The Promise of Diffraction-Limited Spectrometers for PRV and Direct Planet Spectroscopy: From Palomar→Keck →TMT→Space

Charles Beichman, Gautam Vasisht Stephanie Leifer (JPL, California institute of Technology),
Dimitri Mawet, Ricky Nilsson, Jason Fucik, Nem Jovanovic (Caltech),
Mike Fitzgerald (UCLA), Peter Plavchan (George Mason University)

EPRV-4, March 2019

Copyright 2019 JPL, California institute of Technology

Outline of Talk

- What makes Diffraction Limited Spectrometers so great?
- What makes Diffraction Limited Spectrometers hard?
- What are Diffraction Limited Spectrometers good for?
- Where are we hoping to put Diffraction Limited Spectrometers?
- How do we stabilize Diffraction Limited Spectrometers for PRV?
- What is the ultimate application of Diffraction Limited Spectrometers?

What Makes Diffraction Limited Spectrometers Great?

Resolution, R, of a spectrometer is given by $R=2D_{grating} \tan \alpha/(D_{tel}\, \theta_{slit})$
Alternatively, grating size, $D_{grating}$, goes as $D_{grating} = R\,(D_{tel}\, \theta_{slit})/\tan \alpha$

→ For a given R, instrument size scales as $(D_{grating})^2 \sim (D_{tel}\, \theta_{slit})^2$

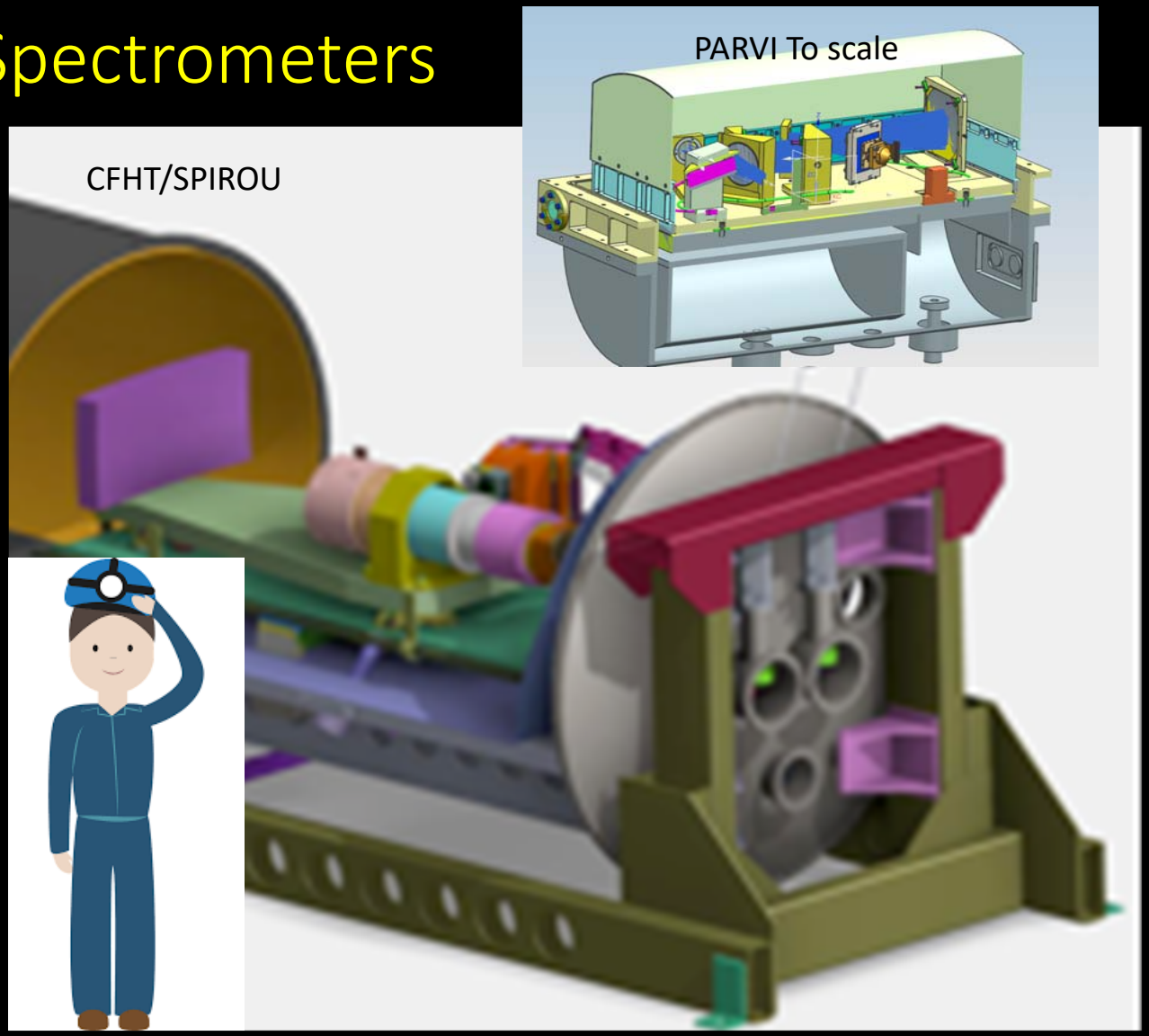
Seeing-limited spectrometers on large telescopes ($\theta_{slit} \sim 0.5''$) are big, hard to stabilize thermally and mechanically → very expensive

For a diffraction limited system, $\theta_{slit}=\lambda/D_{tel}$, and $D_{grating} = R\,\lambda/\tan \alpha$ so instrument optics scale as λ for a given R

Size of diffraction-limited spectrometer is independent of telescope size making them smaller and easier to stabilize → less expensive.

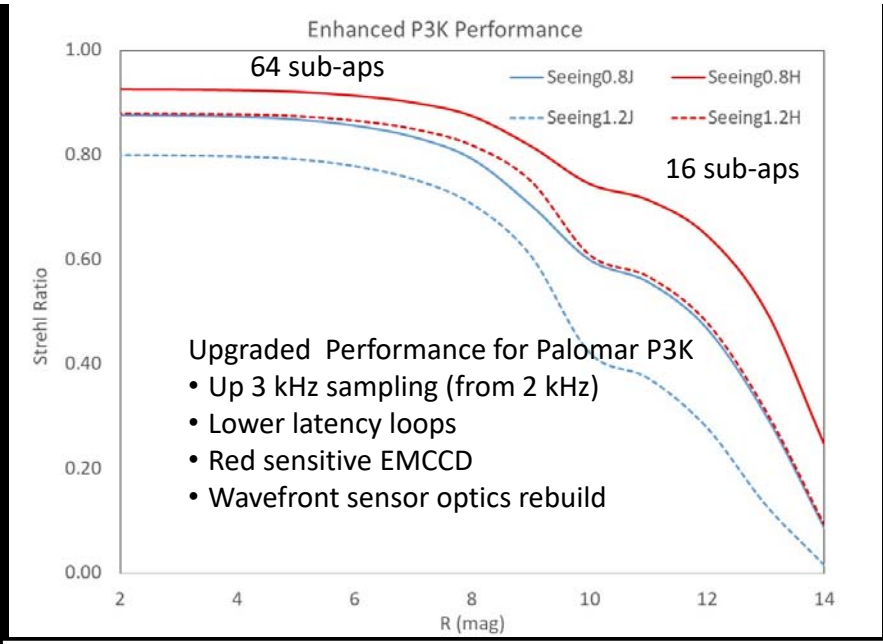
Diffraction Limited Spectrometers Are Compact

