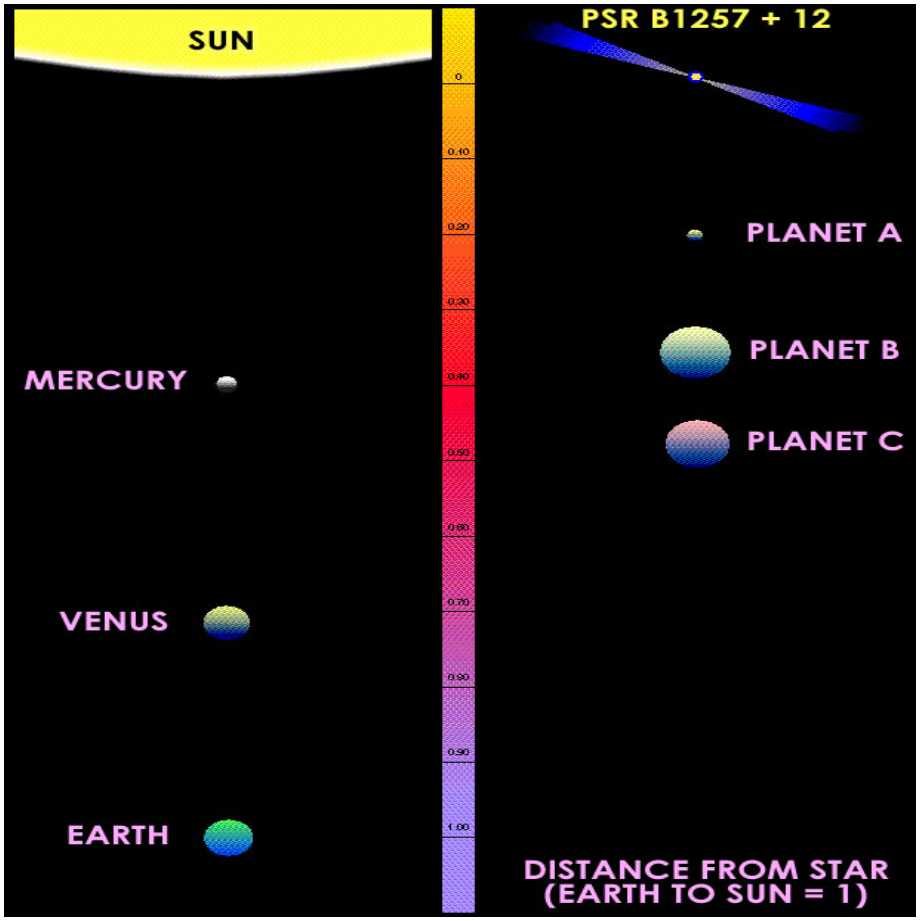
The Instruments Themselves

Suvrath Mahadevan & Francesco Pepe

Earth Mass Planets are NOT hard to detect



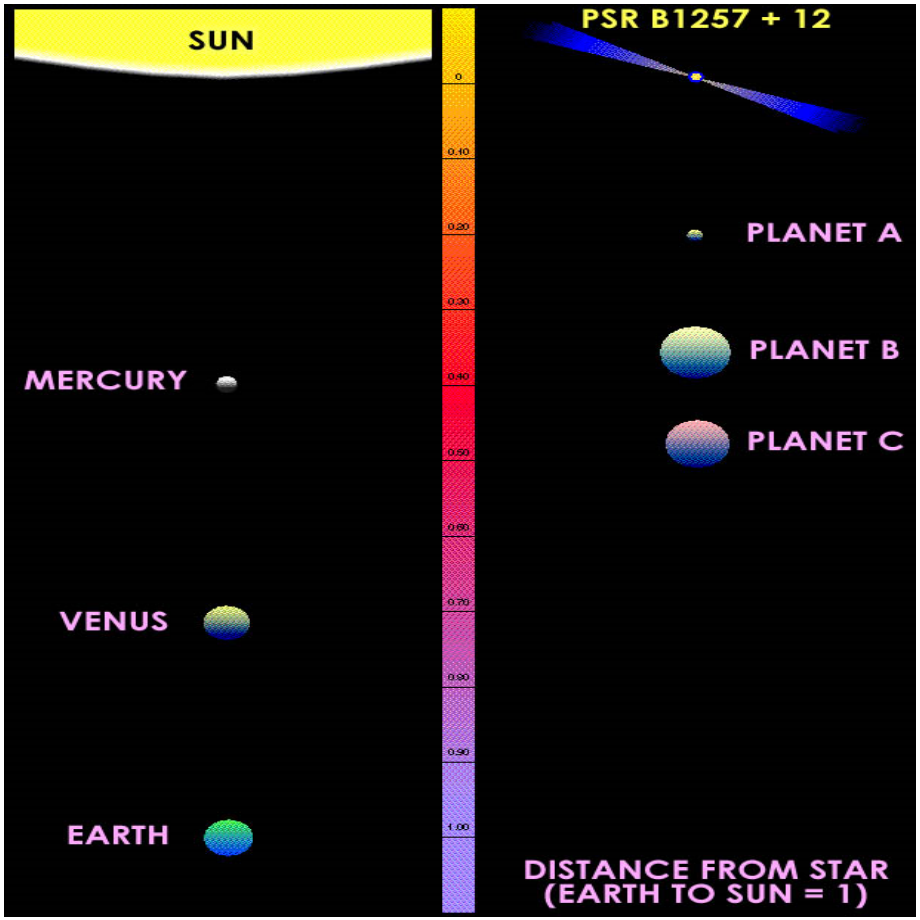
Can Measure Time & Frequency VERY precisely and accurately

Latest clocks are better than 10-19

We Can measures frequency MUCH better than we can measure LENGTH

Pulsar Planets: Discovered Alex Wolszczan and Dale Frail (1992) using precise **timing** of pulses. Rare.

Earth Mass Planets around Sun-Like Stars ARE hard to detect



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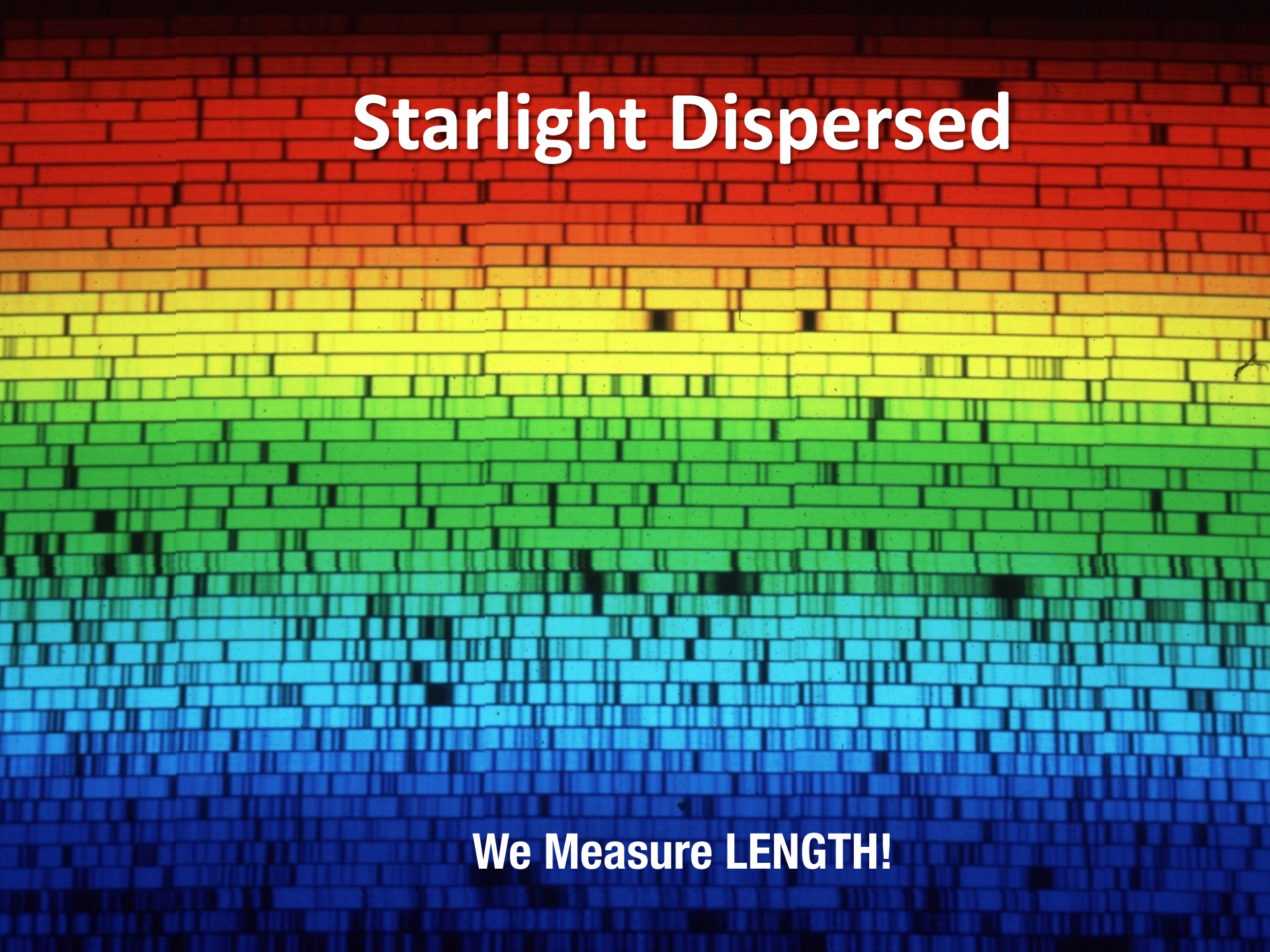
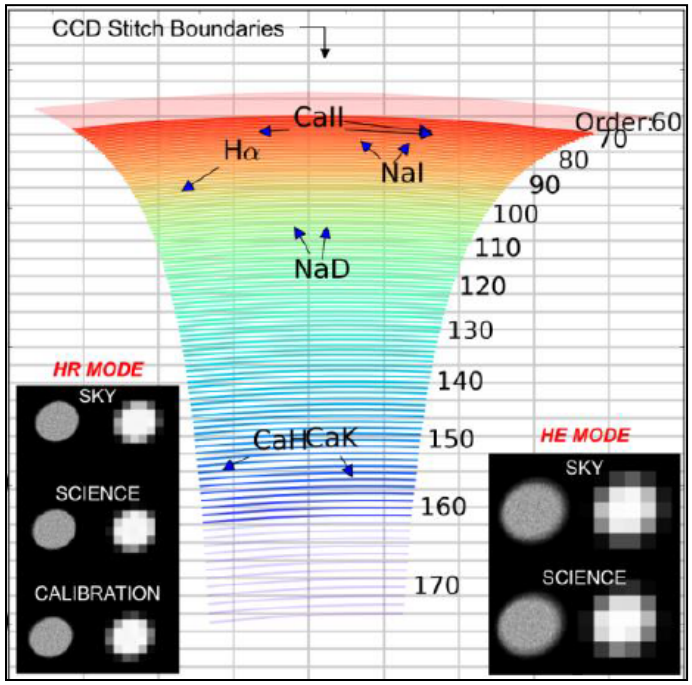
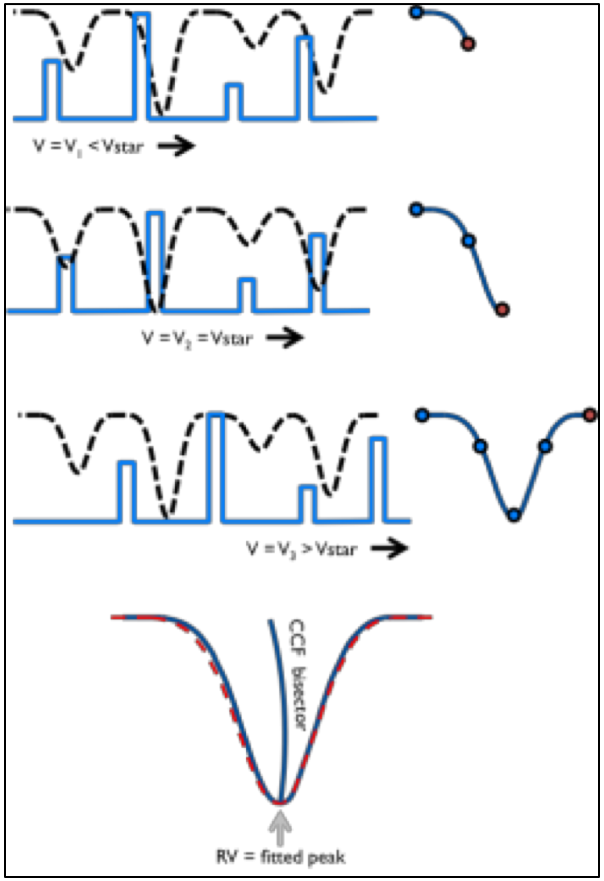
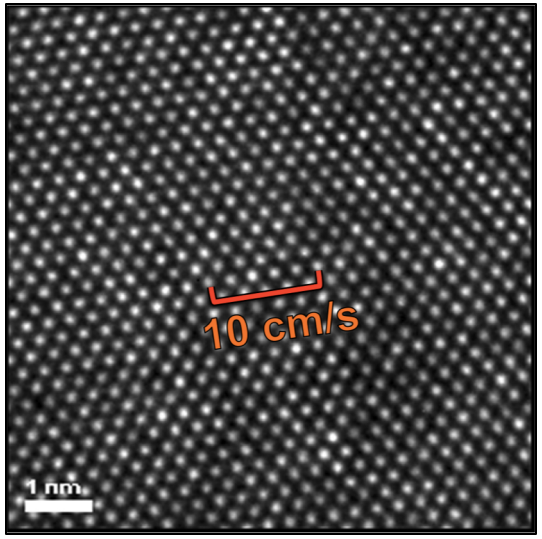

Starlight Dispersed
We Measure LENGTH!

10 cm/s comparable to Silicon Lattice Spacing



NEID 9k x 9k CCD with **10 micron pixels**. Echelle spectral orders from 60 to 170 are shown.





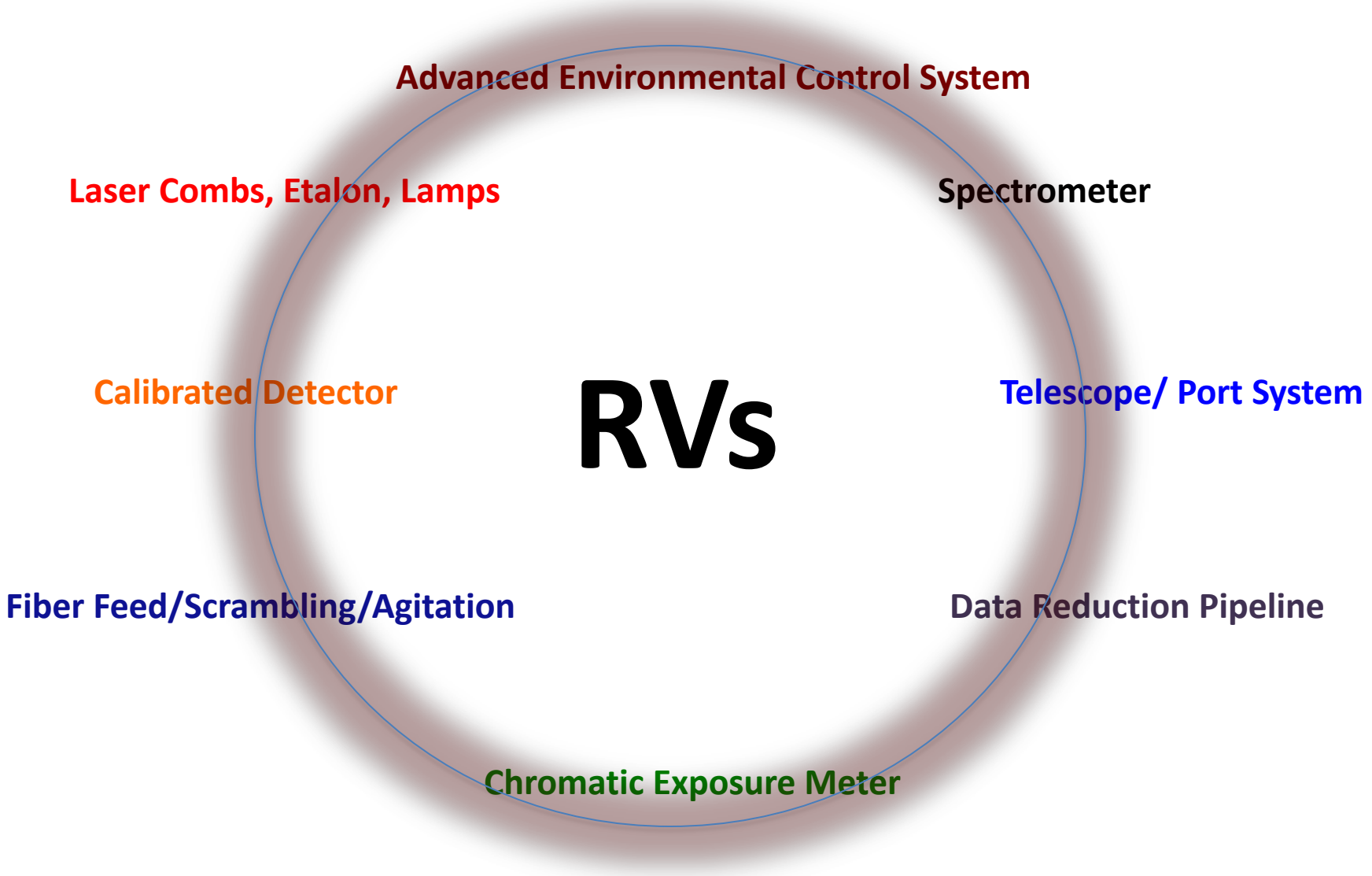
Silicon Lattice: High Resolution TEM Image of **individual Si atoms**. Ki Bun Kin, SPIE 2012

