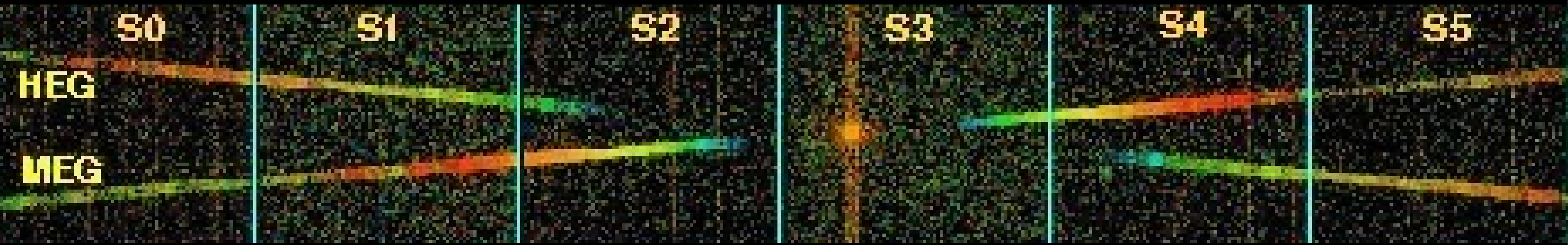
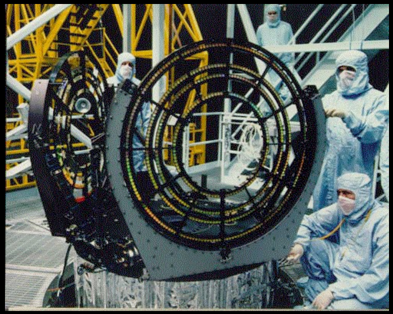
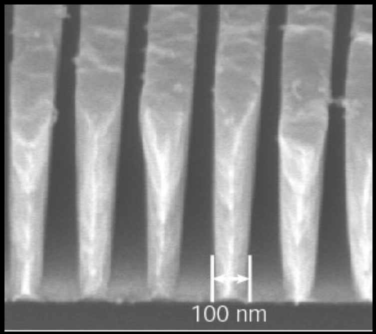


The Three Decades of the Chandra High Energy Transmission Grating (HETG)



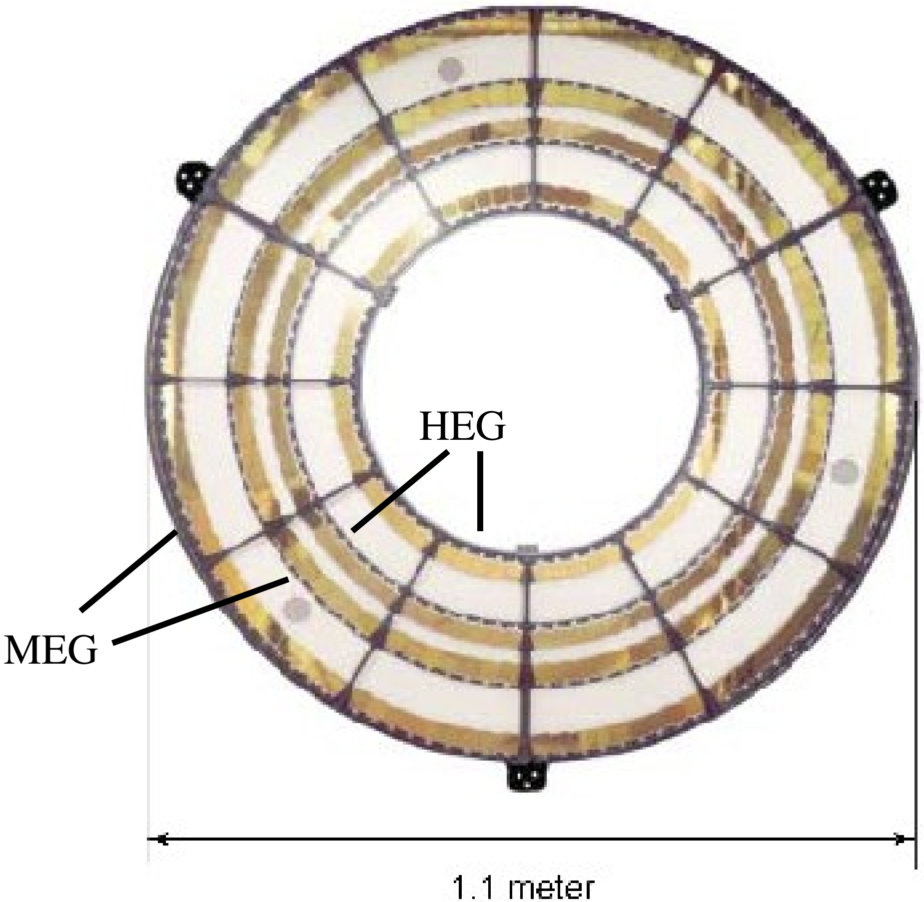


Claude R. Canizares, MIT

Chandra's First Decade of Discovery
September 2009

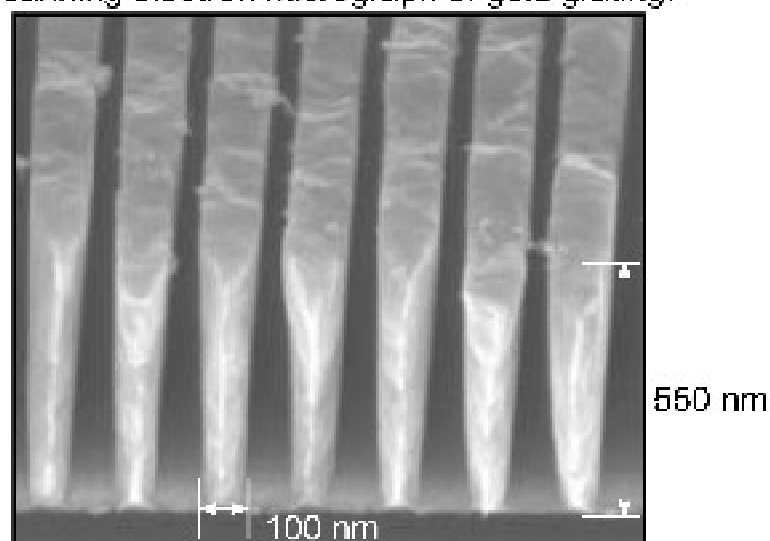
NASA *Chandra X-ray Observatory*
High Energy Transmission Grating Spectrometer (HETGS)

HETGS instrument.

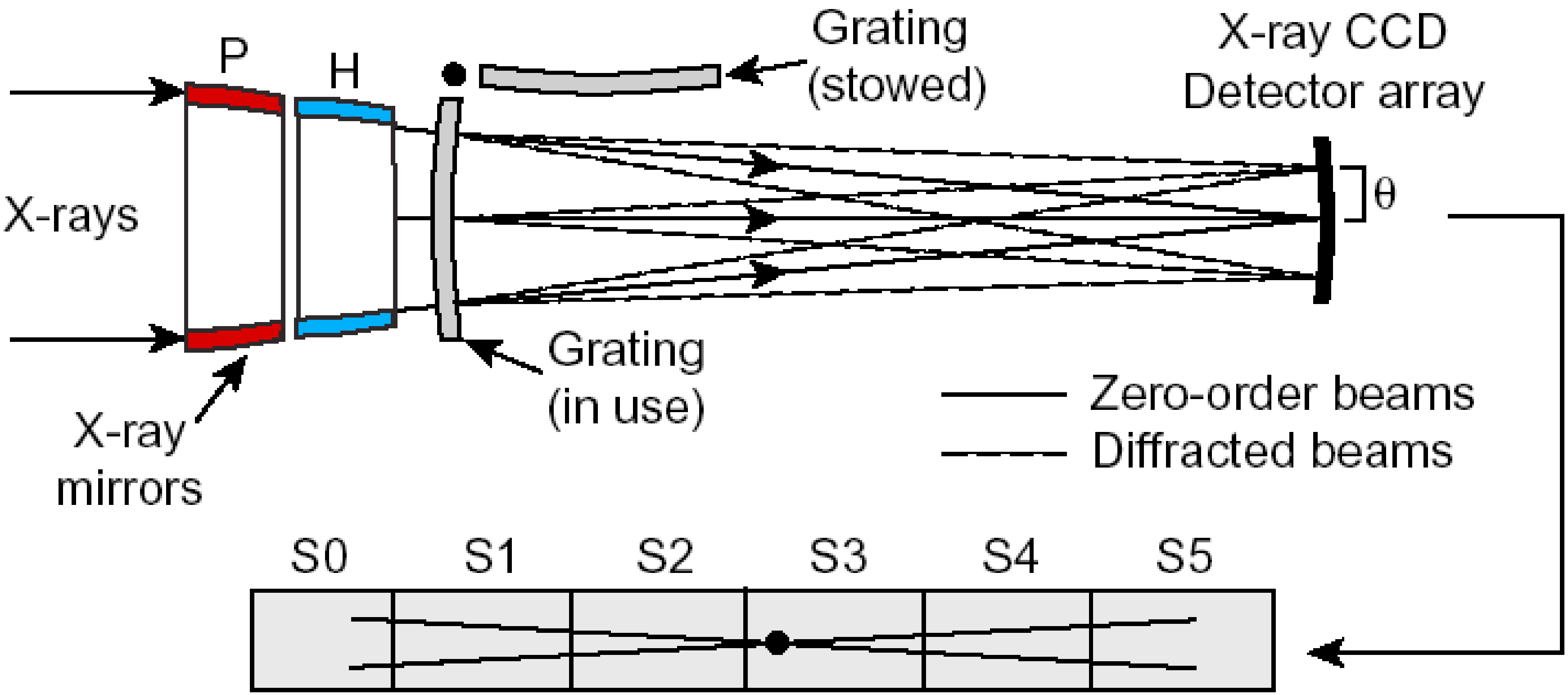


Invar grating frame.

Scanning electron micrograph of gold grating.



