2020 SAGAN SUMMER WORKSHOP

EXTREME PRECISION RADIAL VELOCITY

Wavelength Calibration Sources

for Extreme Precision Radial Velocity Detection of Exoplanets

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NExScI

OVERVIEW

- Why are EPRV calibration sources necessary?
- Characteristics of a good RV calibration source
- Prior methods and performance of spectrograph calibration
- State-of-the-art EPRV calibration sources
  - How they work
  - Capabilities and limitations
- Future potential solutions for future EPRV calibration sources

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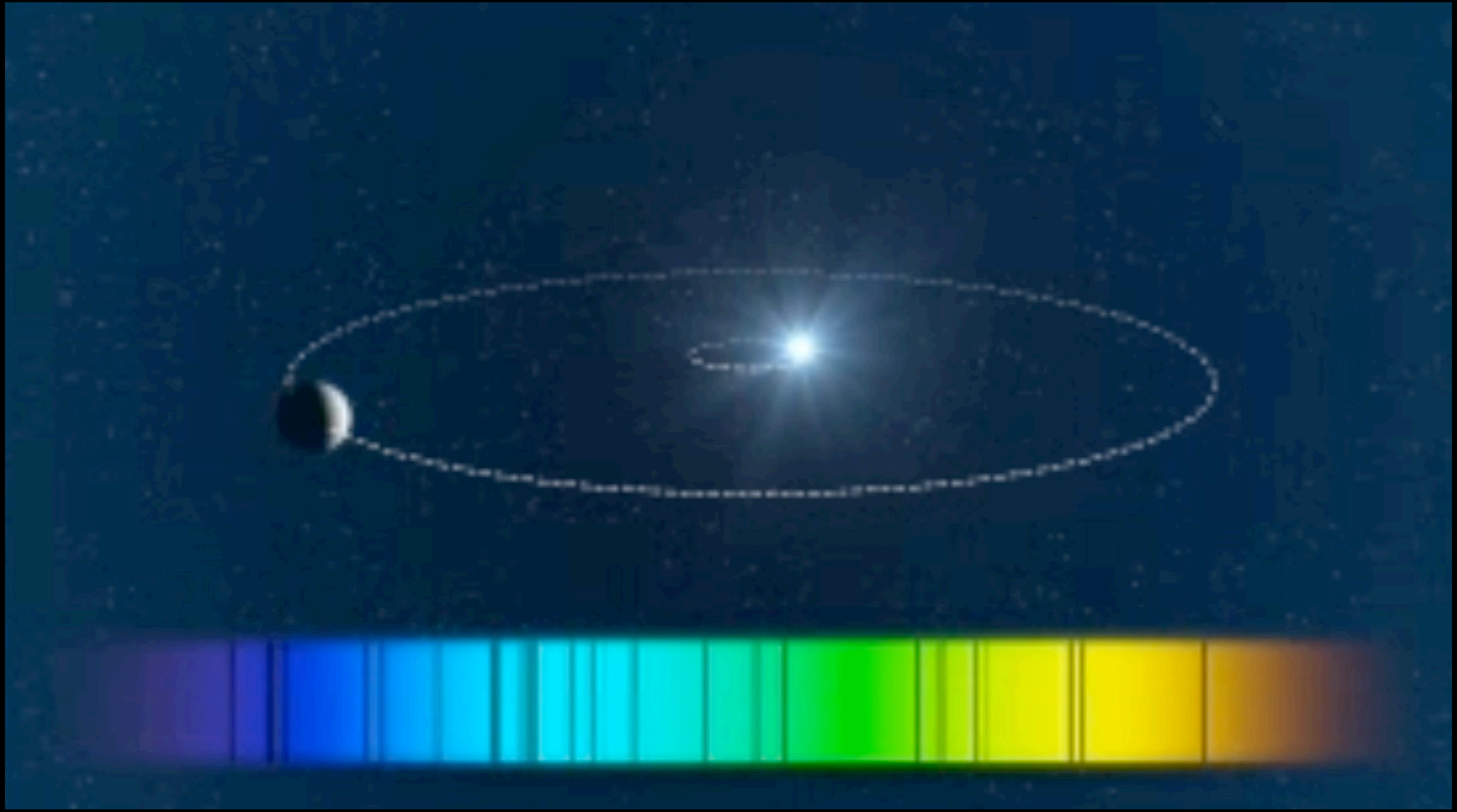
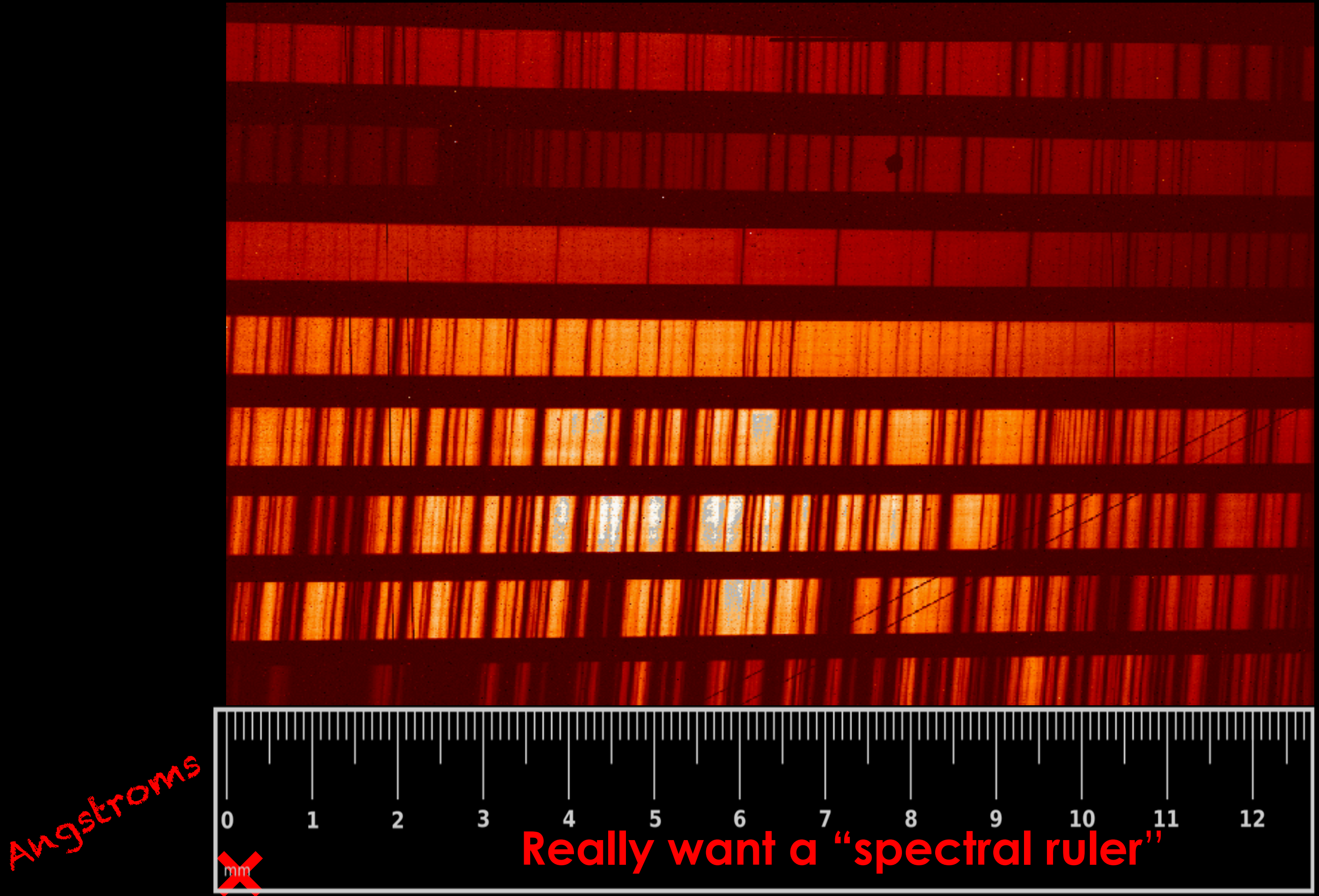
WHY ARE EPRV CALIBRATION SOURCES NECESSARY?

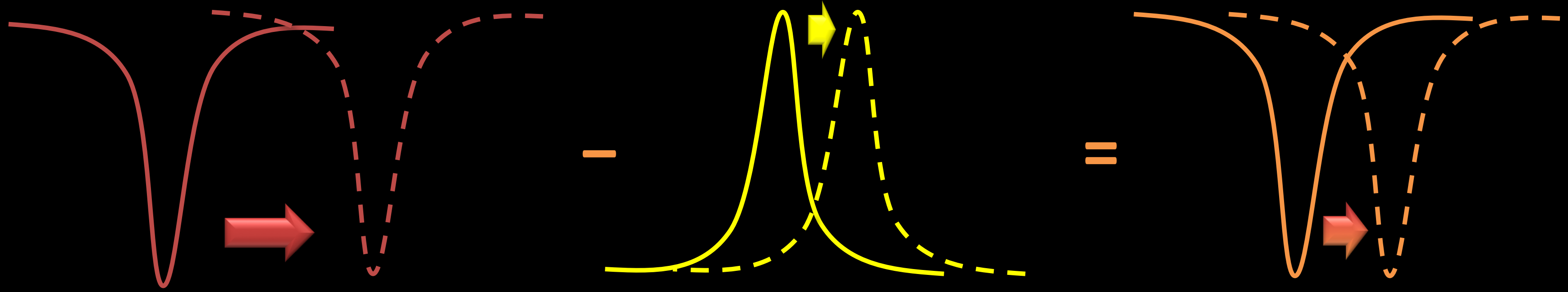


MEASURE MOTION OF STELLAR SPECTRAL FEATURES … *RELATIVE TO WHAT?*



MEASURING THE STELLAR DOPPLER SHIFTS *AND* THE INSTRUMENT DRIFT….TO BETTER THAN 3 PARTS IN TEN BILLION FOR A 9 CM/S SPECTRAL SHIFT

Observed stellar spectral shift **Measured calibration shift** **Stellar RV signal**

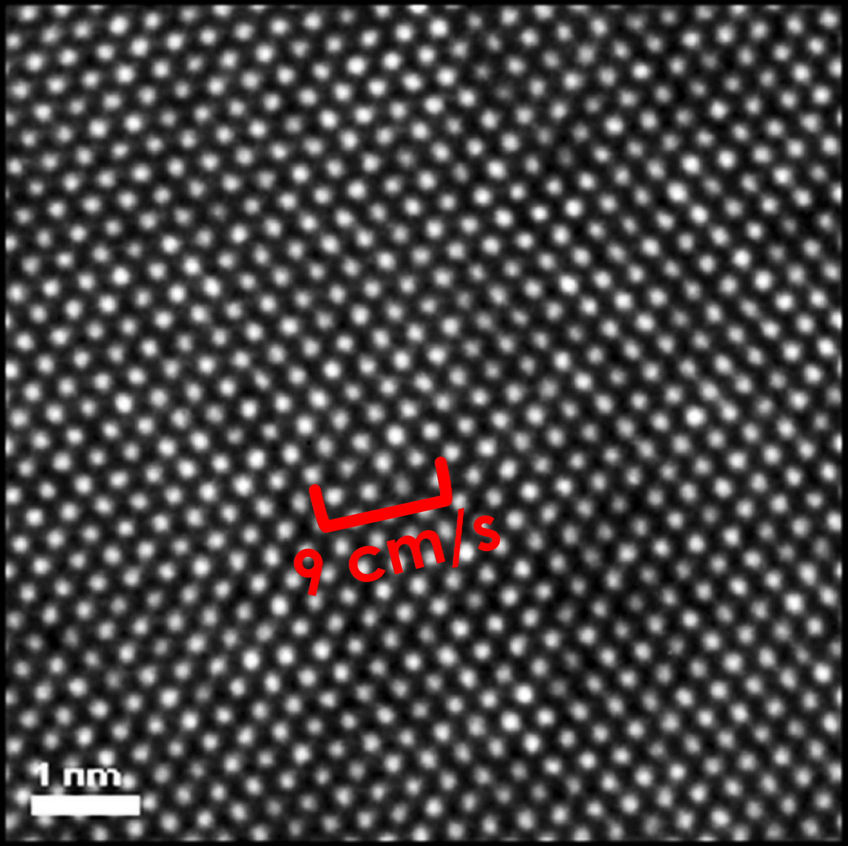


$\Delta\lambda_{OBS}$ $\Delta\lambda_{CAL}$ $\Delta\lambda_{RV} = \Delta\lambda_{OBS} - \Delta\lambda_{CAL}$

