THE NASA X-RAY MISSION CONCEPTS STUDY

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Rob Petre (NASA / GSFC)

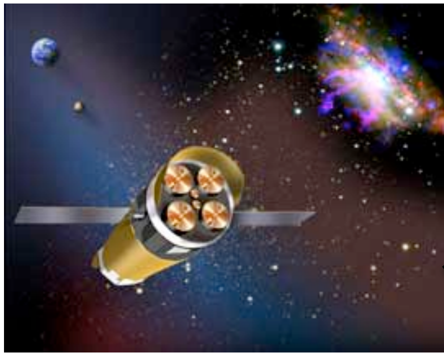
X-ray Mission Concepts Study Scientist

Community Science Team: Joel Bregman (Michigan; Chair), Mark Bautz (MIT), David Burrows (PSU), Webster Cash (Colorado), Christine Jones-Forman (SAO), Steve Murray (JHU), Paul Plucinsky (SAO), Brian Ramsey (MSFC), Ron Remillard (MIT), Colleen Wilson-Hodge (MSFC)

Science Support Team: Andy Ptak (GFSC), Jay Bookbinder (SAO), Mike Garcia (SAO), Randall Smith (SAO)

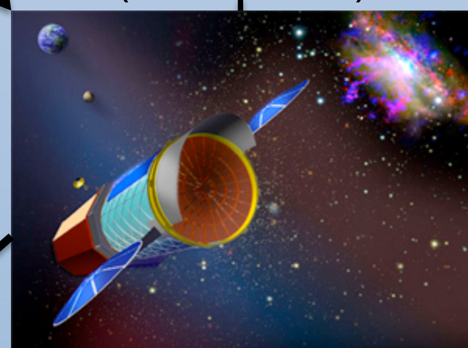
Engineering Support Team: Gerry Daelemans (GSFC), Tony Nicoletti (GSFC), Gabe Karpati (GSFC), Paul Reid (SAO), Mark Freeman (SAO), and others…

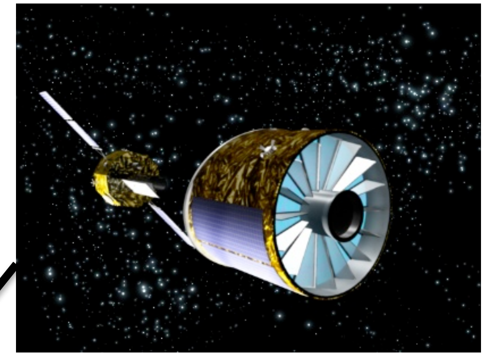
The road to the next major X-ray observatory



Constellation-X
(1996-2008)

IXO
(2008-2011)





XEUS
(2000-2008)

- **Tech. development plan (2011-2012)**
- **Mission architecture assessment, with and without US contribution to Athena (2011-2012)**
- **Mission concept(s) definition (>2012)**

ATHENA??

NASA

ESA

Background behind concepts study

- *IXO* was ranked 4th among large missions in decadal survey report *New Worlds, New Horizons* (*NWNH*)
- *IXO* study activities in US were terminated in fall 2011
  - Prior to termination:
    - Produced mirror development plan consistent with *NWNH* recommendation
    - Developed *AXSIO* concept (*IXO* redesigned to meet decadal constraints)
- In September 2011, NASA HQ initiated concept studies through the PCOS Program Office to identify more cost effective ways to perform *IXO* and *LISA* science

