Modest Resolving Power Spectrometers for the 25 Meter Telescope

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Low Resolution Spectrometer

- In a low background situation, all other things being equal, the detection of phase and its associated "quantum noise" ensures that a direct detection spectrometer will be more sensitive than a coherent spectrometer
- The things that must be equal are:
  1. System throughput, including detective quantum efficiency
  2. Coupling to the telescope
  3. Background must be high enough (or detector sensitive enough) to ensure background performance for direct detection spectrometer
  4. Can the direct detection spectrometer achieve the requisite resolving power?
  5. Spectral multiplexing --- natural for heterodyne systems with reasonable mixer bandwidths – an added complication for direct detection monochometers

Low Resolution Spectrometer

- Most extragalactic line widths are > 30 km s^{-1}, so that R ~ 10,000 is sufficient for optimal line detection
- More often, for distant, unresolved galaxies, and in galactic nuclei, line widths will be quite a bit larger ~ 200 to 300 km s^{-1}, or R ~ 1000 to 1500
- R = 1500, requires a phase delay path length of d = $\lambda \cdot$ 1500 or 30 to 68 cm at 200 to 450 um
  - For an FPI, with finesse ~ 30, this is only 0.5 to 1 cm -- one can easily achieve R ~ 10,000 with an FPI.
  - For a single pass grating spectrometer, one needs the full path (divided by 2) for diffraction limited beams, and a bit more for somewhat wider slits – about 20 to 40 cm long
- These sort of resolving powers are easily achieved with direct detection instrumentation at these wavelengths.

Low Resolution Spectrometer

- What are the requisite detector sensitivities?
  - The spectrometer throughput, $\eta_{spectrometer}$
  - The detector quantum efficiency, η_{dqe}
  - The temperature, T of the background – note that photon bunching is important
  - The warm emissivity, ε, of the background
  - The resolving power, R
  - The solid angle, Ω, that the detector subtends on the sky

Low Resolution Spectrometer

- What are the requisite detector sensitivities?
- For η_{dqe} = 80%, $\eta_{spectrometer}$ = 32%, T = 260 K, and Ω = 1.07 λ^2/A the photon noise limited NEP_{detect} referred to the detector is:

Wavelength	$\eta_{telluric}$	ε_{warm}	NEP_{detect}	NEF_{sky}
200 um	21%	81%	5.0E-17	1.7E-17
350 um	68%	40%	2.1E-17	1.1E-18
450 um	70%	35%	1.6E-17	7.9E-19
620 um	65%	36%	1.3E-17	8.7E-19
740 um	90%	13%	5.3E-18	1.9E-19
870 um	95%	7%	3.3E-18	1.1E-19

- So, for R ~ 1000, the most demanding wavelength is 850 um, for which the detector NEP needs to be ~ 10^{-18} W-$Hz^{-1/2}$
- For the short submm, more modest NEPs are required (and the quantum noise is higher, and bandwidth per GHz is larger) $\Rightarrow$ so one could make an argument for focusing here for direct detection systems.

Grating, or FPI?

The choice between a grating and an FPI is largely science driven

- Gratings can easily be made to spectrally multiplex, but it is more challenging to make a grating that also spatially multiplexes
- An FPI can achieve the best resolving power – throughput product. It is a natural for spatial multiplexing, but not for spectral multiplexing
- An FTS? It is easy to show that if the spectrometer is background limited, an FTS will yield inferior sensitivity