Multiple Paths to Achieve this goal

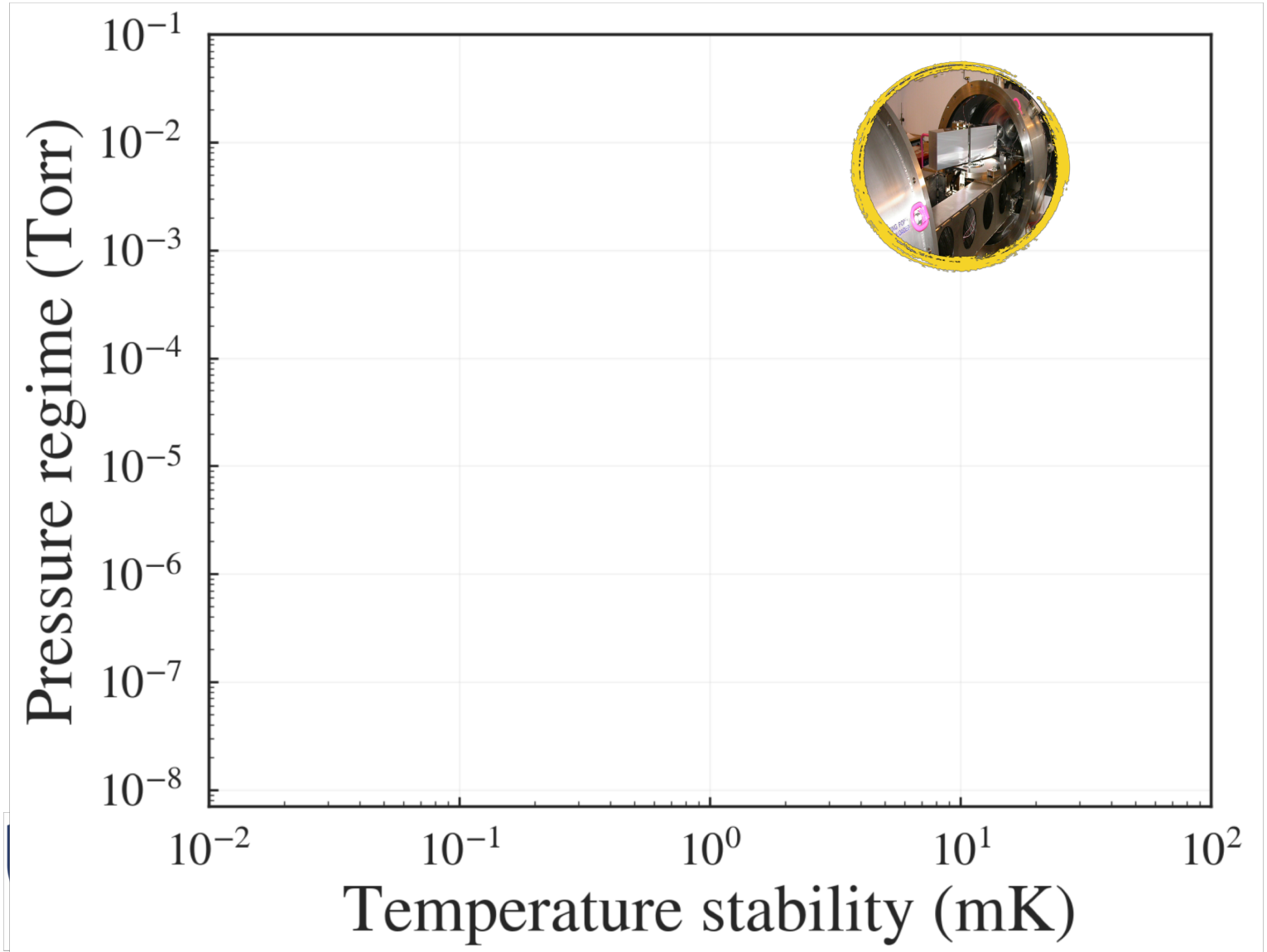
Multiple Paths to Achieve this goal

----and many more paths to not….

Need not just a spectrometer – need a precision RV System



Pushing towards 10cm/s requires sub-milli-Kelvin instrument stability and high-quality vacuum chambers



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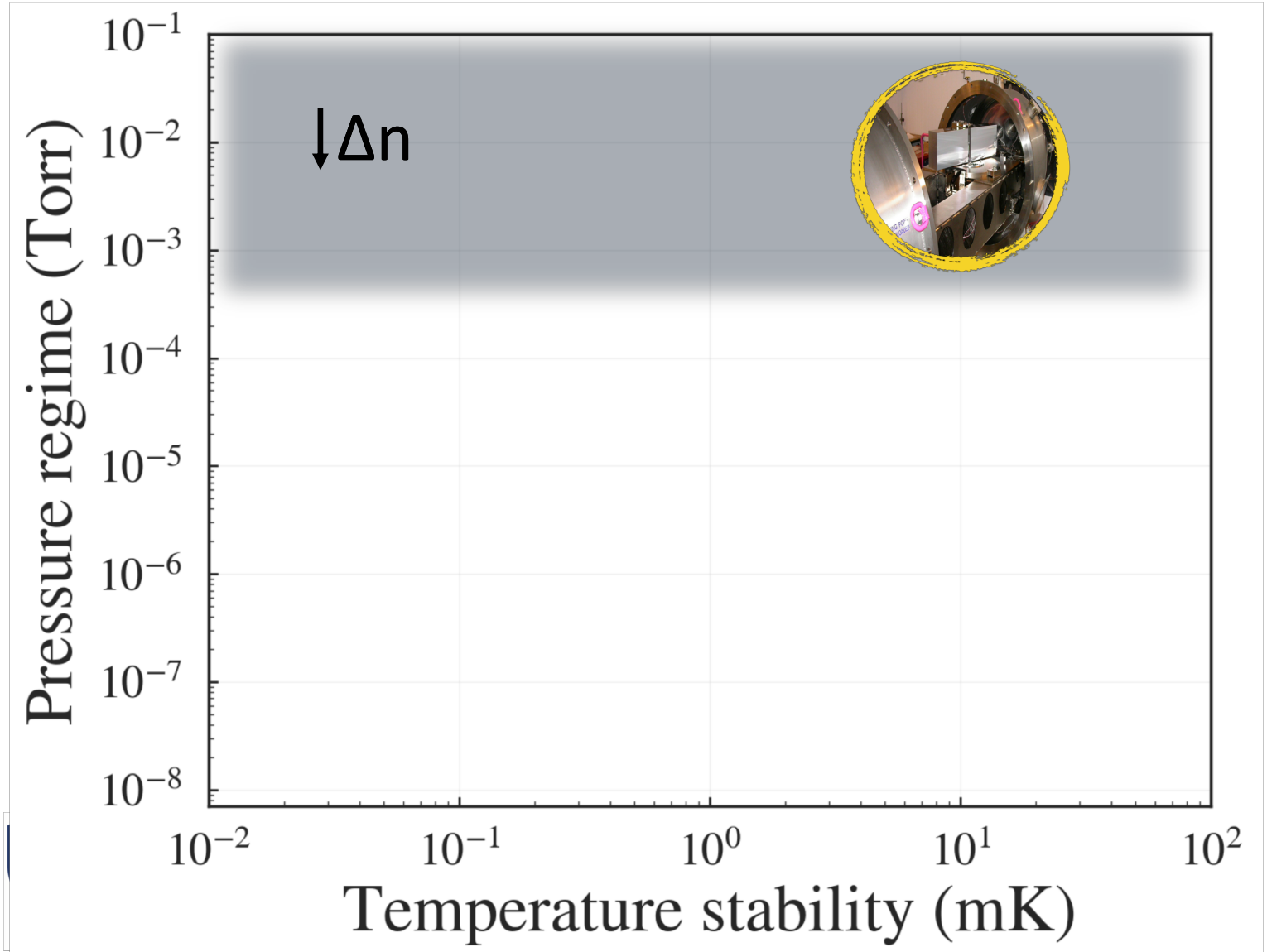

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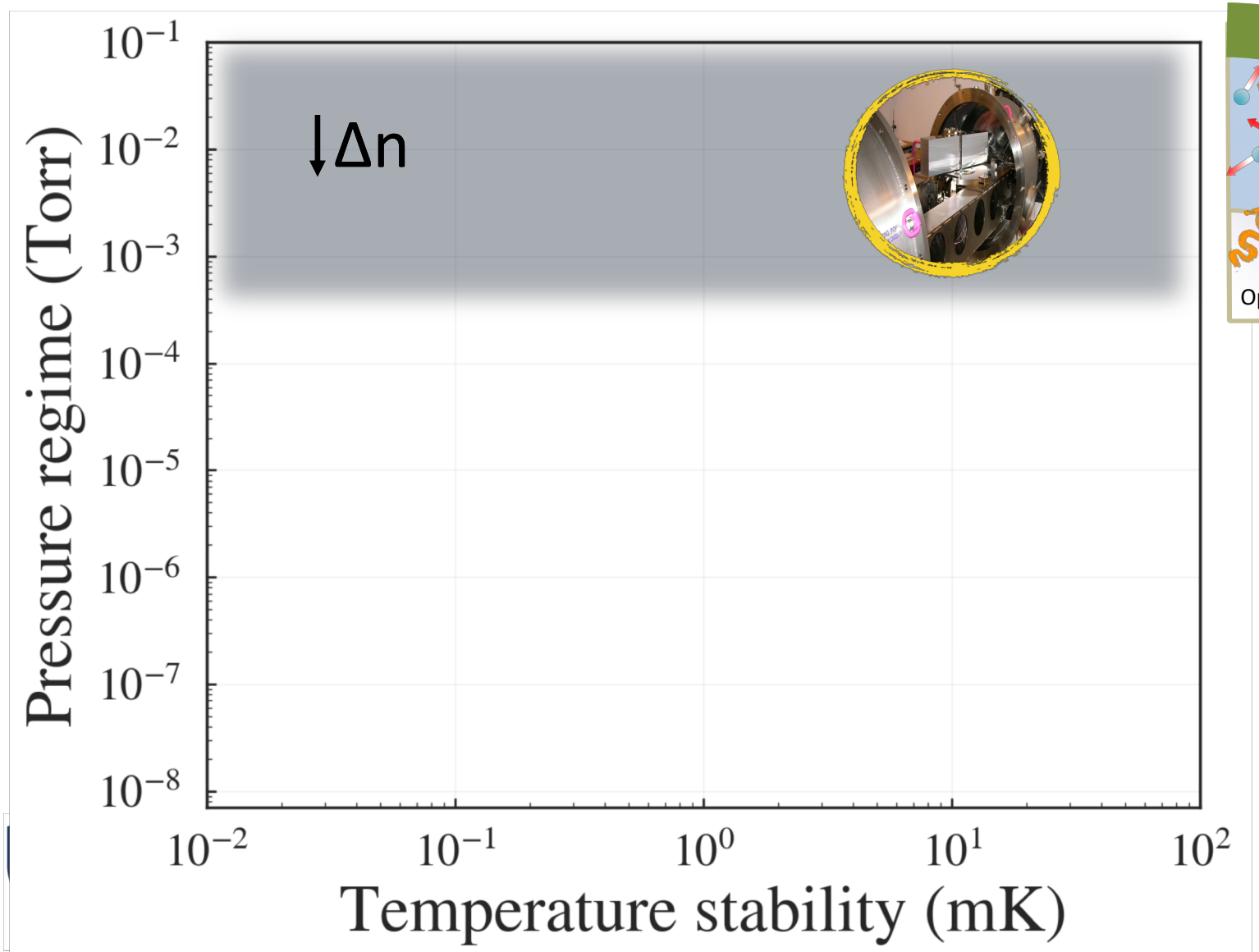

