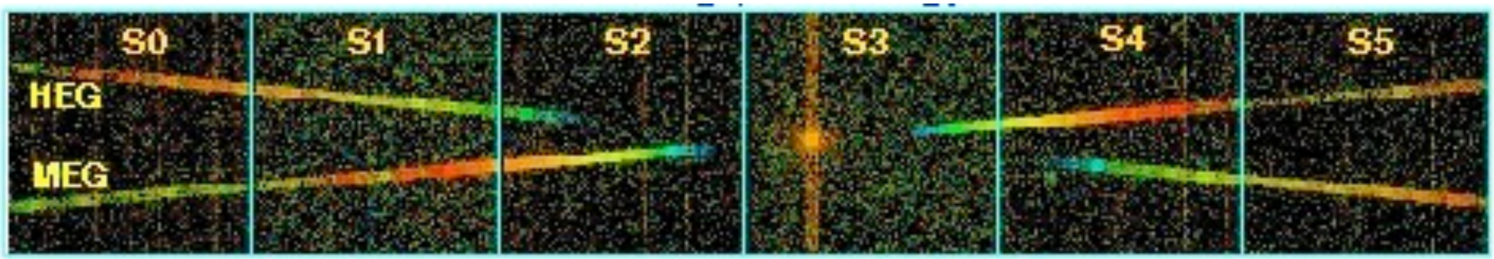
Perspectives on High Resolution X-ray Spectroscopy



Rewards and Challenges

Claude R. Canizares

MIT

July 11-13, 2007

X-ray Spectroscopy Workshop

Cambridge, MA

Rewards of High Resolution X-ray Spectroscopy

Spectroscopy puts most of the "physics" into X-ray astrophysics

See next three days of talks….

Challenges of High Resolution X-ray Spectroscopy

- Instrumentation:
  - Spectrometers are always hard to build
  - X-ray band presents some unique challenges
  - Wave-particle duality meets in the X-ray band
- Data analysis & interpretation:
  - getting out more physics requires putting in more effort
  - high price of entry for observers (perceptions may be even worse than reality)

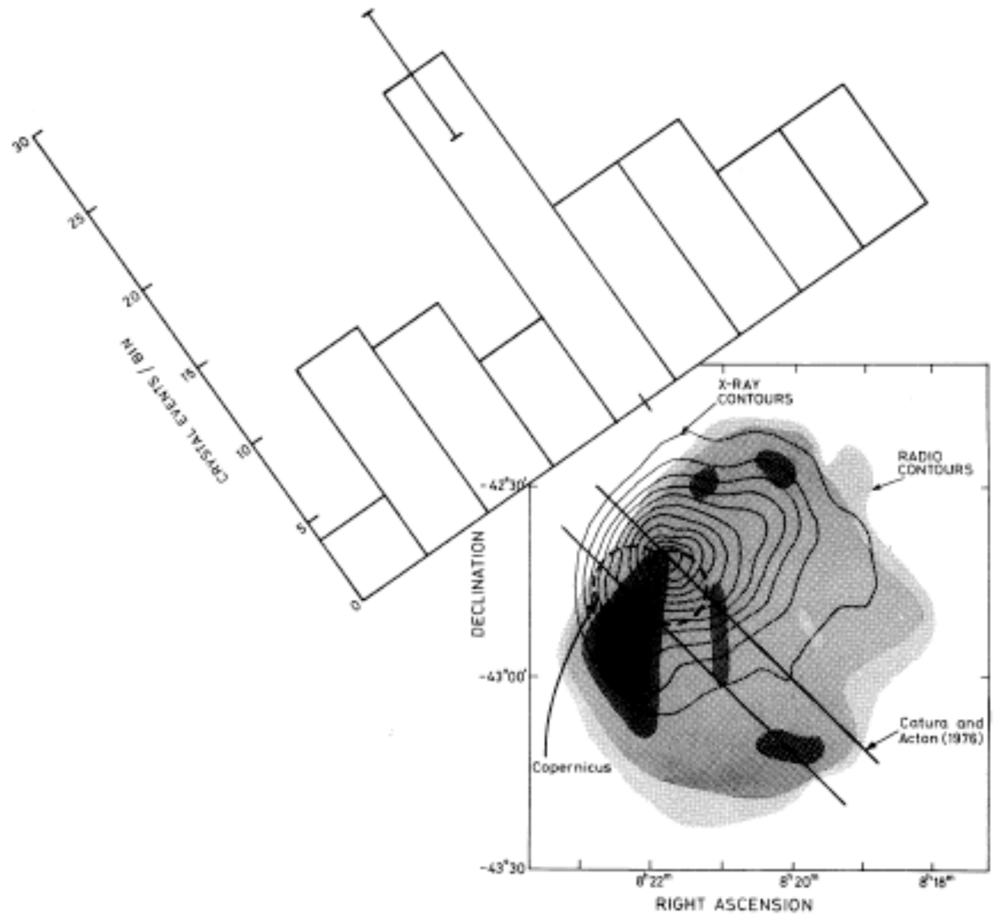


Figure 1. A histogram showing the number of events per Bragg-angle bin of 12 arcmin width, registered during the 160-s observation of the source. The histogram is superimposed on an X-ray map taken from Zarnecki *et al.* (1973). X-ray and radio contours are displayed. Also shown are the regions of soft X-ray emission discussed in the text.

1977

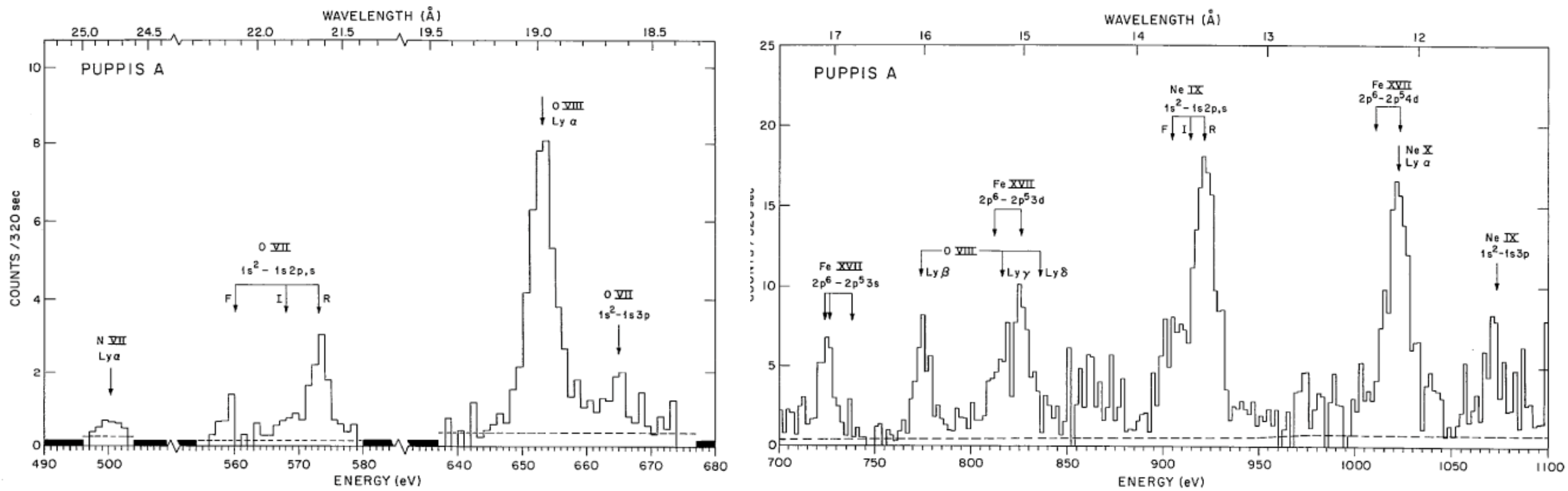
Detection of first X-ray “line” from non-solar source

15 yr after discovery of Sco X-1

6 yr after UHURU

Detection of O VIII Lyα from Puppis A with Bragg crystal spectrometer rocket payload (Zarnecki et al. 1977)

