THE NASA X-RAY MISSION CONCEPTS STUDY

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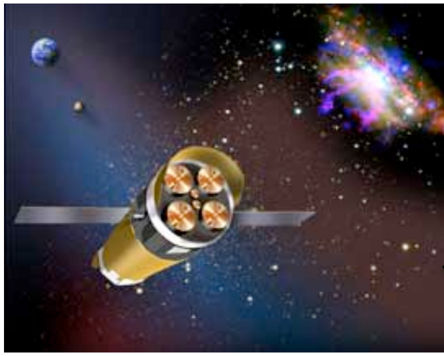
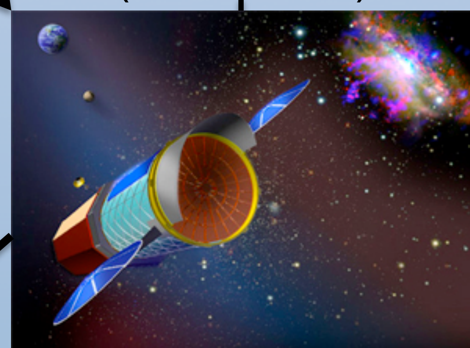
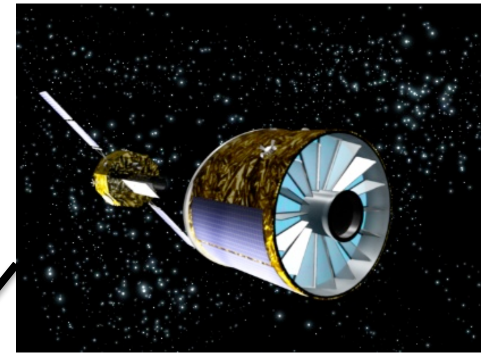
The road to the next strategic X-ray observatory



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)***

*** Purview of the CAA and NASA HQ**

NASA

ATHENA??

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 PCOS Program Office to identify more cost effective ways to perform *IXO* and *LISA* science

