A Grazing Incidence X-Ray Telescope (GI-XRT) for Solar-C

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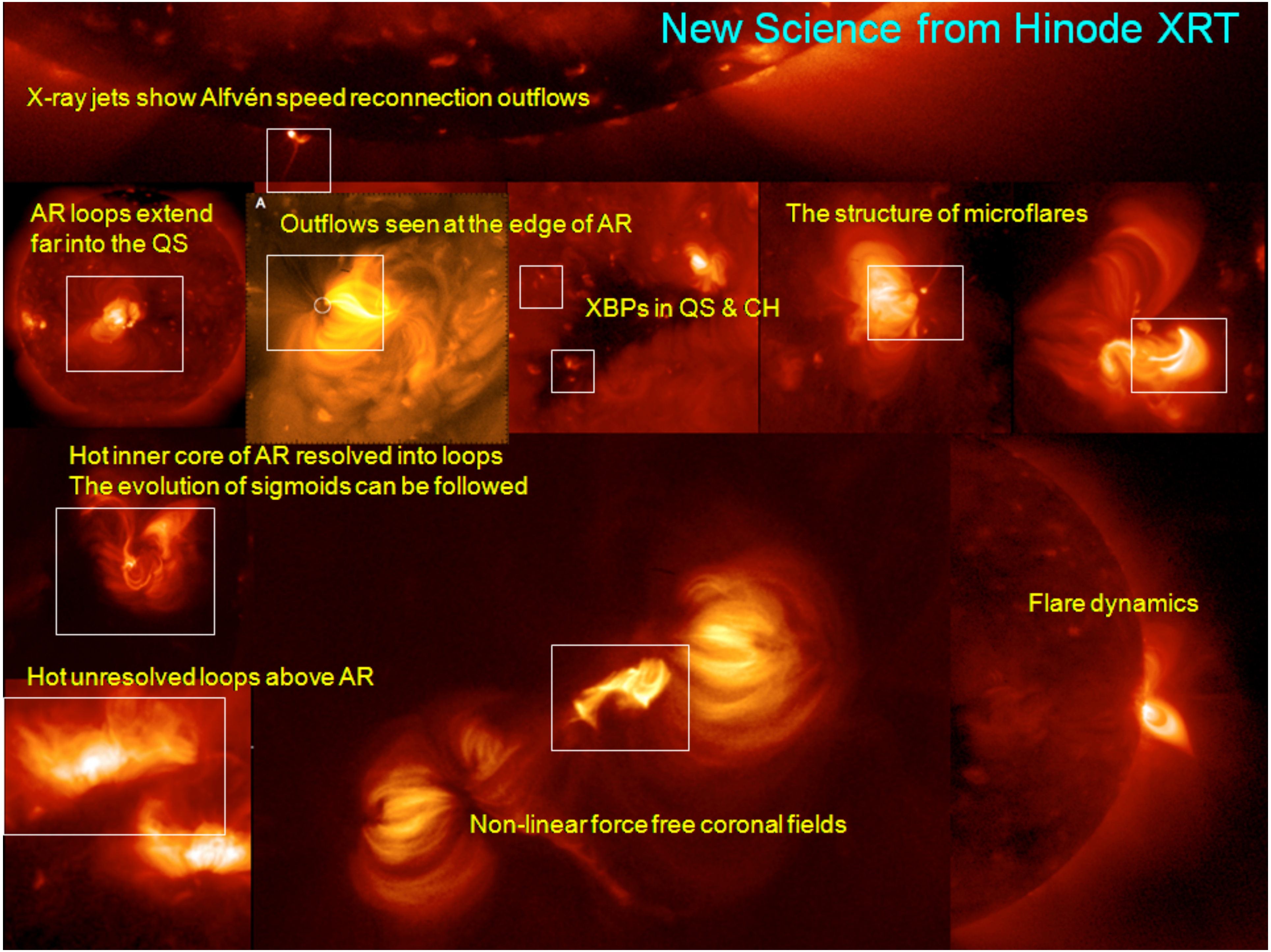


New Science from Hinode XRT
X-ray jets show Alfvén speed reconnection outflows
AR loops extend far into the QS
A
Outflows seen at the edge of AR
XBPs in QS & CH
The structure of microflares
Hot inner core of AR resolved into loops
The evolution of sigmoids can be followed
Flare dynamics
Hot unresolved loops above AR
Non-linear force free coronal fields

Outline

- **GI vs. NI Trade Space**
- **Characteristics of the GI XRT for Solar-C**
- **High energy imaging of the corona**
- **Temperature discrimination**
- **Large dynamic range imaging**
- **Time resolution**
- **Integrated science observations**
  - Ubiquitous Reconnection
  - Ubiquitous Waves
  - MHD and Plasma Processes
- **Conclusions**

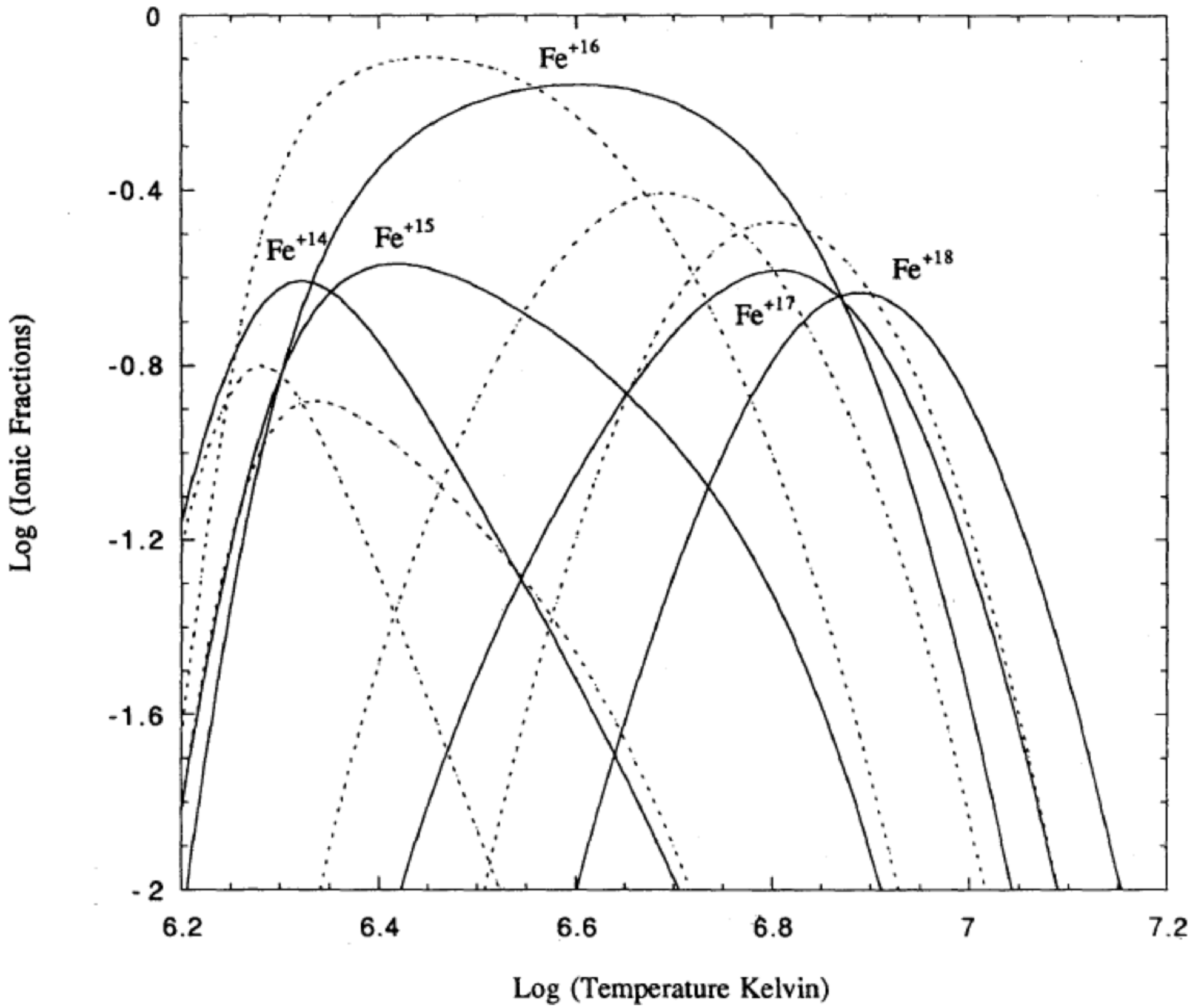
GI vs NI Trade Space

	PRO	CON
GI	▪ Broad temperature response, can see all of coronal plasma ▪ Fe XVII available, the main emission line between 3-8MK ▪ Robust design - energetic photons are easier to detect	▪ Moderate spatial resolution (0.5" - 0.3") possible ▪ Images have a large dynamic range (detector issue) ▪ Need multiple filters for temperature resolution ▪ Image stabilization difficult
NI	▪ Relatively isolated temperature response ▪ High spatial resolution (0.1"-0.03" possible) ▪ Large collecting area possible	▪ Relatively isolated temperature response → multiple telescopes ▪ Charge spreading in detector ▪ Need large entrance filters

Coronal Imaging – Dominance of Fe XVII in Active Corona

- **Fe line fractions as a function of temperature (solid lines are most recent models, Raymond)**
- **Imaging Fe XVII (Fe^{+16}) is critical for following the evolution of magnetic structures before the on-set of instabilities**

