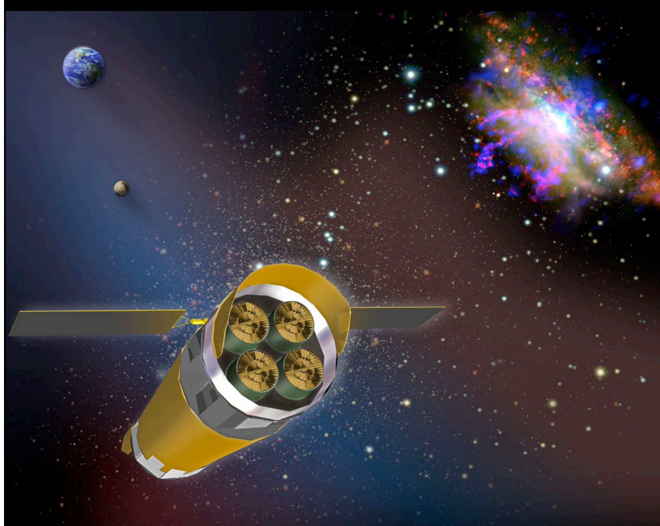
BEYOND EINSTEIN: From the Big Bang to Black Holes

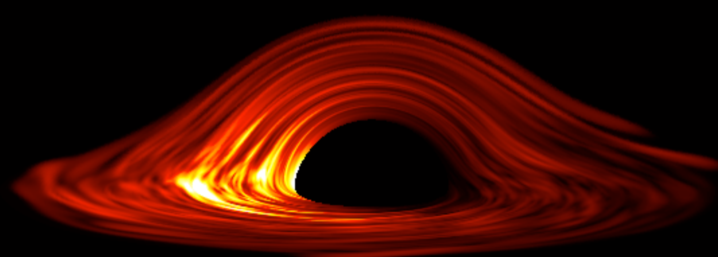
Constellation X

The Constellation X-Ray Mission



Constellation-X

Nicholas White (NASA/GSFC)



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

NASA

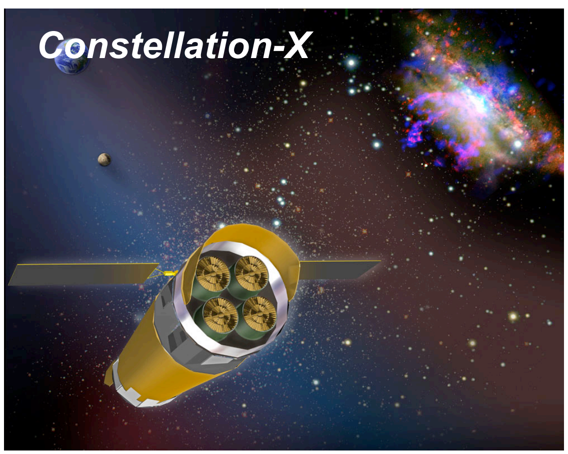
CHANDRA & XMM-Newton brought X-ray Astronomy to the forefront

Chandra imaging 0.5" comparable to typical ground-based O/IR telescopes

For Chandra more than 2200 Guest Investigators to date with 2700 refereed papers, 600 last year alone

Most X-ray spectra from Chandra and XMM have moderate resolution CCD spectra E/ΔE < 30, insufficient for crucial plasma diagnostics

CONSTELLATION-X will open a new window on X-ray spectroscopy



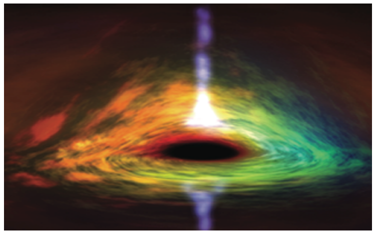
Resolution (E/ΔE): 1250 @ 0.3 – 1 keV and 2400 @ 6 keV required for crucial density, velocity and other diagnostics

Effective area is a 10-100 gain over current missions

R > 1000 spectroscopy to a flux of 2×10^{-15} ergs cm^{-2} s^{-1} (0.1 to 2.0 keV), with 1000 counts in 100,000s, with a limiting sensitivity 10 times fainter

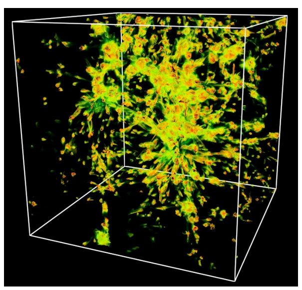
The physics is in the spectra: X-ray Astronomy becomes X-ray Astrophysics

Driving Constellation-X Science Objectives

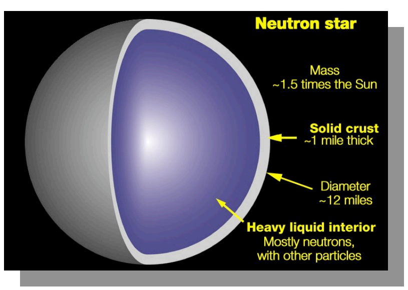


1. **Black Holes:** Using black holes to test General Relativity (GR) and measuring black hole spin evolution with Cosmic time

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



3. **Missing Baryons:** Unambiguous detection of the hot phase of the Warm-Hot Intergalactic Medium (WHIM) at z > 0



4. **Neutron Star Equation of State:** Measuring the mass-radius relation of neutron stars to determine the Equation of State (EOS) of ultra-dense matter

Science Objectives Flow Into Driving Performance Requirements

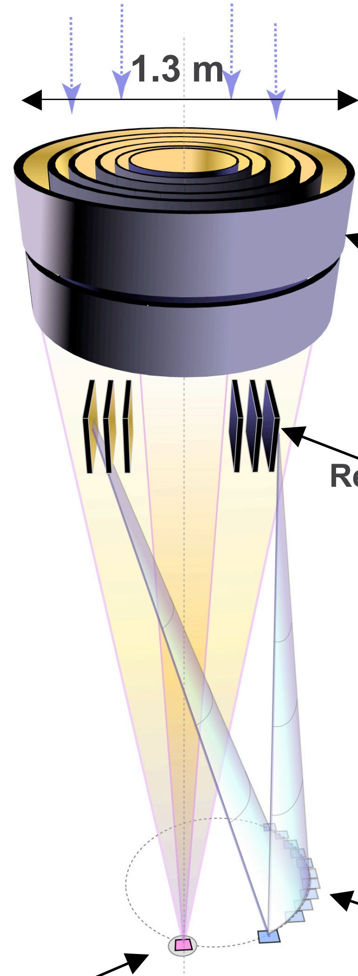
Effective Area:	15,000 cm^2 @1.25 keV 6,000 cm^2 @6 keV 150 cm^2 @40 keV	Black Hole spin evolution with time, Dark Energy using 500 Clusters of Galaxies Black Hole GR Tests Black Hole GR Tests
Spectral Resolution:	1250 @0.3 – 1 keV (1,000 cm^2) 2400 @6 keV	Missing Baryons using many tens background AGN Dark Energy using Clusters of Galaxies
Angular Resolution	15 arc sec (5 arc sec goal) 0.3 – 7 keV 30 arcsec 7.0 – 40 keV	Dark Energy using Clusters, Missing Baryons GR Tests
Field of View	5 x 5 arcmin (10 x 10 arc min goal)	Dark Energy using Clusters
Count Rate	1,000 ct/sec/pixel	Neutron Star Equation of State

These capabilities enable great observatory science and open the window of X-ray spectroscopy for all classes of astrophysical objects from Comets to distant Quasars

Mission Implementation

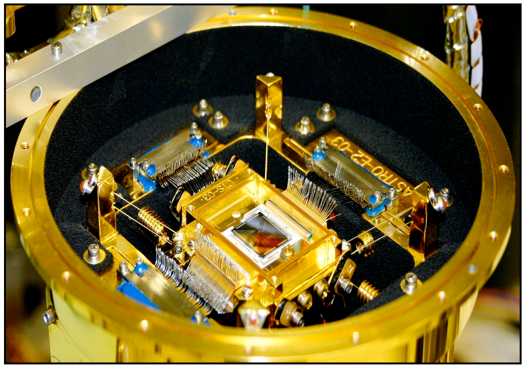
- To meet the science objectives, the technical implementation consists of:
  - 4 SXTs each consisting of a Flight Mirror Assembly (FMA) and a X-ray Microcalorimeter Spectrometer (XMS)
    - Covers the bandpass from 0.6 to 10 keV
  - Two additional systems extend the bandpass:
    - X-ray Grating Spectrometer (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 (not shown)
- Instruments operate simultaneously:
  - Power, telemetry, and other resources sized accordingly

4 Spectroscopy X-ray Telescopes

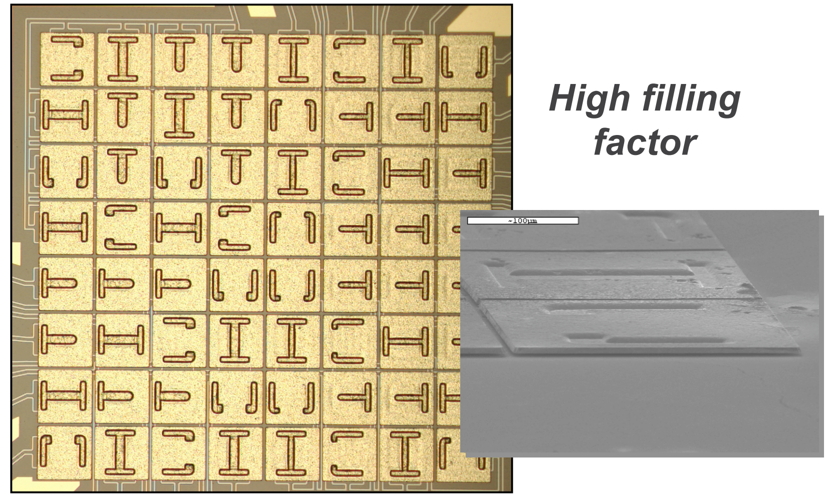


X-ray Microcalorimeter Spectrometer (XMS)

