Progress Toward Applying Lasers to Improving the Precision of Radial Velocity Measurements

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Astronomy of Exoplanets with Precise Radial Velocities
Pennsylvania State University
16-19 August 2010

Ron Walsworth, Gabor Furesz, Alex Glenday, Sylvain Korzennik, Dave Latham, Chih Hao Li, Dave Phillips, Dimitar Sasselov, Willie Torres
CfA
Franz Kaertner, Andrew Benedick*, Noah Chang, Li-Jin Chen
MIT

* See Benedick, et al. in poster session

Outline

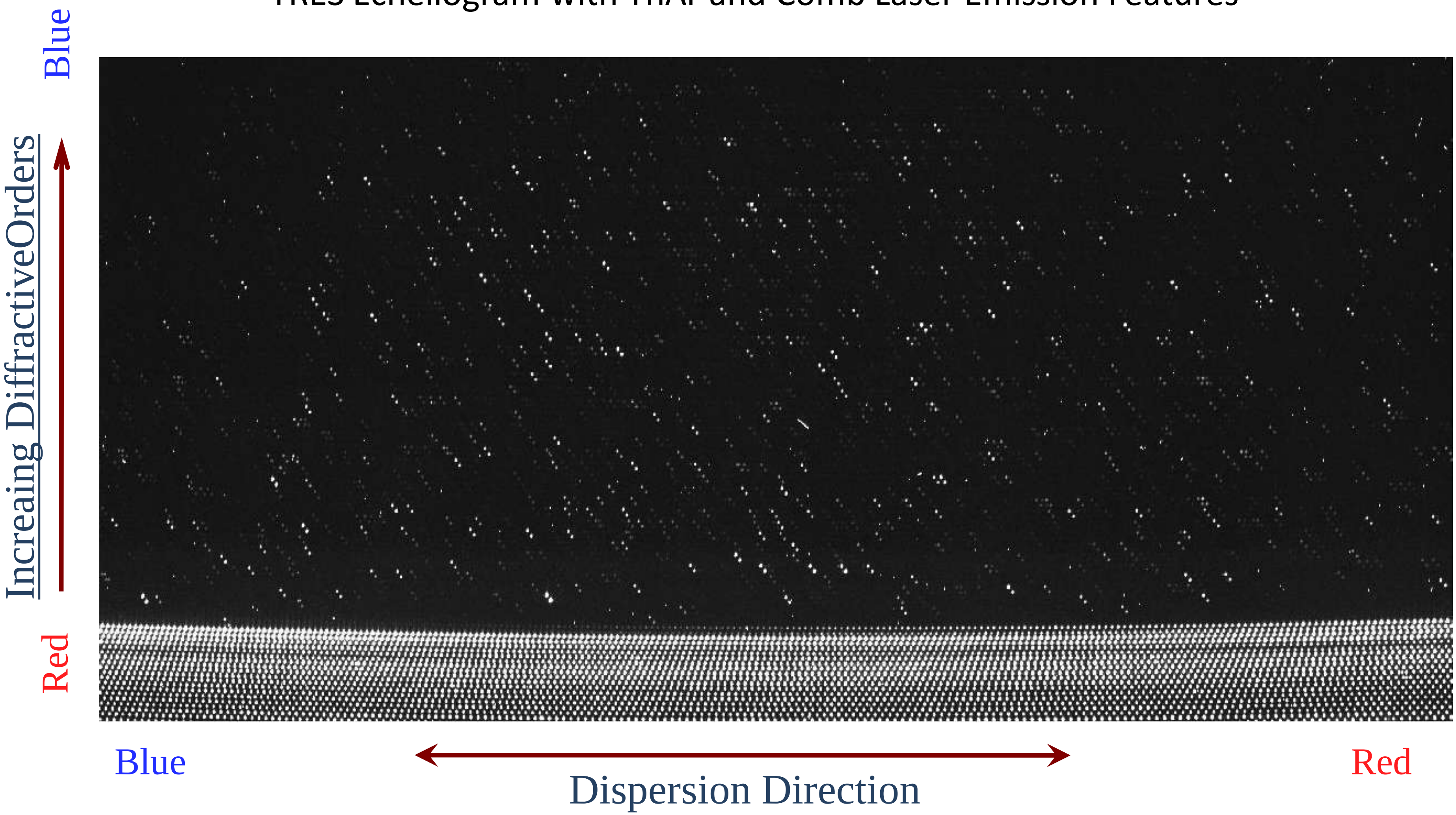
- Why we need comb laser calibrators
- A (very) brief introduction to comb lasers
- A few technical details concerning comb lasers
- Progress towards applying laser frequency combs to PRV
- Near term plans for deploying comb lasers for PRV
- Laser combs in the ELT era (G-CLEF)

