The Constellation X-ray Mission

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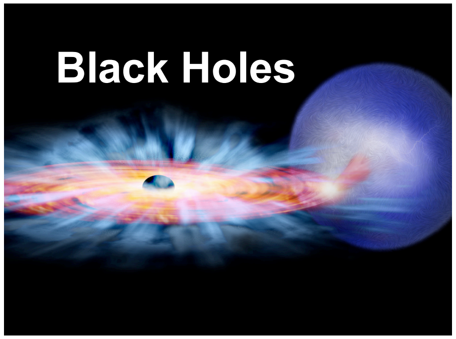
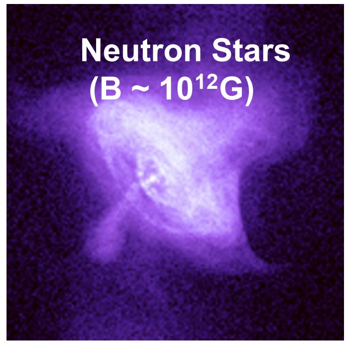
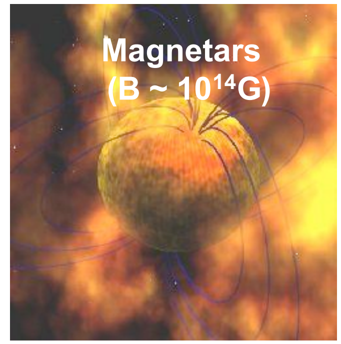
November 7, 2006 Washington DC

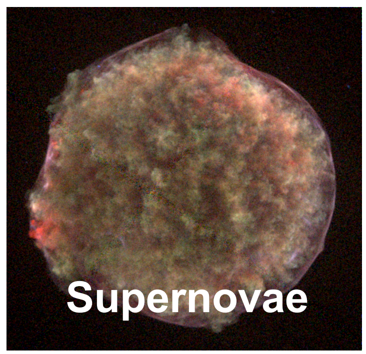
Unlocking the mysteries of Black Holes, Dark Matter and Dark Energy

X-ray emission probes the physics of extreme processes, places and events









- ♣ **High temperatures, intense gravity, strong magnetic fields — explosions, collisions, shocks, and collapsed objects**
- ♣ **Conditions not achievable in earth-bound labs or accelerators**
- ♣ **X-ray observations can only be made from space**

CONSTELLATION-X SCIENCE OBJECTIVES

Black Holes

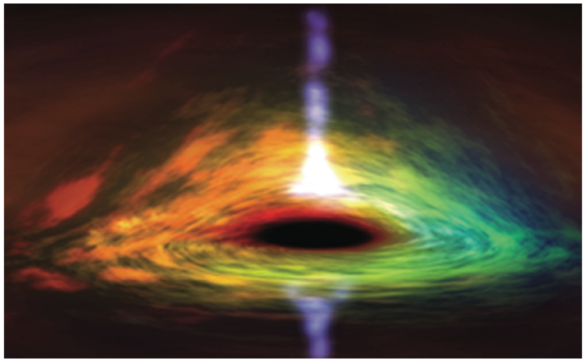
- Observe matter spiraling into Black Holes to test the predictions of strong field General Relativity
- Study distant/faint sources to trace the evolution of Black Holes with cosmic time

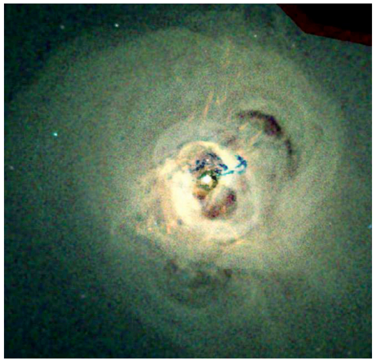
Dark Matter and Dark Energy

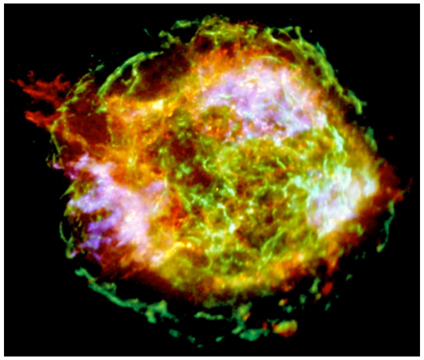
- Use Galaxy Clusters to trace dark matter and as probes for amount and evolution of dark energy

Cycles of Matter and Energy

- Study behavior of matter at extreme densities & magnetic fields using Neutron Stars
- Measure production of heavy elements in Supernovae
- Investigate the influence of Black Holes on galaxy formation
- Search for the hot missing baryons in the Cosmic Web







