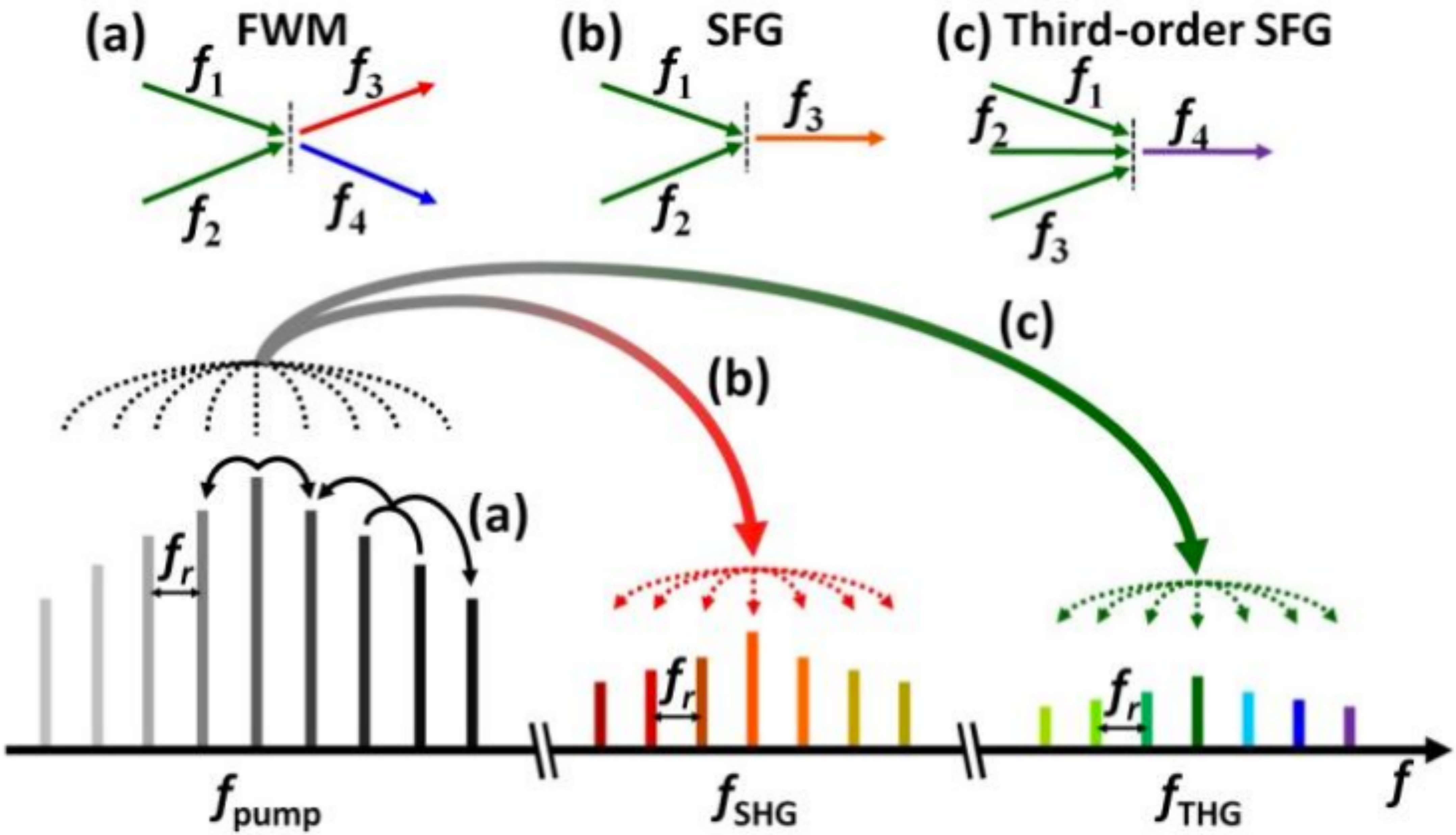




Yale Exoplanet Lab

3. Wavelength Calibration





Jung et al. 2014 Optics Express