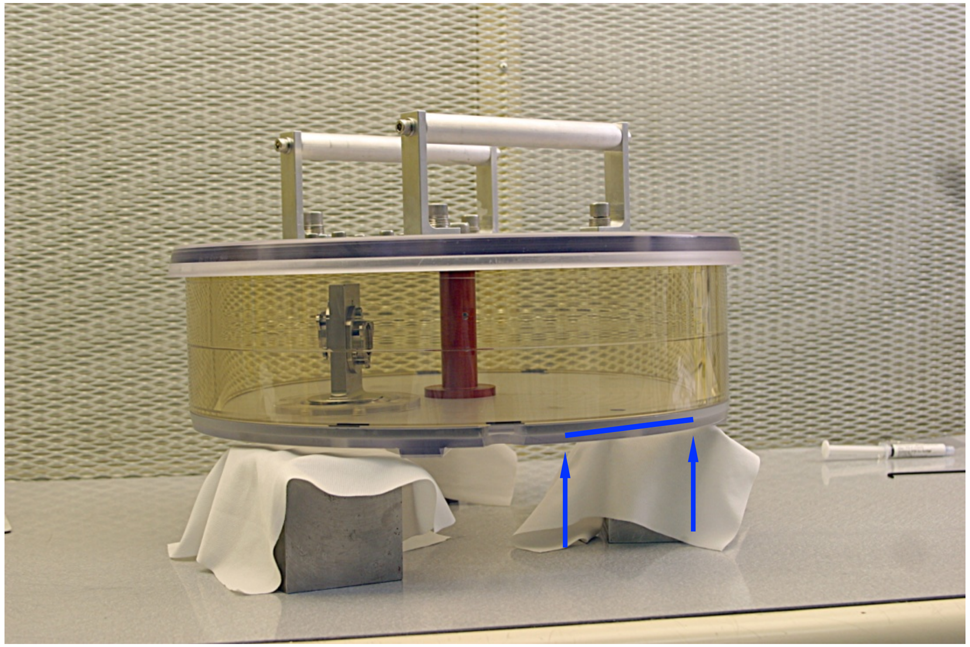
Note Log Scale

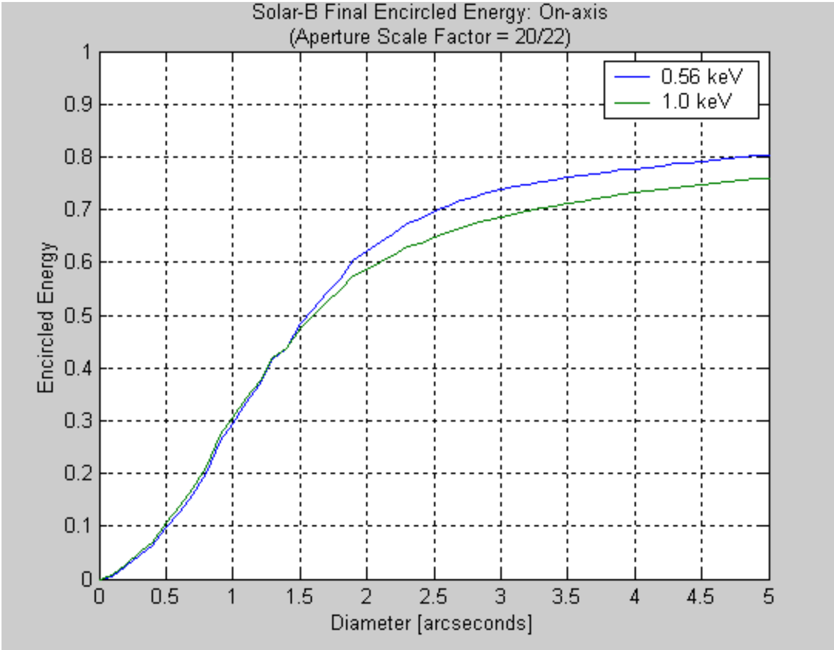


Suggested GI-XRT Characteristics: Geometry

- **4.0 m focal length**
  - 0.5 arcsec pixel at 10μm size
- **25 cm radius (at the intersection of primary and secondary surfaces)**
  - 1.8 deg graze angle at intersection
- **40 mm long primary**
  - and 50 mm long secondary to reduce vignetting off-axis
- **45 deg wide segment of full circle**
  - optic will be polished as a flat, not cylindrical, piece.
- **Wolter-I design**
  - modified for wide field, similar to XRT
- **Flat detector**
  - can be shifted ~0.2 mm forward of on-axis best focus
- **F.O.V.: 2kX2k ≈ 1000 arcsec = 16 arcmin**
  - Full Sun if 4kX4k detector available
  - SAO development program, 8μm pixels, APS sensor, NkXNk

GI-XRT Characteristics: Comparison to XRT Optic



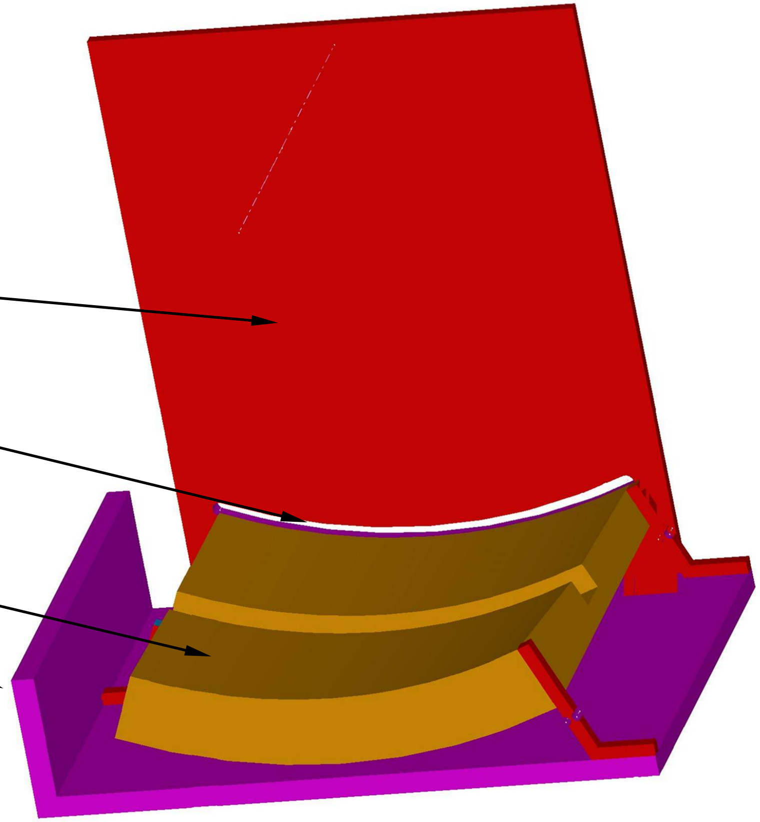


Propose a segment of full optic as indicated above, with larger graze angle for increased collecting area (and longer λ diffraction limit).

Encircled energy curves for XRT flight optic, <2 arcsec diameter @ 50% EE.

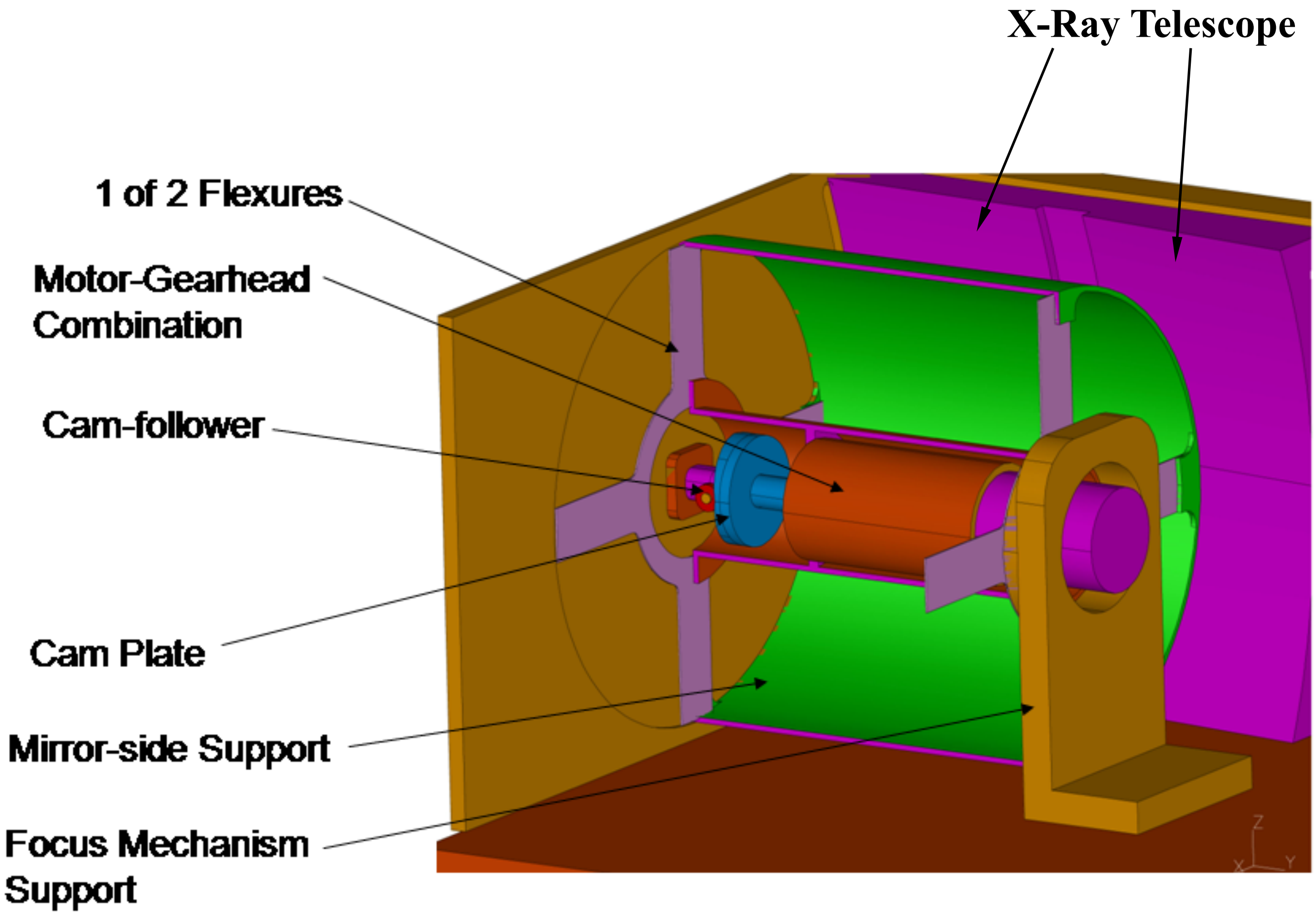
Figuring optic as a flat will allow improved performance – better figure, mid-frequency and microroughness.

GI-XRT Characteristics: View of the Optic



See next slide for detailed view of mirror and mount.