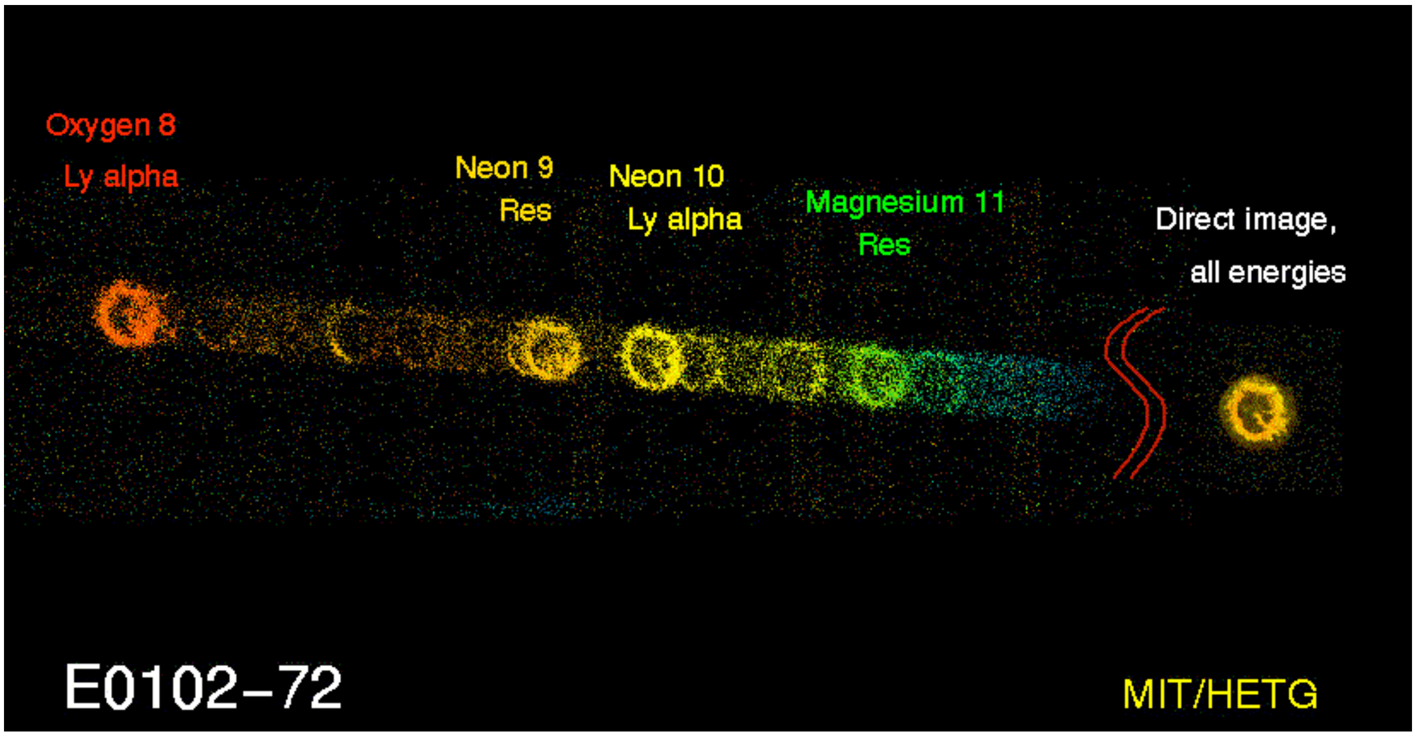
1981 (Uhuru + 10)



Puppis A spectral scan with Einstein Observatory

Focal Plane Crystal Spectrometer (Winkler et al. 1981)

2001 (Uhuru +30, Einstein +20)



Spatially resolved spectroscopy of SNR E0102-72 with Chandra HETG (Flanagan et al., 2001)

Thirty Years of Satellite-borne X-ray Spectrometers

	Dispersive			Non-Dispersive		
Mission	Bragg	TGS	RGS	SSS	CCD	μCal
ANS (74-77)	X					
Ariel 5 (75-78)	X					
OSO-8 (75-79)	X					
Einstein (78-81)	X	X		X		
EXOSAT (83-86)		X				
ASCA (93-01)					X	
Chandra (99-)		X			X	
XMM-Newton (99-)			X			
Suzaku (05-)					X	r.i.p.

Wave-particle duality in X-ray spectrometers

"To Disperse or Not To Disperse"

That is THE Question

Spectrometers require a "standard unit" against which they compare (measure) the incoming radiation

WAVE: A standard of length can be compared to the radiation's wave length λ (generally results in dispersion)

OR

PARTICLE: A standard of energy can be compared to the radiation's particle property, E (no dispersion)

High resolution requires the standard to be precise and "small" relative to the property being measured (necessary but not sufficient)

High sensitivity requires the comparison to be efficient

THERE'S THE RUB!

Spectrometer Complementarity
Cross-over Occurs in X-ray Band

Non-Dispersive $E = h\nu$

Energy Standard (courtesy of nature)

IP, band gap, phonon energy…

$\delta E \sim$ eV (10 ➜ 0.01)

Instruments

- Prop Counters ➜ IPC
- Gas Scint PC ➜ IGSPC
- Si(Li) ➜ CCD
- μCalorimeter
- STJ/TES

Properties

- $\Delta E \sim$ fixed
- Resolving Power = $E/\Delta E \sim E$

Dispersive $\lambda = c/\nu = hc/E$

Length Standard (courtesy of nature or engineering)

crystal lattice spacing (~ Å), grating period (~$10^{2\text{-}3}$ Å)

$\delta x * \theta \sim$ 0.1-0.01 Å

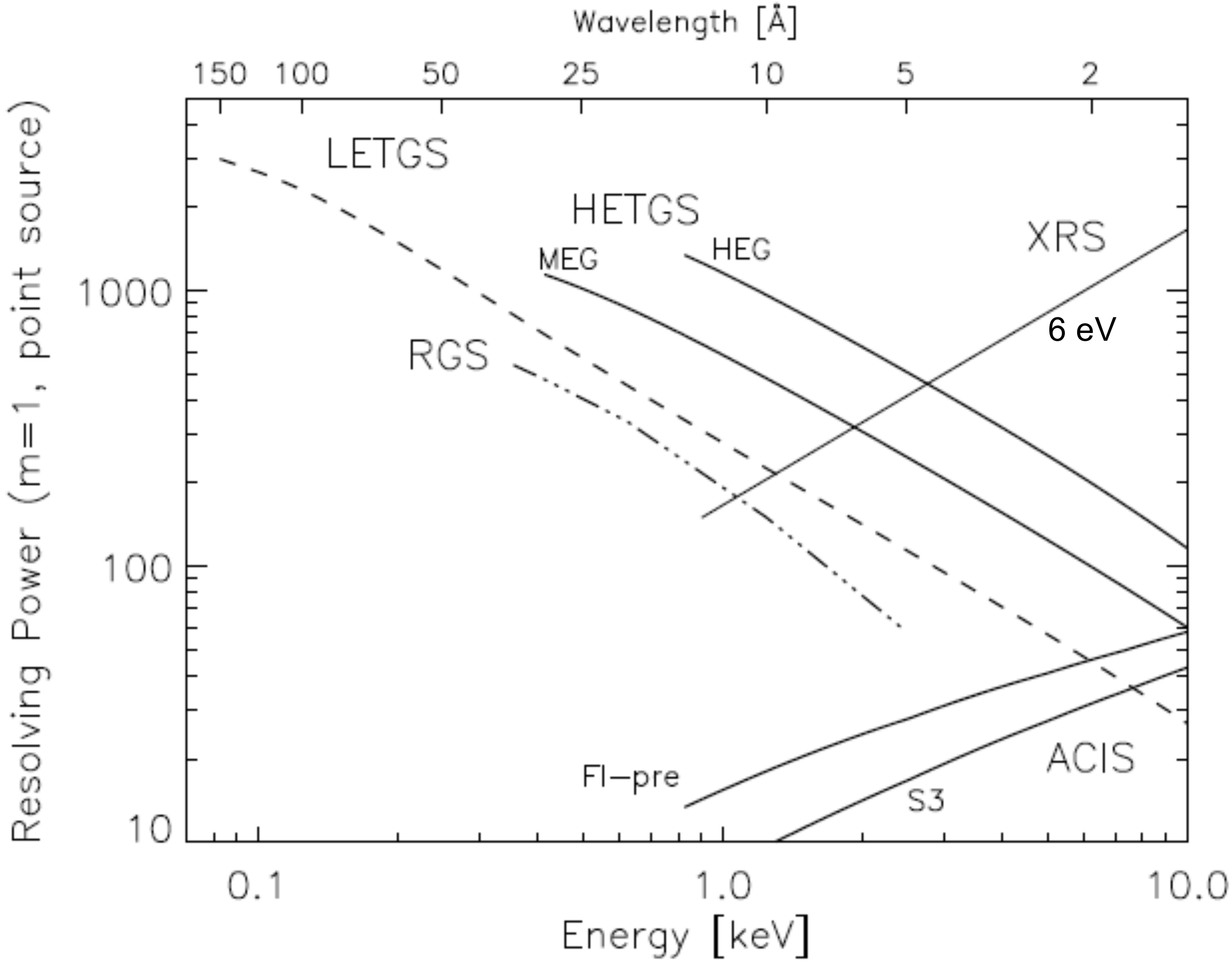
Instruments

- Bragg spectrometers
- Transmission Gratings
- Reflection Gratings

Properties

- $\Delta\lambda$~fixed
- Resolving Power = $\lambda/\Delta\lambda$ ~1/E

Spectral Resolving Power: Chandra, XMM-Newton, Suzaku XRS



Doppler

Plasma Diagnostics

Line ID

Spectral Resolving Power = E/ΔE = λ/Δλ

Canizares et al. 2005

Development of the Chandra High Energy Transmission Grating

<u>20 yr HETG Timeline</u>:

1979-80 CRC & M. Schattenburg collaborate with Henry I. Smith

1983 AXAF RFP (1991/2 launch)

1985 Selected for Phase B study

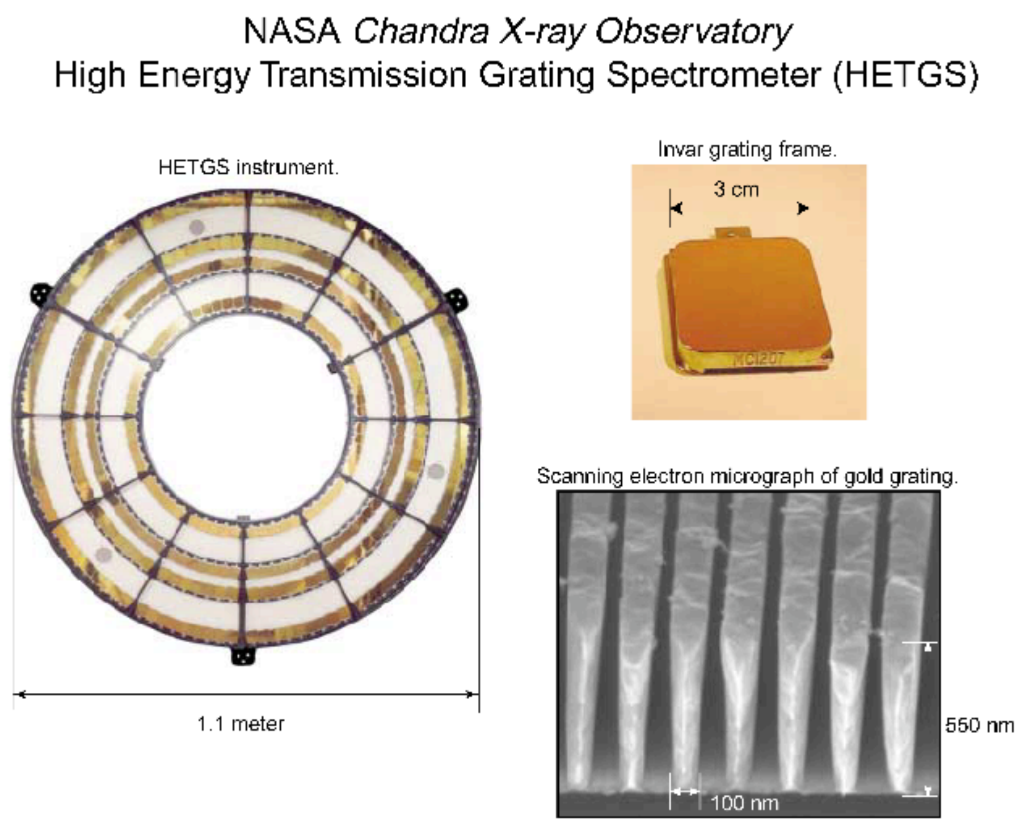
1988 “phased new start” of AXAF (1995/6 launch)

1992 AXAF Restructured (1998 launch)

1995 Critical Design Review CDR

1996 Deliver & Calibrate Completed HETG

1999 Chandra Launch!

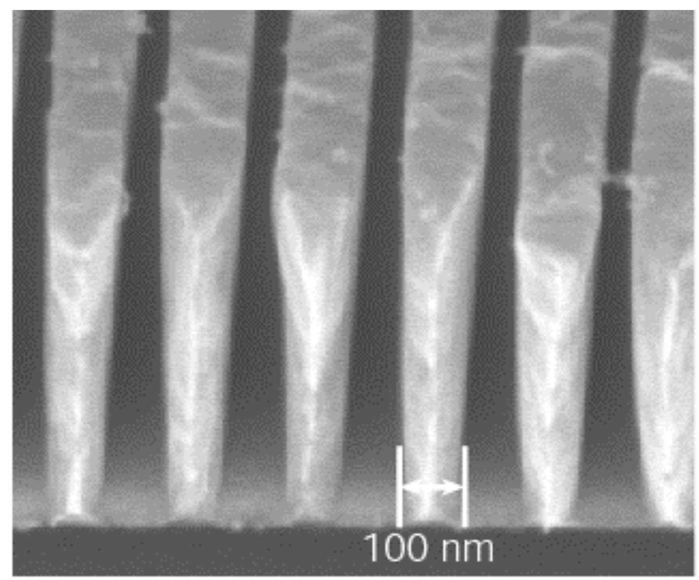


Challenges for HETG Fabrication

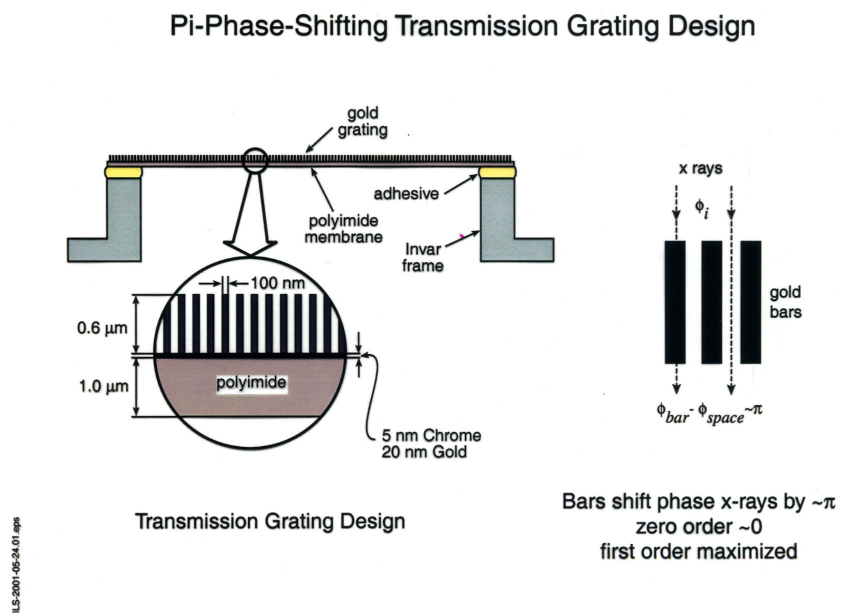
- Spectral Resolution: Achieve grating period of 0.2 μm with precision of < 200 ppm across hundreds of grating facets
- Efficiency over 1.5 decades: Optimize grating bar thickness to provide opacity ~ π phase shift

