Investigating the Differential Limb Coupling Effect for Diffraction-Limited Spectrographs

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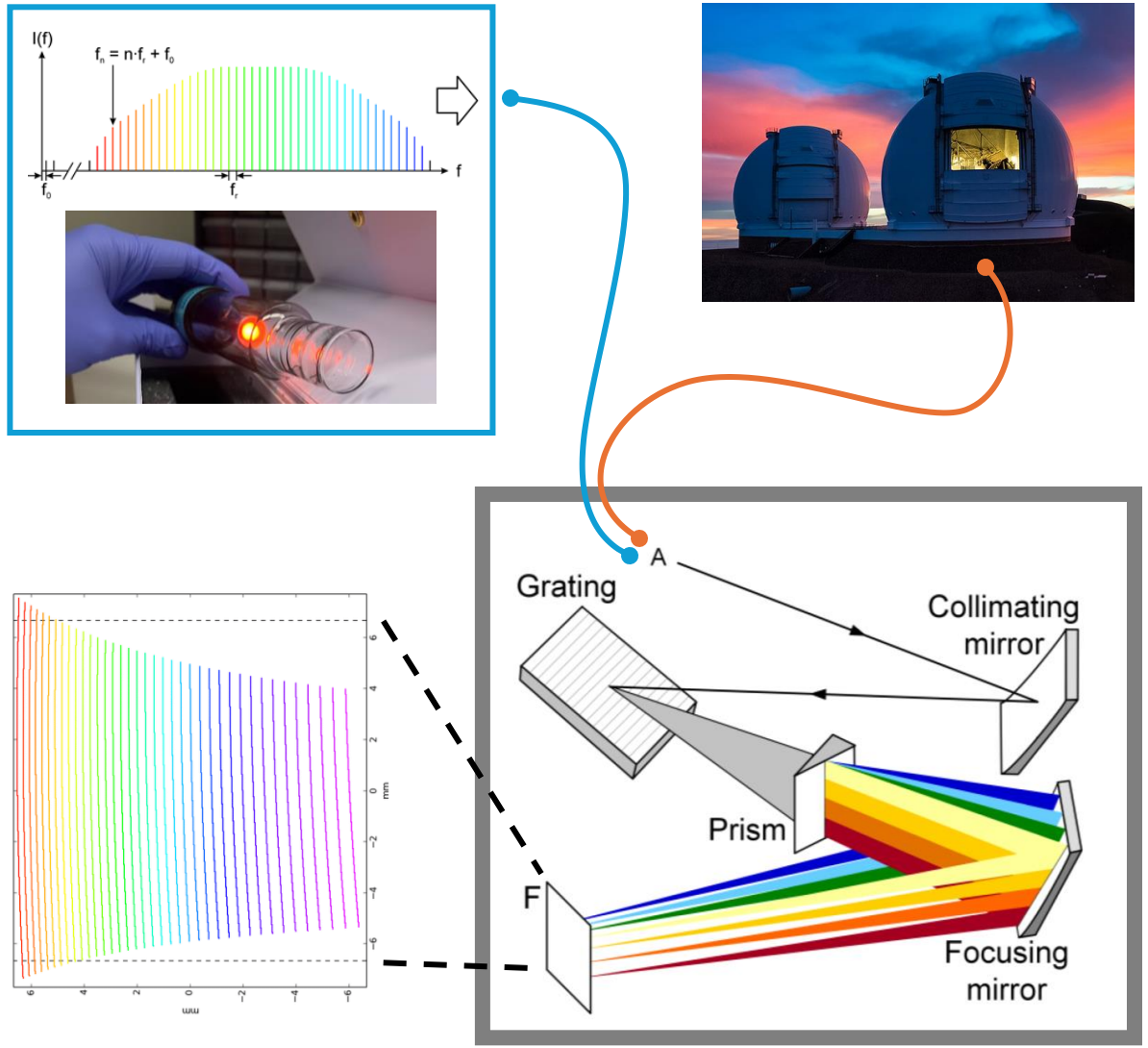
Investigating the Differential Limb Coupling Effect for Diffraction-Limited Spectrographs

The classic radial velocity spectrograph

GOAL: Search for Doppler shifts in the stellar spectrum down to < 1 m/s

- Fiber-fed with multi-mode fibers
- Echelle grating + cross-disperser
- Large detector (CCD/HxRG) capturing many orders at high R
- Calibrated with multiple sources (laser comb, etalon, line lamps)
- Stabilized against temperature, pressure, mechanical shifts, etc.

