LLNL-PRES-813781

BERKELEY CENTER for COSMOLOGICAL PHYSICS

Prepared by LLNL under Contract DE-AC52-07NA27344.

Cosmology at cm/s scale using ultrastable spectroscopic interferometry

David Erskine & Eric Linder

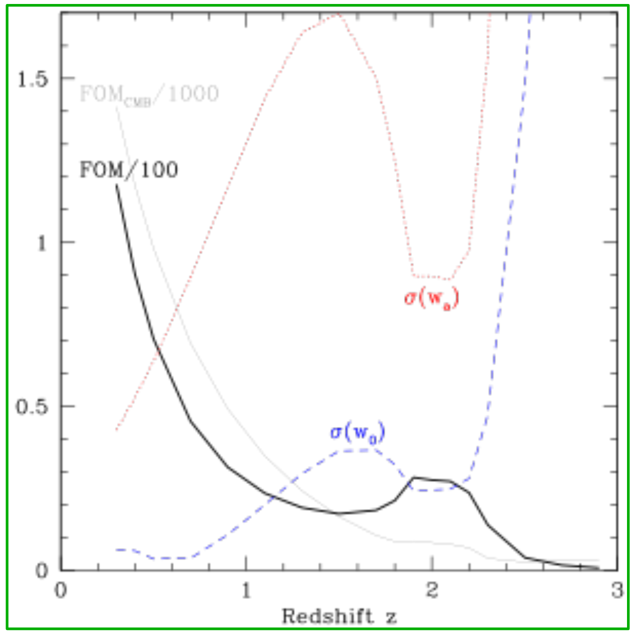
LLNL & UC Berkeley

Snowmass CF4

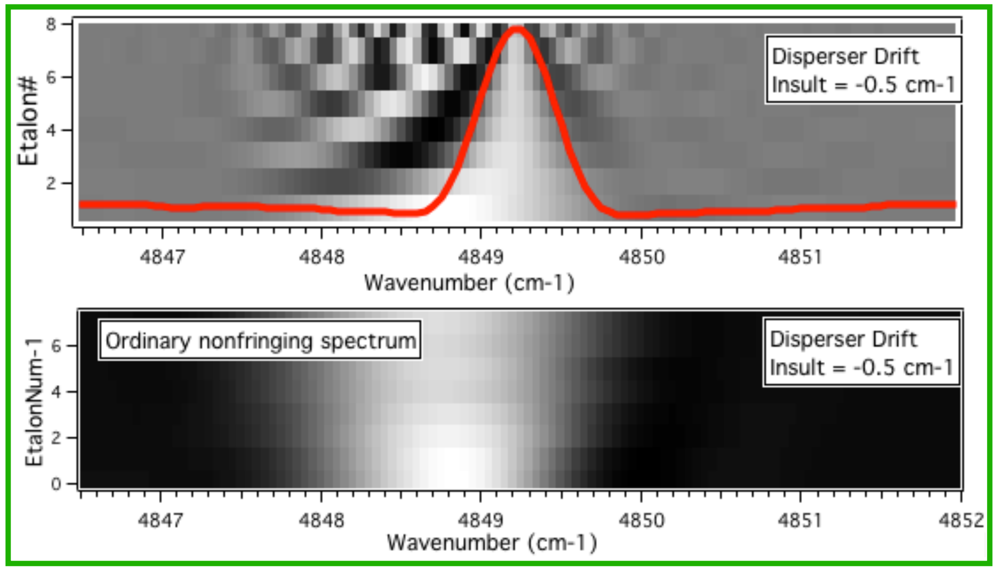
12 August 2020

https://snowmass21.org/cosmic/de_universe

Our portion begins 30 min into 60 min recording at that webpage



"**Direct Acceleration: Cosmic and Exoplanet Synergies**", D. J. Erskine, E. V. Linder, A. Kim, and 10 endorsing coauthors, white paper, Astro2020 Decadal Survey on Astr. and Astrophys., Nat. Acad. Sciences, arXiv:**1903.05656**, Bull. Am. Astr. Soc. 51 (3):53 May (2019). (https://arxiv.org/abs/1903.05656v1)



Acceleration Surveys

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Density survey, Velocity Survey, Acceleration Survey

Einstein: “Acceleration = Gravity”

Achieving cm/s velocity accuracy in spectroscopy enables 4 major science cases:

- Cosmic redshift drift and direct detection of cosmic acceleration
- Earth mass exoplanet detection from radial velocities
- Milky Way structure mapping through stellar accelerations [UL axions]
- Dark matter properties through Milky Way gravity mapping
- Biomedical, National security/remote sensing, Fusion

Breakthroughs on science and technology sides

- Recognition of synergy between science cases

- Recognition that low redshift spectroscopy is sweet spot, complementary

- Technology advances, e.g. crossfading

Cosmic Acceleration

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

"Redshift z gives velocity, Redshift drift ż gives acceleration"

Proposed as cosmology probe McVittie (1962), Sandage (1962). **Revisited in 70s, 80s; dark energy probe** Linder (1997).

Survey: strategy, systematics, full theory Kim, Linder, Edelstein, Erskine 1402.6614 **; Astro2020** Erskine+ 1903.05656

Basics:

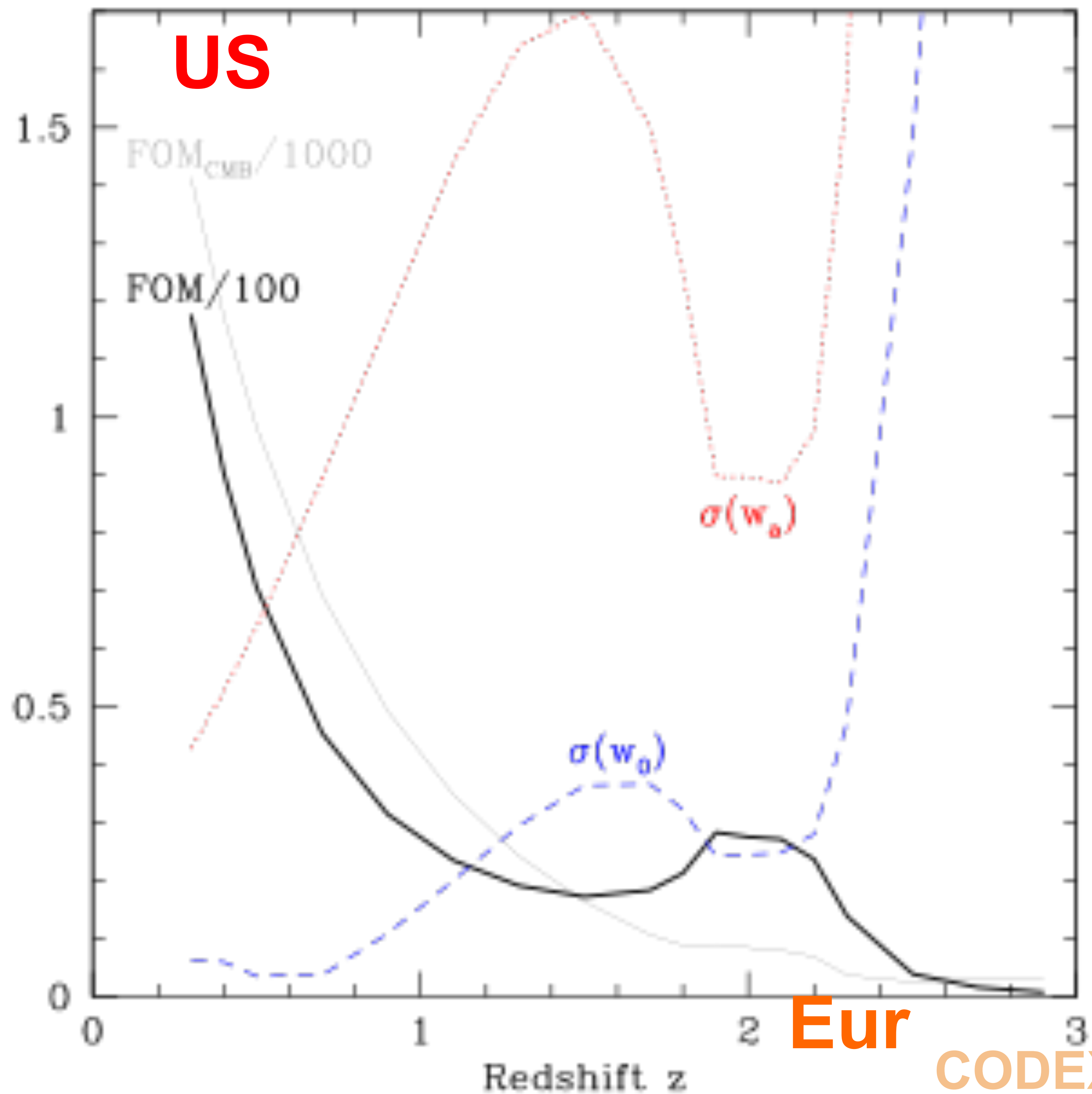
- Differential measurements are more robust than absolute ones.
- Use doublet lines to measure cosmic expansion differentially.
- Use interferometer to compare signals from two arms.
- Use delays "shift symmetry" to cancel instrumental systematics.

Technology: 2016 – demo on Hale Telescope of 10x resolution gain, 20x stability gain. 2018 – GPI 100x resolution gain on biomarkers. 2019 – "crossfading" lab demonstration of 1000x stability gain.

Redshift Drift (+ CMB)

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

If redshift drift z can be measured, it has powerful complementarity with CMB.



$$\dot{z} = H_0(1+z) - H(z)$$

Δz → cm/s (Δt/3y)

Leverage ranges from independent crosscheck to 3x above Stage 4.

Optimal range z<0.5.

Need lots of photons, e.g. ELTs best, 10m ~ok.

CODEX; not differential, not interferometry

Cosmology at cm/s scale using ultra stable spectroscopic interferometry

David Erskine (LLNL)
Eric Linder (Berkeley)

Prepared by LLNL under Contract DE-AC52-07NA27344.

August 12, 2020

Online talk for Snowmass 2021,
Section CF4. Dark Energy and Cosmic Acceleration: The Modern Universe

https://snowmass21.org/cosmic/de_universe

Our portion begins 30 min into 60 min recording at that webpage

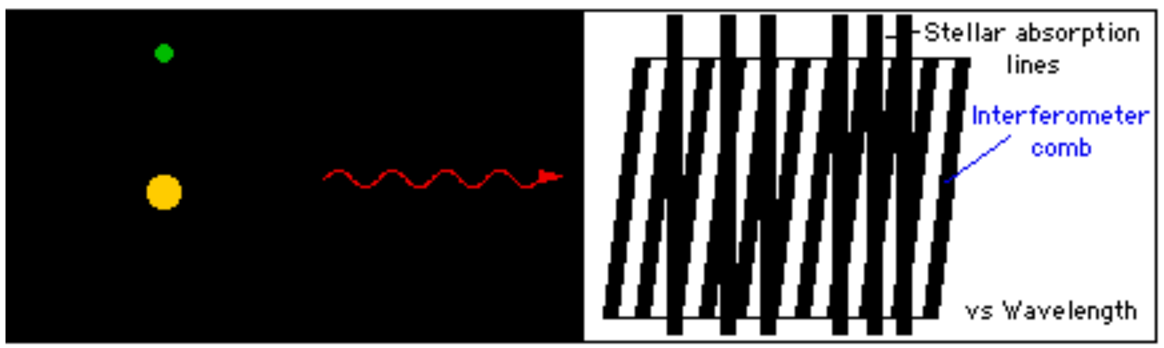
"**A 1000x Stabler Spectrograph using an Interferometer with Crossfaded Delays**", David J. Erskine and Eric V. Linder, Opt. Soc. Am. Optical Sensors and Sensing Congress 2019, Fourier Transform Spectroscopy Topical Mtg., San Jose, CA, June 25-27, 2019, paper FW5b.3. FTS-2019-FW5B.3(SanJose).pdf

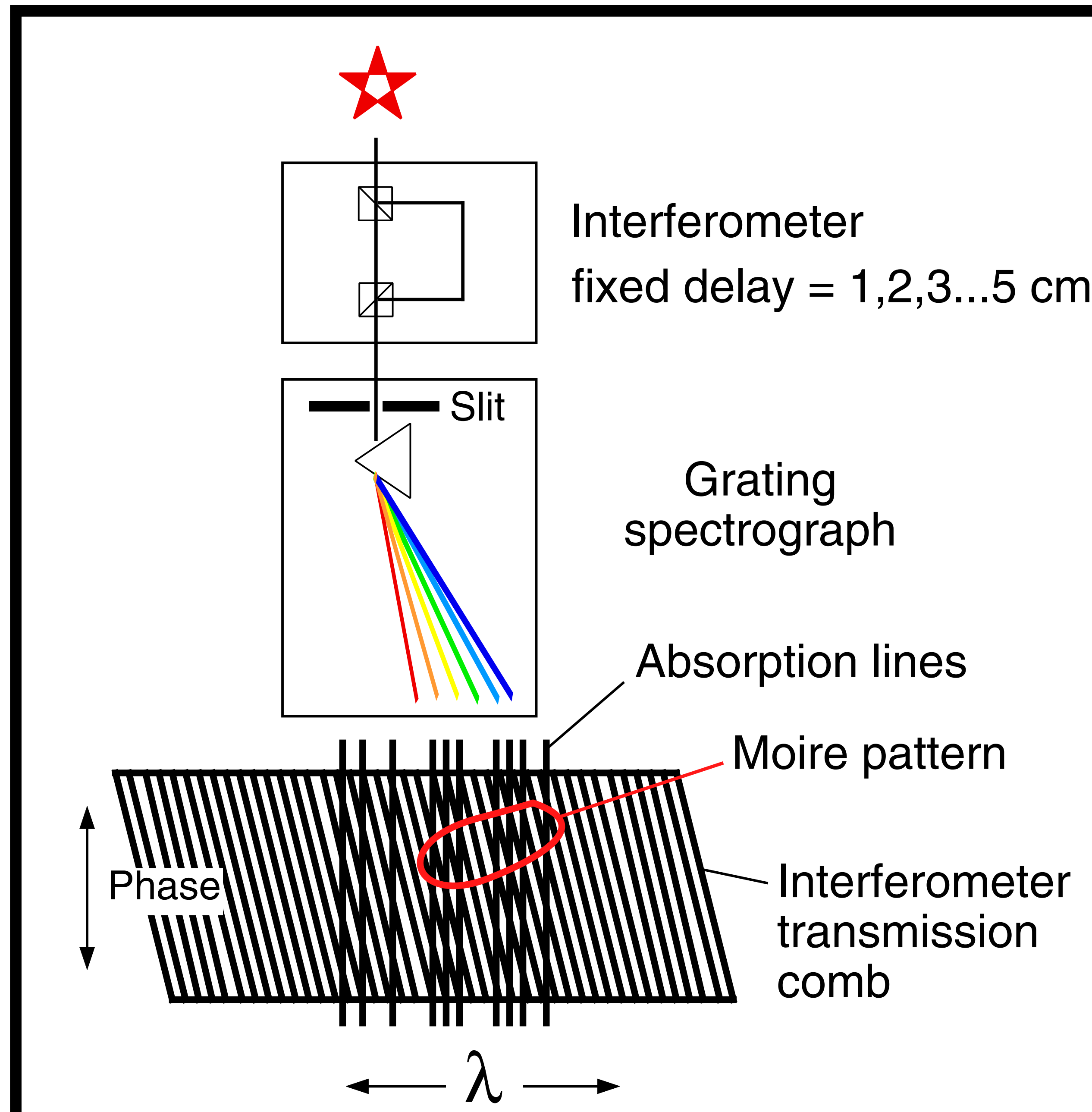
Poster of same title, AAS 234th Mtg., St. Louis MO, June 9-13, 2019. Poster2019AAS-StLouis-Gen.pdf

Abstract

Externally Dispersed Interferometry (EDI) has been used since 1998 to detect exoplanets and perform high resolution spectroscopy,

1 to 3 orders of magnitude more robust to wavelength drifts than conventional dispersive spectrographs





The basic EDI is 1 to 2 orders of magnitude more robust to wavelength drifts than grating spectrograph alone

We have made improvements (called Crossfading) that further boosts the robustness by 1 to 2 orders of magnitude

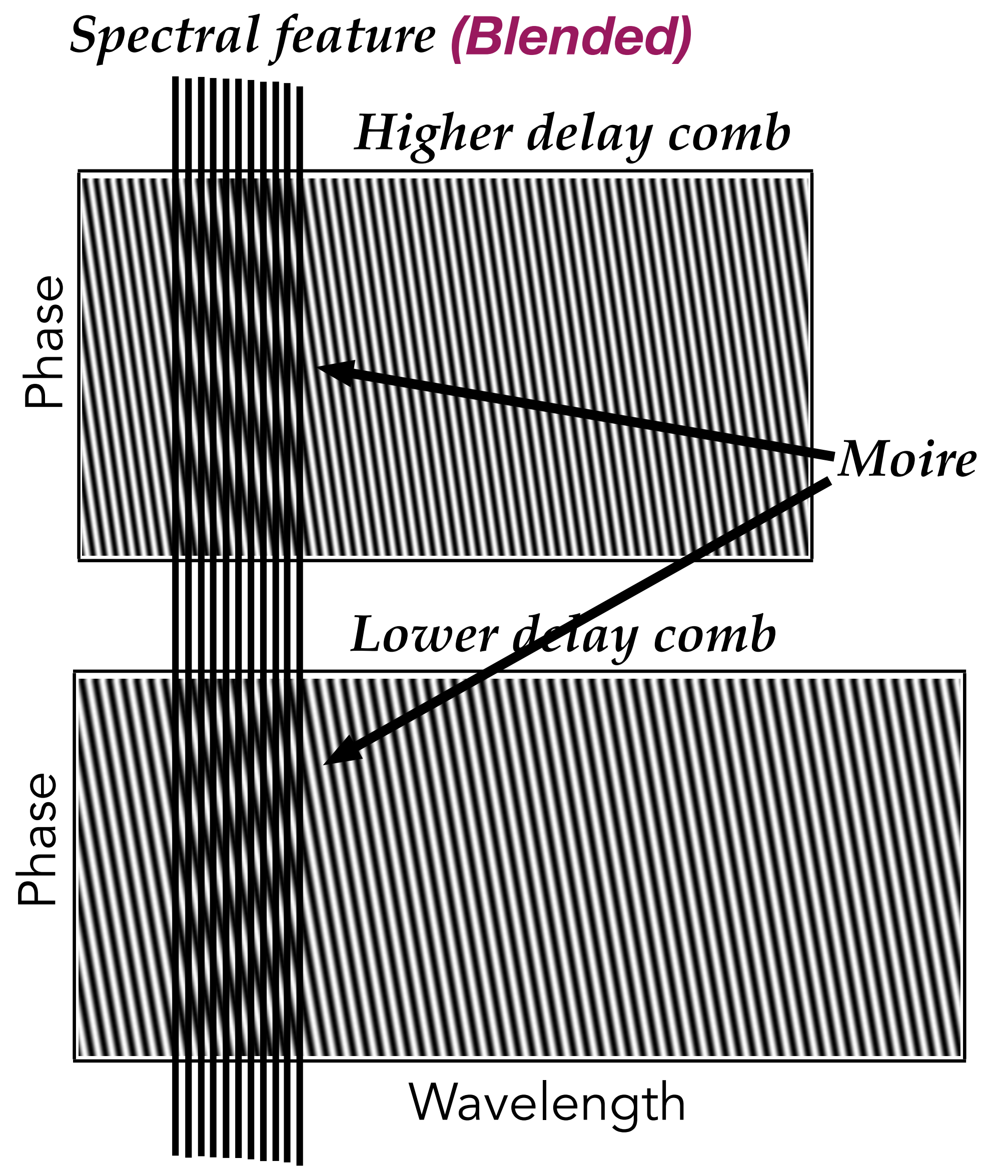
1000x robustness demo'd in simulation

“**High-resolution broadband spectroscopy using externally dispersed interferometry at the Hale telescope: Part 1, data analysis and results**”, D.J. Erskine, J. Edelstein, et al., J. Astr. Tele. Instrm. Sys. 2(2), 025004 (2016). (https://doi.org/10.1117/1.JATIS.2.2.025004)

2018 improvement: use PAIRS of slightly different delays to cancel drift error

Crossfading: Strategically weighted, we CANCEL net reaction to wavelength drift Δx

