BEYOND EINSTEIN: From the Big Bang to Black Holes

Constellation-X

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BEPAC Presentation
Newport Beach: January 30, 2007

Unlocking the mysteries of Black Holes, Dark Matter and Dark Energy

The Constellation X-ray Observatory

- **Introduction of Our Team Members:**
  - Jean Grady – Project Manager
  - Nick White – Project Scientist
  - Rob Petre – Deputy Project Scientist
  - Ann Hornschemeier – Deputy Project Scientist
  - Rich Kelley – Instrument Scientist
  - Gabe Karpati – Mission Systems Engineer
  - Jean Cottam – Instrument Scientist
  - Richard Mushotzky – Science
  - Harvey Tananbaum – Facility Science Team Chair
  - Jay Bookbinder – Mission Scientist
  - Bob Rasche – SAO Project Manager

Agenda

Ann Hornschemeier – Science	**Q1, 4, 6**	**15 min**
Jay Bookbinder – Mission Approach and Instrumentation	**Q19, 23, 2, 5, 7, 12, 16, 13, 8, 35, 36, 37**	**20 min**
Jean Grady – Observatory and Spacecraft, Schedule, Cost, and Risk	**Q21,31, 20, 23, 25, 29, 26, 27, 28, 30, 32, 33, 39, 22**	**20 min**
Harvey Tananbaum – Science Risks, Trades, Descopes, Data Analysis	**Q10, 3, 9, 24, 14**	**5 min**
Nick White – Scientific Reach	**Q18**	**5 min**
Questions covered in written response, but not addressed here	**Q11, 15, 17, 34, 38**	

Ann Hornschemeier – Science	**Q1, 4, 6**	**15 min**
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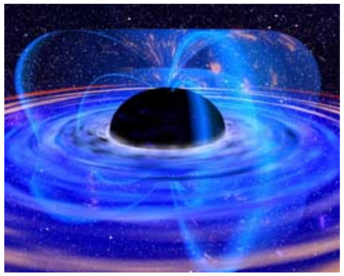
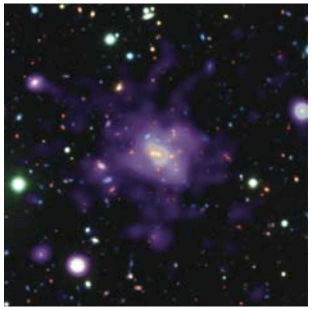
Driving Science Objectives

Black Holes



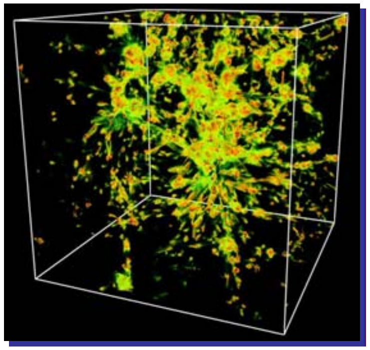
- Use black holes to test General Relativity and measure black hole spin

Dark Energy (and Dark Matter)



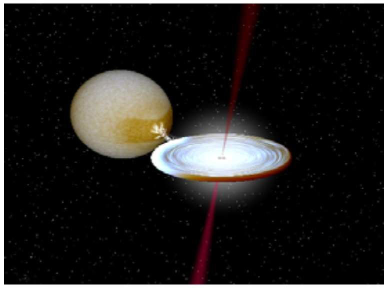
- Use Galaxy Clusters to provide factor of ten improvement in key Dark Energy (DE) parameters

Missing Baryons



- Unambiguous detection of the hot phase of the Warm-Hot Intergalactic Medium (WHIM) at z>0

Neutron Star Equation of State



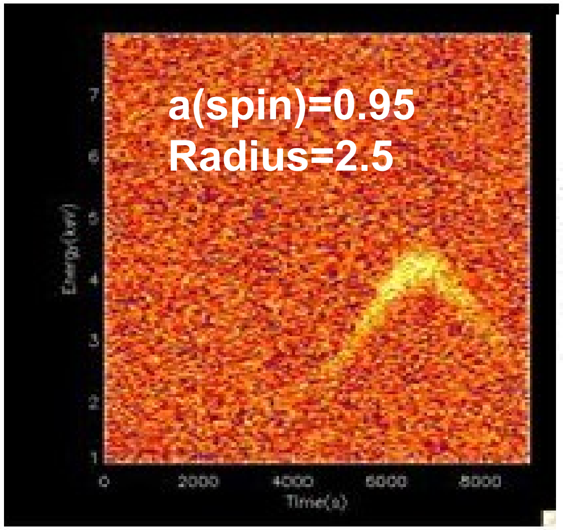
- Measuring the mass-radius relation of neutron stars to determine the Equation of State (EOS) of ultra-dense matter

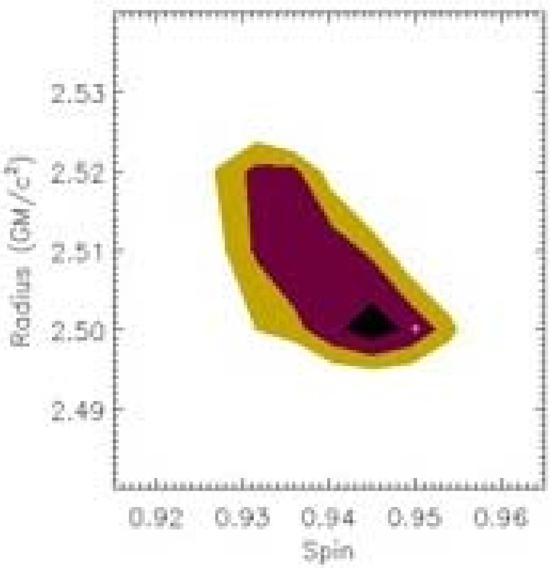
Q1, 4, Q6

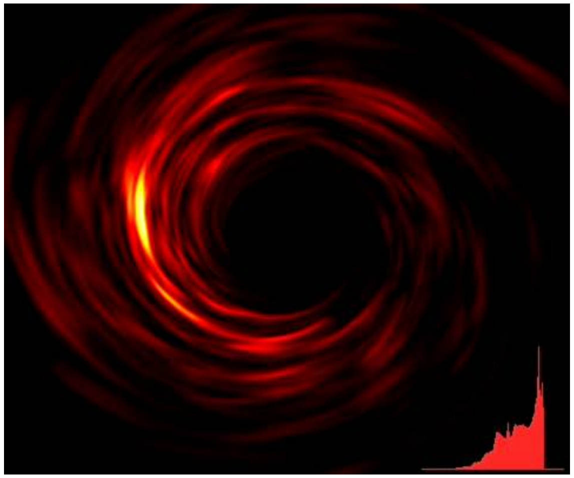
Black Holes:

Use black holes to test General Relativity (GR) and measure black hole spin

- **Con-X will probe close to the event horizon with 100× better sensitivity to:**
  - **Follow dynamics of individual “hot spots” to determine spin as function of radius in disk.**
  - **Spin measurements vs radius provide a powerful consistency check of GR in the strong gravity regime.**



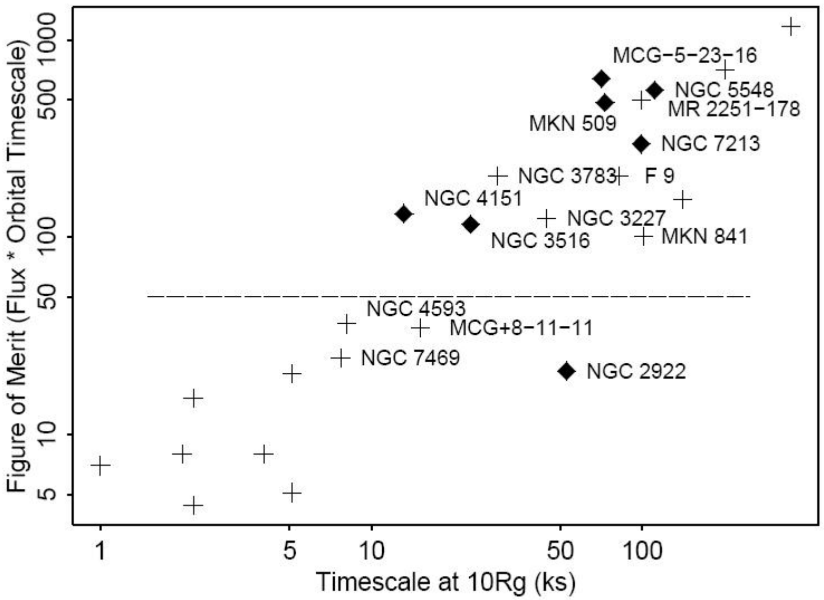




Detectability depends on X-ray flux, line intensity, and orbital timescale

Key to GR tests with hot spots: large collecting area and good spectral resolving power

Black Holes: *Measurements*



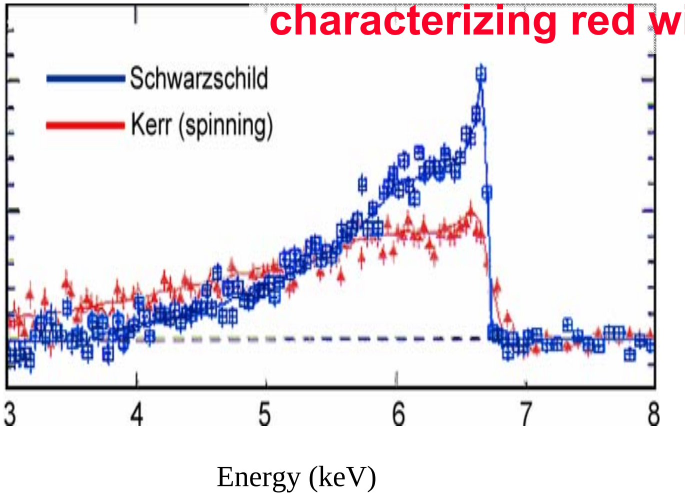
ASCA X-ray sample of AGN

Time-variable Fe K measurements

- For 6000 cm^2 at 6 keV, ~10 targets meet required Figure of Merit > 50

Detailed characterization of broad FeK line to measure spin for several hundred AGN over a range of luminosity and redshift

Key to spin measurement, characterizing red wing

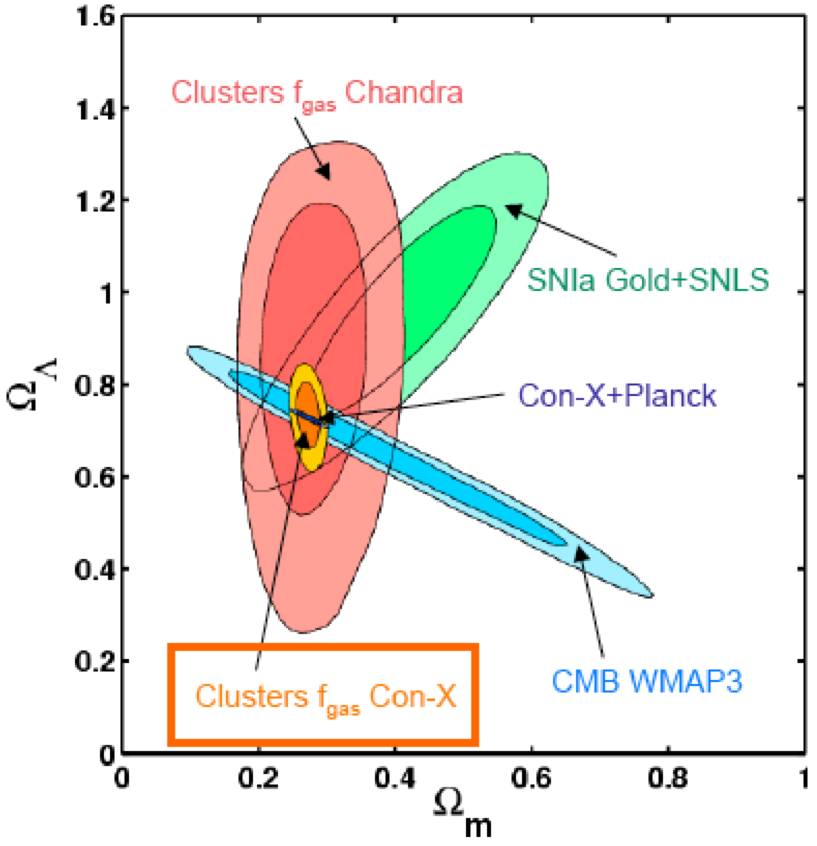


Continuum Is Key For Spin Measurements:

- Require 150 cm^2 at 10-40 keV
- Spectral resolving power R=2400 required to resolve warm absorber (permits continuum to be measured)

Dark Energy:

Improving the constraints on the key Dark Energy (DE) parameters by a factor of ten



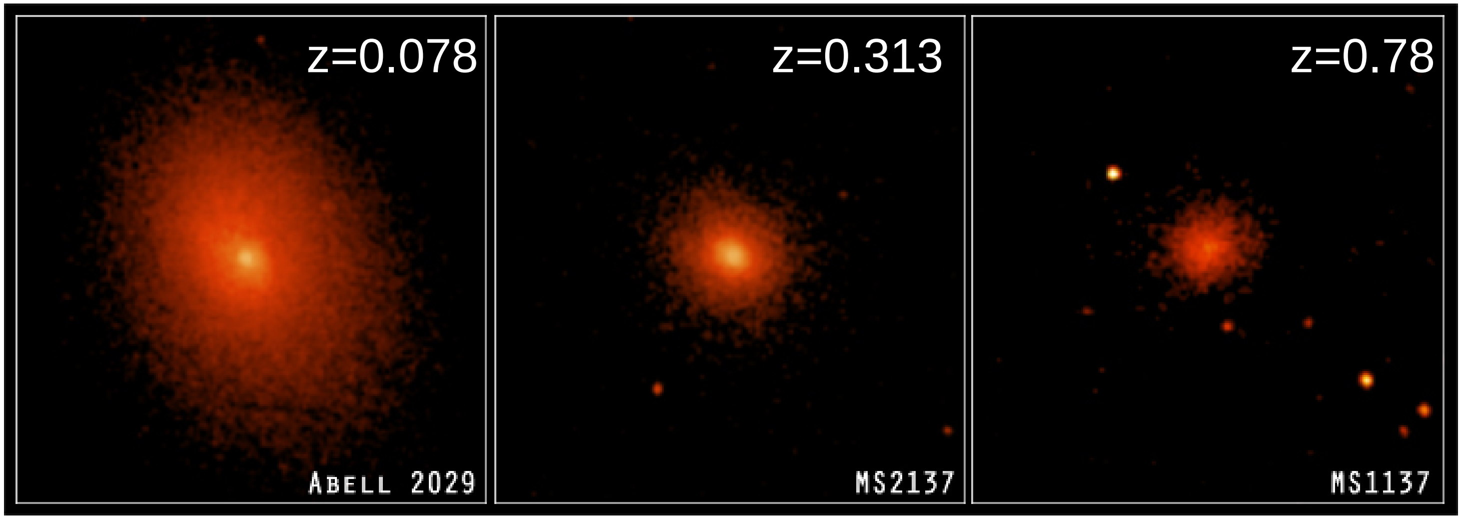
- **Largest gravitationally bound structures in the Universe, most of the normal, baryonic matter lies in the hot X-ray emitting gas (10^6 - 10^8 K)**
- **Measurement #1 (Geometric):**
  Use clusters to measure distance based on gas mass fraction.
- **Measurement #2 (Growth of structure):**
  Use clusters as probe of density perturbation growth in the Universe via cluster mass function vs *z* measurement *(samples from X-ray & submillimeter surveys)*