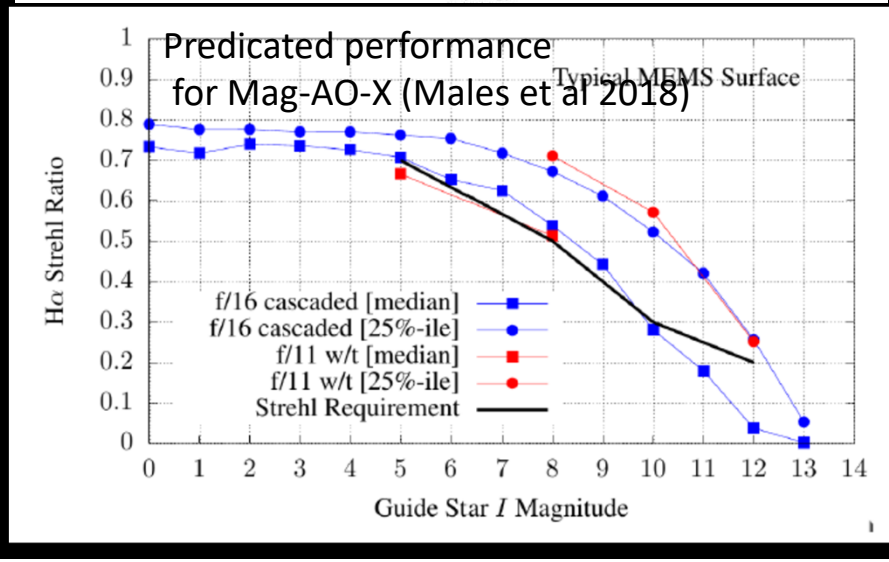
- CFHT/SPIROU
  - R=75,000 with 150 mm pupil at grating (incorporating 12x3 mm image slices)
- HET/HPF
  - R=50,000 with 200 mm pupil
- PALOMAR/KECK/TMT
  - R>100,000 with 25 mm pupil
  - Independent of telescope size



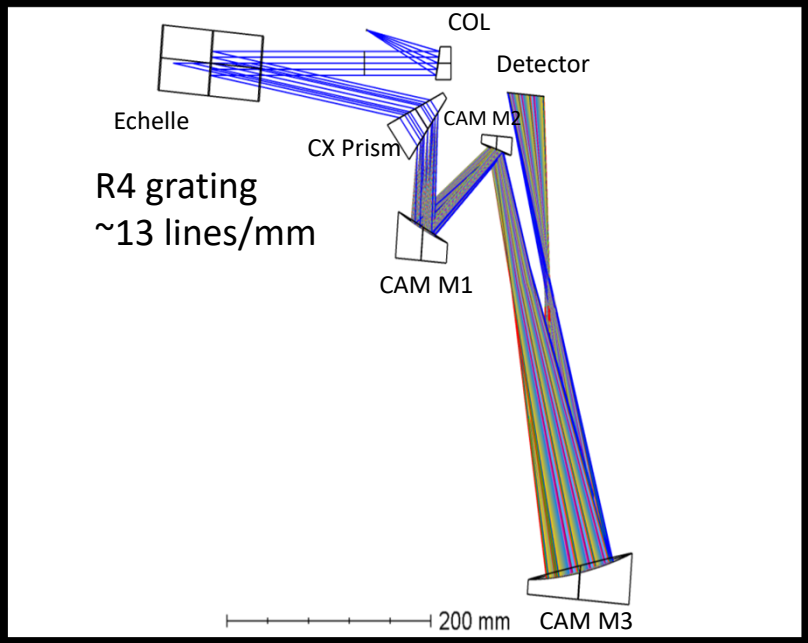
What makes Diffraction Limited Spectrometers Hard?

- Feeding spectrometer with diffraction limited beam with high efficiency
- Require AO with high Strehl at short λ
  - Strehl > 50% at λ> J band (Palomar 3k; Burruss et al 2014)
  - Laser Guide Star with simulated V~9 mag LGS (Keck, TMT) can boost Strehl ratios for faint stars
  - Strehl > 50% at 0.6 μm (Close et al 2014; Males et al 2018)
- PIAA input beam raises coupling efficiency from 59%->87% relative to unapodized beam (Jovanovic et al 2017)
- Goal for overall optical efficiency: 8%-10%



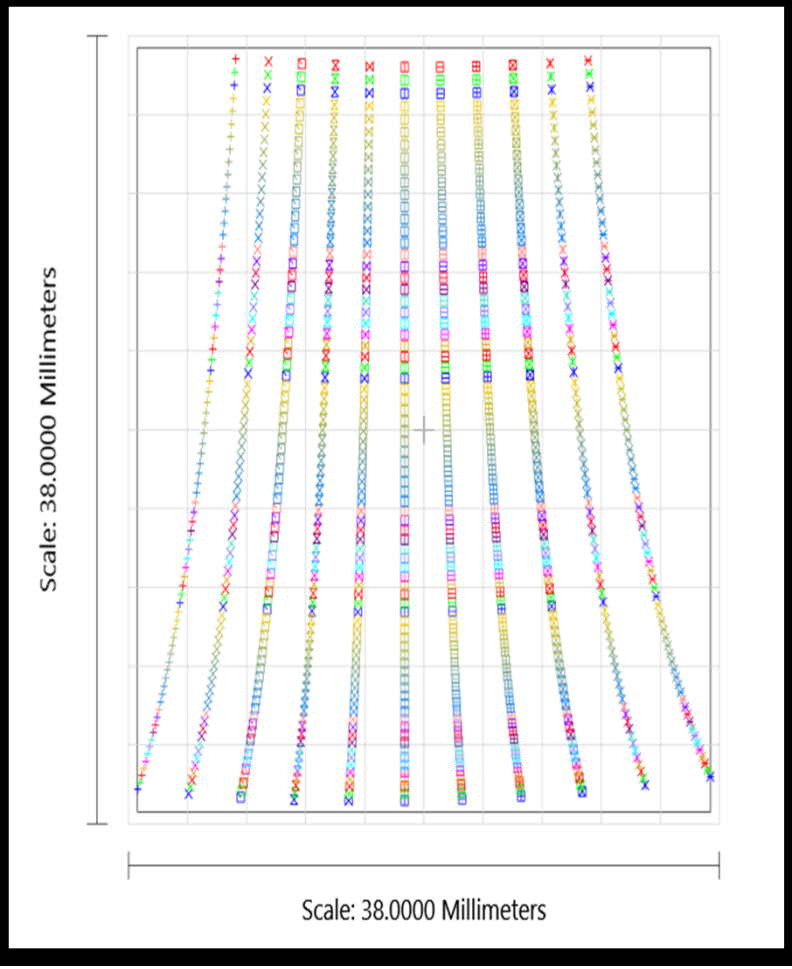


Optical Design for PARVI

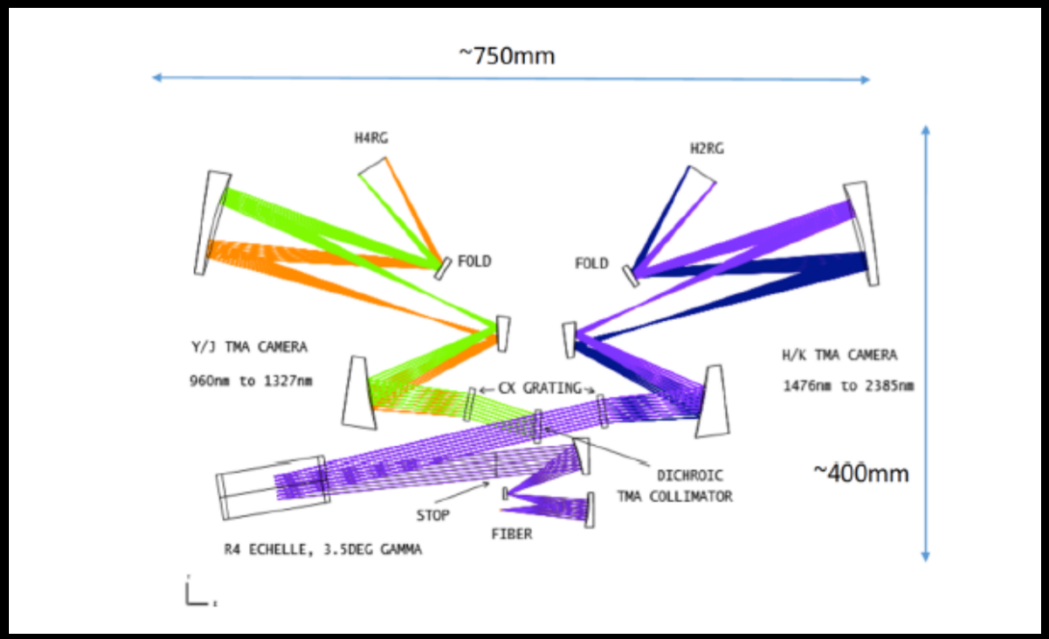


Wavelength (nm)	Sampling (pixels)	Resolution
1110 (J)	1.92	127,942
1368 (J/H)	2.24	109,925
1790 (H)	2.82	87,544

