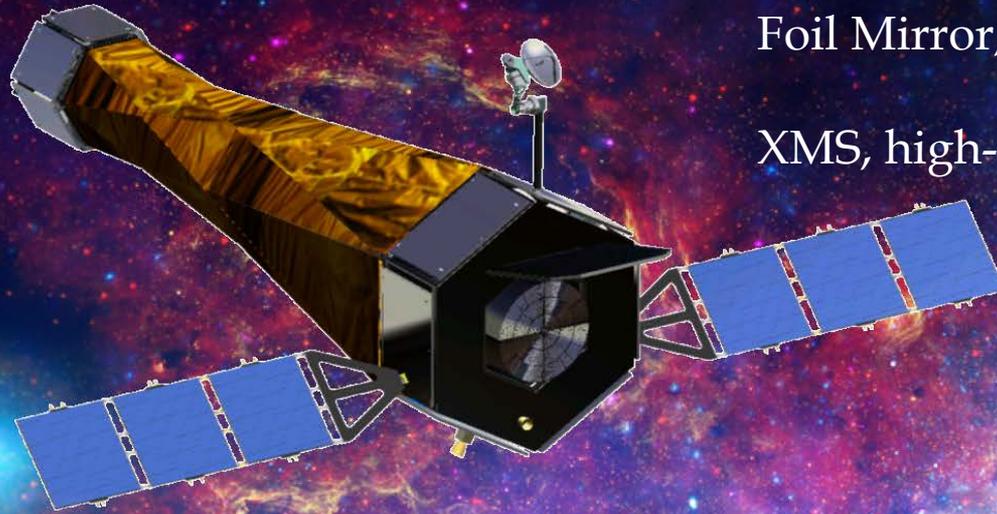


EPE is a Large Area, SPECTROSCOPY (Timing) Mission



Foil Mirror, $>20\times$ ASTRO-H area, 1' PSF

XMS, high-rate, 2.5eV/10eV, 2'/8' FOV

10m Focal Length

“As close to Shovel-Ready as you are going to see” (~2 years on XMS)



NWNH & EOS Panel

‘The Next Step in X-ray Telescopes:’

‘astrophysics-comes mainly from spectroscopy’
(NWNH EOS p 278)

‘The key ... is to feed a calorimeter with...
much larger area’ (p 287)

‘The key component is ... XMS ... with R=1000’
(NWNH p 214)

Con-X was about spectra:

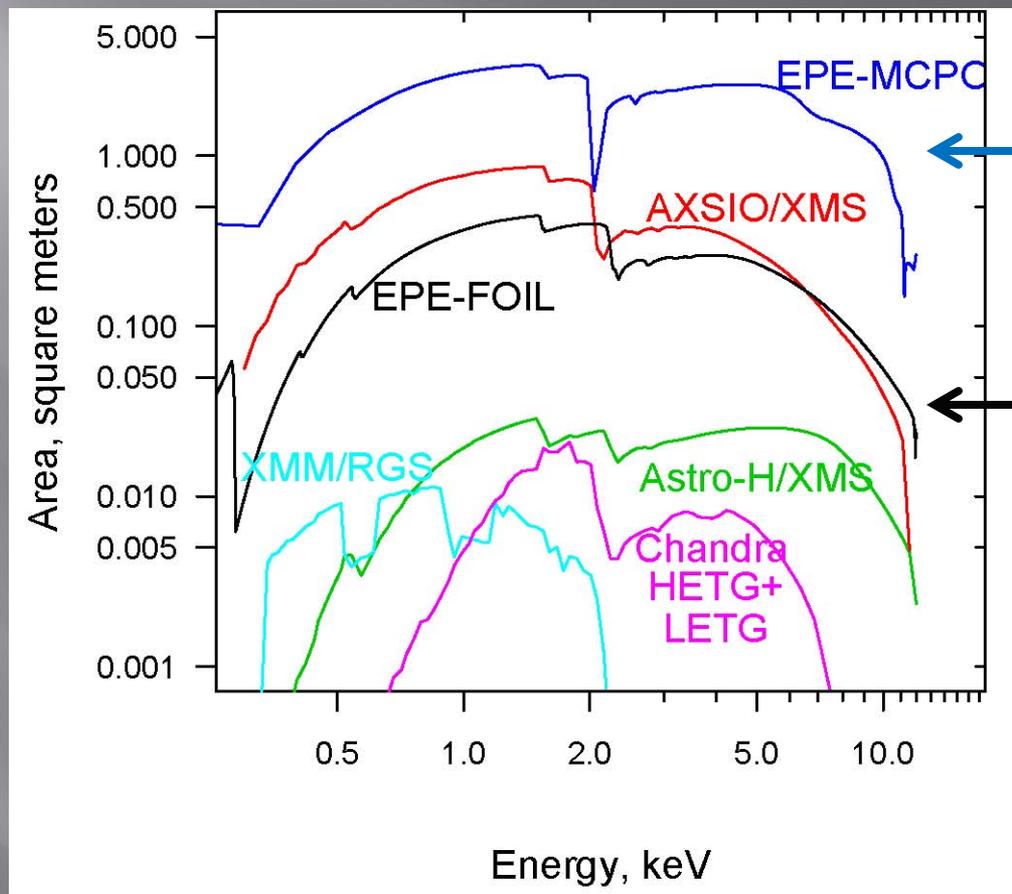
XMS, XGS, HXT, 15” HPD: IXO added imaging:
5” HPD, WFI

NHWH: ‘Area of particular concern ...
achieving 5” (p 214) > \$5B

NWNH EOS: ‘science... not heavily compromised
@ 10” (p 288)

EPE (\$¾B) could start in 1-2 years; avoids optics ‘tall pole’
and can do a large part of IXO science

Effective Area



TRL 2:
Tech devel!

TRL 7-9

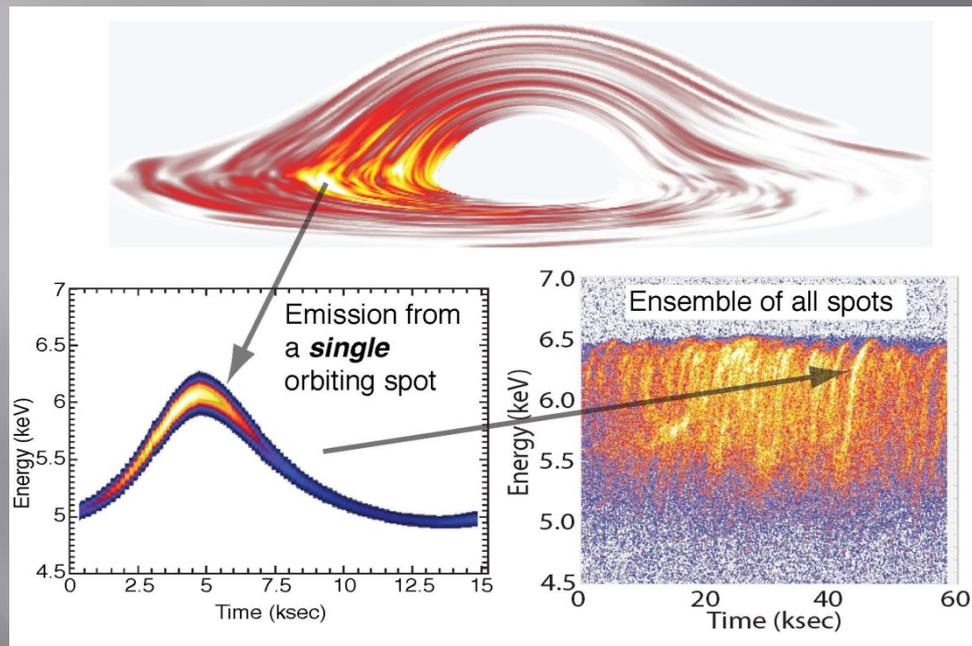
20(200) times ASTRO-H SXS => AXSIO >5 keV

HIGHLY Responsive to RFI, IXO Science (FOM?)

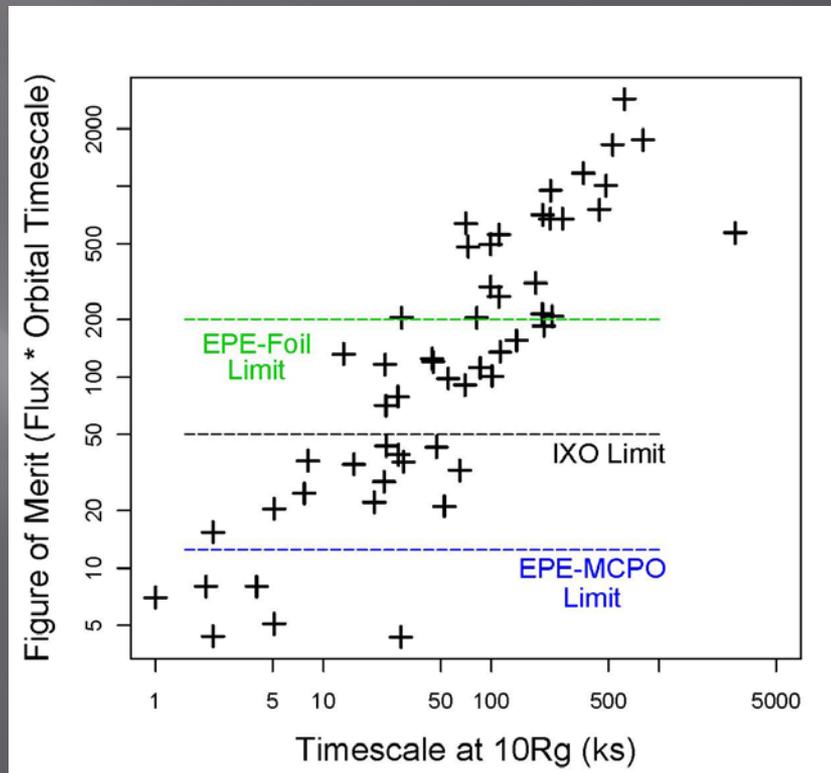
RFI Table 1: Primary IXO Science Objectives Addressed by Extreme Physics Explorer		
Science Question	IXO Measurement	EPE Reach
What happens close to a black hole?	Time resolved high resolution spectroscopy of stellar mass and ~20 super-massive black holes (SMBH)	Time resolved high resolution spectroscopy of stellar mass and >20 (foil) or >60(MCPO) SMBH
When and how did SMBH grow?	Measure the spin in >300 SMBH within $z < 0.2$	Measure spin in >100(foil) to ~1000(MCPO) SMBH
How does large scale structure evolve?	(i.) Find the missing baryons via absorption line spectroscopy of the WHIM over many lines of sight using AGN as illumination sources.	Detection threshold ~70% of IXO; expect detections on 20 lines of sight and of ~100 absorbers
	(ii.) Measure the mass and composition of ~500 clusters of galaxies at redshift < 2	Measure the mass and composition of the 100 brightest clusters from the REFLEX catalog
Connection between SMBH and large scale structure ?	Measure the metallicity and velocity structure of hot gas in galaxies and clusters.	Spatially resolved measurements in several dozen starbursts, ~6 nearby cluster bubbles; energetics of warm absorbers
How does matter behave at very high density?	Measure the equation of state of neutron stars through (i.) spectroscopy and	Unique timing/spectral capability allows phase binning on ms period rotation rates
	(ii.) timing	80% throughput a few Crab fluxes- no diffusing optic, so area matches IXO above 5 keV

ASTRO-H: First 'integral field' spectra, EPE: Significant Samples within classes

What Happens close to a Black Hole (GR)?