Con-X will provide DE parameter constraints competitive with and complementary to other methods

Dark Energy:

Two measurements, identical performance requirements

Chandra relaxed cluster images



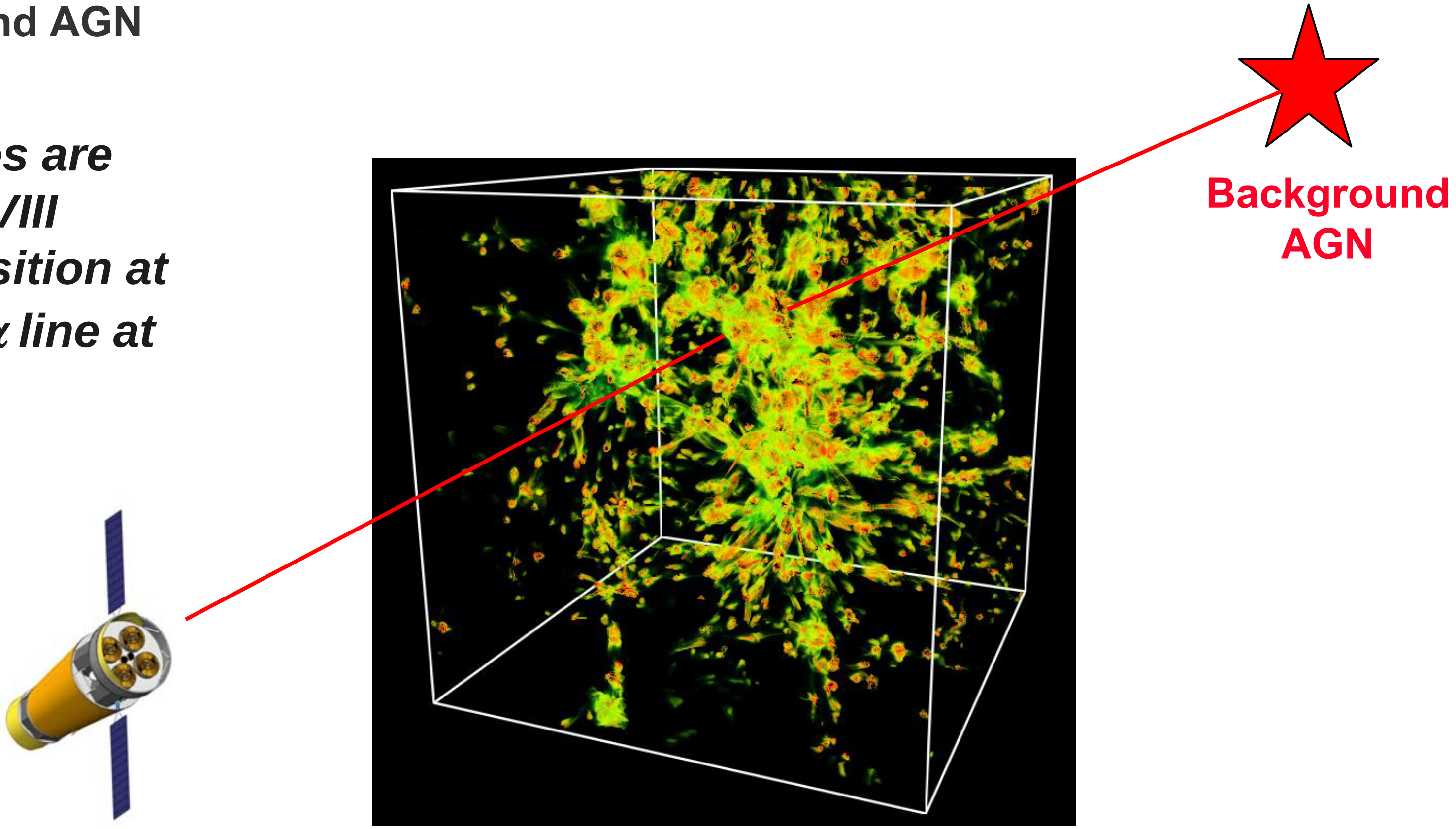
- **High collecting area enables large, efficient snapshot survey (~1000 targets) followed by deeper spectroscopic observations of relaxed clusters**
- **FOV of 5' x 5' needed for measuring surface brightness profiles of these spatially-extended targets**
- **R~2400 at 6 keV required in cluster centers to resolve e.g., turbulence from non-gravitational heating, moderate spectral resolution over rest of FOV enables density/temperature diagnostics**

Missing Baryons:

Unambiguous detection of the hot phase of the Warm-Hot Intergalactic Medium (WHIM) at z>0

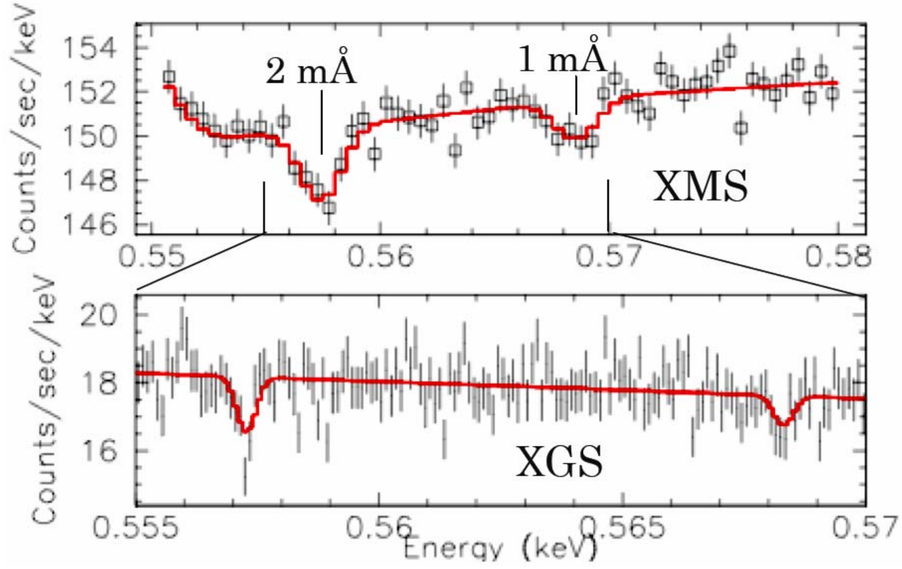
- ~ 60% of the baryonic matter at $z < 2$ is largely undetected.
- Theoretical simulations agree that it resides in filaments of hot (10^5 -$10^{7.5}$ K) gas
- Filaments of this “cosmic web” may be observed in absorption against bright background AGN

Key features are OVII and OVIII (1s-2p transition at 574 eV, Lyα line at 654 eV)



Missing Baryons:

Measuring absorption lines against background AGN

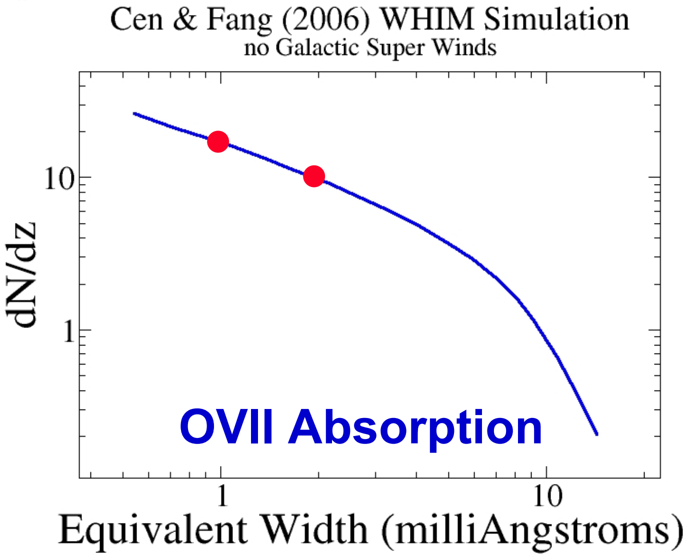


- **Sensitivity for WHIM measurements can be characterized in terms of equivalent width of relevant absorption features**
- **Benchmark measurement: 30 brightest AGN in ROSAT survey (typical redshifts z~0.2-0.3)**

1.0 mÅ filament at z=0.01

2.0 mÅ filament at z=0.03

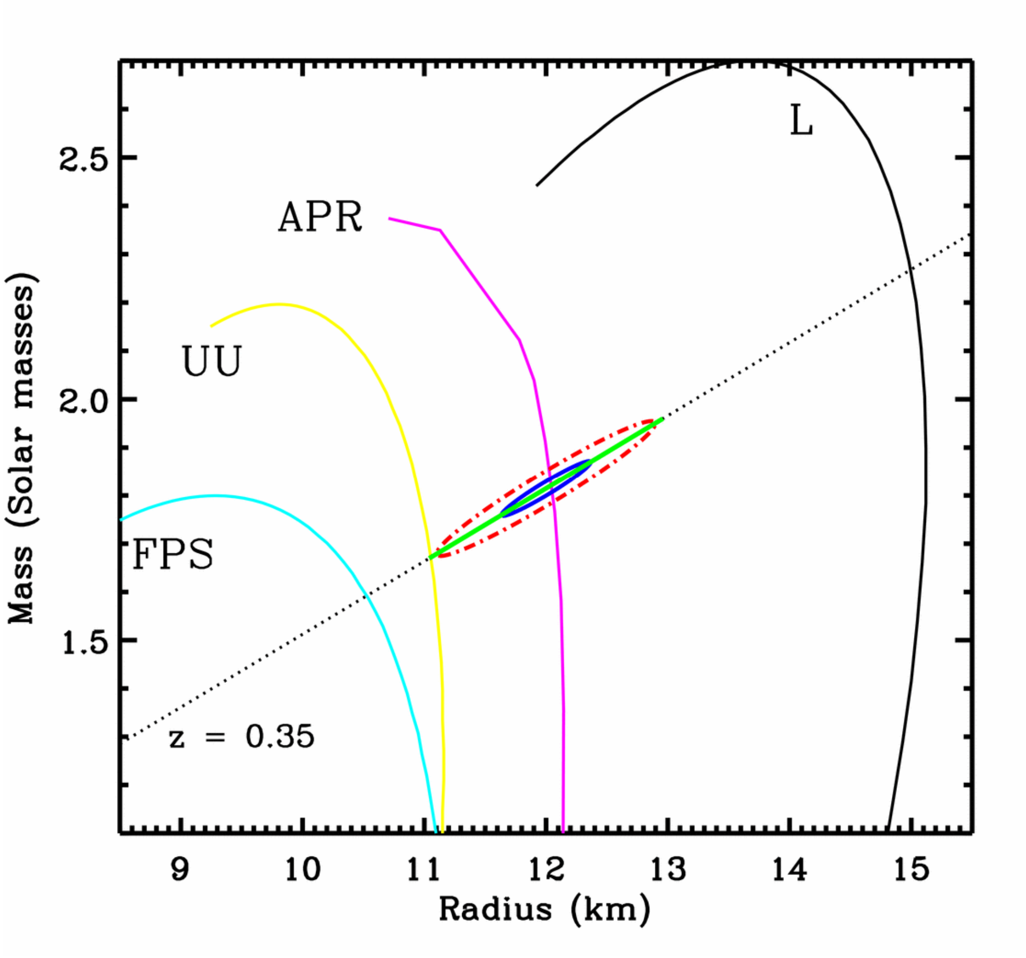
Predicted filament properties as a function of z



- **For Δz = 0.3, to obtain dN/dz~10, need 1 mÅ sensitivity**
- **Independent measurements with the XMS and XGS confirm detection.**

Neutron Stars:

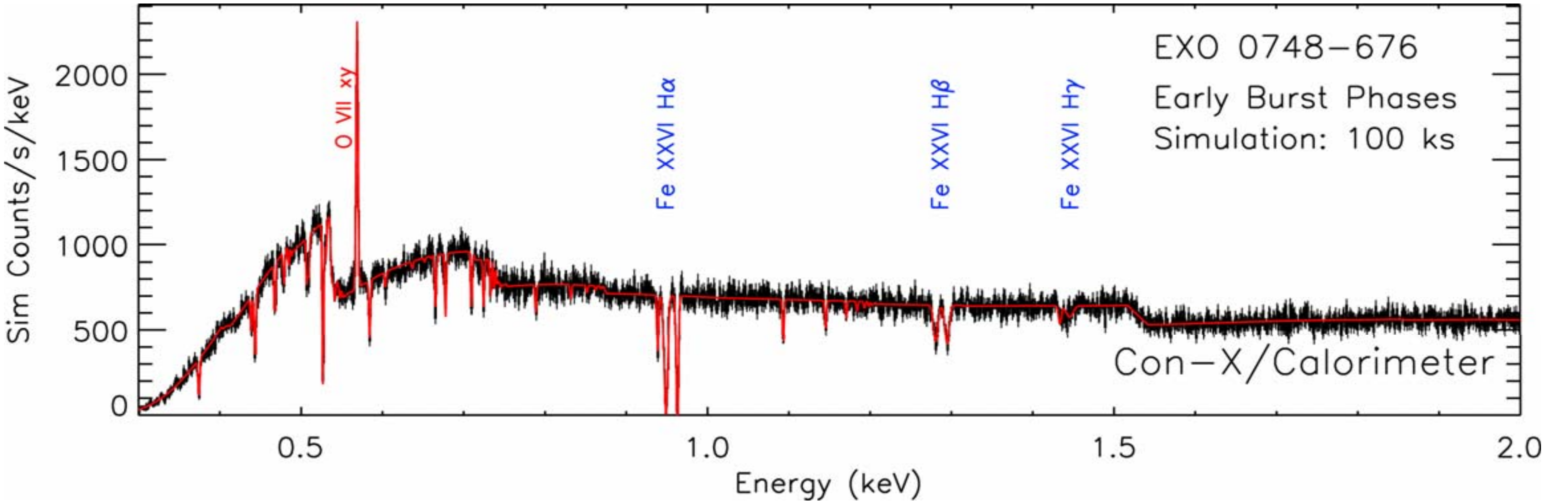
Measuring the mass-radius relation of neutron stars to determine the Equation of State (EOS) of ultra-dense matter



