

# Off-Plane Grating Developments

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## Open University, UK

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- Andrew Holland, et al

## University of Colorado

- Webster Cash
- Thomas Rogers
- Ann Shipley, et al

## Industry partners

- LightSmyth Technologies
- Nanonex Corp.
- XCAM/e2v
- NGAS

*See McEntaffer, et al., 2013, Exp. Astro, in press (arxiv:1301.5531)*

# Importance of grating spectroscopy

## IXO X-ray Science

(as accomplished by missions in the X-ray Study)

Science	IXO	AXSIO	N-CAL	NXGS	NWFI
Strong Gravity	<i>orbiting Fe K<math>\alpha</math></i>	Fulfilled	Partially fulfilled	Not fulfilled	Fulfilled
SMBH Growth	<i>spin survey</i>	Partially fulfilled	Partially fulfilled	Not fulfilled	Partially fulfilled
Evolution of LSS	<i>WHIM</i>	Fulfilled	Partially fulfilled	Fulfilled	Not Applicable
	<i>cluster survey</i>	Partially fulfilled	Partially fulfilled	Not Applicable	Fulfilled
Feedback	<i>cluster imaging</i>	Partially fulfilled	Partially fulfilled	Partially fulfilled	Partially fulfilled
High density matter	<i>NS spectra</i>	Fulfilled	Fulfilled	Partially fulfilled	Not fulfilled
	<i>NS timing</i>	Fulfilled	Fulfilled	Not Applicable	Not fulfilled

**Legend:**

IXO Science Goal is

Fulfilled

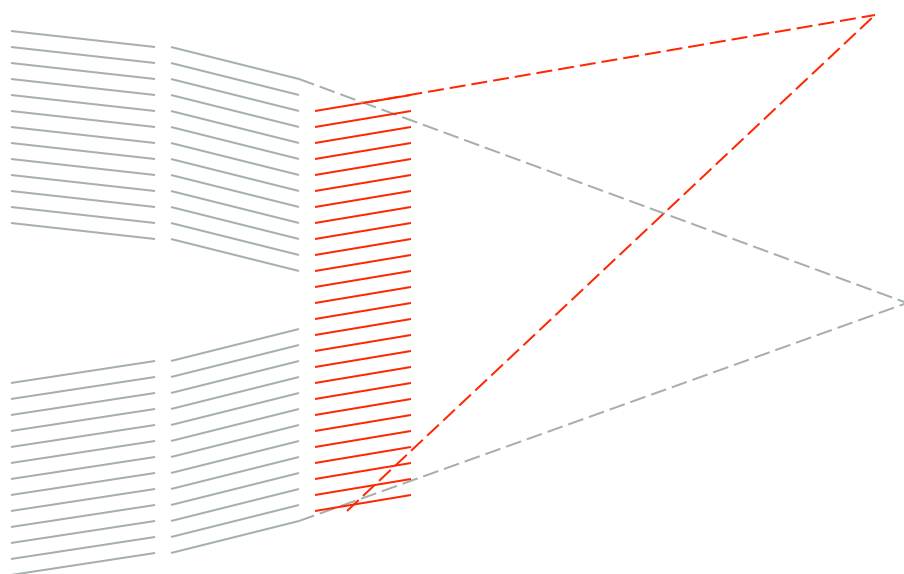
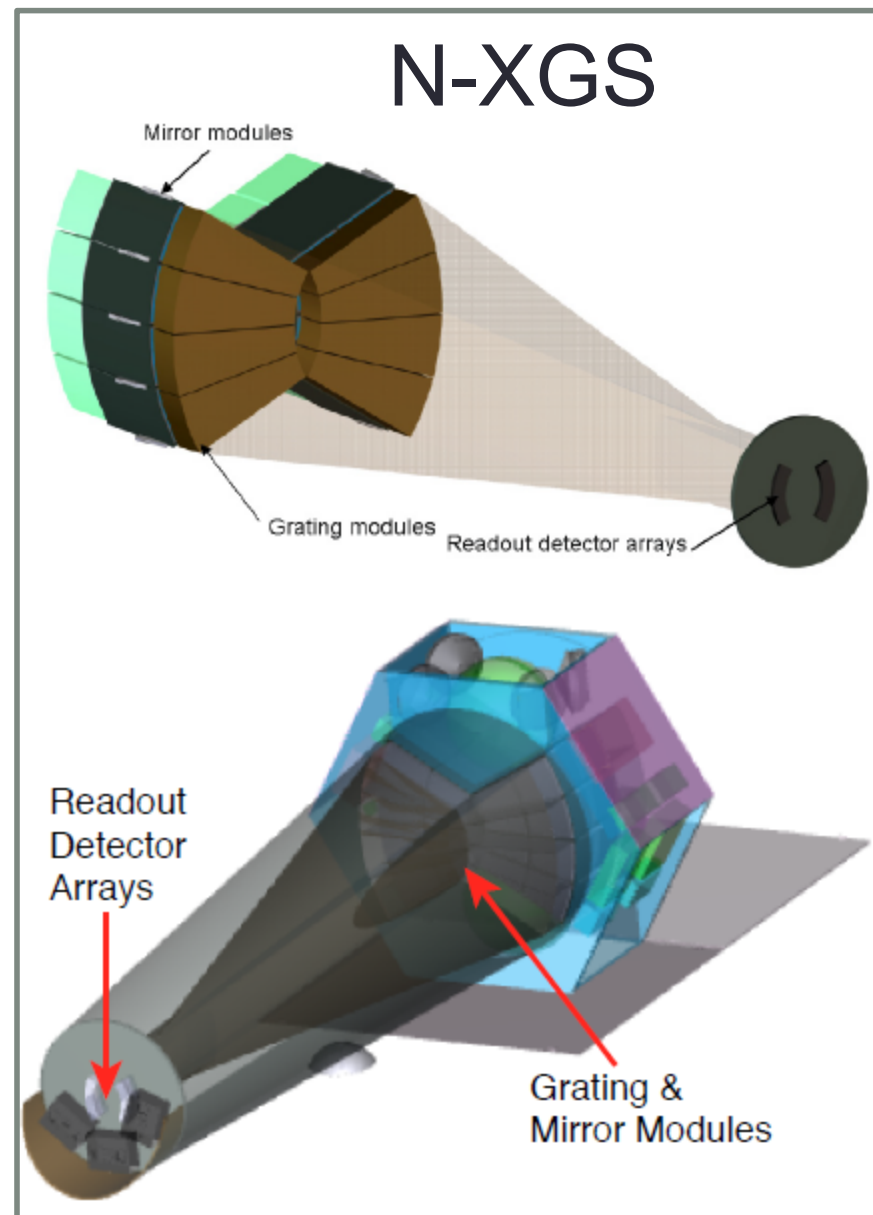
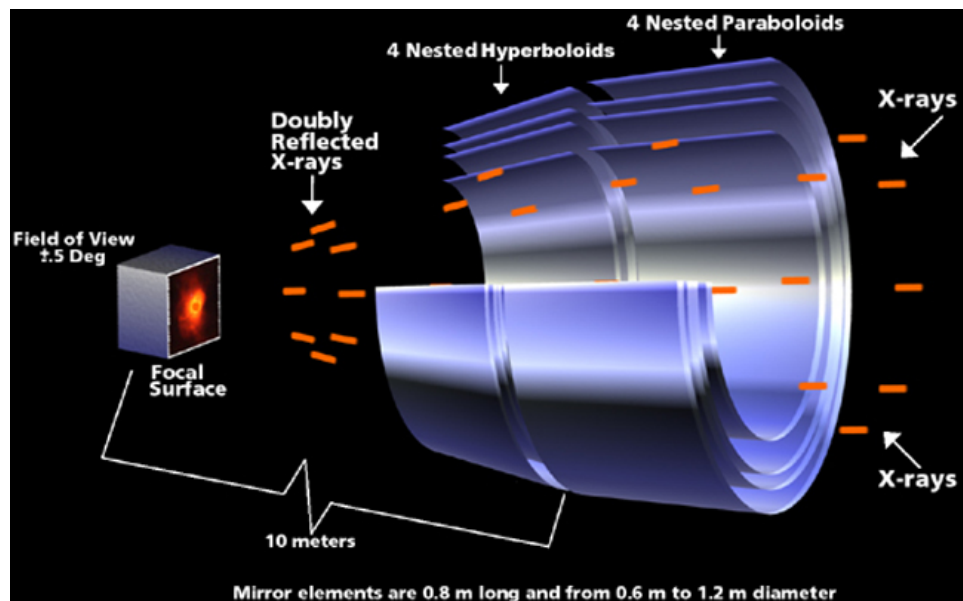
Partially fulfilled

Not fulfilled

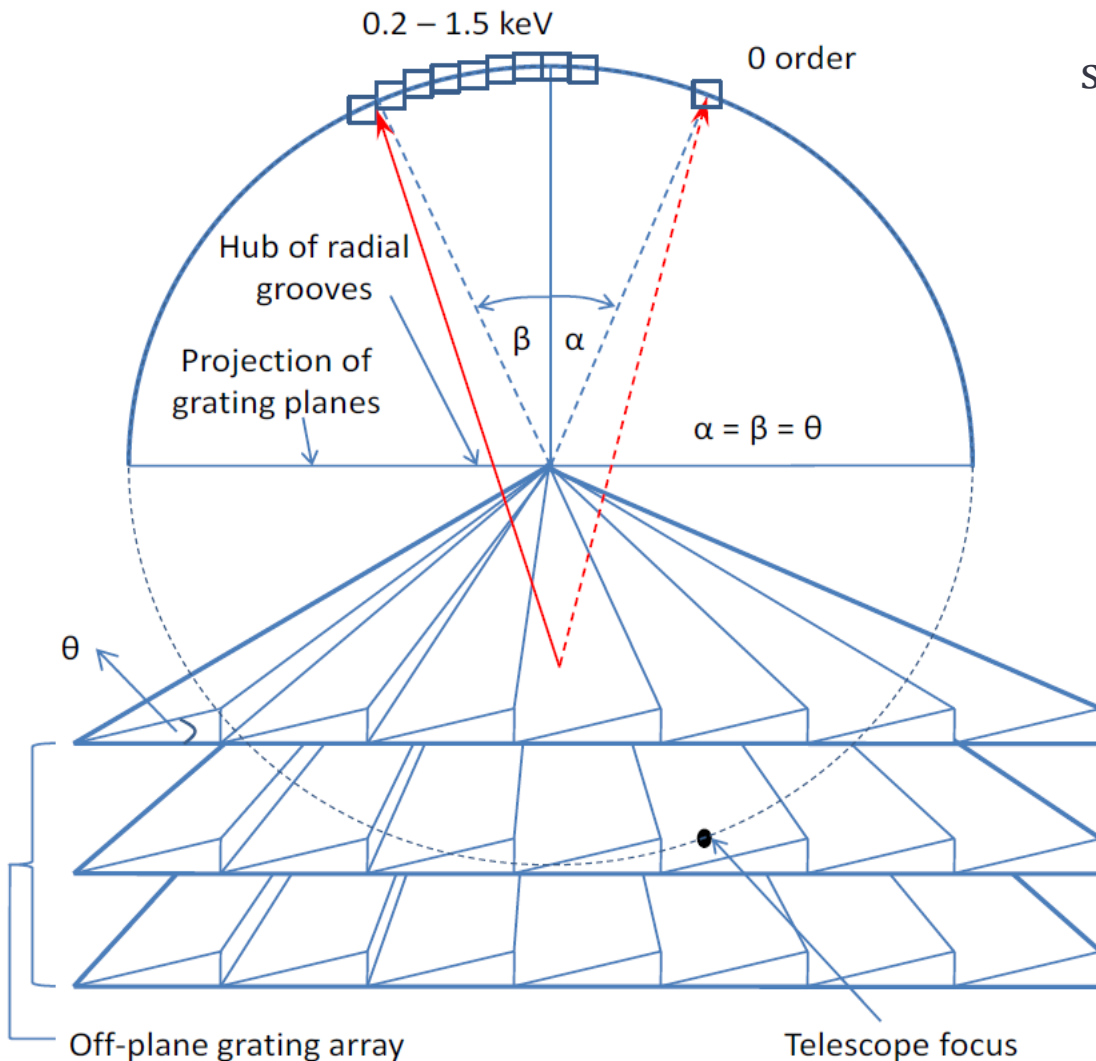
Not Applicable

- Missing baryons
- Galactic feedback
- Stellar coronae
- Charge exchange
- Supernova remnants