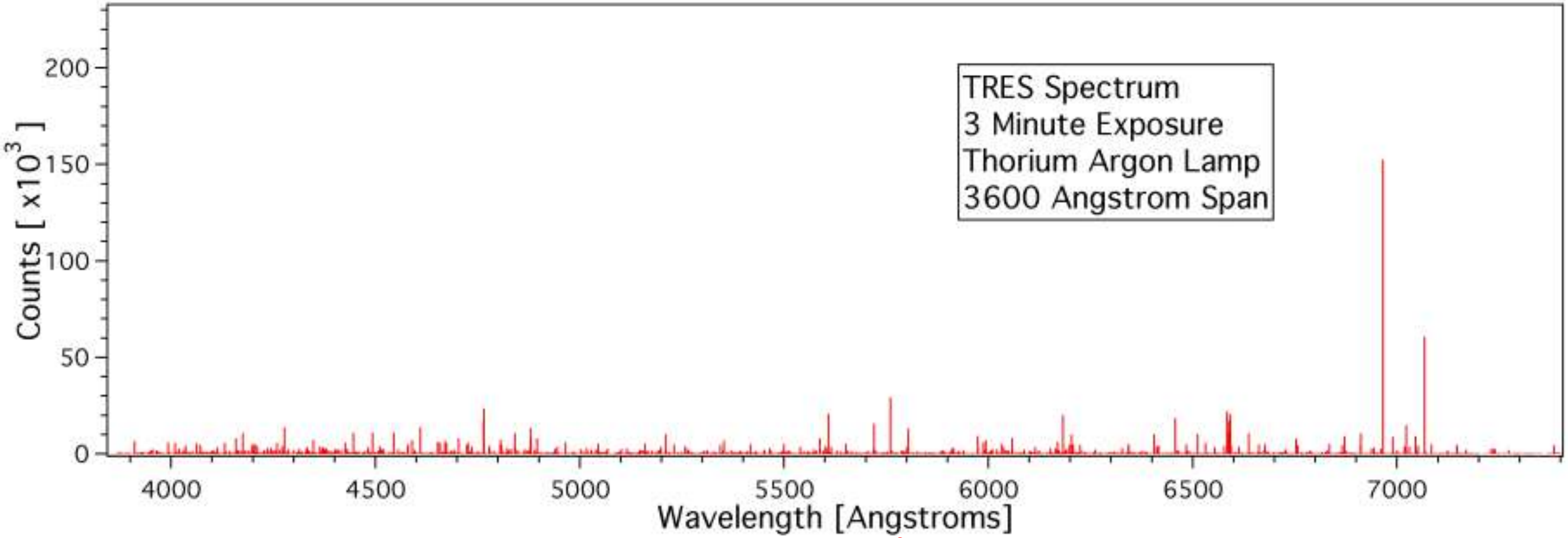
Why We Need Comb Laser Calibrators

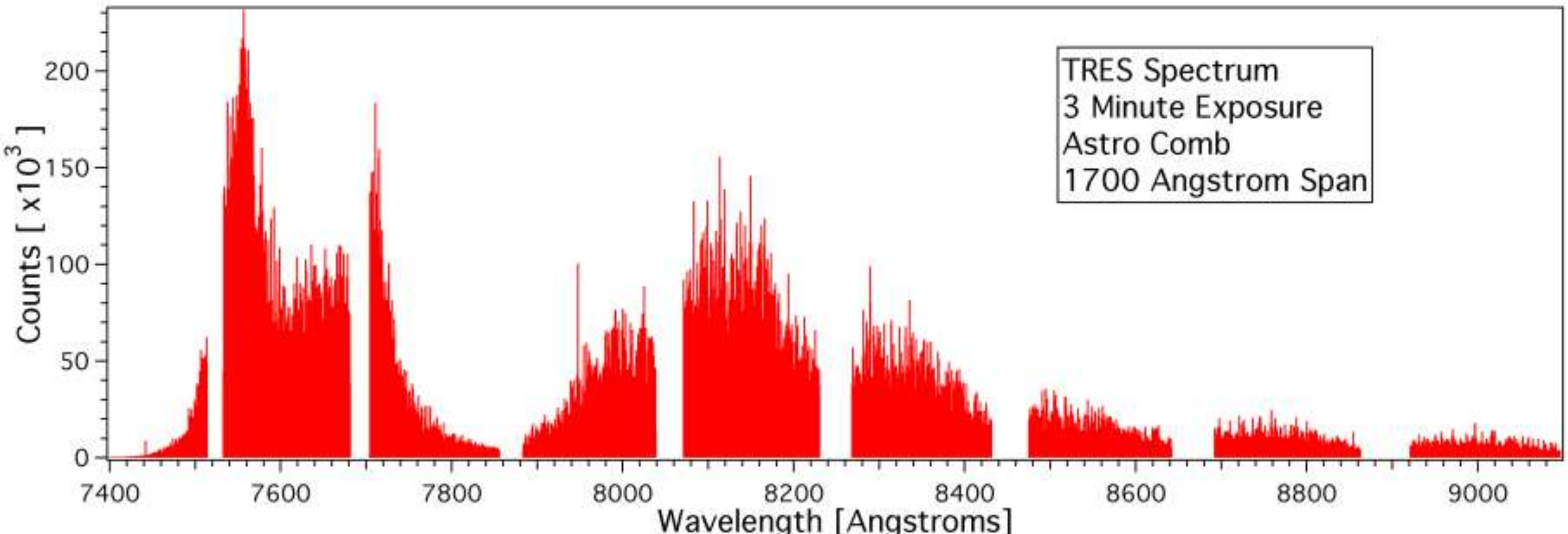
Murphy et al.,2008, MNRAS

Comb Laser Provide a Bright, Tunably Dense Grid of Wavelength Fiducials for Calibration

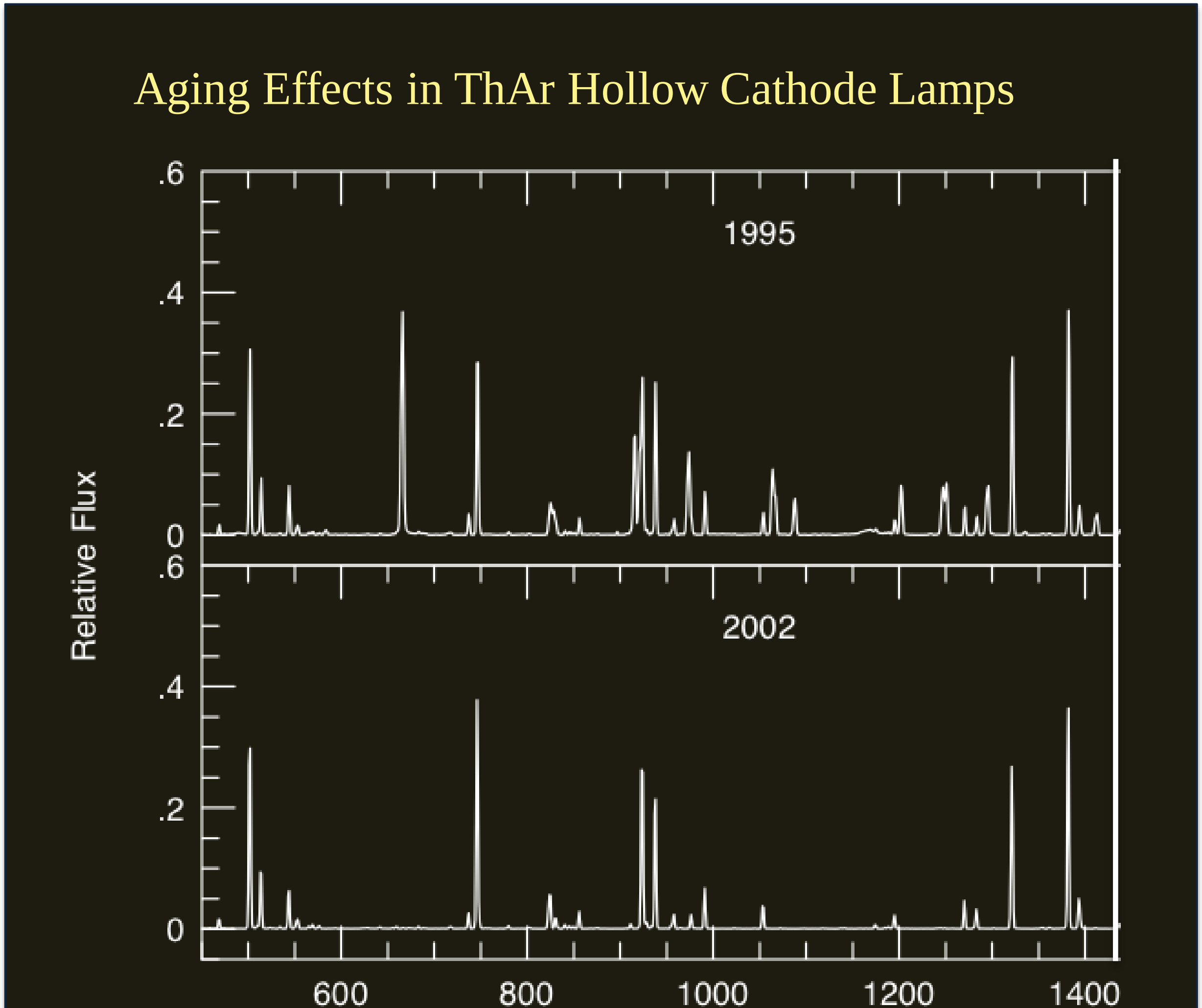
TRES Echellogram with ThAr and Comb Laser Emission Features




TRES Spectrum
3 Minute Exposure
Thorium Argon Lamp
3600 Angstrom Span
Counts [x10^3]
0
50
100
150
200
4000
4500
5000
5500
6000
6500
7000
Wavelength [Angstroms]


TRES Spectrum
3 Minute Exposure
Astro Comb
1700 Angstrom Span
Counts [x10^3]
0
50
100
150
200
7400
7600
7800
8000
8200
8400
8600
8800
9000
Wavelength [Angstroms]

Comb Lasers Are Extremely Stable*



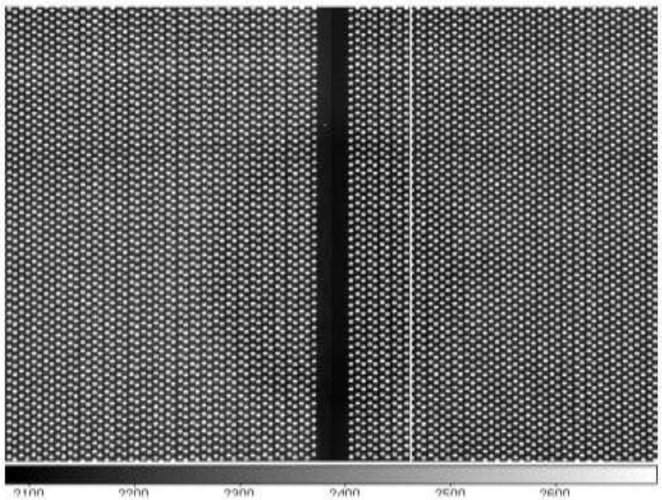
- Discovery of exoearths requires multiyear stability
- More ambitious ELT PRV programs require decadal stabilty
- Combs can be stabilized to $1{:}10^{15}$

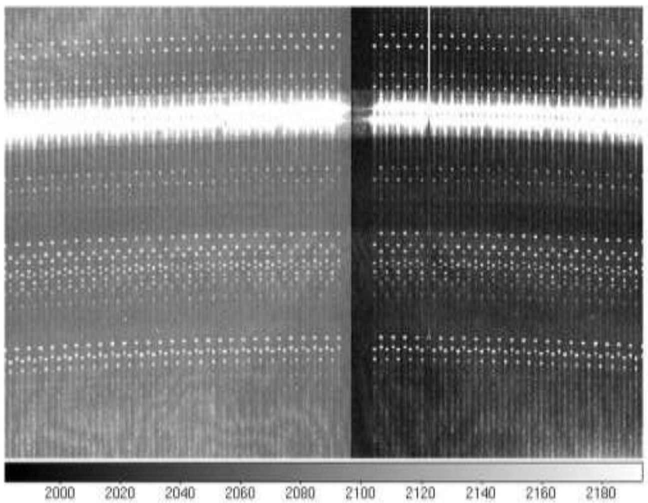
* This figure plagiarized from unidentified individual in the audience.