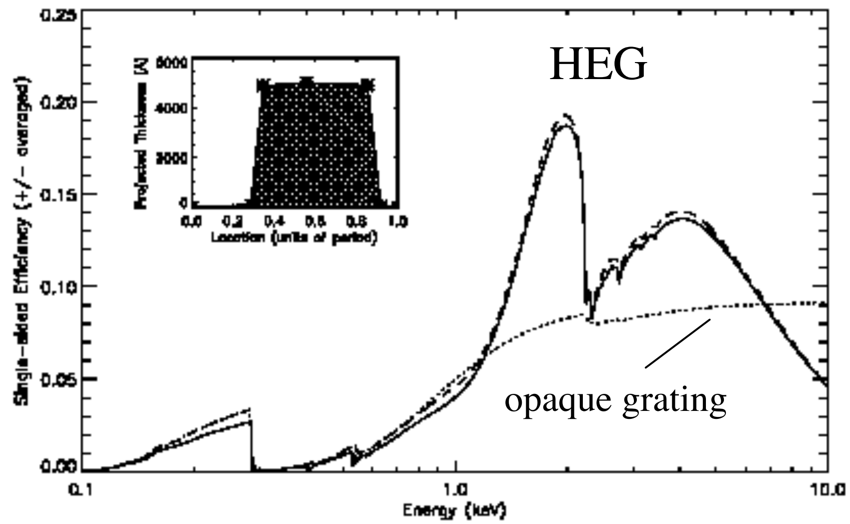
plus

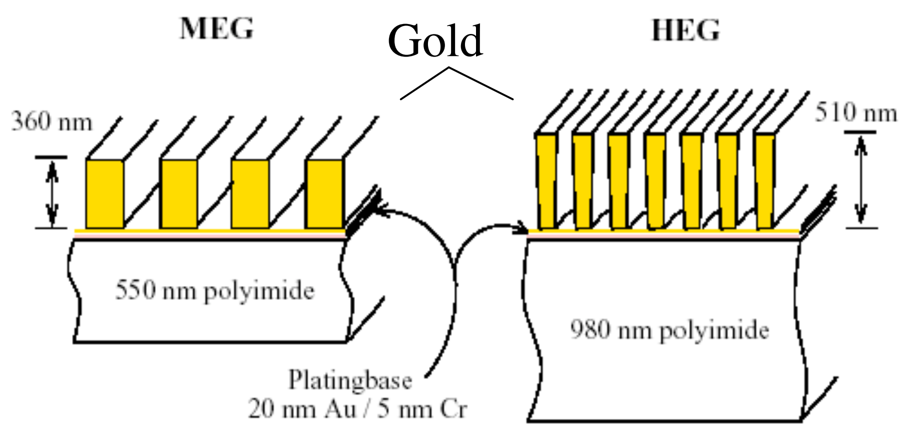
ultra-thin support membranes
high fabrication throughput/yield
measurement & verification
Calibration
Mounting &alignment
Robustness
etc….

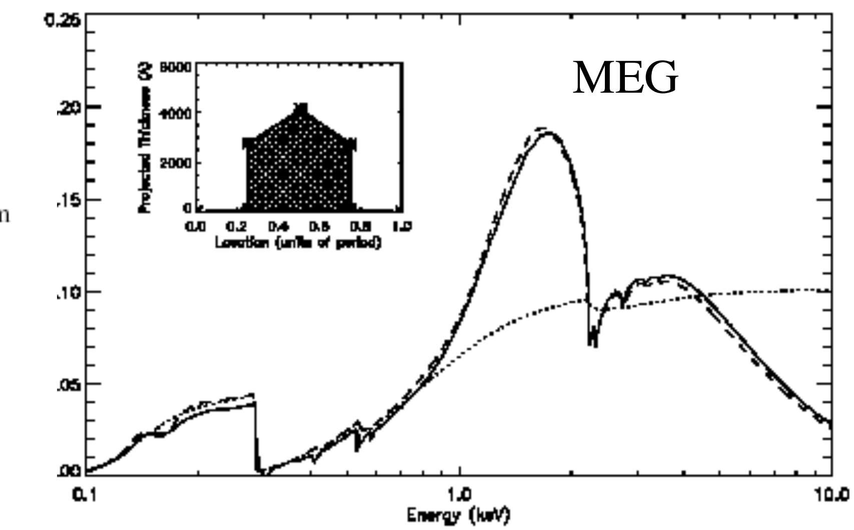


Single-sided grating efficiency (as built)





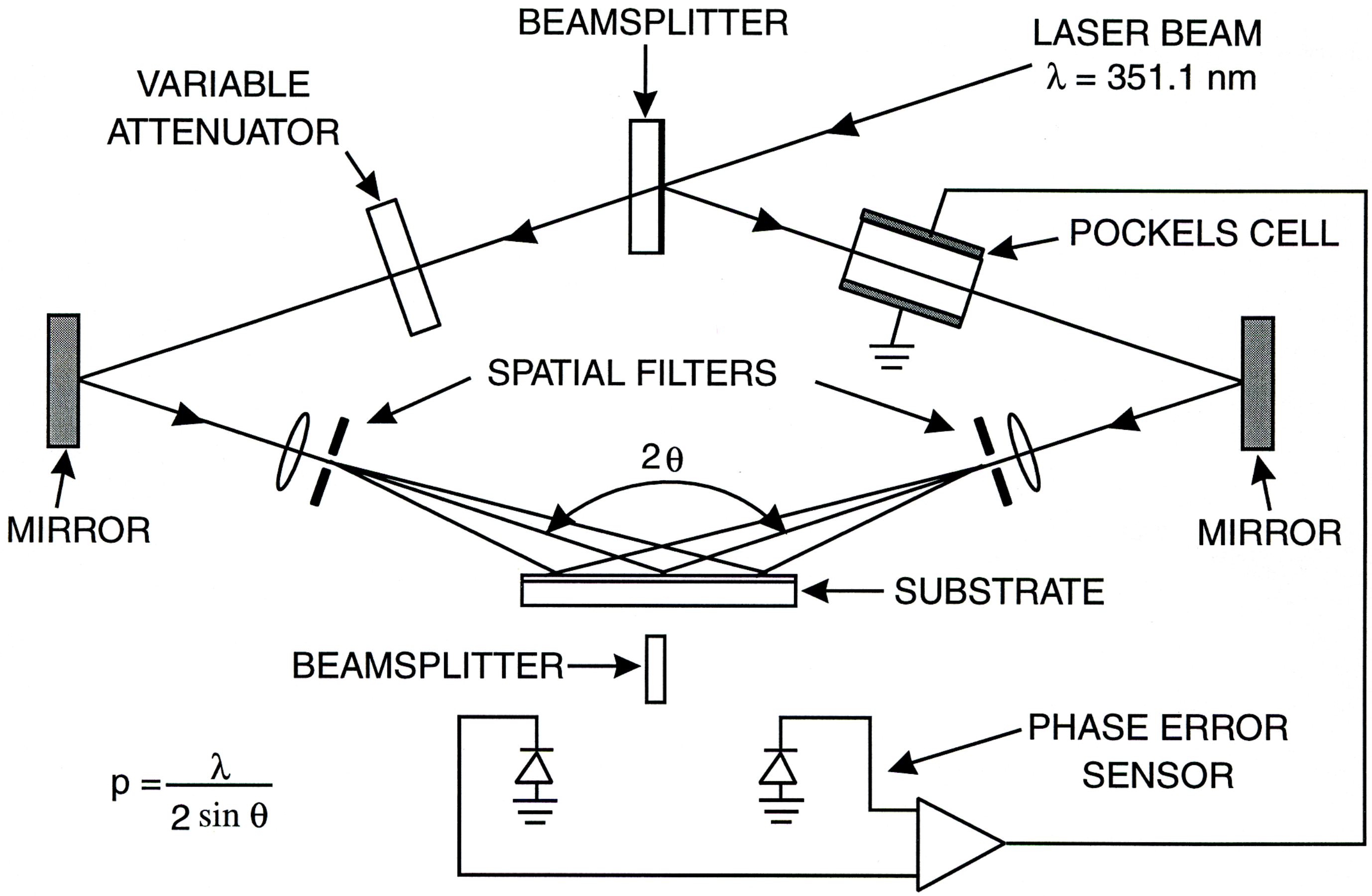




0.1 1.0 E (keV) 10.0

2500 lpmm (0.4 micron period) 5000 lpmm (0.2 micron period)

INTERFERENCE LITHOGRAPHY



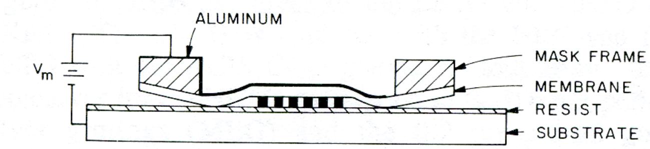
$$p = \frac{\lambda}{2 \sin \theta}$$

X-ray Lithography

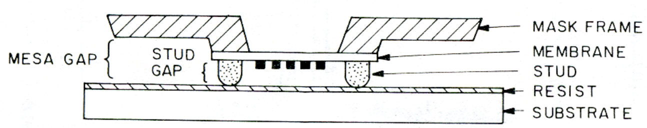
Key technology for replicating a "thin" grating "mask" into many thick, phased gratings with the same period