GI-XRT Characteristics:
Optical Assembly With Focus Mechanism



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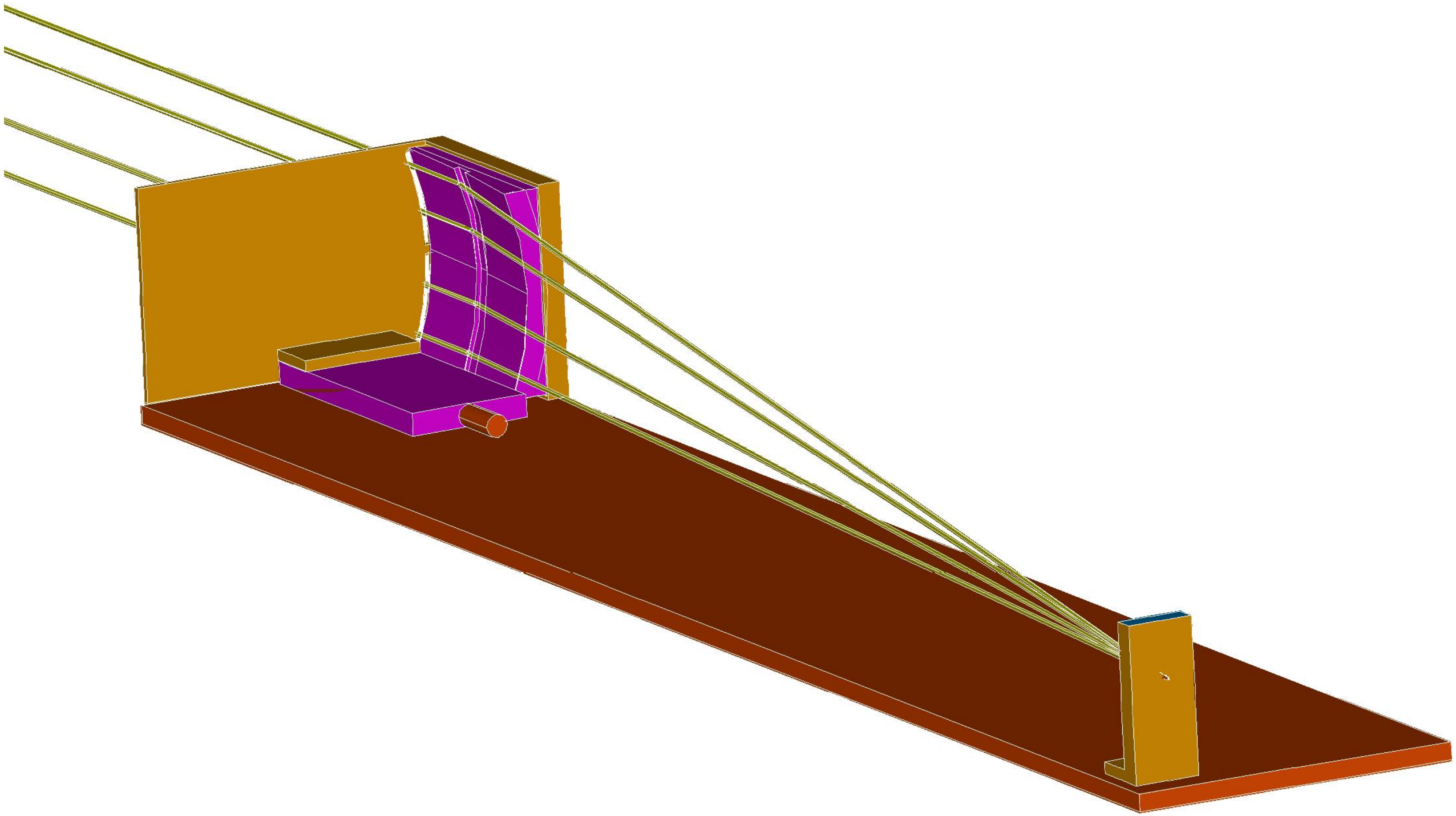
Focus Mechanism (with the Outer and Inner Supports Cut)

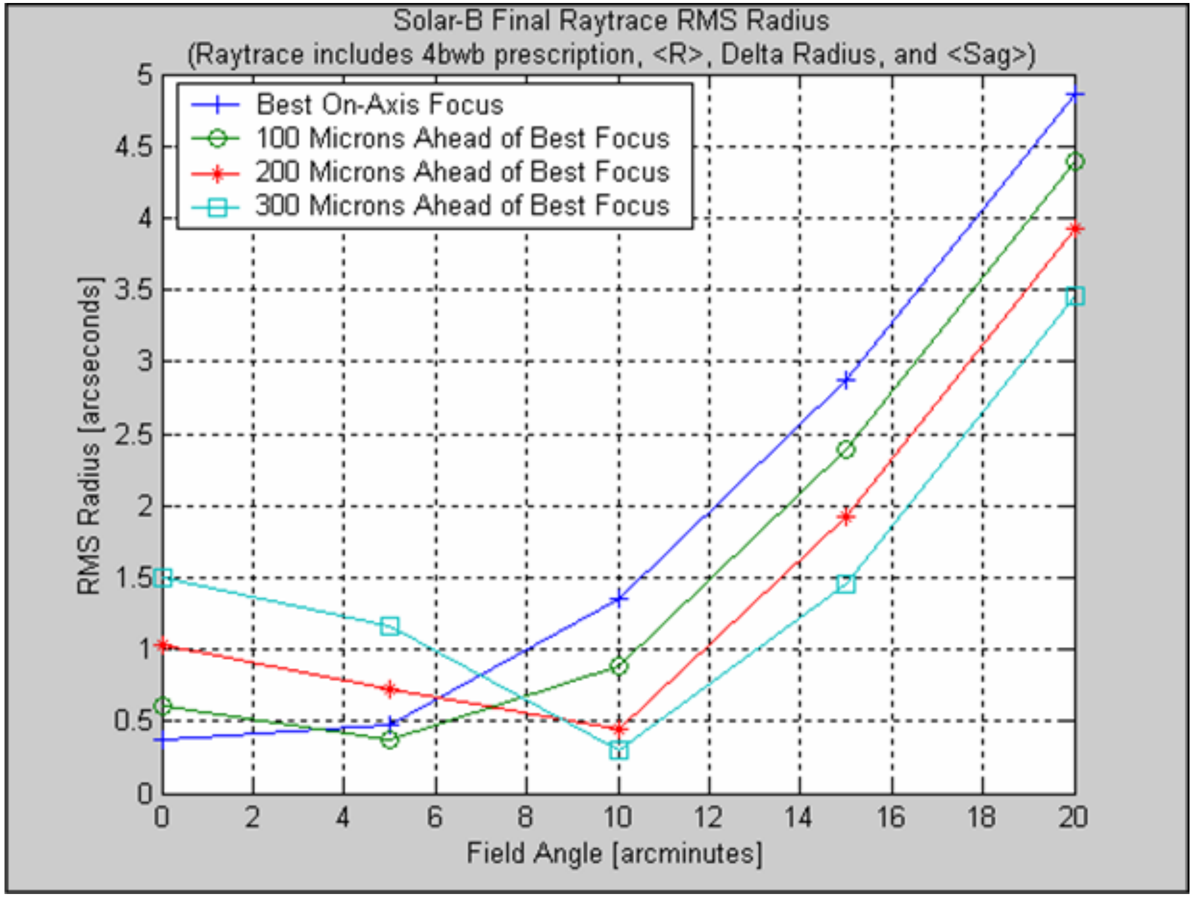
GI-XRT Characteristics:
Full Telescope (Conceptual) – Entrance to Focal Plane



GI-XRT Characteristics:
Flexures Used for XRT Mirror Mount

For GI-XRT the angled portions would not be needed.

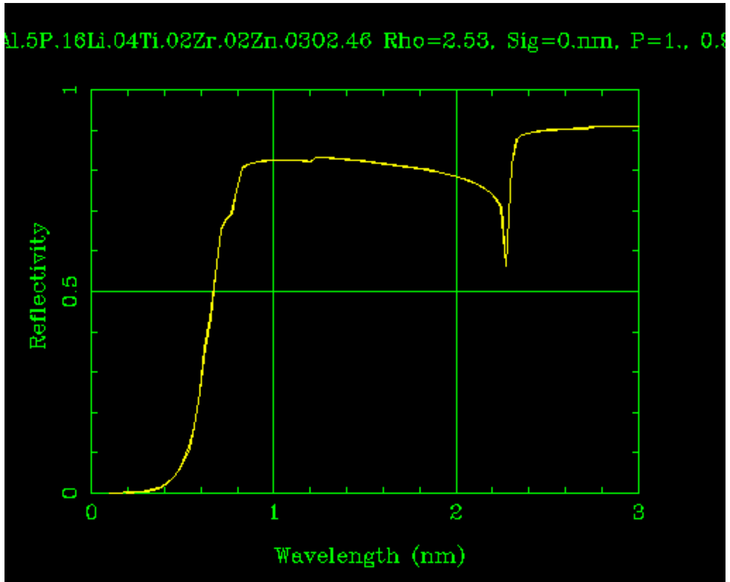
GI-XRT Characteristics:
Resolution v. Field Angle for *Hinode* XRT

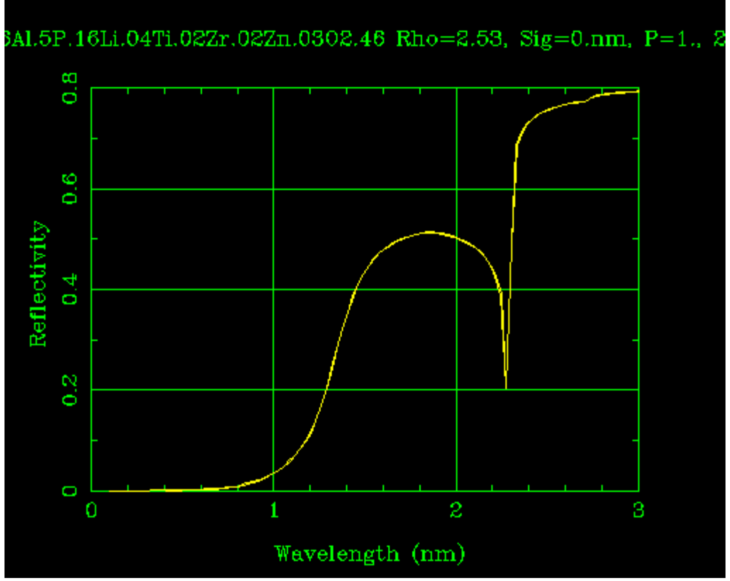


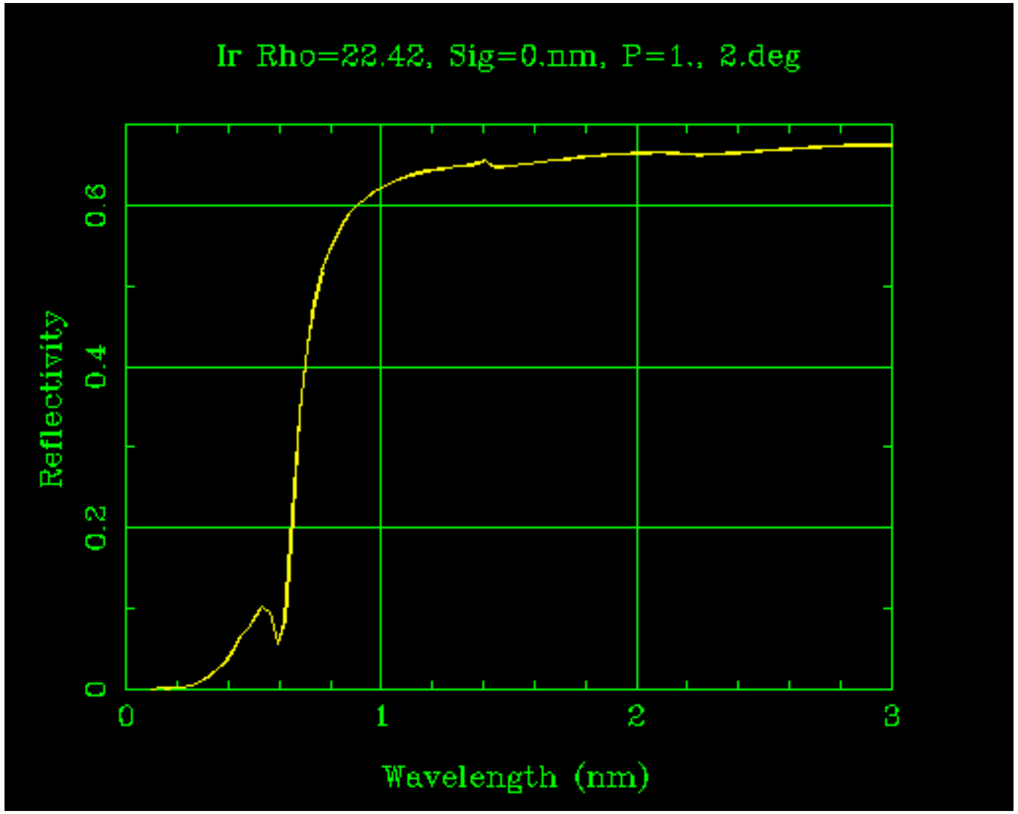
XRT operates at two positions: best on-axis for small f.o.v. and ~200 µm forward of best focus for full field imaging.

