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

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Outline of Talk

- What makes Diffraction-Limited Spectrometers so great?
- What makes Diffraction-Limited Spectrometers so hard?
- What (else) are Diffraction-Limited Spectrometers good for?
- How do we stabilize Diffraction-Limited Spectrometers?
- What are ultimate applications of Diffraction-Limited Spectrometers?
- Where do we want to use 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 $D_{grating} = R\,(D_{tel}\,\theta_{slit})/\tan\alpha/2$

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

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

For a diffraction limited system, $\theta_{slit}=\lambda/D_{tel}$, and $D_{grating} = R\,\lambda/\tan\alpha/2$ so instrument optics scale as λ for a given R

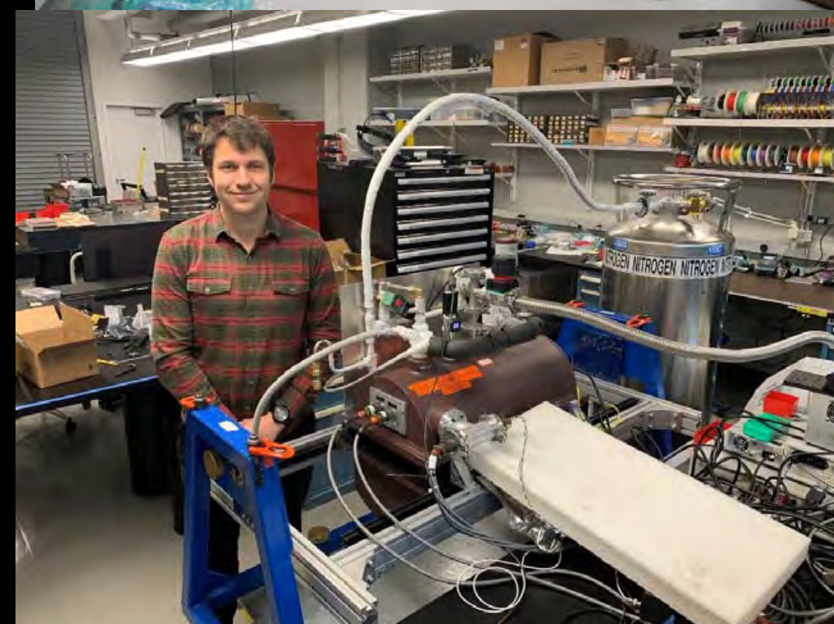
Size of diffraction-limited spectrometer is independent of telescope size making them smaller* and easier to stabilize → less expensive.

**Note to Chris Tinney: R~400,000 no problem!*

Feeding diffraction limited spot into a Single Mode Fiber eliminates modal noise and effects of pointing jitter on Line Spread Function

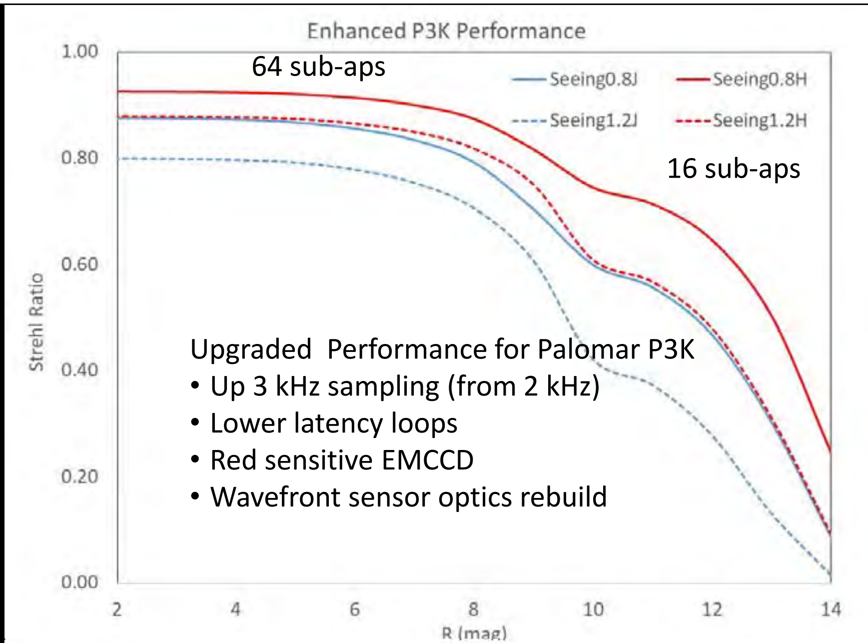
Diffraction-Limited Spectrometers Are Compact

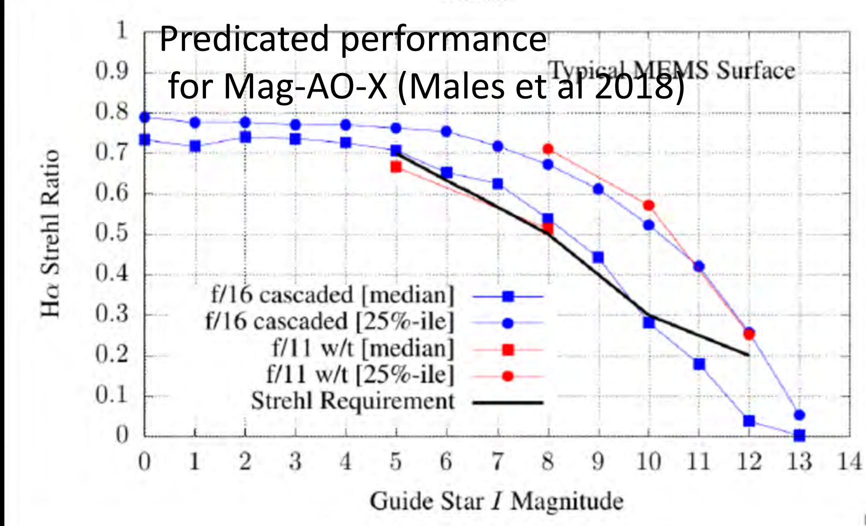
- CFHT/SPIROU
  - R=75,000 with 150 mm pupil with 12x3 mm slices
- HET/HPF
  - R=50,000 with 200 mm pupil
- PALOMAR/KECK/TMT
  - R~100,000 with 25 mm pupil *independent of telescope size*



What makes Diffraction-Limited Spectrometers Hard?

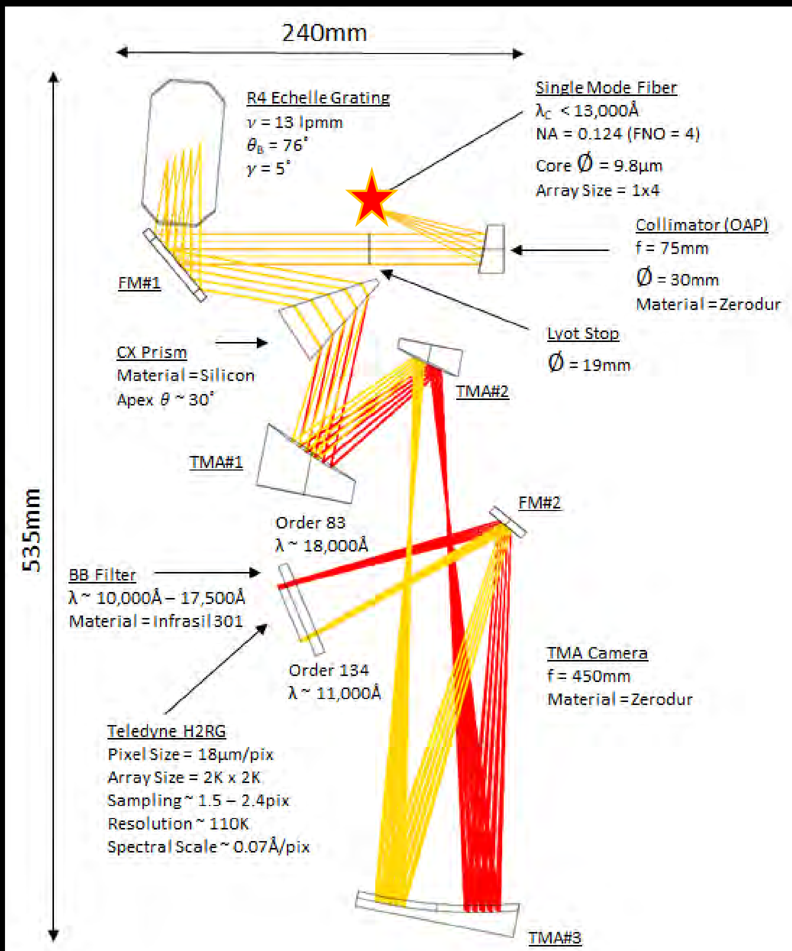
- Feeding spectrometer with diffraction limited beam with high efficiency requires AO with high Strehl
  - Strehl > 50% at λ> J band (Palomar 3k; Burruss et al 2014)
  - Laser Guide Star boosts Strehl for fainter stars
  - Visible AO Strehl > 50% possible at 0.6 μm (Close et al 2014; Males et al 2018)
- PIAA input beam raises coupling efficiency from 59%->87% relative to unapodized beam (Jovanovic et al 2017)
- Goal for overall optical efficiency: >5%





