PARVI: The Palomar Radial Velocity Instrument

a metamorphosis of P1640

G. Vasisht, Jet Propulsion Laboratory, California Institute of Technology

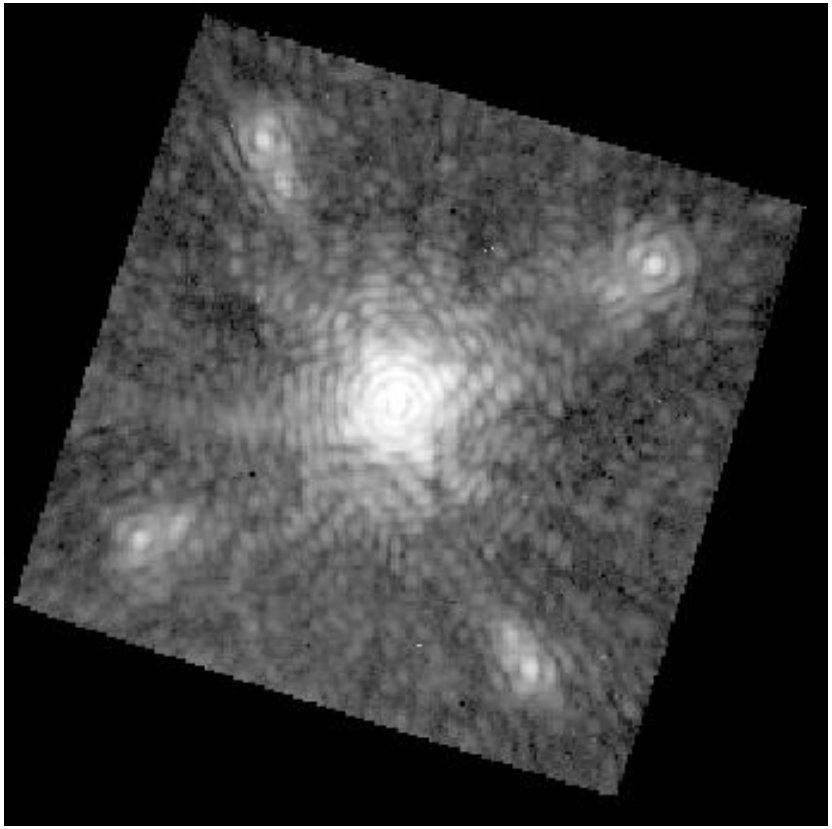
Why now?

- P1640 ends 2017A
- A new backend for Palm 3000
  - With a softer application
- JPL interested in an investment in exploratory PRV

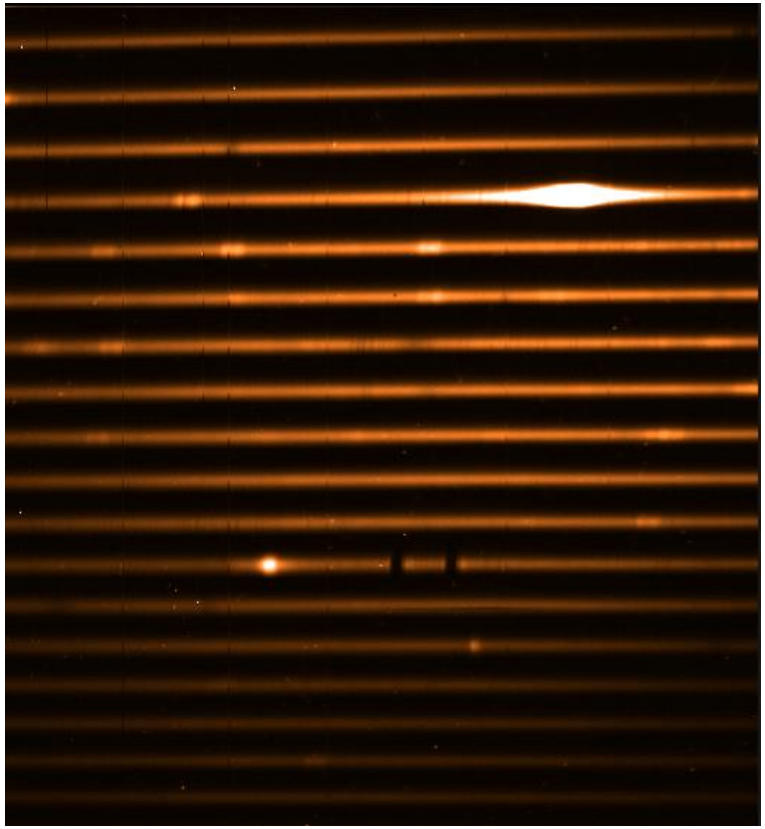
Why Palomar?

- JPL is interested in giving away it’s P200 share in larger strategic chunks

P1640/PARVI metamorphosis



1-Strehl



Strehl

RV Spectrographs

Instrument	Telescope	Measurement precision, Spectral Grasp, Resolution	PI; (relevant publications) / First Light
APF	Lick 2.4 m	1 m/s, 374-970 nm, R=120k / 490-600 with iodine cell	Vogt; (Vogt et al. 2014, Radovan et al. 2010) / 2013
CHIRON	Chile	0.5 m/s over 10 days, 2 m/s over 2 years, R~90k,130k	Debra Fischer; Commissioned 2012; Tokovinin et al (2013)
CODEX	E-ELT	2 cm/s, 370-710 nm, R=120k	Pasquini; (Delabre & Manescau 2010; Pasquini et al. 2010a,b, 2008) / ~2025
Coralie	Euler Swiss Telescope	2 m/s, 391-681 nm, R=50k	(Queloz et al. 1999) / 1998
ESPRESSO	VLT	10 cm/s (5 cm/s), 380-686 nm, R=120k (220k)	Pepe; (Spanò et al. 2012, 2008; Pepe et al. 2010) / 2016
EXPRES	DCT	10 cm/s, 380-700 nm, R~200k	Fischer; 2016-2017
G-CLEF	GMT	20 cm/s, 350-950 nm, R=120k / also MOS mode	Szentgyorgyi; (Szentgyorgyi et al. 2012) / 2021
Hamilton Echelle	Lick: Shane 3m CAT 0.6m	3 m/s, 340-900 nm, R=60-100k, 490-600 with iodine cell	Vogt; (Vogt 1987) / 1986

HARPS-N	TNG 3.6 m	1 m/s, 380-680 nm, R=110,000k	Pepe; (Cosentino et al., 2012, 2014; Langellier et al. 2014) / 2012
HARPS	ESO 3.6 m	1 m/s , 380-680 nm, R=110,000k	Pepe; (Pepe et al. 2000, 2003; Rupprecht et al. 2004, Lovis et al. 2006) / 2002
HIRES	Keck 10 m	2 m/s, 360-1000 nm, R=85k / 490-600 with iodine cell	Vogt; (Vogt et al. 1994) / 1996
HRS	HET	2.5 m/s, 390-1100 nm, R=120k	MacQueen; (Tull et al. 1998) / 2001
LCOGT NRES	Global network of 6 spectrometers	~1-3 m/s, 390-860 nm; R~53k	(Eastman et al. 2014) / 2015-2016
MINERVA	Mt Hopkins 4x0.7 m	~1 m/s, 500-650 nm, R~50k	John Johnson (Swift et al. 2015) / 2015
SHREK	Keck 10 m	1 m/s, 440-590 nm, R=85k / red channel later	Howard & Marcy; (http://nexsci.caltech.edu/keck_strategic_planning_Sep2014.pdf)
Sophie	1.93 m Haute-Provence	3 m/s, 387-694 nm, R=75k	(Perruchot et al. 2008) / 2006
TRES	Whipple Obs 1.5 m	15 m/s, 380-900 nm, R=44k	Szentgyorgyi; (Szentgyorgyi & Furesz 2007) / 2007
Tull Echelle	2.7 m Harlan J. Smith	340-1090 nm, R=60k, 240k	Phillip MacQueen;

Red and Infrared Spectrometers

Instrument	Telescope	Measurement precision, Spectral Grasp, Resolution	PI or relevant publication, First Light
APOGEE	2.5-m Sloan Foundation Telescope	~10 m/s, MOS, 1.51-1.70 microns, R=22.5k	Deshpande et al. (2013)
CARMENES	Calar Alto	~3 m/s; 0.5-1.8, microns, R~80k	Quirrenbach et al. (2012), 2016
CRIRES	VLT	5 m/s, K-band, R~100k	Bean et al. (2010)
CSHELL	IRTF	5 m/s short term, 35 m/s long term, K-band R=46k	Anglada-Escude et al. (2012b), Plavchan et al. (2013a,b)
ESPaDOnS	CFHT	0.3-1 microns, R~70k	Jean-Francois Donati
HPF	HET	~3 m/s, YJ bands R~50k	Mahadevan et al. (2012)
iSHELL	IRTF	~2-3 m/s, HK bands R~75k	Rayner et al. (2012), 2016
iGRINS	Harlan Smith @ McDonald	HK bands, R~40k	Dan Jaffe, (Yuk et al. 2010)
iLocater	LBT	20 cm/s, 0.95-1.10 microns, R=150k	Justin R. Crepp, in design study phase
MINERVA-RED	Mt Hopkins 2x0.7 m	< 1 m/s, 0.8-1.0 microns	Cullen Blake, spectrometer in lab testing phase
NIRSPEC2	Keck	J,H,K,L or M band, R~50k	Ian McLean, in design study phase
SPIRou	CFHT	0.98-2.35 microns, R~70k	Thibault et al. (2012), 2017

PARVI: Basic Characteristics

- Near IR wavelengths (AO fed)
  - Relative unexplored space

PARVI: Basic Characteristics

- Near IR wavelengths (AO fed)
  - Relative unexplored space
- High Spectral Resolution R > 100,000
  - Upgradeable to R of 200,000

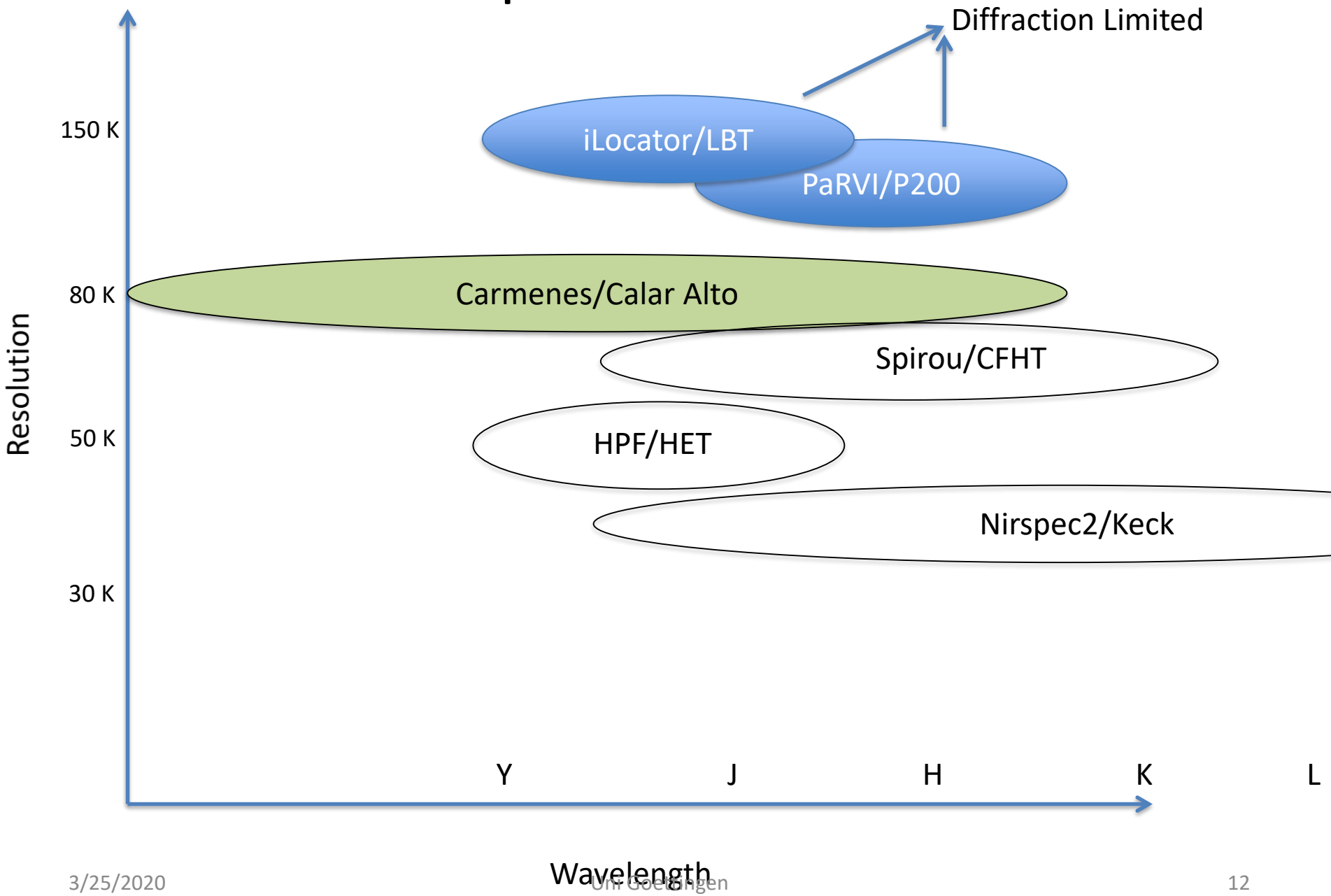
PARVI: Basic Characteristics

- Near IR wavelengths (AO fed)
  - Relative unexplored space
- High Spectral Resolution R > 100,000
  - Upgradeable to R of 200,000
- Highly stable spectrograph
  - Better than 20 cm/s
  - 1 cm/s with upgrades

PARVI: Basic Characteristics

- Near IR wavelengths (AO fed)
  - Relative unexplored space
- High Spectral Resolution R > 100,000
  - Upgradeable to R of 200,000
- Highly stable spectrograph
  - Better than 20 cm/s
  - 1 cm/s with upgrades
- Modest budget
  - But reliant on past investment