GI-XRT Characteristics:

Telescope Wavelength Response

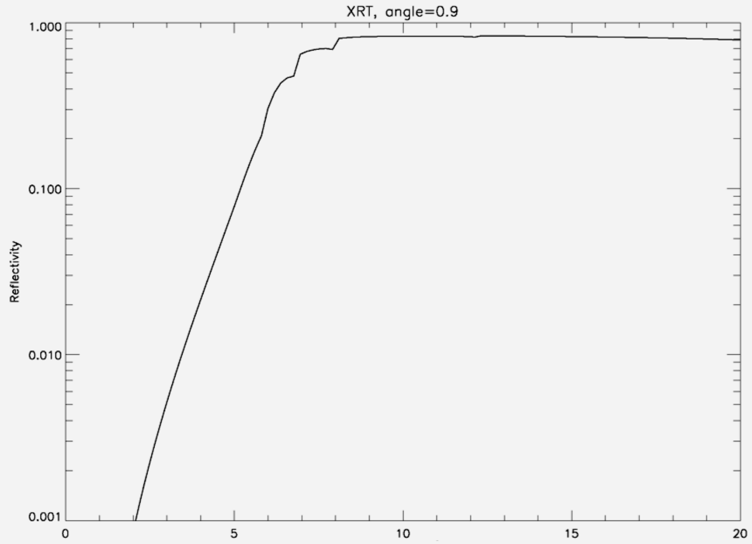


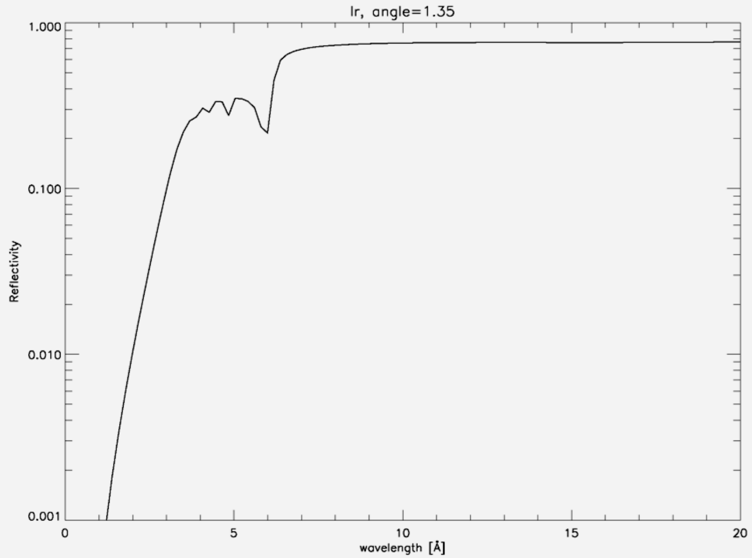


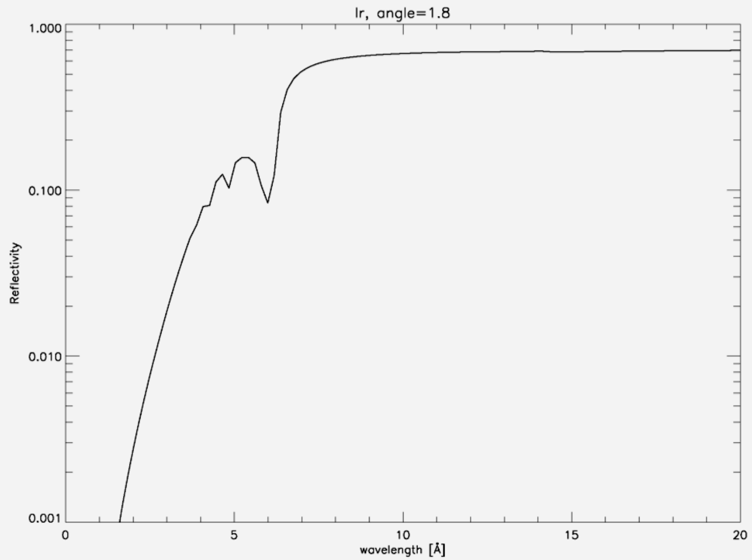


•XRT cut-off (R=10%) is 5.6Å.
•GI-XRT on Zerodur is 12Å.
•With Ir coating, GI-XRT cutoff is 6.2Å (and no dip at OVII)

GI-XRT Characteristics:
Wavelength Response

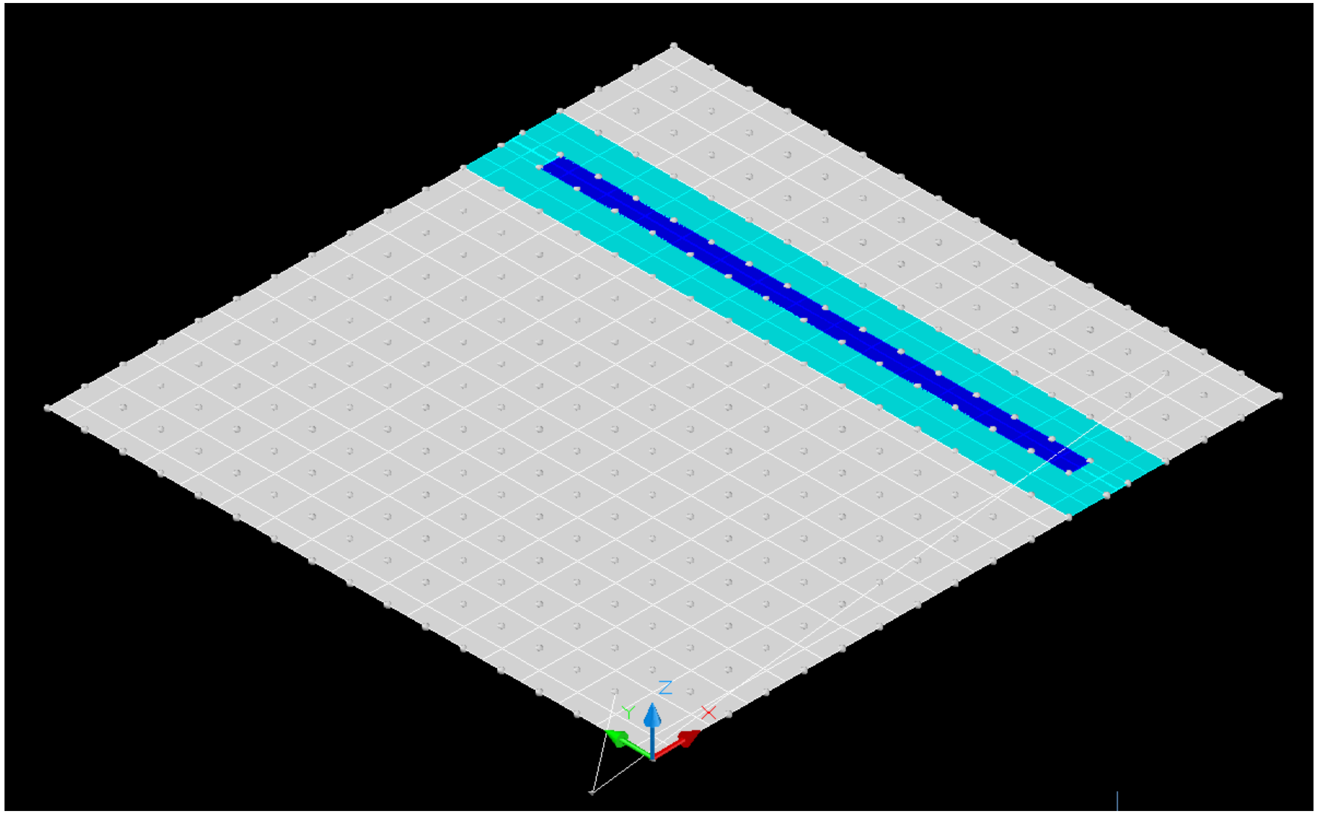






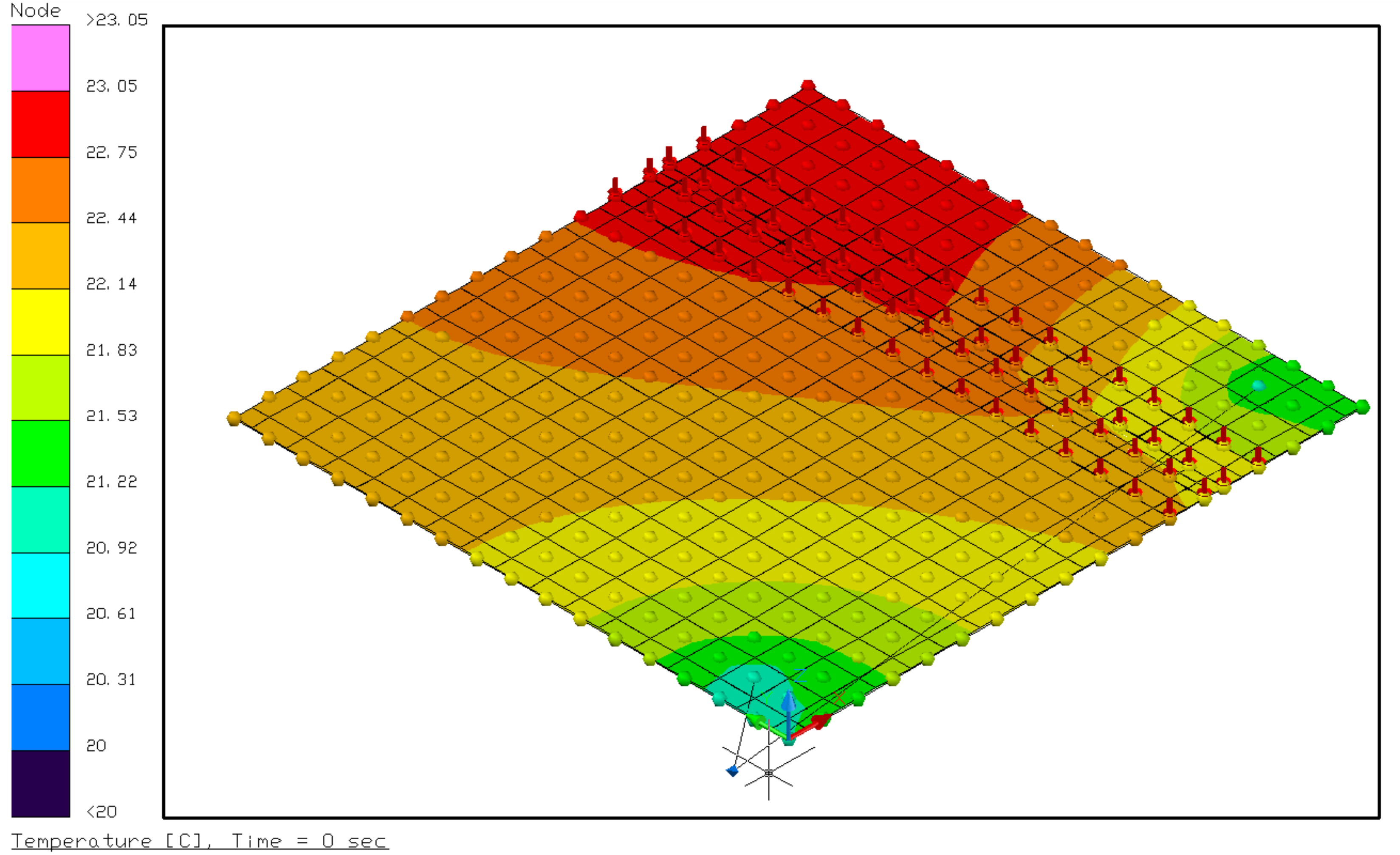
- **XRT cut-off (R=10%) is 5.6Å.**
- **With an Ir coating there is significant response around 5Å for an angle of 1.8 degrees and down to 3-5Å at 1.35 degrees.**

GI-XRT Characteristics:
Entrance Filter Temperature Models



Shown: final heat shield layer with telescope entrance filter installed. Two cases were run: Five solar constants on Al filter (3.5 mm wide) and Five Suns on larger area, 6 mm wide to allow heat shield motions. Assumed cooling straps in LL and UR corners, at 20 C.