- **Neutron stars contain the densest states of matter in the universe.**
- **The nuclear physics that governs the interactions between constituent particles predicts mass/radius relations.**
- **X-ray bursts from LMXBs provide ideal conditions for measuring the Equation of State for neutron stars.**
- **Con-X will provide high S/N atmospheric absorption spectra, and measure burst oscillations for a large sample of neutron stars.**

Neutron Star EOS:

Two measurement techniques:
atmospheric absorption and burst oscillations



Measurement #1 – Absorption spectroscopy:

- **Absorption spectra provide a direct measure of gravitational redshift at surface of the star ($z \propto M/R$).**
- **The measured widths of the lines constrains the NS radius to 5-10% (compare to best present constraints: 9.5-15 km for EXO 0748-676)**

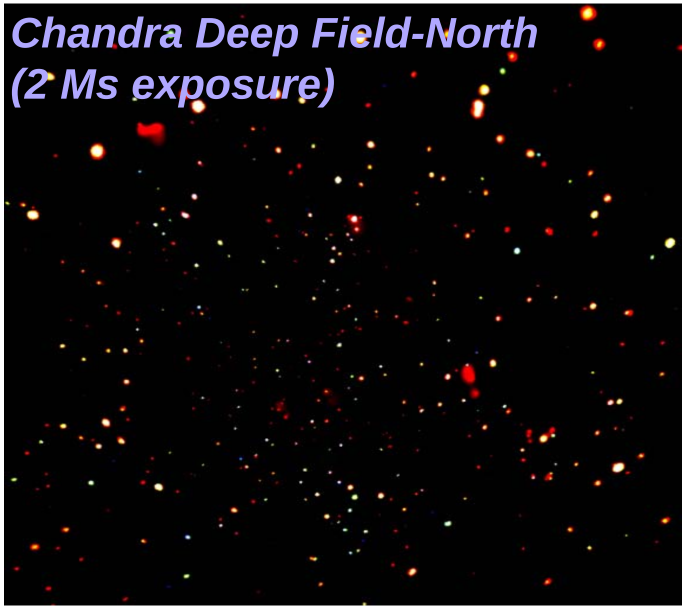
Measurement #2 – Burst oscillations:

- **Pulse shapes of burst oscillations can provide an independent measure of the mass and radius to a few percent. Requires 100 microsec timing and ability to handle count rates up to 0.25 Crab.**

Hydra-A Wise et al 2006

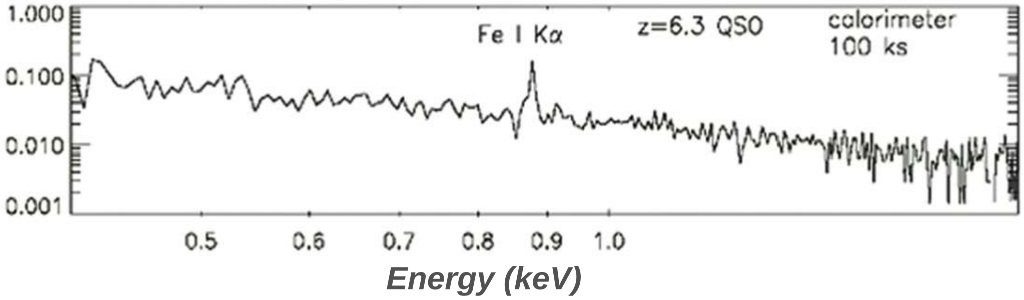
Beyond the 4 Driving Objectives…

Evolution Of Black Holes

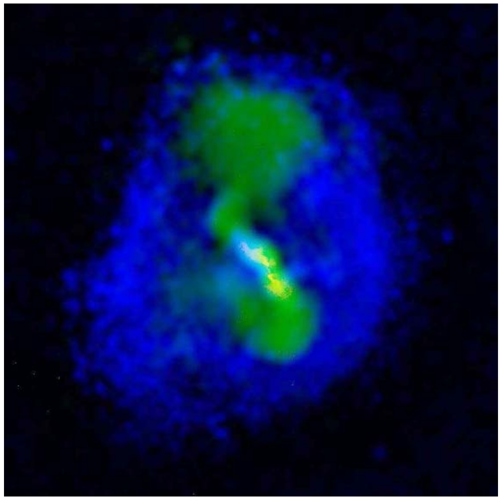


Chandra Deep Field-North (2 Ms exposure)

As follow-on to Chandra X-ray Observatory, Con-X will gather high-resolution X-ray spectra of the elusive optically faint X-ray sources



Cosmic Feedback



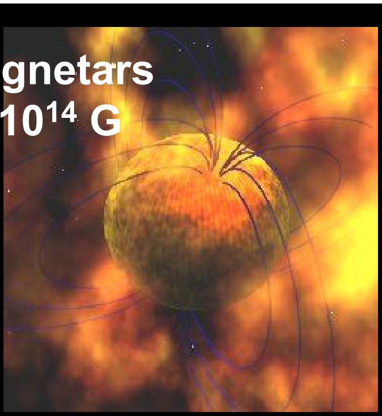
Wise et al. 2006
Hydra A

Large scale-structure simulations require AGN feedback (via jets and/or winds) to regulate the growth of galaxies

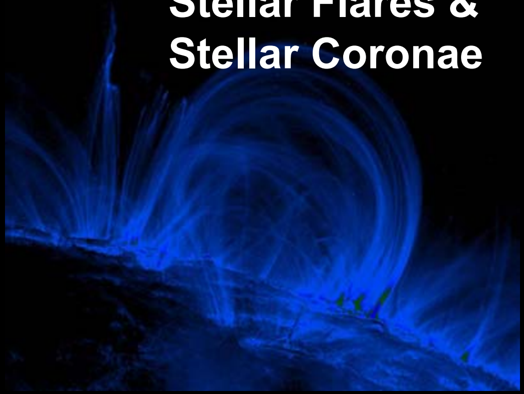
- ***Spatially resolved X-ray spectroscopy required to probe turbulence in cluster cores showing radio bubbles (jets)***
- ***High spectral resolving power required to determine mass outflows in quasars with winds***

Observatory Science

- Con-X enables a large range of science
- A broad scientific community will utilize this facility

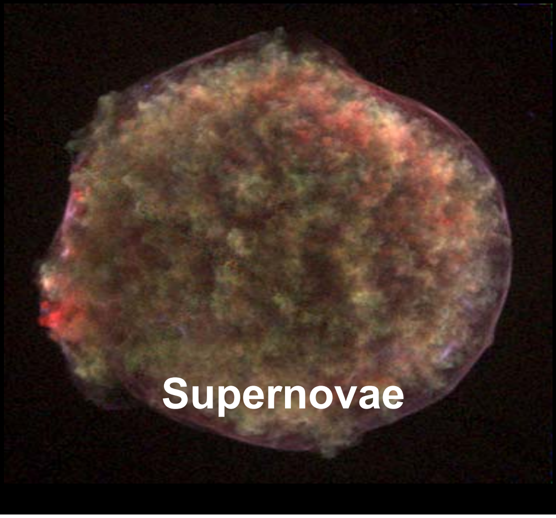


Magnetars
B~10^{14} G



Stellar Flares &
Stellar Coronae

Galactic
Superwinds



Supernovae

AGN jets:
Cosmic Accelerators

Comets

Science Objectives Flow Into Key Performance Requirements

Effective Area:	**15,000 cm^2 @1.25 keV** **6,000 cm^2 @6 keV** **150 cm^2 @40 keV**
Bandpass:	**0.3 – 40 keV**
Spectral Resolution:	**1250 @0.3 – 1 keV** **2400 @6 keV**
Angular Resolution	**15 arcsec 0.3 – 7 keV** **30 arcsec 7.0 – 40 keV**
Field of View	**5 x 5 arcmin**

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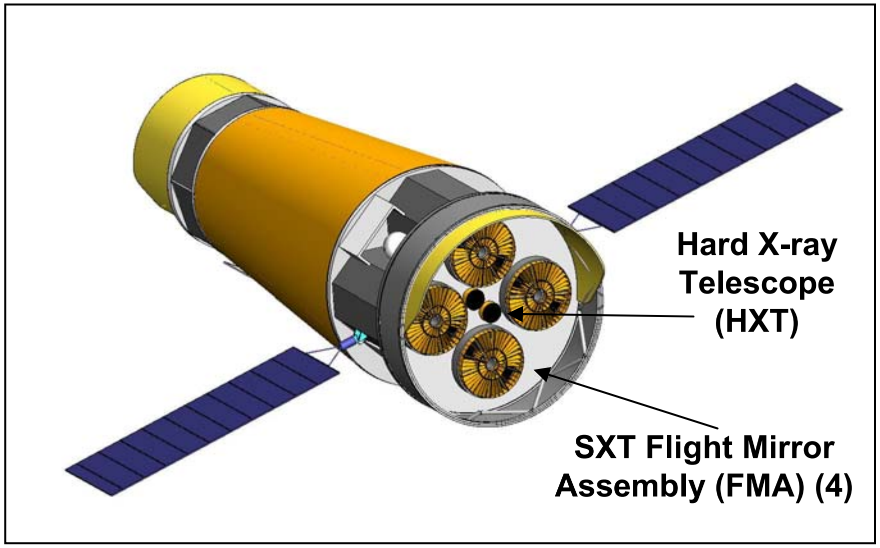
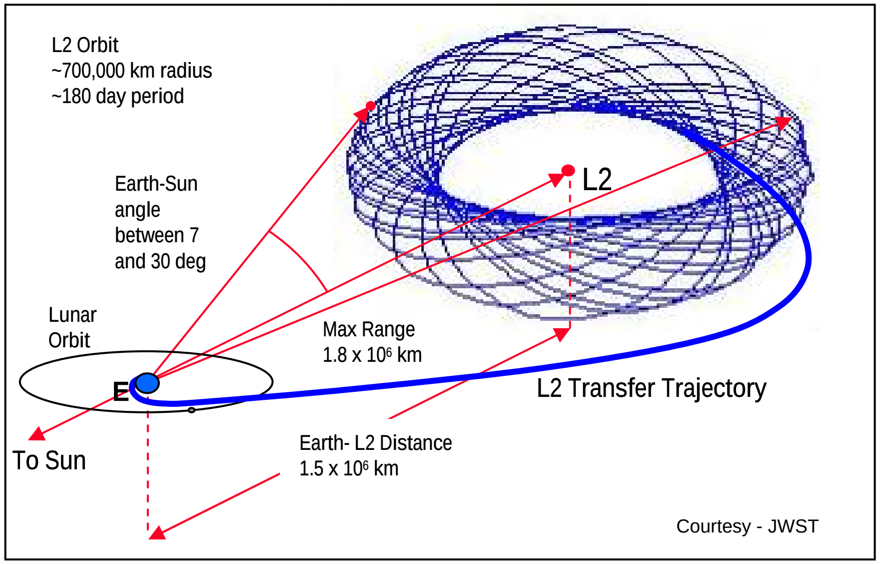
Mission Approach

- High throughput achieved with
  4 telescope systems on a single satellite
  - Complemented by low and high energy instruments
- L2 Orbit; 700,000 km radius halo orbit
  - High operational efficiency
  - Uninterrupted viewing
  - Stable temperature
- Field of regard allows full sky coverage every 180 days
  - Pitch: +/- 20° off Sunline
  - Yaw: +/- 180°
  - Roll: +/- 20° off Sunline
- 5 year life; 10 years on consumables



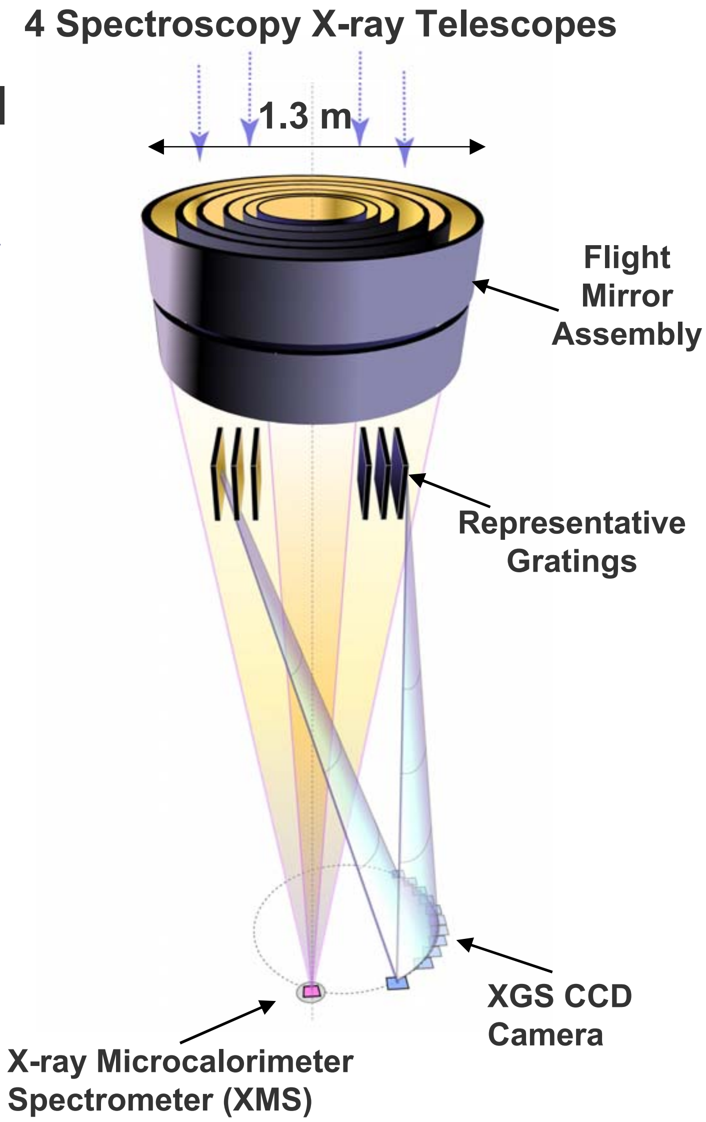


Courtesy - JWST

Q19, 23

Mission Implementation

- **To meet the requirements, our technical implementation consists of:**
  - **4 SXTs each consisting of a Flight Mirror Assembly (FMA) and a X-ray Microcalorimeter Spectrometer (XMS)**
    - **Covers the bandpass from 0.6 to 10 keV**
  - **Two additional systems extend the bandpass:**
    - **X-ray Grating Spectrometer (XGS) – dispersive from 0.3 to 1 keV (included in one or two SXT's)**
    - **Hard X-ray Telescope (HXT) – non-dispersive from 6 to 40 keV**
- **Instruments operate simultaneously:**
  - **Power, telemetry, and other resources sized accordingly**

