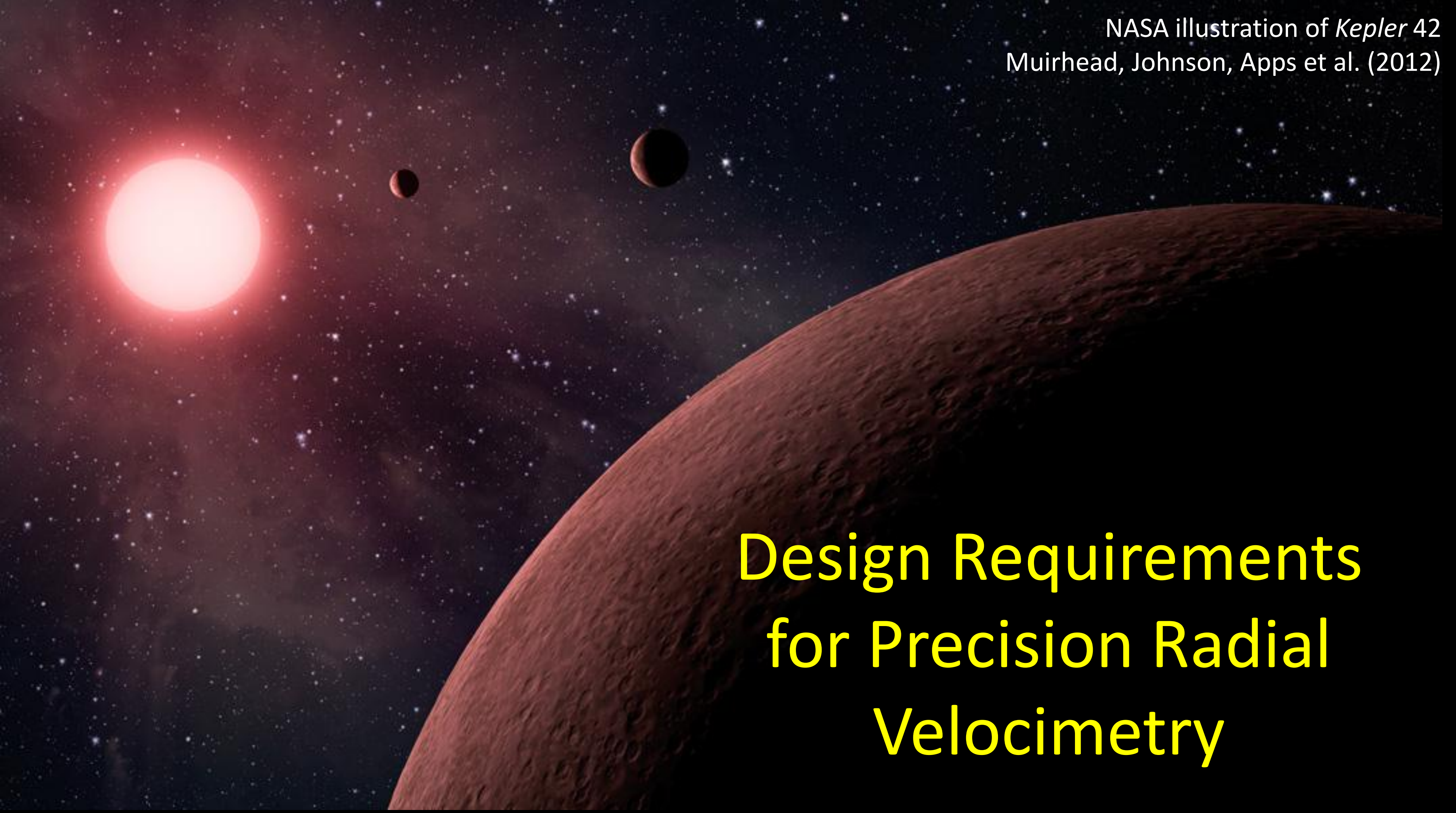


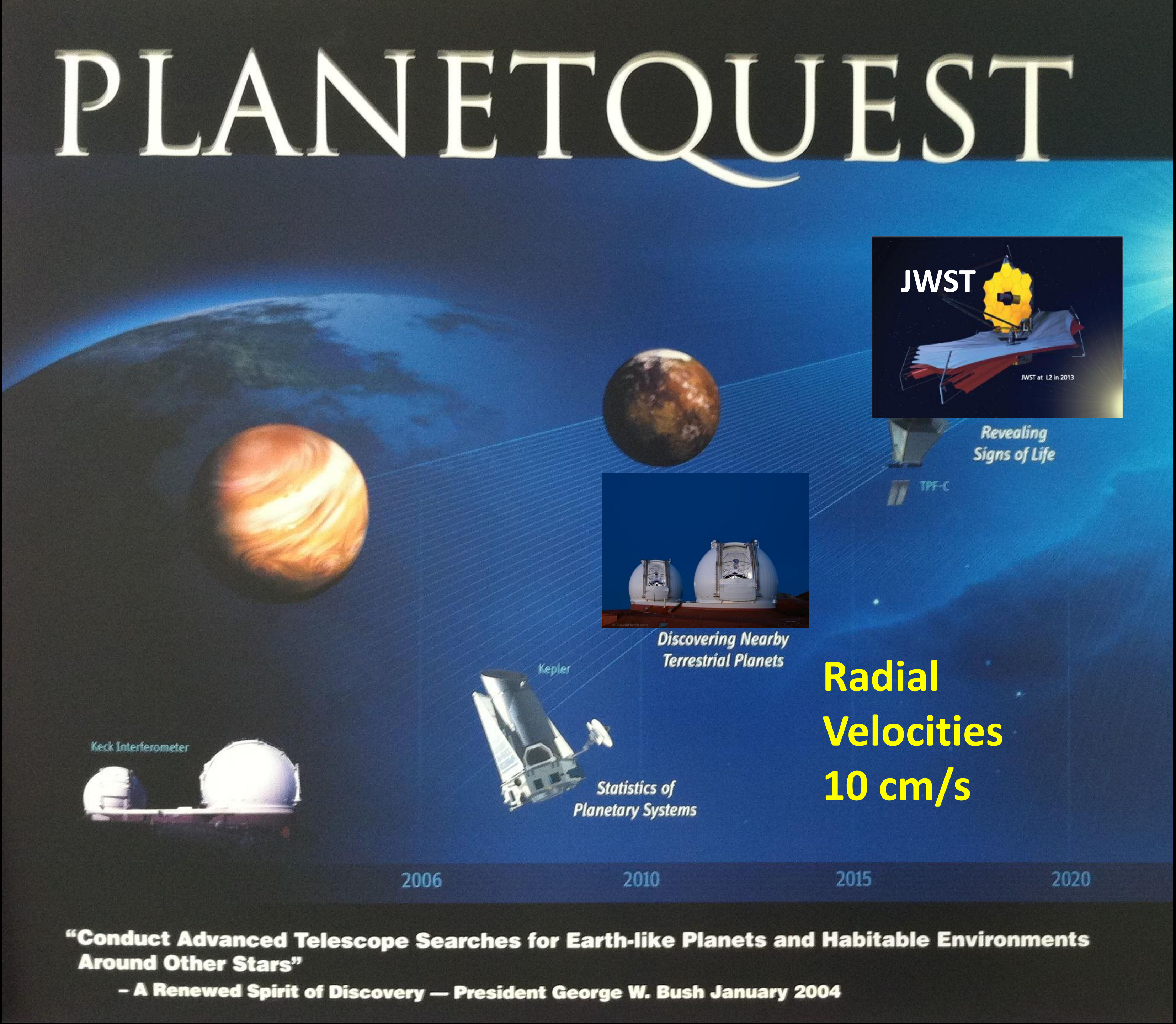
Design Requirements for Precision Radial Velocimetry

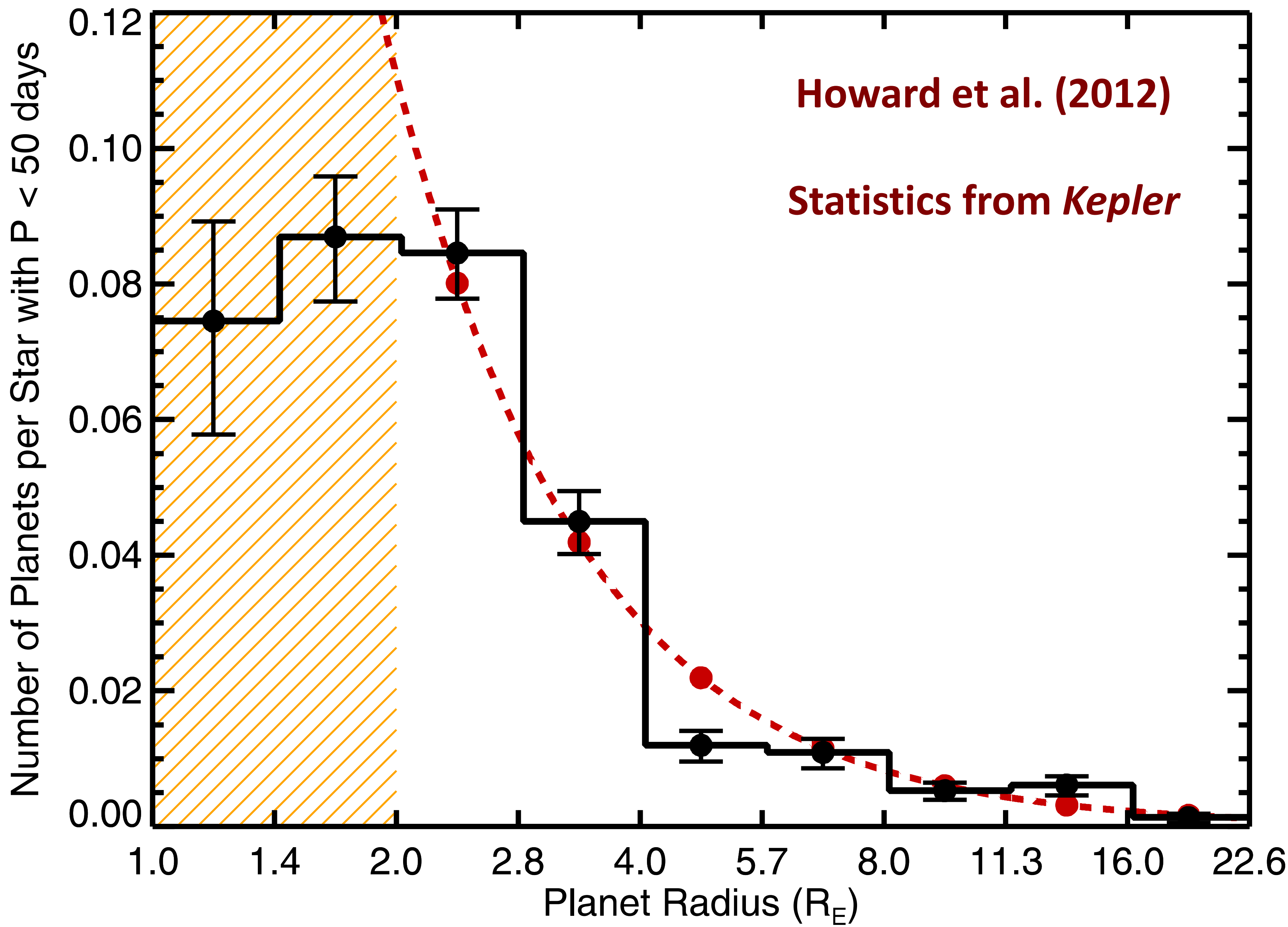
Phil Muirhead
Caltech Postdoctoral Scholar
(on behalf of John Johnson)