# Off-Plane X-ray Grating Spectrometer (OP-XGS)



# Off-plane geometry and technical challenges

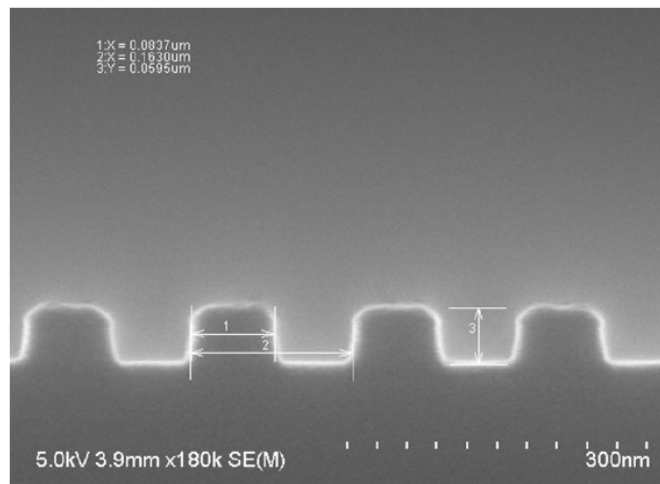


$$\sin\alpha + \sin\beta = n\lambda / d \sin\gamma$$

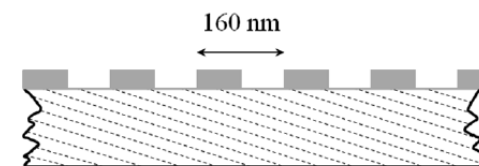
1. Radial profile to control aberration
2. Blazed profile to increase S/N in plus or minus orders
3. Alignment to ensure spectral overlap

# A new grating fabrication technique

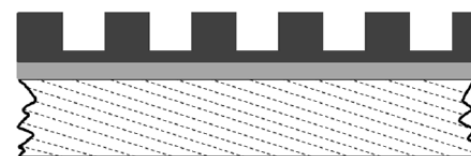
- e-beam lithograph a mask (high density radial pattern)
- Reduction DUV immersion photolith into Si
- Results in a “Pre-master” (left)
- Etch to get a blaze (below)
- Replicate(?)



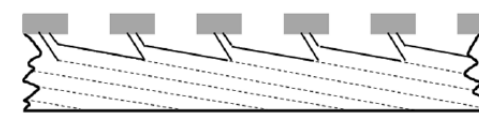
1. Spin coat resist onto nitride coated Si wafer



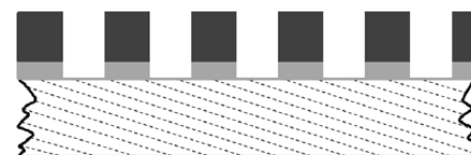
4. Rinse resist with acetone



2. Nanoimprint pre-master into resist



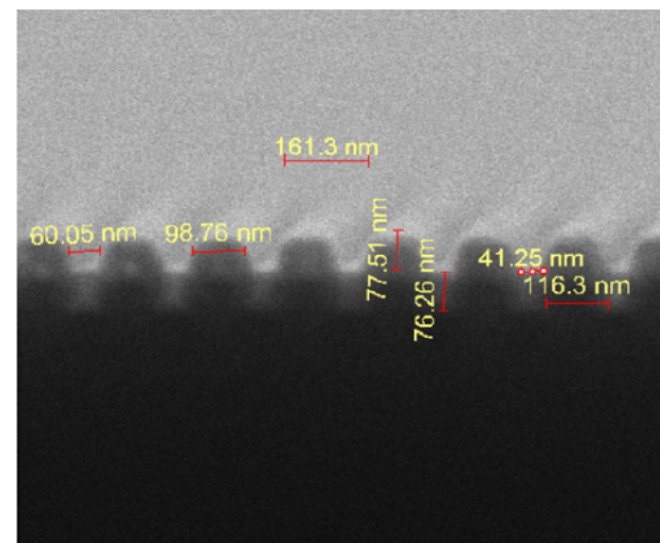
5. Wet etch Si with KOH



3. Reactive ion etch residual resist and nitride



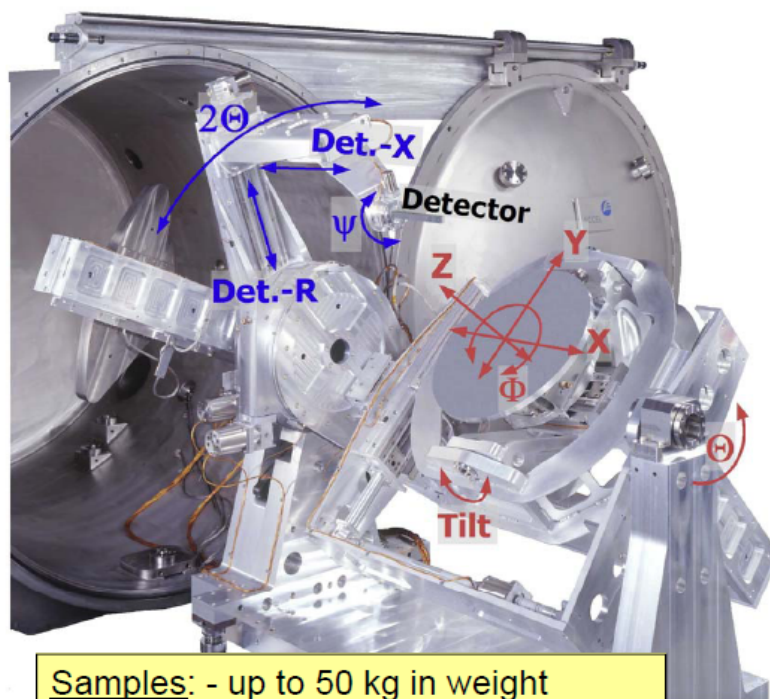
6. Nitride tab removal with HF



# Diffraction Efficiency

- Measure at BESSY PTB
- Allows 2-D sampling of focal plane

## BESSY PTB's EUV Reflectometer



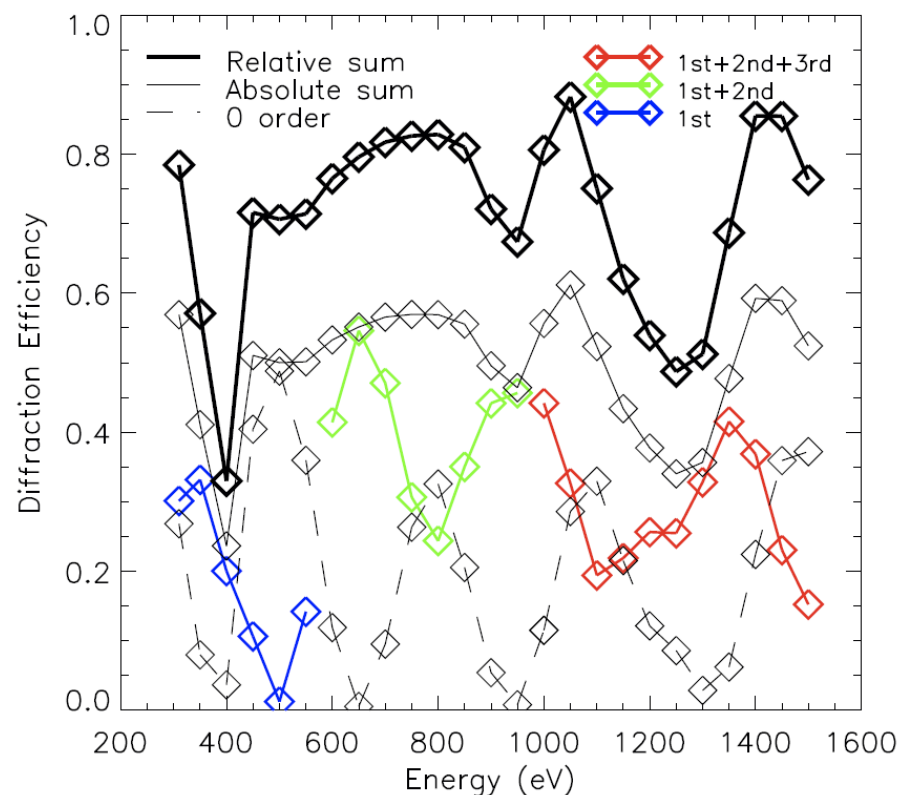
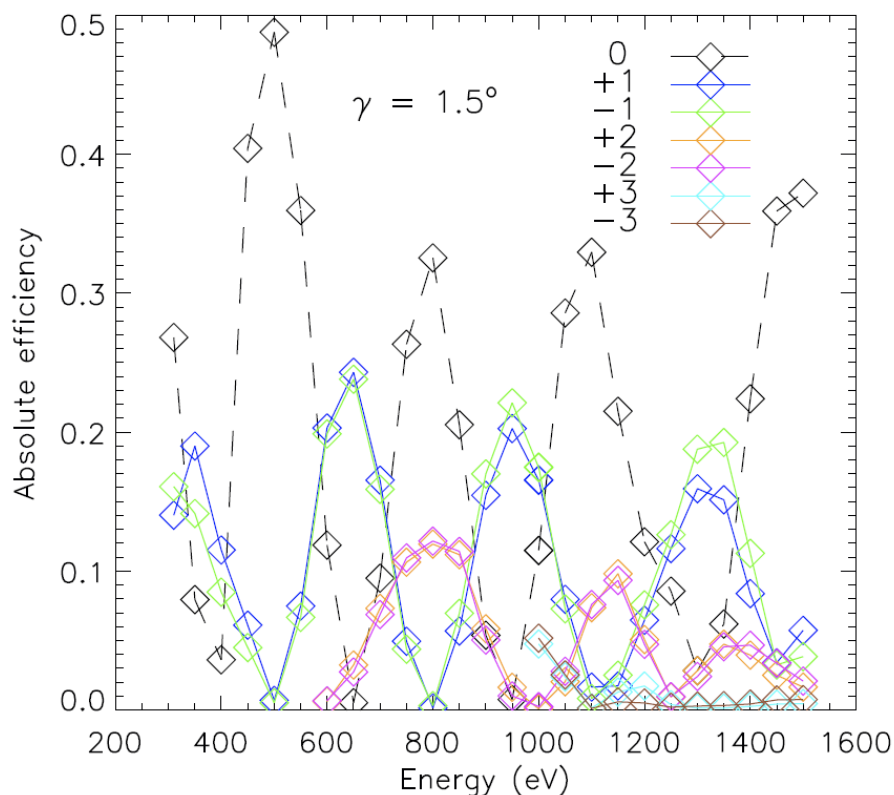
Samples: - up to 50 kg in weight  
- up to 550 mm in diameter

