# Study Analysis Group 8: Requirements & Limits of Future Precise Radial Velocity Measurements

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# RV SAG 8 Goals

This group will evaluate the future role of RV measurements in the exoplanet field, both scientific and programmatic, and will attempt to assess the resources required fulfill this goal.

"… to search for planetary bodies and Earth-like planets in orbit around other stars." (U.S. National Space Policy, June 28, 2010)

→ See ExoPAG 6 talk for full charter



Peter Plavchan, Dave Latham

# SAG 8 current status

- Received written contributions from a broad swath of the PRV community
- This talk is the beginning of the final process for contributions from the community:
  - A complete report circulated amongst co-authors, with comments due Jan 21
  - Draft report available at:
    - http://www.plavchan.com/pubs/PlavchanLathamRVSAGwhitepaper20150101.pdf
  - Report will be circulated to exopag-announce with comments due Feb 20
  - Report will be submitted to APS for approval March 2nd, and then posted to arXiv
    - Subsets of analysis may be submitted for peer-reviewed publication

# SAG 8 report co-authors

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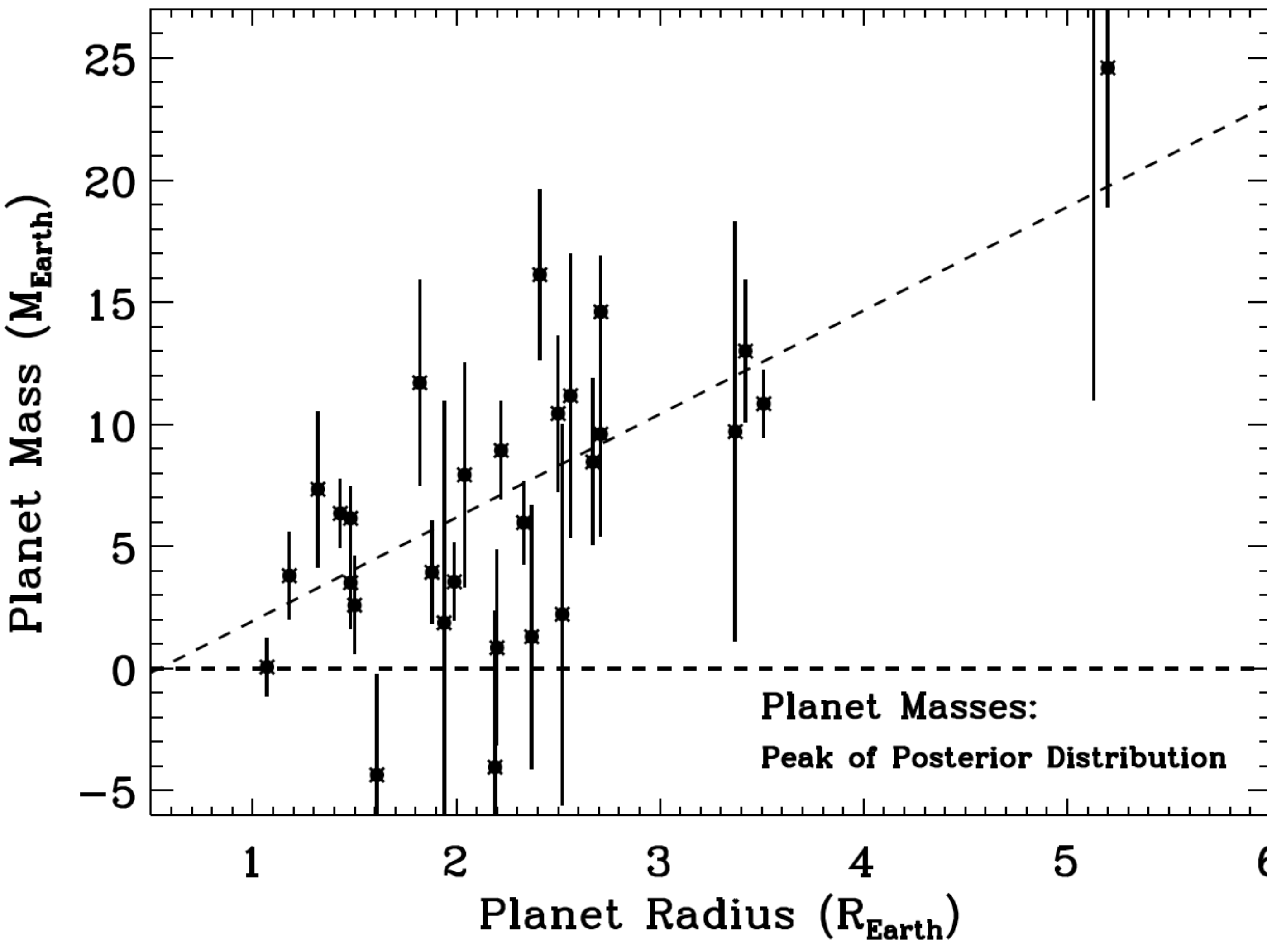
# Summary of PRV support for NASA mission science objectives

| Mission | Target identification for mission science yield optimization | Follow-up validation & characterization of low mass transiting exoplanets | Exoplanet mass & orbit determination |
|---|---|---|---|
| Kepler | | ✓ | ✓ |
| TESS | ✓ | ✓ | ✓ |
| JWST | ✓ | ✓ | ✓ |
| AFTA/Coronagraph/ probe direct imaging | ✓ | | ✓ |
| Future Flagship direct imaging | ✓ | | ✓ |

# Kepler Experience with HIRES (2-3 m/s)

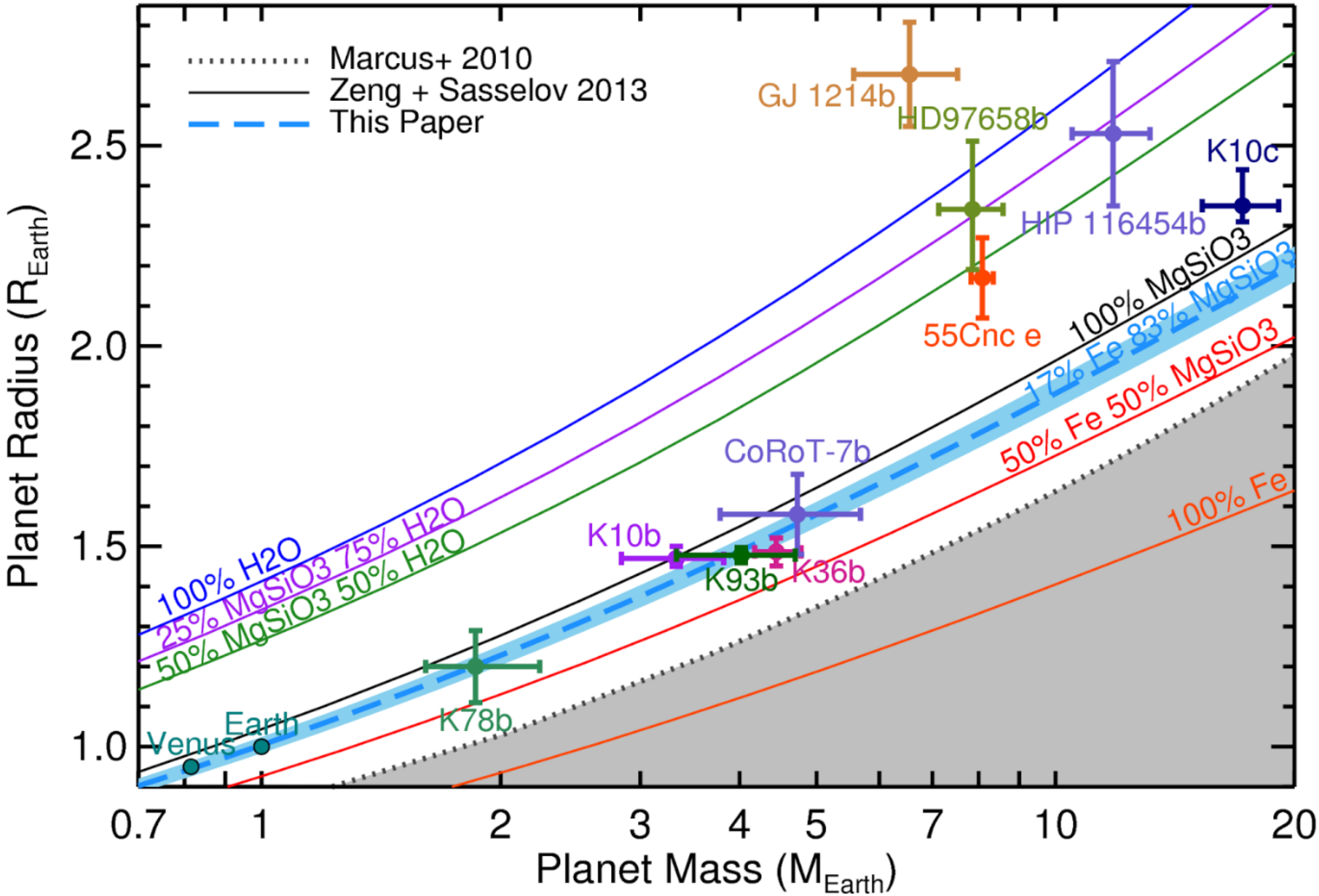
- Four seasons of HIRES following up small planets
  - Three- or four-sigma masses for Kepler 10b and 78b
    - Kepler 10b: V = 11, $P$ = 0.84 d, $M = 4.6 \pm 1.2\ M_{Earth}$, $K$ = 3.3 m/s, $N_{obs}$ = 42
    - Kepler 78b: V = 12, $P$ = 0.36 d, $M = 1.69 \pm 0.41\ M_{Earth}$, $K$ = 1.66 m/s, $N_{obs}$ = 84
  - 49 candidates around 22 stars, detectable if rocky
      - Roughly 100 nights NASA plus California time
  - Better than two-sigma masses for 16, one-sigma for 14

Mass vs. Radius for 30 planets followed up with HIRES on Keck1 over four seasons
16 have masses better than 2 sigma, 14 better than 1 sigma
Role of the transit ephemeris is critical



# Kepler Experience with HARPS-N (70 cm/s)

- 2.5 seasons of HARPS-N following a dozen small planets
  - Six-sigma masses for Kepler 10b and 78b
    - Kepler 10b: $M = 3.31 \pm 0.49$ $M_{Earth}$, $N_{obs} = 137$, $K = 2.47$ m/s
    - Kepler 78b: $M = 1.86 \pm 0.32$ $M_{earth}$, $N_{obs} = 137$, $K = 1.96$ m/s
    - Kepler 93b
    - Kepler 36b




Dressing et al. 2015

# White Paper "Thesis"

The demands on telescope time for NASA mission support, especially for systems of small planets, will exceed the number of nights available using instruments now in operation by a factor of at least several for TESS alone.