Con-X test arrays achieve 2.5 eV at 6 keV



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

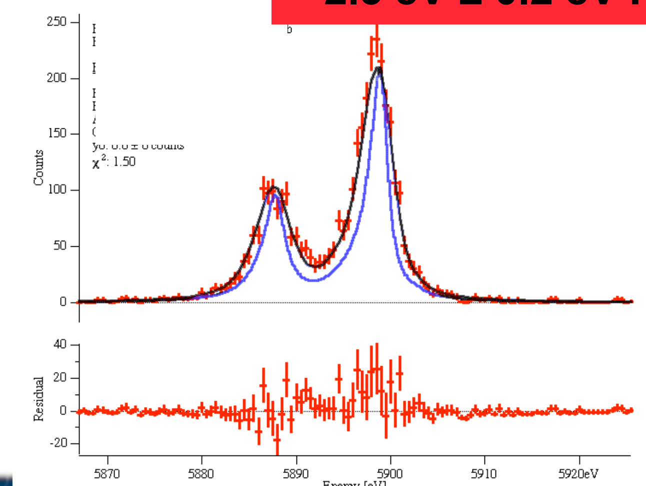


High filling factor

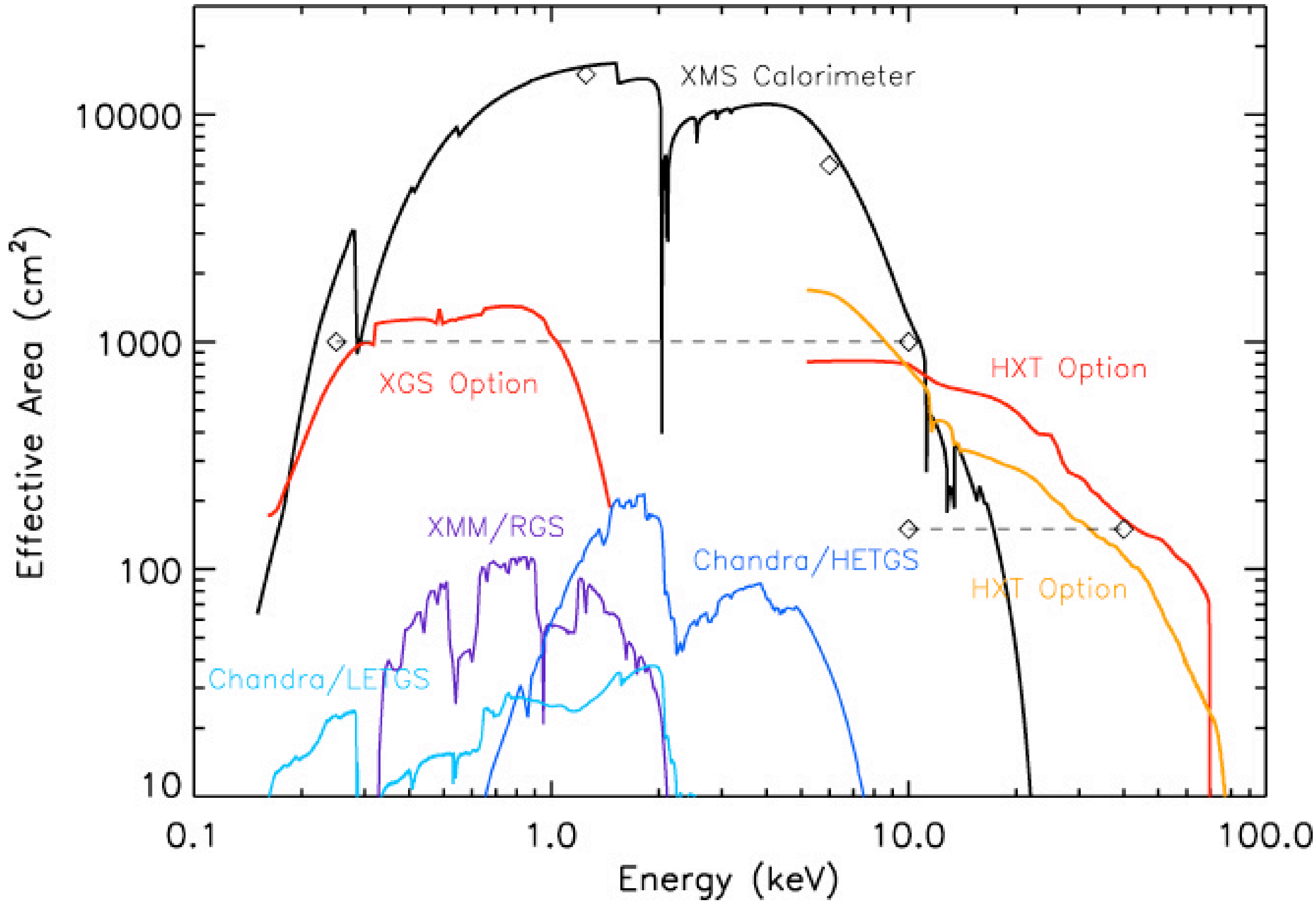
8 x8 development Transition Edge Sensor array: 250 μm pixels