Grating Spectrometers

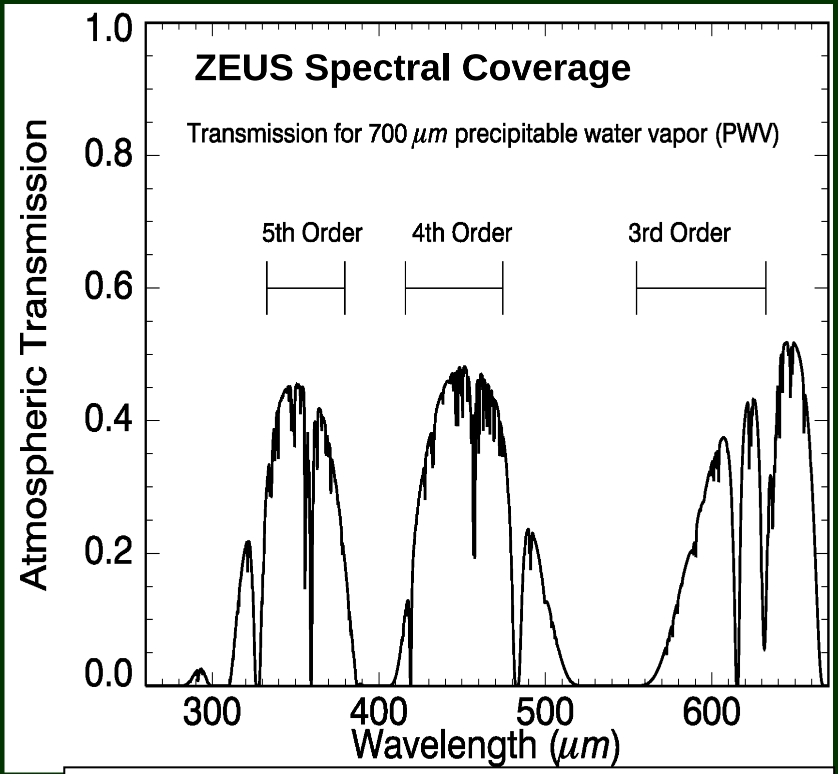
- *If one wishes the highest sensitivity in a single line over a modest field of view, one should build an integral field spectrometer*
  - *Different slit positions are imaged onto different sections of a 2-d array*
  - *Resolving power and spectral coverage are sacrificed here*
- *If one wishes the most bandwidth coverage for point source detection, one should build an echelle grating spectrometer*
  - *Different orders of the echelle can be tuned to different telluric windows*
  - *The 2-d array can be arranged as to give full instantaneous coverage of a telluric window*

To maximize point source sensitivity,and to facilitate line searches (particulary redshifted [CII]) we have constructed an echelle grating spectrometer we call ZEUS

The Redshift (z) and Early Universe Spectrometer (ZEUS)

- An echelle grating spectrometer
- *R ~ 1000 in three telluric bands: 350, 450, and 620 um (5th, 4th, and 3rd order of the echelle)*
- *Diffraction limited beams (~ 6" and 10" on JCMT)*
- *4 $\times$ 64 pixel array of GSFC TES sensed pop-up detectors*
- *Detectors are undersampled so that 64 pixels yields ~ 64 resolution elements thereby maximizing spectral coverage*
- *Requisite detector sensitivity ~ 1 $\times 10^{-17}$ $WH^{-1/2}$*

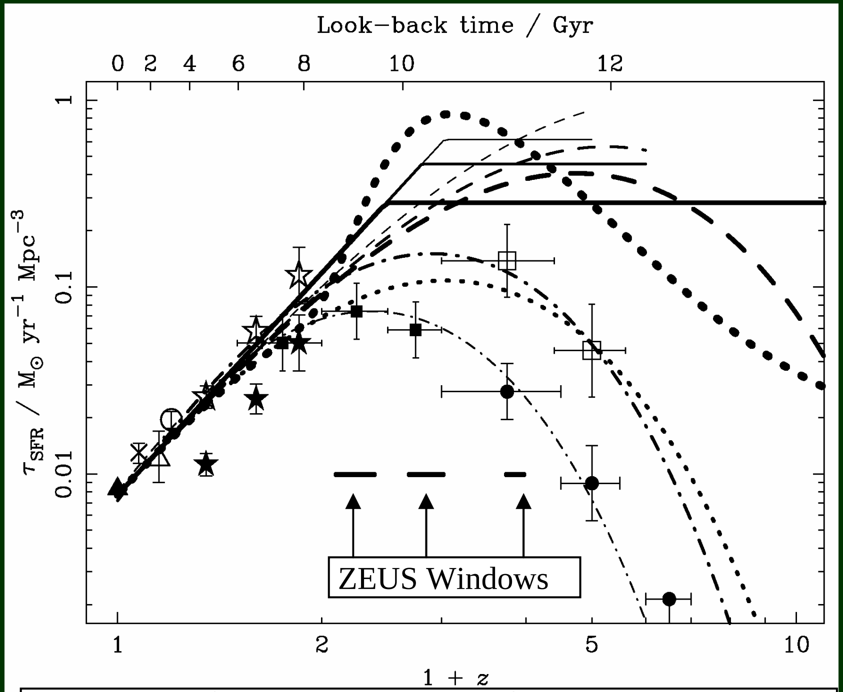
Currently testing the system with 1 $\times$ 32 pixel thermister sensed array