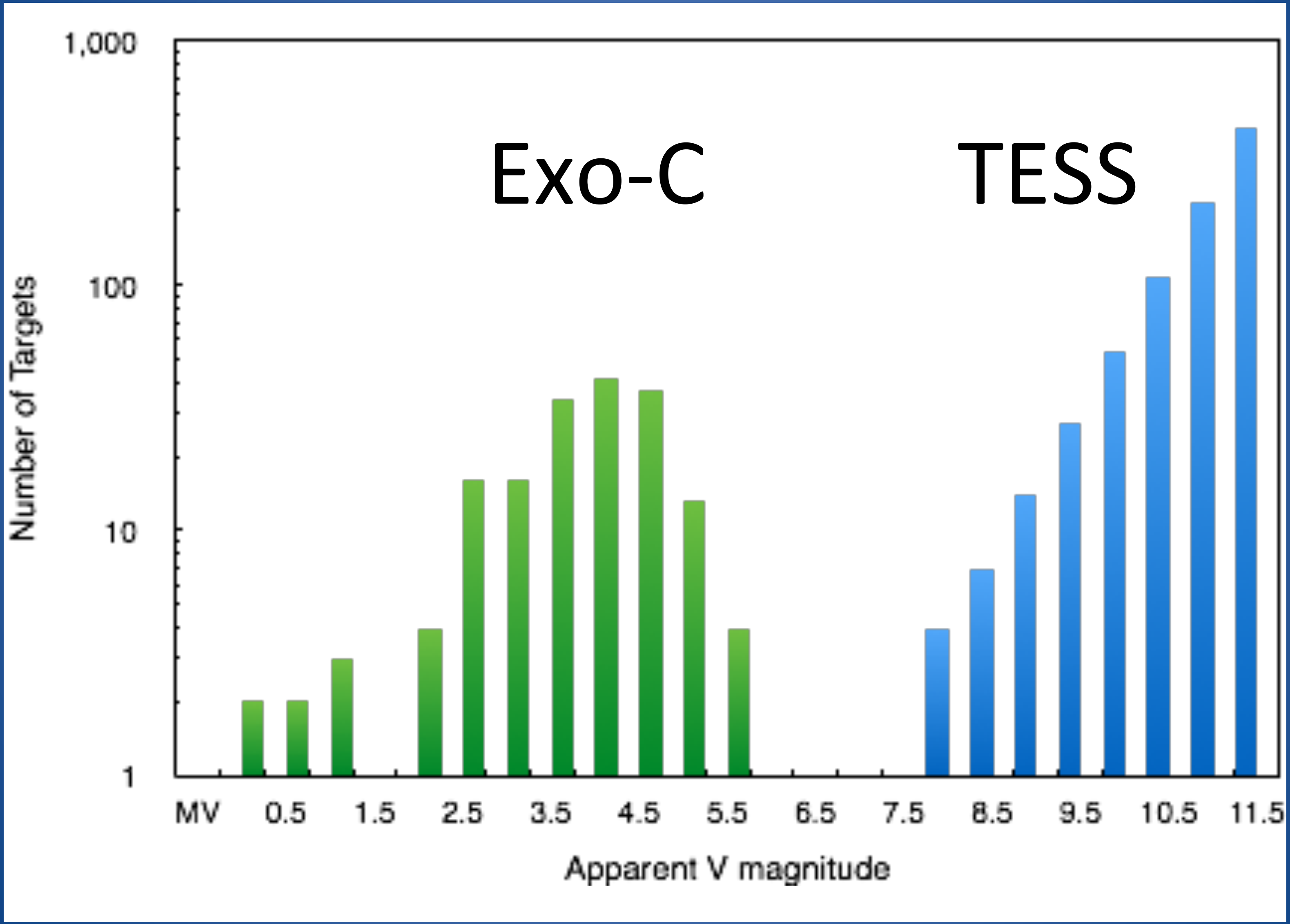
Pushing down towards true Earth twins will require more photons (i.e. larger telescopes), more stable spectrographs than are currently available, better calibration, and better correction for stellar jitter.

# Four Hypothetical Scenarios to support NASA missions with PRVs

- Dedicated 4-m with optical HARPS-like 50 cm/s
  - Masses and densities for TESS transiting planets
  - PRV survey of candidates for AFTA-type mission
- Access to 10-m with 5 cm/s performance
  - Push towards orbits for true Earth twins
  - Requires much better correction of stellar jitter
- Access to 4-m with infrared 50 cm/s
  - Masses for habitable planets around M dwarfs
  - A path forward for stellar jitter?
- Diffraction-limited access with 5 cm/s performance

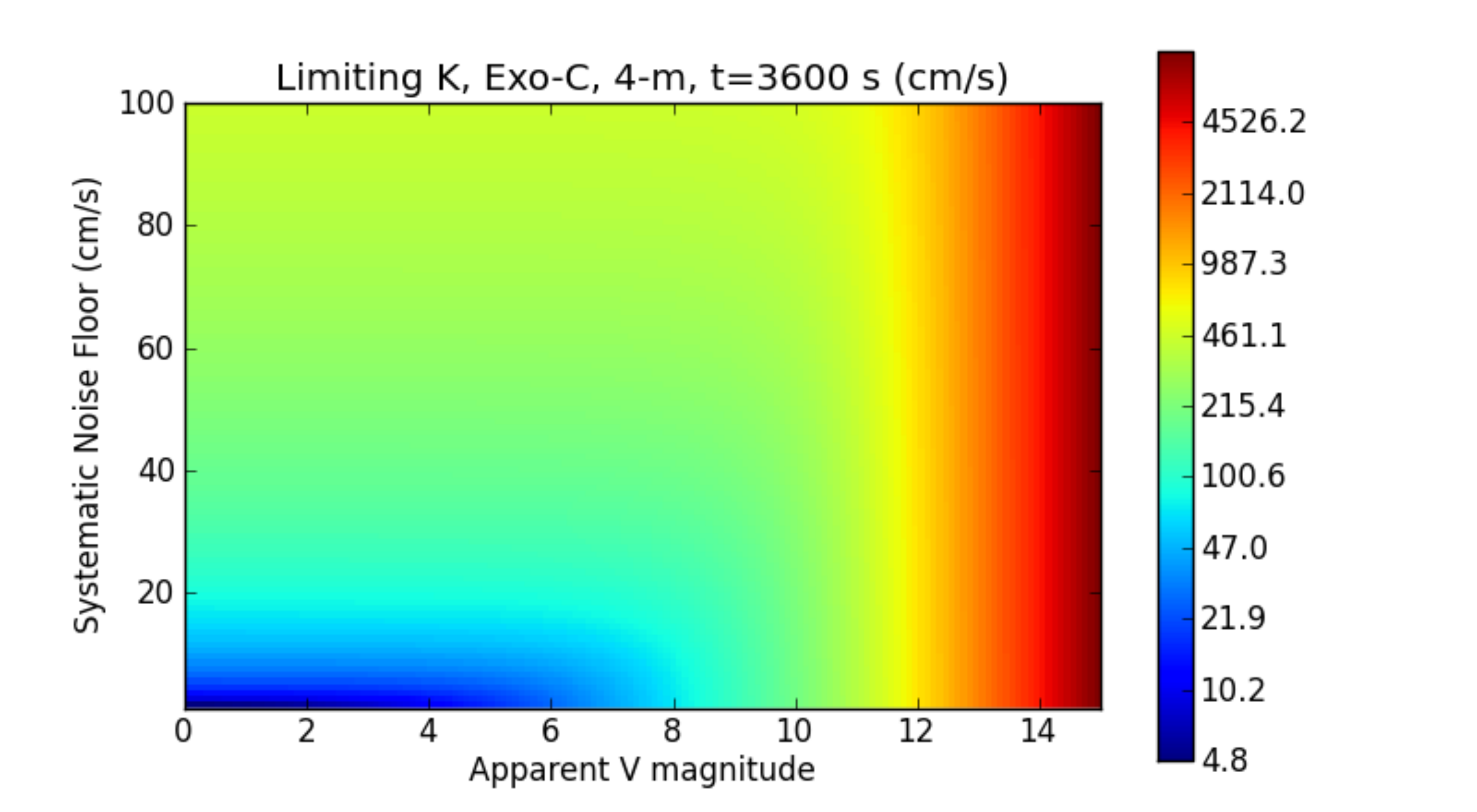
# Howard & Fulton (2014)

- 76 targets (~25%) overlap between Lick/Keck PRV samples and AFTA-type direct imaging target lists
- The median PRV completeness limit:
  - ~$M_{Saturn}$ at ~1 AU
  - ~3 $M_{Jupiter}$ at ~8 AU
  - Scatter ~10x in mass
- Compare that to Exo-C expected sensitivity:
  - 2 $R_{Earth}$ objects out to 1.5 AU
  - Saturn-sized objects to 7 AU
- Long-term need to extend out to wider orbits
  - Volunteers from the community unlikely
- Need better instrumentation stability to take advantage of expected Exo-C direct imaging sensitivity