- 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

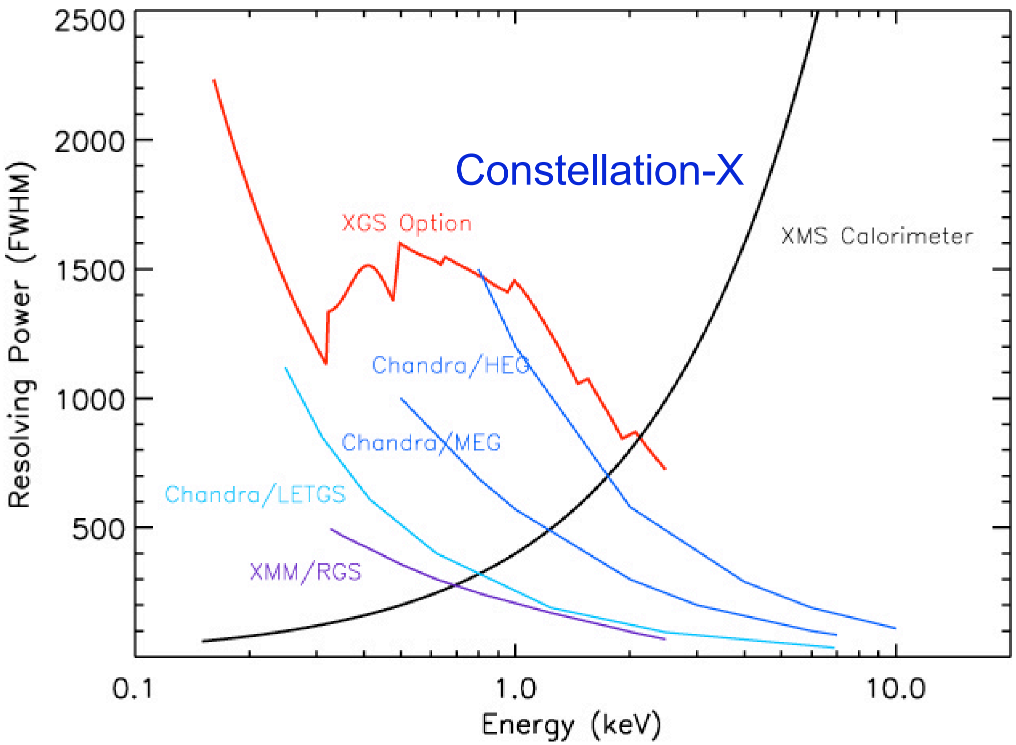
2.5 eV ± 0.2 eV FWHM

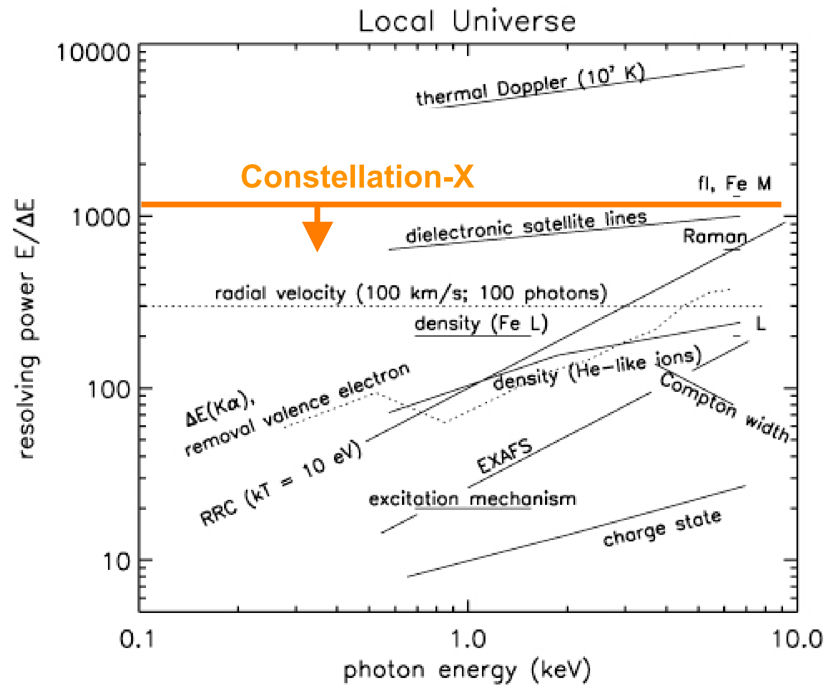


Constellation-X Effective Area

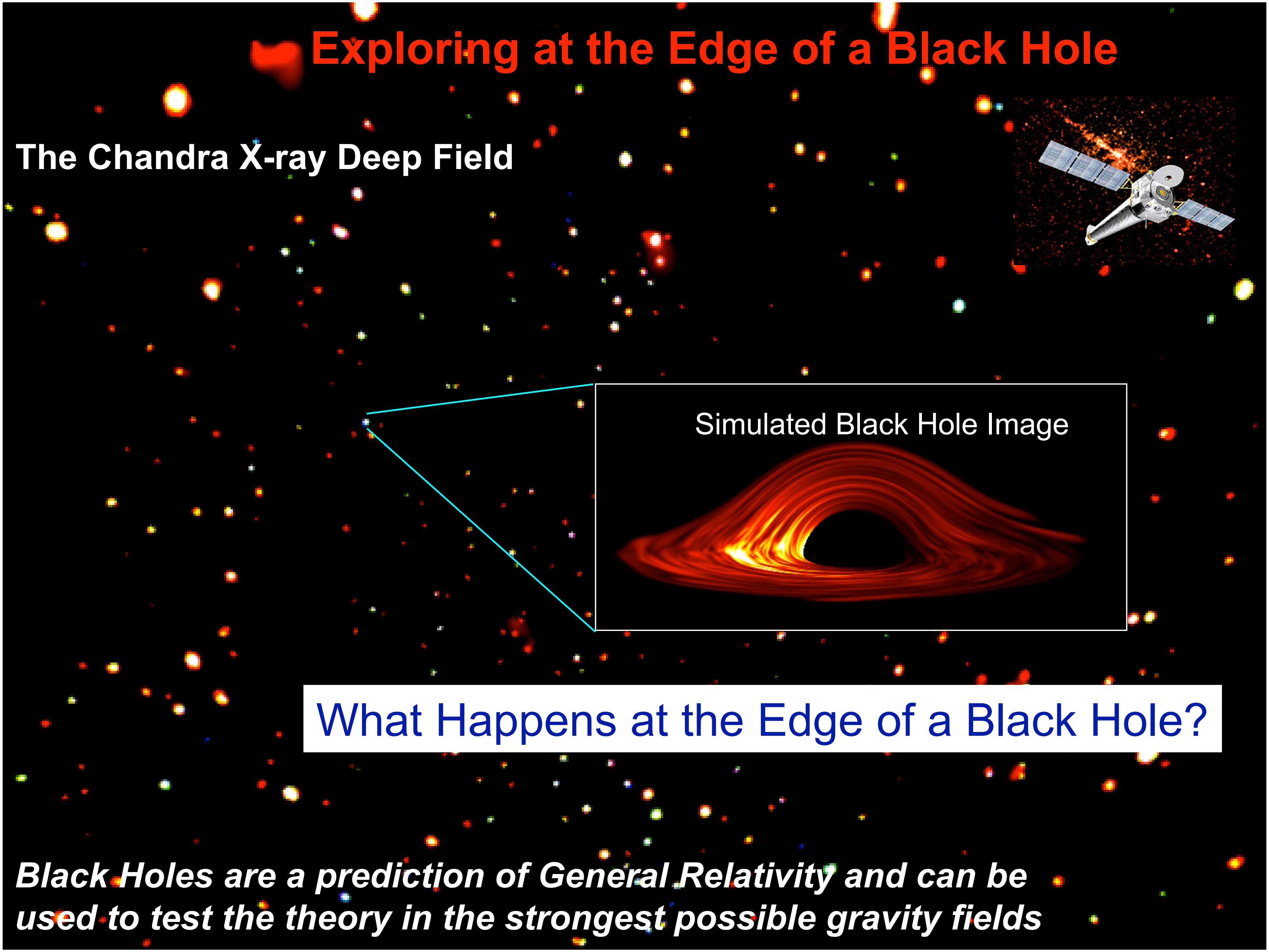


Spectral Capability



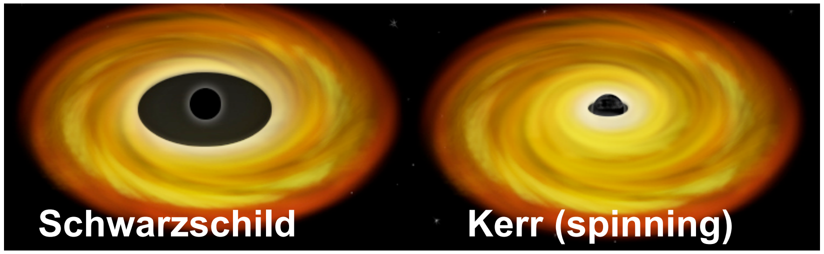


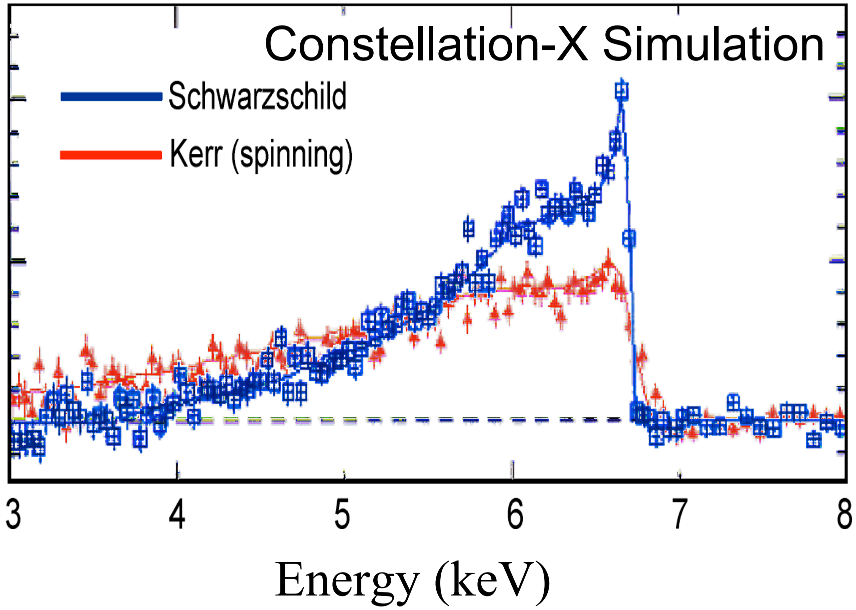
The Constellation-X energy band contains the K-line transitions of 25 elements Carbon through Zinc allowing simultaneous direct abundance determinations using line-to-continuum ratios, plasma diagnostics and at iron K bulk velocities of 200 km/s or better


Exploring at the Edge of a Black Hole
The Chandra X-ray Deep Field
Simulated Black Hole Image
What Happens at the Edge of a Black Hole?
Black Holes are a prediction of General Relativity and can be used to test the theory in the strongest possible gravity fields

Black Hole Science with Constellation-X

- Nature is providing us with a new and direct probe of strong field General Relativity in the vicinity of Black Holes
- Relativistically broadened iron K lines have been detected from within 6 gravitational radii of Black Hole by ASCA, XMM-Newton, Chandra and Suzaku
- Constellation-X will test the predictions of GR in the strong gravity limit on orbital timescales near the event horizon
- Current observation times to resolve detailed profiles are typically 1 day, compared to orbital timescales of an hour for 10^7 solar mass black hole
- Further progress towards using this feature as a strong gravity diagnostic requires Constellation-X



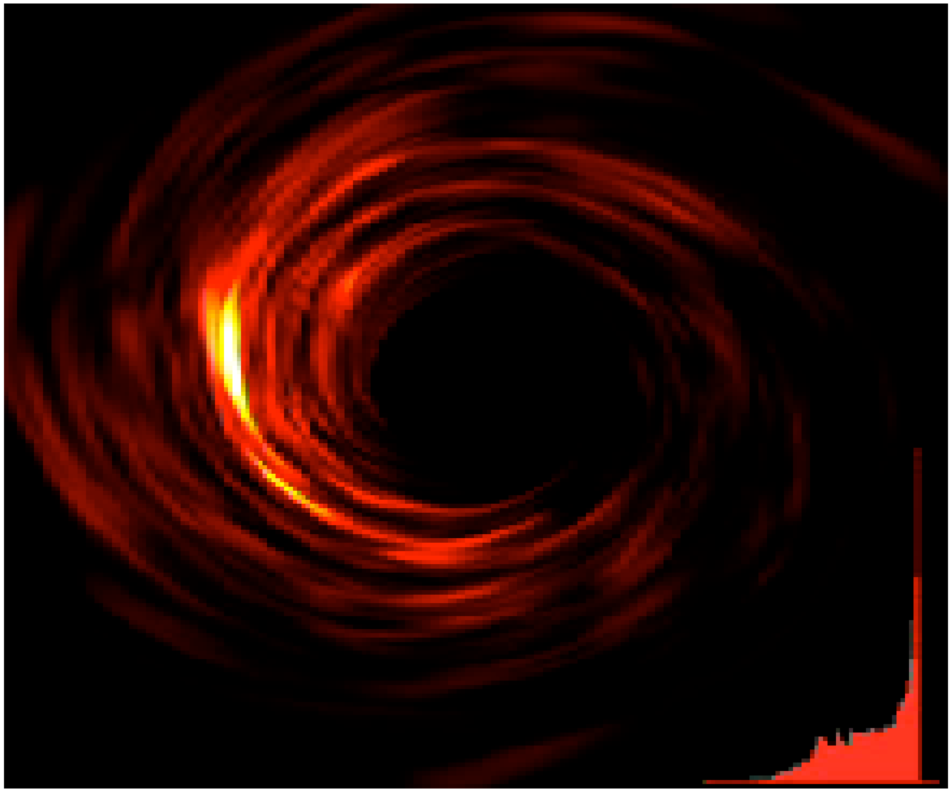


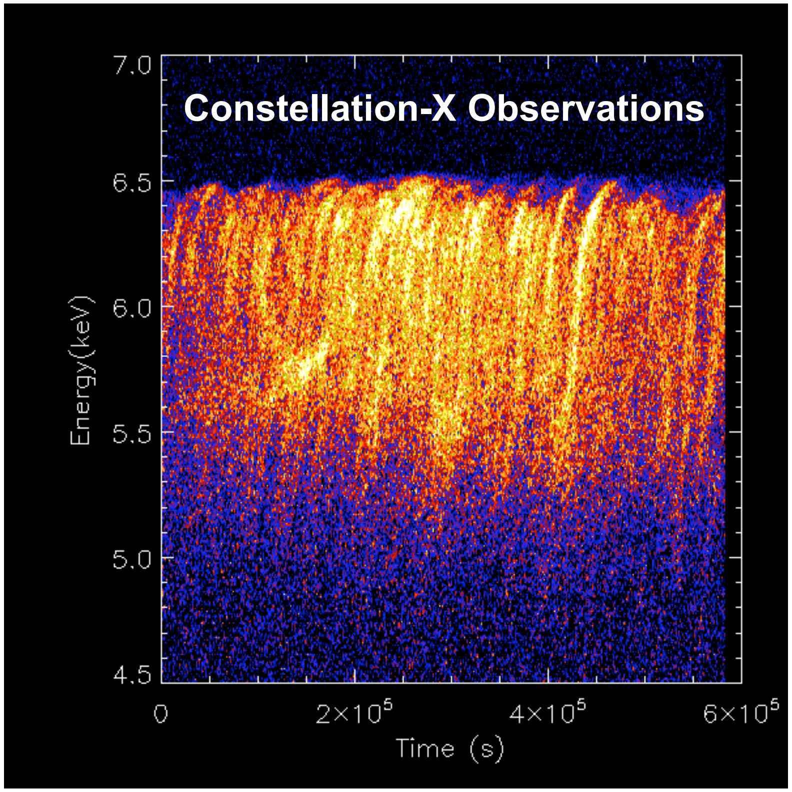
Very Broad Line = Spinning BH

Constellation-X Observing Strong Gravity

Constellation-X will study detailed line variability on orbital times scale close to event horizon in nearby supermassive Black Holes:

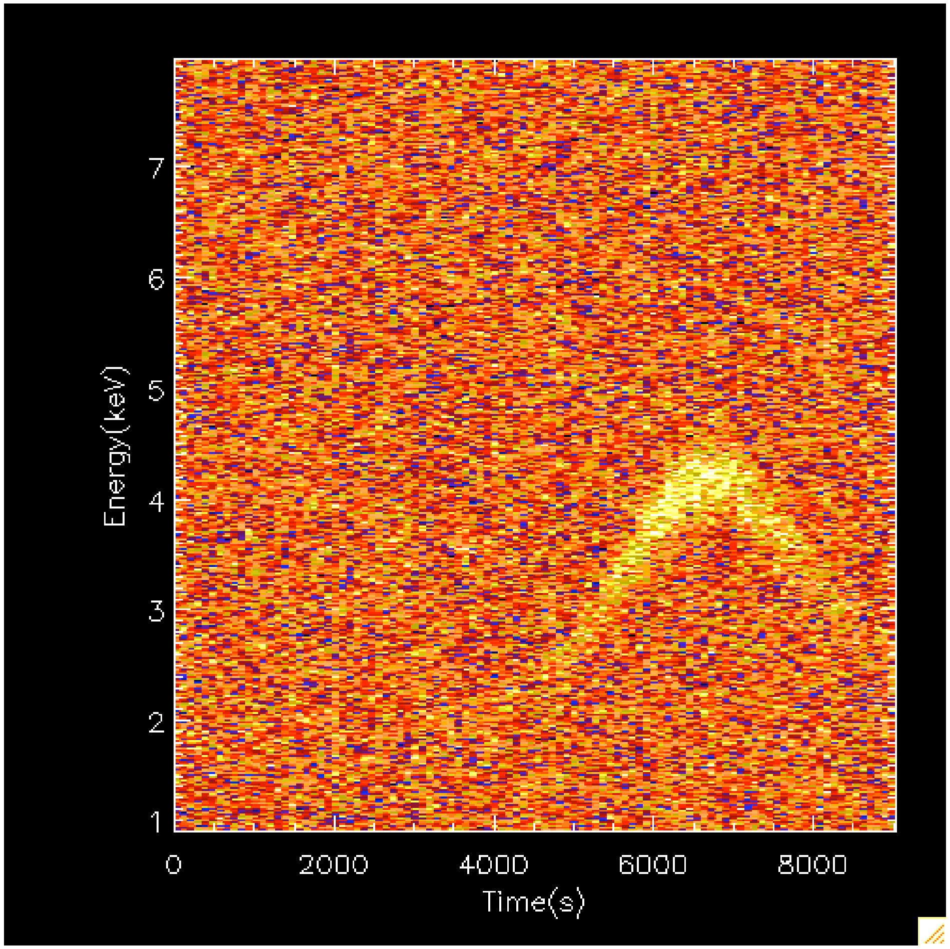
- Dynamics of individual “X-ray bright spots” in disk to determine mass and spin
- Quantitative measure of orbital dynamics: Test the Kerr metric





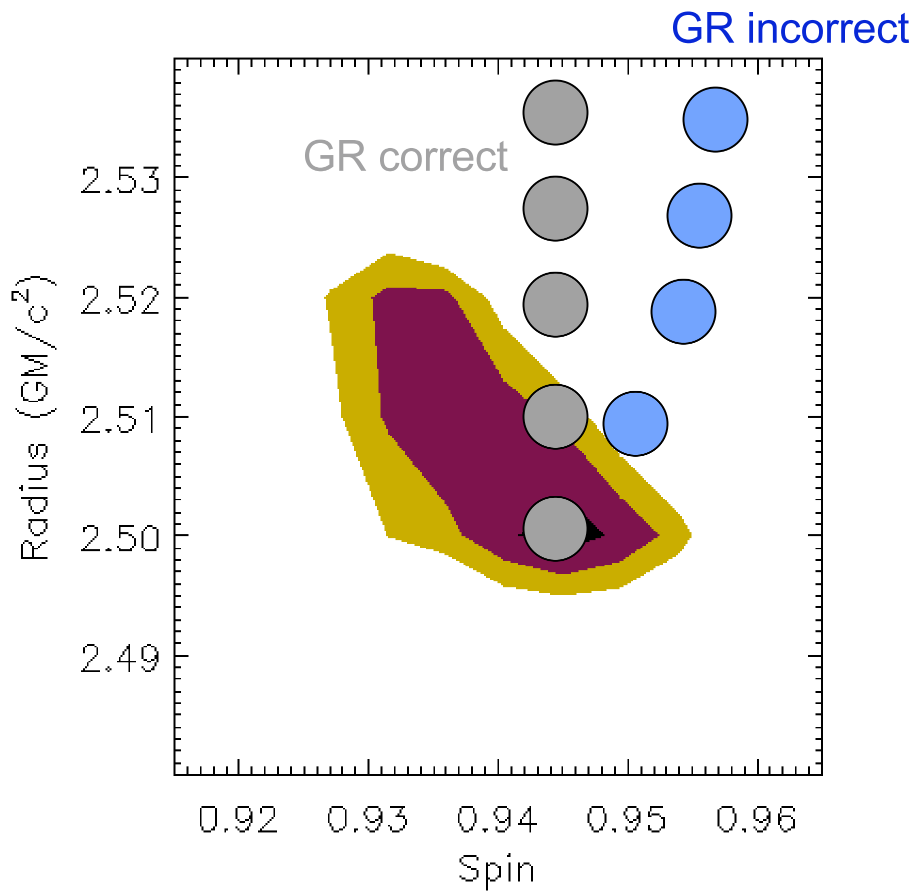
Magneto-hydro-dynamic simulations of accretion disk surrounding a Black Hole (Armitage & Reynolds 2003)