Comb lasers have the potential to perform broadband calibration across the entire optical – NIR passband

… but more on this later.

Lasers Are Versatile Calibrators at Red Wavelengths





Tunable Laser Calibration Frame

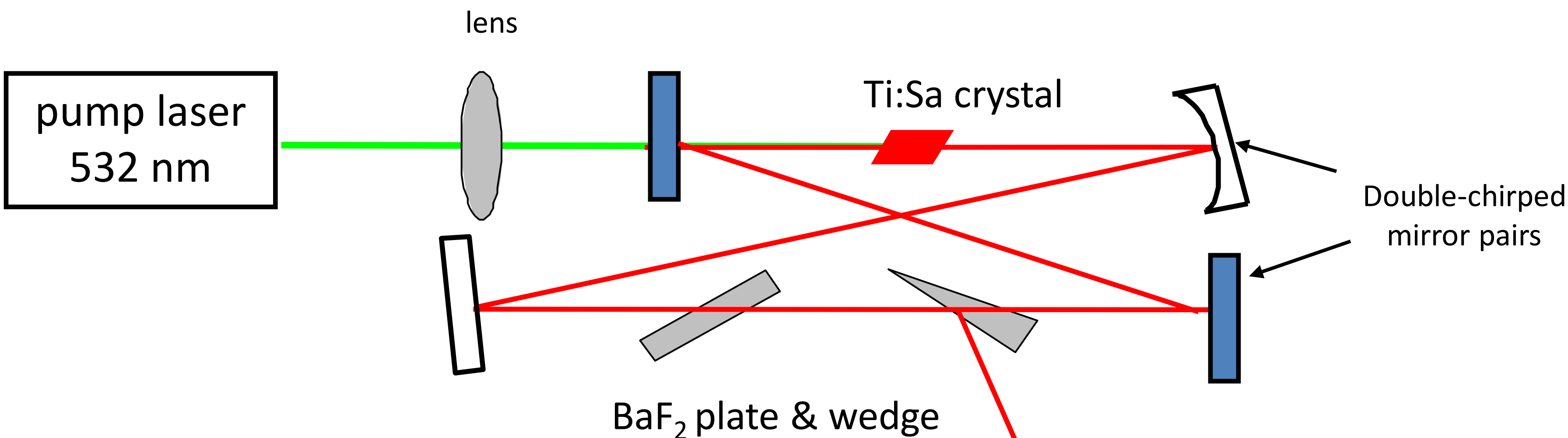
ThAr Calibration Frame

n.b.: Scattering, fringing, saturation effects

A Very Brief Introductions to Comb Lasers

Mode-locked femtosecond comb laser

Kerr-lens mode-locking

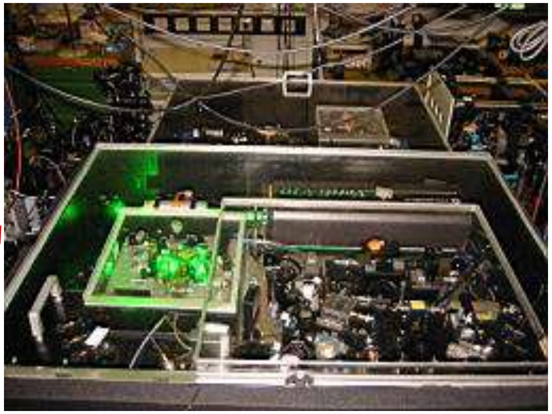


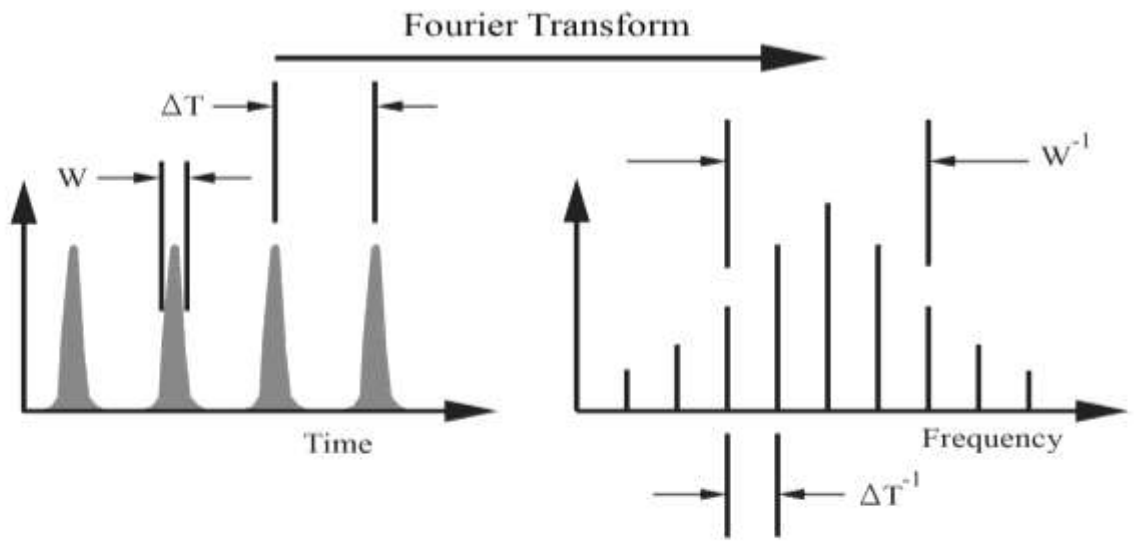
State-of-the art:

τ_{pulse} ~ 3.5 fs

T_{Rep} ~ 1 ns

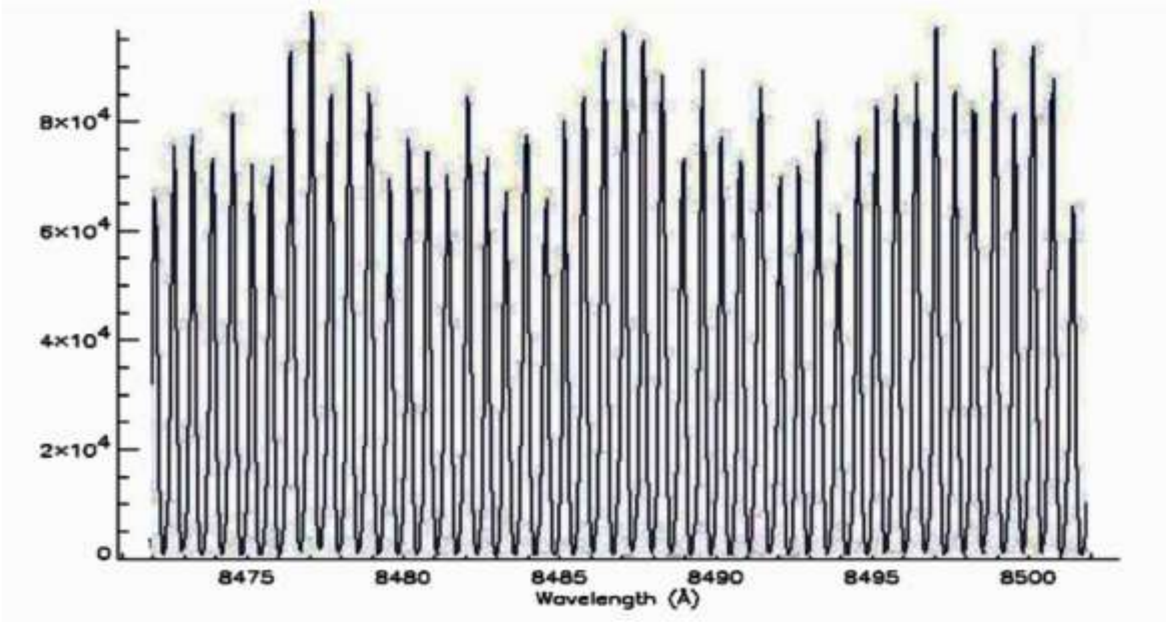
e.g. Menlo Systems Octavius



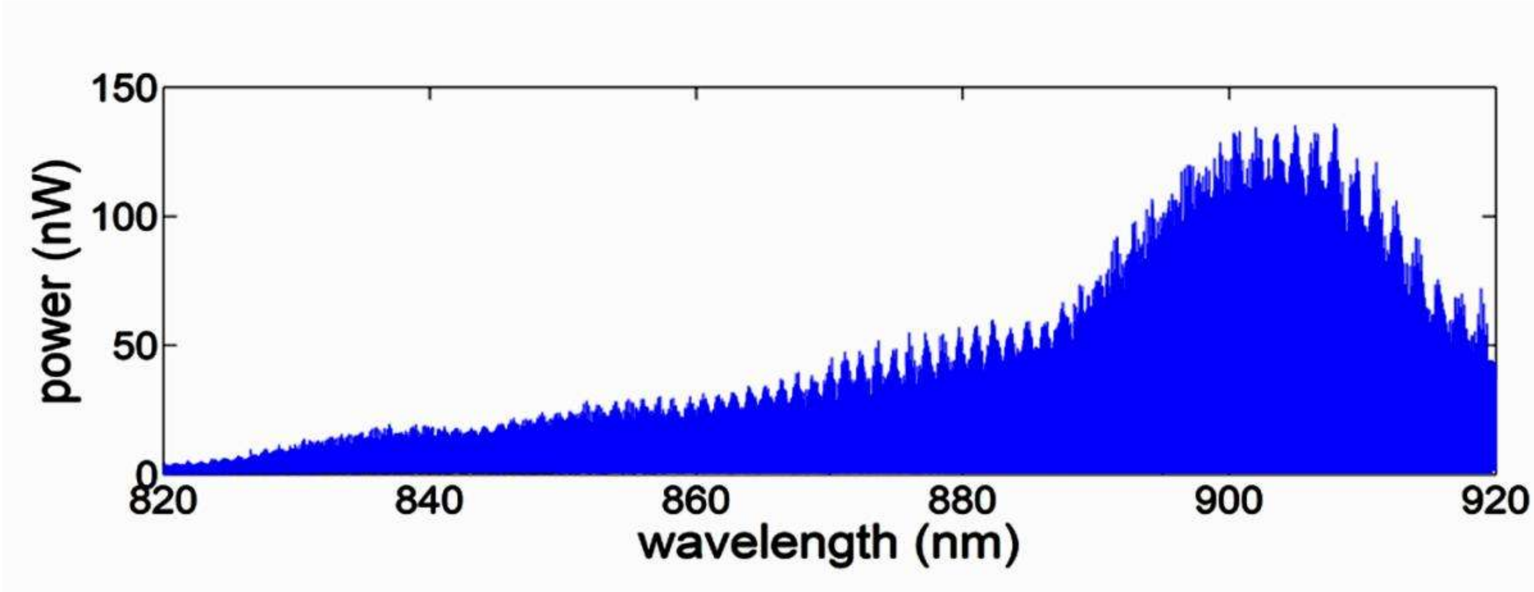


Comb Laser "Cartoon"

Comb Laser Data



A Few Technical Details Concerning Comb Lasers



•Comb "tines are too narrowly spaced to resolve with astronomical spectrograph (R~40,000-150,000)
•Lines spacing (~$1x10^{-3}$Å) requires R~10^6 optical spectrograph
•Solution is to "prune" (i.e., thin out) the comb, e.g. with an etalon

IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 25, NO. 1, JANUARY 1989

Increase in Laser Repetition Rate by Spectral Selection

THEODORE SIZER, II

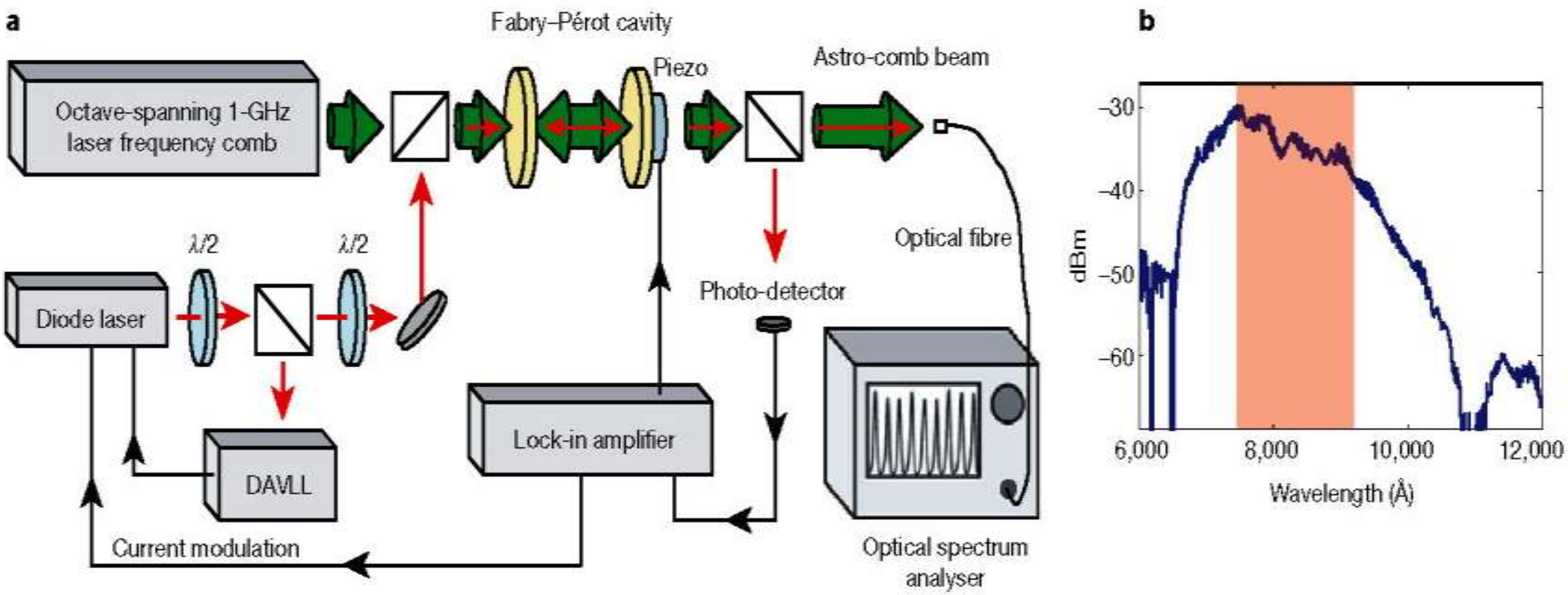
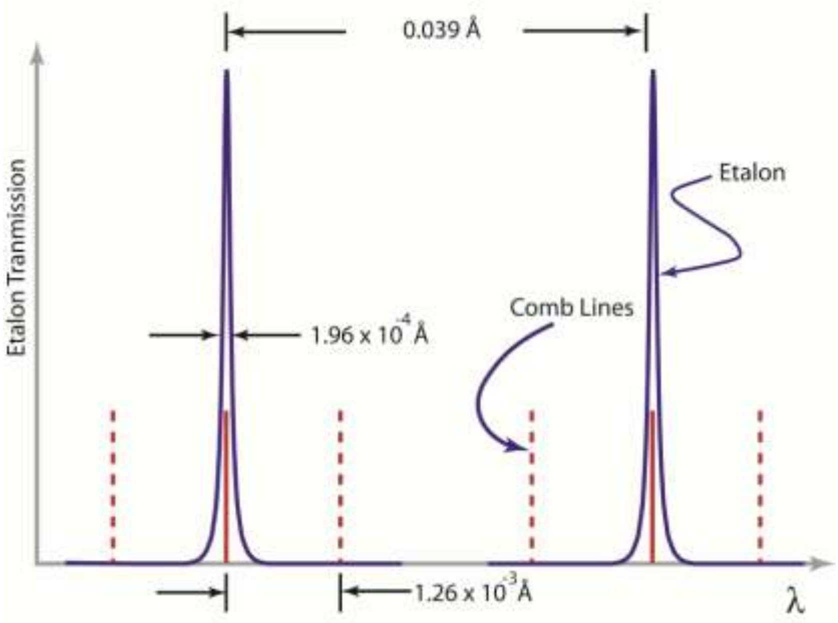