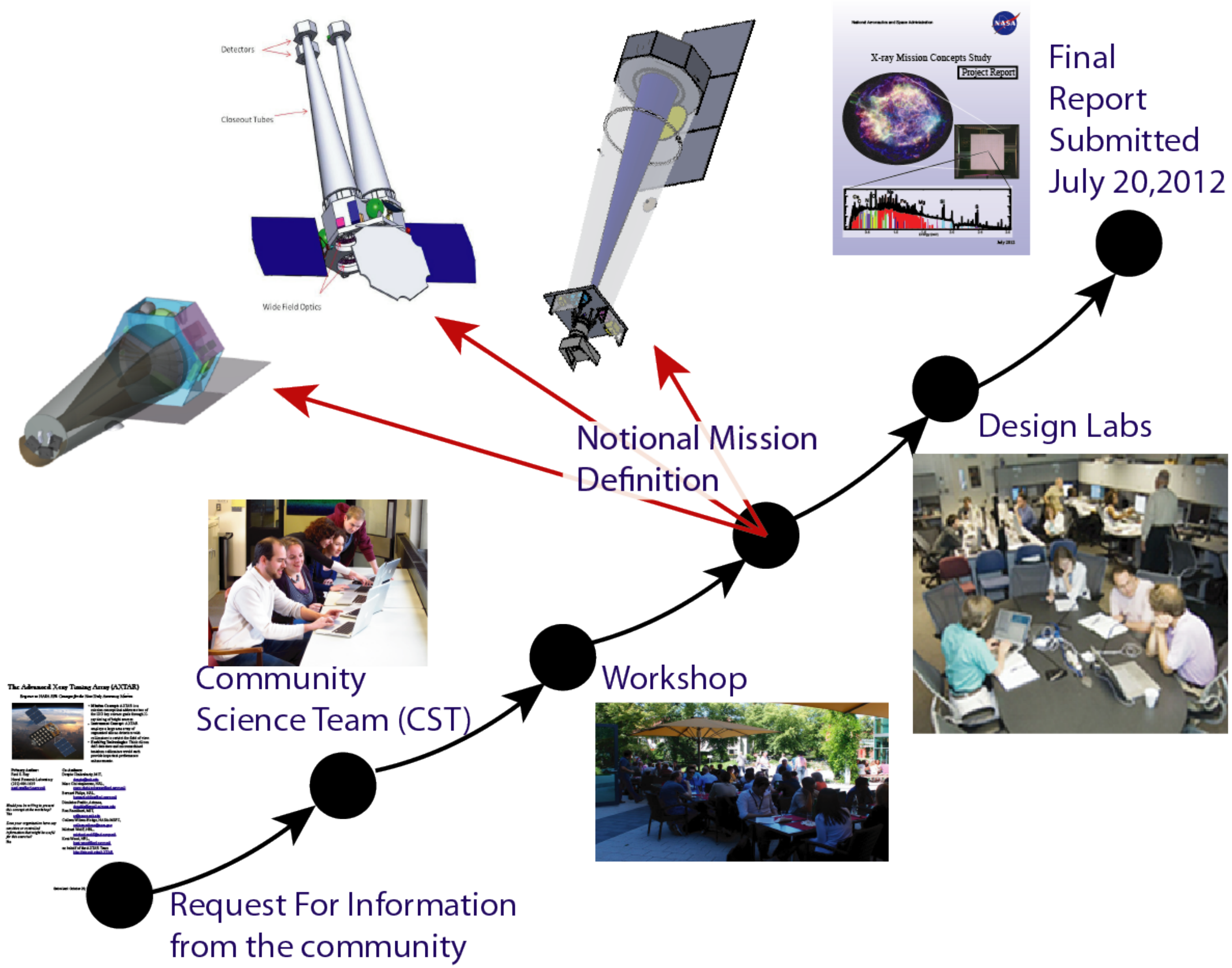
NASA X-ray Concepts Study

- **Objectives**
  - Determine the range of science objectives of *IXO* that can be achieved at a variety of lower cost points
  - Explore mission architectures and technical solutions that are fundamentally different from the heritage designs
  - Fully engage the community and ensure that all voices are heard, all perspectives considered
  - Create data for a report that describes options for science return at multiple cost points for X-ray astronomy
- **Deliver final report to NASA HQ that:**
  - Describes and analyzes trade space of science return vs. mission cost
  - Summarizes the mission concepts developed during the study and how they relate to the trade space and other mission concepts that were not developed in a design lab
  - Summarizes the RFI responses and the workshop and describes how they were folded into the whole study

Key questions addressed by *IXO*

- **What happens close to a black hole?**
  - Time resolved high resolution spectroscopy of the relativistically-broadened features in the X-ray spectra of stellar mass and supermassive black holes.
- **When and how did supermassive black holes grow?**
  - Measure the spin in SMBH; distribution of spins determines whether black holes grow primarily via accretion or mergers.
- **How does large scale structure evolve?**
  - Find and characterize the missing baryons by performing high resolution absorption line spectroscopy of the WHIM over many lines of sight using AGN as illumination sources.
  - Measure the growth of cosmic structure and the evolution of the elements by measuring the mass and composition of clusters of galaxies at redshift < 2.
- **What is the connection between SMBH formation and the evolution of large scale structure (i.e., cosmic feedback)?**
  - Measure the metallicity and velocity structure of hot gas in galaxies and clusters
- **How does matter behave at high density?**
  - Measure the equation of state of neutron stars through (i) spectroscopy and (ii) timing.