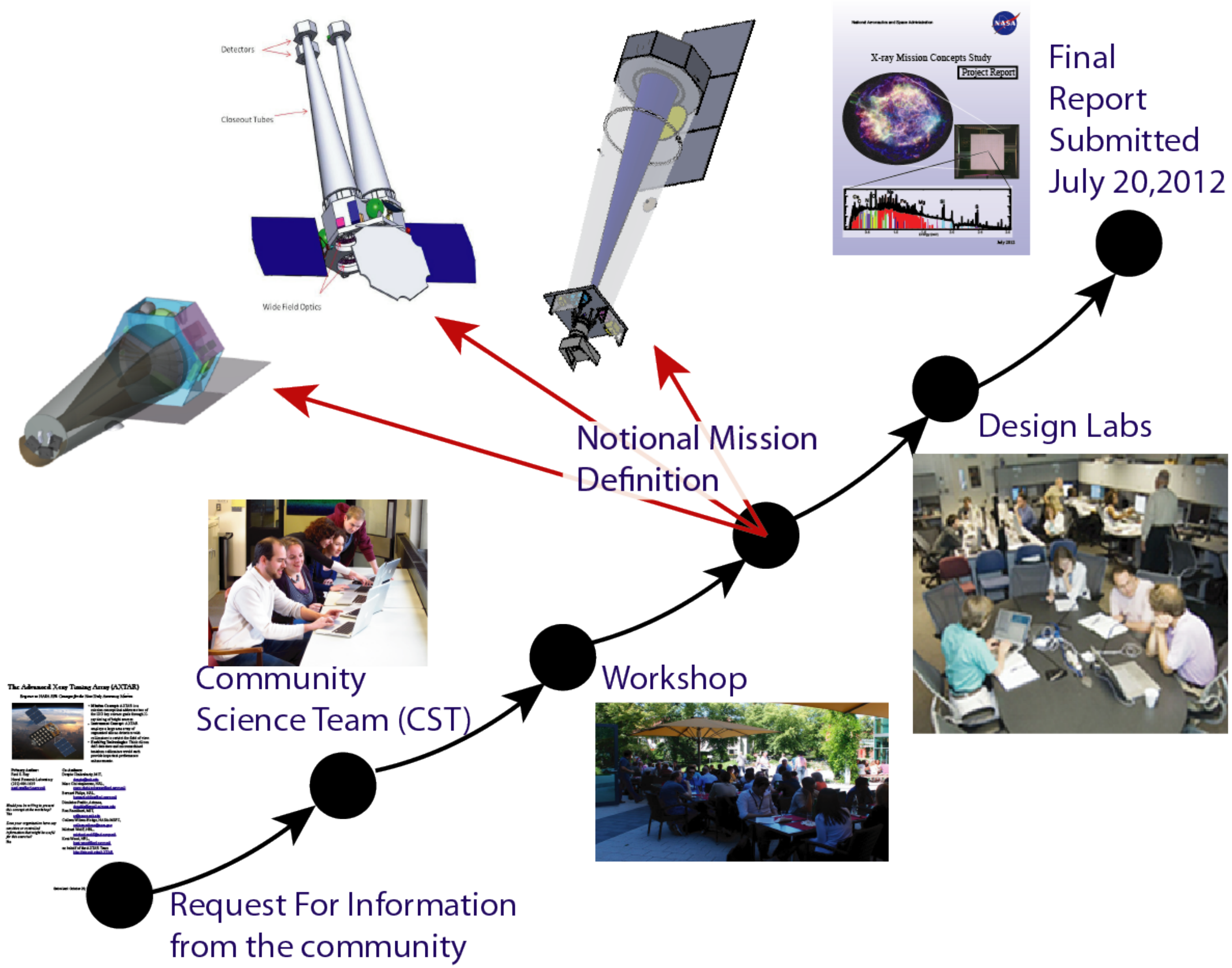
NASA X-ray Concepts Study

- **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
  - In the aggregate, the notional missions should probe various points of the science return vs. mission cost trade space.
  - 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

By **developing technology first** to **minimize risk** and **reduce mission complexity** (relative to *IXO*), a mission that captures most of the fundamental *IXO* science at a fraction of the *IXO* cost can be developed.

The notional missions that were studied cost less than the current X-ray flagship missions (*Chandra, XMM*) yet will greatly outperform them 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
  - *N-CAL* – calorimeter mission
  - *N-WFI* – wide field imaging survey mission
- Determined which notional missions would have highest science yield in anticipation of possible Cosmic Visions 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 studied through GSFC's Mission Design Laboratory (MDL)
  - 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 (same as *AXSIO*)
- 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 instrument concept refined through dedicated GSFC IDL study
- Mission cost estimate: $1.18B