Testing GR via consistency of measurements



$F=5\times10^{-11}$ erg/s/cm2; EW=20eV; $M=6\times10^{7}$
r=2.5 ; a=0.95 ; i=30 degrees

If GR is correct, Con-X measured spin and mass should be independent of radius of bright spot

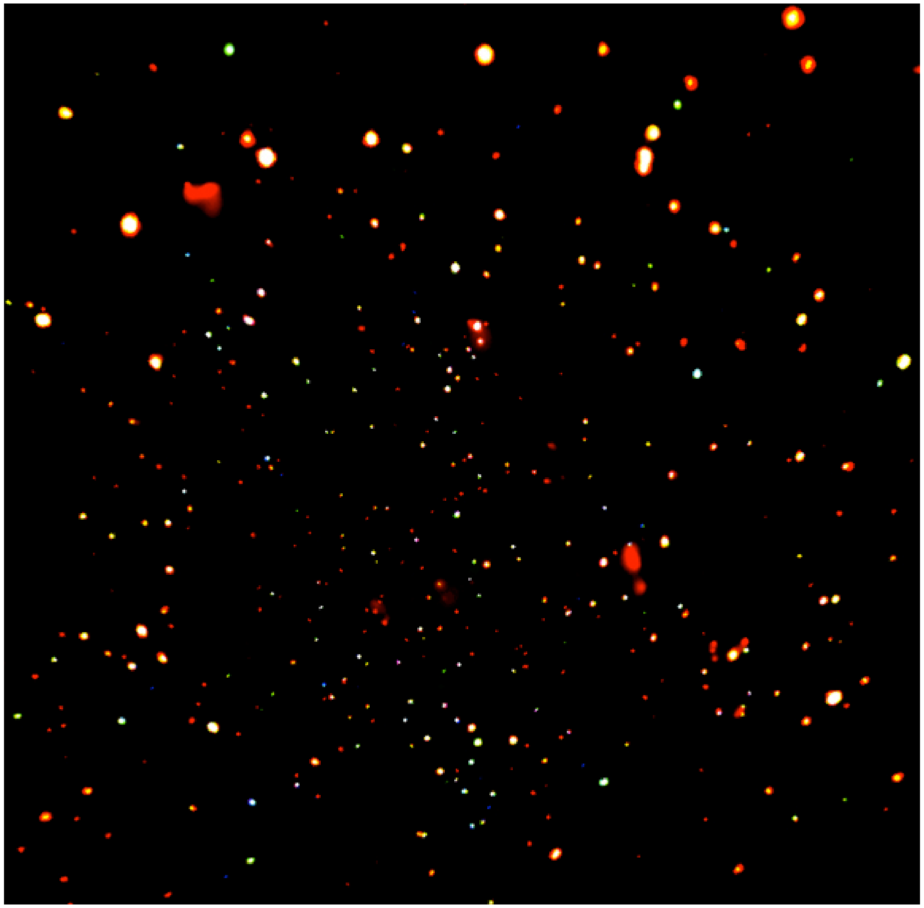


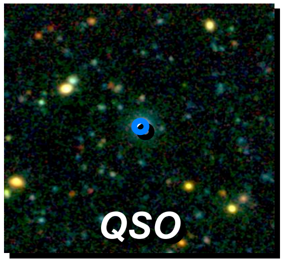
C. Reynolds University of Maryland

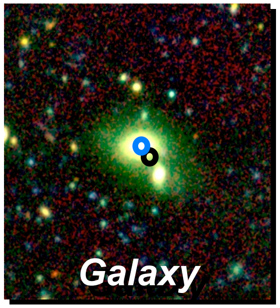
The Chandra Deep Fields

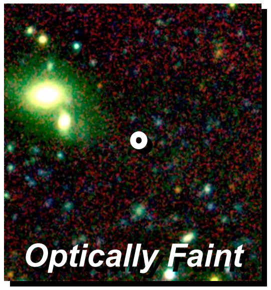
Chandra has resolved the X-ray background into active galactic nuclei (AGN) with a space density of a few thousand per sq deg

2 Megasecond Observation of the CDF-N (Alexander et al. 2003)







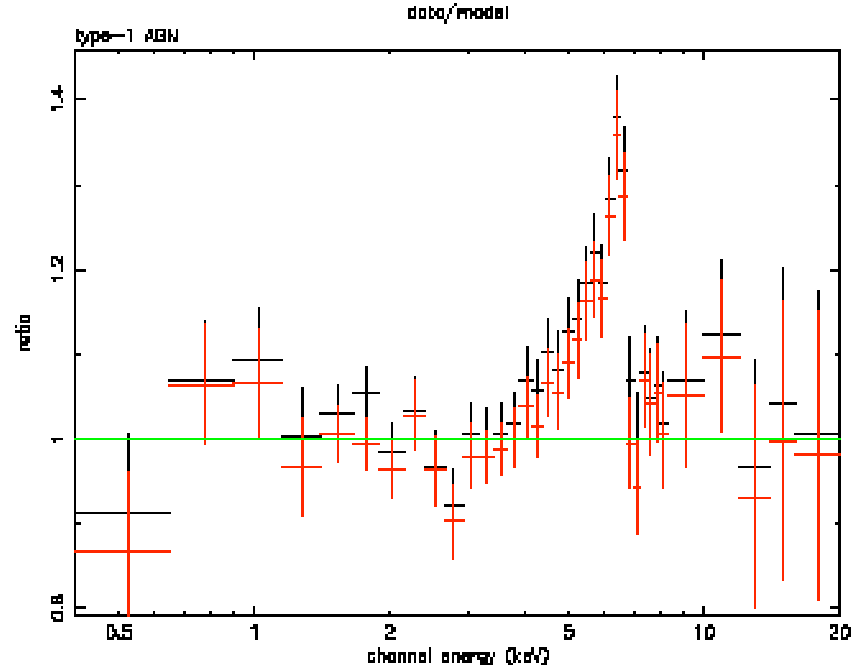


Chandra sources identified with mix of active galaxies and normal galaxies, many are optically faint and unidentified

The High Redshift Universe with Constellation-X

- ♣ Strebylanska et al. (2005) find relativistically broadened Fe K lines with equivalent widths of hundreds of eV in the XMM Lockman Hole survey:
  - – Line detected from stacking many objects on top of each other
- ♣ Constellation-X will be able to measure such lines over 0 < z < 6.5, and even from 6.5 < z < 8.0:
  - – For individual systems
  - – Constellation-X may *identify* z > 6.5 AGN via X-ray spectroscopy alone using the Fe Kα line

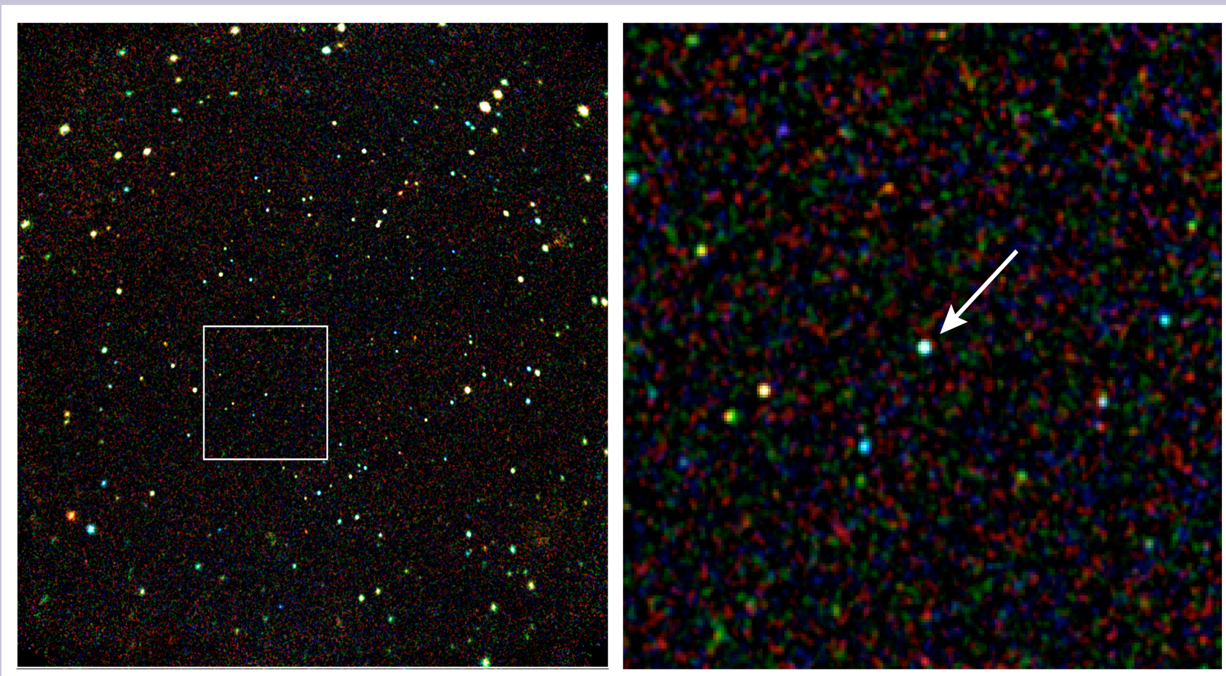
Streblyanska et al (2004)
astro-ph/0411340