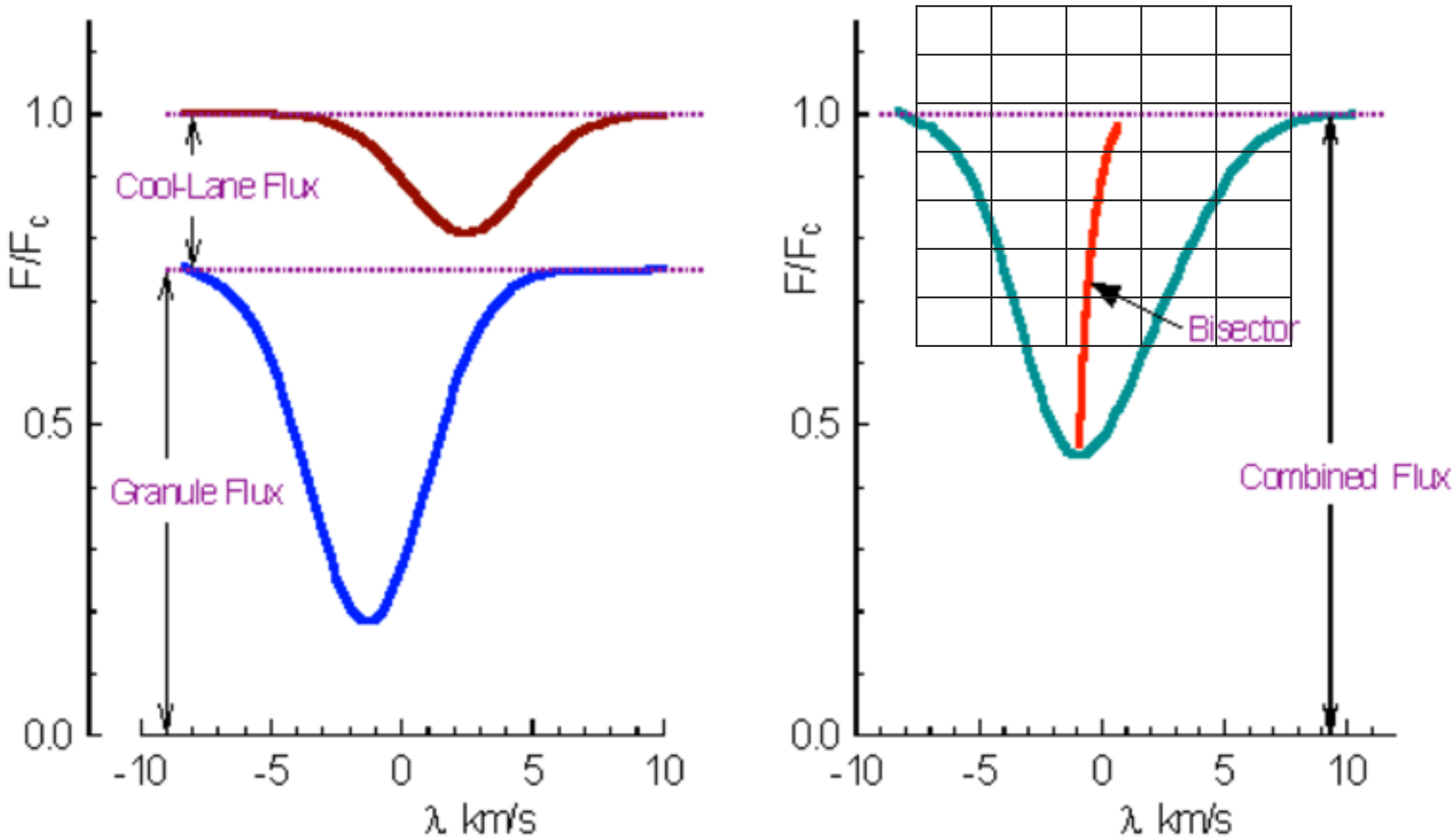
3. Wavelength Calibration

Wavelength Calibration: Menlo LFCs