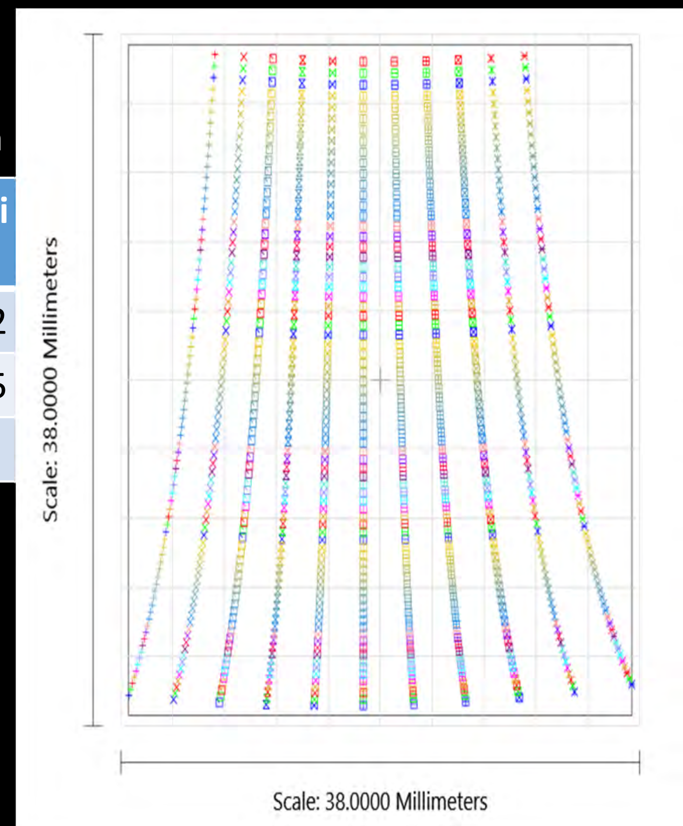
Optical Design for PAlomar Radial Velocity Instrument (PARVI*)

**Multum in PARVO*
or "Much in Little"



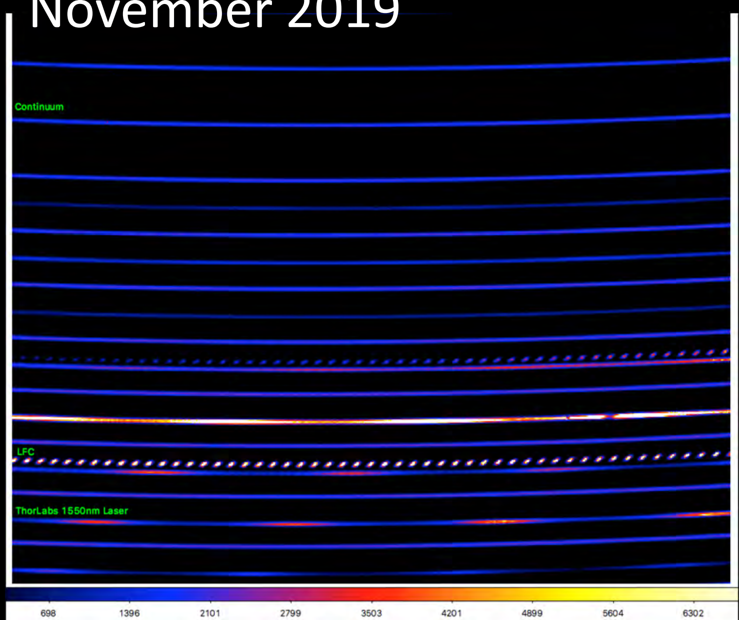
Total Orders: 75
Order Range: 120 – 194
Free Spectral Range: 6nm - 15nm
Spectral Range: 1000 nm - 2500 nm

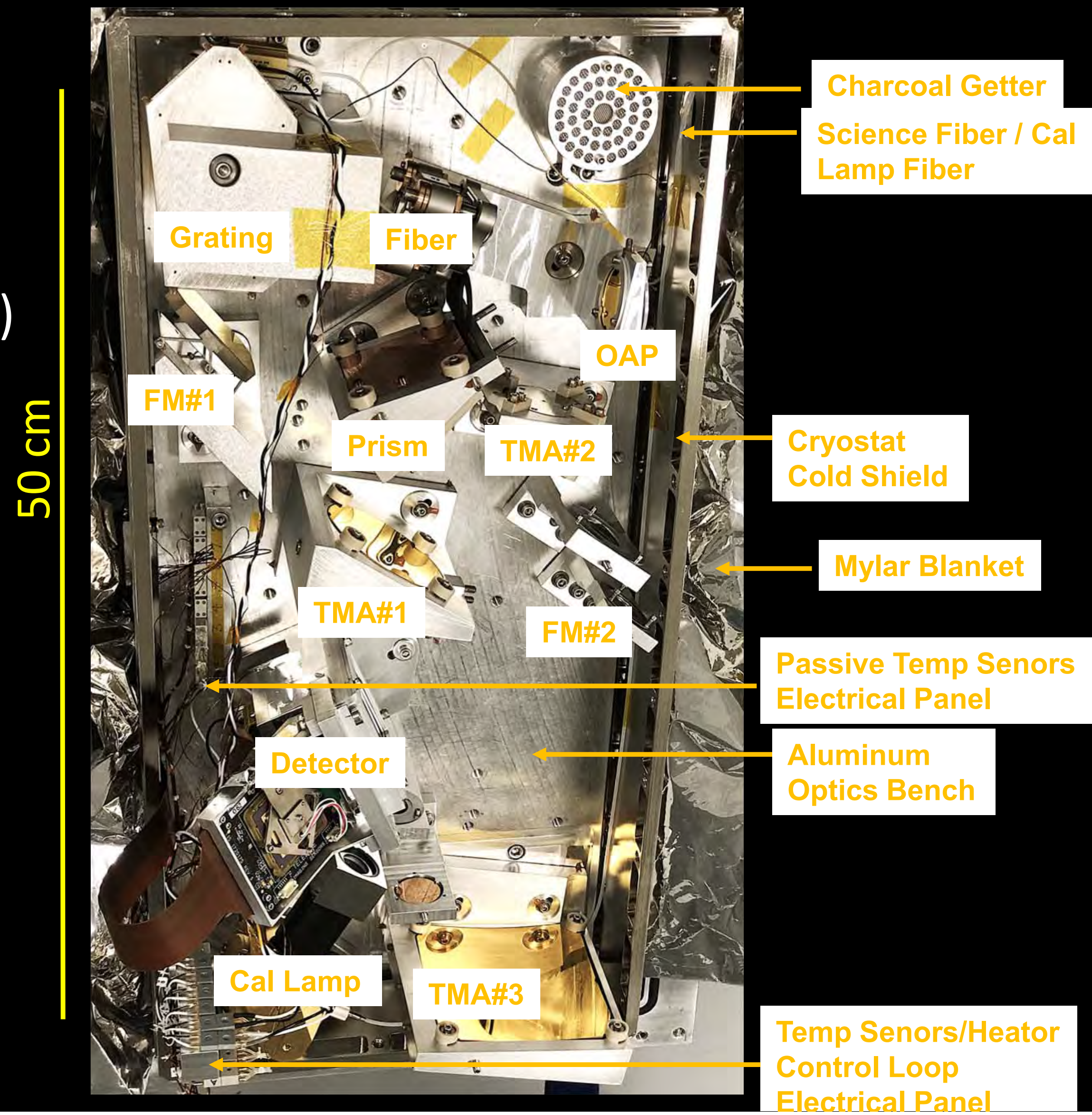
Wavelength (nm)	Sampling (pixels)	Resolution
1110 (J)	1.92	127,942
1368 (J/H)	2.24	109,925
1790 (H)	2.82	87,544



PARVI Build-up in Lab

- Major components (Aluminum or Zerodur) in place with engineering grade R4 grating (Bach Engineering)
- On-going cold testing with H2RG
- On-sky July 2019. Routine ops November 2019