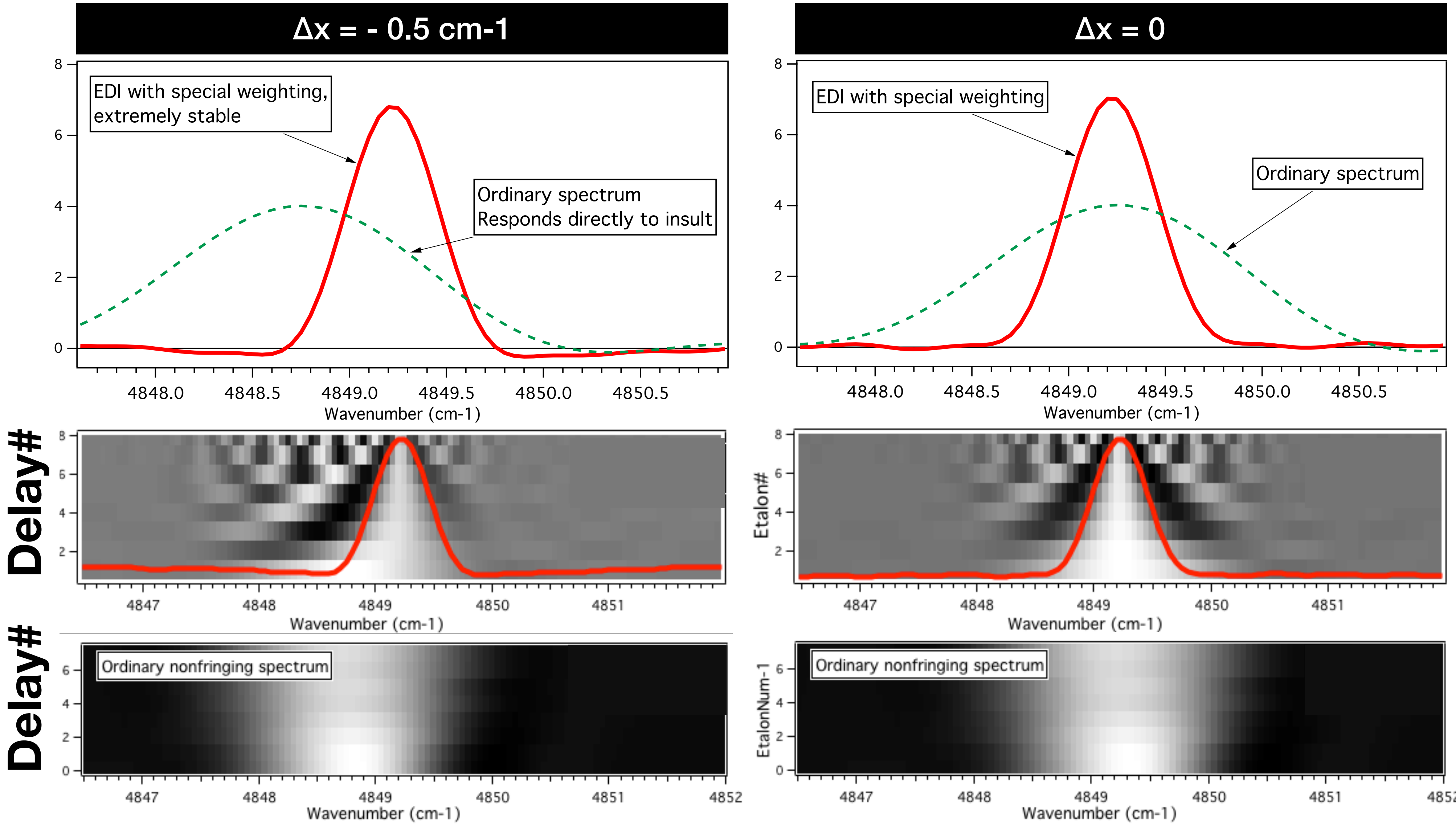
These Moire patterns have opposite slopes for high and low delay interferometers



The pair is 2 or 3 orders of magnitude more robust to wavelength drift Δx

Demo: 1000x stability gain compared to conventional

Demo used real multiple-delay EDI data from Mt. Palomar, but artificially imposed Δx drift, showed 1000x smaller output wavelength drift than does conventional.



“**A 1000x Stabler Spectrograph using an Interferometer with Crossfaded Delays**”, David J. Erskine and Eric V. Linder, Opt. Soc. Am. Optical Sensors and Sensing Congress 2019, Fourier Transform Spectroscopy Topical Mtg., San Jose, CA, June 25-27, 2019, paper FW5b.3. FTS-2019-FW5B.3(SanJose).pdf

Motivation

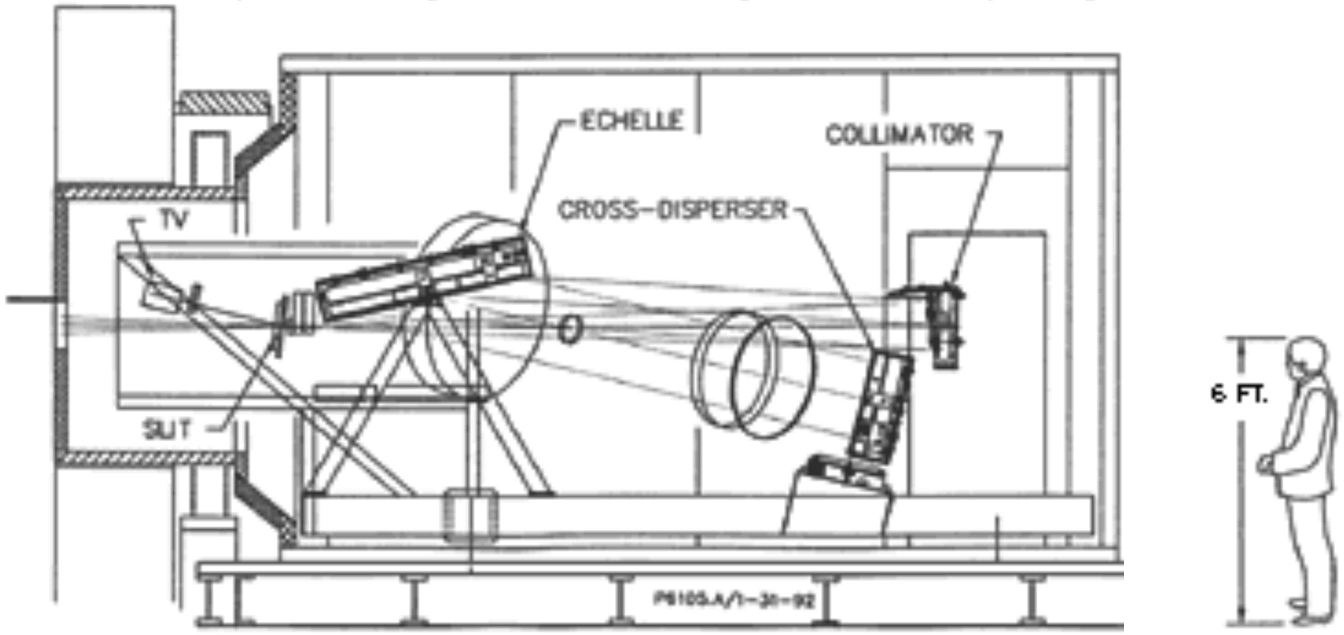
Astrophysics (cosmology, exoplanet search), biophysics (Raman spectroscopy), and general science need precision optical spectrographs, which are STABLE over long periods of time, light efficient, light weight, compact, inexpensive

Susceptible to drift Δx along wavelength axis of detector

DISPERSIVE (grating or prism) optical spectrographs are conventional. But for cosmology and exoplanet requirements are large, massive, and expensive

The conventional method:

A large dispersive spectrograph



Keck Obs. Spectrograph **Res ~ 50,000**

$4 million, 8 tons, 5 m length

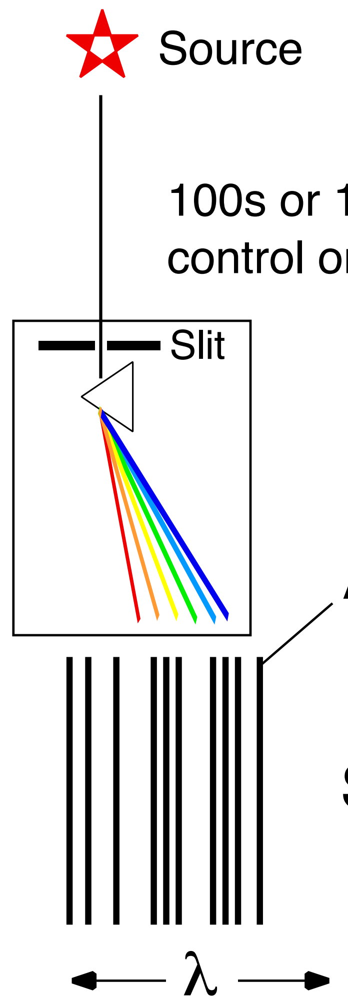
Drawbacks: high cost, large size & weight

Susceptible to drift along wavelength axis of detector

Dispersive spectrograph

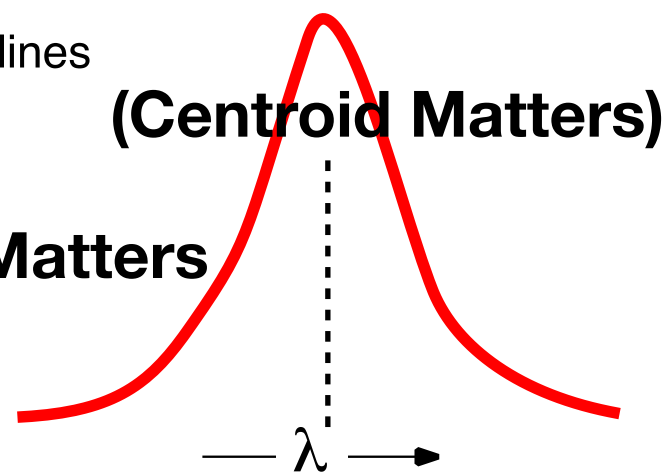
Assumes linear correspondence between detector pixel positions and wavelength

100s or 1000s of degrees of freedom to control or measure, 1 per grating groove

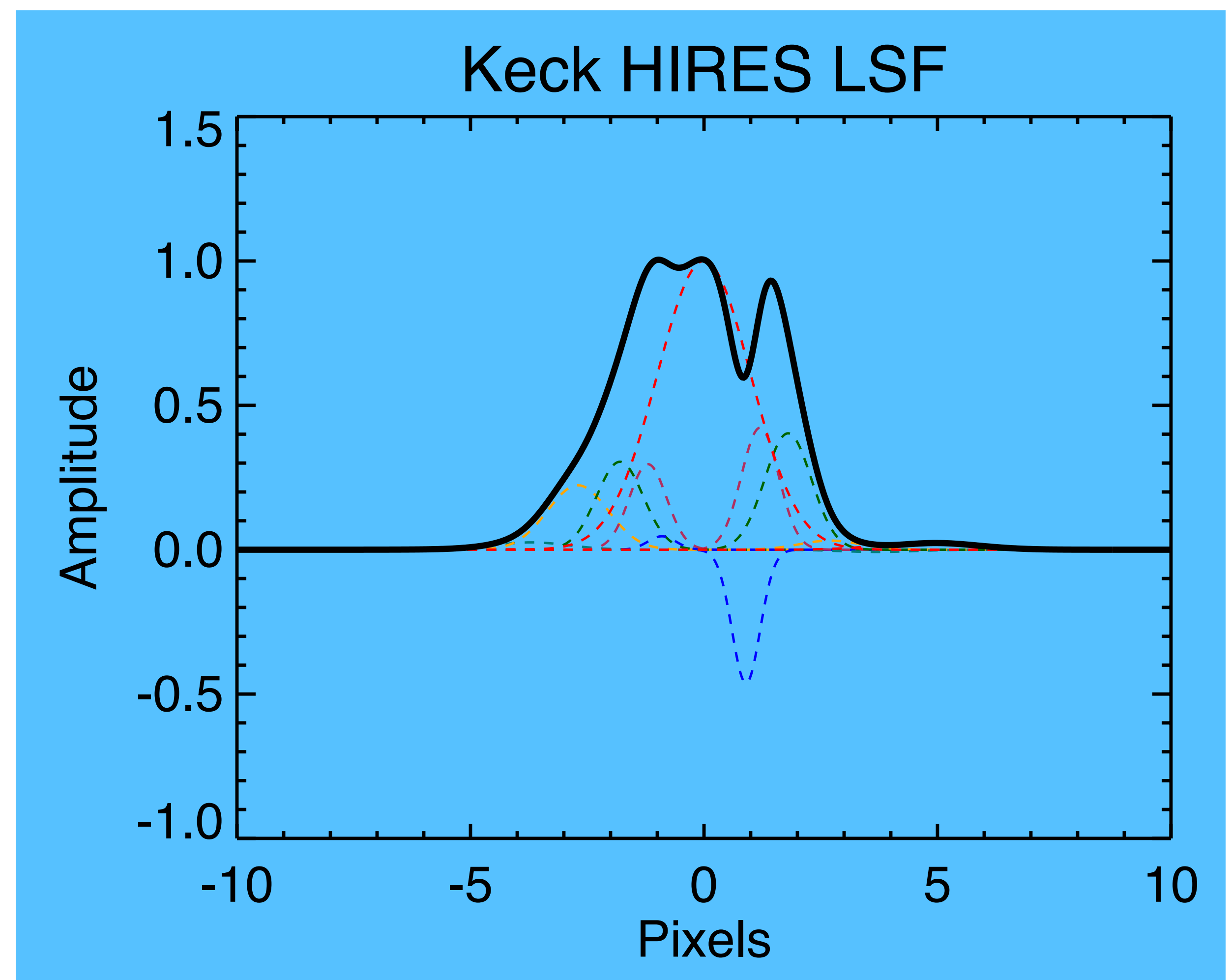


Distorted peak from uncontrolled degrees of freedom

Shape Matters



Atmospheric induced distortions in brief exposure of a narrow line



Doppler Planet Search, conventional method for Earth-like's: Requires high resolution dispersive spectrograph stable to ~0.01 milli-pixel (0.03 m/s) over year long time scales

(based on typical 3 pixels per 10 km/s solar rotational linewidth)

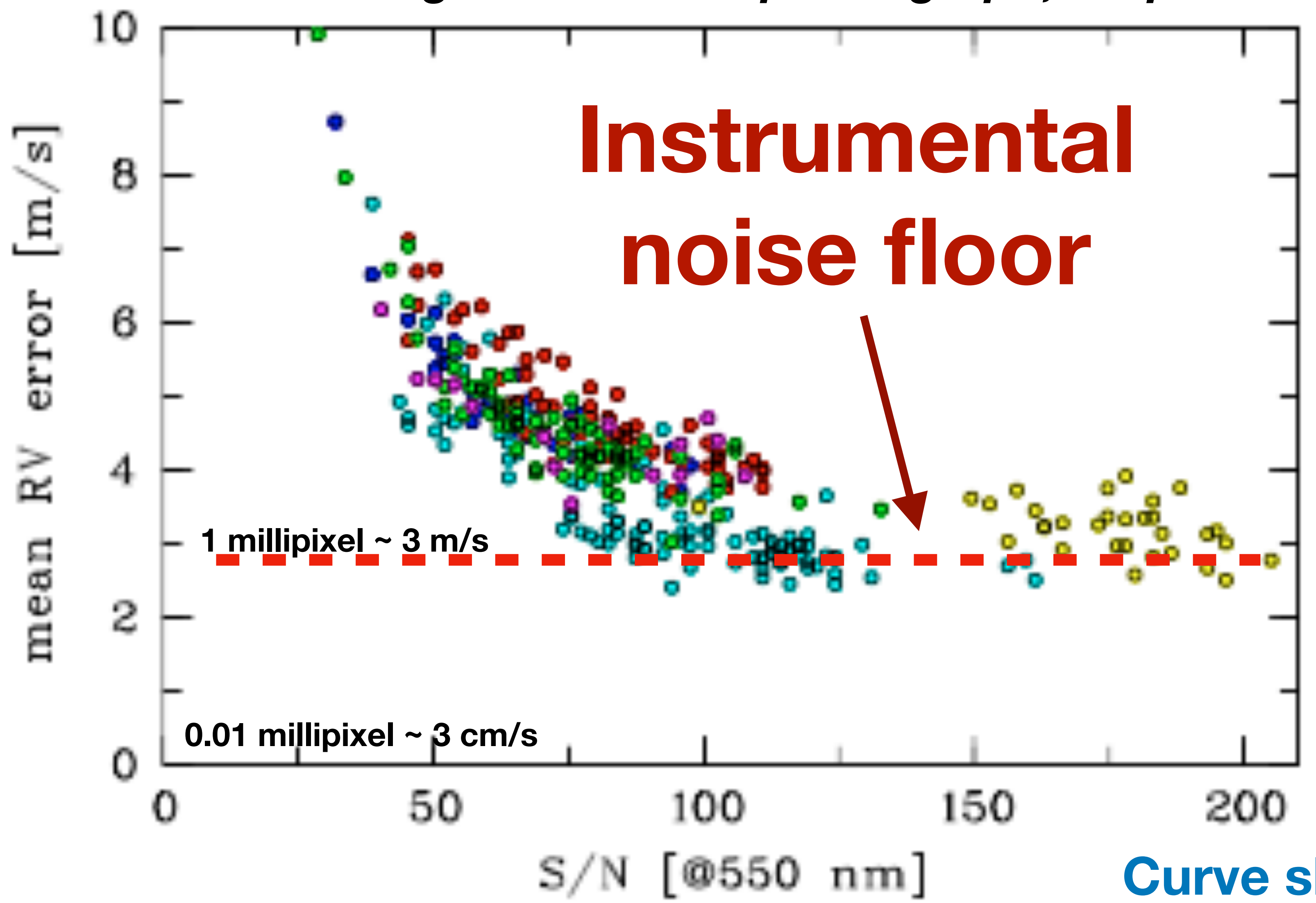
(Earth produces ~0.1 m/s Doppler tug on sun)

Instrumental drifts prevent reaching photon limited performance

1 in a Billion dimensional stability required

(0.03/3x10^8 = 10^-10, fractional wavelength Doppler change)

Conventional high resolution spectrograph, for planet search



HRS spectrograph at Hobby-Eberly Telescope

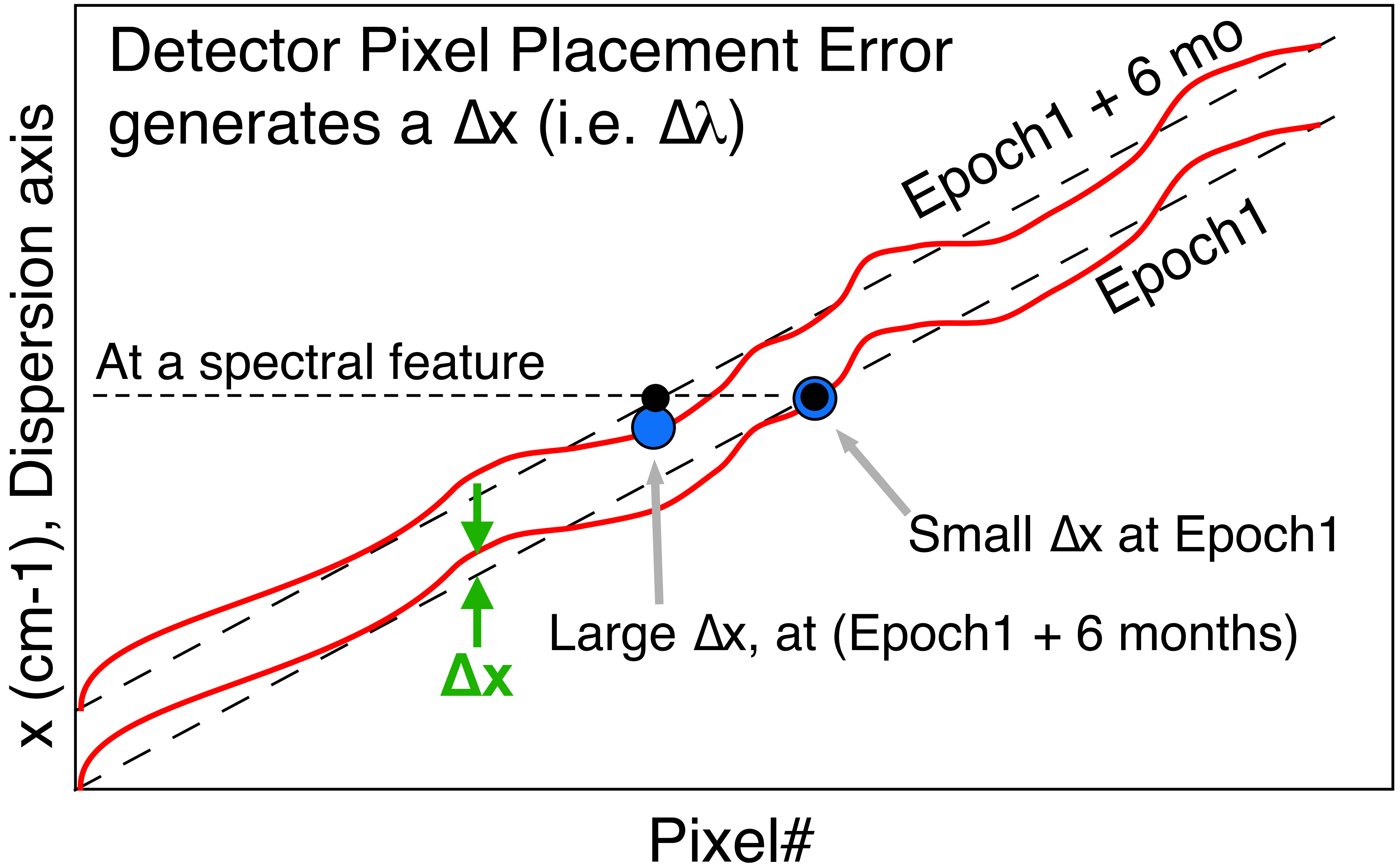
Curve should continue downward if no instrument drifts