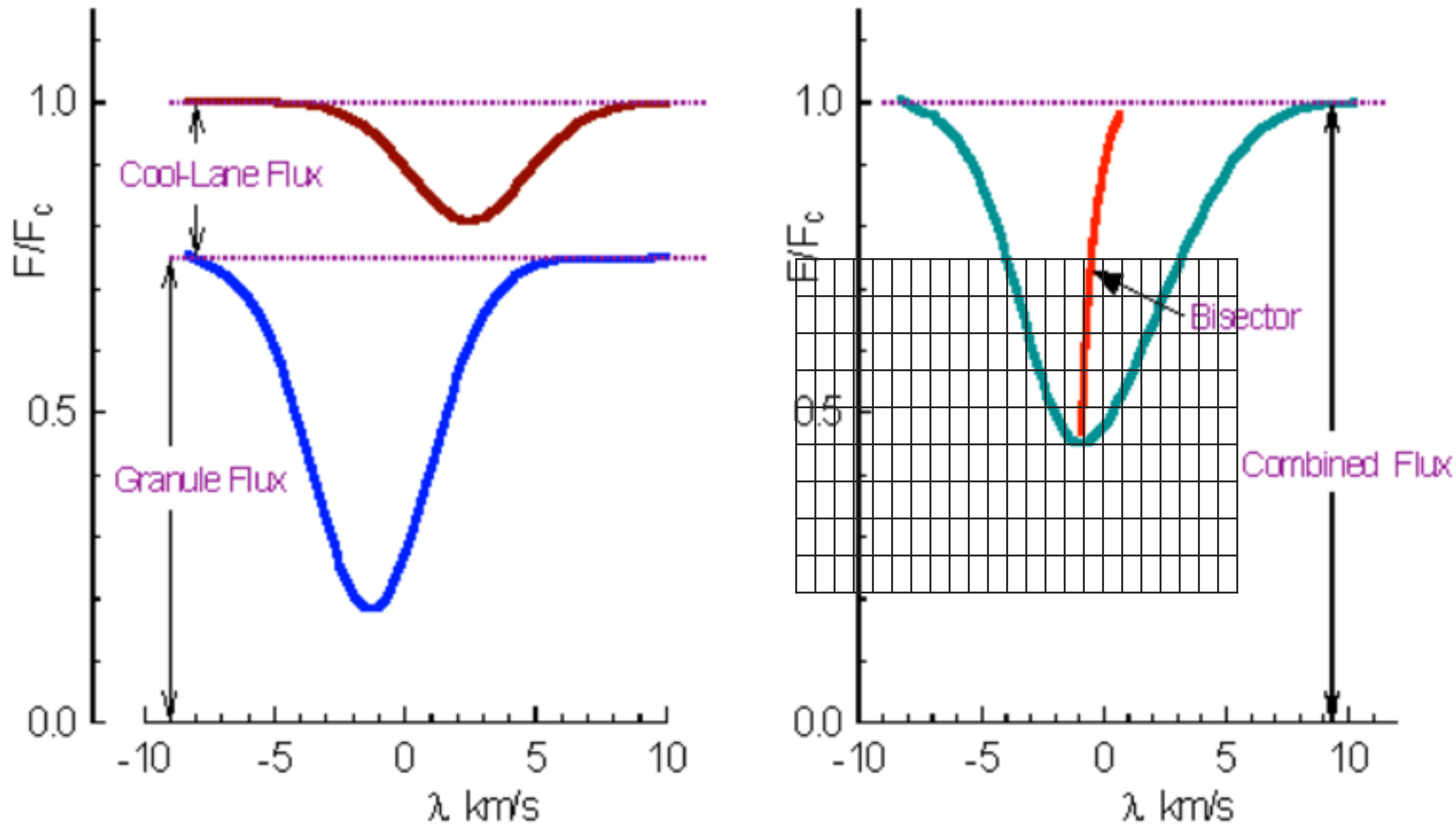
Menlo Systems Laser Frequency Comb
400nm - 1 micron
25 GHz comb
Intensity flat to 3dB