PARVI in R-λ space



Large Aperture

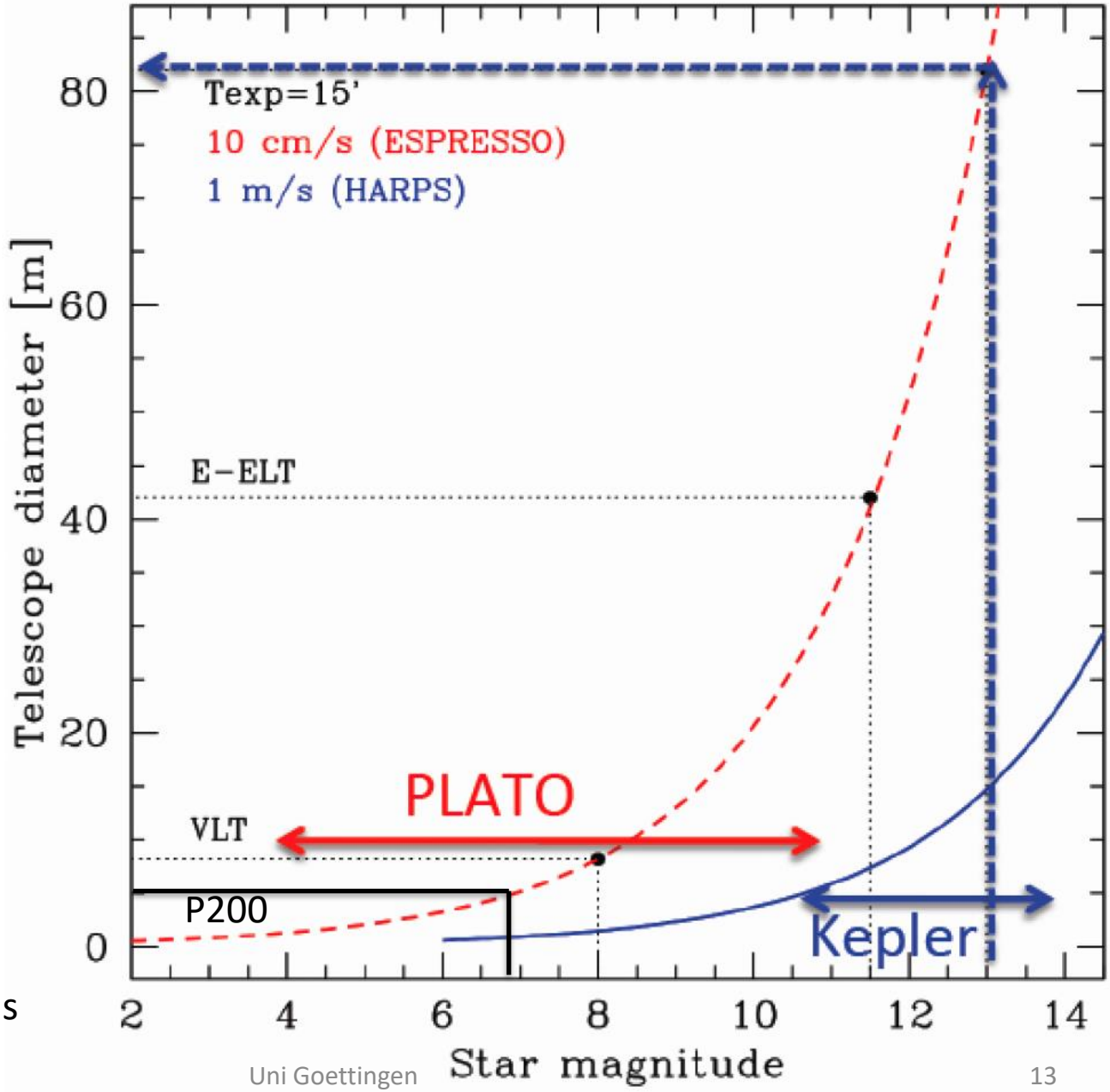


Fig. adapted from
C. A. Watson
and H. Cegla PhD Thesis

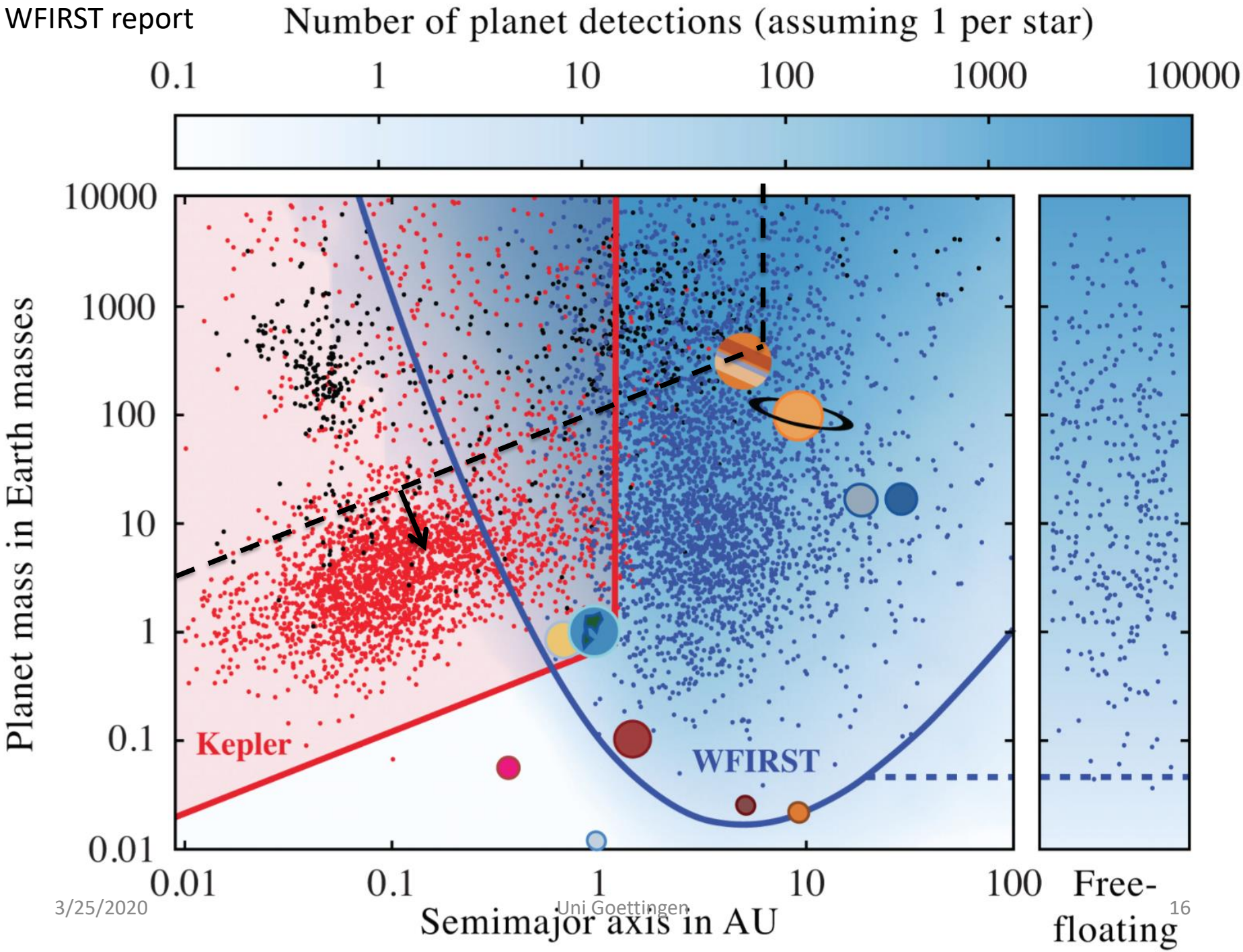
Remainder of the talk

- Science
- Implementation

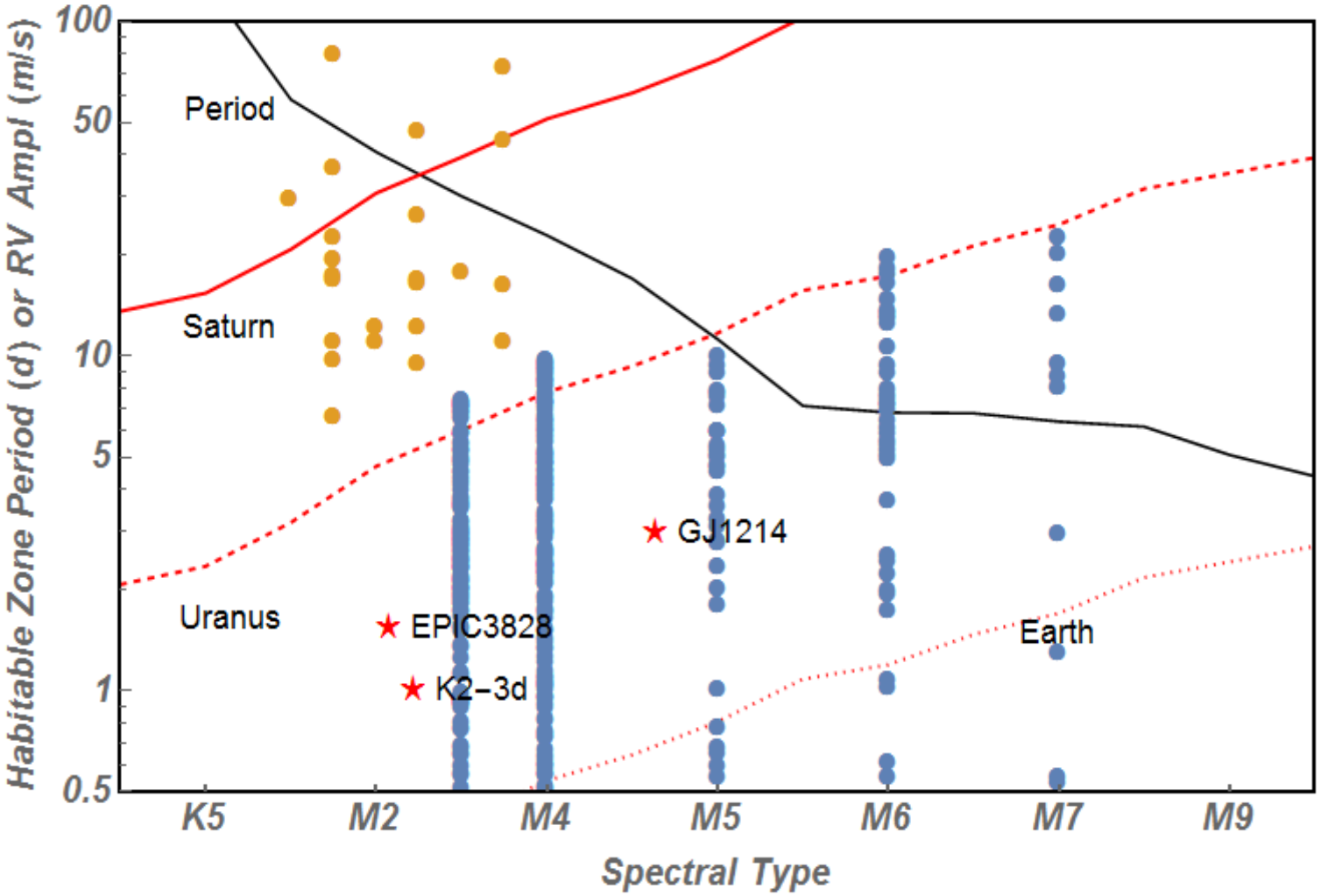
Science Drivers

1. Exoplanetary demographics and dynamics

WFIRST report



M-star Survey



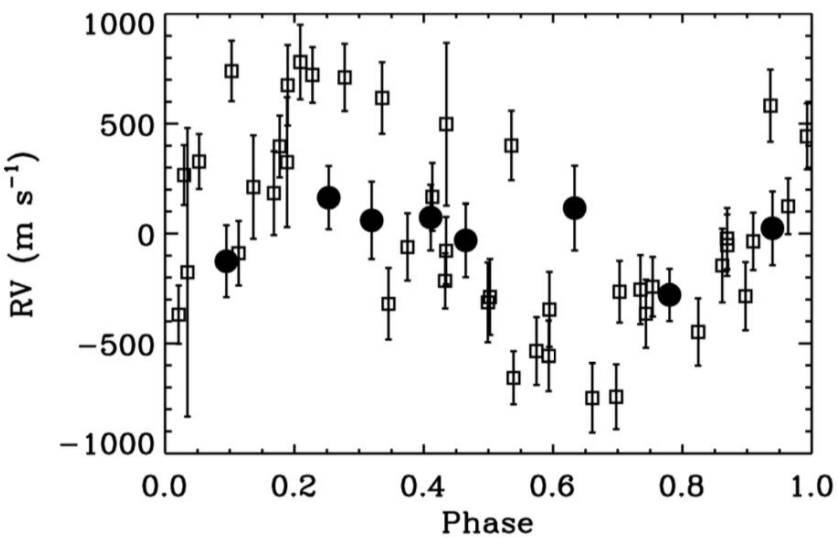
From Beichman

Other

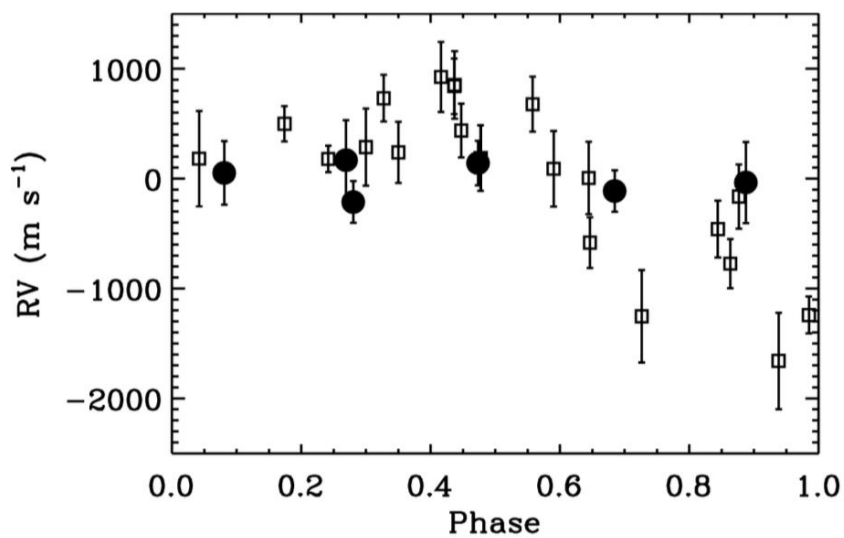
- Also G, K stars + Young stars
  - Technical: evaluate nIR RV jitter
  - Perhaps in concert with optical spectrographs