Time axis scaled by 3x for EPE area



BAT-58 month update by T. J. Turner
More than 20 reachable with EPE
ASTRO-H requires FOM=3000

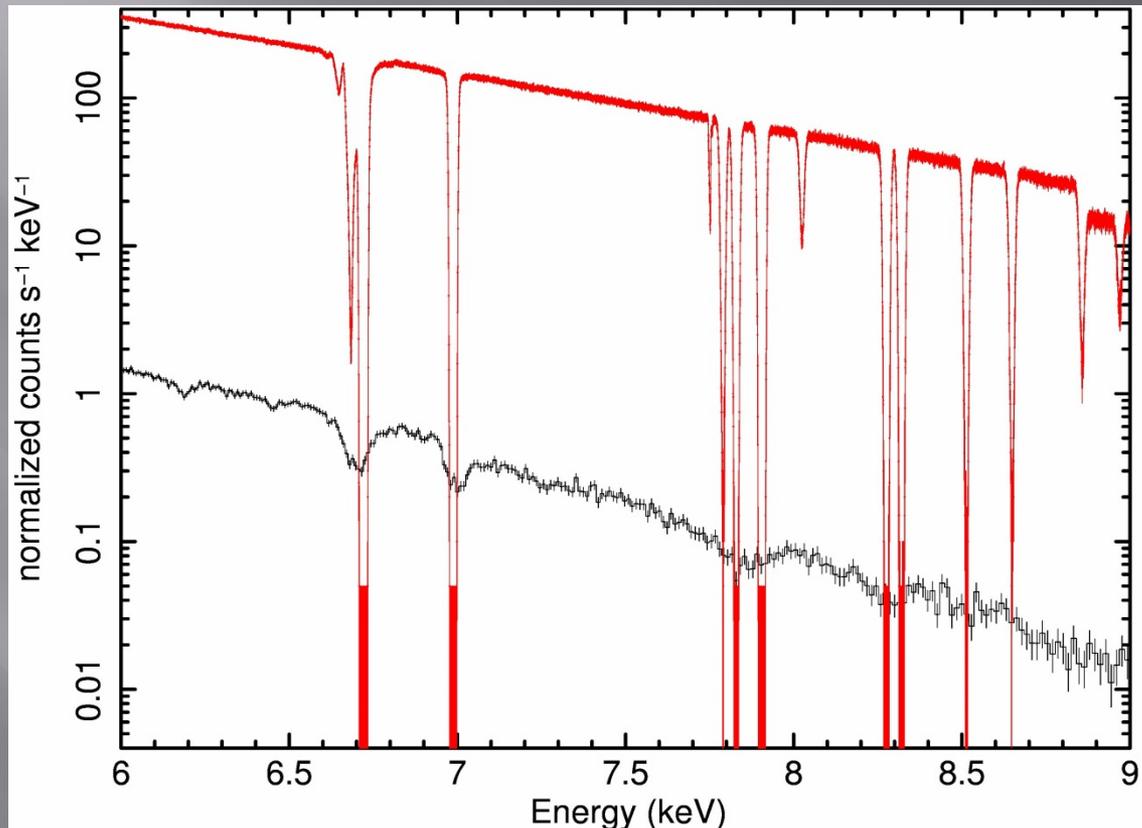
What Happens close to a Black Hole (accretion)?

GRO J1655-40

EPE/XMS

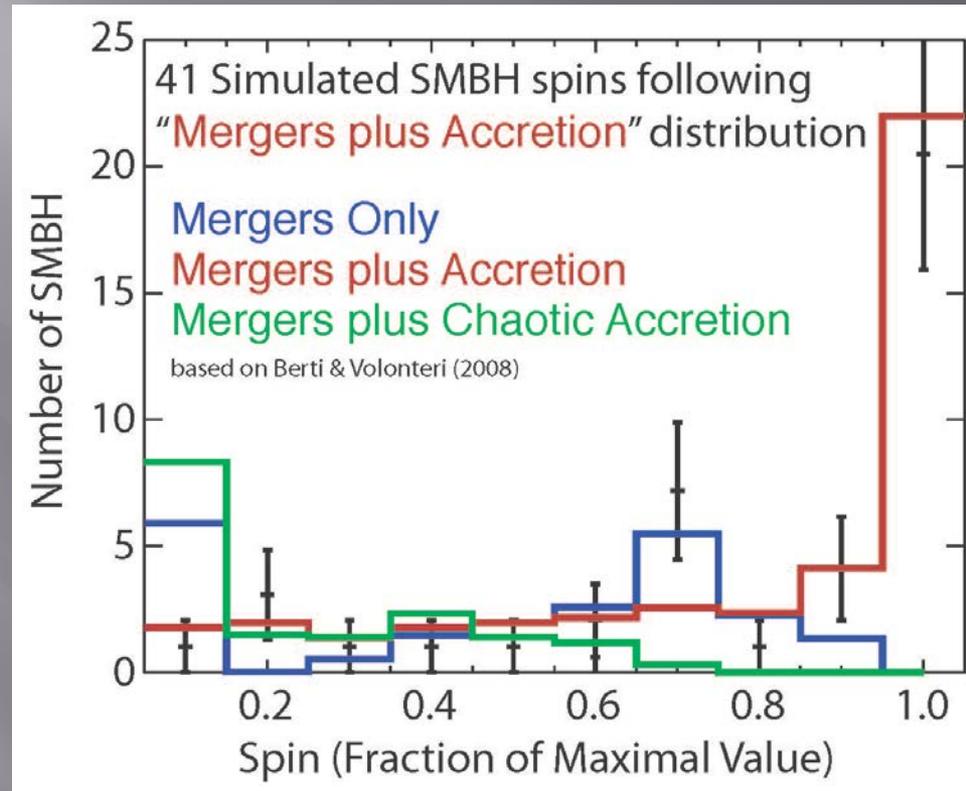
CXO/HETG

50ks



Premier HETGS results: Magnetic wind. High-rate XMS, 300x count rate, gives terrific diagnostics (new J. Miller simulation)

How do SMBH Grow?

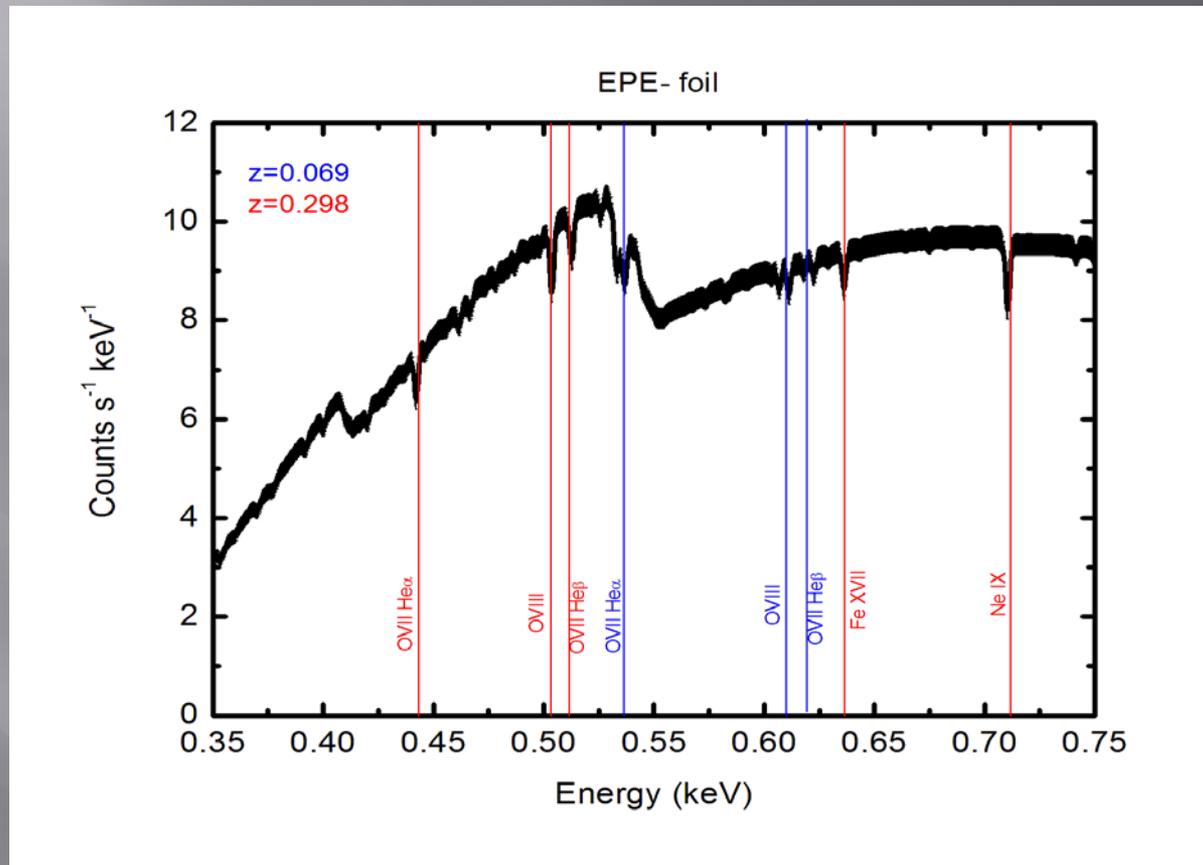


>40 pre-BAT, >100 with BAT-58 month, NEED XMS due to absorption!

New simulations by L. Brenneman, spin to 10% needs 10^5 counts if clean, 10^6 if complex,

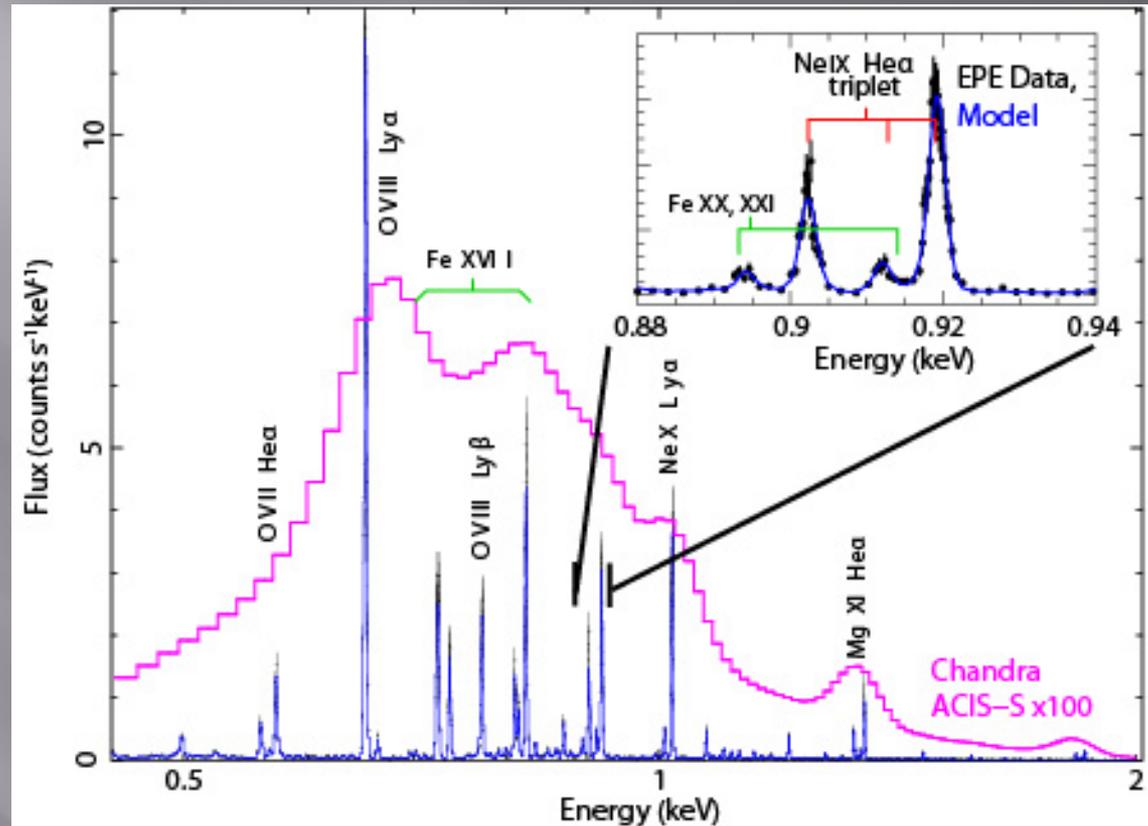
Spin for ~ 200 in 10Ms (198 Seyfert 1.0s in BAT-58),

Evolution of Large Scale Structure: WHIM



New simulations by E. Ursino & M. Galeazzi; 20 bright AGN $\times 0.5\text{ms@}$, 100 filaments
See here $z=0.069$ and $z=0.298$. EPE has 70% capacity of IXO for this.