AND THIS IS WHAT A 9 CM/S SHIFT IN RADIAL VELOCITY LOOKS LIKE* ON A SILICON DETECTOR

Velocity "*plate scale*" of typical R~100,000 spectrometer:

~6 cm s^{-1} nm^{-1}



1/1000th of a pixel

TEM image of silicon wafer lattice (typical CCD)

* From S. Halverson, 2018 Sagan Summer Workshop: https://www.youtube.com/watch?v=Xq4hXRORBx0&t=215s

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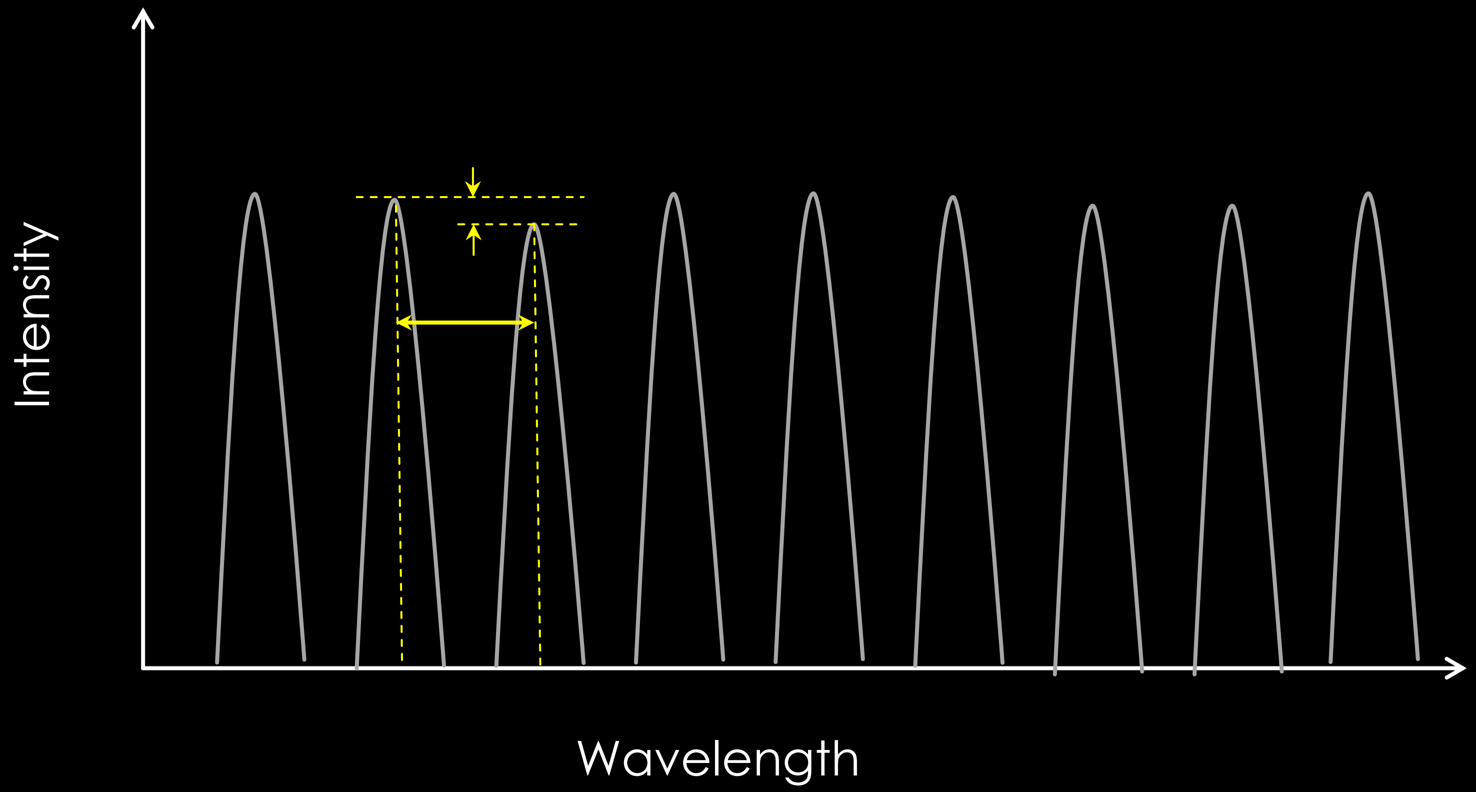
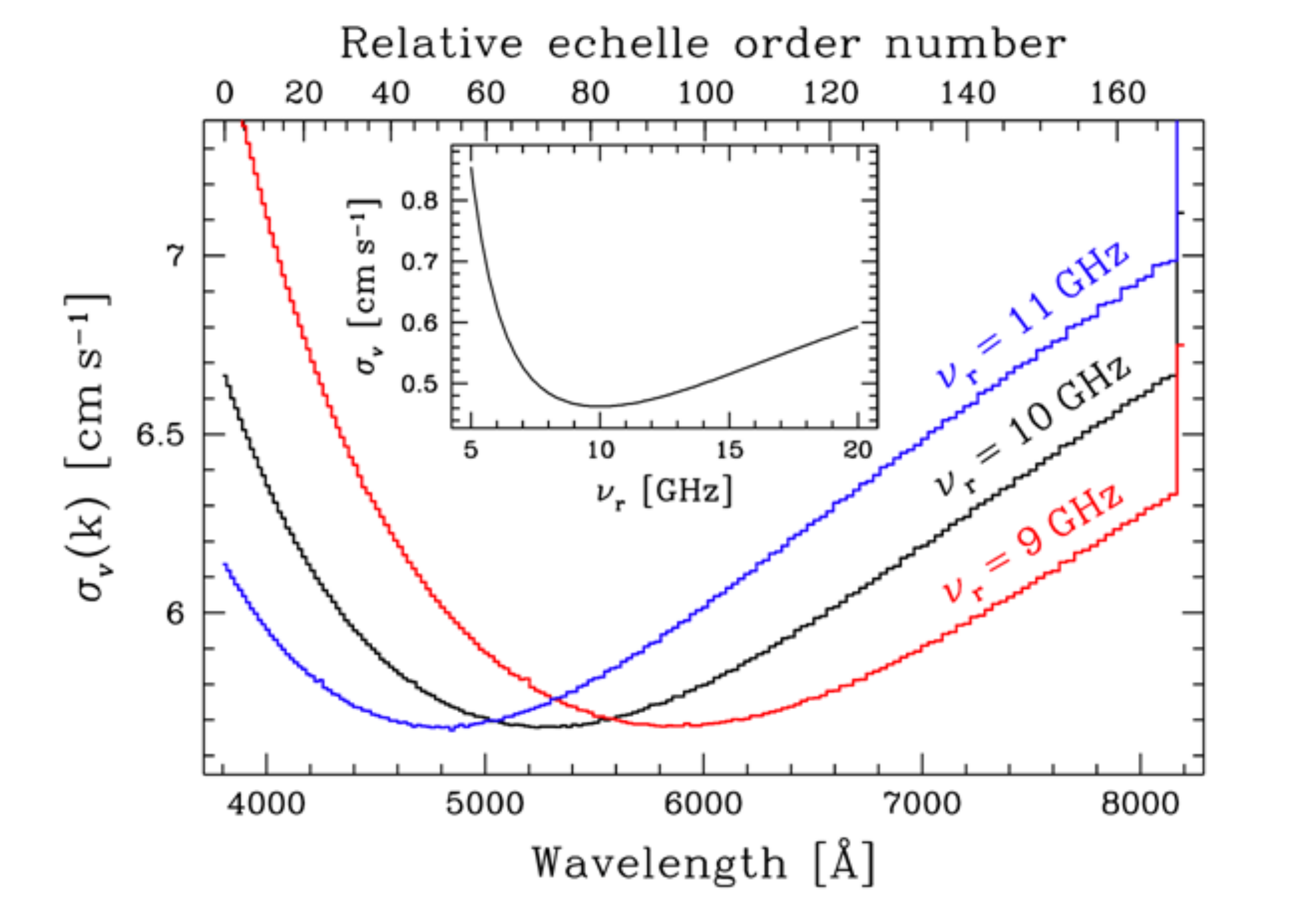
WHAT MAKES A GOOD CALIBRATION SOURCE?

- SPECTRAL COVERAGE OVER FULL INSTRUMENT BANDPASS
  - VISIBLE BAND FOR EPRV REQUIRED
  - NIR MAY BE USEFUL FOR STELLAR ACTIVITY MITIGATION
- HAS A UNIFORM, DENSE GRID OF LINES
  - HOW FAR APART DO THEY NEED TO BE? – DEPENDS UPON SPECTROGRAPH RESOLUTION





Results from comb simulations with R=150,000, (S/N)max = 500 and $\beta_{d,max}$ = 0.01. The spectrograph's resolution (FWHM) is sampled with 3 pixels and each echelle order is assumed to be 2048 pixels long. The main panel shows the expected velocity precision available from each echelle order ($\sigma_v(k)$, for three different line spacings while the inset shows the total velocity precision σ_v, integrated over the full wavelength range of the simulated spectrum, 380 nm – 820 nm (Murphy, 2007) .

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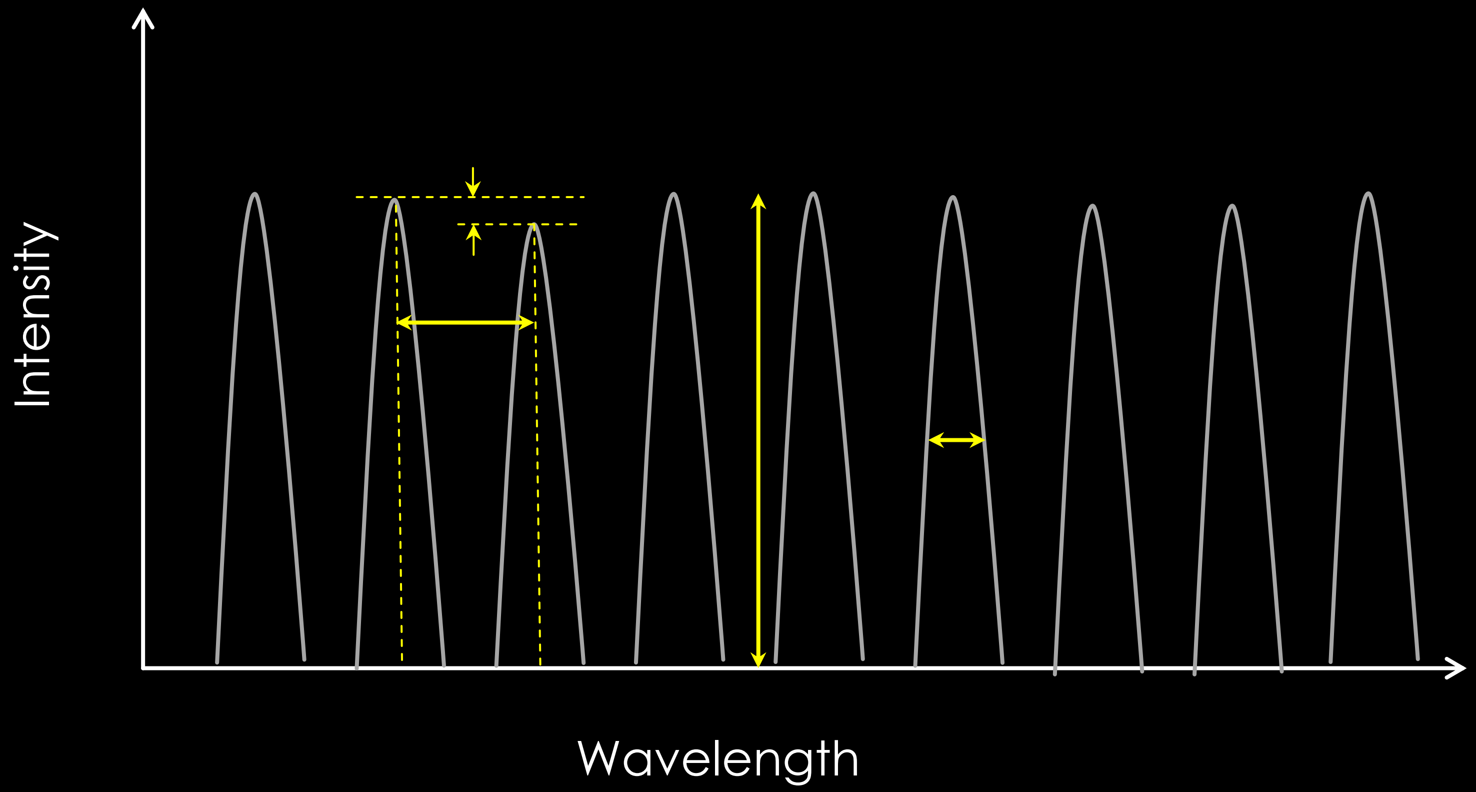
EXTREME PRECISION **RADIAL** VELOCITY