Total Orders: 75
Order Range: 120 – 194
Free Spectral Range: 6nm - 15nm
Spectral Range: 1000 nm - 2500 nm

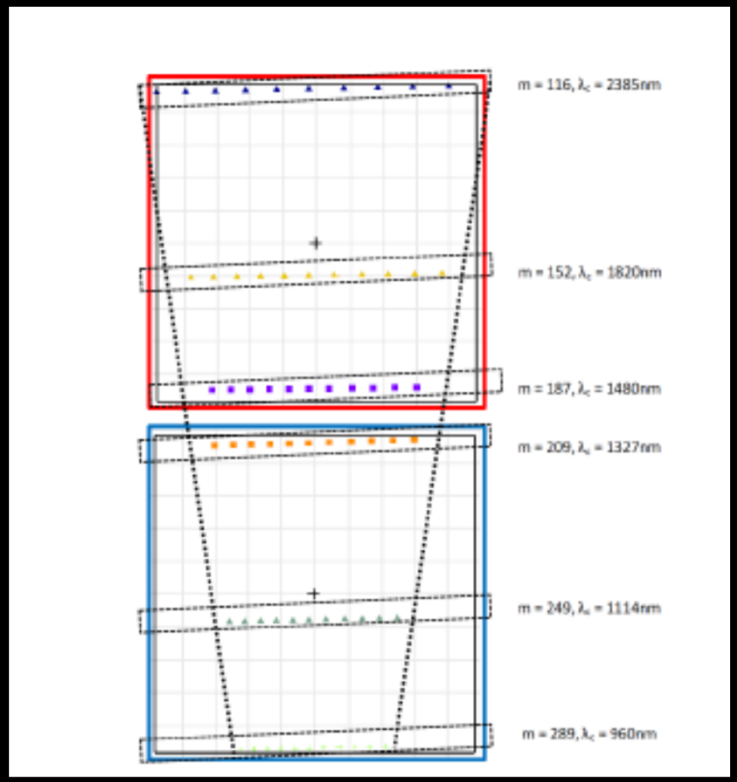


Optical Design for HISPEC/MODHIS



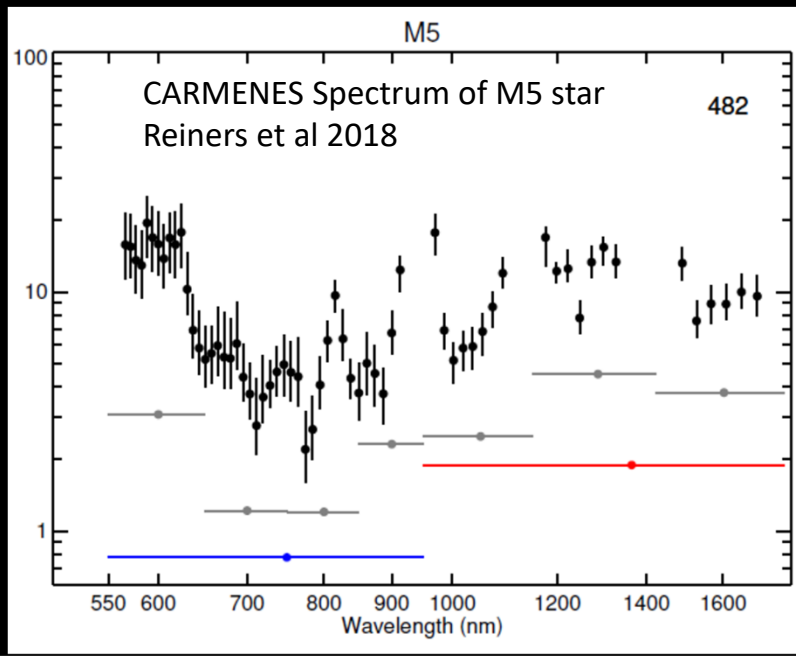
Wavelength (nm)	Sampling (pixels)	Resolution
1110 (J)	1.92	127,942
1368 (J/H)	2.24	109,925
1790 (H)	2.82	87,544

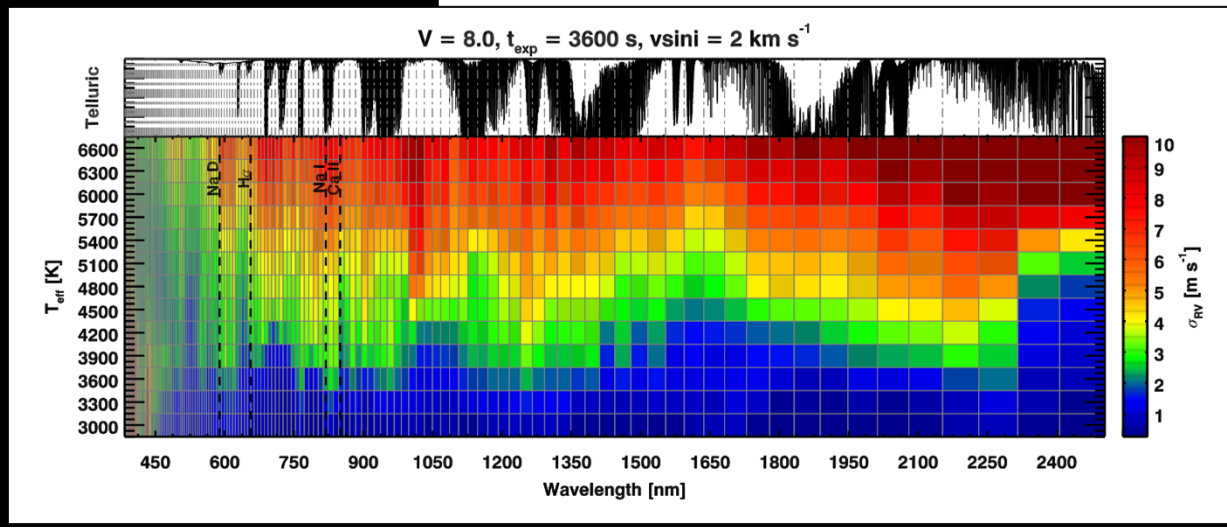
Total Orders: 75
Order Range: 120 – 194
Free Spectral Range: 6nm - 15nm
Spectral Range: 1000 nm - 2500 nm



What are Diffraction Limited Spectrometers Good for?

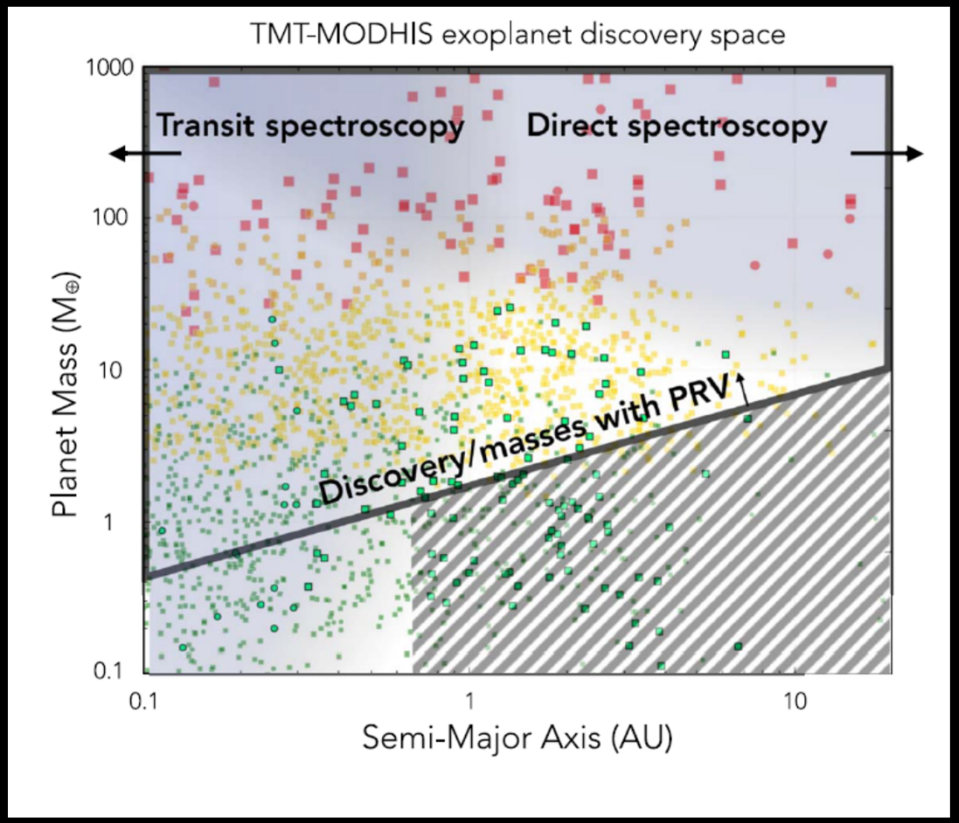
- NIR PRV advantageous for late type (>M5) or for active stars (Reiners et al 2018)
  - Surveys of late type M stars (>M5) and transit follow-up (1 m/s)
  - Surveys of mature but active stars where lower NIR jitter may reach lower mass planets (1-10 m/s)
  - Surveys of young stars for hot Jupiters (10s of m/s)
  - Stellar hosts in tight binaries
  - Brown dwarf binaries with LGS
- Vis & NIR spectra at R>150,000 would help mitigate jitter by resolving individual stellar lines (Dumusque et al; Lanza et al; Wise et al --- 2018)