Constellation-X Addresses 8 of 11 Quarks to Cosmos Questions

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

Fundamental results τττ Major contribution ττ Discovery space τ

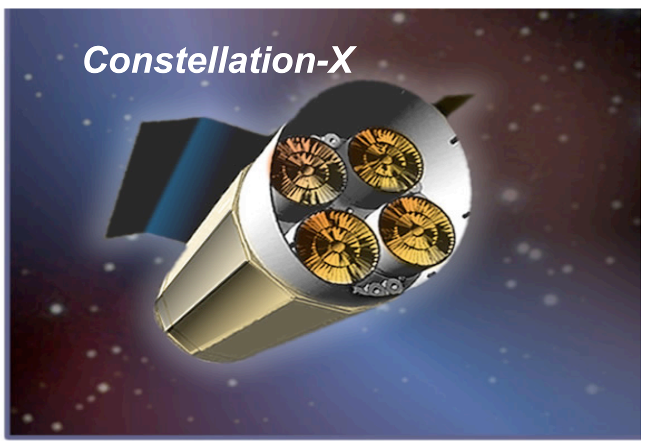
CHANDRA launched 1999 brought X-ray Astronomy to the forefront

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

More than 2000 Guest Investigators to date publishing nearly 500 refereed papers per year

Most X-ray spectra from Chandra have moderate resolution CCD spectra $E/\Delta E < 30$, insufficient for crucial plasma diagnostics

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



Resolution ($E/\Delta E$): 300-1500

Effective area is a 50-100 gain over current missions

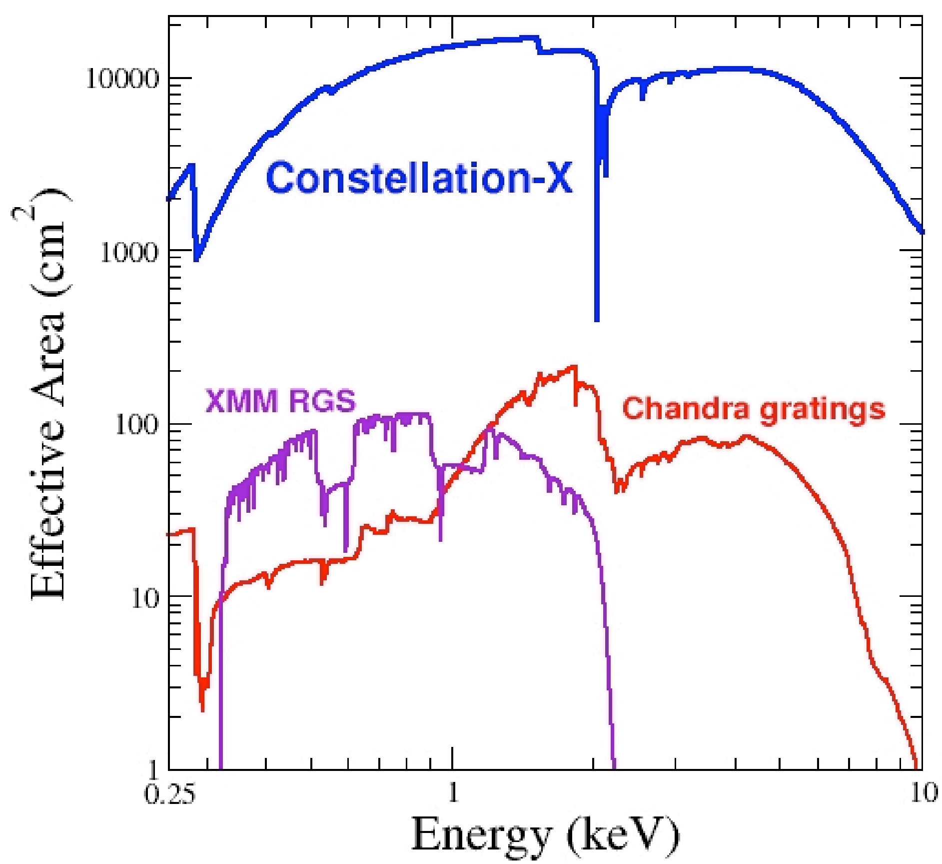
Constellation-X fills a critical gap required to address the Beyond Einstein science goals

Science priority recognized by the 2000 *Astronomy and Astrophysics in the New Millennium decadal survey*, second only to JWST among major space initiatives

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

Key Constellation-X Capabilities

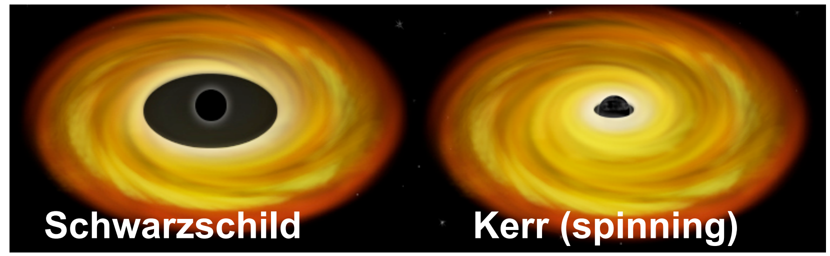
Comparison of X-ray mission collecting areas