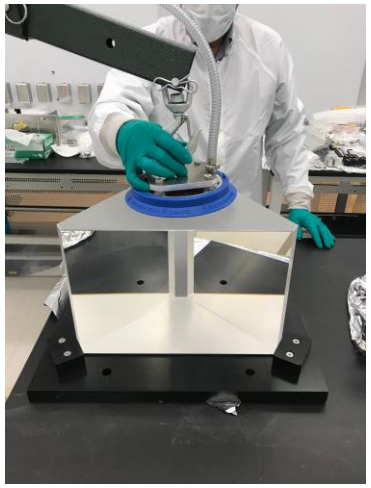


T. Wilken+ 2012; S. Halverson; E. Tweedie/WMKO; G. Raskin+ 2018; Y. Zhang+ 2022

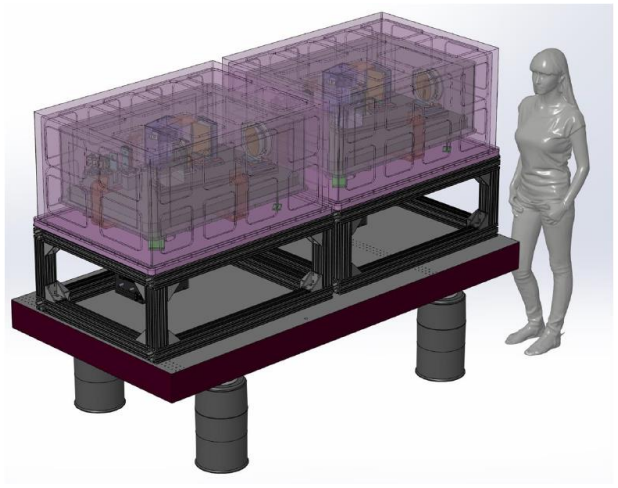
Why go diffraction-limited?

- Optics of a seeing-limited spectrograph scale with telescope size ($A\Omega$)
- Using single-mode fibers eliminates modal noise
- Direct spectroscopy of planet/BD companions and crowded GC fields

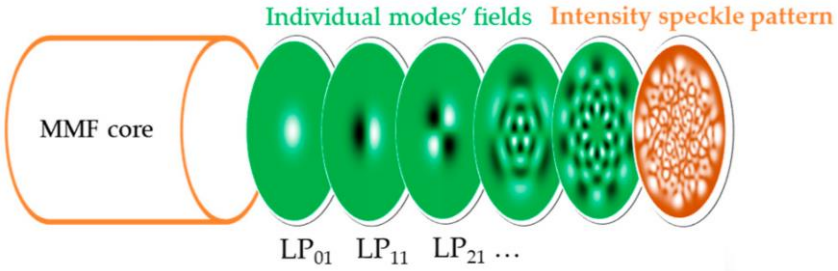
NEID (3.5 m WIYN)

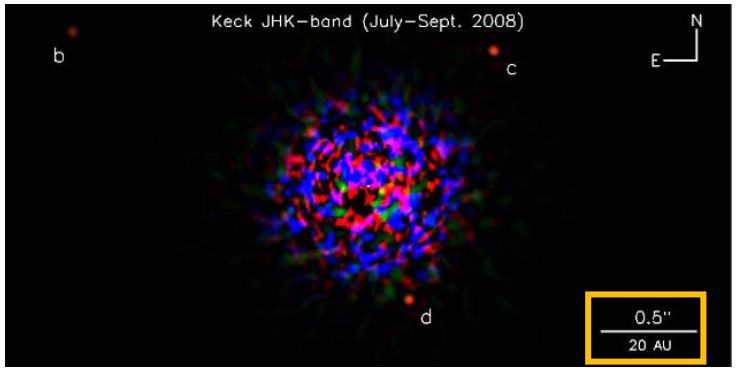


HISPEC (10 m Keck II)