Axis	Range
$\Theta$	$-30^\circ$ to $95^\circ$
Tilt	$-10^\circ$ to $10^\circ$
$\Phi$	$0^\circ$ to $360^\circ$
X	-90 mm to 90 mm
Y	-10 mm to 300 mm
Z	-15 mm to 140 mm
Det. X	0 mm to 120 mm
Det. R	150 mm to 550 mm
Det. $\Psi$	$0^\circ$ to $180^\circ$
$2\theta$	$-5^\circ$ to $190^\circ$

Accuracy: 10  $\mu\text{m}$  or 0.01 $^\circ$

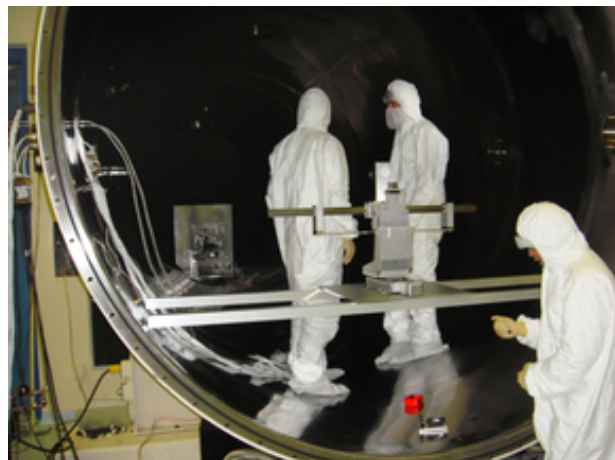
Diameter: 2 m  
Length: 2.1 m  
Weight: 3 t

# Efficiency Results



- $\alpha = 0$ ; higher orders at lower energies in evanescence
- Low duty cycle causes groove well/top interference
- Blaze should 1) remove latter, 2) take power from 0 order, 3) provide flatter efficiency response over energy – all shown theoretically/empirically

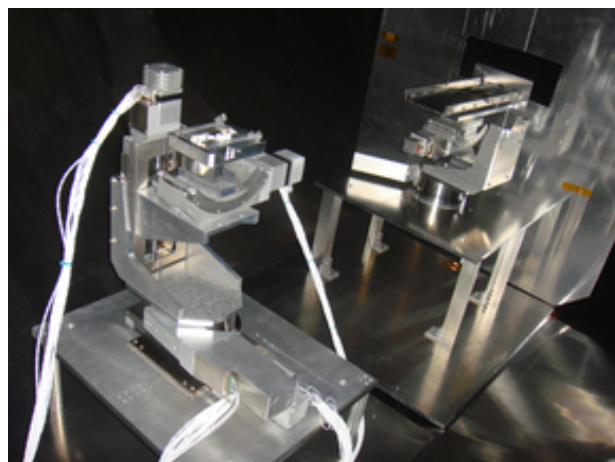
# Spectral Resolving Power Tests at MSFC



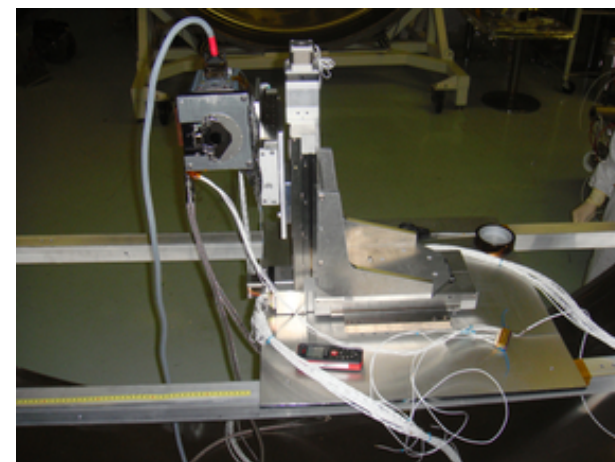
a) Installation



b) GSFC Optics  
TDM



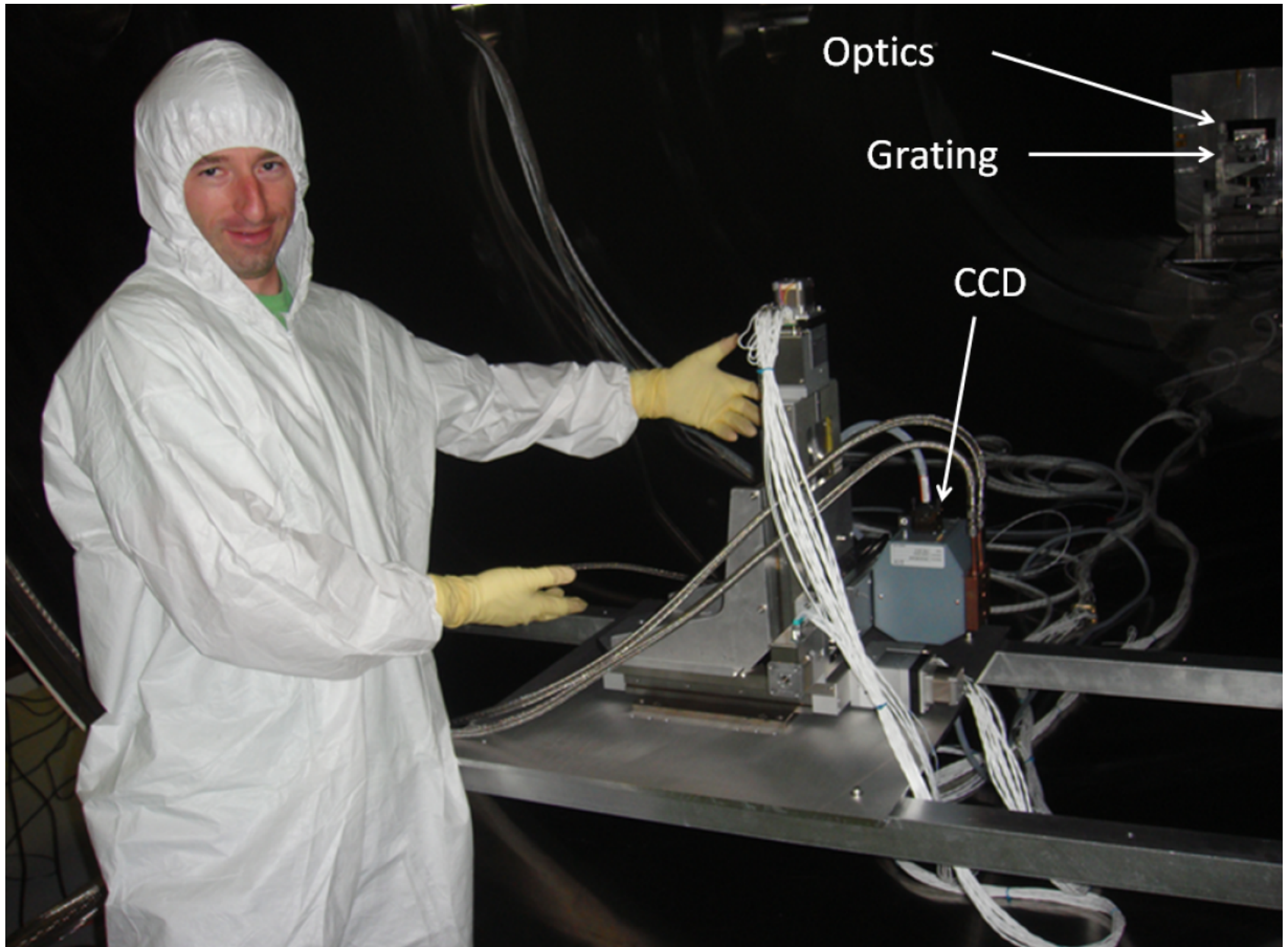
a) Optics + Gratings



a) CCD + stages





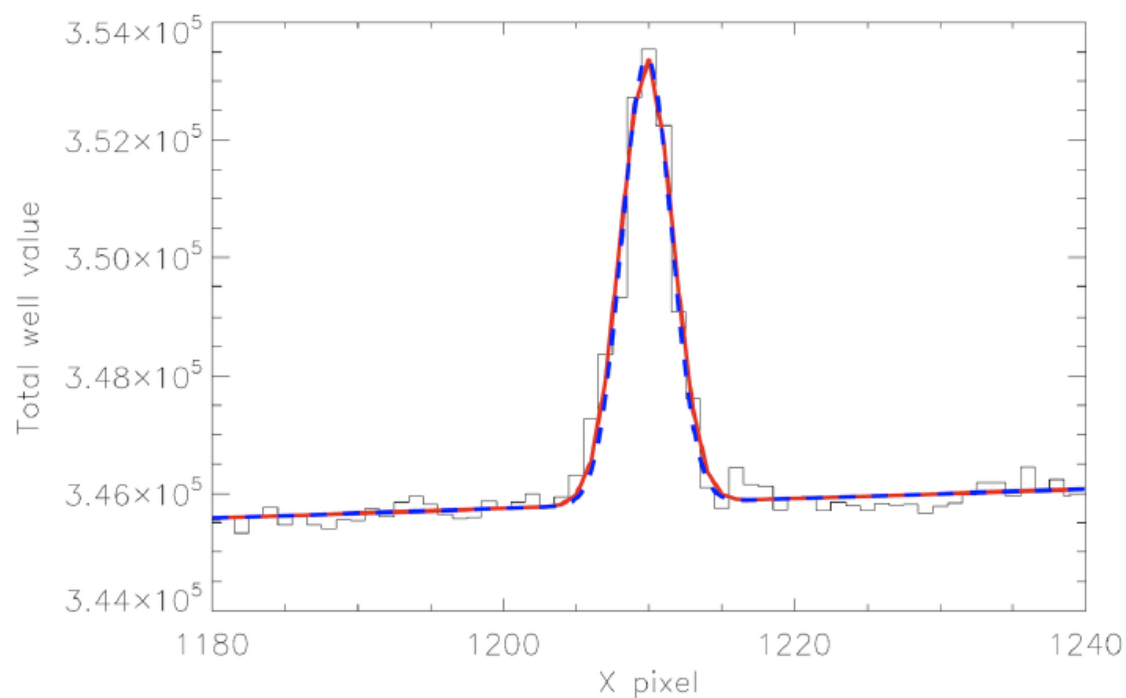
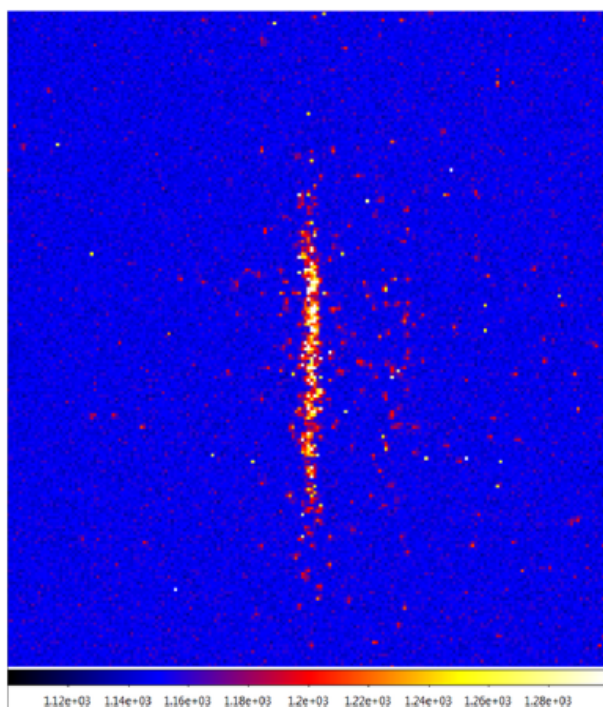