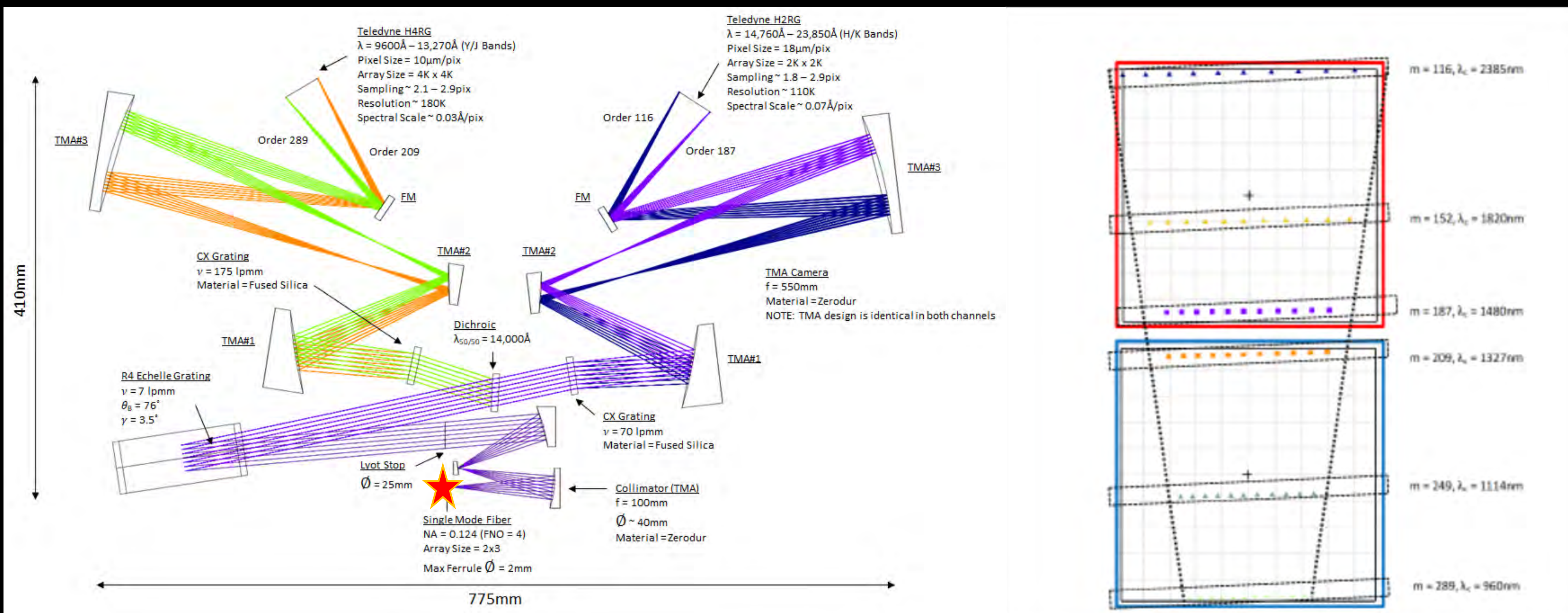




Optical Design for Keck/HISPEC and TMT/MODHIS

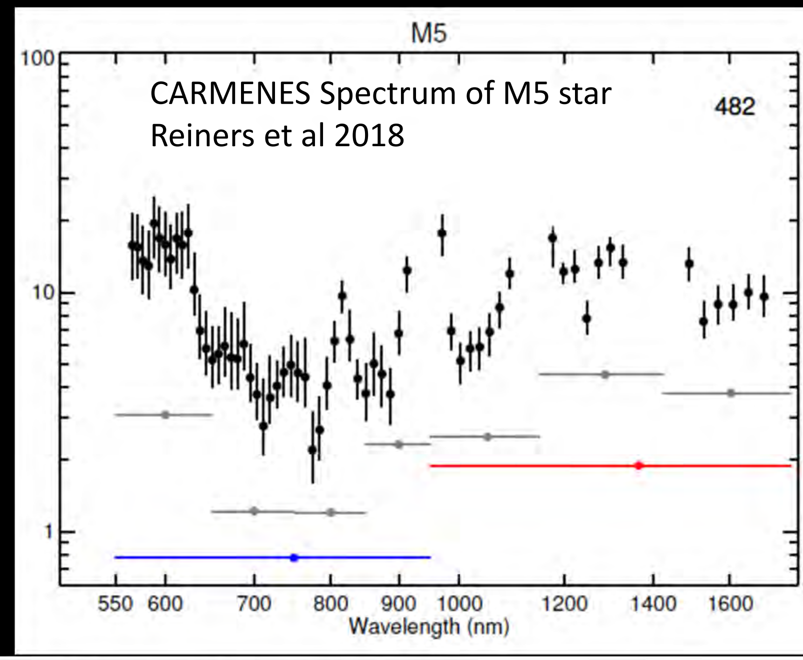
Total Orders: 75
Order Range: 120 – 194
Free Spectral Range: 6nm - 15nm
Spectral Range: 1000 nm - 2500 nm

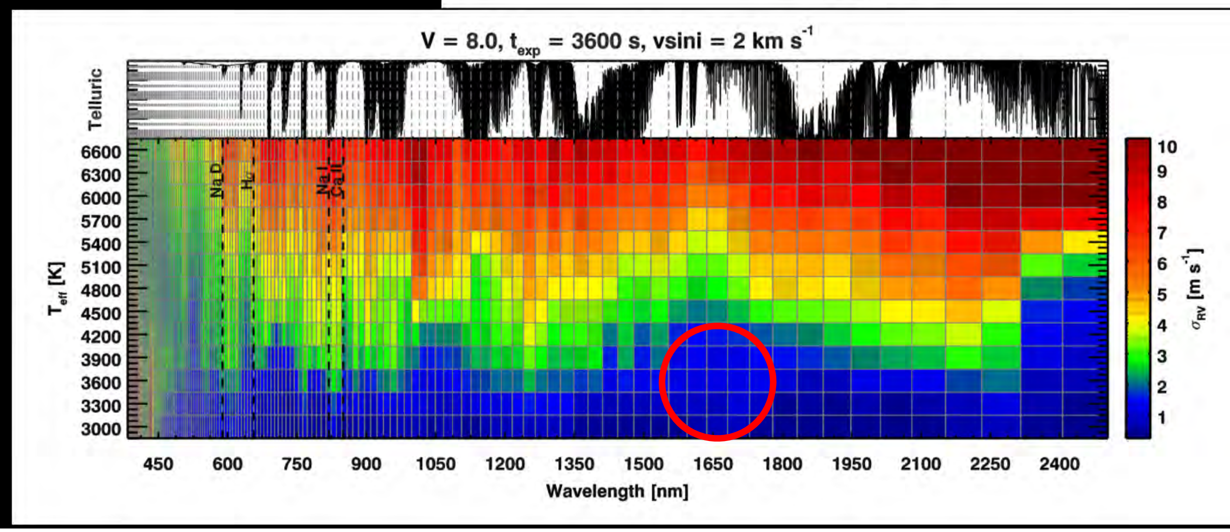
Wavelength (nm)	Sampling (pixels)	Resoluti on
1110 (Y/J)	2-3	196k
1368 (J/H)	2-3	123k
1790 (K)	2-3	91k



What are Diffraction-Limited Spectrometers Good for (PRV)?

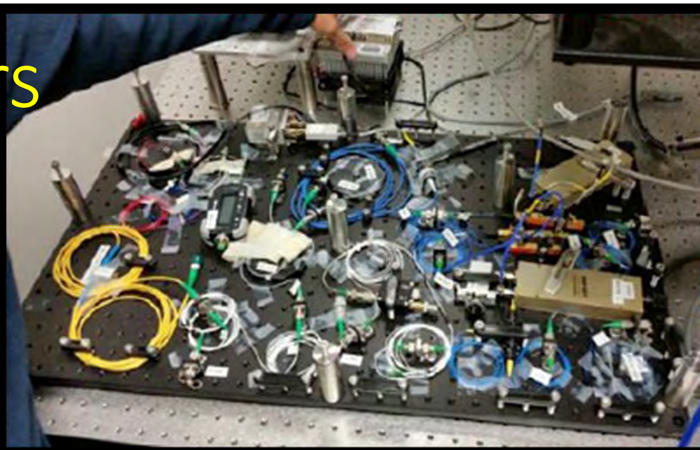
- NIR PRV advantageous for late type (>M5) or for active stars (Reiners et al 2018)
  - Surveys of young stars for hot Jupiters (10s of m/s)
  - Surveys of late type M stars (≥M6) and transit follow-up (1 m/s)
  - Surveys of mature but active stars where lower NIR jitter may reach lower mass planets (1-10 m/s)
  - Transit host star in tight binaries
  - Brown dwarf binaries with LGS
- Vis & NIR spectra at R>150,000 can help mitigate jitter by resolving individual stellar lines (Dumusque et al; Lanza et al; Wise et al --- 2018)