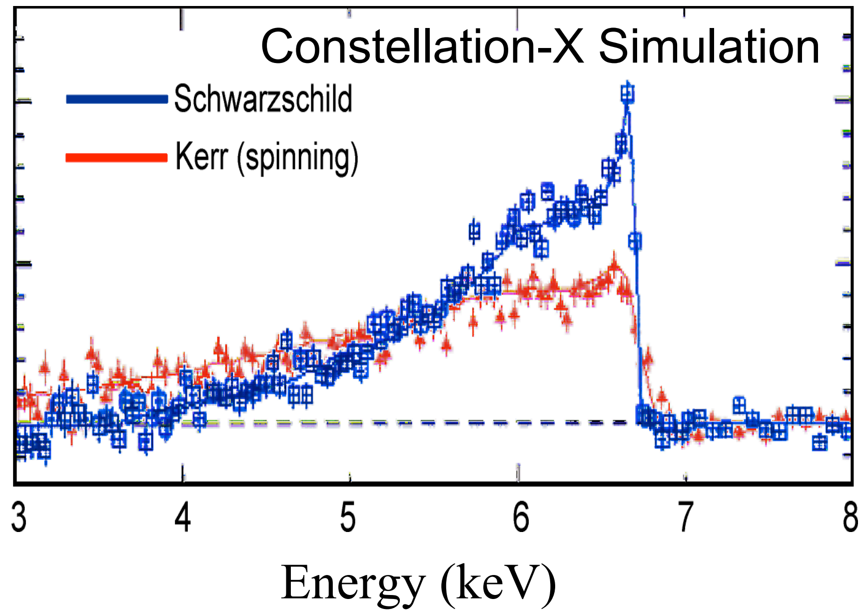


- A factor of 50-100 increased area for high resolution X-ray spectroscopy
- Angular resolution requirement of 15 arc sec (goal of 5 arc sec HPD)
- Field of View 2.5 x 2.5 arc min with 32 x 32 pixels (goal of >5 x 5 arc min)
- Ability to handle 1,000 ct/sec/pixel required for studies of nearby black holes and neutron stars