Infrared PRVs

- For spotted stars, IR PRVs appear less susceptible

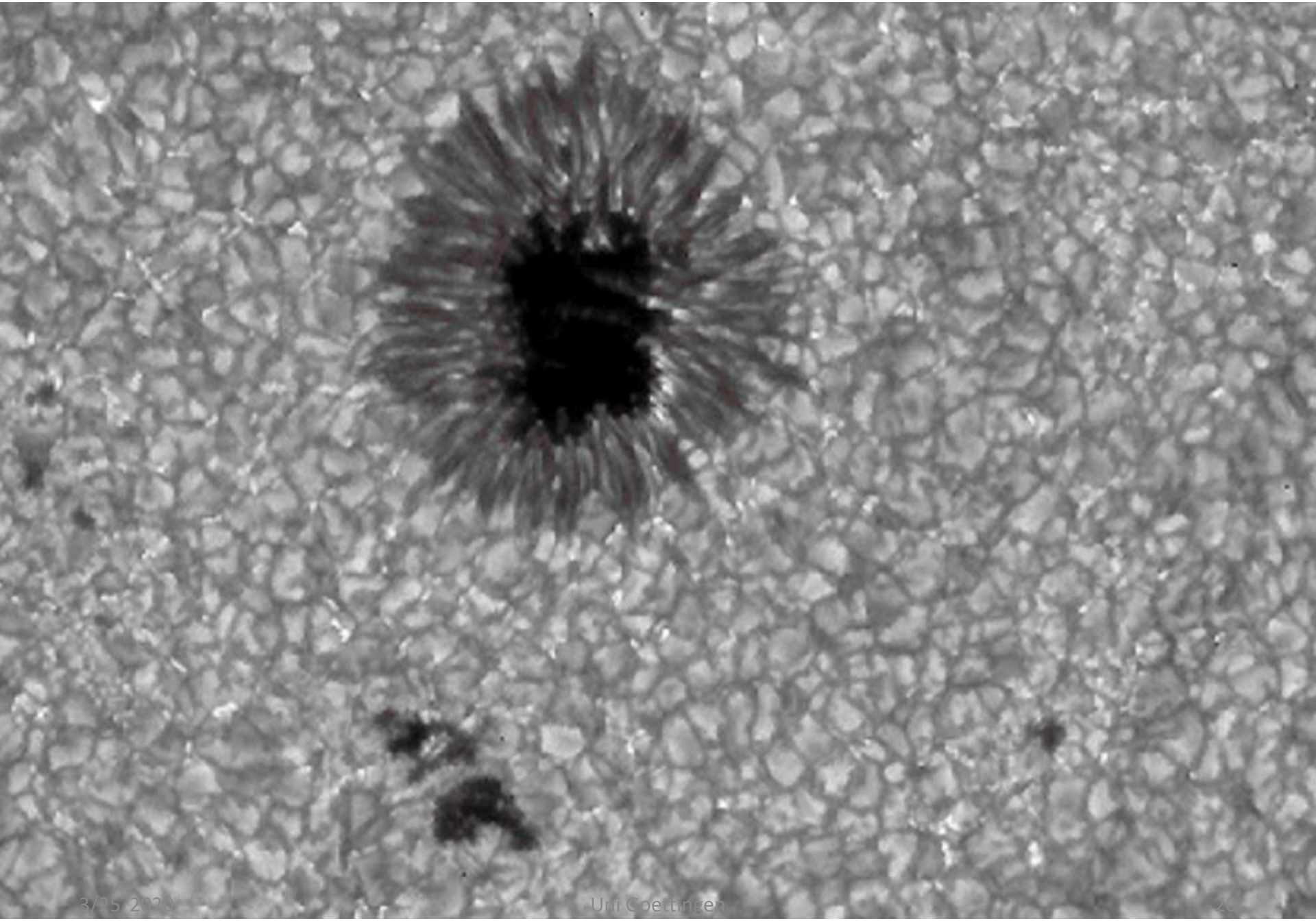


DN Tau

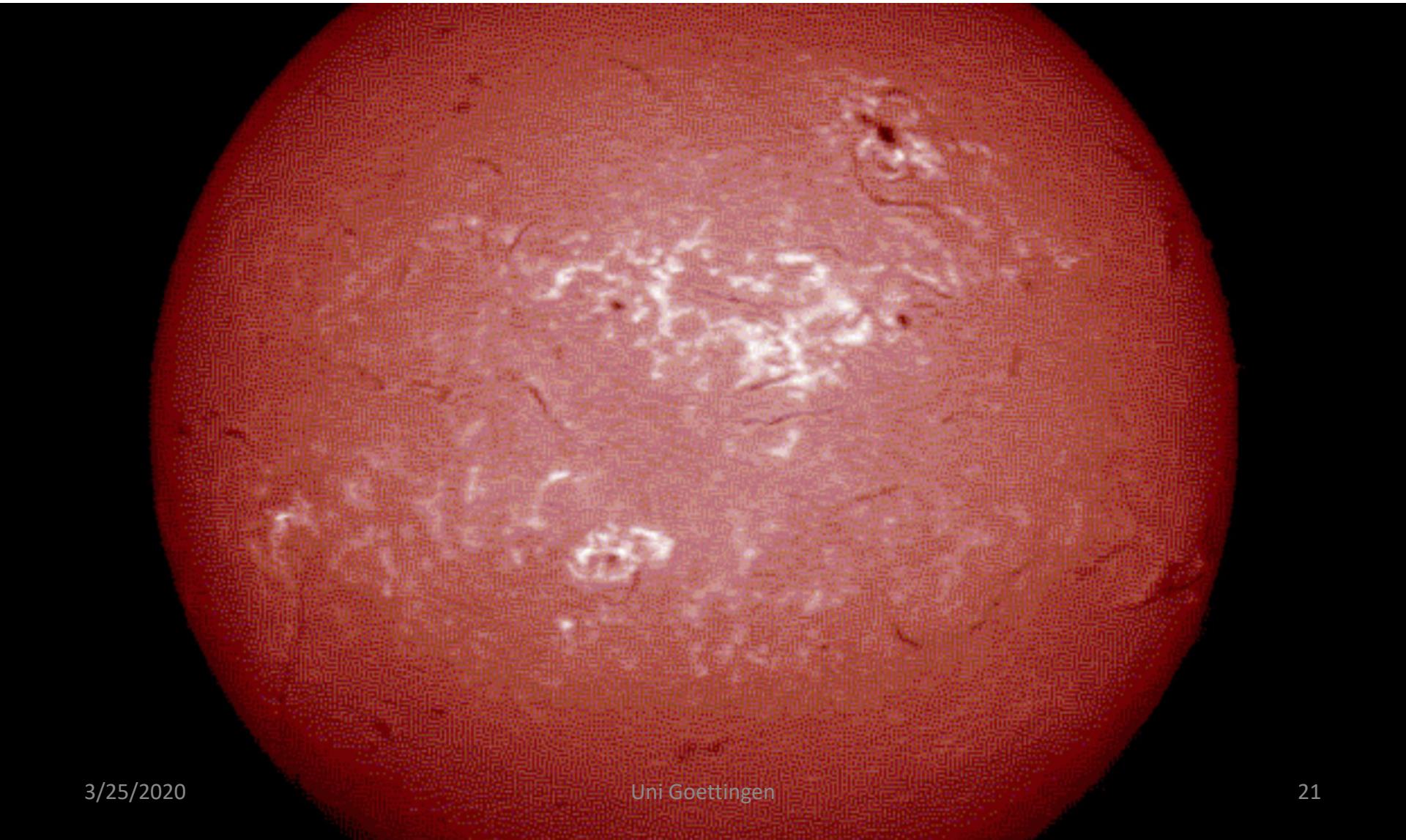


V836 Tau

Prato et al. 2008; also Mahmud et al. 2011



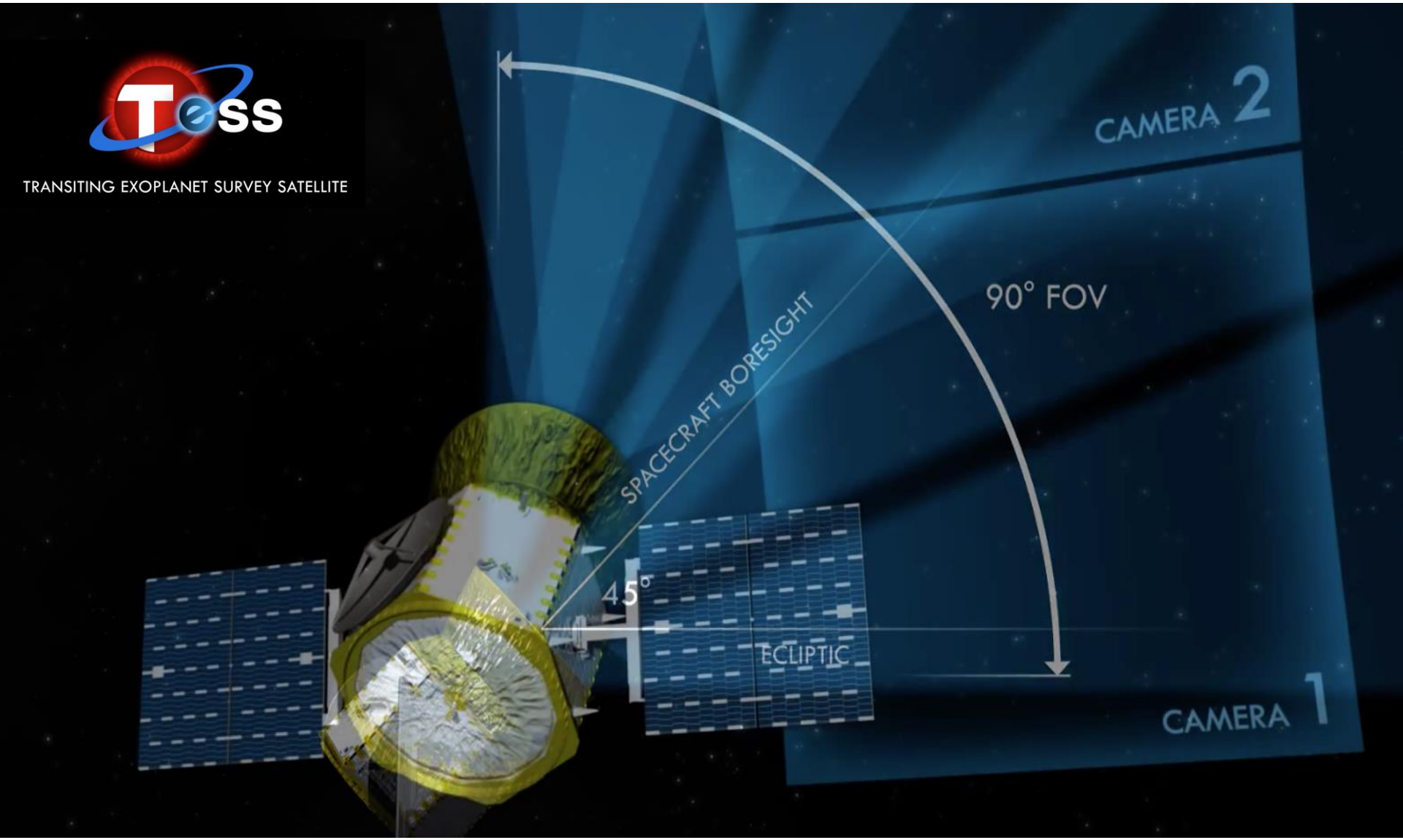
Flaculae/Plages



Science Drivers

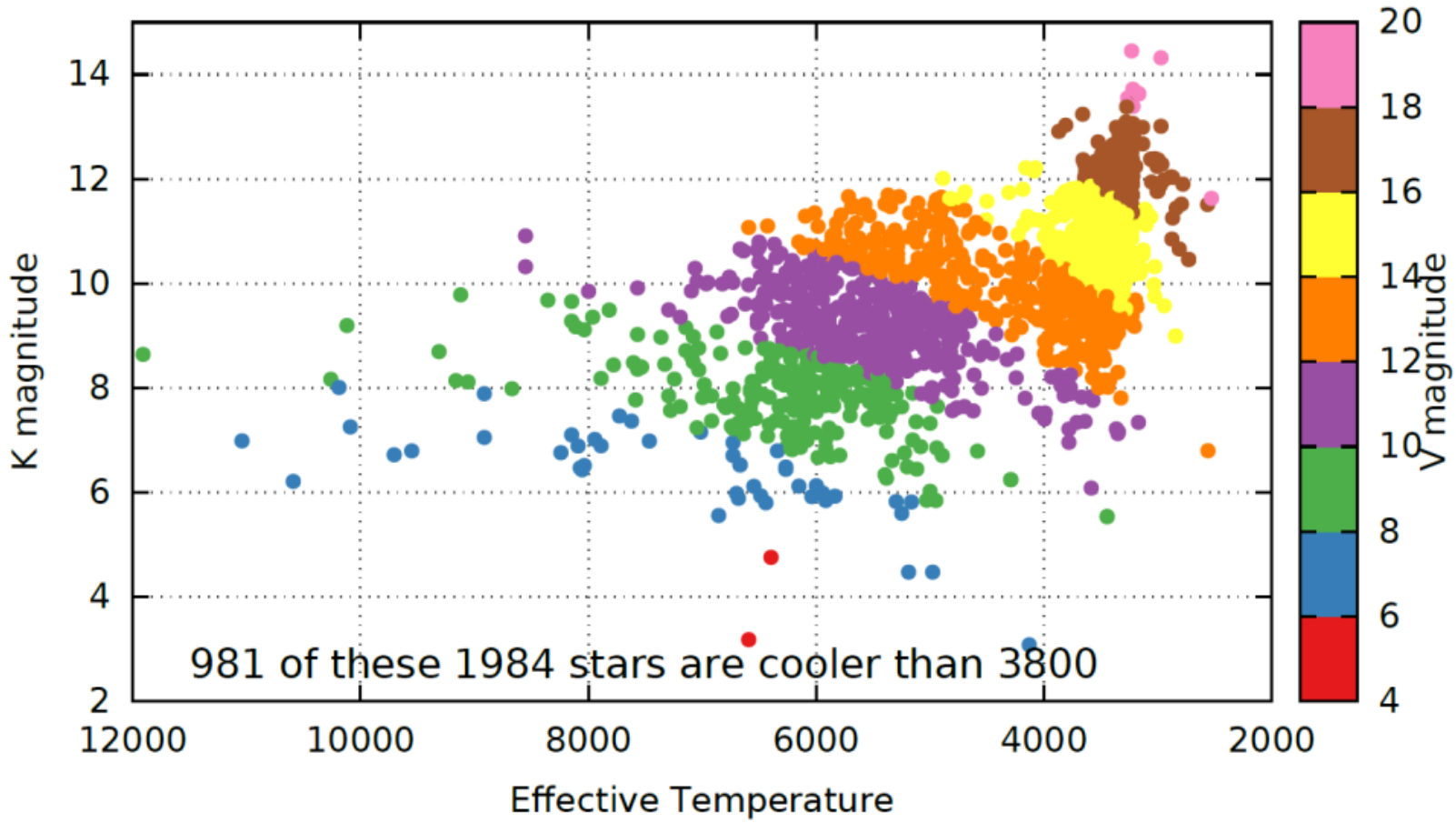
1. Exoplanetary demographics and dynamics
2. Follow up of transiting planets for bulk density characterization and orbital motion

Ricker et al. 2014



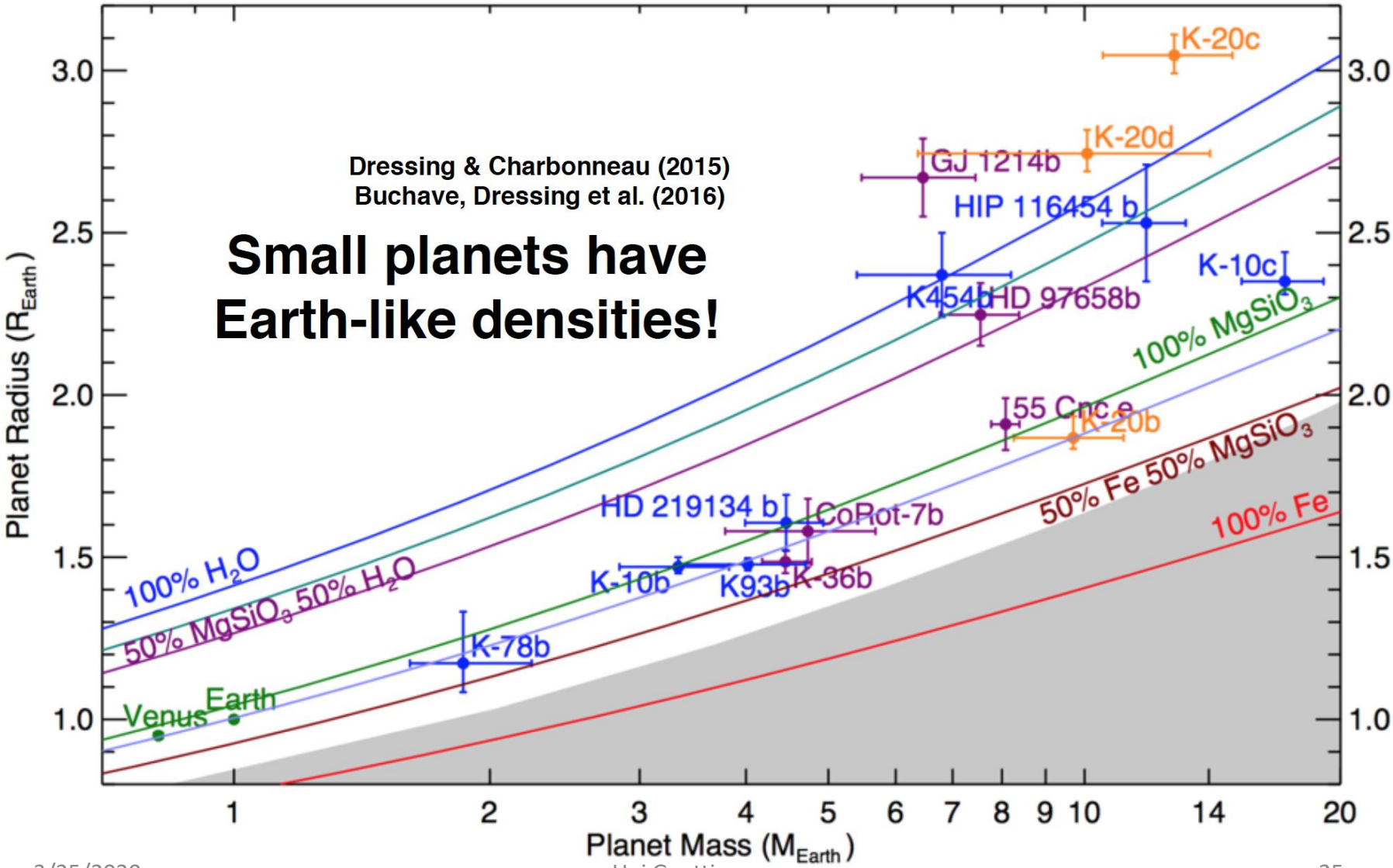
Fixed in inertial space for 27 days or 2 orbital periods

TESS follow-up



Sullivan et al.; Beichman et al.;