Another problem:

Detector manufacturing pixel registration irregularities (~milli-pixel) that are "baked in"

Cannot be fixed by conventional mitigations (vacuum tank, thermal control, fiber scrambling)

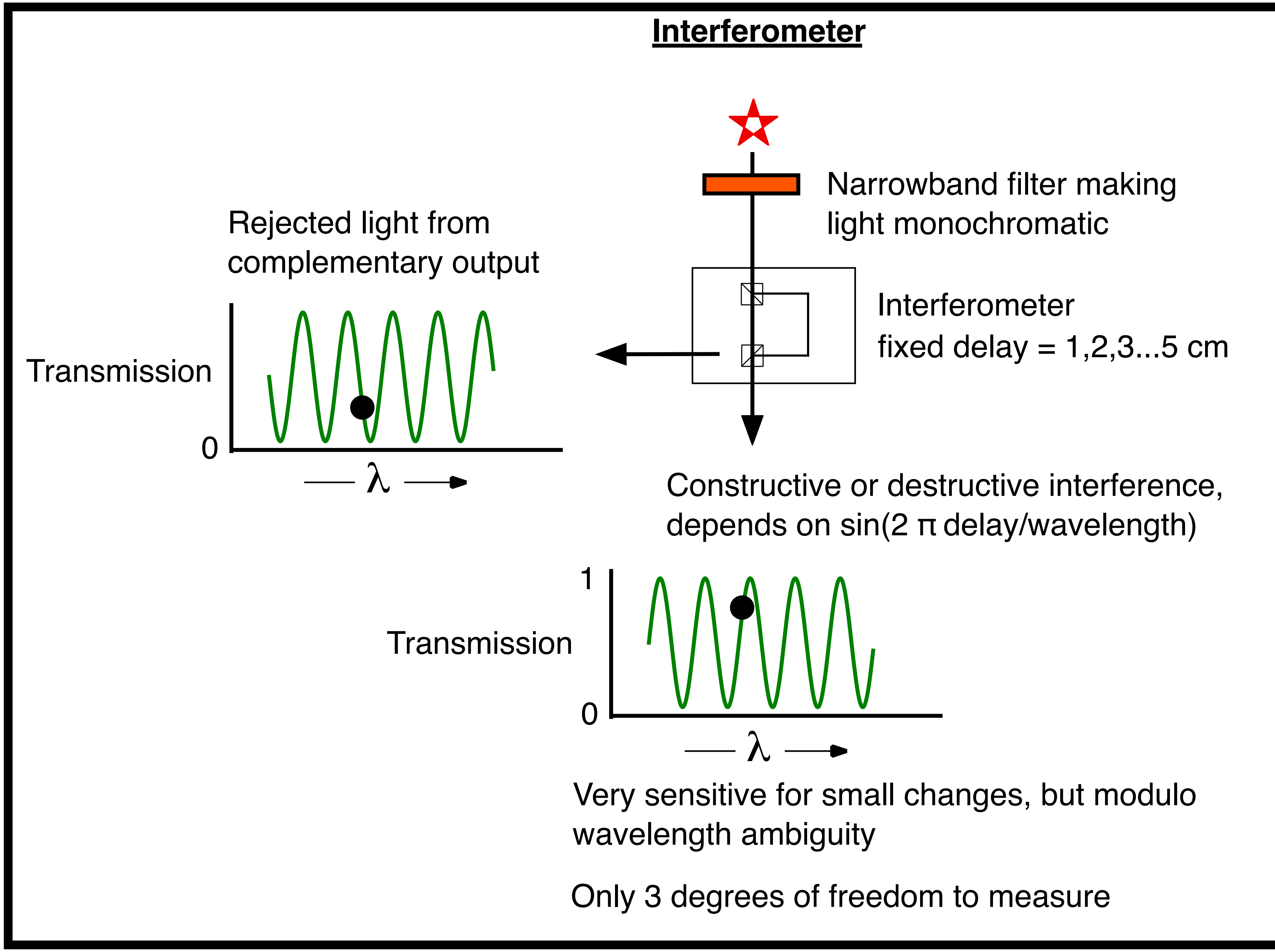
After 6 months, significant pixel shift due to large Doppler velocity change of Earth's around sun



Another way, but imperfect

PURE INTERFEROMETRY has the desired precision, compactness, low weight and inexpense,

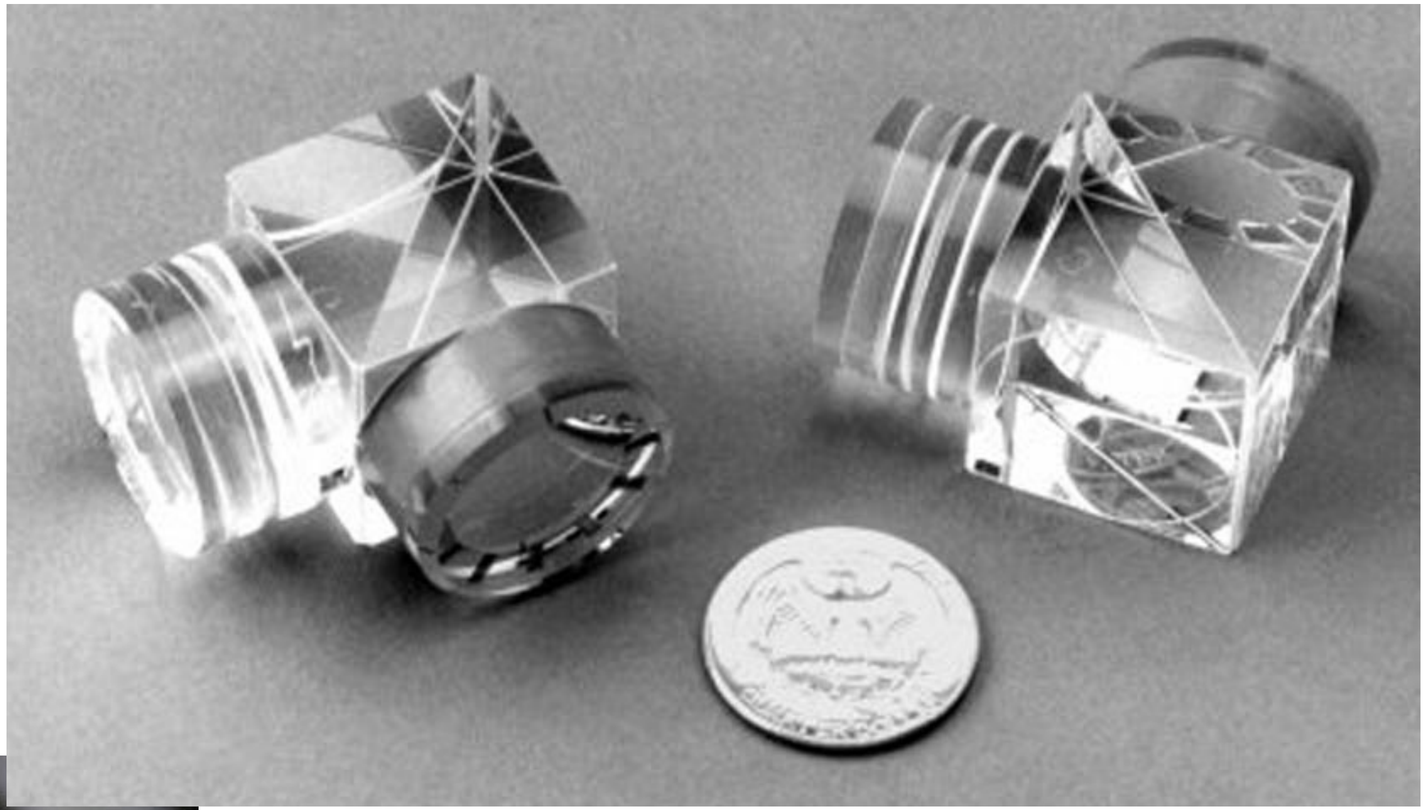
but has insufficient bandwidth for low flux astrophysical sources in visible light

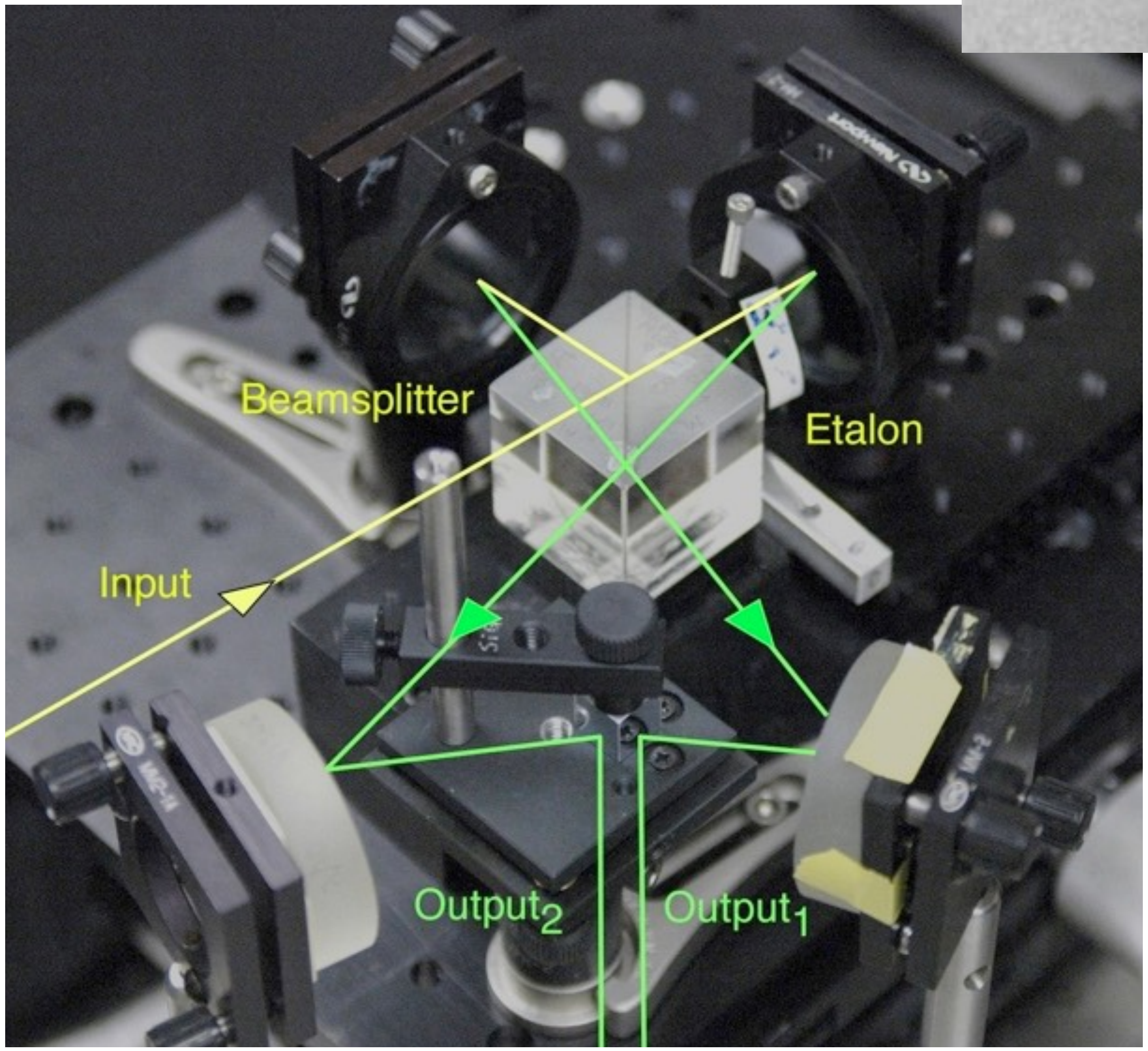


Interferometers can be compact

Few cm size

Monolithic interferometers used by Nat. Sol. Obs. for Doppler





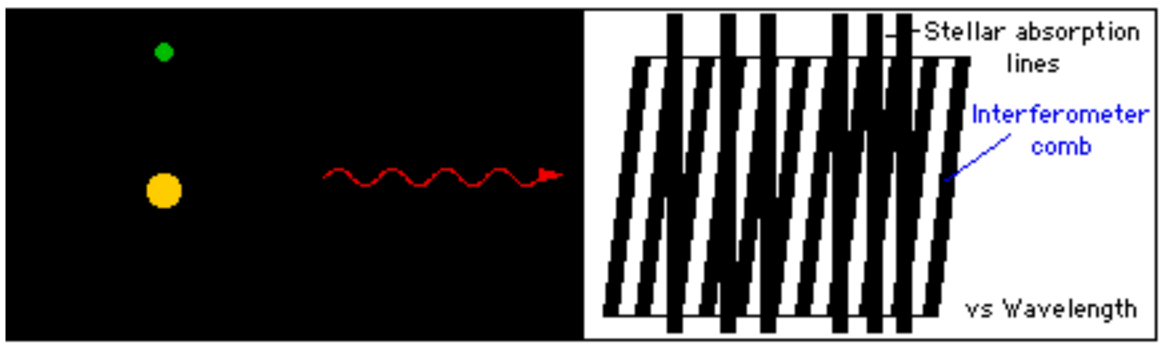
Dual outputs for high efficiency

Both complementary outputs can be directed to spectrograph for nearly ideal flux efficiency

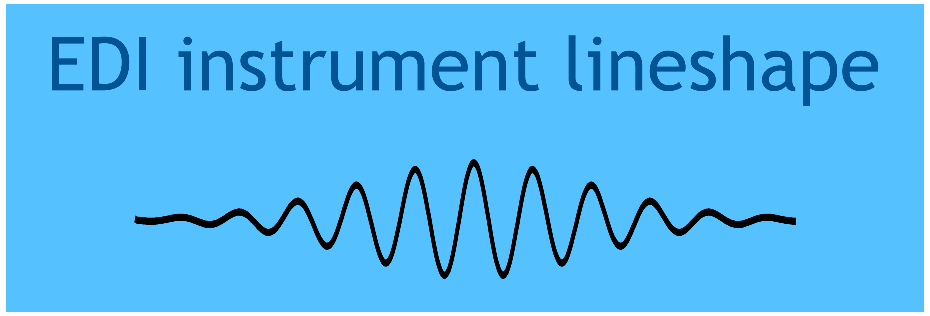
Solution:

A hybrid method DISPERSED INTERFEROMETRY (EDI) has been demonstrated for Doppler exoplanet search and high resolution spectroscopy

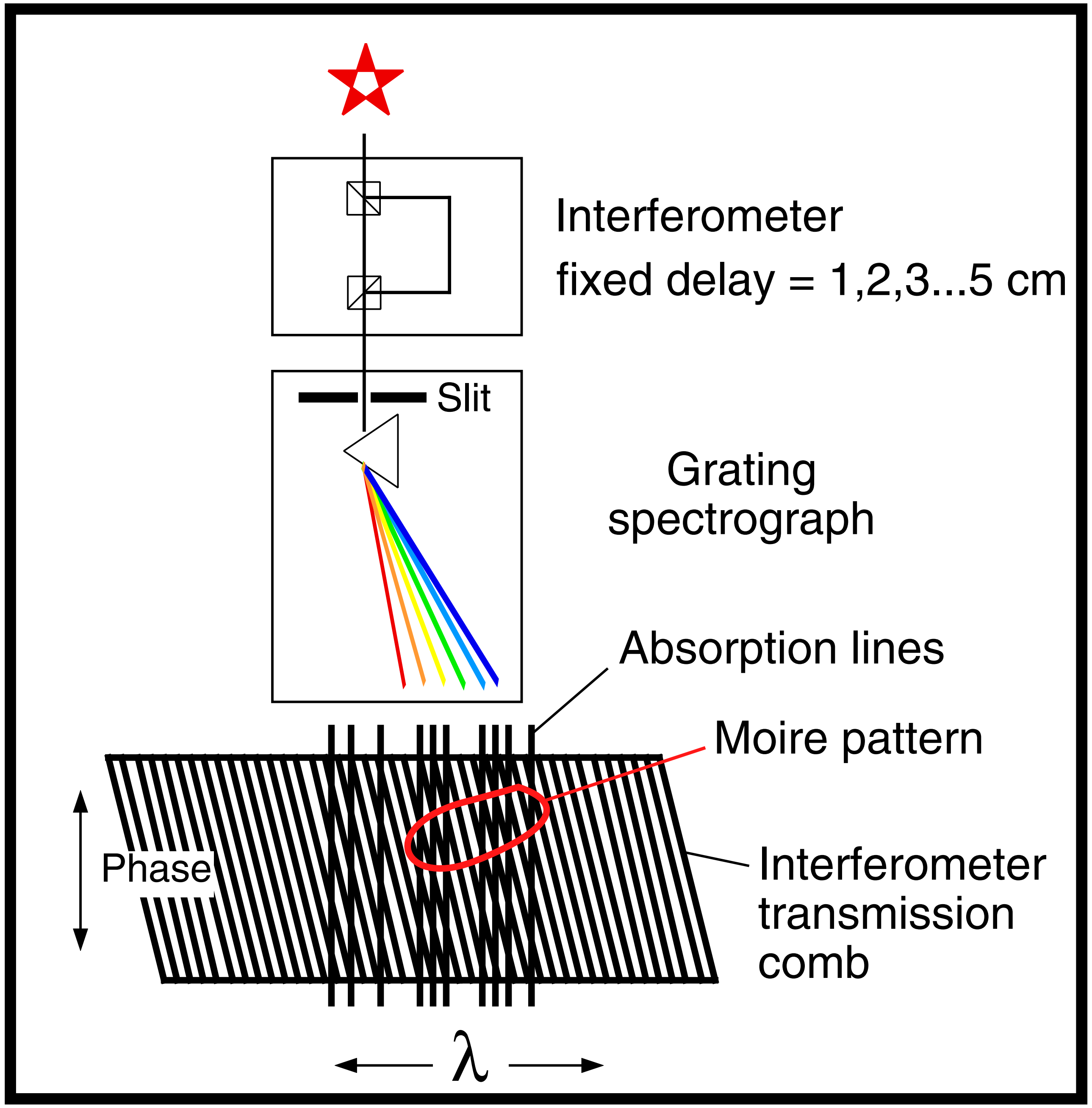
Combines precision and compactness of the interferometer with the high photon light efficiency of a grating