Study Phases



Study Boundary Conditions

- The basis for discussion and definition of concepts for further study was how well concepts addressed the breadth of exciting *IXO* science objectives, as endorsed by NWNH.
- We did **NOT** revisit decadal survey decisions regarding science questions or mission priorities.
- We studied *representative* missions for the various cost classes. The goal was to assess the fraction of *IXO* science that can be performed vs. mission cost.
- No recommendation for a specific mission or a preferred cost class was given in the final report. This is the responsibility of NASA and its advisory structure.

RFI responses

- 30 received: 14 mission concepts, 12 enabling technology
  - Variety of concepts in nominal “cost bins” (<$600M, $600M-$1B, > $1B)
  - Degree of fulfillment of *IXO* science goals largely scaled with concept cost
  - Small missions skirted edges (typically one science goal)
  - Medium, large addressed one or more topics directly
- Technology responses addressed wide range of technology: optics, gratings, calorimeters and other detectors, structures
- All responses posted on PCOS website

Report bottom line

X-ray observatories in the $1B class that address most or all of the IXO science objectives are feasible for start within this decade, but only if technical risk is controlled by prior development of key technology to TRL-6.

The notional missions that were studied were all in this cost range -- less than the current X-ray flagship missions (*Chandra, XMM*) -- yet will greatly outperform current missions in critical ways, producing breakthrough science around which the *IXO* concept was developed.

Notional Missions

- Using RFI responses as guidance, the CST defined three single instrument notional missions, plus *AXSIO* as a dual instrument mission
    - *N-XGS* – grating mission (target cost ≤ $1B)
    - *N-CAL* – calorimeter mission (target cost ≤ $600M)
    - *N-WFI* – wide field imaging survey mission (target cost ≤ $1B)
- The CST determined which notional missions would have the highest science yield for the two possible ESA L-1 selection outcomes:
    - Case I: *ATHENA* selected: *N-XGS*
    - Case II: *ATHENA* not selected: *N-CAL*
- Single instrument notional missions *as an ensemble* fulfill or make significant progress on all *IXO* science objectives