4. Astrophysical noise

Line-bisector analysis



4. Astrophysical noise



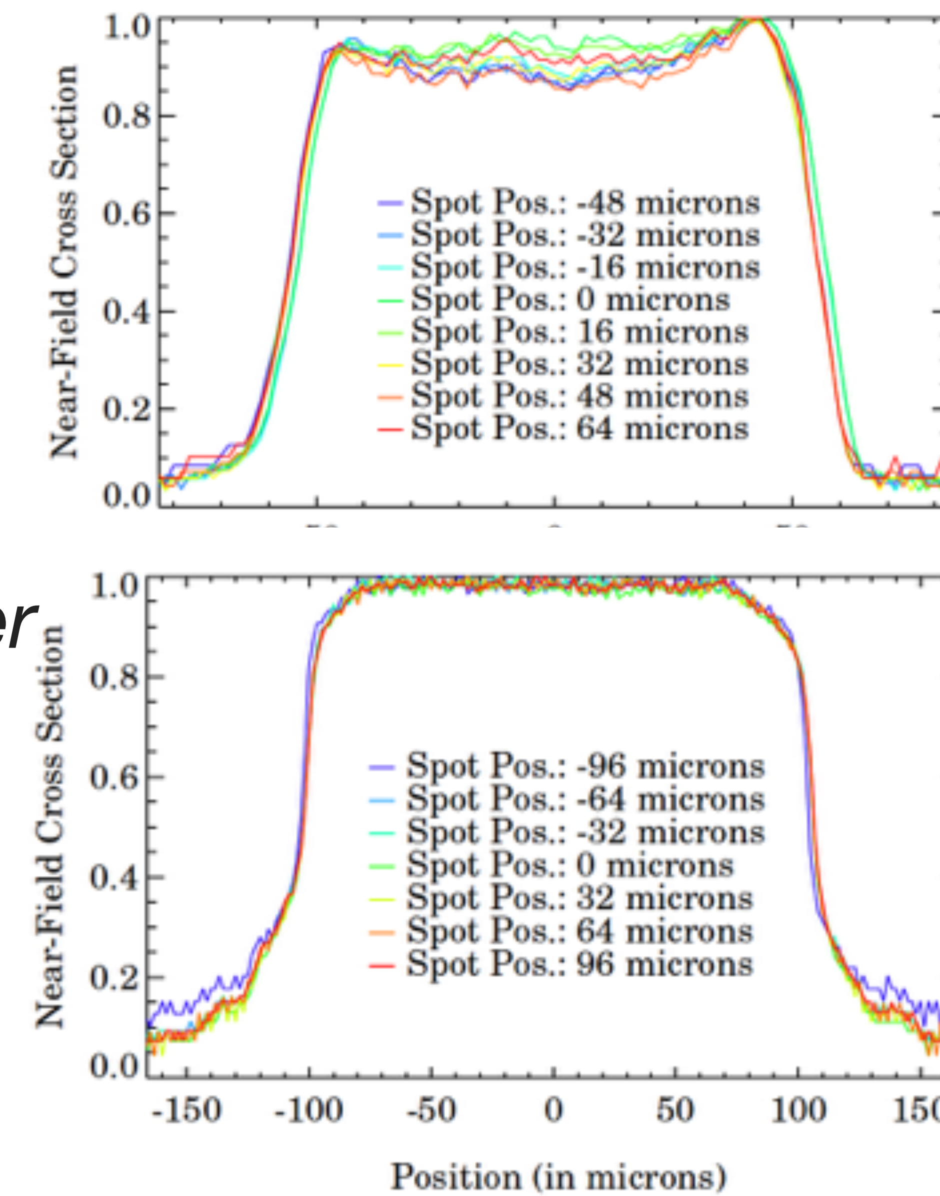
Issue is no longer a matter of designing an instrument for Doppler precision, but designing one that can distinguish stellar signals, which will have a color dependence, from Doppler shifts.