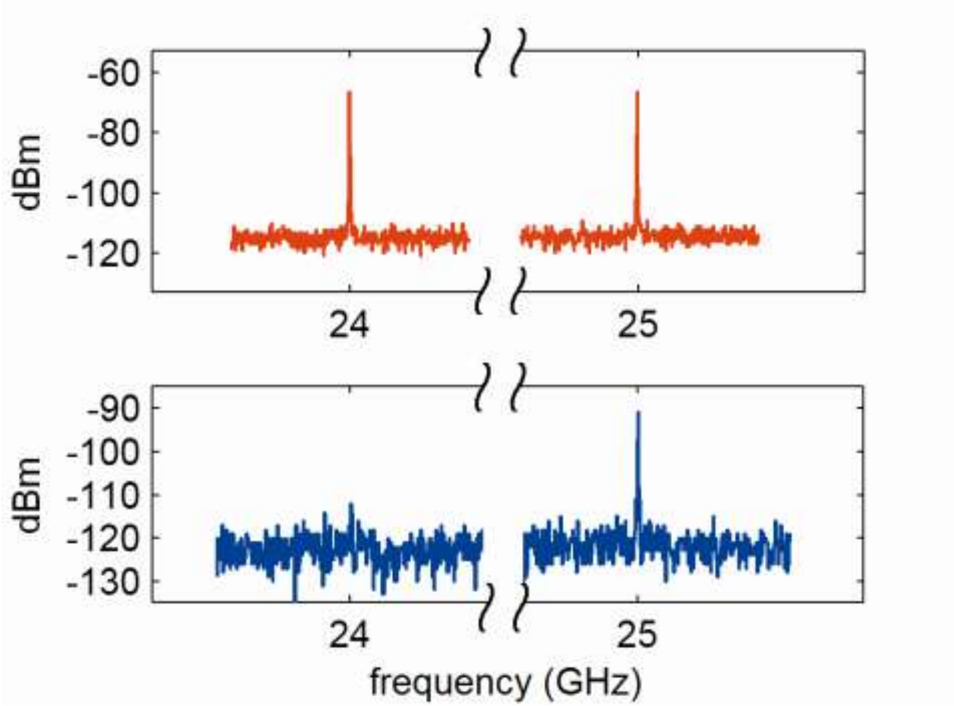
Figure 1 | Block diagram of the astro-comb. a, A stabilized 1-GHz frequency comb ('source-comb') using a mode-locked femtosecond laser passes through an FP cavity that filters out unwanted comb lines and increases the line spacing to at most 40 GHz (~1 Å). For the demonstration spectra shown in this paper, the output beam from the astro-comb is collected by a single-mode fibre and measured using an optical spectrum analyser (Ando 6317) with resolution ~8 GHz and reproducibility ~2 GHz. **b,** Output spectrum of the 1-GHz source-comb. Typical operating parameters of the source-comb[13] are 600 mW of output power and an output spectrum from 6,000 Å to 12,000 Å with 9.3 W of pump power. The shaded area is the spectral range in which the current FP cavity mirrors have small GDD and hence provide good suppression of extraneous comb lines. The quantity dBm is ten times the logarithm of the power referenced to 1 mW.

*DAVLL = Dichroic atomic vapour laser lock

Li, et al., 2008, Nature
see also: Braje et al. 2008



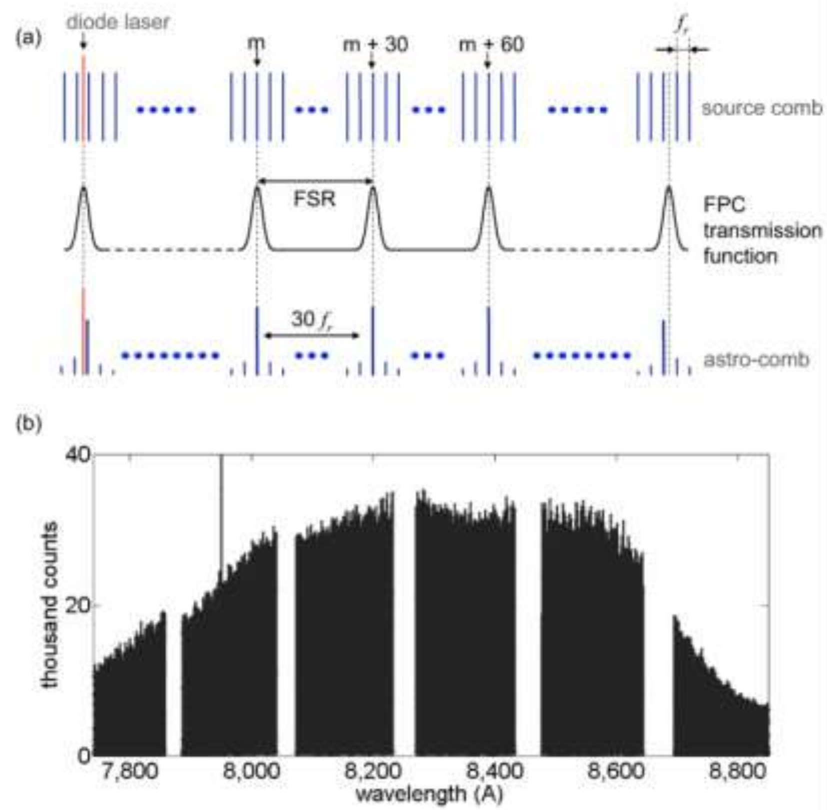
Finesse ~200 @ 8000 Å



25 dB suppression (1/320) in 24th beatnote

Etalons for PRV are hard!

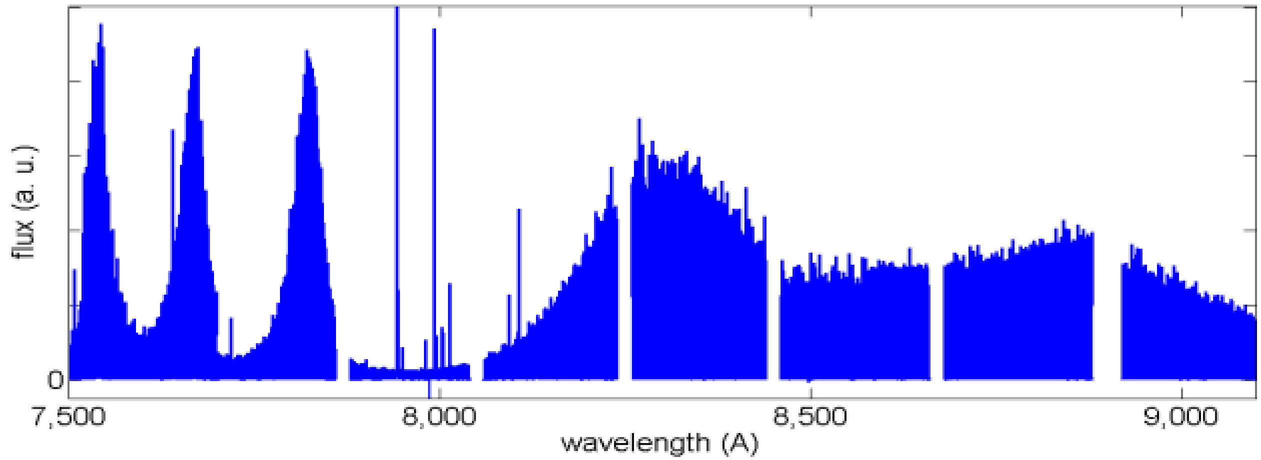
- Question of bandwidth vs. sidemode suppression
- Coating design – dispersion compensation
- Coating manufacture
- Coating characterization



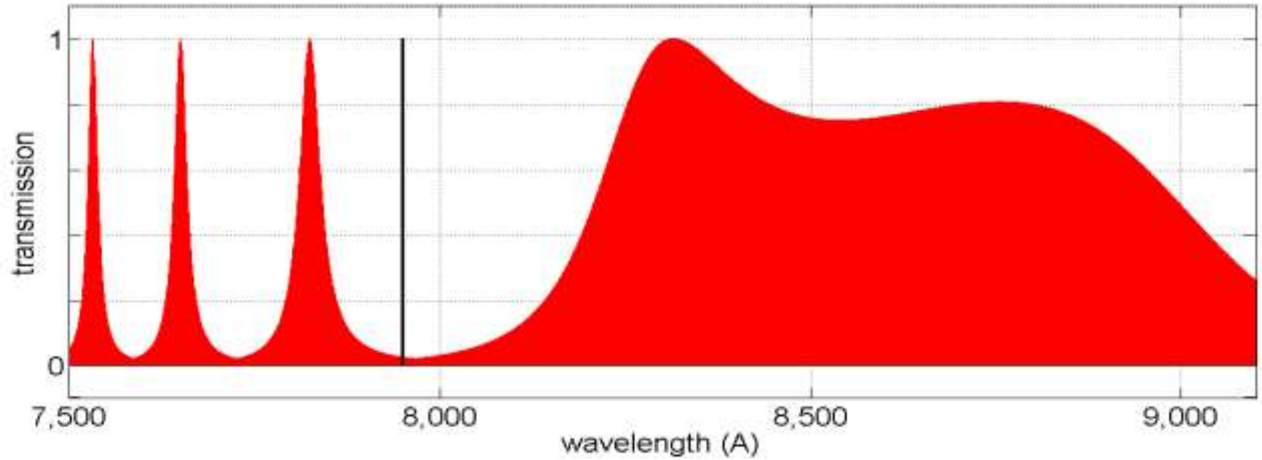
Li et al., 2010, Optics Express

Progress Toward Applying
Laser Frequency Combs to PRV
(Spanning the Optical Passband)