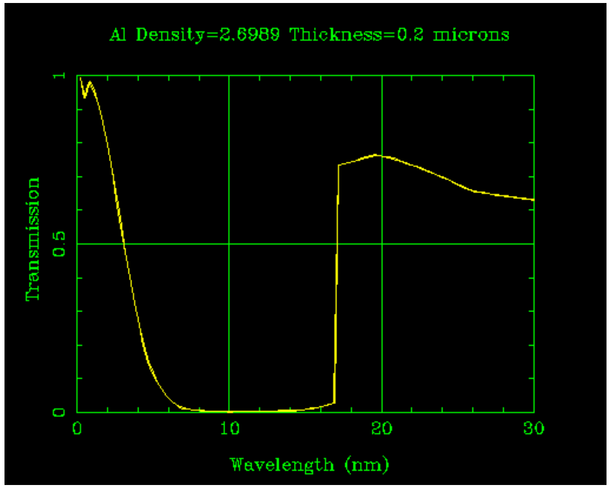
GI-XRT Characteristics: Results



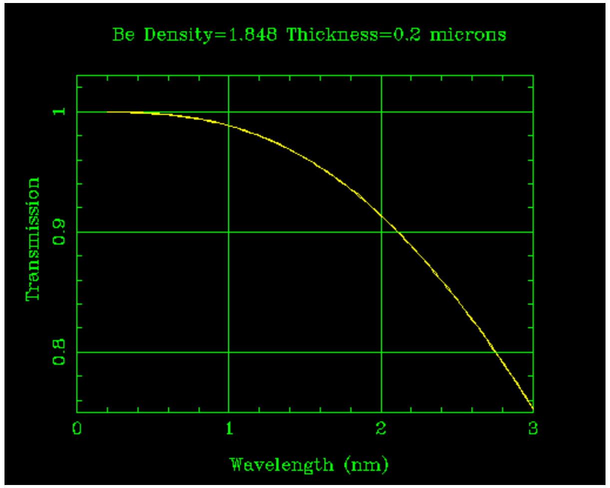
Worst-case model (larger illuminated area) shows ~3 C rise at worst location.
Total power conducted through straps is 1.1 W.

Coronal Imaging: Analysis Filters

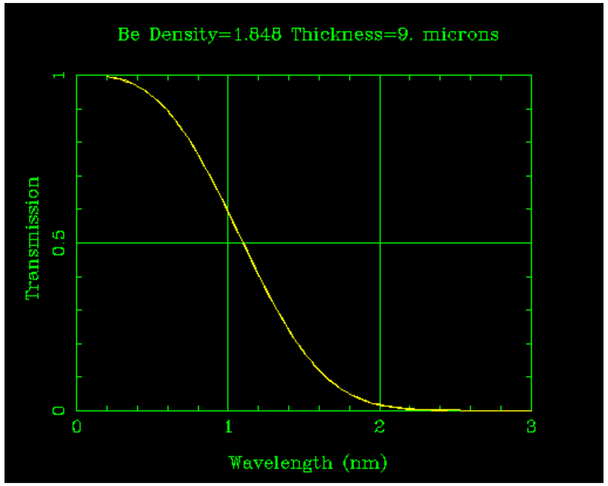
- **We can consider a wheel with several positions for X-ray spectral diagnostics.**
- **Right: Al entrance filter (from 1-300Å)**
- **Four thicknesses of Be at focal plane filters (from 1-30Å).**