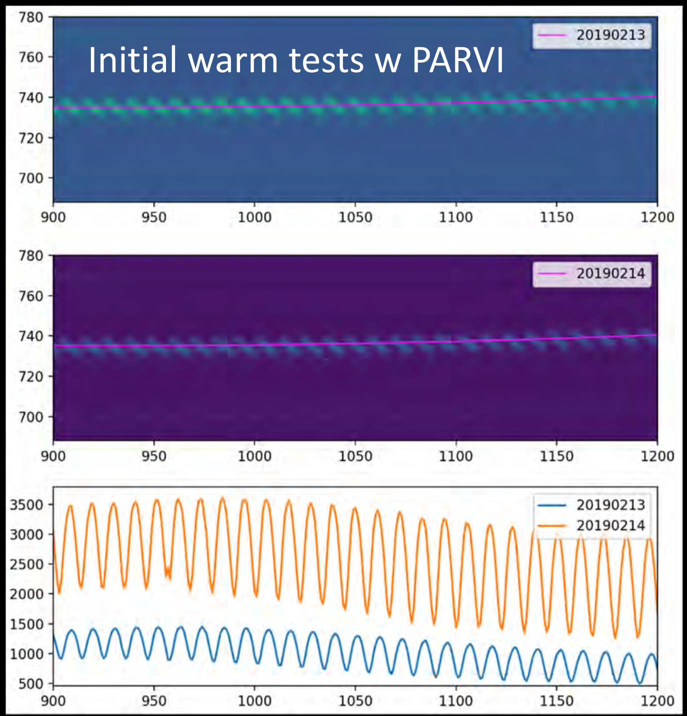


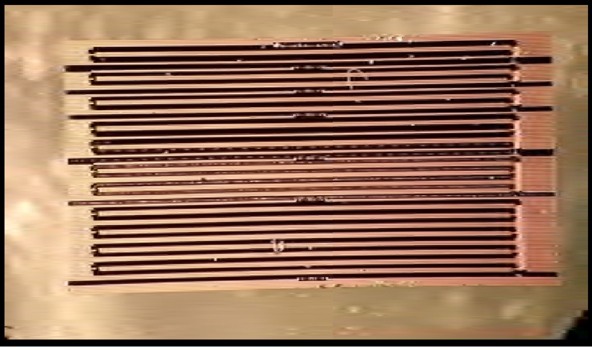


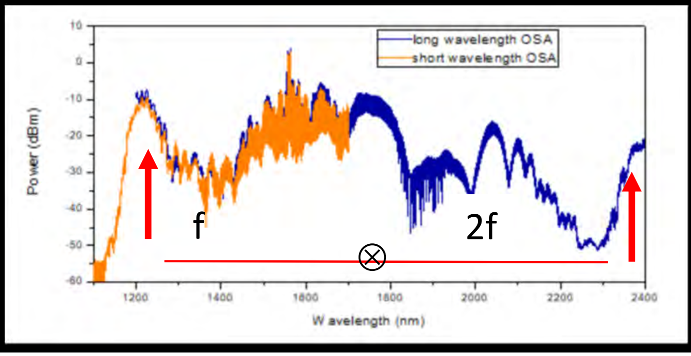
How Do We Stabilize PRV Spectrometers

- In Stage-1:
  - EOM Laser Frequency Comb (LFC) with 12 GHz (0.1 nm) spacing tied to acetylene pump laser (Yi et al 2016) for <30 cm/s precision or a fiber laser comb for <10 cm/s precision (HPF implementation, Halverson 2014)
- In stage 2:
  - Octave spanning comb broadened with SiN waveguide enables f-2f stabilization
  - Heterodyne combination of *f & 2f* generates 1.58 GHz beat tied to Atomic Clock frequency standard (GPS)
  - Stabilization to $<10^{-12}$ (< mm/s)



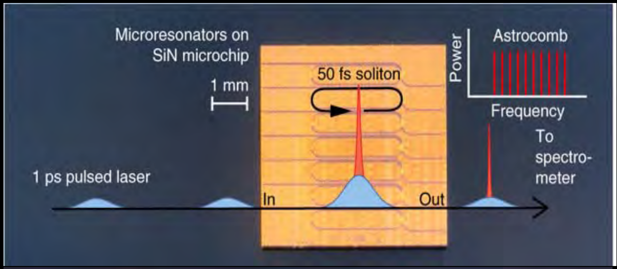


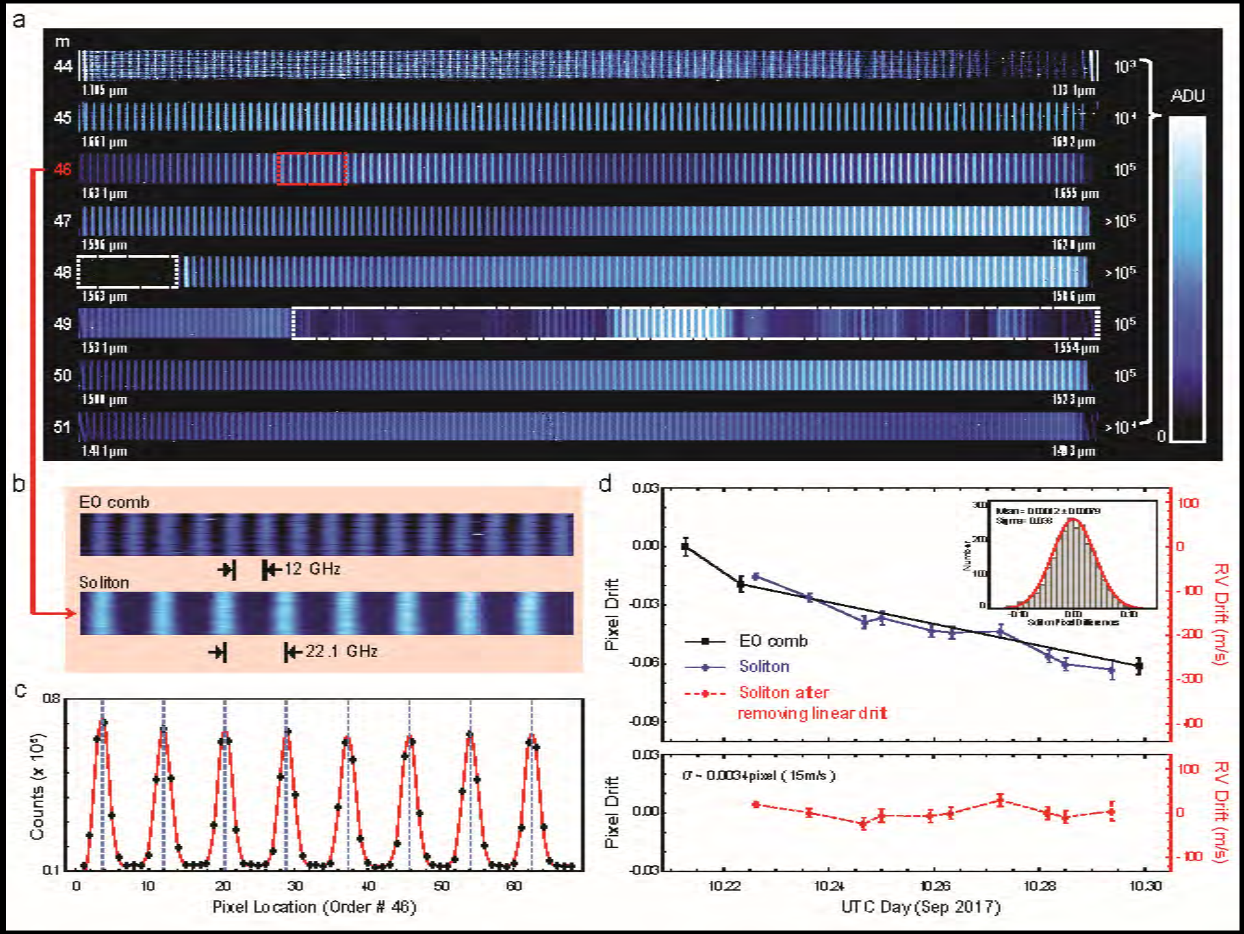




The Future: LFC's on a chip!