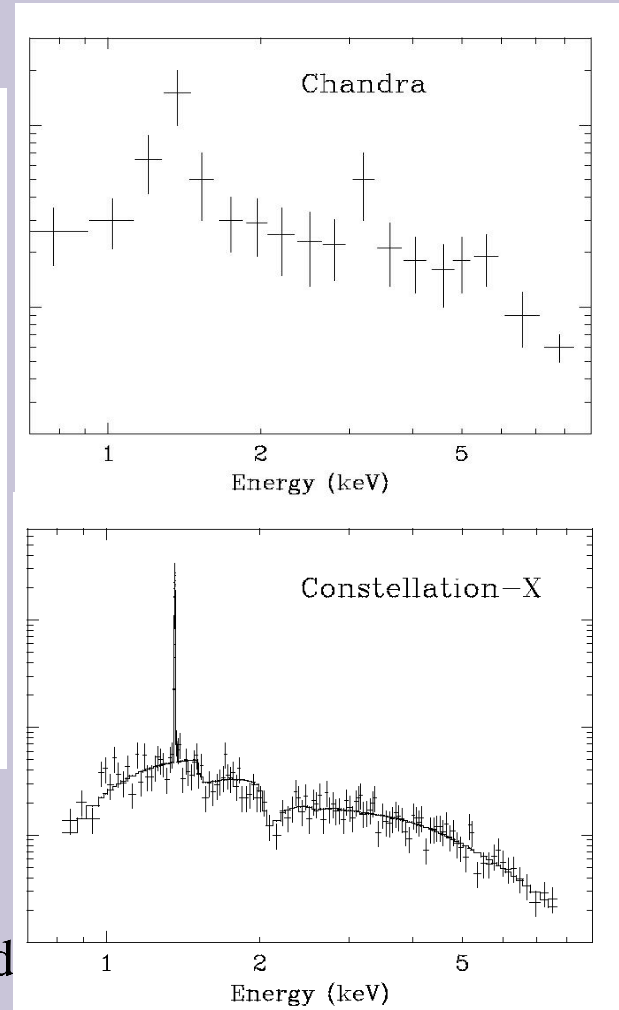


Stacked XMM spectrum of 53 Type 1 AGN

Constellation-X Identification of Faint Chandra Sources

The high redshift universe of AGN



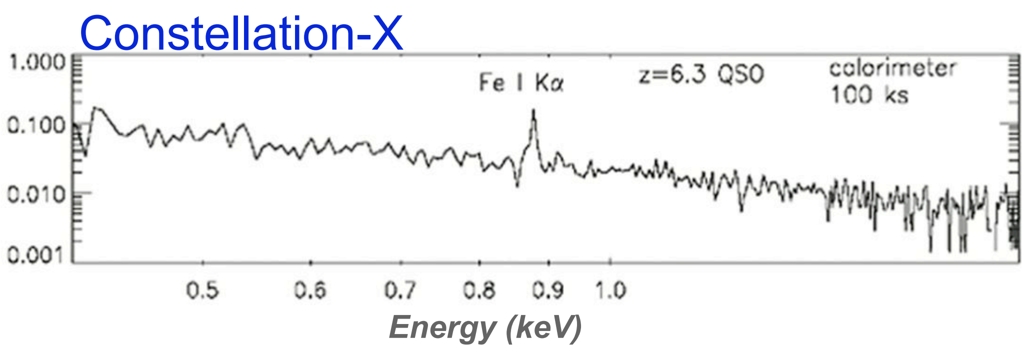


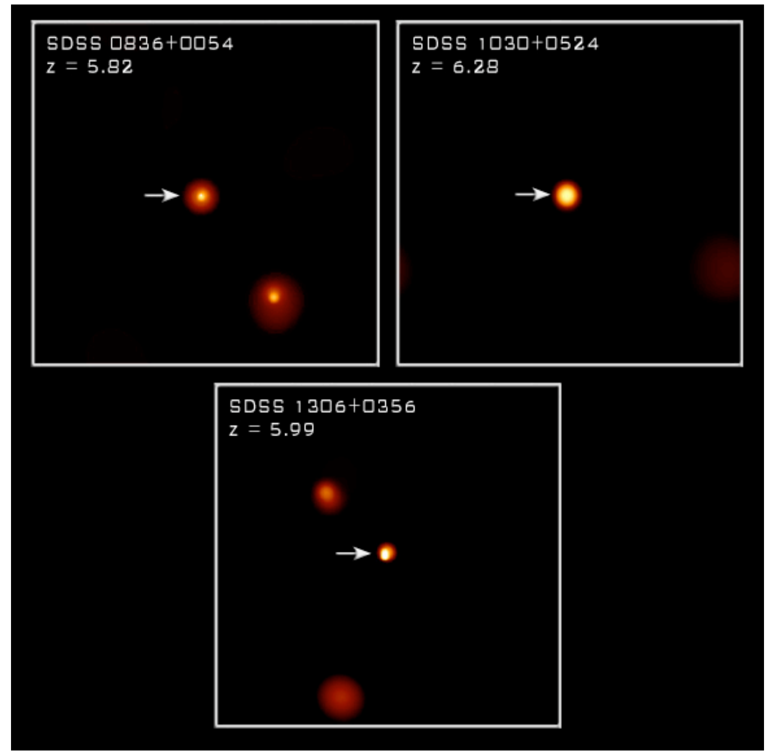
Constellation-X will gather high quality spectra of these faintest X-rays sources that make up the X-ray background, like this z = 3.7 type II quasar discovered serendipitously by *Chandra*.

Constellation-X Spectroscopy of High Redshift QSOs

Chandra has detected X-ray emission from multiple high redshift quasars at z ~ 6 found in the Sloan Digital Sky Survey (3 examples shown)

Flux of 2-10 x 10^{-15} erg cm^{-2} s^{-1} beyond grasp of XMM-Newton, Chandra or Suzaku high resolution spectrometers, but within the capabilities of Constellation-X to obtain high quality spectra

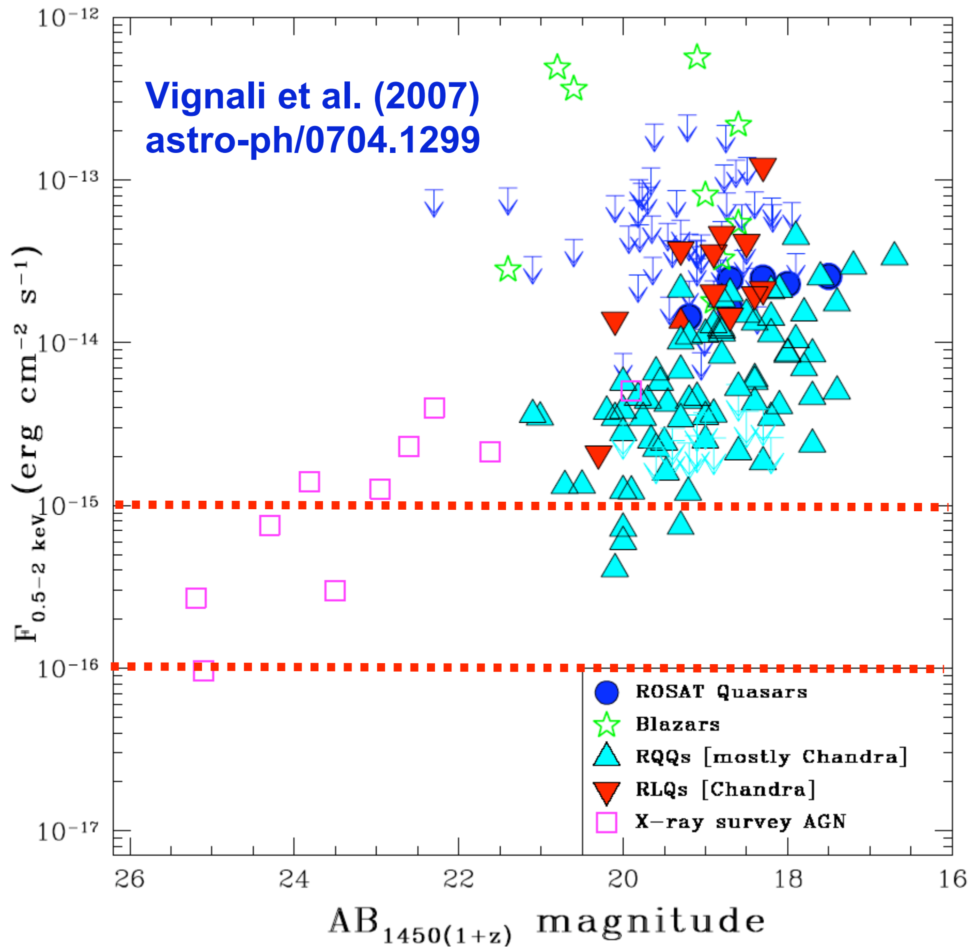




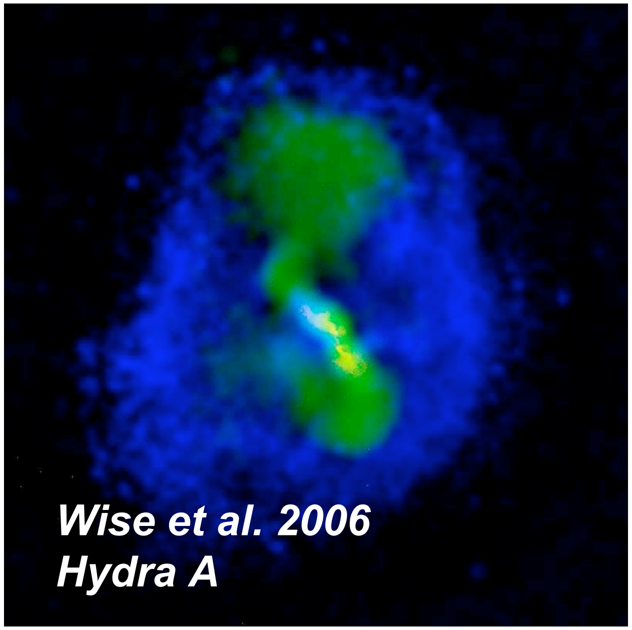
High resolution spectroscopy of QSOs enables study of the evolution of black holes with redshift and probe the intergalactic medium of the early universe

Constellation-X QSO Evolution: *z*>4 AGN discovered by Chandra/XMM-Newton

- ♣Number of X-ray detections at $z > 4$ has increased from 6 in 2000 to ≈ 100 today.
- ♣Example science topics
  - Are there any differences in accretion disk environment of luminous AGN over observed 12 billion year interval?
  - Is there an "X-ray Baldwin Effect" where e.g., covering fraction decreases with luminosity, explaining the lack of Fe Kα lines in these high-z AGN (e.g., Page et al. 2004)?
- ♣*Constellation-X* has the sensitivity to identify and study Fe Kα emission lines in individual high-redshift AGN, providing insight into the conditions necessary to produce iron K-alpha emission and its evolution with redshift.



Cosmic Feedback

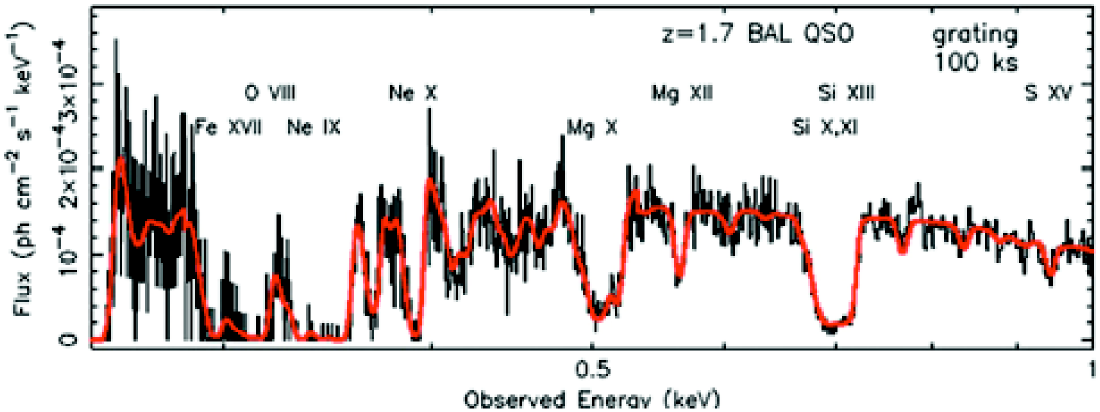


Wise et al. 2006
Hydra A

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

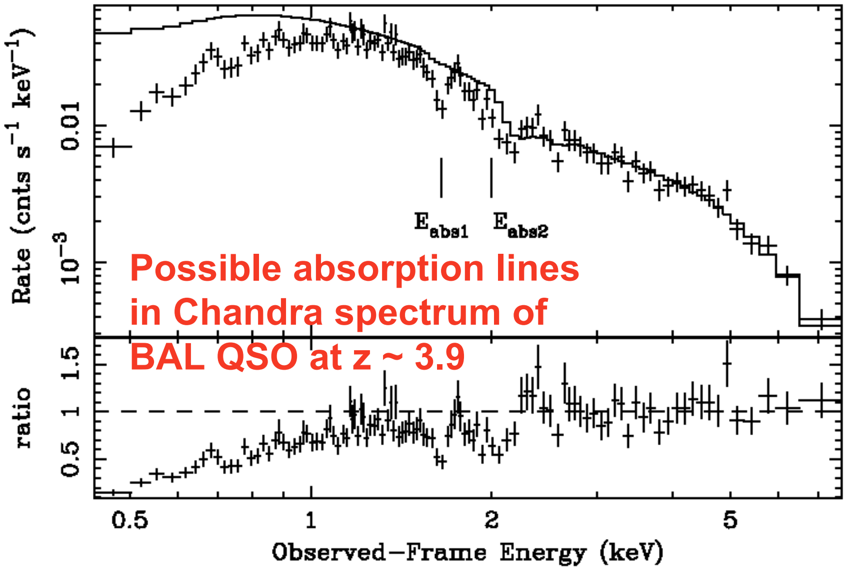
- *Spatially resolved X-ray spectroscopy required to probe turbulence in cluster cores showing radio bubbles (jets) and Constellation-X will have velocity resolution of 200 km/s or less*
- *High spectral resolving power required to determine mass outflows in quasars with winds*