Planet Whisperer code: PCA+Dictionary learning for sparse data sets (like neural nets)

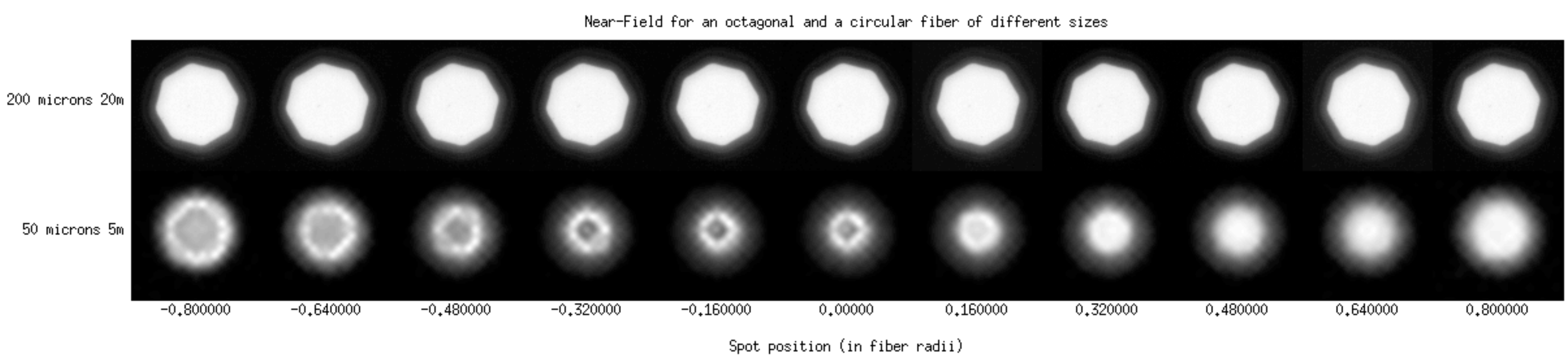
5. PSF stability

Circular fiber

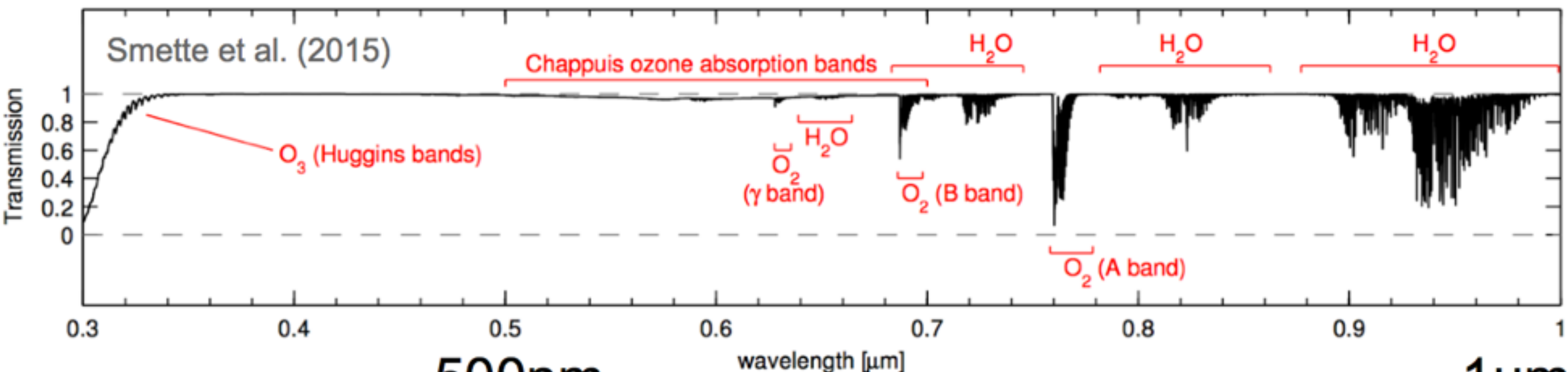
Octagonal fiber



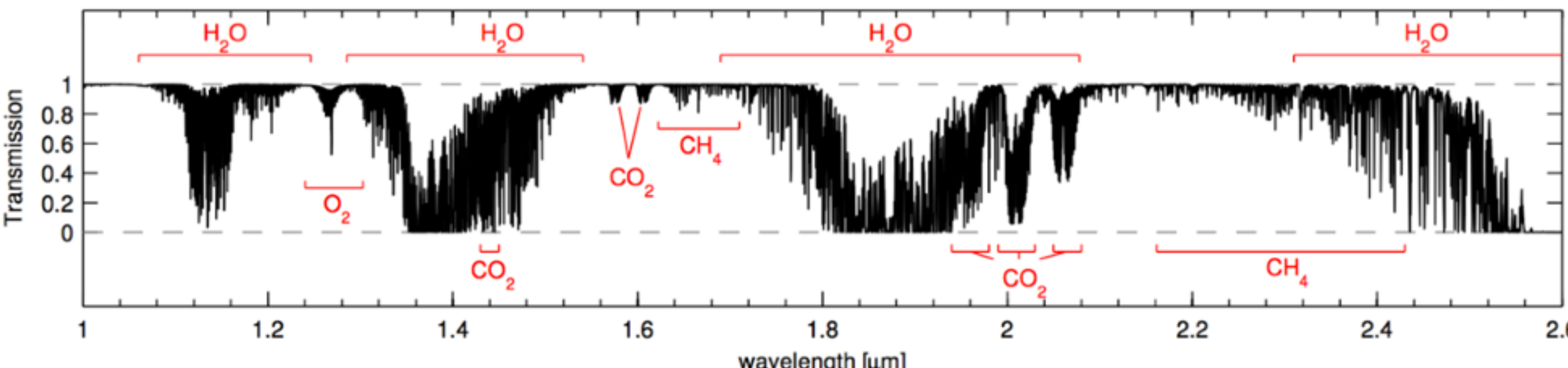
Spronck et al. 2010



6. Analysis errors



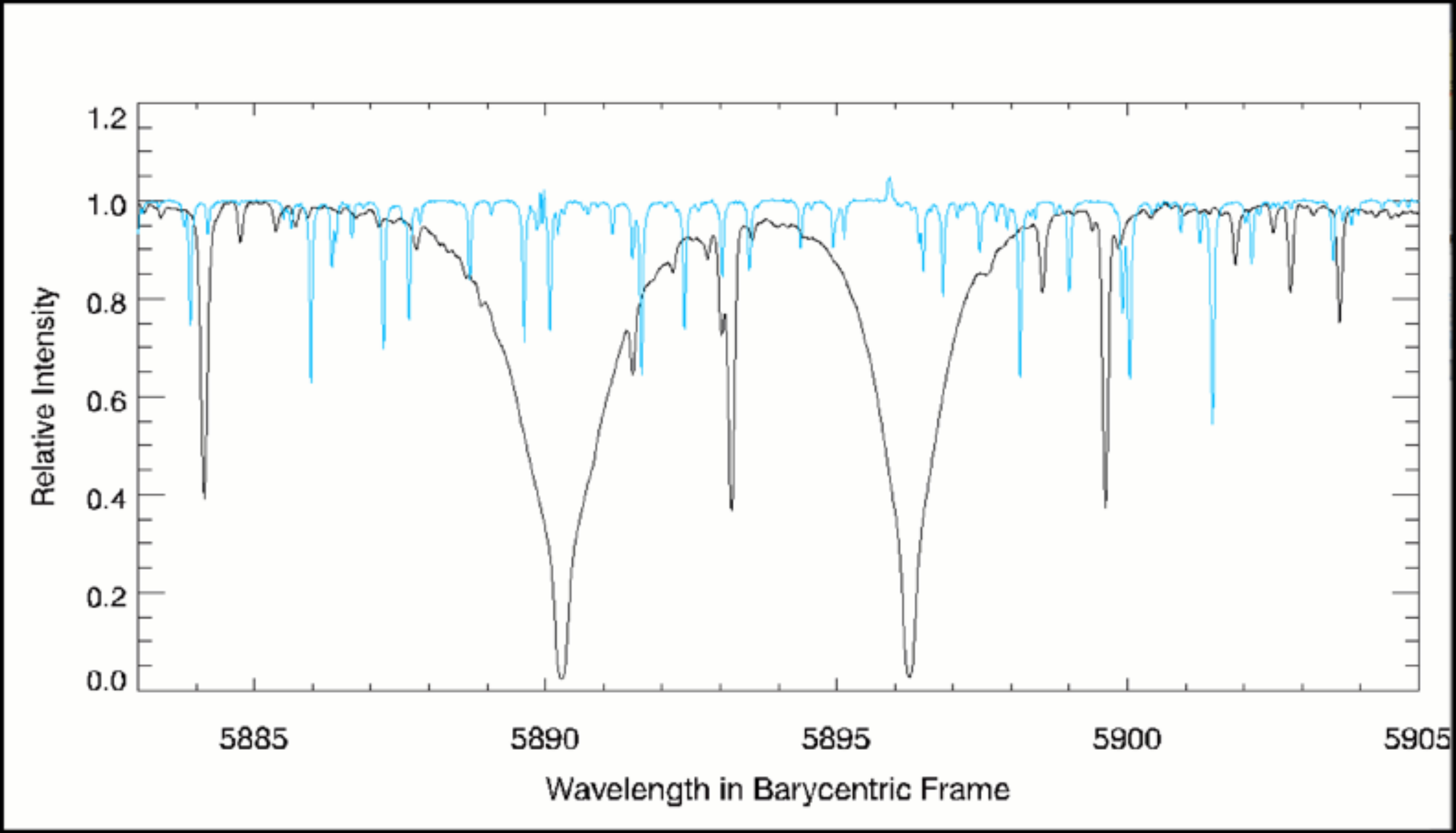
500nm
1µm



1µm
2.6µm