# Resolution results

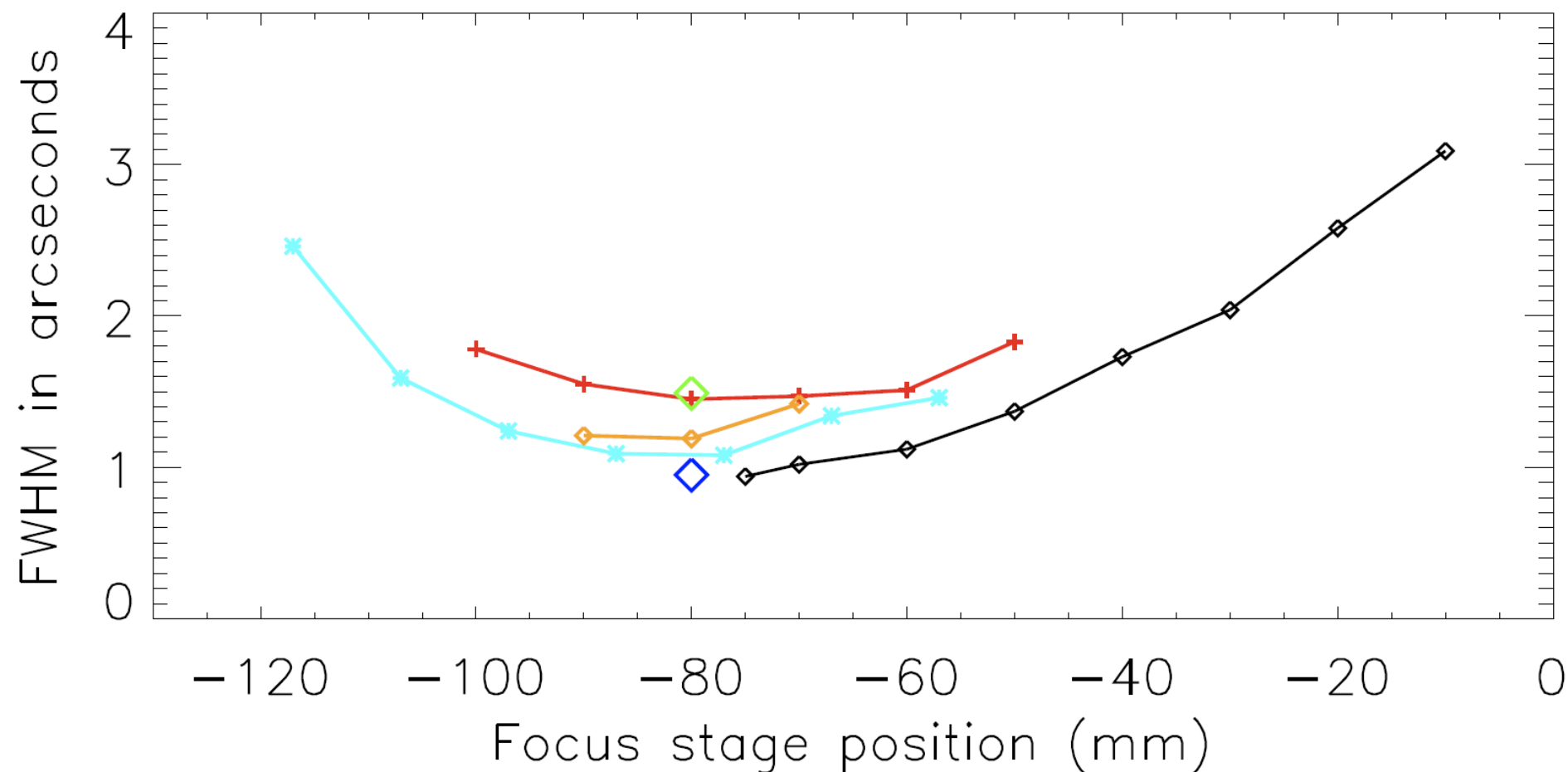
- Mg-K $\alpha$  fluorescence line @ 0.925 keV
- Detected at  $\pm 1^{\text{st}}$ ,  $\pm 2^{\text{nd}}$ , and  $\pm 3^{\text{rd}}$  orders
- Resolution  $\approx$  900, 1300, 1300, respectively

!!!

??

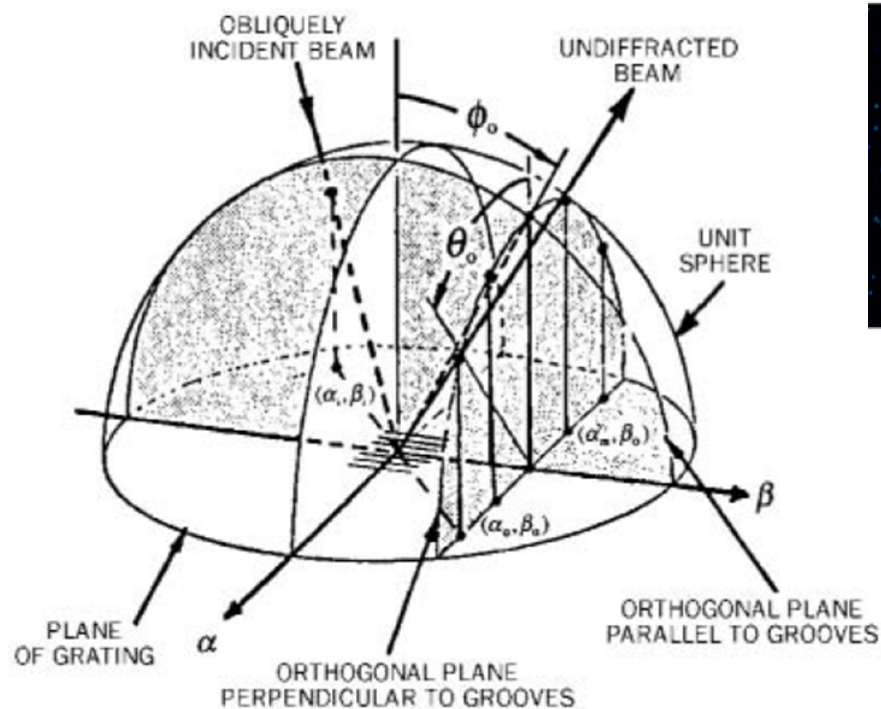


# Focal dependence on source flux



Zero order focus results: Black diamonds - focus run on Day 1 with Manson electron beam current at 0.16 mA; Red crosses - focus run on Day 2 with Manson beam current at 0.5 mA; Cyan asterisks - focus run on Day 3 with Manson beam current at 0.16 mA; Green and Blue diamonds - focus checks on Day 4 with Manson beam at 0.5 mA and 0.16 mA, respectively; Orange diamonds - focus check on Day 5 with Manson beam at 0.16 mA.

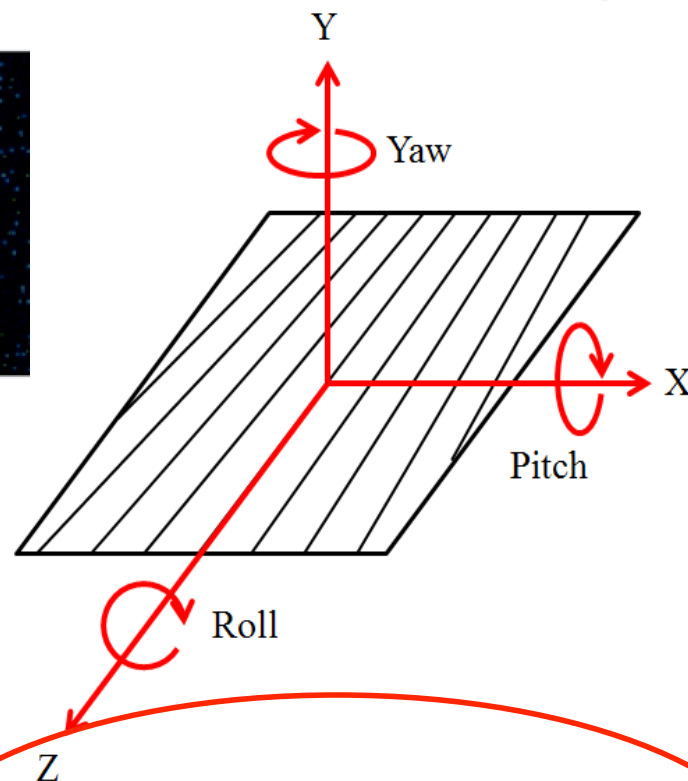
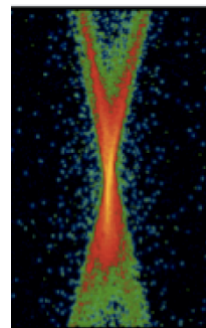
# Grating alignment and module design



Harvey & Vernold (1998)