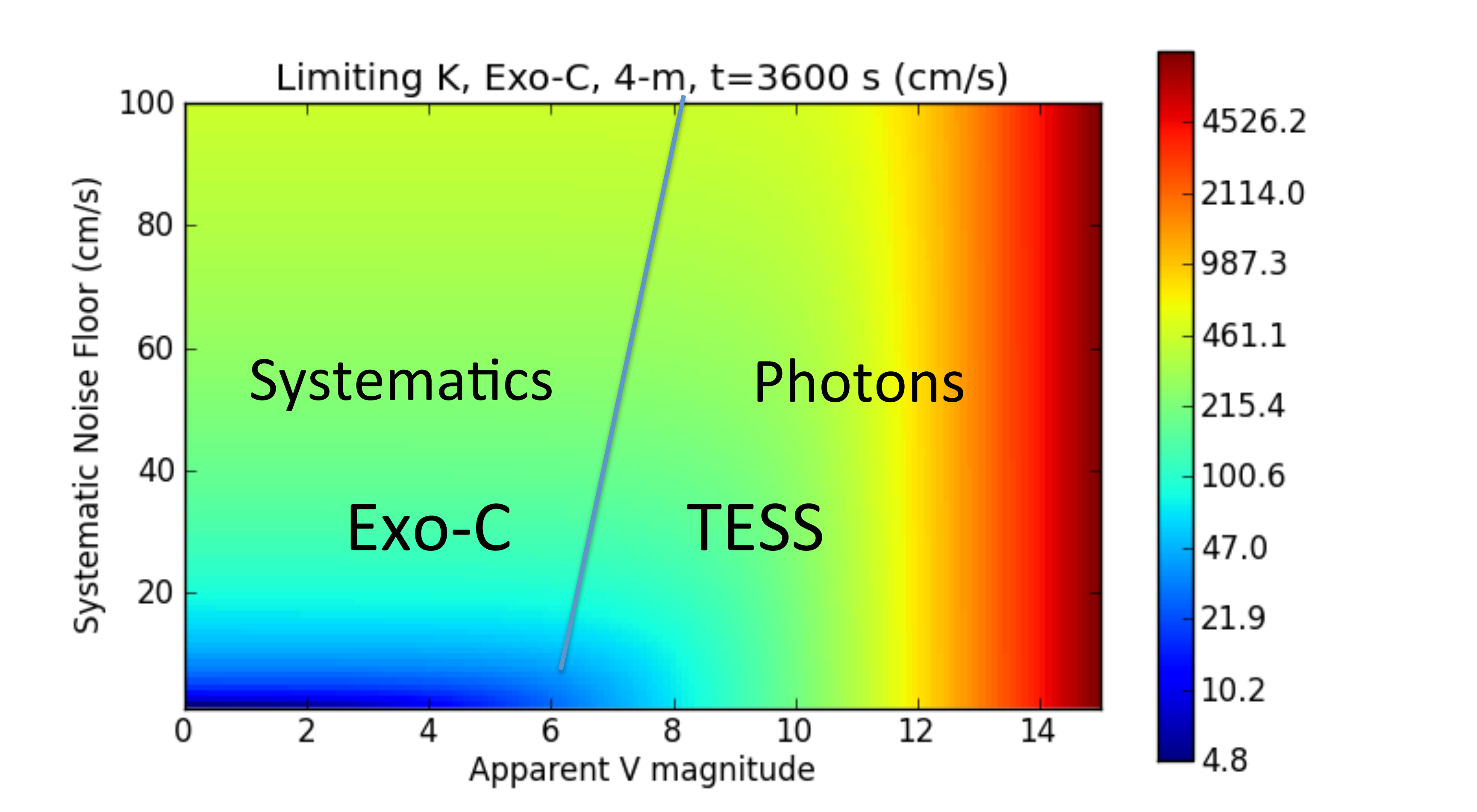


Exo-C
TESS
1,000
100
10
1
Number of Targets
MV
0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
Apparent V magnitude

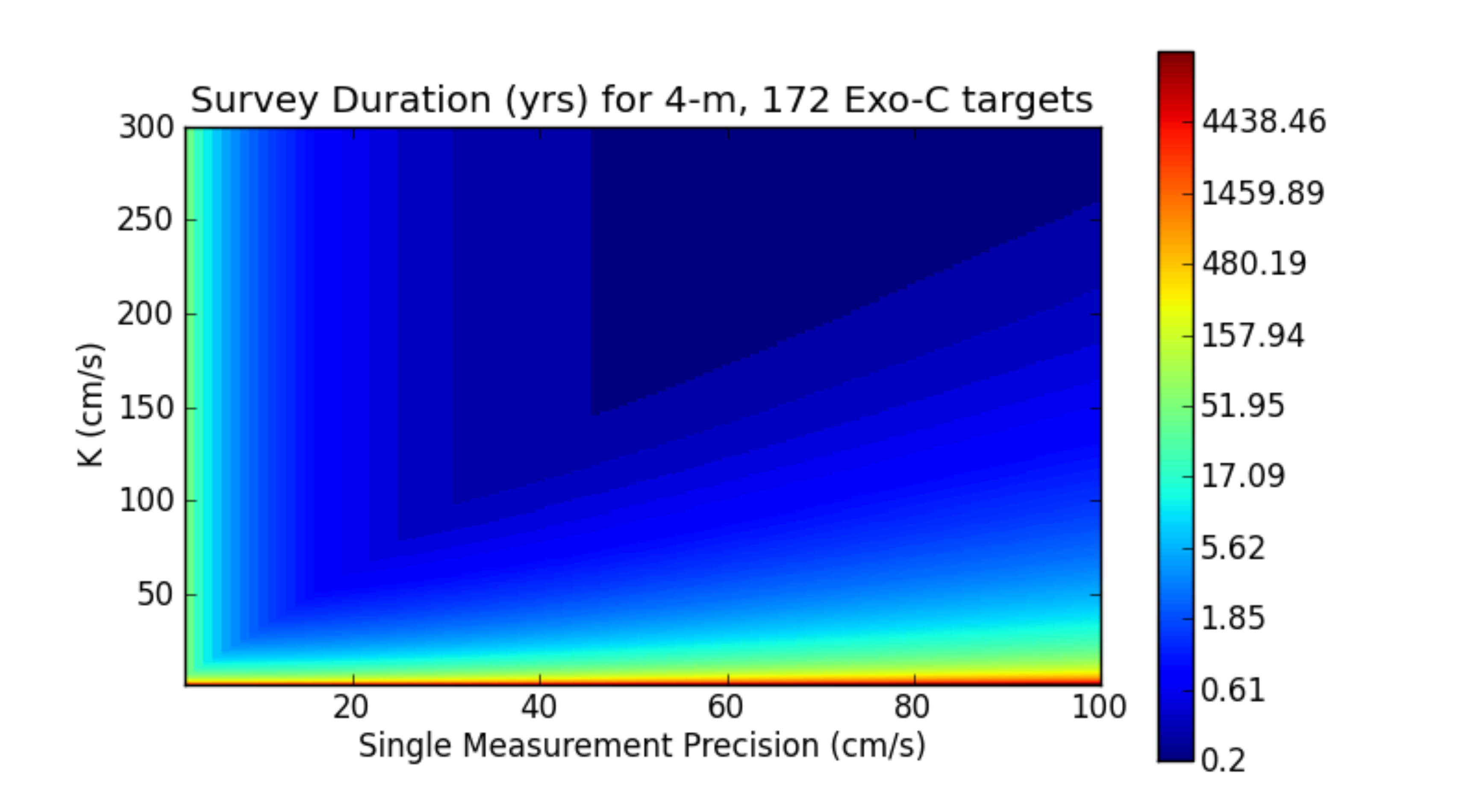
# Fixed Integration Time Survey (0.46yr TESS, 1.28yr Exo-C)



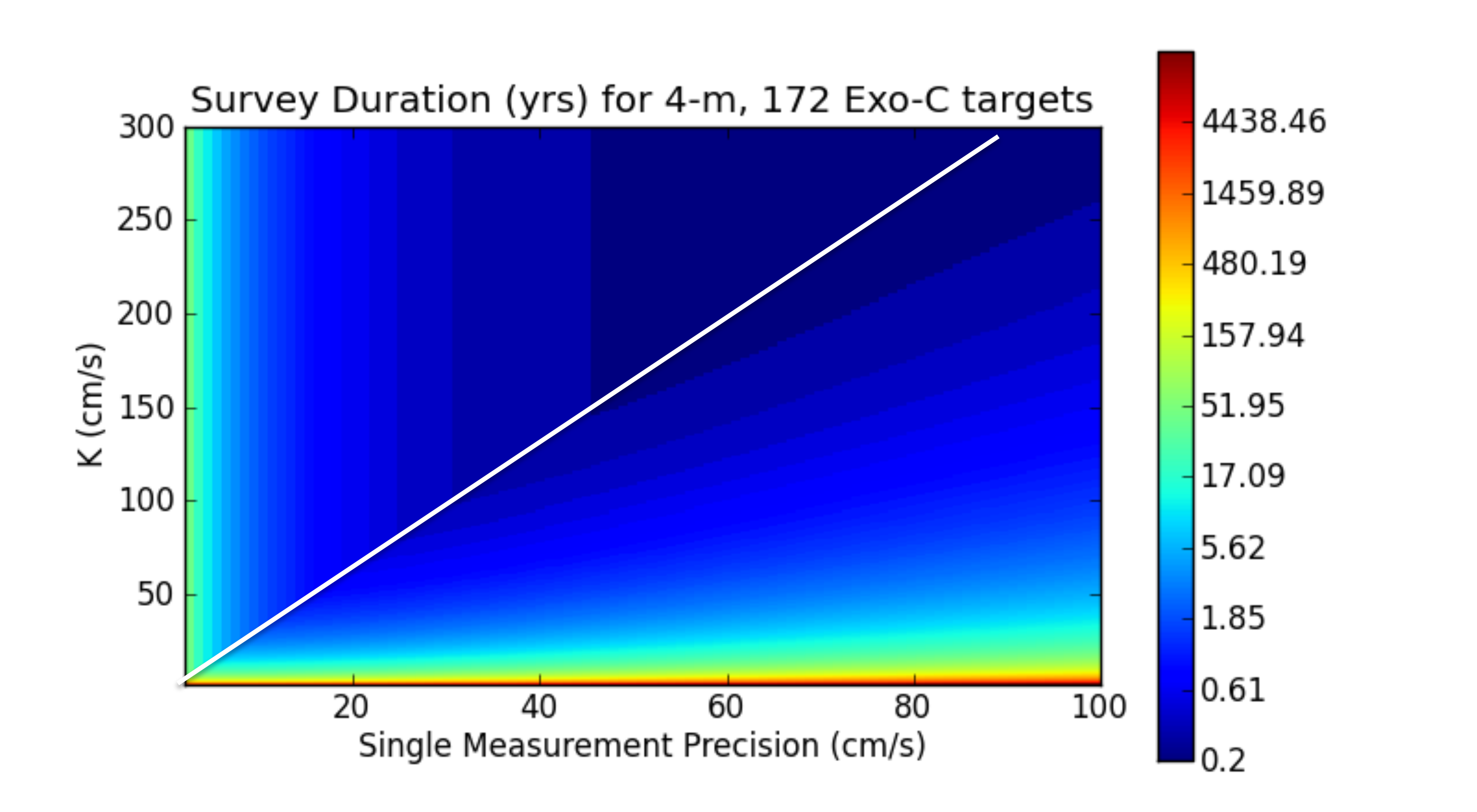
# Fixed Integration Time Survey (0.46yr TESS, 1.28yr Exo-C, $N_{obs}$=10)