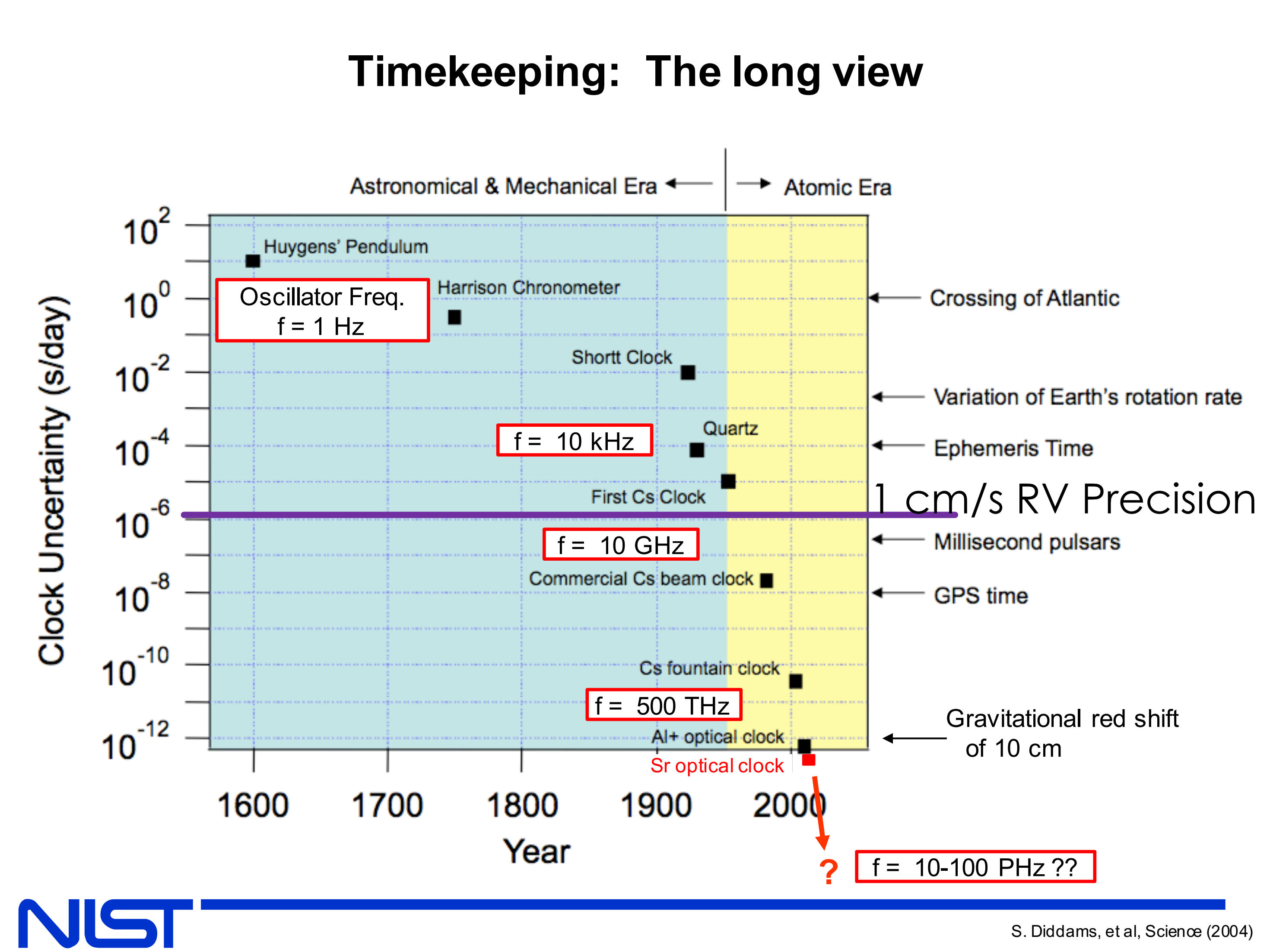
WHAT MAKES A GOOD CALIBRATION SOURCE?

- Spectral coverage over full instrument bandpass
  - Visible band for EPRV required
  - NIR may be useful for stellar activity mitigation
- Has a uniform, dense grid of lines
  - How far apart do they need to be? – depends upon spectrograph resolution
- Intensity of each line ~matches starlight
  - Don't want to saturate detector
  - Want good SNR
- How narrow do the lines have to be?
  - Lots of leeway here – can be ~GHz linewidth
  - Just so long as the centroid…
- Doesn't move
  - At least by an amount ~order of magnitude less than the signal
  - That means, for EPRV, frequency stability better that 1 part in 3×10^{11}, or 1 cm/s

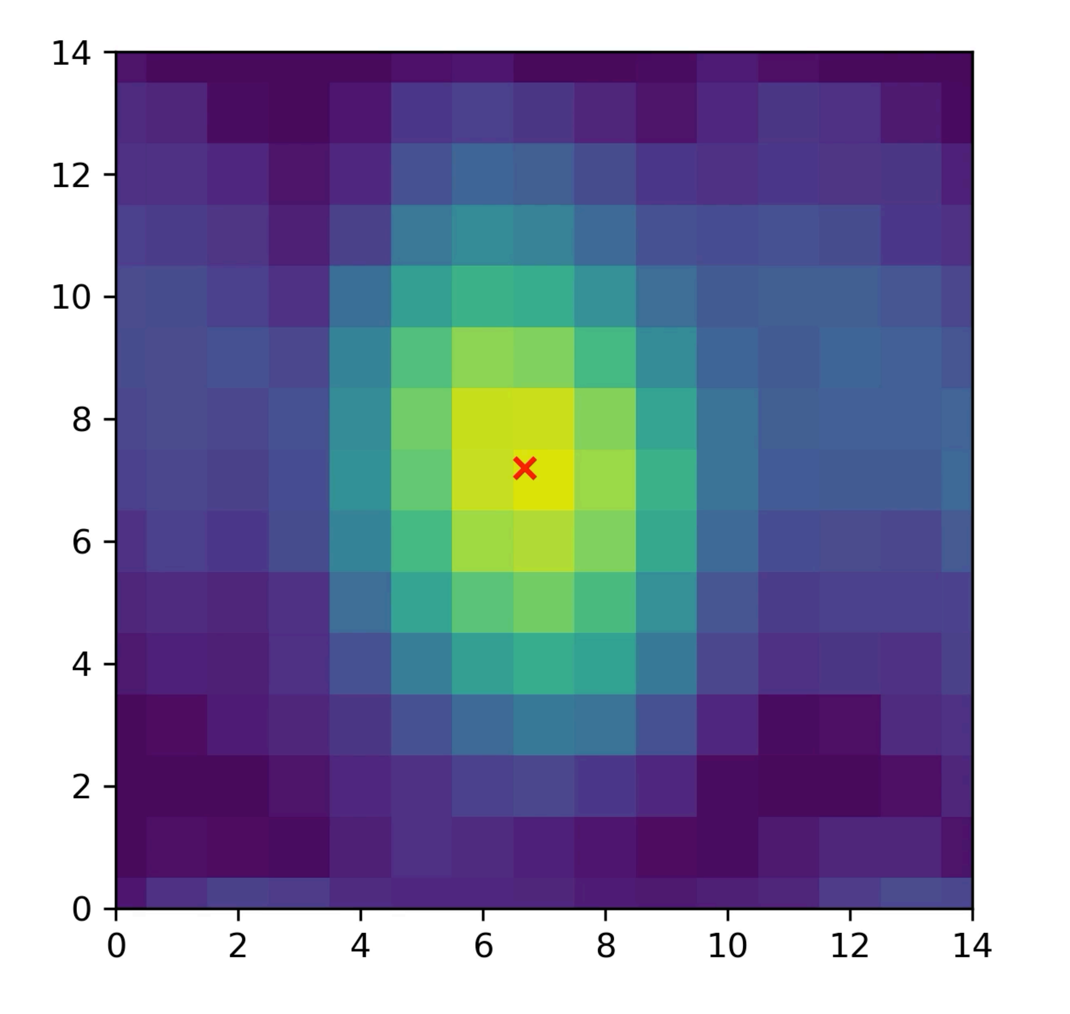


MEASURING FREQUENCY STABILITY

- How hard is it to attain frequency stability of 3E-11?
- Nowadays – that not hard!



A NOTE ON INTENSITY STABILITY



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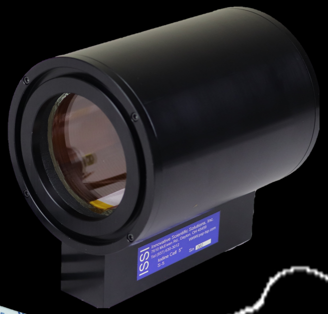
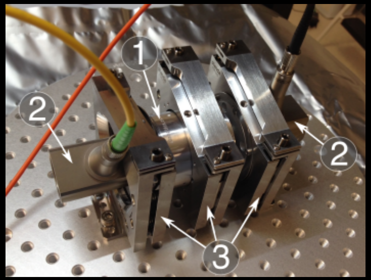
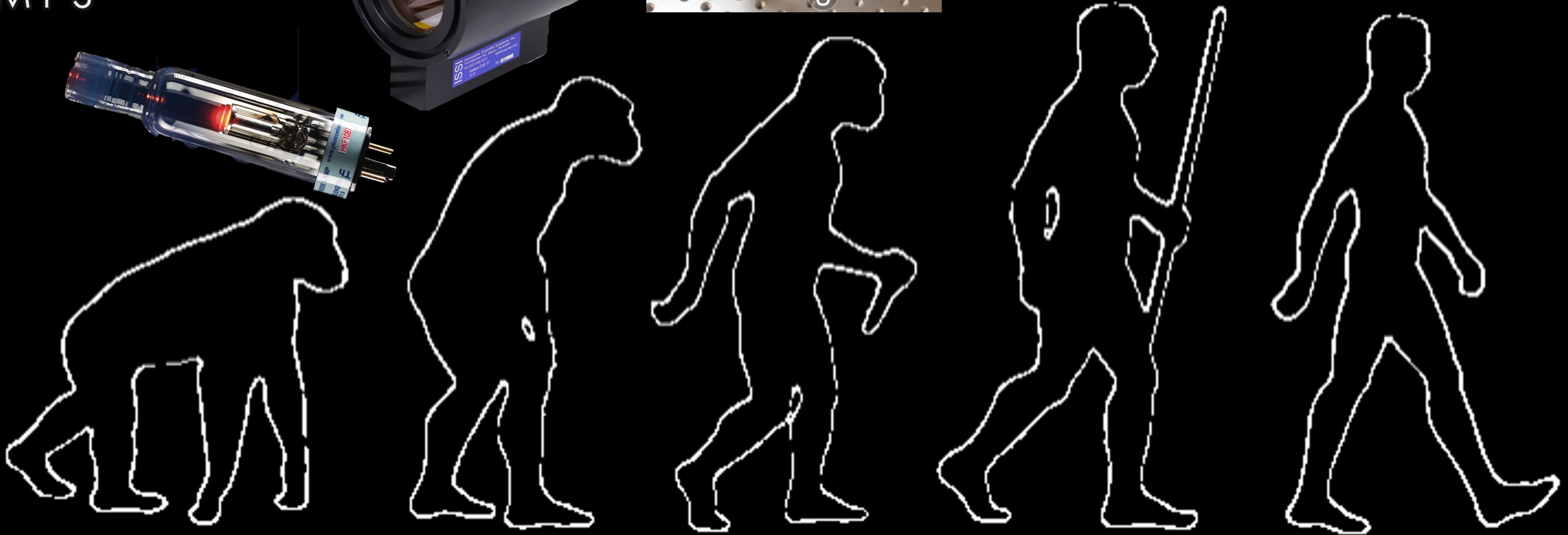
EVOLUTION OF PRV CALIBRATION SOURCES