- Kerr Soliton microresonator generates LFC on a chip
- Tests at Keck at 1.5 μm (Suh et al 2018) and GIANO-B spectrometer at the Telecopio Nazionale Galileo (TNG) (Obrzud et al 2018)
- Operation from 0.8 to 2.4 μm

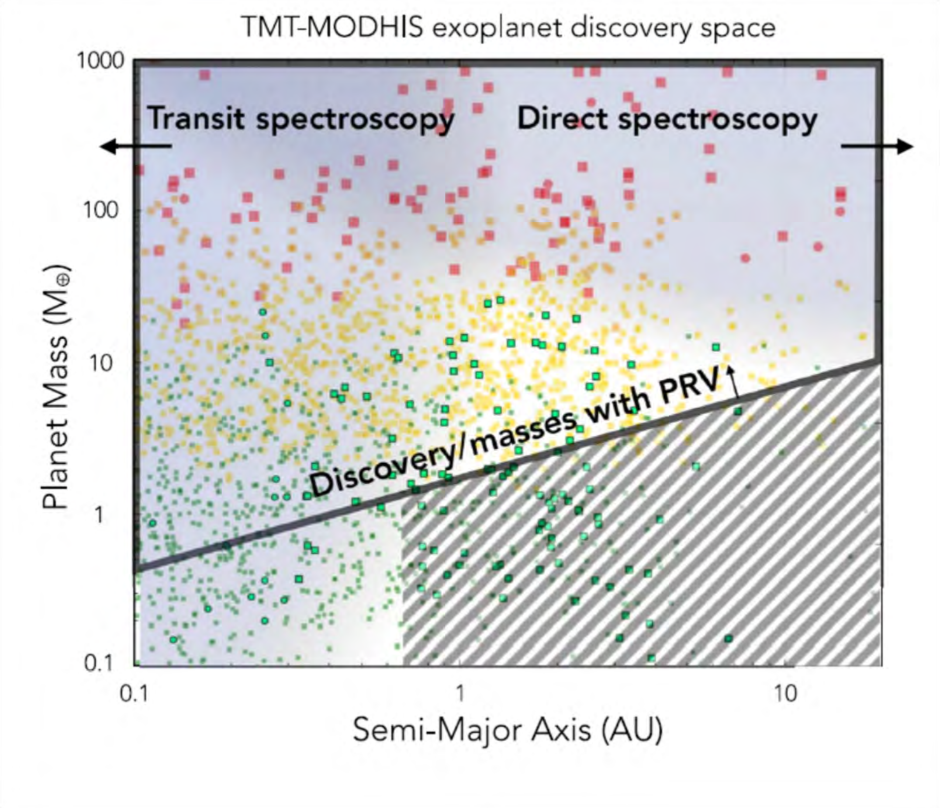




What Else are Diffraction-Limited Spectrometers Good For?

Direct high resolution spectroscopy with or without coronagraphy

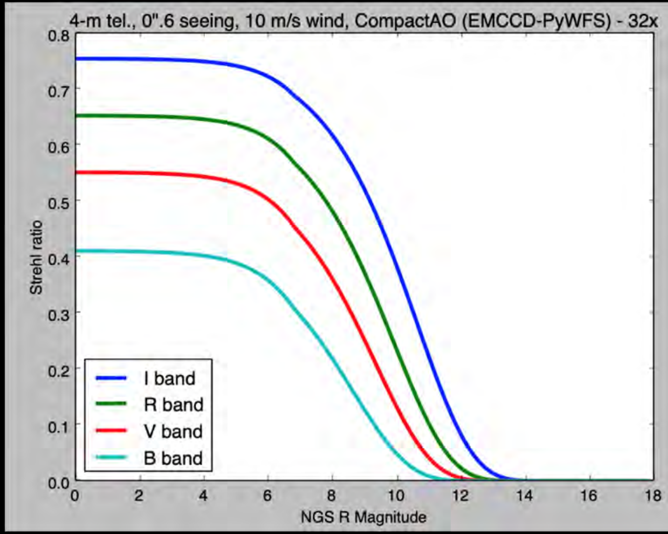
- Turn hot Jupiters into SB2 binaries
- Determine stellar and exoplanet masses
- Map molecule distribution in directly imaged planets
- Measure planet spin (length of day)
- Make Doppler map for cloud dynamics, global circulation, winds, weather
- Determine composition, C/O ratio
- Reflected light using high dispersion spectroscopy + coronagraphy



- *Progression of capabilities from Palomar →LBTI/iLocator → TMT (MODHIS) will advance science from hot Jupiter → Earths orbiting M stars*

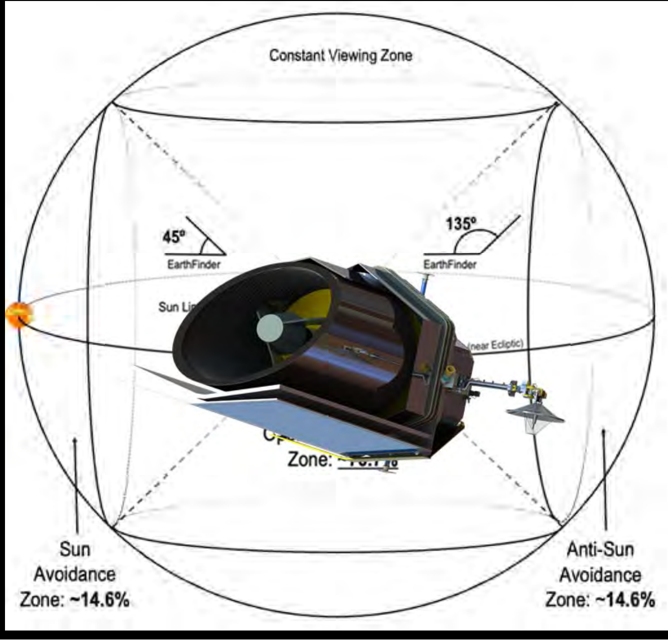
What Are Ultimate Applications of Diffraction-Limited Spectrometers?

- Compact spectrometers for Visible PRV
  - Advanced AO can deliver >50% Strehl for<8 mag
  - Achieve very high resolution (R>150,000) to utilize numerous 4 m telescopes for intensive surveys



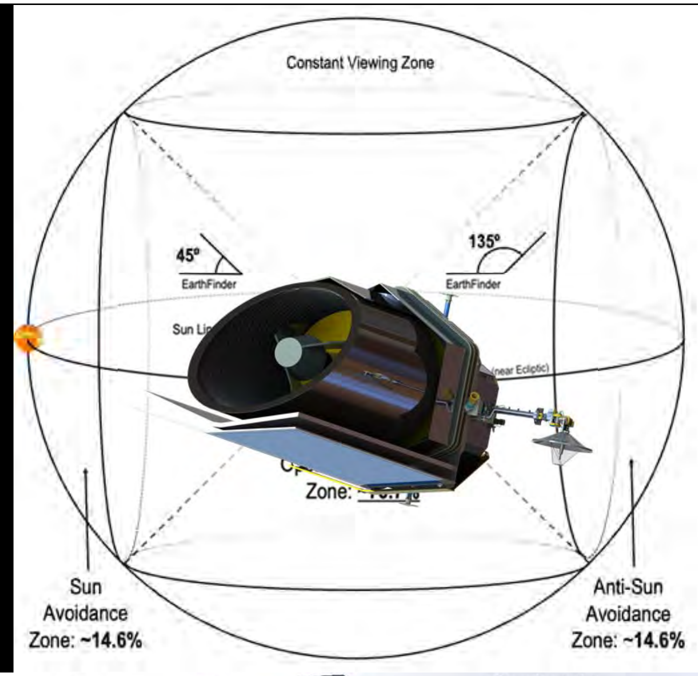
EarthFinder --- A NASA Probe Class Study (Plavchan, PI)

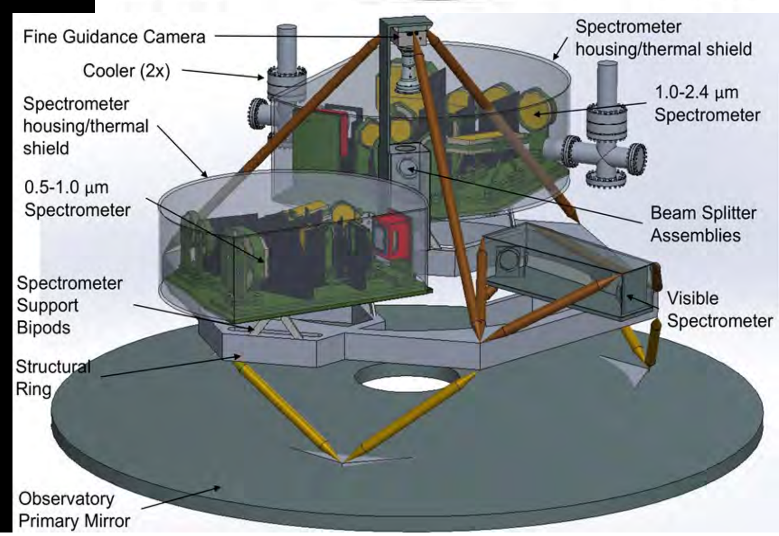
- Evaluate the *scientific rationale* for going to space:
  - What do you gain from space?
    - Bypass limits of Earth's atmosphere in visible & NIR (tellurics)
    - Use broad spectral grasp to "solve" stellar jitter?
    - Improve cadence to minimize day/month/year aliases
- Space telescope offers new paradigm for PRV science essential to achieving <10 cm/s long term precision
  - Wavelength coverage (UV to NIR) at R ~150,000
  - High observing cadence to minimize aliasing