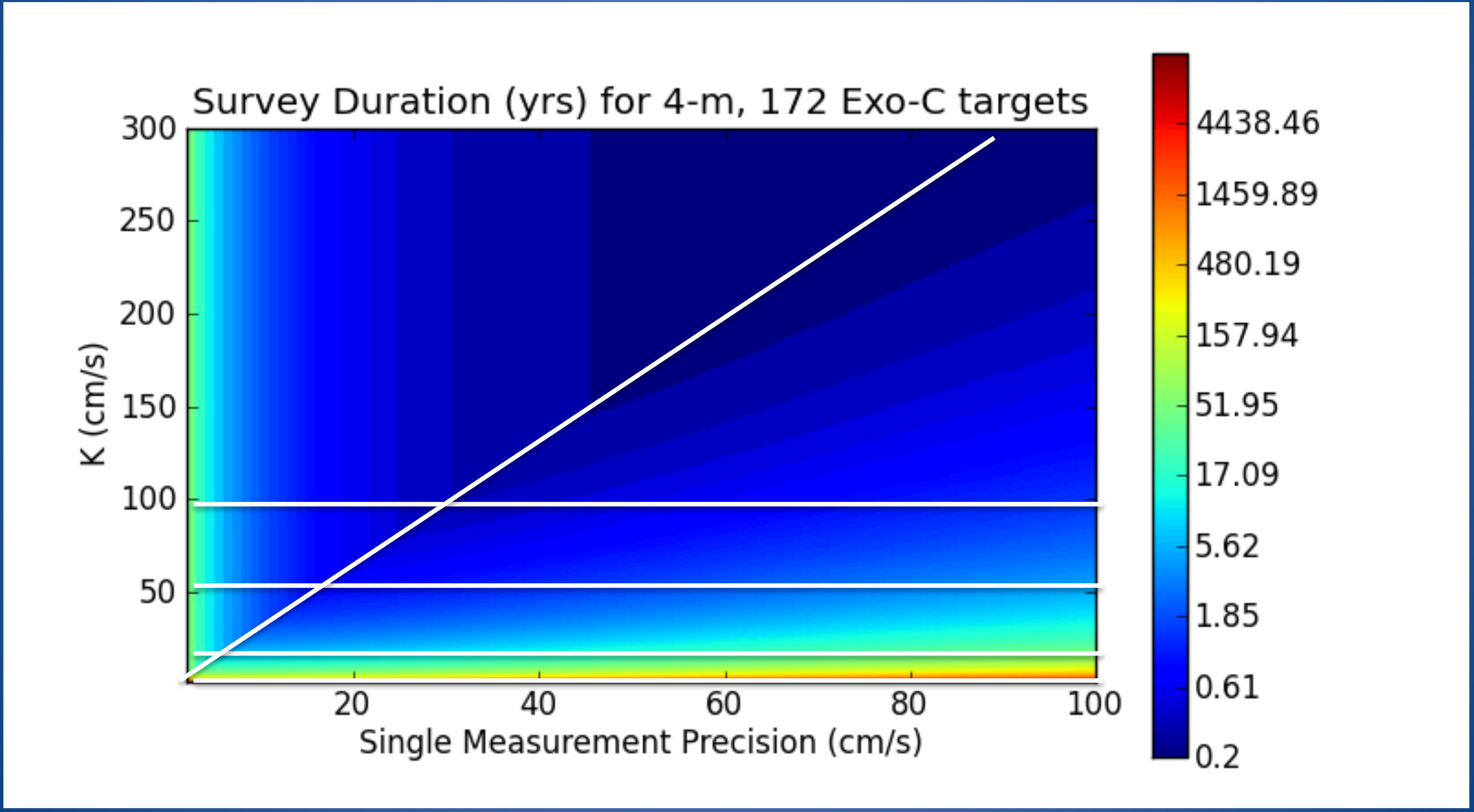
# Fixed Measurement Precision Survey
# min($N_{obs}$)=10