Interferometer has only 3 degrees of freedom



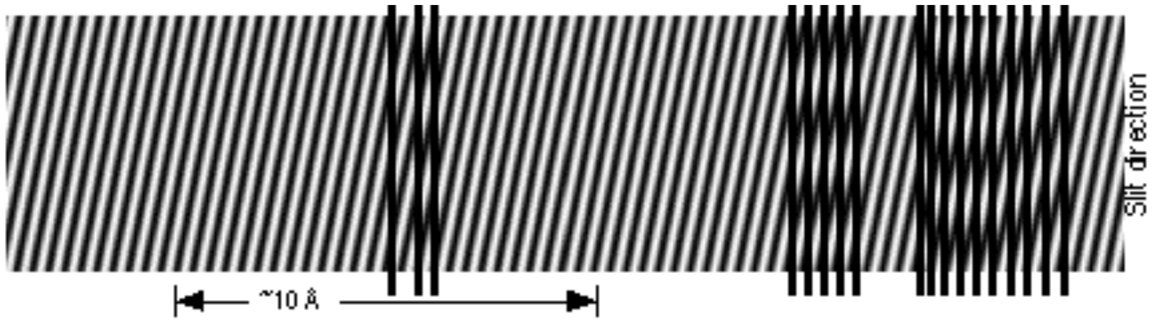
Much easier to measure a precise wavelength



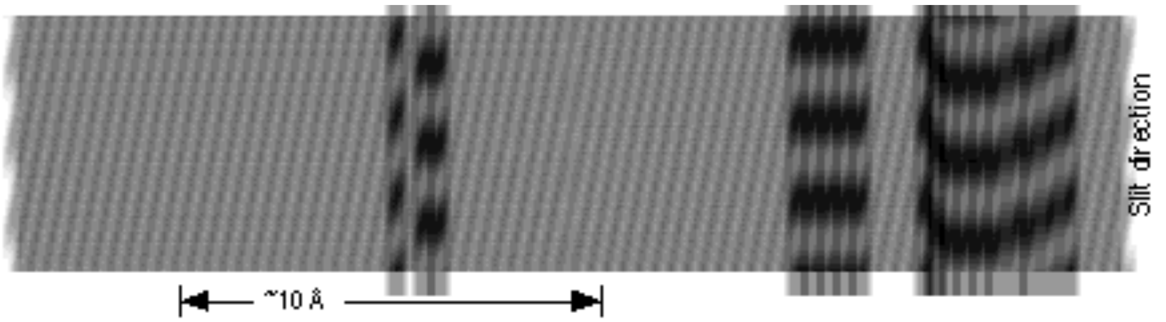
Moire effect allows use of lower resolution gratings

Interferometer comb is tilted here (phase varies spatially across slit) to aid visualization

Unblurred case (high res spectrograph)



Blurred case (low res spectrograph)

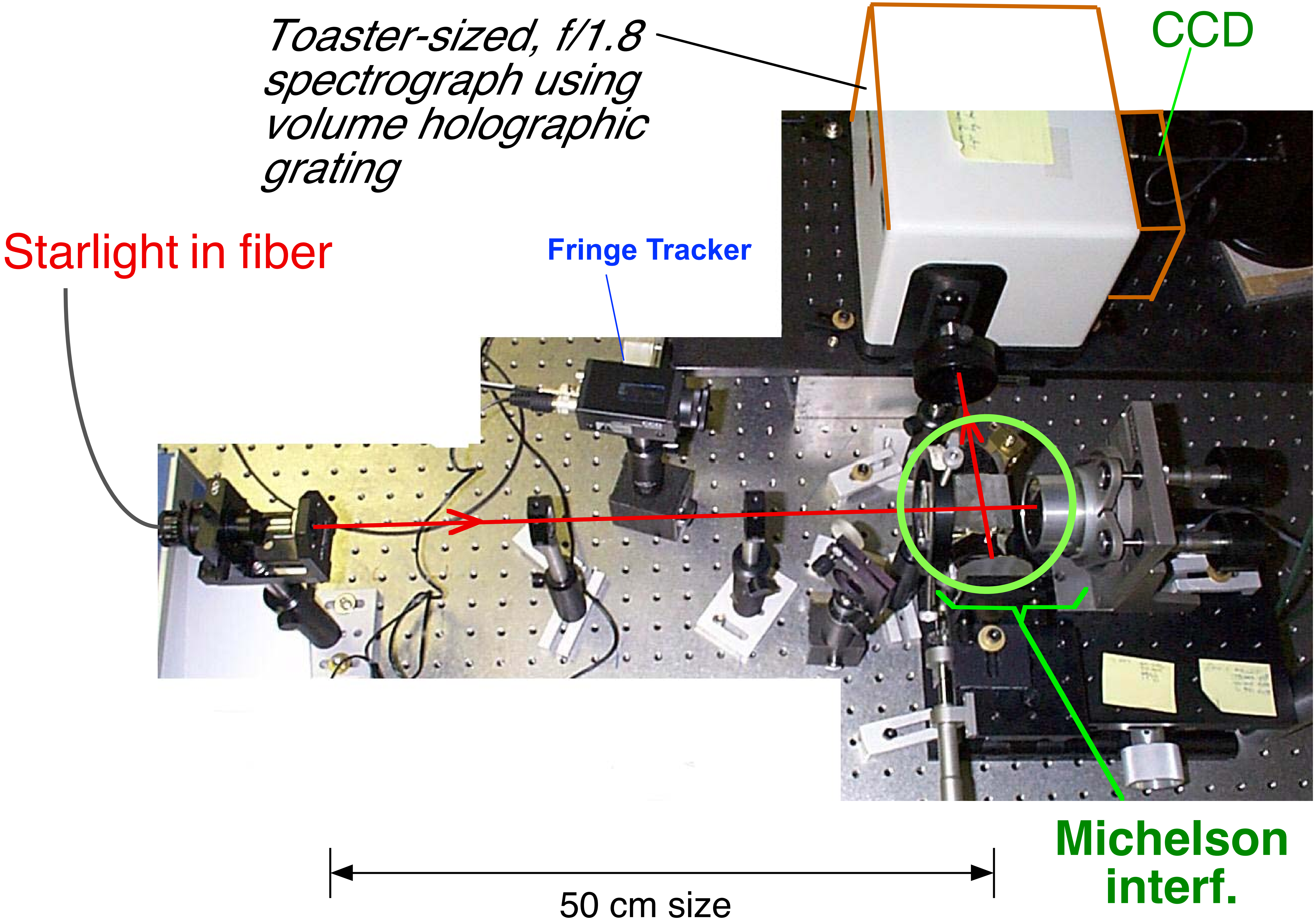


High resolution spectrographs not necessary to measure small changes in wavelength

(The interferometer comb does not need to be resolved)

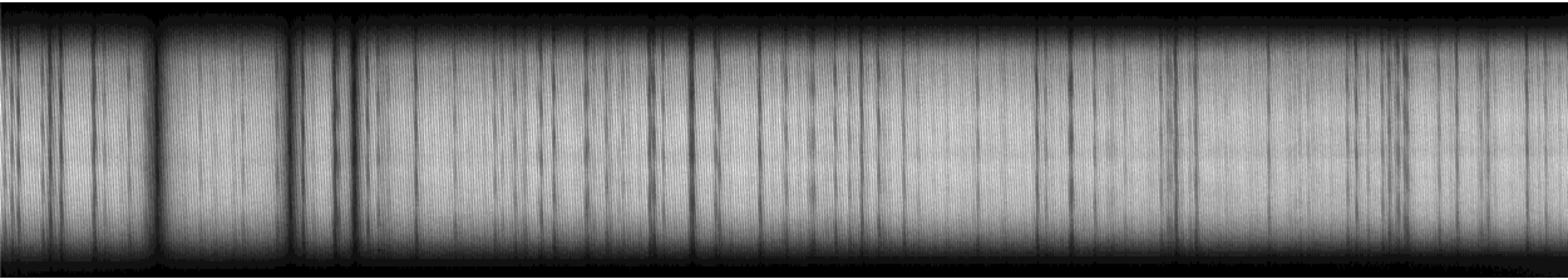
Example single-delay EDI, with no conventional mitigations

Compact EDI + Disperser (1999)

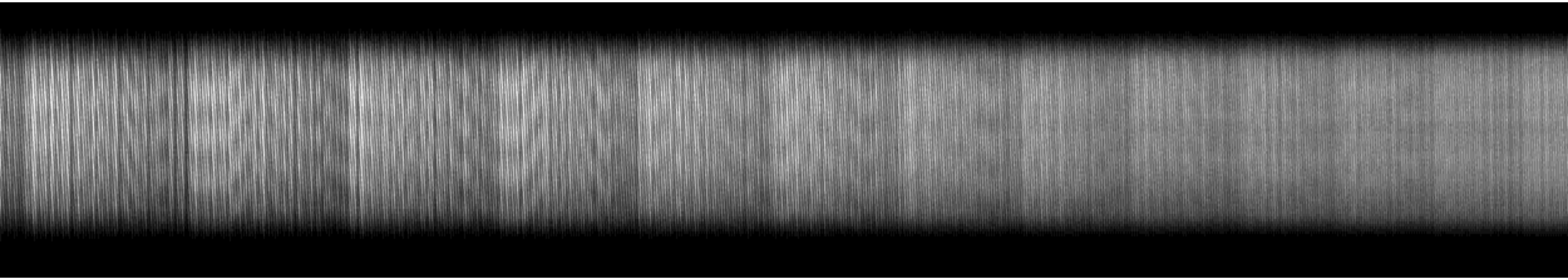


Measured sunlight and iodine data 1998

Sunlight (phase is artificially dithered to simulate Doppler)



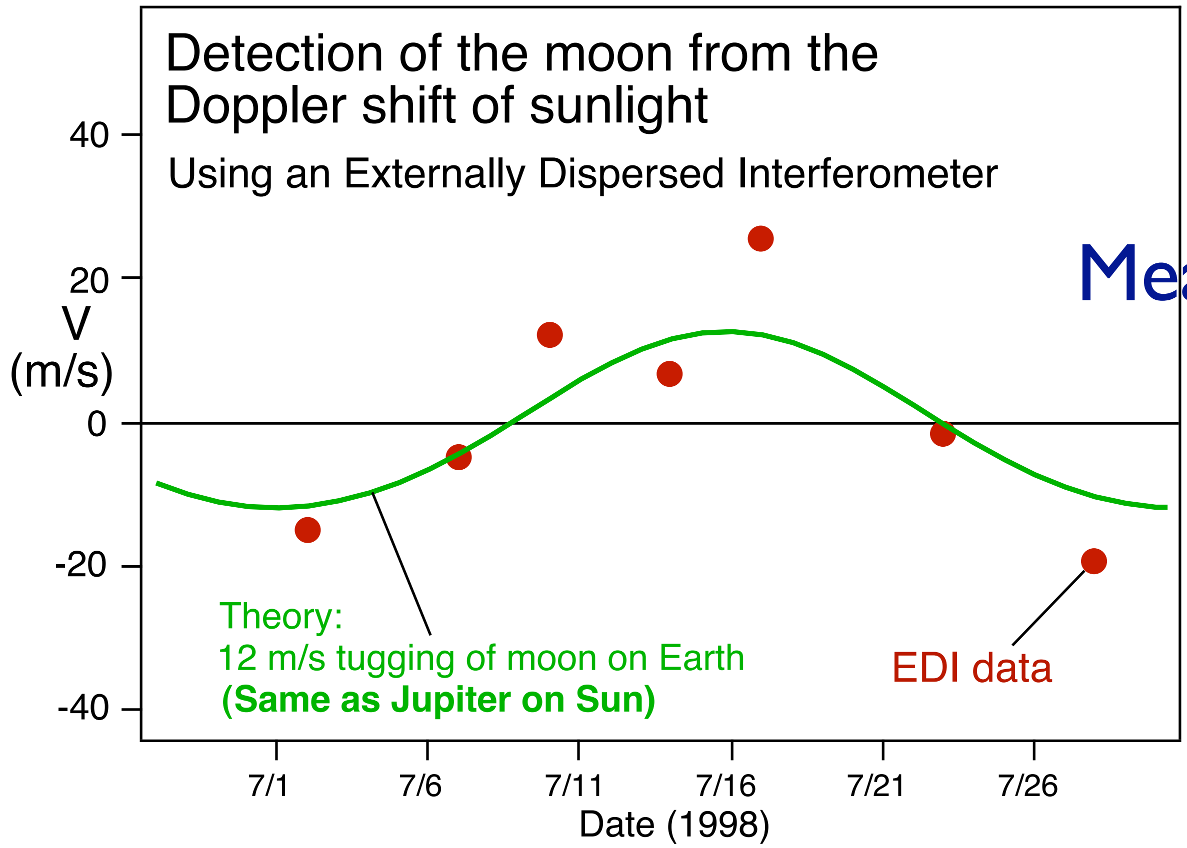
White light through iodine cell



Relative phase shift of (sunlight - iodine) reveals solar motion, independent of interferometer delay drift

1998 single-delay EDI on sunlight, in open air (!)
without vacuum tank or thermal control

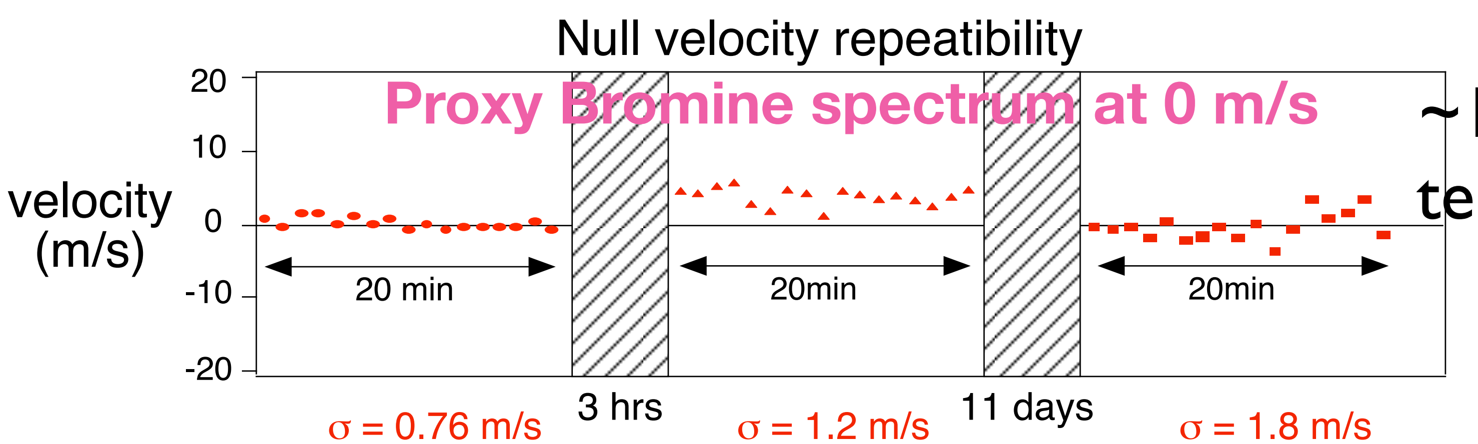
EDI has m/s precision, without environmental controls



1 month test

Measure Moon pulling Earth

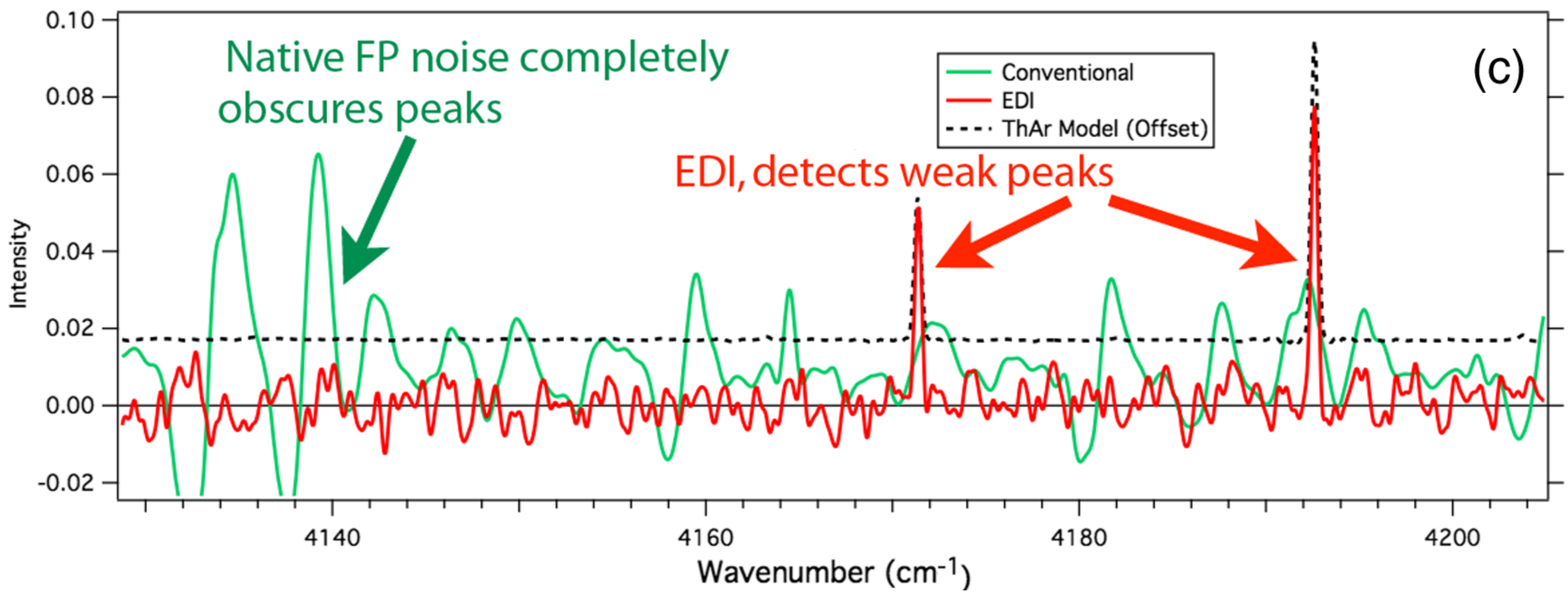
12 m/s amplitude effect



~1 m/s short term stability

Another practical benefit of EDI:

EDI is robust to bad pixels and other FIXED PATTERN (FP) errors because it dithers between 3 exposures comparing differences



Only the EDI curve (red) agrees with ThAr model (black dashes)

The conventional spectrograph (green) was completely obscured by FP noise

Exoplanets have been discovered with EDI technique in 2005* (HD102195) and 2016** (HD87646)

*J. Ge, J. van Eyken, S. Mahadevan, C. DeWitt, et al., "The first extrasolar planet discovered with a new-generation high-throughput Doppler instrument," ApJ 648, 683–695 (2006), astro-ph/0605247.

**B. Ma, J. Ge, et al., "VERY LOW-MASS STELLAR AND SUBSTELLAR COMPANIONS TO SOLAR-LIKE STARS FROM MARVELS. VI. a GIANT PLANET AND a BROWN DWARF CANDIDATE IN a CLOSE BINARY SYSTEM HD 87646," Astronomical Journal 152, 112 (2016).

RD100 innovation award in 2006

R&D 100 The 44th Annual Awards

World-Class Technologies
FOR R&D AND BEYOND

The 44th Annual R&D 100 Awards honor the world's best innovators and their innovations.

The editors of R&D Magazine are proud to announce the winners of the 44th Annual R&D 100 Awards. This annual competition recognizes excellence in innovation—on a global scale. Indeed, the technologies and techniques highlighted in the following pages are among the most innovative ideas from today's technology powerhouses in academia, government, and industry, worldwide.

Selection of R&D 100 winners is a sophisticated process, lasting nearly a full year, and involving a judging panel of almost 50 independent technical experts who lend their expertise in evaluating the details of the product entries compared to other existing products and technologies.

This year's winners will be honored at a Black Tie Awards Gala in the Grand Ballroom of Chicago's Navy Pier on October 19th. This event is in conjunction with a public exhibition showcasing a sample of this year's winning technologies.

From analytical instruments to lasers, to life science to x-ray devices, the winners of the 2006 R&D 100 Awards will have a definitive impact on research, industry, and daily life.

We recognize the development teams that have made these technologies possible. We invite you to join this elite group of scientists and engineers in the 2007 R&D 100 Awards Competition—it's never too early to enter. Visit www.rdmag.com for details. Congratulations to all of this year's winners!