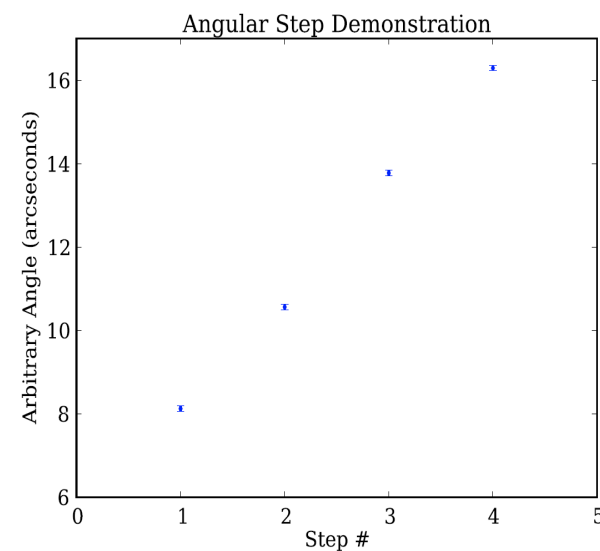
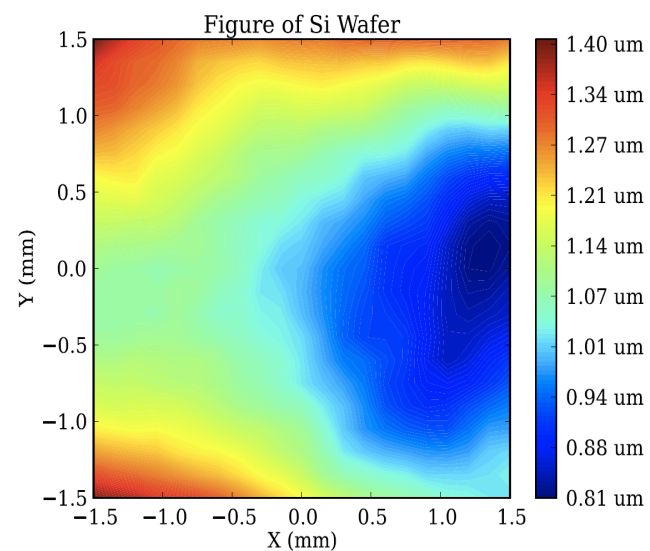
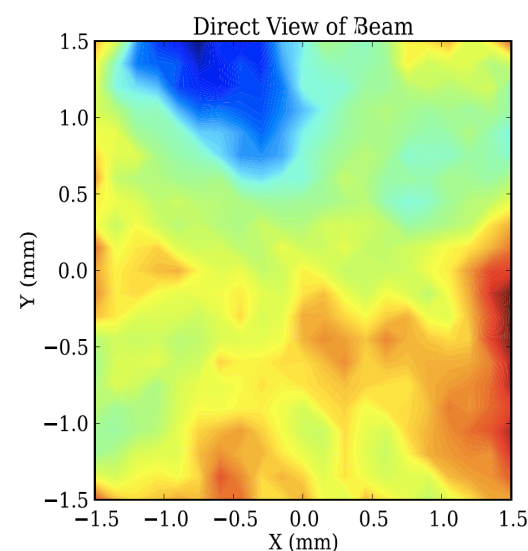
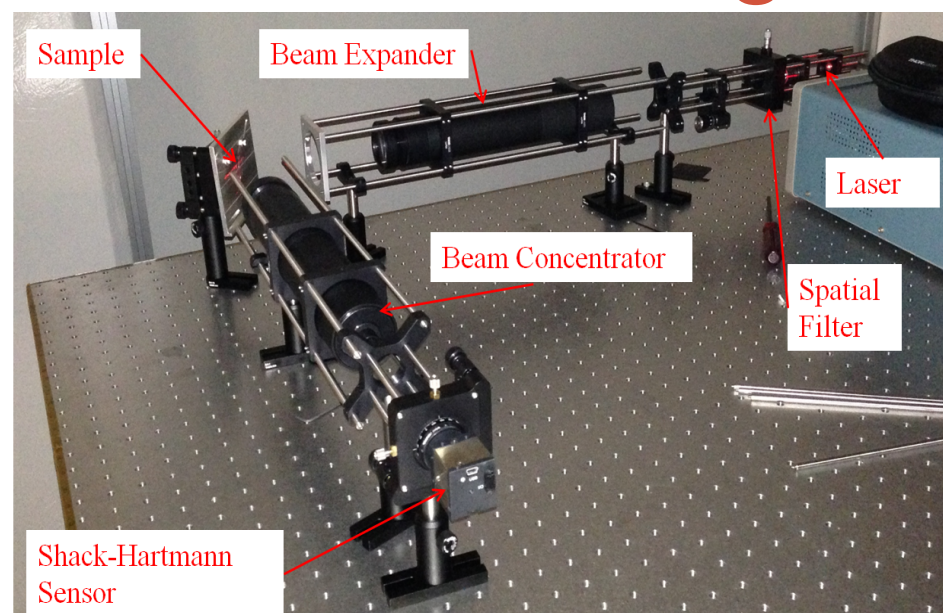
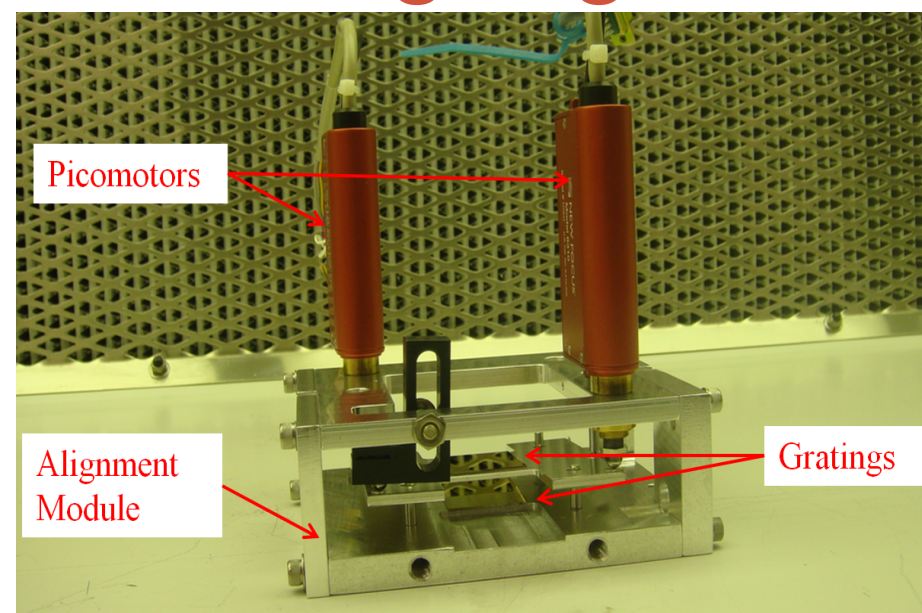
$$\Delta x = L(\alpha \downarrow m, 1 / \beta \downarrow m, 1) - L(\alpha \downarrow m, 0 / \beta \downarrow m, 0)$$

$$\Delta y = L \downarrow f \tan[\arcsin(\gamma \downarrow m, 1)] - L \downarrow i \tan[\arcsin(\gamma \downarrow m, 0)]$$

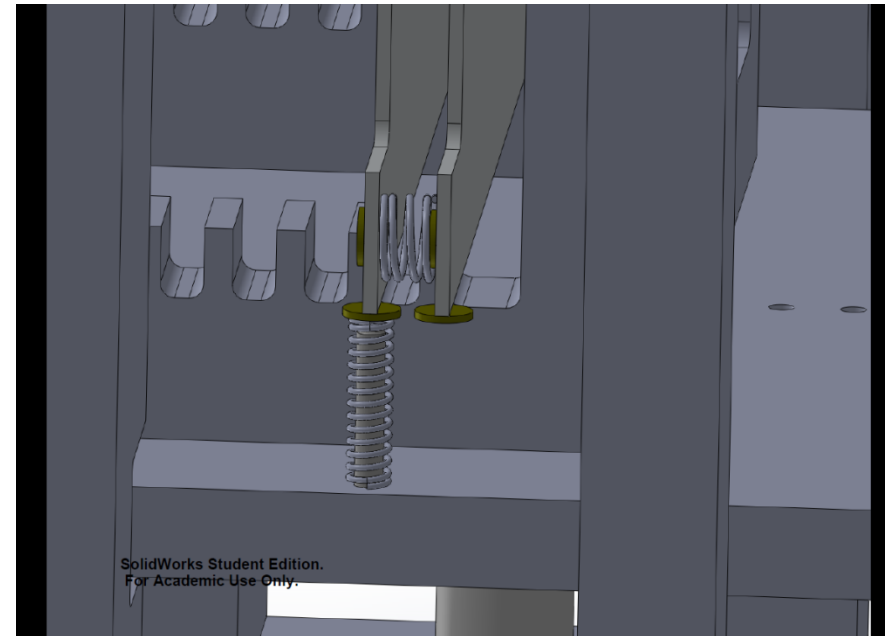
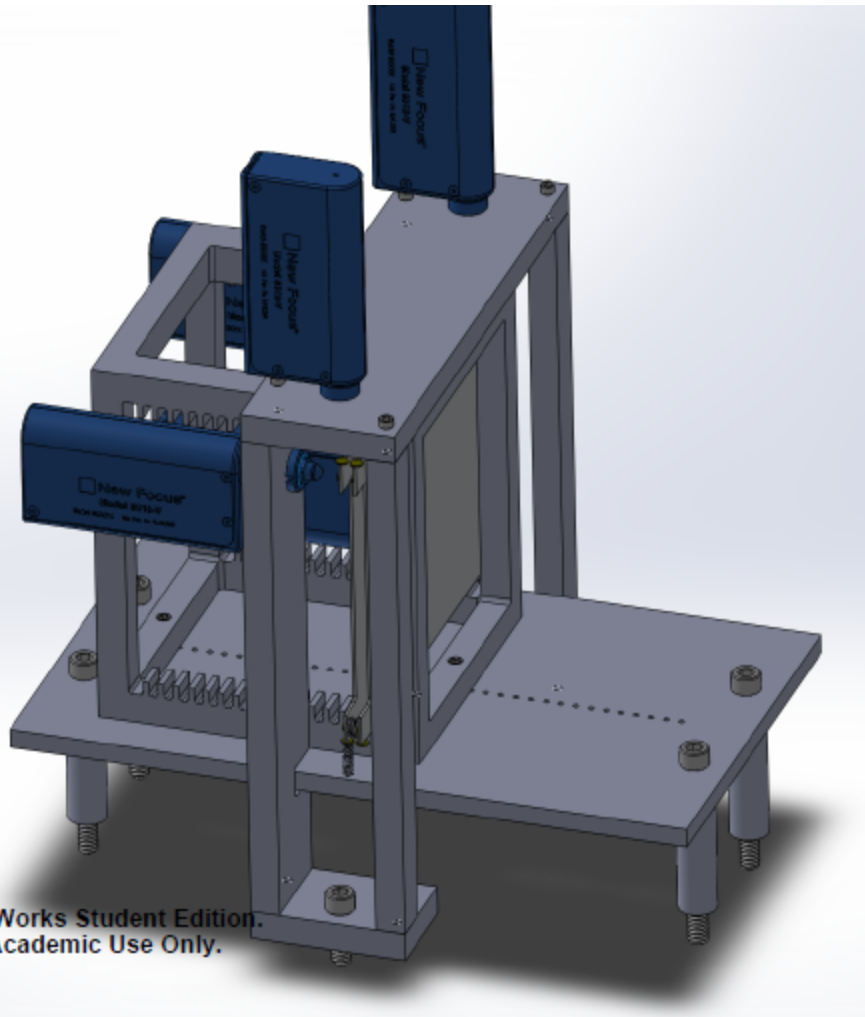


DOF	2.35 $\sigma$		DOF	2.35 $\sigma$	
X	-317 $\mu\text{m}$	+317 $\mu\text{m}$	Pitch	-4.5"	+4.5"
Y	-124 $\mu\text{m}$	+124 $\mu\text{m}$	Yaw	-8.3"	+8.3"
Z	-1.56 mm	+1.56 mm	Roll	-22"	+22"

# Grating alignment and module design



# Grating Module Rev 2

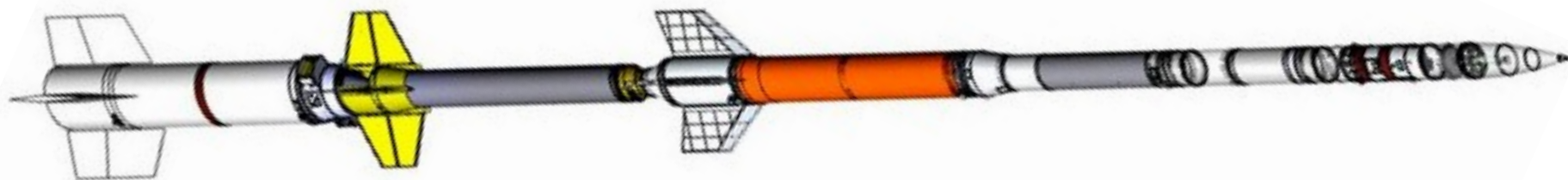


# Accomplishments and plans

- Radial, high density grating fabricated
- Measured high efficiency over relevant energies
- Measured high spectral resolving power matching theoretical expectations at first order
- Higher order resolving power limited by facility issues
- Alignment metrology and methodology consistent with achieving tolerance requirements
- Blaze grating (recently ~successful)
- Measure high efficiency on blazed gratings
- Measure high spectral resolving power on blazed gratings
- Limit source size or increase beam length
- Design, fabricate, and test aligned modules of blazed gratings (a new SAT... hopefully)