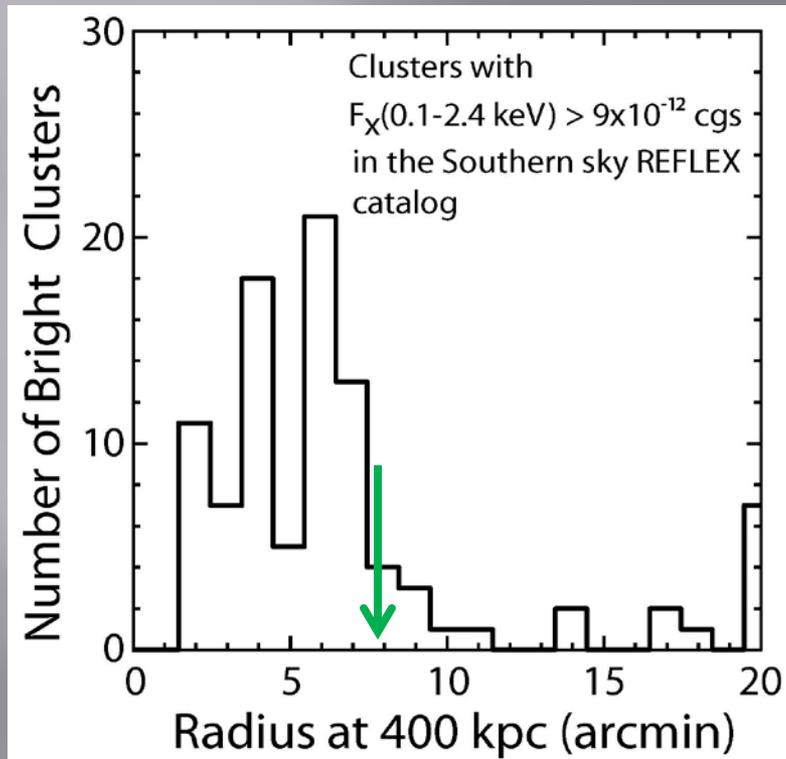
Enrichment of WHIM/Starbursts



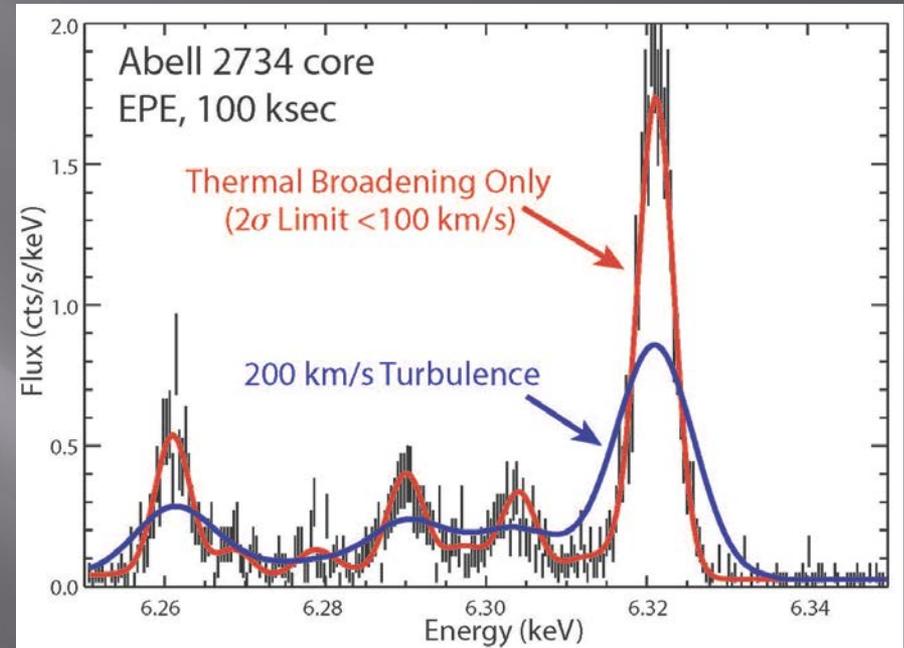
XMS resolution critical to starburst winds:
abundances, density, velocity, temperature

Spatially resolve >dozen,
integrated properties in 2 dozen (vs few for ASTRO-H)

Cluster Mass/Composition



Mostly low-z:
 100 REFLEX clusters easy to $1/3 R_{500}$
 RESOLVED with $1'$ PSF, $8'$ FOV (HYDRA!)
 Expect ~dozen with ASTRO-H

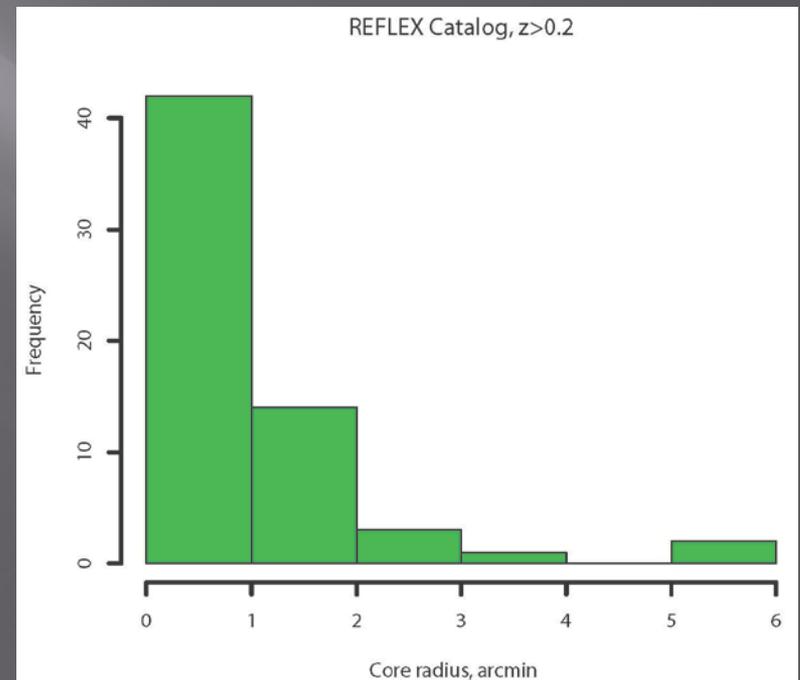
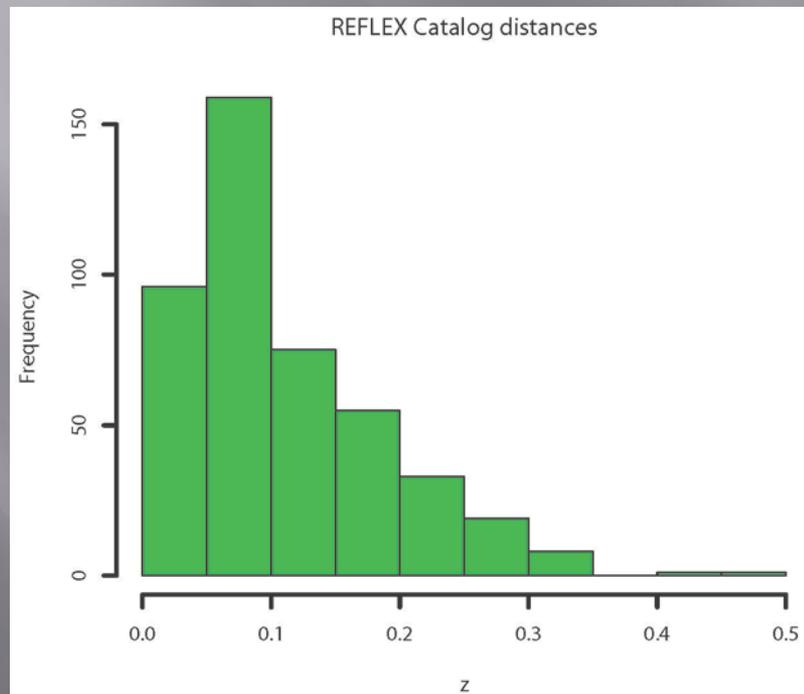


Turbulence/Non-Thermal
 Pressure support = Resolve
 Important unknown in cluster masses
 Images from ROSAT

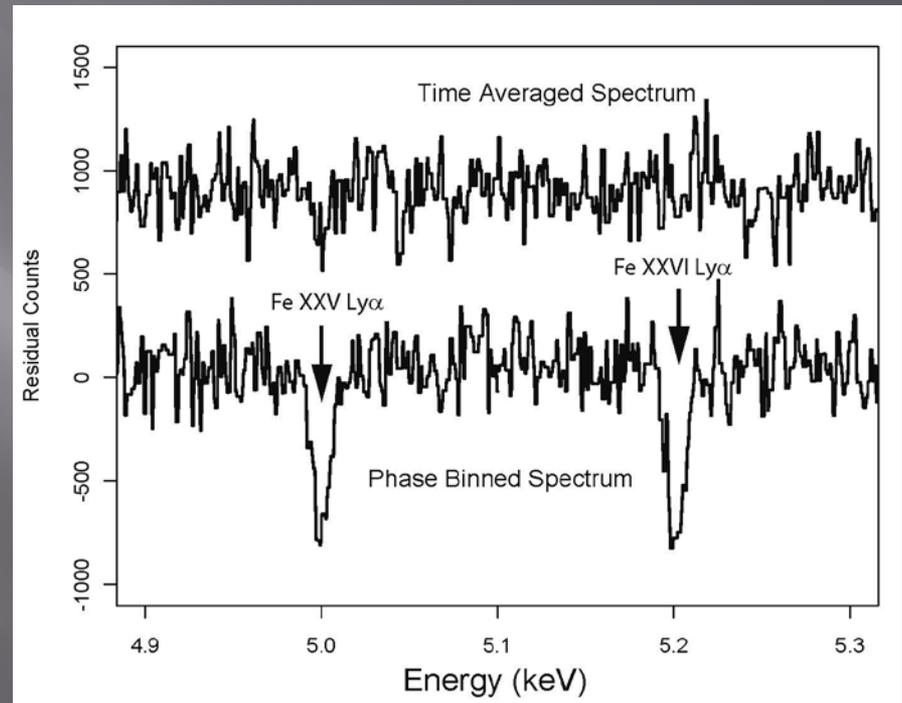
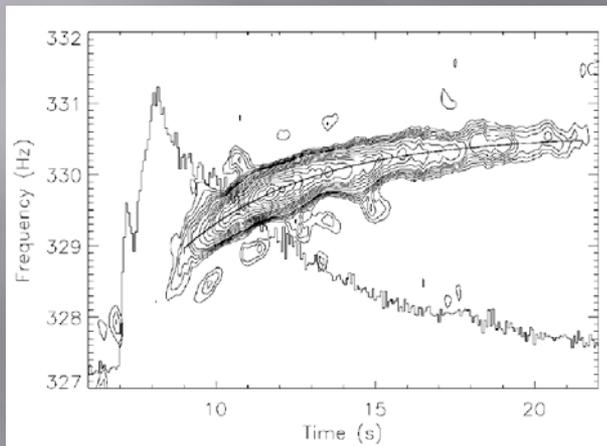
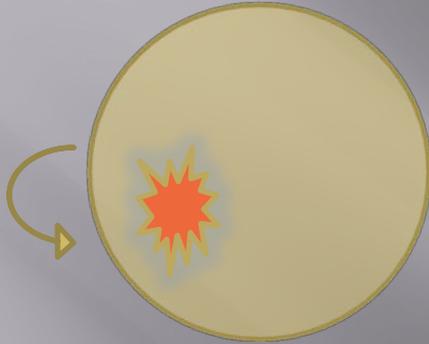
Feedback: Warm absorber/outflows,
 Resolve bubbles only in ~6 largest

Cluster Mass/Composition vs z?