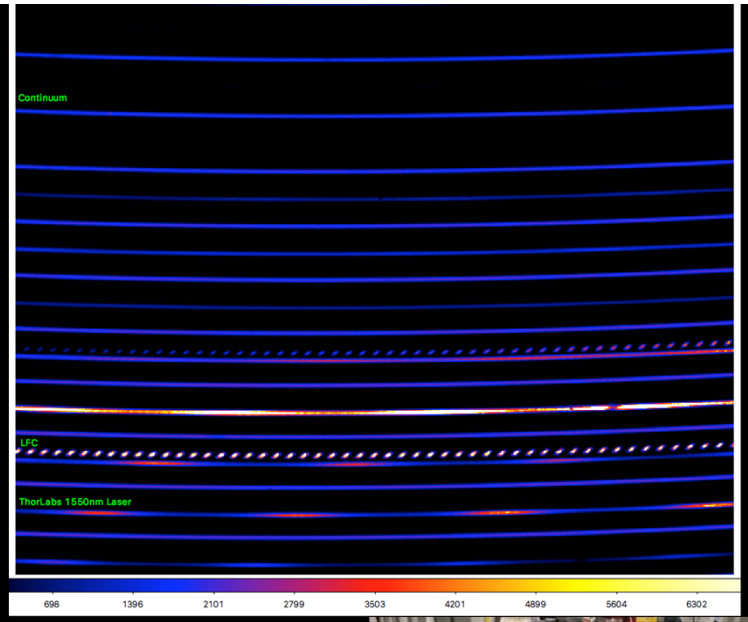
What (Else) are Diffraction Limited Spectrometers Good for?

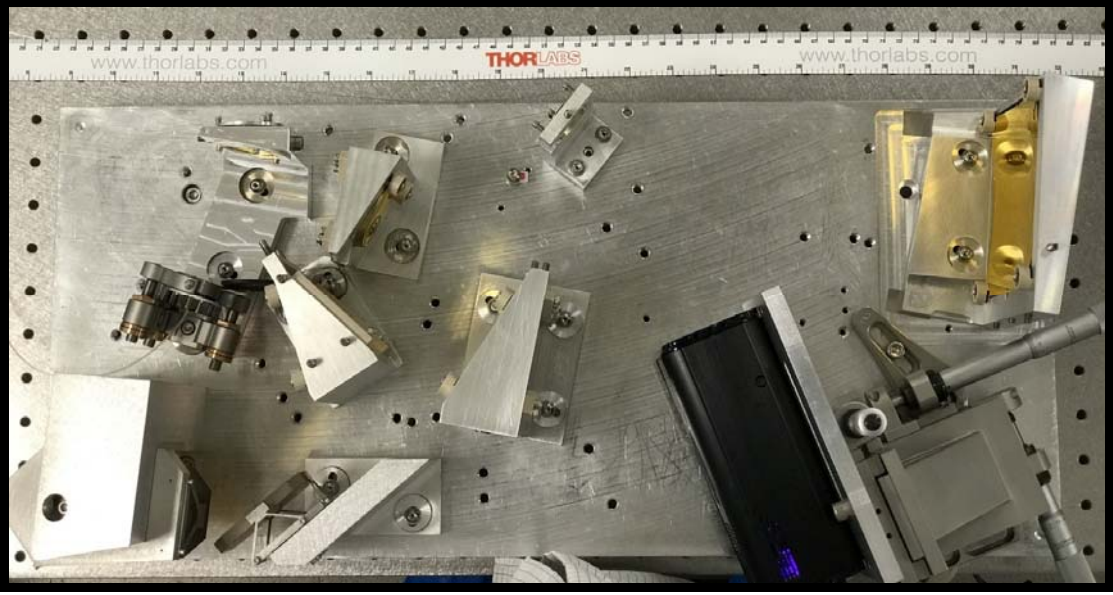
- Progression of instrumentation from Palomar to from Keck (HISPEC) & LBTI/iLocator, to TMT (MODHIS) will advance science capabilities from giant planets down to Earths orbiting M stars
- Direct high resolution spectroscopy with or without coronagraphy
  - Turn hot Jupiters into SB2 binaries
  - Determine stellar and exoplanet masses
  - Map molecule distribution in directly imaged planets
  - Measure planet spin (length of day)
  - Make Doppler map for cloud dynamics, global circulation, winds, weather
  - Determine molecular composition, C/O ratio
  - Reflected light using high dispersion spectroscopy + coronagraphy

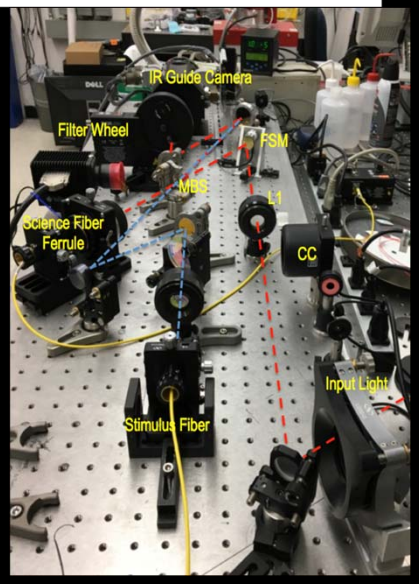


PARVI Build-up in the Lab

- Most major components in place with engineering grade R4 grating
- Expecting first tests with H2RG detector in late February