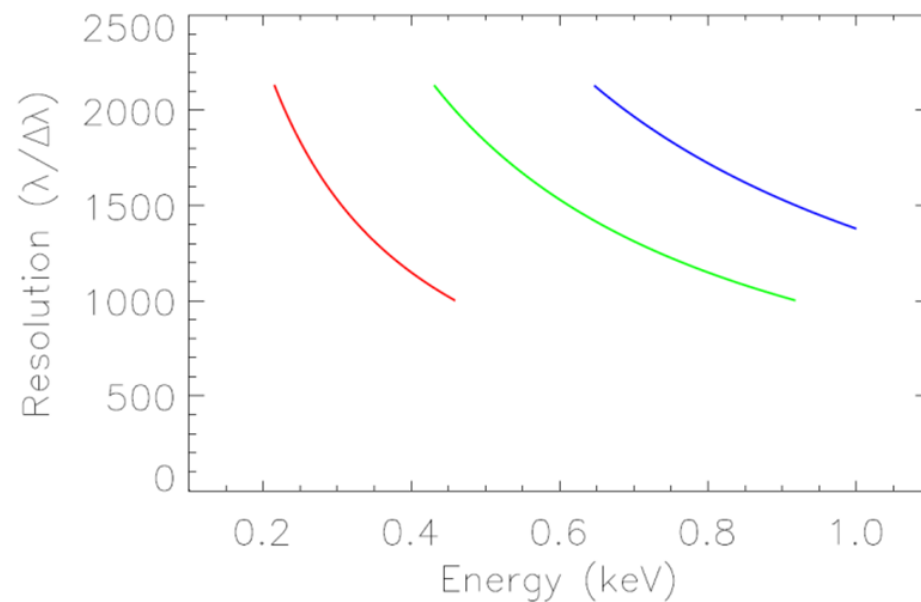
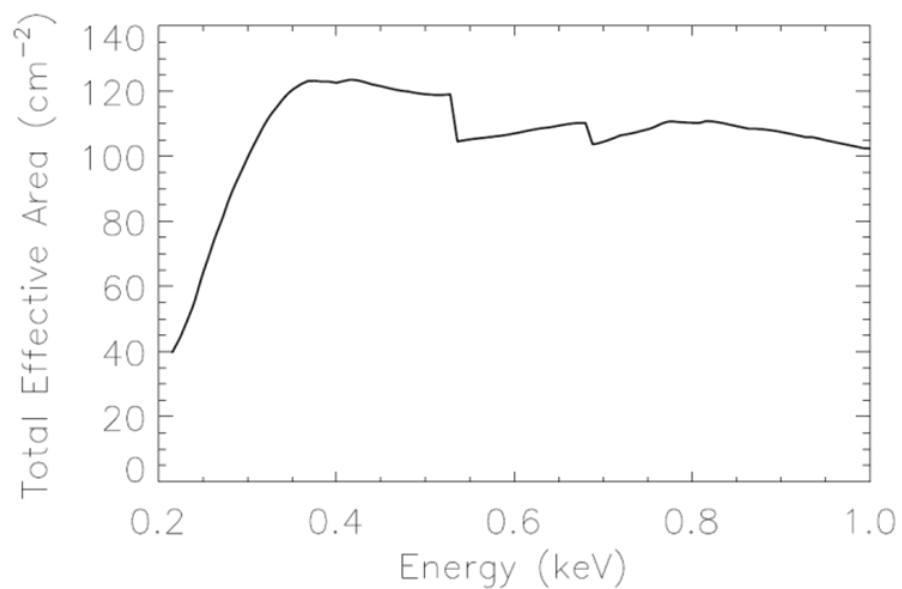
# NASA - APRA

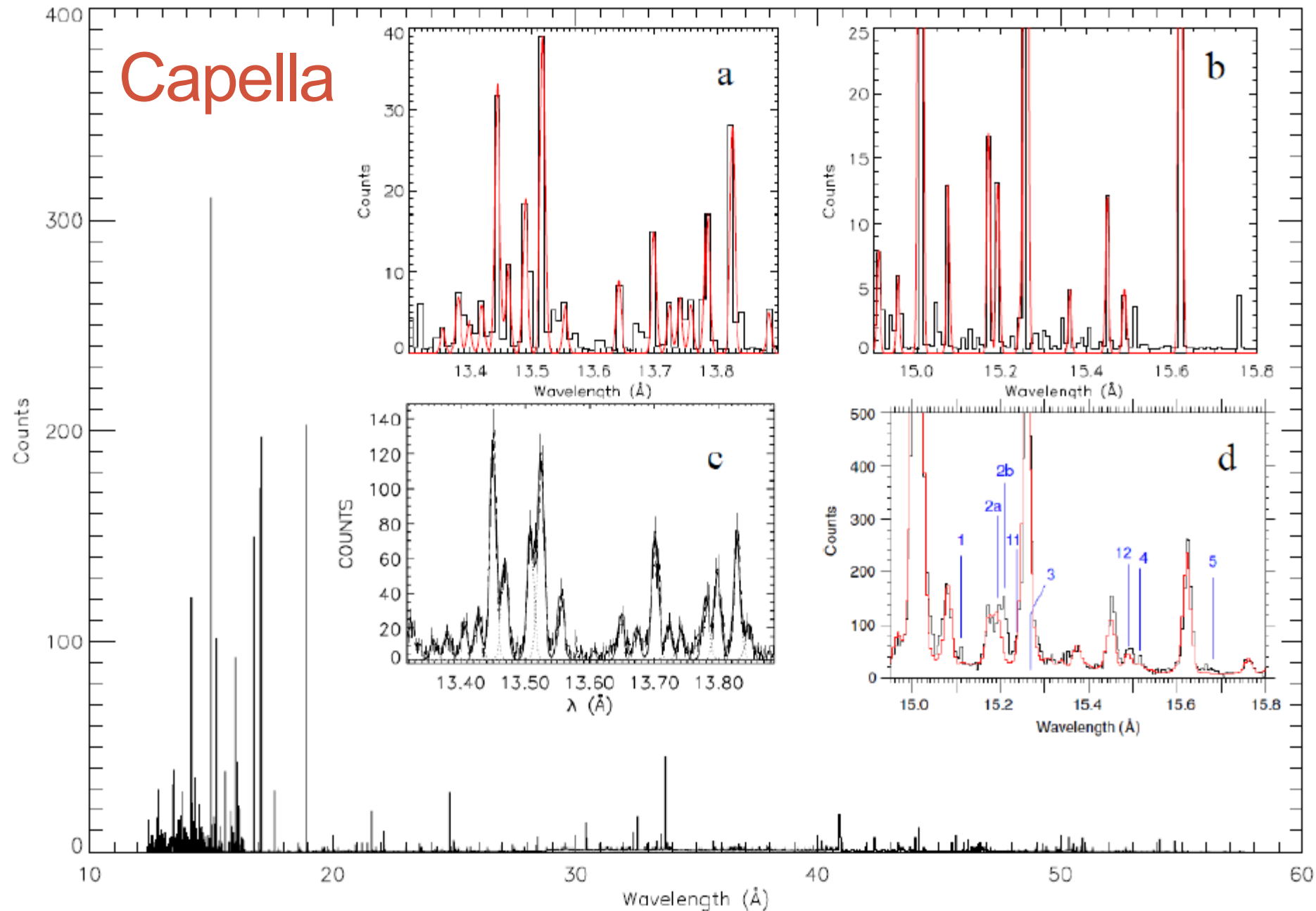
- 5-year suborbital rocket program
- Off-plane Grating Rocket Experiment (OGRE)
- Increase flight readiness of gratings as well as optics and CCDs...
  - Optics supplied by Goddard Space Flight Center
  - Gratings ,+++ at Iowa
  - CCD camera supplied by Open University + e2v Technologies