PLANETQUEST

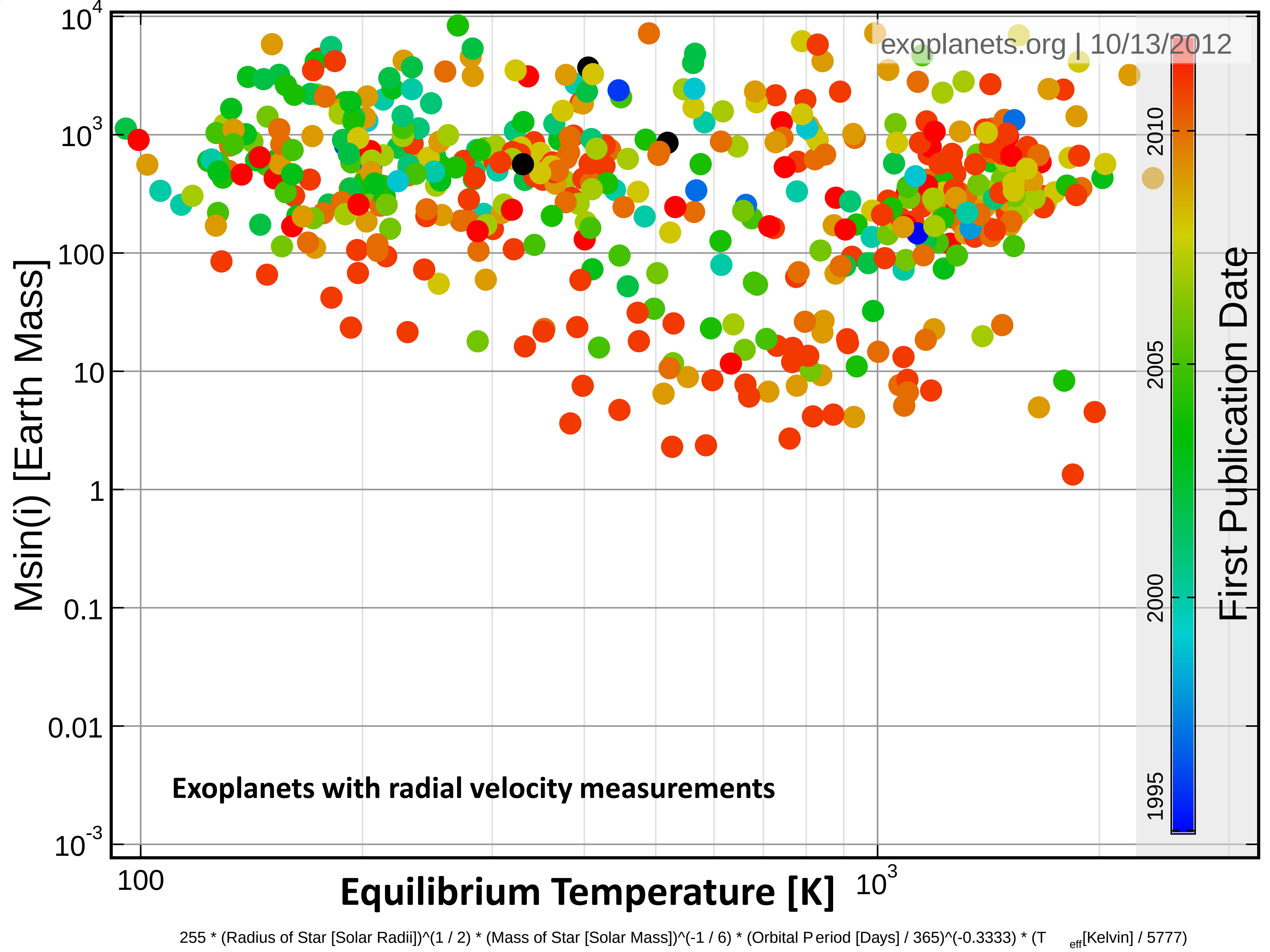
"Conduct Advanced Telescope Searches for Earth-like Planets and Habitable Environments Around Other Stars"

– A Renewed Spirit of Discovery — President George W. Bush January 2004

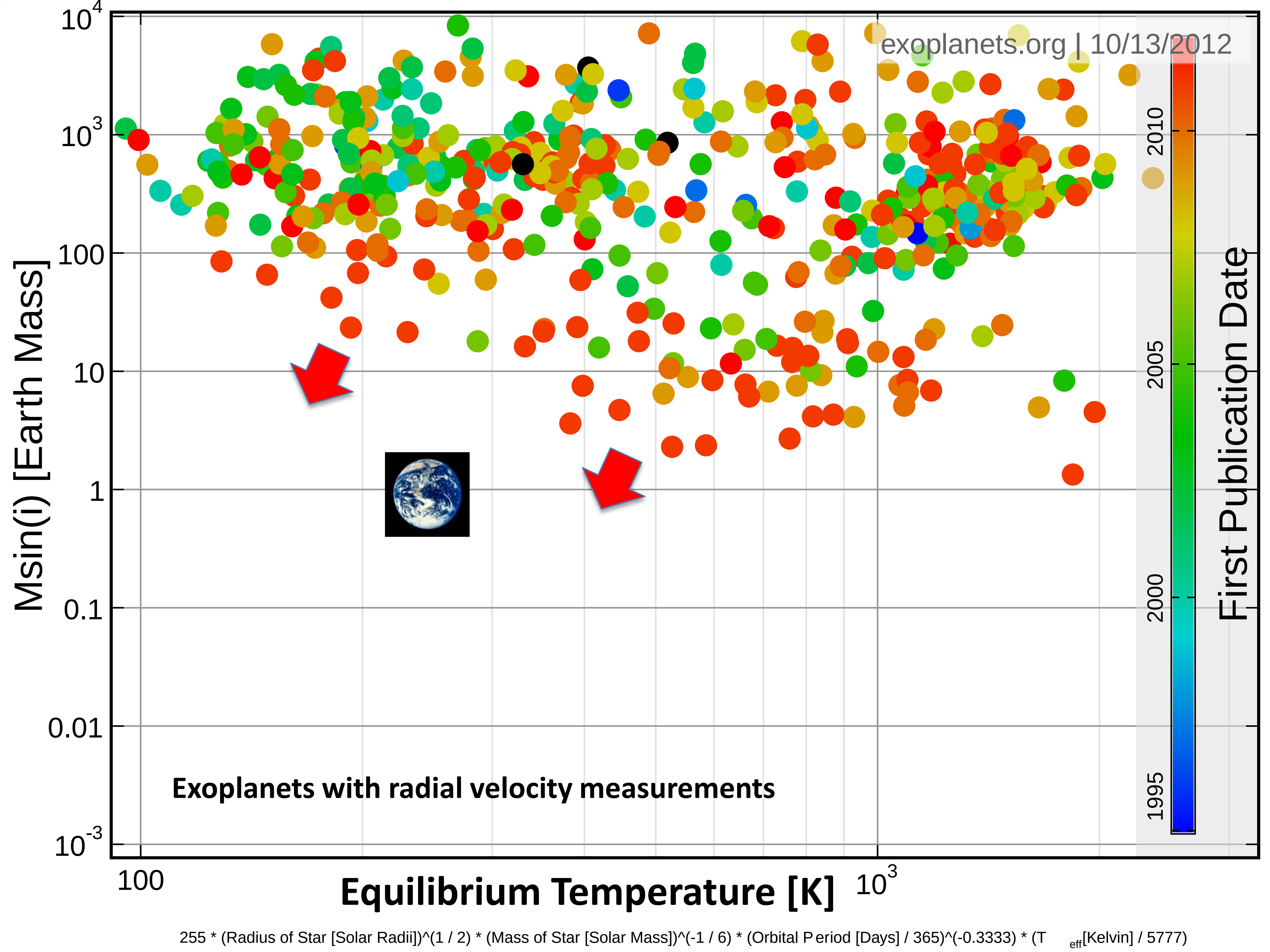

PLANETQUEST
JWST
JWST at L2 in 2013
Revealing Signs of Life
TPF-C
Discovering Nearby Terrestrial Planets
Kepler
Statistics of Planetary Systems
Keck Interferometer
Radial Velocities 10 cm/s
2006
2010
2015
2020
"Conduct Advanced Telescope Searches for Earth-like Planets and Habitable Environments Around Other Stars"
– A Renewed Spirit of Discovery — President George W. Bush January 2004



Howard et al. (2012)
Statistics from *Kepler*
Number of Planets per Star with P < 50 days
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1.0
1.4
2.0
2.8
4.0
5.7
8.0
11.3
16.0
22.6
Planet Radius (R_E)



exoplanets.org | 10/13/2012
Exoplanets with radial velocity measurements
Msin(i) [Earth Mass]
10^4
10^3
100
10
1
0.1
0.01
10^{-3}
100
10^3
Equilibrium Temperature [K]
255 * (Radius of Star [Solar Radii])^(1 / 2) * (Mass of Star [Solar Mass])^(-1 / 6) * (Orbital Period [Days] / 365)^(-0.3333) * (T_{eff}[Kelvin] / 5777)
First Publication Date
2010
2005
2000
1995



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2010
2005
2000
1995
First Publication Date