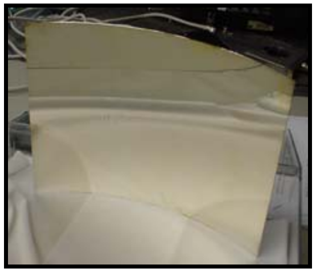


Q2, 19, 5

Flight Mirror Assembly

Forming

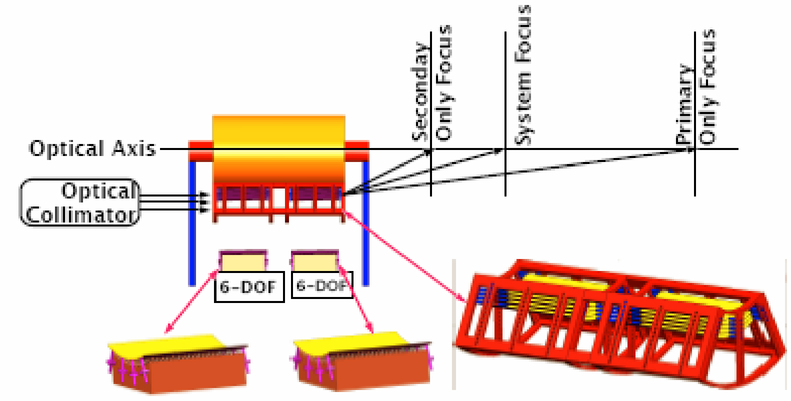
Mirror segment on a precisely figured mandrel

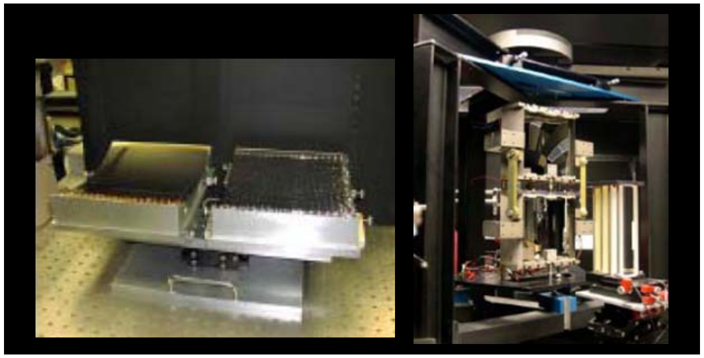


X-ray mirror

Angular Resolution Req't: 9.9 arcsec HPD

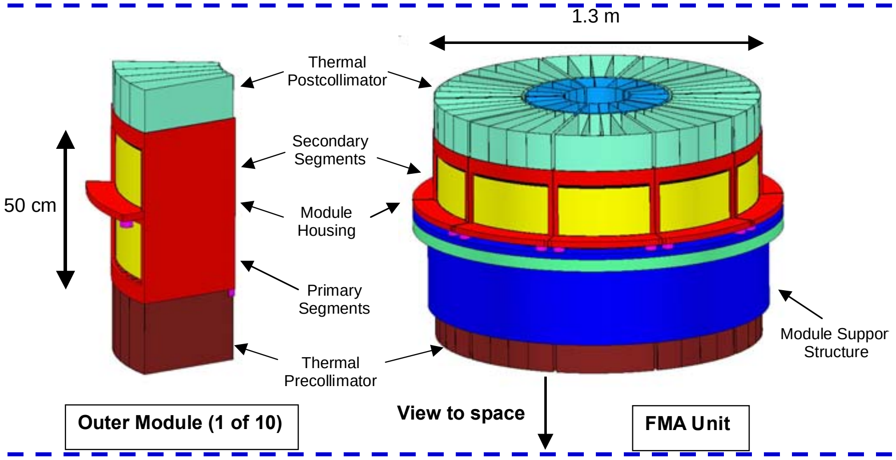
Alignment & Bonding

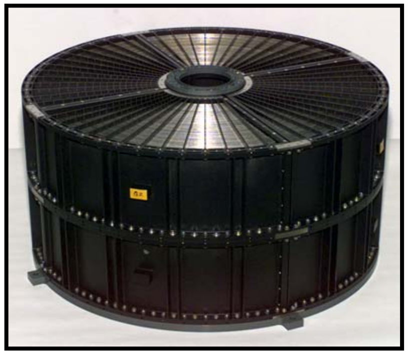




Passive (L) and active (R) alignment approaches – Not metrology limited

Assembly



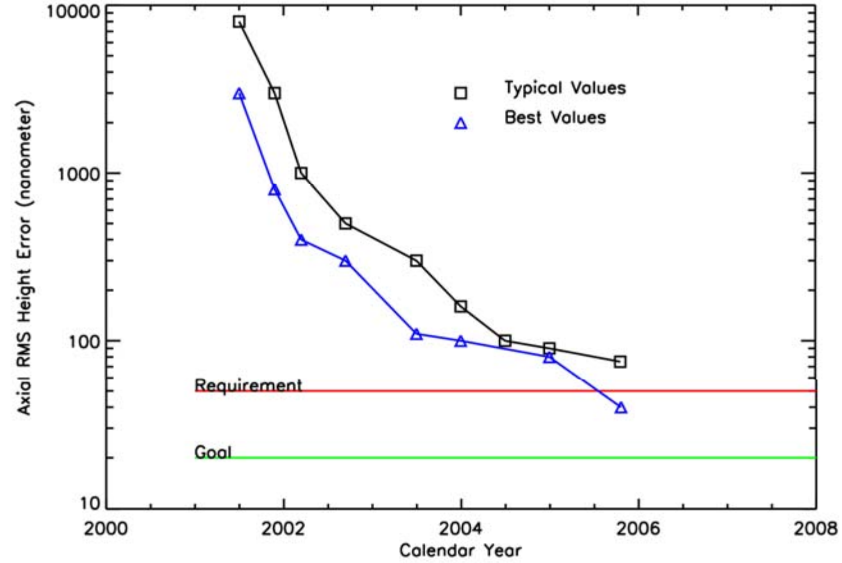


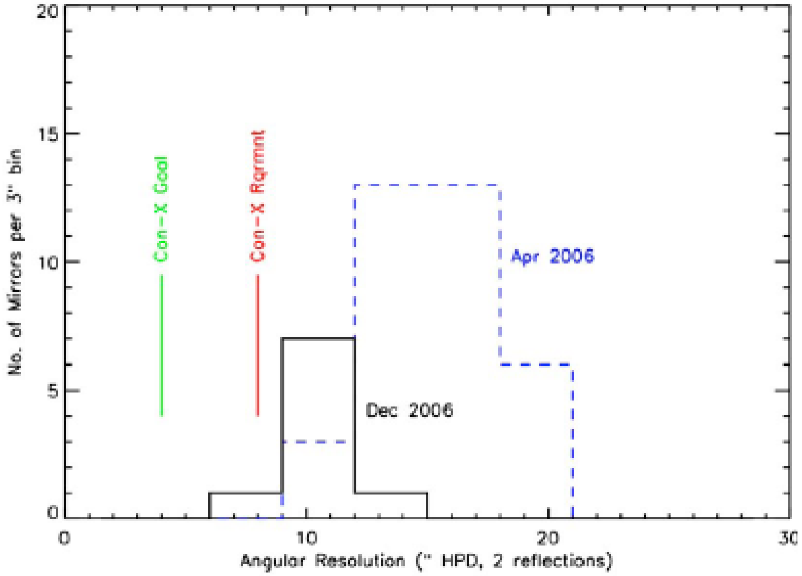
Suzaku flight mirror (40 cm diameter)

Angular Resolution Req't: 12.5 arcsec HPD

Q7, 12

Mirror Segment Fabrication Progress

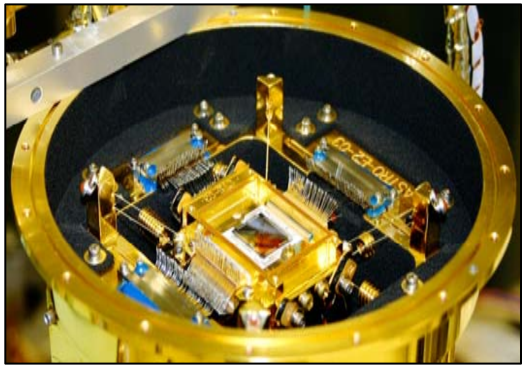




- RMS amplitude has improved to ~ required level
- Angular resolution improved by ~ 50% within year to within ~ 30% of requirements

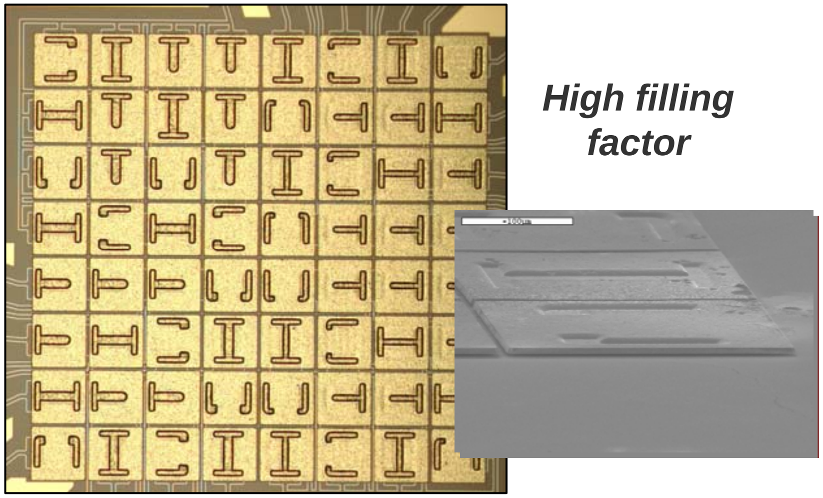
Q7, 12

X-ray Microcalorimeter Spectrometer (XMS)



Suzaku X-ray calorimeter array achieved 7 eV resolution on orbit

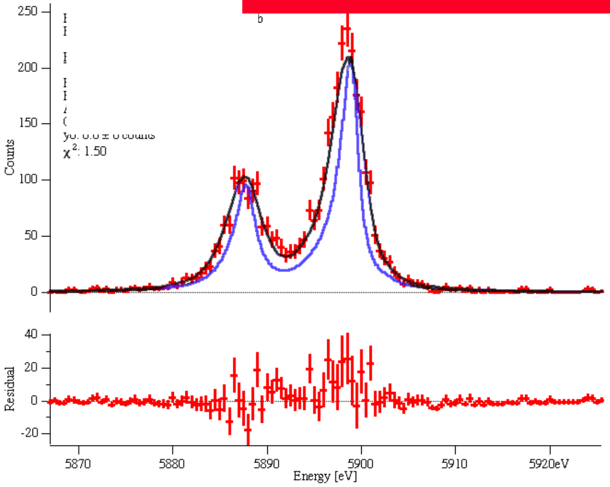
Con-X test arrays achieve 2.5 eV at 6 keV



High filling factor

8 x8 development Transition Edge Sensor array: 250 μm pixels

2.5 eV ± 0.2 eV FWHM

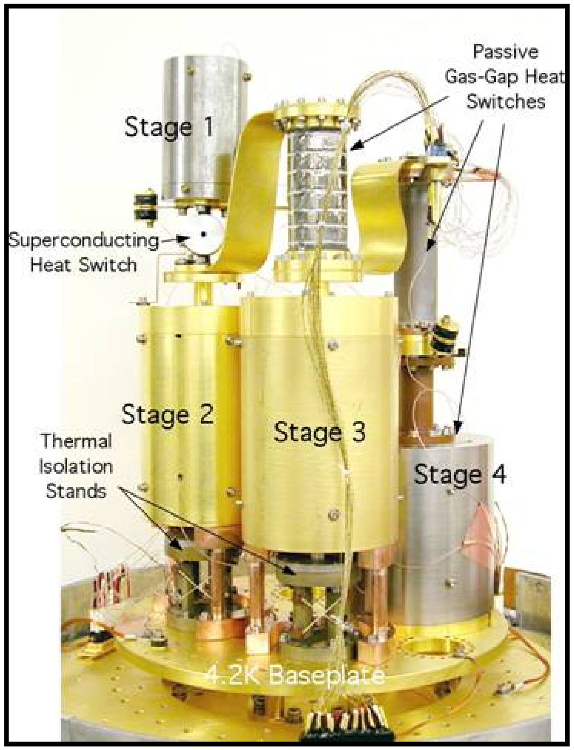


- **XMS key requirements:**
  - Bandpass: 0.6 to 10 keV
  - Field of view:
    - 5 arcmin x 5 arcmin via extended position sensitive microcalorimeters
  - Spectral resolving power:
    - 2.5 eV in core array (2.5 x 2.5 arcmin)
    - 8 eV for outer array
- **Transition Edge Sensor (TES), NTD/Ge and magnetic microcalorimeter technologies under development**

Q7, 12

ADR and Cryocooler

- **XMS supporting technologies:**
  - Key requirements:
    - No cryogens
    - Continuous cooling for array to ~50mk
  - Adiabatic Demagnetization Refrigerator (ADR)
    - Salt pills, magnets, assembly and manufacture same design as Suzaku XRS
  - Cryocooler
    - Cooling at ~6K
    - Advanced Cryocooler Technology Development Program (ACTDP) completed in 2005 for JWST, TPF and Con-X
    - Three different technologies can meet Con-X requirements