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

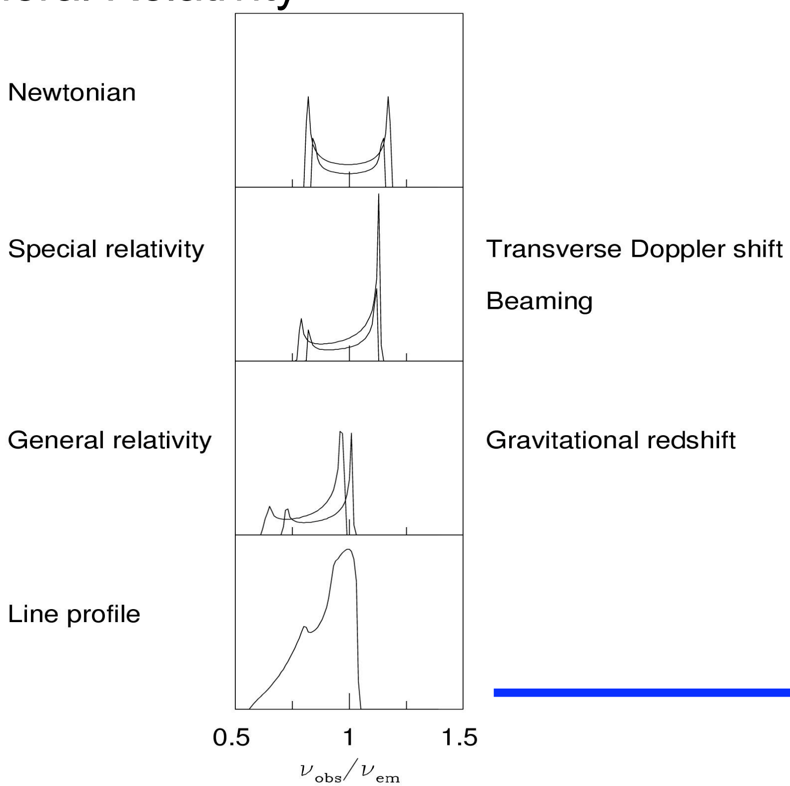


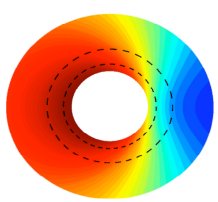


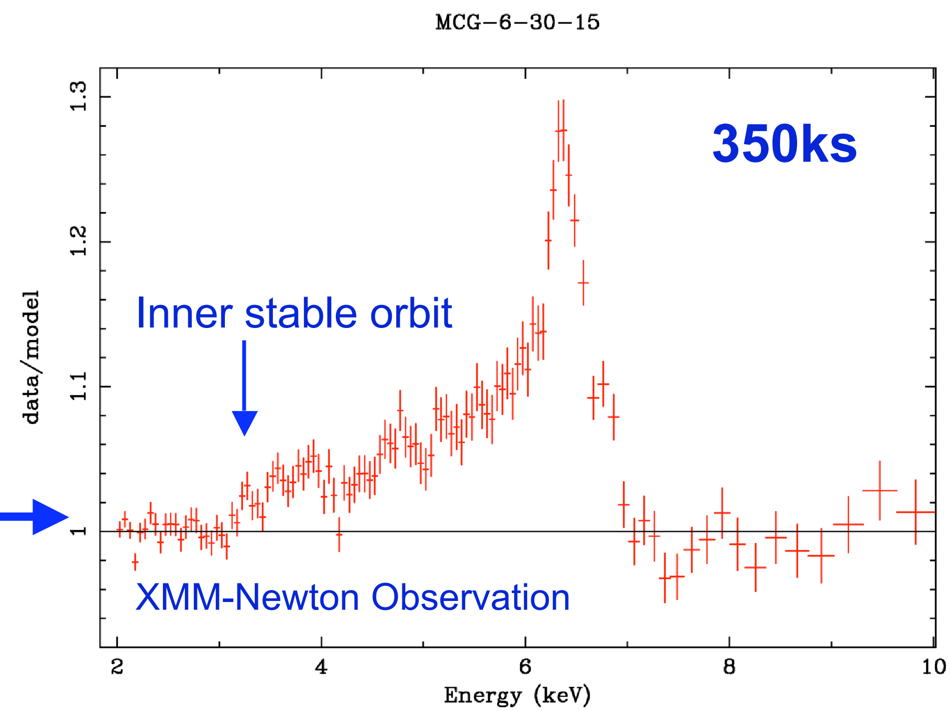
Very Broad Line = Spinning BH

Black Hole Relativistic Iron K Lines

Fluorescent iron K line from an accretion disk close to the Black Hole event horizon reveals the redshift and broadening from the effects of *strong gravity* predicted by General Relativity