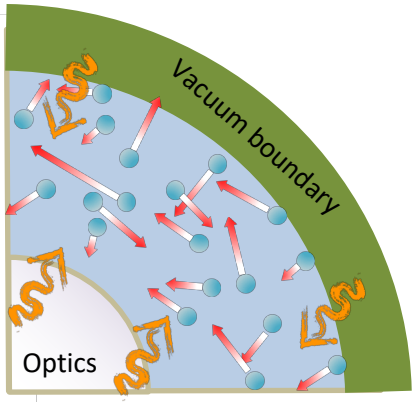

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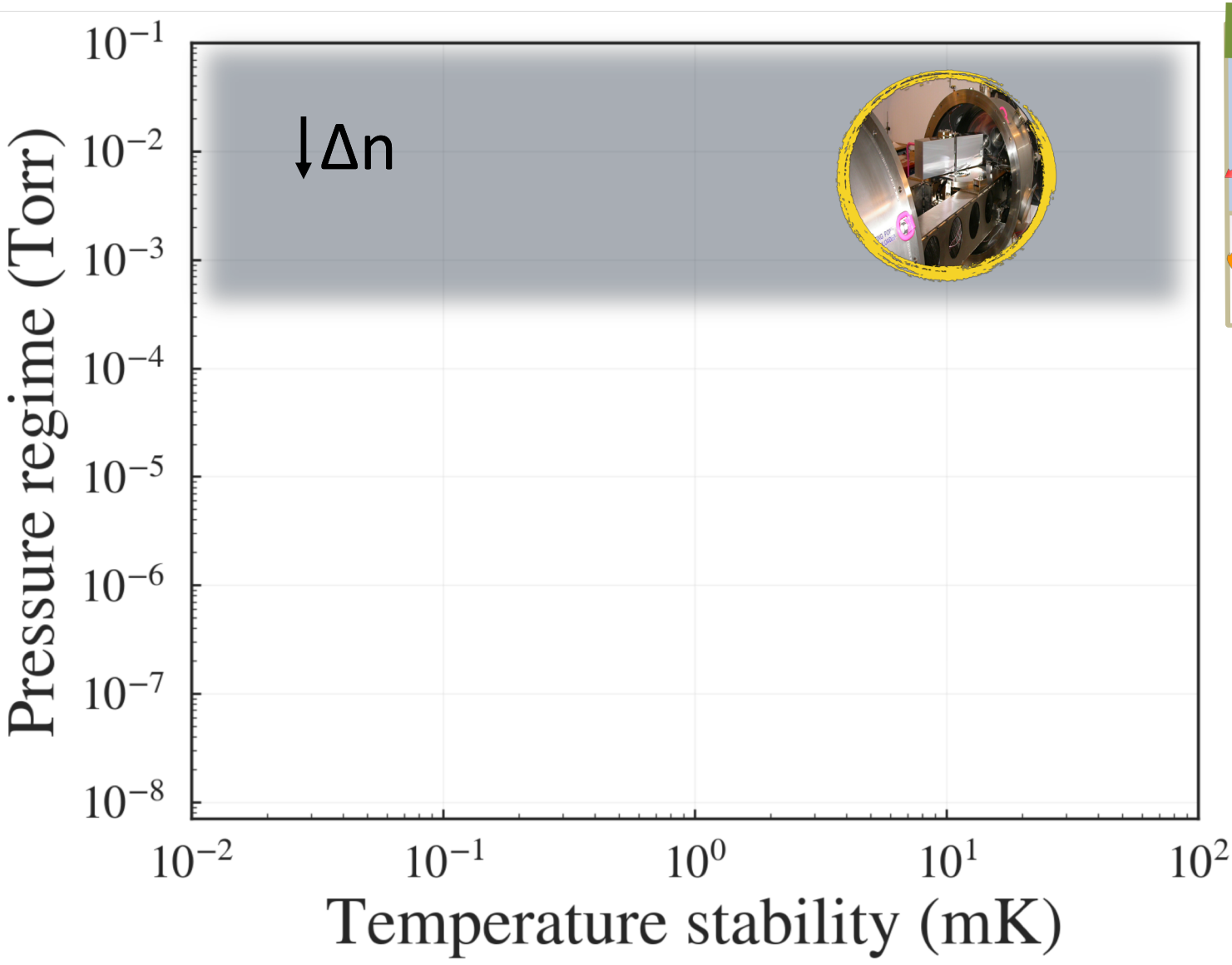
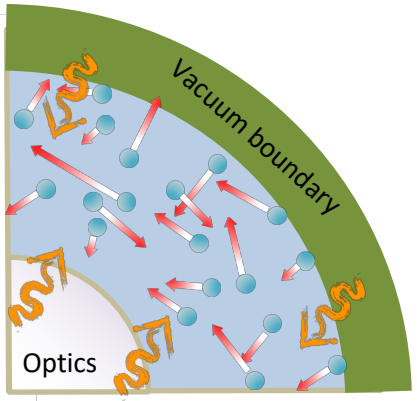
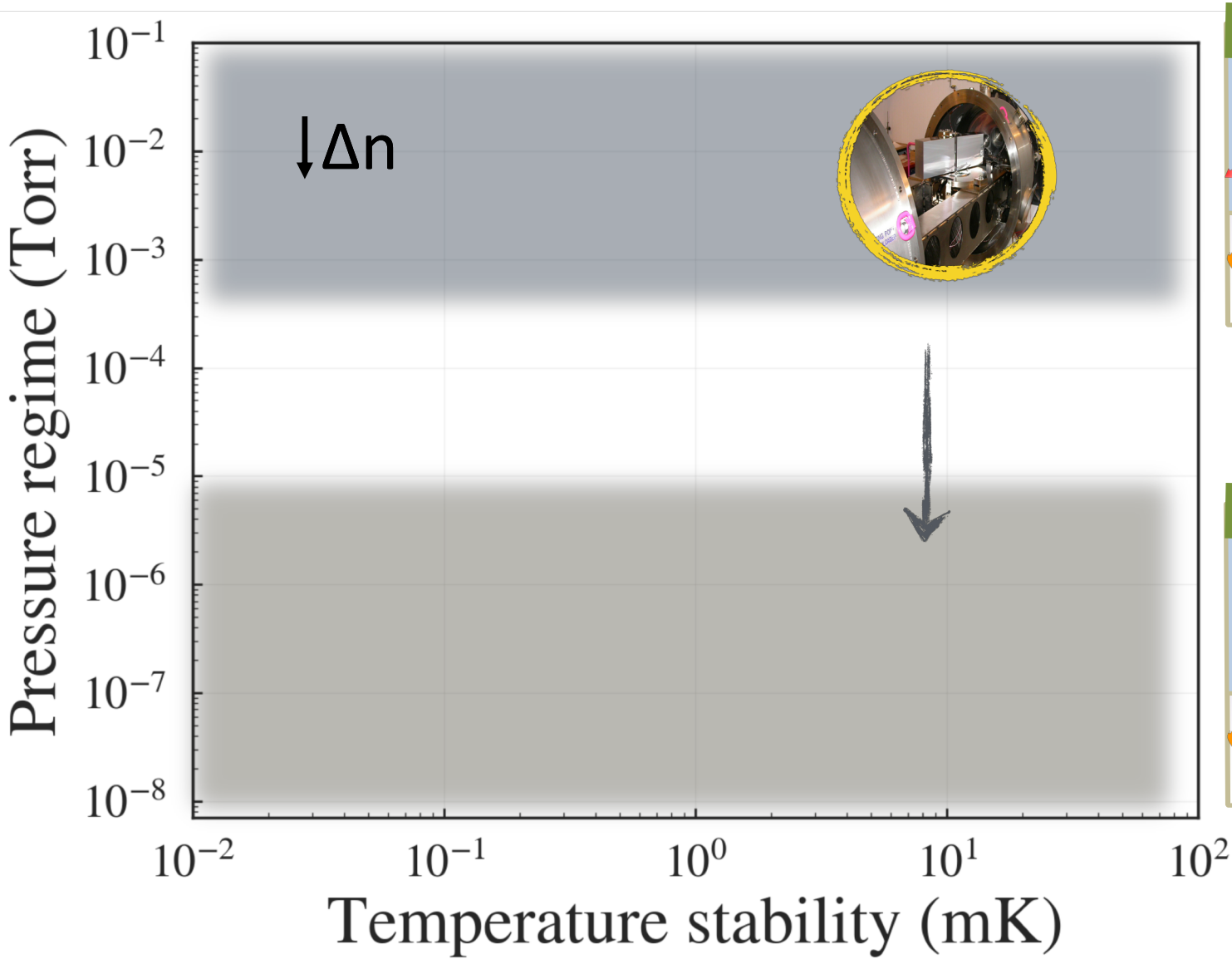
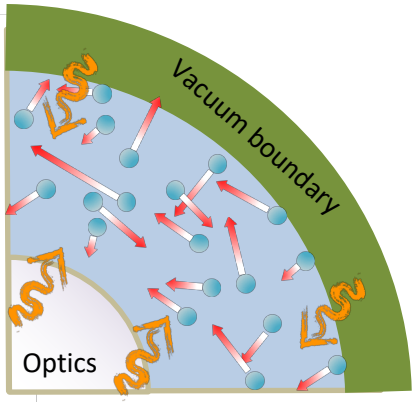




Convection
Radiation

Pushing towards 10cm/s requires sub-milli-Kelvin instrument stability and high-quality vacuum chambers





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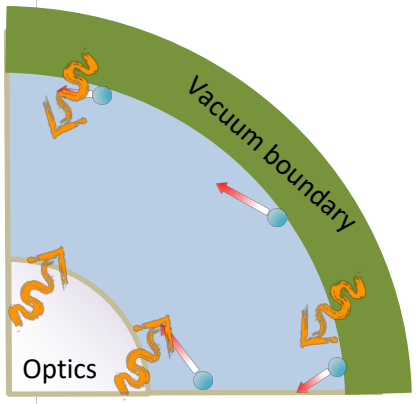

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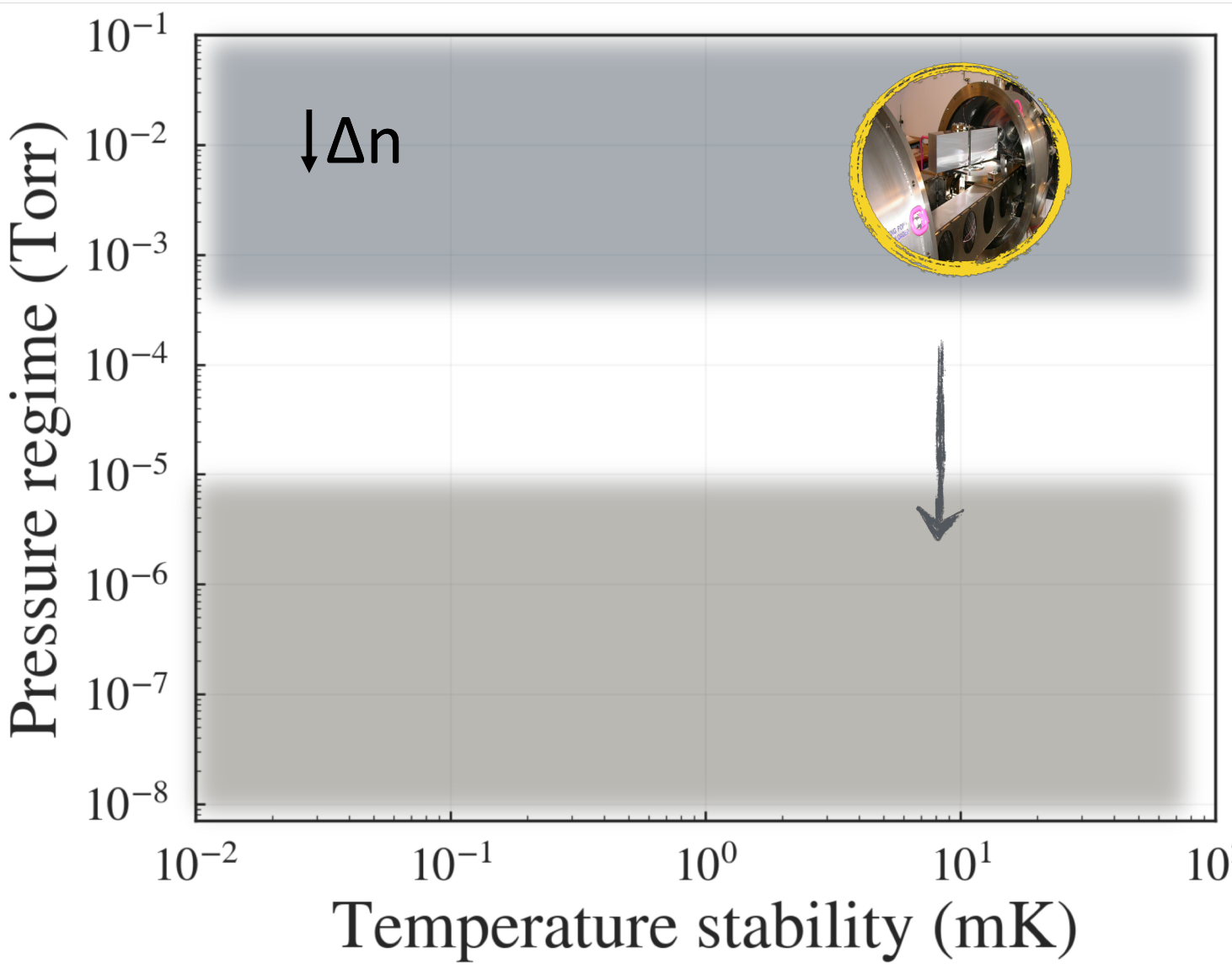

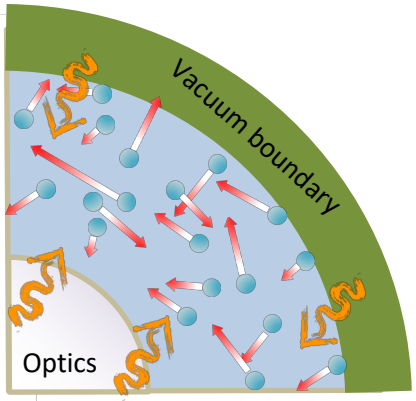

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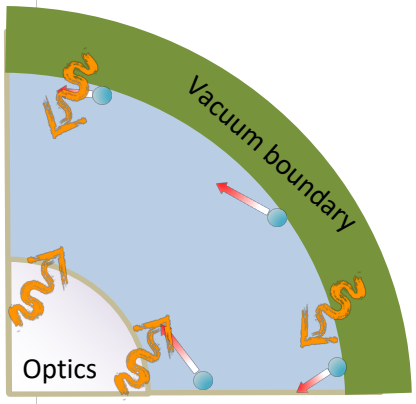

✗ Convection
Radiation

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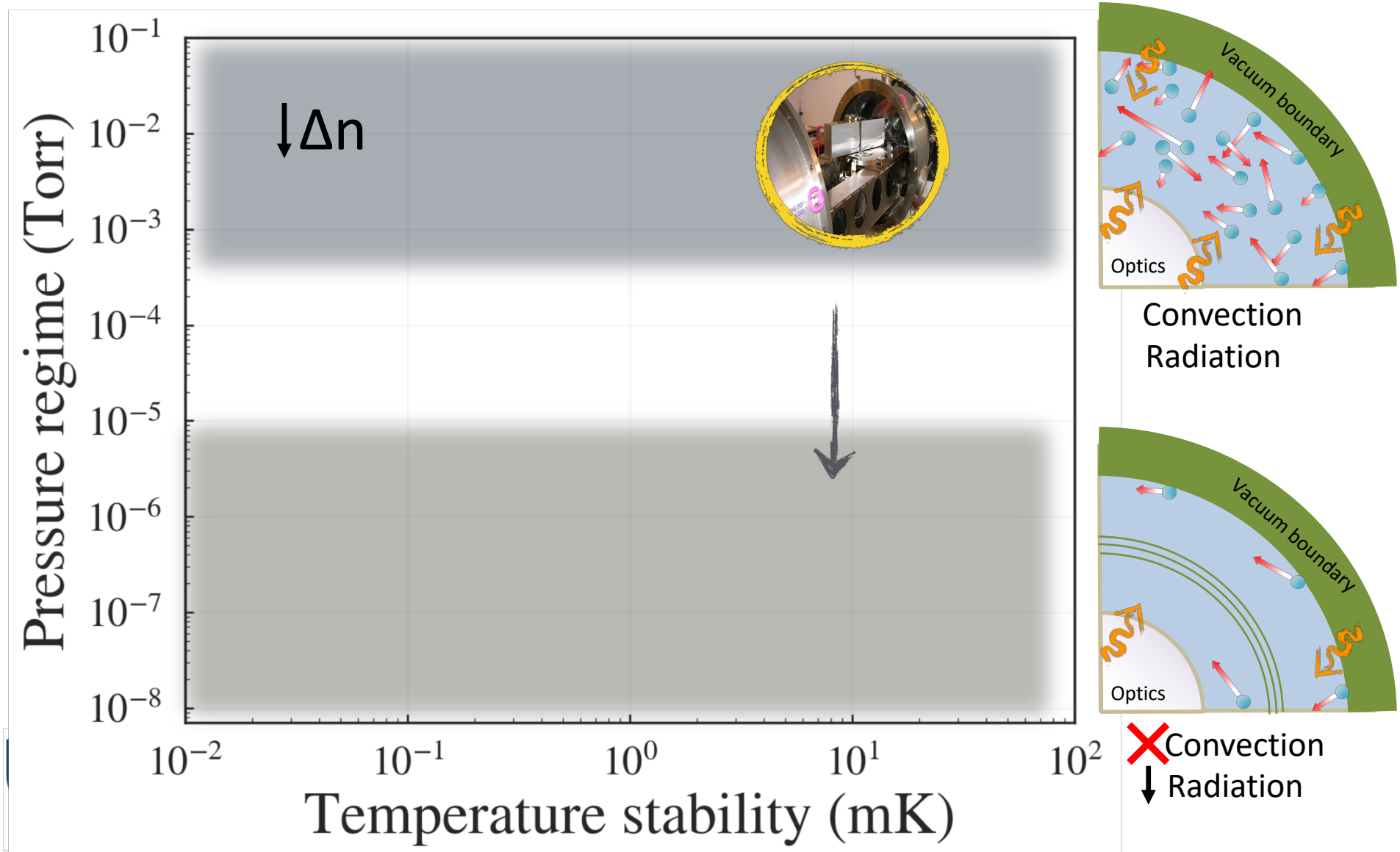

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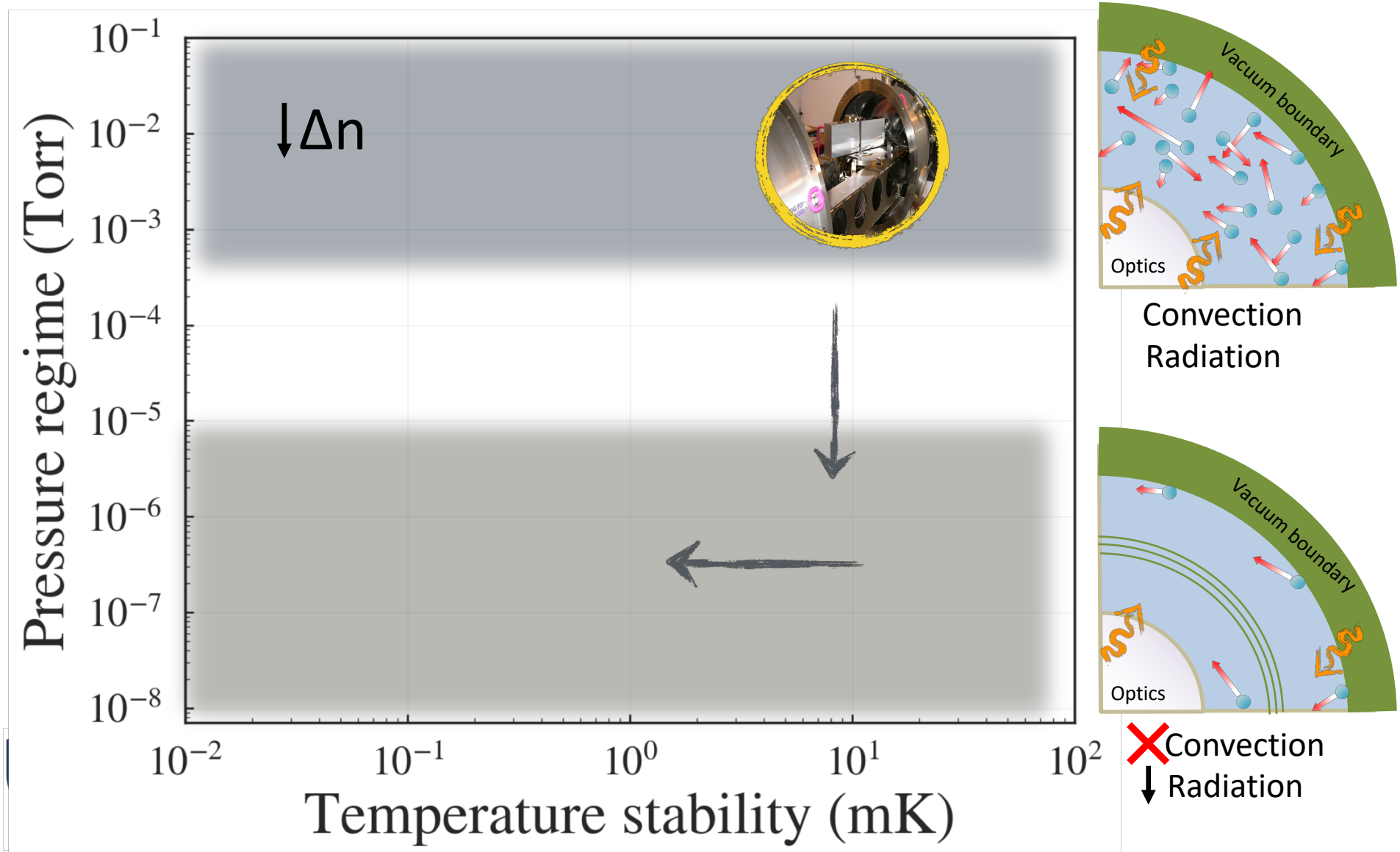