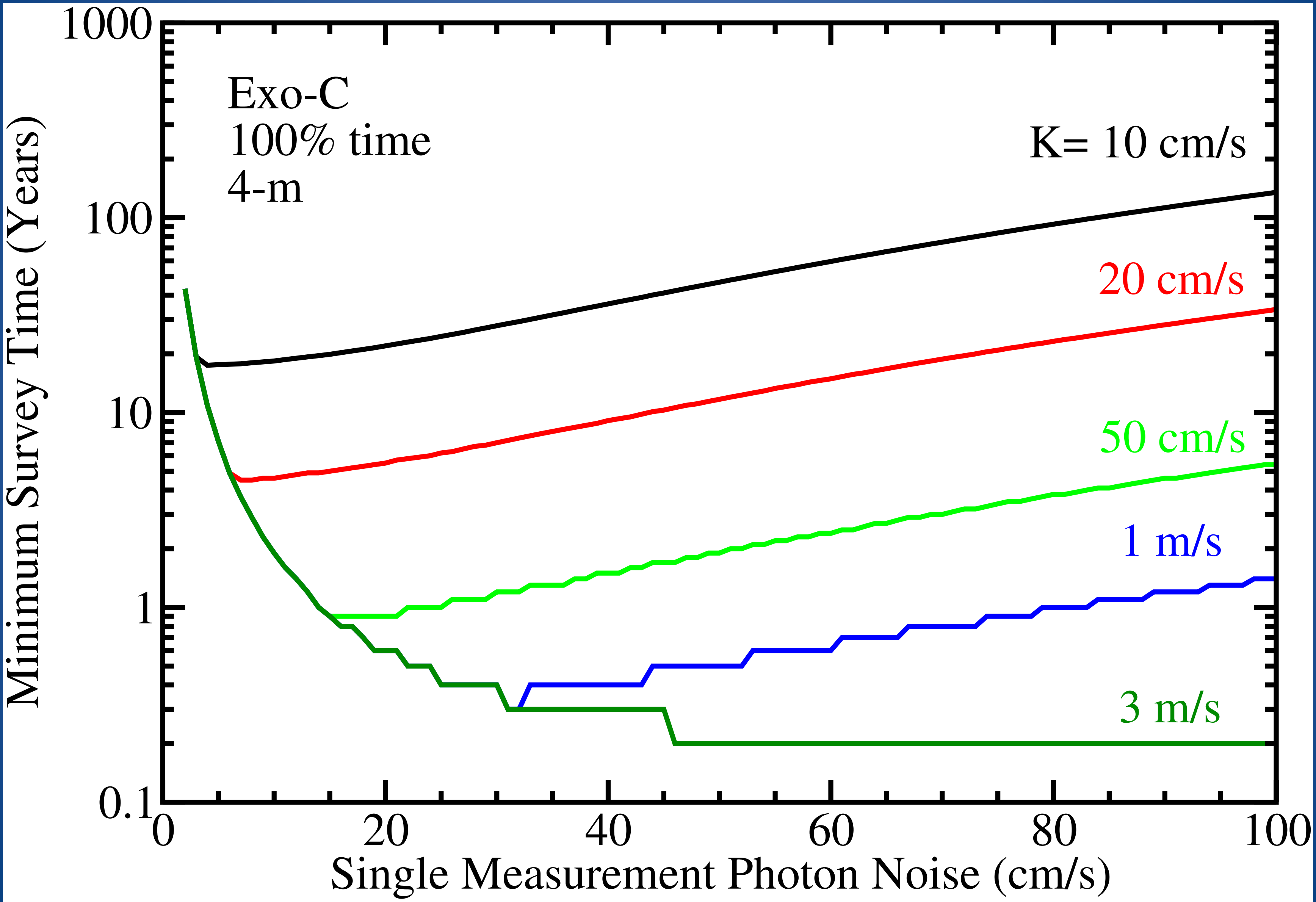


# Fixed Measurement Precision Survey
# min($N_{obs}$)=10

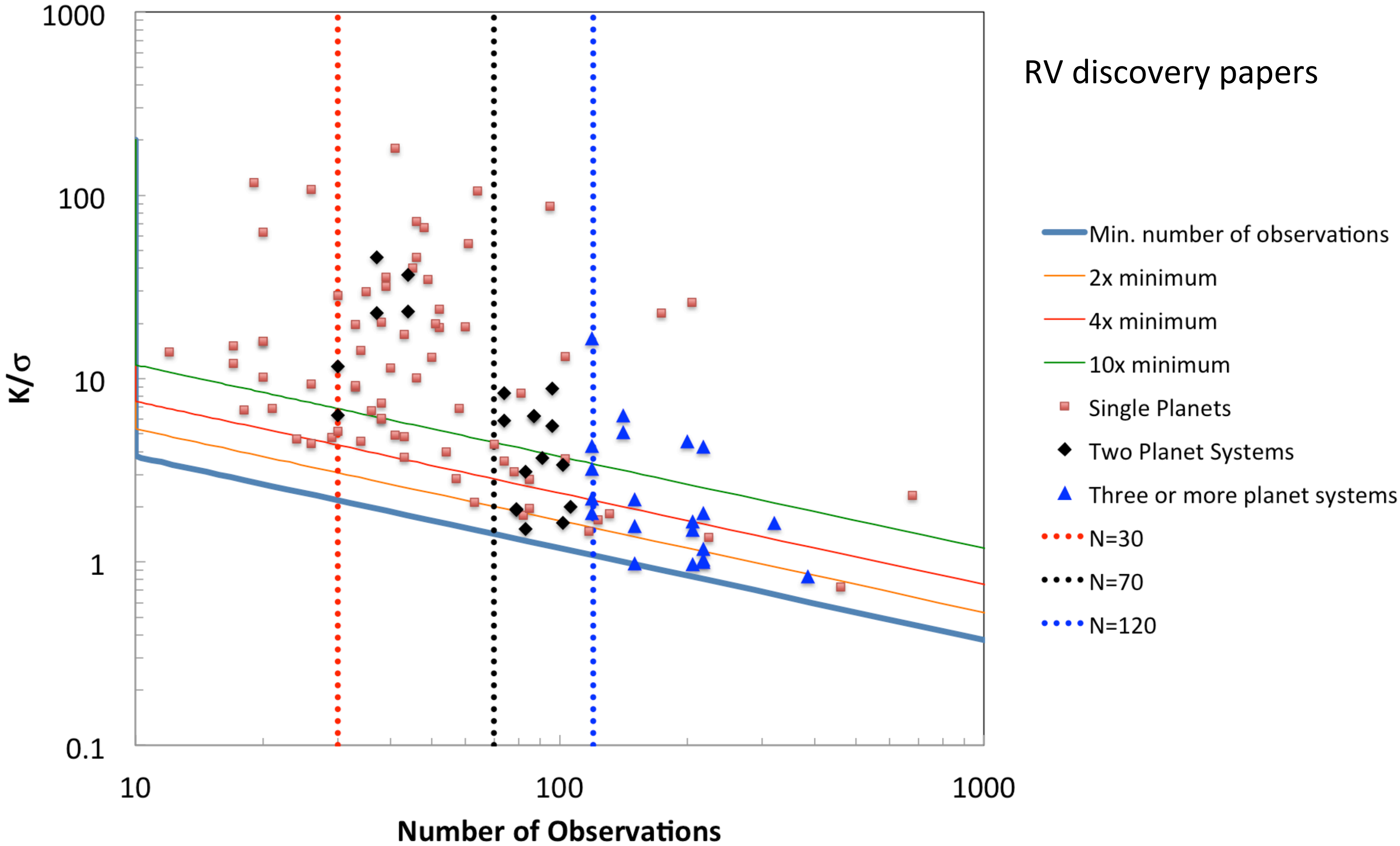


# Fixed Measurement Precision Survey
# $\min(N_{obs})=10$




Exo-C
100% time
4-m
K= 10 cm/s
20 cm/s
50 cm/s
1 m/s
3 m/s
Minimum Survey Time (Years)
1000
100
10
1
0.1
0
20
40
60
80
100
Single Measurement Photon Noise (cm/s)

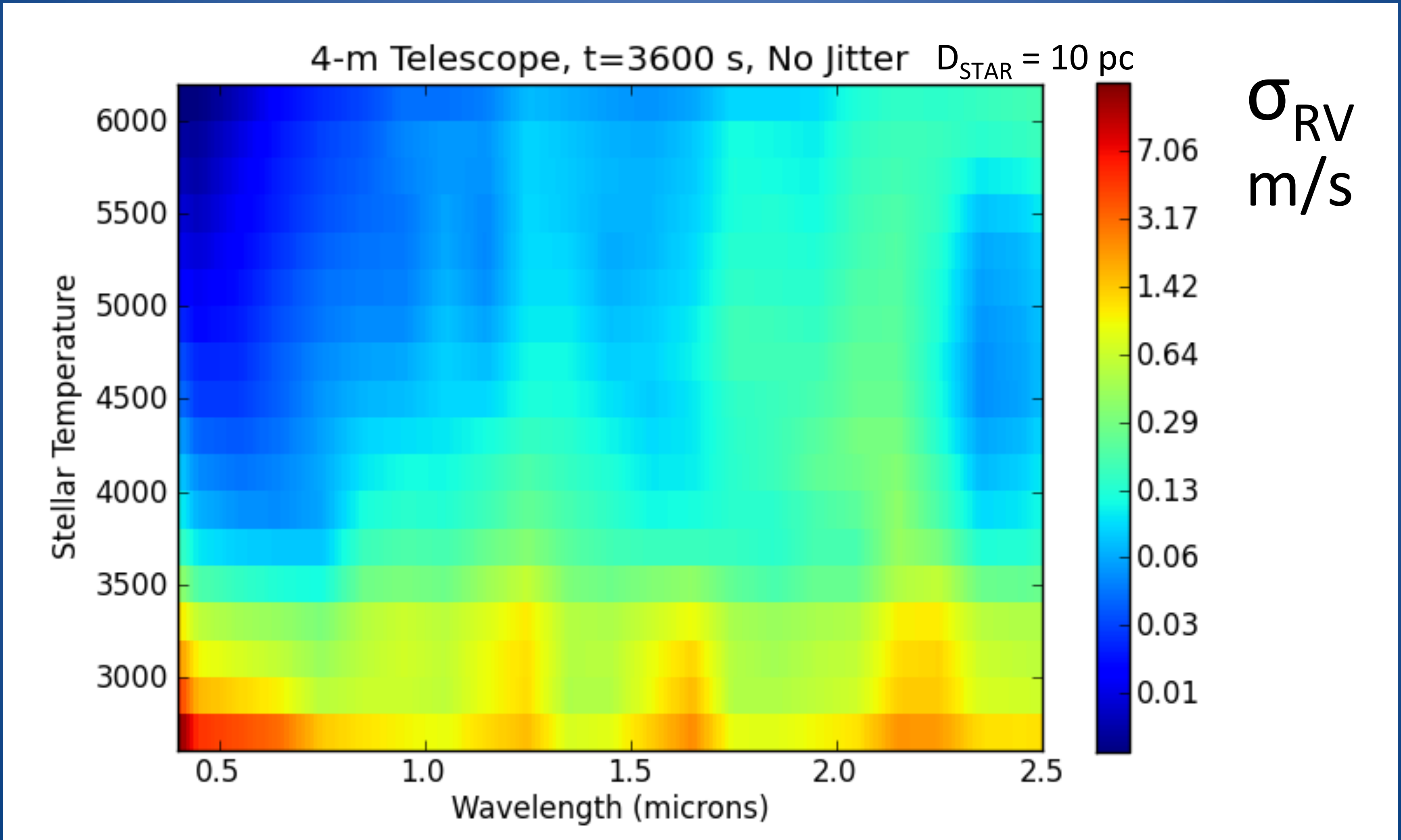
# Are 10 epochs really enough?



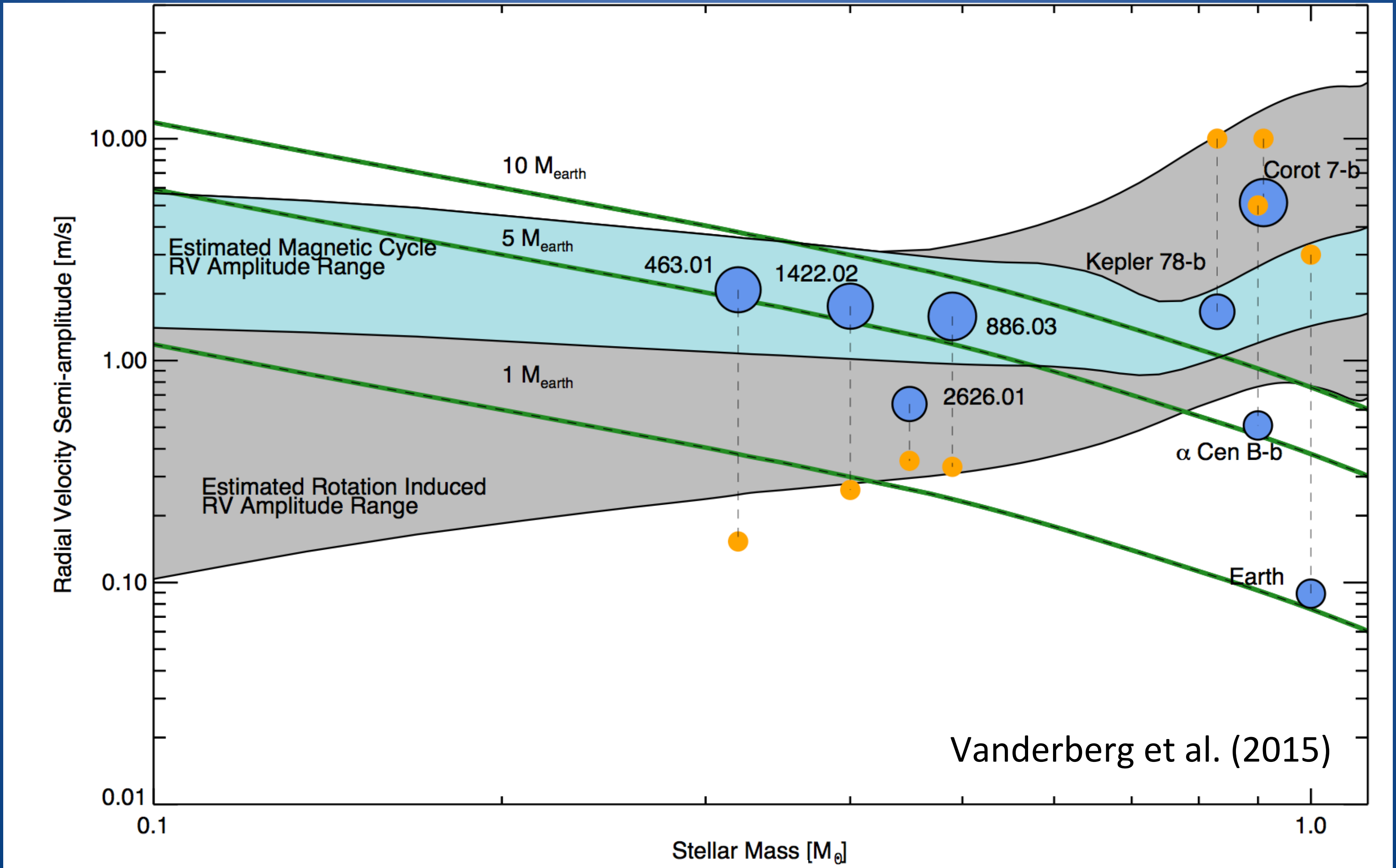
# Access to 4-m with NIR 50 cm/s

- Is the NIR advantageous for M Dwarfs?
- What about stellar jitter?