Mass-Radius Relation



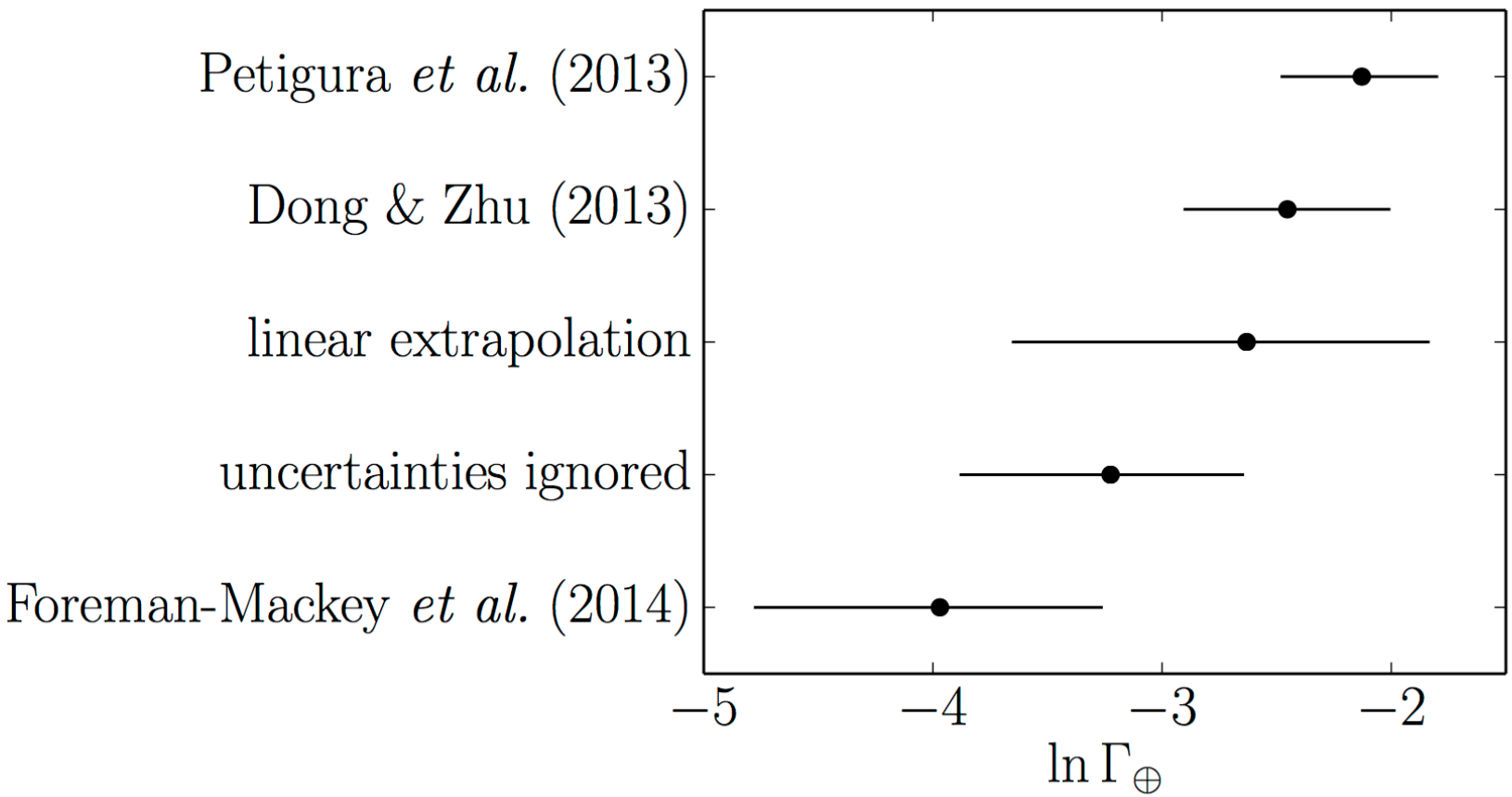
Science Drivers

1. Exoplanetary demographics and dynamics
2. Follow up of transiting planets for bulk density characterization and orbital motion
3. Identification of the closest exoplanets for imaging characterization

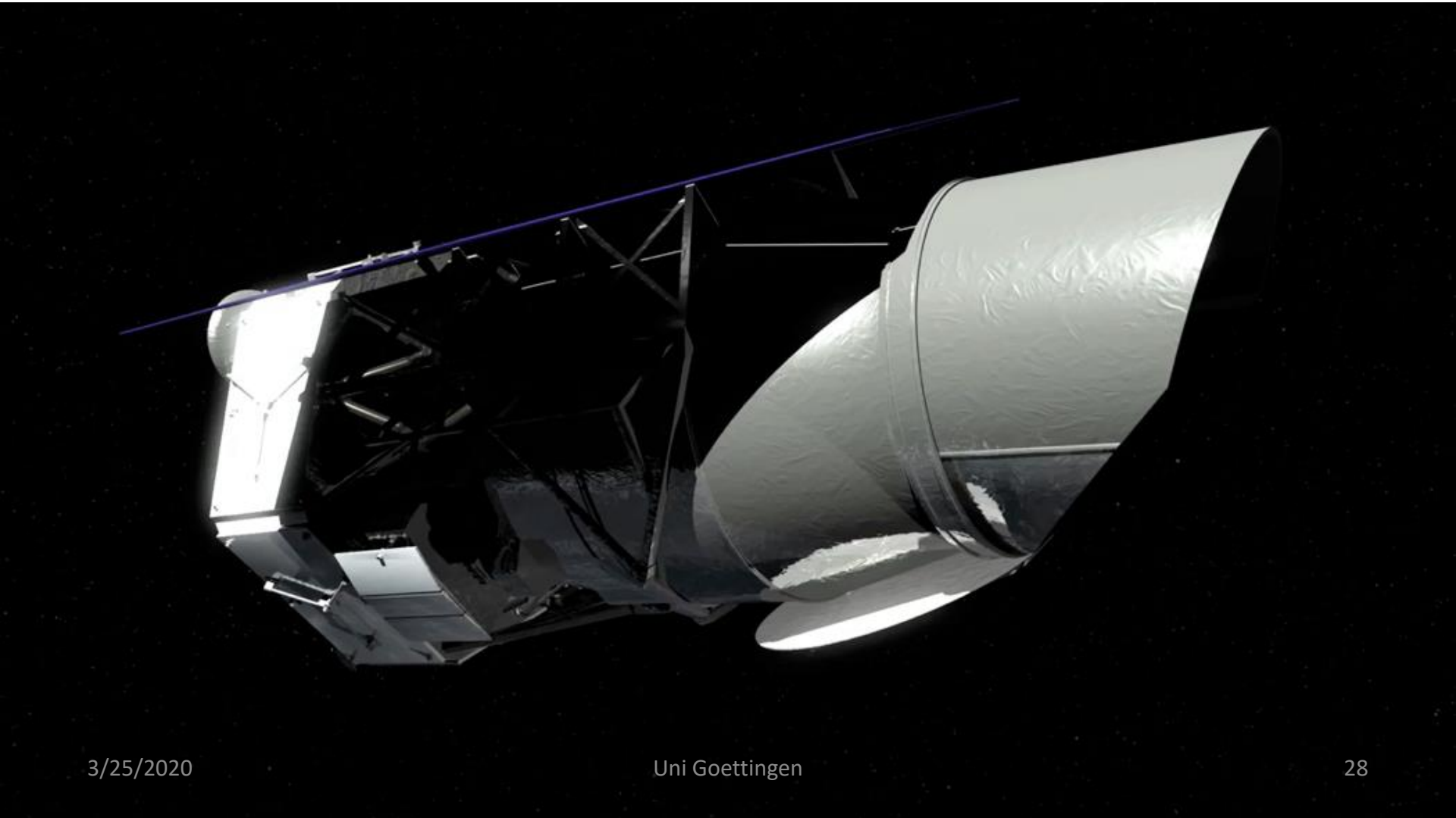
Estimates of η_E from Kepler vary significantly

Adapted from Foreman-Mackey et al. 2014

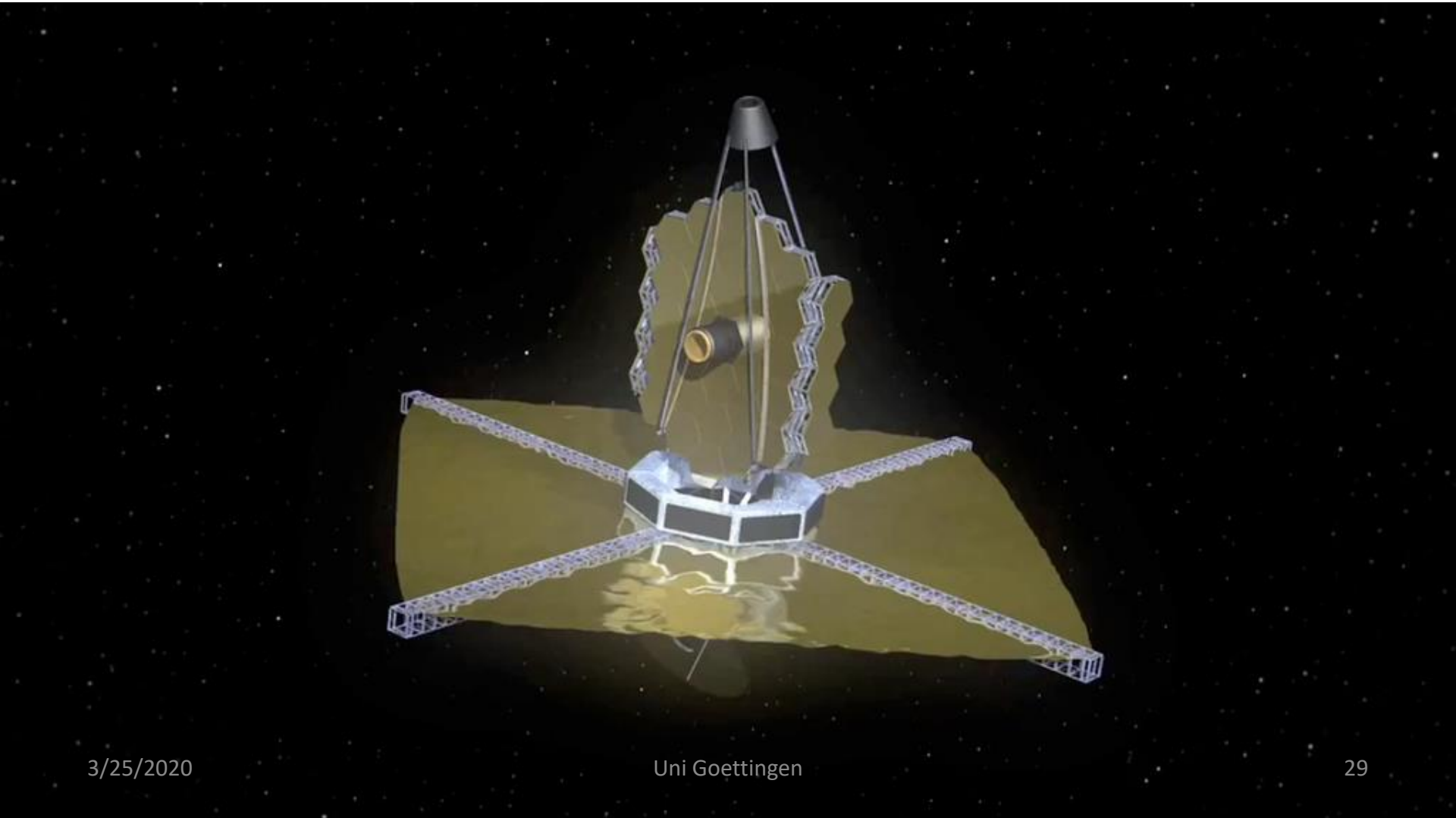
Traub 2016

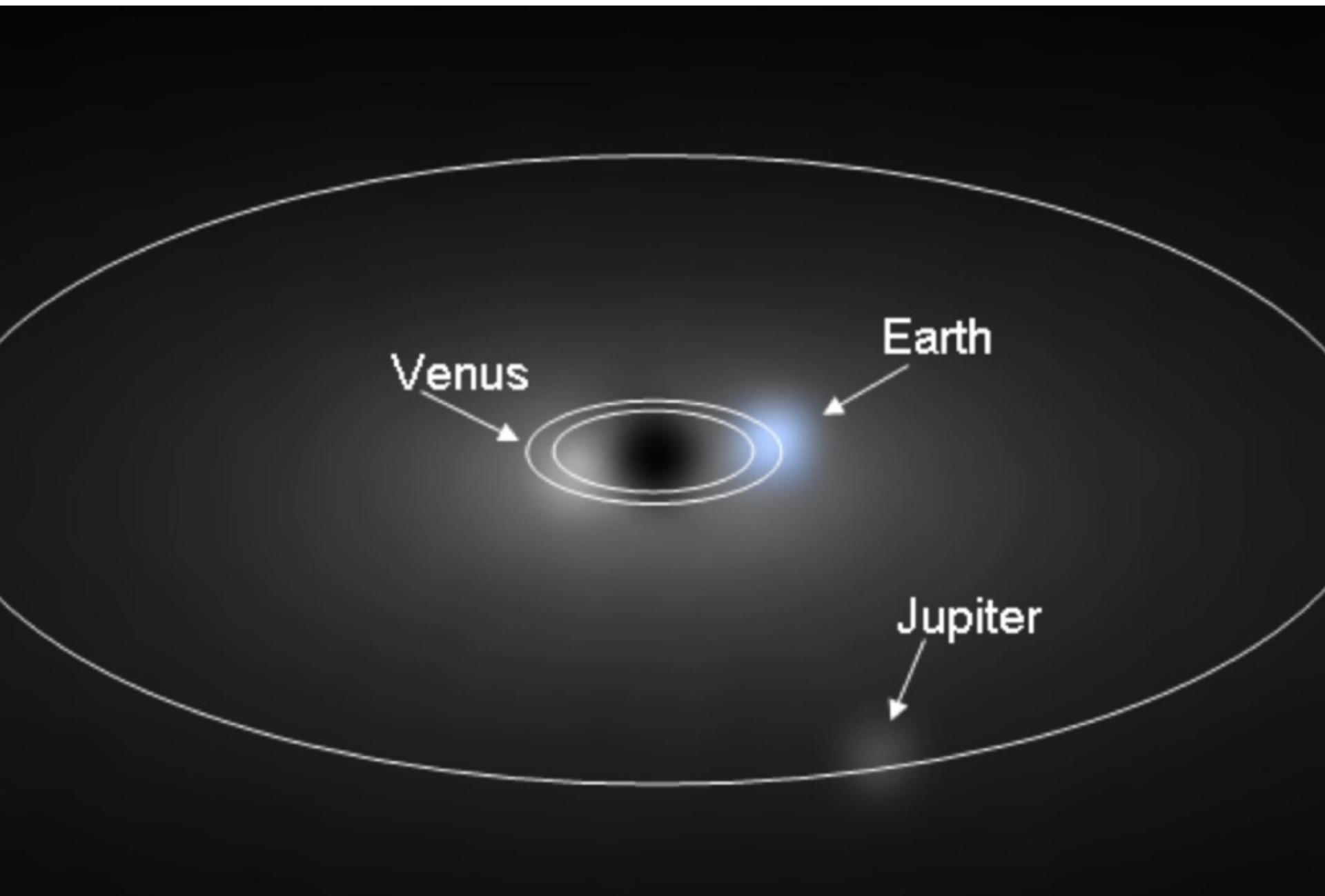


WFIRST 2020s

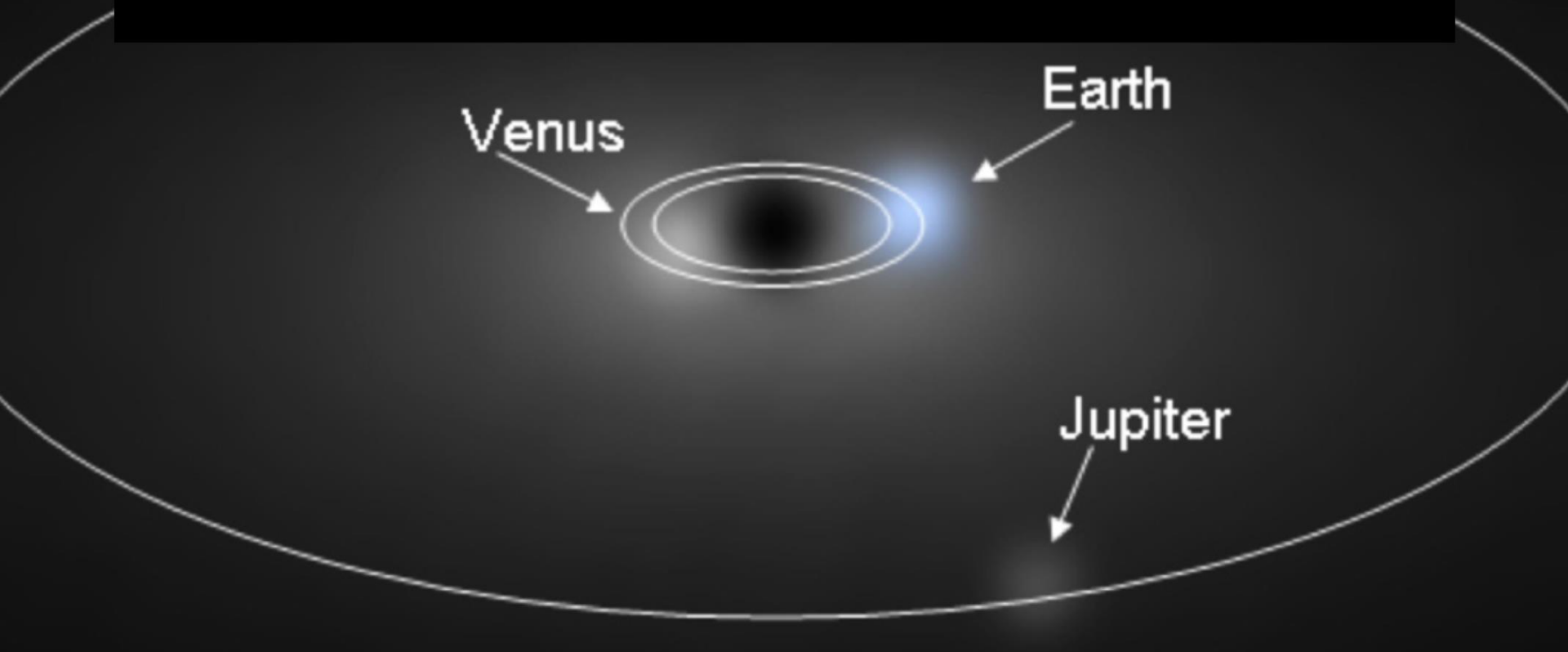


HabEx or LUVOIR (2030s ?)