- $BG = 2 \times 10^{-14}$ (0.02 c/s) ergs/cm²/s/arcmin²
- >50 clusters at $0.2 < z < 0.5$ with core surface brightness much higher than BG

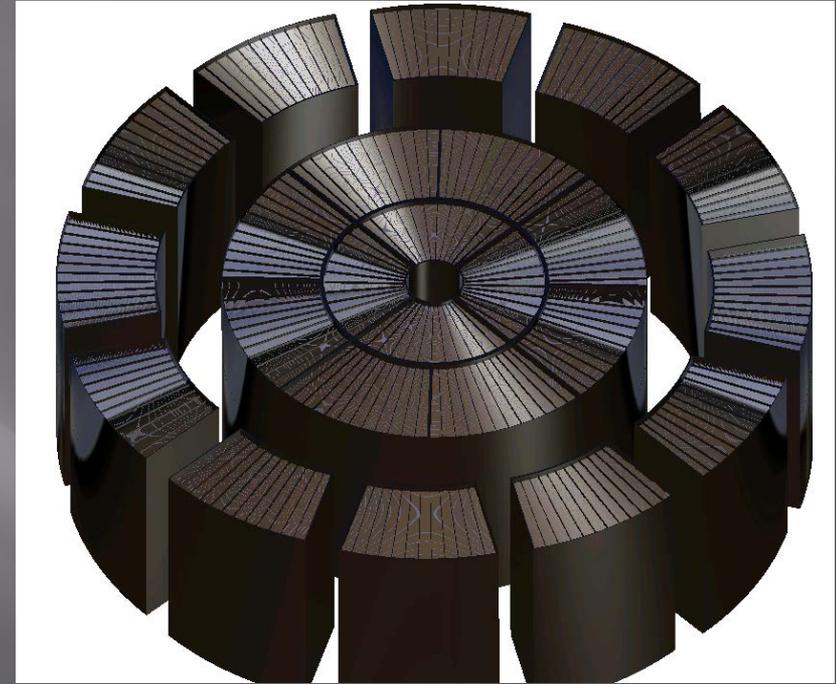
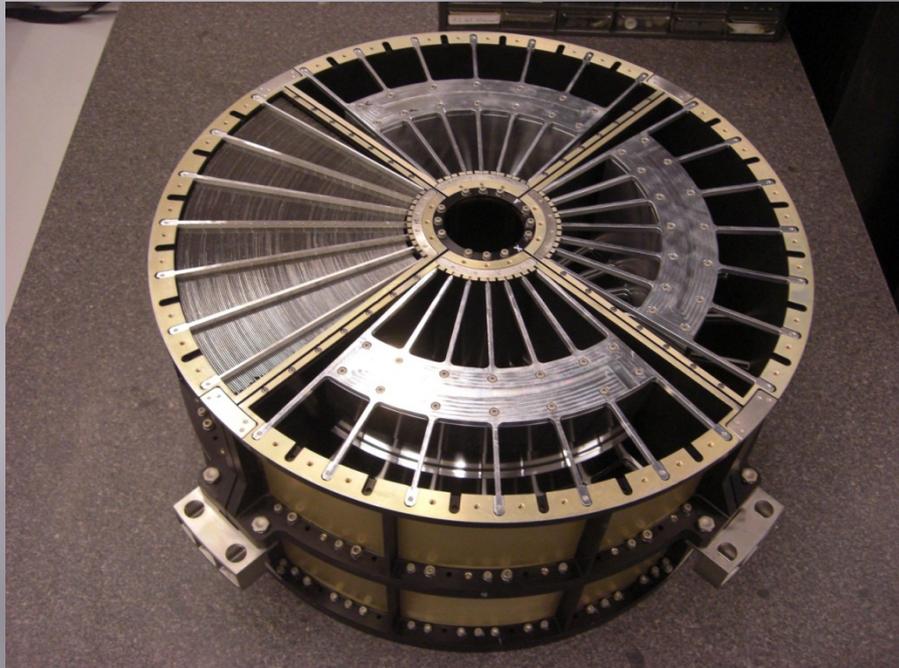


Neutron Star Science



- Phase binning on fast rotators (rates \sim RXTE)
- Lines intrinsically narrow (slow rotators easy, Terzan 5)
- Timing, resolution of calorimeter allows!

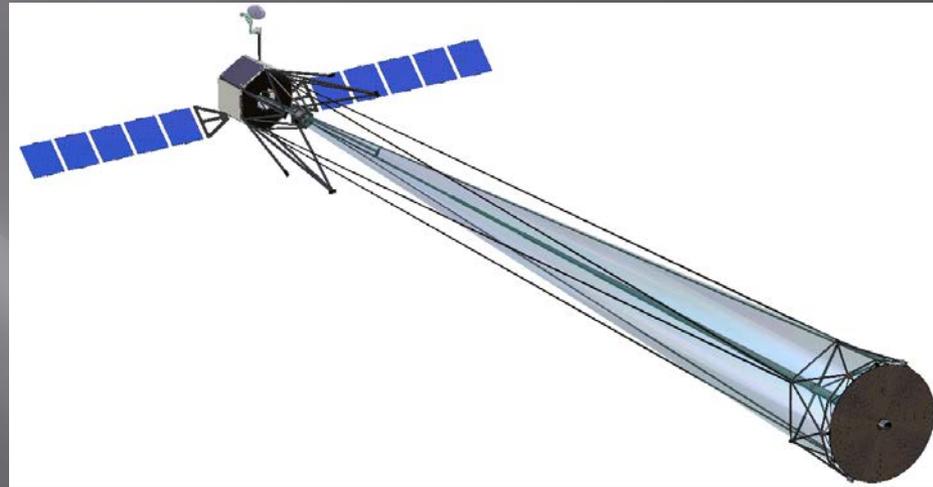
Technologies: High TRL Mirror



- Astro H Test model
 - 1.1 arcmin PSF measured
 - Launch Feb 2014
 - High TRL! (8)
 - LOW cost - \$2.6m

- Scaled Up Astro H Design, >20x area
 - Focal Length Changed to 10 Meters
 - Additional Mirror Sectors Added
 - Need to design 2x longer reflectors
 - Segment into 2 (4 total) pieces

Technologies: Low TRL mirror



- 4.2m diameter MCPO
 - 4m² at 1keV, 2.5m² at 6keV (!)
 - LOW TRL, 2-3
 - Extensive technology development
 - Latest results (Bepi-Columbo) 5'-6'

- 40m Focal Length
 - 'Tensegrity' boom, TRL~7
 - Adds \$169m to cost rack-up

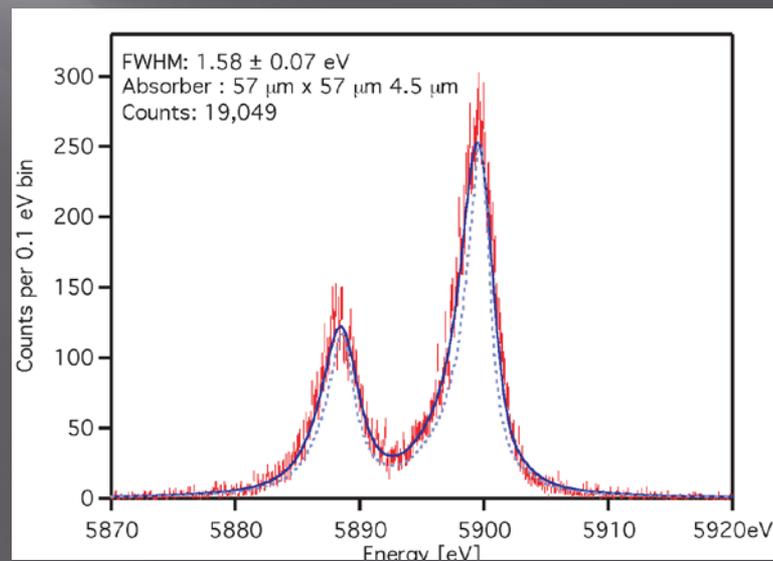
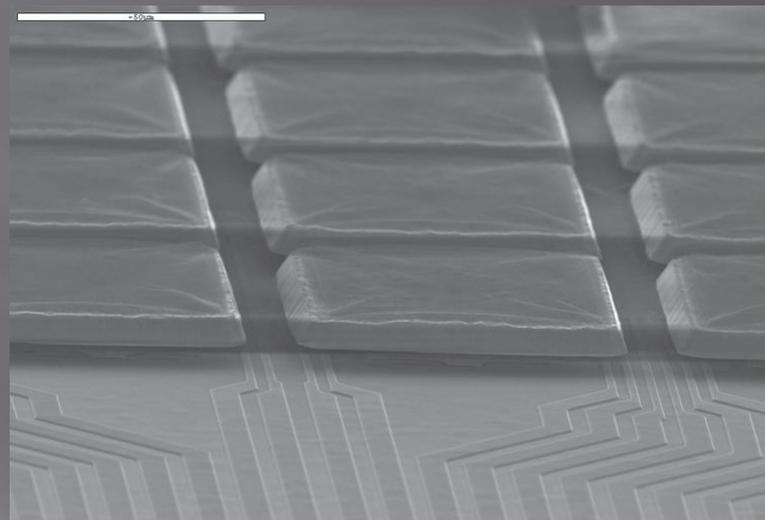
Calorimeter

EPE: 3 Crab, 70,000 c/s

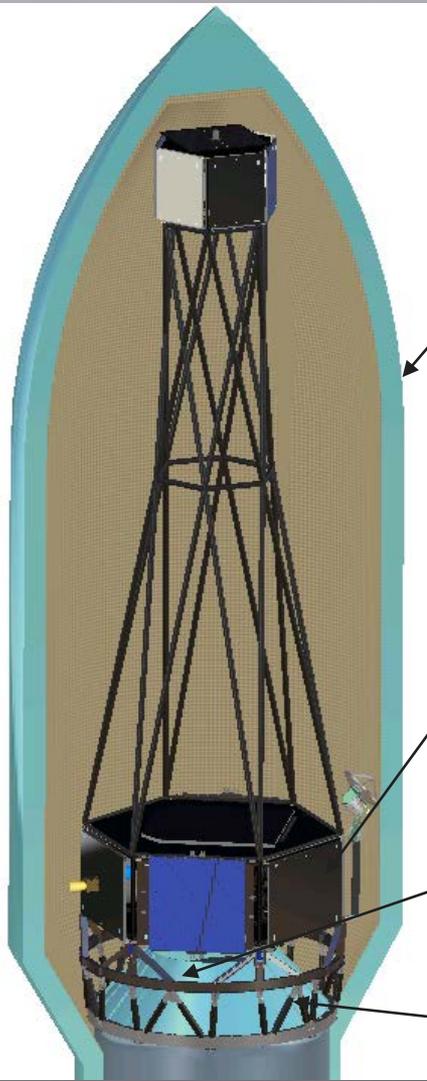
2', 40x40
2.5eV/3''
150 c/s

8', 20x20x(2+2)
600u/~10eV

Current Results:
75u, 32x32 array
1.6eV FWHM



SPACECRAFT/LAUNCHER



Falcon 9

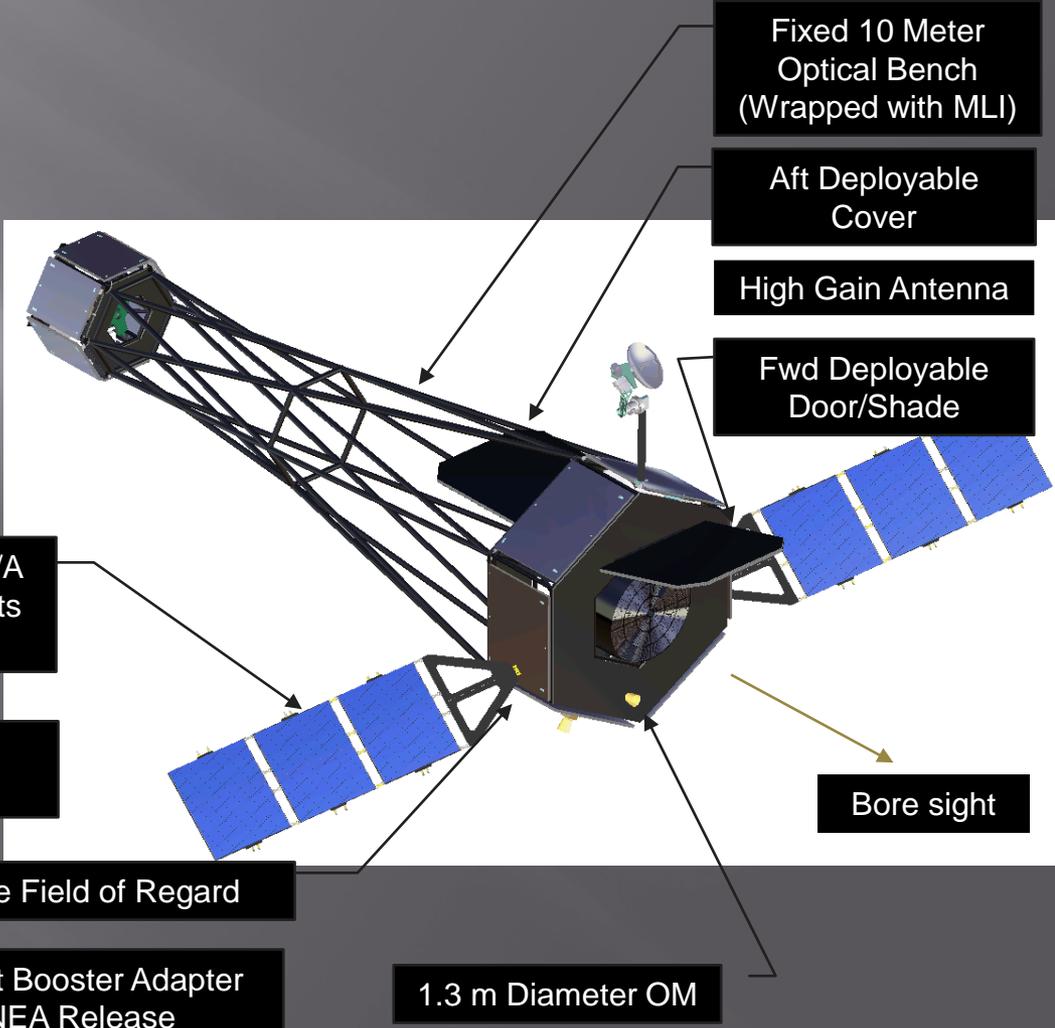
Two 1500 Watt S/A Wings (3000 Watts Total)