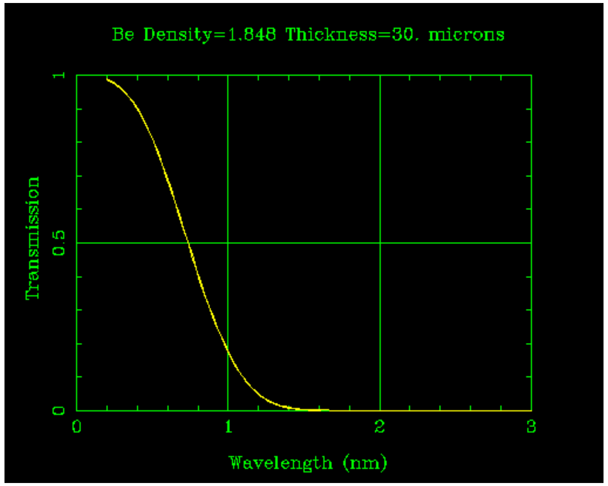
Al, 2000 Å



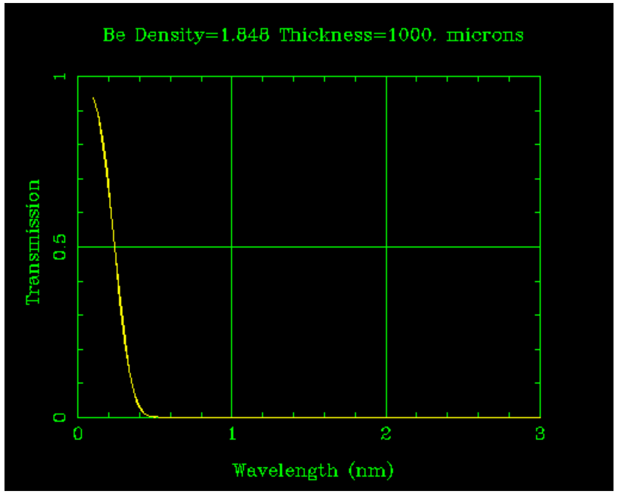
Be, 2000 Å



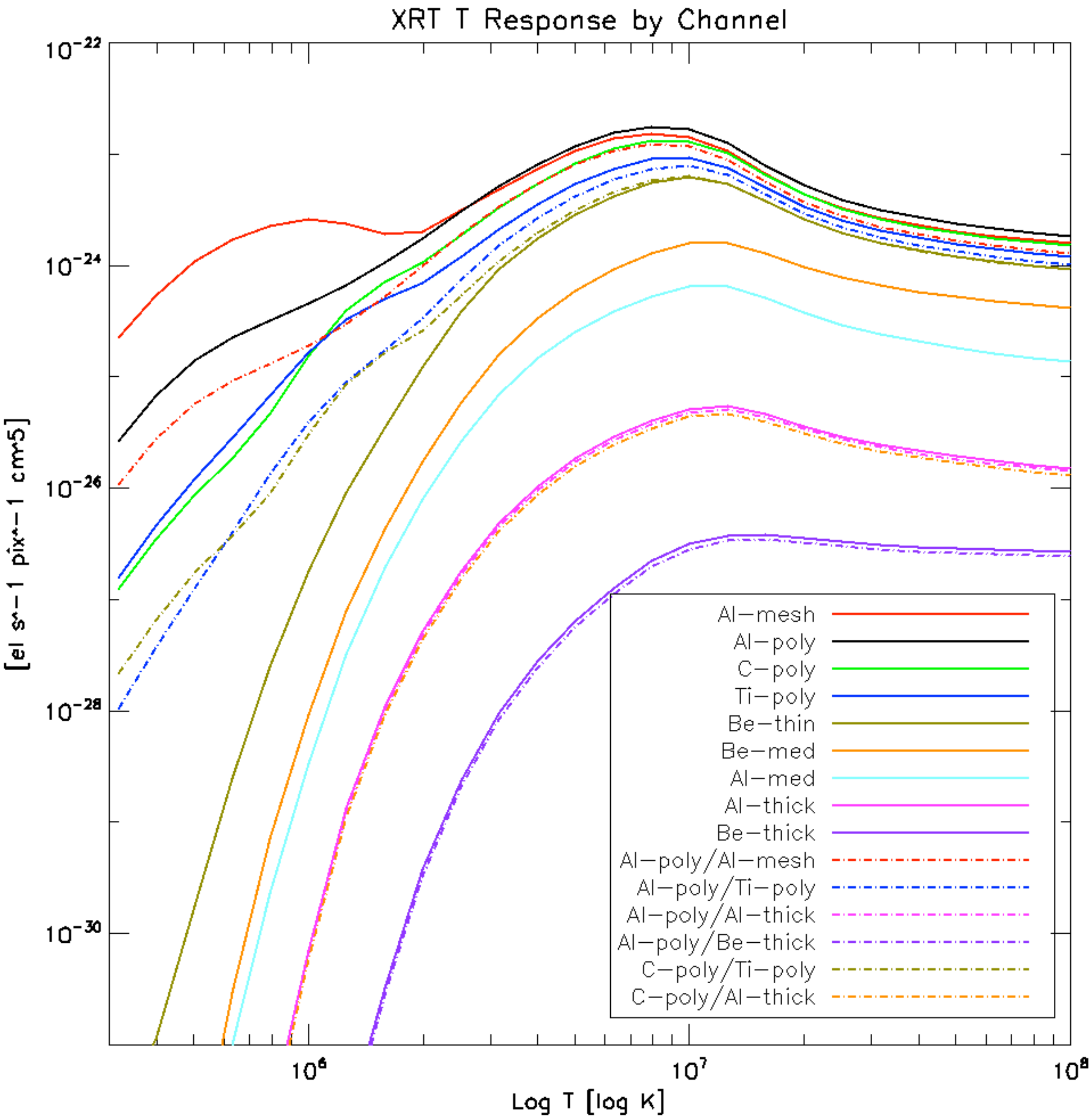
Be, 9 μm



Be, 30 μm

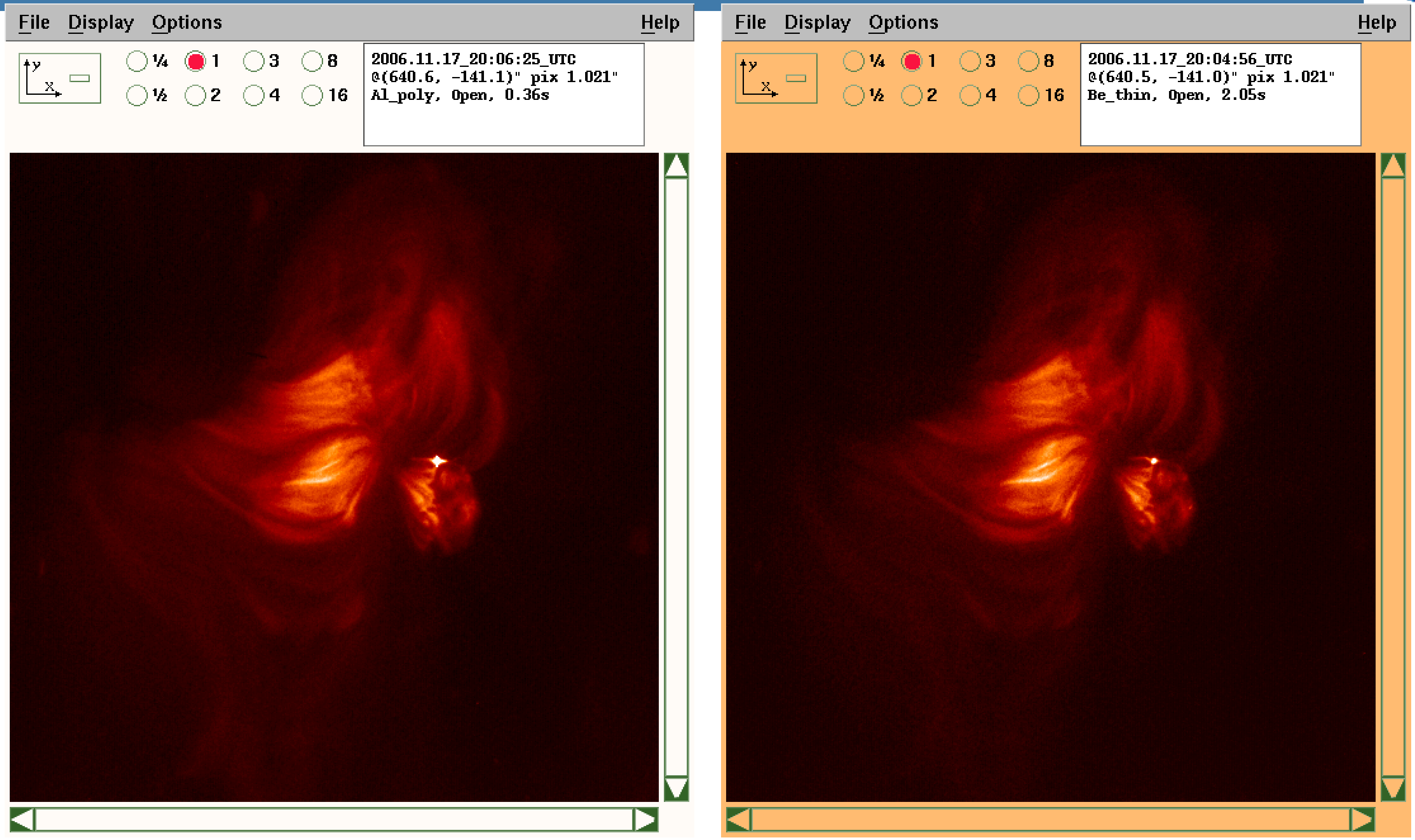


Be, 1 mm



Temperature sensitivity of XRT Filters.
GI-XRT will have better high temperature discrimination.

Expected Exposure Times for GI-XRT

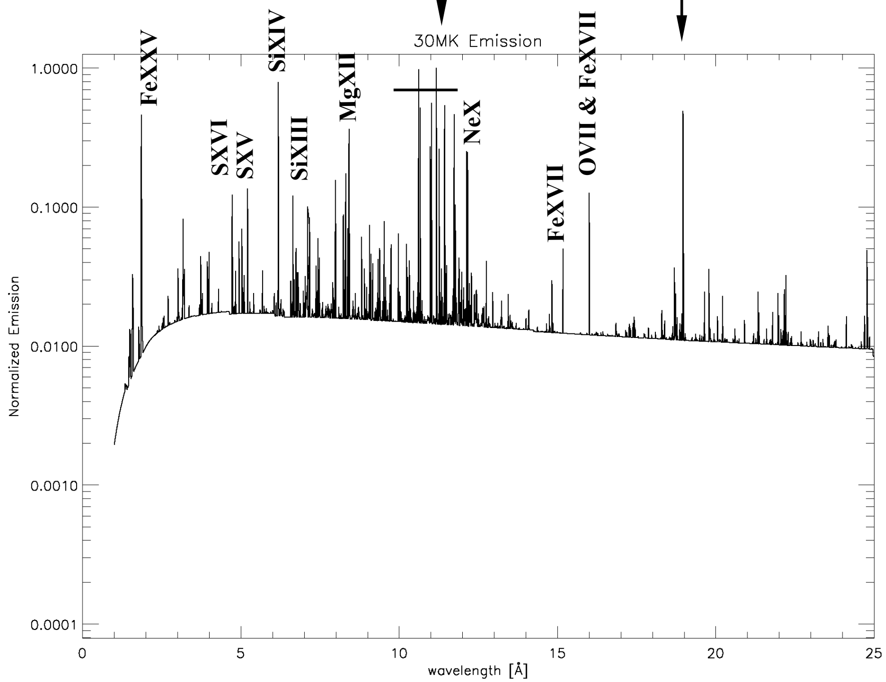


XRT observations of a quiescent AR in Al/Poly (0.36s) and Thin Be [=9 µm] (2.0s). GI-XRT has $A_{geom} = 2.5\ cm^2$, about same as XRT. For linear unresolved features, expect ~same τ_{exp}.

High Energy Imaging

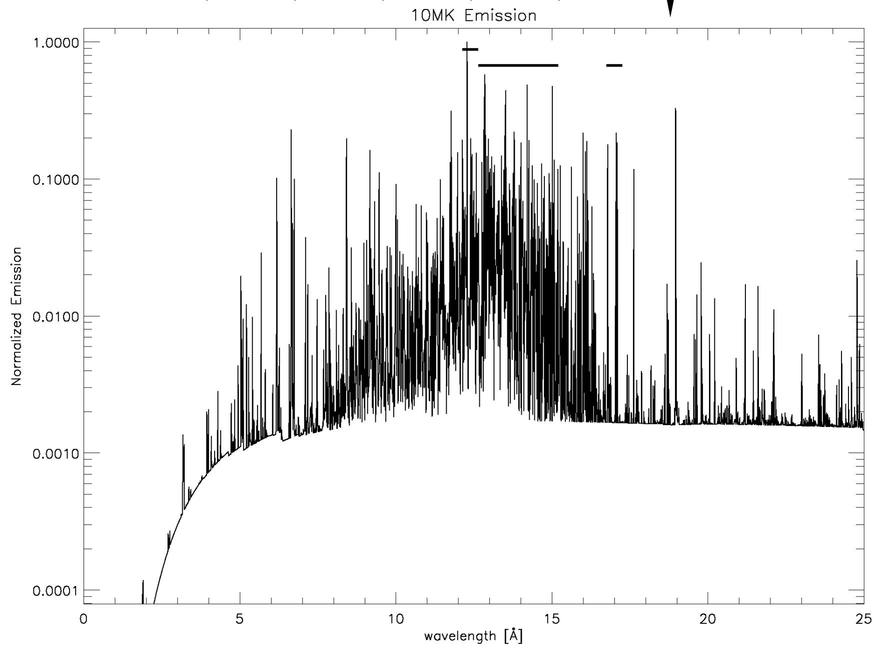
- Imaging below from below 5 Å to a diffraction limit of 60-100Å

Fe XXIV: 10.65, 10.66, 10.78, 11.3, 11.45
Fe XXIII: 11.0, 11.74
O VIII: 18.97



30 MK

Fe XXI: 12.29
Fe XX: 12.82, 12.83, 12.91, 12.93, 12.95
Ni IX: 13.45
Fe XIX:13.46, 13.50, 13.52
Fe XVIII: 14.22
Fe XVII: 15.01, 15.26, 15.46, 16.79, 17.05, 17.1
O VIII: 18.97