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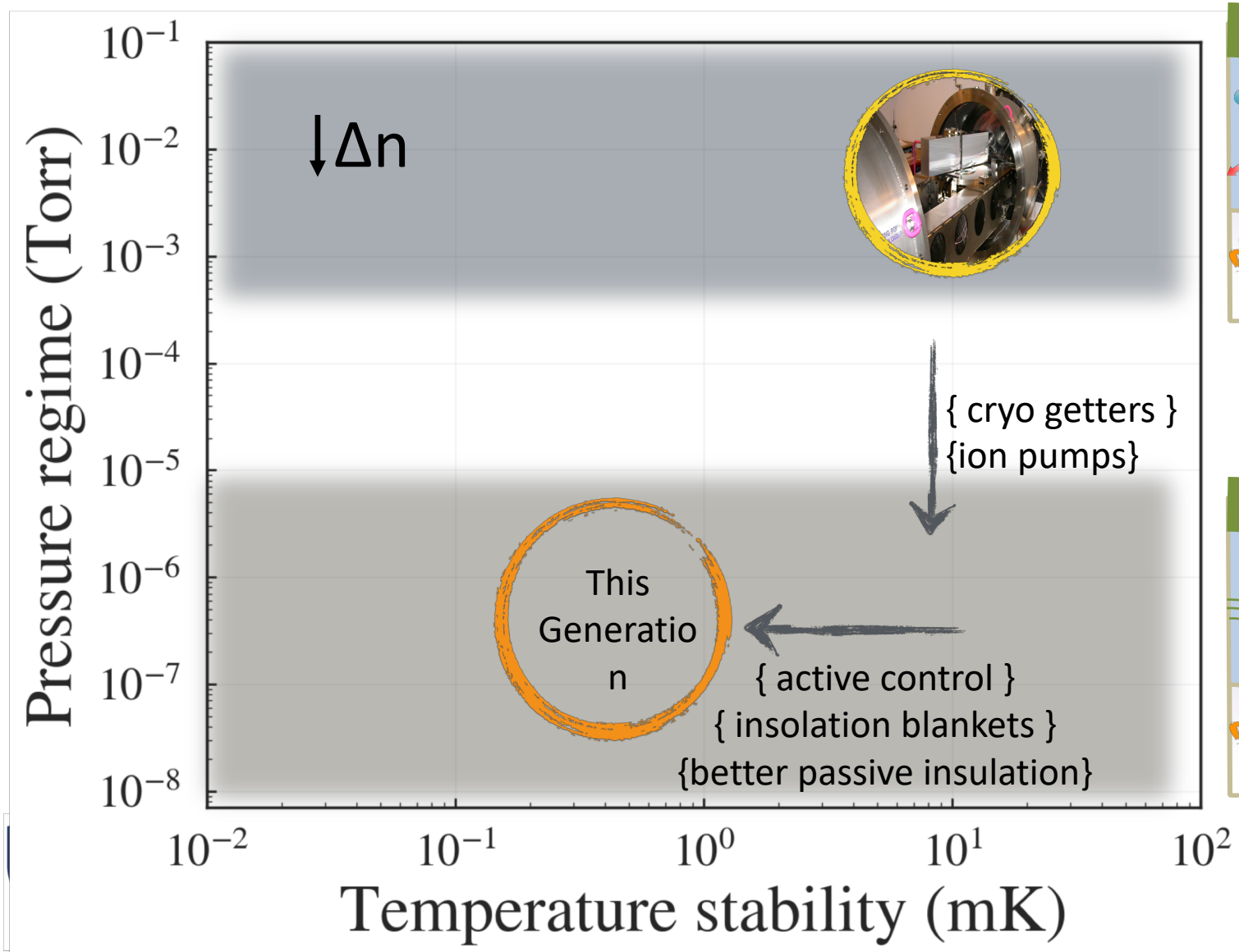

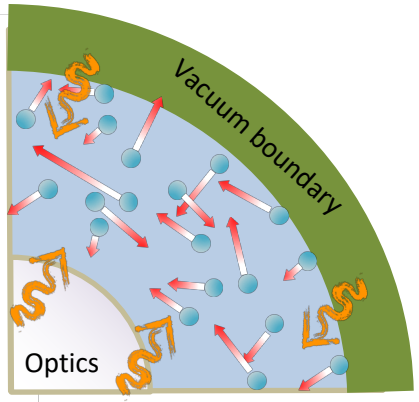

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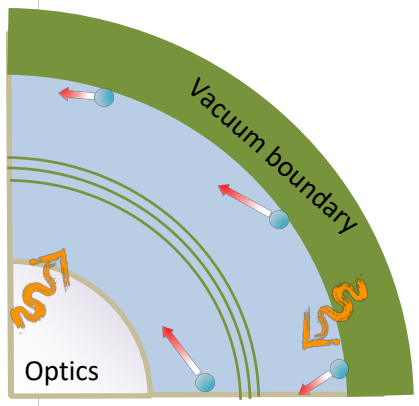


Convection
Radiation

Extreme Environmental Control

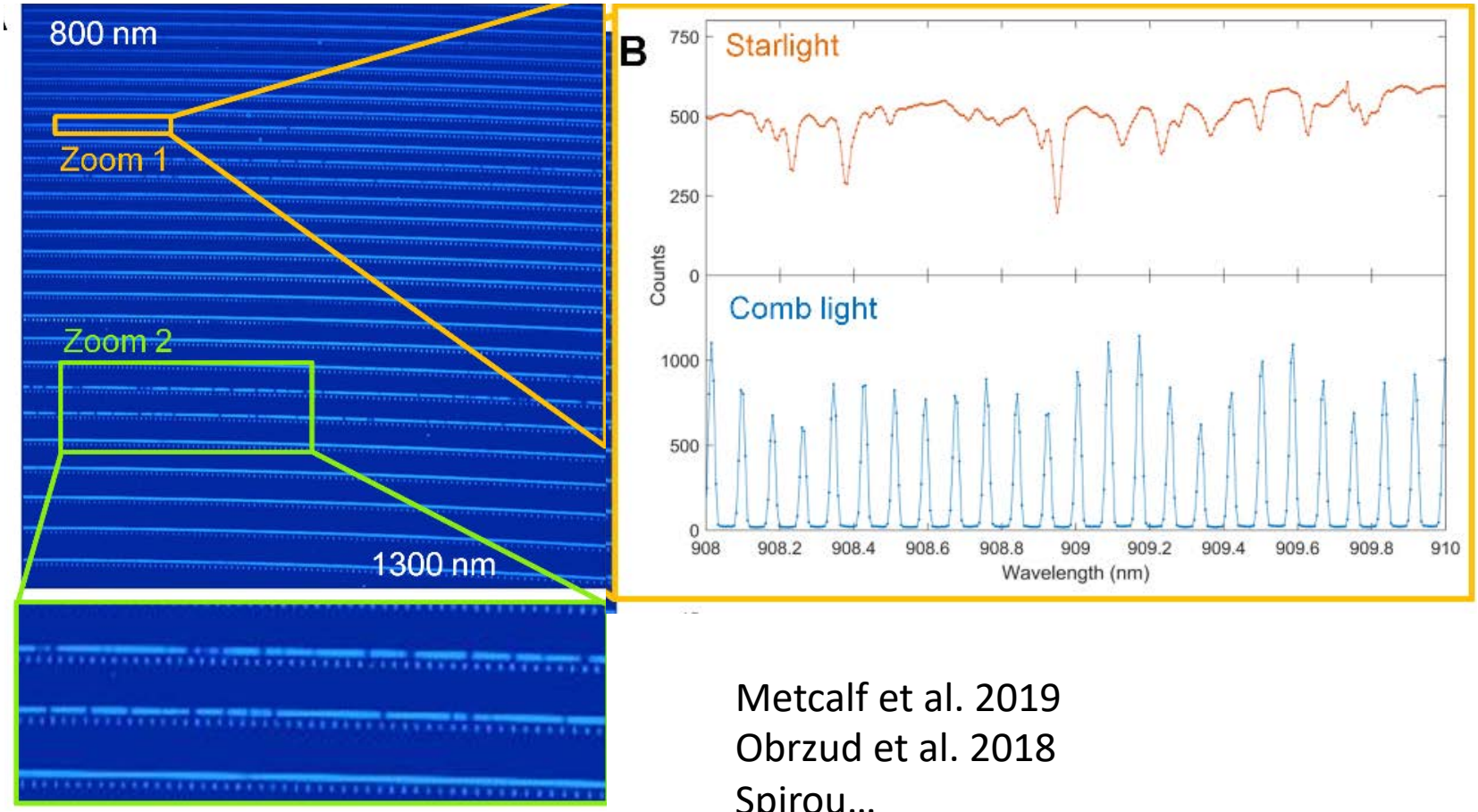
Every Instrument and Location in Observatory Environment is Different

Architectures include Detectors in separate vacuum enclosures as well as detectors integrated into main vacuum chamber.

Molecular conduction matters! High vacuum (<10-6 Torr) needed if a cold detector is in the main chamber. Lower (10^-4 Torr) okay if detector decoupled significantly.

Changing vacuum pressure, even at 10^-6 Torr levels, can change thermal coupling.

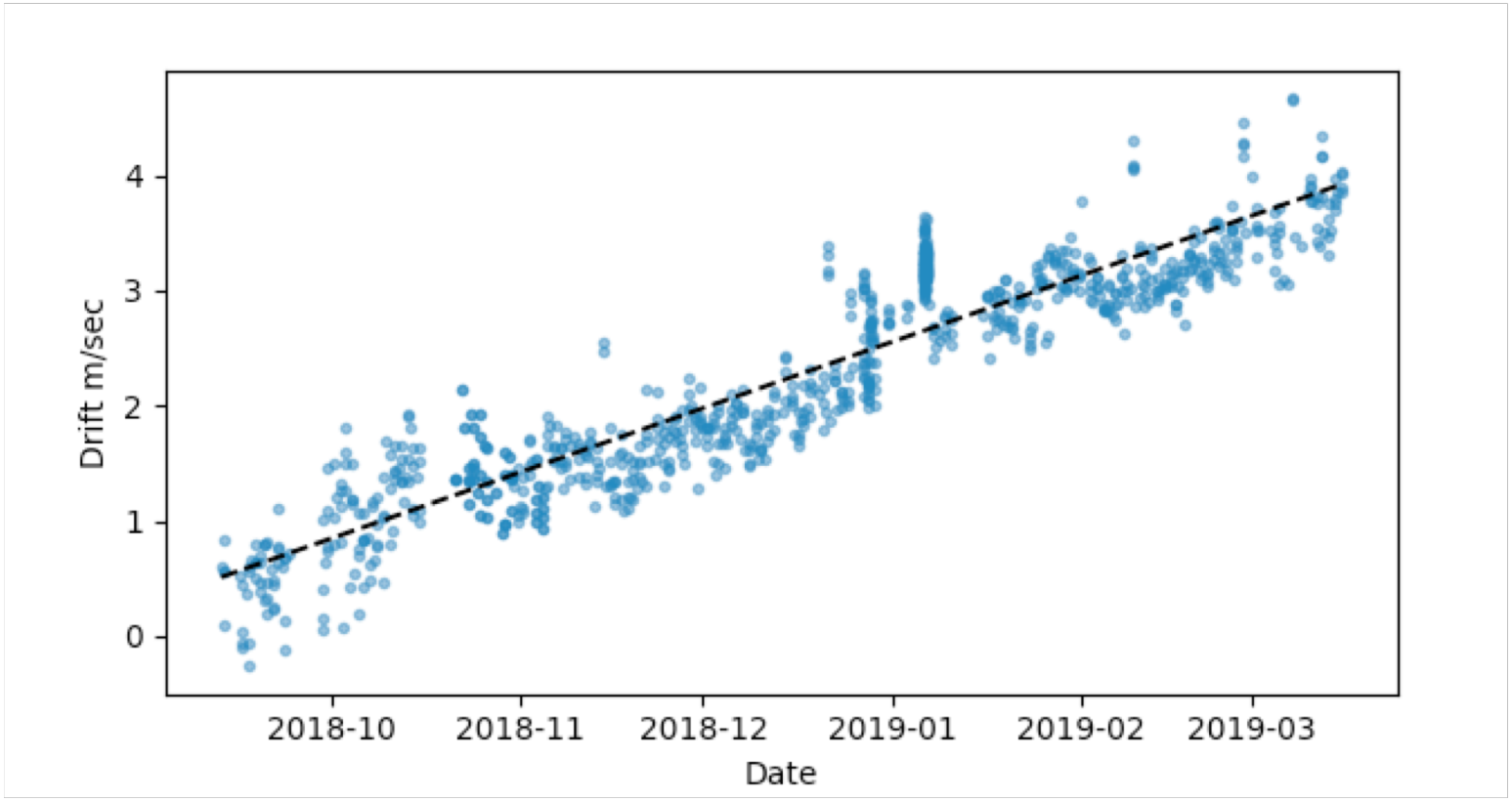
Laser Combs



Metcalf et al. 2019
Obrzud et al. 2018
Spirou…

Fully Spectrum Covering Operational Laser Combs running every day with precision RV instruments are now a thing.