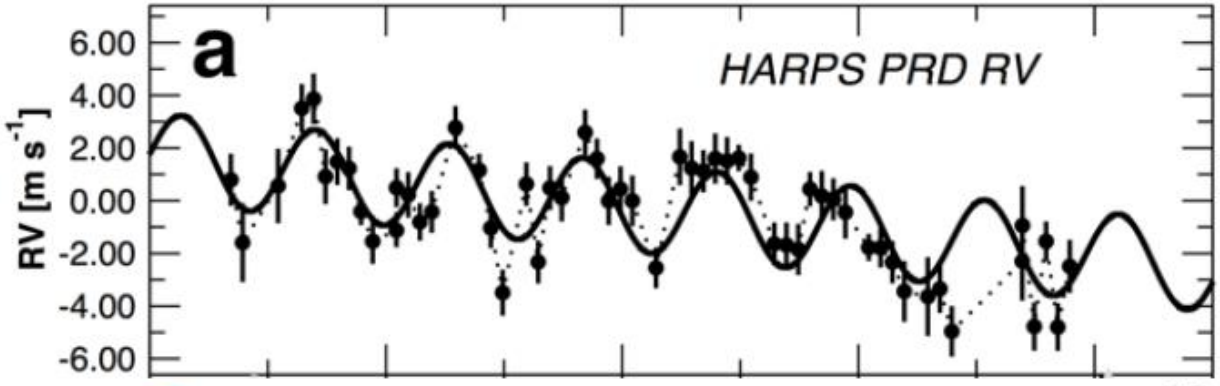


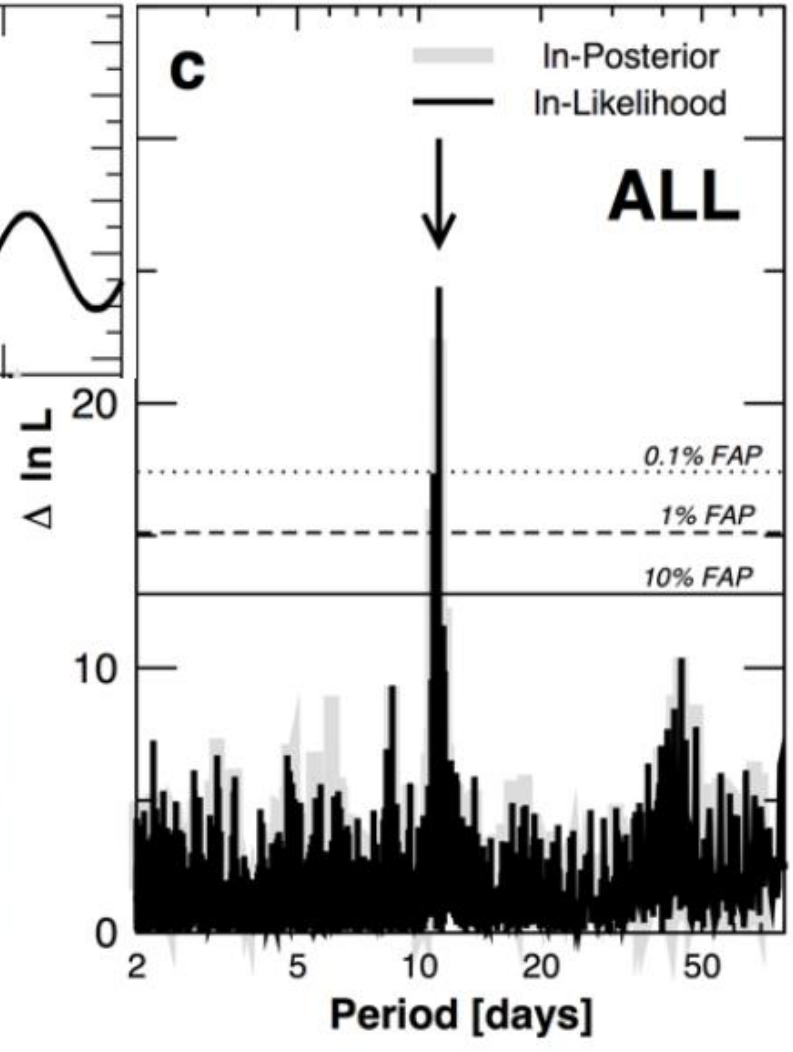

Earth
Venus
Jupiter

How many stars do we need to look at?
How big (expensive) does the telescope need to be?
Will we know where to look?

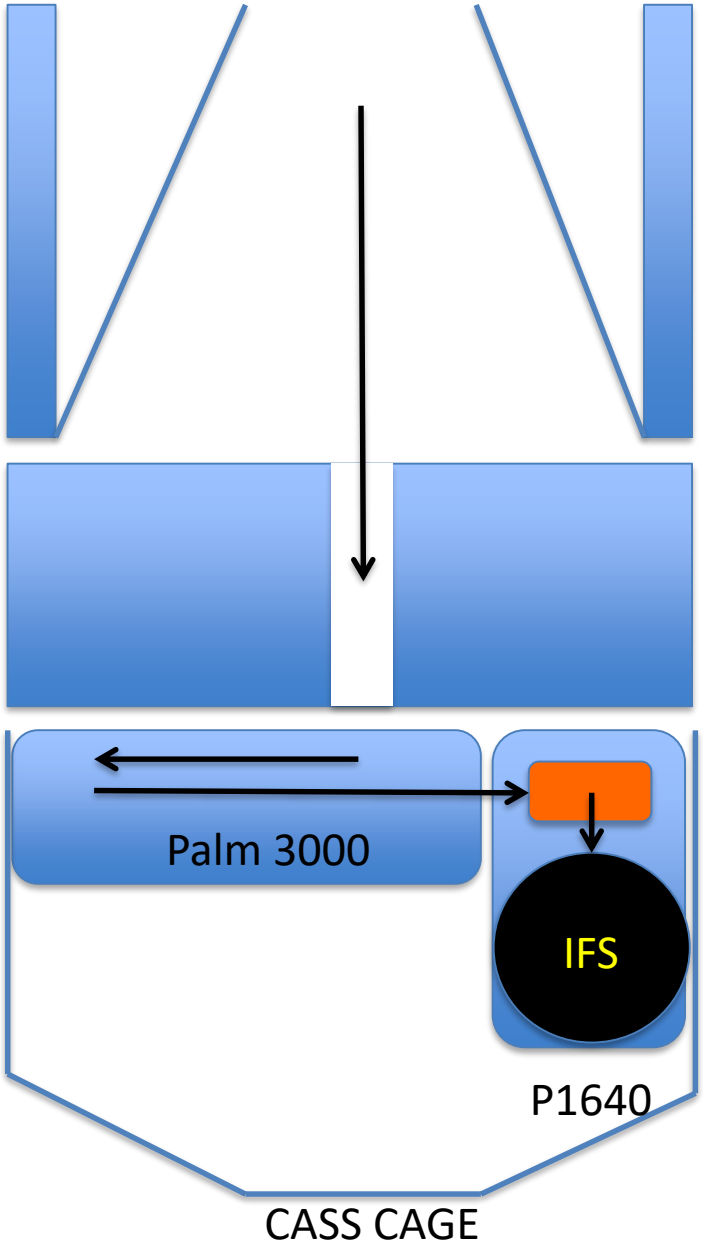


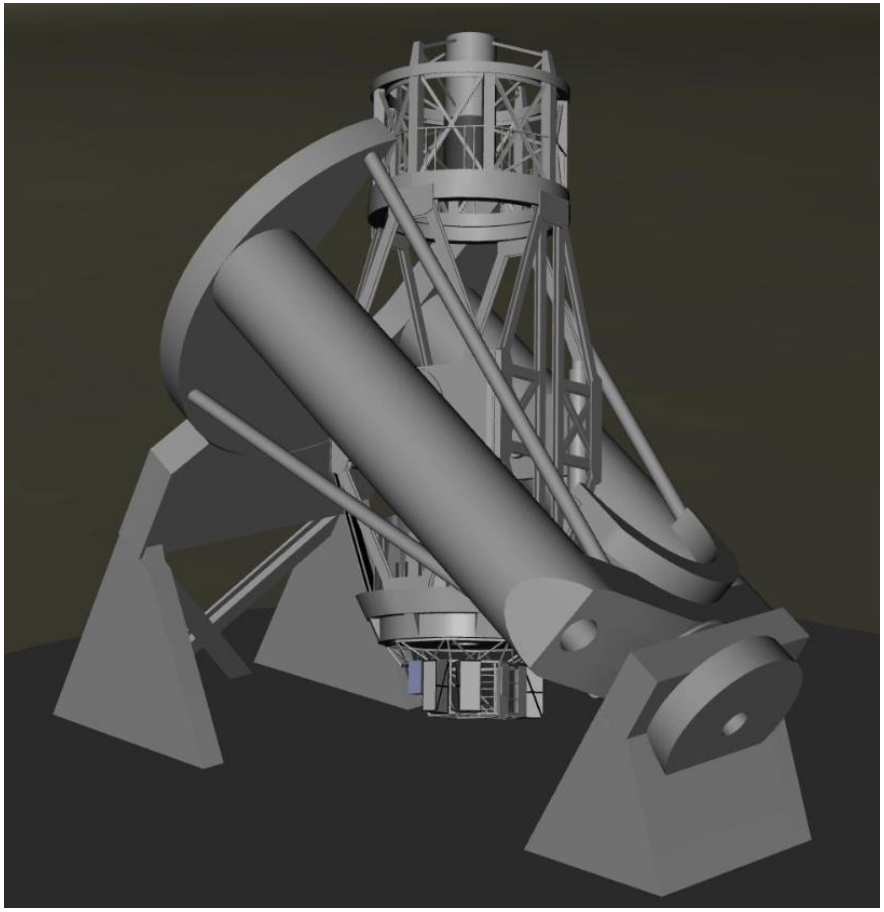
Proxima Cen b - RVs inform direct imaging missions!