NEID Team; HISPEC Team

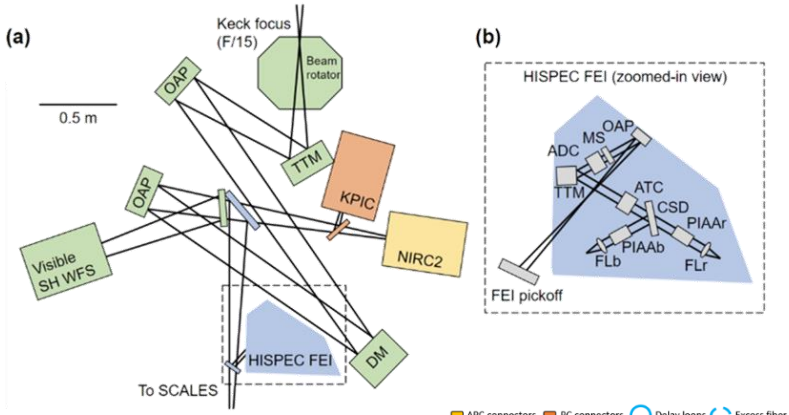




I. Chapalo+ 2024; C. Marois+ 2008

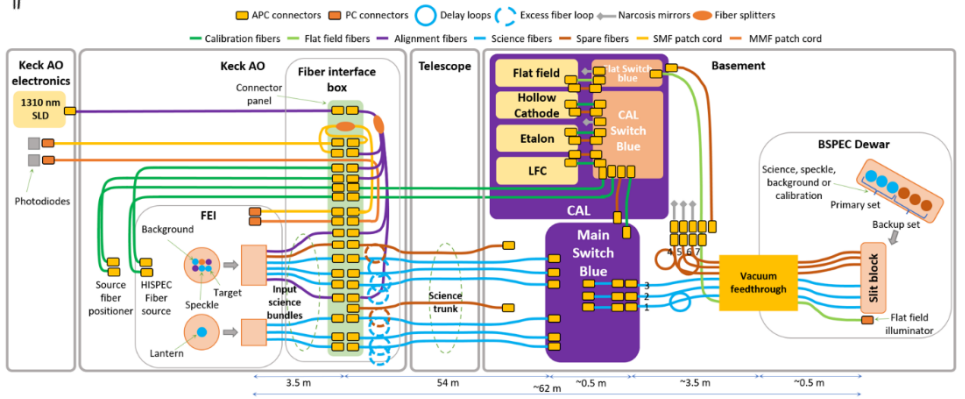
Keck/HISPEC

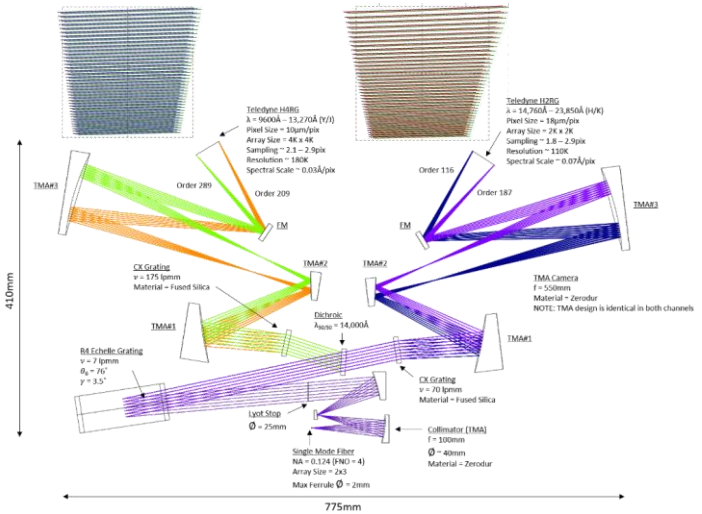
- 0.98-2.46 μm at R~100,000, split into yJ + HK channels
- Single-mode fibers fed by upgraded Keck II AO (HAKA)
- Star can either be on-axis or offset by up to 3”/6”
- Targeting instrumental precision of 30 cm/s
- Currently in build phase, expected first light in 2027
- Pathfinder for TMT/MODHIS