Precision Radial Velocity Requirements

- ***Photon Noise***
  - Telescope Area * N nights per year
  - Spectrometer Resolving Power (R>50k)
  - Spectrometer simultaneous bandwidth (~100s nm)

- ***Systematic Noise***
  - Stability and calibration (~1 um physical)
  - Stellar jitter. Rotating spots and p-modes
    - Stationary noise process, overcome with high *cadence*

Precision Radial Velocity Requirements

- ***Photon Noise***
  - Telescope Area * …
  - Spectromete… …30k)
  - Spectrometer… …ous bandwidth (~100s nm)
- ***Systematic Noise***
  - Stability a…
  - Stellar jitte… …es
    - Stationary… …me with high *cadence*

Optimize by CALCULATION

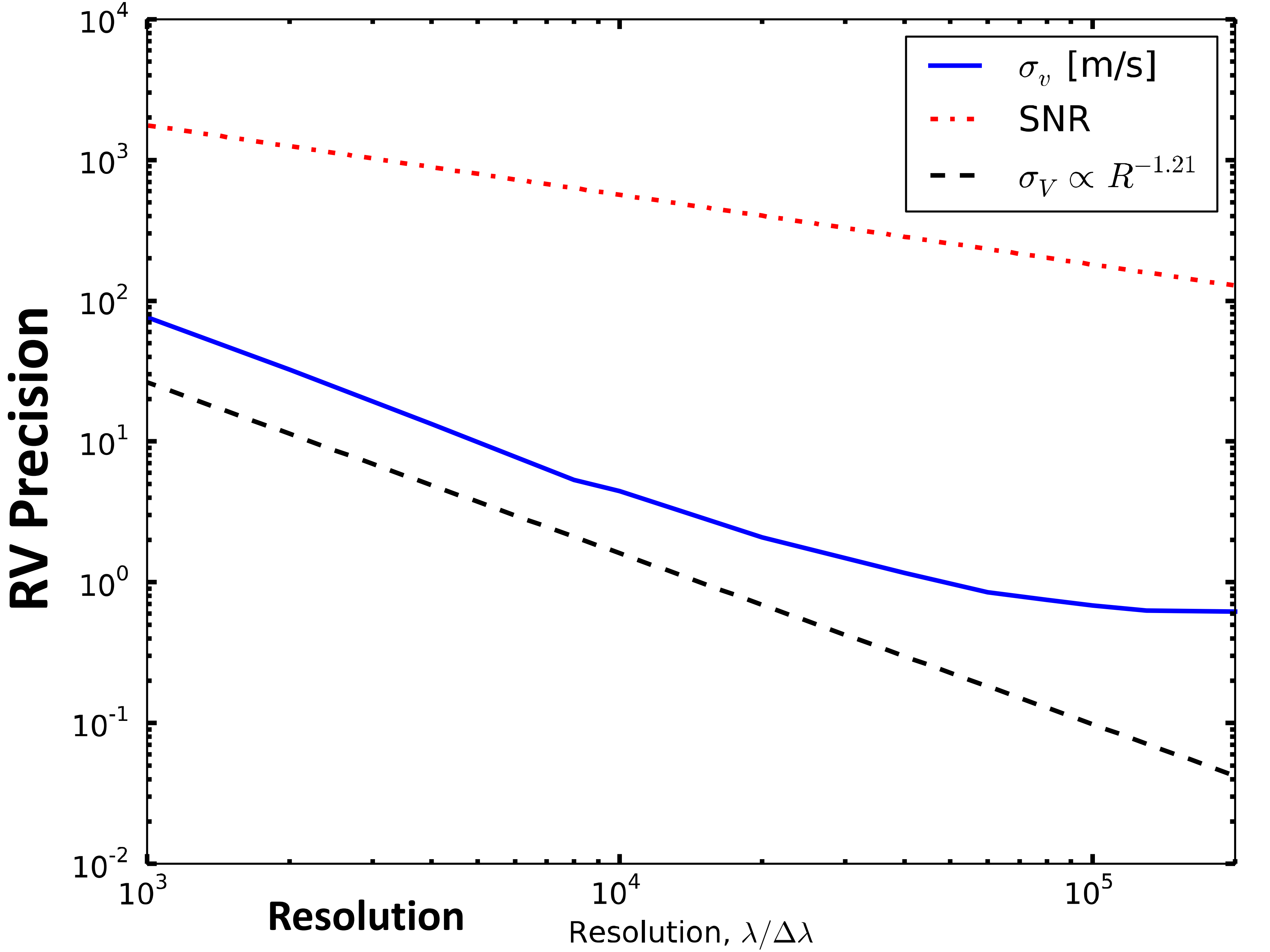
Optimize by SIMULATION and EXPERIMENT

Michael Bottom

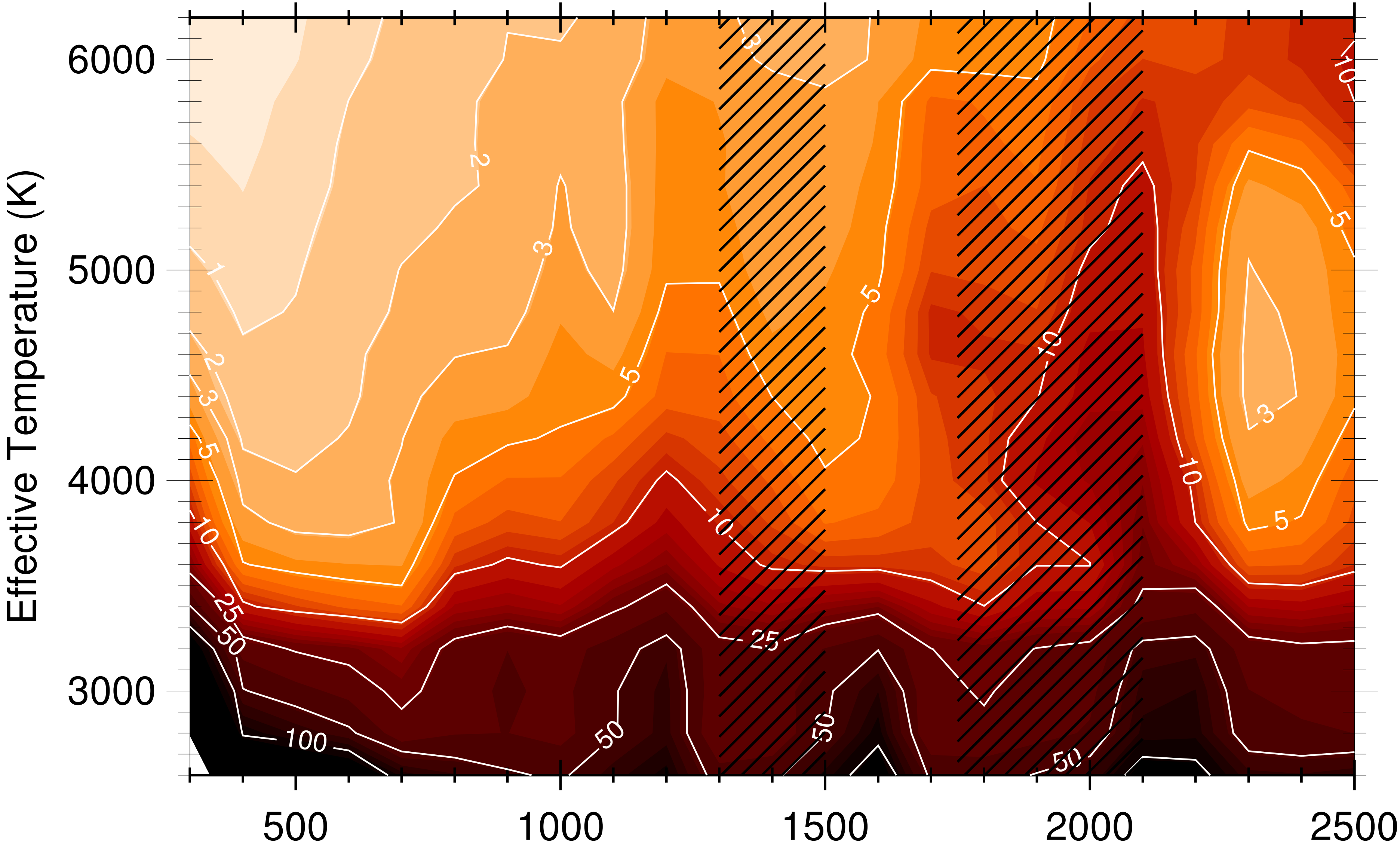
Bottom, Muirhead, Johnson, Blake *submitted to PASP*

- Quantitatively assess **survey yield** as a function of Doppler spectrometer specifications:
  - Resolution
  - Wavelength coverage

Photon Noise
(fundamental limit)