Etalons: Etalon Drift Tracked with HPF LFC



< 2cm/s/day (ULE Passive Etalon)

Some VERY preliminary results that drift is not achromatic

CCDs

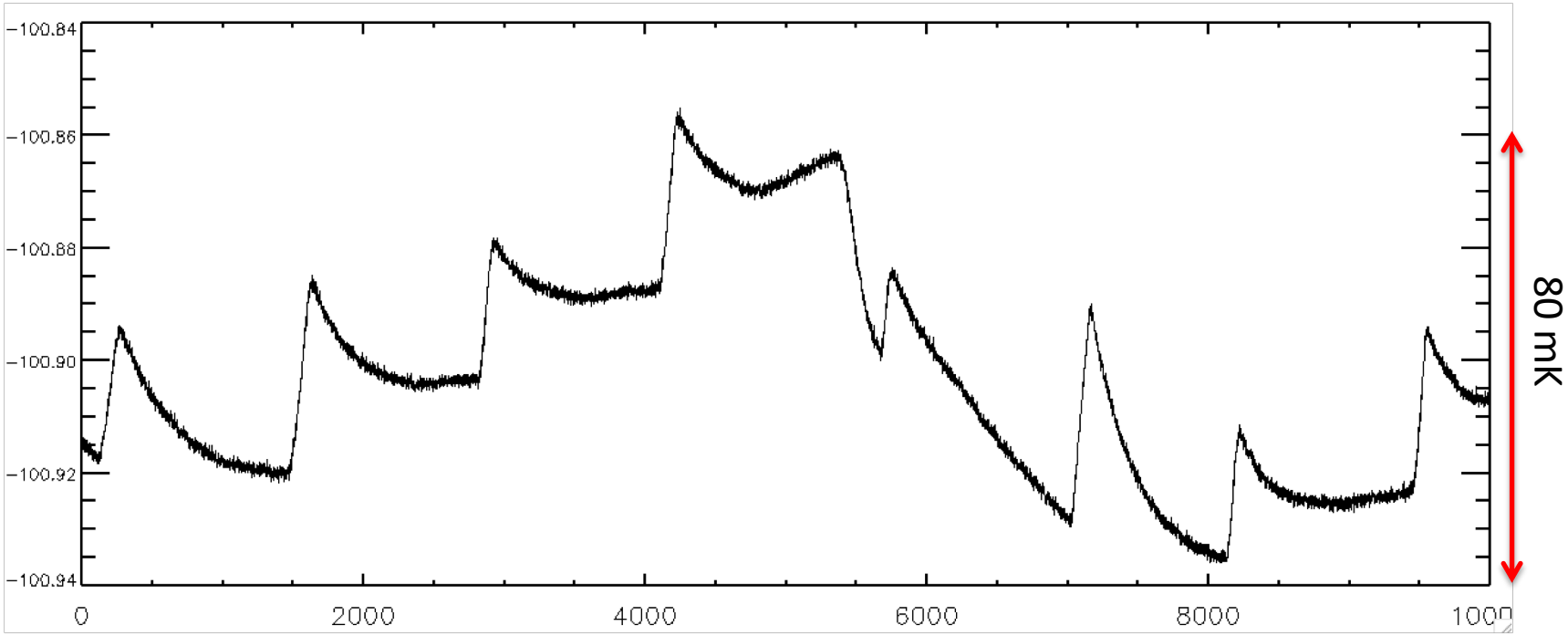
10 cm/s ΔRV corresponds to a physical shift in the detector plane of approximately 2 nm

CCD is a variable heat source due to readout process:

Can be a substantial fraction of a Watt for large-format, multi- output CCD

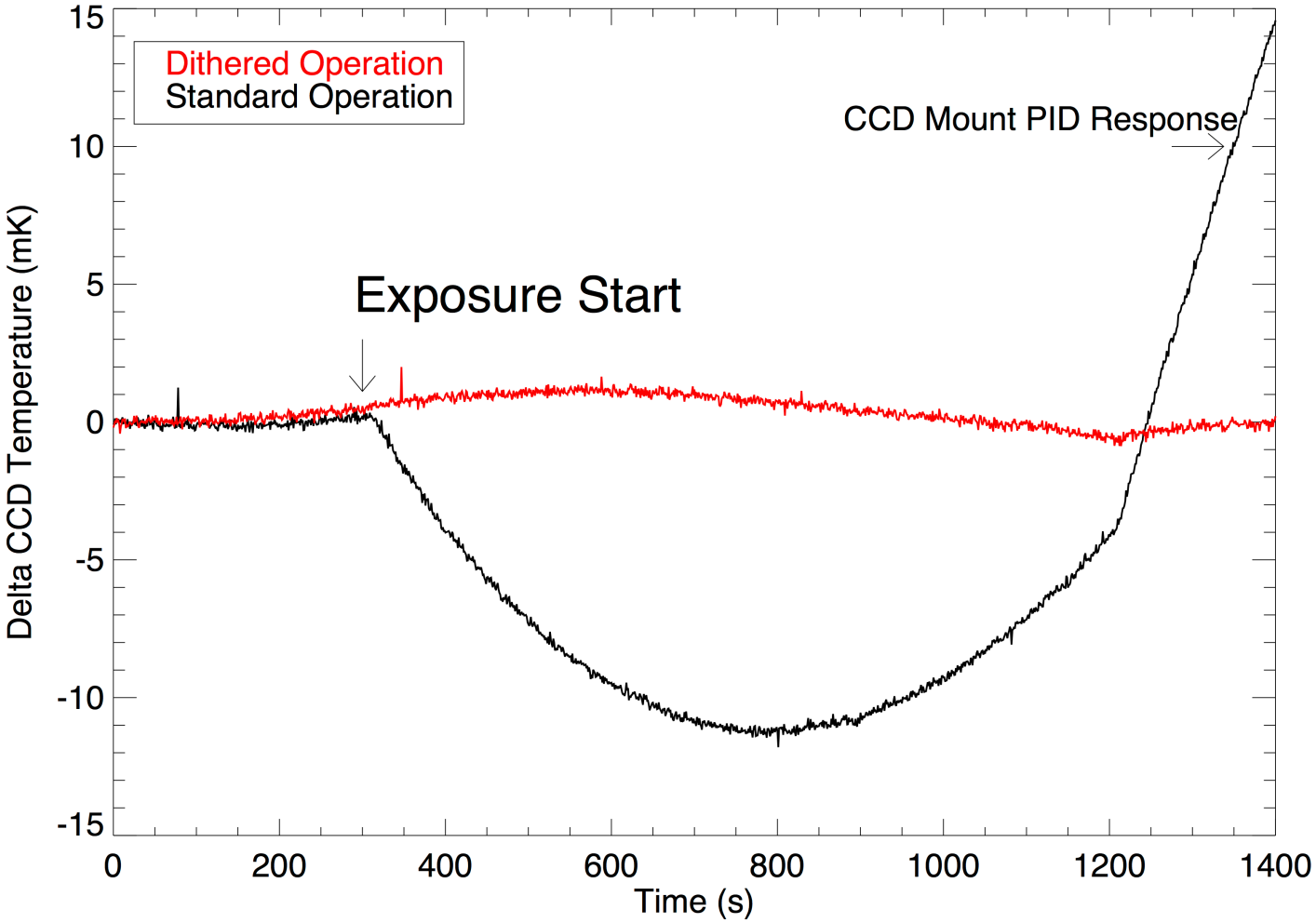
It is very important to monitor the temperature of the CCD package directly (RTD on package) to understand issues related to detector thermal variations

CCDs



Variation in CCD package temperature during a long series of calibration images

CCDs



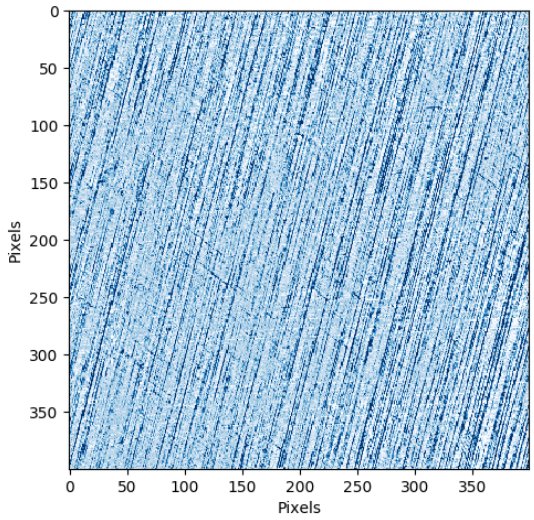
Comparison of CCD thermal variations for two different clocking mechanisms.

CCDs: Charge Transfer Inefficiency (CTI)

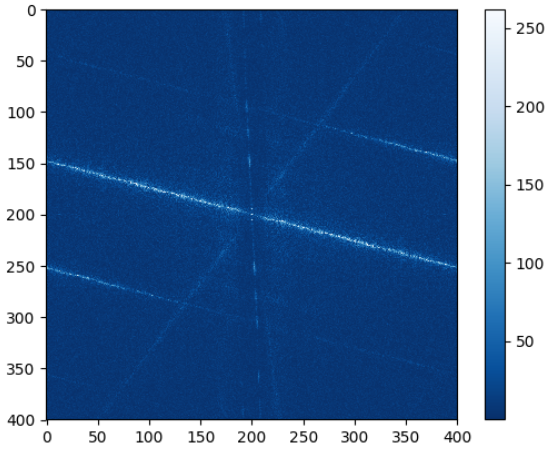
Exposing to Same S/N minimizes CTI issues, which are calibratable in principle, but avoidable

P mode averaging has desired deterministic time for exposures (Chaplin et al. 2019)

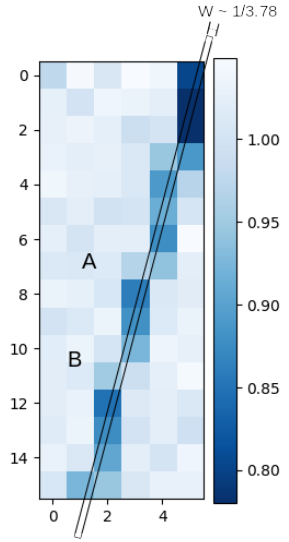
H2RGs



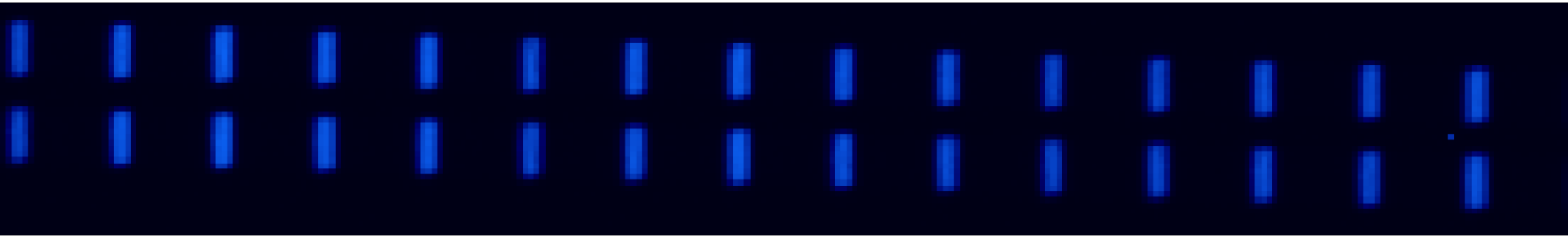
(a)



(b)



(c)

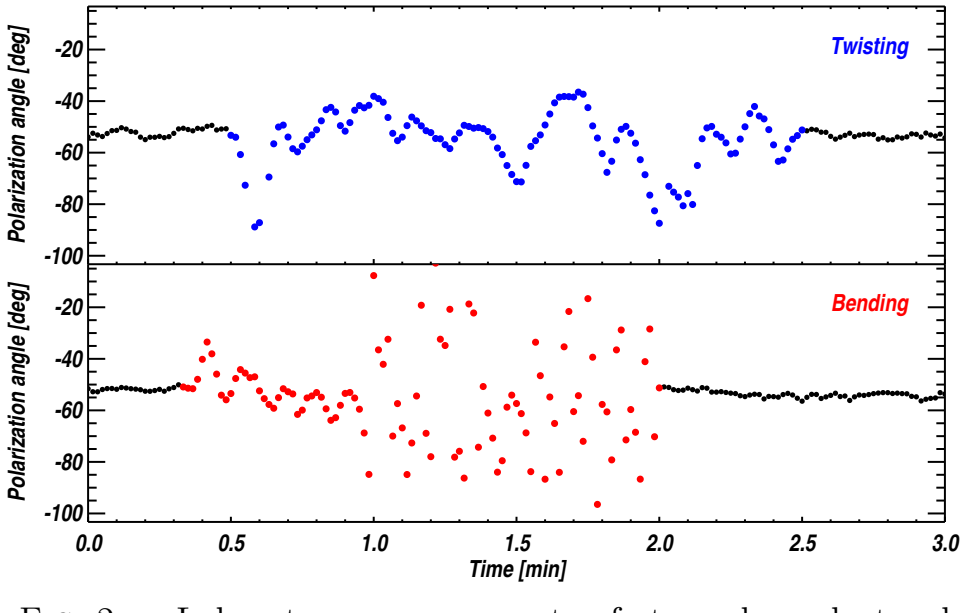


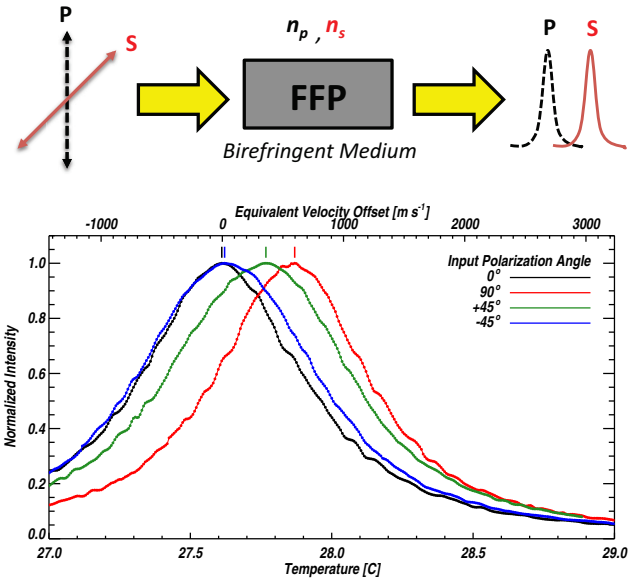
Cross-Hatch Patterns clearly seen in HPF data. RV scatter worse in these areas compared to cleaner areas.

Single Mode Fibers

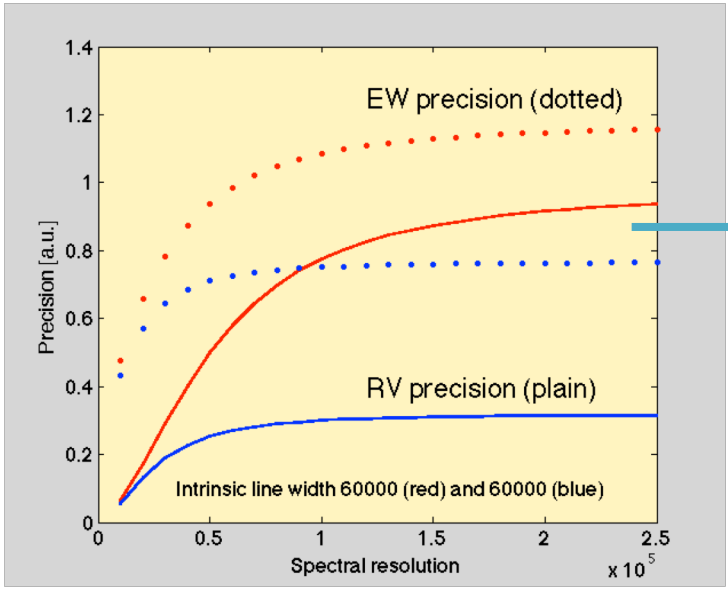
…are of course not.

They have TWO polarization modes. Do not ignore polarization sensitive and selective components in the instrument stream





Photon-noise limited precision?