—The Editors of R&D Magazine

To view a full archive of past R&D 100 winners, visit: www.rdmag.com/rd100ach

Finding a Planet in the Stars

One of the most exciting and recent applications of high-resolution spectroscopy has been in the search for planets around distant stars through the measurement of stellar spectra. This Doppler Planet Search has been fully realized with the development of the **Externally Dispersed Interferometry (EDI)** by David Erskine at the Lawrence Livermore National Laboratory, Calif., and Jerry Edelstein in the Space Sciences Laboratory at the Univ. of California, Berkeley.

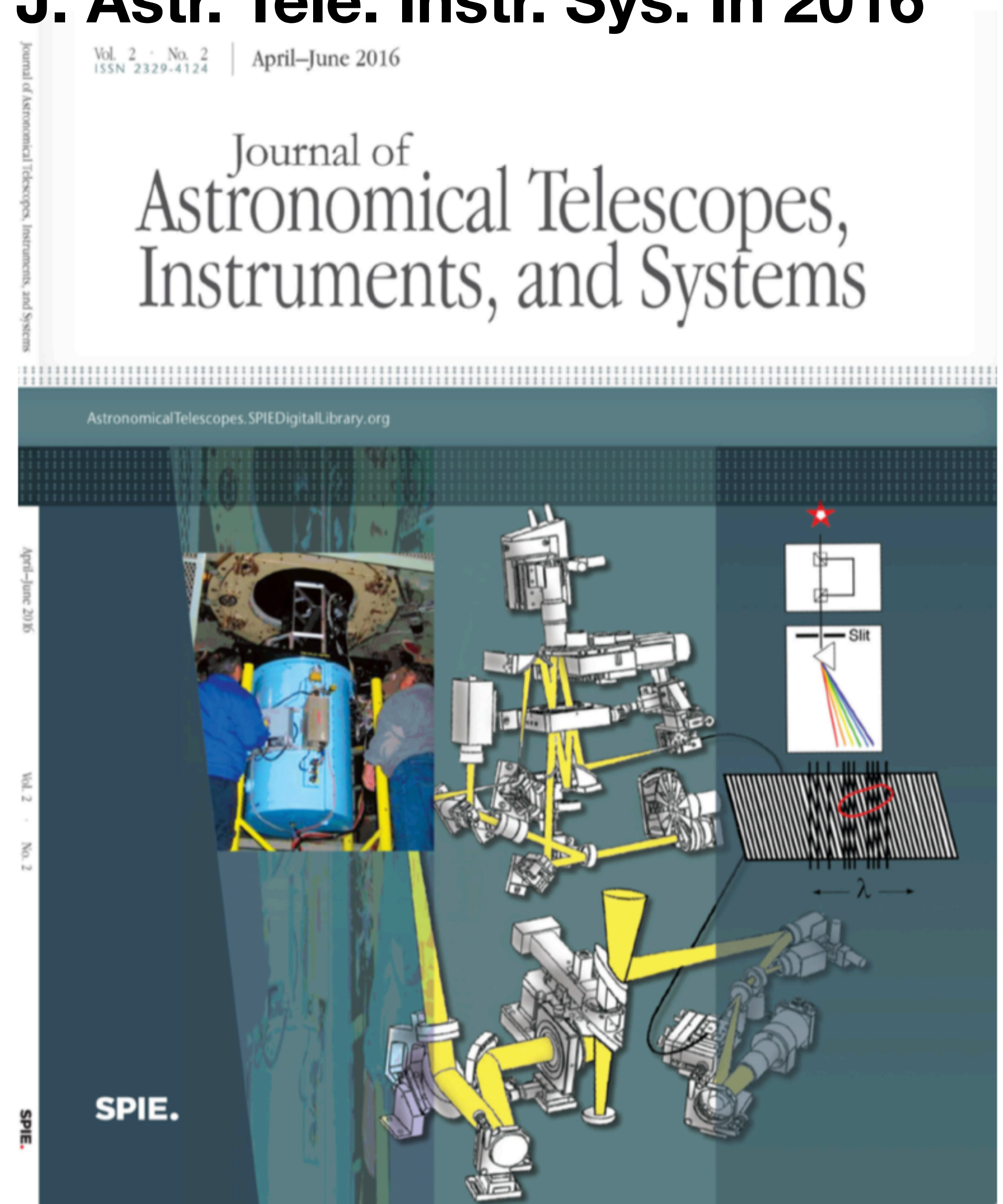
EDI is dramatically less expensive ($14,000 vs. $4 million) for making the highly precision measurements required that will enable the hundreds of medium-sized (~1-m) telescopes around the world to participate in the Doppler Planet Search. Already, EDI has detected the planet around 51 Pegasi and discovered a new planet in the constellation Virgo.

The tugging of a planet orbiting a star causes the star to wobble, with a period of a few days, weeks, or months and an amplitude of 10 to 100 m/sec. This creates a small Doppler shift in the wavelength of the stellar spectrum that acts like a fingerprint relative to a spectral reference. The EDI has the precision to detect this precision through its combination of a wide-angle fixed-delay interferometer and a dispersive spectrograph. The Doppler measurement is performed by the interferometer which creates non-overlapping fringes that are embedded in the spectrum created, thus resulting in a Doppler measurement that is up to 10,000 times more robust than competing systems.

▶ More info: www.llnl.gov

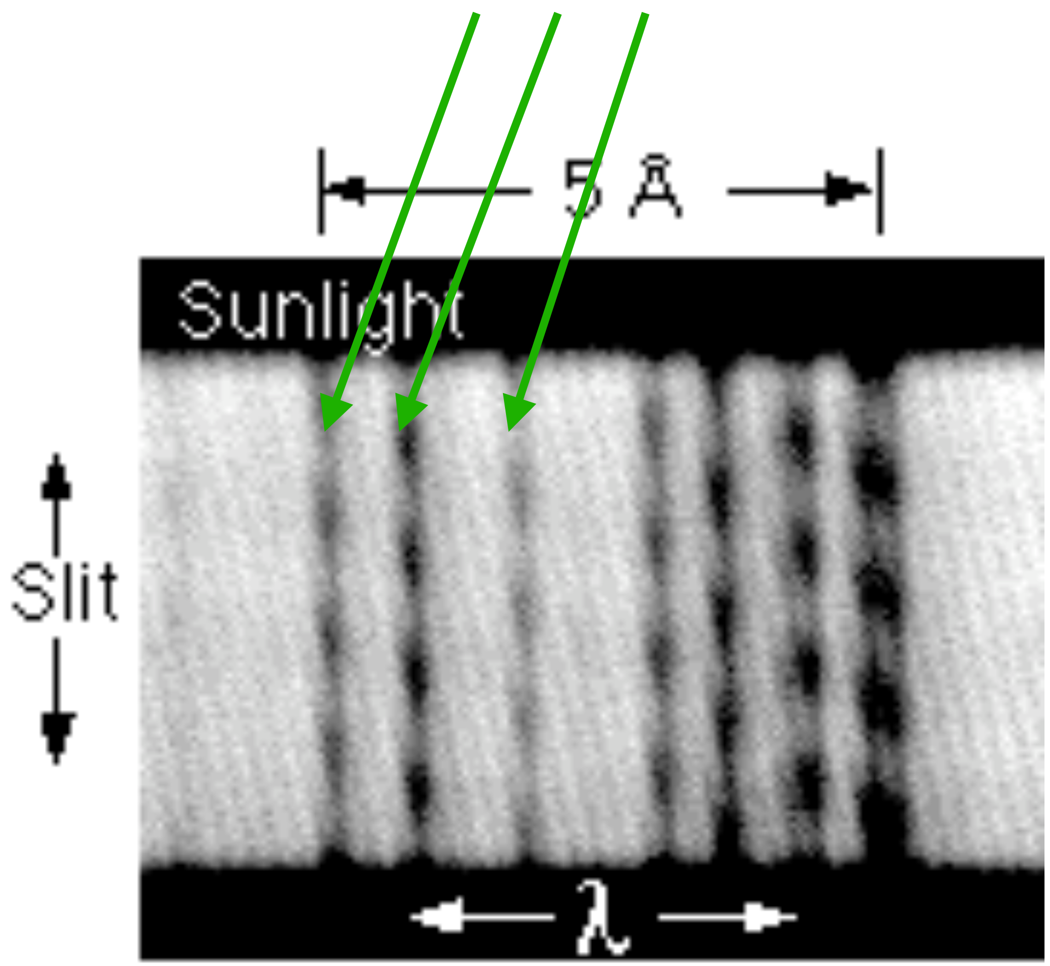
18 R&D Magazine September 2006 www.rdmag.com

Cover of J. Astr. Tele. Instr. Sys. In 2016



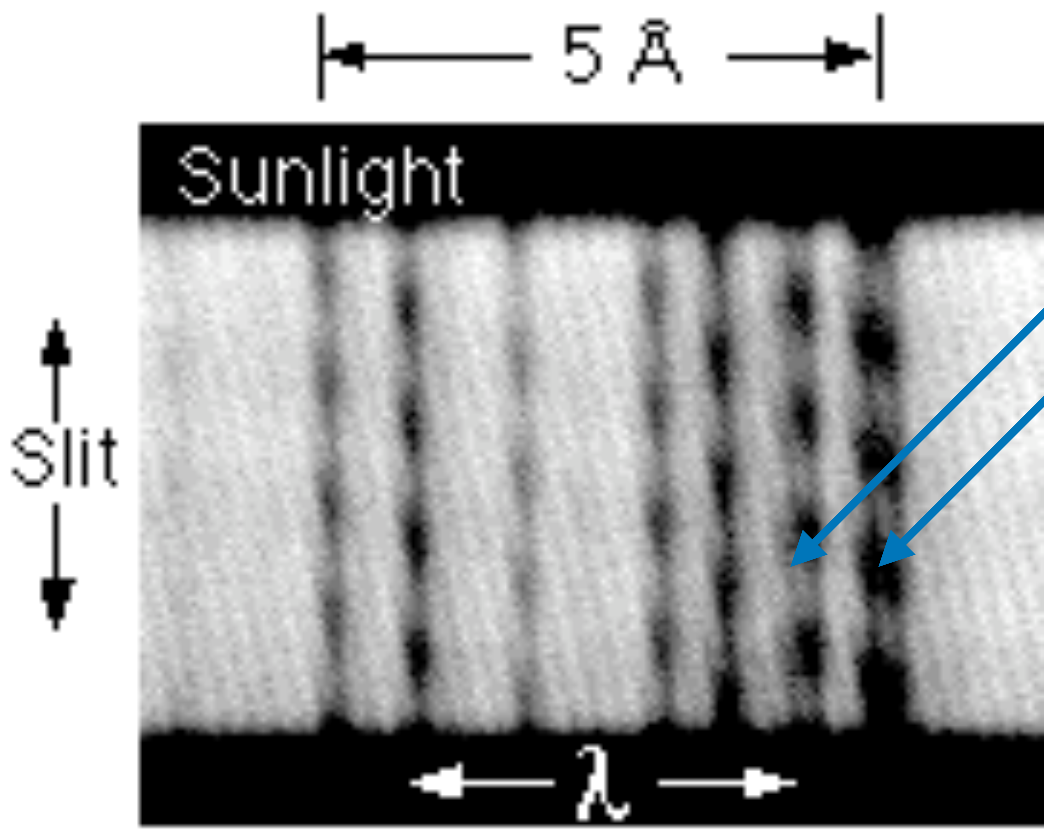
Motivation for the 2018 Crossfading improvement

ISOLATED spectral lines are extremely stable with EDI under Δx drift



Since input spectrum is married to interferometer transmission comb and drifts same amount on detector horizontally

Motivation for the 2018 Crossfading improvement



Problem: BLENDED lines produce a small phase reaction to a Δx drift

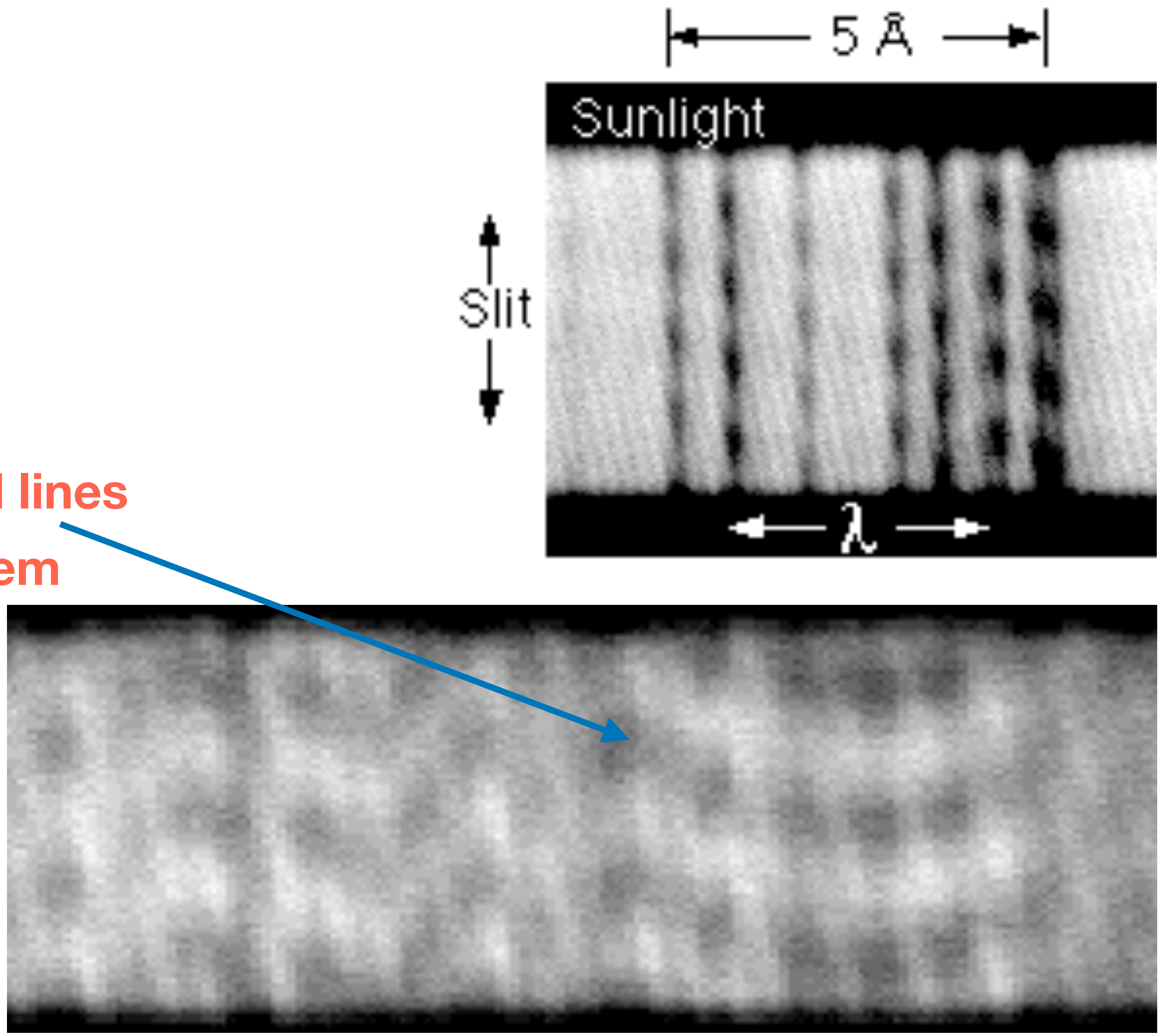
(This reaction for EDI is already ~10x smaller than for conventional spectrographs).

But we discovered we can make it even smaller with crossfading!)

Motivation: Blended features can convert an instrumental wavelength shift into a phase error