Table 5.1-4: Primary IXO/Decadal Science Objectives Addressed by Notional Configurations					
Science Question	**IXO Approach**	**AXSIO ($1.5B)**	**Notional Cal ($1.2B)**	**Notional Grating ($0.8B)**	**Notional WFI ($1.0B)**
What happens close to a black hole where strong gravity dominates?	Measure the strong gravity metric via time resolved high resolution spectroscopy of stellar mass and ~30 SMBH at Fe-K and possibly Fe-L	Measure the strong gravity metric via time resolved high resolution spectroscopy of stellar mass and ~20 SMBH at Fe-K and possibly Fe-L [1]	Measure the strong GR metric via time resolved high resolution spectroscopy of stellar mass and ~ 10 SMBH at Fe-K [2]	Measure the strong GR metric via time resolved high resolution spectroscopy of stellar mass and ~ a few SMBH at Fe-L (speculative) [2-3]	Measure the strong GR metric via time resolved low resolution spectroscopy of stellar mass and ~ 10 SMBH at Fe-K [2]
When and how did SMBH grow?	Mergers and accretion impart differing amounts of spin to SMBH. Determine how SMBH grow via measuring the distribution of spin using >300 SMBH within z < 0.2 using orbit-averaged relativistic Fe-K lines	Measure how SMBH grow via determining the distribution of spin using ~60 nearby SMBH using orbit-averaged relativistic Fe-K lines [2]	Measure how SMBH grow via determining the distribution of spin using ~40 nearby SMBH using orbit-averaged relativistic Fe-K lines [2]	Measure how SMBH grow via constraining the distribution of spin using a few nearby SMBH using orbit-averaged relativistic Fe-L lines (speculative) [3]	Measure when SMBH grow via determining the census of AGN out to z~6; measure AGN power spectrum to infer the halo occupation density over a range in z [1-2]
How does large scale structure evolve?	(i.) Find the missing baryons and determining their dynamical properties via absorption line spectroscopy of the WHIM over >30 lines of sight using AGN as illumination sources.	Find the missing baryons and determining their dynamical properties via grating absorption line spectroscopy of the WHIM over >30 lines of sight using AGN as illumination sources. [1]	Find the missing baryons via absorption line spectroscopy of the WHIM over <30 lines of sight using AGN as illumination sources (speculative). [2-3]	Find the missing baryons and determining their dynamical properties via absorption line spectroscopy of the WHIM over >30 lines of sight using AGN as illumination sources. [1]	
	(ii.) Measure the evolution of the cluster mass function using ~500 clusters of galaxies at redshift 1-2	Measure the evolution of the cluster mass function using ~ 150 clusters of galaxies at redshift 1-2 [2]	Measure the evolution of the cluster mass function using 50-100 clusters of galaxies at redshift 1-2 [2]		Measure cluster mass function by detecting 5000 clusters, ~ 1000 at z>1 in surveys (TBD); detection of protoclusters at earliest stages of formation (z~2) [1]
Connection between SMBH and large scale structure ?	Determine the energetics of SMBH outflows via measurements of the velocity structure of hot plasma in ~300 galaxies and clusters; measure the metallicity distribution in galaxies and their halos	Determine the energetics of SMBH outflows via measurements of the velocity structure of hot plasma in ~70 galaxies and clusters; measure the metallicity distribution in galaxies and their halos [2]	Determine the energetics of SMBH outflows via measurements of the velocity structure of hot plasma in ~50 galaxies and clusters; measure the metallicity distribution in galaxies and their halos [2]	Determine the energetics of SMBH outflows in ~ 30 AGN winds via ionization time variability; probe hot galaxy halos via background AGN absorption lines [2]	Measure metallicity distribution in ~ 100 clusters at z> 1; measuring morphology of ~ 100 clusters at z > 1 [2]
How does matter behave at very high density?	Measure the equation of state (mass and radius) of neutron stars via spectroscopy of ~ 30 bright neutron star X-ray binaries.	Measure the equation of state (mass and radius) of neutron stars via spectroscopy of ~ 20 bright neutron star X-ray binaries [1]	Measure the equation of state (mass and radius) of neutron stars via spectroscopy of ~ 20 bright neutron star X-ray binaries [1]	Measure the equation of state (mass and radius) of neutron stars via spectroscopy of rare transient slow-rotator neutron star X-ray binaries [2-3]	Measure the equation of state (mass and radius) of neutron stars via spectroscopy of a few bright neutron star X-ray binaries, using absorption lines in the burst rise and tails (speculative). [3]
	Measure the equation of state (mass and radius) of neutron stars via timing of ~ 30 bright neutron star X-ray binaries.	Measure the equation of state (mass and radius) of neutron stars via timing of ~ 20 bright neutron star X-ray binaries [1]	Measure the equation of state (mass and radius) of neutron stars via timing of ~ 20 bright neutron star X-ray binaries [1]		Measure the equation of state (mass and radius) of neutron stars via timing of a few bright neutron star X-ray binaries during burst rises and tails. [3]