A Red Comb Laser



Red Comb Data



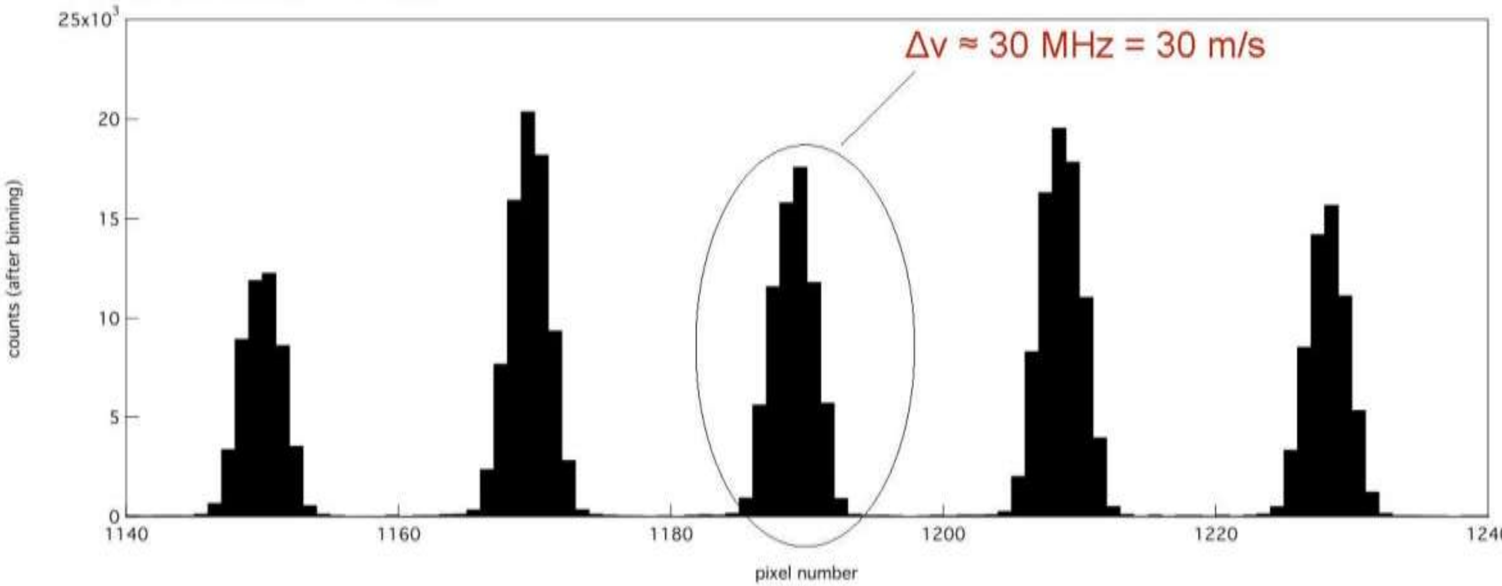
Red Comb Model

TRES SNR estimate

$$\delta\nu = A\frac{\mathrm{FWHM}}{S/N \times \sqrt{n}}$$

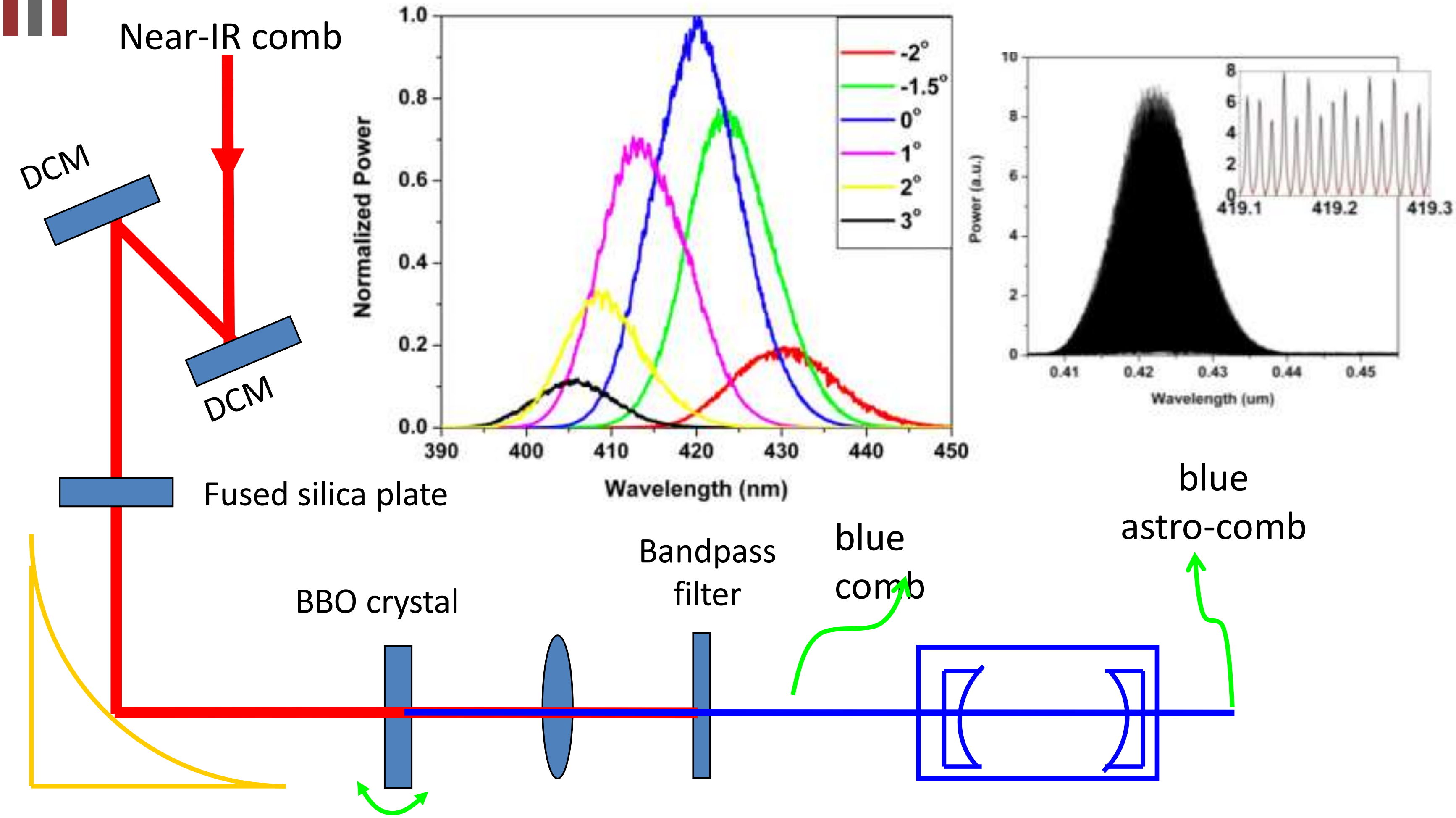
"High-precision wavelength calibration with laser frequency combs," M. T. Murphy, et al., astro-ph/0703622v1.

$A \approx 0.7$
FWHM ≈ 10 GHz
$(S/N)_{max} \approx 300$
$(S/N)_{3\,min} \approx 100$
$n \approx 6$ pixels
Medium fiber at TRES