Spectral coverage of ZEUS, superposed on the Mauna Kea windows.

The Redshift (z) and Early Universe Spectrometer (ZEUS)

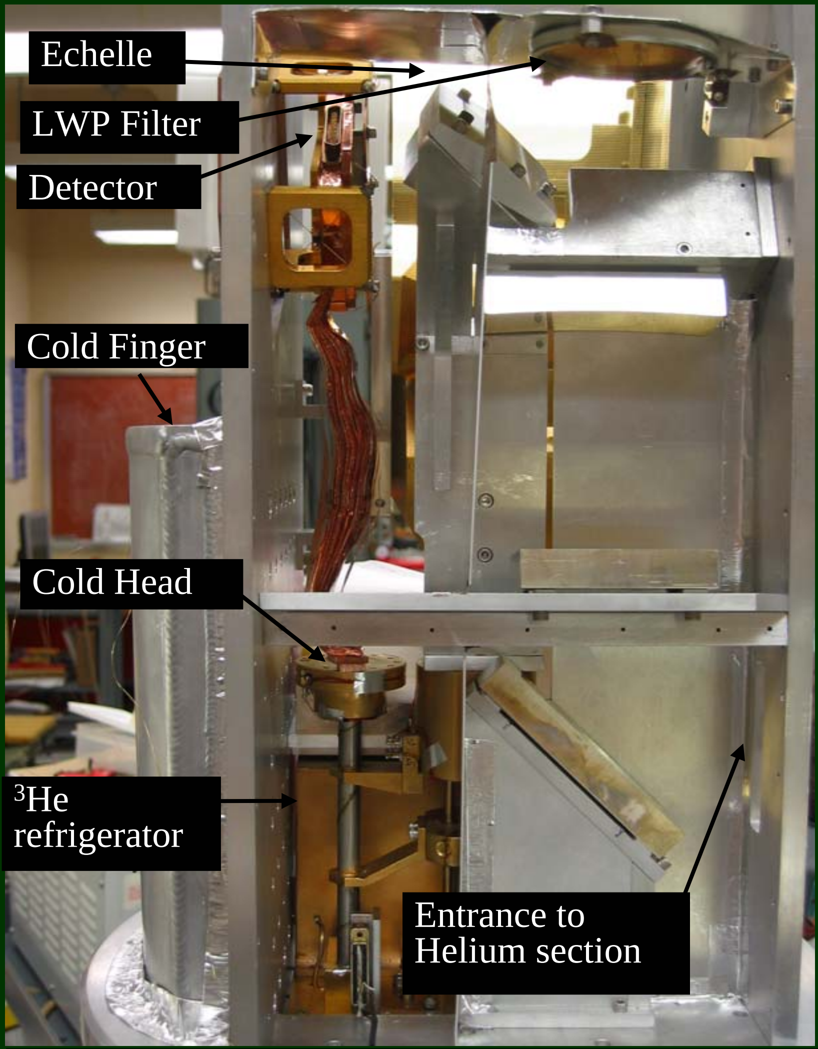
- ZEUS can detect redshifted [CII] from and SCUBA source that falls into the telluric windows
  - *SNR ~ 40 to 20 from z =1.2 to 2.9*
  - *Probability ~ 40%*
- *Covers just the region of redshift space where the most evolution per co-moving volume occurs*
- *On a the 25 m telescope would go a factor of 25 deeper still*



Estimates of the comoving star formation history (B5). Filled squares and circles toward the bottom represent the original Madau plot based on optical/UV HDF observations (M4). Open squares correct this data for dust extinction (P3). The 7 upper curves are models that are consistent with the SCUBA data. The solid lines beneath the curves mark the redshft ranges accessible to ZEUS.