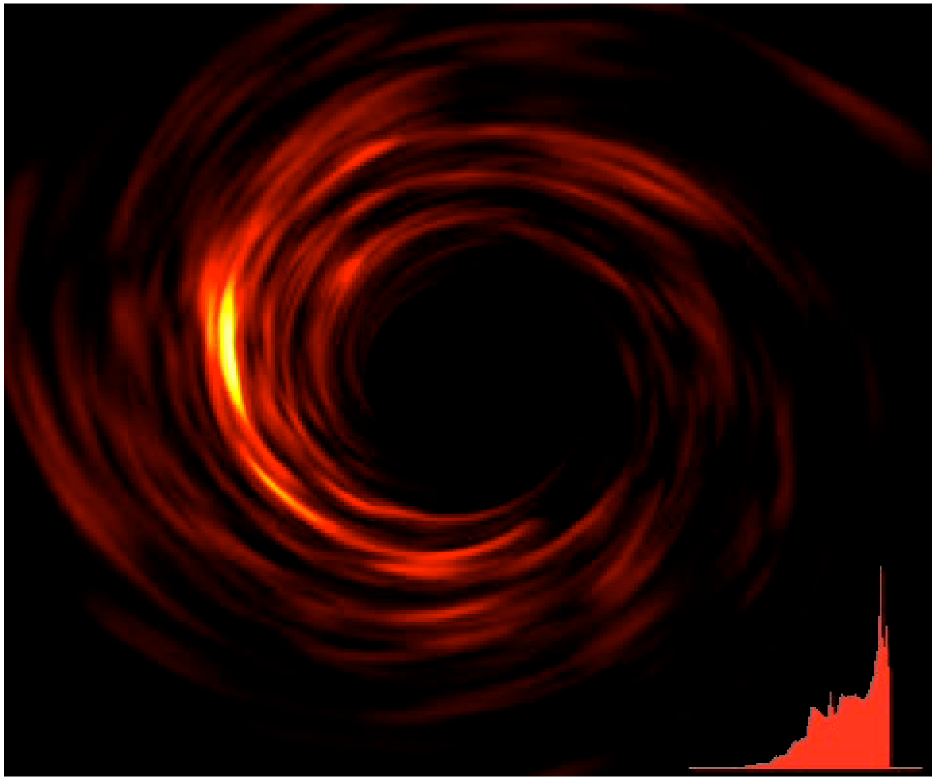


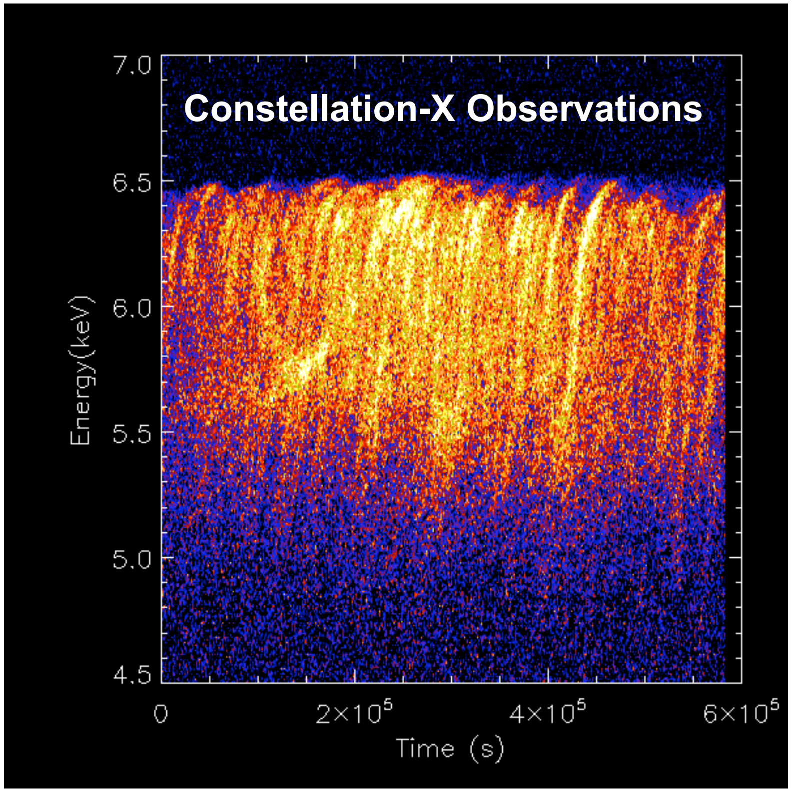
Fabian 1989, Laor 1990, Dovciak 2004, Beckwith & Done 2005

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:

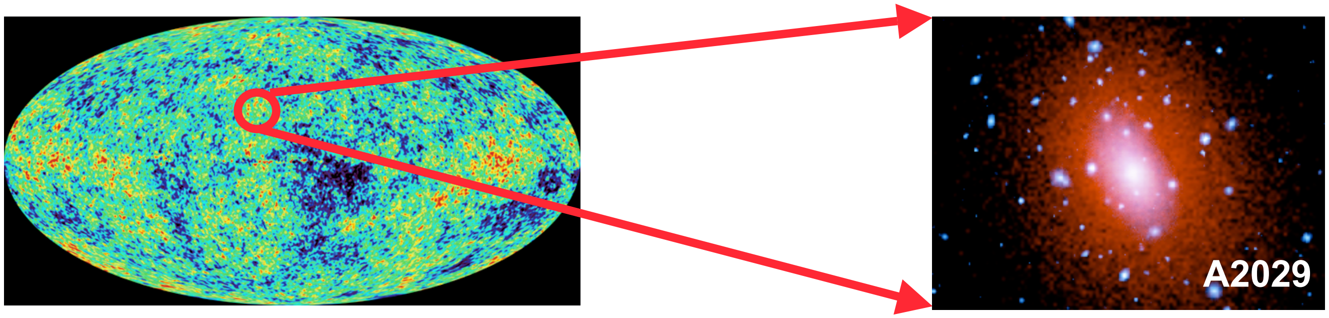
- Dynamics of individual "X-ray bright spots" in disk to determine mass and spin
- Quantitative measure of orbital dynamics: Test the Kerr metric





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

Galaxy Clusters as Cosmological Tools



Baryonic mass dominated by X-ray emitting gas which traces the Dark Matter

X-ray observables are temperature, abundance, flux, gas velocity field, & brightness profile to give cluster mass, gas fraction & velocity structure of the cluster

Significant impact on Cosmology from X-ray Observations of Galaxy Clusters:

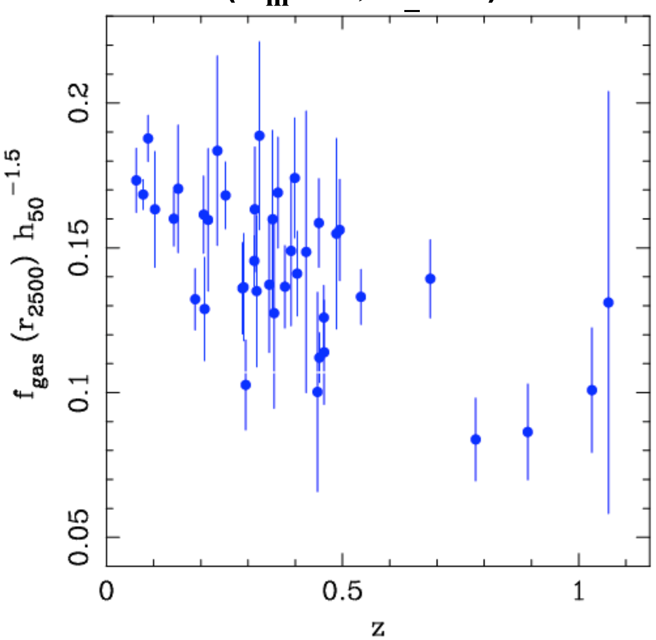
- **1993:** Dark matter to baryon fraction determined to be 6:1. With baryons amounting to ~4% closure density from Big Bang Nucleosynthesis indicates Ω_M ~28% — *early evidence for what we now call Dark Energy*
- **1998:** Measured the amplitude of primordial density fluctuations $\sigma(8)$ ~ 0.7, rather than unity, meaning structure formed later (result now validated by WMAP3)
- **2004:** Galaxy clusters shown to be powerful probes for measuring Dark Energy
- **2006:** Independent accurate determination of Hubble constant using the S-Z effect (Chandra+submm) comparable to (and in agreement with) the HST determined value

Gas Fraction Technique

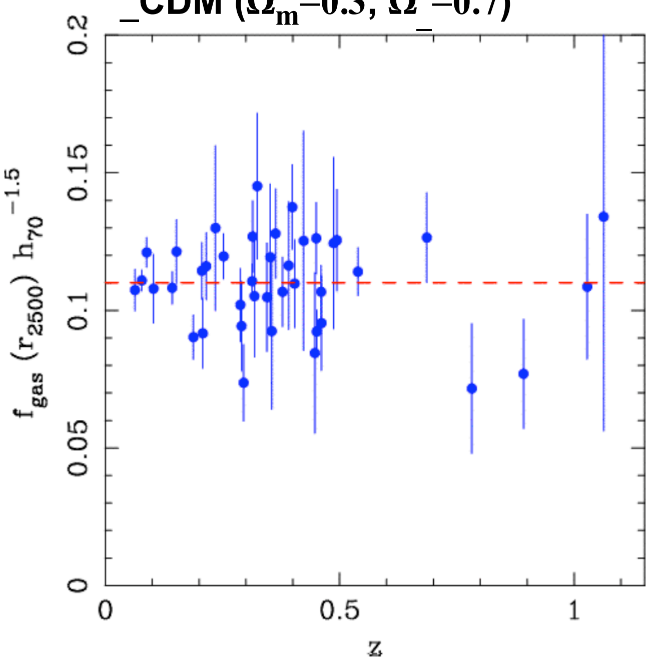
The Gas Fraction f_{gas} (z) is approximately the same for all galaxy clusters

The X-ray measured f_{gas}(z) values depend upon assumed distances to clusters $\boldsymbol{f_{gas} \propto d^{1.5}}$ which introduces apparent systematic variations in f_{gas}(z) depending on the differences between the reference cosmology and the true cosmology

SCDM (Ω_m=1.0, Ω_=0.0)



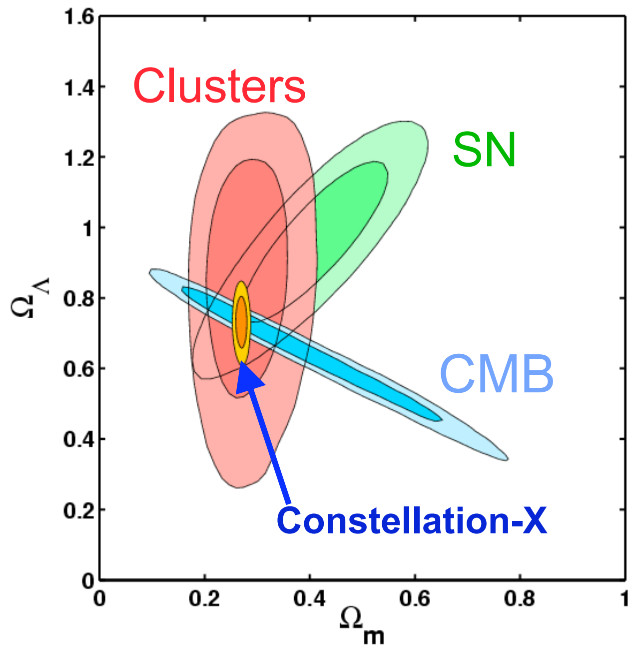
CDM (Ω_m=0.3, Ω=0.7)