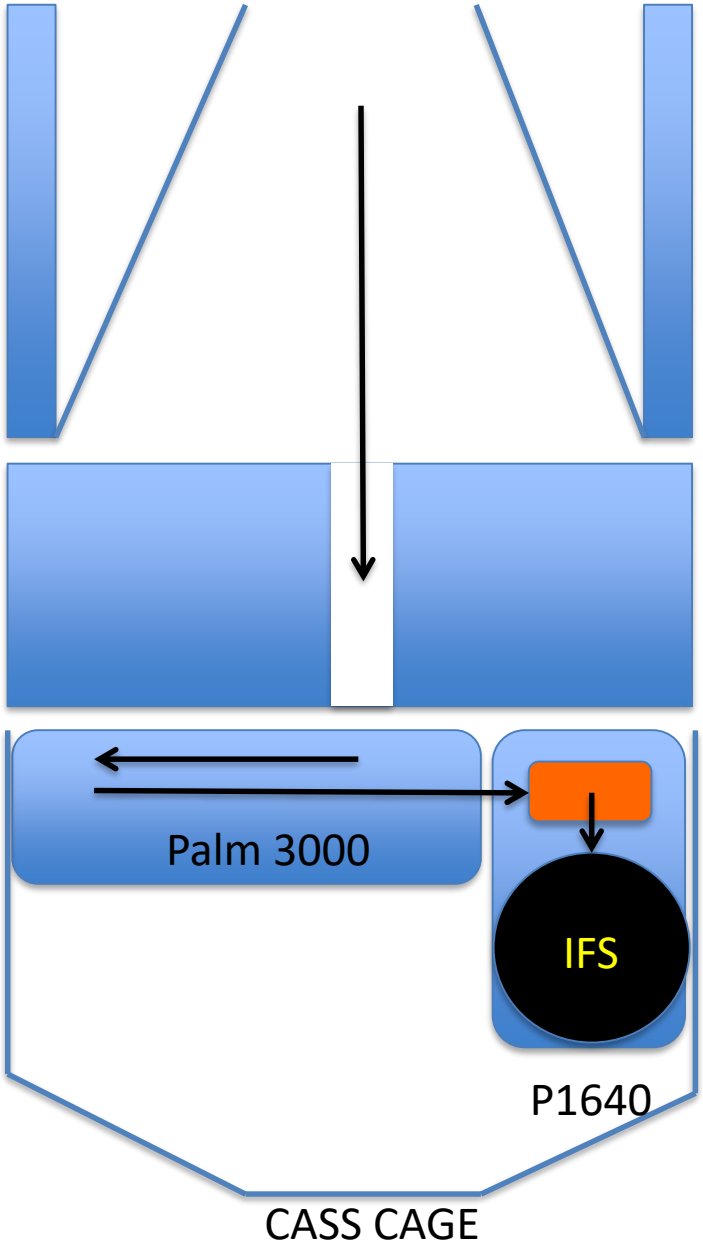


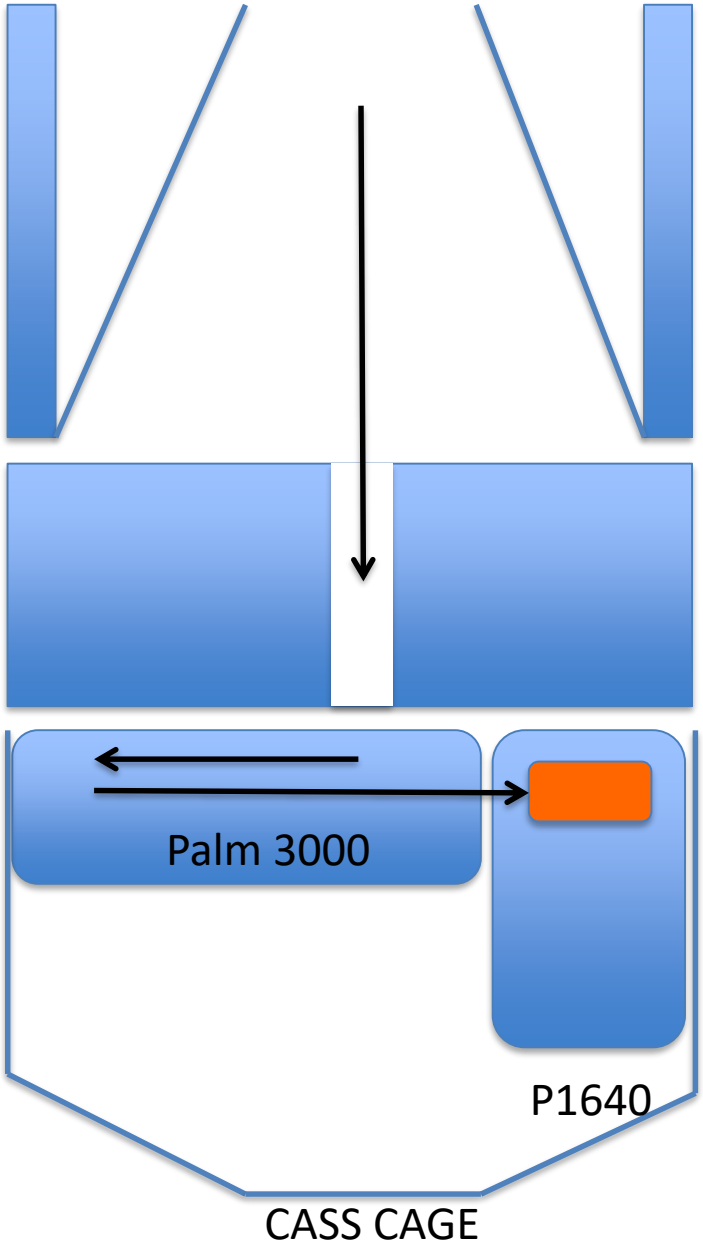
Implementation

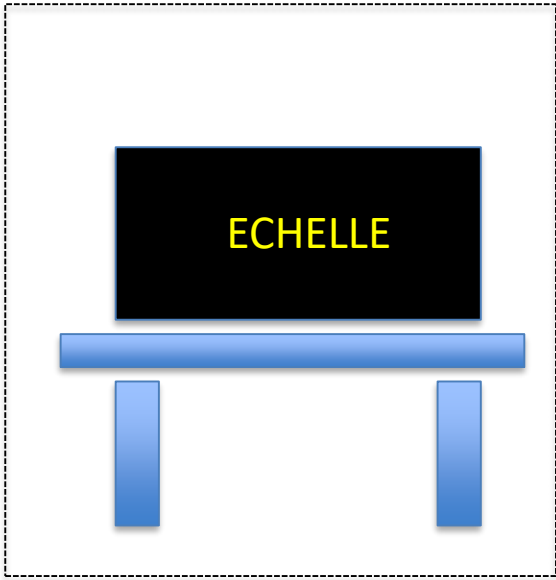


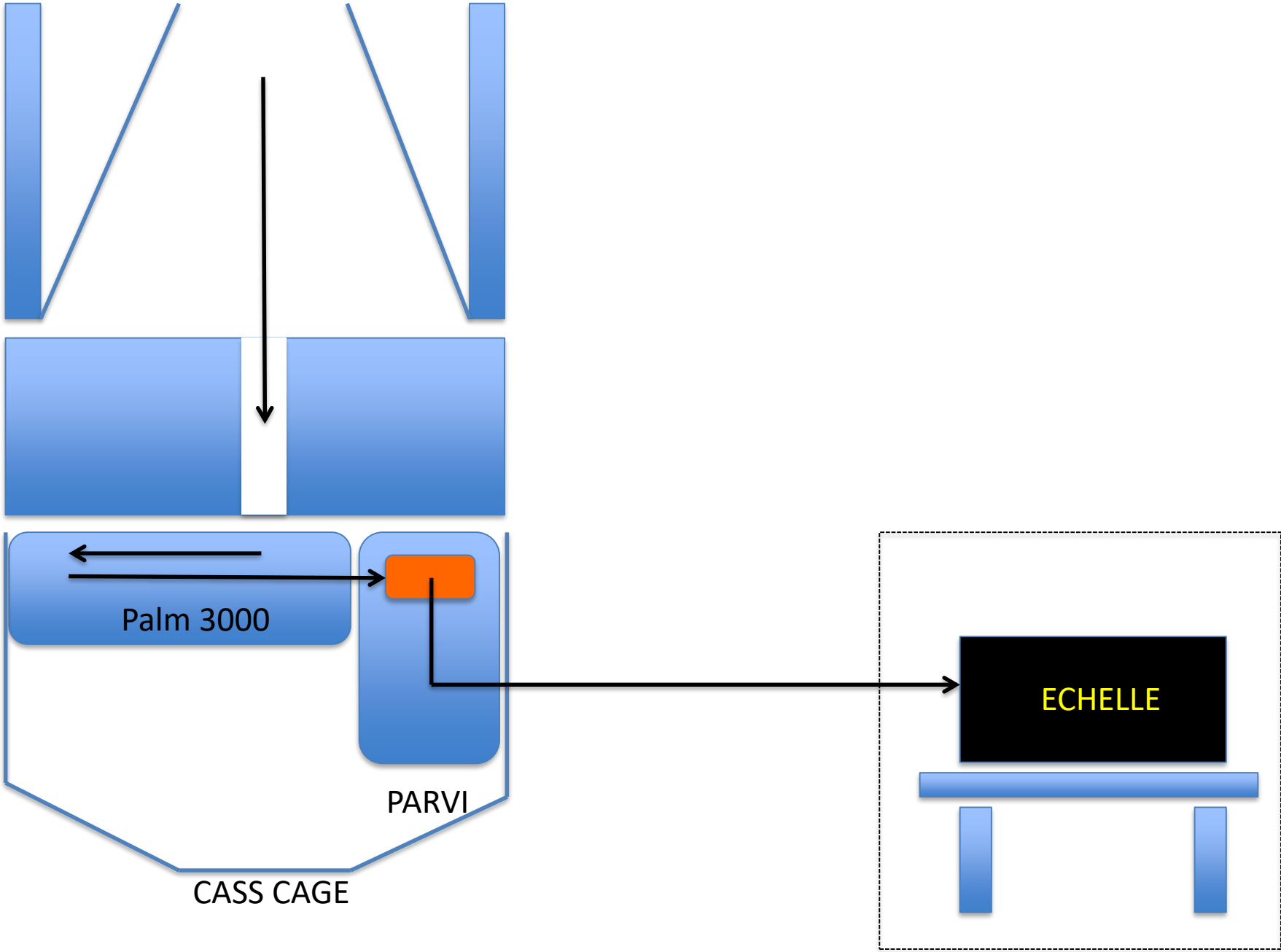


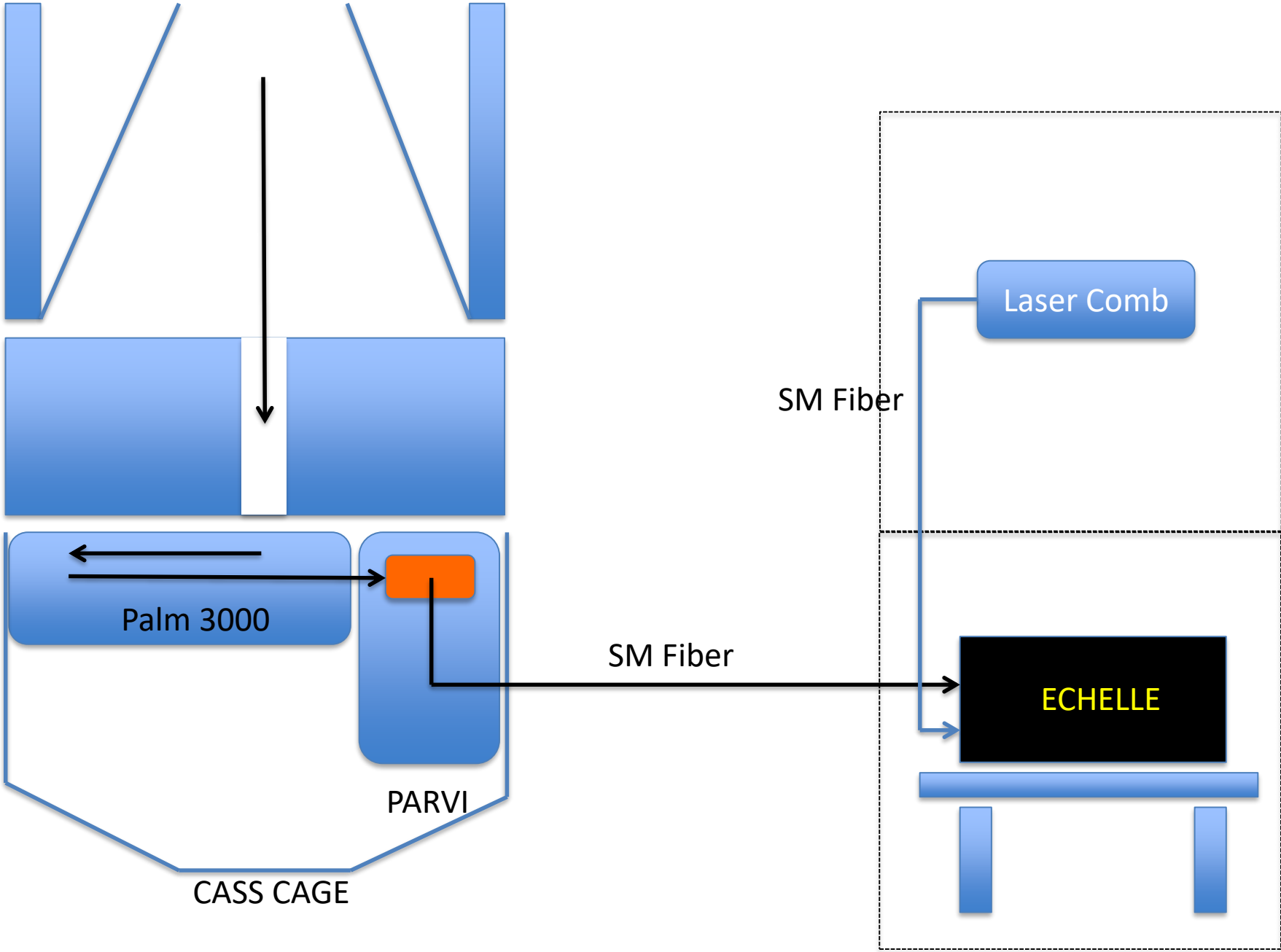
Seldon's model


Palm 3000
IFS
P1640
CASS CAGE


Palm 3000
P1640
CASS CAGE


ECHELLE


Palm 3000
PARVI
CASS CAGE
ECHELLE


Laser Comb
SM Fiber
Palm 3000
SM Fiber
ECHELLE
PARVI
CASS CAGE

The Case for Adaptive Optics

- Compact spectrographs
- Low backgrounds
- Single mode (SM) fibers
  - Uncommon in astronomy
- Natural compatibility with laser frequency combs

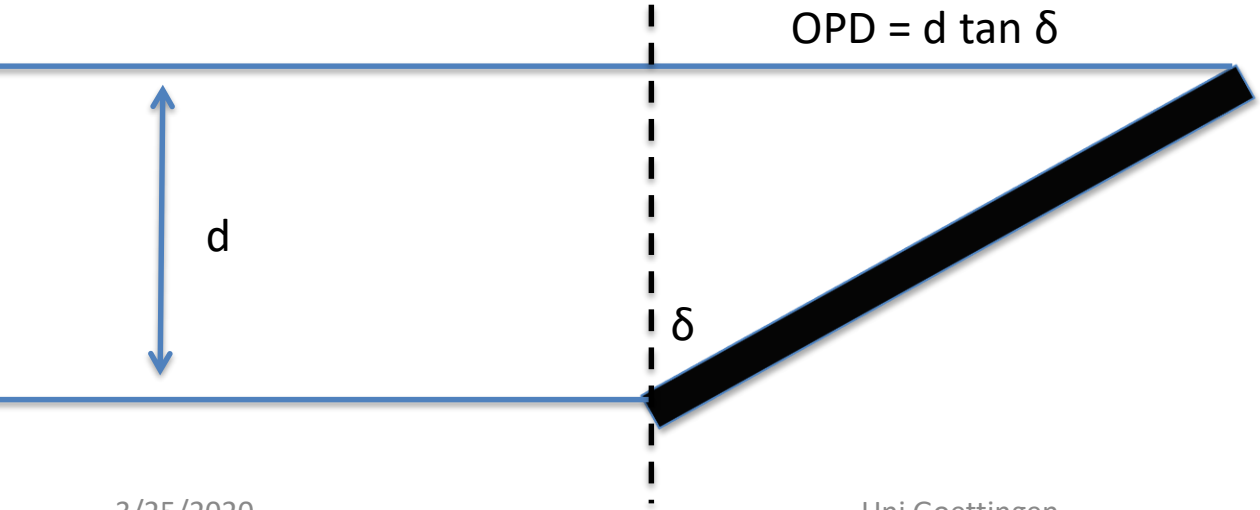
Diffraction Limited Spectrographs are small