•OM / Spacecraft Module

SADA's for Large Field of Regard

6 Point to 18 Point Booster Adapter with 6 Point NEA Release

T3302 PAF – SpaceX Version



Fixed 10 Meter Optical Bench (Wrapped with MLI)

Aft Deployable Cover

High Gain Antenna

Fwd Deployable Door/Shade

Bore sight

1.3 m Diameter OM

Mass Rack-up

Assembly Level								Unit mass (Kg's)	Qty	Basic Mass (Kg's)	MGA (%)	MGA (Kg's)	Predicted Mass (Kg's)
Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8						
EPE Observatory - Wet										1234.05	22%	268.05	1502.10
Propellant - Monoprop										78.03	21.7%	16.95	94.98
EPE Payload										569.68	21.7%	123.83	693.51
Optics Module Assy										308.76	22.2%	68.46	377.22
FMA										259.84	16.6%	57.38	317.21
Bore Sight STA										3.87	14.0%	0.32	4.19
Spare Line								0.00	0	0.00	30.0%	0.00	0.00
Misc Hardwre								2.00	1	2.00	30.0%	0.60	2.60
Harness OM								3.00	1	3.00	30.0%	0.90	3.90
Deployable Door/Shade										12.55	30.0%	3.77	16.32
Deployable Cover - Aft								20.00	1	20.00	20.0%	4.00	24.00
FMA MLI								7.50	1	7.50	20.0%	1.50	9.00
Instrument Module Assy										250.27	21.3%	53.42	303.68
Instrument Module										243.59	21.1%	51.41	295.00
IM Truss								35.67	1	35.67	30.0%	10.70	46.36
IM Equipment Panels										21.17	30.0%	6.35	27.52
XMS Assy										154.75	16.3%	25.24	179.99
Payload Accomodation - Misc								2.00	1	2.00	6.0%	0.12	2.12
Thermal Hardware								10.00	1	10.00	30.0%	3.00	13.00
IM Harness								20.00	1	20.00	30.0%	6.00	26.00
Cryo Cooler Ambient Radiator Assy										4.68	30.0%	1.40	6.08
Cryo Cooler Ambient Radiator								2.83	1	2.83	30.0%	0.85	3.68
OSR's								0.89	1	0.89	30.0%	0.27	1.15
Adhesive								0.46	1	0.46	30.0%	0.14	0.60
Interface Structure								0.50	1	0.50	30.0%	0.15	0.65
IM MLI								2.00	1	2.00	30.0%	0.60	2.60
Payload Misc.										10.65	18.3%	1.95	12.60
Primary Intergating Structural Assy										235.51	30.0%	70.65	306.17
Forward Hexagonal Box Truss										80.02	30.0%	24.00	104.02
Tower Truss										155.50	30.0%	46.65	202.14
EPE Spacecraft (Dry)										350.83	16.1%	56.61	407.45
Spacecraft Secondary Structures & Mechanisms										68.63	27.8%	19.07	87.71
Avionics										217.70	10.5%	25.53	243.23
Propulsion										26.518	7.6%	2.019	28.538
Thermal										33.98	26.5%	8.99	42.98
Payload Support Misc.										4.00	25.0%	1.00	5.00

Close to MEL - so could to PRICE-H costing

ROM Costing - Grass Roots and Mass-only Model (s/c)

Description	WBS #	\$M (FY11)	Notes
Management	1,2,3	50	15% wrap on optics, detector, and s/c
Science	4	59	Science team starts L-2 years, goes L+4
Optics	5	26	ASTRO-H scaled and then doubled
XMS+cryo	5	136 +10m	Single string cryo, redunant electronics, ICU included in S/C +8' FOV
S/C	6	178	NGAS mass, JSC SVLCM mass only model (-NASCOM) FY2011
Ops	7	30	
LV	8	100	Falcon 9
GDS	9	20	
MSI&T	10	20	
EPO	11	5	
Total, no reserves		620	
Reserves		149	30%, no reserves on GO, LV, EPO
Grand Total		774 784	+8' FOV
GO Program		22.5	Assumes 150 \$50K grants/year, included in WBS 4 cost above
Science program includes GO and \$4M/year in science and support by GTO team			

¾ Billion seems be common for Medium calorimeter or grating missions

Q/A

How will the much higher collecting area of EPE compensate for reduced spectral resolution specifically for WHIM measurements?

S/N for detection of WHIM absorption lines scales like $\sqrt{\Delta E / \text{Area}}$. Putting in the appropriate numbers for EPE and IXO, we find that EPE has 70% of the power of the IXO gratings. The simulations shown in Fig 6 were done using the EPE response and show that 20 AGN and 100 filaments are detectable with a 10ms program, essentially matching science return that could have been done with IXO.

How well do measurements on arc minute scales of turbulent velocities in clusters of galaxies constrain models?

Global turbulence values will be significant. The values will be weighted towards the central regions of clusters (since emissivity scales as density squared), but the results will be sensitive to models. Global turbulence is dominated by cluster dynamics (mergers, infall and internal dynamics). 1) Higher effective viscosity will reduce the global value, so global levels are a probe of that (very poorly known) quantity. 2) Turbulence levels will be a probe of dynamical state. If these values were available, they would take on a significance similar to temperatures.

Q/A

With the limited angular resolution, how can it be determined if measurements of gas turbulence in clusters are due to AGN outbursts rather than to mergers?

Both of these questions point to the limitations of the 1 arcmin PSF. With this PSF, EPE will be limited to doing these measurements on nearby clusters, ie, the REFLEX survey where the radii are much bigger than 1 arcmin. Since these clusters are resolved, one can map the turbulence to see if it is higher in association with radio lobes (indicating AGN outburst) or higher along an extended feature (shock front). Note that the RELFEX clusters have already been imaged with ROSAT. Figure 9 shows that 200 km/sec turbulence is easily measured, matching what could be done with IXO. While EPE is clearly not IXO, it represents a very significant advance (20x more area) over the only planned calorimeter mission with US involvement, ASTRO-H.

It isn't clear how observations of bursting neutron stars are carried out. Is the idea to stare at a burster with a high burst rate, or to trigger an observation with some other indication of bursting activity?

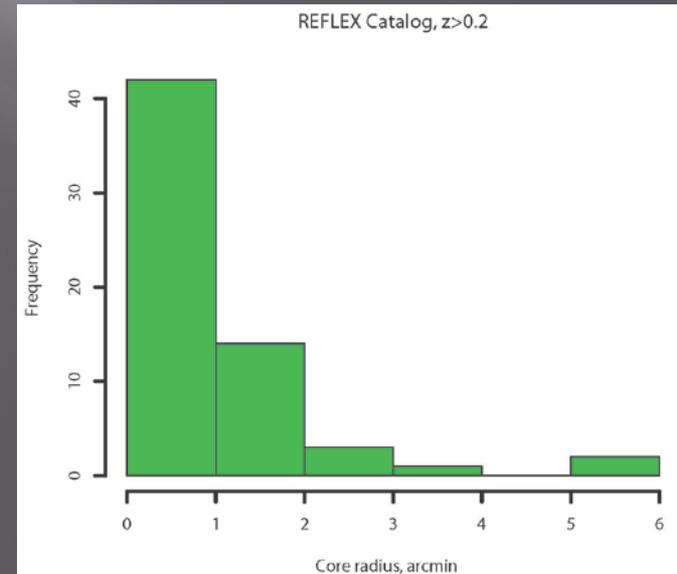
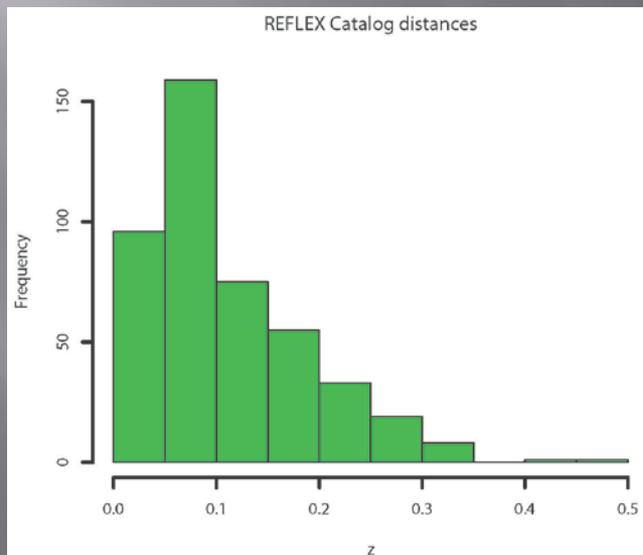
Both techniques could work. The simulations shown in Figure 10 are based on 4U1728-34, which bursts every few hours so a long stare would be highly effective.

Q/A

Over what range of redshift will the metal enrichment measurements be made? Over what redshift range are measurements required to determine when and how the metals are produced?

For nearby galaxies, the spectral resolution of the calorimeter will allow the relative fraction of SNIa and SNII to be determined via abundance differences.

The EPE background is estimated to be 2×10^{-14} ergs/cm²/s/arcmin² (0.3-10keV), corresponding to 0.02 c/s in the 1 arcmin beam. The REFLEX catalog does contain ~ 50 clusters at $0.2 < z < 0.5$, and the core surface brightness of these clusters is well above this limit. These may not be resolved with EPE, but integrated abundances can be measured. See the figures below on the z distribution and core radius of REFLEX clusters.



Q/A

Since the beam fills the detector field of view, how would instrument background be determined? Do the effective area curves account for the fraction of the collecting area that actually falls on the detector plane?

The XMS as written in the RFI was very far from optimized. The solution to this (and several other) questions is the inner/outer XMS arrangement used in several of the RFIs. For EPE we would surround the inner 2 arcmin array with a 2x2 hydra outer array of 12'' = 600 micron pixels with 10eV resolution, extending the FOV out to 8 arcmin. This would require another 20x20 TES, would add ~\$10m to the cost, and would bring the total number of TES to 1975, still less than planned for IXO. This then allows for the background to be measured and the area curves are approximately correct as shown. Additionally, the non-sky instrument background can be determined from spectra taken prior to opening the cryostat gate valve - just as for Astro-E2 and Astro-H, and the addition of a simple filter wheel could block all external x-rays for repeated background measurements.

Q/A

2.5 eV resolution corresponds to Δv of 117 km/s at 6.4 keV. How can the instrument resolve 100 km/s gas velocities (p. 6)?

Figure 9 on page 6 does not mean to imply that 117 km/sec can be resolved, only that with the 2.5eV resolution of the EPE XMS that 100 km/sec turbulence can be well separated from 200 km/sec. The figure is based on a simulation folded through the EPE response. Note that many of the other RFIs also show the same thing (ie, AXSIO, SAHARA).

What is the operational status of the “code division multiplexing” technique?

There are ongoing APRA and internally funded programs that should bring this to TRL 6 within 2 years.

8-channel CDM read-out has been demonstrated on pixels slower than is needed for EPE (see pdf attached). We have demonstrated 4-channel CDM while reading out 4 pixels of the faster type of pixels upon which the EPE design is based (75-micron pixels), and achieved under 4 eV energy resolution at 6 keV for this demonstration.

There is no doubt that greater development of this CDM multiplexing capability is needed for EPE - the same development that is also assumed for the AXSIO central array.

Q/A

What is the distribution of energy resolution on the existing 32x32 pixel TES arrays?

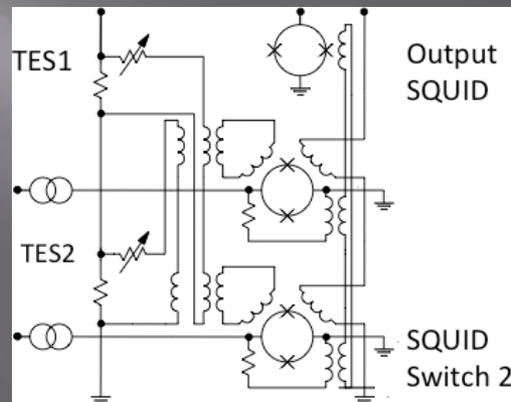
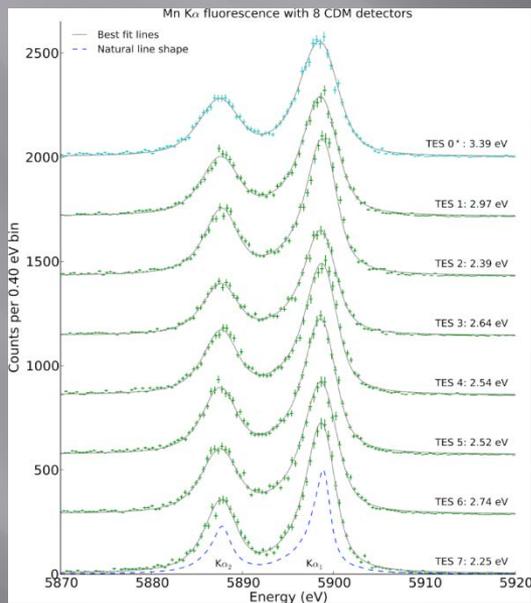
Not yet measured, but should be possible to calibrate this to sufficient accuracy to carry out the observations described herein.