EarthFinder: Taking PRV to Space

- Study brightest 50 targets for imaging missions
- 1.45 m telescope in Earth-trailing/L2 orbit
  - Visible Spectrometer: 0.4-0.96 μm at R=170,000 (0.6/λ)
  - Near-IR Spectrometers: 0.96-2.4 μm at R=170,000 (1.6/λ)
  - Small UV Spectrometer for MgII chromospheric activity: 0.28-0.38 μm
- No Telluric atmospheric effects ☺
- Extreme Resolution and λ coverage to reduce jitter
  - R>150,000 & continuum normalization for line analysis
  - Vis-NIR color to isolate jitter from Doppler signals
- L2 Orbit for Instrument Stability
  - Line Spread Function from single mode fibers
  - mK thermal control for <10 cm/s measurement accur.
  - Micro-resonator LFC for 1 cm/s long term stability
- High cadence (70% of sky >180d; 30% CV) reduces aliasing



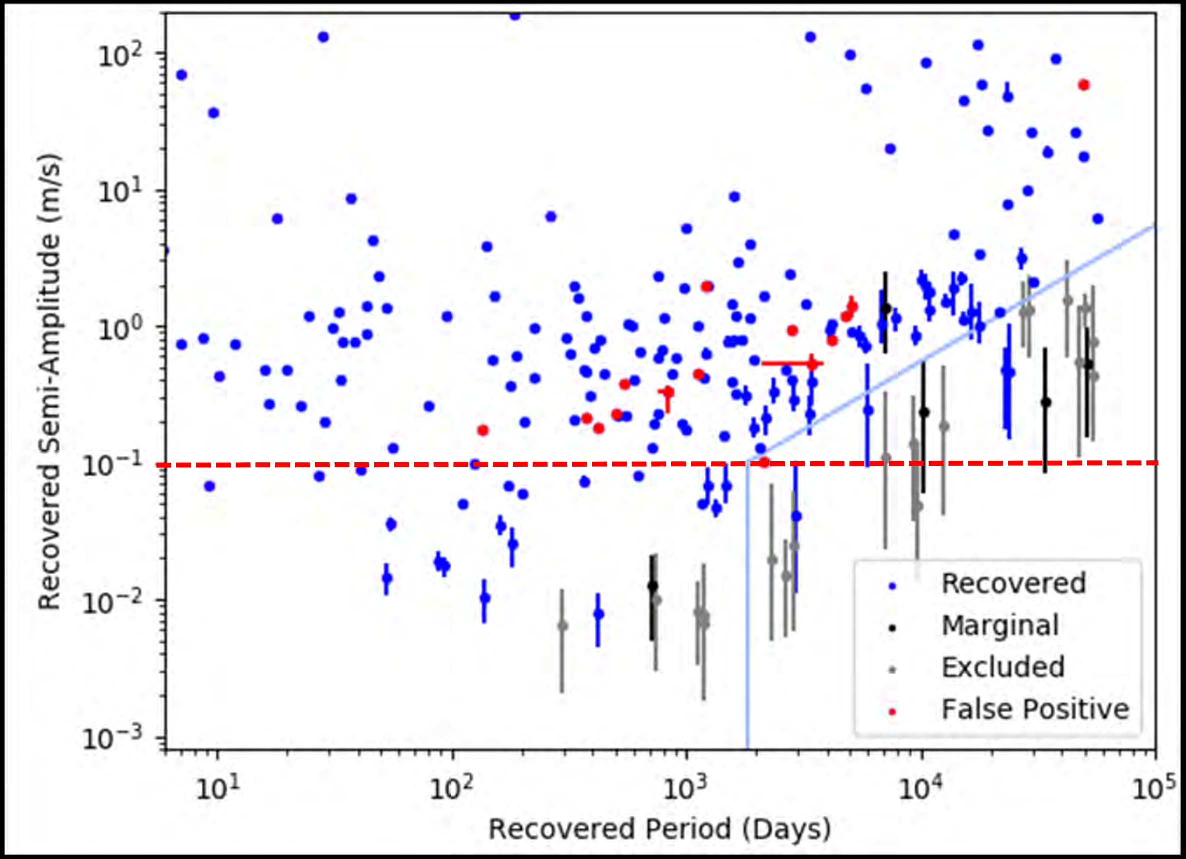


EarthFinder Yields HZ Earth Analogs

- 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 stars and BDs
  - UV spectroscopy from space
  - He I 1 μm direct detection
  - And more!



Where Do We Want To Put Diffraction-Limited Spectrometers?

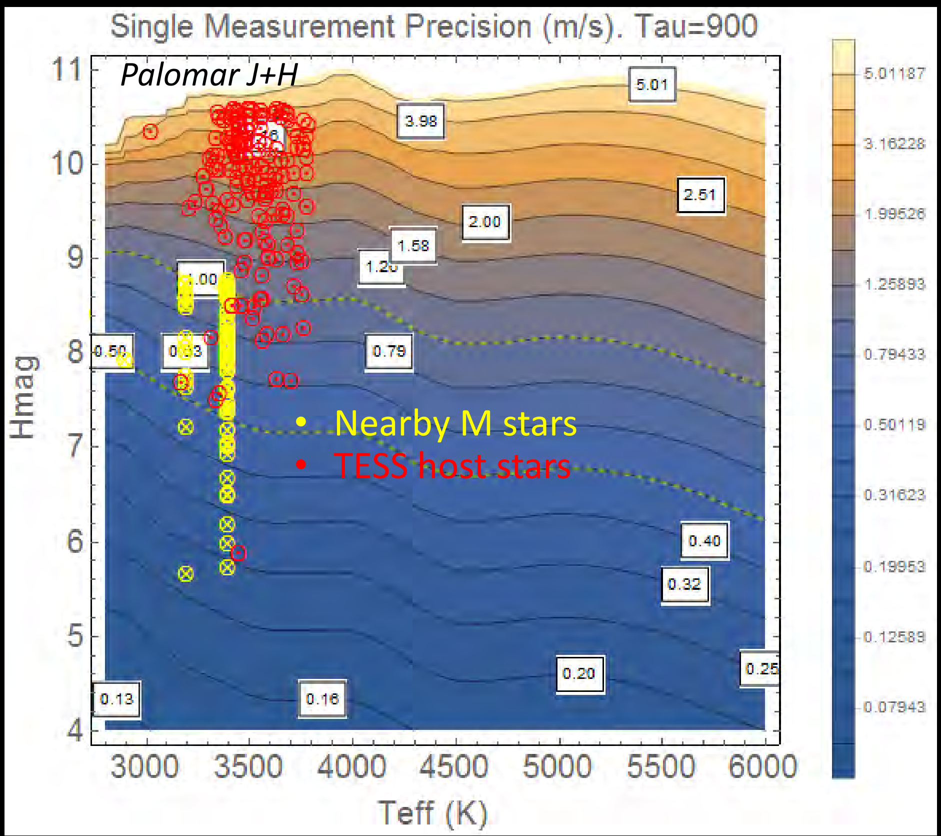
Everywhere!