ZEUS

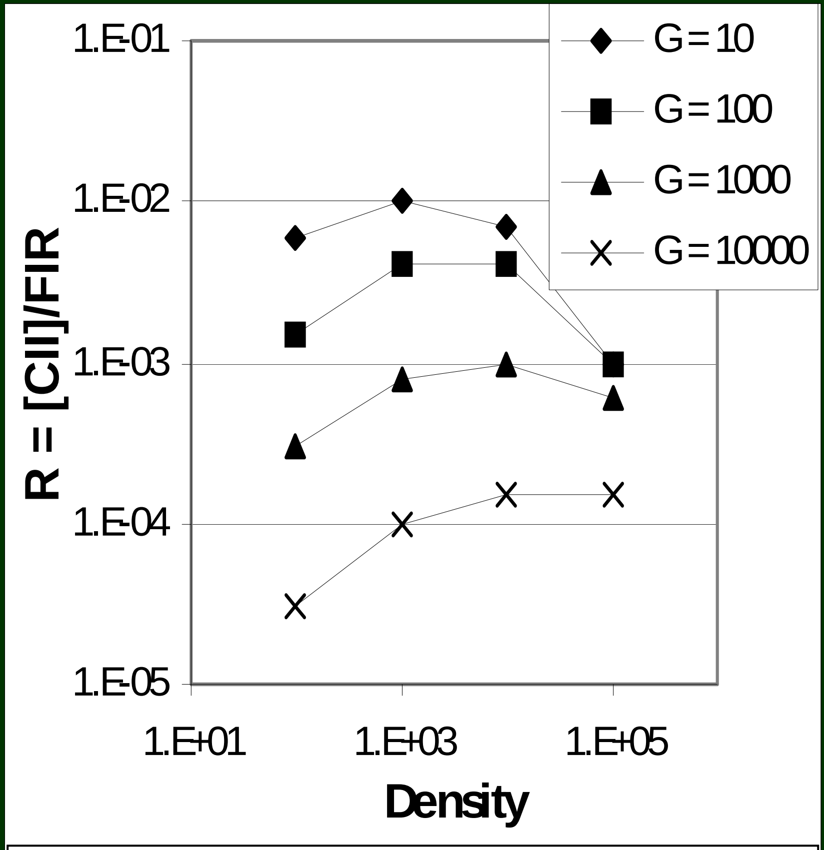
- *Detector sensitivity requirements are modest enough that a dual stage ^{3}He refrigerator (T ~ 250 mK sufices – much less trouble than an adiabatic demagnetization refrigerator*
- *Spectral tuning is easy – turn the grating drive chain*
- *Switching telluric windows is easy – turn a (milli K) filter wheel*
- *Nitrogen and helium cryostats are modified KAO echelle spectrometer cryostat (KEGS – thanks to Terry)*
- *First TES array to arrive quite soon*



Interior of ZEUS with some baffles removed. The collimating mirror is hidden behind the middle wall baffles.

ZEUS and Redshifted [CII]

- *The [CII]/far-IR continuum is a sensitive indicator of the strength of the ambient ISRF*
- *Detection of the line gives a handle on the concentration of the starburst*
- *ULIGS have weak [CII] which may mean AGN contribution, or far-IR arising from dense HII regions*
- *The physics is in the line ratio!*