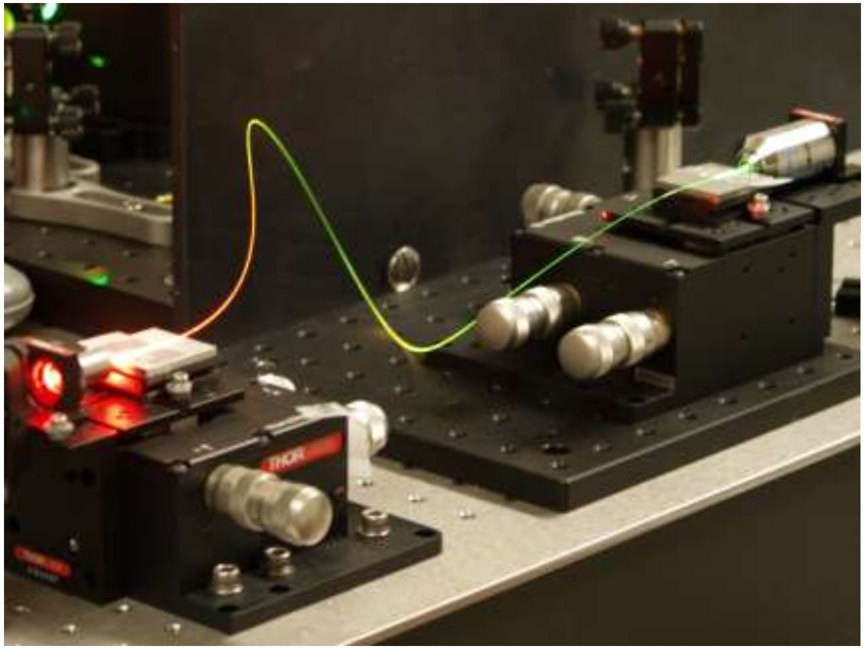


~200 feature per order / 5 orders covered by comb

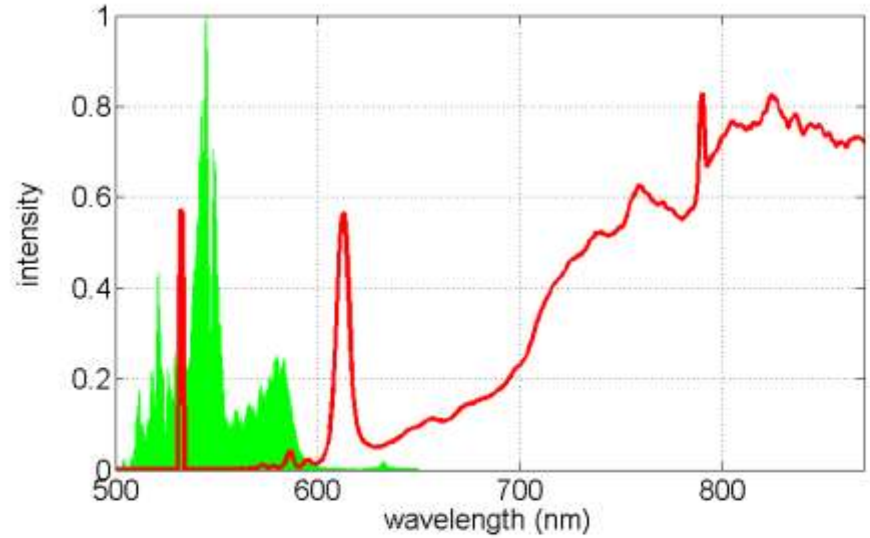
A Blue Comb Laser



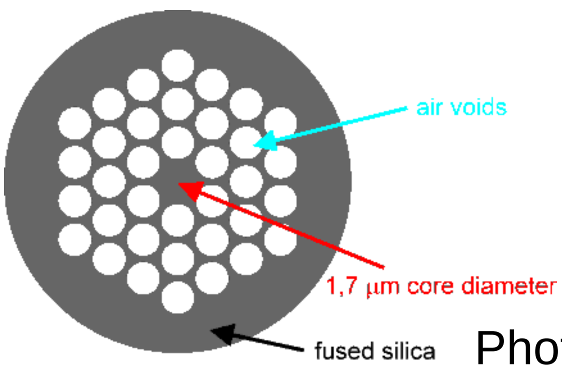
Benedick et al. 2010 “Visible Wavelength Astro-Comb”, Optics Express
also poster this conference.



A Green Laser Comb



Green source comb (green shaded area) generated from a 1 GHz Ti:sapphire frequency comb (red curve).



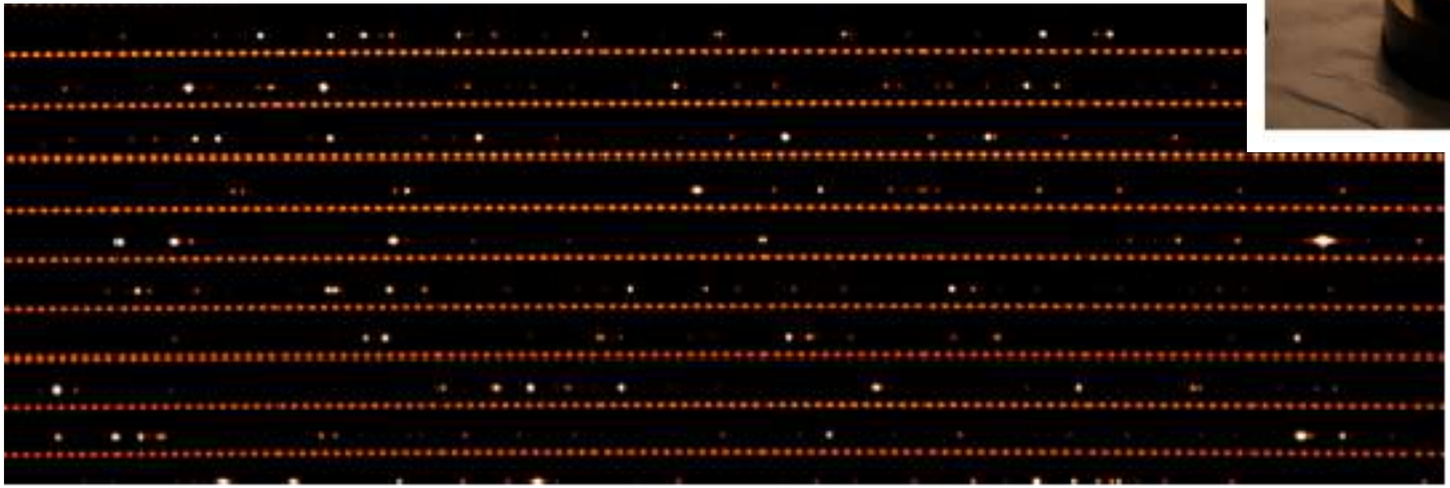
Photonic Crystal Fiber (PCF)

Near Term Plans for Deploying Comb Lasers for PRV

- HARPS North
- Harvester
- Other (but not many) PRV Instruments

… However, comb lasers that cover the entire optical passband are still in the future.

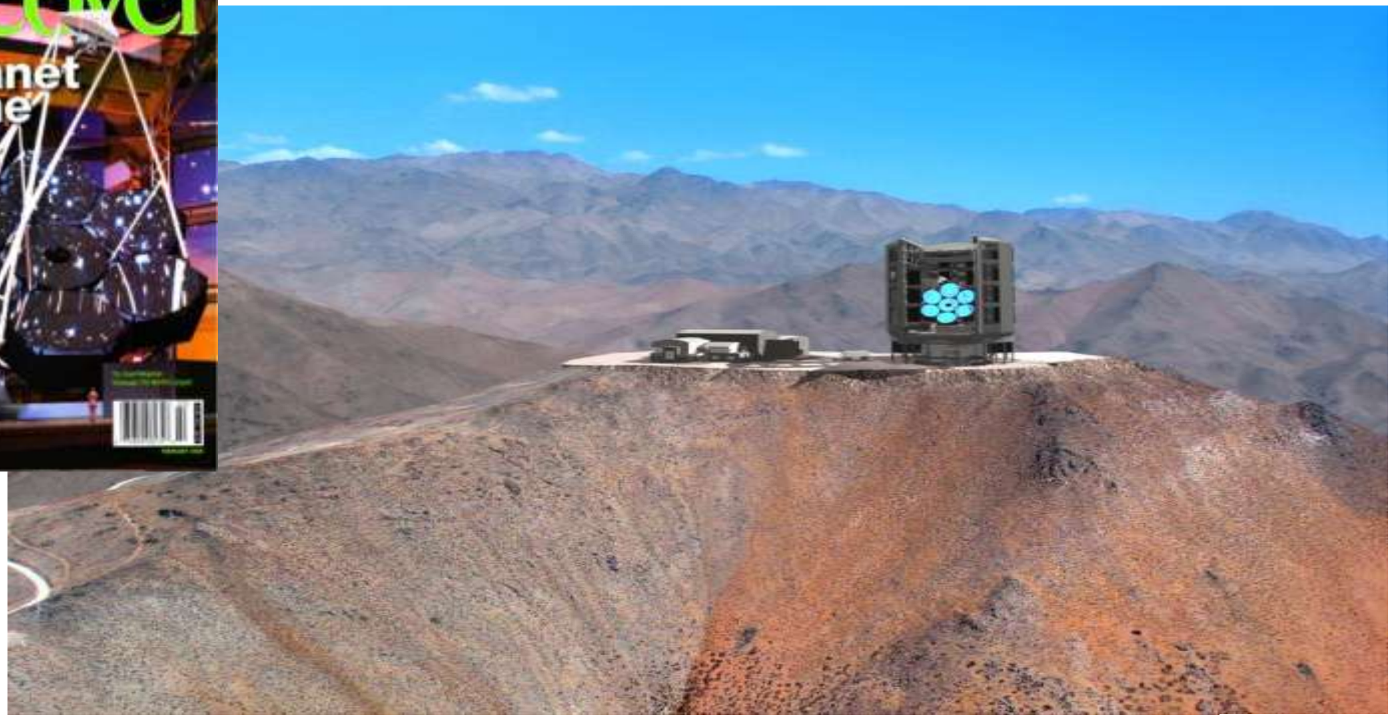
Geneva ultrastable etalon can bootstrap stability of comb lasers across optical band and bridge gaps in frequency coverage.