Fabrication throughput required high intensity, plasma X-ray machine (Hampshire Instruments)

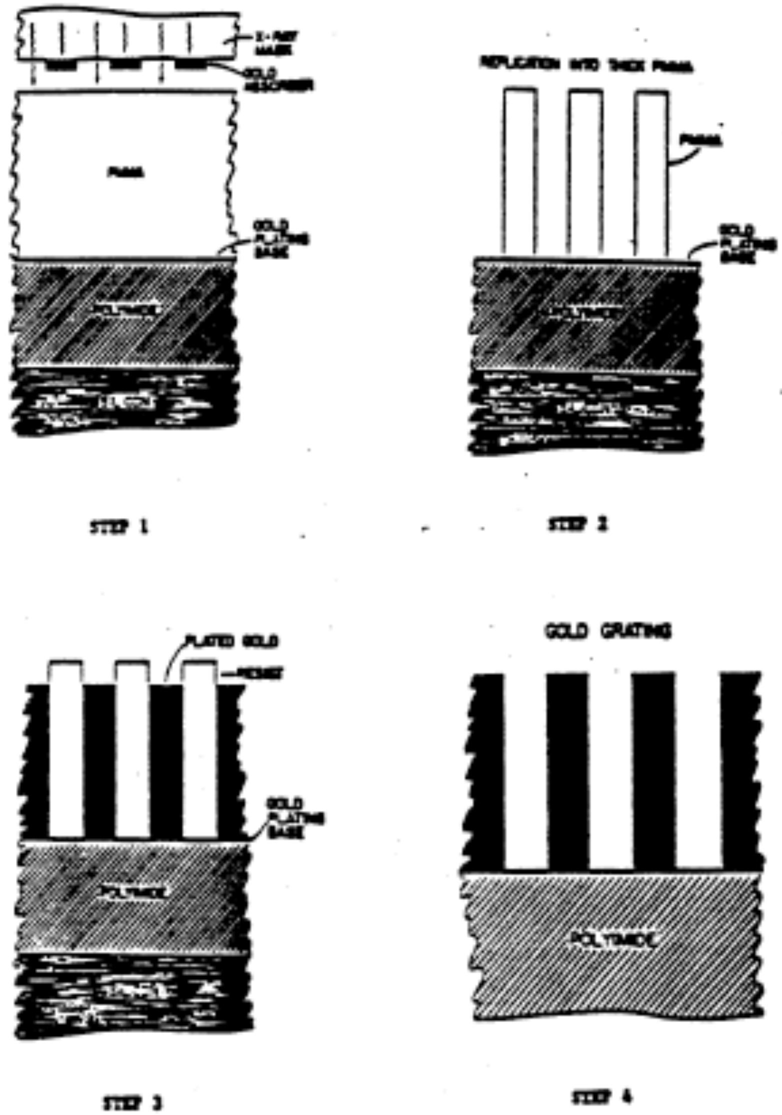
Also requires new micro-gap mask technologies



a) CONTACT X-RAY NANOLITHOGRAPHY



b) MICROGAP X-RAY NANOLITHOGRAPHY



1993 Hampshire Instruments ceases operation

X-ray lithography no longer viable!

Fortunately, thanks to ~14 years of development, Schattenburg had developed the technology to make thick masks

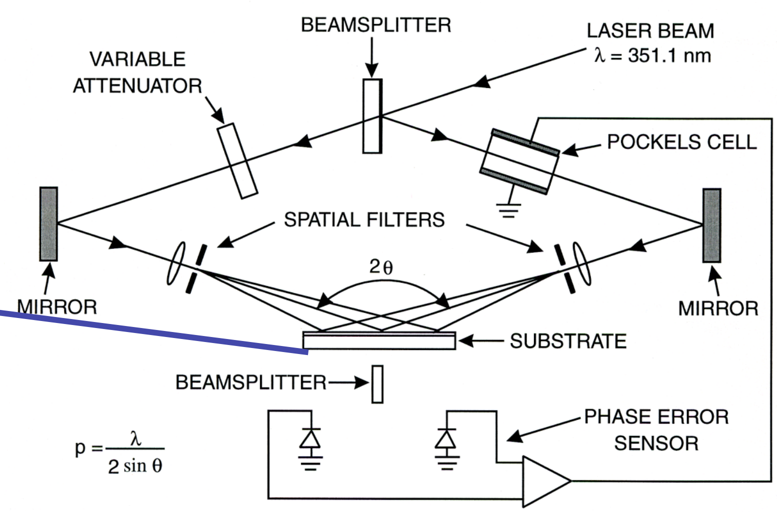
By locking UV interference to standard grating, he achieves < 150 ppm period control over 100's of gratings

Recovery plan allows HETG to continue on schedule and in budget

Observe Moire pattern on standard grating

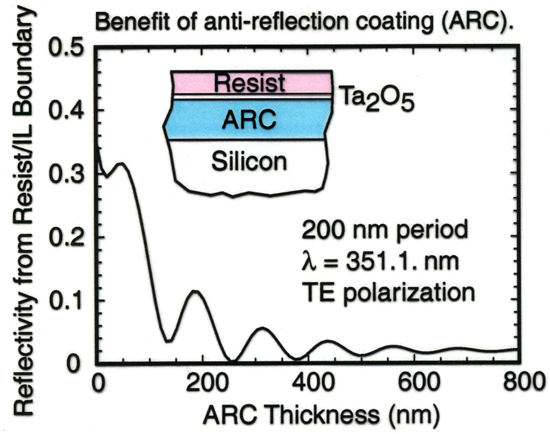
to lock period

INTERFERENCE LITHOGRAPHY

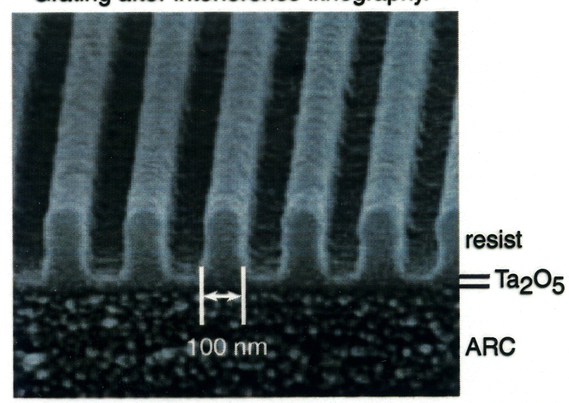


Gold Transmission Grating Fabrication Process

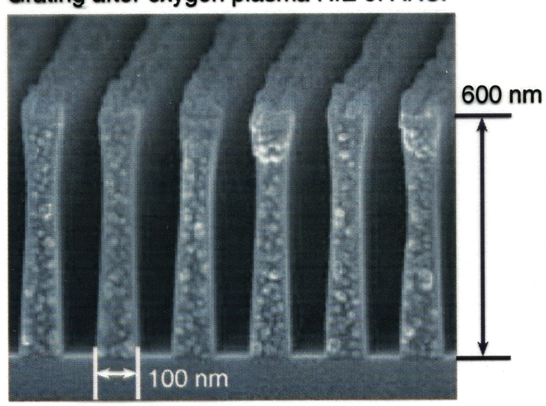
Benefit of anti-reflection coating (ARC).



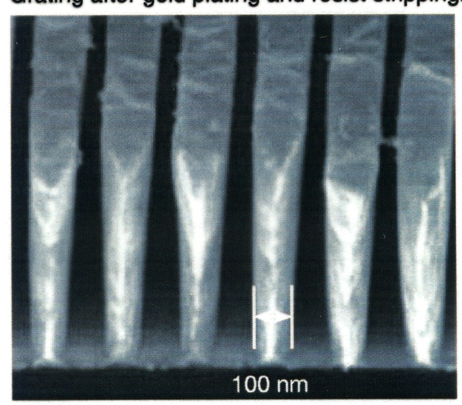
Grating after interference lithography.