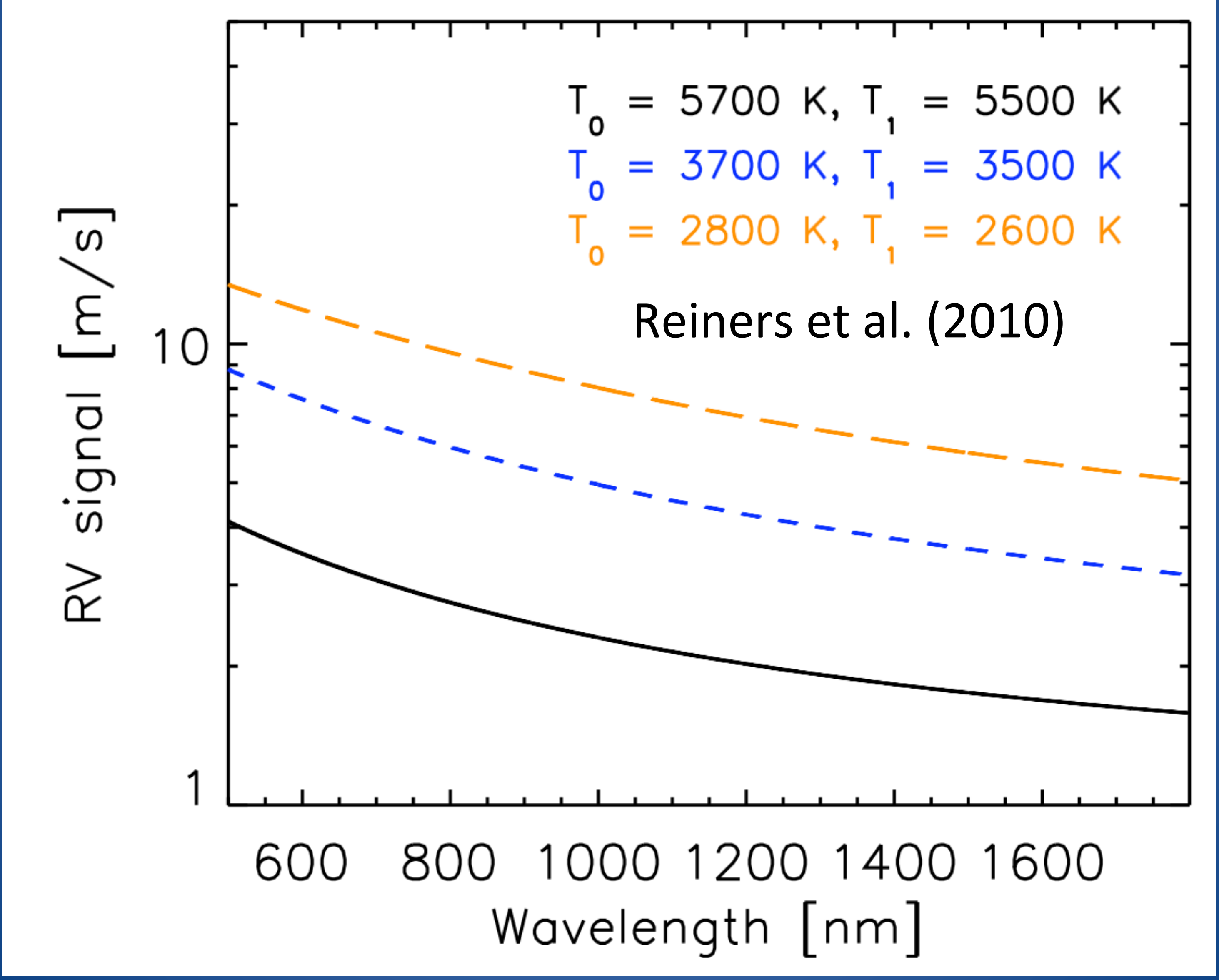
# Scaled from Bottom et al. (2013)



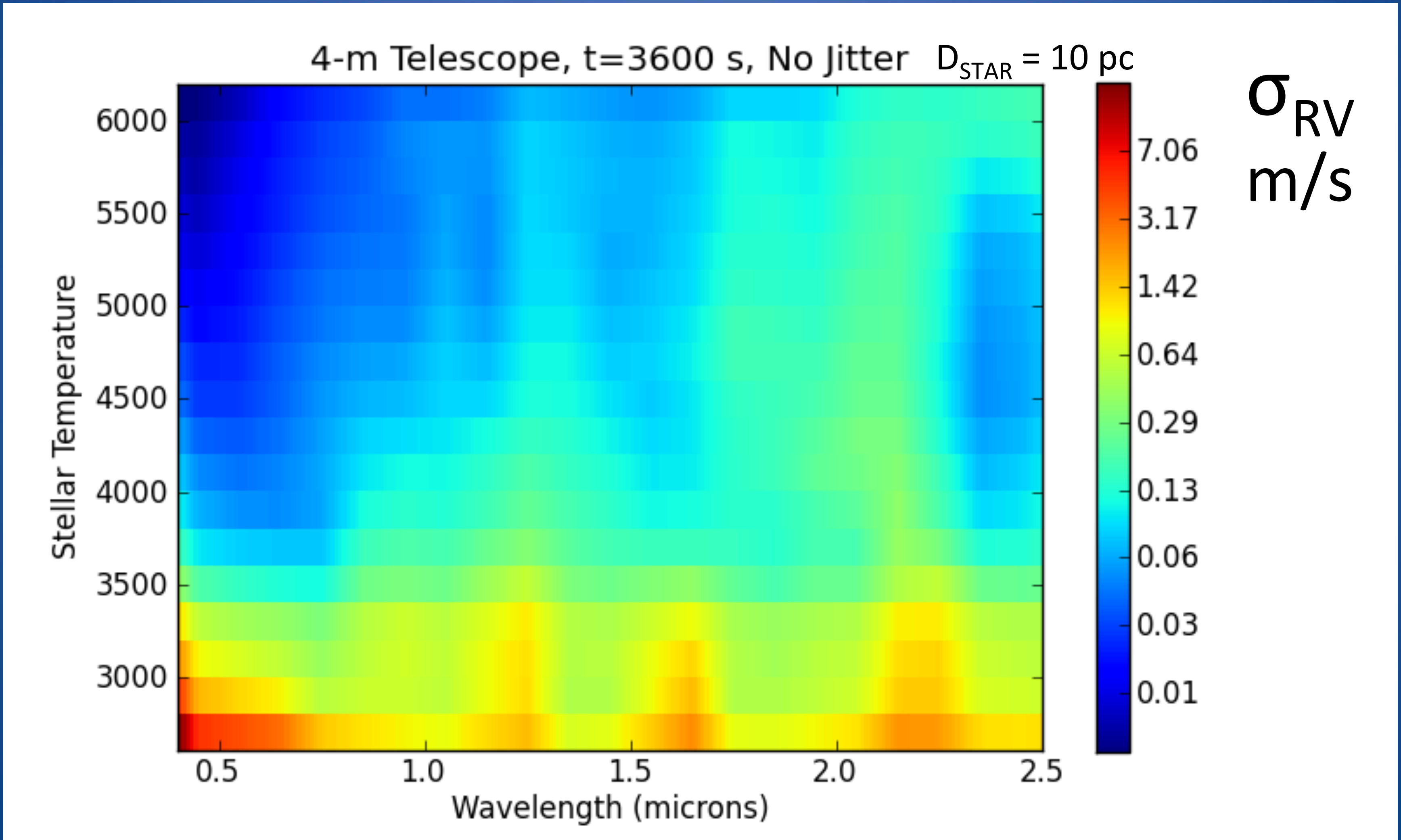
# Stellar Jitter (Spectral Type)