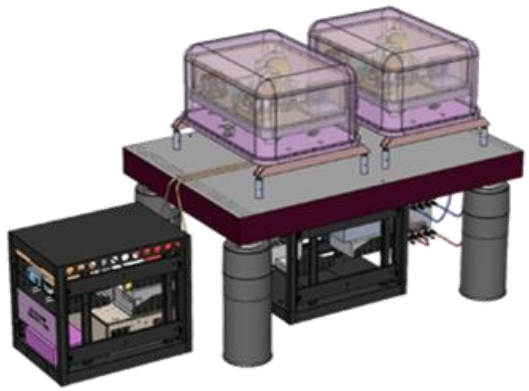


HISPEC

W. M. KECK OBSERVATORY





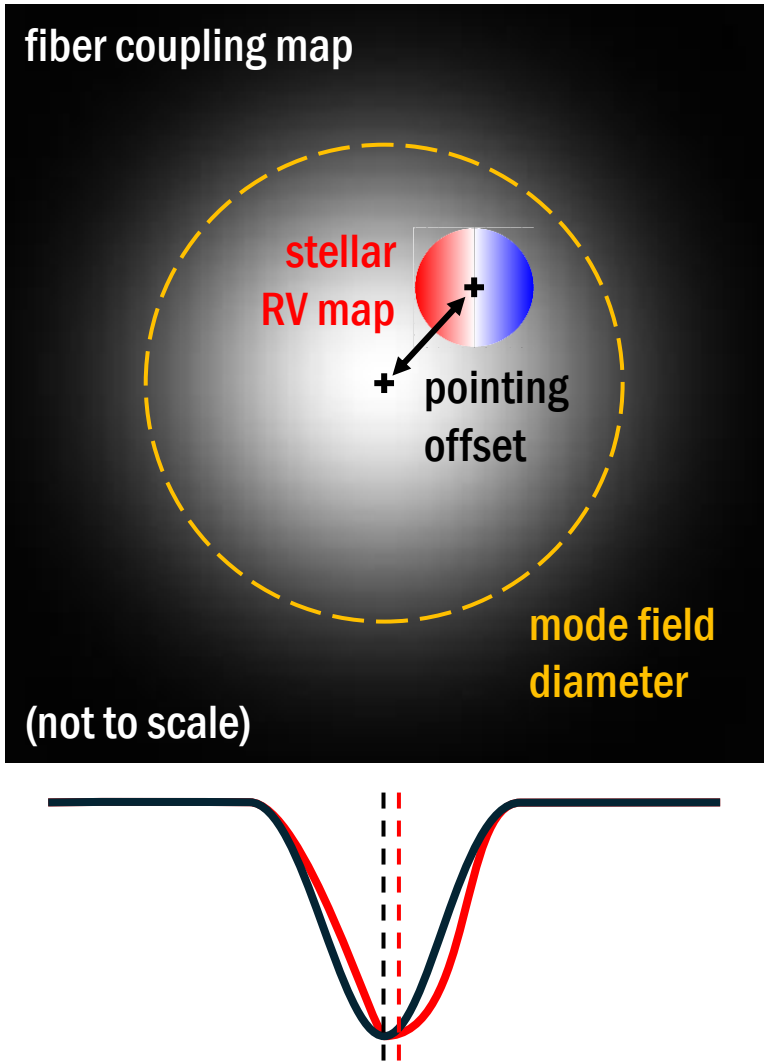


HISPEC Team (DDD)

Investigating the Differential Limb Coupling Effect for Diffraction-Limited Spectrographs

Differential Limb Coupling (DLC) (A. Baker+ 2024, Proc. SPIE)