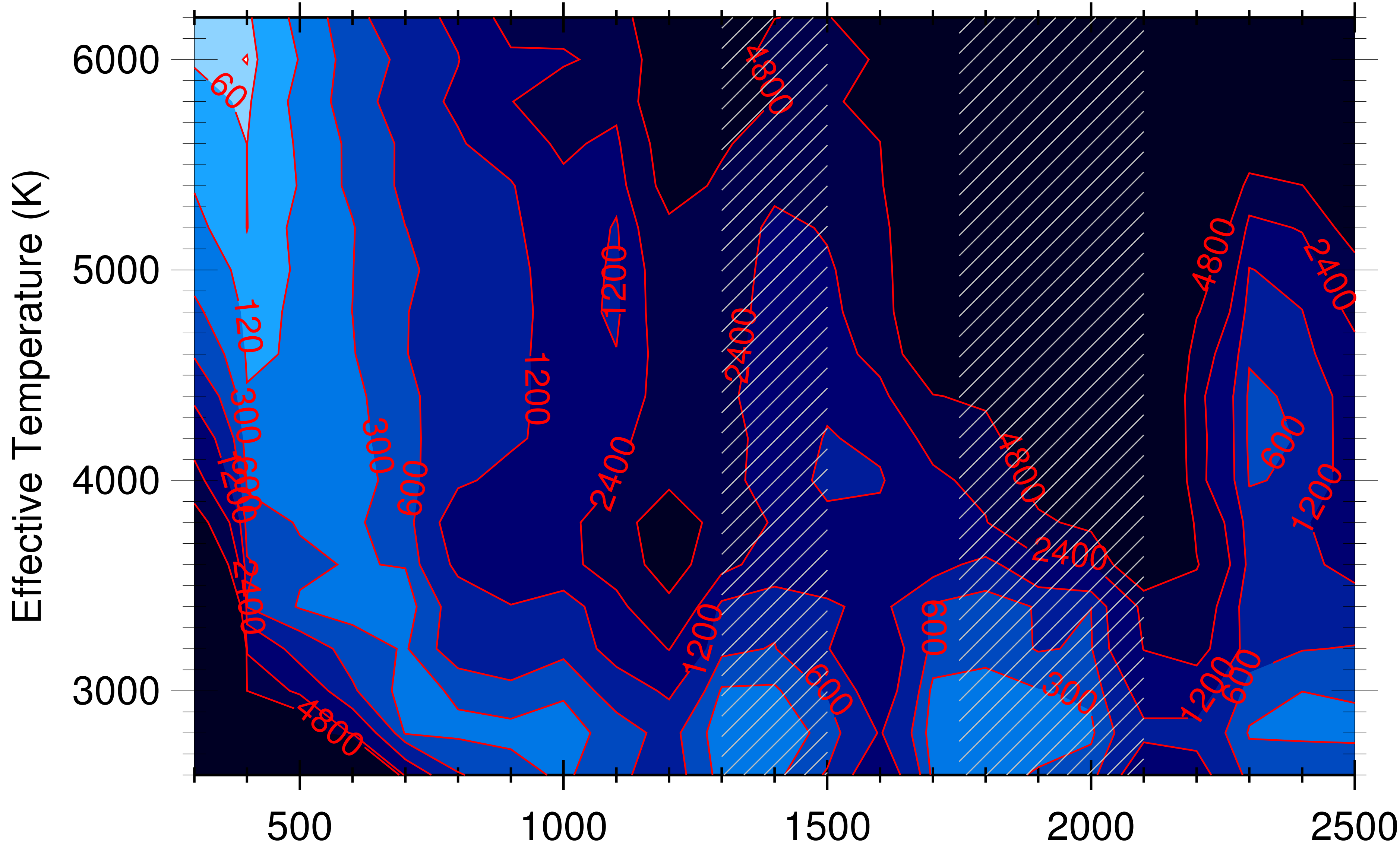


RV Precision
Resolution
Resolution, $\lambda/\Delta\lambda$
σ_v [m/s]
SNR
$\sigma_V \propto R^{-1.21}$
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}