Chandra HETG Schematic



Key features needed for an HETG design:

- HIGH SPECTRAL RESOLUTION (R~1000):
  - ~5000 lpmm (p=0.2 µm, bar thickness=0.1 µm)
  - fabrication of hundreds of identical grating elements to tolerances of ~100 ppm
- HIGH EFFICIENCY: over 1.5 decades of energy (0.4 - 8 keV)
  - ~0.5-1.0 µm tall (>5:1 aspect ratio grating bars)
- HIGH RELIABILITY: gratings rugged enough to withstand launch and space environment

Order of magnitude beyond previous gratings

HETG Timeline: the first decade

1979 Beginning of transmission grating development for AXAF (CRC, Mark Schattenburg with H. I. Smith)

1983 AXAF RFP issued (launch date 1991-2)

- Proposal selected for Phase B study

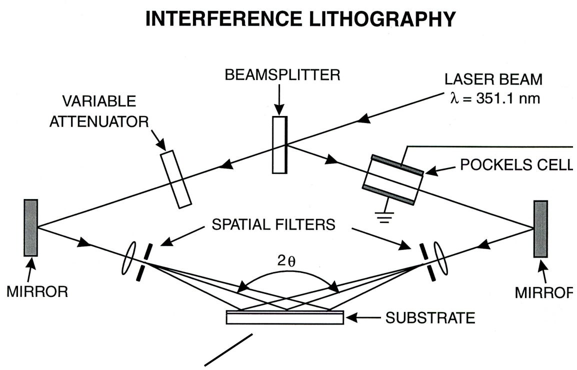
(1986 Challenger disaster)

1988 AXAF approved for "phased new start"

1989 HETG Accepted for AXAF

(launch date 1995-6)

Proposed Fabrication Method: X-ray Lithography



mask

Replicate a Master (thin grating mask fabricated via UV lithography) into many thick, phased gratings with the same period using X-ray lithography