- Emission Lamps
- Gas cells
- Etalons





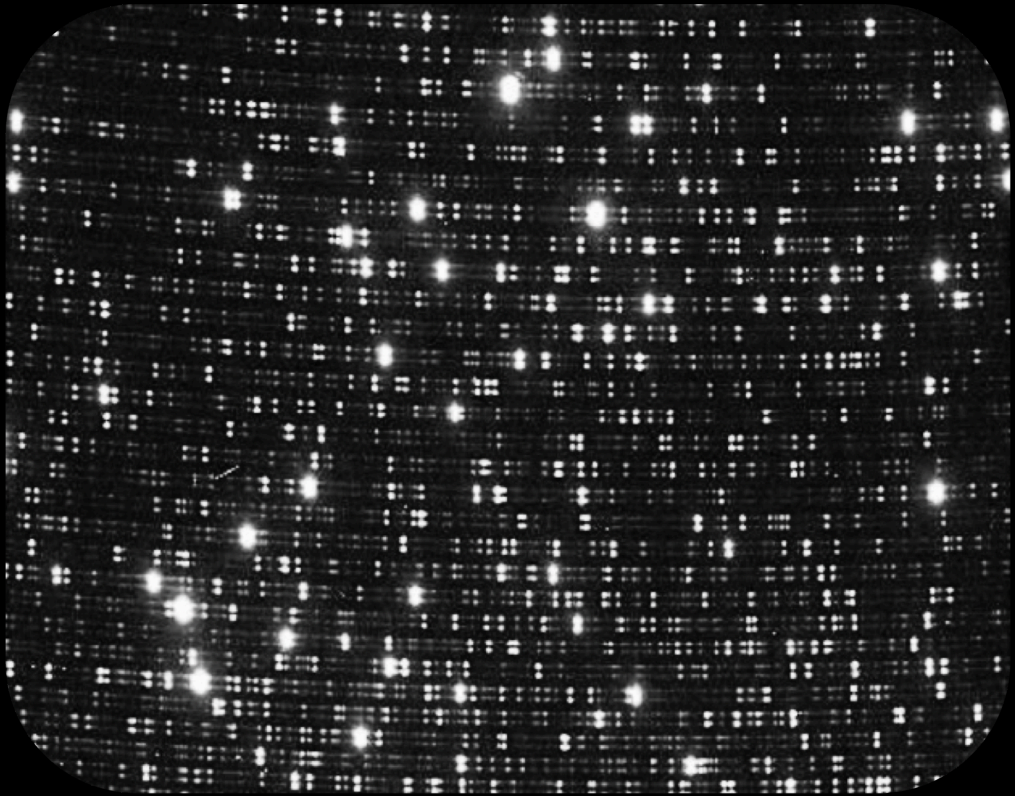


EMISSION LAMPS

Th-Ar emission lamp

RV precision has been limited to ~1 m/s

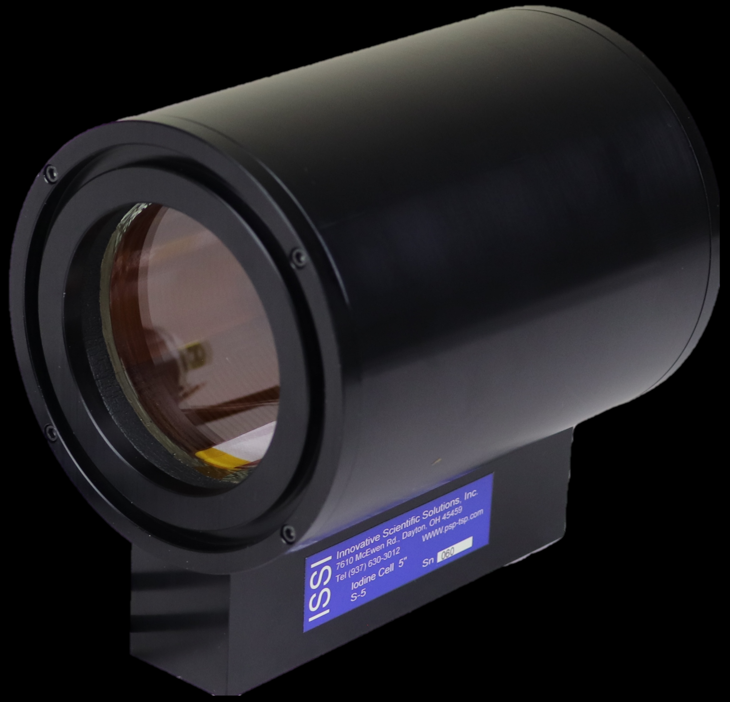
Simultaneous Calibration:



Th-Ar spectrum on PARAS instrument

IODINE GAS CELLS

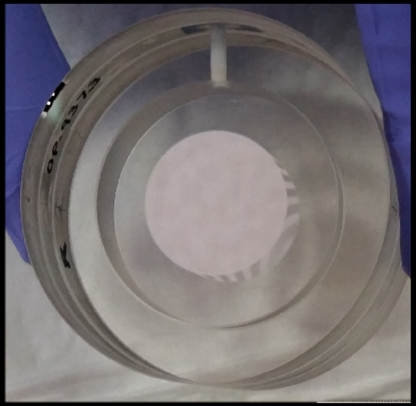
- PROS:
  - SAME LIGHT PATH AS STARLIGHT – SUPERIMPOSED SPECTRUM
  - SIMPLE, LOW COST
- CONS:
  - LIMITED SPECTRAL COVERAGE - 510 TO 620 NM
  - LIGHT LOSSES OF ABOUT 25%
  - THE SUPERIMPOSED ABSORPTION SPECTRUM ALSO MASKS LINE PROFILE VARIATIONS THAT MIGHT BE DIAGNOSTIC OF STELLAR ACTIVITY*
- IN NIR METHANE GAS CELLS



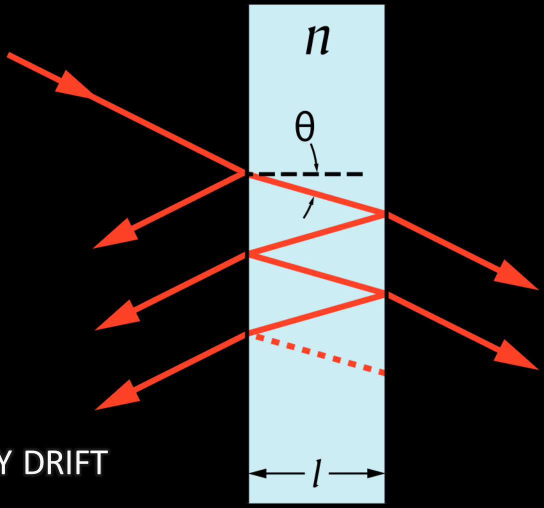
RV precision has been limited to ~1 m/s

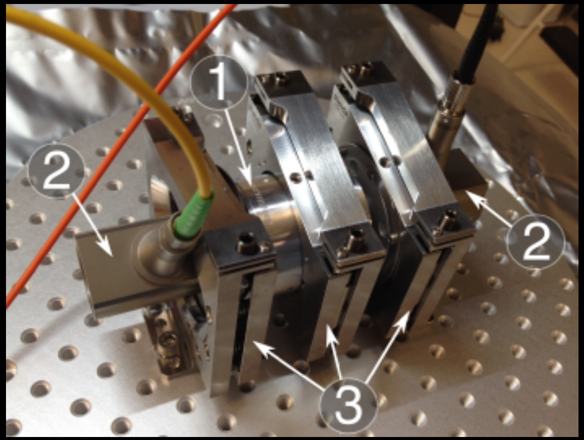
*Fischer et al (2016)

FABRY–PÉROT ETALONS

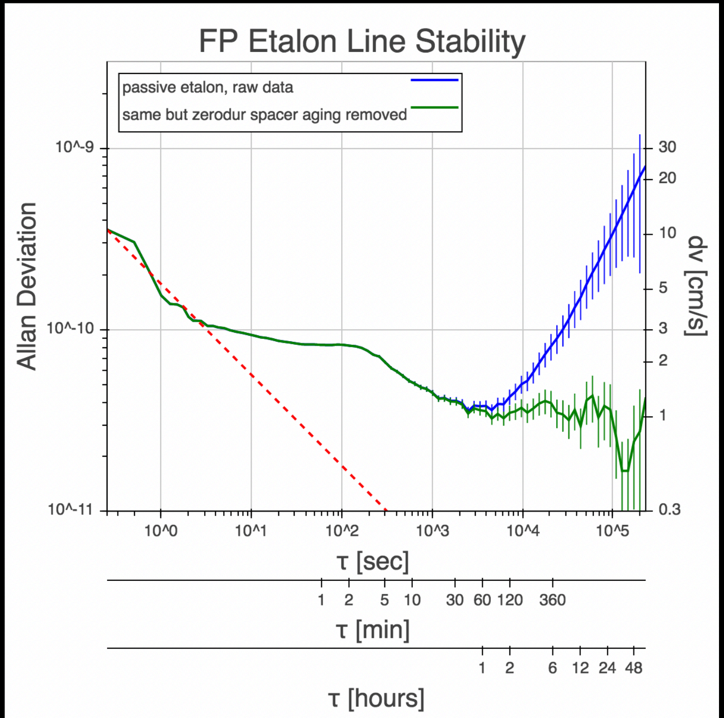


- USED ON STATE-OF-THE-ART PRV SPECTROGRAPHS: NEID, HPF, ESPRESSO, HARPS, AND MAROON-X FOR SIMULTANEOUS ILLUMINATION
- PROS:
    - SIMPLE PASSIVE DEVICES, QUASI-UNIFORM GRID OF LINES
    - BROAD SPECTRAL COVERAGE
    - CAN ENGINEER FOR DESIRED LINE SPACING
- CONS
    - REQUIRES HIGH THERMAL STABILITY AND CONTROL
    - TRACKING ONE MODE IS INSUFFICIENT FOR TRACKING THE FREQUENCY DRIFT OF OTHER MODES
    - ZERODUR AGING