Example EDI data

Sunlight

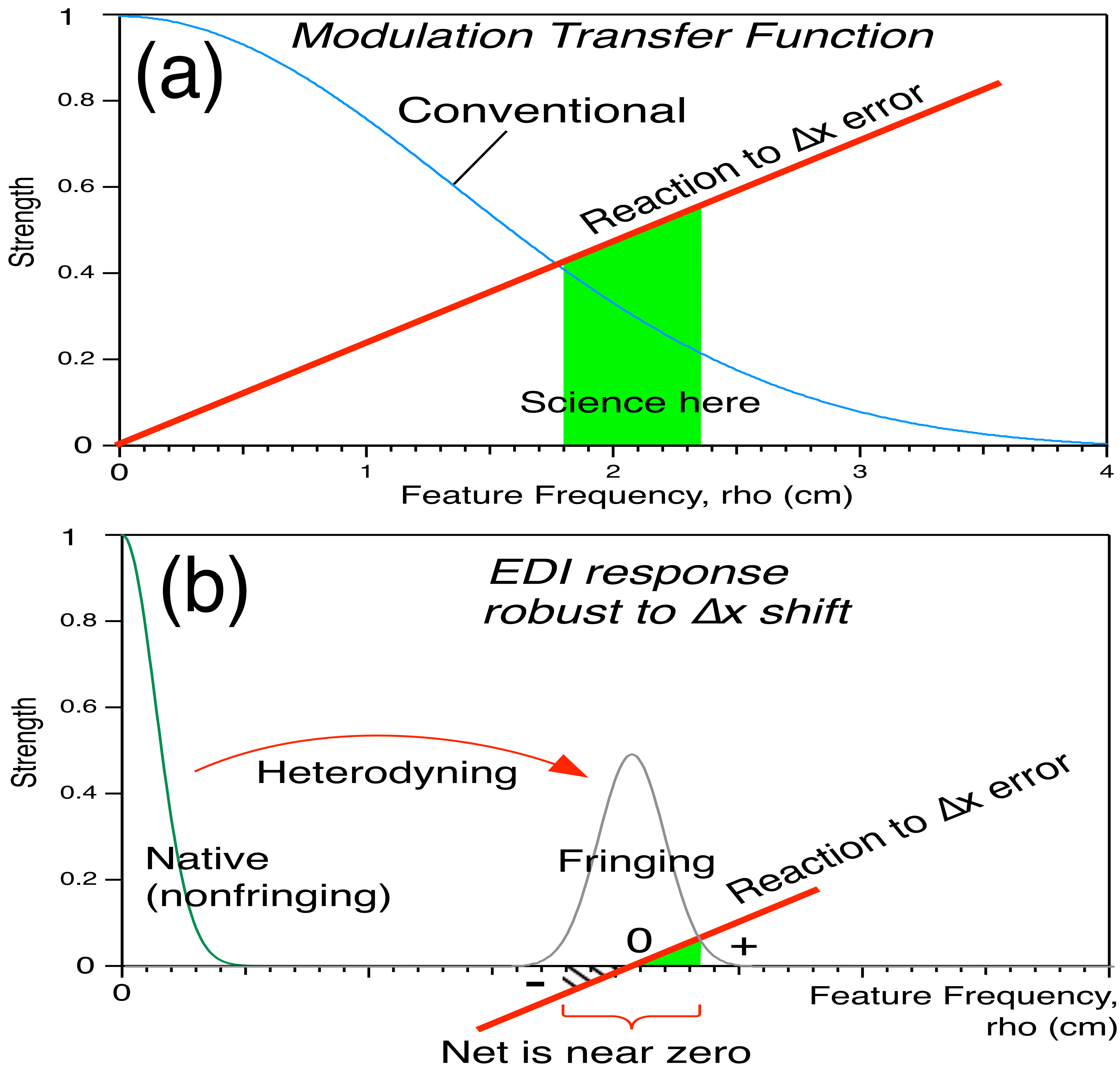


"Smile" feature is a set of blended lines

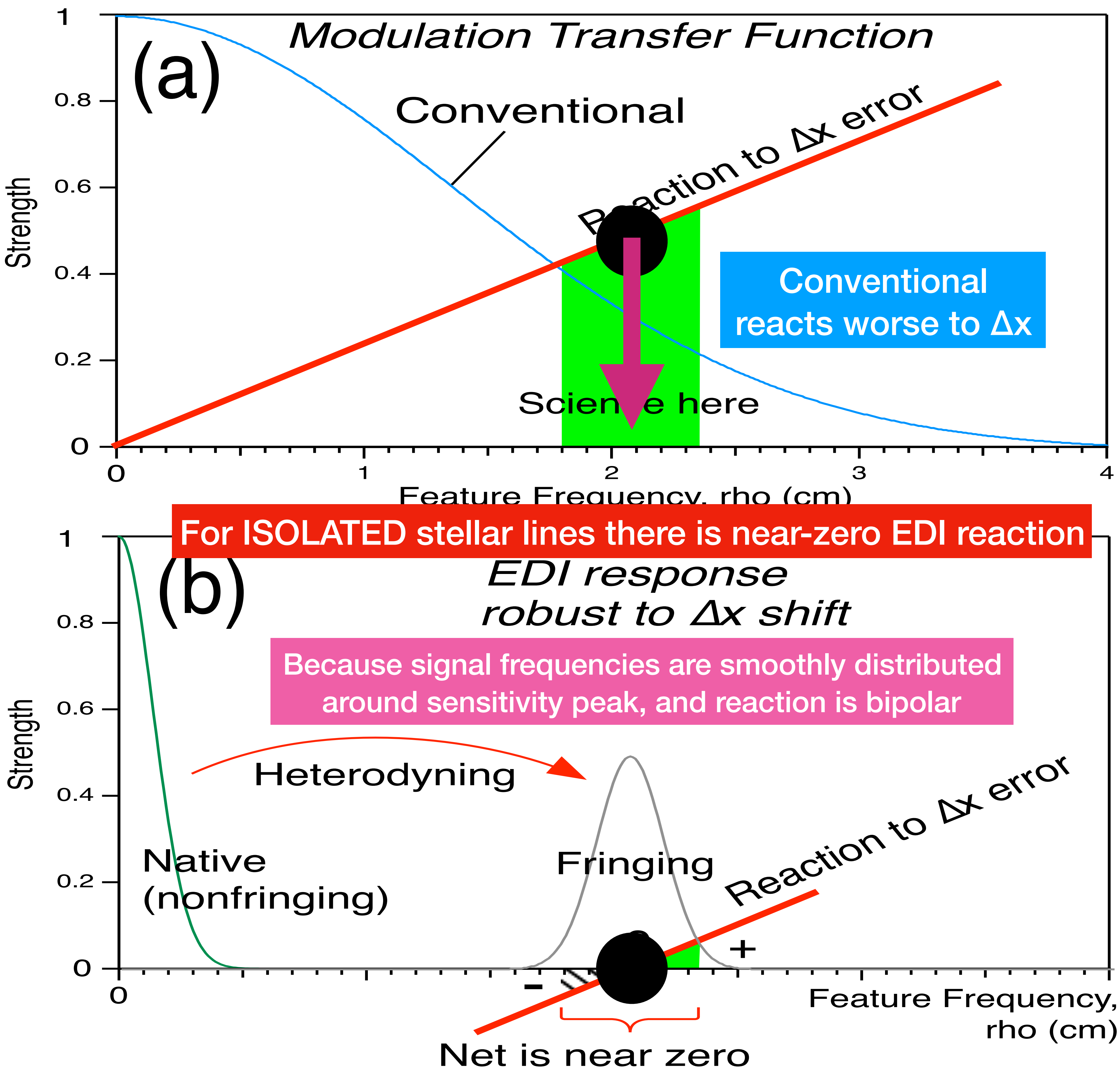
Slopes in the Moire are the problem

Iodine

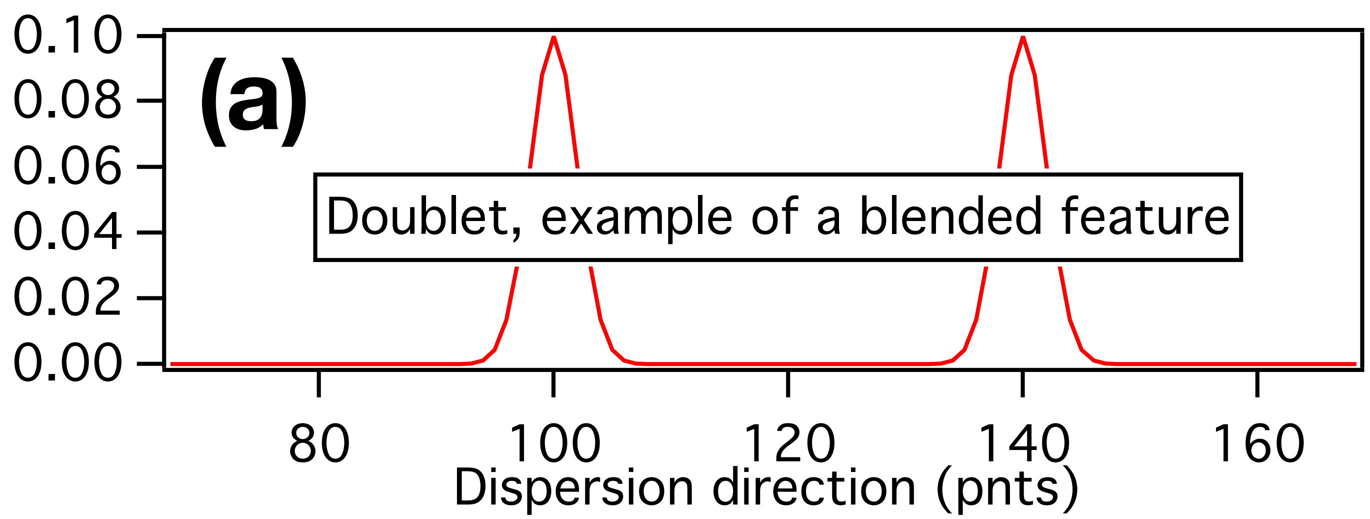
Wavelength (Δx) drift viewed in Fourier space



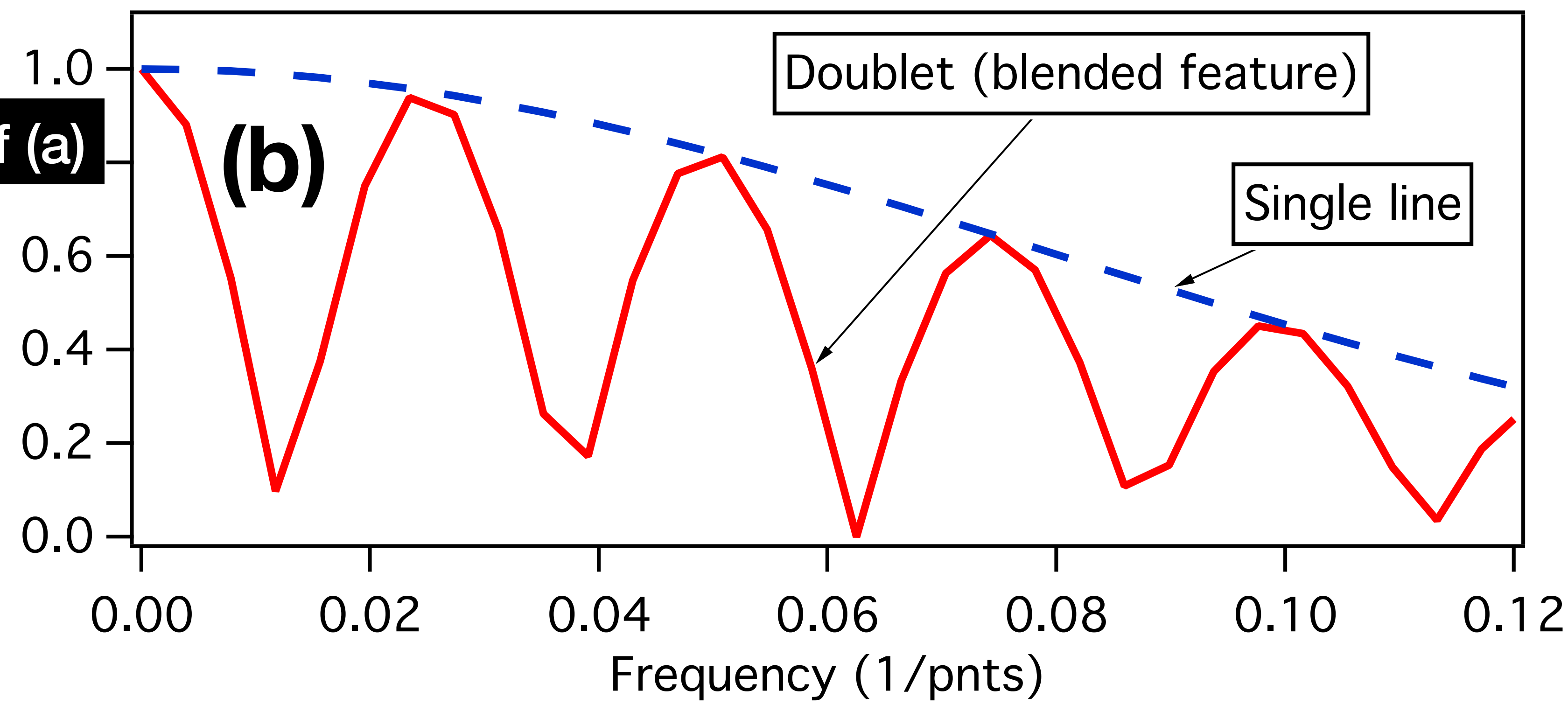
Case: isolated feature

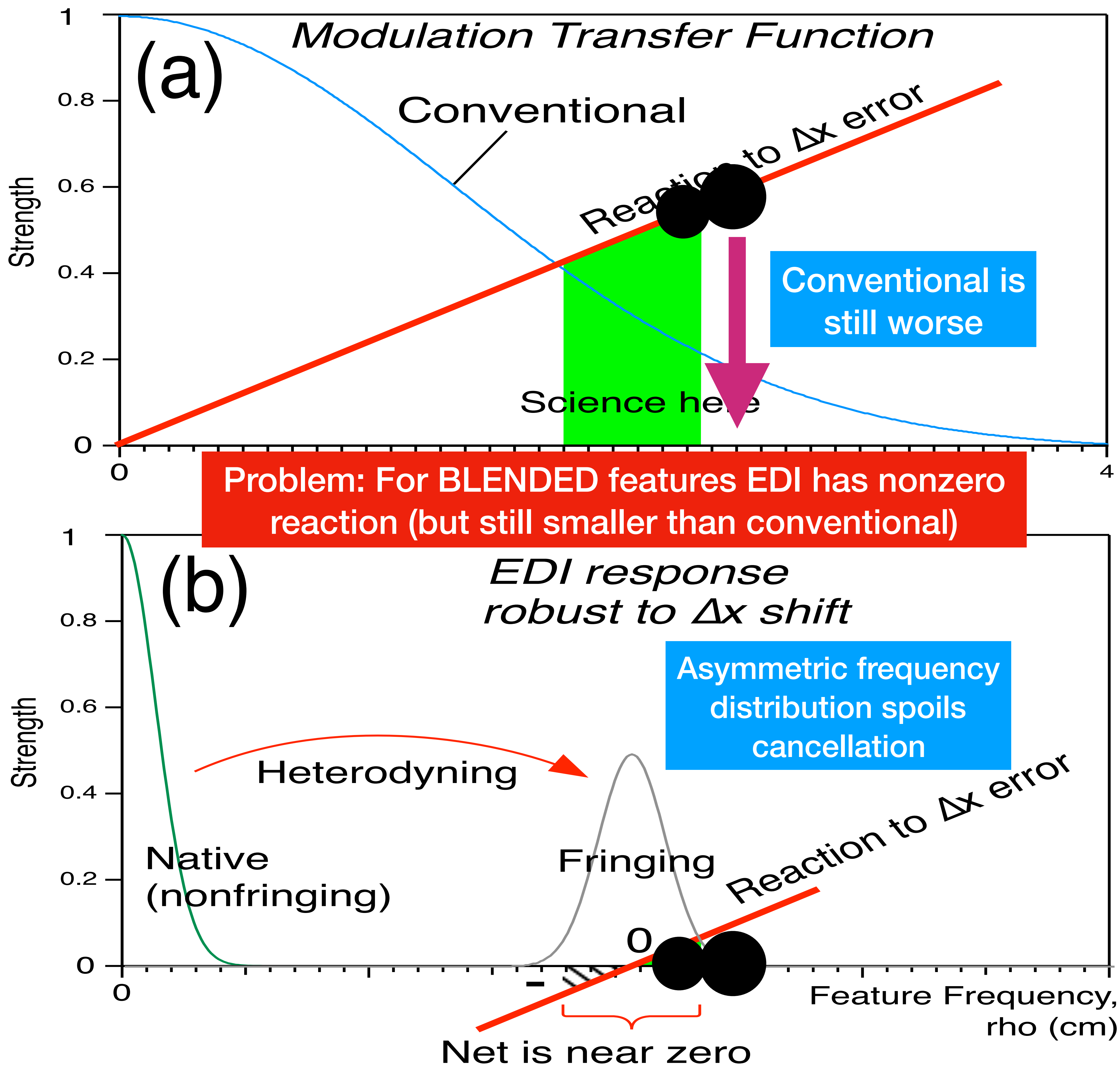


However BLENDED features have LUMPY frequency distributions



Fourier transform of (a)



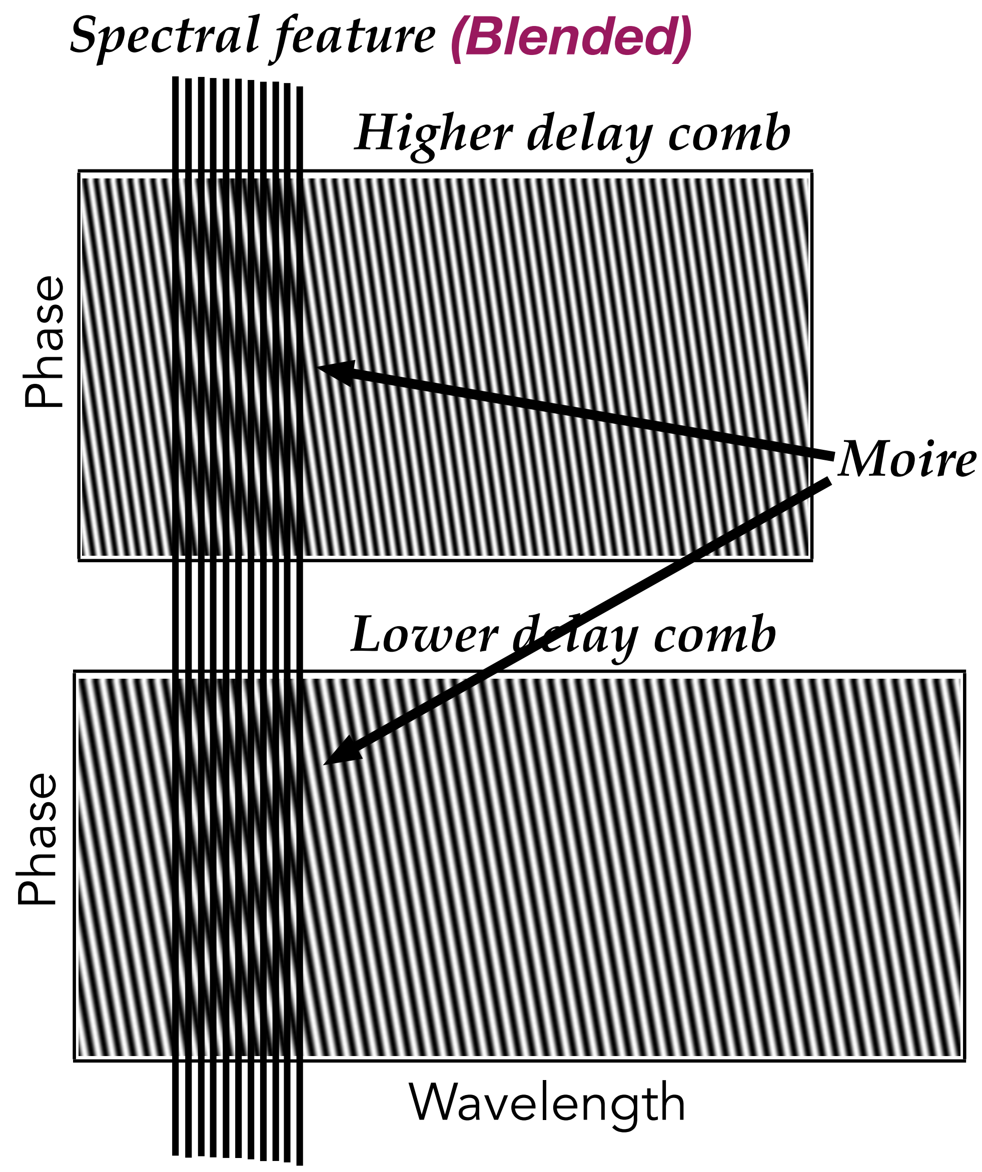


(a)
Modulation Transfer Function
Conventional
Reaction to Δx error
Conventional is still worse
Science here
Strength
1
0.8
0.6
0.4
0.2
0
0
4
Problem: For BLENDED features EDI has nonzero reaction (but still smaller than conventional)
(b)
EDI response robust to Δx shift
Asymmetric frequency distribution spoils cancellation
Heterodyning
Native (nonfringing)
Fringing
Reaction to Δx error
0
-
Net is near zero
Feature Frequency, rho (cm)

2018 Solution: use PAIRS of slightly different delays to cancel drift error

Crossfading: Strategically weighted, we CANCEL net reaction to wavelength drift Δx

These Moire patterns have opposite slopes for high and low delay interferometers



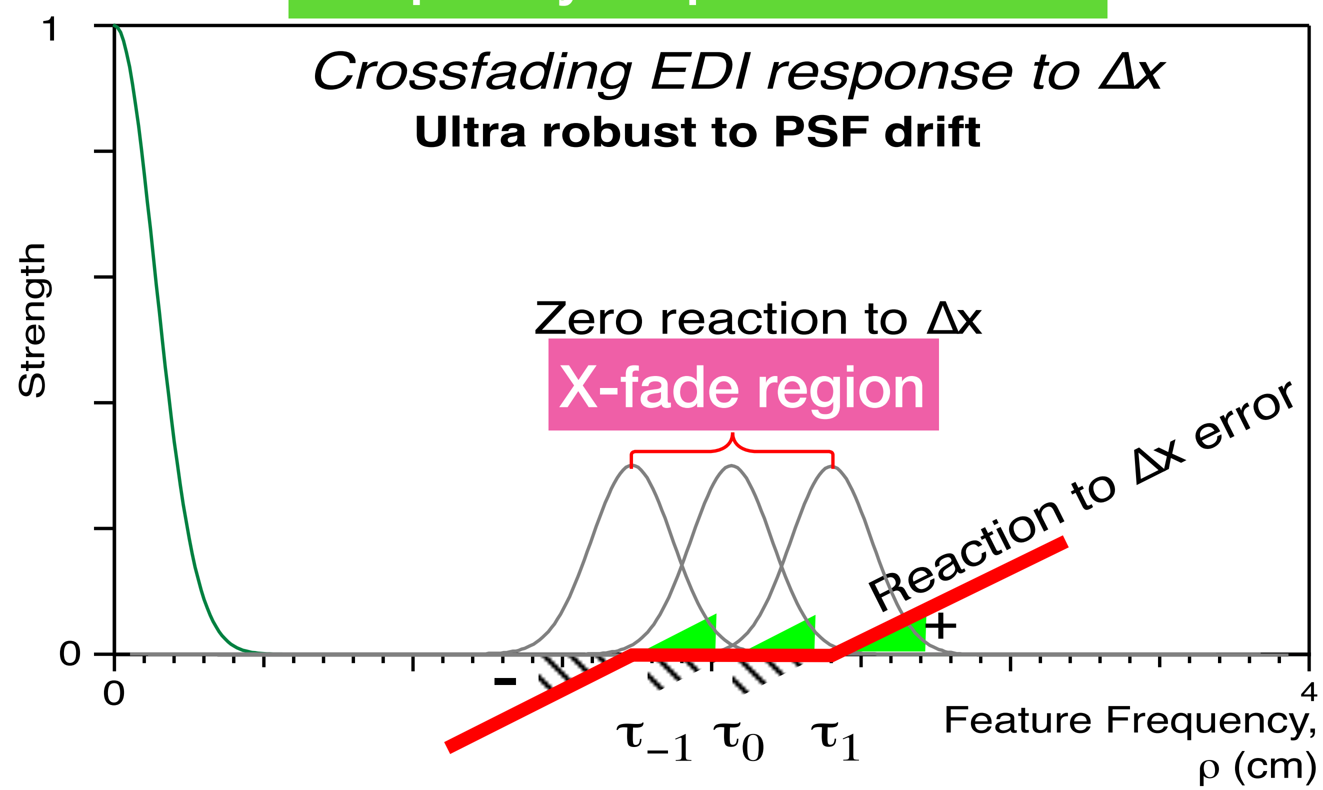
The pair is robust to wavelength drift Δx