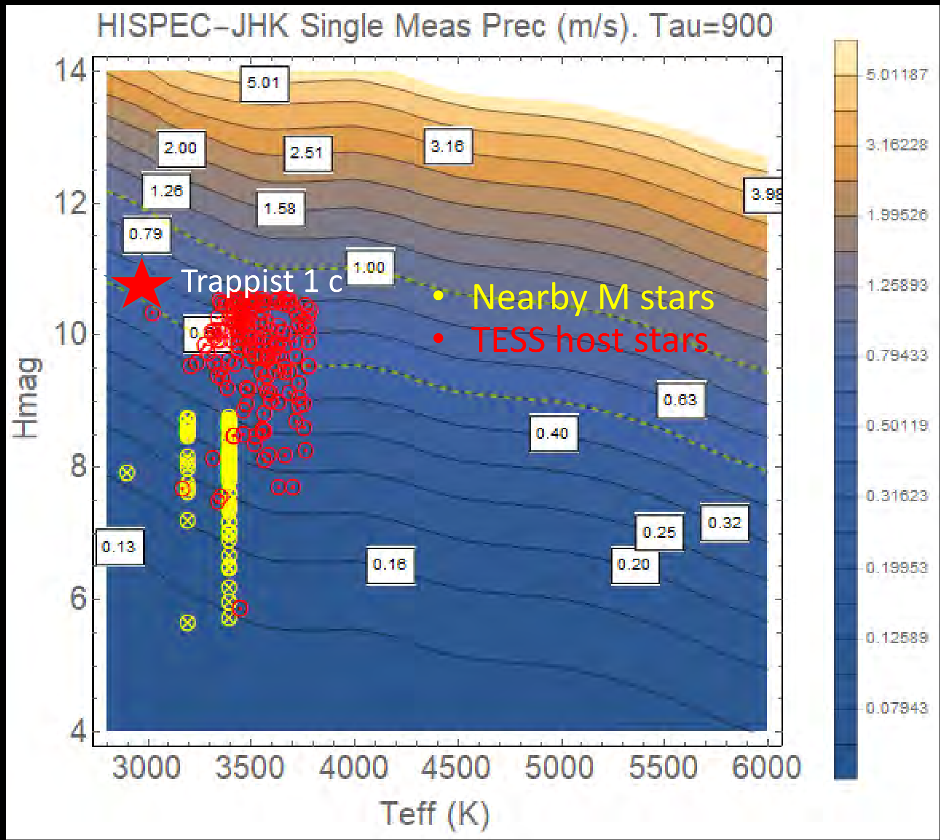
[redacted]

Backup

Single Measurement Precision at Palomar and Keck

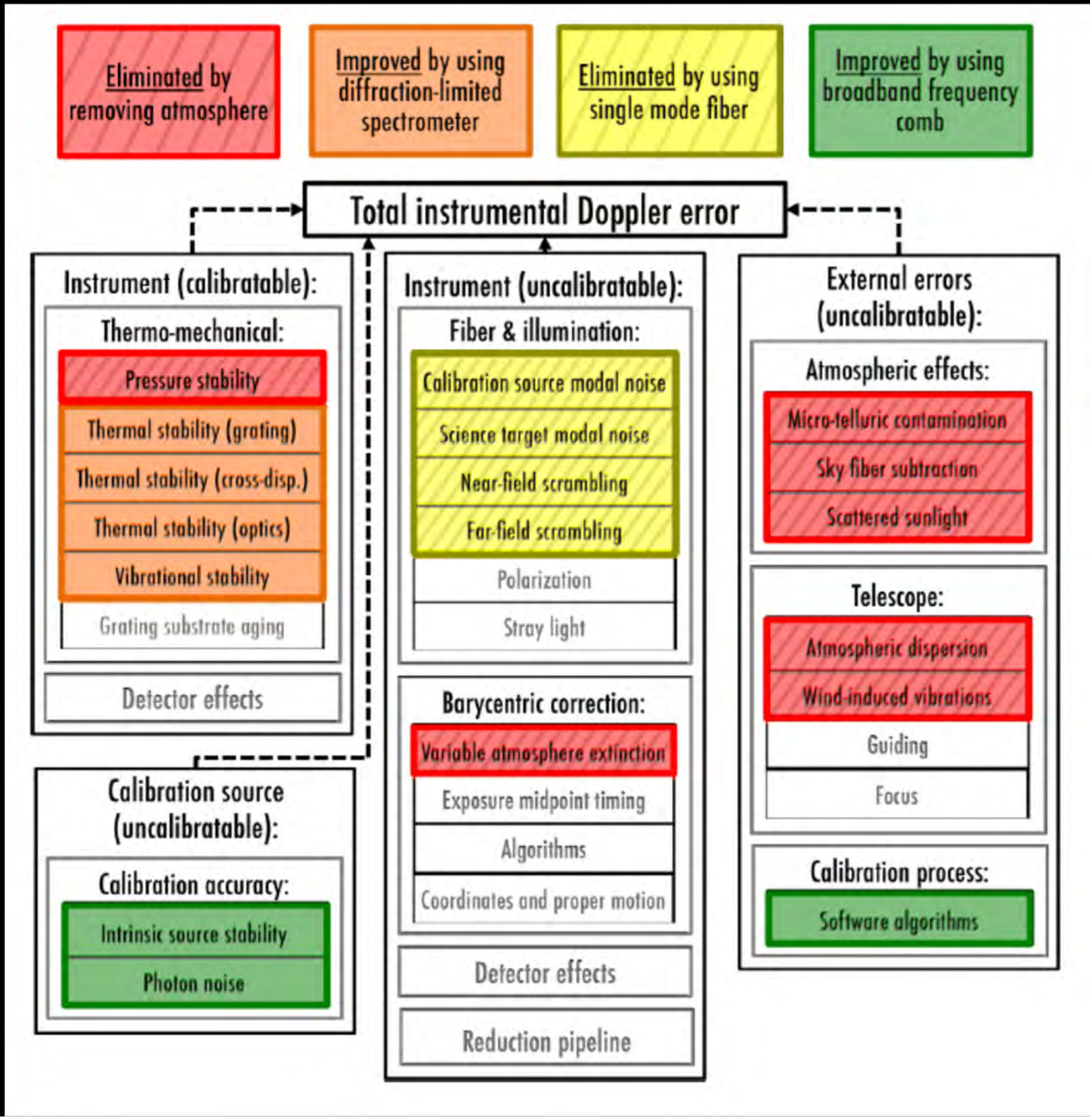
Photon limited single measurement precision at Palomar/PARVI (J+H) and Keck/HISPEC (H-only) is at or below 1 m/s although atmosphere may limit to ~1-3 m/s depending on H_2O