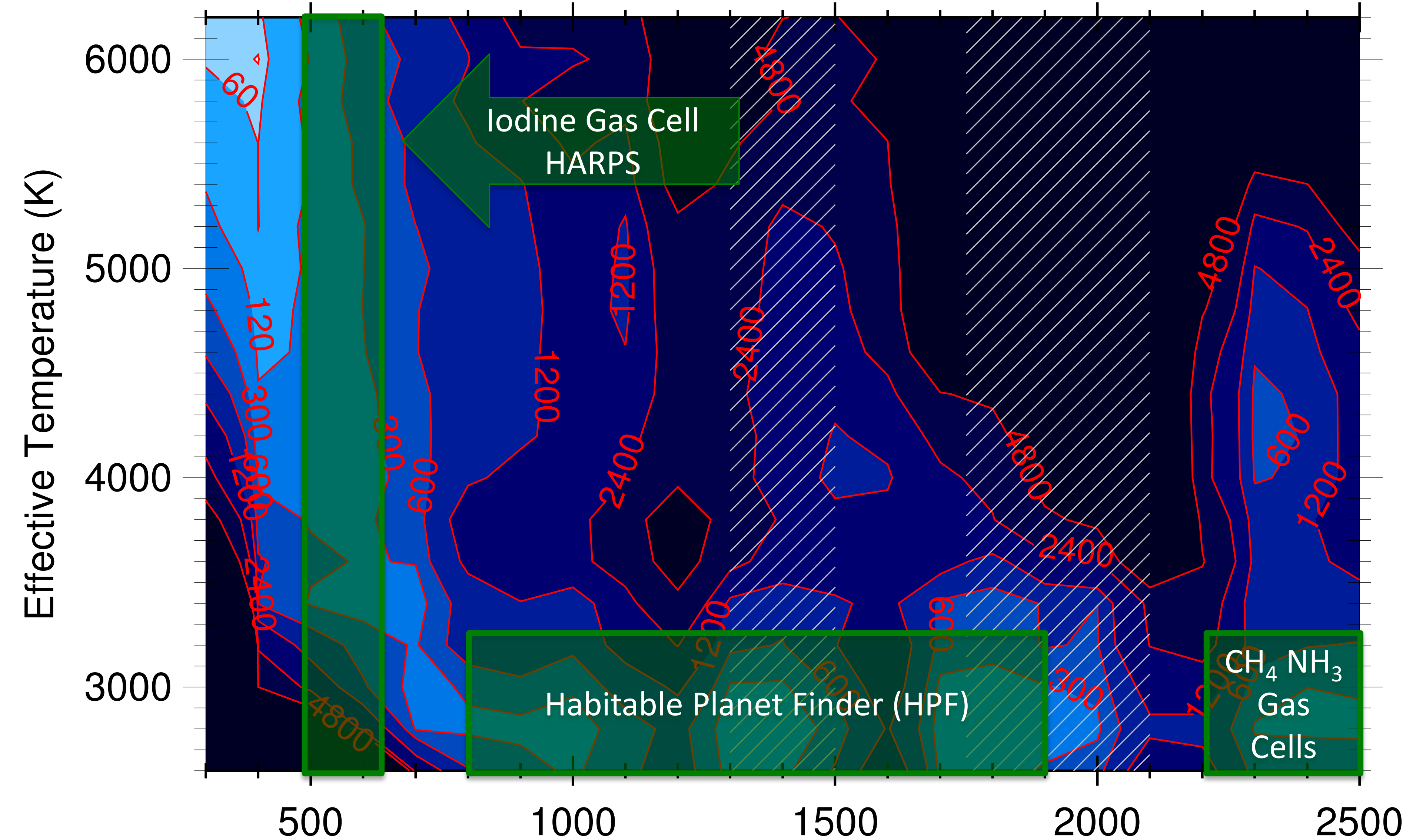
Bottom et al. *submitted*

Relative Doppler precision for fixed integration time, star at 10 pc



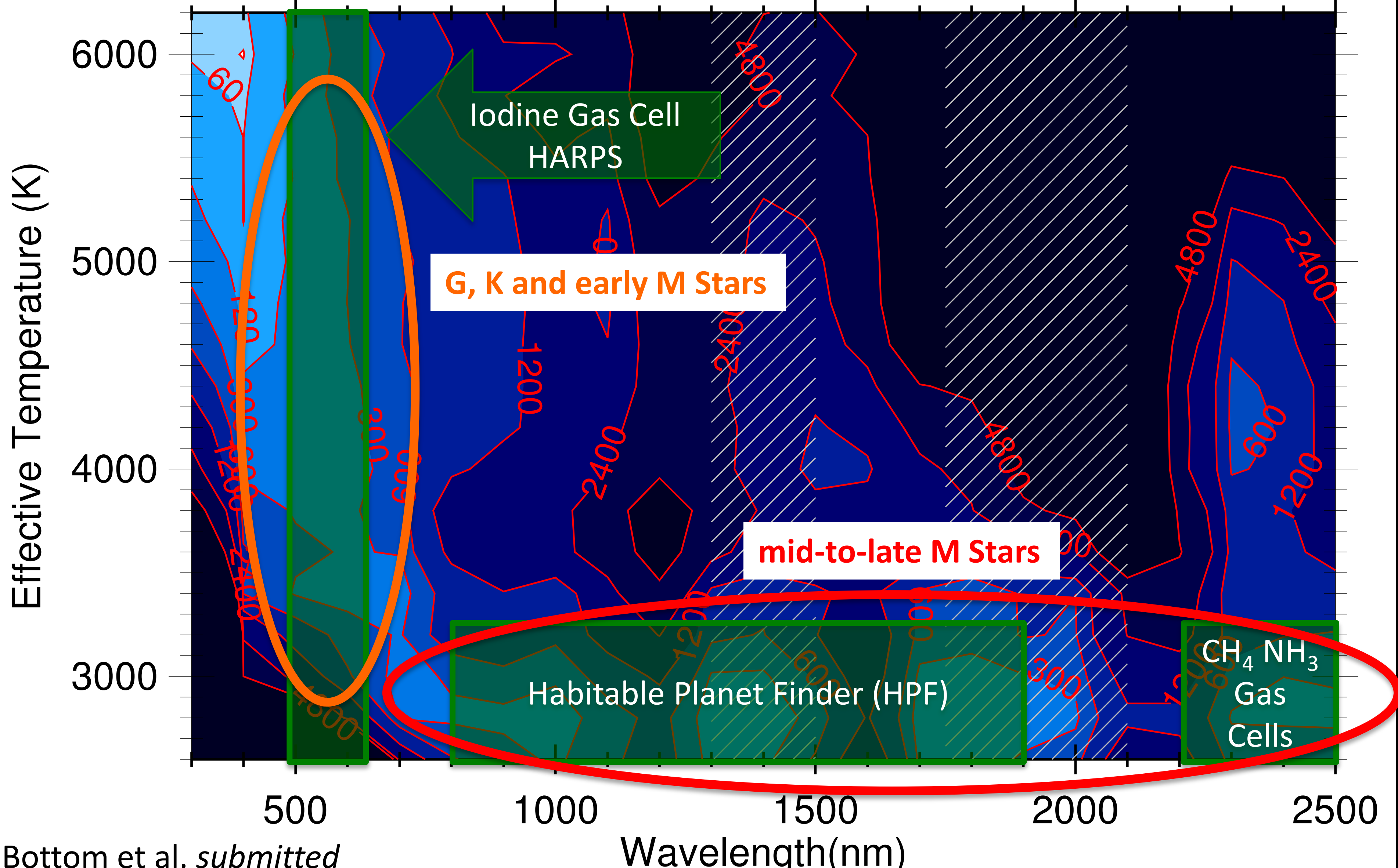
Bottom et al. *submitted*

Relative integration time to detect a planet in the HZ, star at 10 pc



Bottom et al. *submitted*

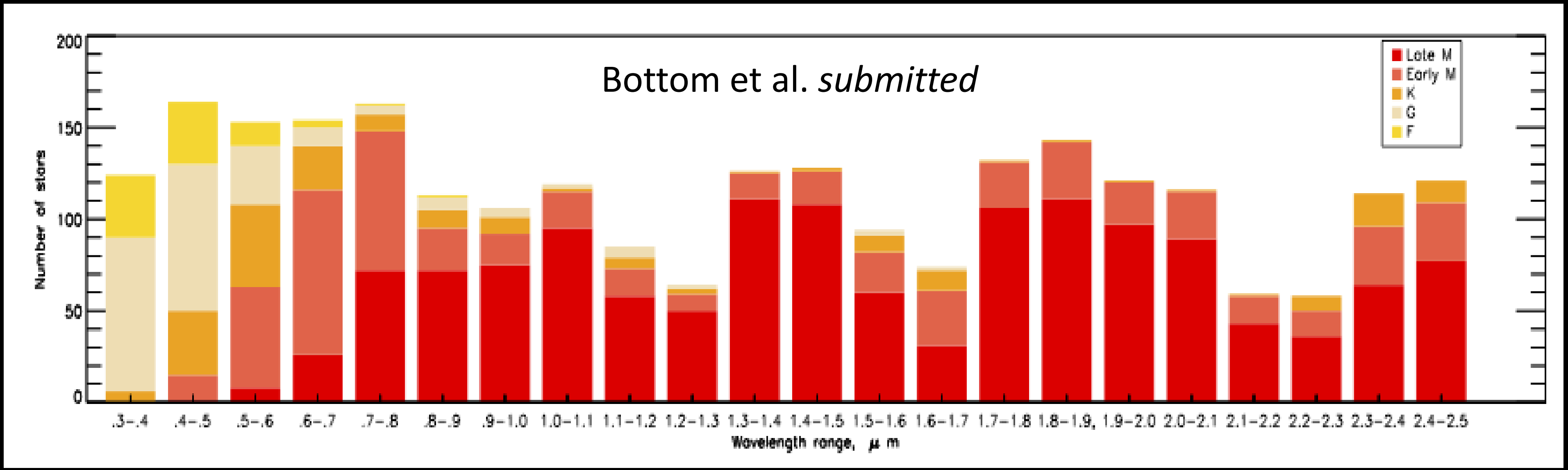
Relative integration time to detect a planet in the HZ, star at 10 pc



Bottom et al. *submitted*

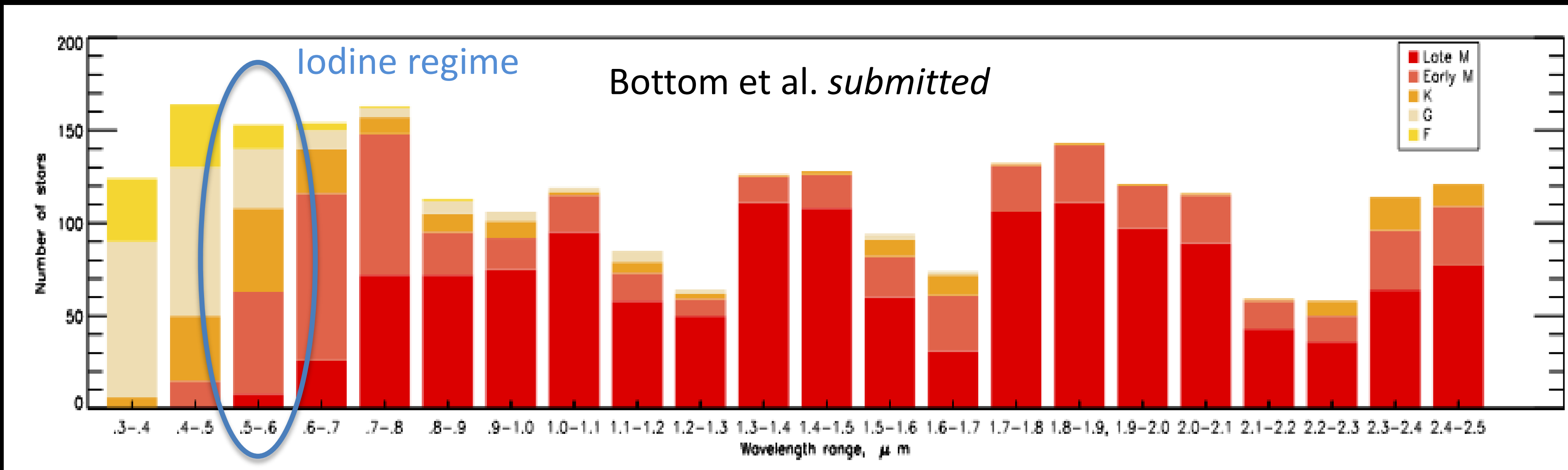
Relative integration time to detect a planet in the HZ, star at 10 pc

RECONS 7 pc Sample



- Mike calculated number of stars you can survey for 5 M_{Earth} planets in the HZ for fixed observing time and tele size

RECONS 7 pc Sample



- Mike calculated number of stars you can survey for 5 M_{Earth} planets in the HZ for fixed observing time and tele size