32x32 arrays of 75-micron pixels have been fabricated but not yet tested. The uniformity of performance in 8x8 arrays of these pixels with a lower Tc seems at least as good as those for regular sized TESs in arrays with planar wiring, and arrays with stripline wiring should improve uniformity even further (stray magnetic fields from current flowing in regular "planar" wiring has the potential to degrade uniformity). 32x32 arrays of 75 micron pixels with stripline wiring to all 1024 pixels have been designed and currently are being fabricated. In general, the potential problem of fields from currents that are closer to TESs in small pitch designs appears to be more than mitigated by the much smaller area of TESs - ie. the smaller TESs are much less sensitive to magnetic fields than larger ones. In addition, the 150-micron pitch of EPE will reduce this sensitivity further over 75-micron devices.

Q/A

2.4.3 Update on Code Division multiplexer (CDM)

We have made very good progress on CDM. In the figure below (a) we show results from an 8-pixel CDM demonstration. The seven modulated pixels are all sub-3 eV. As is usual in CDM, pixel 0 is not switched like the other pixels, and so it has degraded resolution due to worse $1/f$ and pickup. We only include it here for completeness. Just as for the recent TDM measurements, the frame rate is $t_{\text{row}} = 400$ ns. For these measurements this frame rate is currently limited by the inability to pass data out through the digital feedback electronics any faster than this, the new room-temperature hardware necessary for this will be available soon. The 400 ns frame rate used for these measurements was somewhat conservative and not yet optimized. We estimate that it could currently be reduced down to 360 ns straightforwardly.

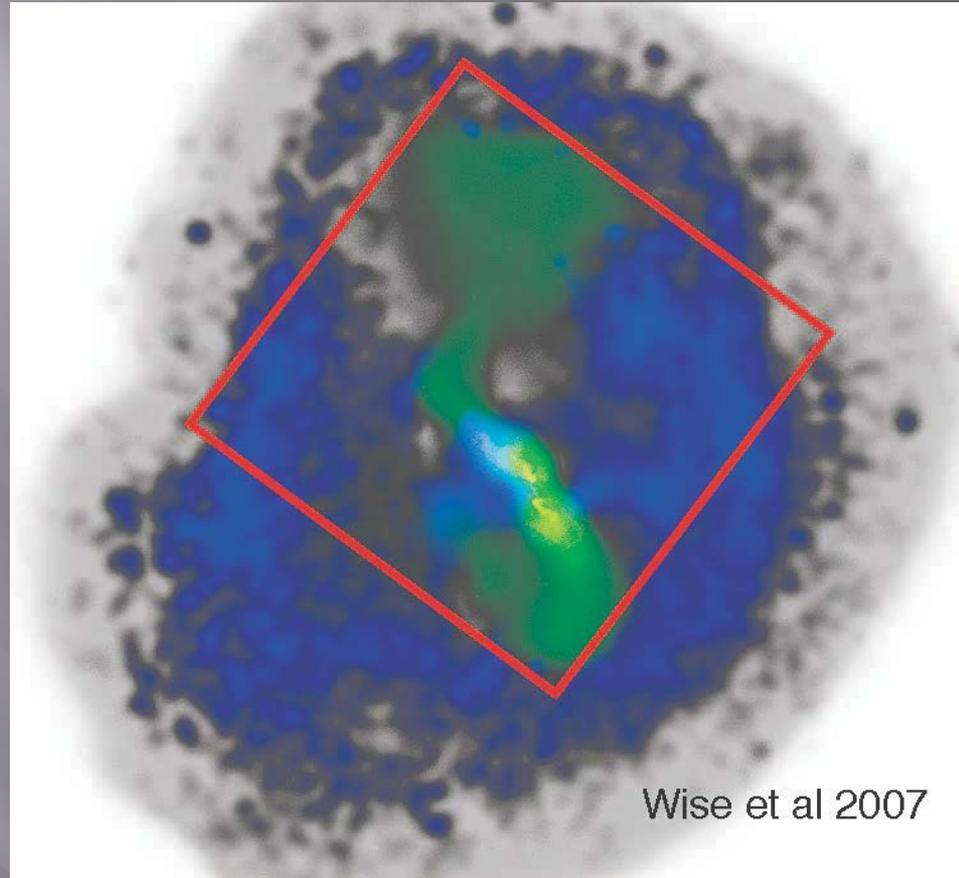


(a) The resulting MnK α spectra from an 8-pixel CDM experiment using flux-couple code division multiplexing. (b) Fluxed coupled CDM circuit when just 2 TESs are coupled.

The amount of energy resolution degradation from CDM multiplexing can in principle be reduced by up to a factor of 5.7 over TDM for the read-out of 32 rows, and this factor reduces to 2.8 when considering 8 rows. A full characterization of the detector array that produced this result has not yet been completed and only rough estimates have been made of levels of energy resolution degradation that was due to the CDM read-out of between 0.2 and 0.4 eV.

Backup follow

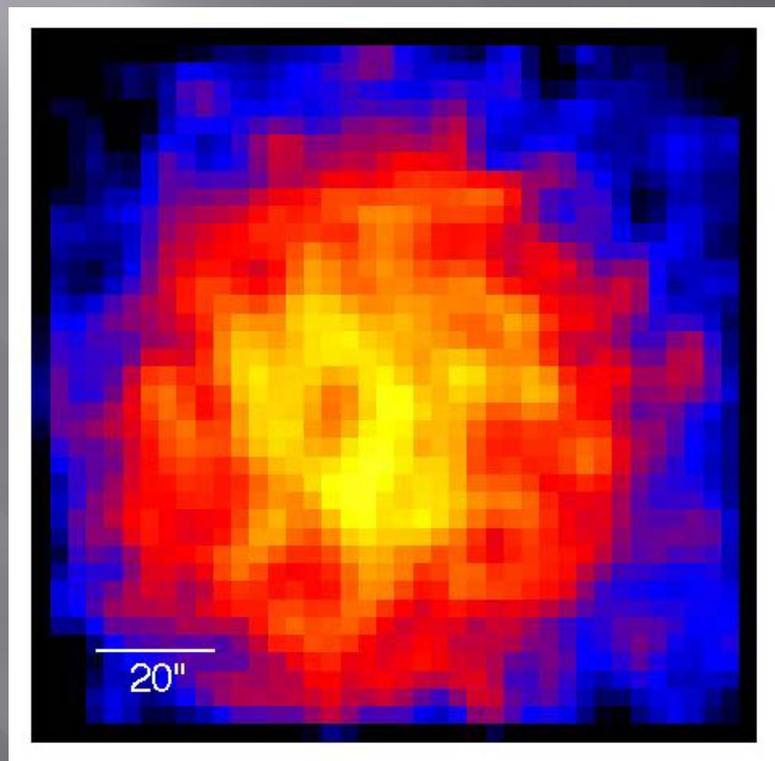
Feedback: Cluster Bubbles



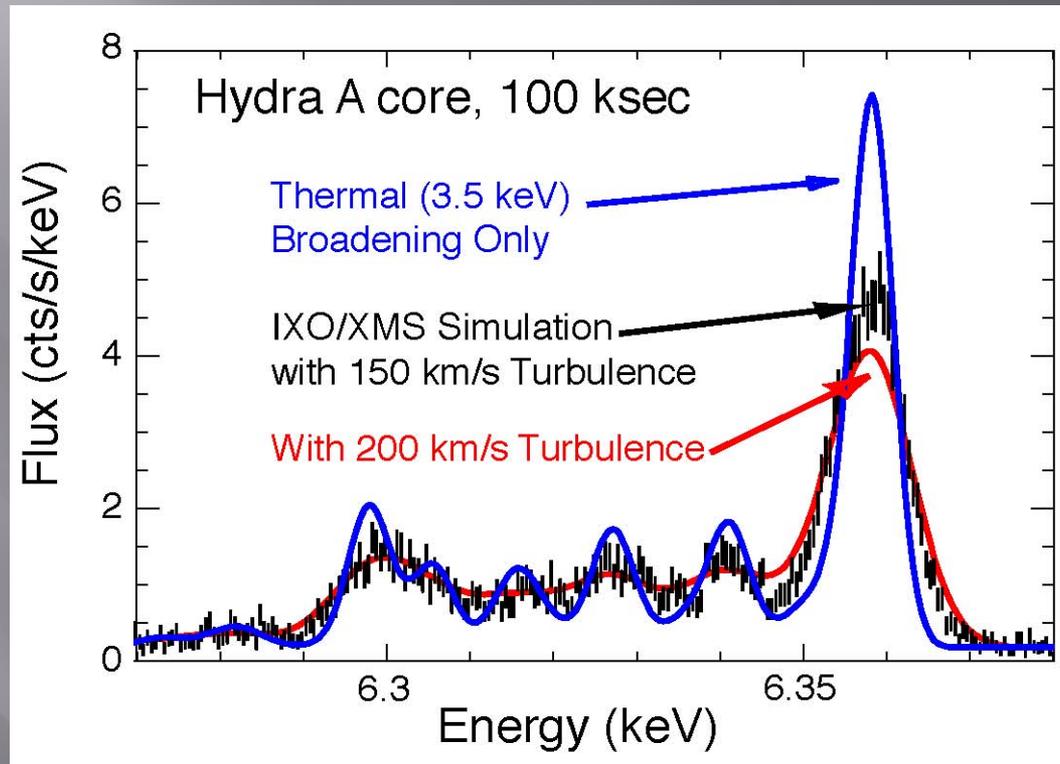
Hydra-A, 5 arcmin box
~dozen cluster/groups bubbles >1 arcmin,
~dozen clusters/groups bubbles ~0.5 arcmin
(Birzan et al 2008)

ASTRO-H, ~10 clusters

A2734



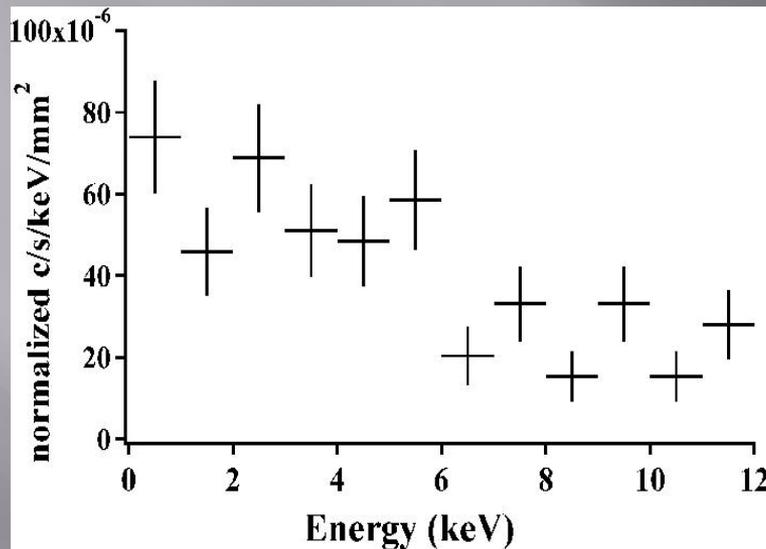
Feedback: Turbulence



~300ks with EPE (6keV area ~1/3 IXO)
Measure Non-virial pressure support
Measure bulk motions

Background Estimate

Suzaku XRS (LEO) -> x4 for L2 orbit (Suzaku/CXO ccd rates)



40m: Dominated by non-rejected particles (or secondaries), 0.24 c/s/PSF, Equivalent to 3×10^{-14} erg/cm²/s (2-10 keV)
Full ~20,000 Sources in RASS reachable (limit 5×10^{-13} erg/cm²/s (0.5-2.0 keV))

10m: Particle BG ~ 0.016 c/s/PSF
Equivalent to 3×10^{-14} erg/cm²/s (2-10 keV)