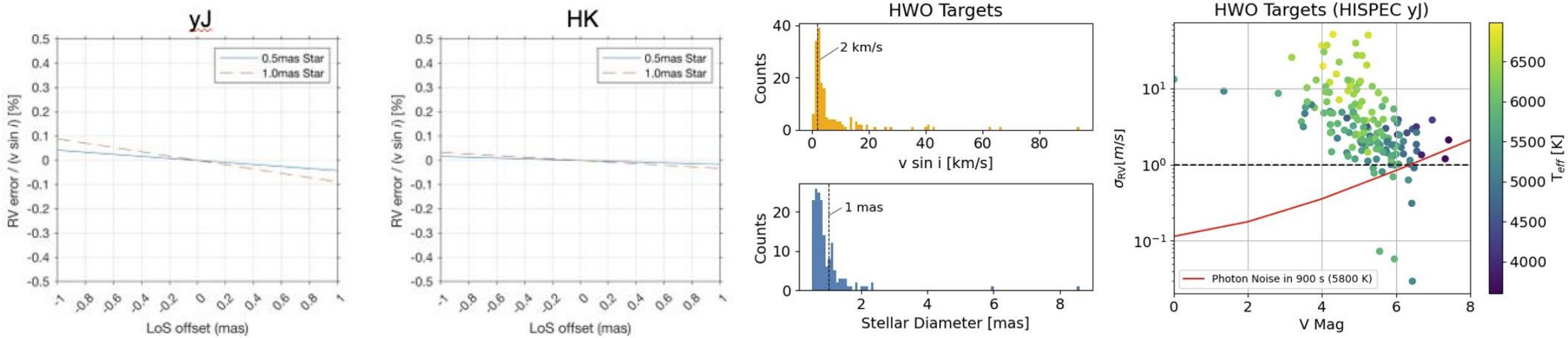
- Nearby/large stars are partially resolved at the diffraction limit
  - λ_{diff} = 1.22 × (1 μm / 10 m) = 25 mas
  - Typical nearby EPRV star = 1 mas
- If the input fiber is not perfectly centered, red/blue-shifted sides of the stellar disk are coupled unequally into the instrument
  - Stellar spectrum is distorted, resulting RVs have non-astrophysical bias
  - Pointing offset (and thus RV bias) will change between observations



Differential Limb Coupling (DLC) (A. Baker+ 2024, Proc. SPIE)

- Simulations predict $\Delta\mathrm{RV} \propto \alpha_{\mathrm{offset}} \left(\frac{\lambda}{D_{\mathrm{tel}}}\right)^{-2} \delta_{\mathrm{star}}\, v \sin i$
- For a typical EPRV target and a pointing offset of 1 mas…
  ΔRV would be ~m/s for Keck/HISPEC and ~10 m/s for TMT/MODHIS

Keck



BUT: DLC has not yet been directly measured on-sky

Investigating the Differential Limb Coupling Effect for Diffraction-Limited Spectrographs

How do we observe DLC?

Must be a **diffraction-limited** spectrograph

$$\Delta \mathrm{RV} \propto \alpha_{\mathrm{offset}} \left(\frac{\lambda}{D_{\mathrm{tel}}}\right)^{-2} \delta_{\mathrm{star}}\, v \sin i$$

Use the tip-tilt controls to deliberately offset by tens of mas

Palomar/PARVI

- Covers JH at R~60,000
- Fed by the 200-inch (5.1 m) Hale Telescope via P3K AO system
- Should be RV-stable at the few m/s level