Con-X simulation of BAL QSO (S.Gallagher, UCLA)



Con-X will reach the powerful AGN outflows in the quasar epoch (1<z<4)

Out flows in high redshift QSOs

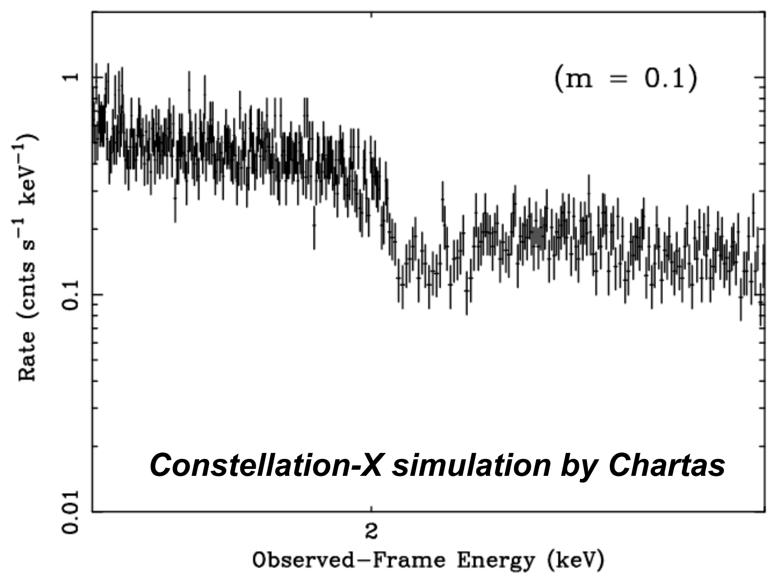


Chartas et al (2002) and Hasinger et al (2002) have discovered highly ionized and variable absorption iron K features in the spectra of APM 08279+5255, a z~3.9 broad absorption line quasar

Magnified by factor of 50-100 by gravitational lens, gives a taste of Constellation-X observations --- albeit at low "CCD-resolution"

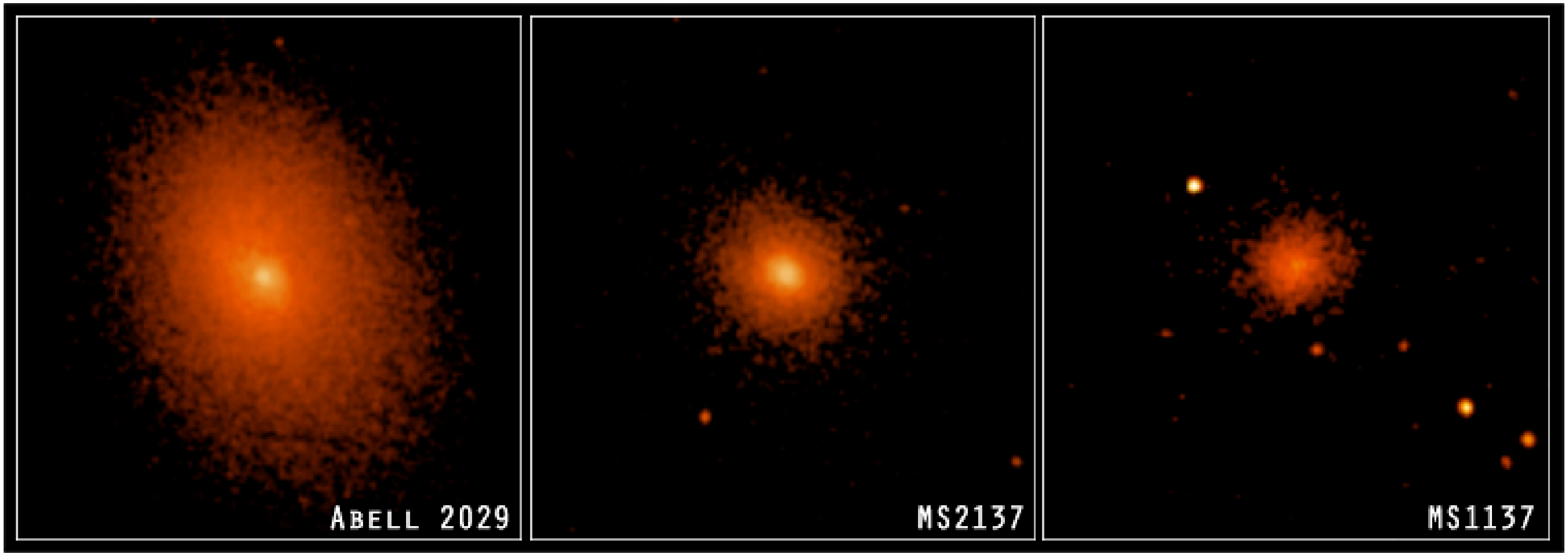
Features probably come from outflows and related to 12,000 km/s winds seen in UV.

Features are are low "CCD-resolution", high resolution spectroscopy by Constellation-X will allow following the time variability and structure of features



Constellation-X simulation by Chartas

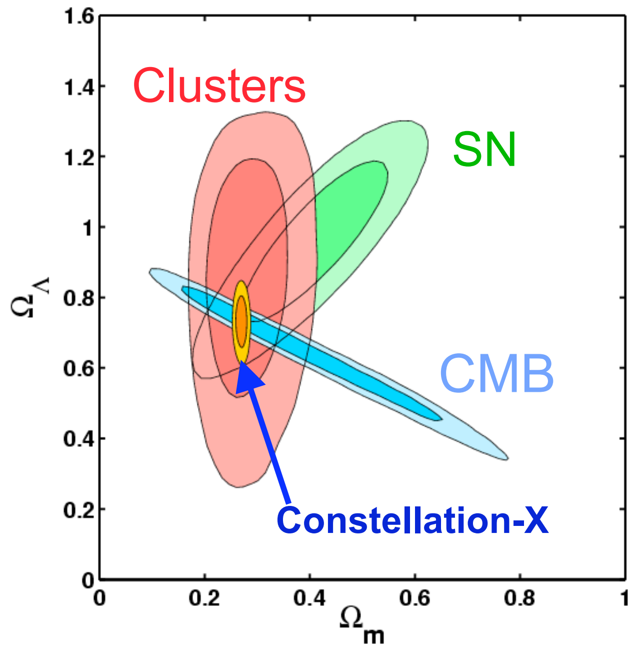
Chandra data on Clusters

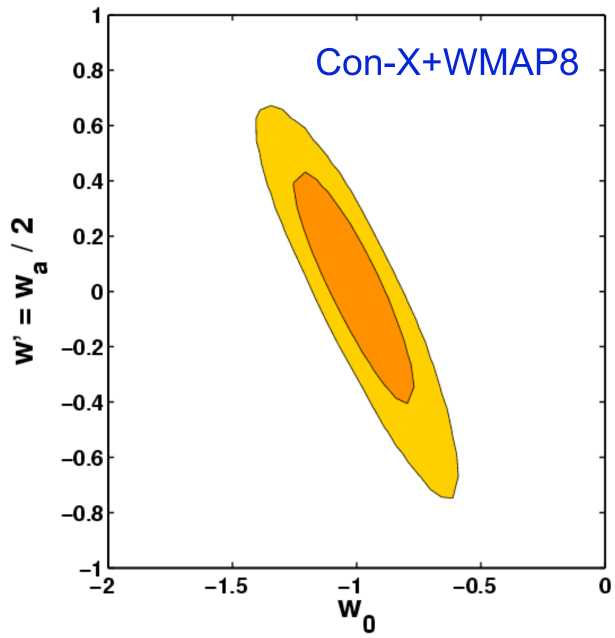


Cluster of Galaxies can be used to constrain Dark Energy in two ways: 1) their evolution is very sensitive to Cosmology and 2) they are “standard candles” thru gas mass fraction and SZE distance measures

The Clusters to use are the most dynamically relaxed, highly X-ray luminous clusters spanning the redshift range $0<z<1.1$

Dark Energy Cosmology with Constellation-X





Factor of ten improvement

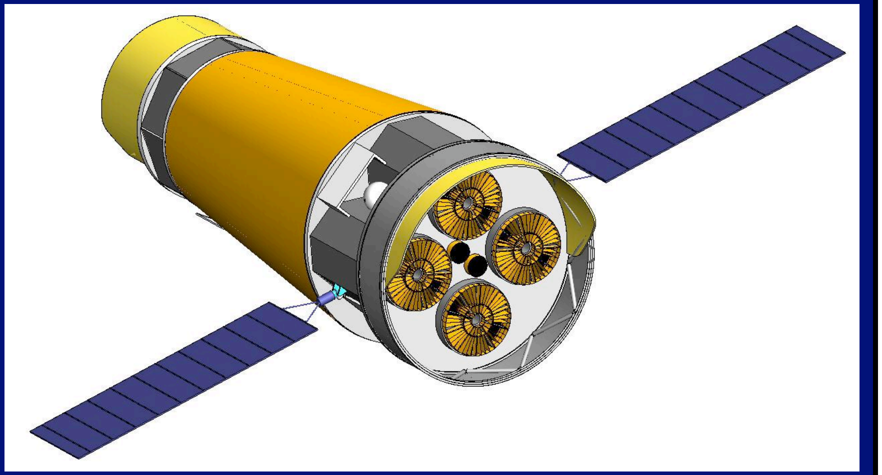
In the terms of the Dark Energy Task Force Figure of Merit this is a Stage IV result

Rapetti, Allen et al 2006 (Astro-ph/0608009)

- Using the gas mass fraction as a standard ruler measures f_{gas} to 5% (or better) for each of 500 galaxy clusters to give Ω_M=0.300±0.007, Ω_Λ=0.700±0.047
- Cluster X-ray properties in combination with sub-mm data measure absolute cluster distances via the S-Z effect and cross-check f_{gas} results with similar accuracy
- Determining the evolution of the cluster mass function with redshift reveals the growth of structure and provides a powerful independent measure of Cosmological parameters (see papers by Vikhlinin, Nagi, Kravtsov)

Mission Implementation Approach

- Four X-ray telescopes with common design, manufacture, assembly, and testing
- Manageable mirror dimensions and 10m focal length provide required area
- Single spacecraft, single launch with proven subsystems and launch vehicles
- Mission success (via longer exposures) even with loss of one detector