SpaceCraft

- ▣ Northrup Grumman (NDA)
- ▣ 40m extendable bench
 - ▣ Boom TRL 7
 - ▣ Mass ~1500kg to 1900kg with MGA
 - ▣ Optic mass ~same as foil (but 10x area)
- ▣ 10m fixed bench
 - ▣ Mass ~1200kg to 1500kg with MGA
 - ▣ s/c components all 'off the shelf', should come in < \$1m/kg

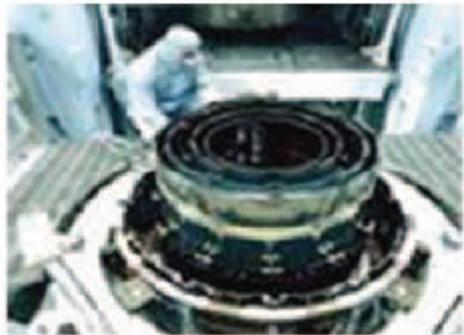
Cost Rackup

Mission Life		3	
			changes for v4
WBS		EPE-v4	
WBS 1,2,3	123	45	
science	4	47	science team starts L-2 years, goes L+4
Optics	5	26	Astro-H scaled and then doubled
XMS+cryo	5	172	
S/C	6	100	
Ops	7	30	
LV	8	100	Falcon 9
GDS	9	20	
MSI&T	10	18	6% on optics, detector, and s/c
TOTAL		557	
EPO	11	5	
		562	
RESERVES		130	30%, no reserves on go, lv, epo
Grand Total		692	
GO Program:		22.5	
			(assumes 150 50K grants/year)
			Science program also assumes \$4M/year in science by GTO team

Large Area, MIDEX: Require very light optics

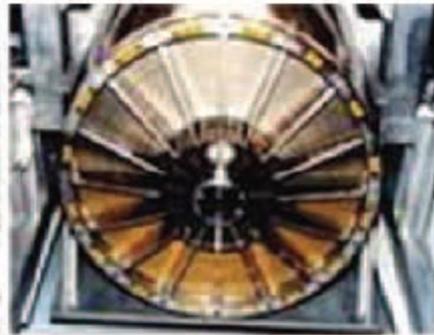
- ▣ Low mass/effective area – thin substrate
- ▣ Low cost(?) – production line manufacturing
- ▣ Rigid, simplifying mounting

Bavdaz et al 2010



Chandra
18500 kg/m²

250mm



XMM-Newton
2300 kg/m²

3-7 mm(Ni)



IXO-SPO
200 kg/m²

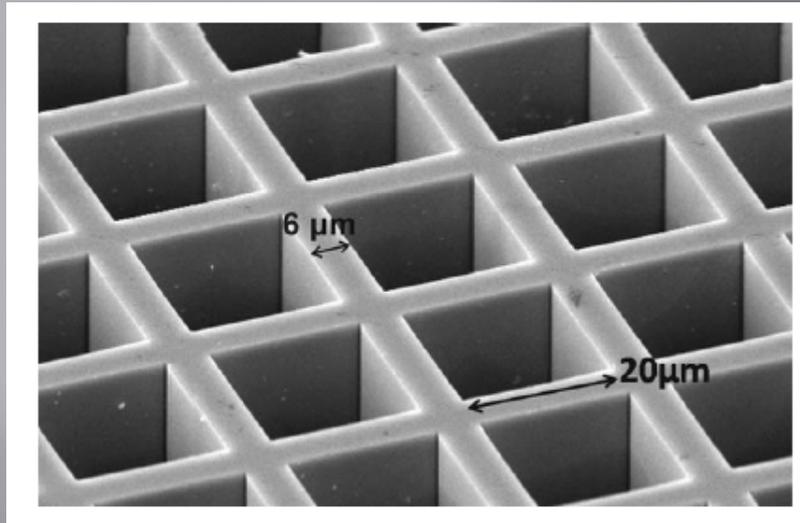
0.17mm



MCPO
5-25 kg/m²

0.006mm

EPE enabled via MCPO



MCPO= Realization of Lobster Eye design (Angel 1979)

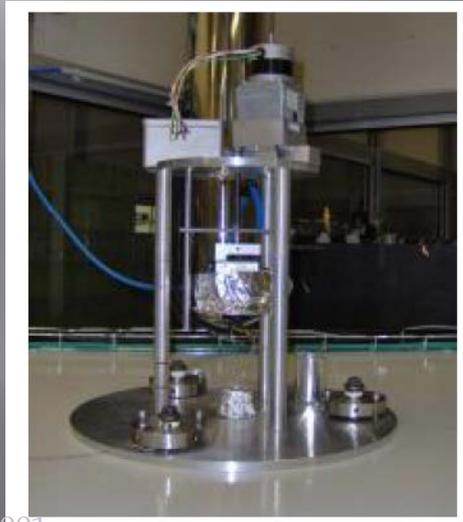
Proposed as ISS/Lobster-ASM

Proposed as part of Super-Swift Explorer from GSFC

Proposed as STORM Solar-Wind Monitor, GSFC space physics

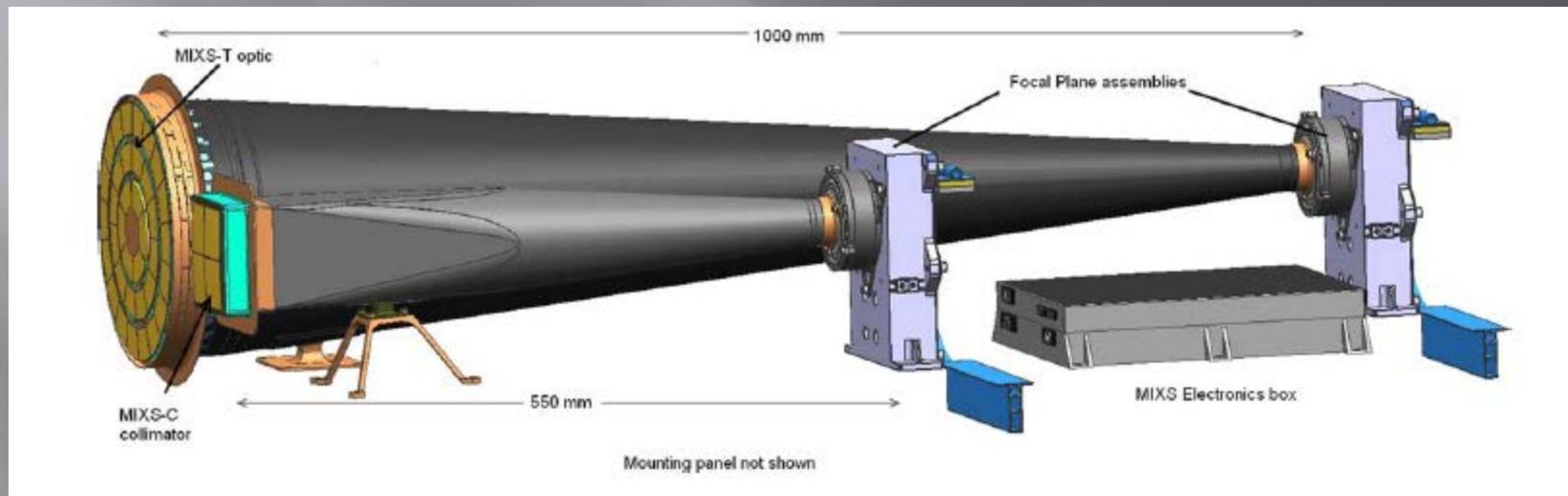
Considered as XEUS/IXO mirror

ESA invested \$1m+ in Photonis



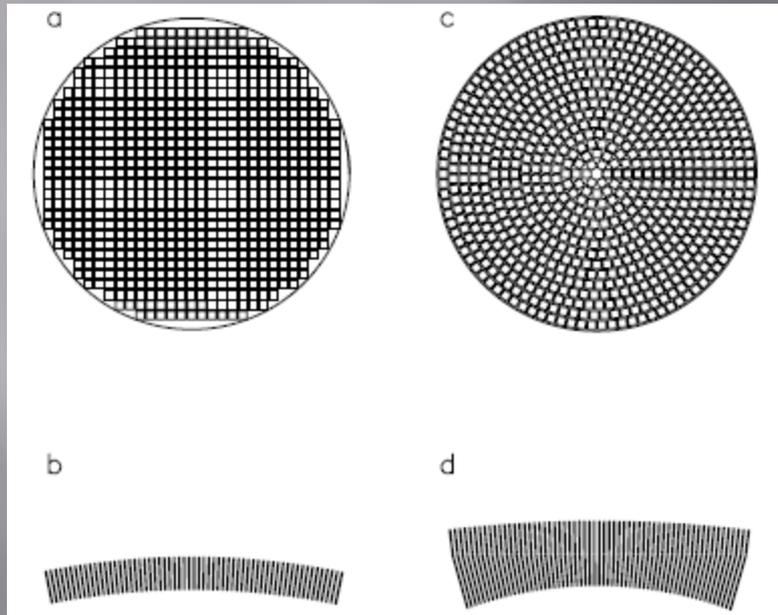
MCPO Flight Missions

- ▣ Bepi-Columbo, 2013 Launch, +6y to Mercury
- ▣ SVOM GRB mission (France/China, 2013)



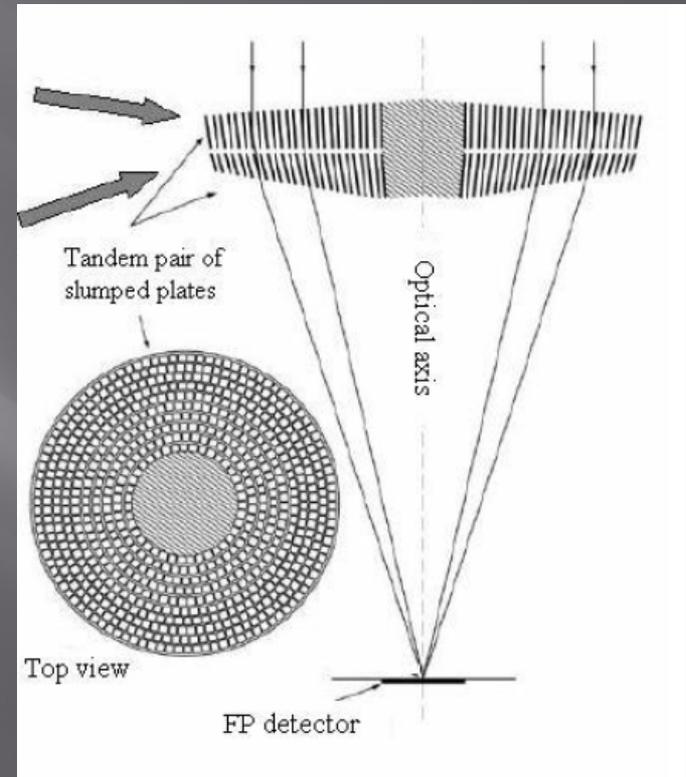
~Wolter-1 optics, ~5 arcmin PSF, ~50cm², 0.5-7.5 keV, 9kg(!)