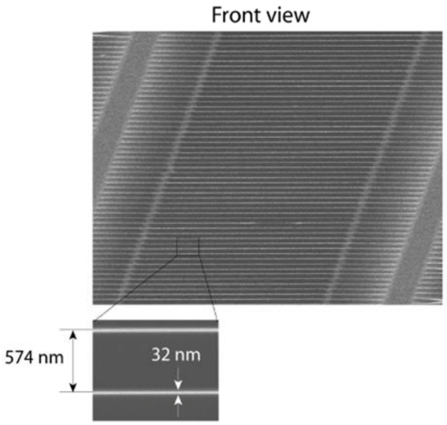
Technology Demonstration Continuous ADR for Con-X

Operating T ~35mK achieved

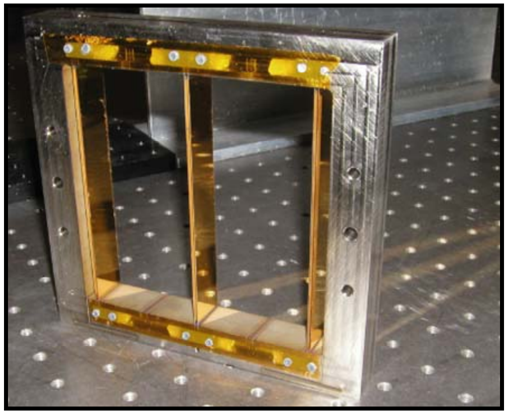
Q7, 12

X-ray Grating Spectrometer (XGS)

- **XGS key requirements:**
  - Effective area >1000 cm^2 from 0.3 to 1 keV
  - Spectral resolving power 1250 over full band
- **Two concepts under study for the grating arrays:**
  - Transmission grating
  - Off-plane reflection grating
  - Heritage from Chandra, XMM, and sounding rockets
- **CCD detectors:**
  - Back-illuminated (high QE below 1 keV),
  - Fast readout with thin optical blocking filters
  - Heritage from Chandra, XMM, Suzaku



Electron micrograph of blazed transmission grating



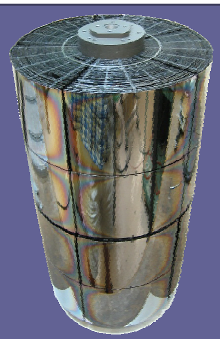
Three mounted off-plane gratings for sounding rocket

Q7, 12

Hard X-ray Telescope (HXT)

- HXT key requirements:
  - Effective area of 150 cm^2 from 6 to 40 keV
  - Spectral resolving power 10 over full band
  - 30 arcsec HPD
- Two potential technologies for the mirrors
  - Nickel Shell & Glass Segment
  - Highly nested optics with multilayer coatings
  - X-ray tests show 30 – 40 arcsec performance
  - Heritage from XMM, Swift, HEFT, HERO, InFocus
- CdZnTe detectors well understood from balloon flights (HERO, HEFT, InFocus)

Prototype glass mirror acoustics tested at JPL facility



HEFT 72-shell glass mirror optic

2 nested nickel mirror shells in X-ray test at PANTER

CdZnTe hybrid pixel detector

CdZnTe vibration test

Q7, 12

Technology Summary and Plans

- Mirror and instrument technologies are well on the way toward meeting requirements for Con-X
- Key upcoming technology demonstrations:
  - Fabrication of mirror segments with 1 kg/m^2 areal density meeting required angular resolution – late 2007
  - Demonstrate mirror in flight-like mount meeting 15 arcsec angular resolution, environmentally tested – 2009
  - 32 x 32 pixel “core” microcalorimeter demo array meeting requirements – 2008
  - Full 5 x 5 arcmin microcalorimeter focal plane demonstration – 2009
- Technology development schedules provided in response to BEPAC RFI
- Engineering units anticipated for Flight Mirror Assembly and Instruments post-technology development

Q16

Operations Modes and Data Volumes

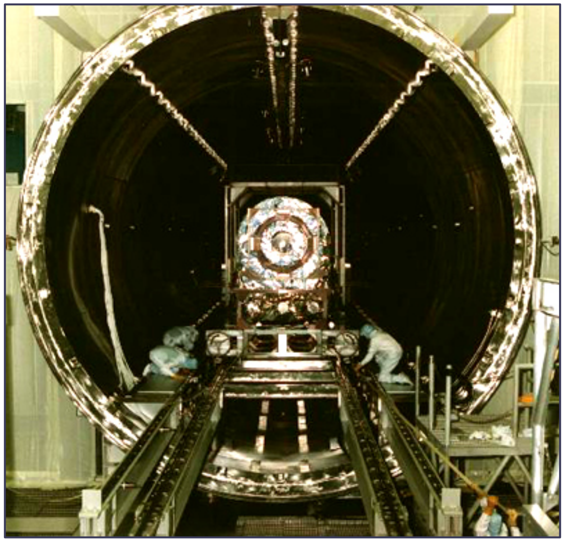
- Instrument operations are inherently simple
  - Detectors view the same source
  - Minimal number of operational modes
    - Science operations are typically a single mode
    - Engineering modes include calibrations, s/w loads, diagnostics etc.
- Instrument data rates and volumes (over 5 year mission)

Instrument	Data Rate (Ave/Peak)	Volume
XMS	38/300 kbps	7.4 TB
XGS	87/867 kpbs	17.6 TB
HXT	17/150 kbps	3.4 TB
TOTAL	142/1317 kbps	28.6 TB

Q13, 8

Calibration

- Calibration philosophy and structure based on Chandra
- Bottoms-up calibration
  - Sub-system level calibrations constrain physical models of telescope system
- Ground calibrations utilizes existing facilities
  - XRCF beam can fully illuminate the FMA aperture
- Flight calibrations
  - Combination of well-known celestial and on-board sources
  - Cross-calibration with other missions



XRCF Main Chamber

X-ray Calibration Facility (XRCF) at MSFC

Q13

Mission Operations

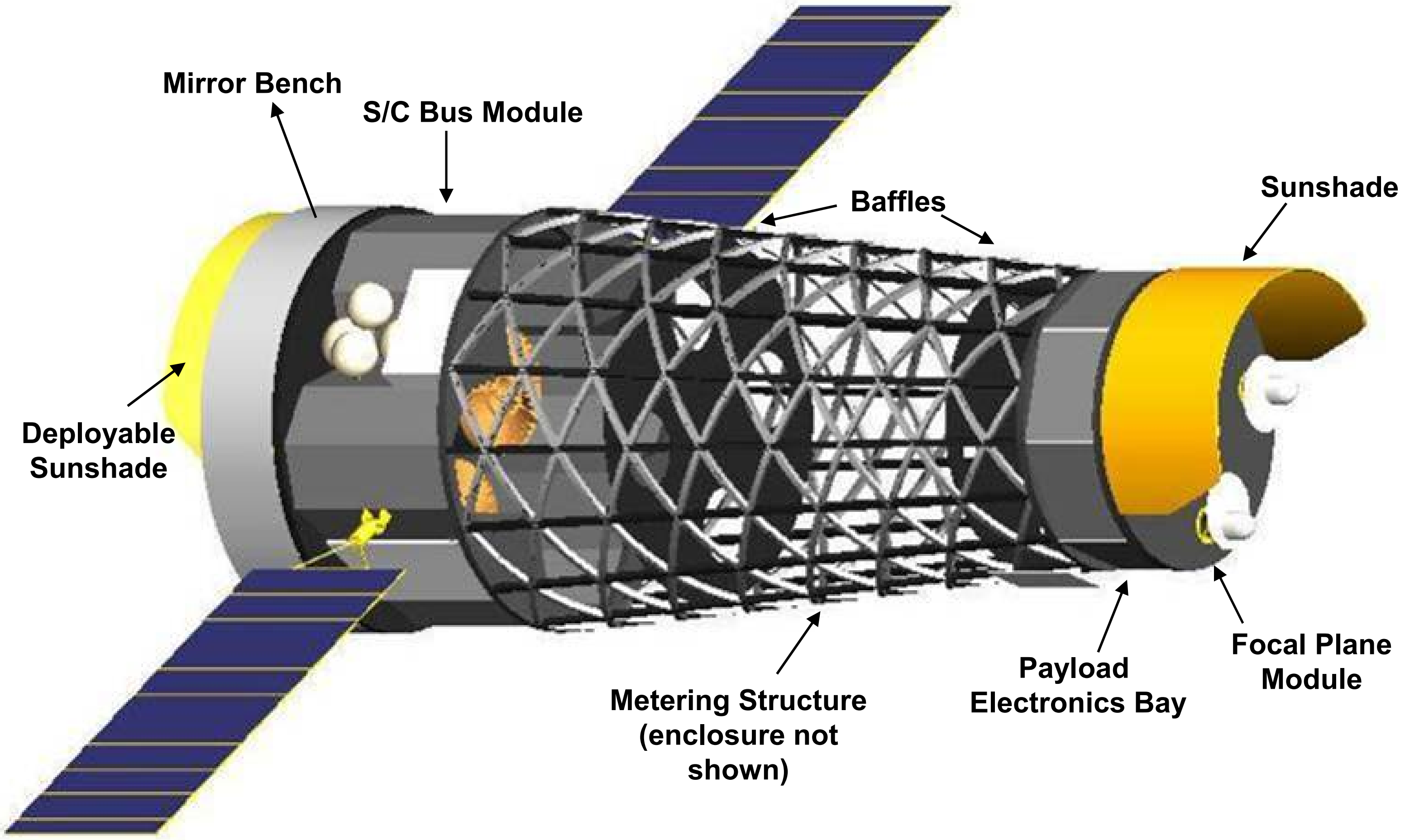
- Constellation-X Operations Concept is well developed:
  - Based on the Chandra model
- Constellation-X will be a facility class observatory:
  - Programs selected via competitive Peer Review
- Constellation-X operates as a queue-scheduled observatory:
  - Pointing at selected targets in the most time efficient way consistent with science and observatory constraints
  - No unusual mission or operational constraints
  - No unusual communication requirements
- Time on a target (pointings):
  - 10^3 to 10^6 sec; observations may have several pointing intervals

Panoramic view of the Chandra Operations Center

Q35, 36, 37

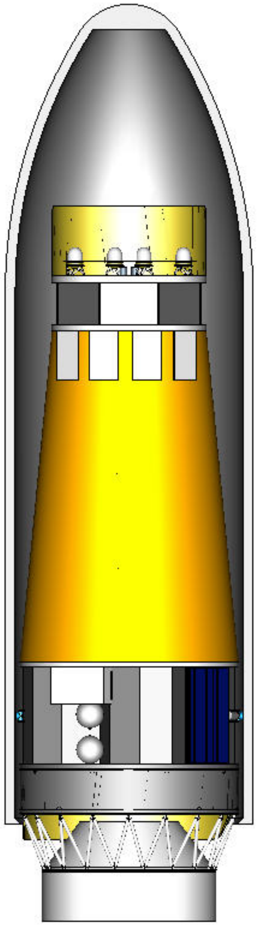
Ann Hornschemeier – Science	**Q1, 4, 6**	**15 min**
Jay Bookbinder – Mission Approach and Instrumentation	**Q19, 23, 2, 5, 7, 12, 16, 13, 8, 35, 36, 37**	**20 min**
Jean Grady – Observatory and Spacecraft, Schedule, Cost, and Risk	**Q21,31, 20, 23, 25, 29, 26, 27, 28, 30, 32, 33, 39, 22**	**20 min**
Harvey Tananbaum – Science Risks, Trades, Descopes, Data Analysis	**Q10, 3, 9, 24, 14**	**5 min**
Nick White – Scientific Reach	**Q18**	**5 min**
Questions covered in written response, but not addressed here	**Q11, 15, 17, 34, 38**	

Observatory Configuration



Q21, 31

Launch and Mass Summary



Con-X in Atlas V 551

Payload Mass			
	Estimate (kg)	Estimate (kg)	Allocation (kg)
Flight Mirror Assembly	1572.0	30%	2043.6
X-ray Microcalorimeter Spectrometer	708.0	30%	920.4
X-ray Grating Spectrometer	100.0	30%	130.0
Hard X-ray Telescope	100.0	30%	130.0
Miscellaneous Payload Items	35.6	30%	46.3
Payload Total	**2515.6**	**30%**	**3270.3**

S/C Bus Mass			
	Estimate (kg)	Contingency	Allocation (kg)
C&DH	92.4	30%	120.1
Attitude Control	68.0	30%	88.4
Communications	30.0	30%	39.0
Mechanisms	146.6	30%	190.6
Structure	981.2	30%	1275.6
Power	104.0	30%	135.2
Propulsion	48.0	30%	62.4
Thermal	186.3	30%	242.1
Harness	188.0	30%	244.4
S/C Bus Total	**1844.5**	**30%**	**2397.8**

Launch Mass Summary			
	Estimate (kg)	Contingency	Allocation (kg)
Payload Total	2515.6	30%	3270.3
S/C Bus Total	1844.5	30%	2397.8
Separation System	164.8	30%	214.3
Observatory Dry Mass	**4524.9**	**30%**	**5882.3**
Propellant Mass	257.4	30%	334.6
Observatory Wet Mass	**4782.3**	**30%**	**6217.0**
Throw Mass: 6305 kg		**Project Margin**	**88.0**

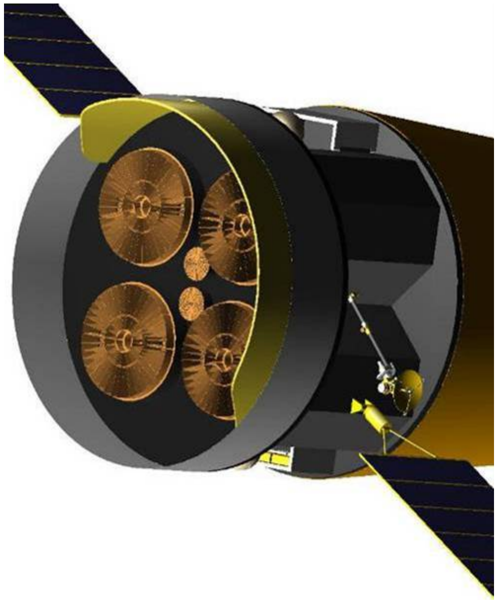
6217 kg Wet Mass

88 kg Margin

30% overall contingency

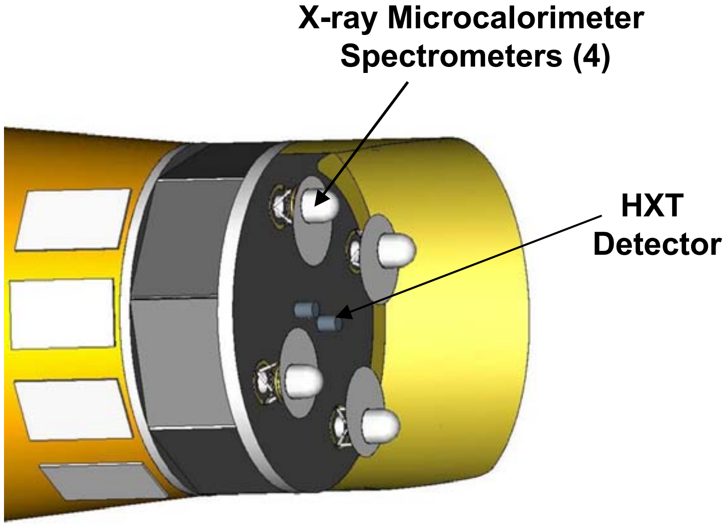
Q20, 21, 23, 25

Payload Accommodations



- Mirror Accommodations
  - Four 1.3 m dia SXT FMA’s and 1 - 2 HXT Mirrors co-aligned on Mirror Bench
  - Sunshade keeps sun light off mirrors
  - Heaters maintain mirrors at room temperature
  - Mirror covers provide protection during launch and orbit transfer