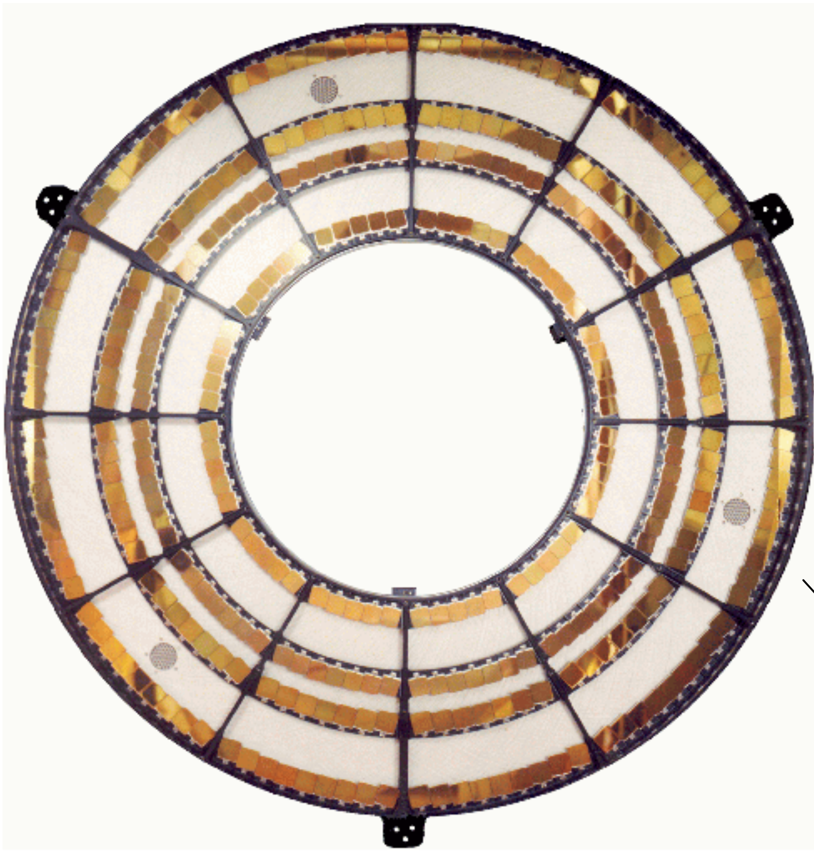
Grating after oxygen plasma RIE of ARC.



Grating after gold plating and resist stripping.



MLS-2001-05-25.02.eps

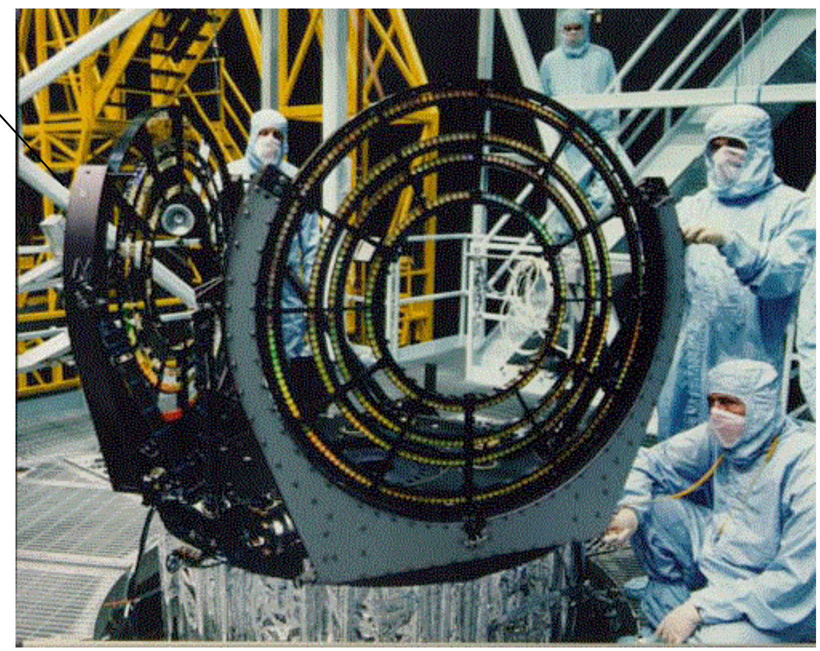


High Energy Transmission Grating

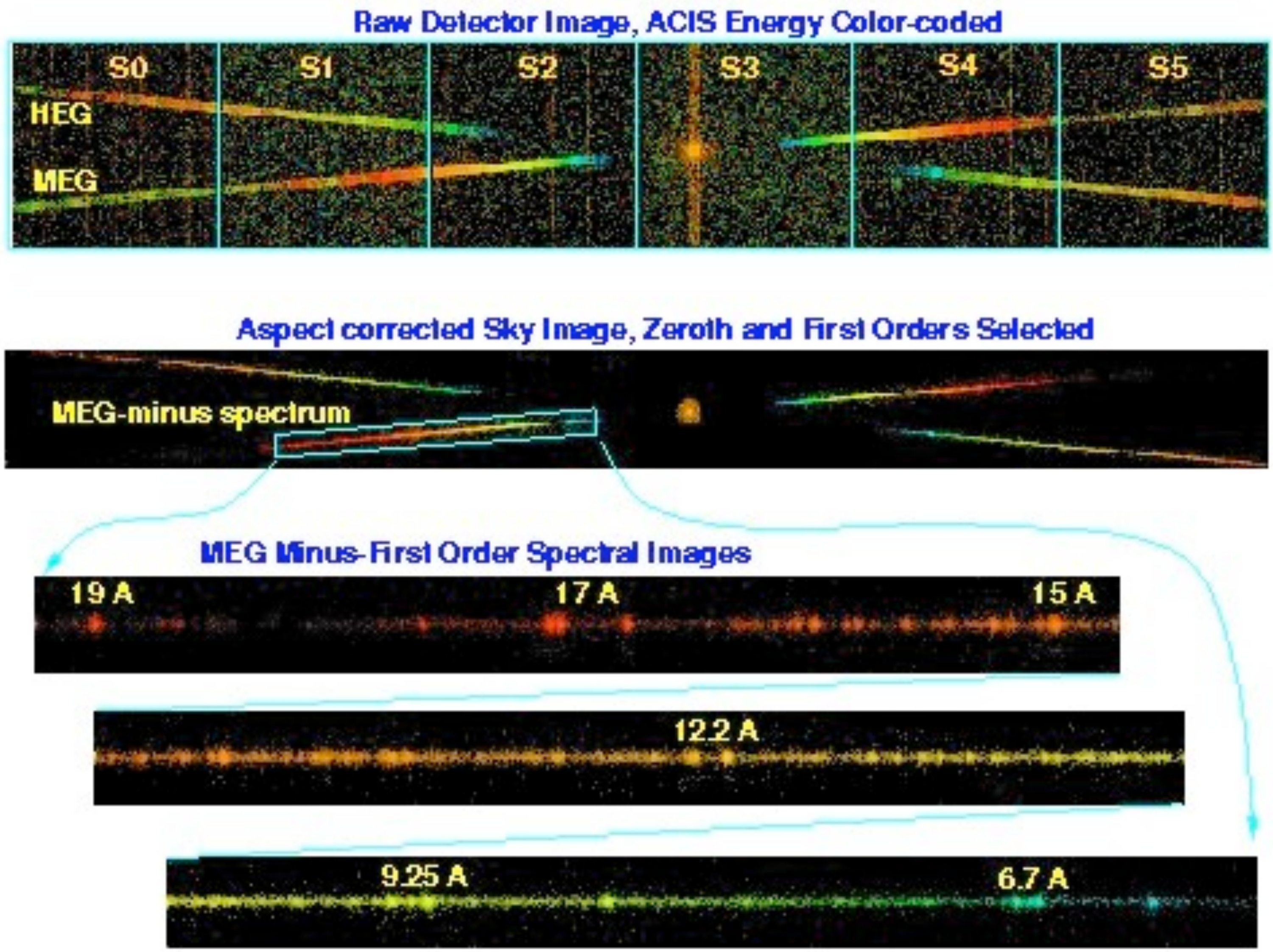
336 grating facets aligned to <1 arc min tolerance