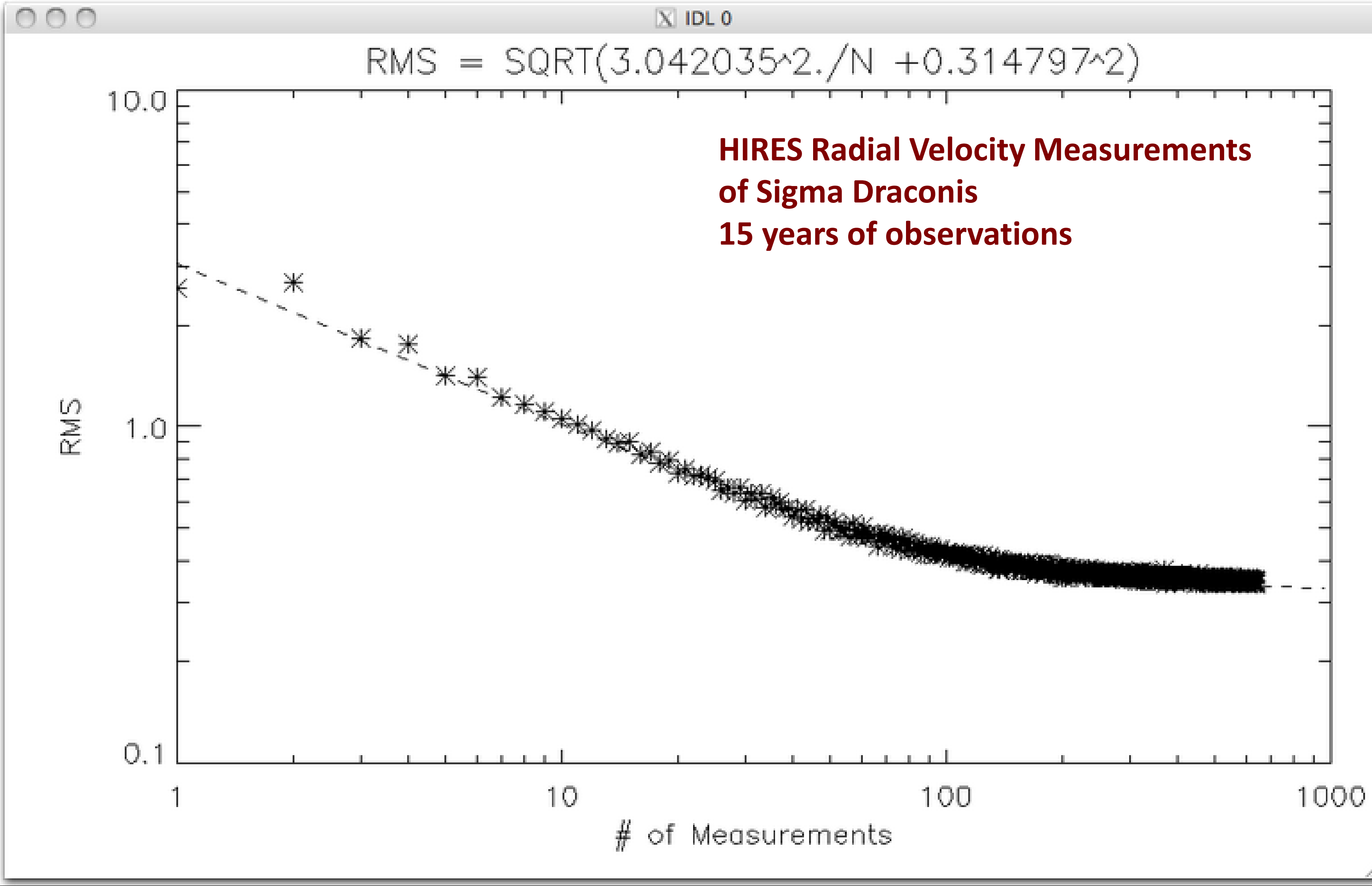
Iodine-Calibrated Regime

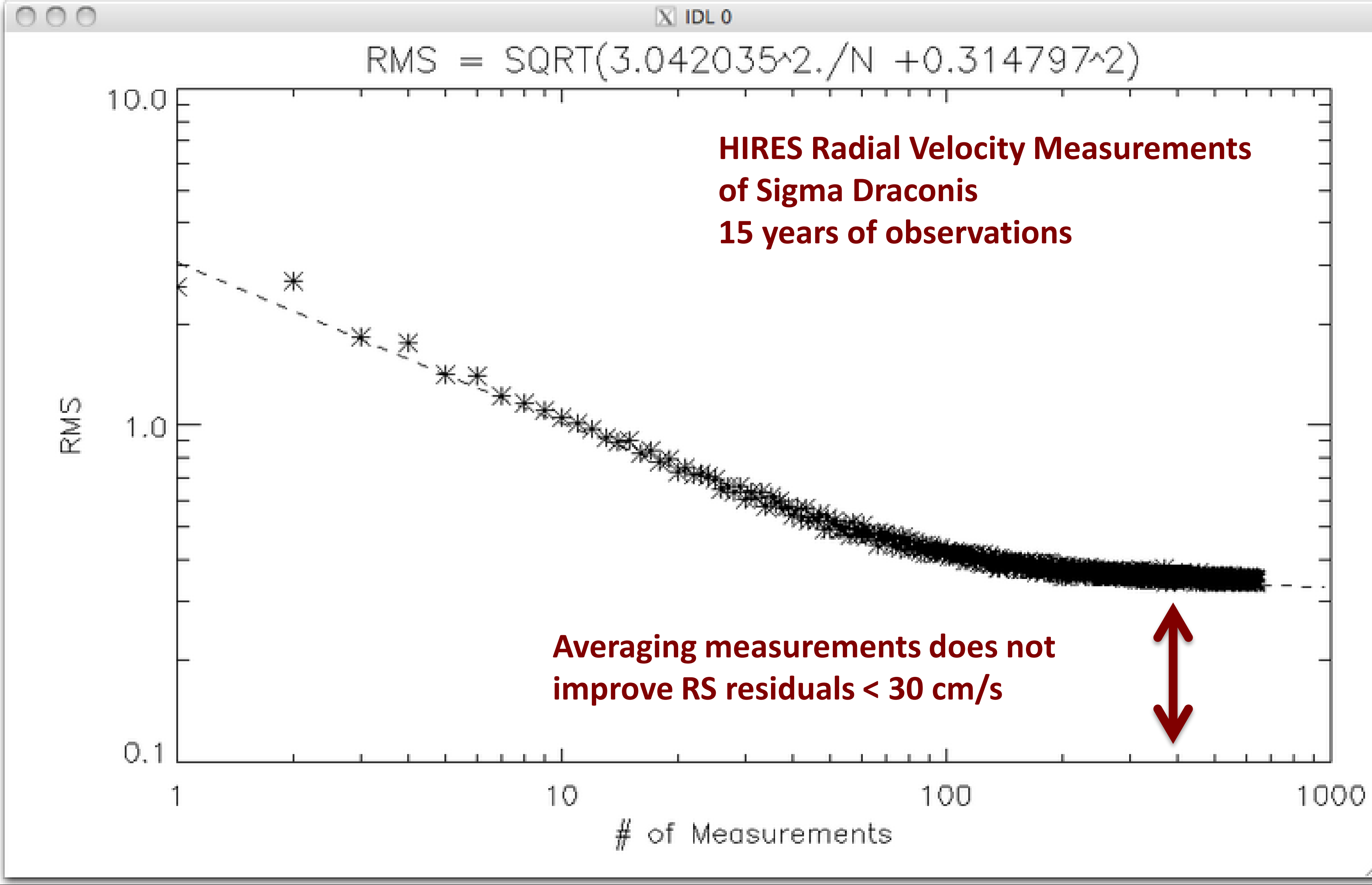
- 500 to 620 nm best place to search for habitable-zone planets around nearby G,K & early-M dwarfs via the Doppler method.

- But so far we have only considered *photon noise*

Systematic Noise

(defined as a noise source we cannot isolate)


IDL 0
RMS = SQRT(3.042035^2./N +0.314797^2)
HIRES Radial Velocity Measurements
of Sigma Draconis
15 years of observations
10.0
1.0
0.1
RMS
1
10
100
1000
# of Measurements



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RMS
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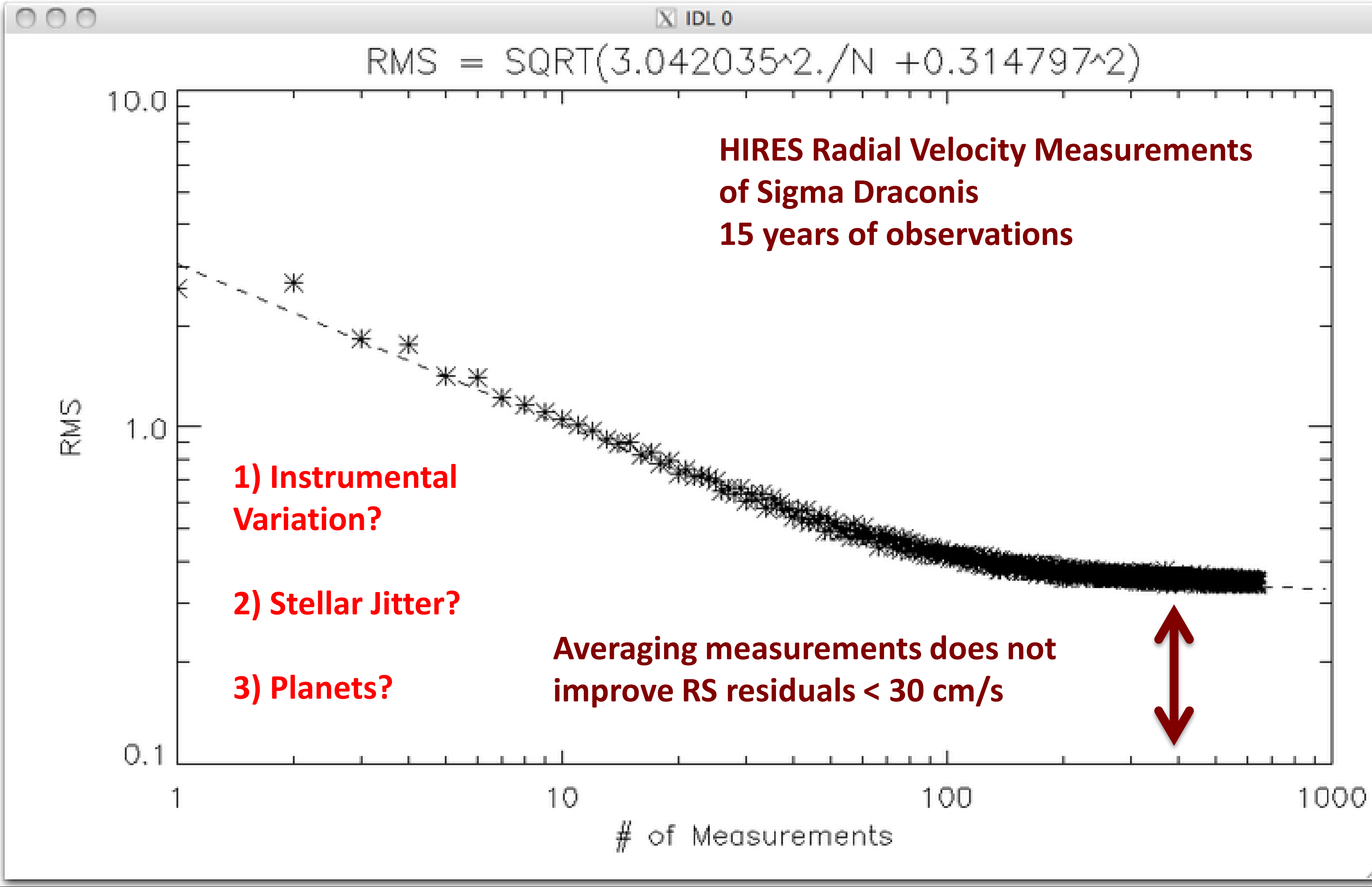
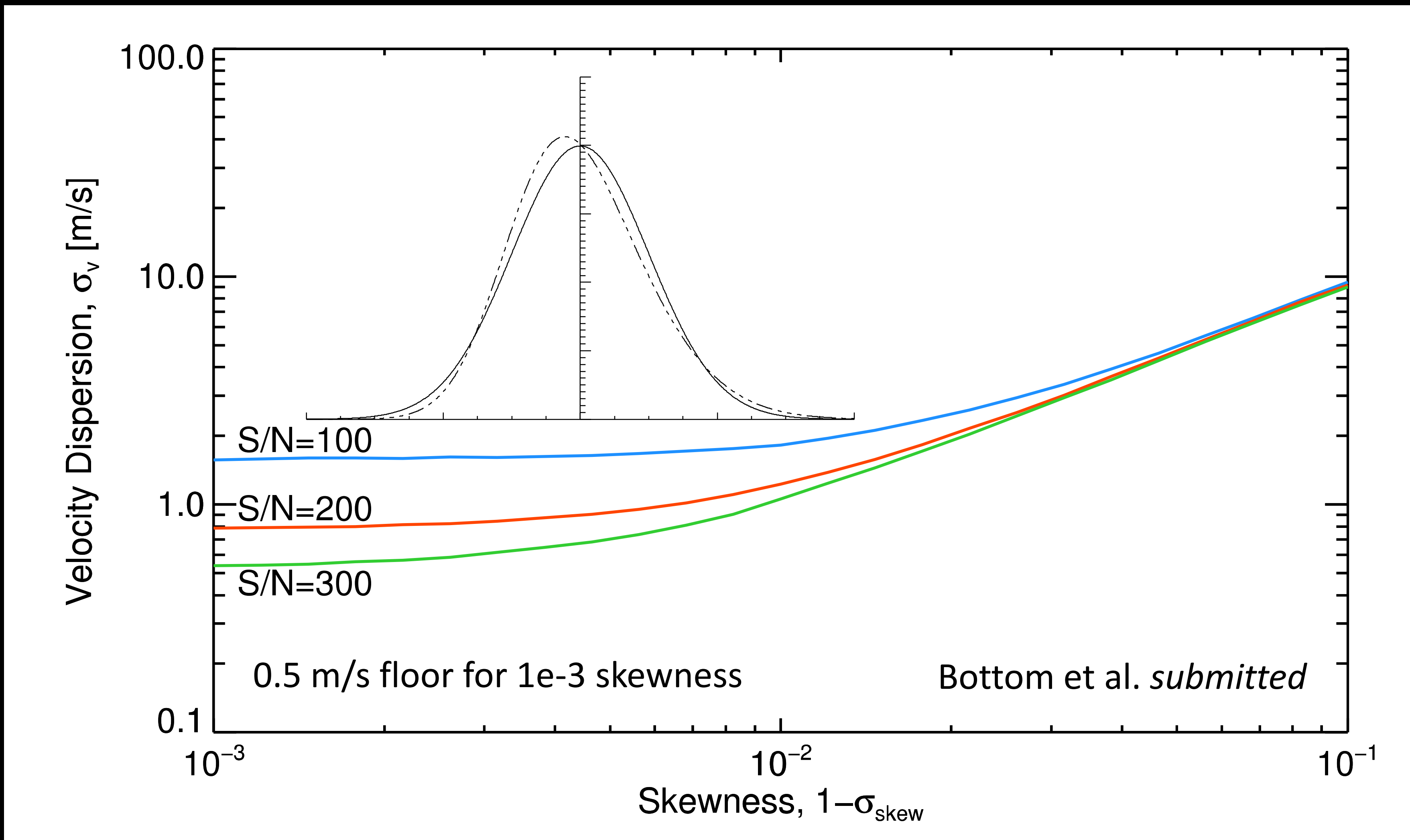
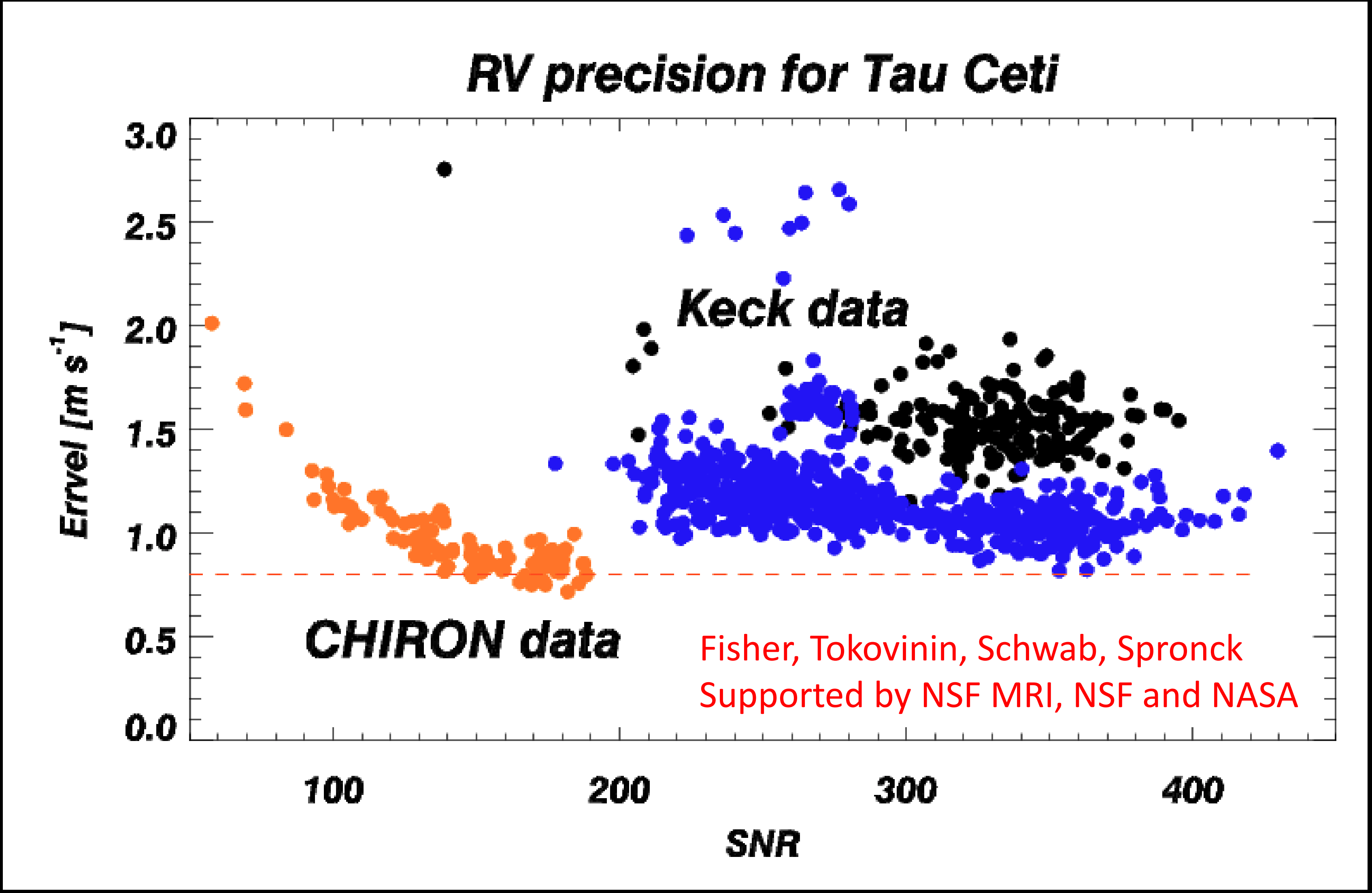