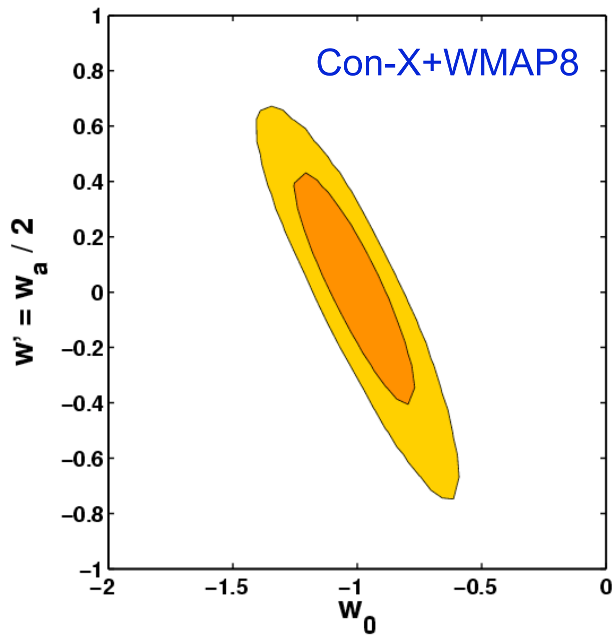


_CDM clearly favoured over SCDM cosmology

From Steve Allen KIPAC/SLAC

Dark Energy Cosmology with Constellation-X





Factor of ten improvement

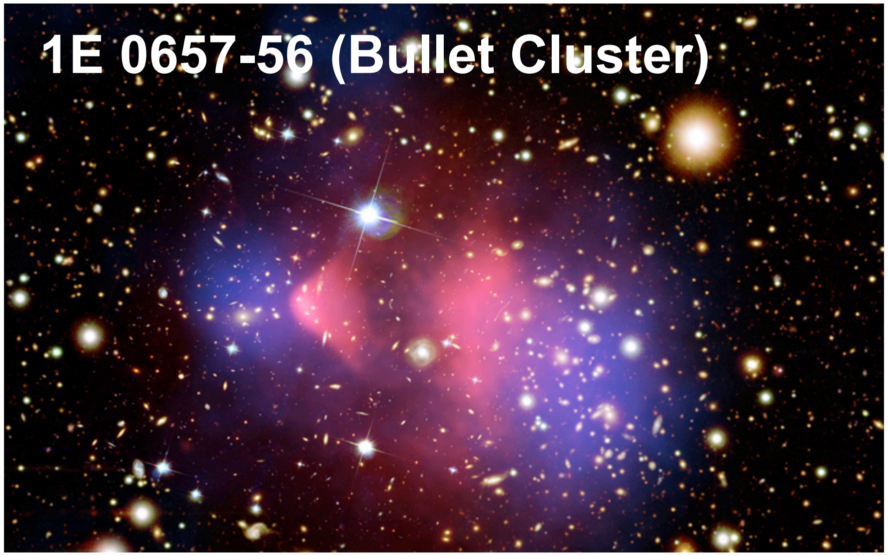
In the terms of the Dark Energy Task Force Figure of Merit this is a Stage IV result