HEG: inner two rings

MEG: outer two rings



HETG observation of Capella



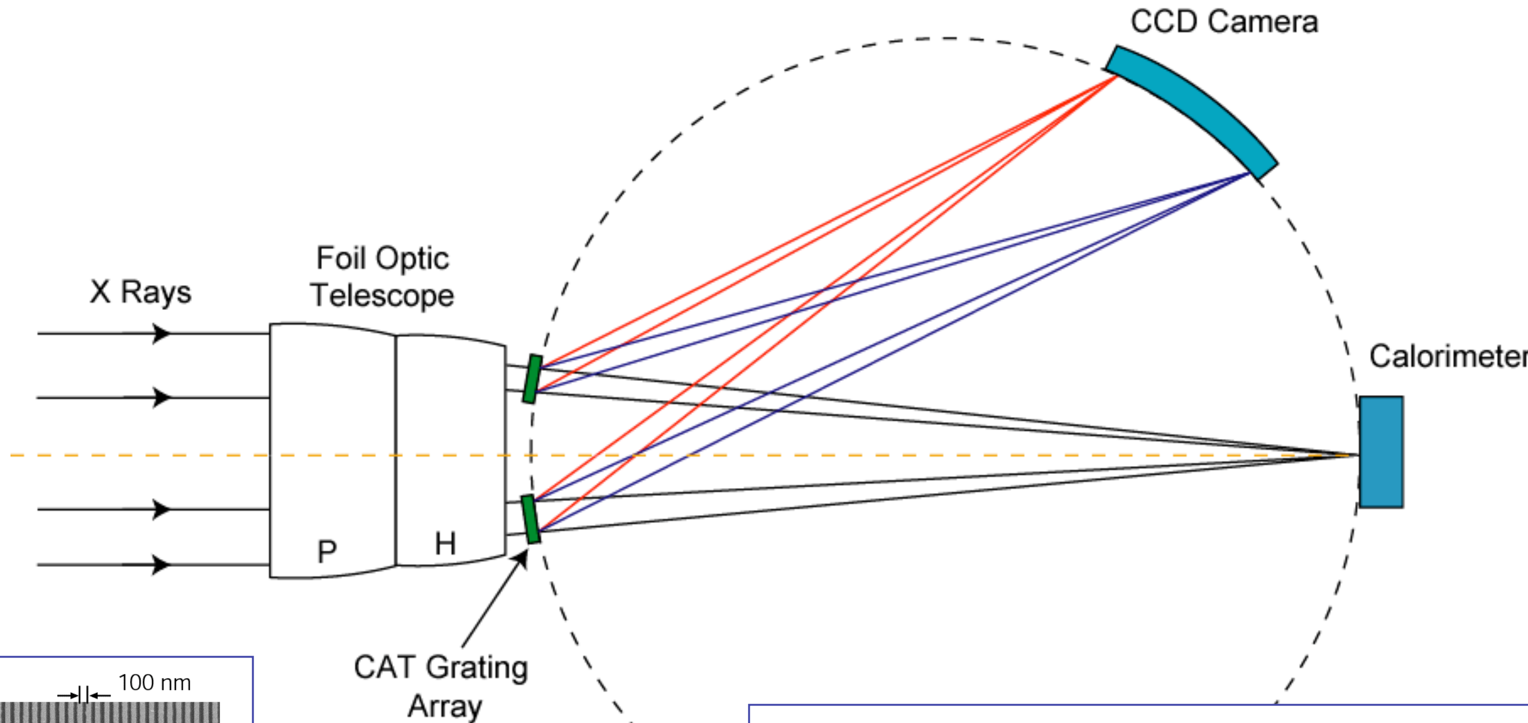
Technology marches on…

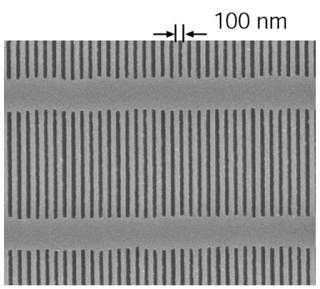
- New breakthrough: Critical Angle Transmission (CAT) Grating
  - 4x higher dispersion
  - 4-5x higher efficiency
  - Blazed for single sided diffraction

- Fabricated using anisotropic etching of Si

(see talk by Ralf Heilmann)

Con-X CAT Grating Spectrometer Concept



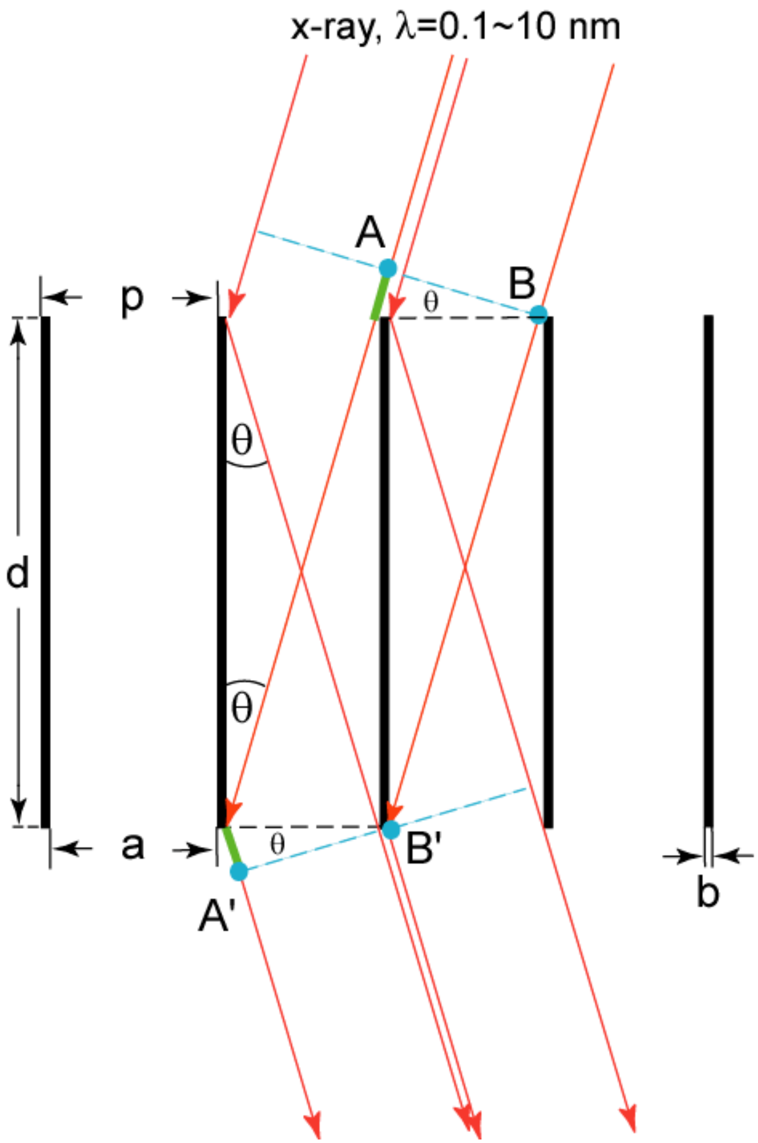


10,000 l/mm transmission grating

Advantages:

- low mass
- relaxed assembly tolerances
- high diffraction efficiency
- 4X dispersion of Chandra HETGS
- no pos. orders (i.e., smaller detector)

Critical Angle Transmission



Constructive interference when:
path length difference (PLD)
between A' and B'

PLD = 2 p sin(θ) = m λ

Blazing: high diffraction efficiency when diffracted order coincides with specular reflection off of grating facet

Refractive index and critical angle for x-ray and EUV :