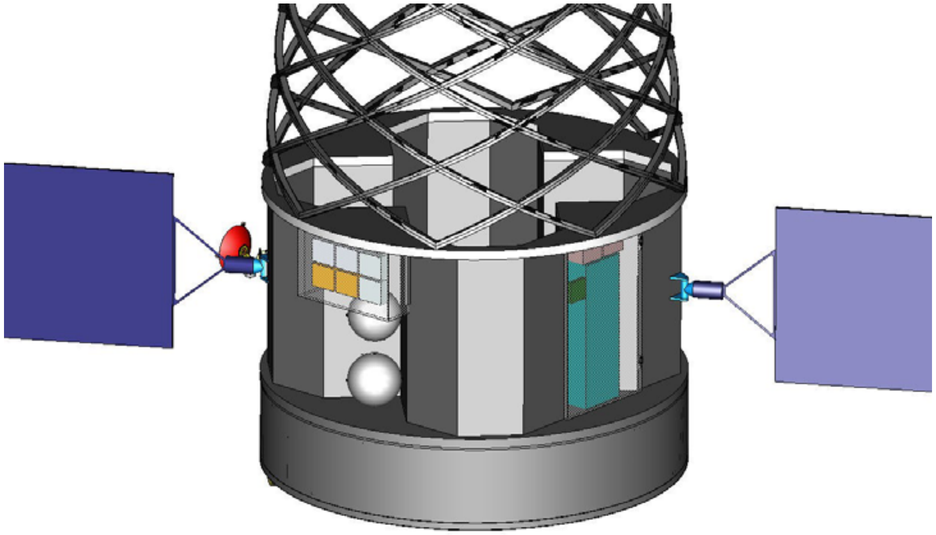
- Detector Accommodations
  - X-ray Microcalorimeter Spectrometers (XMS), X-ray Grating focal plane camera (not shown) and HXT detectors mount in Focal Plane Module
  - Payload Electronics Bay for warm electronics and XMS cryocooler
  - Sunshade and cold view to space support <100K on XMS “cryogen-less” cryostat shell
  - Loop heat pipe takes heat from cryocooler



Q21, 31

Spacecraft Bus Characteristics

- Mechanical
  - Modular design supports parallel integration and test activities
- Thermal
  - Traditional thermal control (blankets, heaters, thermostats)
- Propulsion
  - Sized for maximum throw mass for 10 years
- Attitude Control
  - Pointing knowledge: 5, 5, 20 arcsec (3 sigma)
  - Slew of 60 degrees completed in 1 hour
- Electrical Power
  - 22 m^2 Solar Array provides 4200 W End of Life (10 yrs)
- Command and Data Handling
  - Data rate: 150 kbps (avg); 1325 kbps (peak)
  - Two days storage capacity (144 Gbit)



S/C Bus Module

- Communications
  - High gain antenna to DSN 34 m
  - 30 minute daily contacts, Ka-band for science
- Mission Assurance
  - High level of redundancy for “Class B” mission

Q20, 21, 25, 29

Spacecraft Summary

- Overall spacecraft system requirements well within state-of-the-art
  - All spacecraft requirements can be met with existing technology, no technology development required
  - Direct spaceflight heritage on all components
- S/C Risks are very low to low
  - Deployables are highest risk
  - Contamination control also warrants attention
- Spacecraft trades planned for Phase A will further refine and optimize implementation concept

Q26, 27, 28, 30, 32

Project Organization

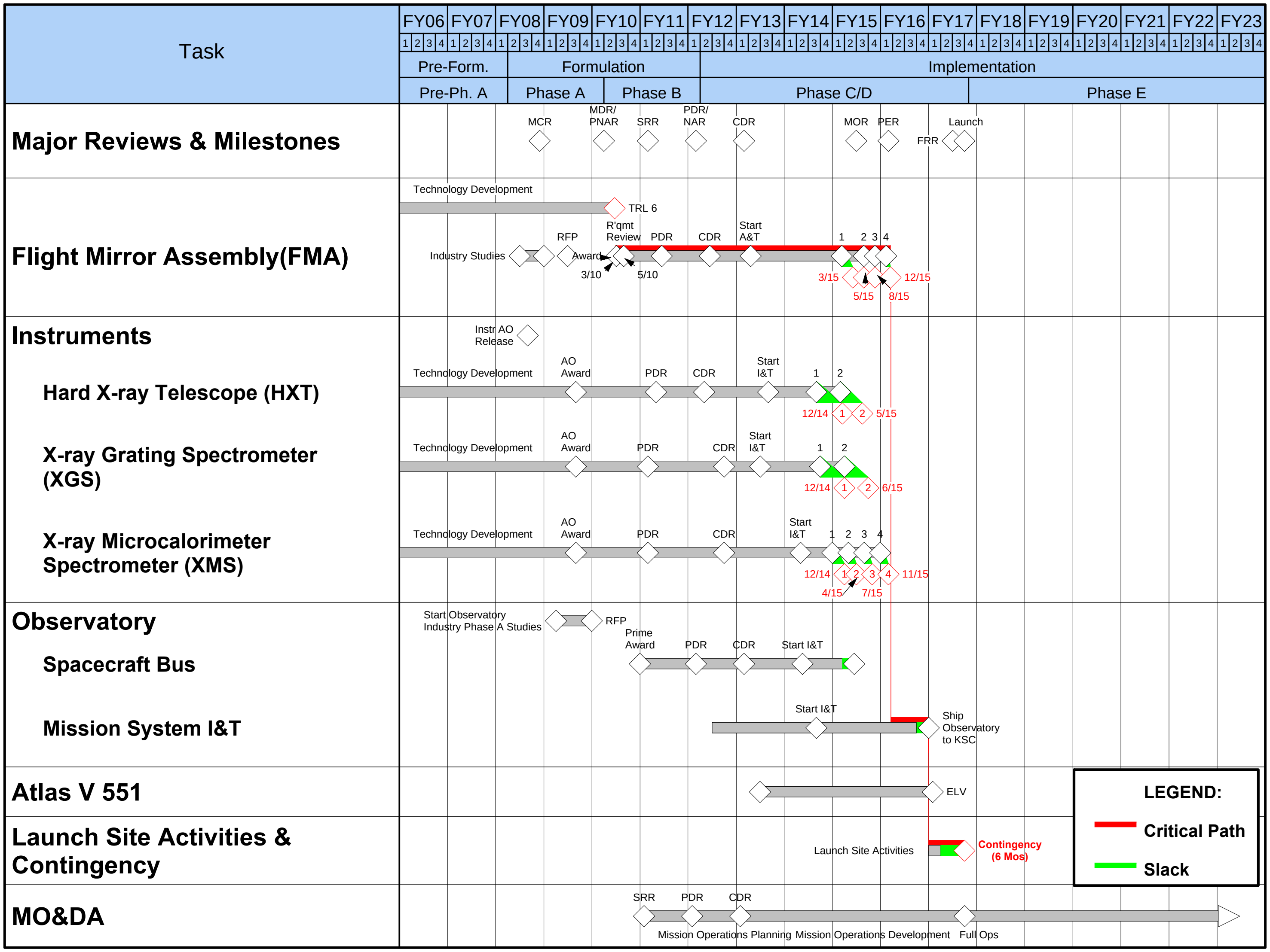
- Project Management
  - NASA/GSFC
- Science Team
  - GSFC, SAO, Facility Science Team/Science Working Group
- Mission Systems Engineering
  - Led by GSFC
  - Supported by Smithsonian Astrophysical Observatory (SAO), Observatory Prime, FMA and instrument developers
- Instruments:
  - Selected thru Announcement of Opportunity (AO)
- Flight Mirror Assembly
  - Selected thru Request for Proposal (RFP)
- Observatory Prime
  - Selected thru RFP
- Mission Operation and Data Analysis
  - SAO

Schedules

- Launch June 2017
- Flight Mirror Assembly (FMA) and Observatory industry studies with multiple potential partners precede flight solicitation
- FMA Technology development continues through technology transfer to industry for flight build (award in March 2010)
- Other Key Competitive Awards:
  - Instruments: May 2009
  - Observatory Prime: October 2010
- Schedule critical path runs through the SXT Flight Mirror Assembly
- Total schedule reserve on critical path is 9 months
- Schedules for Flight Mirror Assembly, each instrument, and technology development efforts provided in RFI response

Q33

Top Level Mission Schedule



Q33

Cost

- **Mission total: $2.16B Real Year ($1.74B in FY07 dollars)**
  - End-to-end including prior funding ($51M) and 5 years on-orbit operations
- **Method of estimation**
  - Grass roots, supported by PRICE-H on hardware elements
  - Folds in Chandra and other spaceflight experience
  - Launch vehicle cost estimate provided by KSC
- **Modest ramp-up assumed in FY08**
  - Technology development
  - Prepare for instrument AO, industry studies
- **Budget Reserves**
  - 20% in FY09, 25% in Phase B
  - 30% on Phase C/D (exclusive of launch vehicle)
  - 5% on Phase E

Q39

Cost Summary

	Pre-A		Phase A		Phase B		Phase C/D						Phase E					Total	Total
$M (RY)	**Prior**	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**FY17**	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**RY**	**FY07**
Concept Study	20.1	3.0	6.8	21.9														51.9	50.9
Project Management					5.2	6.1	7.3	6.8	7.1	6.9	6.3	3.7						49.4	40.7
Systems Engineering					5.9	7.0	7.4	7.6	7.5	7.2	6.4	3.2						52.1	43.1
Safety & MA					2.8	3.4	3.6	3.7	3.8	3.6	3.5	2.1						26.4	21.7
Technology Development	30.9	3.2	7.8	13.1	7.3													62.3	60.6
Science					6.6	7.8	9.3	10.8	14.7	19.8	19.6	21.7						110.4	88.3
Flight Mirror Assembly					14.3	37.1	38.7	40.8	40.4	15.3	0.9							187.5	158.4
XMS				3.7	16.0	18.1	33.0	41.6	32.7	25.5								170.6	143.4
XGS				1.7	13.0	15.1	19.2	17.9	14.8	4.9								86.6	74.0
HXT				1.0	5.8	7.3	8.7	7.7	4.2	1.5								36.1	31.1
Spacecraft					5.3	37.1	65.1	59.8	49.7	17.7								234.7	197.4
Gnd Data System Dev					0.6	0.8	3.6	4.5	7.1	11.9	12.8	13.3						54.6	42.7
MSI&T					0.0	0.0	1.4	2.2	4.2	17.3	28.8	18.0						71.8	55.1
Launch services					0.0	1.0	1.0	1.9	40.6	81.8	97.5	53.9						277.6	213.9
MO&DA					0.1	0.1	0.1	0.2	0.3	0.3	3.7	8.7	70.4	71.7	71.0	65.4	50.6	342.7	232.6
EPO					0.4	0.6	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.9	0.9	0.9	0.9	9.4	7.0
Reserves	0.0	0.0	1.5	8.3	20.8	35.1	59.4	61.3	56.1	39.7	24.8	14.3	3.6	3.6	3.6	3.3	2.6	338.0	278.4
Total	**51.0**	**6.2**	**16.1**	**49.7**	**104.1**	**176.7**	**258.5**	**267.3**	**283.6**	**254.0**	**204.9**	**139.9**	**74.8**	**76.2**	**75.4**	**69.6**	**54.1**	**2162.1**	**1739.3**

Q39

Overall Mission Risk Summary

#1 Technology development funding

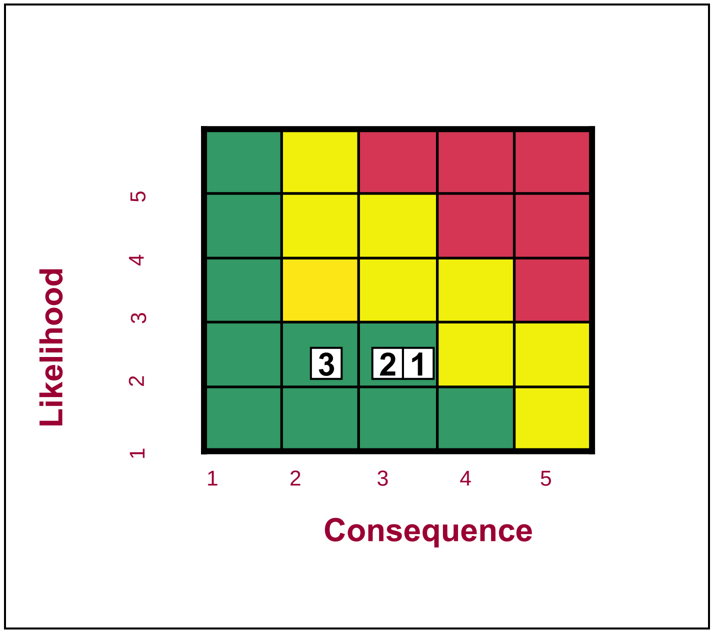
- Impact: Could impact overall mission schedule
- Likelihood: Low, Consequence: Moderate
- Mitigation: Leverage alternate sources

#2 FMA Manufacture Schedule

- Impact: Could consume schedule reserve
- Likelihood: Low, Consequence: Moderate
- Mitigation: Early interaction with industry; consider parallel vendors

#3 Mission Mass growth

- Impact: May erode overall mass contingency
- Likelihood: Low, Consequence: Low
- Mitigation: Optimization, trade, vigilance



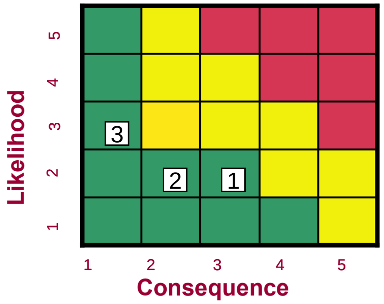
Q22

Ann Hornschemeier – Science	**Q1, 4, 6**	**15 min**
Jay Bookbinder – Mission Approach and Instrumentation	**Q19, 23, 2, 5, 7, 12, 16, 13, 8, 35, 36, 37**	**20 min**
Jean Grady – Observatory and Spacecraft, Schedule, Cost, and Risk	**Q21,31, 20, 23, 25, 29, 26, 27, 28, 30, 32, 33, 39, 22**	**20 min**
Harvey Tananbaum – Science Risks, Trades, Descopes, Data Analysis	**Q10, 3, 9, 24, 14**	**5 min**
Nick White – Scientific Reach	**Q18**	**5 min**

Three Primary Risks for Science and Instruments

- **Risk #1: Unable to meet 15 arcsec (HPD) angular resolution**

  Dominated by mirrors. Demonstrated performance projects to 17 arcsec system. Technology development ongoing. Small impacts on limiting flux for new sources and maximum redshift of clusters for Dark Energy studies.