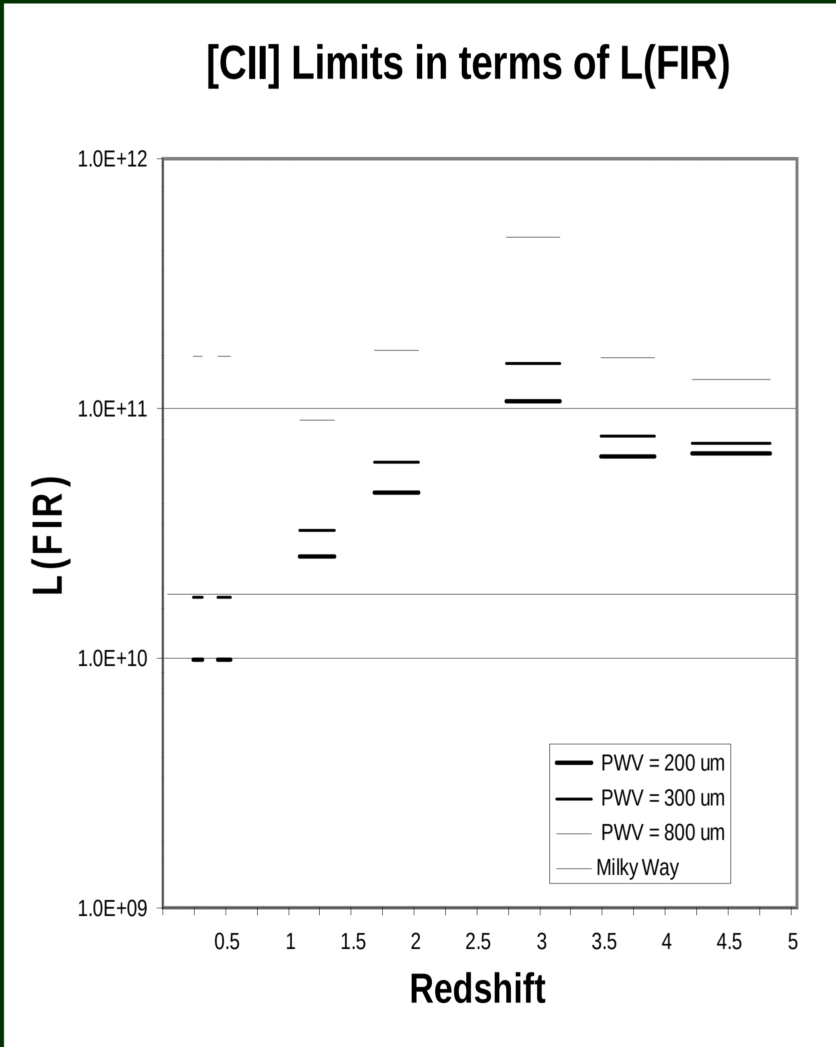


The [CII]/far-IR continuum ratio as a function of G (from Kaufmann et al)