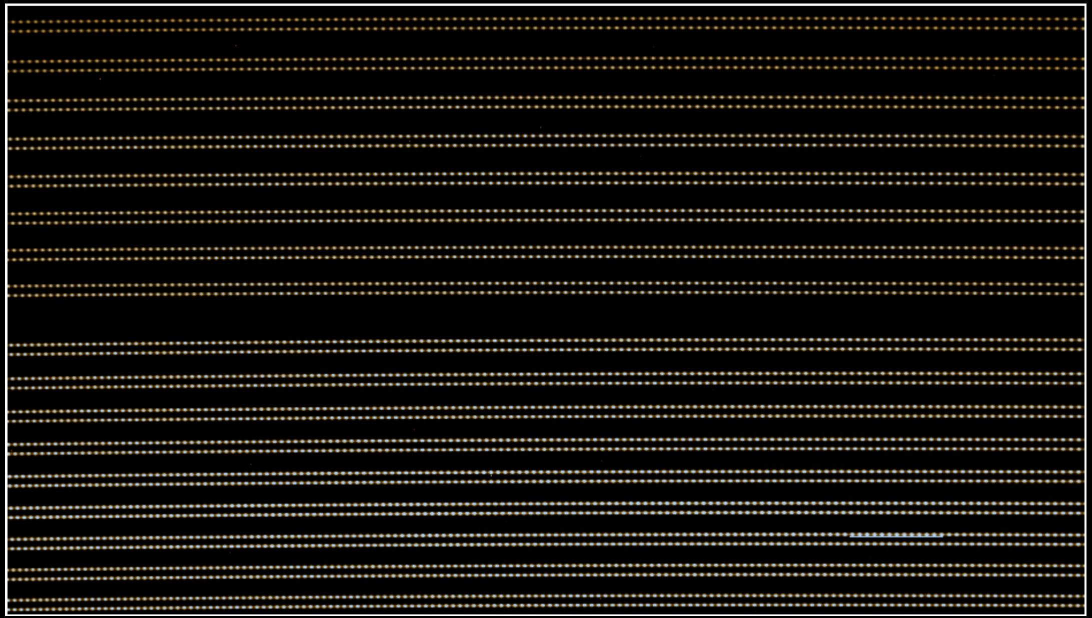




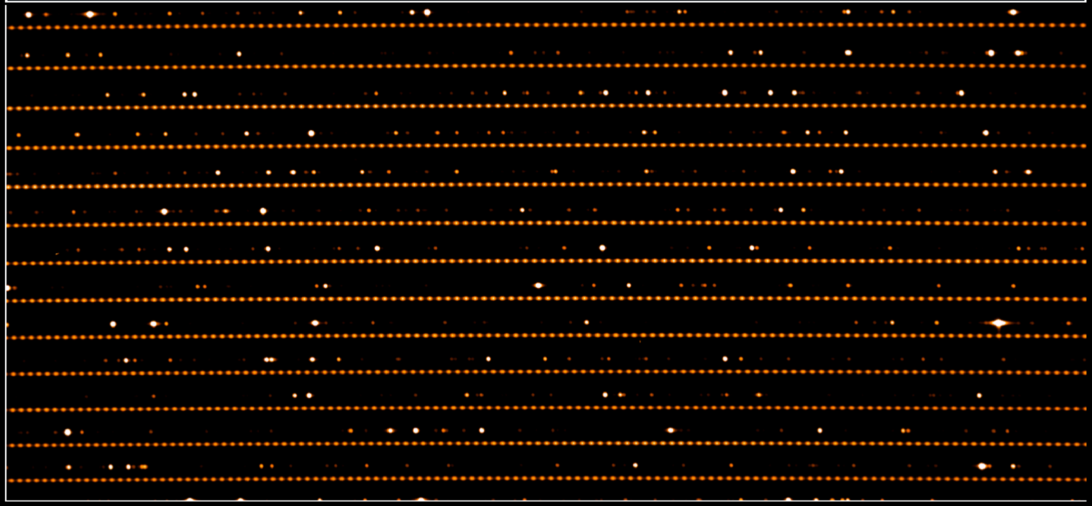
FP ETALON PERFORMANCE



HARPS FP CALIBRATOR SPECTRUM →



MAROON-X ETALON STABILITY CURVE ←

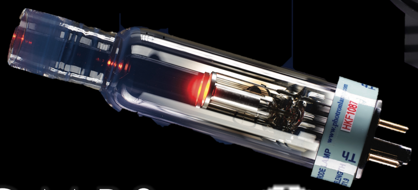


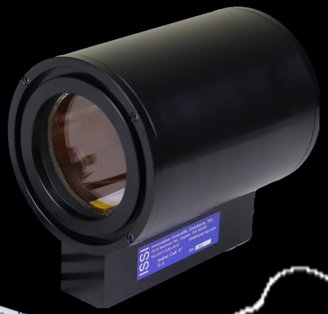
RV Precision ~3 cm/s over days

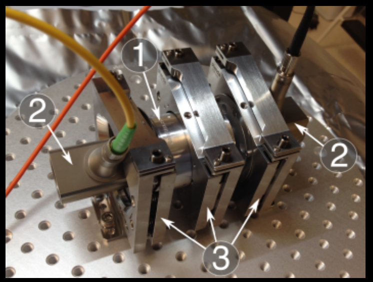
* FROM F. PEPE, ESPRESSO FABRY-PÉROT CALIBRATOR TEST REPORT, VLT-TRE-ESP-13520-9202, (2016).

EVOLUTION OF PRV CALIBRATION SOURCES

- Emission Lamps
- Gas cells
- Etalons
- Frequency combs

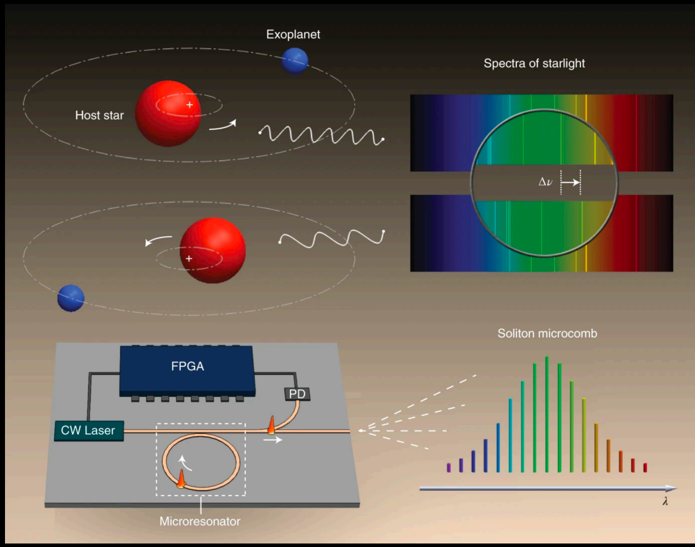




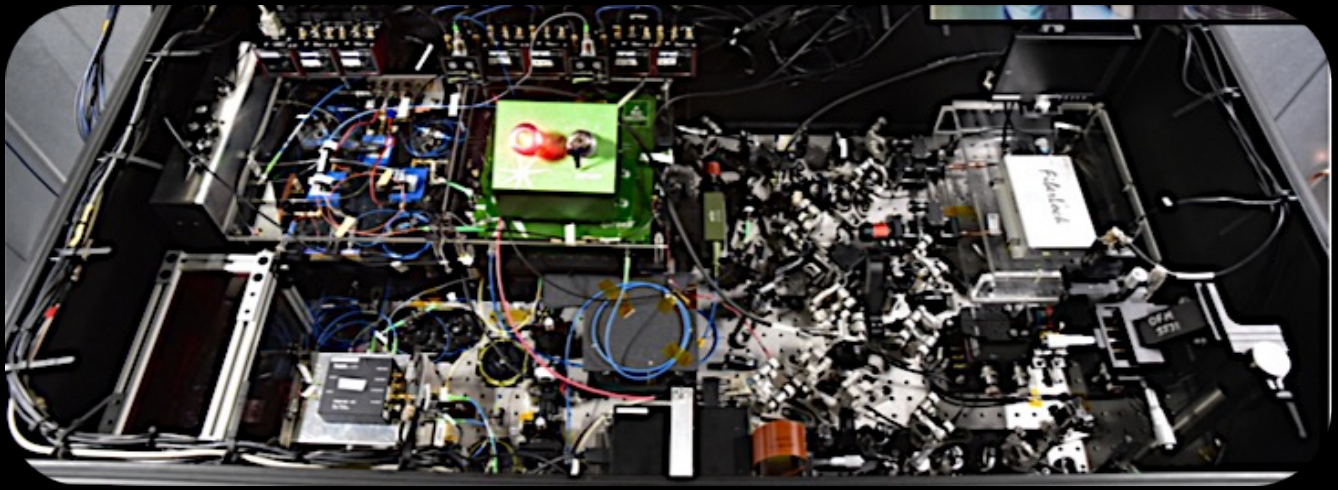


FREQUENCY COMBS

- Mode locked laser combs
  - NIR Compact fiber laser combs
- Electro-optic modulation frequency combs
- Microcombs

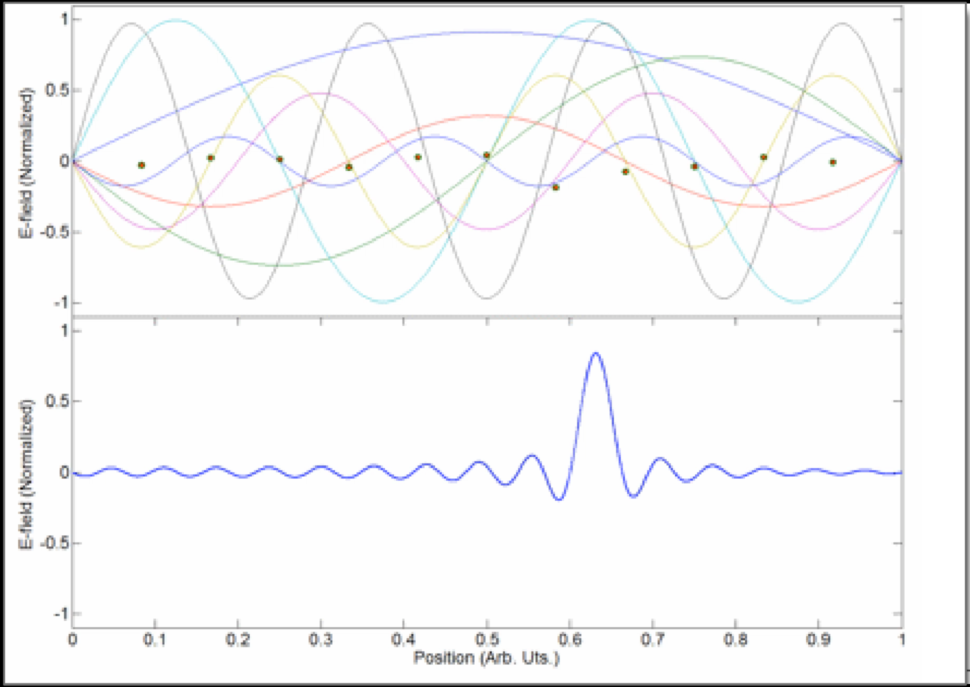


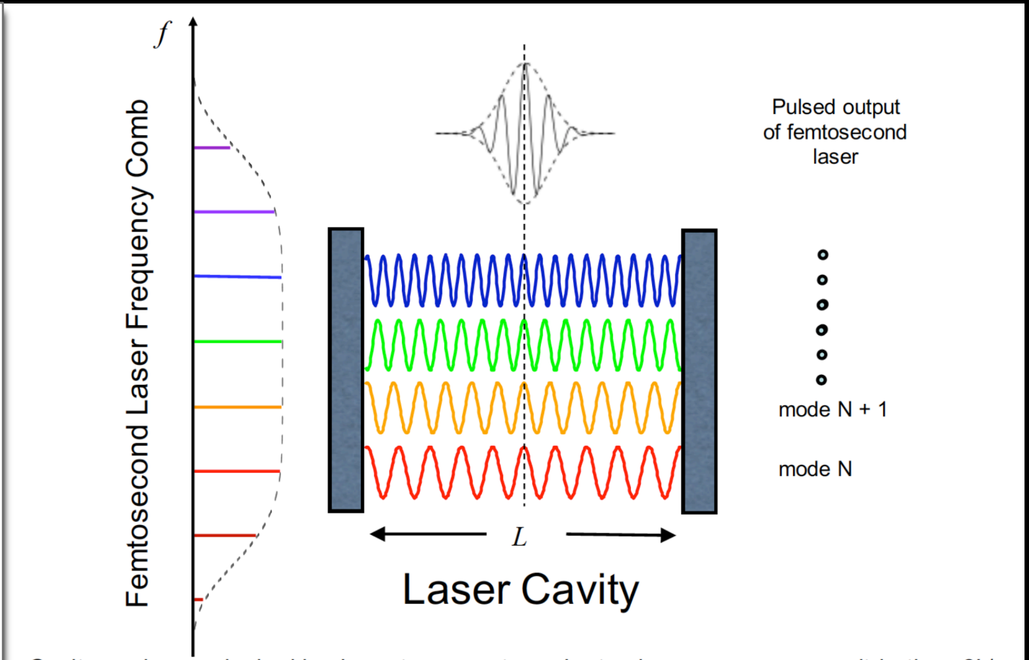
RV precision <1 cm/s



MODE LOCKED LASER COMBS

- Pulse repetition rate ~ 100s of MHz (mode spacing = $c/2L$, allowed modes= $L = q\lambda/2$, where q is an integer)
- Femtosecond pulses → 100s of nm spectral coverage