- **Risk #2: Unable to extend XMS FOV to 5 x 5 arcmin**

  Hybrid approach with 32 x 32 pixels for 2.5 arcmin core and position sensitive outer array. Consequence is multiple pointings for extended sources.

- **Risk #3: Difficult to accommodate XGS and HXT**

  Range of XGS and HXT concepts under consideration. Integration might require modest increase of mass. Plan for early selection of all instruments via competitive AO.

Q10

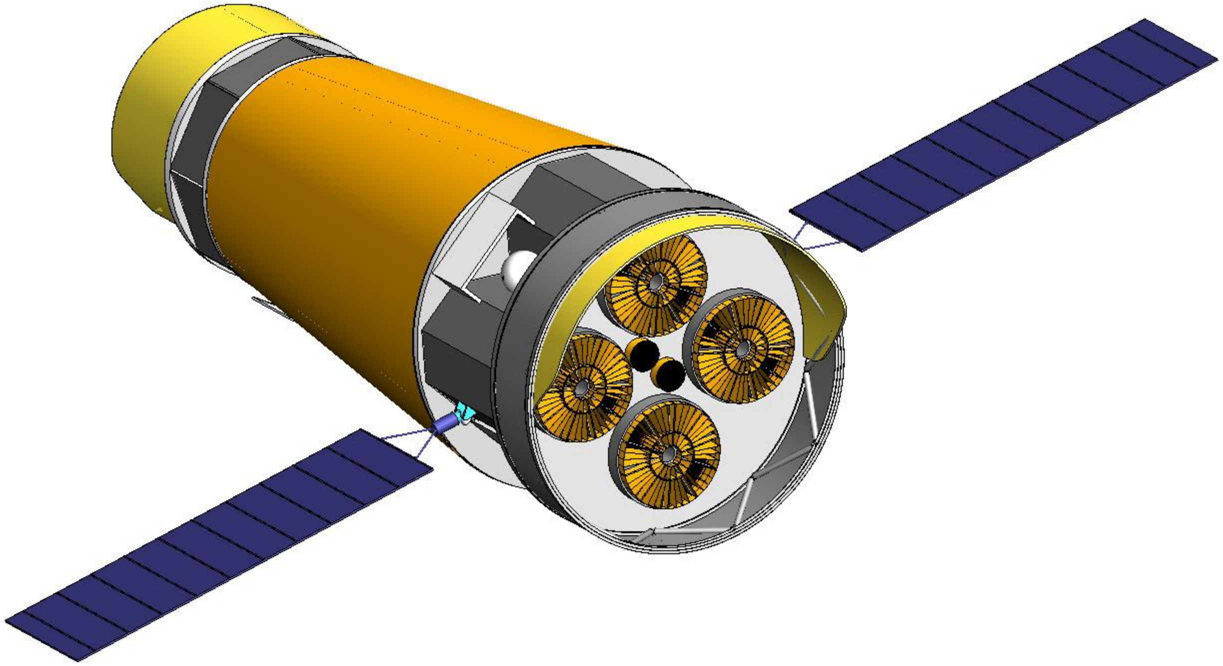
Most Demanding Measurement and Descope Options

- Most Demanding Measurement
  - Iron line variability to test GR in strong gravity limit
  - Drives area at 6 keV
- Identified 3 Descope Options in written response
  - Removal of outer FMA shells most viable – only option discussed here
    - Tailor to needed mass reductions — outer 16 shells total 340 kg
    - Area loss at lower energies offset via longer exposure times
    - Fewer targets over mission lifetime
    - Minimal loss of area at 6 keV (<2%)
    - Minimizes impact on GR tests

Q3, 9

Identify and Describe Key Trades

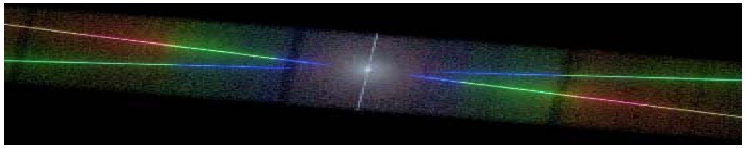
- Trades on orbit choice, orbit insertion, launch vehicle, optical bench, and number of SXTs completed – basis for implementation approach
- Trades on instrument details ongoing
- Trades on spacecraft underway and will increase with industry involvement

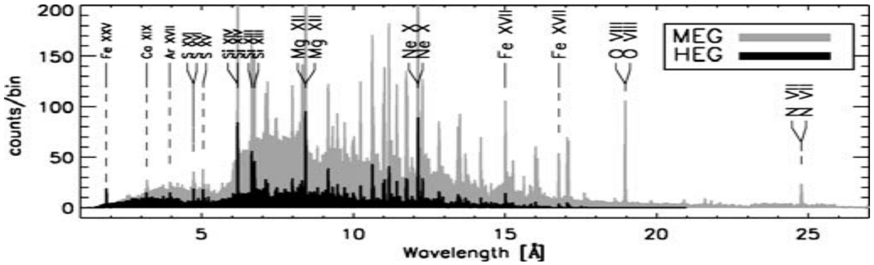


Q24

Complexity of Data Analysis

- Constellation-X data very similar to Chandra, XMM, Suzaku





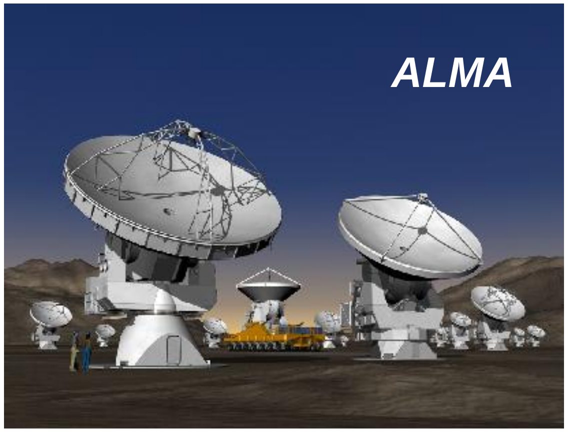
- Standard processing tools based on Chandra and Suzaku convert raw telemetry to event files: positions, energies, and times
- Analysis tools based on Chandra, XMM, Suzaku, RXTE, etc. generate images, spectra, and light curves
- Augment with updated atomic physics and plasma models for detailed spectral analysis and interpretation

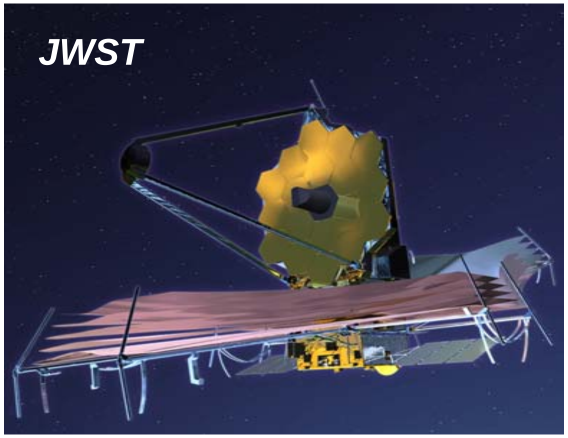
Q14

Ann Hornschemeier – Science	Q1, 4, 6	15 min
Jay Bookbinder – Mission Approach and Instrumentation	Q19, 23, 2, 5, 7, 12, 16, 13, 8, 35, 36, 37	20 min
Jean Grady – Observatory and Spacecraft, Schedule, Cost, and Risk	Q21,31, 20, 23, 25, 29, 26, 27, 28, 30, 32, 33, 39, 22	20 min
Harvey Tananbaum – Science Risks, Trades, Descopes, Data Analysis	Q10, 3, 9, 24, 14	5 min
Nick White – Scientific Reach	Q18	5 min

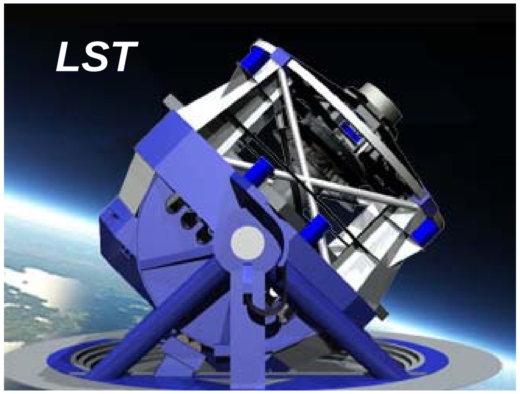
Compare the scientific reach of your mission with that of other planned space and ground-based missions

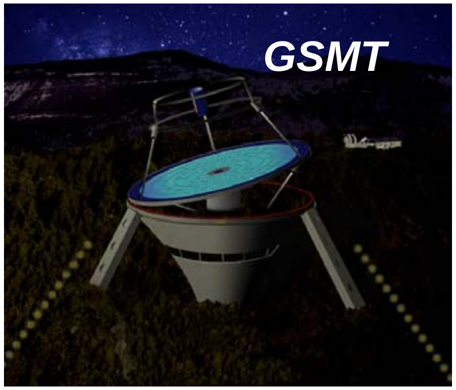
Sub-mm

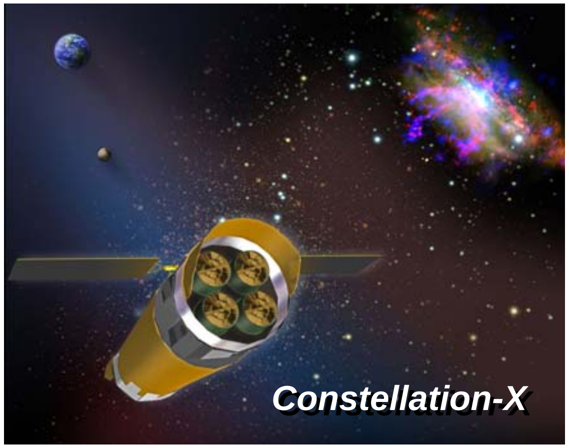




IR







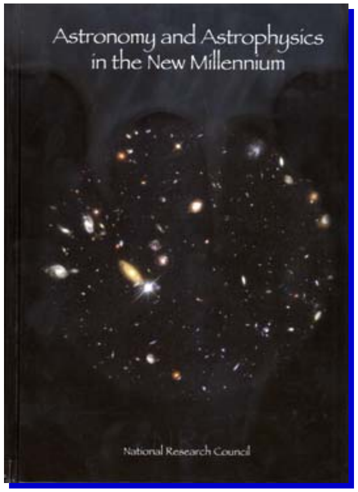
X-ray

Optical

The two order of magnitude increase in capability of Constellation-X is well matched to that of other large facilities planned for 2017

Q18

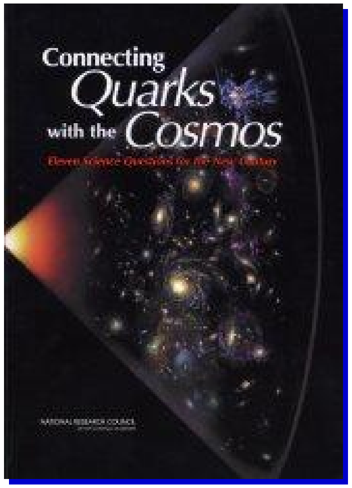
Science Reach – Previous Academy Reports



Astronomy and Astrophysics in the New Millennium

National Research Council

The Astronomy and Astrophysics in the New Millennium “decadal survey” set the stage for these future space and ground based “Great Observatories” and ranked Constellation-X as the second priority for large new space observatories



Connecting Quarks with the Cosmos

Eleven Science Questions for the New Century

NATIONAL RESEARCH COUNCIL

The Quarks to Cosmos science assessment and strategy for research at the intersection of Physics and Astronomy strongly endorsed the Constellation-X mission as *“holding great promise for studying black holes and for testing Einstein’s theory in new regimes*”

A mid-course review in 2005 by the CAA endorsed these reports and found there was no need to *“reexamine the AANM report or undertake an in depth mid-course review of the scientific goals or recommended priorities” … “the committee is concerned that the careful balance that is crucial to the field be maintained”*

Q18

Science Reach per Dollar

- The ability of Constellation-X to address many timely topics results in a very high science yield per dollar

Topic	Percent Time	Cost
Black Hole	30%	$649M
Dark Energy	18%	$389M
Neutron Star Equation of State	14%	$303M
Missing Baryon	11%	$238M
Observatory Science	27%	$584M
Total Mission Cost		$2162M

- The cost of each topic as a fraction of the total Constellation-X mission cost is very competitive when compared to a stand alone dedicated mission
- This is the concept of a “Great Observatory” where a mission driven by focused science goals, at the same time provides a major increase in capability applicable across many science areas and in doing so engages a broad science community with a large discovery space

Q18

Constellation-X Addresses 8 of 11 Quarks to Cosmos Questions

Did Einstein have the last word on gravity?	Black Holes	♦♦♦
What is the nature of the Dark Energy?	Galaxy Clusters	♦♦♦
What is the Dark Matter?	Galaxy Clusters	♦♦
Are there new states of matter at exceedingly high density and temperature?	Neutron Stars	♦♦♦
How were the elements from iron to uranium made?	Supernova Remnants Galaxy Clusters	♦
How do cosmic accelerators work and what are they accelerating?	Black Holes Supernova Remnants	♦♦
Is a new theory of matter and light needed at the highest energies?	Neutron Stars (10^{14}G)	♦
What are the masses of the neutrinos, and how have they shaped the evolution of the universe?	Galaxy Clusters	♦