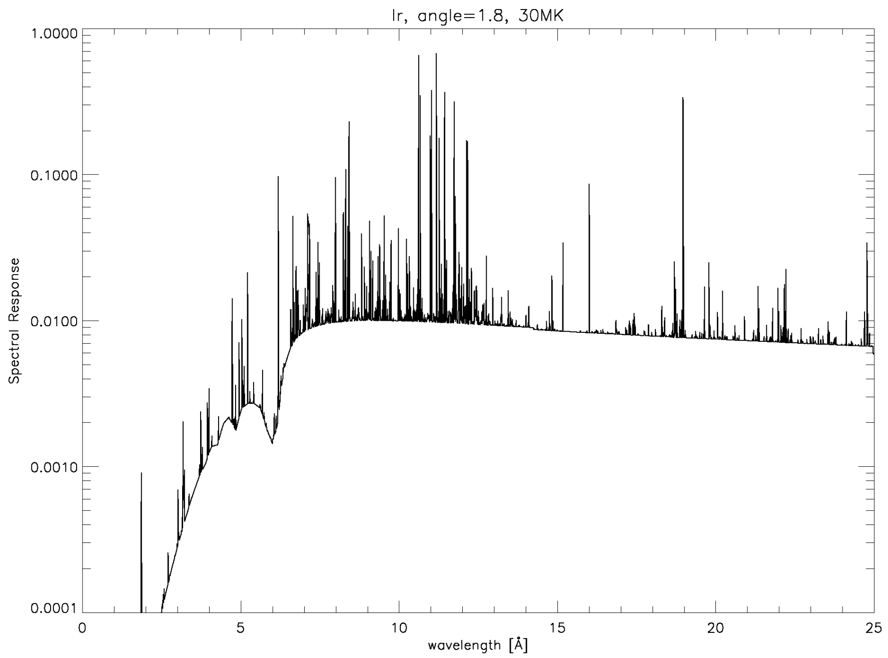


10 MK

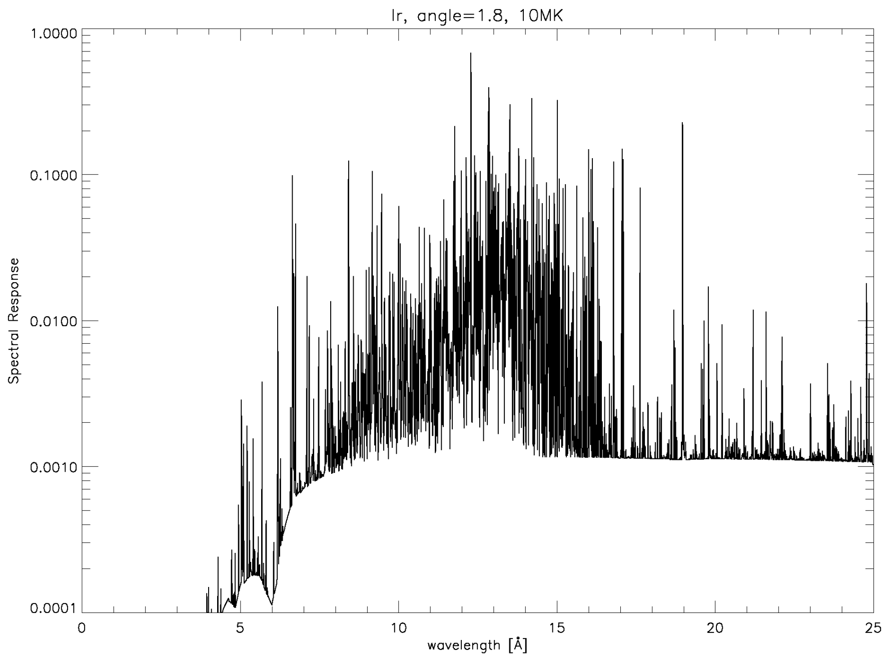
Testa, 2008

High Energy Imaging

- **Spectral Response with an angle of 1.8 degrees and Ir coating**



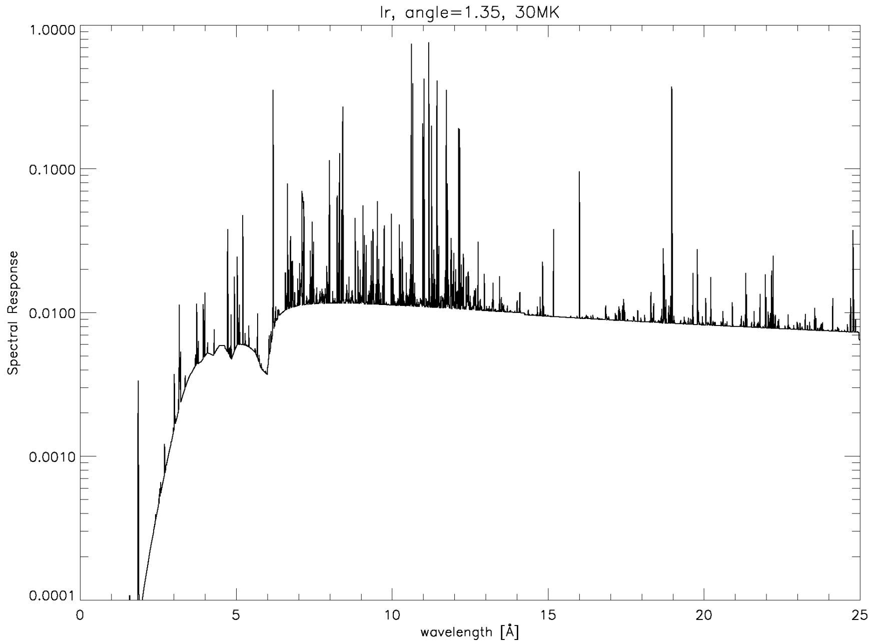
30 MK



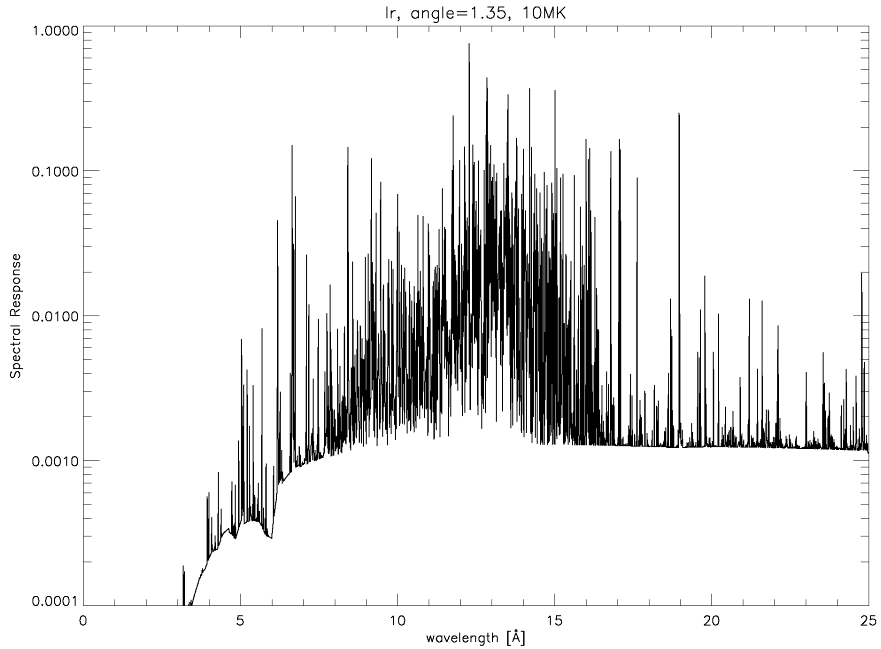
10 MK

High Energy Imaging

- **Spectral response with an angle of 1.35 degrees and Ir coating**



30 MK

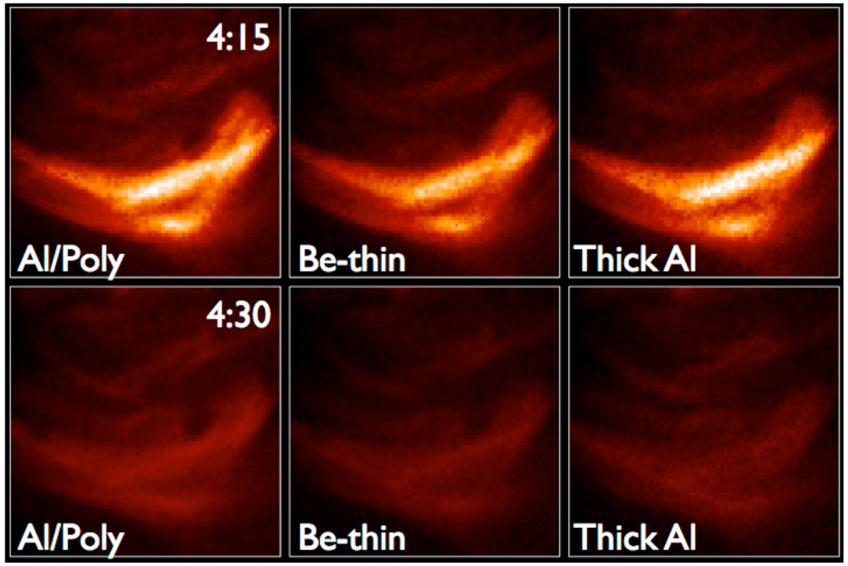


10 MK

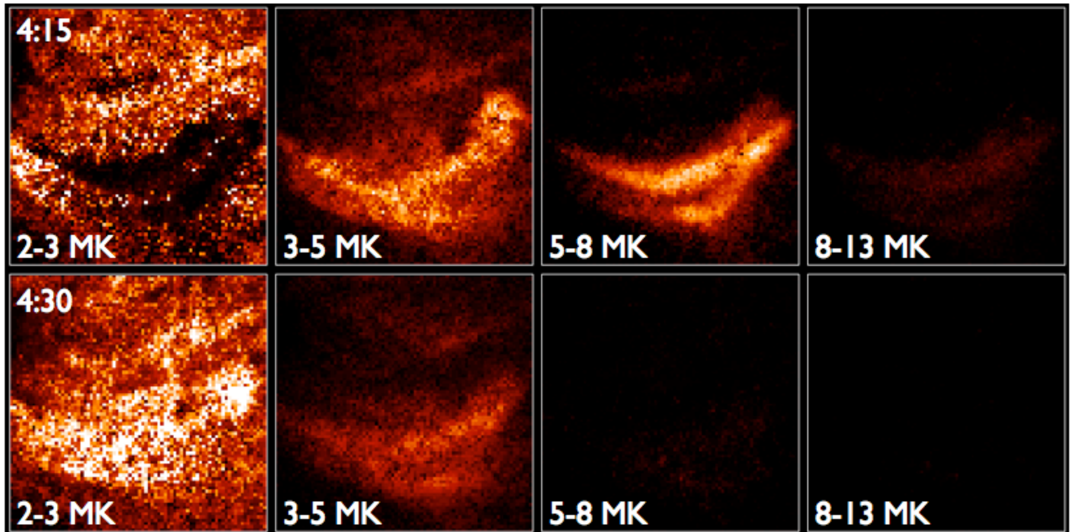
Temperature Discrimination

- **If an integrating detector is used a large set of filters is needed for energy discrimination.**
  - Coarse temperature discrimination is possible with 2-3 filters.
  - Full differential emission measures can be built using 6-12 filter combinations.
  - There is a trade off between high cadence and temperature discrimination
- **Photon counting detectors give true imaging-spectroscopy**
  - Focal plane filters are needed to prevent flux pile-up during flares.
  - See the next talk for details

Dec 13, 2007 B8 Flare

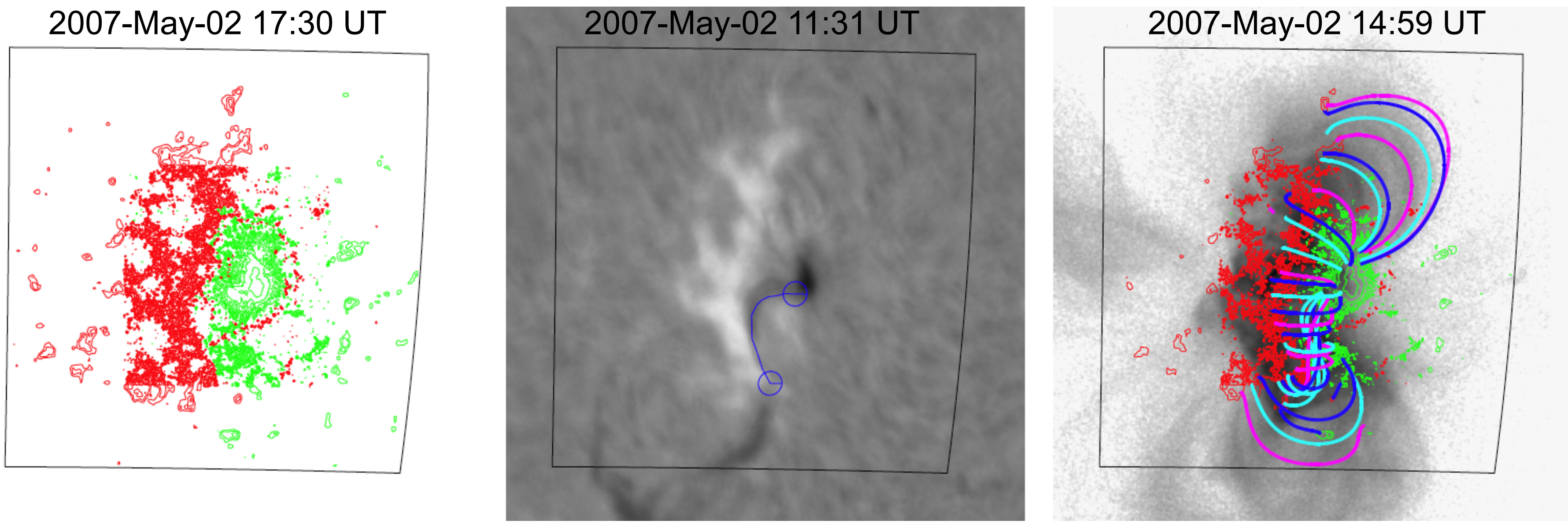


Emission Measure Maps



(Reeves, 2008)