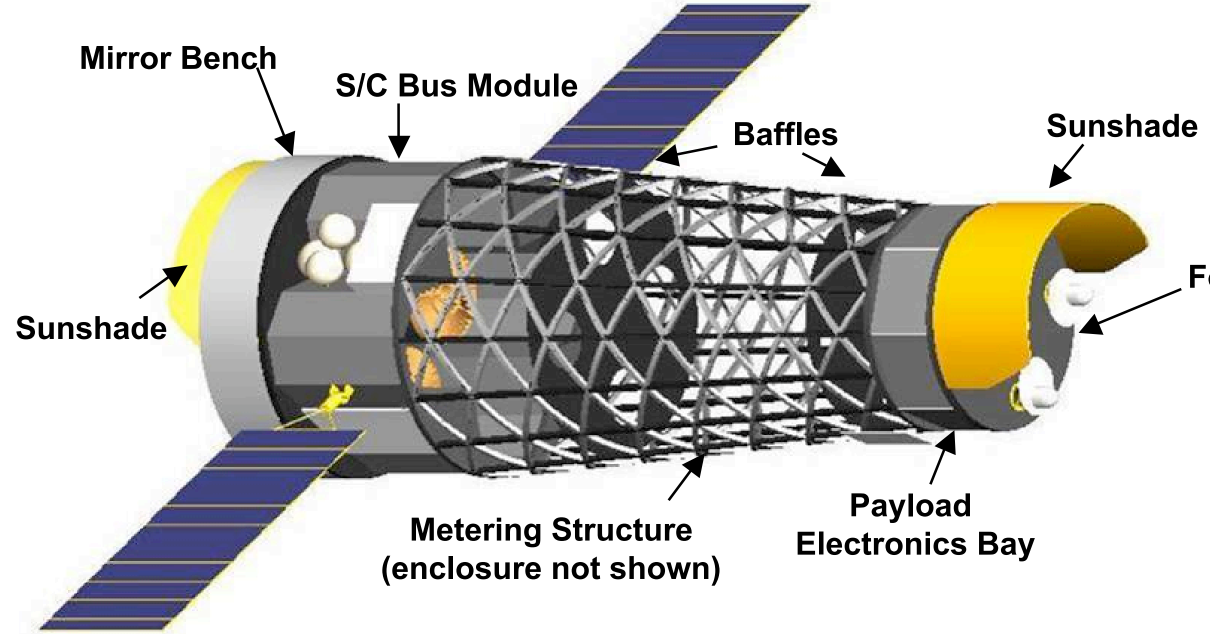
Approach Reduces Risk and Costs

CY '98	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16	'17	'18	'19	'20	'21	'22

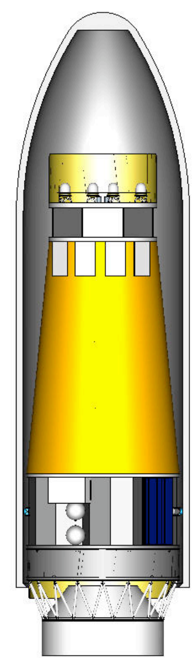
Preformulation | **Formulation** | **Implementation** | **MO&DA**

Instr AO · **CDR** · **Launch**

Observatory Configuration



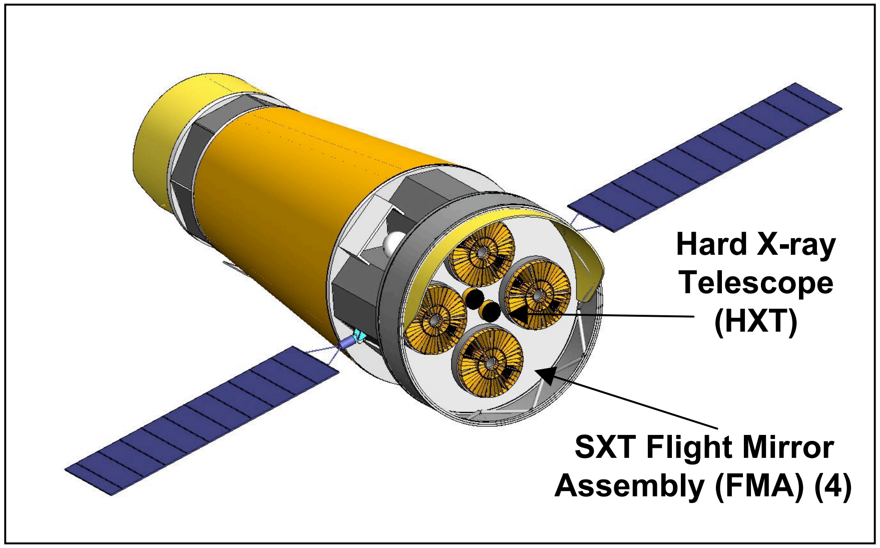
Launch Mass	6217 kg, includes 30% contingency plus margin
Average Power	22 sq m of solar array provide 4200W end-of-life (10 yr on consumables)
Data	150 kbps (avg); 1325 kbps (peak); two days storage capacity (144 Gbit)
Pointing (3_)	Knowledge 5, 5, 20 (pitch yaw, roll)
Spacecraft Bus	Existing components, no new technologies
Modular Design	Supports parallel integration and test
Reliability	No performance degradation w/ single point failure

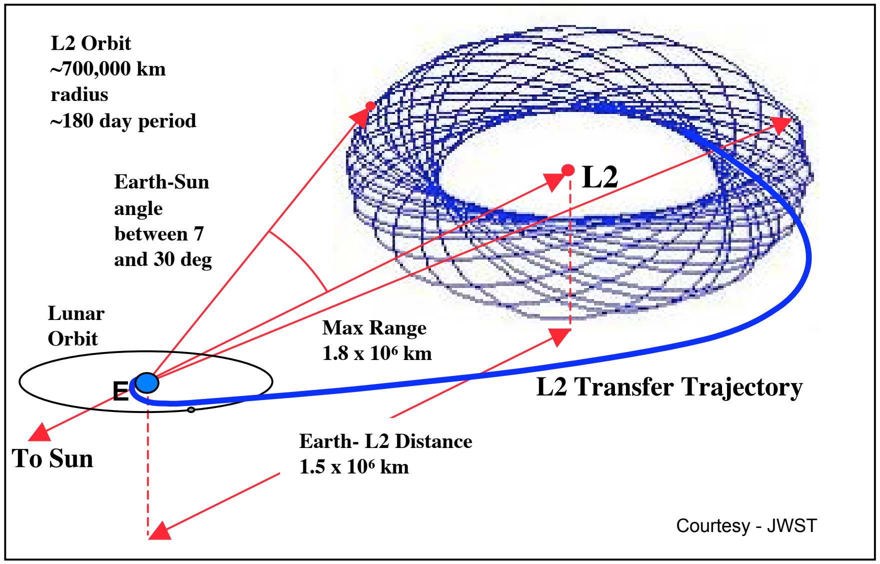


Con-X in Atlas V 551

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

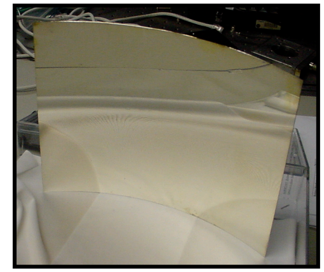




Flight Mirror Assembly

Forming

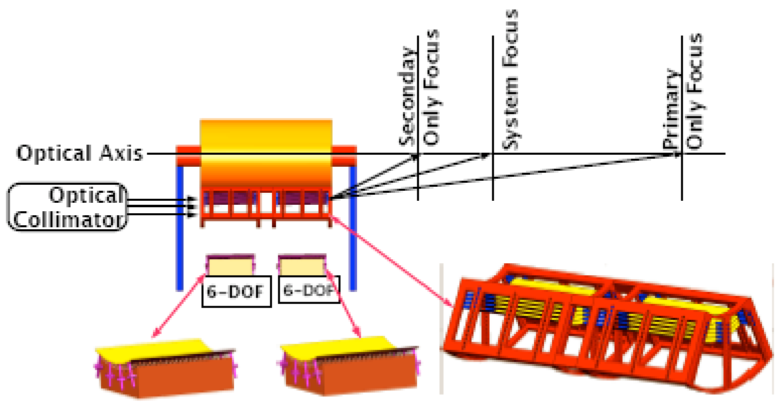
Mirror segment on a precisely figured mandrel