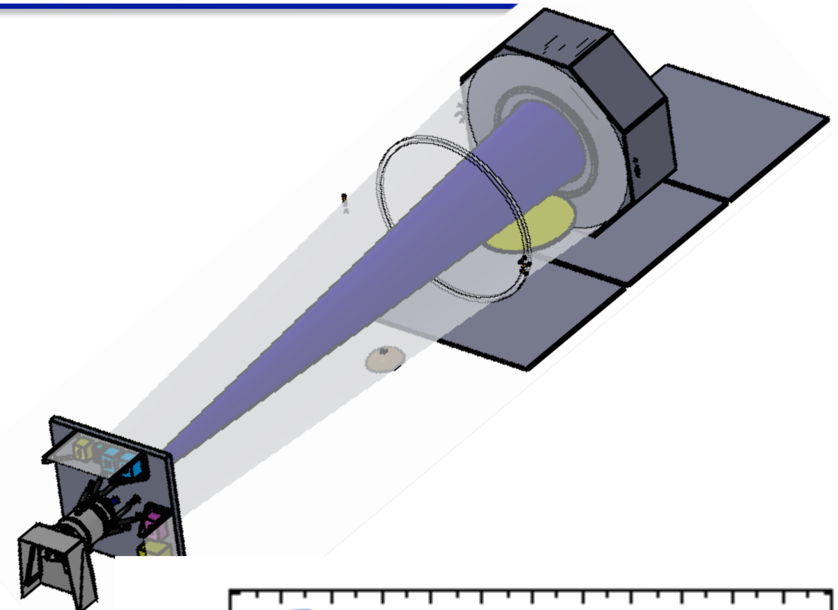
Legend:
[1] Accomplishes IXO science goal fairly well
[2] Accomplishes IXO science goal moderately well
[3] Accomplishes IXO science goal marginally

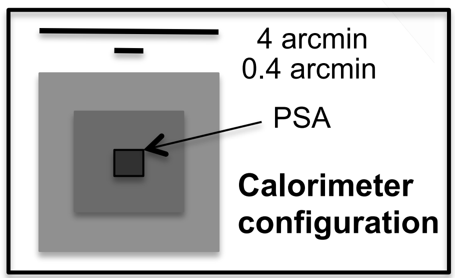
Common assumptions and processes for costing

- **Assumptions:**
  - Three year lifetime
  - L2 orbit
  - All technology is at TRL 6
  - All missions are Class B, with 85 percent probability of success at 3 years
  - Mid-decade start (2017); launch in early 2020's (exact timescale is mission dependent)
  - Total cost is borne by NASA; covers phases A-F, including launch vehicle and GO grants
- **Processes:**
  - All concepts were studied through GSFC's Mission Design Laboratory (MDL)
  - Calorimeter instrument was studied and costed through GSFC's Instrument Design Laboratory (IDL)
  - Same costing methodology: PRICE-H for spacecraft and instruments (when possible); grassroots for science, operations; standard "wraps" for others
  - 30 cost percent reserve applied to all hardware

Notional Calorimeter Mission (*N-CAL*)

- 1.8 m diameter segmented mirror with 9.5 m focal length and 10 arcsec resolution
- 5,000 cm^2 at 1 keV; 2,000 cm^2 at 6 keV
- 4 arcmin field of view calorimeter with central array for timing
- Optical analog would be like going from a 4 m to a 10 m class telescope while replacing a CCD camera with an integral field unit
- Calorimeter concept refined through dedicated GSFC IDL study
- Mission cost estimate: $1.18B





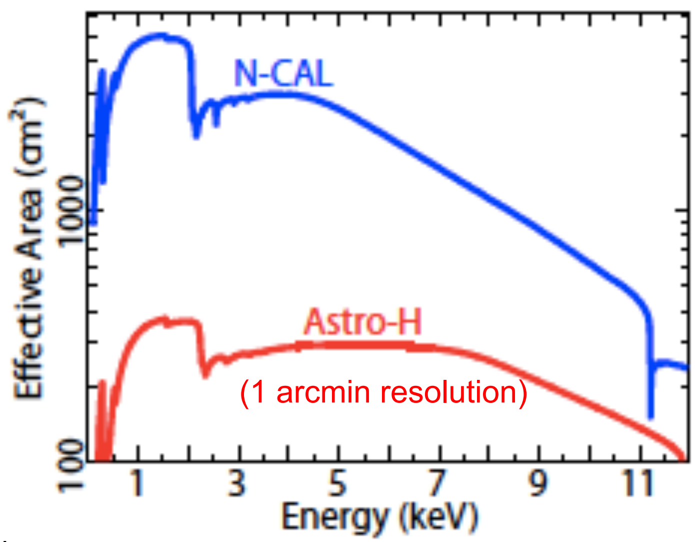
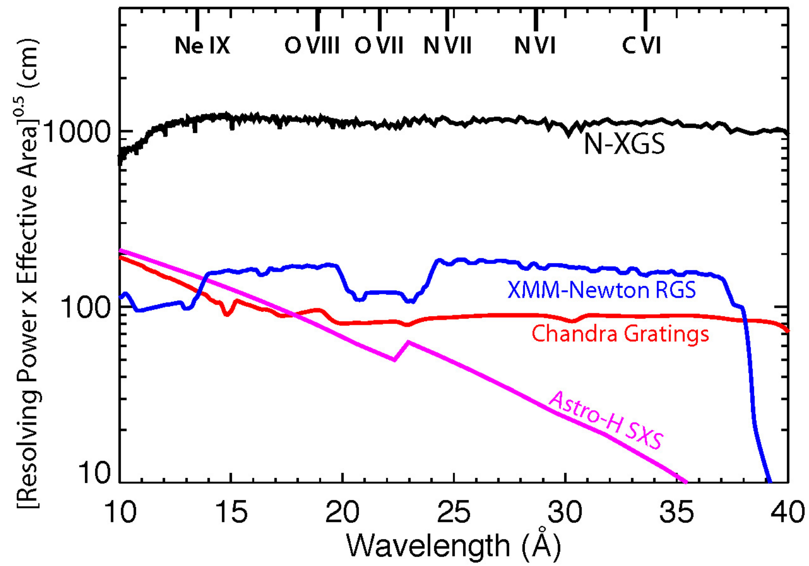