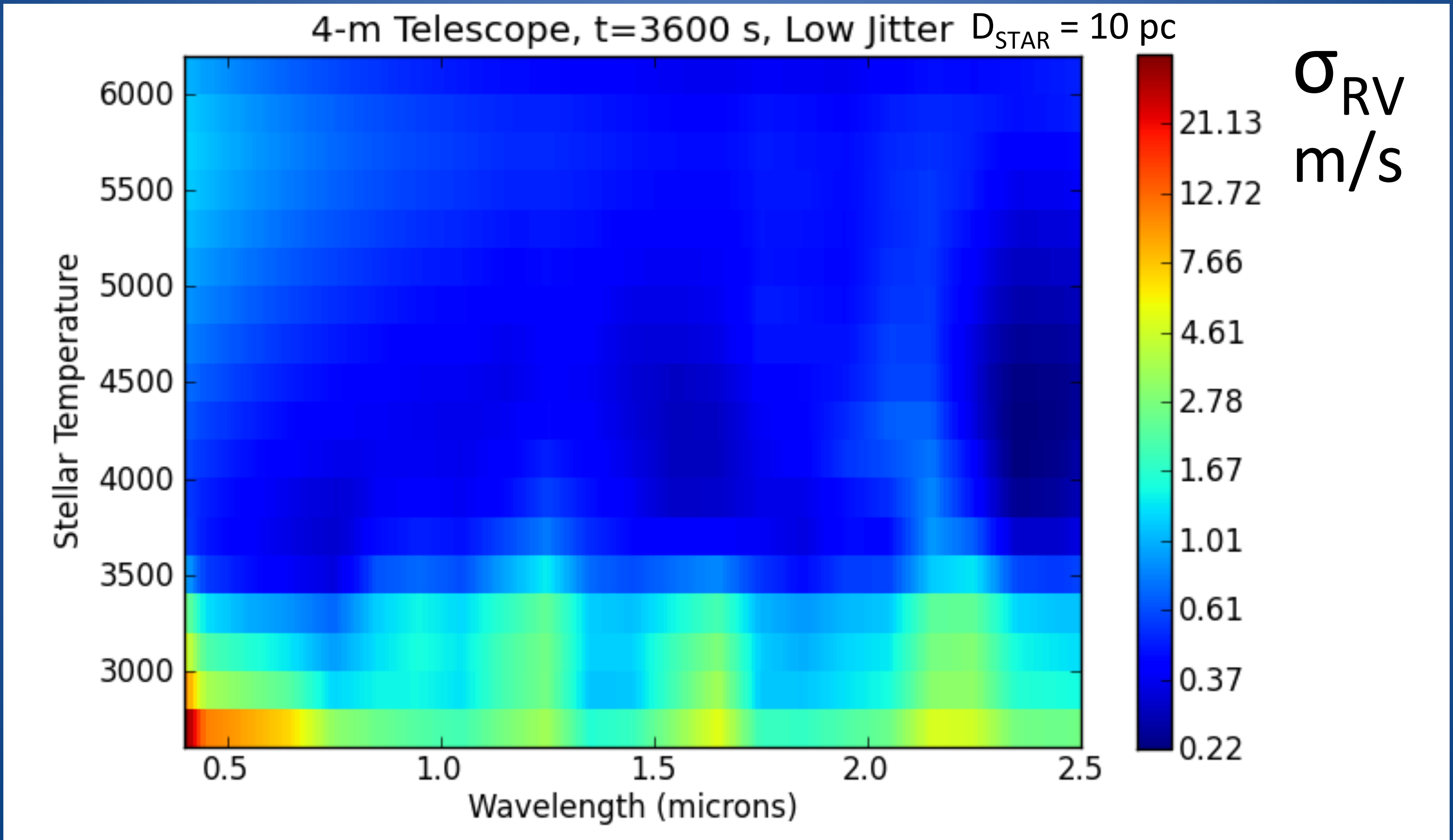
# Stellar Jitter (λ) α 1/λ



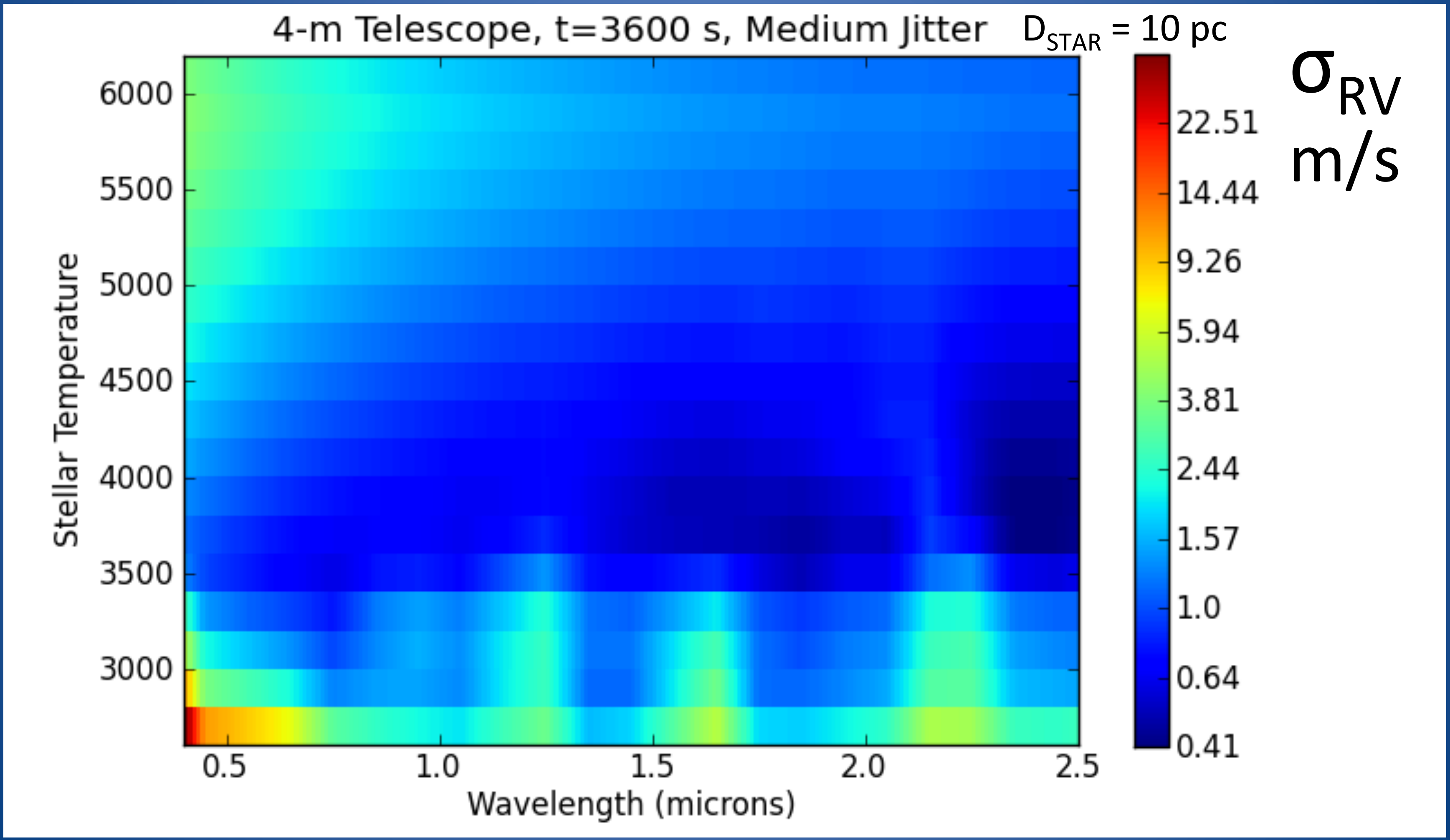
# Scaled from Bottom et al. (2013)