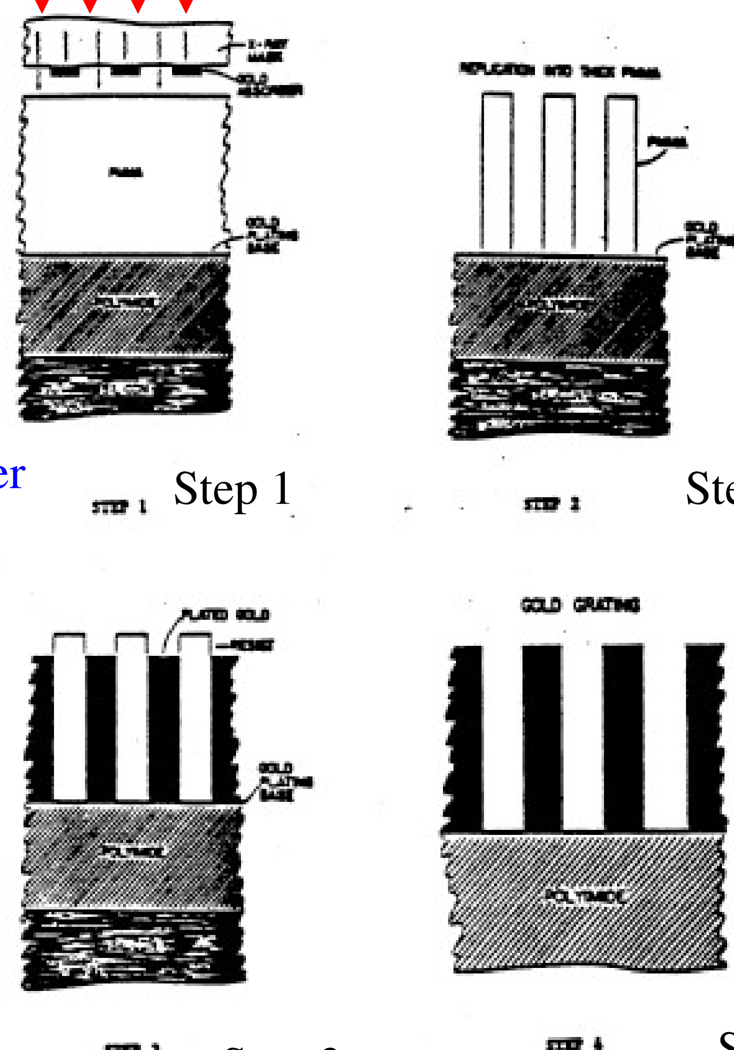
Soft X-rays

Thin mask of correct period

Photoresist

Polyimide support

Si Wafer



Step 1

Step 2

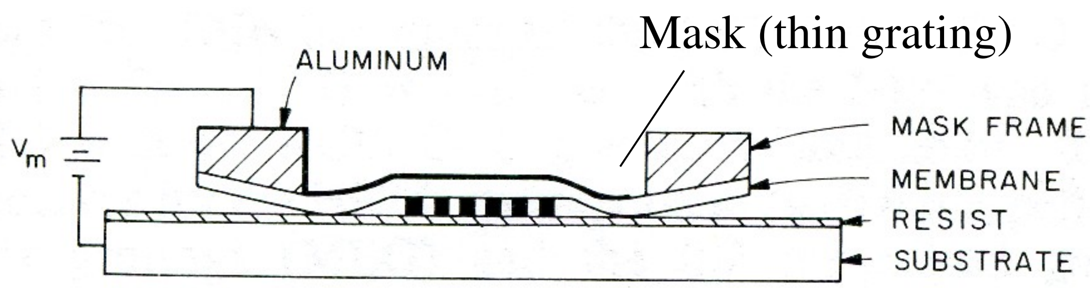
Finished grating

Step 3

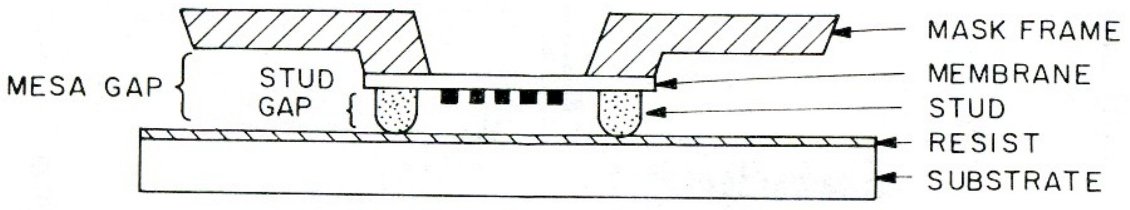
Step 4

1984 Proposal

Invention of Micro-gap X-ray Nanolithography

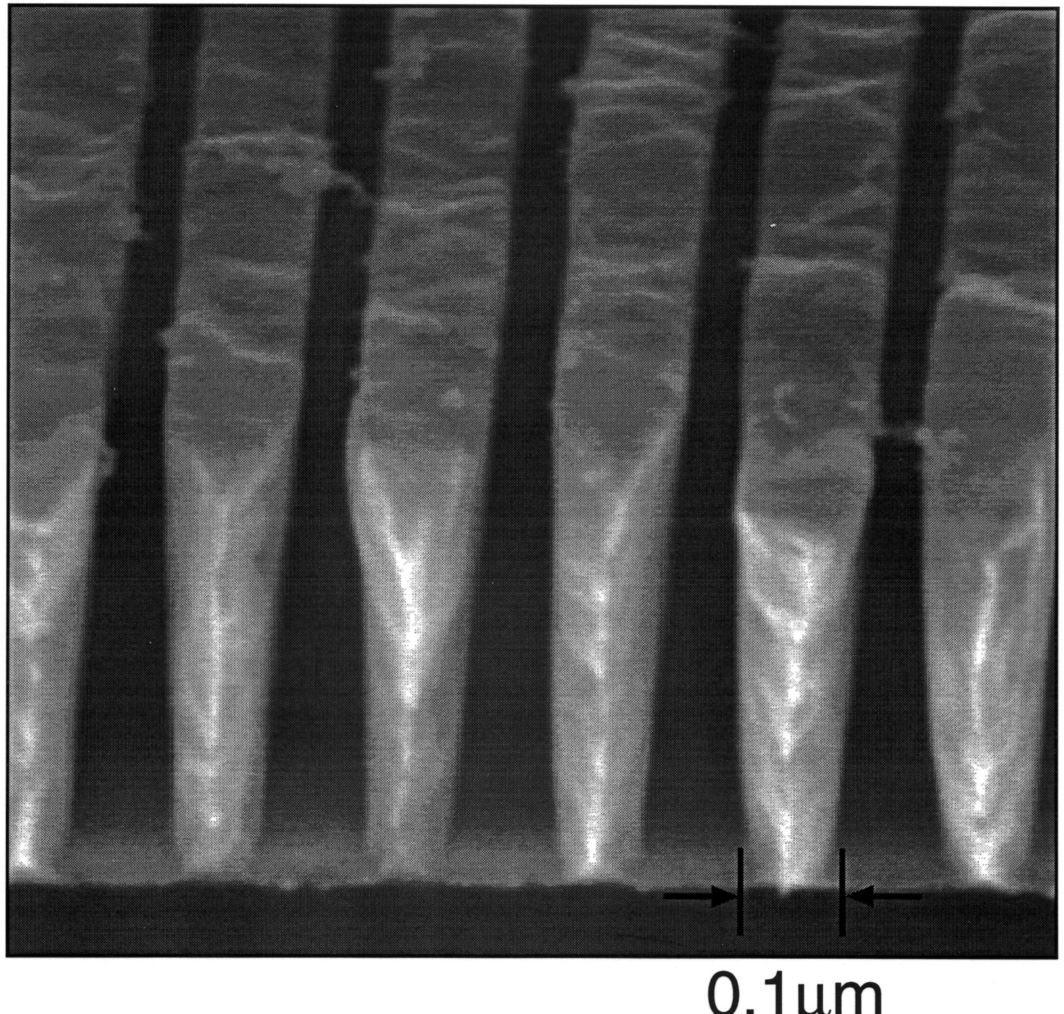


a) CONTACT X-RAY NANOLITHOGRAPHY



b) MICROGAP X-RAY NANOLITHOGRAPHY

AXAF Gold Transmission Grating



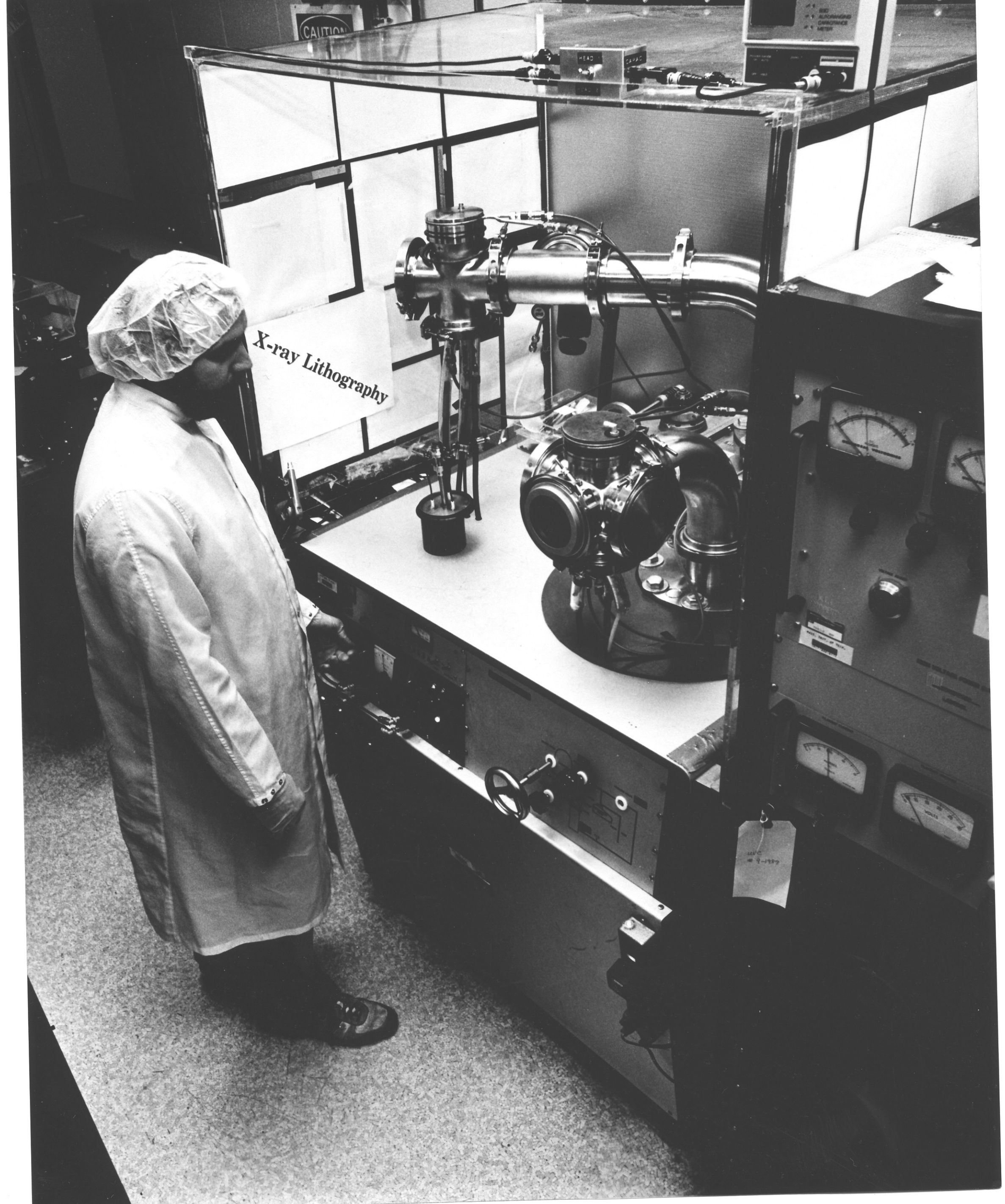
X-ray Lithography Station

Soft X-ray (Cu L line)

Exposure time ~24-36 hrs per grating!

We (and industry) needed a high intensity X-ray machine

Only supplier was Hampshire Instruments



HETG Timeline: the second decade

1989 HETG Accepted for AXAF

3 AXAF Restructured to AXAF-I and AXAF-S;

4 HETG Systems Requirements Review (SRR)

HETG Timeline: the second decade

1989 HETG Accepted for AXAF
3 AXAF Restructured to AXAF-I and AXAF-S;
4 HETG Systems Requirements Review (SRR)

2 Hampshire Instruments ceases operations;
X-ray lithography no longer viable

HOW COULD WE POSSIBLY BUILD
~700 NEAR-PERFECT GRATINGS ??

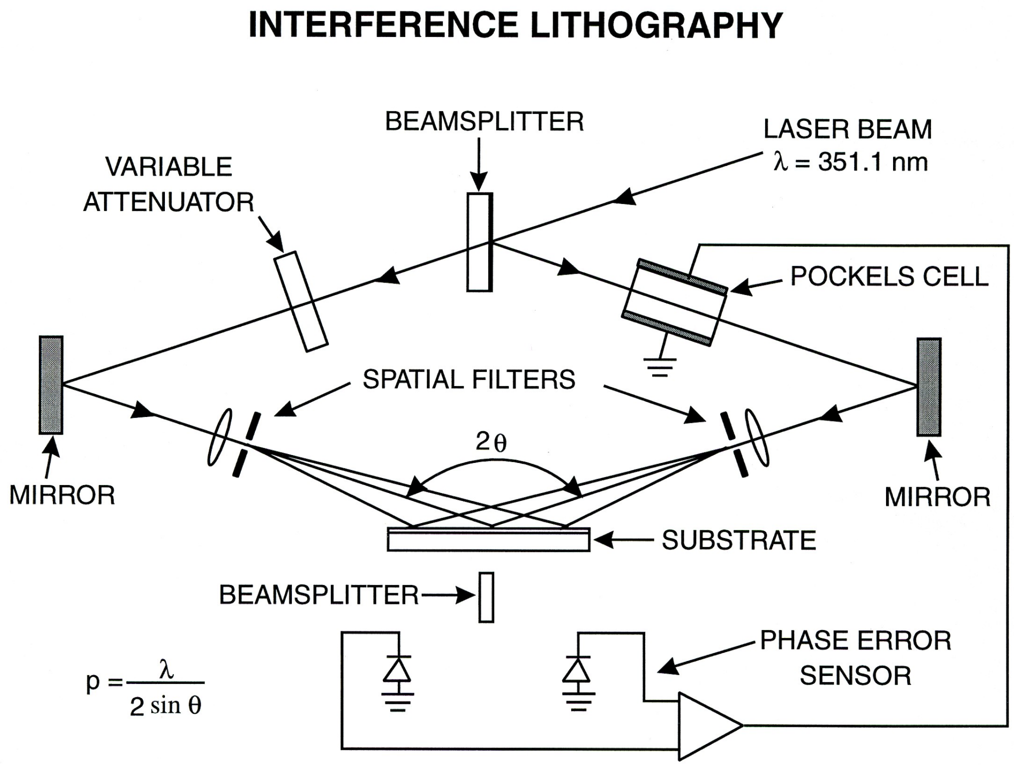
Key breakthrough by Schattenburg:

For each exposure, lock UV interference pattern to standard grating (on wafer) using Moire pattern

MLS demonstrates repeatability to less than ~200 ppm (within few weeks!)

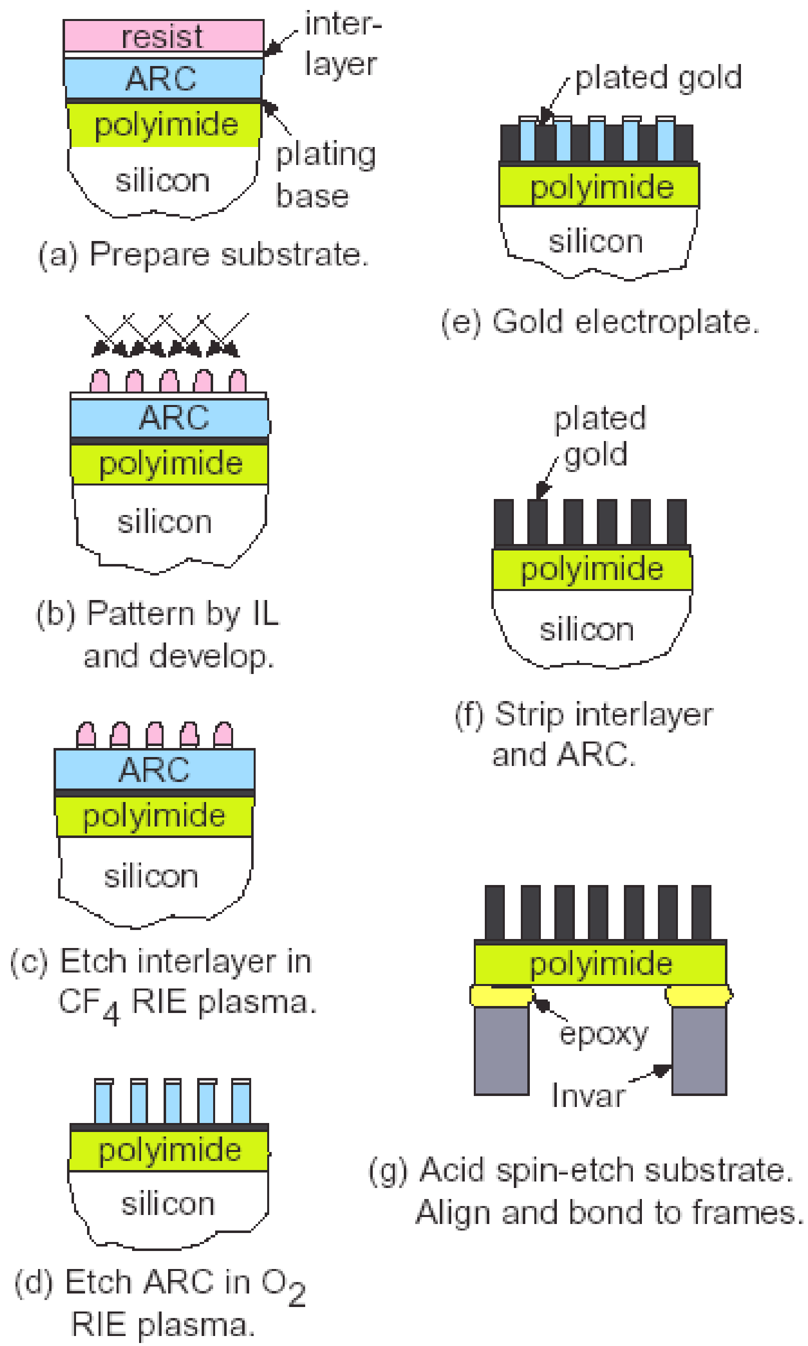
Thinks he can achieve high aspect ratio by plasma etching rather than X-ray lithography

Now the masks have become the gratings



<u>Simplified HETG Fabrication Process</u>

Dozens of technological innovations by Schattenburg and his team; several key patents for processes now widely in use by VLSI industry



(a) Prepare substrate.

(b) Pattern by IL and develop.

(c) Etch interlayer in CF_4 RIE plasma.

(d) Etch ARC in O_2 RIE plasma.

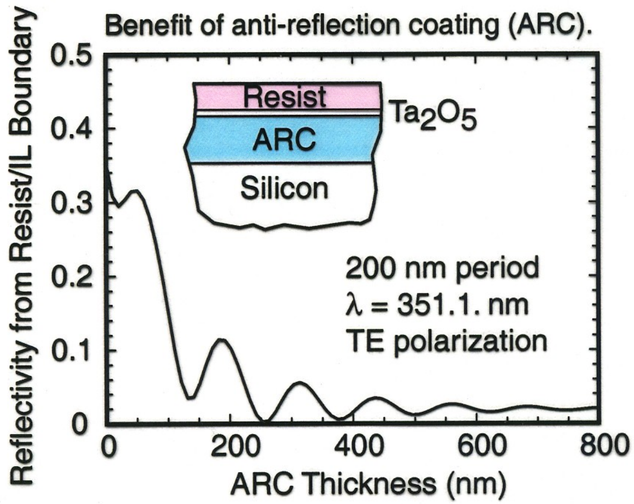
(e) Gold electroplate.