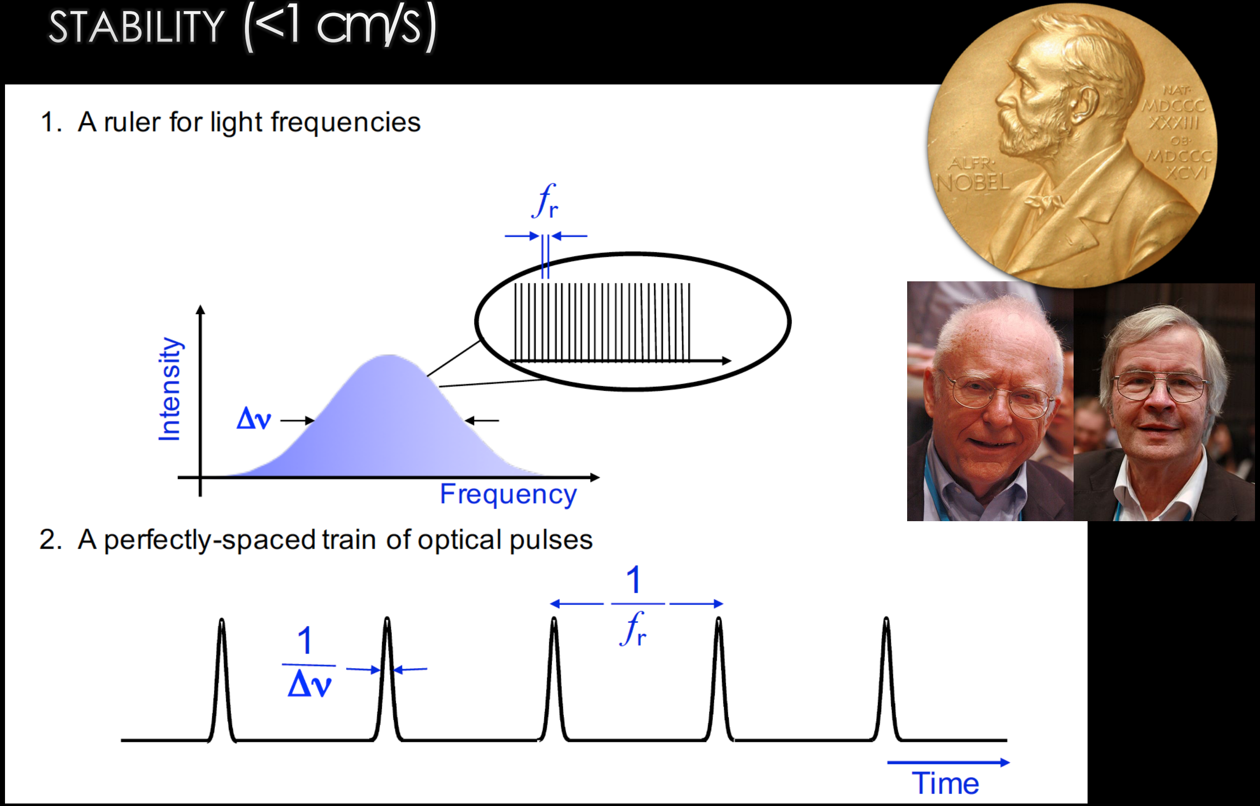




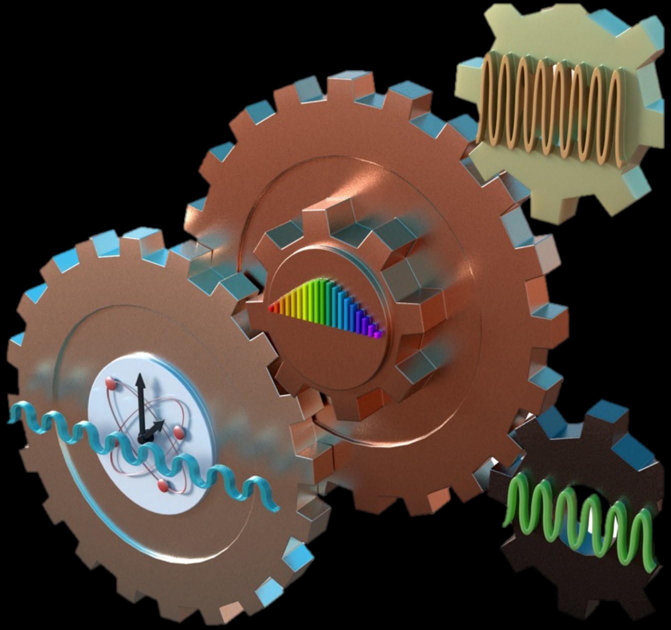
→ Cavity modes are locked in phase to generate a short pulse once every roundtrip time $2L/v_g$

SELF-REFERENCED FREQUENCY COMBS

- MODE LOCKED LASER, *F*-2*F* TECHNIQUE, CREATES A "CLOCKWORK" BETWEEN THE OPTICAL AND RADIO (RF) DOMAINS TO TIE OPTICAL FREQUENCIES TO THE DEFINITION OF THE SI SECOND FOR LONG TERM STABILITY (<1 cm/s)

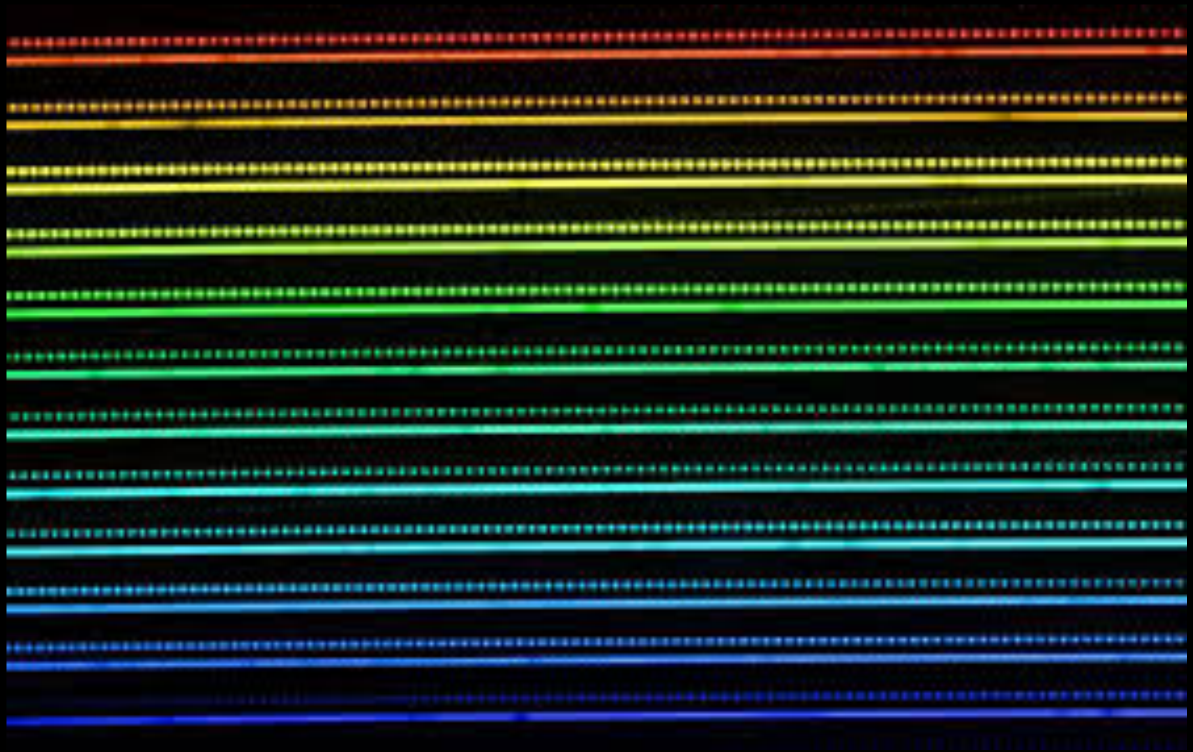


Diddams, 2016



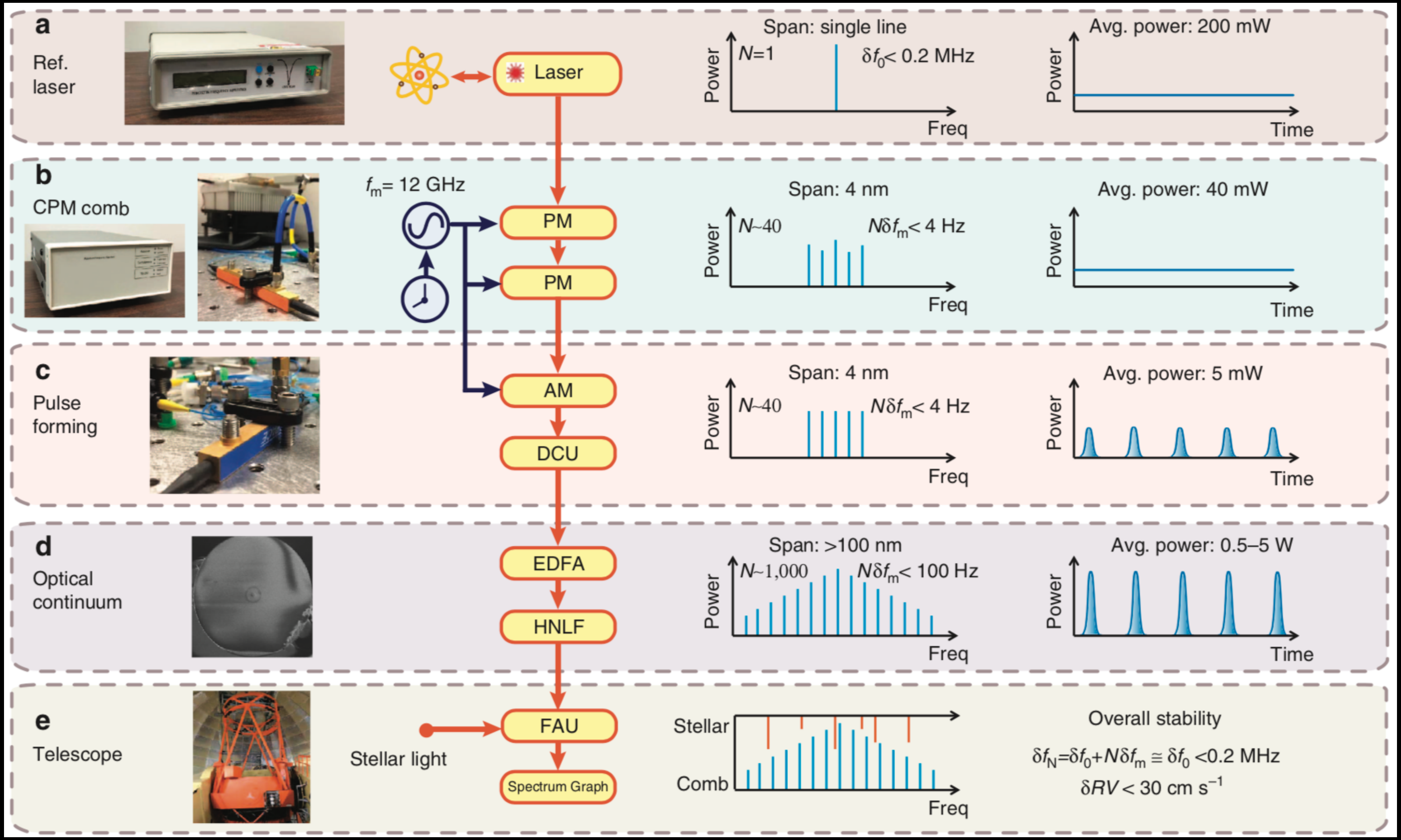
Keck Institute for Space Studies (2018)

ASTROCOMBS



EO COMBS

- Built from commercial telecom parts :
  - affordable, robust, reliable
  - pumped at 1.5 and 1 micron
- Spectrally broadened with HNLF or non-linear photonics waveguides
- Have been made octave-spanning for f-2f self referencing
- Also line locked
  - To line referenced pump laser
  - To fiber laser comb



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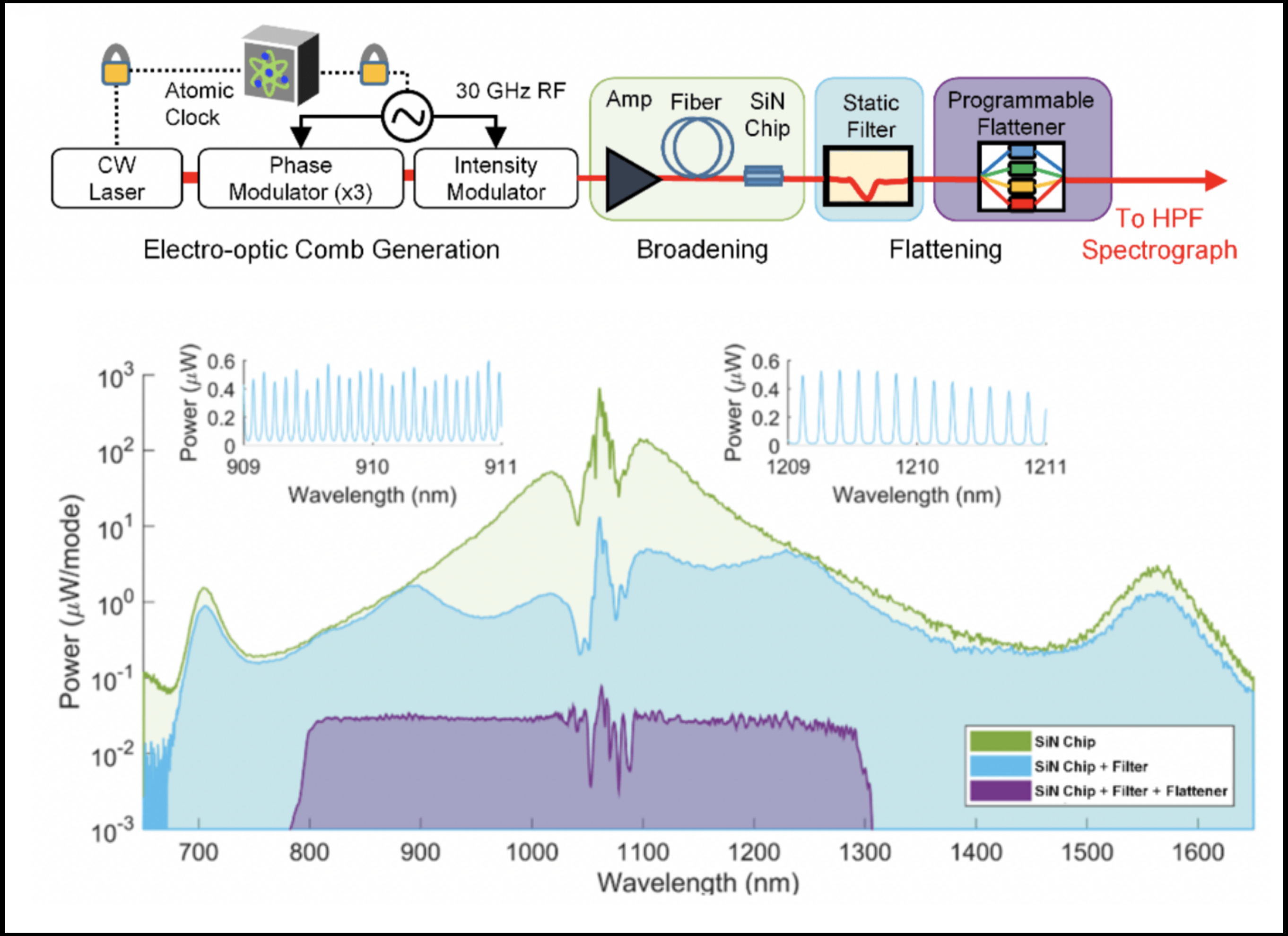
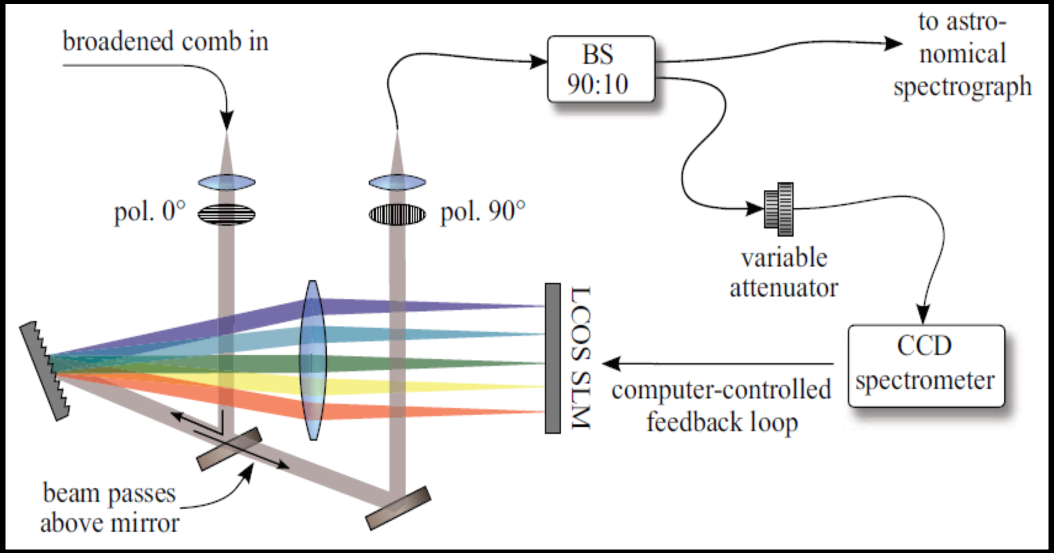
EXTREME PRECISION RADIAL VELOCITY