Fundamental results ♦♦♦ Major contribution ♦♦ Discovery space ♦

Summary

- **High science per dollar — Constellation-X addresses 8 of the 11 Quarks to Cosmos Questions, with the focus on Black Holes as tests of GR, Dark Energy, and neutron star equation of state**
- **Constellation-X based on flight proven optics and instruments — a two order of magnitude increase in capabilities transforming X-ray Astronomy into X-ray Astrophysics — without requiring technical breakthroughs**
- **Constellation-X engages a large community of scientists with success “guaranteed” based on already known targets with measured fluxes**
- **Constellation-X will be a “Great Observatory” — a unique and essential element in the ground and space-based exploration of the Cosmos as envisioned in the 2000 Decadal Survey**

Numbered List of Questions Mapped to RFI (Sci & Inst)

	Science and Instrumentation
1	Describe the scientific objectives and the measurements required to fulfill these objectives.
2	Describe the technical implementation you have selected, and how it performs the required measurements.
3	Of the required measurements, which are the most demanding? Why?
4	Present the performance requirements (e.g. spatial and spectral resolution, sensitivity, timing accuracy) and their relation to the science measurements.
5	Describe the proposed science instrumentation, and briefly state the rationale for its selection.
6	For each performance requirement, present as quantitatively as possible the sensitivity of your science goals to achieving the requirement. For example, if you fail to meet a key requirement, what will the impact be on achievement of your science objectives?
7	Indicate the technical maturity level of the major elements of the proposed instrumentation, along with the rationale for the assessment (i.e. examples of flight heritage, existence of breadboards, prototypes, etc)
8	Briefly describe the overall complexity level of instrument operations, and the data type (e.g. bits, images) and estimate of the total volume returned.
9	If you have identified any descope options that could provide significant cost savings, describe them, and at what level they put performance requirements and associated science objectives at risk.
10	In the area of science and instrumentation, what are the three primary technical issues or risks?
11	Fill in entries in the Instrument Table to the extent possible. If you have allocated contingency please include as indicated, if not, provide just the current best estimate (CBE).
	Science and Instrumentation (Optional)
12	For the science instrumentation, describe any concept, feasibility, or definition studies already performed (to respond you may provide copies of concept study reports, technology implementation plans, etc).
13	For instrument operations, provide a functional description of operational modes, and ground and on-orbit calibration schemes.
14	Describe the level of complexity associated with analyzing the data to achieve the scientific objectives of the investigation.
15	Provide an instrument development schedule if available.
16	Provide a schedule and plans for addressing any required technology developments, and the associated risks.
17	Describe the complexity of the instrument flight software, including estimate of the number of lines of code.
18	Compare the scientific reach of your mission with that of other planned space and ground-based missions.

Numbered List of Questions Mapped to RFI (Mis Design)

	Mission Design
19	Provide a brief descriptive overview of the mission design (launch, orbit, pointing strategy) and how it achieves the science requirements (e.g. if you need to cover the entire sky, how is it achieved?)
20	Provide entries in the mission design table to the extent possible. Those entries in italics are optional. For mass and power, provide contingency if it has been allocated, if not – provide just your current best estimate (CBE). To calculate margin, take the difference between the maximum possible value (e.g. launch vehicle capability) and the maximum expected value (CBE plus contingency).
21	Provide diagrams or drawings (if you have them) showing the observatory (payload and s/c) with the components labeled and a descriptive caption. If you have a diagram of the observatory in the launch vehicle fairing indicating clearance, please provide it.
22	Overall (including science, mission, instrument and S/C), what are the three primary risks?
	Mission Design (Optional)
23	If you have investigated a range of possible launch options, describe them, as well as the range of acceptable orbit parameters.
24	If you have identified key mission tradeoffs and options to be investigated describe them.

Numbered List of Questions Mapped to RFI (S/C Imp)

	Spacecraft Implementation
25	Describe the spacecraft characteristics and requirements. Include, if available, a preliminary description of the spacecraft design and a summary of the estimated performance of the spacecraft.
26	Provide an overall assessment of the technical maturity of the subsystems and critical components. In particular, identify any required new technologies or developments or open implementation issues.
27	What are the three greatest risks with the S/C?
	Spacecraft Implementation (Optional)
28	If you have required new S/C technologies, developments or open issues and you have identified plans to address them, please describe (to answer you may provide technology implementation plan reports or concept study reports).
29	Describe subsystem characteristics and requirements to the extent possible. Such characteristics include: mass, volume, and power; pointing knowledge and accuracy; data rates; and a summary of margins.
30	Describe the flight heritage of the spacecraft and its subsystems. Indicate items that are to be developed, as well as any existing instrumentation or design/flight heritage. Discuss the steps needed for space qualification.
31	Address to the extent possible the accommodation of the science instruments by the spacecraft. In particular, identify any challenging or non-standard requirements (i.e. Jitter/momentum considerations, thermal environment/temperature limits etc).
32	Define the technology readiness level of critical S/C items along with a rationale for the assigned rating.
33	Provide a preliminary schedule for the spacecraft development.
34	Spacecraft Characteristics Table (Optional – fill out any known entries if you have selected an implementation.)

Numbered List of Questions Mapped to RFI (Mis Ops)

Mission Operations	
35	Provide a brief description of mission operations, aimed at communicating the overall complexity of the ground operations (frequency of contacts, reorientations, complexity of mission planning, etc). Analogies with currently operating or recent missions are helpful.
36	Identify any unusual constraints or special communications, tracking, or near real-time ground support requirements.
37	Identify any unusual or especially challenging operational constraints (i.e. viewing or pointing requirements).
38	Mission Operations and Ground Data Systems Table (Optional – provide only if you have selected a S/C and operations implementation)
39	Total Mission Cost Funding Profile Template

Acronyms and Abbreviations

Å	Angstrom
AANM	New Millennium Survey
ACIS	AXAF CCD Imaging Spectrometer
ACS	Attitude Control System
ACTDP	Advanced Cryocooler Technology Development Program
ADR	Adiabatic Demagnetization Refrigerator
AETD	Applied Engineering Technology Directorate
AGN	Active Galactic Nucleus
AH	Ampere-hour
Al	Aluminum
ALMA	Atacama Large Millimeter Array
AO	Announcement of Opportunity
arcmin	arc minutes
arcsec	arc seconds
ASCA	Advanced Satellite for Cosmology and Astrophysics
Au	Gold
BEPAC	NRC Beyond Einstein Program Assessment Committee
BH	Black Hole
BHFP	Black Hole Finder Probe
BI	Back-Illuminated
Bi	Bismuth
Bps	bits per second
C	Carbon
C	Celsius
C&DH	Command and Data Handling
CAA	Committee on Astronomy & Astrophysics
CADR	Continuous Adiabatic Demagnetization Refrigerator
CalDB	Calibration Database
CBE	Current Best Estimate
cc	cubic centimeters
CCD	Charge-Coupled Device
CCSDS	Consultative Committee for Space Data Systems
Cd	Cadmium
CDA	Centroid Detector Assembly
CdZnTe	Cadmium Zinc Telluride
ChIPS	Chandra Imaging and Plotting System
CIAO	Chandra Interactive Analysis of Observations
CIT	California Institute of Technology
cm	centimeter
CP/CM	Center of Pressure/Center of Mass
cps	counts per second
CPU	Central Processing Unit
Cs	Cesium
CTE	Coefficient of Thermal Expansion
CTI	Charge Transfer in Efficiency
cts	counts
Cu	Copper
CXC	Chandra X-ray Center
CXSOC	Constellation-X Science and Operations Center
C_t	Critical Temperature
CZT	Cadmium Zinc Telluride
DC	Direct Current
DE	Dark Energy
DETF	Dark Energy Task Force
DM	Dark Matter
DOF	Degree-of-Freedom
DSN	Deep-Space Network
E	Energy
EELV	Evolved Expendable Launch Vehicle
EEPROM	Electronically Erasable Programmable Read-Only Memory
EGSE	Electrical Ground Support Equipment
ELV	Expendable Launch Vehicle
EMI/EMC	Electromagnetic Interference/Compatibility
EOL	End of Life
EOS	Earth Observing System
ESA	European Space Agency
ETU	Engineering Test Unit
EU	Engineering Unit
eV	electron Volts

Acronyms and Abbreviations (cont.)

Fe	Iron
FFT	Fast Fourier Transform
FITS	Flexible Image Transport System
FMA	Flight Mirror Assembly
FOM	Figure of Merit
FOV	Field of View
FPC	Focal Plane Camera
FPM	Focal Plane Module
FRR	Flight Readiness Review
FSW	Flight Software
FY	Fiscal Year
G	Gravitational Constant
Gbit	Gibabit
Gbytes	Gigabytes
Ge	Germanium
gm	gram
GMST	Greenwich Mean Sidereal Time
GN&C	Guidance, Navigation & Control
GR	General Relativity
GS	Ground System
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
GUI	Graphical User Interface
H	hyperbolic
H/K	Housekeeping
He	Helium
HEFT	High Energy Focusing Telescope
HEO	High Earth Orbit
HERO	High Energy Replicated Optics
HETE	High Energy Transient Experiment
HETG(S)	High Energy Transmission Grating (Spectrometer)
HEW	Half Energy Width
HGA	High Gain Antenna
HPB	High-Pressure Bridgeman
HPD	Half Power Diameter
HQ	Headquarters
HRC	High Resolution Camera

HV	High Voltage
HXT	Hard X-ray Telescope
Hz	Hertz
I	Iodine
I&T	Integration and Test
I/F	Interface
ID	Inner Diameter
IMDC	Integrated Mission Design Center
InFOCμS	International Focusing Optics Collaboration for μCrab Sensitivity
IR	Infrared
IRU	Inertial Reference Unit
ISS	International Space Station
JDEM	Joint Dark Energy Mission
JWST	James Webb Space Telescope
J/T	Joule/Thompson
K	Kelvin
kbps	kilobits per second
kByte	Kilobyte
keV	Kilo Electron Volt
kg	ilogram
kHz	KiloHertz
KOH	Potassium Hydroxide
KSC	Kennedy Space Center
ksec	kilosecond
LCC	Life Cycle Cost
LEO	Low Earth Orbit
LETG(S)	Low Energy Transmission Grating (spectrometer)
LISA	Laser Interferometer Space Antenna
LL	Lincoln Labs
LLNL	Lawrence Livermore National Labs
LRF	Line Response Function
LRR	Launch Readiness Review
LST	Large Survey Telescope
LV	Launch Vehicle
LV	Low Voltage
LVPC	Low Voltage Power Converter
LVPS	Low Voltage Power Supply
LZP	Level Zero Processing

Acronyms and Abbreviations (cont.)

m	meter
m/s	meters per second
MBE	Molecular Beam Epitaxy
MHz	Megahertz
MIT	Massachusetts Institute of Technology
mK	milliKelvin
MLI	Multilayer Insulation
mm	millimeter
Mo	Molybednium
MO&DA	Mission Operations and Data Analysis
MOC	Mission Operations Center
Ms	millisecond
MSE	Mission Systems Engineer
MSFC	Marshall Space Flight Center
MUX	Multiplexer
mW	milliWatt
N	Neutron
NASA	National Aeronautics and Space Administration
Nb	Niobium
NeXT	Non-thermal Energy eXploration Telescope
NIST	National Institute of Standards and Technology
nm	nanometers
NRAO	National Radio AstronomyObservatory
NS	Neutron Star
NSF	National Science Foundation
NTO	Nitrogen tetroxide (or dinitrogen tetroxide), rocket fuel
OAP	Optical Alignment Pathfinder
OB	Optical Bench
OBC	On-Board Computer
OCC/SOC	Operations Control Center/Single Operations Center
OD	Orbit Determination
OD	Outside Diameter
ODRM	Observation Design Reference Mission

OGS	Objective Grating Spectrometer
OS	Operating System
OSS	Office of Space Science
OSSMA	Office of Systems Safety and Mission Assurance
PHA	Pulse Height Amplitude
PMD	ropellant Management Device
PoST	Position Sensitive TES
PSE	Power Supply Electronics
PSF	Point Spread Function
Psia	pounds per square inch, absolute
QPO	Quasi-Periodic Oscillation
RF	Radio Frequency
RFI	Request for Information
RGS	Reflection Grating Spectrometer
RMS	Root Mean Square
ROM	Rough Order of Magnitude
ROSAT	Roentgen-Satellite
RSDO	Rapid Spacecraft Development Office
RXTE	Rossi X-ray Timing Explore
SAO	Smithsonian Astrophysical Observatory
S/A	Solar Array
SBIR	Small Business Innovative Research
S/C	Spacecraft
SDO	Solar Dynamics Observatory
SDRAM	Synchronous Dynamic Random Access Memory
sec	second
SEP	Science Enhancement Package
Si	Silicon
SMBH	SuperMassive Black Hole
Sn	Tin
SNL	Space Nanotechnology Laboratory
SPT	South Pole Telescope
SQUID	Superconducting Quantum Interference Device
SXT	Spectroscopy X-ray Telescope

Acronyms and Abbreviations (cont.)

Ta	Tantalum
TB	Thermal Balance
TBD	To Be Determined
TBR	To Be Resolved
Tbyte	Terrabyte
TCP/IP	Transmission Control Protocol/ Internet Protocol
TDRSS	Tracking and Data Relay Satellite System
Te	Tellurium
TES	Transition-Edge Spectrometer
Ti	Titanium
TLM	Telemetry
TLRD	Top-Level Requirements
TM	Telescope Module
TOO	Target of Opportunity
TPF	Terrestrial Planet Finder
TRIP	Technology Readiness and Implementation Plan
TRL	Technology Readiness Level
TT&C	Tracking, Telemetry and Command
TV	Thermal Vacuum
TWTA	travelling wave tube amplifiers

μsec	microsecond
µm	micrometer
UTC	Universal Time Coordinated
ULX	UltraLuminous X-ray source
VLT	Very Large Telescope
W	Watt
WHIM	Warm-Hot Intergalactic Medium
XEUS	X-ray Evolving Universe Spectroscopy Mission
XGS	X-ray Grating Spectrometer
XIS	X-ray Imaging Spectrometer (on Japanese Mission Suzaku)
XMM	X-ray Multi-Mirror Mission
XMS	X-ray Microcalorimeter Spectrometer
z	red shift
Zn	Zinc
ZOC	Zero Order Camera