IDL 0
RMS = SQRT(3.042035^2./N +0.314797^2)
HIRES Radial Velocity Measurements
of Sigma Draconis
15 years of observations
1) Instrumental
Variation?
2) Stellar Jitter?
3) Planets?
Averaging measurements does not
improve RS residuals < 30 cm/s
RMS
10.0
1.0
0.1
1
10
100
1000
# of Measurements

Instrumental Profile Stability: Dominant Effect

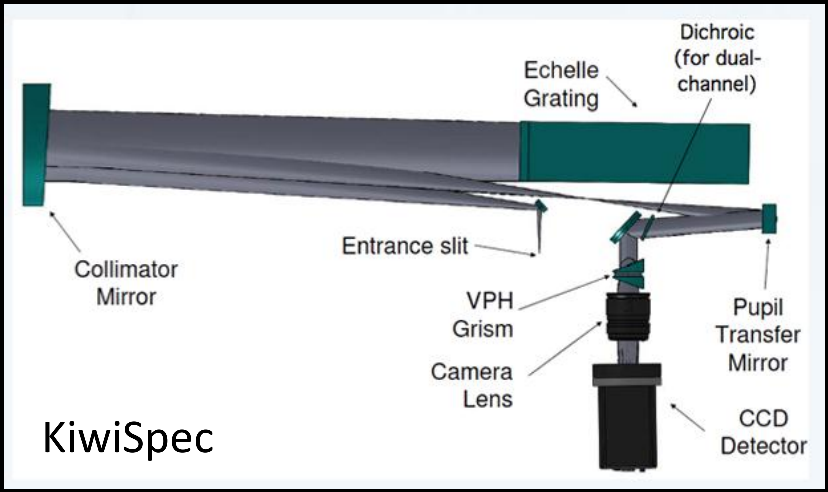


Instrumental Profile Stability: Stabilize with Fiber Scrambling



That Leaves Jitter and Short-period Planets

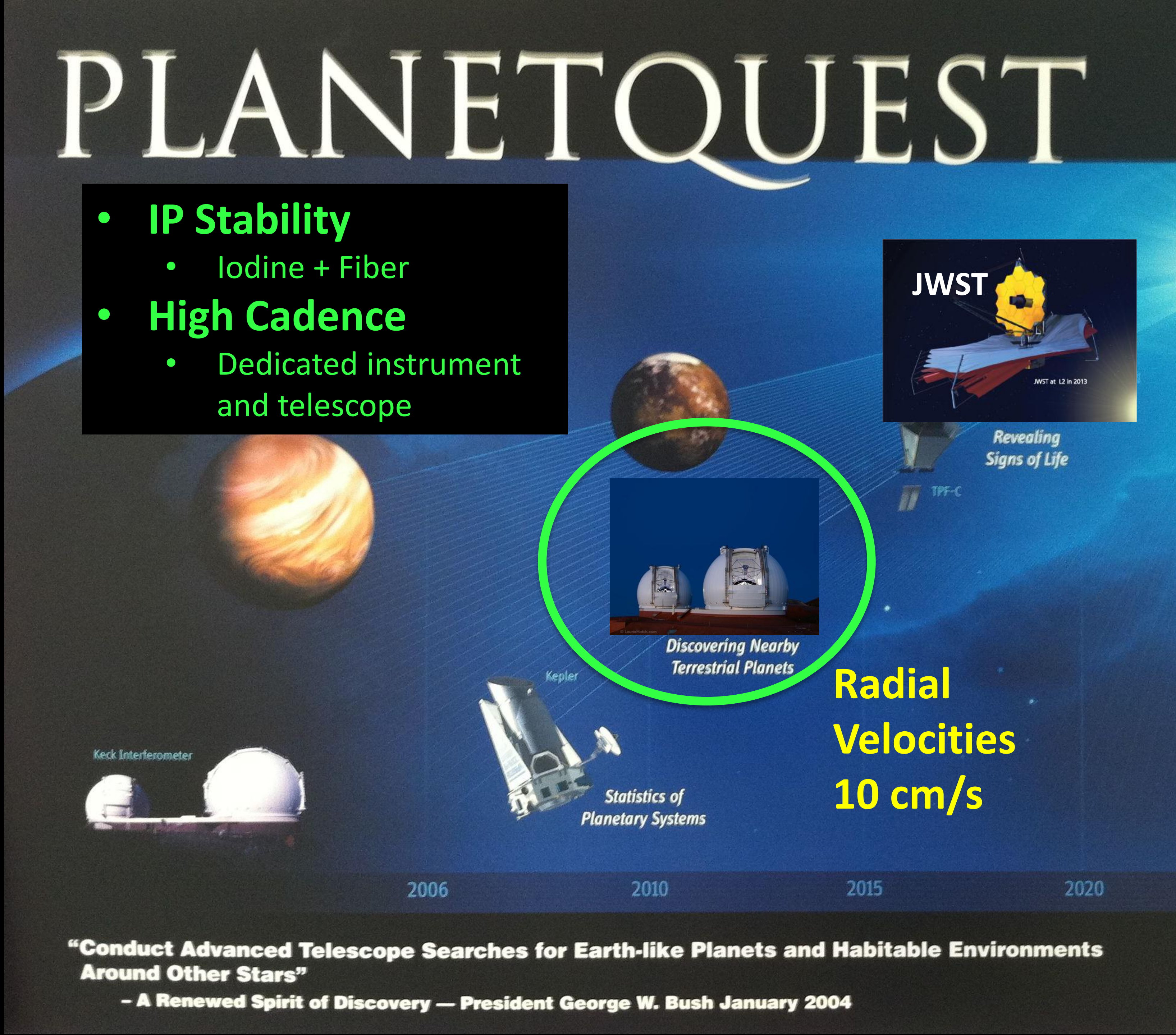
- Both can be overcome with *high-cadence* observations.
- An RV measurement *every night*.
- Project *Minerva*



Johnson, Wright, McCrady, Swift, Muirhead, Bottom, Hogstrom

- **IP Stability**
  - Iodine + Fiber
- **High Cadence**
  - Dedicated instrument and telescope