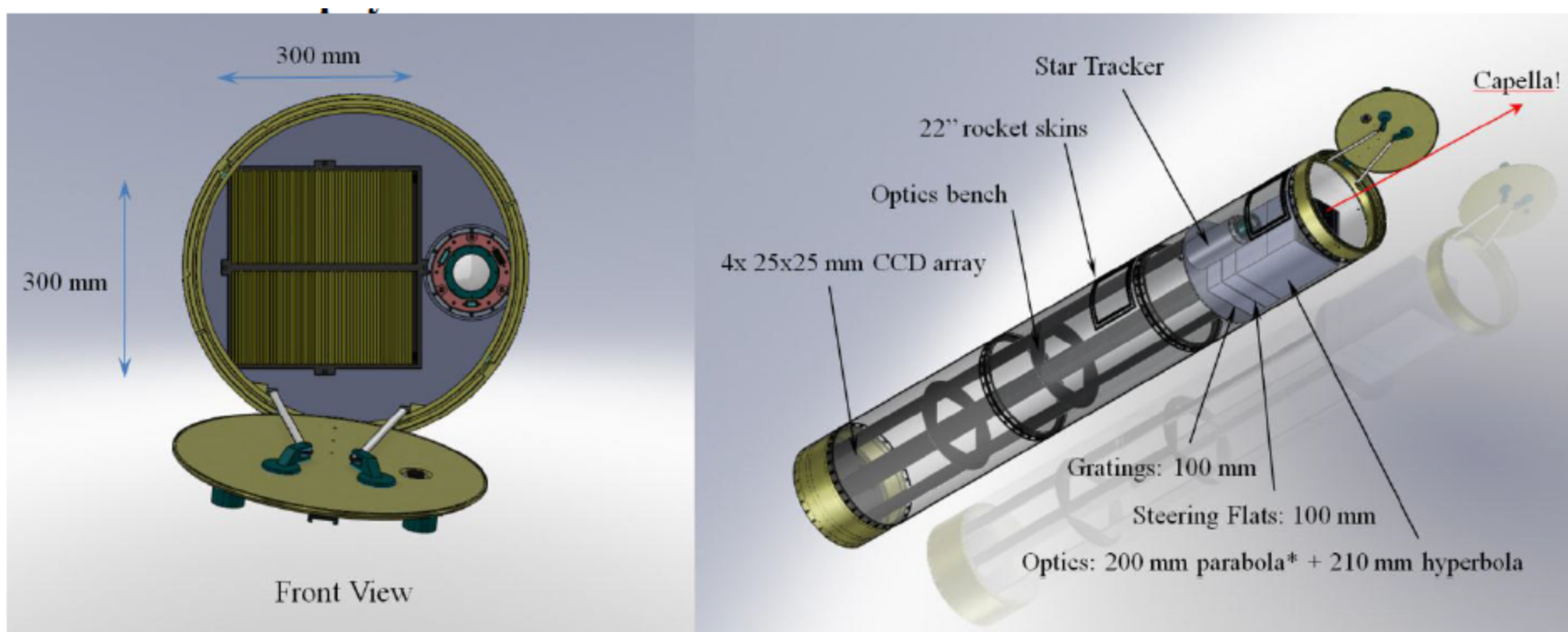


# OGRE performance





# Payload



# Launch 2017!

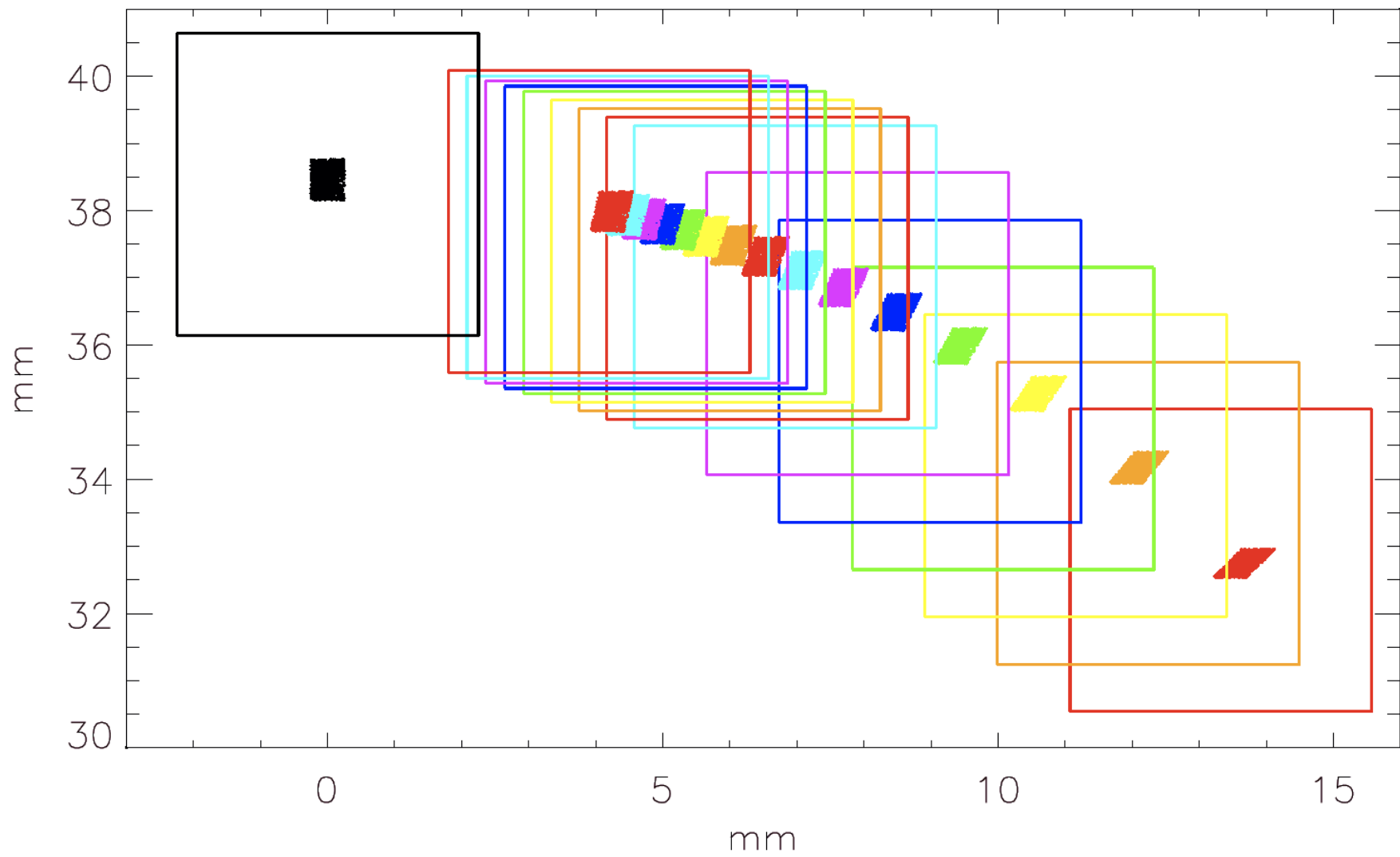
# Summary

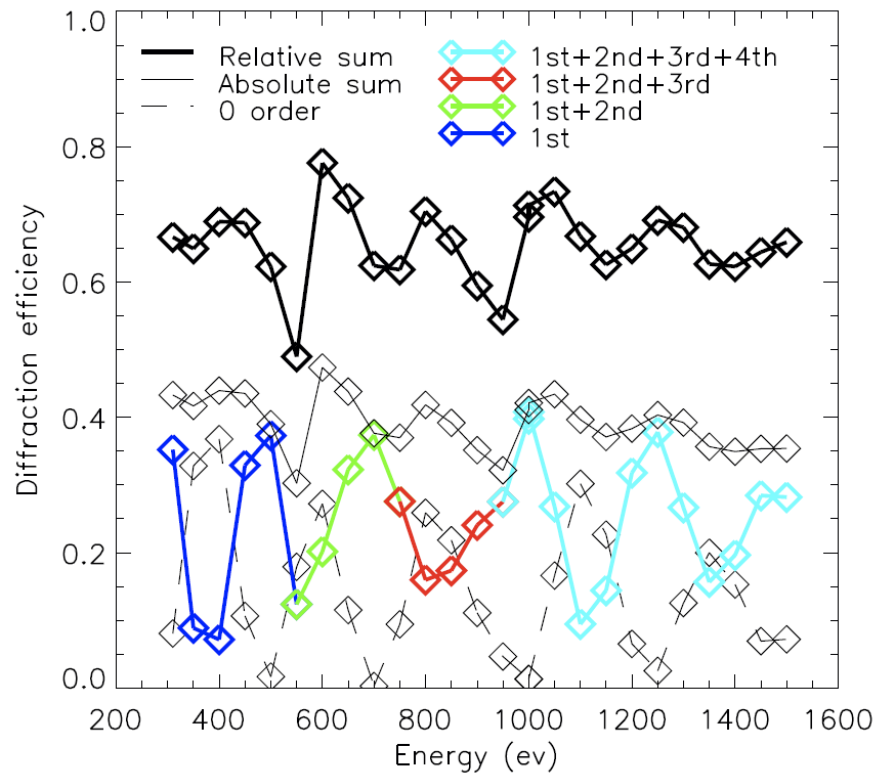
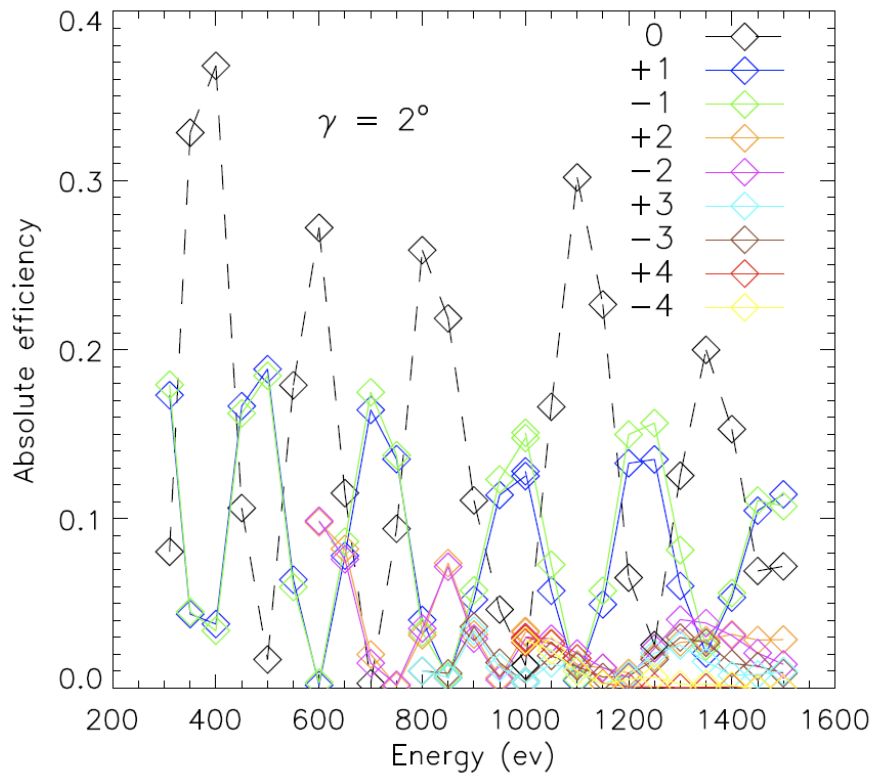
- Grating spectrometers are critical to future X-ray science goals
- Off-plane gratings provide a method for obtaining high throughput and spectral resolving power
- A new fabrication method has been identified.
  - Initial steps have been taken to produce a high density, radially ruled groove profile
  - Initial performance results are consistent with requirements
  - Blazing processes are understood and underway
  - Alignment tolerances are identified
  - Alignment methodologies and module mounts have been implemented with a development plan in place
- Technology development programs have accelerated grating studies and provided a well defined path until a mission is identified

# Acknowledgements

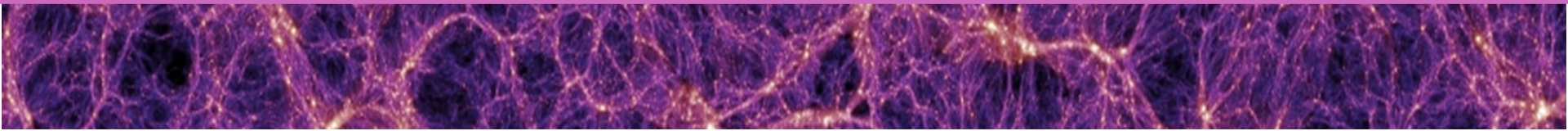
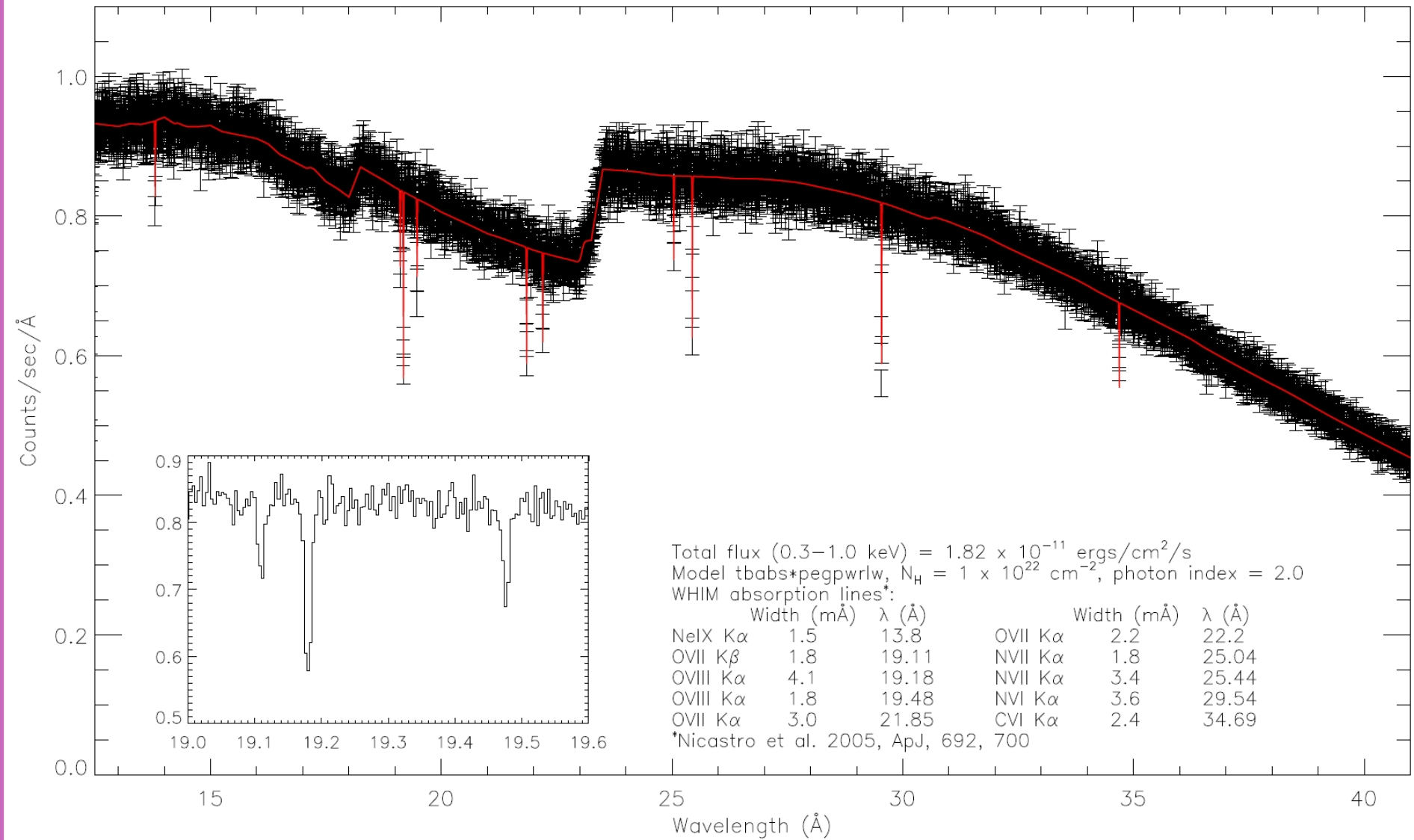
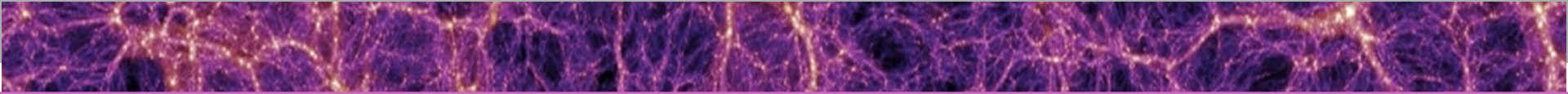
- NASA – Strategic Astrophysics Technology grant (SAT)
  - NNX12AF23G, ...?
- NASA – Nancy Grace Roman Technology Fellowship (RTF)
  - NNX12AI16G, ...?
- NASA – Astronomy and Physics Research and Analysis (APRA)
  - NNX13AD03G
  