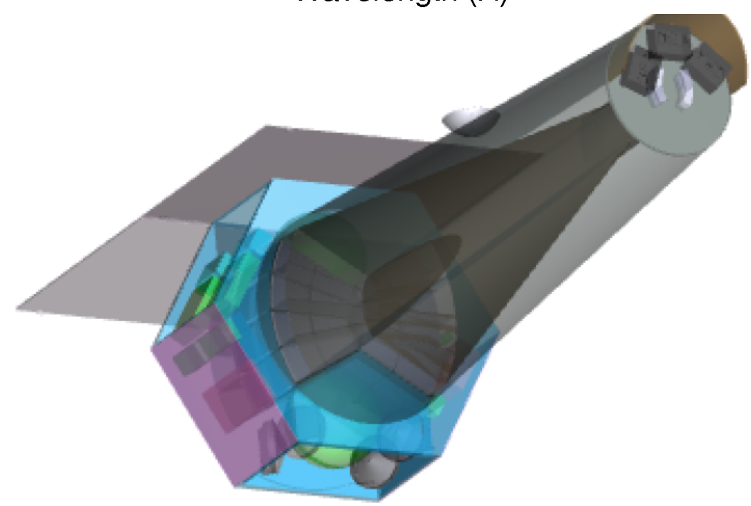
Table 5.4-2. Details of the Calorimeter Array

Array	FOV	# of pixels	Pixel size	resolution	# of TESs
Inner PSA	0.16 $arcmin^2$	256	1.5 × 1.5 arcsec	2 eV	256
Outer #1	5.5 $arcmin^2$	544	6.0 × 6.0 arcsec	3 eV	544
Outer #2	10.3 $arcmin^2$	1040	6.0 × 6.0 arcsec	6 eV	260

Notional Gratings mission (*N-XGS*)

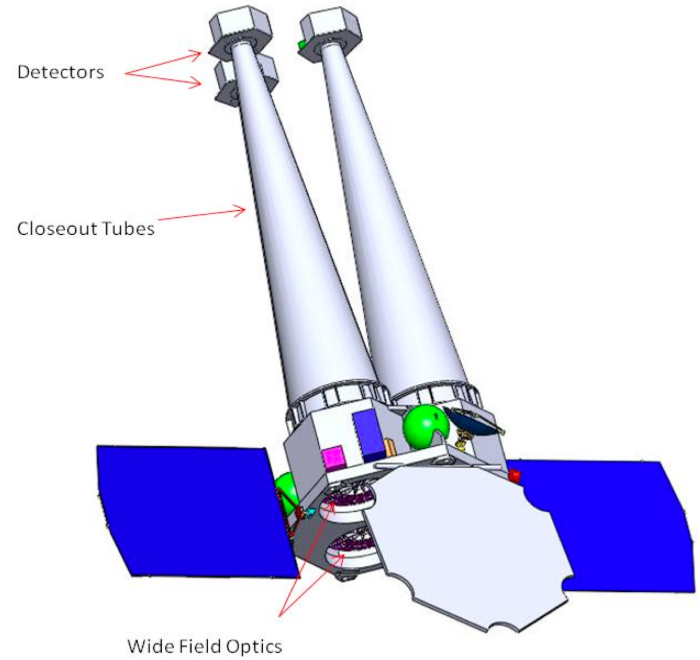
- $\lambda/\Delta\lambda > 3000$ and area > 500 cm^2 across 0.2-1.2 keV band
- At the wavelength of the critical O VII lines (for example) this is 220 times better than the Chandra soft gratings and 80 times better than the *XMM* RGS
- Two independent spectrometers: 30° mirror arc + grating + CCD array
- Design is independent of grating choice (CAT vs. OPG)
- Mission cost estimate: $780M
    - Difference between goal and estimate due in part to use of generic design