Solution: Crossfading between two or more overlapping delays

X-fading idea: Using pairs of high & low delays we can CANCEL wavelength drift Δx

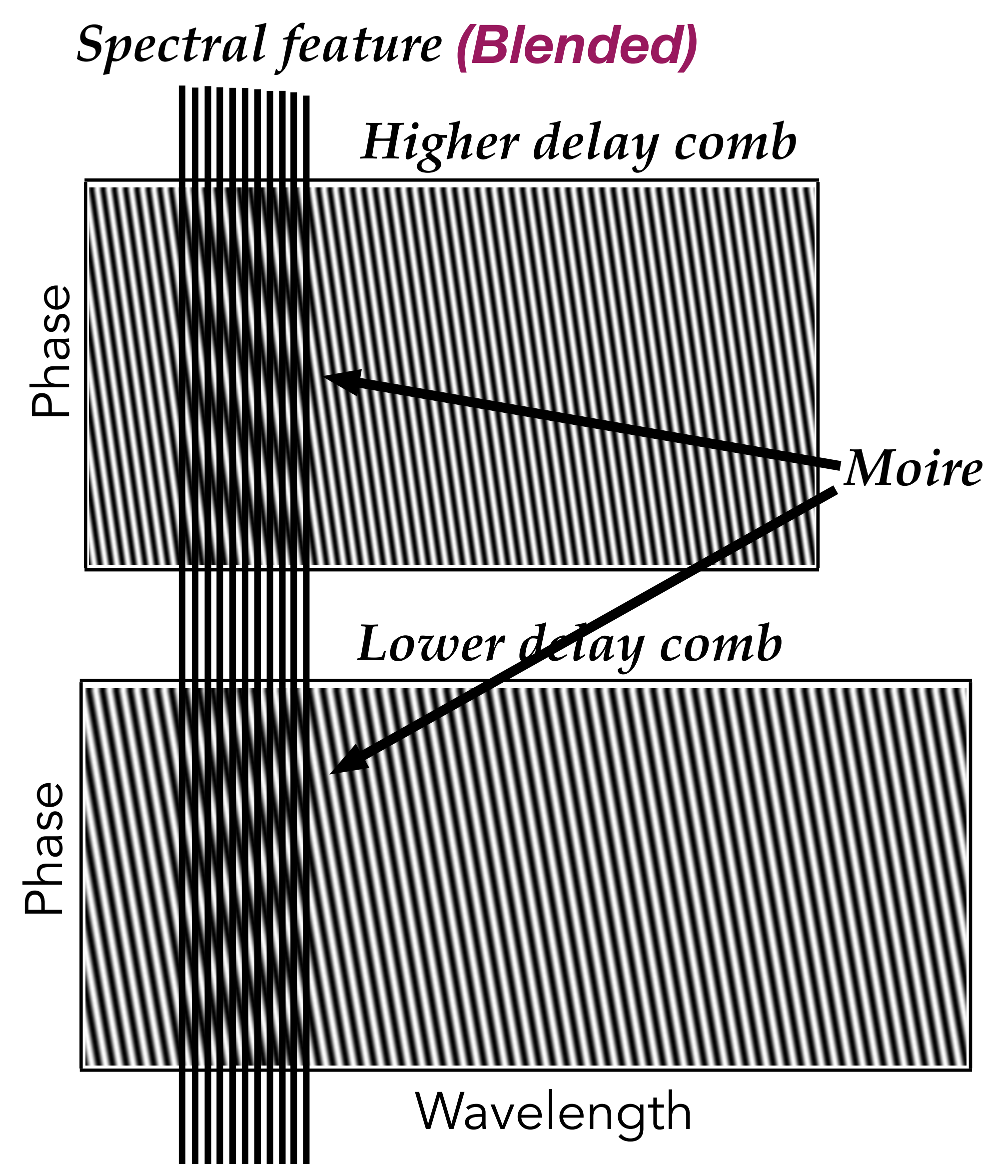
(Case of 3 delays)

Frequency response of X-EDI



(Case of 2 delays)

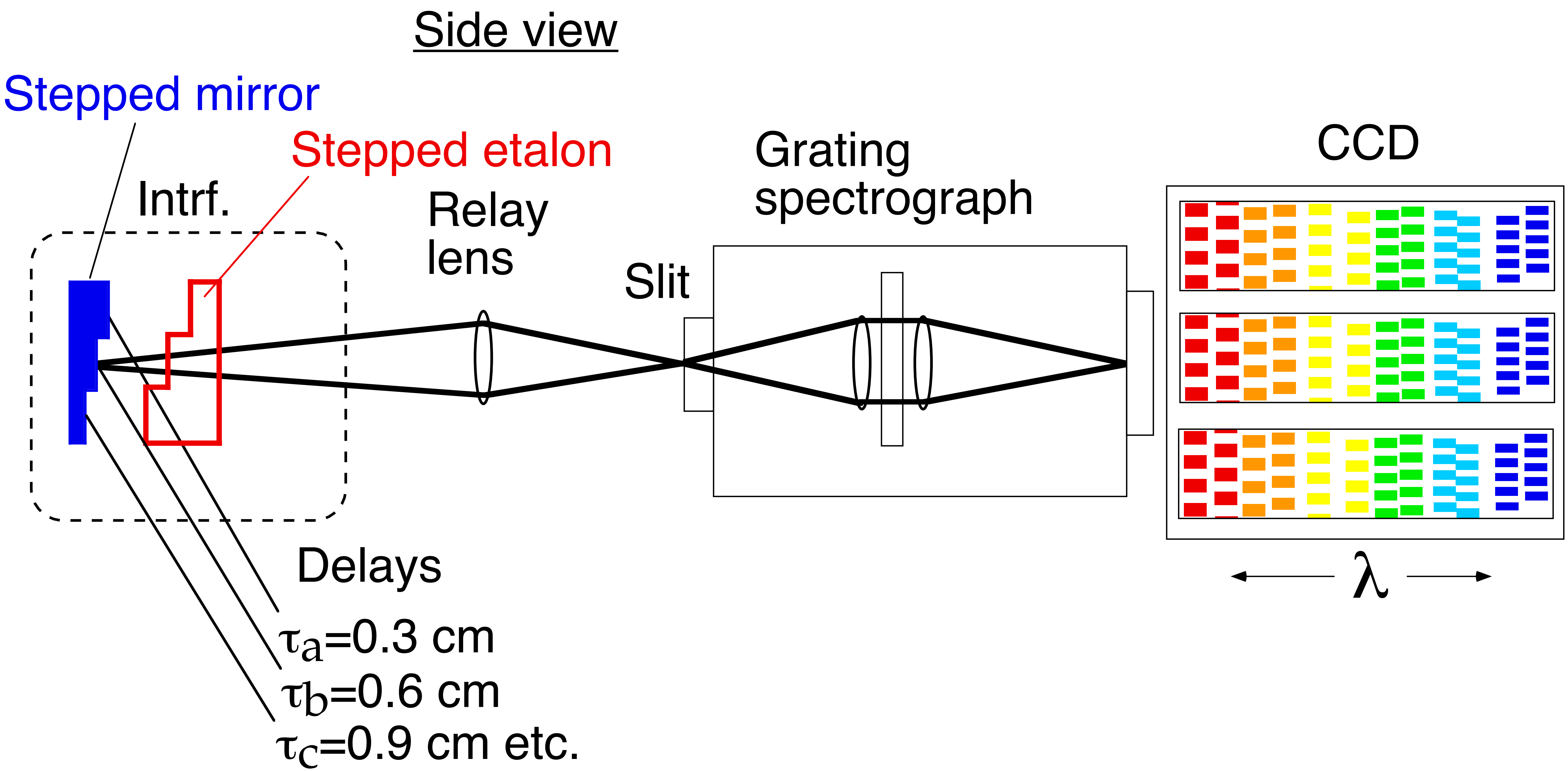
These Moire patterns have opposite slopes for high and low delay interferometers



The pair is robust to wavelength drift Δx

X-fading concept realized in 2014, 3 years after EDI data taking ended in 2011. X-fading software made practical by 2018.

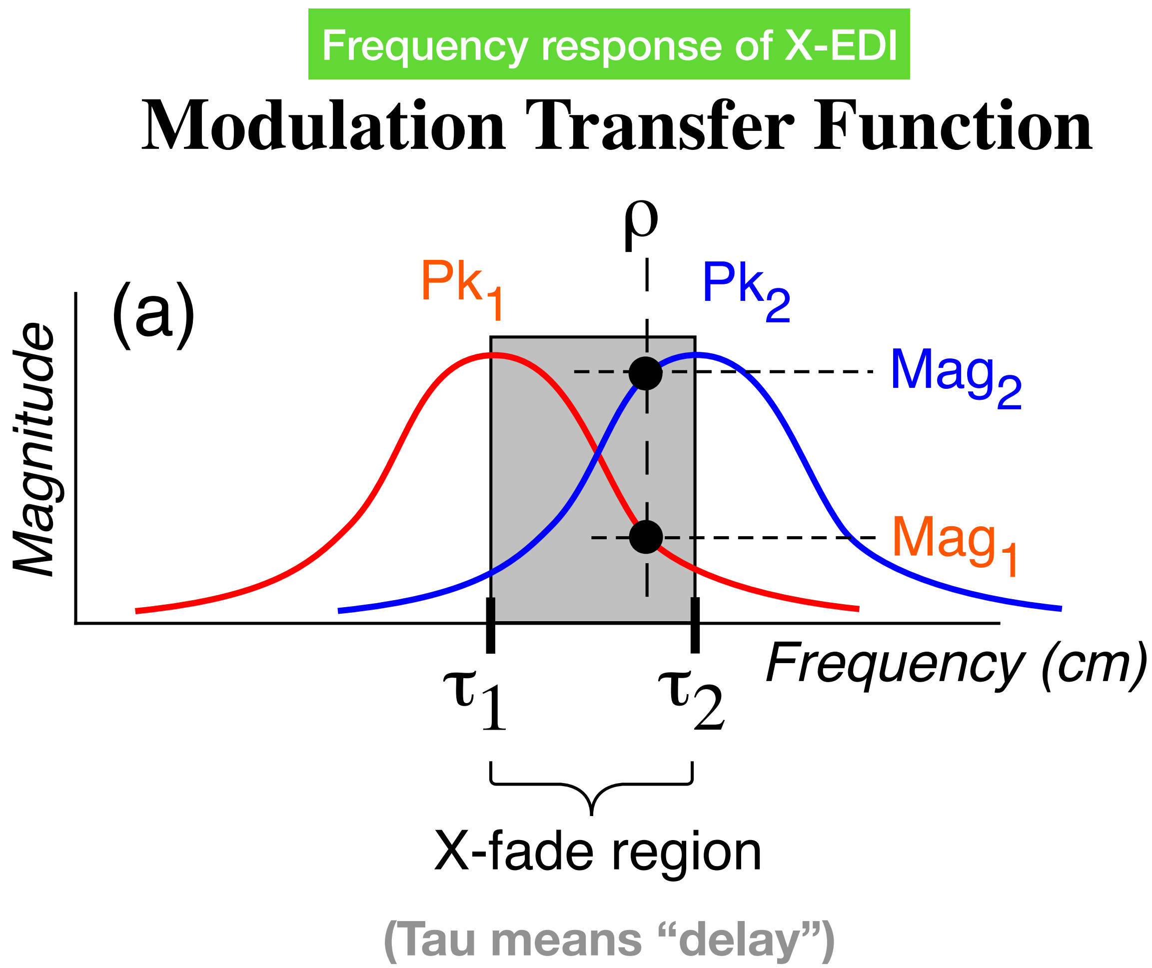
Means for achieving simultaneous drift Δx on all delays

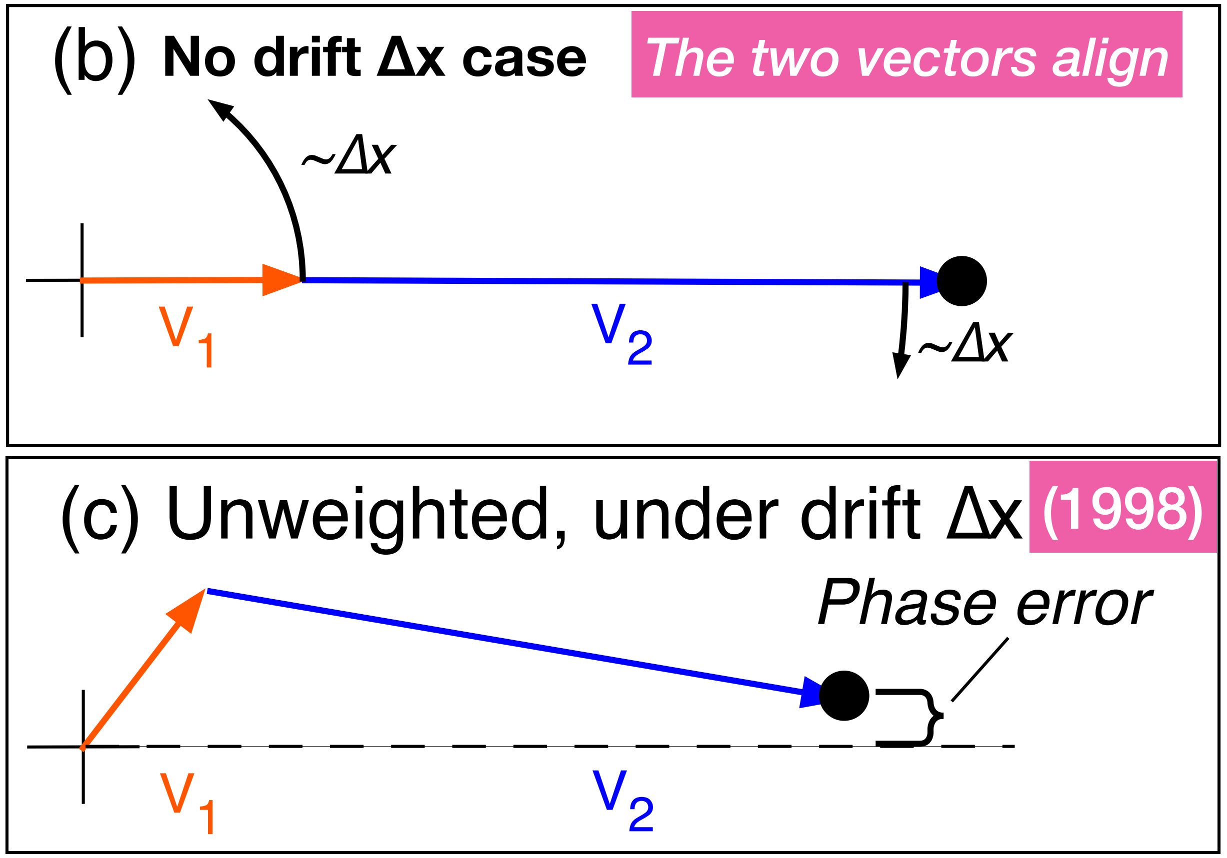


(Etalons are glass slabs creating delay)

Scheme for an interferometer with multiple pairs of simultaneous delays, since ideal crossfading cancellation requires the same drift for each of the two delays.

The high and low frequency portions of sensitivity peaks twist phase in **OPPOSITE** directions, under wavelength drift Δx

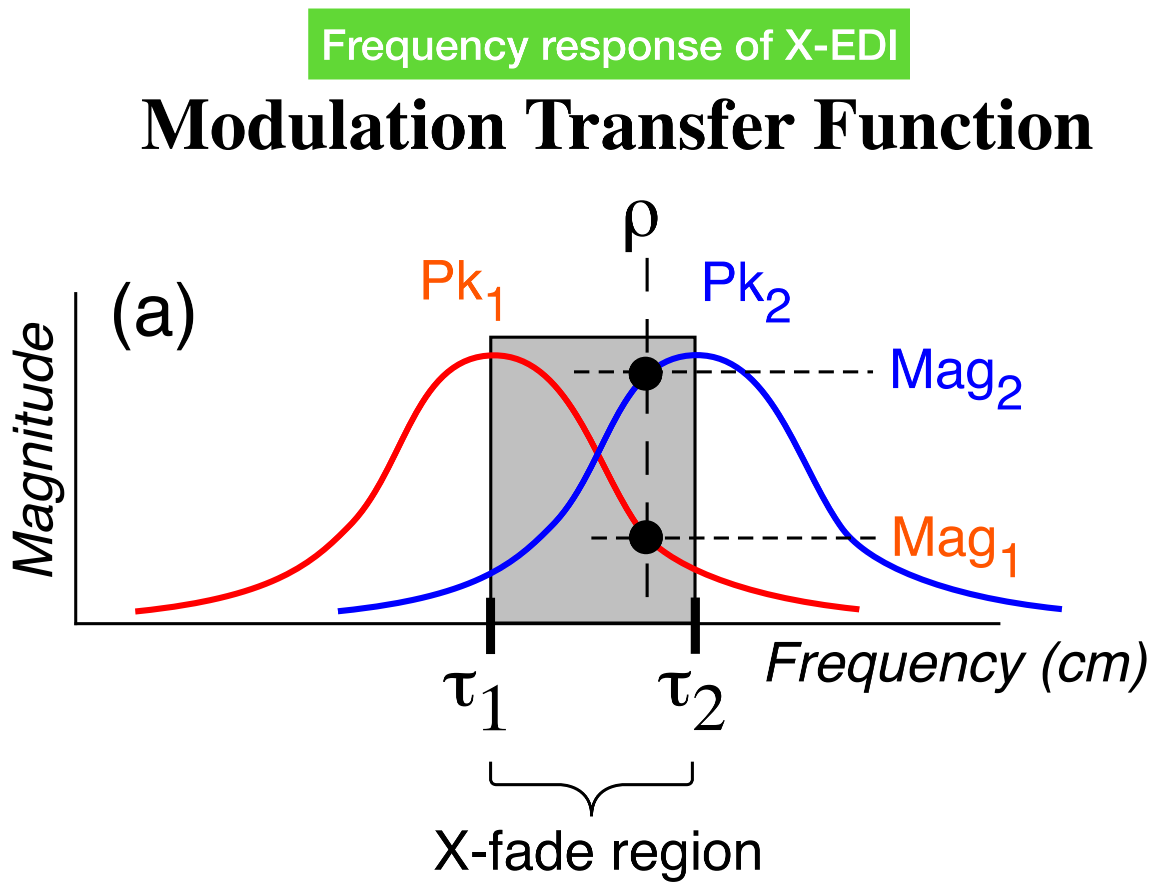




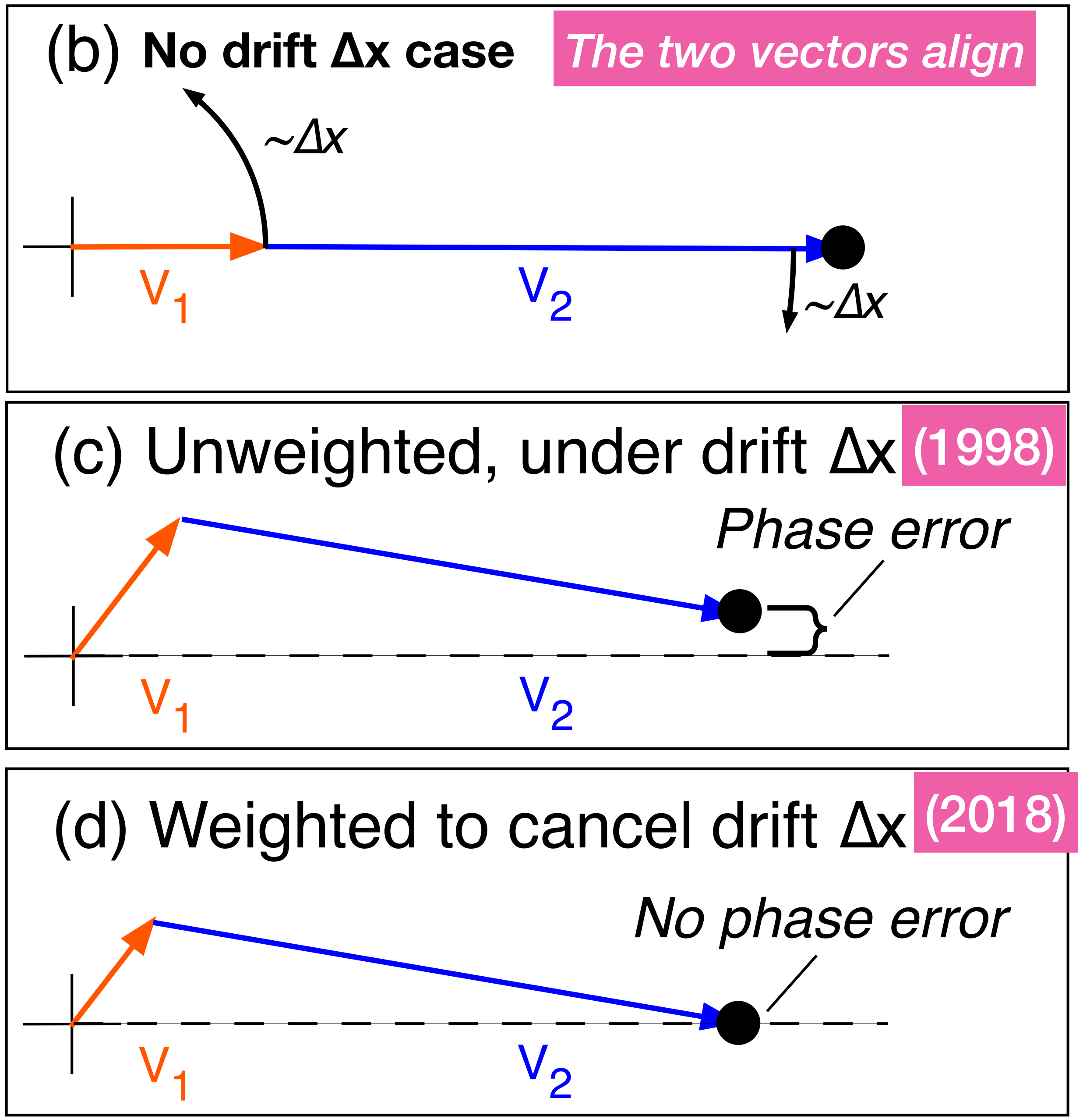
Doing dumb-simple addition can partially cancel the net phase rotation