THE HABITABLE PLANET FINDER EO COMB



FLATTENING THE COMB SPECTRUM



Probst et al, 2015

EVOLUTION OF PRV CALIBRATION SOURCES

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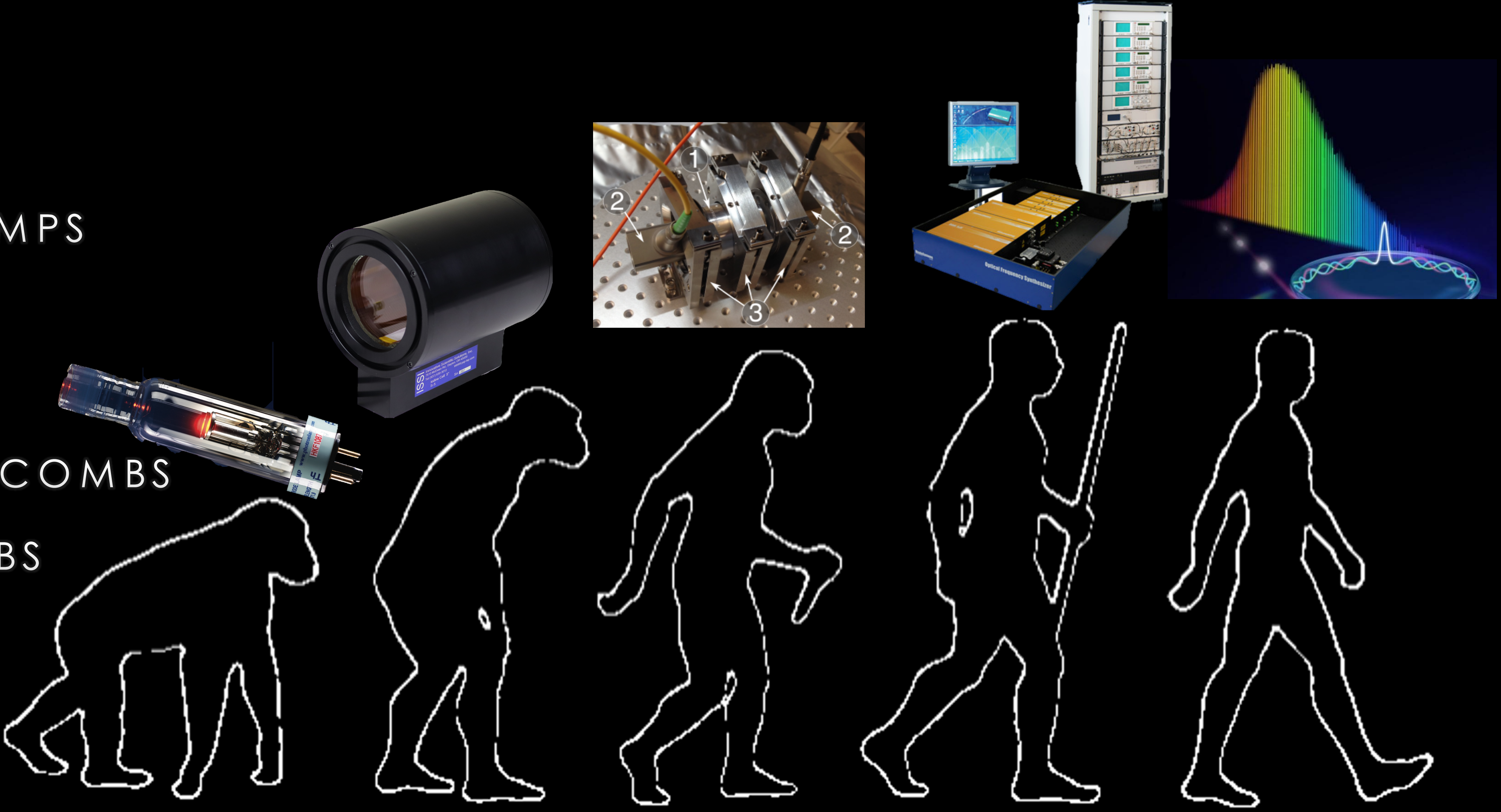
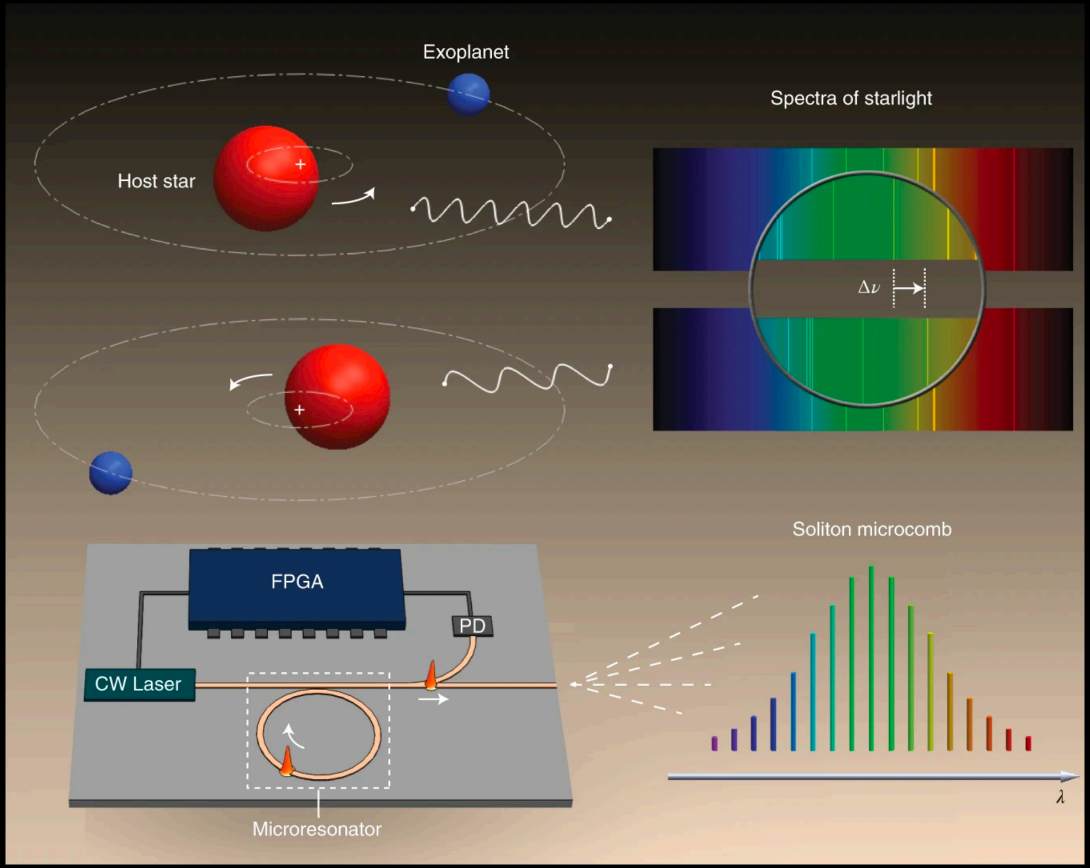
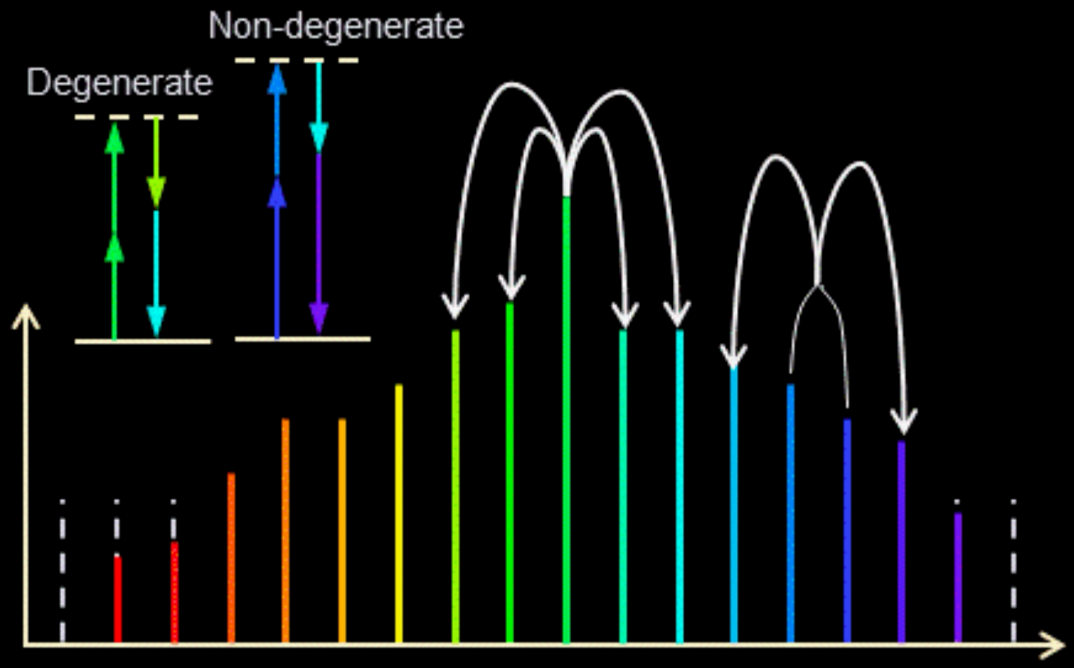
- Frequency combs
- Microcombs