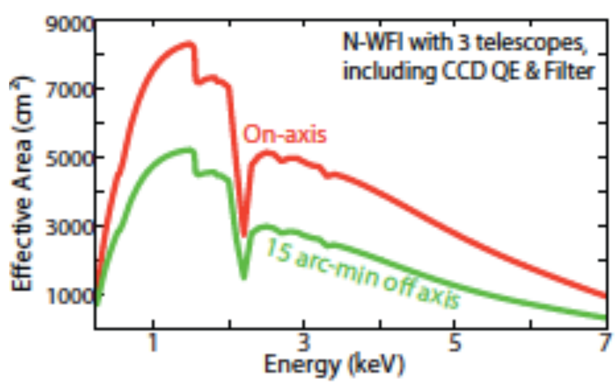


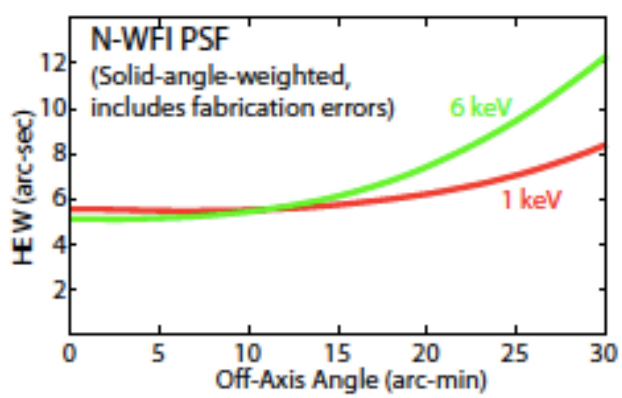


Notional Wide Field Mission (*N-WFI*)

- *N-WFI* is the best of the notional missions for deep surveys
- Three identical telescopes, each with 1 m diameter, 6 m focal length full shell mirror plus CCD detector
- Angular resolution <7 arcsec across >24 arcmin field of of view
- Mission cost estimate: $950M