(This is called "accidental" X-fading)

The high and low frequency portions of sensitivity peaks twist phase in OPPOSITE directions, under wavelength drift Δx



(Tau means "delay")



Doing a weighted sum can perfectly CANCEL the reaction to Δx

(This is called "**strategically weighted**" X-fading)
(or "**special weighting**")

Traditional & X-EDI, stability gains MULTIPLY their benefits

(TRC = Translational Reaction Coefficient)

$$\Delta\lambda_{out} = \Delta x * TRC$$

Traditional mitigations reduce the wavelength shift Δx

X-EDI reduces reaction to Δx in the processed output

TRC = 1 without X-EDI,
TRC ~ 0.01 to 0.001 with X-EDI

Using **BOTH** traditional mitigations and EDI is optimal

$$\Delta\lambda_{out} = \Delta x * 1$$

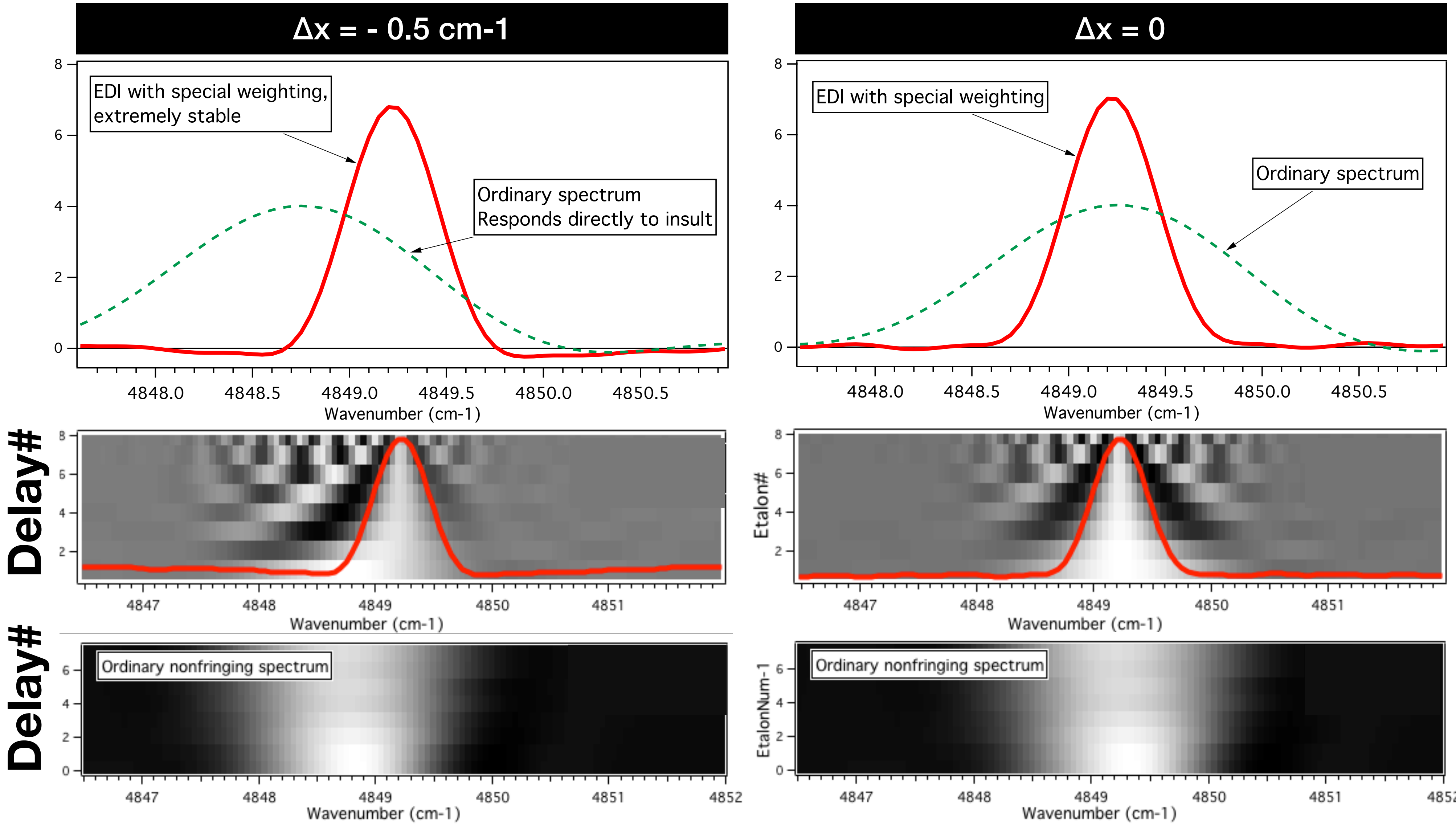
(Conventional spectrographs)

$$\Delta\lambda_{out} = \Delta x * 0.001$$

(EDI with multiple delays)

Demo: 1000x stability gain compared to conventional

Demo used real multiple-delay EDI data from Mt. Palomar, but artificially imposed Δx drift, showed 1000x smaller output wavelength drift than does conventional.



“**A 1000x Stabler Spectrograph using an Interferometer with Crossfaded Delays**”, David J. Erskine and Eric V. Linder, Opt. Soc. Am. Optical Sensors and Sensing Congress 2019, Fourier Transform Spectroscopy Topical Mtg., San Jose, CA, June 25-27, 2019, paper FW5b.3. [FTS-2019-FW5B.3(SanJose).pdf]

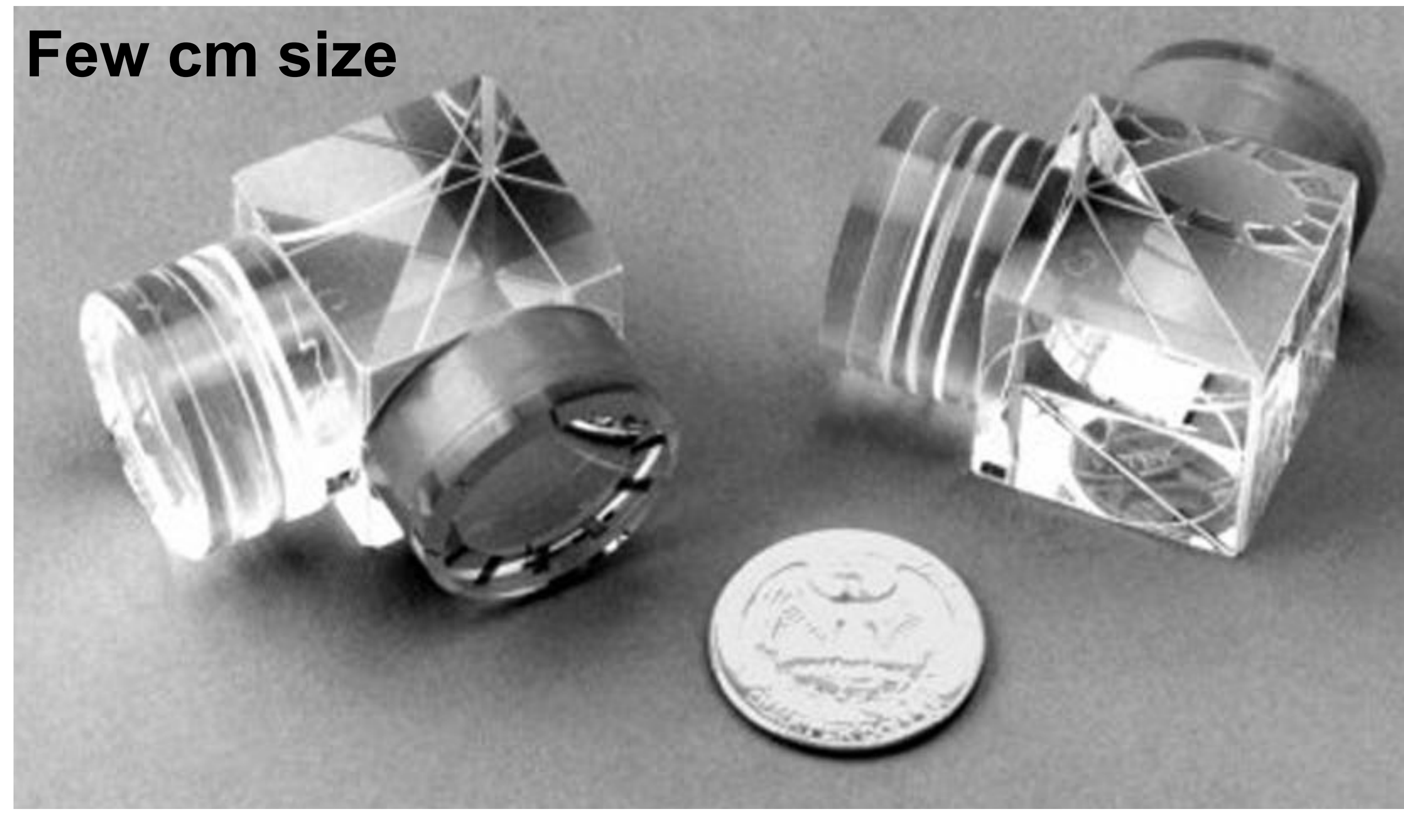
Path forward: We envision small inserts temporarily added like a filter to existing observatory spectrographs

Insert interferometer in front of existing grating spectrographs

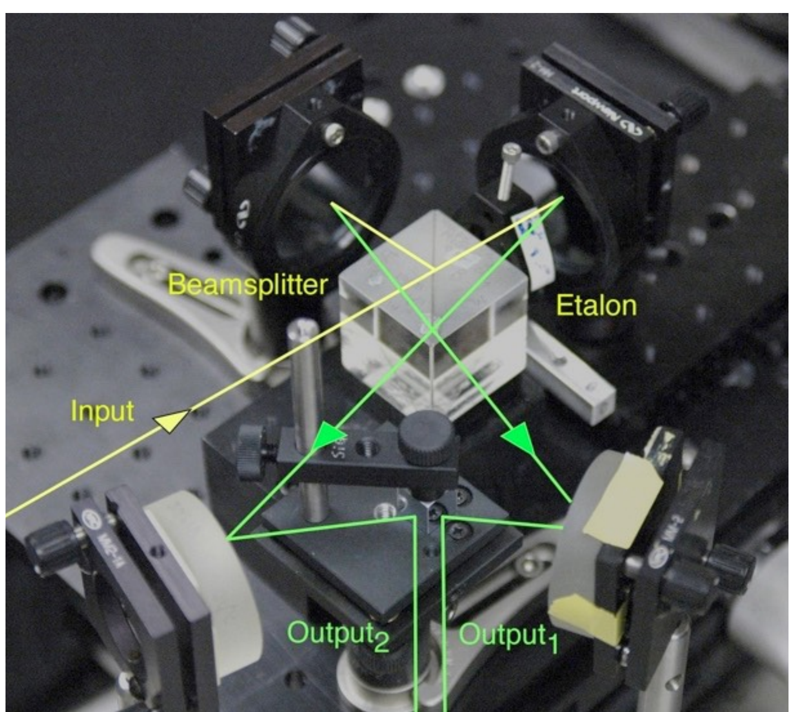
Move into beam- observe- move out of beam

Does not prevent regular observations

Reference spectra such as ThAr lamp or iodine

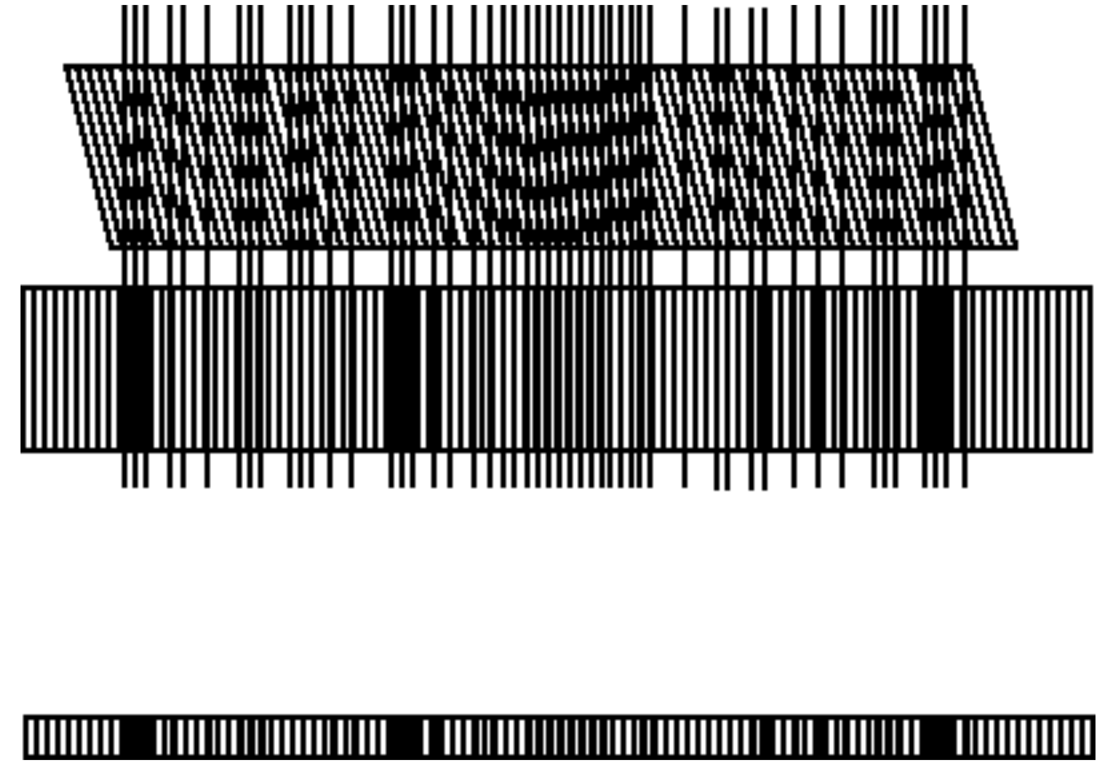


Several intrf. having different delays could be mounted on a "filter wheel"



Dual outputs for high efficiency

We have already tested EDI at facility instruments



In some interferometers we make phase uniform across beam

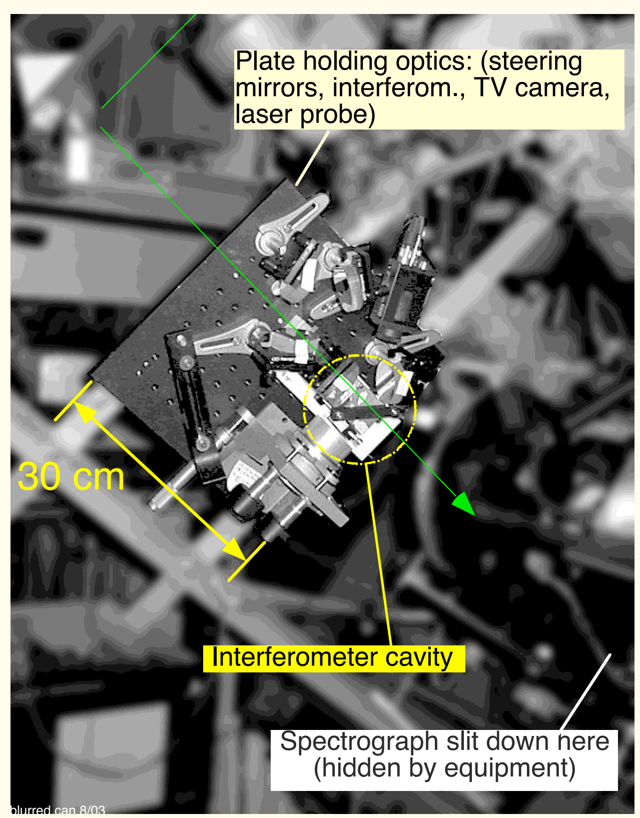
Take four 90 degree shifted exposures

This allows use with narrow beams such as echelle grating spectrographs at Lick Obs (2003), Mt. Palomar (2008-11)

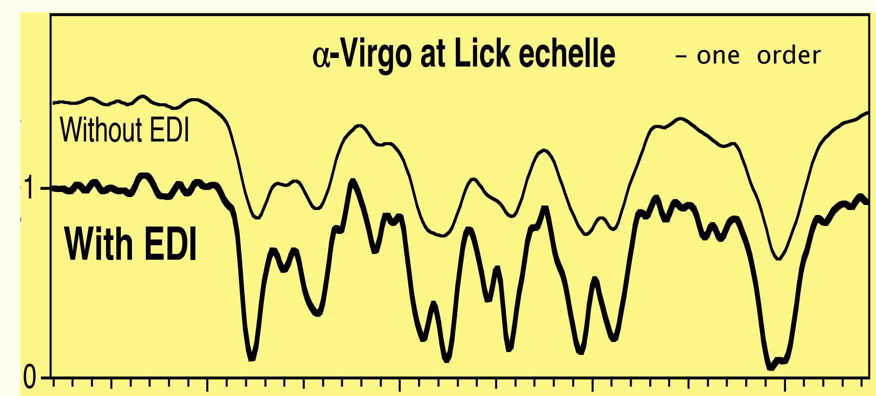
A resolution boost of 2x was demo'd with a single delay, and 10x using multiple delays

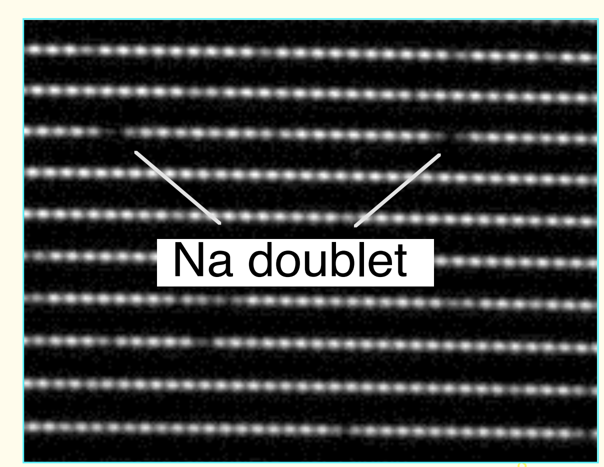
On Telescope: EDI Echelle Spectroscopy

EDI Res. ~100k with Res. 50k slit



Lick – Hamilton feed
(single output)





Echelle Data: Interferometer fringes beating with a sample of echelle spectrum orders

Done with main talk

Others slides for questions

EDI is robust to bad pixels and other fixed pattern errors because it dithers between 3 exposures comparing differences

BAD PIXELS do not produce peaks in EDI (red) curve, only in conventional (green)