(f) Strip interlayer and ARC.

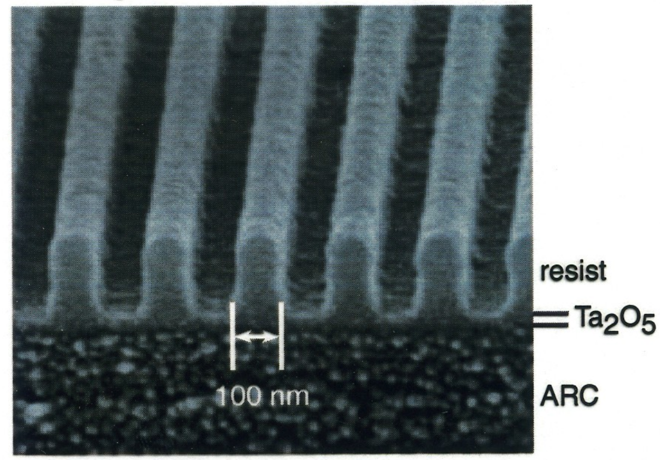
(g) Acid spin-etch substrate. Align and bond to frames.

Gold Transmission Grating Fabrication Process

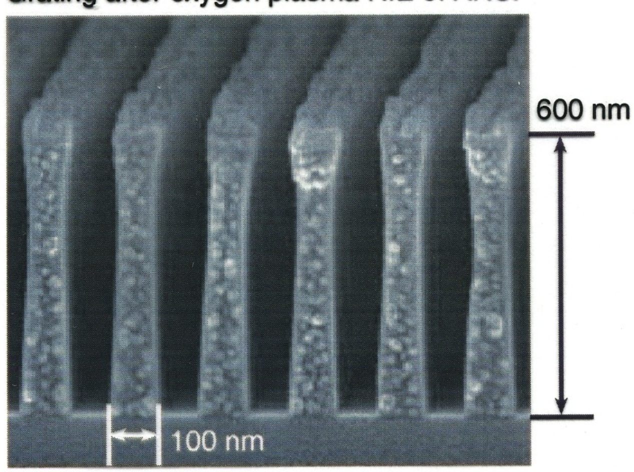
Benefit of anti-reflection coating (ARC).



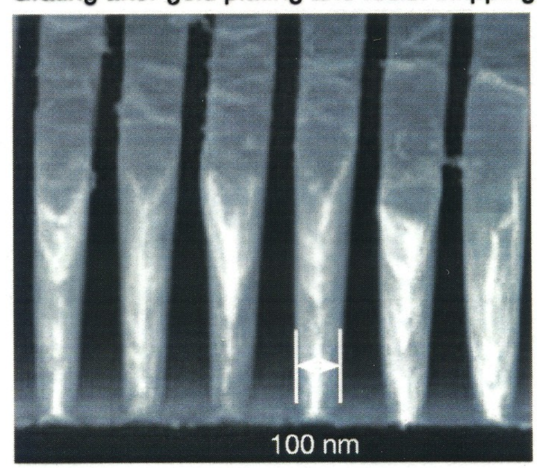
Grating after interference lithography.



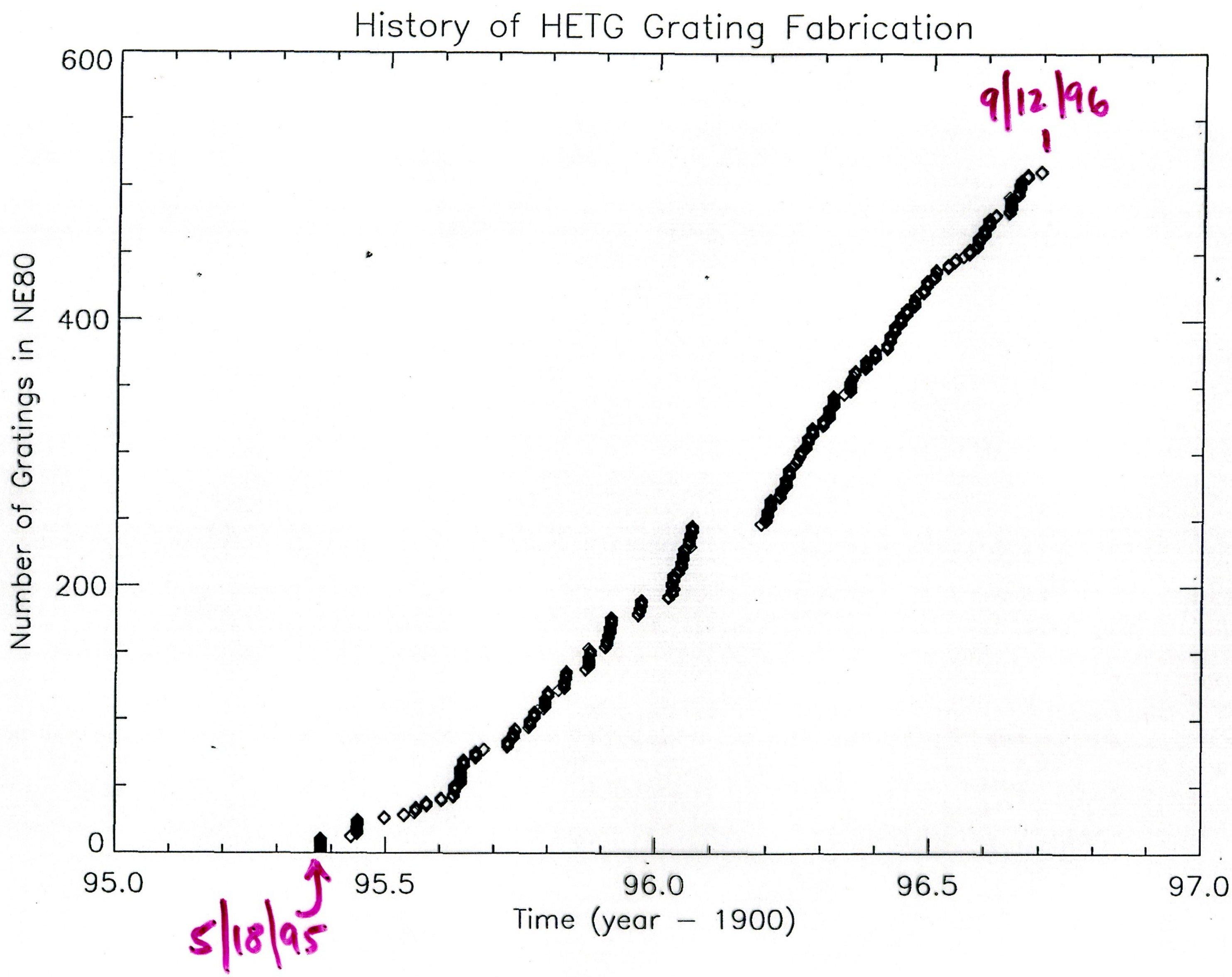
Grating after oxygen plasma RIE of ARC.



Grating after gold plating and resist stripping.



MLS-2001-05-25.02.eps



History of HETG Grating Fabrication
Number of Gratings in NE80
0
200
400
600
95.0
95.5
96.0
96.5
97.0
Time (year - 1900)
5/18/95
9/12/96

HETG Timeline: the second decade

1989 HETG Accepted for AXAF

3 AXAF Restructured to AXAF-I and AXAF-S;

4 HETG Systems Requirements Review (SRR)

1993 Hampshire Instruments ceases operations; X-ray lithography abandoned

8 Preliminary Design Review (PDR)

1995 Critical Design Review CDR

1996 Deliver & Calibrate Completed HETG

1999 Chandra Launch!

With profound admiration and gratitude for the HETG Team

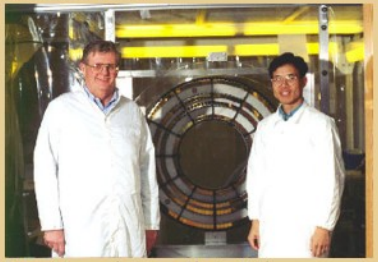
Fabrication

Back row:
Bob Fleming, Mark Schattenburg, Roger Millen, Bob Sisson, Hank Smith.
Front row:
Rich Aucoin, Jeanne Porter, Jane Prentis, Pat Hindle.

Testing

Dick Elder, Bill Forbes, Bob Laliberte, Ed Warren, Mike Enwright.

Mechanical



Don Humphries, Chris Pak

Support

Kim Farrell, Dave Breaslau.

Science

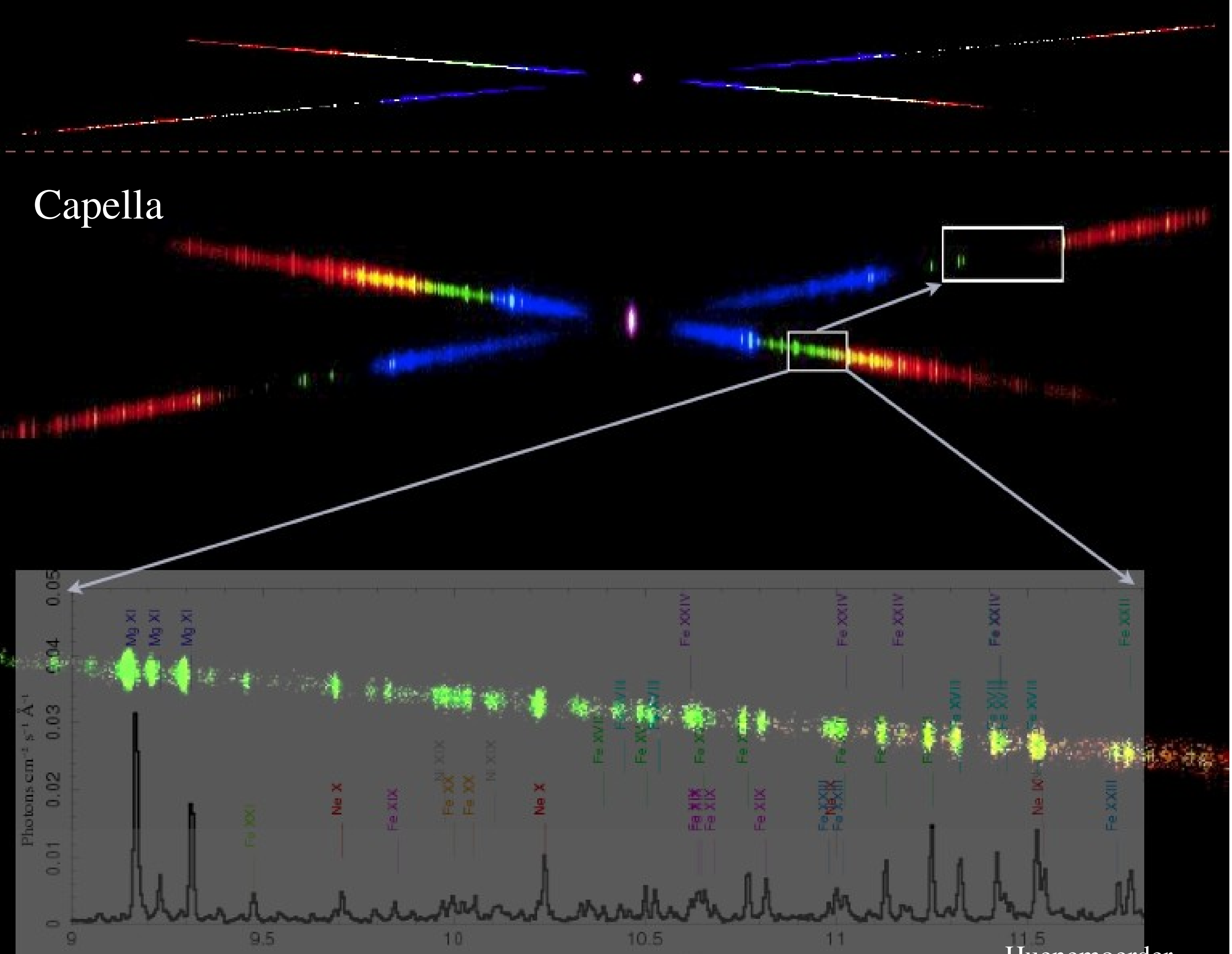
Kathy Flanagan, Mike McGuirk, Mark Schattenburg, Claude Canizares, Dan Dewey, Dick Elder.