Radial Velocities 10 cm/s

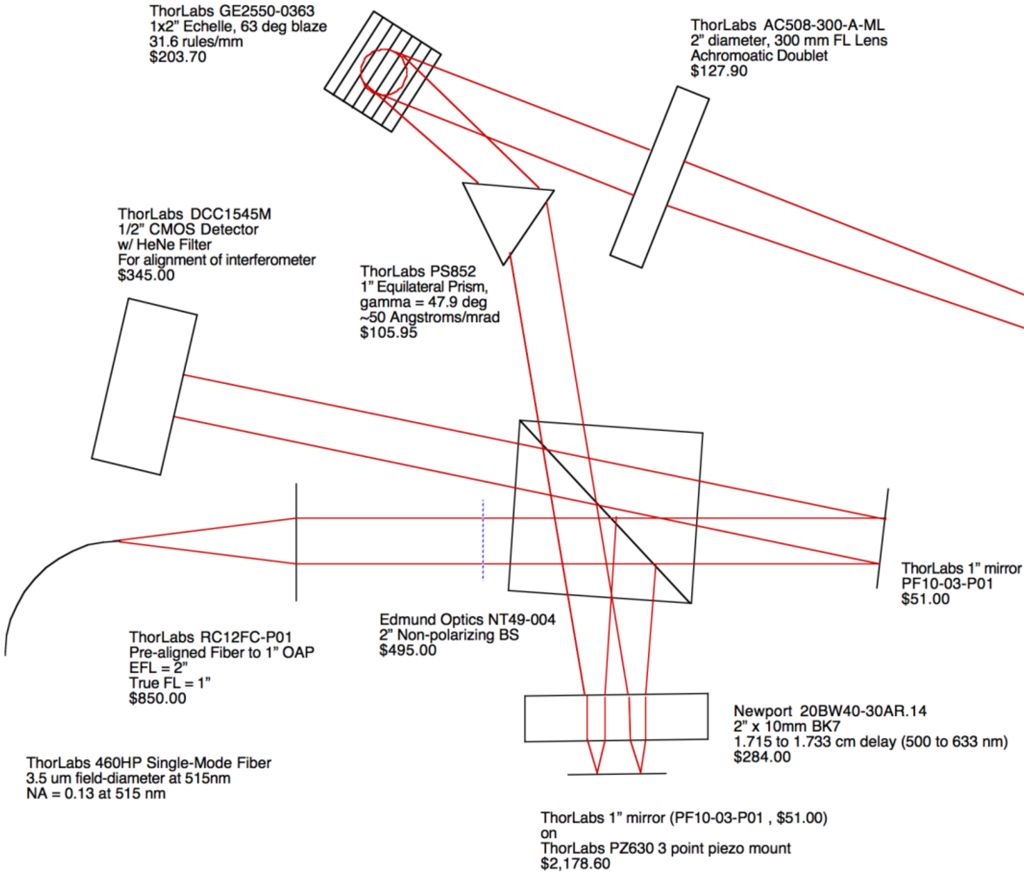


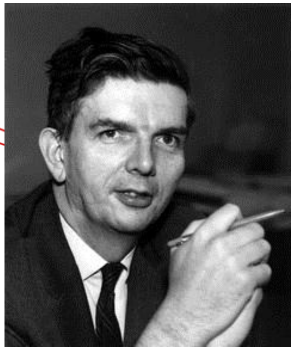
Future of Radial Velocities

- High TRL barge is headed towards big dedicated spectrographs, big telescopes, laser combs…

- …but low TRL speed boats are fun

New Low TRL Project: LAEDI





Robert H. Dicke

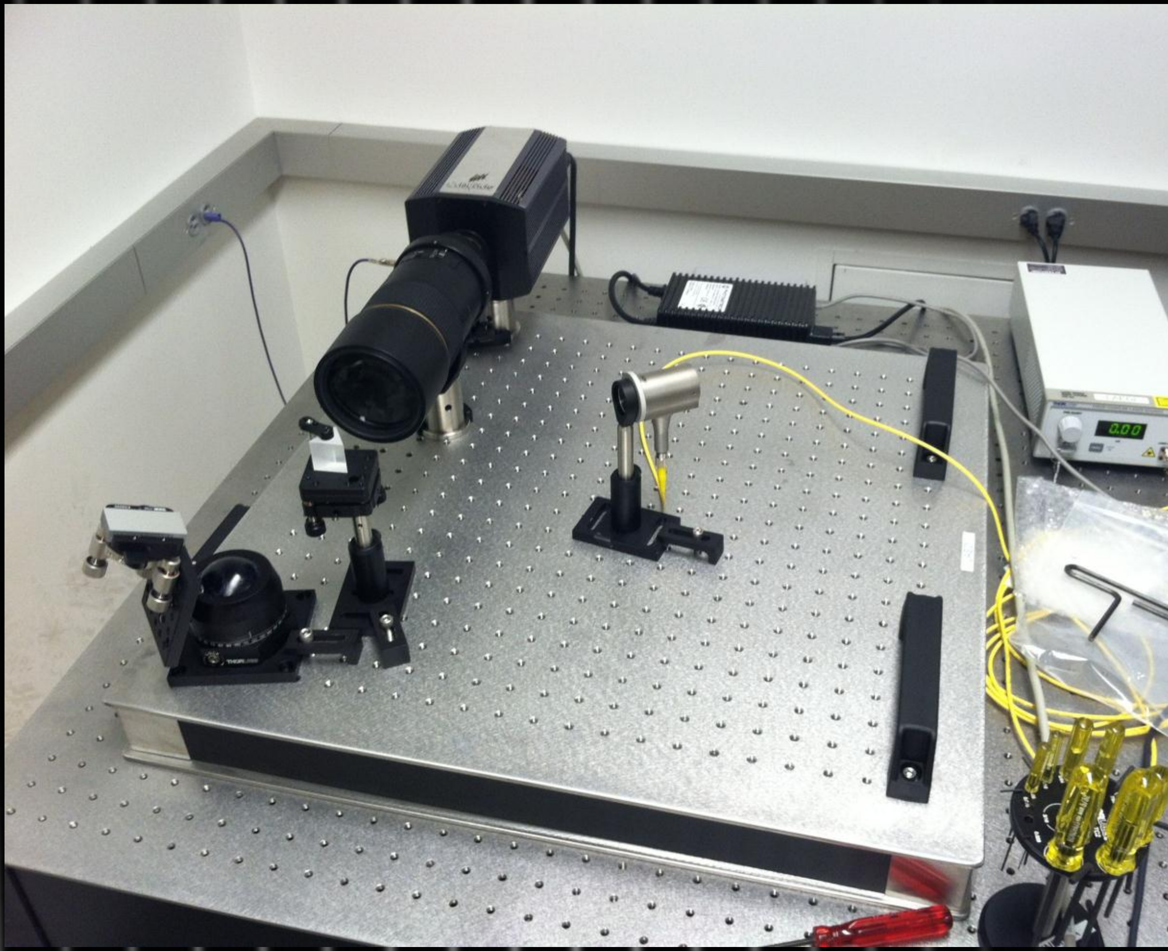
- **Lock-in Amplified Externally Dispersed Interferometer**
- **2012 JPL DRDF award winner!**
- **P. Muirhead, G. Vasisht (Co-Pis), K. Wallace, R. Jensen-Clem, M. Bottom, J. Johnson**

New Project: LAEDI

Uses a zero-readnoise detector

Single-mode fiber feed for high coherence

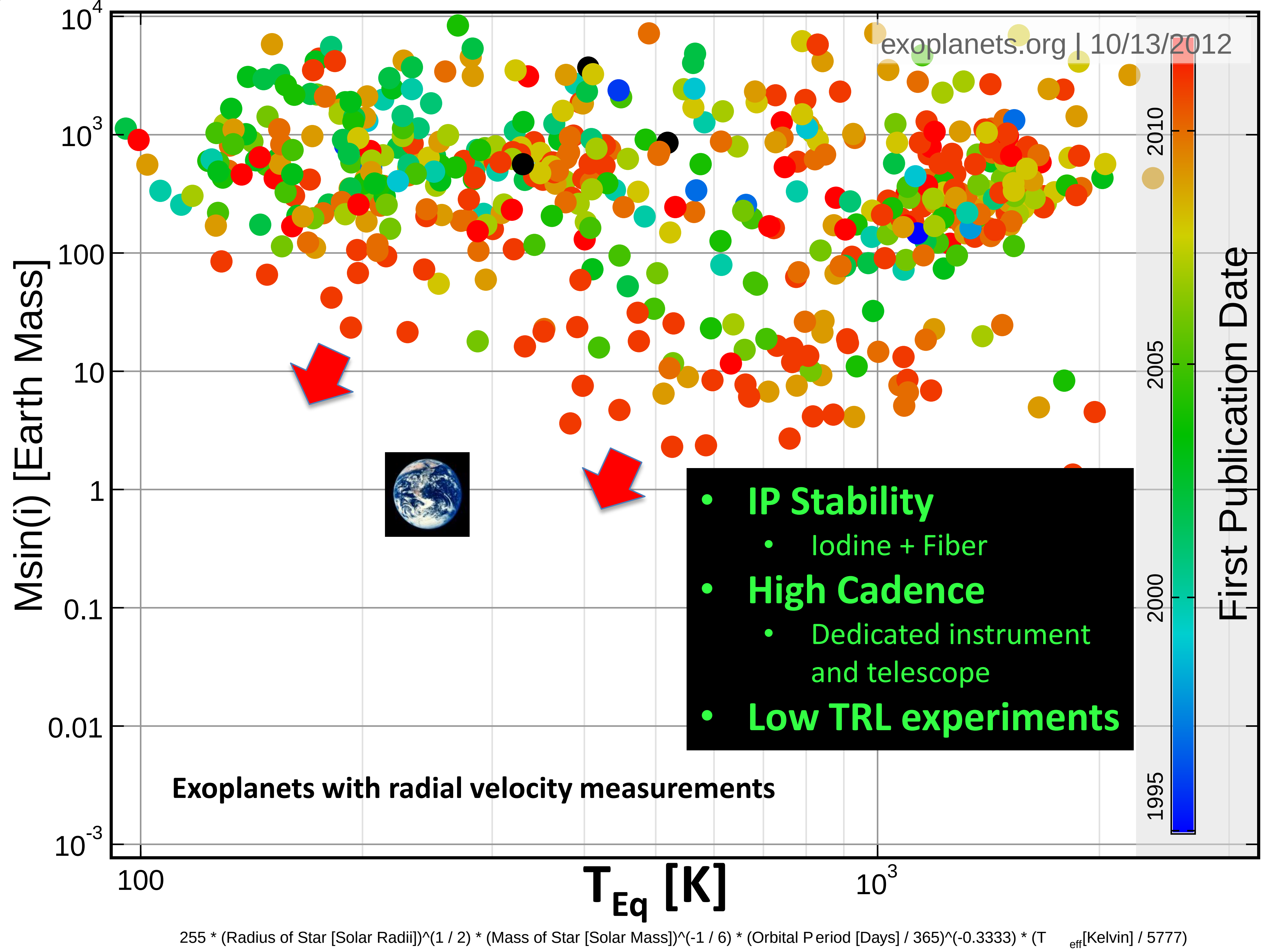
Frequency locked-laser for mm/s OPD calibration.



New Project: LAEDI

Spectrograph first light on FRIDAY!

Thanks to students Rebecca Jensen-Clem and Michael Botto



exoplanets.org | 10/13/2012
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