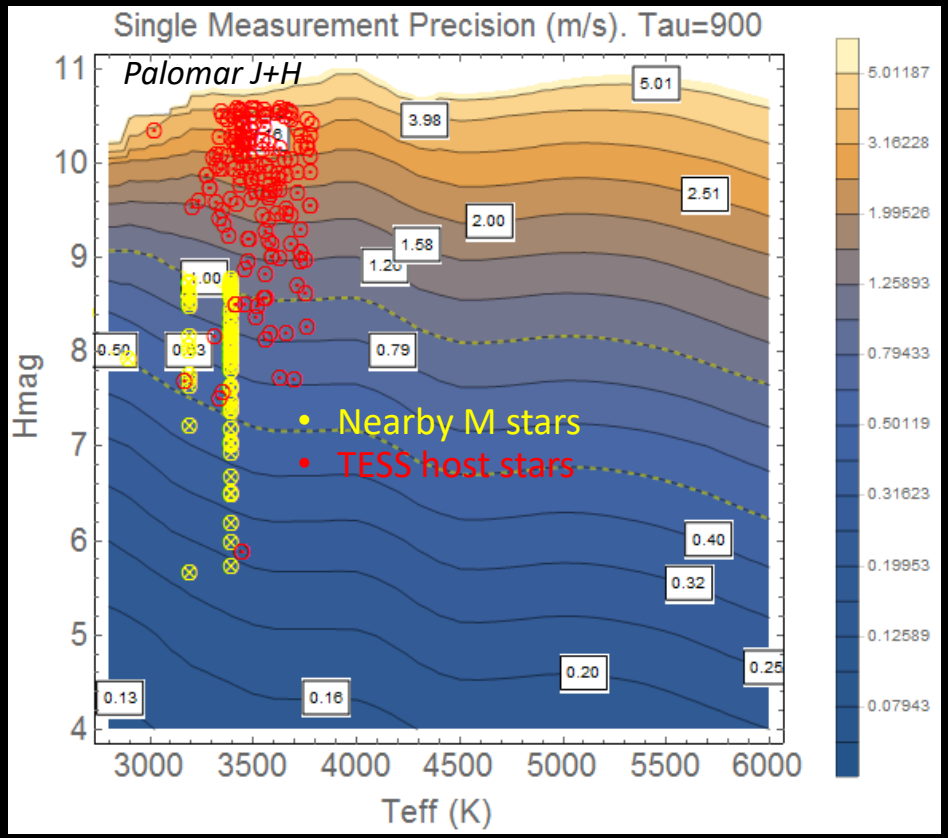


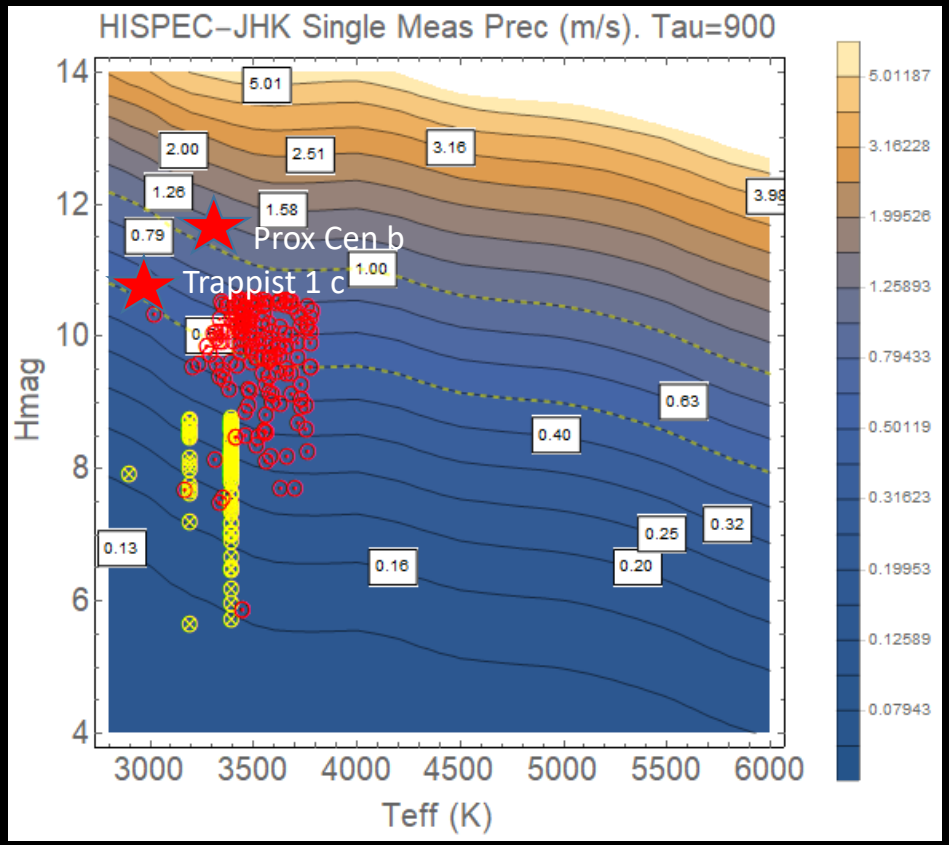




Single Measurement Precision at Palomar and Keck

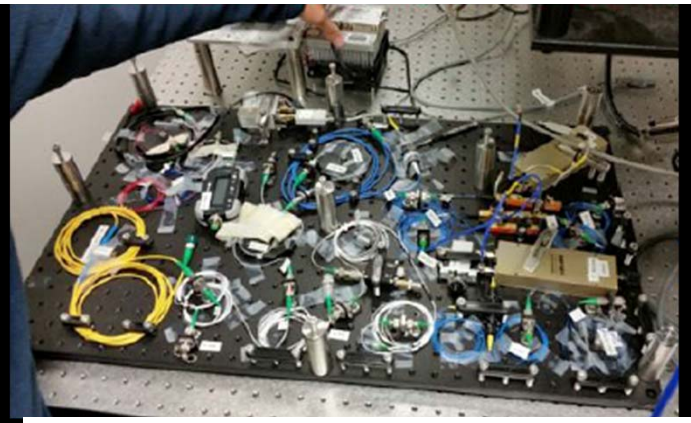
Photon limited single measurement precision at Palomar/PARVI (J+H) and Keck/HISPEC (H-only) is at or below 1 m/s although atmosphere may limit to ~1-3 m/s depending on H_2O

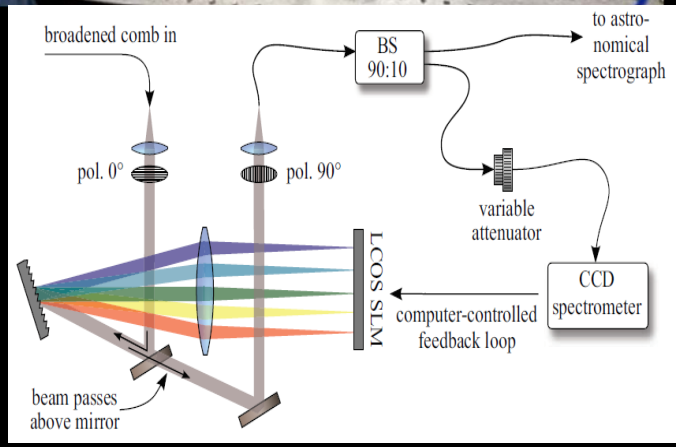


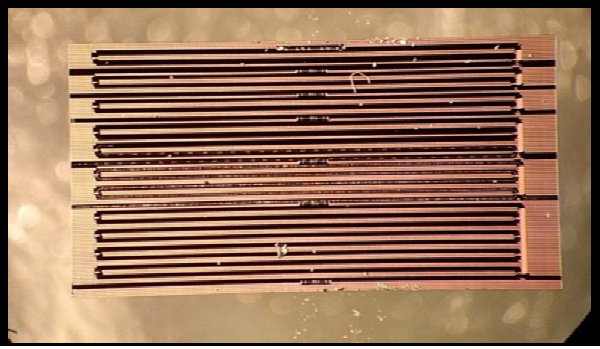


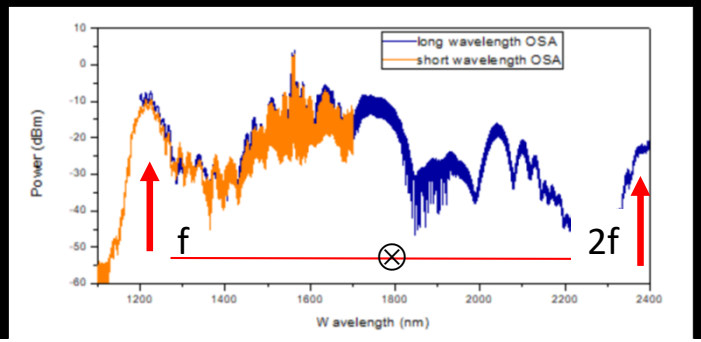
EOM LFCs for Precision Reference

- In Stage-1:
  - EOM comb with intrinsic 12 GHz (0.1 nm) spacing tied to acetylene laser (Yi et al 2016) for <30 cm/s precision
  - Custom spectral flattener will operate at H band provides uniform LFC comb lines
- In stage 2:
  - Octave spanning comb broadened with SiN waveguide for f-2f self-referencing for <cm/s stability
  - Heterodyne combination of *f & 2f* generates 1.58 GHz beat tied to Atomic Clock frequency standard (GPS)
  - Feedback stabilizes LFC to sub- cm/s long term stability