Inspiration

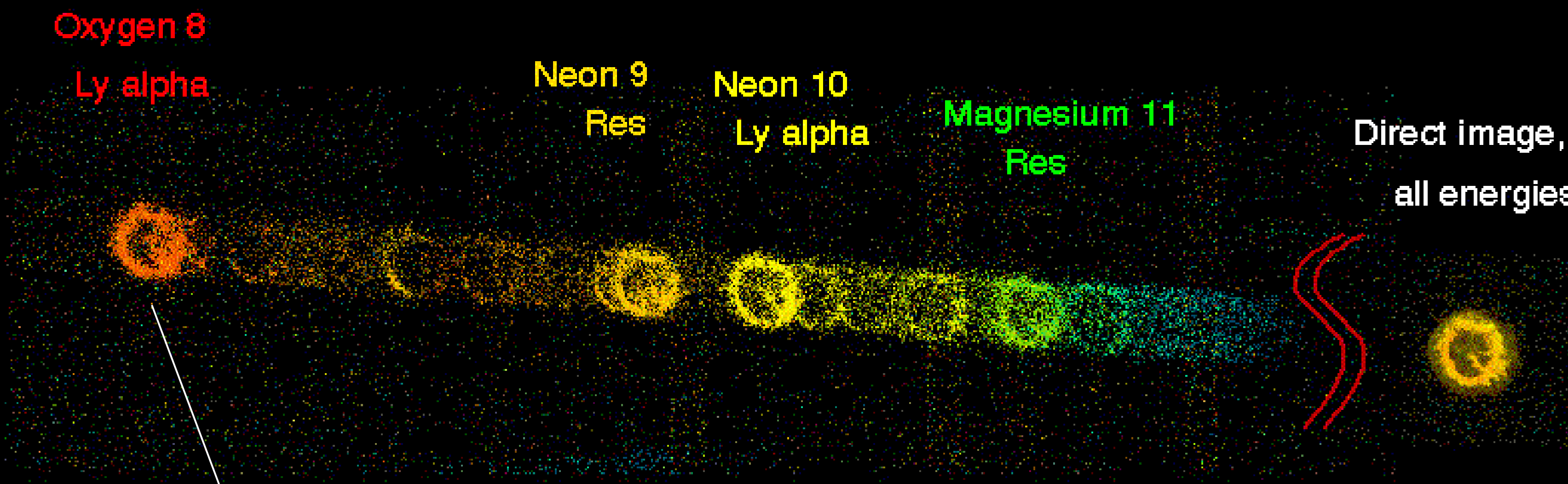
Al Levine, Claude Canizares, Gene Galton, Angie[for Tom] Markert

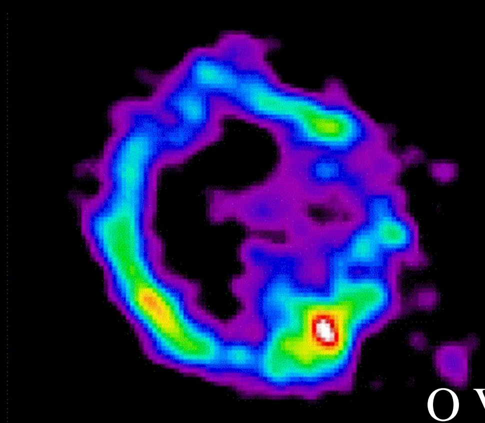
Tom Markert

1948-1996

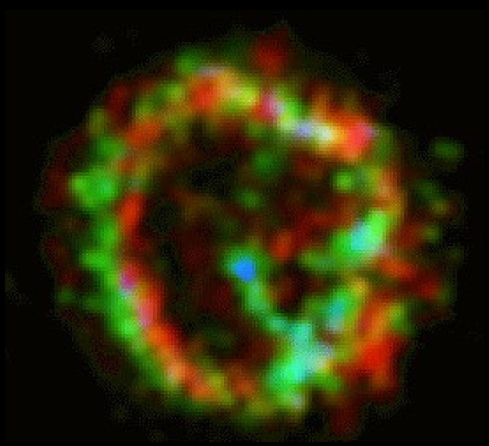

Capella
Photons cm⁻² s⁻¹ Å⁻¹
Mg XI
Mg XI
Mg XI
Ne X
Ne X
Fe XXIV
Fe XXIV
Fe XXIV
Fe XXIV
Fe XXIII
Fe XXIII
Fe XIX
9
9.5
10
10.5
11
11.5

SNR E0102-72



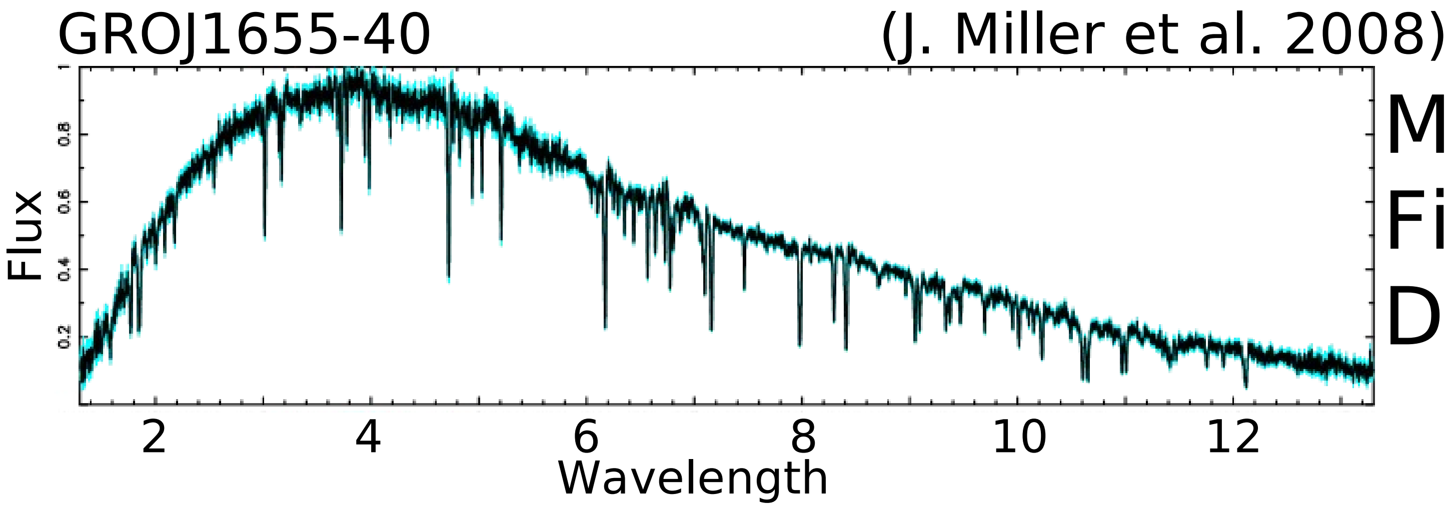


O VIII Ly α

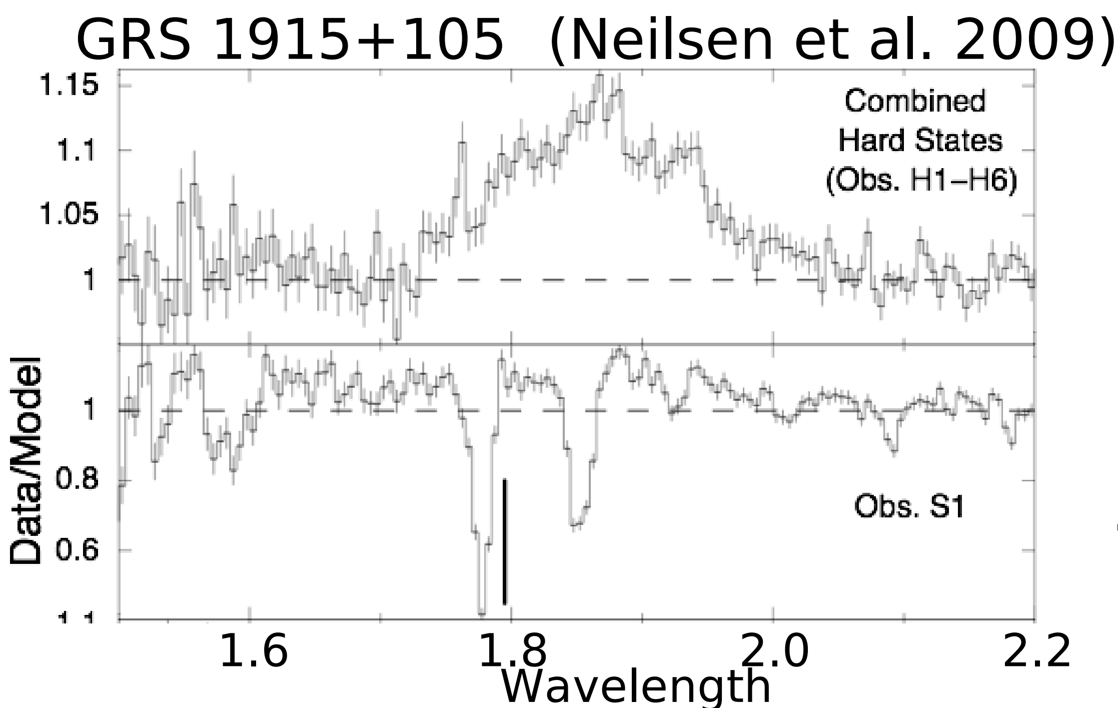


Flanagan et al.