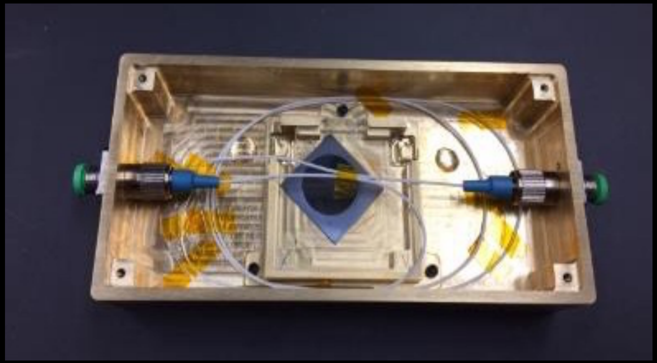


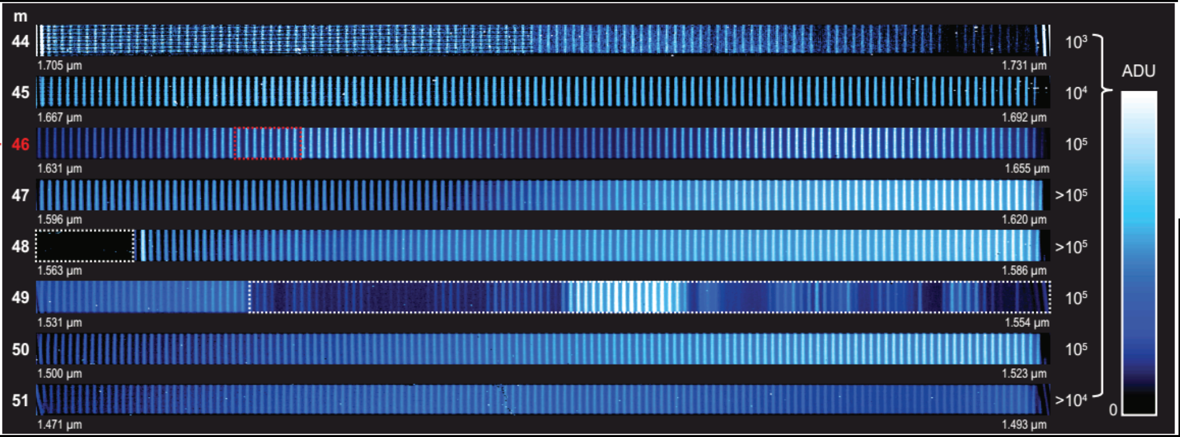
MICROCOMBS

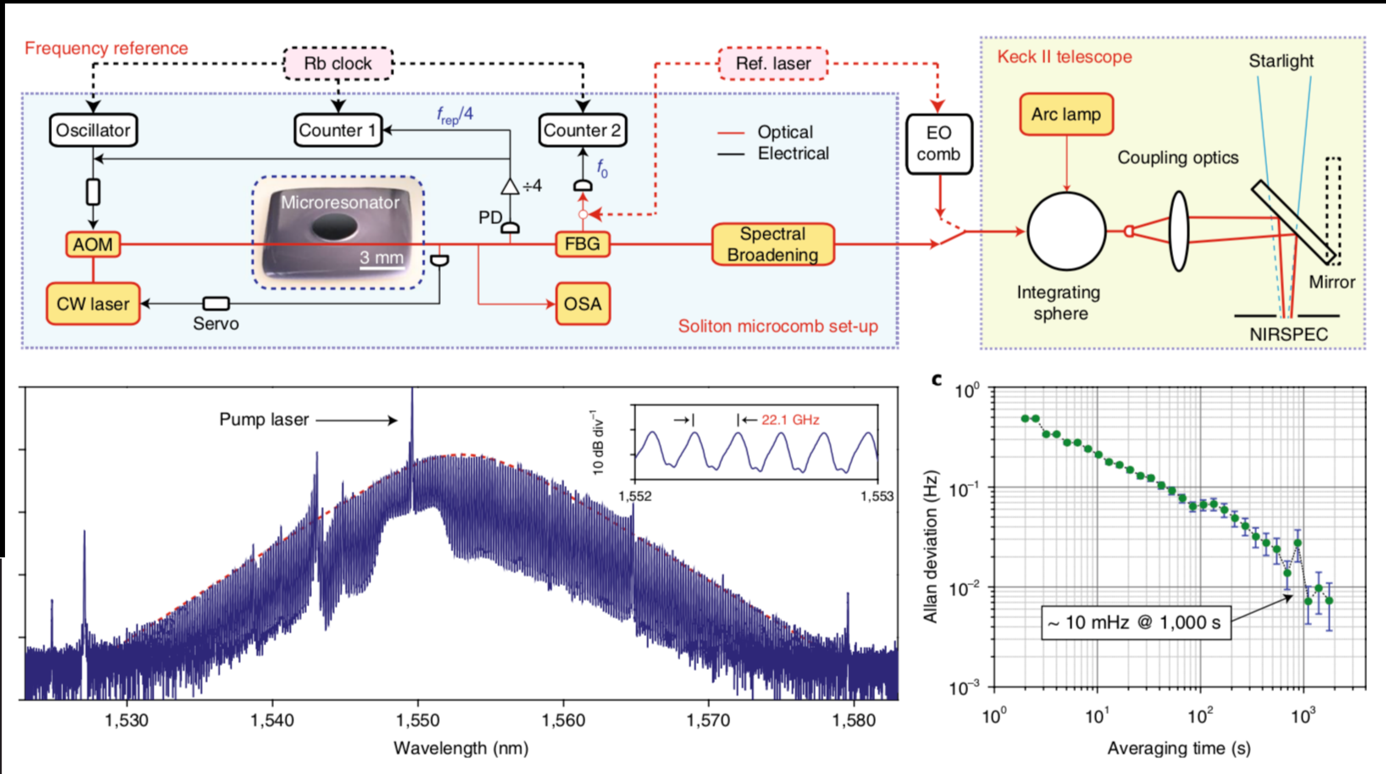

Exoplanet
Spectra of starlight
Host star
Δν
Soliton microcomb
FPGA
PD
CW Laser
Microresonator
λ


Non-degenerate
Degenerate

A MICROCOMB AT KECK OBSERVATORY





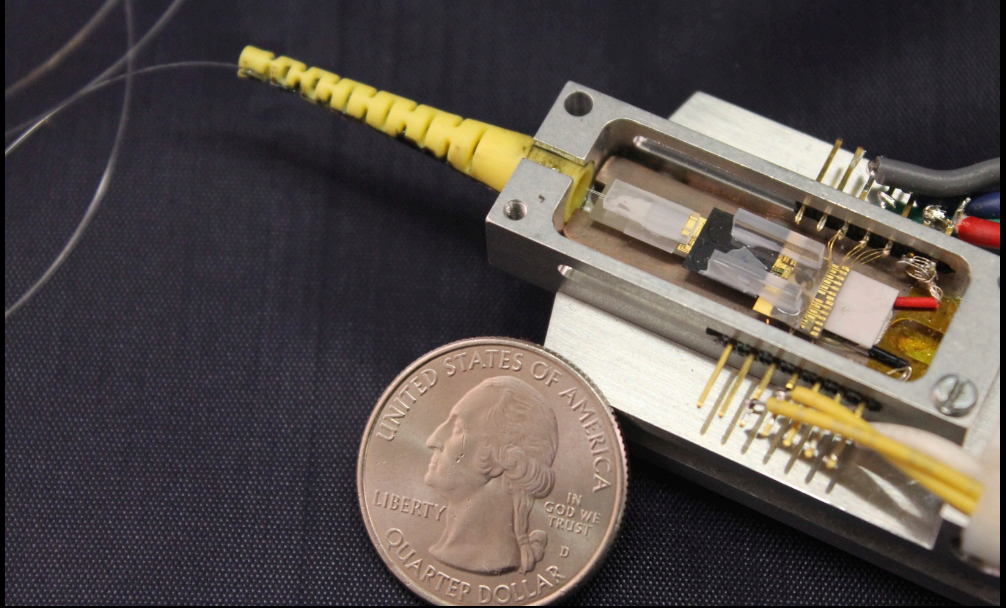


WHAT LIES AHEAD

- MICROCOMBS
  - RESEARCH IN CREATING BROADER MICROCOMB SPECTRA
- RESEARCH IN WHISPERING GALLERY MODE RESONATOR ETALONS
  - LINE REFERENCED TO A FREQUENCY COMB-LOCKED LASER

WGM RESONATOR ETALON ILLUMINATED WITH 633 NM LIGHT

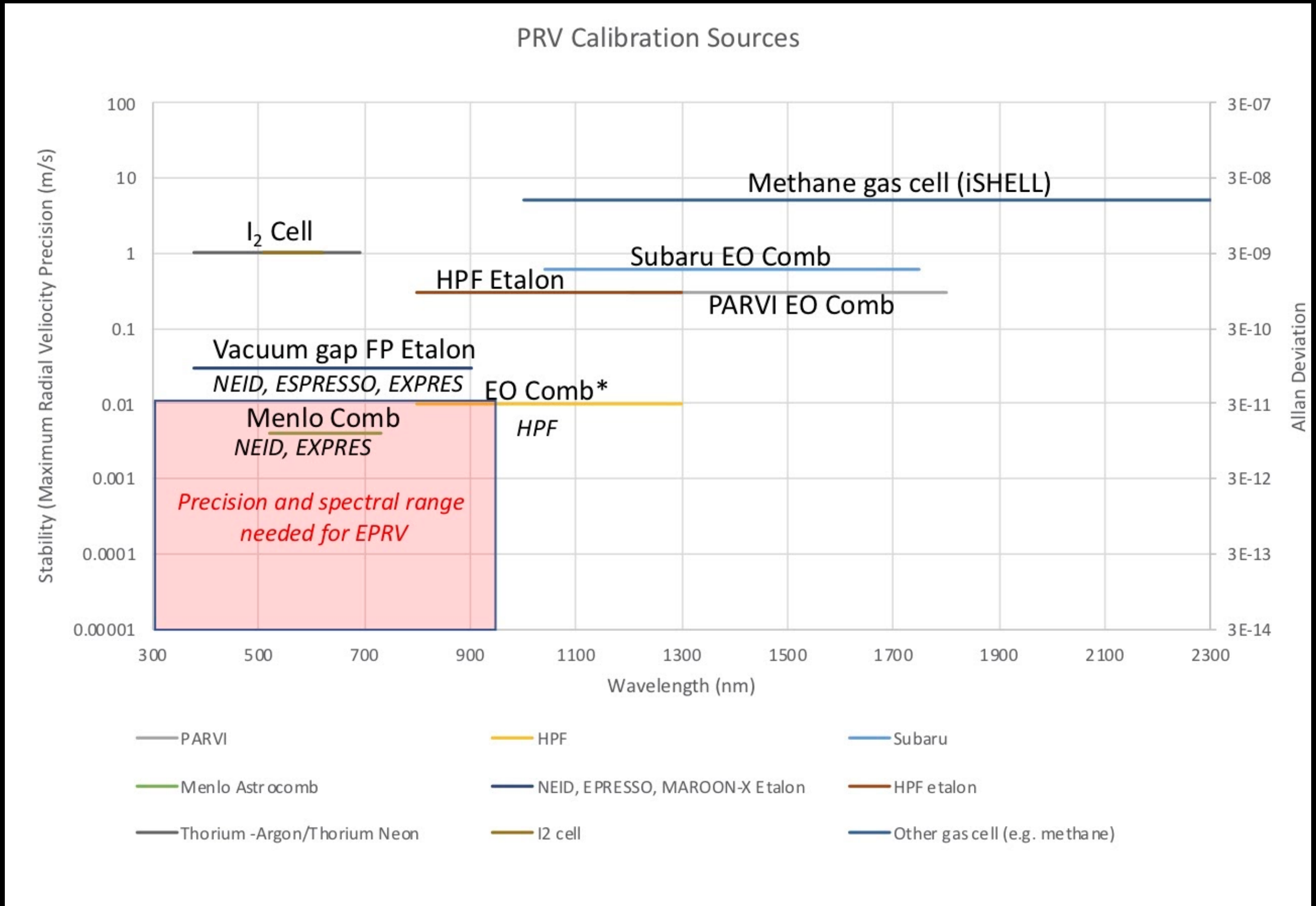
TURN-KEY SOLITON MICROCOMB



Shen, B., Chang, L., Liu, J. *et al.* Integrated turnkey soliton microcombs. *Nature* **582,** 365–369 (2020). https://doi.org/10.1038/s41586-020-2358-x

SUMMARY

- EPRV Calibration sources are a critical, enabling component of RV instruments.
- Achieving 9 cm/s RV precision over years requires calibration sources at the cutting edge of technology.
- Optical frequency combs represent the "gold standard" of calibration sources, but are still not reliably available at wavelengths blue of 500 nm.
- Optical etalon technology has not yet been pushed to its limits and still holds promise for EPRV applications



THANK YOU!

ACKNOWLEDGEMENT: THIS PRESENTATION WAS PREPARED AT THE JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, UNDER A CONTRACT WITH THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (80NM0018D0004).