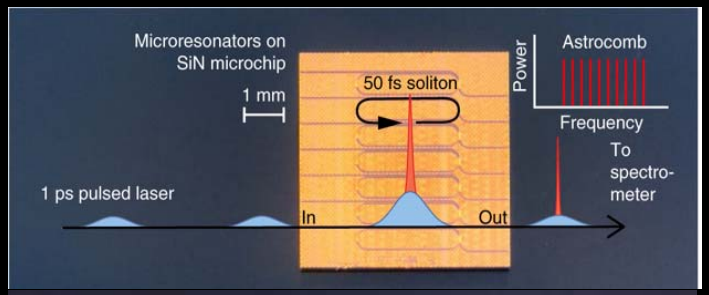


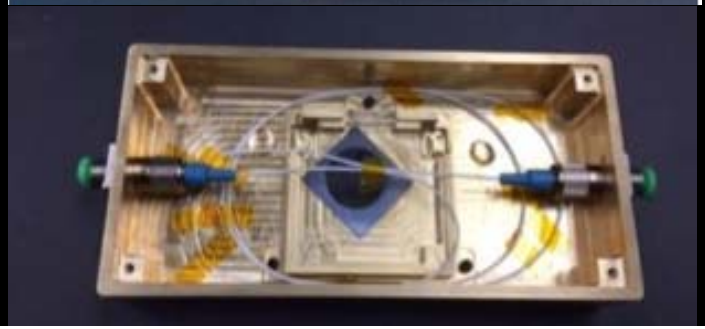


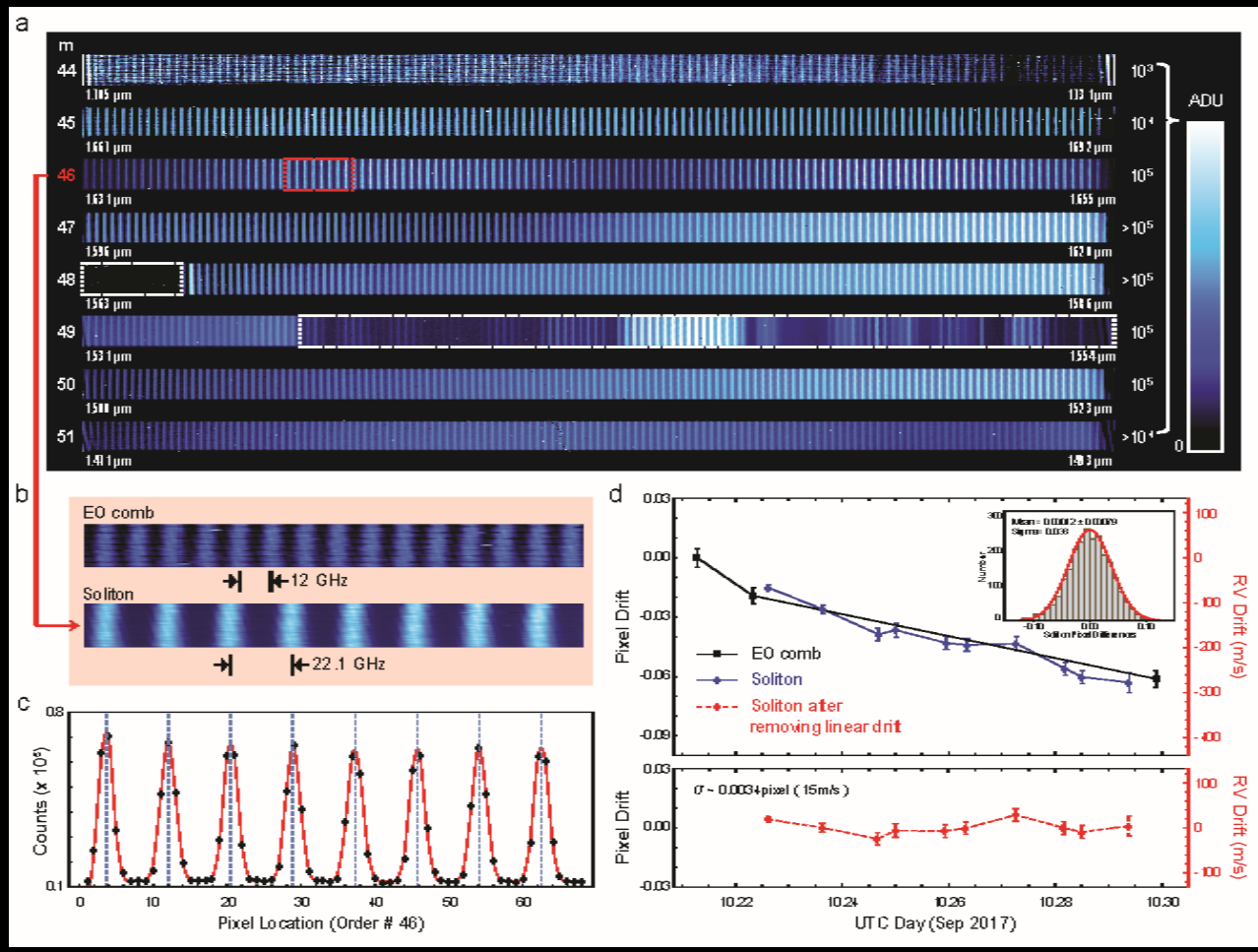


The Future: LFC's on a chip!

- Kerr Soliton microresonator generates LFC on a chip
- Tests at Keck at 1.5 mm (Suh et al 2018) and GIANO-B spectrometer at the Telecopio Nazionale Galileo (TNG) (Obrzud et al 2018)





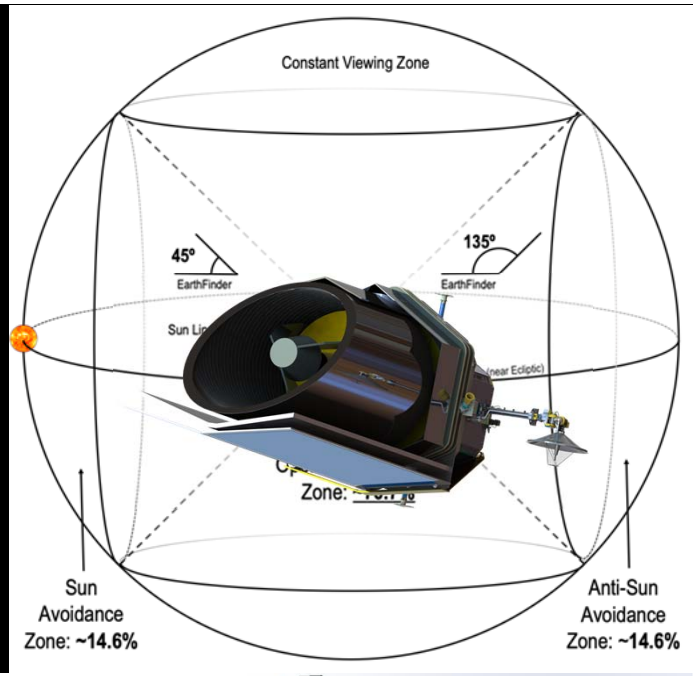


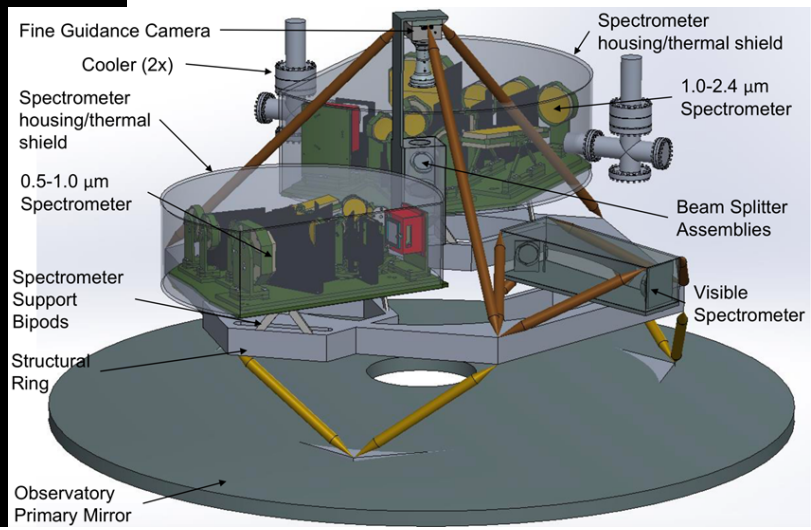
What Is The Ultimate Application Of Diffraction Limited Spectrometers?