Disk Winds in Black Hole X-ray Binaries

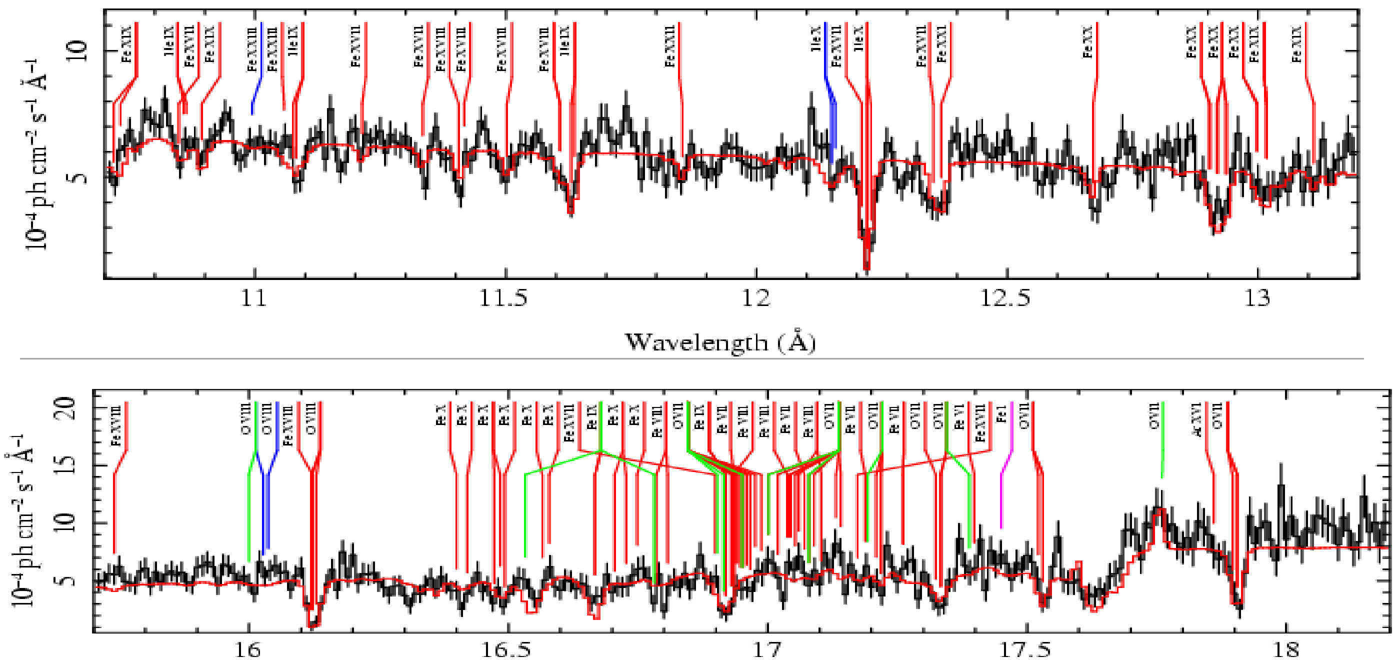


Magnetic Fields Drive Disk Winds

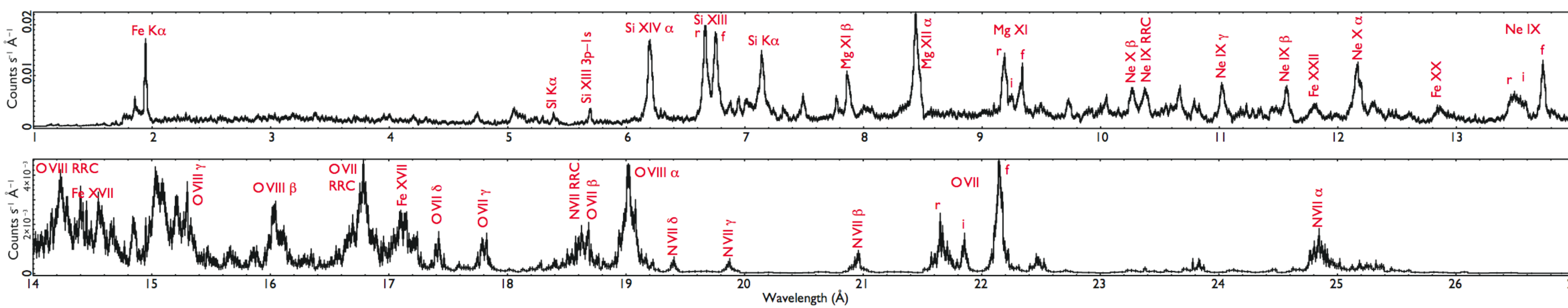


Disk Winds Suppress Jets

Environments of Active Galactic Nuclei



MCG-6-30-15 Lee et al.



NGC 1068 Evans et al. 2009

http://tgcat.mit.edu

914 *analysis ready* observations

308 distinct objects:

623 HETG/ACIS

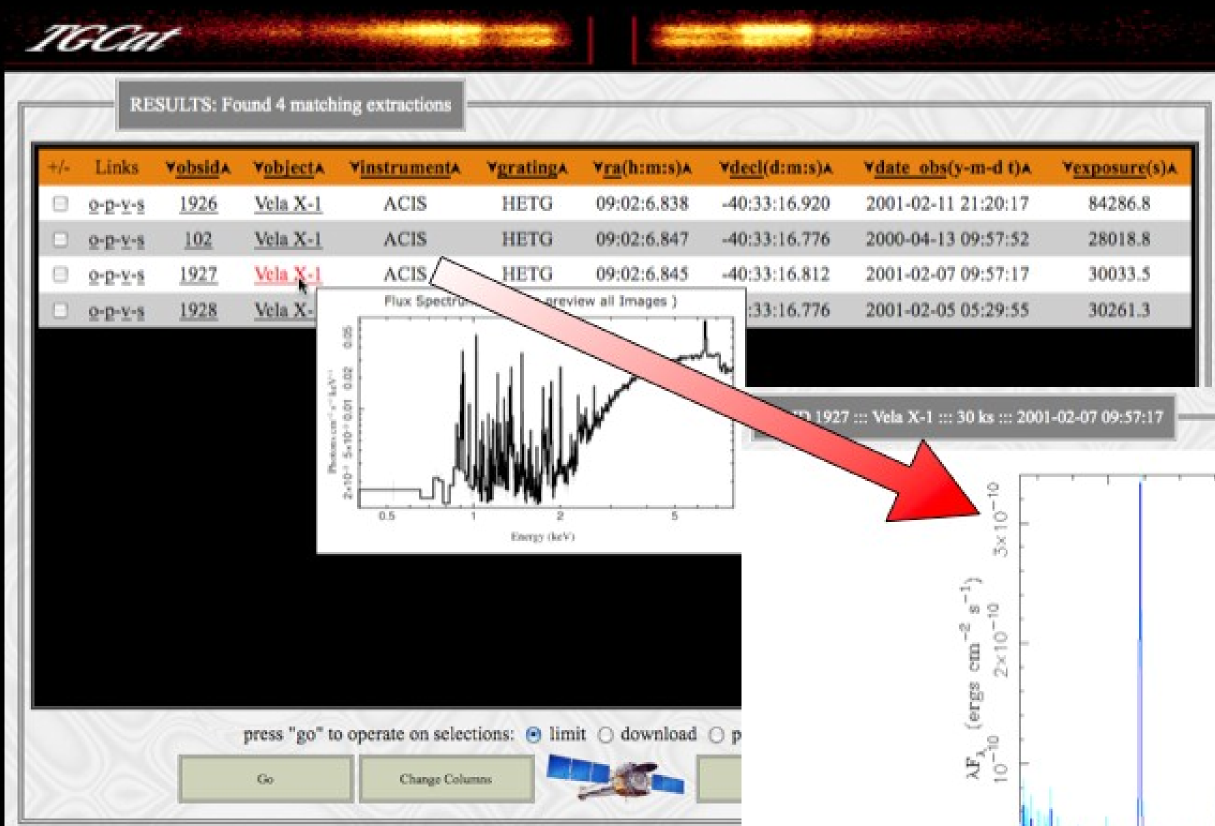
91 LETG/ACIS

200 LETG/HRC

Verification & Validation (V&V):

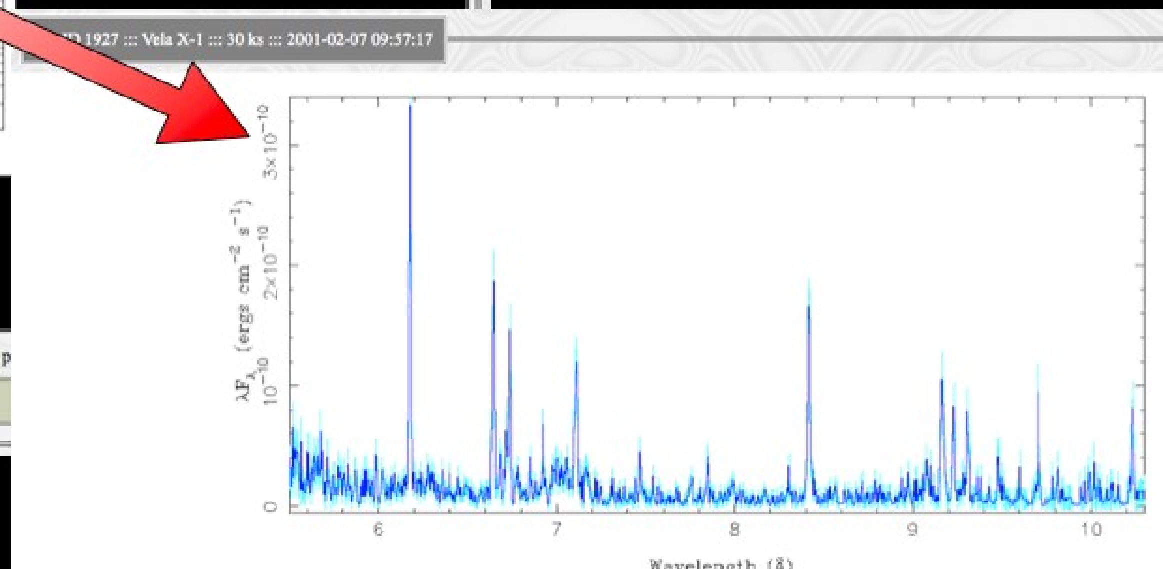
All products manually examined for zeroth order position, extraction region, & confusing sources.