- *Thank you for your attention!*

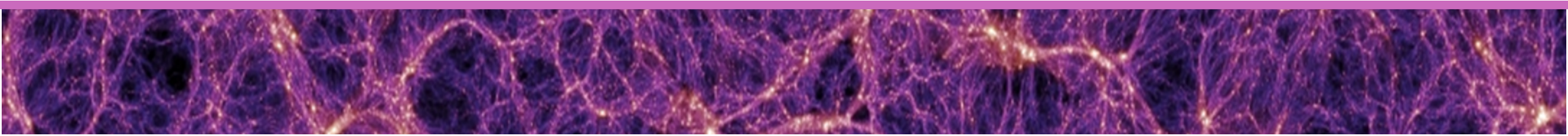
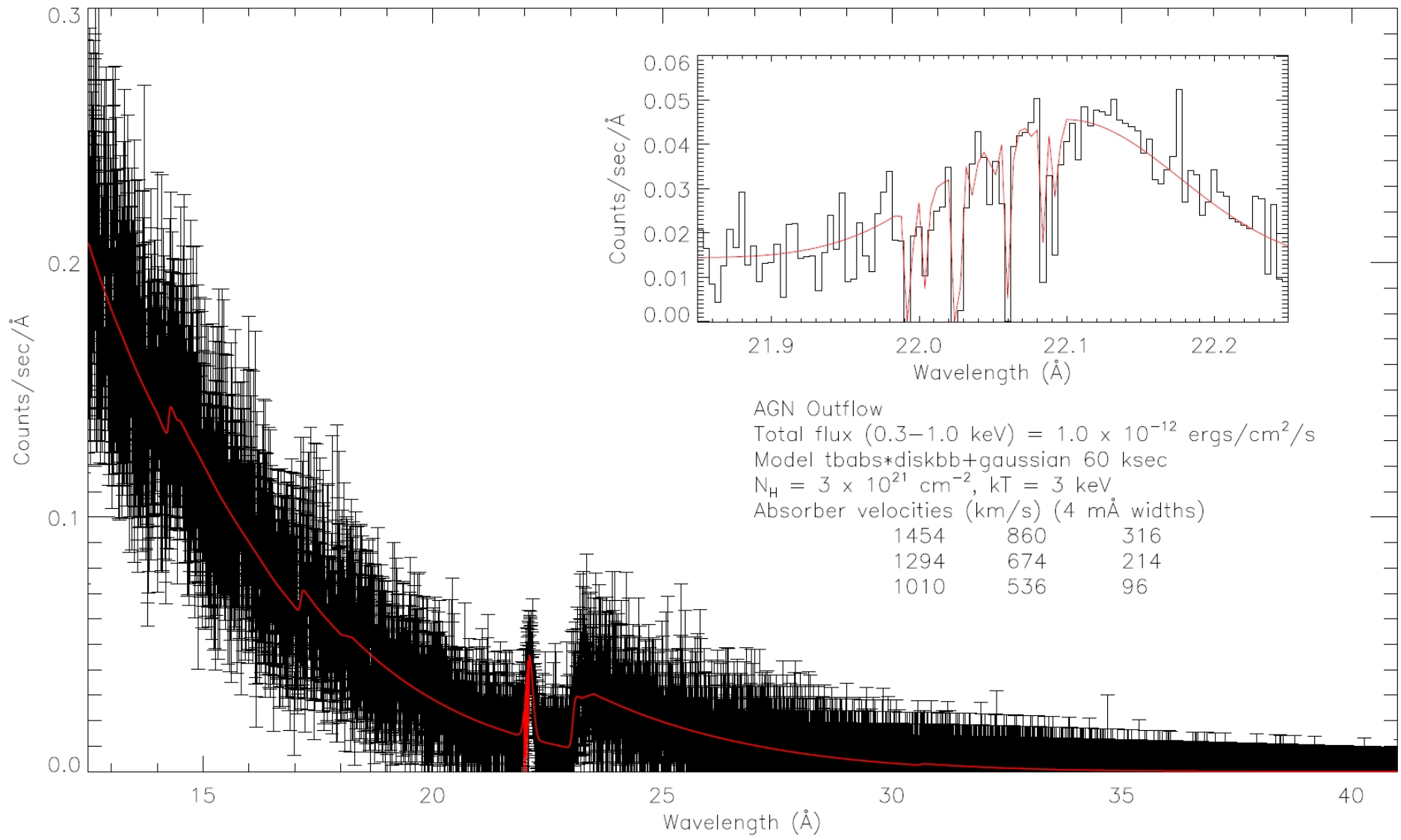
Back-up slides

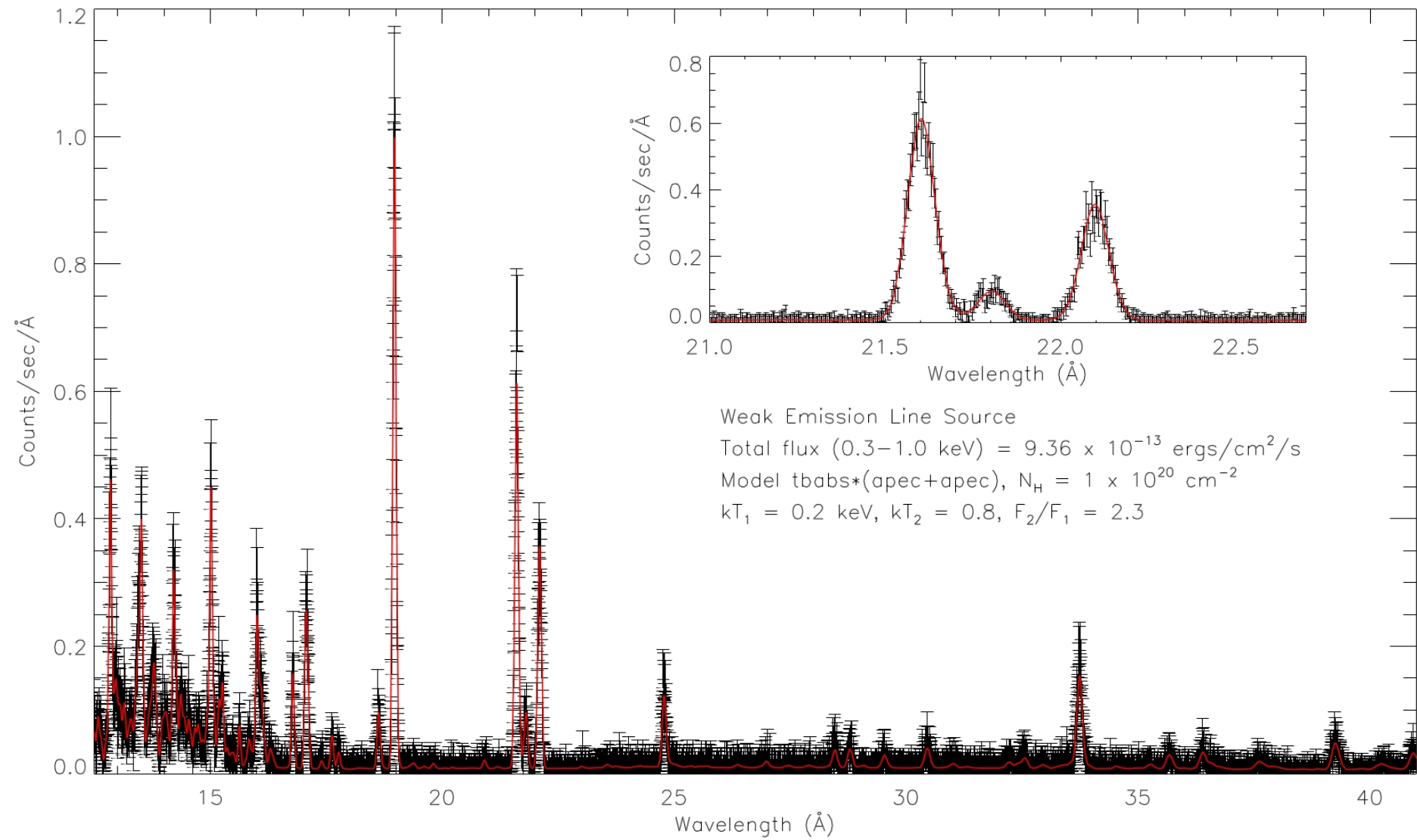


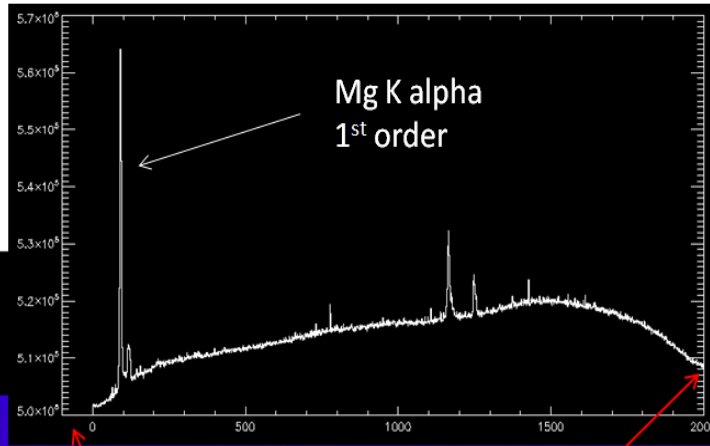












0 order

-1<sup>st</sup> order