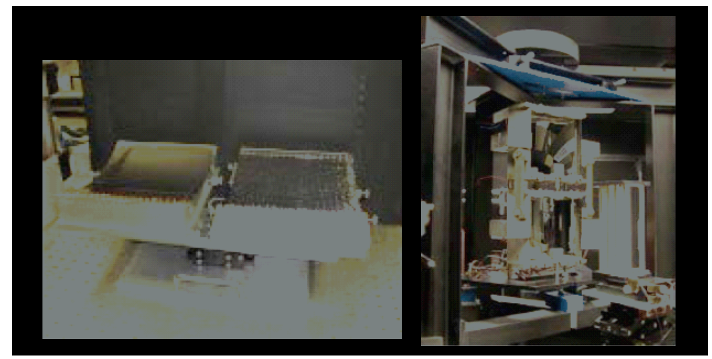


X-ray mirror

Angular Resolution Req't: 9.9 arcsec HPD

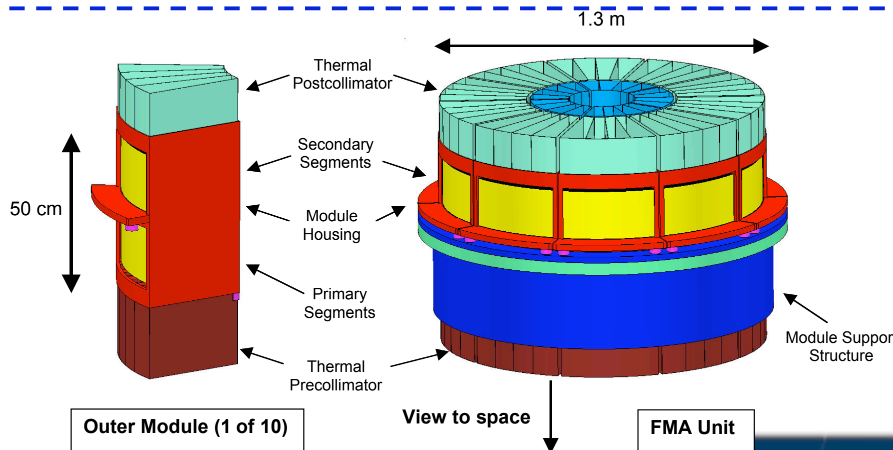
Alignment & Bonding

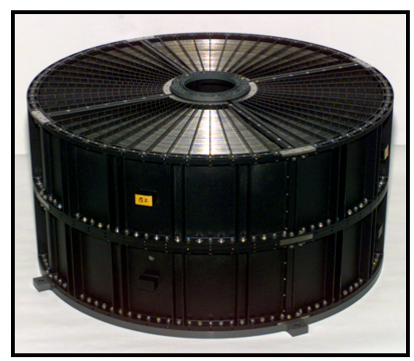




Passive (L) and active (R) alignment approaches – Not metrology limited

Assembly

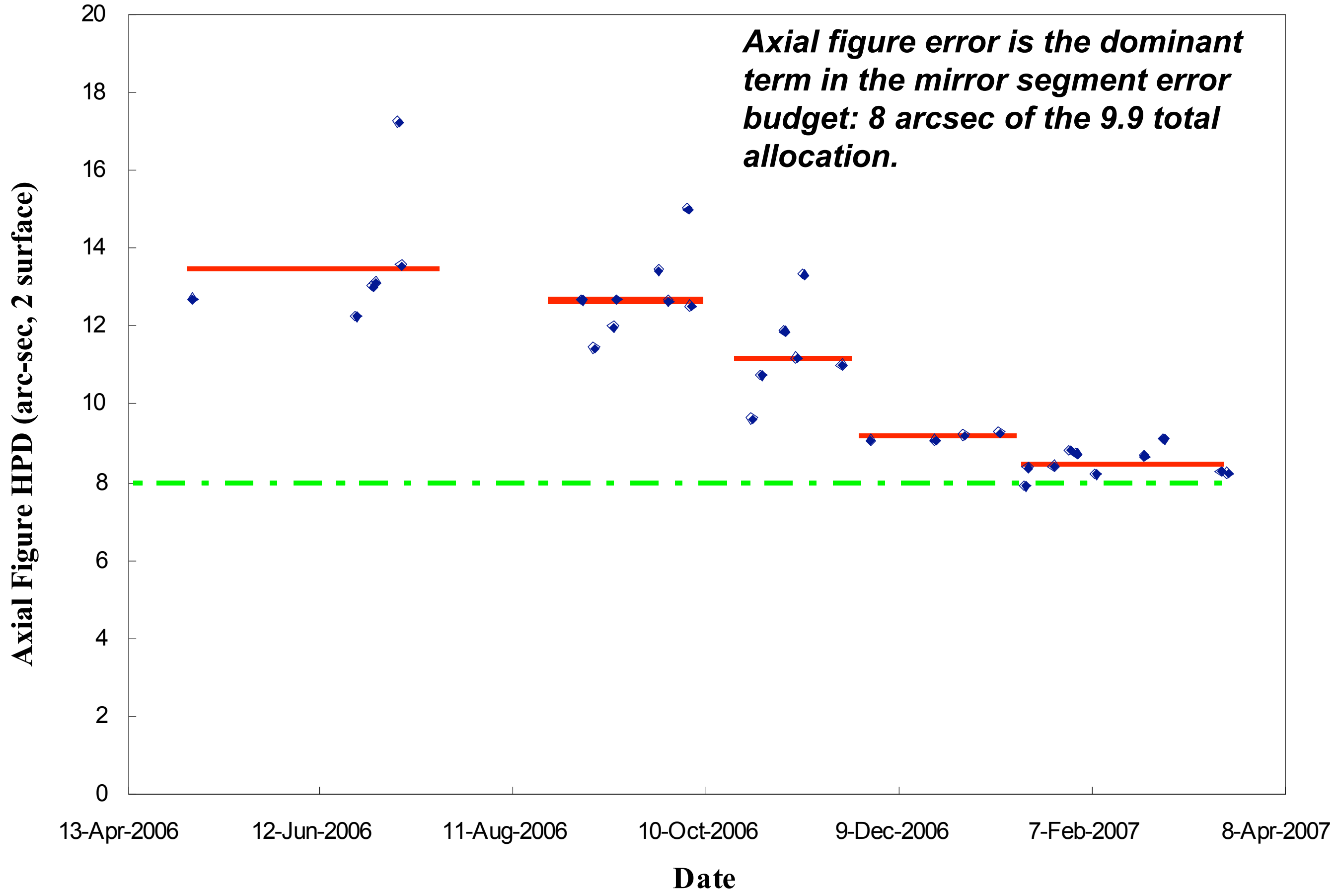




Heritage Suzaku flight mirror (40 cm diameter)

Angular Resolution Req't: 12.5 arcsec HPD

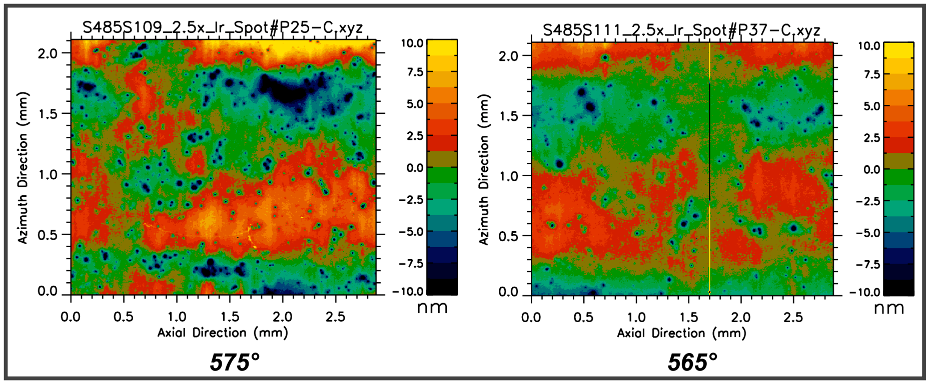
SXT Mirror Segment Progress



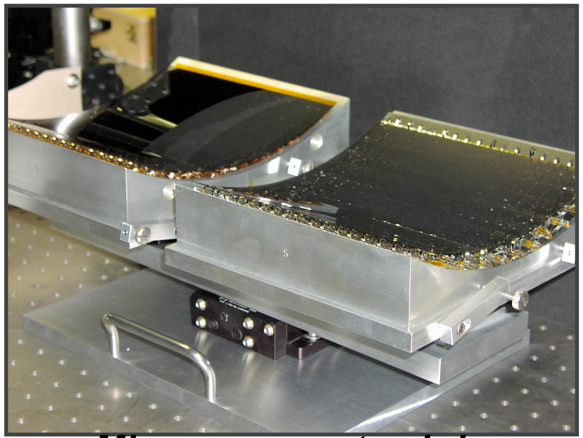
Mirror segment forming process improvements introduced over the past year have led to consistent improvement in segment performance, as indicated by the axial figure HPD. The most recently produced segments are approaching the performance requirement, indicated by the green dashed line.

Technology Progress
Spectroscopy X-ray Telescope (SXT) Mirror Technology Development

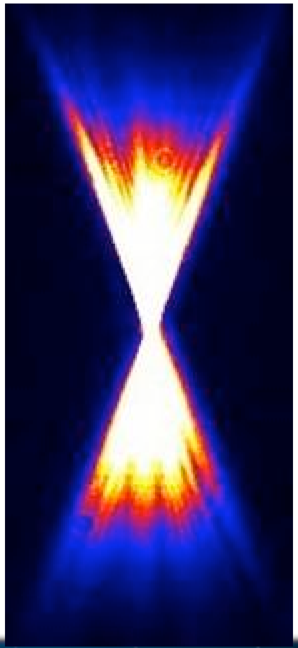
- Mirror Segment Fabrication
  - Current emphasis is improving high frequency error
  - Lowering mirror segment forming temperature produced encouraging results
  - Investigation of alternate materials and finish for forming mandrels underway
- Mounting and Alignment
  - Aligned a pair of mirror segments (for the first time) and achieved focus of 1.6 arcsec RMS radius (req't is 2.0 arcsec)
  - Stability of mount being optimized in prep for X-ray test



High frequency error reduced by lowering forming temperature

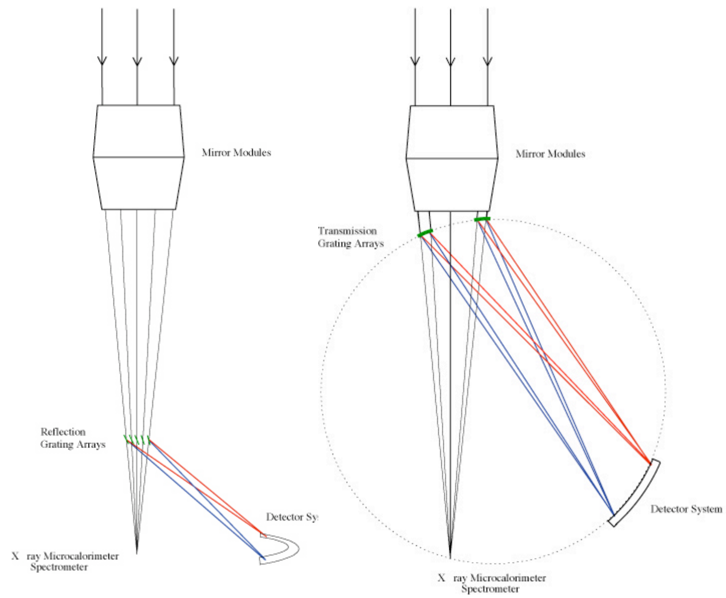


Mirror segment pair in cradle system



X-ray Grating Spectrometer (XGS)

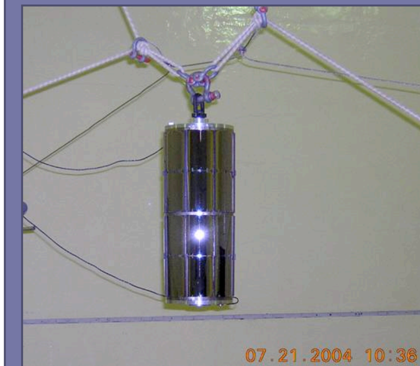
- XGS key requirements:
  - Effective area >1000 cm^2 from 0.3 to 1 keV
  - Spectral resolving power 1250 over full band
- Two concepts under study for the grating arrays:
  - Fixed transmission grating
  - Off-plane deployed reflection grating
  - Heritage from Chandra, XMM, and sounding rockets



- CCD detectors:
  - Back-illuminated (high QE below 1 keV),
  - Fast readout with thin optical blocking filters
  - Heritage from Chandra, XMM, Suzaku

Hard X-ray Telescope (HXT)

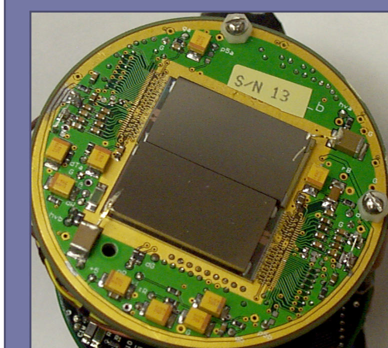
- HXT key requirements:
  - Effective area of 150 cm^2 from 6 to 40 keV
  - Spectral resolving power 10 over full band
  - 30 arcsec HPD
- Two potential technologies for the mirrors
  - Nickel Shell & Glass Segment
  - Highly nested optics with multilayer coatings
  - X-ray tests show 30 – 40 arcsec 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

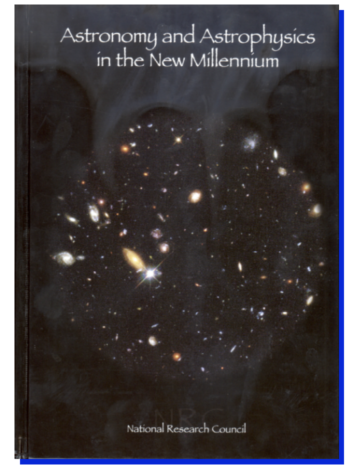
2 nested nickel mirror shells in X-ray test at PANTER



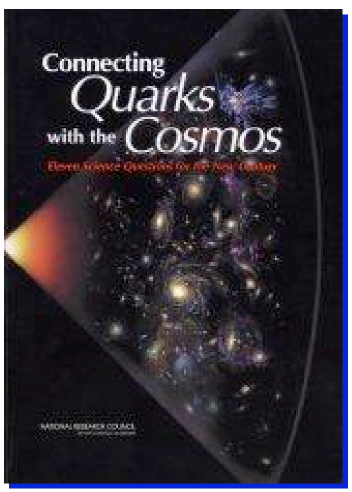
CdZnTe hybrid pixel detector

CdZnTe vibration test

Science Priority – US National Academy Reports



The Astronomy and Astrophysics in the New Millennium "2000-2010 decadal survey" ranked Constellation-X as the next to follow JWST in the large space observatory category and highlighted in particular the missions black hole science goals



The Quarks to Cosmos science assessment and strategy for research at the intersection of Physics and Astronomy in 2003 strongly endorsed the Constellation-X mission as *"holding great promise for studying black holes and for testing Einstein's theory in new regimes*" -- mission addresses 8 of 13 questions

Current Status

- Constellation-X is an approved NASA astrophysics mission, currently pre-phase A with the focus on technology development and optimizing the mission configuration
  - Recently completely a reconfiguration study that streamlined the mission configuration and maintained the science goals
- Constellation-X is the next major NASA astrophysics observatory, to follow after JWST (2013 launch), based on its ranking in the 2000 Decadal survey - budget wedge opens around 2009/2010 with 2017/18 the earliest realistic launch date
- A National Academy Review is currently examining the five Beyond Einstein missions (Con-X, LISA, JDEM, Black Hole Finder, Inflation Probe) to resolve conflicting advice between 2000 Decadal Survey and Quarks to Cosmos Academy reports and will recommend in Sept 2007:
  - which Beyond Einstein mission should be launched first, and
  - technology investments for the 2010 decadal survey

Summary

- ♣ Constellation-X opens the window of X-ray spectroscopy with a two order of magnitude gain in capability over current missions
- ♣ The science goals driving the need for this new capability are:
  - Black Holes: precisions tests of GR in the strong field limit and determination of Black Hole spin in a large sample
  - Dark Energy: precision Cosmology using clusters of galaxies to tightly constrain Dark Energy parameters using both distance and growth of structure
- ♣ Constellation-X is a Great Observatory that will enable a broad range of science that will engage a large community — Astrophysicists, Cosmologists, and Physicists through an open General Observer Program

http://constellation.gsfc.nasa.gov