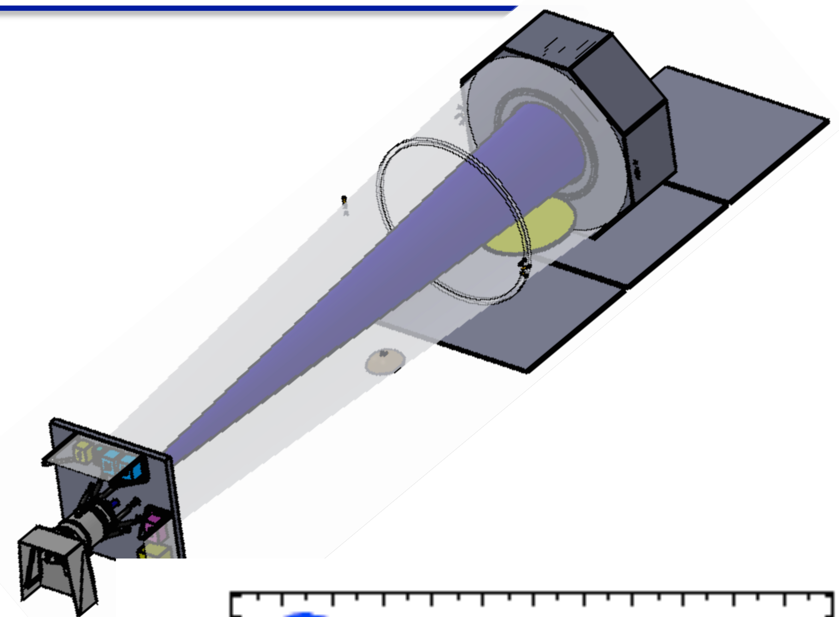
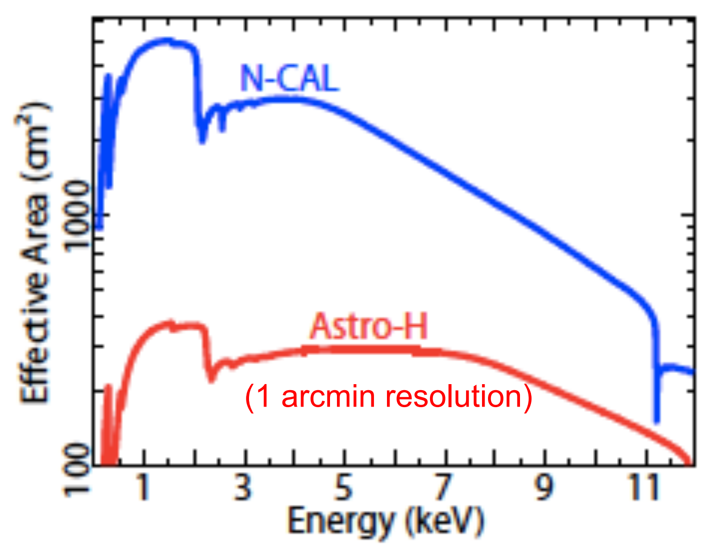


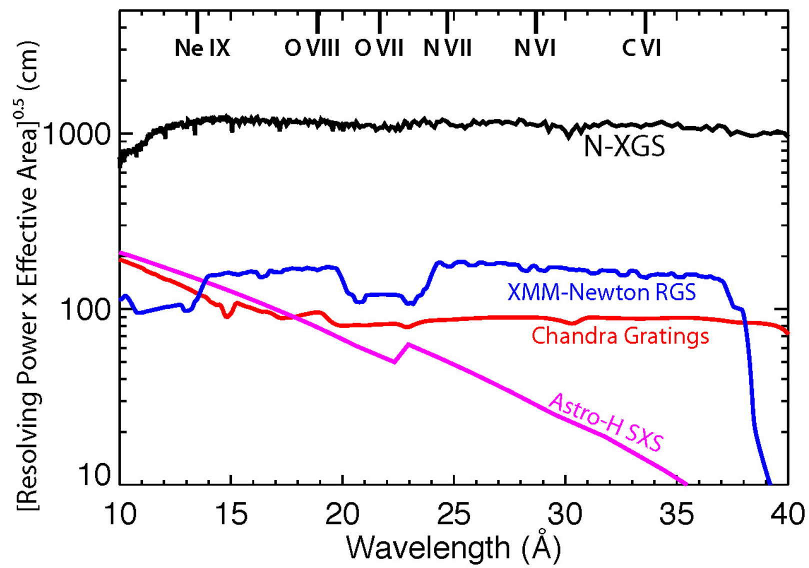
Table 5.4-2. Details of the Calorimeter Array