$n=1-\delta+i\beta$, $\delta<<1$, $\beta<<1$, $\beta\neq0$

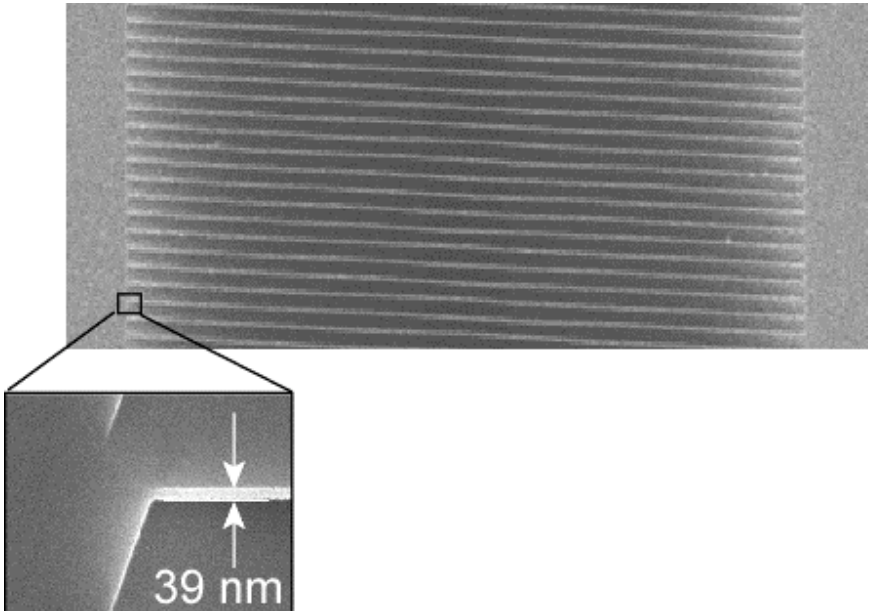
$\theta_c=(2\delta)^{1/2}$: ~1 ~ 2°

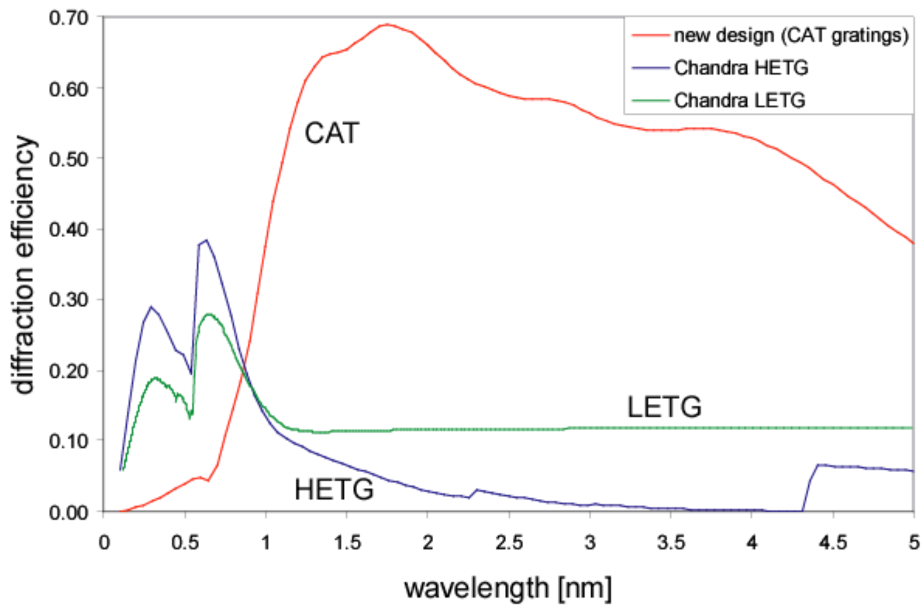
High reflectivity when:

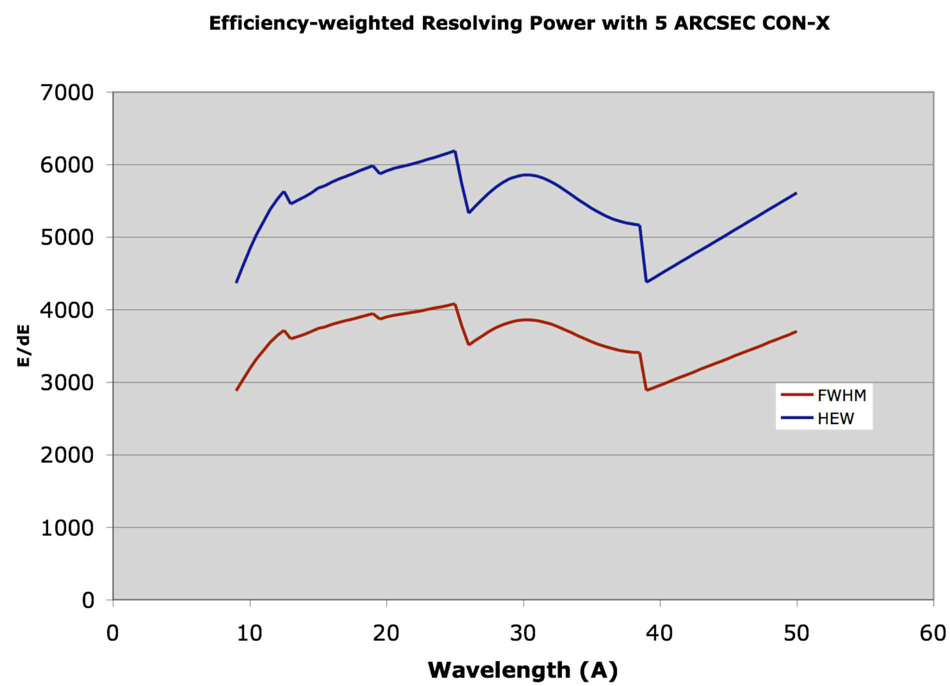
$\theta < \theta_c$, total external reflection

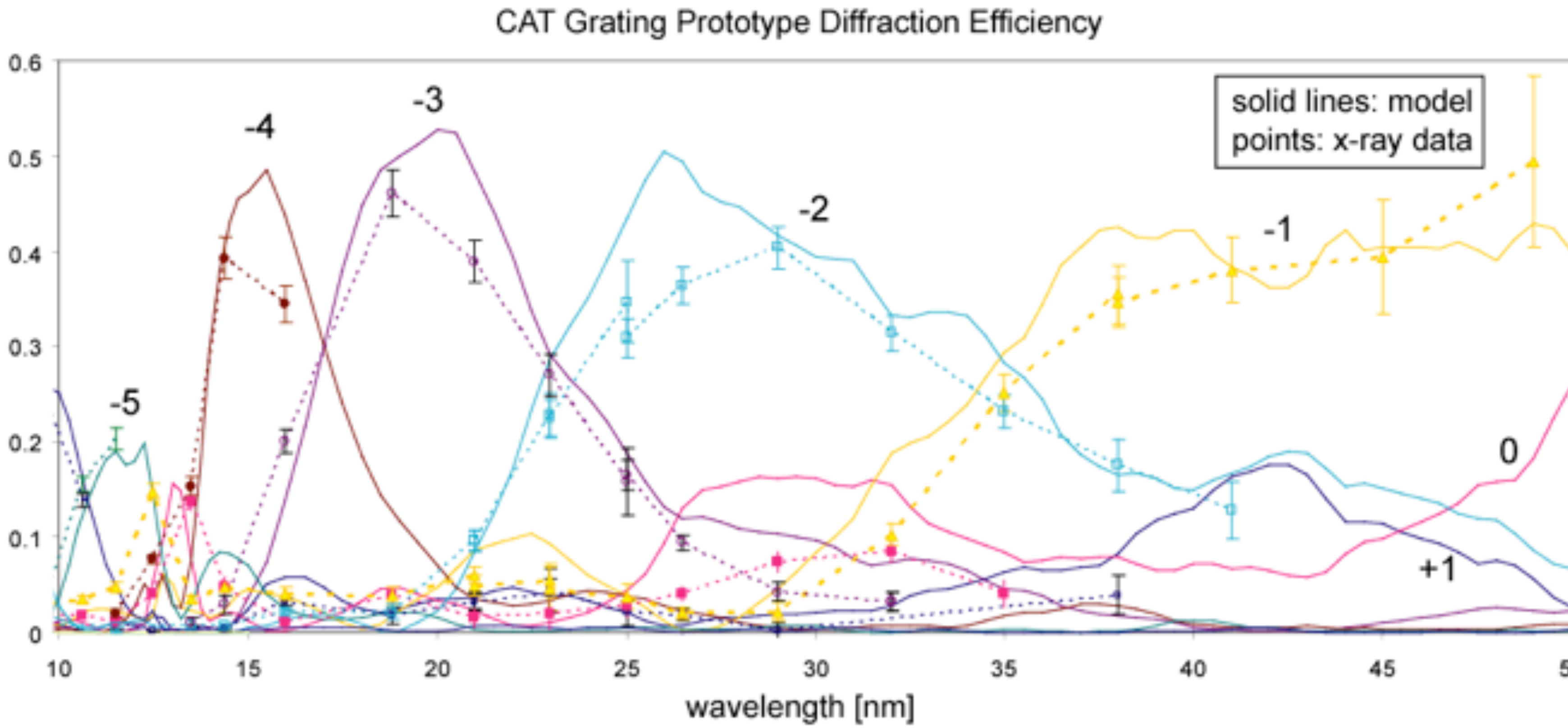
⇨ **Critical-Angle Transmission (CAT) Grating**

CAT Grating for Constellation X









Synchrotron measurements of Prototype CAT Grating Efficiency vs. Model

My personal concerns:

Exciting new technologies are in the pipeline

But NASA is under-investing in new technologies for high resolution X-ray spectroscopy (and optics!)

The community of scientists engaged in high resolution X-ray spectroscopy is still too small compared to the potential scientific yield

Important to engage wider community and push for adequate support of technology, modeling, & analysis tools.

Reach out and touch someone!