Pepe 2019, Handbook of Instrumentation

$$\frac{R \cdot FOV \cdot D_{Tel}}{D_{Coll} \cdot \tan\beta} = const$$

$$N_{pix} \sim \frac{\lambda\lambda}{\lambda} \cdot R \cdot s^2 \, N_s^2$$

R = Resolving power

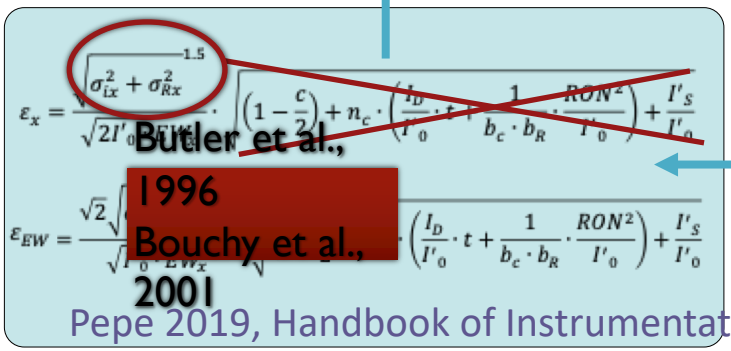
s = sampling

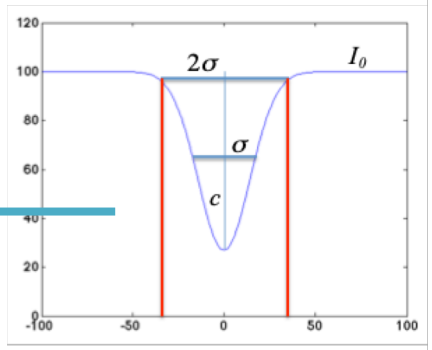
$\lambda\lambda$ = band width

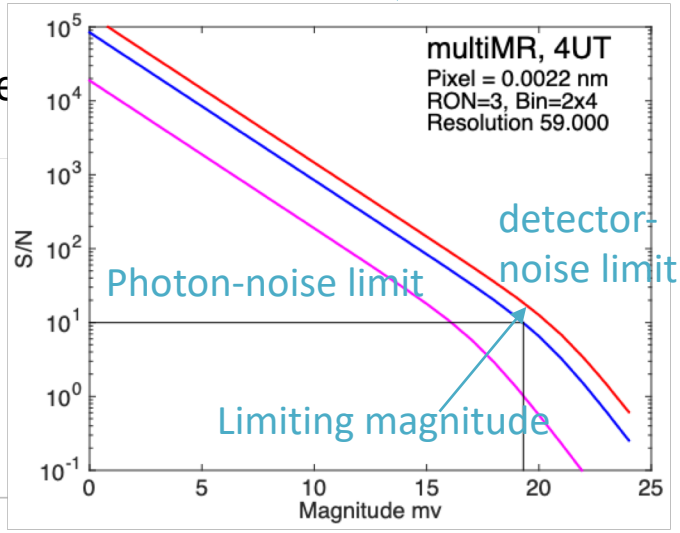
Npix = Number of pixels

Ns = Sampling

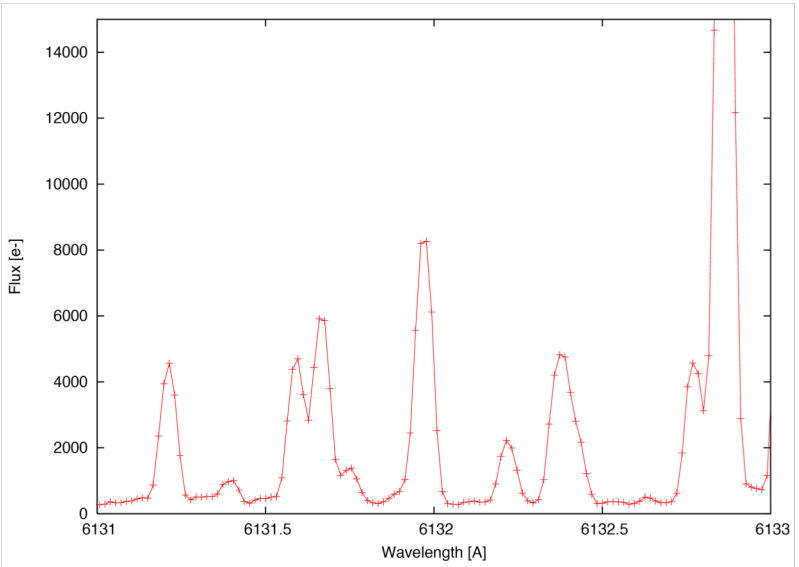
Dcoll = Collimated be

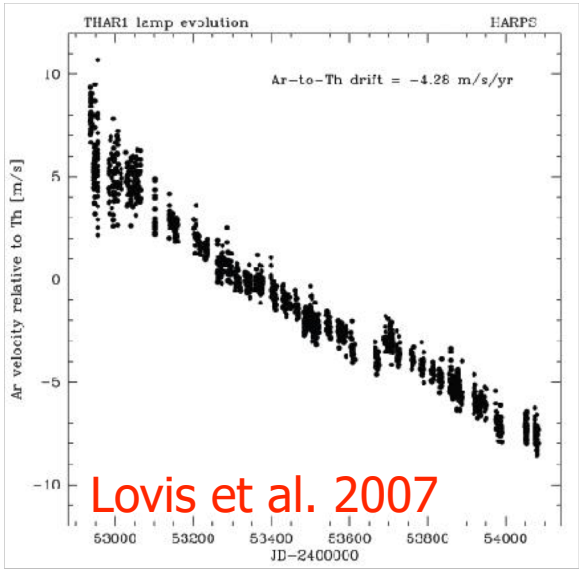


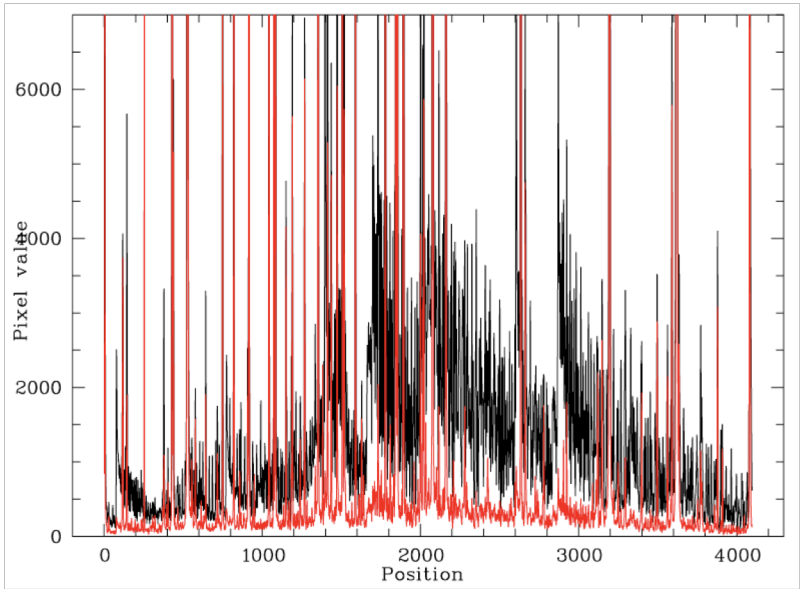


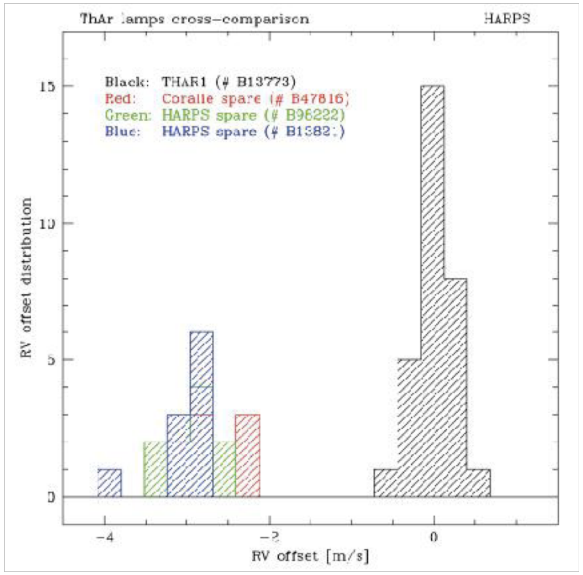


Limitations from present calibration sources

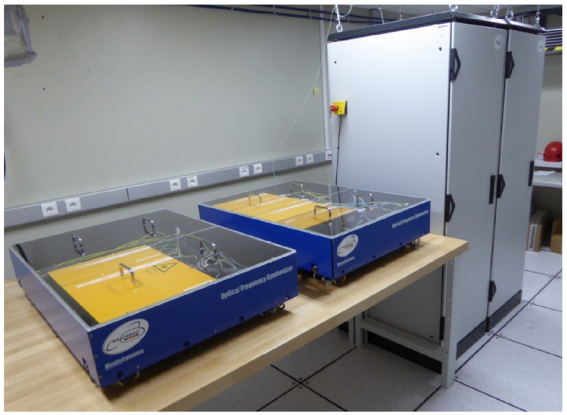


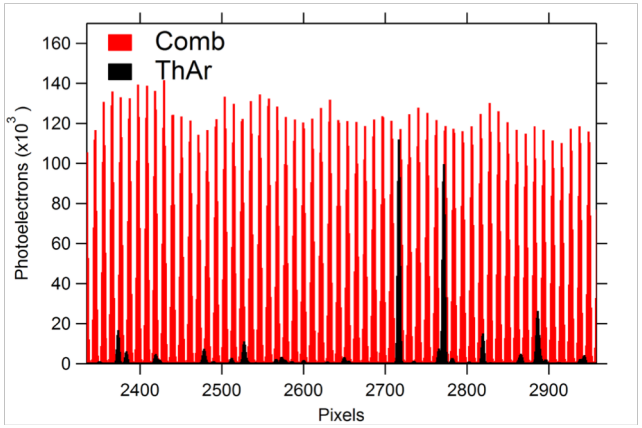


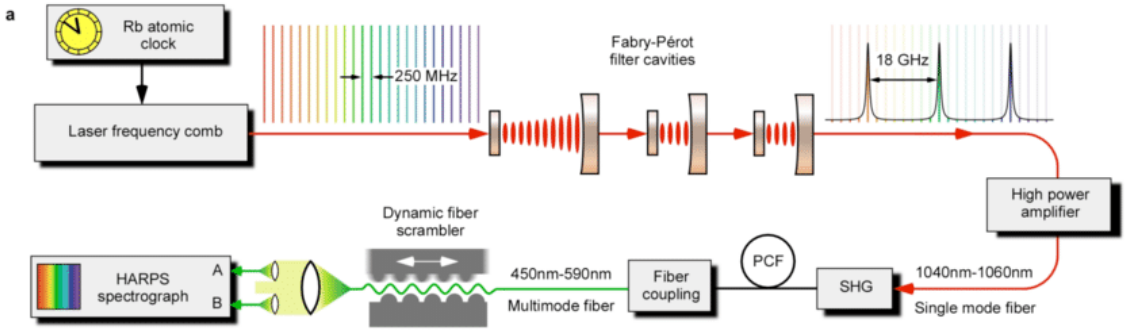


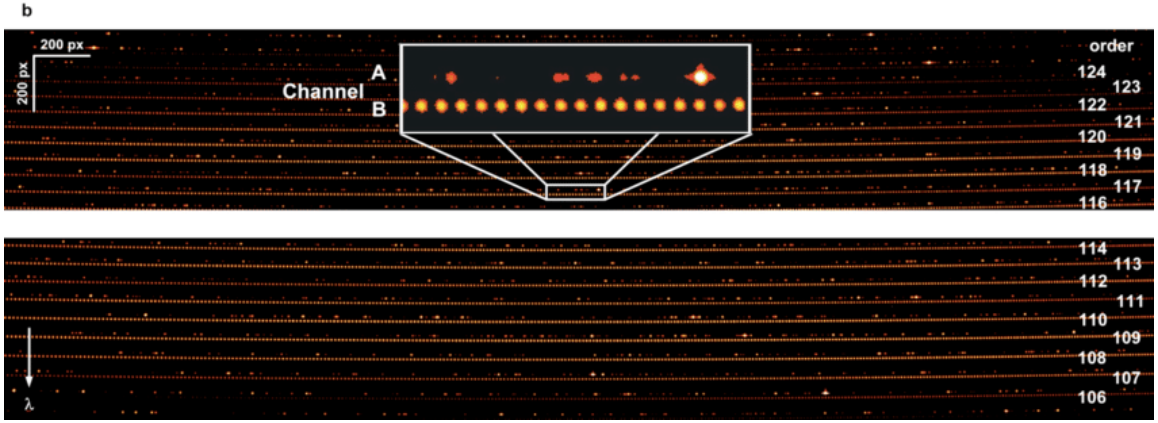


The LFC - The ‘perfect’ calibrator







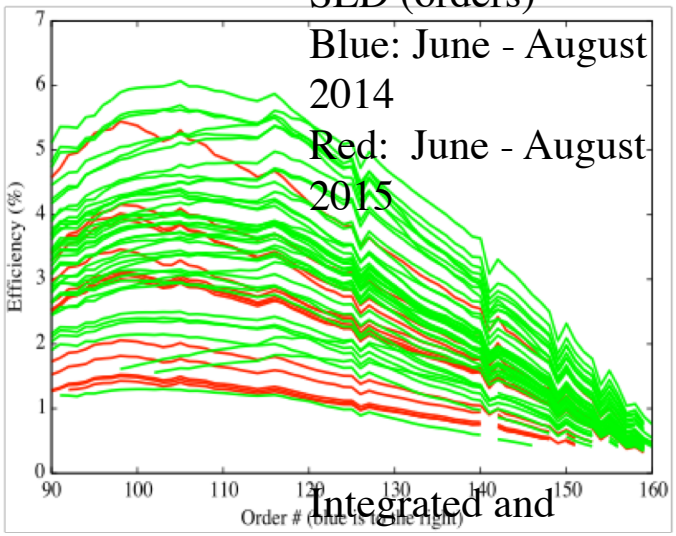


- Constant line separation
- High precision
- low dynamic range
- Absolute accuracy
- Extremely narrow lines (->IP)

- Reliability …
- Full spectral coverage

Fiber scrambling and efficiency, but… IP modelling, repeatability, wavelength accuracy?

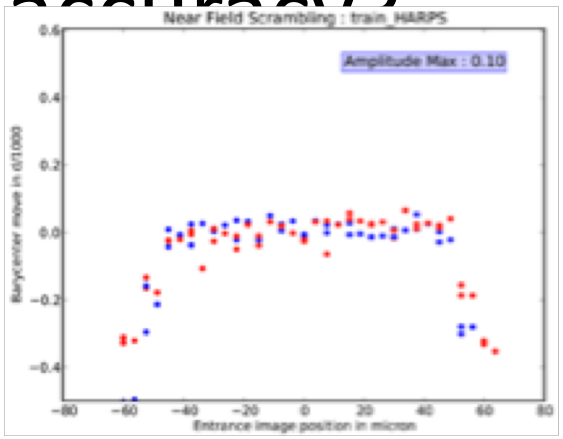
Pepe et al. 2015, The Messenger

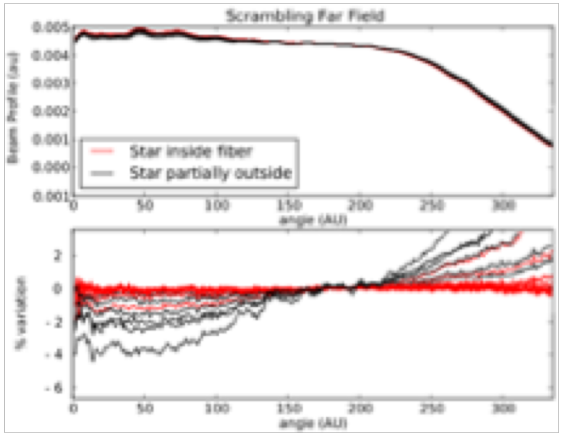


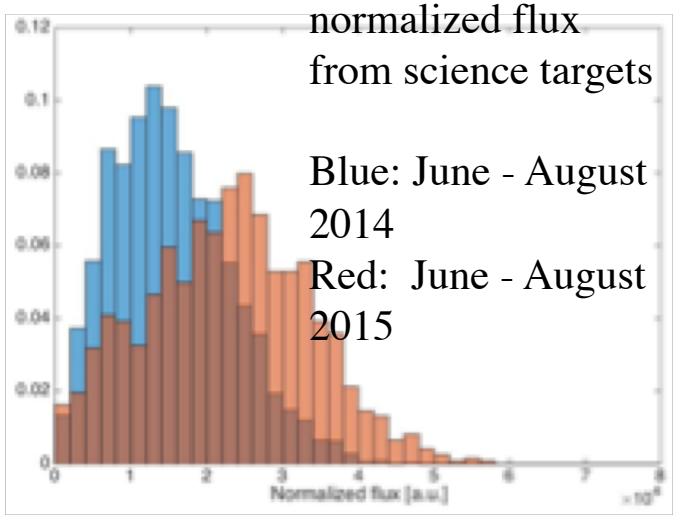
SED (orders)