Magnetic Field Line Mapping

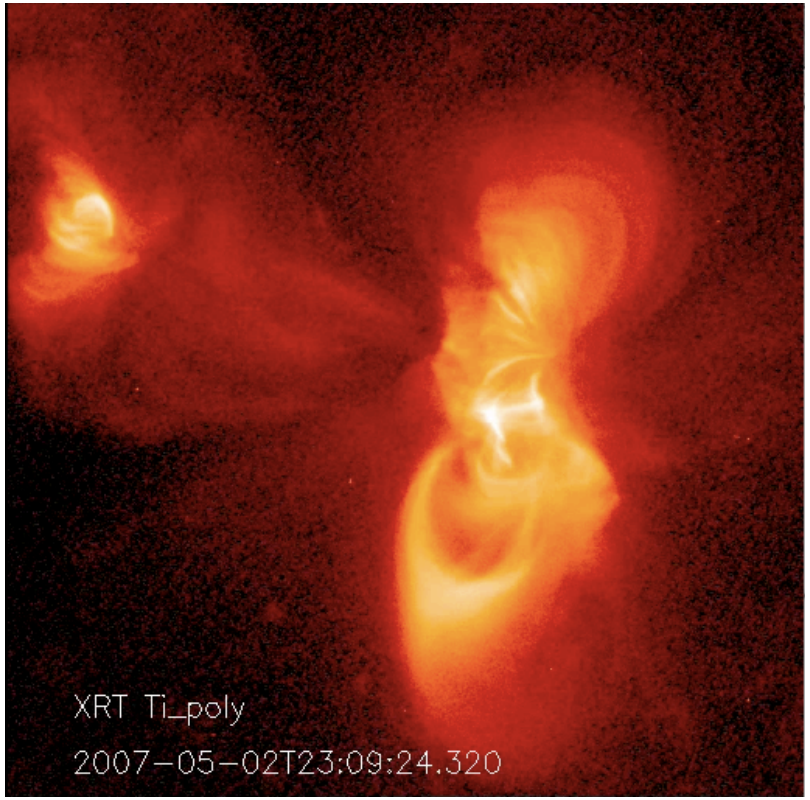


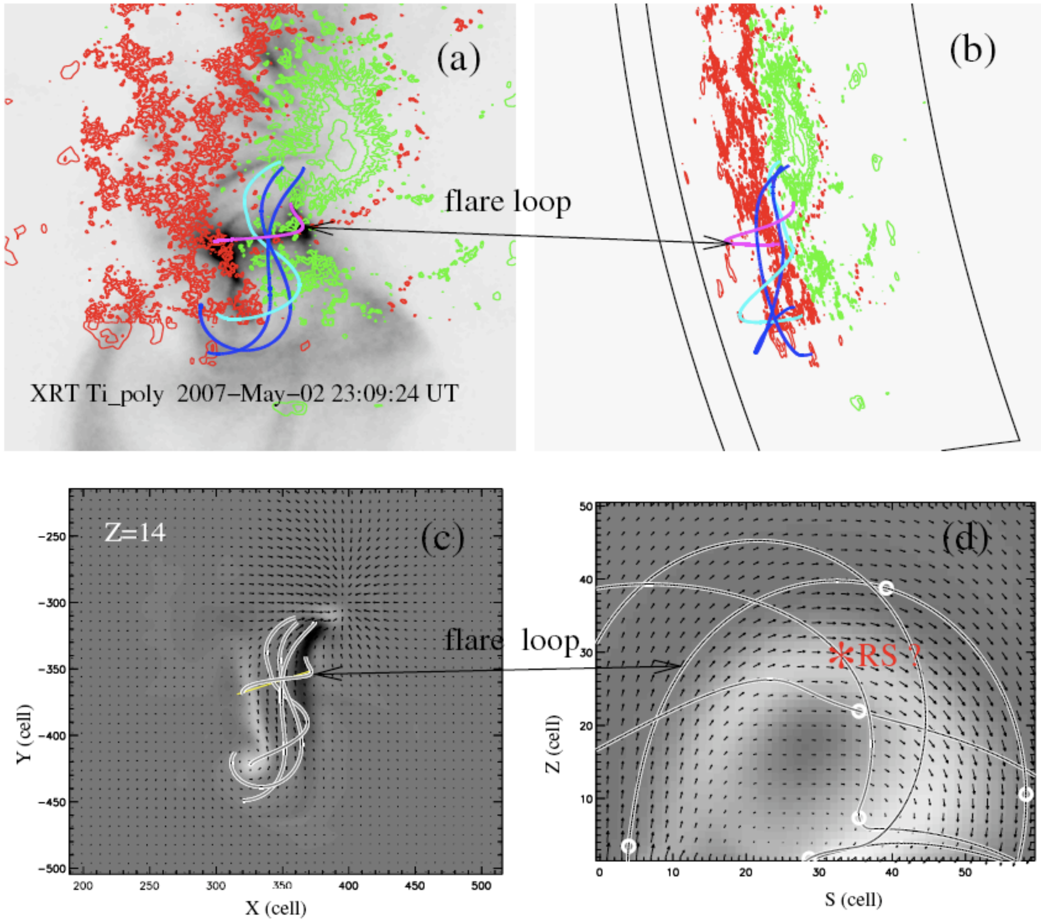
MDI+SOT/SP KSO/H-alpha XRT MDI+SOT/SP

PF model → Insert Flux Rope → (Magneto Friction) → NLFFF Model

(Su, etal 2008)

Magnetic Field Line Mapping





Large dynamic range in coronal emission

- **A key problem with seeing all of the plasma is that the dynamic range of the image exceeds the dynamic range of the CCD by orders of magnitude.**
- **Active pixel sensors allow (in principle) for separate exposure times at each pixel.**
  - An image is built from pixels read at different rates. Consider a 5s integration: in the core of the AR the pixels may be read 20 times (0.25s exposures), while the pixel seeing large loops are exposed for the full 5s. The accumulated image is then formatted and stored for processing.
  - With an APS the cadence can be set based on the physical process being studied. If a low cadence is acceptable, long integration times can be used without concern for saturated images.
  - The Automatic Exposure Control program is built into the detector for these devices.
- **Seeing all of the coronal plasma**
  - Essential for following the topology of complex and dynamic magnetic structures.
  - Separating out the hot plasma - using a set of thick filters.
  - Observing transitions from closed to open field lines - coronal dimming.

Integrated Science Observations

Physical Process	Question/problem	Measurements	Observations							
			Imaging			Spectropolarimetry		Spectroscopy		Other
			Photosphere	Chromosphere	Corona	Photosphere	Chromosphere	Chromosphere	Corona	
Ubiquitous Reconnection	Magnetic Field Requirments	Vector Magnetic Field				X	X			
		Field Connectivity		X	X					
	Plasma Requirements	Temperature			X			X	X	
		Density						X	X	
		Velocity		X	X			X	X	
	Particle Acceleration	Location of non-thermal particles								Radio Hard X-Ray
		Super-hot plasma			X				X	
		Particle impact in chromosphere	X	X				X		
		Evolution of non-thermal distribution								Radio Hard X-Ray
	Trigger	Field Connectivity		X	X	X	X			
		Coronal null points			X					
		Current sheet		X	X				X	
	Energy Balance	Plasma flow		X	X			X	X	
		Acceleration along jet		X	X			X	X	
		Temperature		X	X			X	X	
		Non-thermal particles								Radio Hard X-Ray
		Helicity			X	X	X			
		Magnetic energy			X	X	X			
	Reconnection Rate	Inflow to current sheet			X			X	X	
		Outflow reconnection exhaust			X				X	
		Footpoint motion across fields	X	X		X	X			
Ubiquitous Waves	Wave Identification	Transverse waves		X	X					
		Intensity oscillations		X	X					
		LOS velocity						X	X	
	Wave Energy, Transport & Dissipation	Wave amplitude		X	X			X	X	
		Wave propogation and reflection		X	X			X	X	
		Localized wave heating		X	X					
		Wave initiation		X	X					
MHD and Plasma Processes	Stability and Instability	Magnetic Free Energy		X	X	X	X			
		Magnetic Helicity		X	X	X	X		X	
	Topological Constraints	Null Points		X	X	X	X		X	
		Separators & Quasi-Separators		X	X	X	X		X	
	Beta ~1 plasma	Radiative Processes		X			X	X		
		Diffusion		X			X	X		
		Reconnection		X	X		X	X		

Integrated Science Observations

- **Ubiquitous Reconnection**
  - Magnetic requirements for reconnection
    - Vector Fields in photosphere and chromosphere
    - Coronal mapping of field lines before during and after reconnection event
    - NLFFF models
  - Plasma requirements for reconnection
    - Identification of pre-reconnection loops
    - Pre-reconnection plasma properties: density & temperature
  - Types of reconnection:Sweet-Parker, Petschek, Hall MHD, QSL
    - Field configurations around reconnection site
    - In-flow velocities
    - Reconnection outflows, exhausts
  - Particle acceleration
    - Requirements: When does it occur - (needs Hard X-ray or radio)
    - Energy contribution: measure energy deposition in the chromosphere
    - Direct looptop heating:
  - Plasma acceleration
    - Jets
    - Outflows/exhausts
  - Dissipation processes
    - Direct heating in closed loops
    - Micro-flares, nano-flares

Integrated Science Observations

- **Ubiquitous Waves**
  - Identification of wave types: fill in the K-Omega diagrams for the solar atmosphere
    - Transverse oscillations
    - Intensity oscillations
    - LOS velocity oscillations
  - Wave energy, transport and dissipation
    - Wave amplitude
    - Wave propagation and reflection
    - Localized wave heating
    - Wave initiation

Integrated Science Observations

- **MHD and Plasma Processes**
  - MHD stability and instability
    - The onset of ideal instabilities
    - Transition to adjacent meta-stable states
  - MHD topological constraints
    - Null points in the solar atmosphere
    - Separators and Quasi-separators
    - Helicity and energy
  - Beta ~ 1 plasma
    - Radiative processes
    - Magnetic field diffusion
    - Reconnection

Conclusions

- **Broadband X-Ray observations are critical for understanding the coronal response to photospheric and chromospheric magnetic field evolution.**
  - The primary coronal emission line if Fe XVII, this can only be imaged with a soft x-ray telescope.
  - Hot and super hot thermal plasma is most easily seen in soft x-rays. Following the rapid evolution of this plasma can only be done with a soft x-ray telescope.
  - Seeing both the bright and faint coronal plasma is possible with a new Active Pixel Sensors
- **Temperature discrimination from 1MK to 50MK is possible with a single telescope**
  - DEM studies with Hinode/XRT have demonstrated that multi-filter observations can be used to measure the thermal evolution of coronal plasmas
  - Photon counting detectors offer the promise of true spectral imaging!
- **New mirror designs extend GI capabilities to shorter wavelengths and higher spatial resolutions**
  - A factor of two increase in imaging will give us a dramatically new look at the corona
  - Increased sensitivity to hot and super-hot plasma will allow us to study fundamental physical processes at work in the corona.