- EarthFinder --- A NASA Probe Class Study for ASTRO2020
- Evaluate the *scientific rationale* for going to space vs. staying on the ground:
  - What do you gain from space? → Can we "solve" stellar activity?
  - What can't you do from the ground?→ Bypass limits of Earth's atmosphere
- The Team
  - PI: Peter Plavchan
  - Instrument & Mission: Gautam Vasisht, Chas Beichman
  - Tellurics: Sharon Wang
  - Stellar Activity: Heather Cegla, Xavier Dumusque
  - Ancillary Science: Courtney Dressing, Peter Gao

EarthFinder: Taking PRV to Space

- Study brightest 50 targets for direct imaging missions
- 1.45 m telescope in Earth-trailing/L2 orbit
  - Visible Spectrometer: 0.60.96 μm at R=170,000 (0.6/λ)
  - Near-IR Spectrometers: 0.95-2.4 μm at R=170,000 (1.6/λ)
  - Small UV Spectrometer for MgII chromospheric activity: 0.28-0.38 μm
- No Telluric atmospheric effects
  - RV errors of 3 cm/s (blue), 10 cm/s (red), 1 m/s (NIR)
- Extreme Resolution and wavelength coverage for jitter
  - R>150,000 and continuum normalization for line by line analysis
  - Vis-NIR color to isolate jitter from Doppler signals
- L2 Orbit for Instrument Stability
  - Line Spread Function from single mode fiber at all wavelengths
  - mK thermal control for <10 cm/s single measurement accuracy
  - Micro-resonator LFC for 1 cm/s long term stability
- Steady Cadence (70% of sky >180d; 30% CV) to reduce aliasing

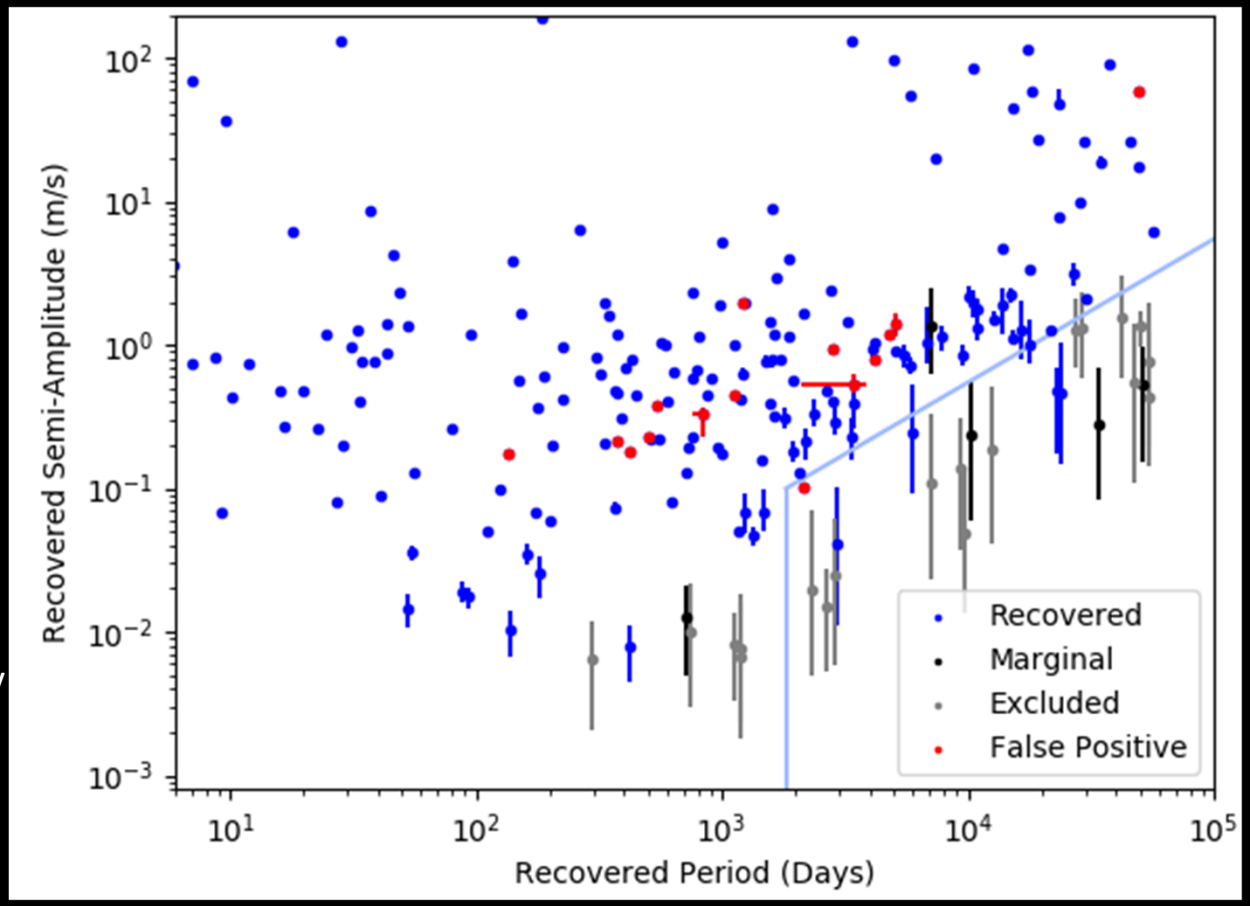




Backup

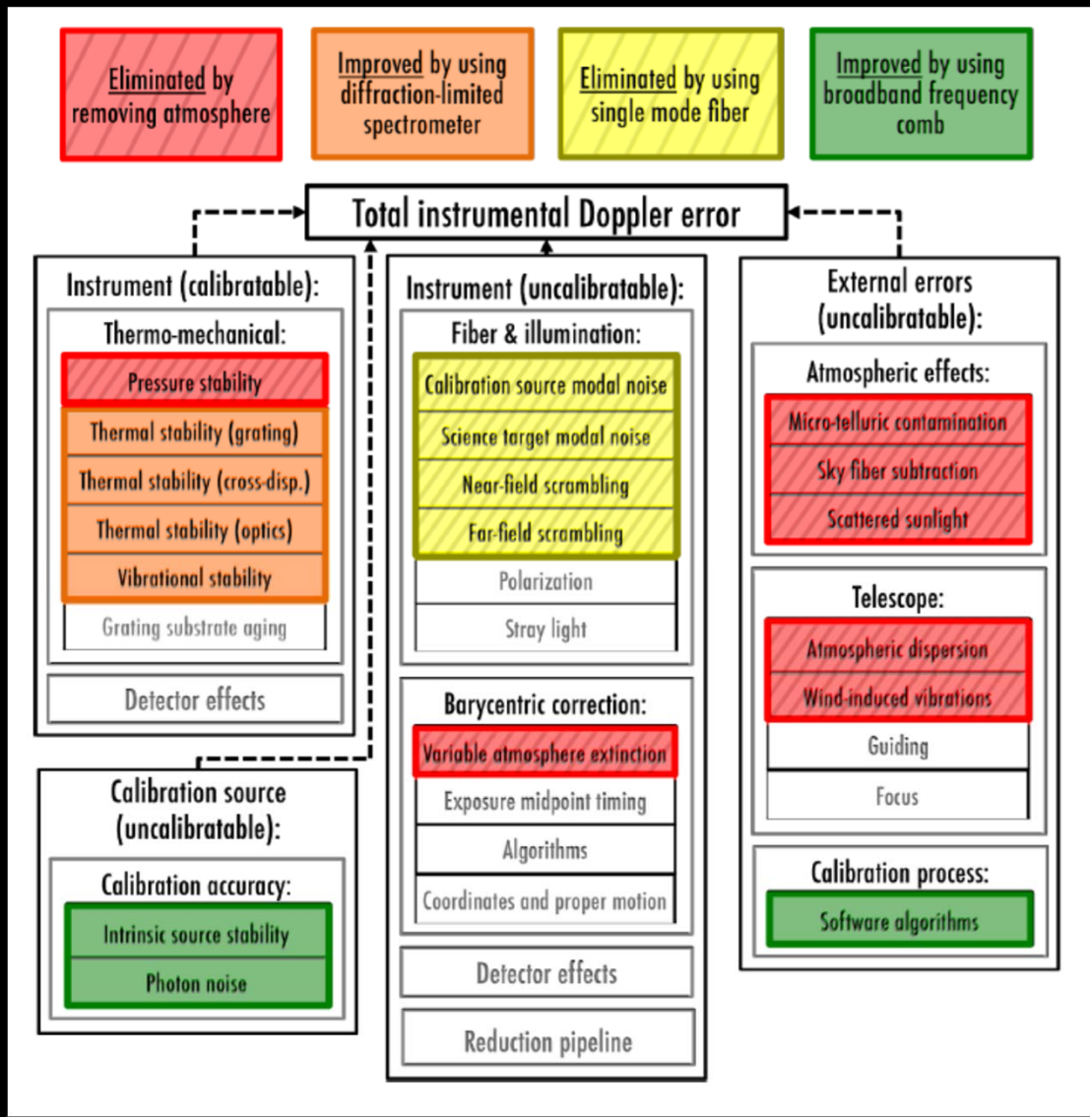
EarthFinder Mission Yield

- Simulated yield from 5 year survey of 63 HabEx targets
  - Simulated planetary systems
  - Simulated space-cadence with EarthFinder field of regard
  - Perfect stellar activity correction
- → Excellent recovery of many systems with 10 cm/s signals!
- Strong ancillary science cases:
  - Asteroseismology
  - Water in the local Universe
  - UV space capability
  - He I 1 µm direct detection spectroscopy
  - And more!