Recently reprocessed to apply CALDB 4.1



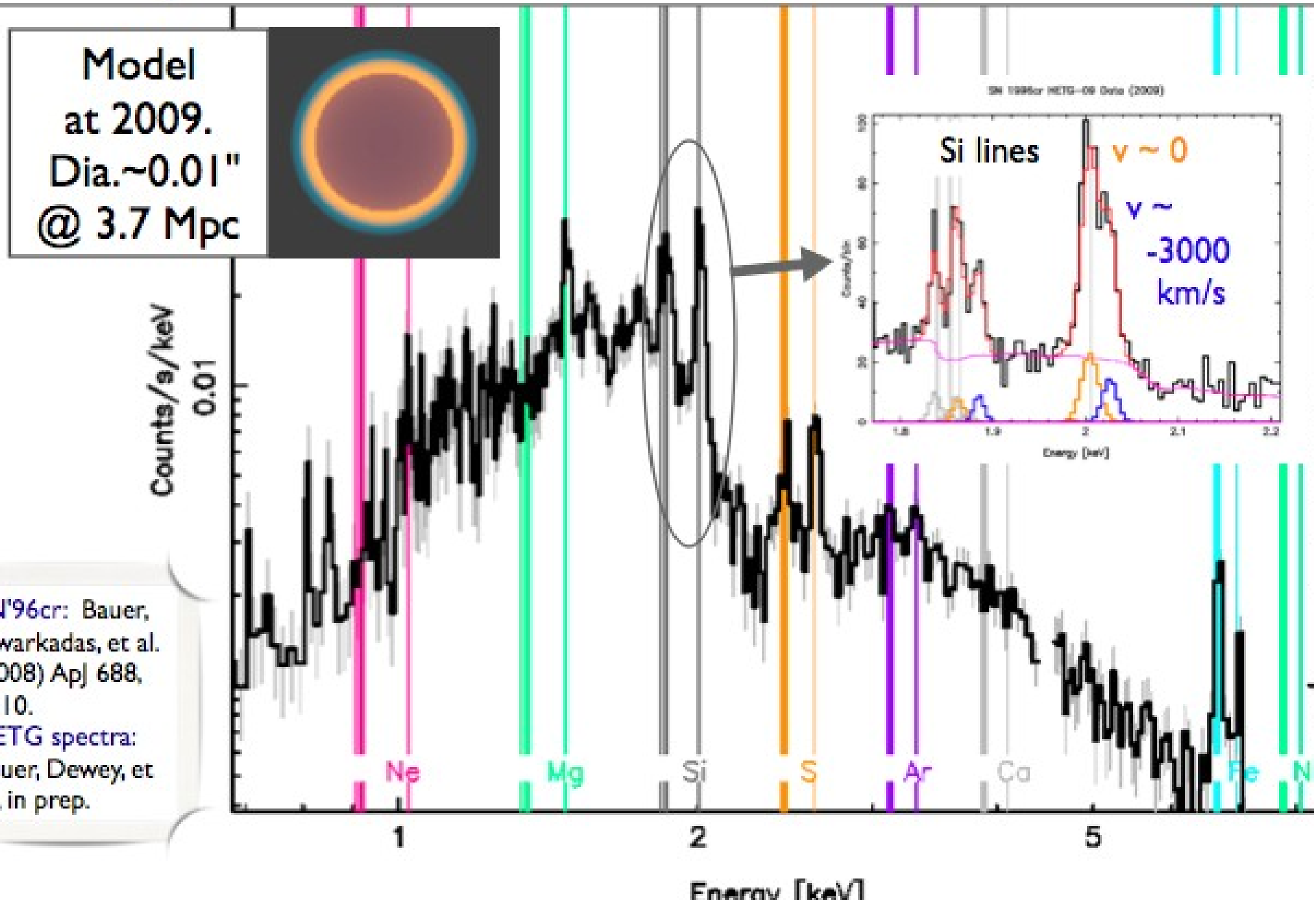
+/-	Links	obsid	object	instrument	grating	ra(h:m:s)	decl(d:m:s)	date_obs(y-m-d t)	exposure(s)
	o-p-v-s	1926	Vela X-1	ACIS	HETG	09:02:6.838	-40:33:16.920	2001-02-11 21:20:17	84286.8
	o-p-v-s	102	Vela X-1	ACIS	HETG	09:02:6.847	-40:33:16.776	2000-04-13 09:57:52	28018.8
	o-p-v-s	1927	Vela X-1	ACIS	HETG	09:02:6.845	-40:33:16.812	2001-02-07 09:57:17	30033.5
	o-p-v-s	1928	Vela X-				:33:16.776	2001-02-05 05:29:55	30261.3

Search, sort, select, preview, plot, download, ...



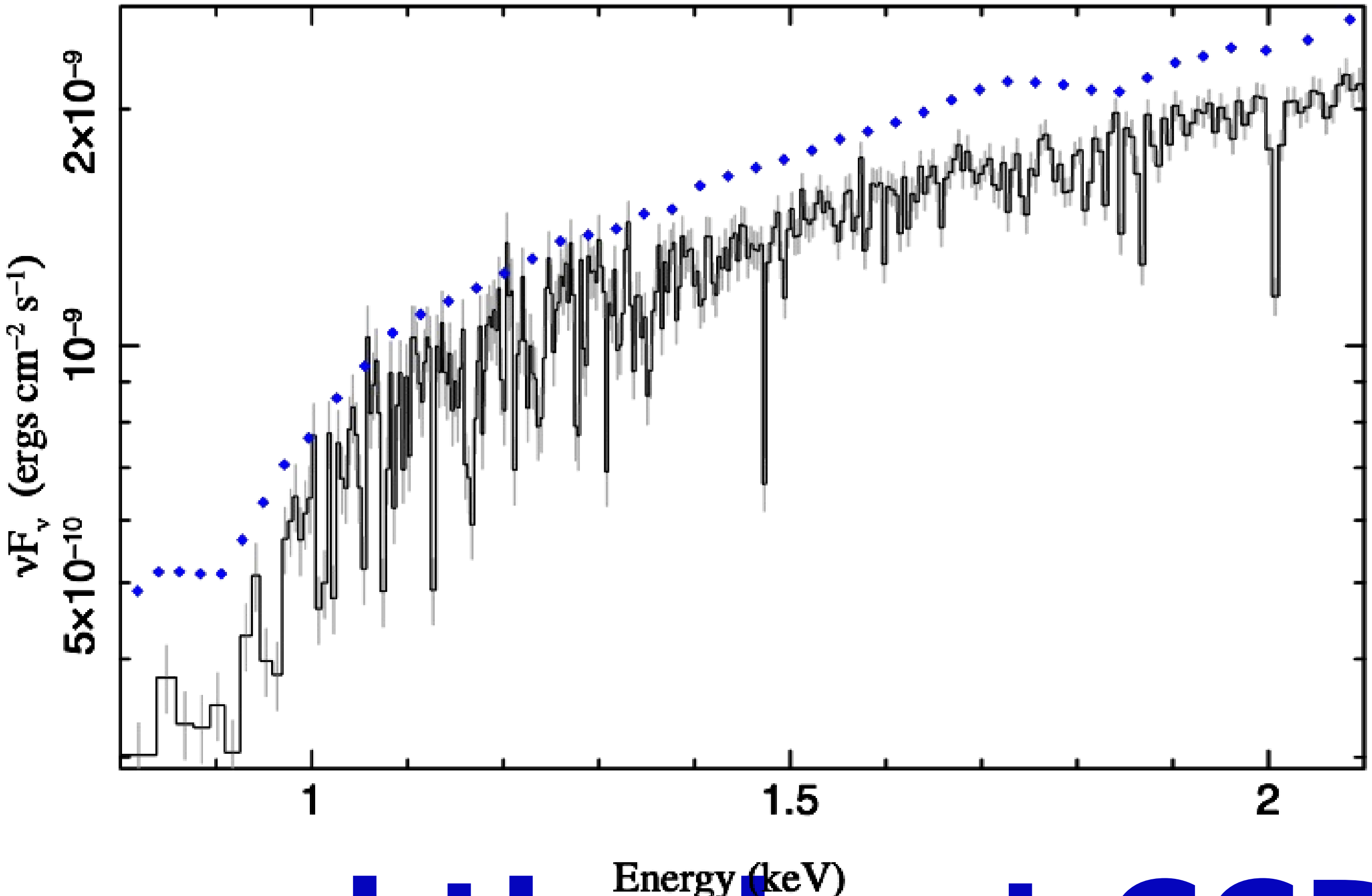
SN 1996cr w/HETG (485 ks) circa 2009 (PI: F.E. Bauer)

Flux increased years after explosion: bubble-shell CSM structure.
Line shapes w/o red-shifted emission: SN core blocks backside.