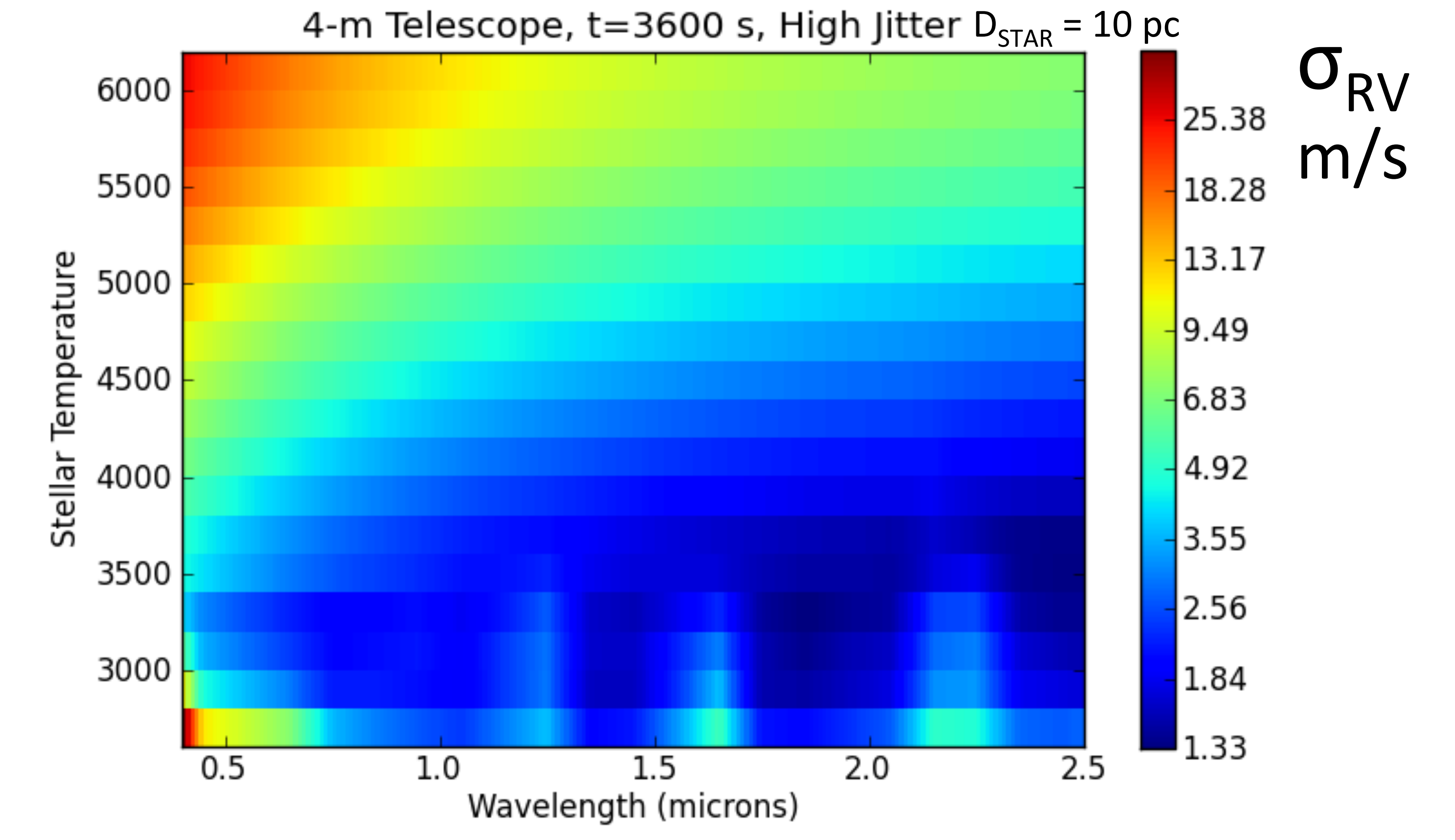
# Bottom et al. (2013) w/ Jitter



# Bottom et al. (2013) w/ Jitter



# Bottom et al. (2013) w/ Jitter



# Conclusions

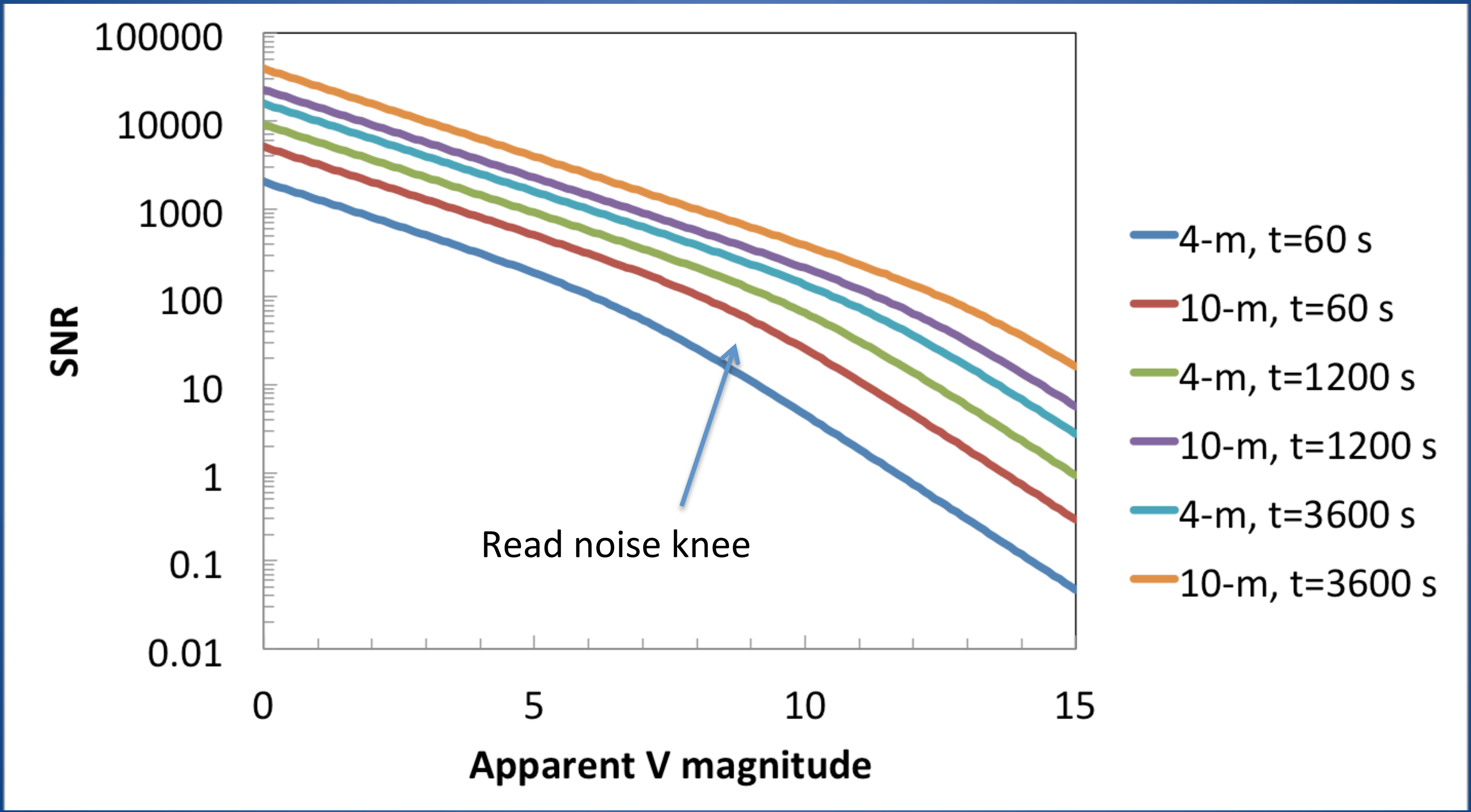
- Both ~50 cm/s and ~5 cm/s visible spectrographs on 4 and 10 meter class telescopes respectively offer the capability for the identification of Neptune-mass and larger exoplanets for Exo-C direct imaging.
- Additionally, a ~5 cm/s visible spectrograph capability on a 10-m class telescope could enable the detection of Earth analogs for a future flagship direct imaging mission.
- Minimum survey durations of ~15 years will be necessary (either due to orbital period or photons), requiring a long-term survey commitment and investment for both the survey and follow-up of candidate exoplanets.

# Conclusions 2

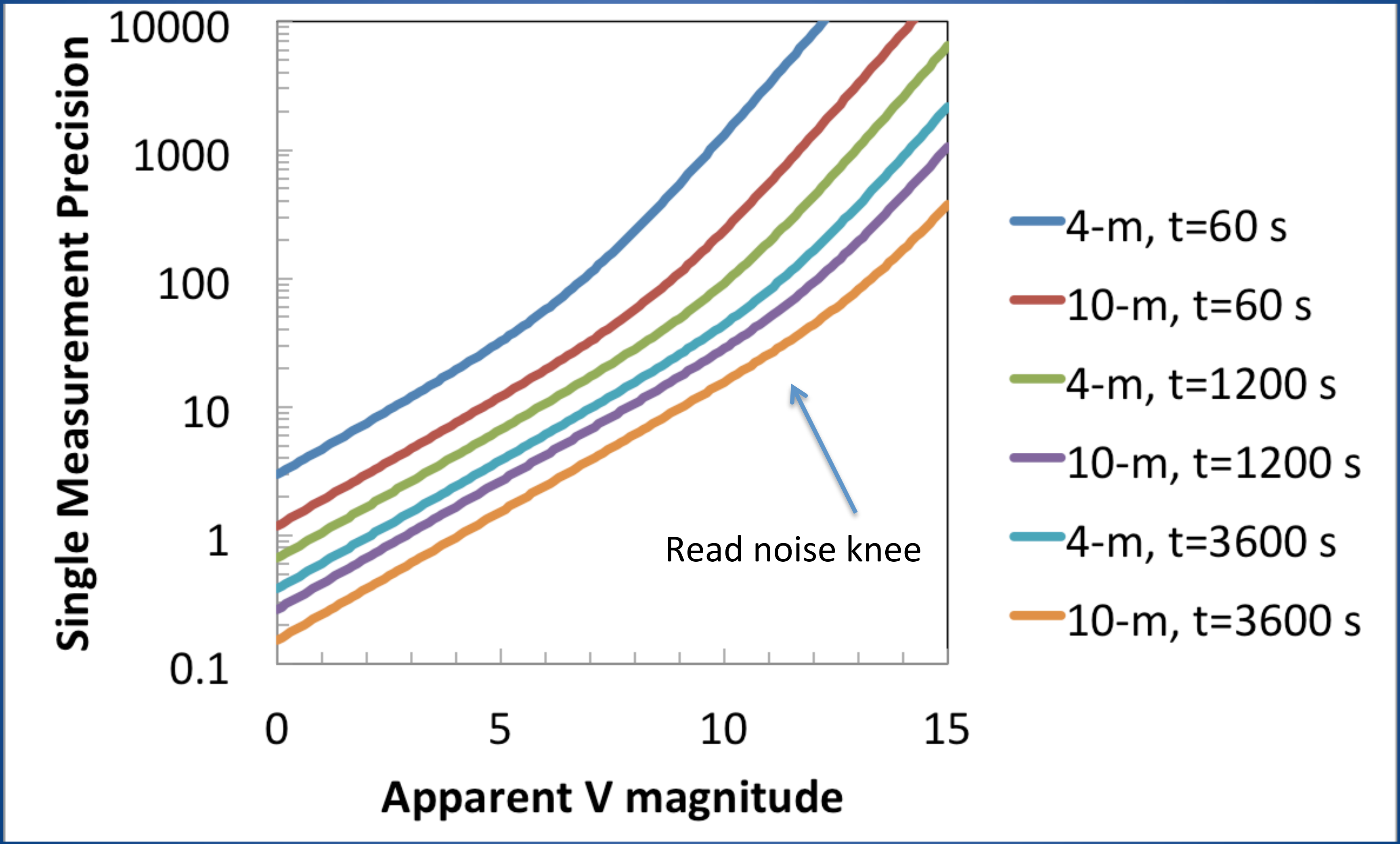
- Even low stellar jitter, when not detrended, can triple the RV uncertainty compared to photon noise alone, for a given effective temperature and wavelength of observation.
- Stellar jitter, when treated as a systematic noise term, dominate the limiting RV precision for stars with T>4000 K, even for relatively quiescent stars, with integration times of 1 hour on 4-m and 10-m telescopes.
- For F dwarfs and early G dwarfs, stellar jitter is less pronounced for $\lambda > 1$ micron. However, for relatively quiescent stars, the NIR offers only marginal advantage over the visible. The NIR advantage is more prominent for more active stars.
- For mid-to-late G, K and early M dwarfs, in the presence of any stellar jitter, the optimal wavelength regime of observation appears to be $\lambda > 2.3$ microns with the CO absorption bandhead. Thus, NIR PRVs are critical to reach sub-m/s exoplanet signals.
- We expect risk associated with NIR PRV instrumentation to be retired in the coming 2-3 years as the next generation of NIR PRV spectrometers comes online.

# Extra Slides

# SNR($m_V$) (R=100k, 10% efficiency, …)



# $\sigma_{RV}(m_V)$



Single Measurement Precision
10000
1000
100
10
1
0.1
0
5
10
15
Apparent V magnitude
Read noise knee
4-m, t=60 s
10-m, t=60 s
4-m, t=1200 s
10-m, t=1200 s
4-m, t=3600 s
10-m, t=3600 s

# $\sigma_{RV}(m_V)$ with noise floor