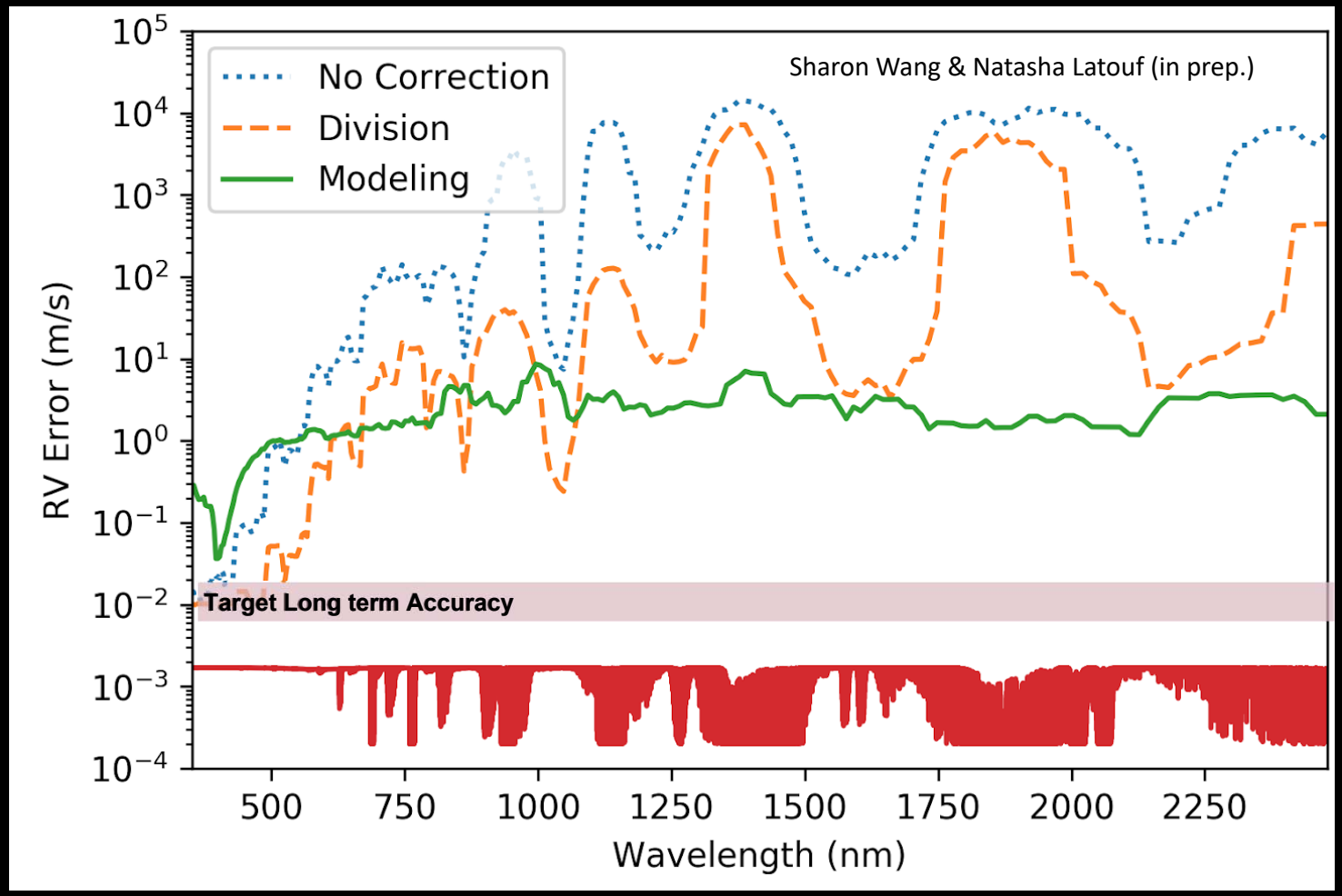
EarthFinder Performance

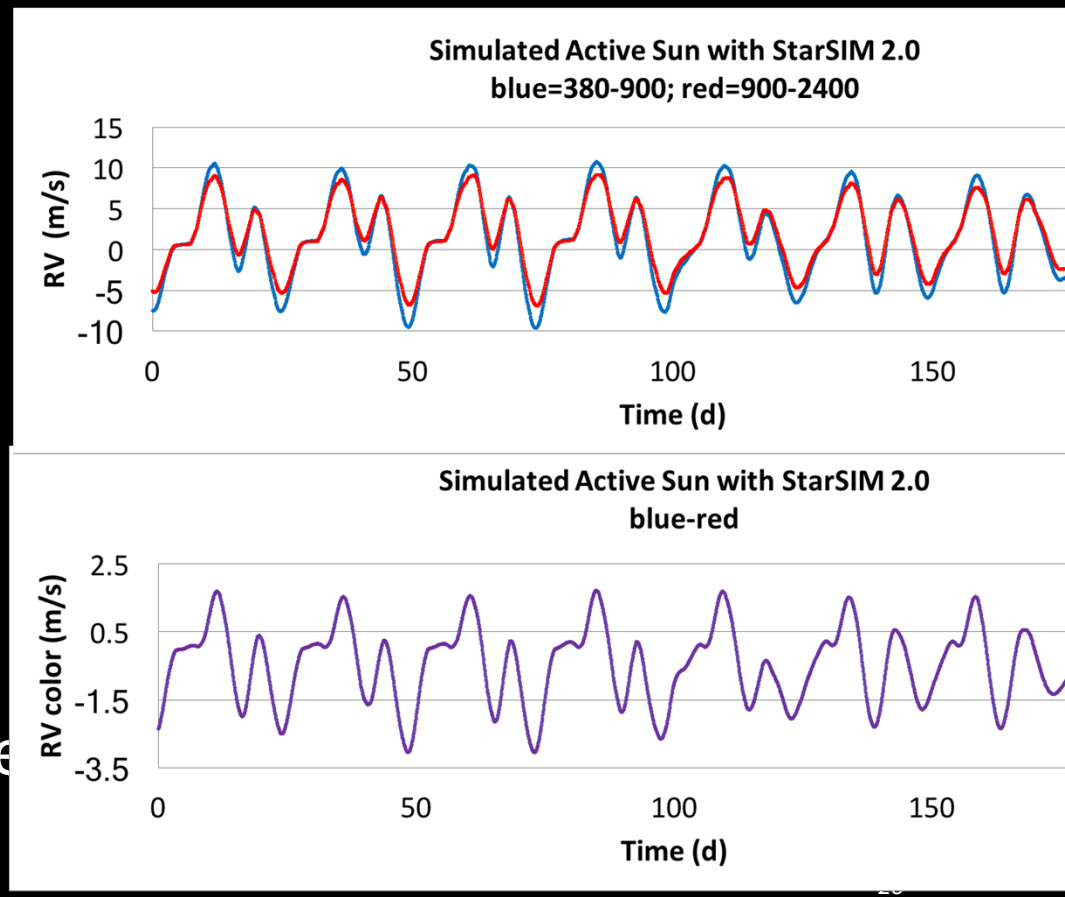
- Diffraction Limited Spectrometer in space eliminates or mitigates many instrumental problems relative to ground-based seeing limited instruments



Will The Earth's Atmosphere Limit RV Precision?

- Yes, if $\lambda > 0.8$ µm necessary to correct stellar activity!
- Earth's atmosphere introduces RV errors of 3 cm/s in the blue, 10 cm/s in the red, & 1 m/s in the NIR



Wavelength Coverage Mitigates stellar Jitter

- Simultaneous RV color subtracts planet signal(s) yielding "clean" measure of chromatic activity!
- To zeroth order, activity RV α RV color, so planet signal is α RV - Cx(RV color)
- Simple model using visible-NIR color shows 61% reduction in stellar activity using only a simple linear-scaling model