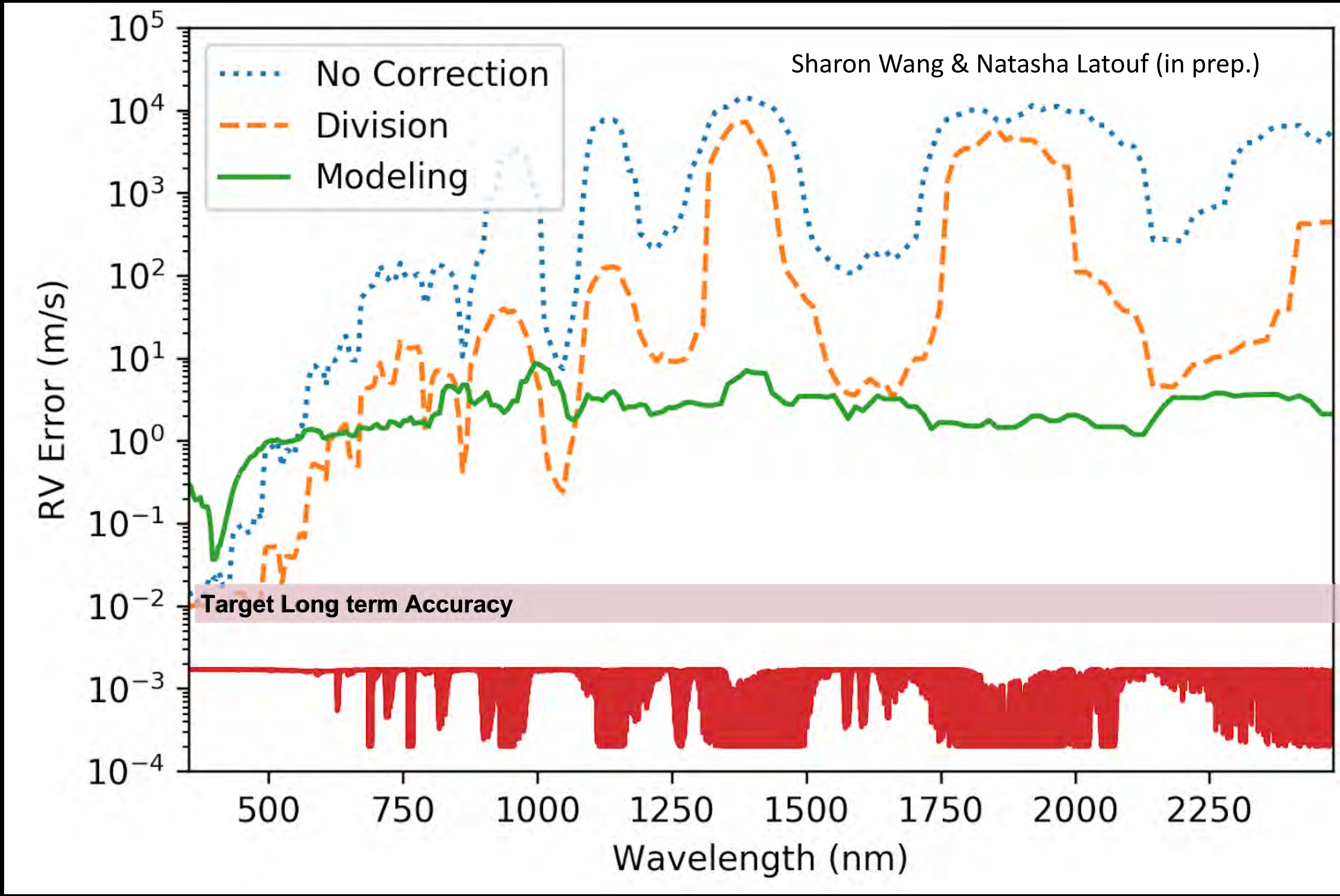
EarthFinder Performance

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



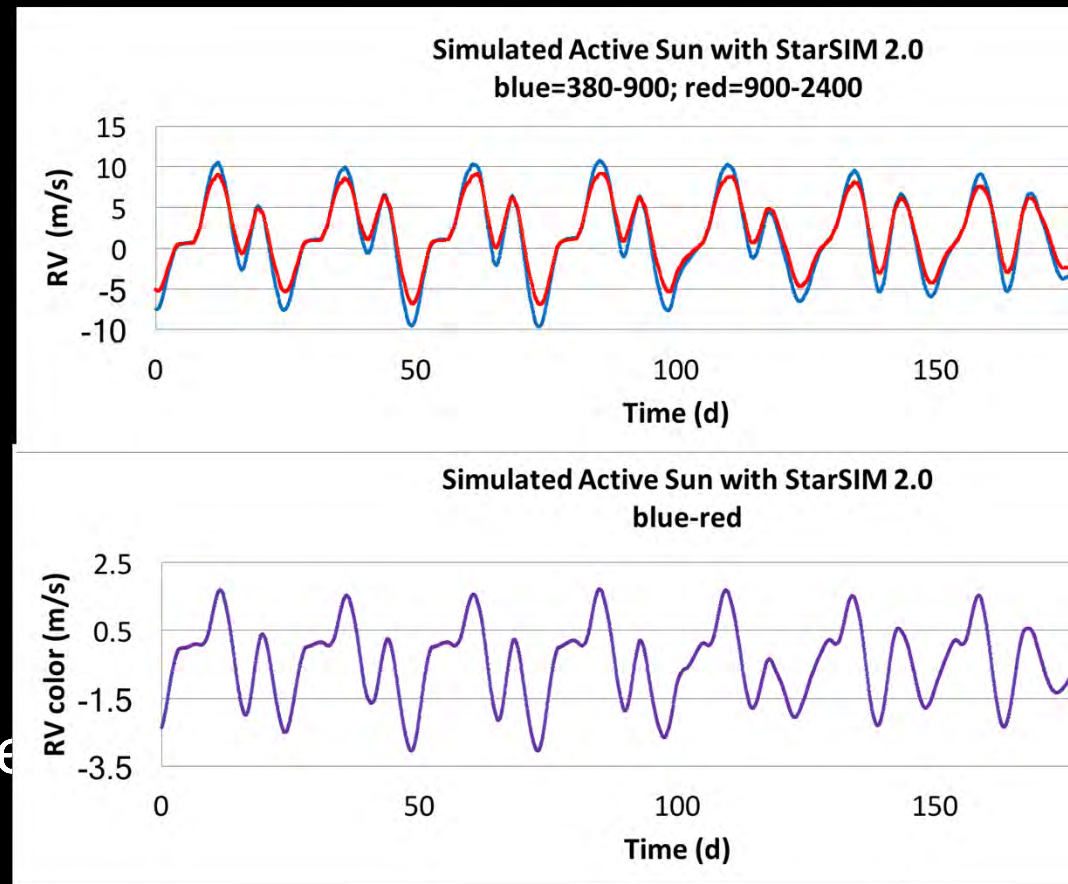
Will The Earth's Atmosphere Limit RV Precision?

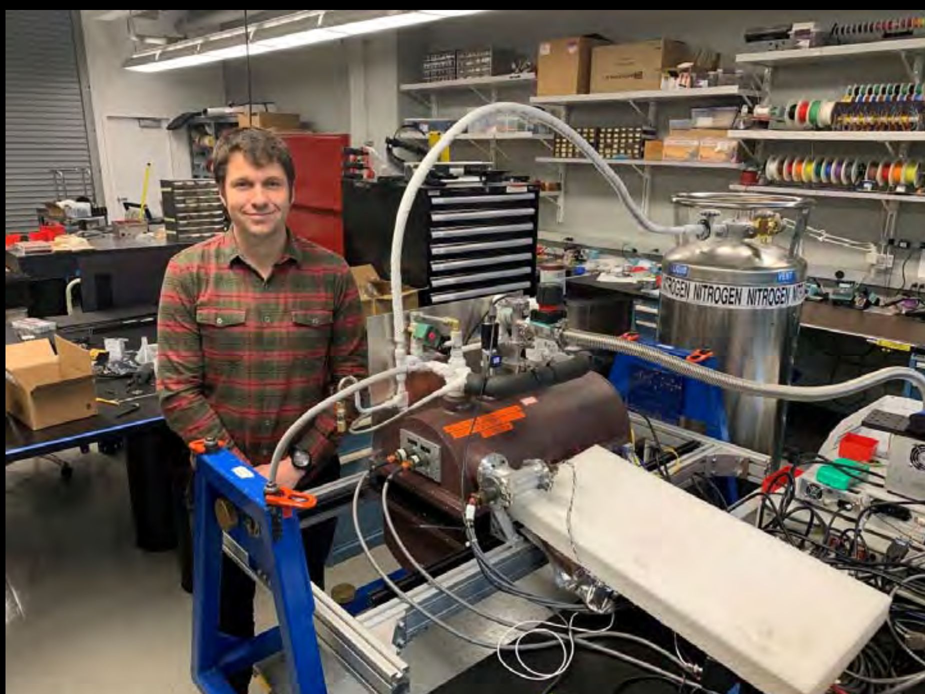
- Yes, if $\lambda > 0.8$ µm necessary to correct stellar activity!
- Earth's atmosphere introduces RV errors of 3 cm/s in the blue, 10 cm/s in the red, & 1 m/s in the NIR



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

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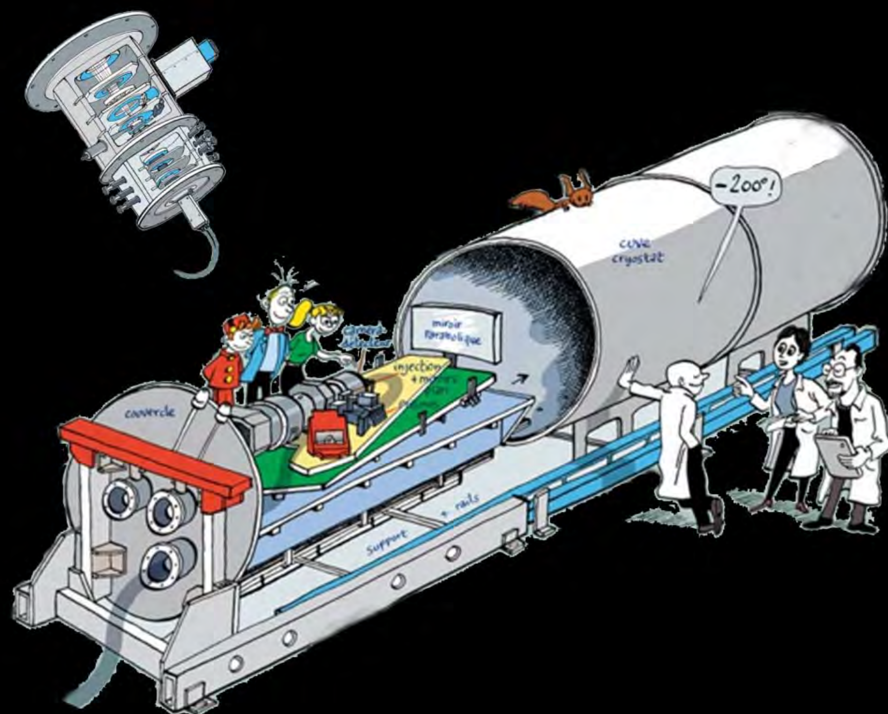
-200°!
cuve
cryostat
miroir
parabolique
couvercle
support
+ rails