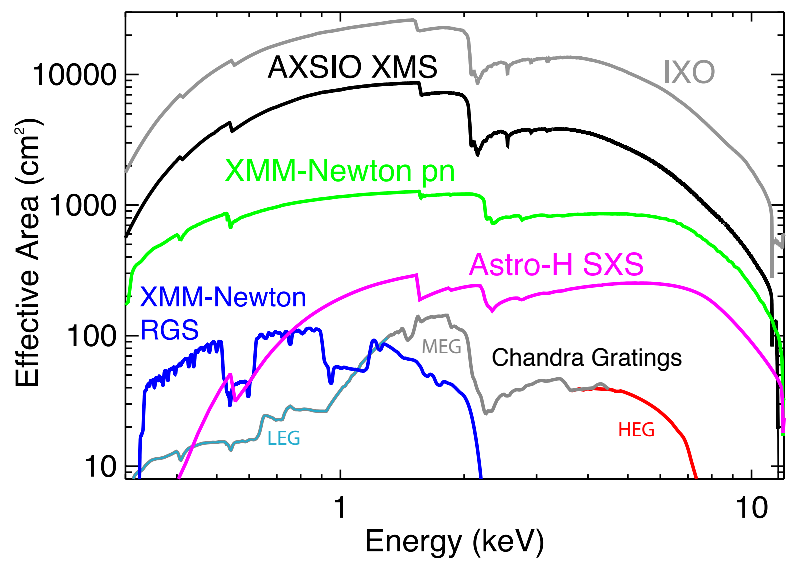






AXSIO

- *AXSIO* serves as the representative "large" mission
  - Designed to meet NWNH recommendations (<$2B)
- Combines *N-CAL* and *N-XGS* but with a larger mirror (2x *N-CAL*)
- Incorporated refined calorimeter concept from *N-CAL*
- When re-evaluated under same guidelines as notional missions, cost estimate is $1.5B
- Optics: 10 m focal length; 0.9m^2 at 1.25 keV; 0.2m^2 at 6 keV; 10" resolution (5" goal)
- Calorimeter: 4' field of view array with < 3 eV resolution (same as *N-CAL*)
- Grating: $\lambda/\Delta\lambda$ >3000; ~1000 cm^2 (0.3-1.0 keV)



Notional mission comments

- **Concepts show that *IXO* objectives can be largely achieved at a cost of < $2B, and a significant share for ≤ $1B**
  - These costs assume that all technology has attained TRL-6 before mission start
- These mission concepts should be viewed as truly “notional,” not as missions proposed for implementation
- Concepts are sufficiently promising so that further study of some or all is warranted to refine design and cost
  - More detailed study should include independent cost estimates

Notional mission costs

- Design, and thus costs, of notional missions have *not* been optimized
  - These are "point" designs, based on a ~1 week concurrent engineering effort
- Considerable cost savings to NASA are possible
  - Optimization could produce considerable cost reductions
  - Total cost to NASA could be reduced through strategic partnerships
    - e.g., cooler from Japan
  - Descopes could reduce cost without losing science objectives
    - Reduce N-CAL mirror outer diameter – keeps Fe line science and imaging spectroscopy at the cost of low energy effective area

Enabling Technology

- The study team used RFI responses on enabling technology to understand technology needs for notional missions and beyond
- Notional mission cost estimation assumed TRL 6; instruments and mirrors are currently at TRL 3-4
- Report identifies key instrumentation needs for each notional mission and provides a minimum cost for bringing to TRL 6
- In addition, the report identifies long term technology needs for missions beyond the current suite (e.g., high resolution optics and large format calorimeters)

Technology cost estimate for notional missions

Table 6.7-1. Notional Mission Estimated Technology Development Costs

Technology	Current Performance	Goal	Applicable Missions	Cost per year (M$)	# years	Total cost (M$)	Ref
Calorimeters	16 pixels, TRL4	1840 pixels, TRL6	*AXSIO*, *N-CAL*	3.3	6	20	Kilbourne
Slumped glass optics	8.5", TRL4	10", TRL6	*AXSIO*, *N-CAL*, *N-XGS*	3	3	9	Zhang, CST
Wide field optics	17", TRL4	7", TRL6	*N-WFI*	4	4	16	CST
CAT gratings	TRL3	TRL6	*AXSIO*, *N-XGS*	2.7	3	8	CST/IXO Tech. Dev. Plan
OPG gratings	TRL3	TRL6	*AXSIO*, *N-XGS*	1	3	3	McEntaffer
X-ray CCDs for *N-WFI*	1k × 1k, TRL9	2k × 2k	*N-WFI*	1	2	2	CST
X-ray CCDs for *N-XGS*	0.3 Hz frame rate	15 Hz frame rate	*N-WFI*, *AXSIO*	1.5	2	3	CST
Total				15.5		57	

- Estimates are from RFI responses:
  - Assume single development, not parallel
  - Are optimistic
- Investment areas can be selected to match desired mission's needs
- Realistic estimate falls between total here and $200M in *NWNH*

Next Steps

- A Technology Development Plan for the critical technology for the notional missions (mirrors, calorimeters, gratings, …) will be developed over the next few months
  - Refine timescale, cost to bring needed technology to TRL 6
  - Used by NASA to identify technology supported through SAT
- A follow up study will be performed to maximize the science return for a $1B class mission concept
- Goal is to provide input needed by NASA for its mid-decade implementation plan