Blue: June - August 2014

Red: June - August 2015



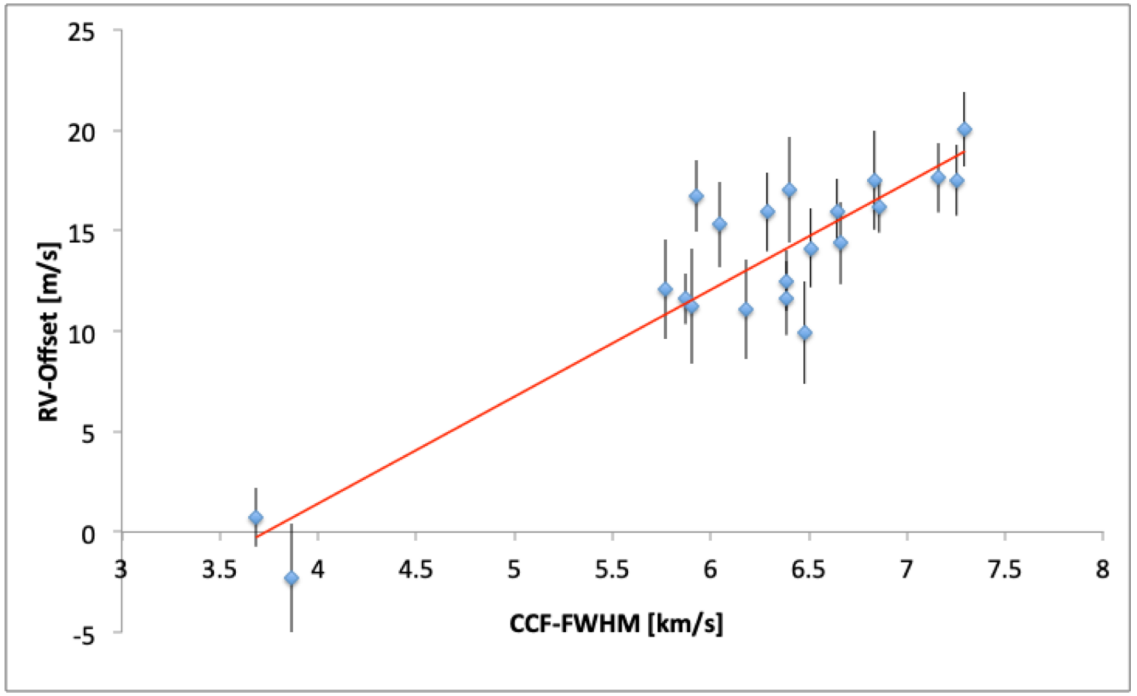




Integrated and normalized flux from science targets

Blue: June - August 2014

Red: June - August 2015



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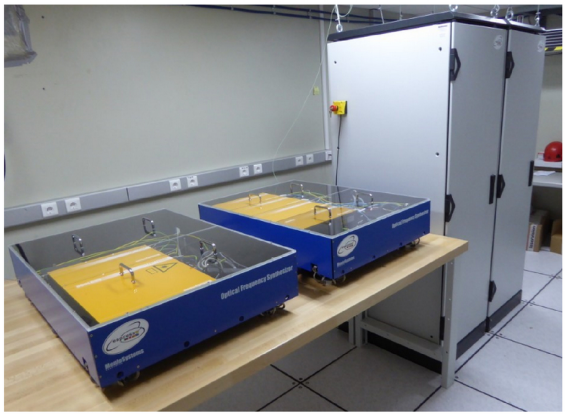
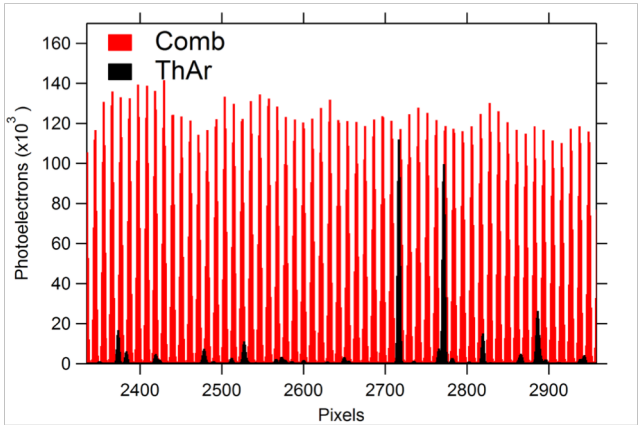
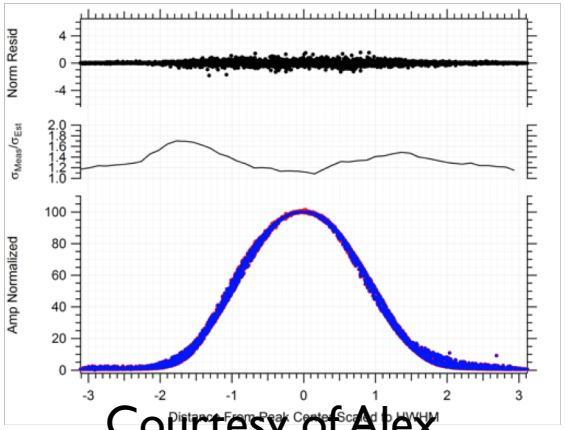
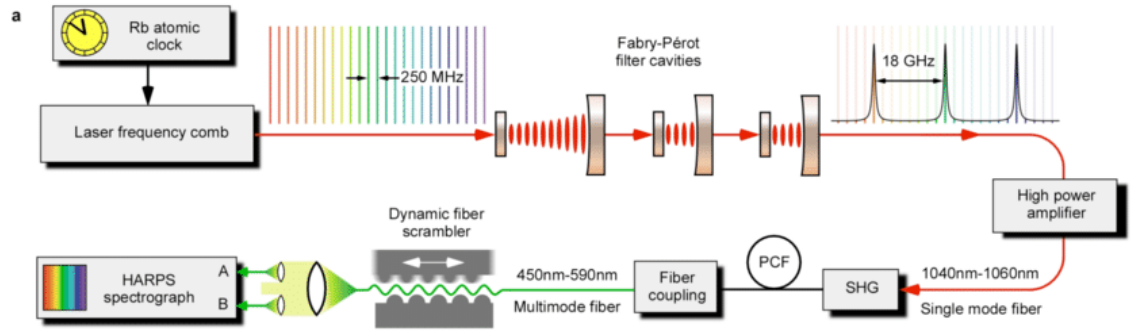
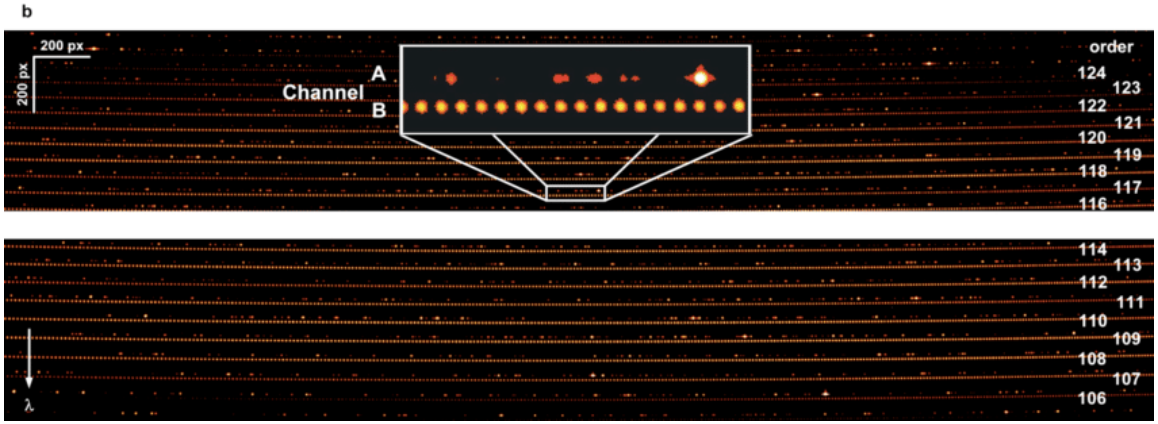






Courtesy of Alex Glenday, CfA



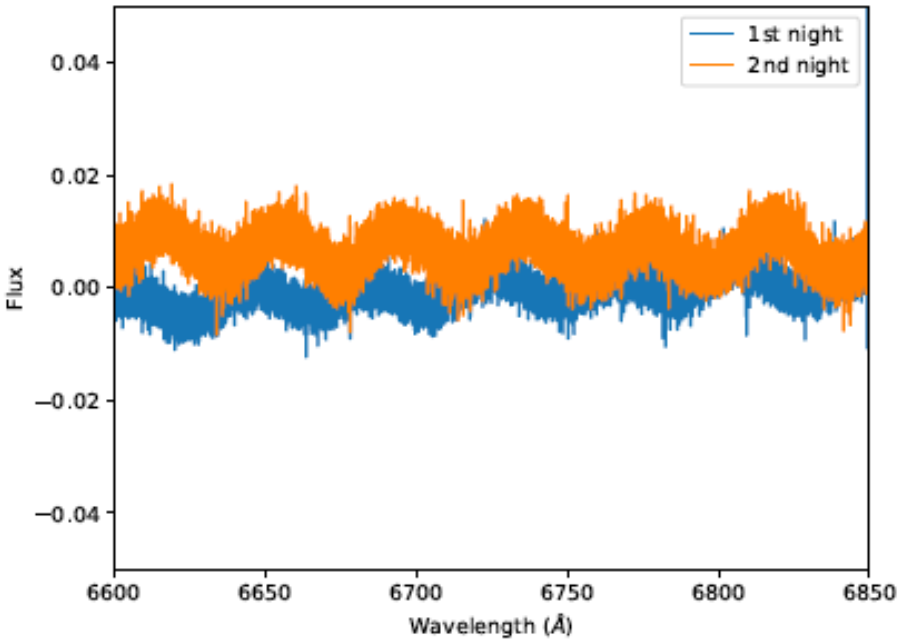


- Constant line separation
- High precision
- low dynamic range
- Absolute accuracy
- Extremely narrow lines (->IP)

- Reliability …
- Full spectral coverage

Non-perfect (and varying) flat fielding

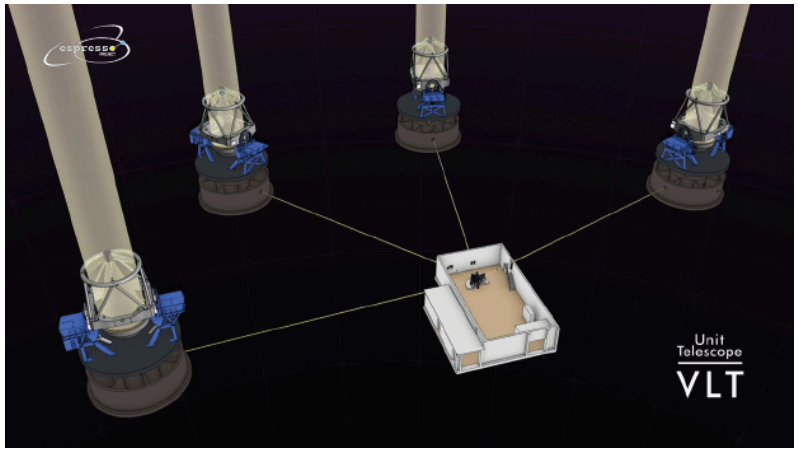
Private Communication Romain Allart

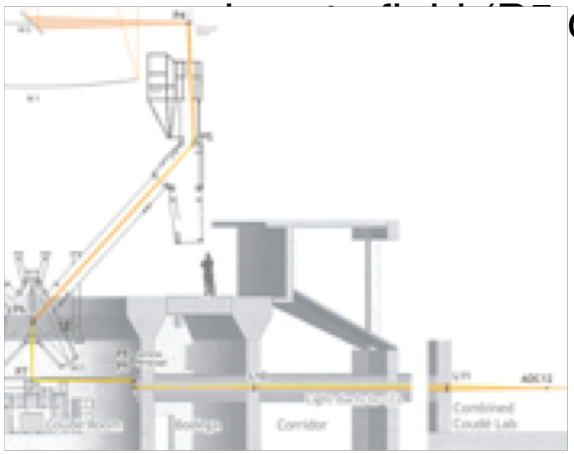


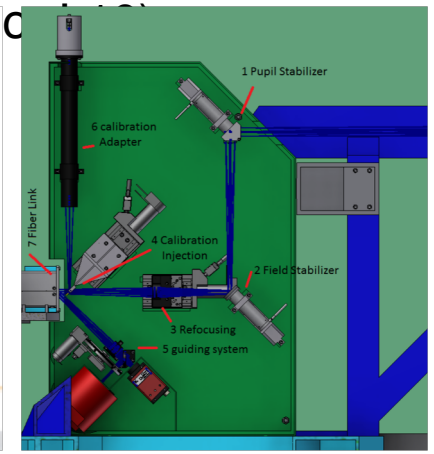
Wiggles appear when dividing spectra from different telescope positions.

Spectrograph to be excluded, since wiggle depend on telescope position and are not present in spectral FF.

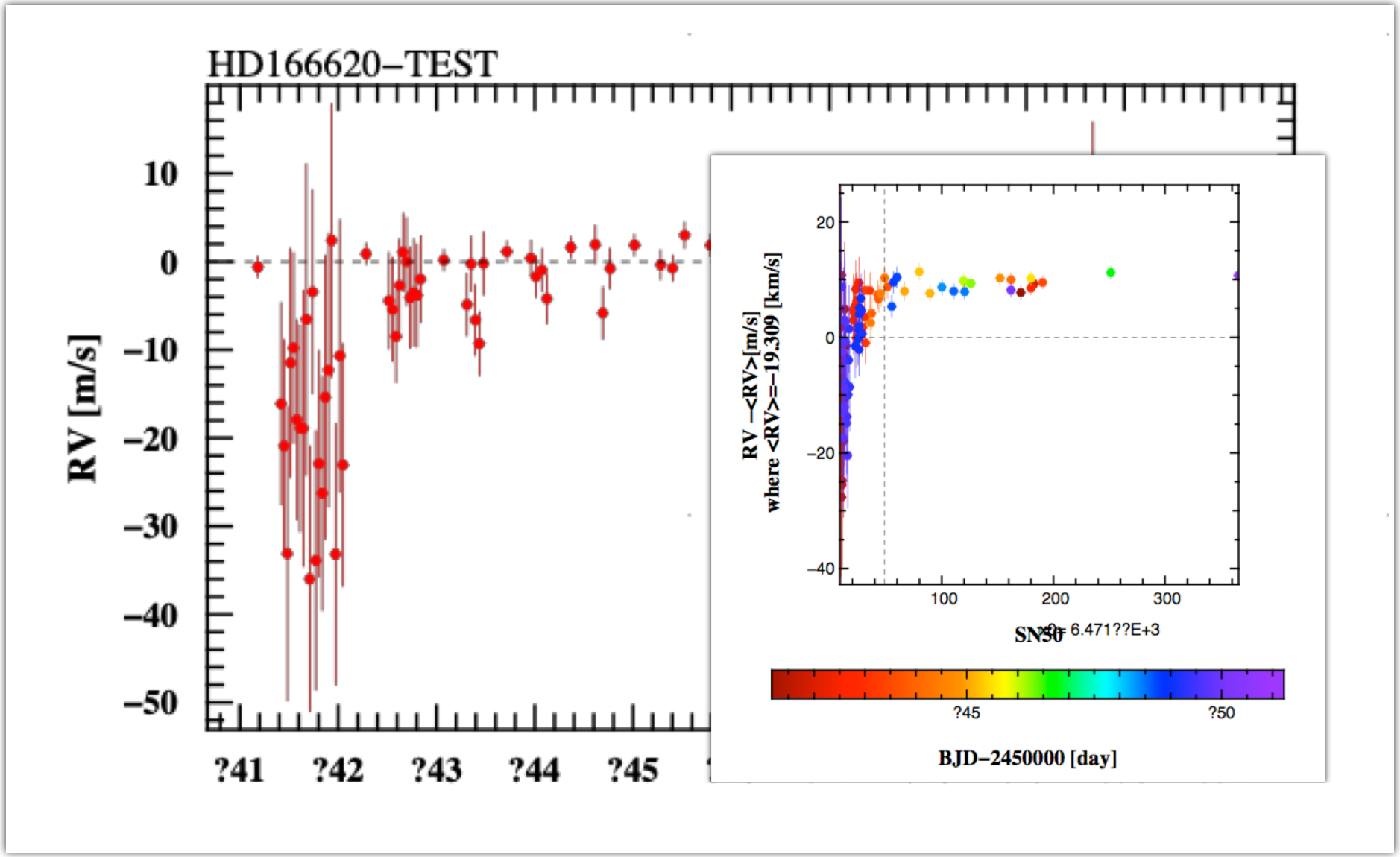
Originally ADC suspected, by revealed wrong. Must be component