Fast-rotating A/F stars

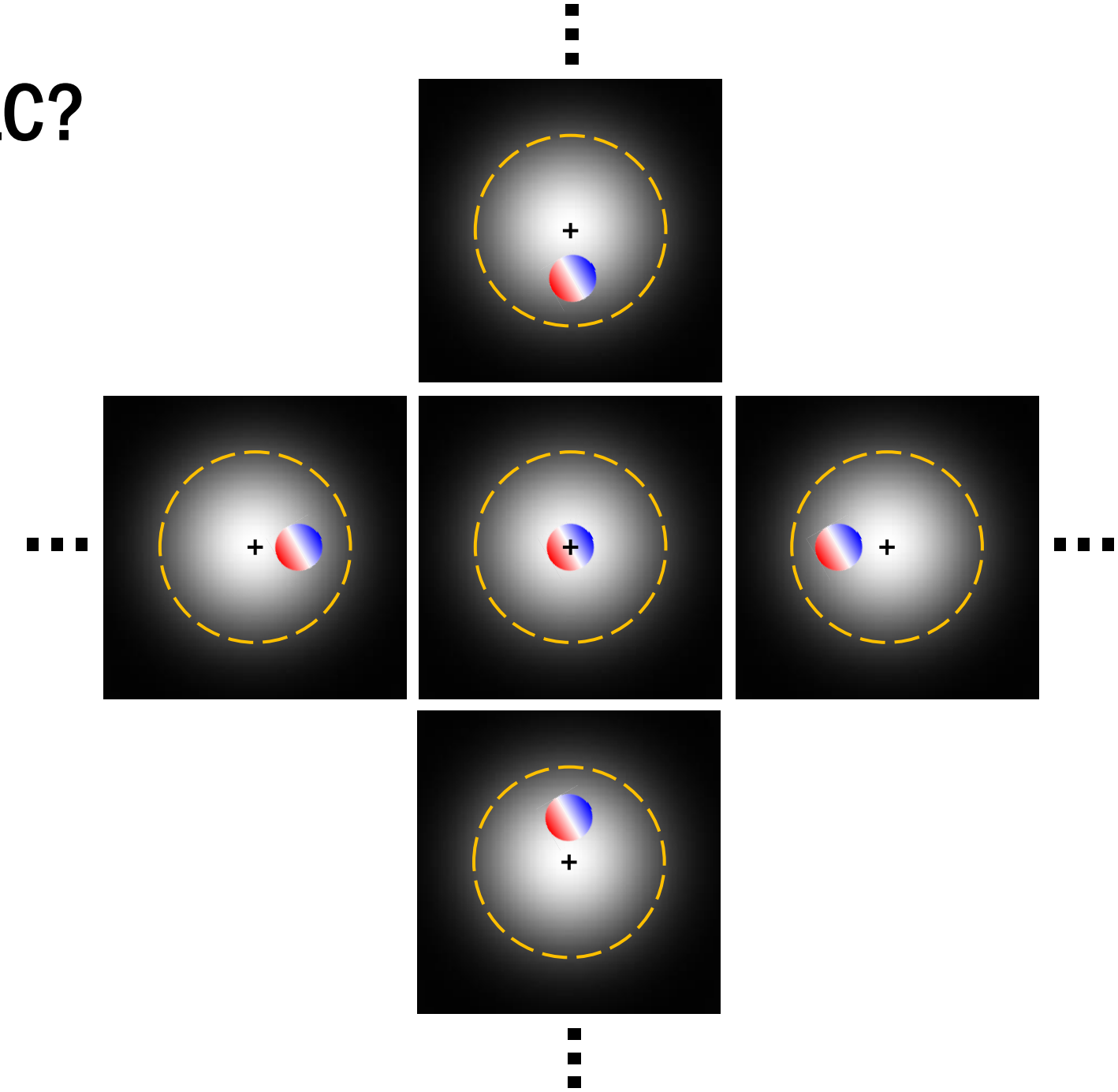
- Angular size ~ 1-2 mas
- vsini < 70 km/s (or else lines get excessively broadened)

Moderately-rotating K/M giants

- Angular size ~ 10-20 mas
- vsini ~ 10 km/s

How do we observe DLC?

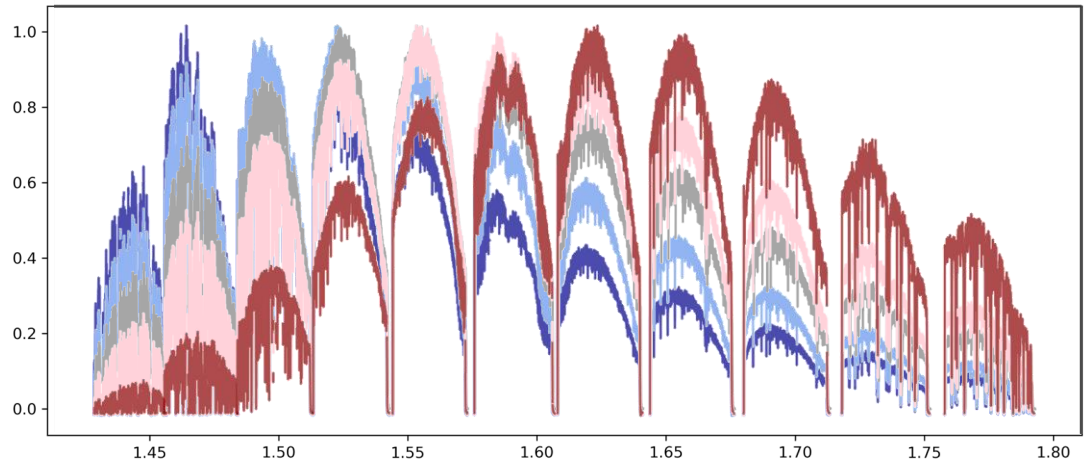
- On-axis: Standard RV observing mode
  - Sets the RV zeropoint ($\gamma_{\rm RV}$)
- Off-axis: Offset fiber from star in steps of ~15 mas
  - X pattern since we don't know orientation of the stellar spin axis
  - Expected ΔRV > 100 m/s per step for our targets
- Obtained ~3 nights of PARVI data in 25A/B