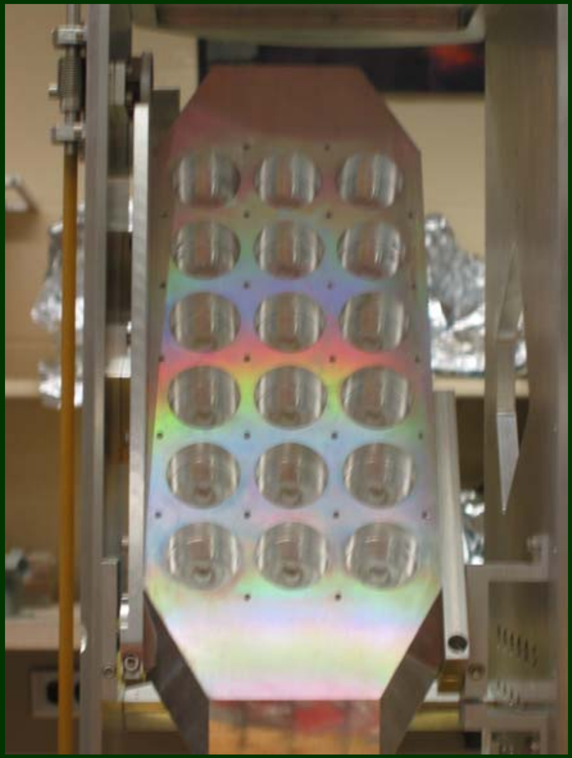
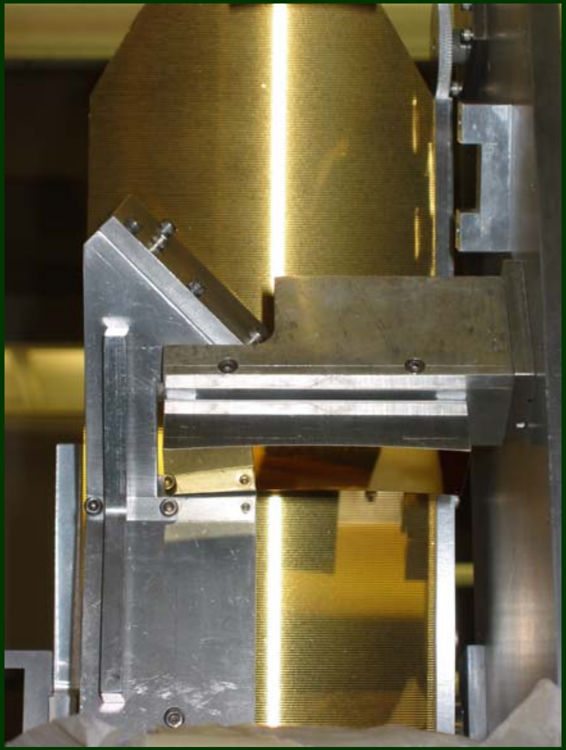
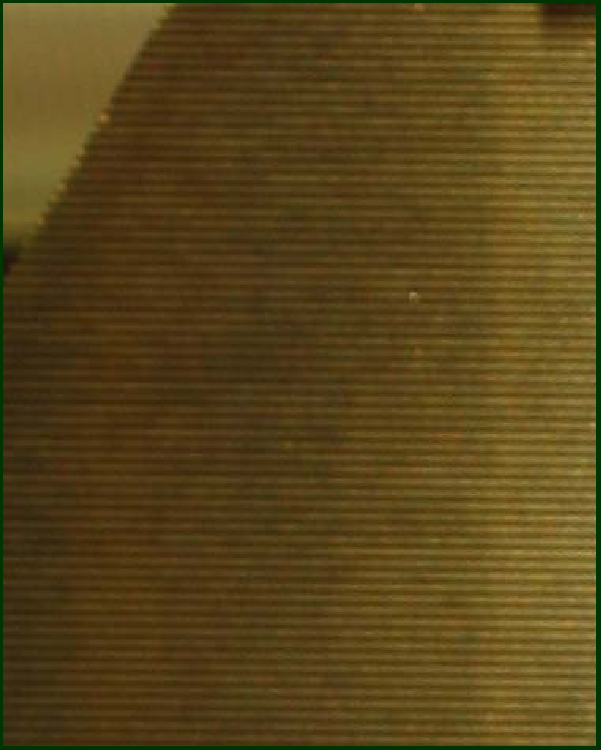
Redshifted [CII] Emission

- *Canonical [CII]/far-IR continuum ~ 0.3%*
- *This ratio is detectable at redshifts in excess of 5 for $L_{far\text{-}IR} > 5 \times 10^{10} L_{\odot} \sim 2 L_{Milky\ Way}$!*
- *ULIGS have $L > 10^{12} L_{\odot}$, and [CII]/far-IR > 0.03% --*

  still detectable!
- *It is the lower luminosity systems that are most interesting with respect to galaxy assembly*
- *[CII] line is uniquely bright, but redshifts can be verified (again with a gain to the physical understanding) by observing the [NII] 122 or 205 um lines.*