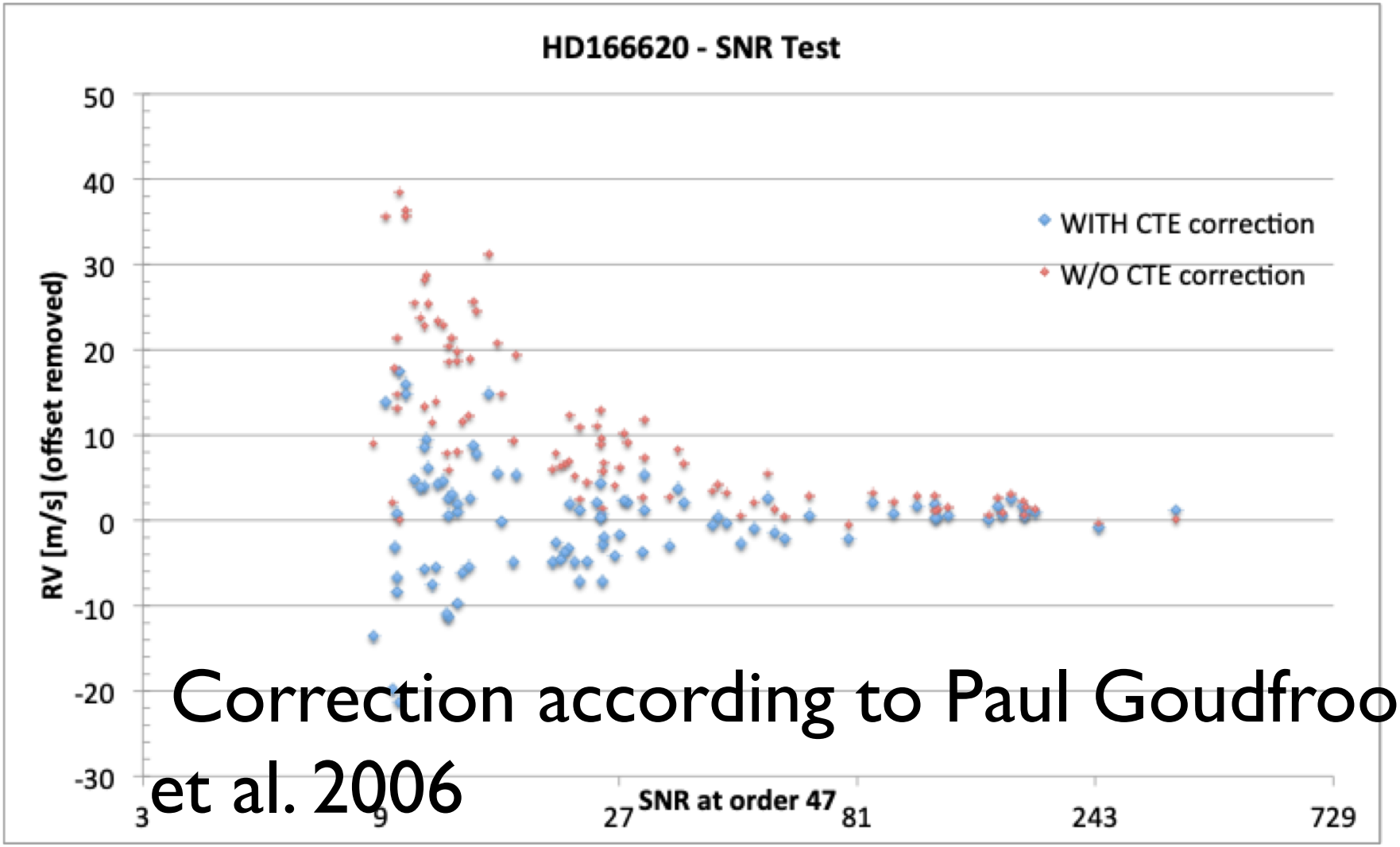




CTE Problem: SNR test

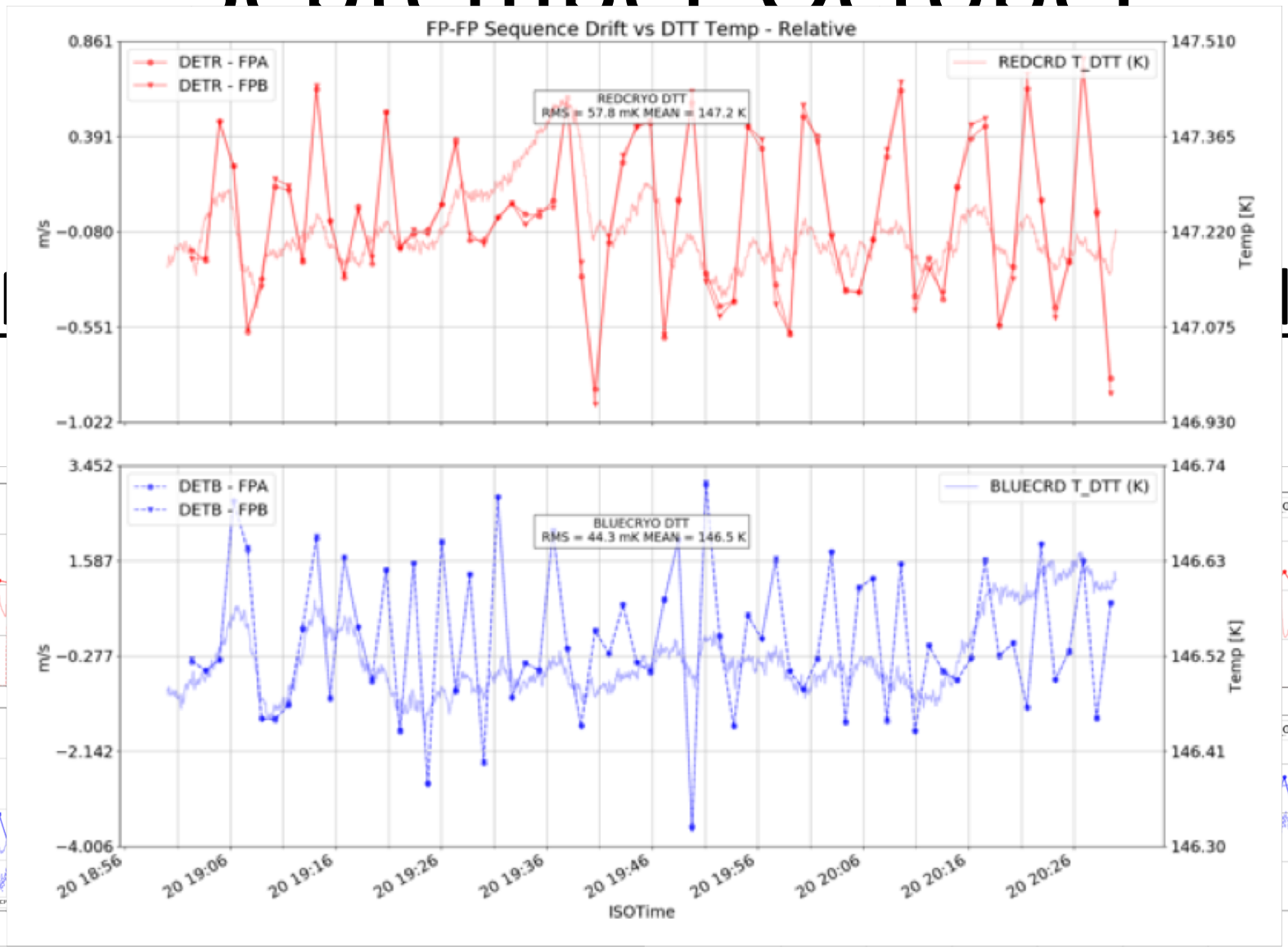


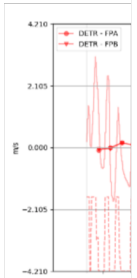
CTE Problem: solution

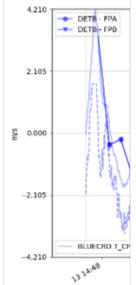


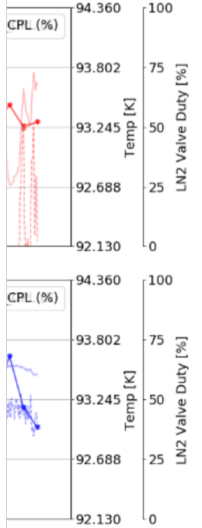
Correction according to Paul Goudfrooij et al. 2006

September-October



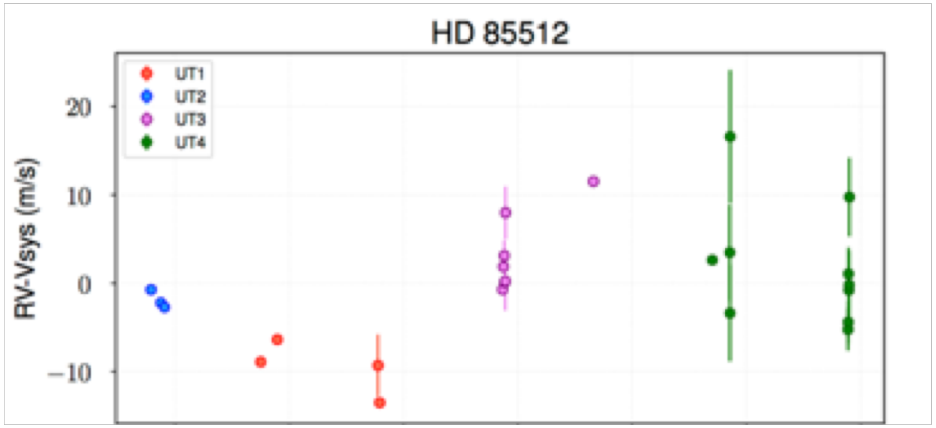


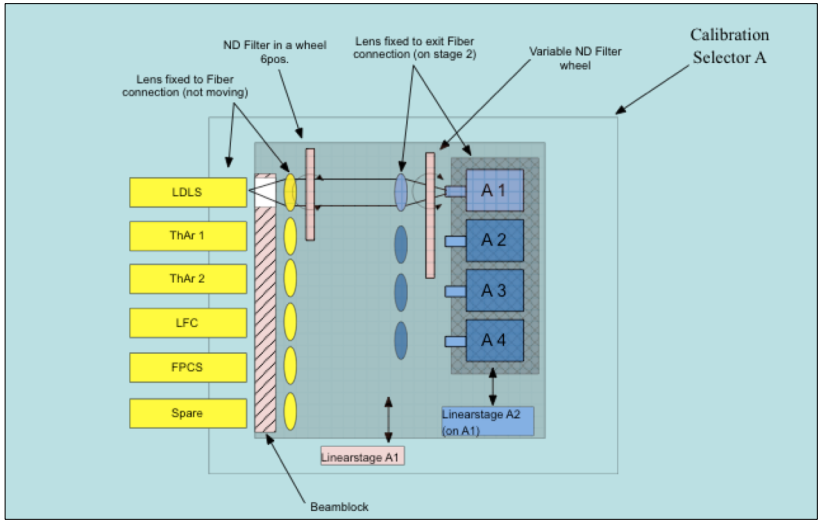


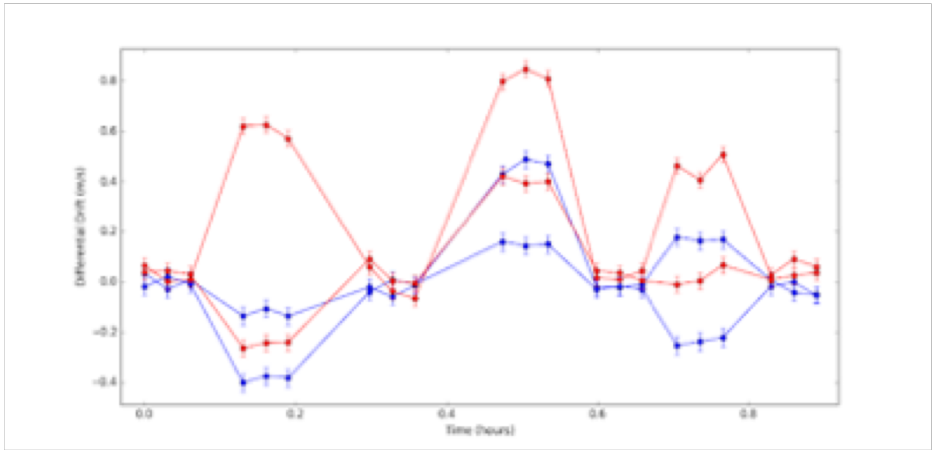


mjd

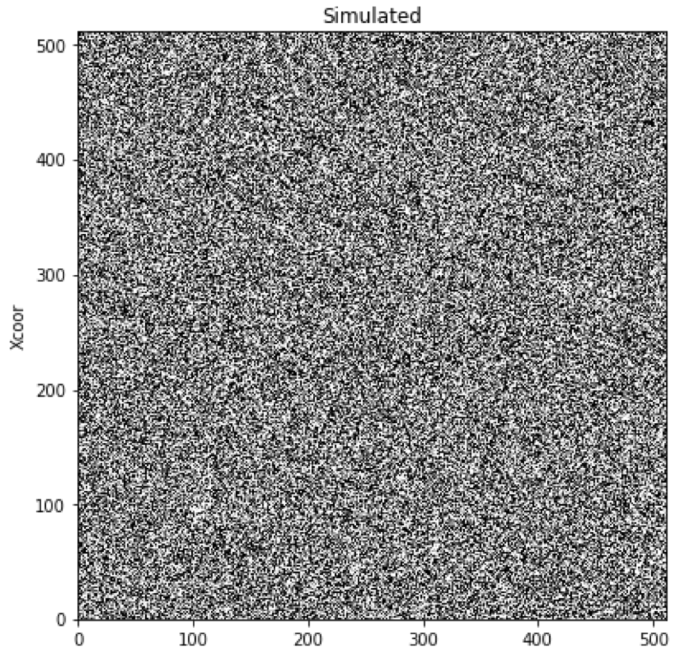
Uhhhhh, the Fabry-Pérot ….

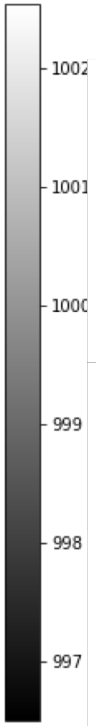


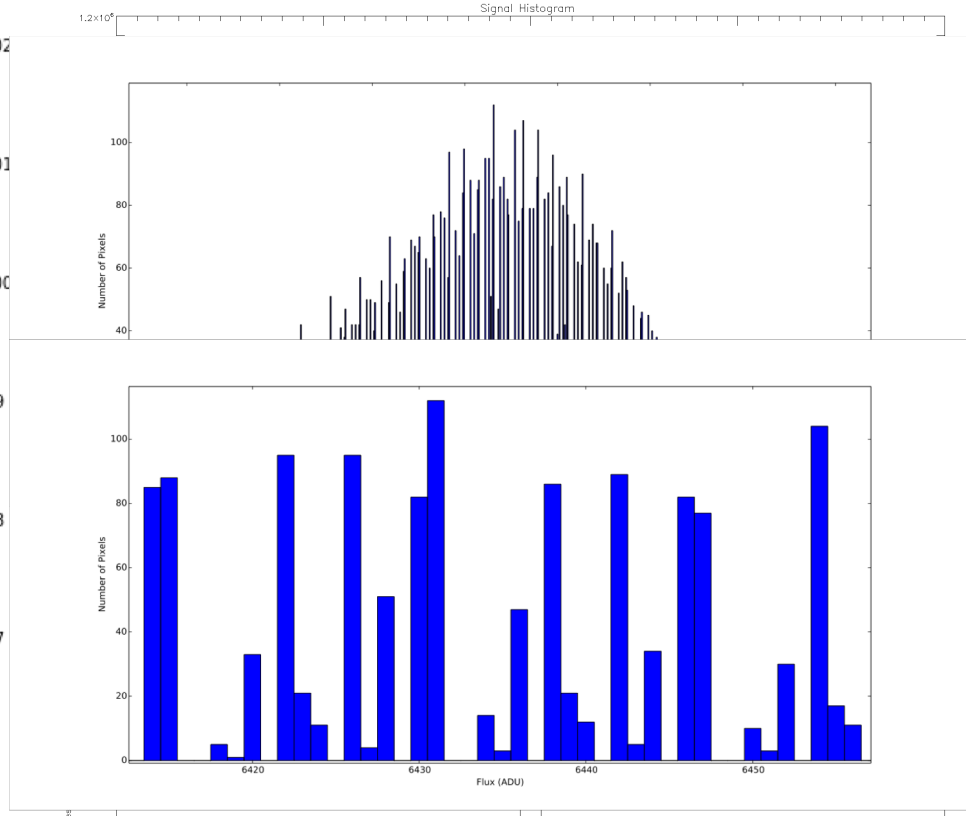


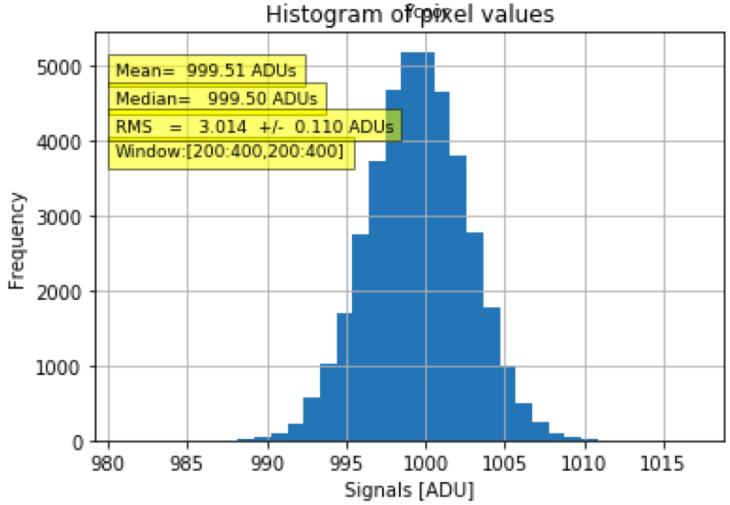


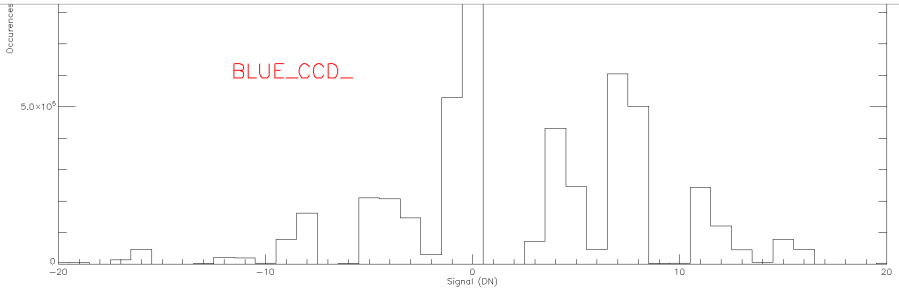
Watch your back …











Achieving sub-m/s precision