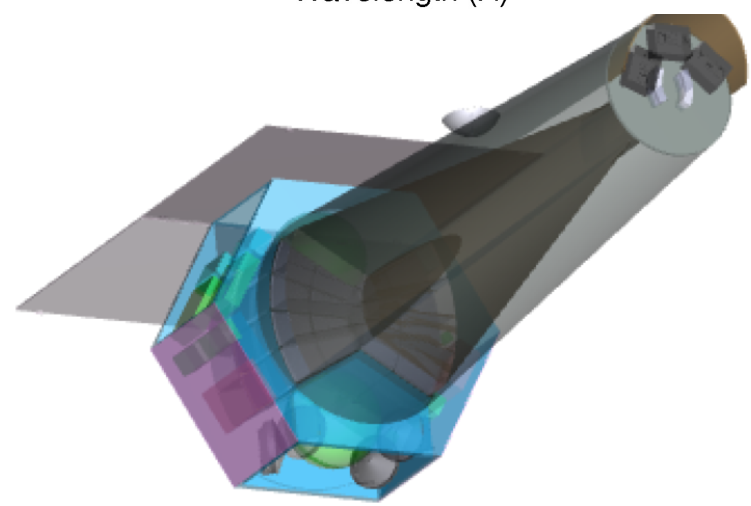
Array	FOV	# of pixels	Pixel size	resolution	# of TESs
Inner PSA	0.16 arcmin²	256	1.5 × 1.5 arcsec	2 eV	256
Outer #1	5.5 arcmin²	544	6.0 × 6.0 arcsec	3 eV	544
Outer #2	10.3 arcmin²	1040	6.0 × 6.0 arcsec	6 eV	260



Notional Gratings mission (*N-XGS*)

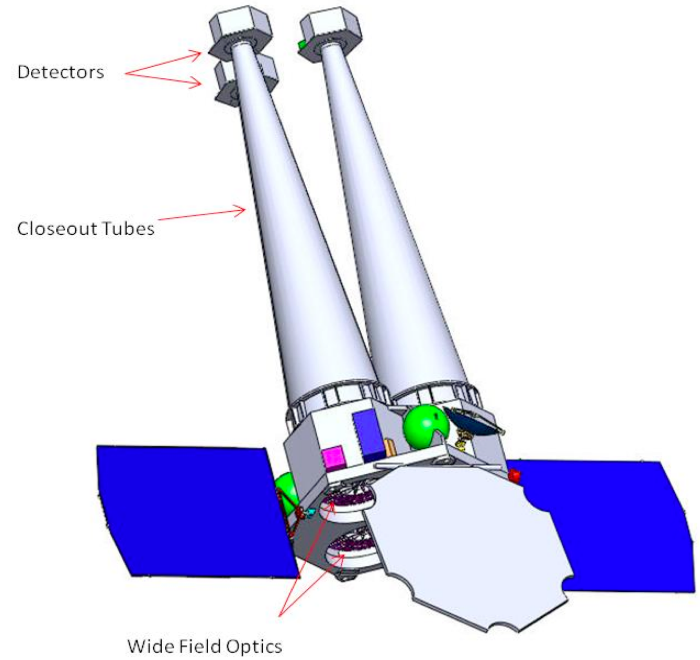
- $\lambda/\Delta\lambda > 3000$ and area > 500 cm^2 across 0.2-1.2 keV band
- At the wavelength of the critical O VII lines (for example) this is 220 times better than the Chandra soft gratings and 80 times better than the *XMM* RGS
- Two independent spectrometers: 30° mirror arc + grating + CCD array
- 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