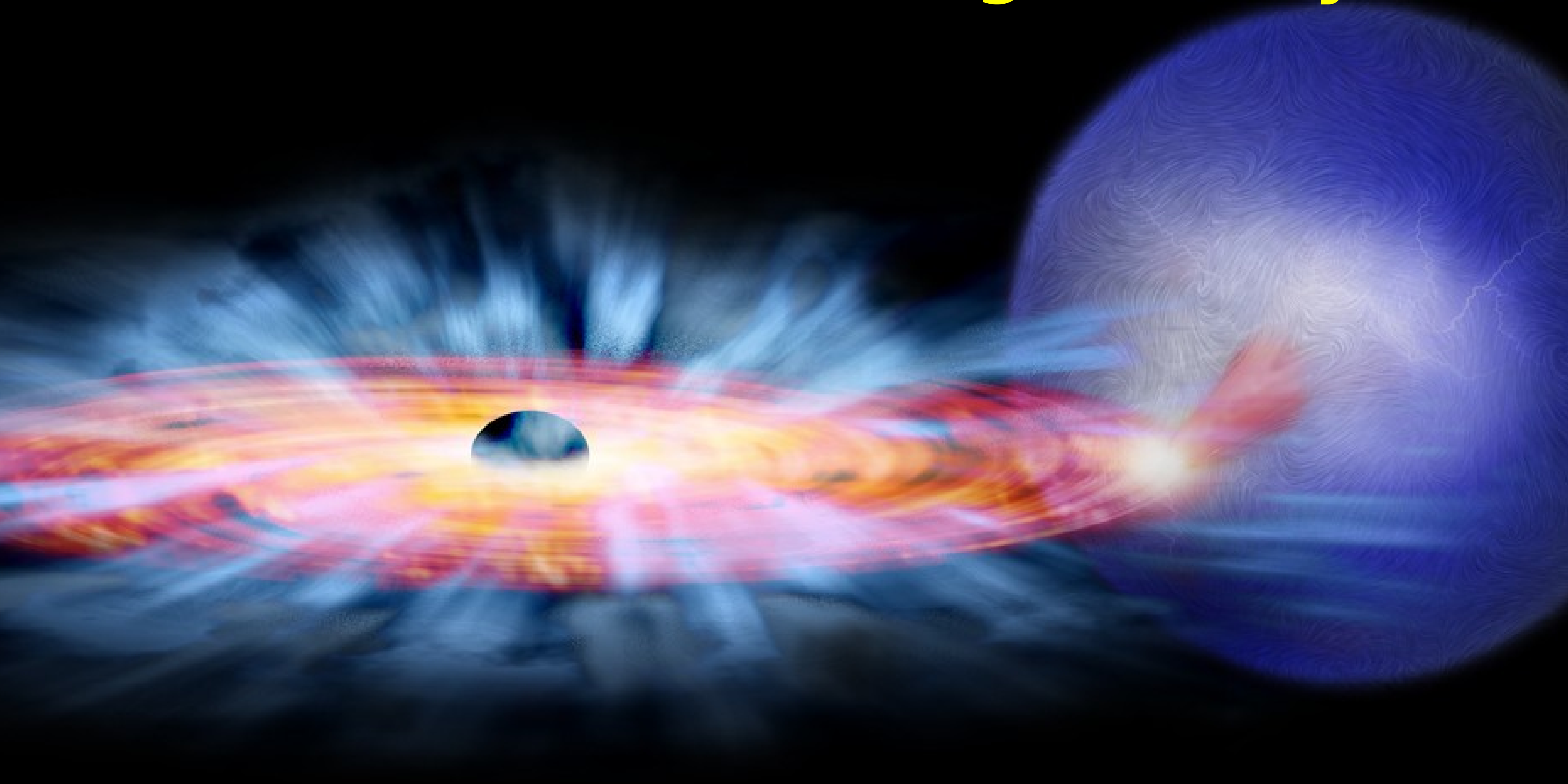
SN'96cr: Bauer, Dwarkadas, et al. (2008) ApJ 688, 1210.
HETG spectra: Bauer, Dewey, et al., in prep.

Cyg X-1 Disk & Atmosphere Viewed with HETG ...



... and the best CCDs (Suzaku)

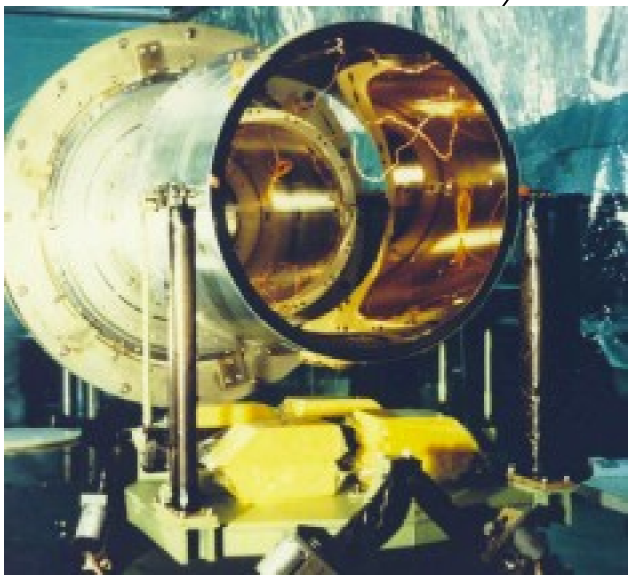
Understanding the Atmosphere Crucial for Constraining the Physics

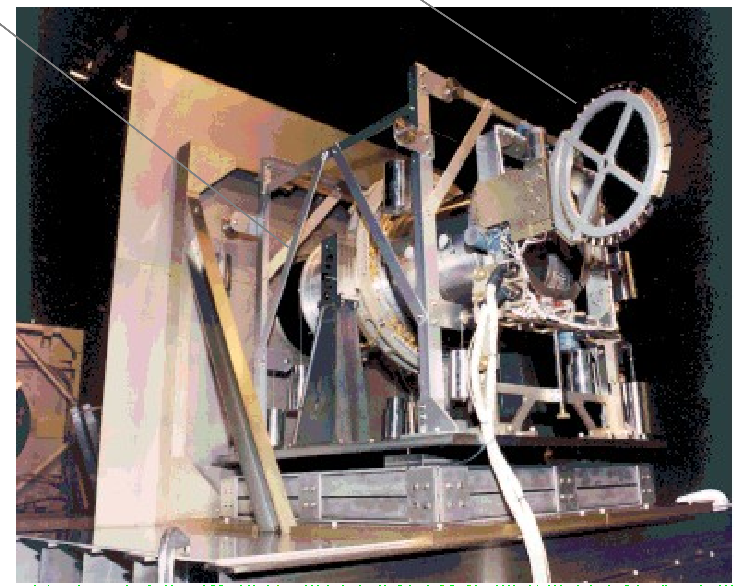


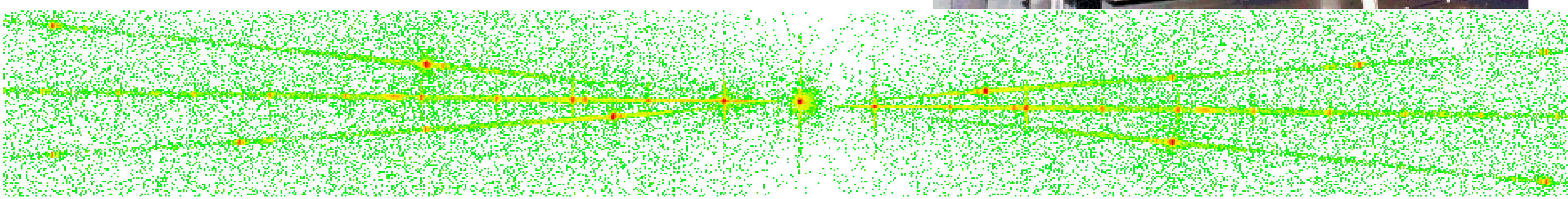
Magnetic driving? Transitions from Disks to Jets?

Test Mirror Assembly (TMA)

Grating facets on wheel (in open position)





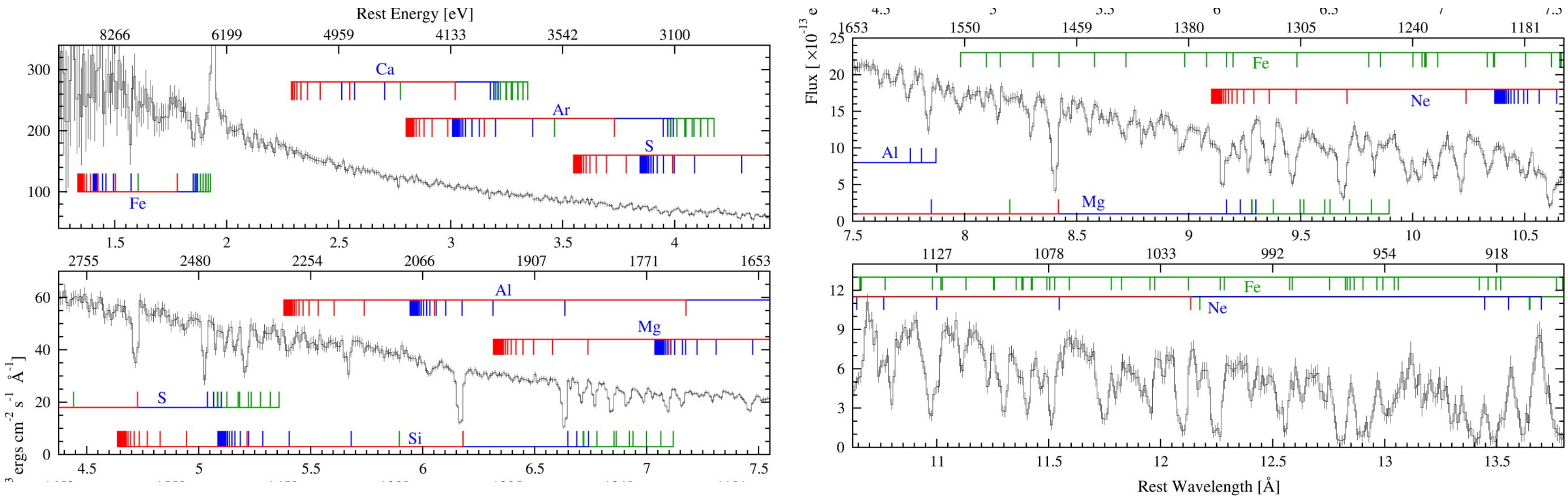


<u>1996 TMA Objective Grating Assembly (TOGA) test at MSFC/XRCF</u>

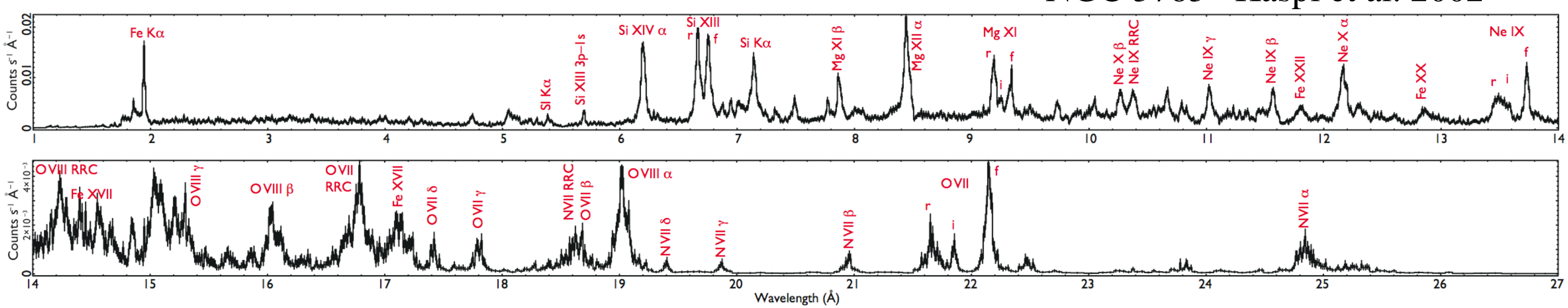
Twelve years after initial proposal, the first real evidence that grating assembly would perform as expected!!

"[expletive deleted]!!! I might even use the gratings!"   --- Leon van Speybroeck

Environments of Active Galactic Nuclei



NGC 3783 Kaspi et al. 2002



NGC 1068 Evans et al. 2009