Challenging for NIR spectroscopy from the ground

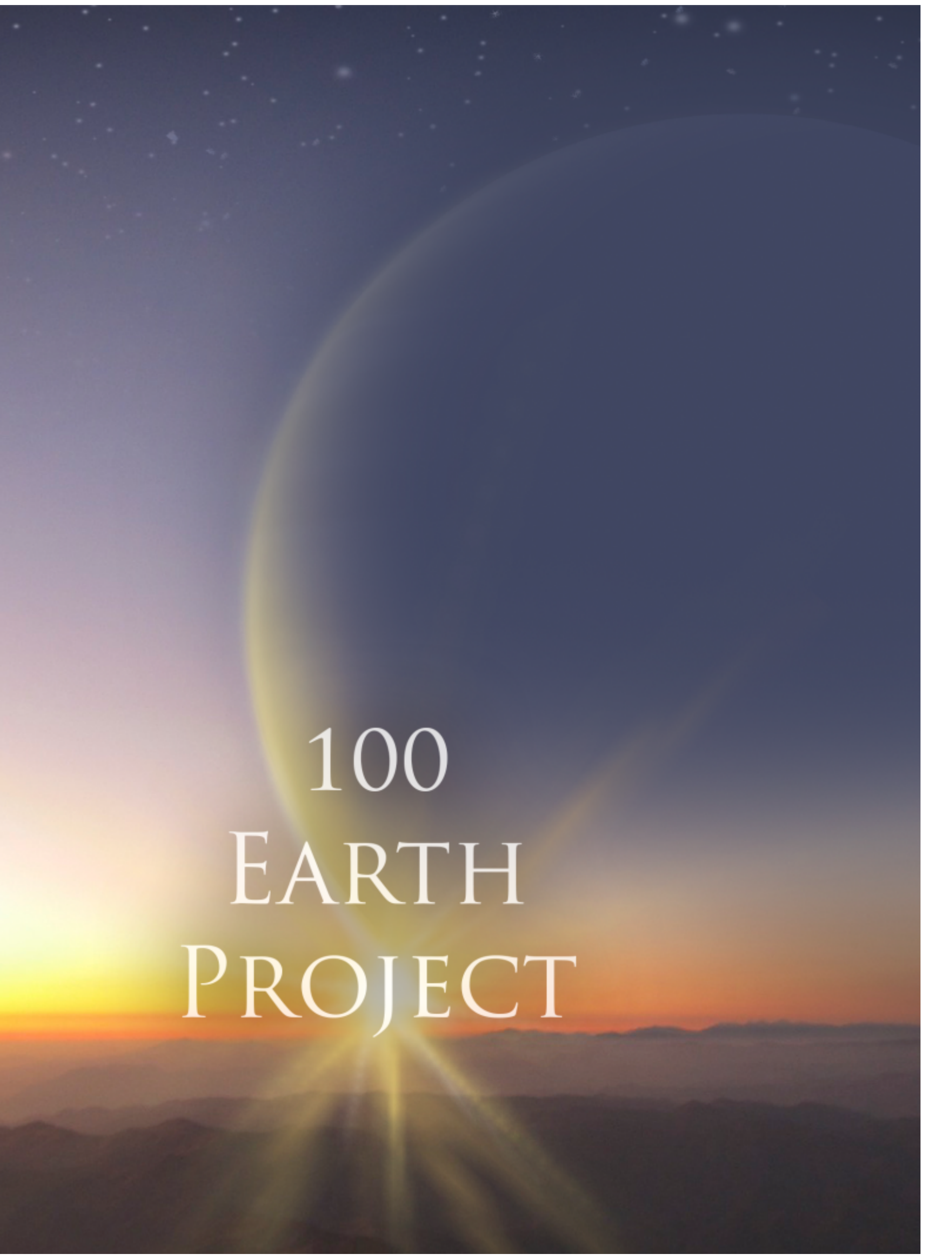
6. Analysis errors



Single measurement precision: 15 cm/s
Long term measurement (RMS noise): 25 cm/s

telluric contamination….. ?
astrophysical noise……...30 cm/s w/fitting
focus and guiding……… 10 cm/s
software fitting errors……10 cm/s
detector errors…………...5 cm/s
stray light…………………TBD
microvibrations…………. 3 cm/s
flux dependent CTE…….few cm/s
barycentric corrections…1 cm/s

EXPRES at the DCT: 100 Earths Project
Commissioning in summer 2017



Next generation spectrometer

- *optimal engineering for extreme stability of instrument*
- *double scrambling of the light into the spectrometer*
- *Menlo LFC wavelength calibrator*
- *choose the right stars to survey (low noise?)*
- *solve for stellar signals ("noise")*

LFC applications for exoplanet detection
Enabling, not just improving.

1. wavelength calibration to 1 cm/s
2. ideal diagnostic of instrumental PSF (SLSF)
3. allows for deconvolution to recover higher fidelity spectrum
4. detector characterization
    - stitching errors in CCD fabrication
    - intrapixel QE variations
    - pixel dimension non-uniformity