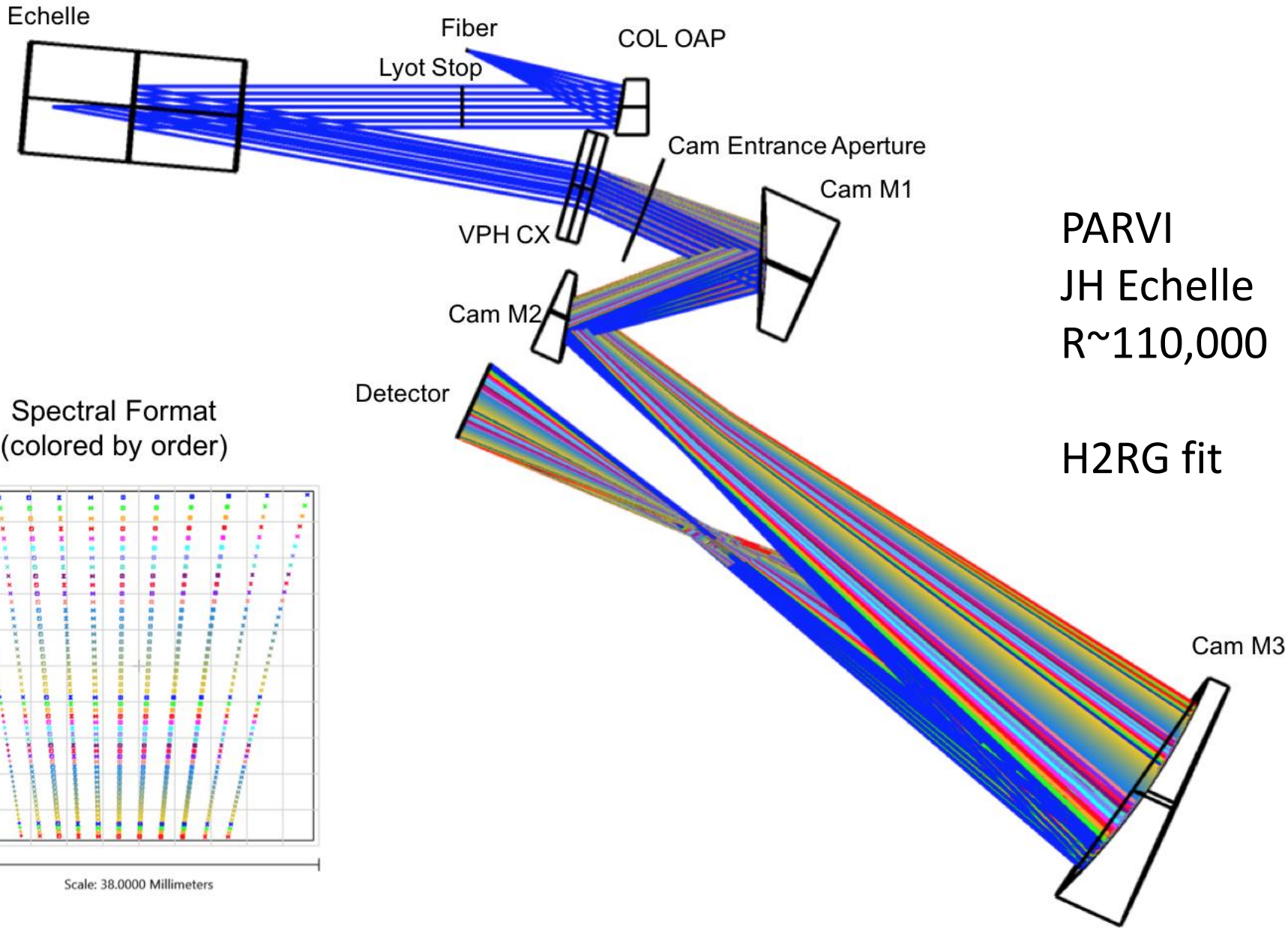
- Diffraction limit

$$R_0 = 2d \tan d / l$$

- Seeing limit

$$R = \frac{2d \tan d}{l}\left(\frac{r_0}{D}\right)$$

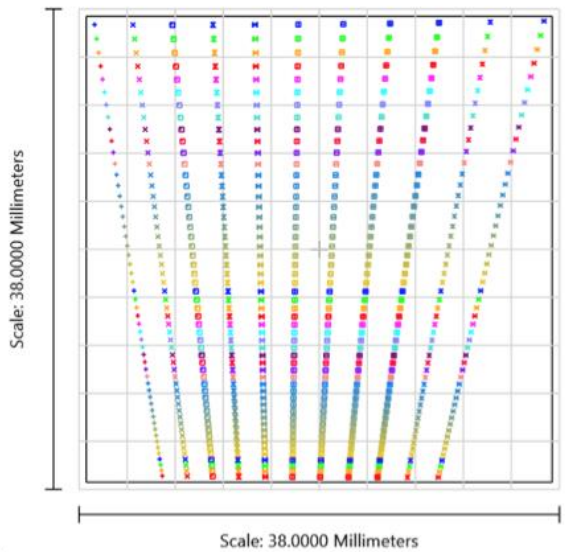




PARVI
JH Echelle
R~110,000

H2RG fit

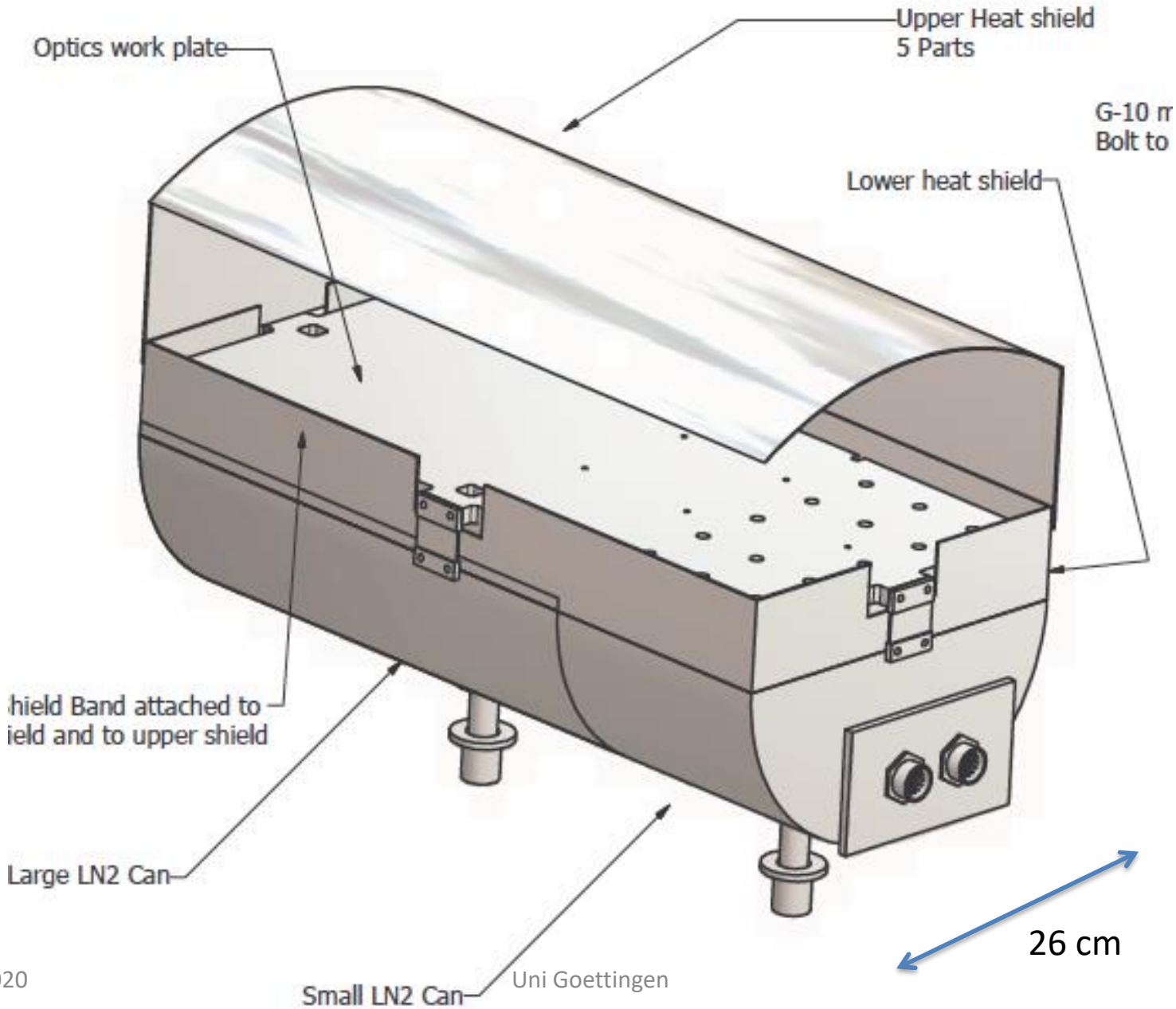
Spectral Format
(colored by order)



200 mm

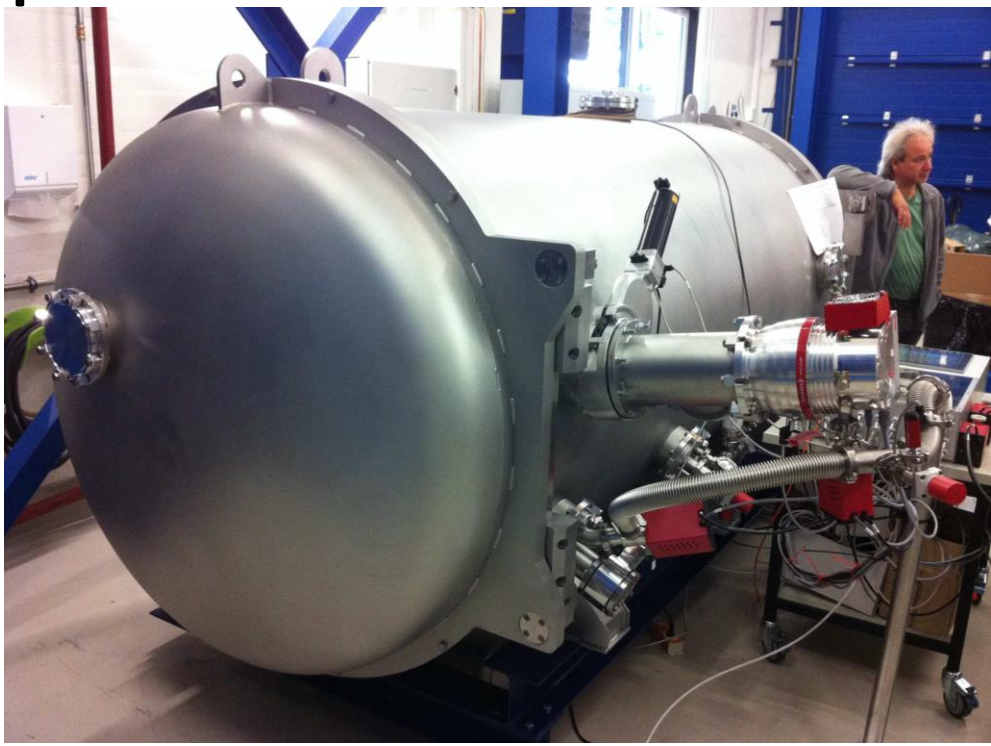
From J. Fucik

Project 1640 Dewar



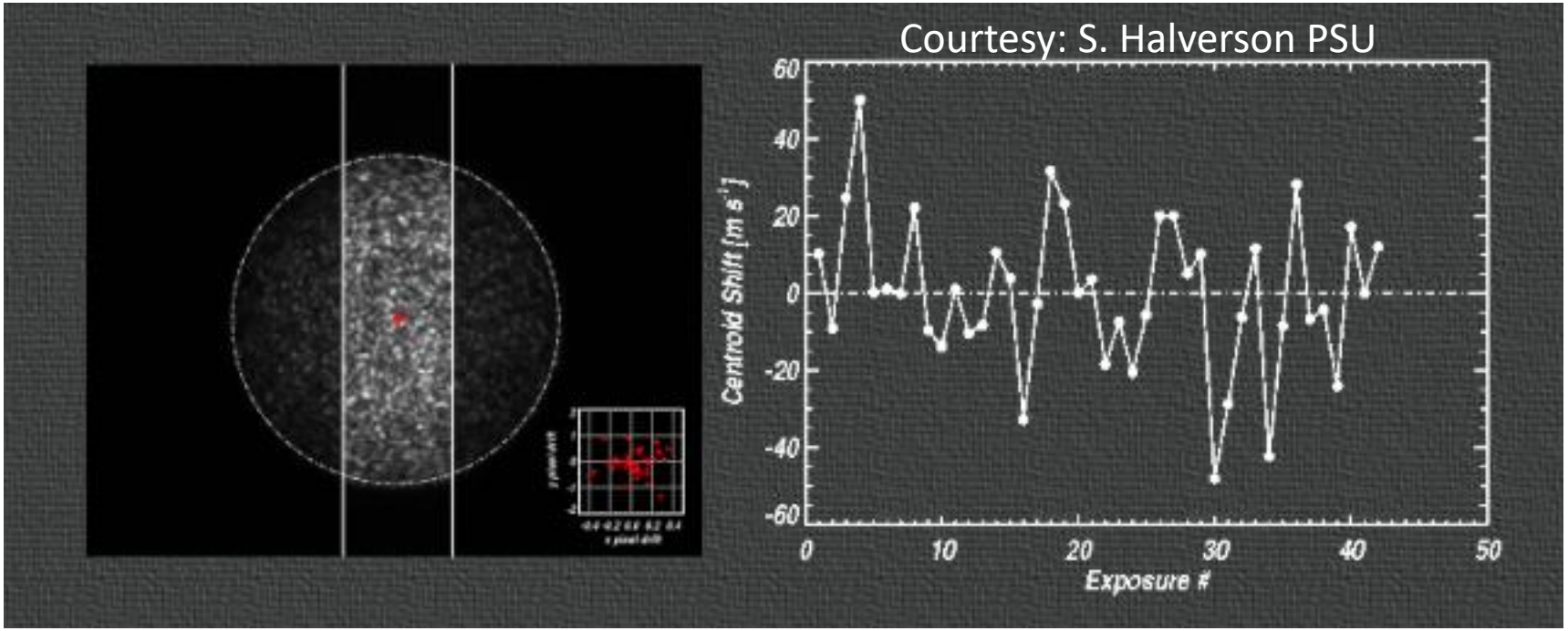
See limited spectrographs are large and expensive

- Carmenes (Quirrenbach et al. 2016)
- R~75 k
- Cost ~ 30 M Euro



Carmenes nIR channel

SM fibers have no modal noise

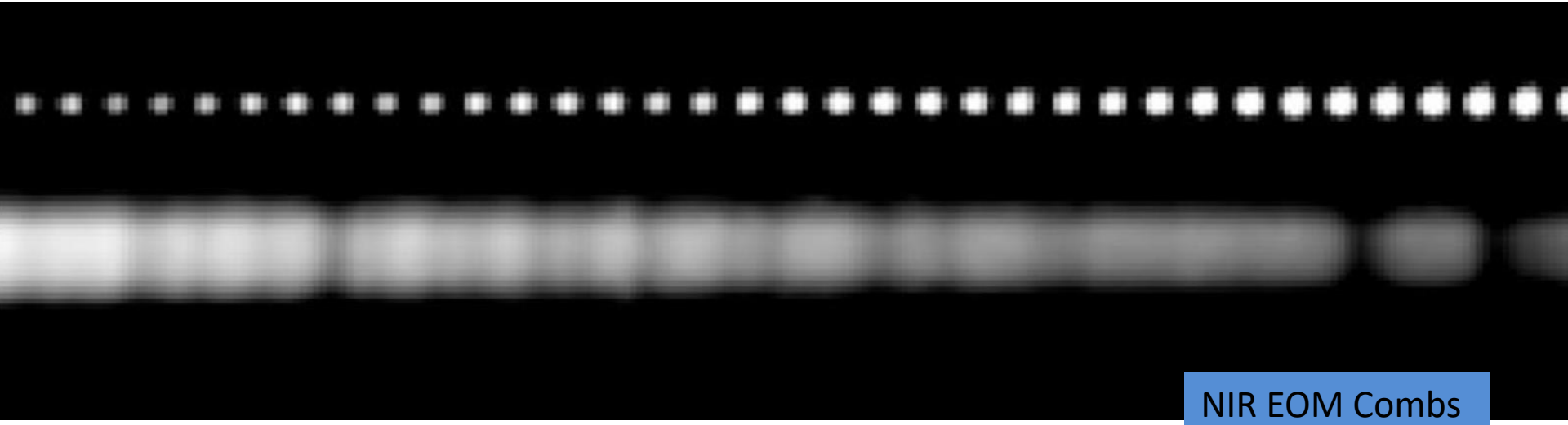


… and greatly reduced sky background

But have coupling losses …

$$Coupling = f_{MM} \acute{} \; Strehl$$

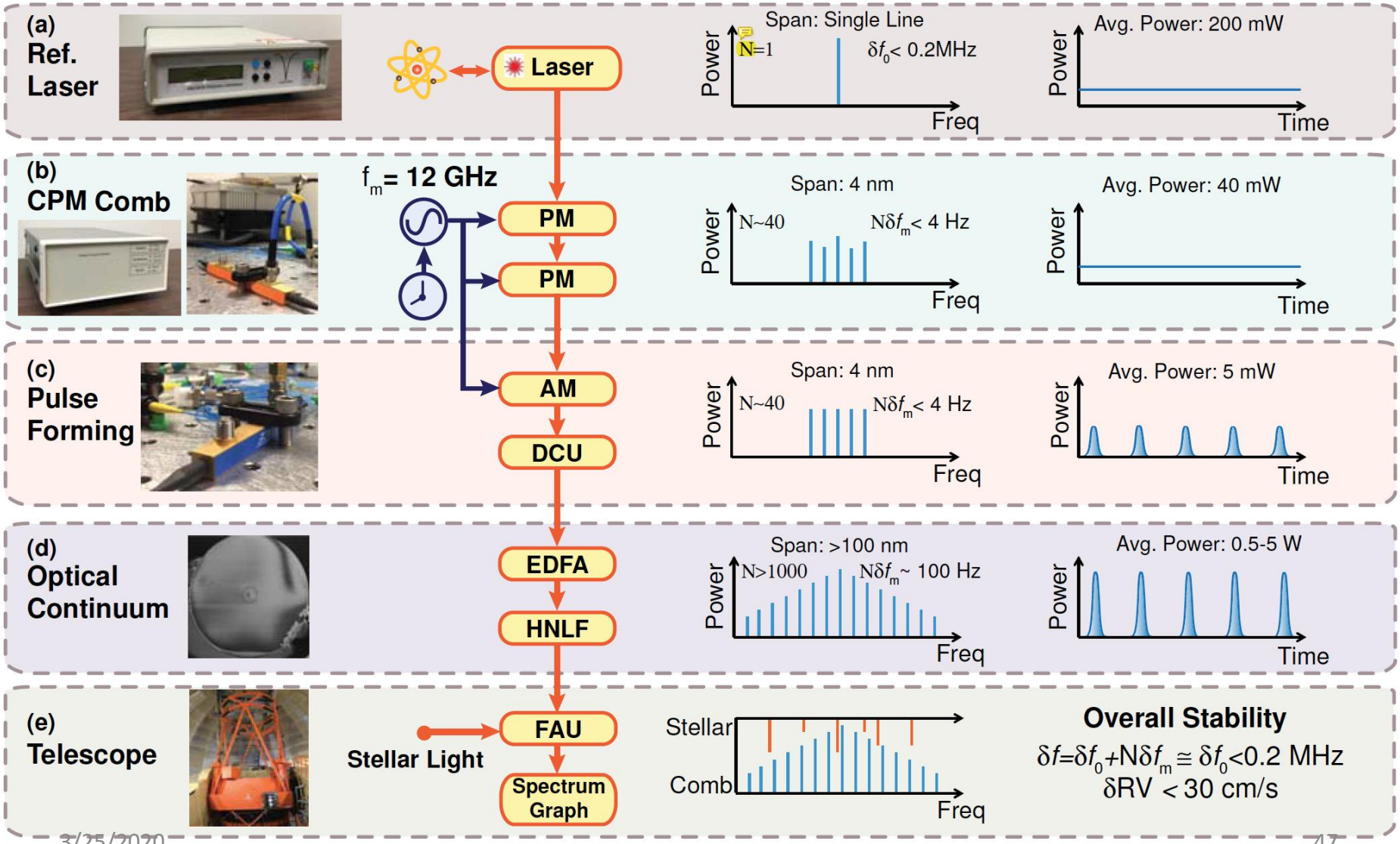
SM fibers well suited to LFC injection



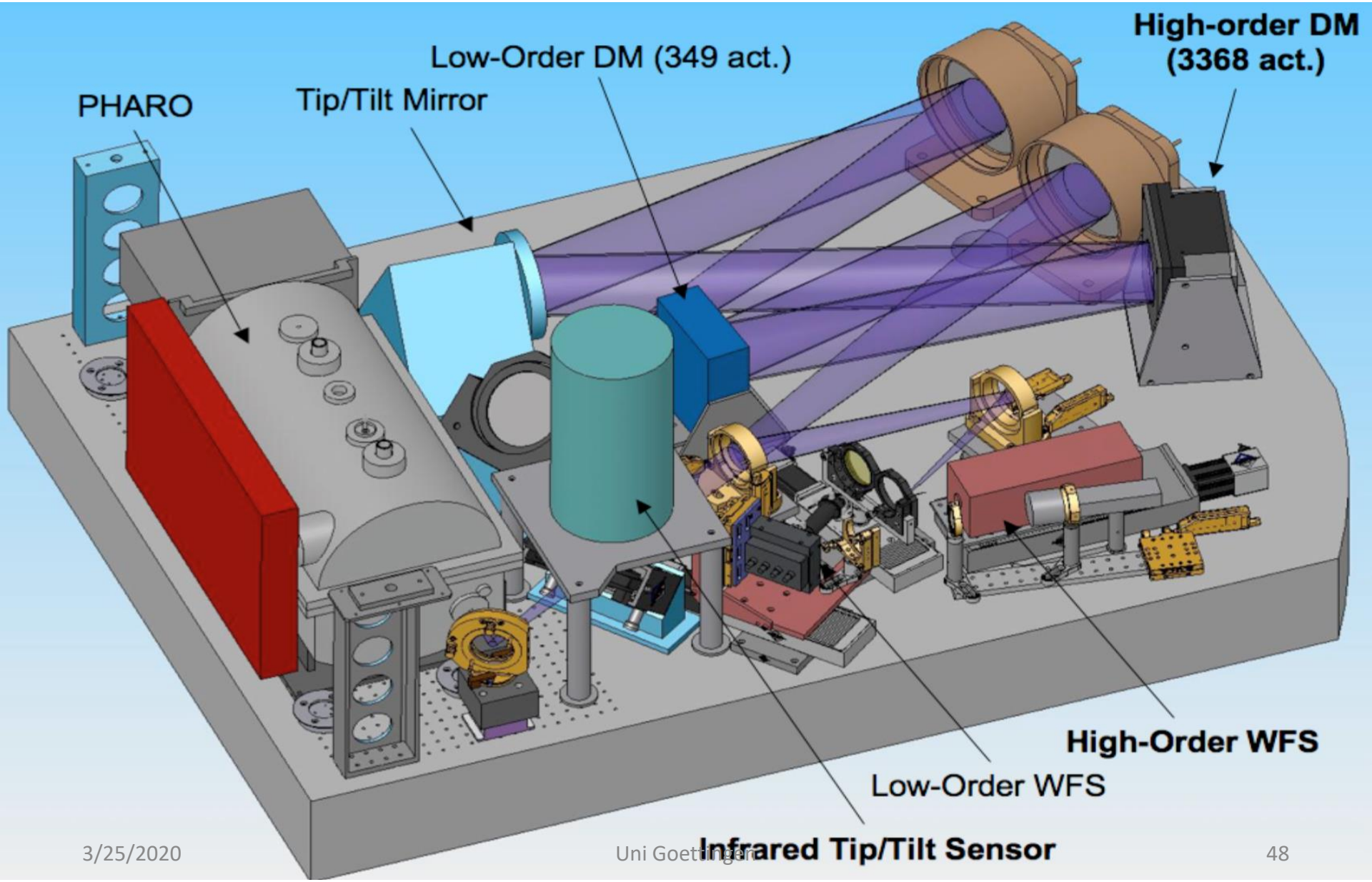
NIR EOM Combs (Yi et al 2016) Vahala group in CIT applied physics