See Wildi et al. 2010 "A Fabry-Perot calibrator of the HARPS radial velocity spectrograph: performance report", Proc. SPIE 7735-181

Laser combs in the ELT era

Laser combs in the ELT era - The GMT-CfA Large Earth Finder (G-CLEF)

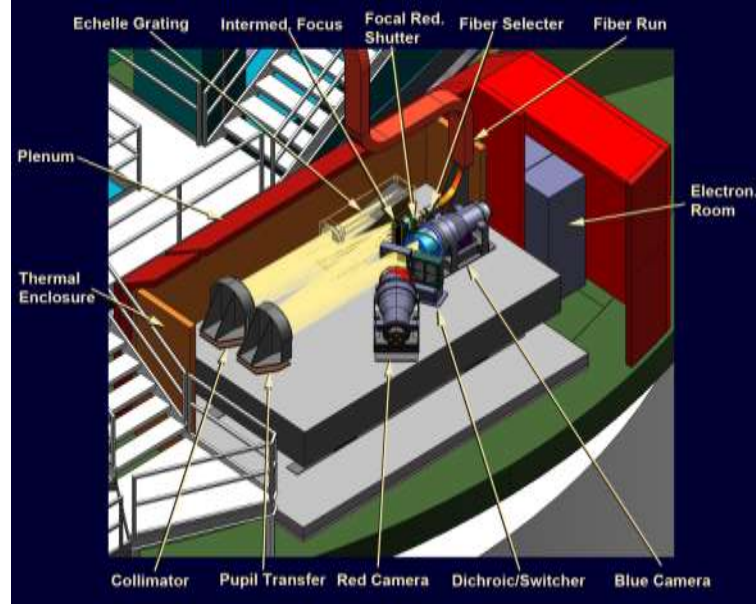


The Giant Magellan Telescope
Australia (AAL, ANU), U. of Arizona, Carnegie, U. of Chicago, Harvard U., Korea (KASI), Smithsonian, U. of Texas, Texas A & M

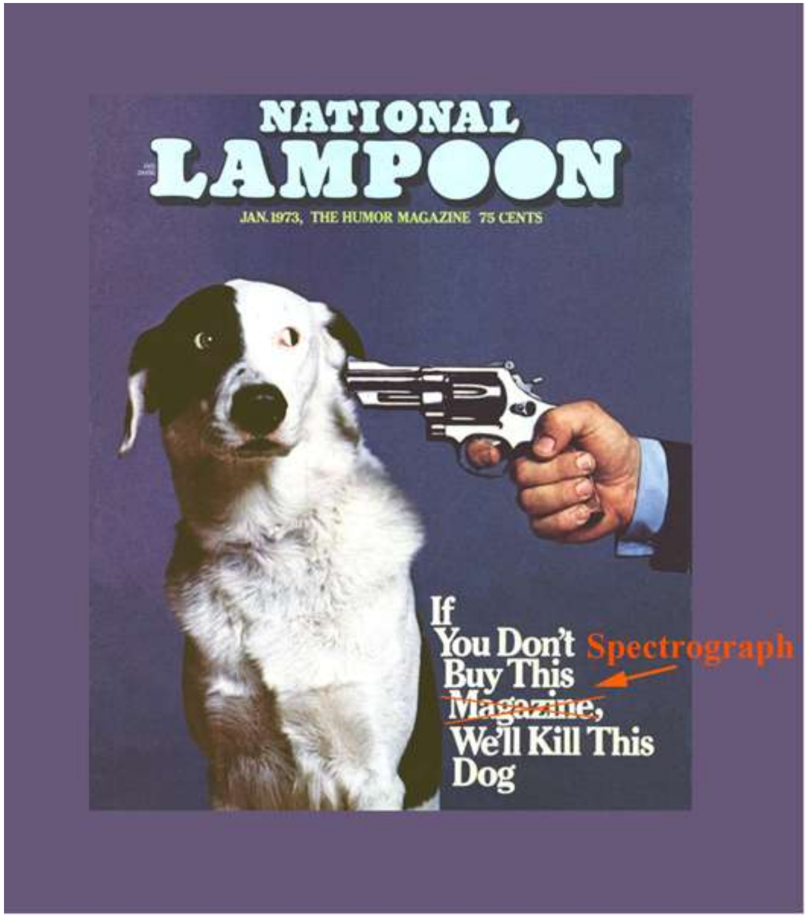
G-CLEF
Smithsonian, Harvard U., U. Catolica

G-CLEF Parameters

- Passband 3500Å – 9500Å
- Two arm (red/blue) camera
- Selectable resolution ~ 20,000 – 150,000
- Grating 300 mm x 1200 mm, R4
- Fiber feed only
- Beam diameter = 300 mm
- Asymmetric white pupil design
- Vacuum enclosure
- Gravity invariant mounting
- Nested thermal control enclosures
- EPRV science requires pupil slicing 25m primary into 8.4m subapertures

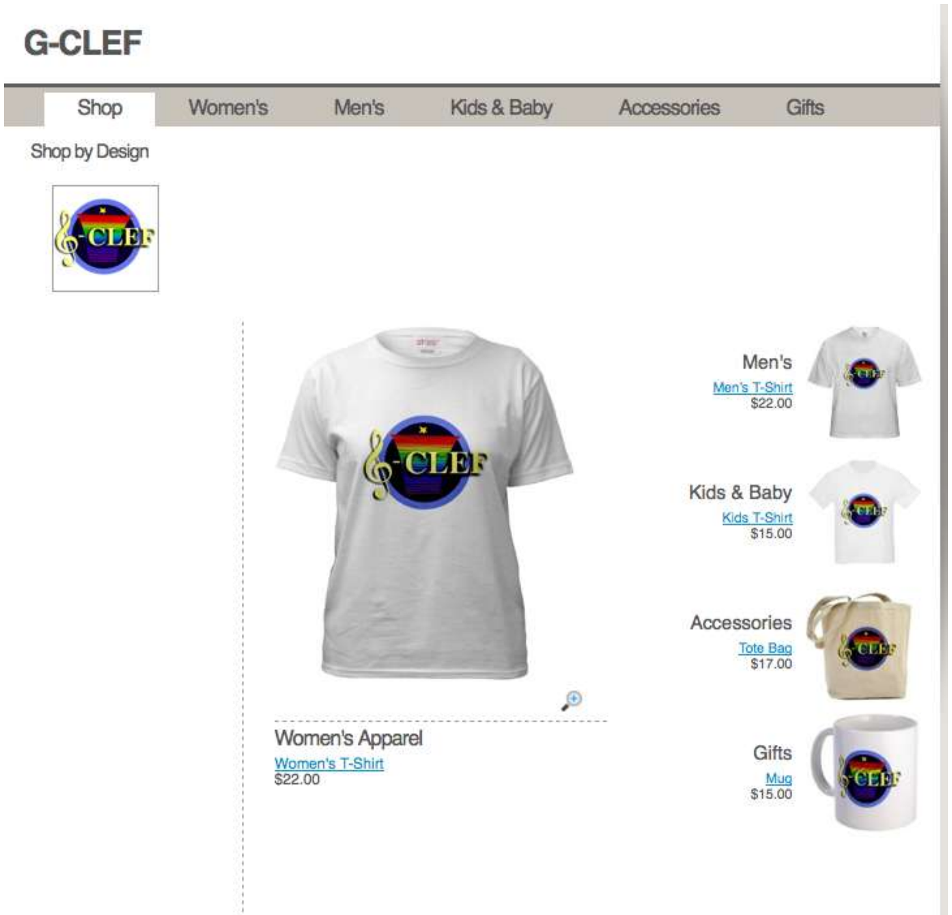


Why do we need G-CLEF (The Hard Sell)



Warning: G-CLEF is the only PRV-capable instrument being considered for any US ELT

G-CLEF Franchise-ware



http://www.cafepress.com/GCLEF1

All Profits to the G-CLEF Foundation to support needy PIs, engineers and scientists