ZEUS Grating

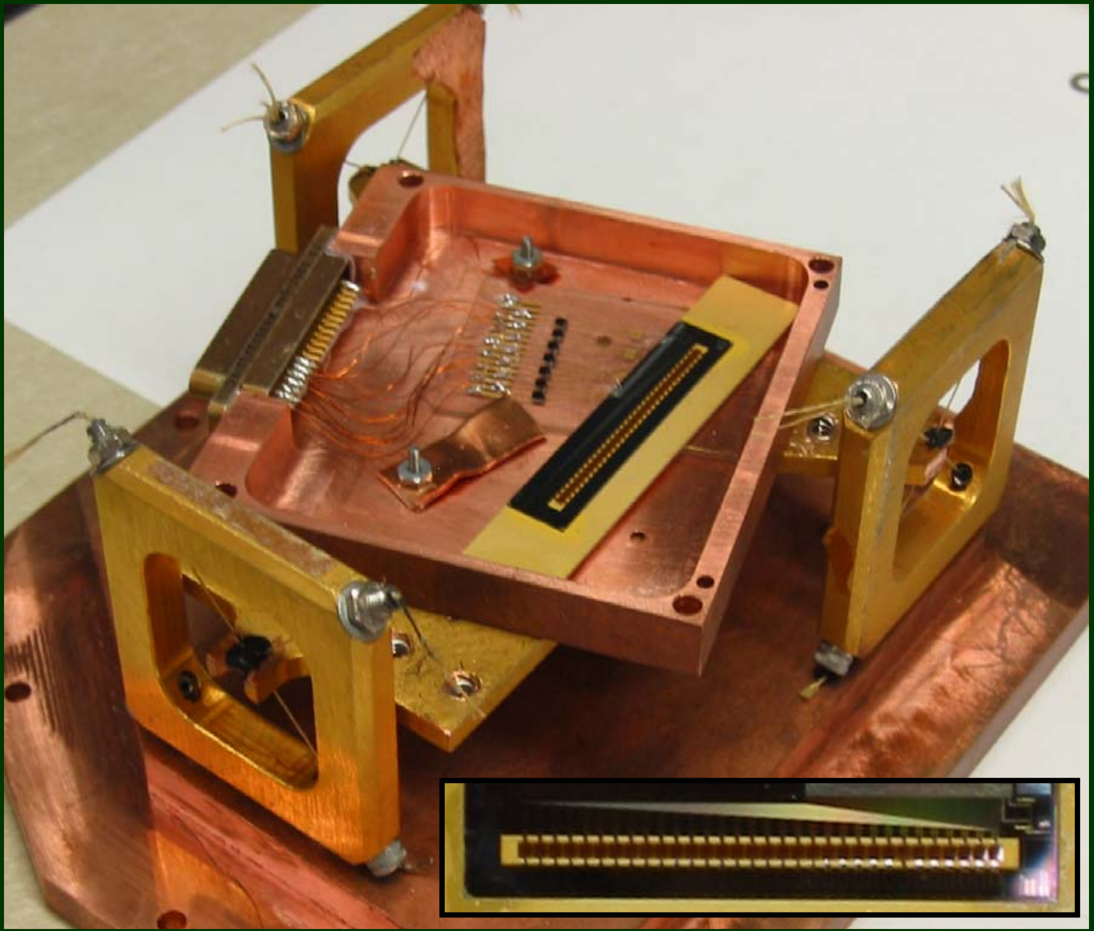
- *Grating is an R2 echelle (blazed at 63.43°)*
- *Blazed at 359 μm in 5th order (groove spacing 992 μm).*
- *The 5th and 4th orders of the grating then nicely cover the 350 and 450 um telluric windows*
- *35 cm long to capture all the light as it is tipped over its entire 57° to 73° range of motion.*
- *Manufactured by Zumtobel Staff GmbH (Austria).*

ZEUS

Putting the “re” into research

ZEUS Array

- *Current test array is 1 $\times$ 32 themister sensed array*
- *Expect delivery of larger format TES array soon*



ZEUS's thermistor sensed 1×32 pixel array in its low thermal conductance Kevlar support system before being installation. **Inset:** close-up of array.

A Strawman Line Search Spectrometer

Echelle grating spectrometer

- Select orders to match windows
- Pick R ~ 1000 to optimally detect extragalactic lines
  - Makes it easier to get broad spectral coverage with modest array formats
  - Makes it easier to be background limited
  - Makes the dewar dimensions modest ~ 1 meter x 0.5 meters
- Need about 200 pixels along the dispersion direction
  - Wish to fully sample
  - Typically, telluric windows are 10% wide, so fully sampling at R ~ 1000 means we need ~ 200 pixels
  - Note that spectral coverage is not much greater than with ZEUS
- Would like as many pixels as possible in cross dispersion dimension, but likely limited to ~ 32 due to optical degradations
- Array format: 32 $\times$ 256
  - Likely TES sensed, SQUID multiplexed bolometers at 250 mK