EOM H-band Comb: Developed over a 2 year Caltech-JPL Collaboration

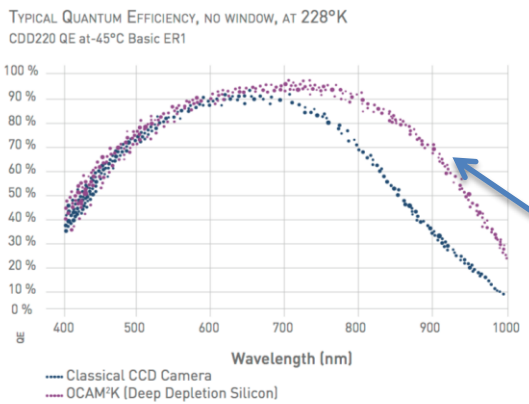
Caltech-JPL EOM Comb



Palm 3000

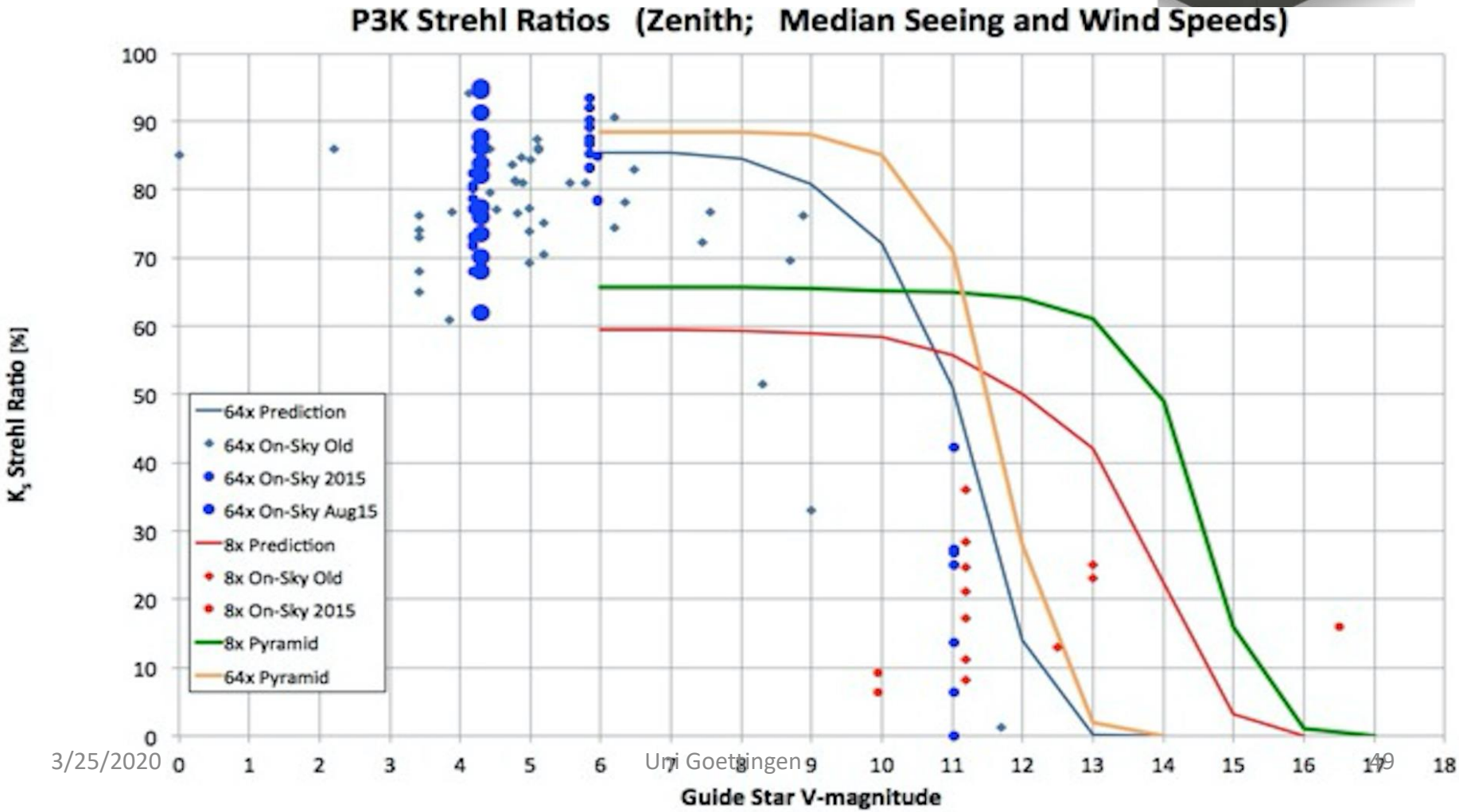

High-order DM
(3368 act.)
Low-Order DM (349 act.)
PHARO
Tip/Tilt Mirror
High-Order WFS
Low-Order WFS
Infrared Tip/Tilt Sensor

P3K Upgrades



New deep depletion EMCCD

New WFS cam
Low latency



Fast track project

	FY16Q3	FY16Q4	FY17Q1	FY17Q2	FY17Q3	FY17Q4	FY18Q1	FY18Q2	FY18Q3	FY18Q4	FY19Q1	FY19Q2	FY19Q3	FY19Q4
	PAL16A/B	PAL16B	PAL16B	PAL17A	PAL17A/B	PAL17B	PAL17B	PAL18A	PAL18A/B	PAL18B	PAL18B	PAL19A	PAL19A/B	PAL19B
				P1640 De-commission		TESS Launch Dec 2017		First TESS data (South)			JWST Launch Oct 2018	First TESS data (North)		
Phase A														
Spectrometer Design & Layout	XXX													
Echelle grating selection	XXX													
Fiber Feed Concept	XXX													
Thermal Concept: LN2 or cooler	XXX													
Dewar Decision: P1640 or new	XXX													
Phase B														
Grating Procurement		XXX												
Detailed Optical Layout		XXX												
Detailed Mechanical Design		XXX												
Fiber Feed Design			XXX											
Detailed Thermal Concept			XXX											
Manufacture Spectrometer H/W			XXX											
Procure Thermal Control H/W			XXX											
Phase CD														
Assemble Spectrometer in Lab				XXX										
Assemble H band Comb					XXX									
Assemble Spectrometer into P1640					XXX									
Complete P3K fiber feed					XXX									
Phase E														
Install at Palomar in Coude Rom						XXX								
Initial On-Sky Commissioning							XXX							
Initial Observations								XXX	XXX	XXX	XXX			

On-sky March 2018

Collaboration

- Instrument/Science
  - G. Vasisht, C. A. Beichman
  - D. Mawet, J. Fucik, R. Dekany, L. Hillenbrandt (Caltech)
  - R. Oppenheimer (AMNH)
- Laser Frequency Comb
  - S. Leifer (JPL), K. Vahala, X. Yi (Caltech)
- PRV expertise
  - D. Fischer (Yale), P. Plavchan (Miss. St.)

PARVI is a fundamentally different approach

If we keep making the same observations with the same instruments, we will improve the SNR and population size, but we will basically have the same results and the field will stagnate; advances in strategy, analysis and instrumentation are required to reach higher RV precision and to push into new parameter space.

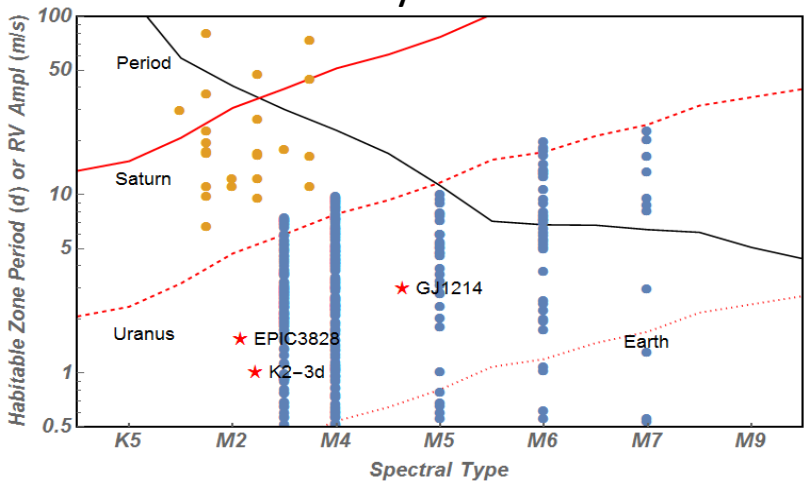
Fischer et al. 2016

Thanks!

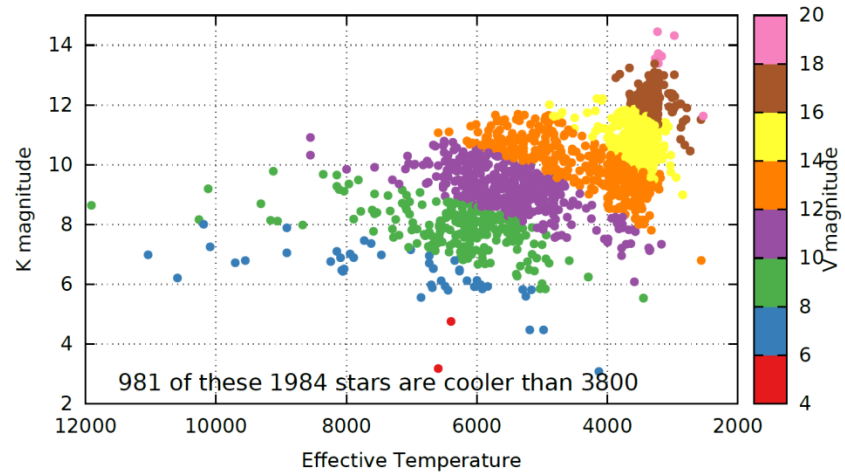
PARVI will be the world's first comb-calibrated, fiber-fed, diffraction-limited (NIR) spectrograph

Science Targets

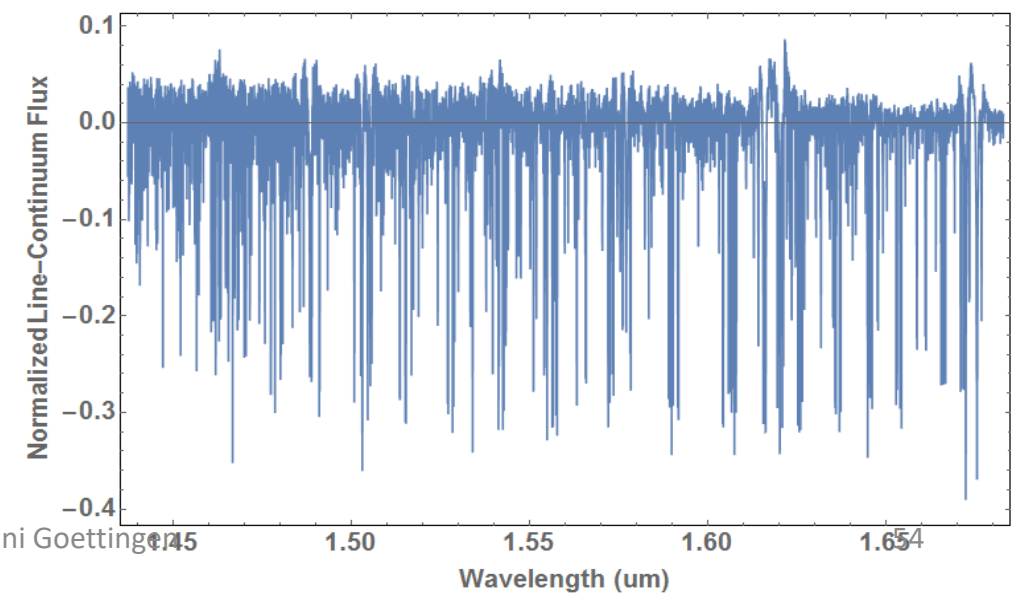
M star Survey



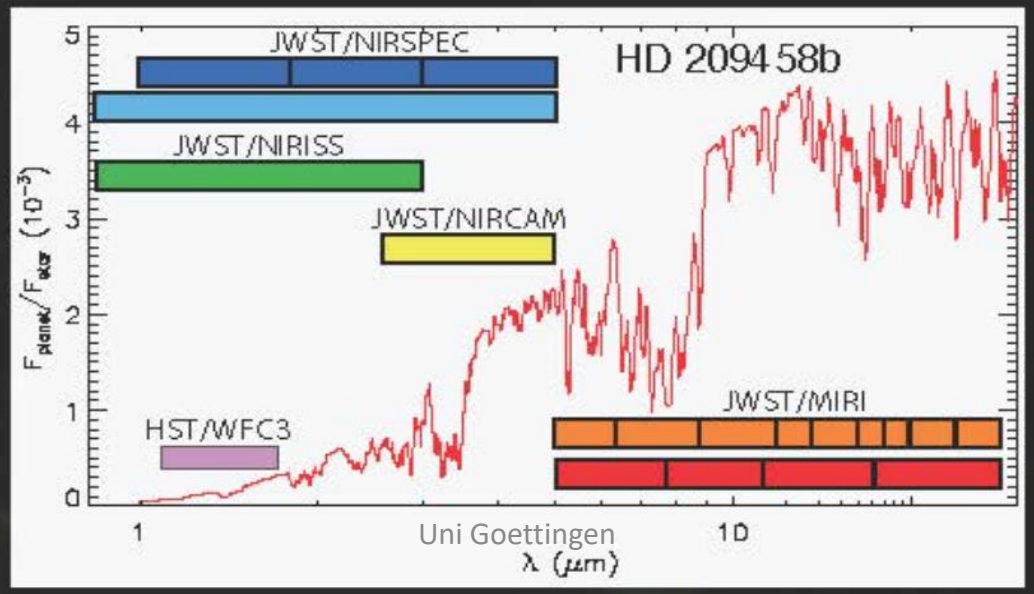
TESS Follow-up



A normalized NextGen model with a smoothed continuum removed for a M3 star (3500 K) has a wealth of spectral features. Detailed modeling shows that with a continuum SNR/pixel ~ 100 these features provide adequate content to achieve ~1 to 3 m/s RV precision.



JWST with characterize transiting planet atmospheres (0.6-20 microns)



Recommendations for the future of PRV

- Stable spectrometers
  - Optical spectrometers with spectral line content
  - Infrared spectrometers with suppressed stellar contamination (spots, plages)
- Proper treatment of stellar noise
  - Distinguishing stellar noise and Keplerian velocities requires high R (>150,000) and high sampling (high SNR)
  - Optical + IR
- Moderate to large telescopes
  - SNR
  - Cadence

Fischer et al. 2016