Wolter-1 vs Lobster



Willingale et al 1998

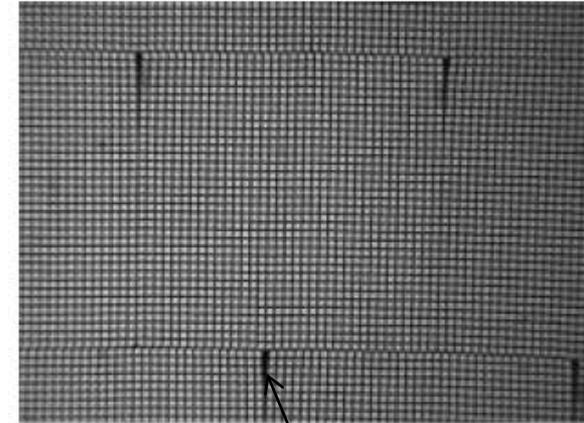
Radial Packing,
Wolter-1 Optics
(conical approx)



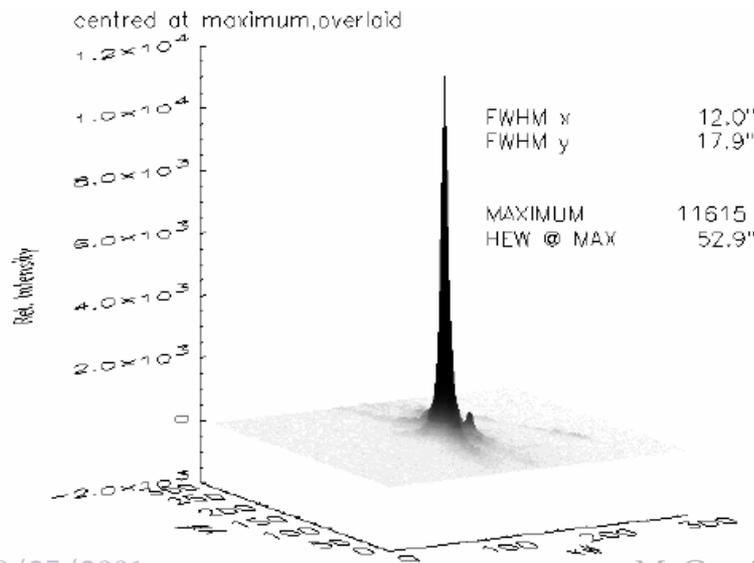
Wolter-1 packing



Block of radially stacked multifibres is sliced and etched to form plates

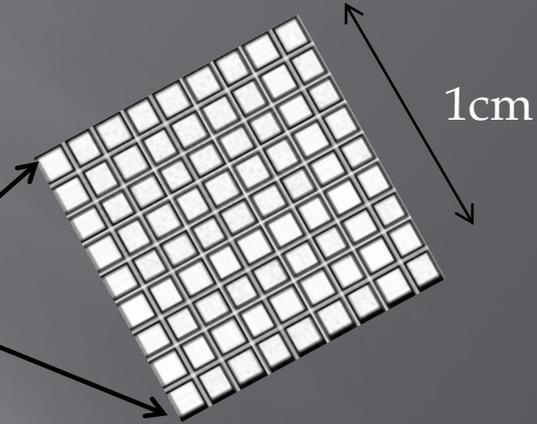
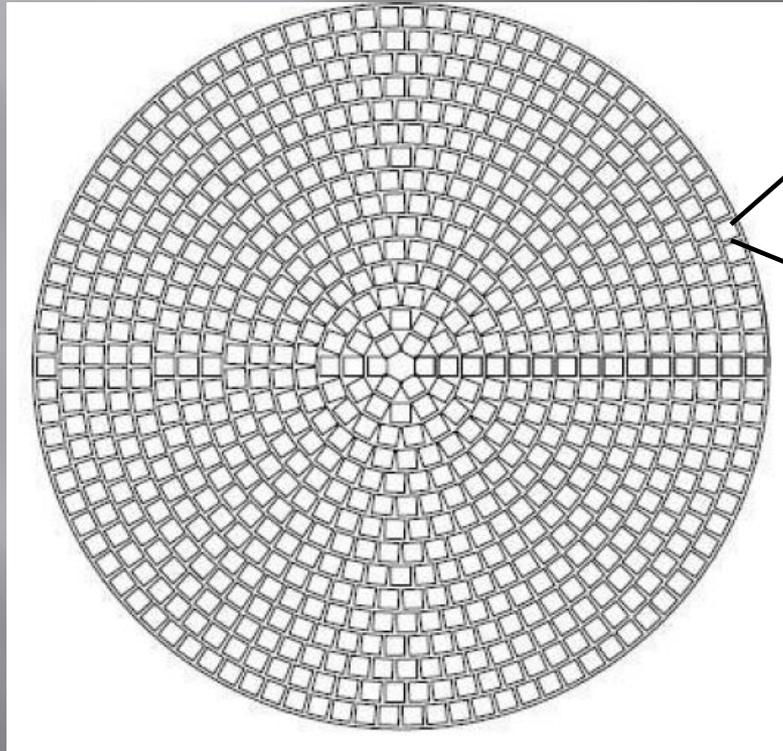


Wallace et al 2006



~arc-min HEW over small sections,
Defects at multi-fiber boundaries

EPE: Approximate Radial Packing

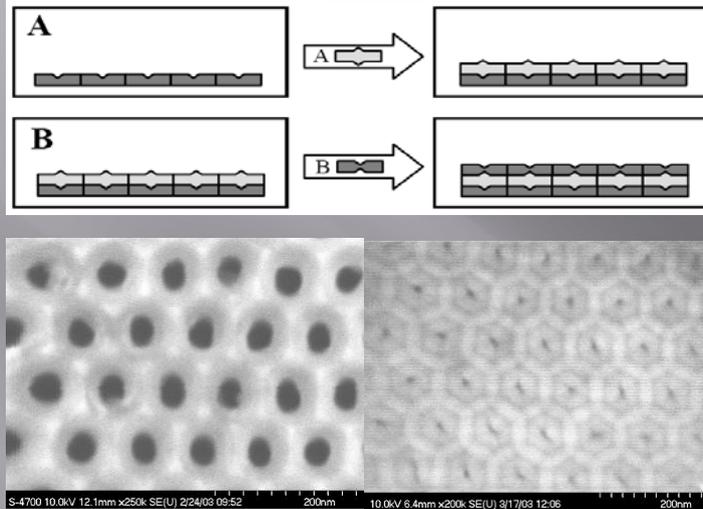


1cm = 0.85 arc-min
at 40m focal length

60 μ pores, 6 μ
webbing good
match for 40m

L/D 60-160

ADL Coatings for Improved Area



Atomic Layer Deposition allows conformal monolayers of high-Z reflectors (Ir), uniform to great depth.

ALD Thin Film Materials

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt									
		Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
		Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lw		

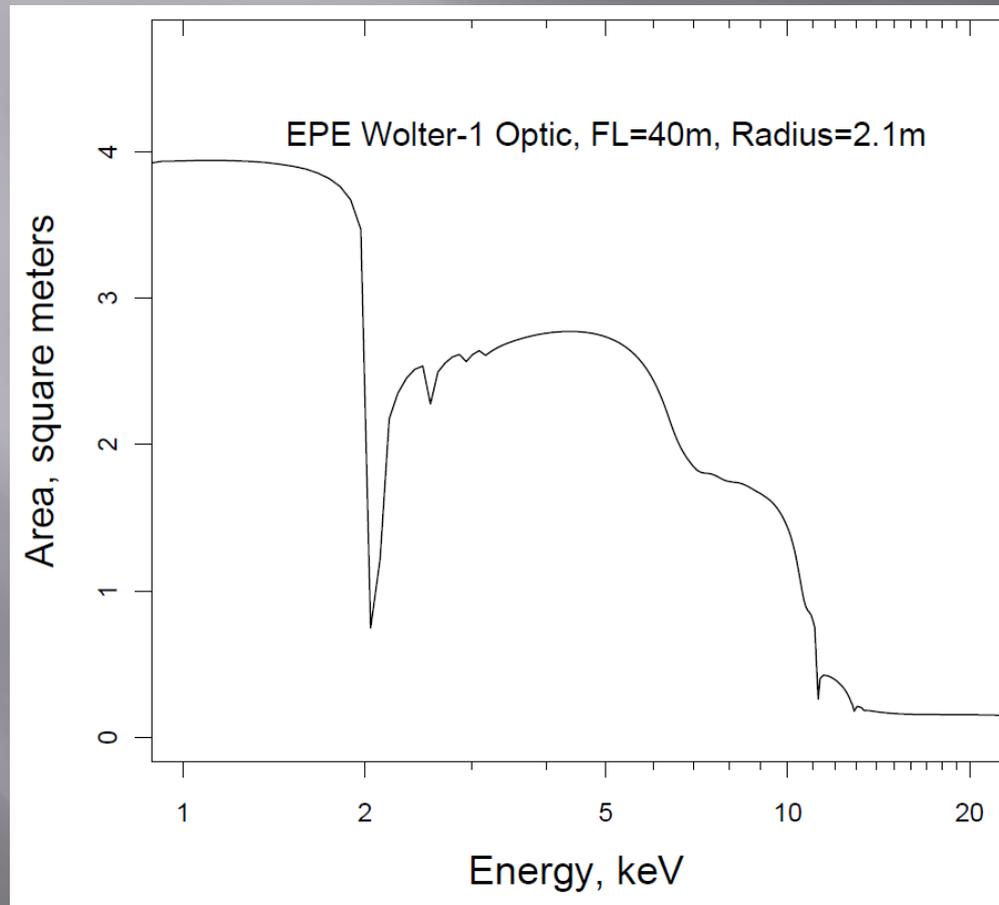
Multi-layers possible (Si/W), very high energies?



EPE: MIDEX Mass, Premier Science

- MIDEX Mass:
 - 50 kg mirror
 - 180 kg single string calorimeter
 - s/c mass ~payload
 - 500kg = MIDEX (1/2 Swift)
- Premier BH and NS Science:
 - 2.5m² at 6keV – Resolve orbits at Event Horizon, dozens of sources
 - >1m² at 10keV – BH Spin survey vs. time, 1000 sources
 - Timing + spectral resolution – NS EOS via absorption lines, straightforward and robust
- Modest Back-ground with ~1 arc-min PSF
 - Spectra of all ~20,000 RASS sources
 - BG < RASS flux, RASS sources ~ 1 c/s

2.1m radius optic Area



Assumptions:

Wolter-1 conical approx
60% OAR (83% possible)
Random pair alignment
25% support obscuration
(maximum for IXO)
perfectly smooth

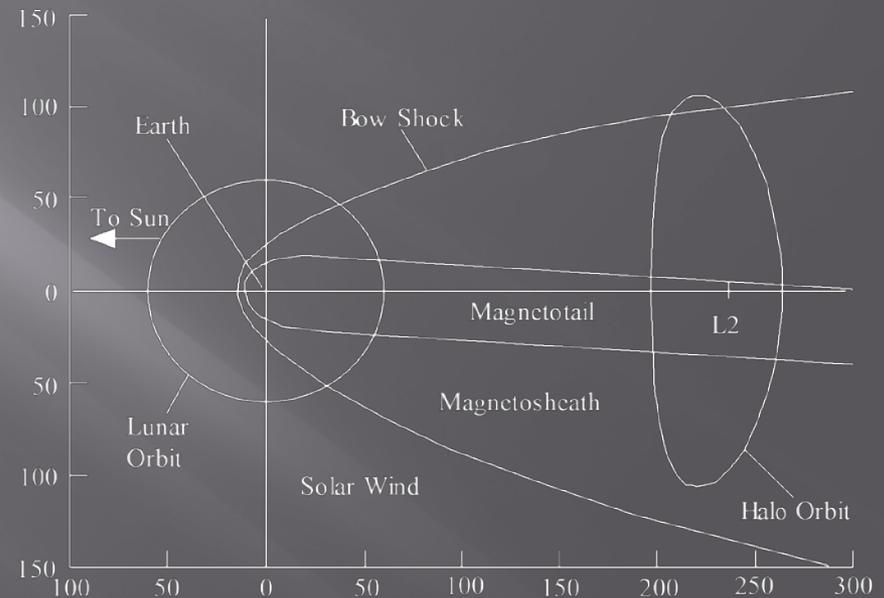
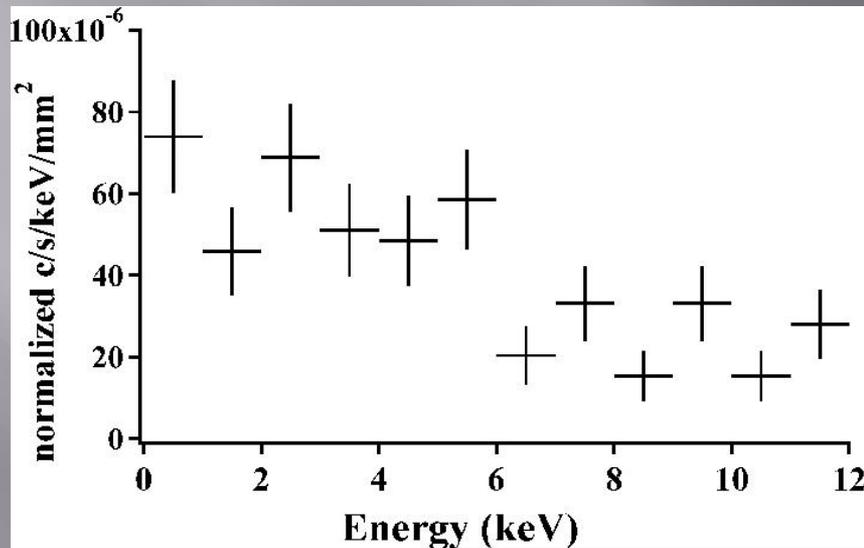
4m² at 1.25 keV

2.5m² at 6 keV

>1m² at 10keV

Background Estimate

Suzaku XRS (LEO) \rightarrow $\times 4$ for L2 orbit (Suzaku/CXO ccd rates)



Dominated by non-rejected particles (or secondaries), 0.24 c/s/PSF,
Equivalent to 3×10^{-14} erg/cm²/s (2-10 keV)
Full $\sim 20,000$ Sources in RASS reachable (limit 5×10^{-13} erg/cm²/s (0.5-2.0 keV))