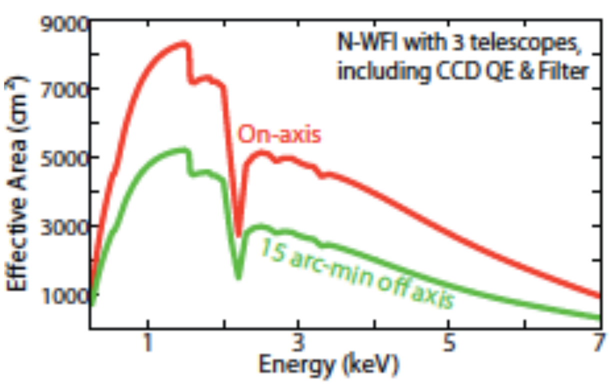


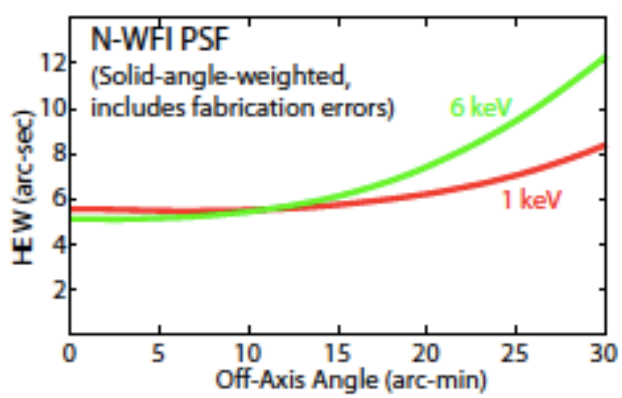


Notional Wide Field Mission (*N-WFI*)

- *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

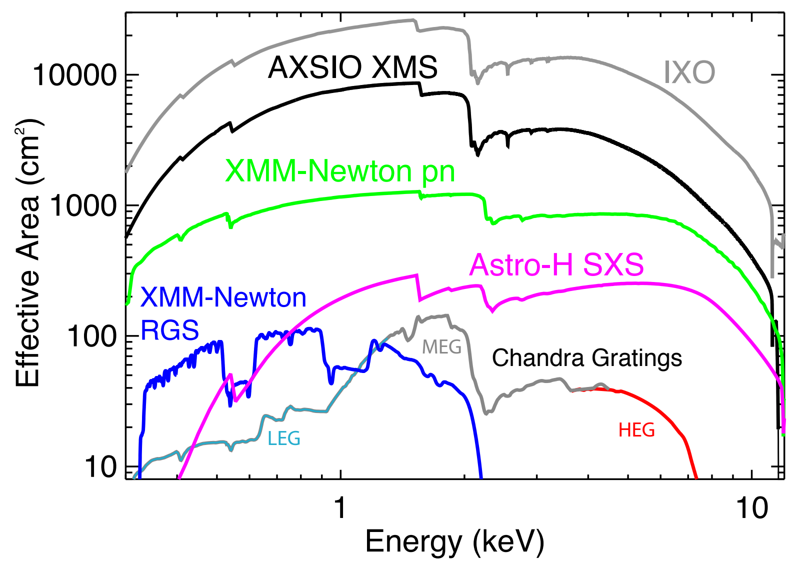






AXSIO

- *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; $0.9 m^2$ at 1.25 keV; $0.2 m^2$ at 6 keV: 10" resolution (5" goal)
- Calorimeter: 40X40 array with < 3 eV resolution (same as *N-CAL*)
- Grating: $\lambda/\Delta\lambda$ >3000; ~1000 cm^2 (0.3-1.0 keV)



Comments/Caveats about notional missions

- These mission concepts should be viewed as truly "notional," not as missions proposed for implementation
  - Concepts show that *IXO* objectives can be largely achieved at a cost of < $2B, and a significant share for ≤ $1B
- These are "point" designs, based on a ~1 week concurrent engineering effort
  - Design, and thus costs, have *not* been optimized
  - Considerable cost savings possible through optimization
- Assumed that full mission cost would be paid by NASA
  - Total cost to NASA could be reduced through strategic partnerships

Enabling Technology

- 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
- Key instrumentation needs for each notional mission are identified, and a minimum cost for bringing to TRL 6 is provided
- In addition, report identifies long term technology needs for missions beyond current suite (e.g., high resolution optics and large format calorimeters)

Technology cost estimate

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 highly 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
- 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