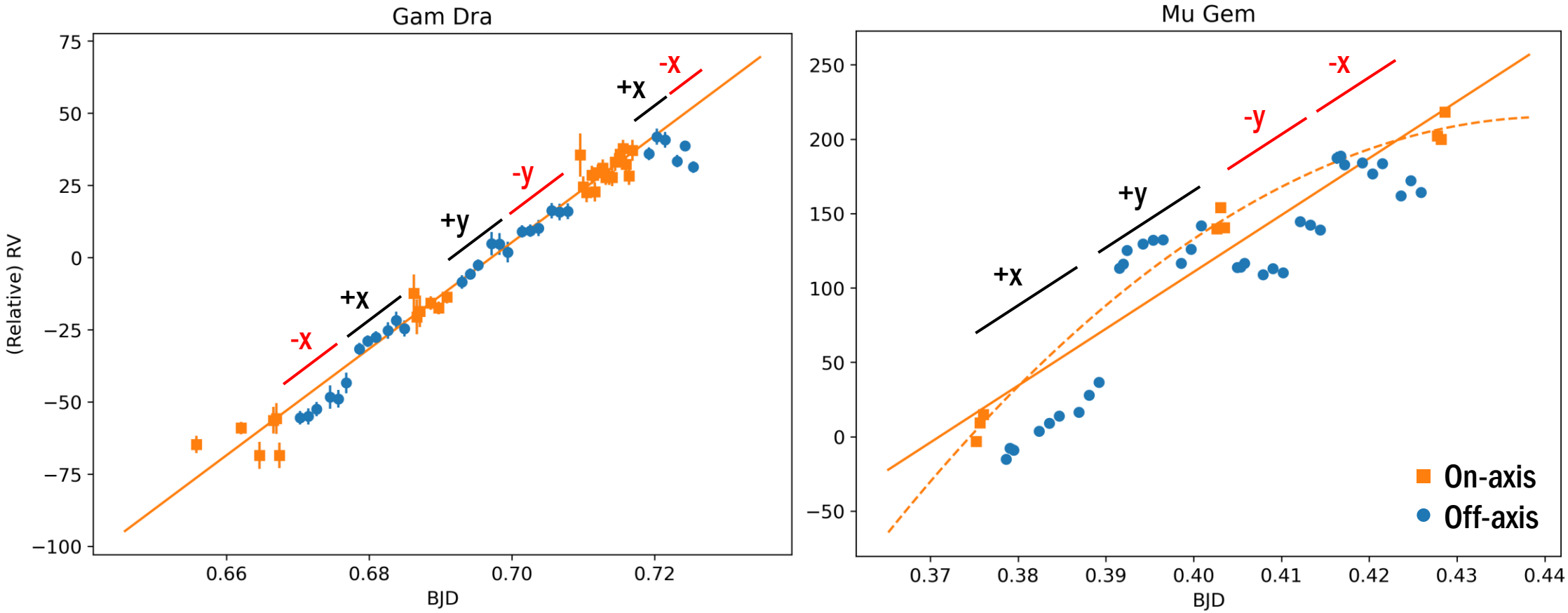
Isolating DLC from PARVI RVs is harder than we thought...

- J-band wavesol (extrapolated from H-band LFC) is inaccurate
  - Derived a new J-band solution with UNe
- Only a few nights of data = Template bias slope (A. Silva+ 2025)
  - Getting more template data – but PARVI orders have shifted due to a thermal cycle
  - CCF RVs? (for M-stars in the NIR?) Forward model RVs?
- No ADC = Differential atmospheric refraction
  - Solution TBD

(actually from a similar DLC experiment with KPIC)



Results in progress (SERVAL RVs)



Summary

- Diffraction-limited spectrographs could be a promising new architecture for exoplanet RVs and spectroscopy
  - But nearby/large stars become partially resolved at the diffraction limit
- Differential Limb Coupling = light from different parts of the stellar disk is coupled into the instrument with varying efficiency
  - Causes RV offsets if pointing varies (by mas) between observations
  - Simulations predict that DLC could dominate the instrumental RV error budget (~m/s for Keck/HISPEC, 9x larger for TMT/MODHIS) unless we mitigate it
- We have devised observations with PARVI to directly measure DLC
  - Data analysis is complex, but we are hard at work – stay tuned!

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