Rapetti, Allen et al 2006

- 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

Dark Matter with Constellation-X

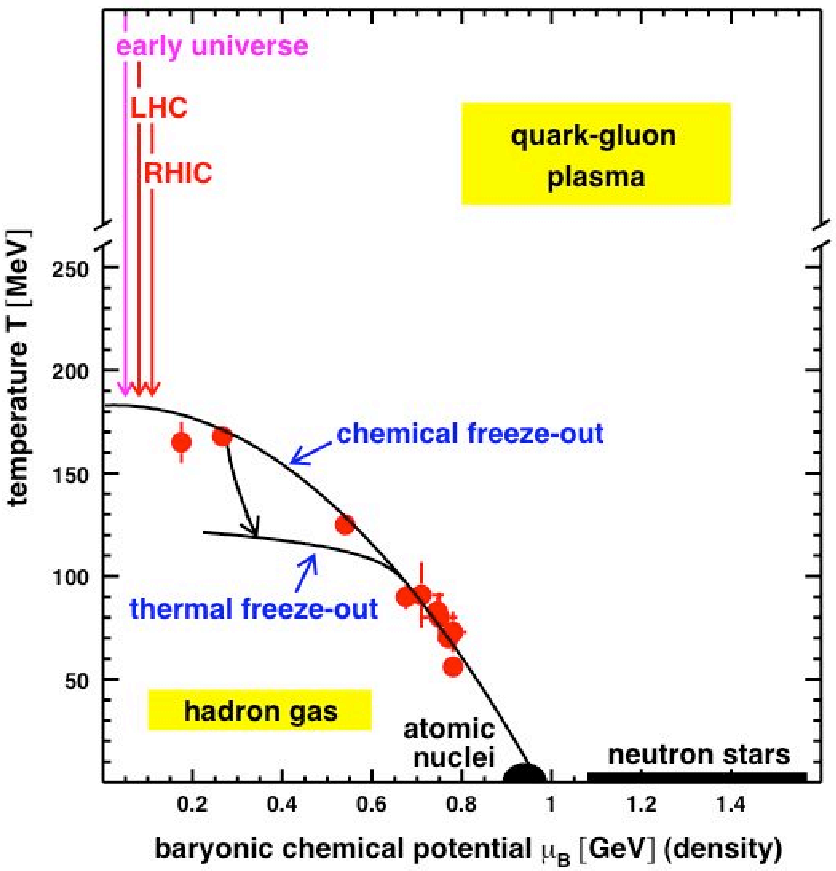
- **Tracing Dark Matter:** Constellation-X will enable the first mapping of the velocity field of Galaxy Clusters to ~100 km/s
  - Measure turbulence, mass motion, Black Hole heating and feedback, cluster mergers, detailed abundances, and ionization mechanisms
  - Provides a precise mapping of the Dark Matter distribution to test Cosmological structure formation

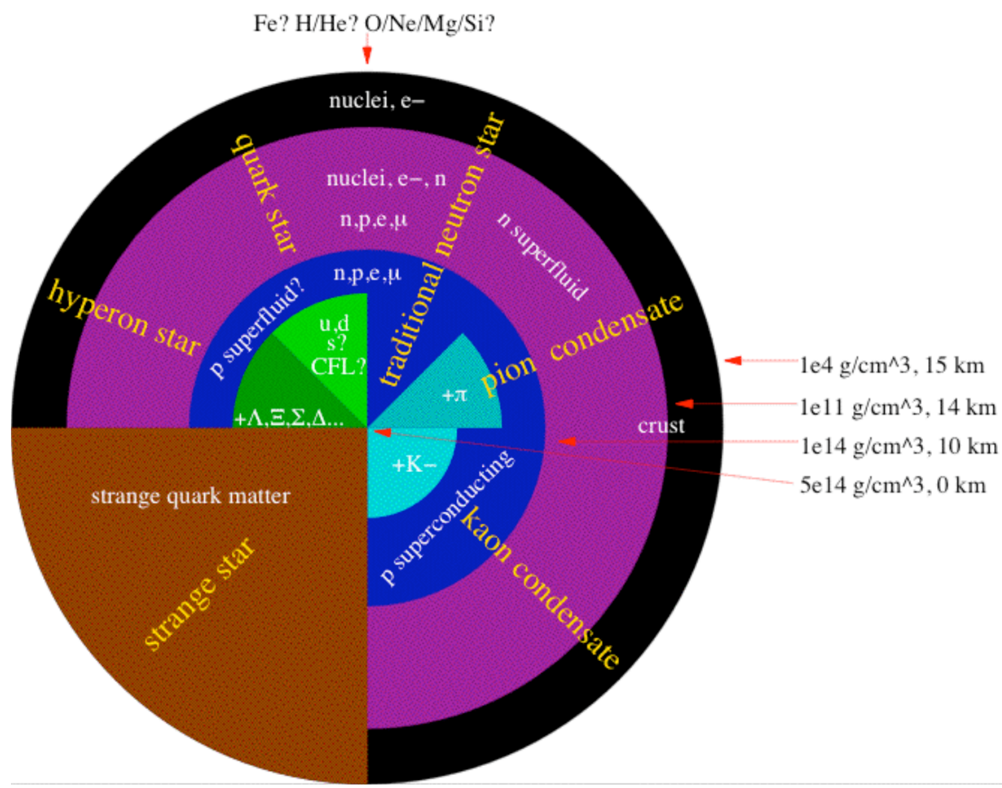


Chandra X-ray Observations of a merging Cluster where the dark matter in the clusters (blue) is clearly separate from the normal matter (pink), directly ruling out modified gravity models (Markevitch et al 2006)

- **Discovery Space:** Sterile neutrinos are proposed with a mass ~1-20 keV as a possible warm Dark Matter candidate (Dodelson & Widrow 1994; Watson et al. 2006)
  - Con-X will constrain models for dark matter in sterile neutrinos or any other decaying warm dark matter candidate with a mass in the 0.5-10 keV range by directly detecting the emission line from the decay, or provide a factor of 100 improved upper limit over current X-ray observations with XMM-Newton

Inside a Neutron Star

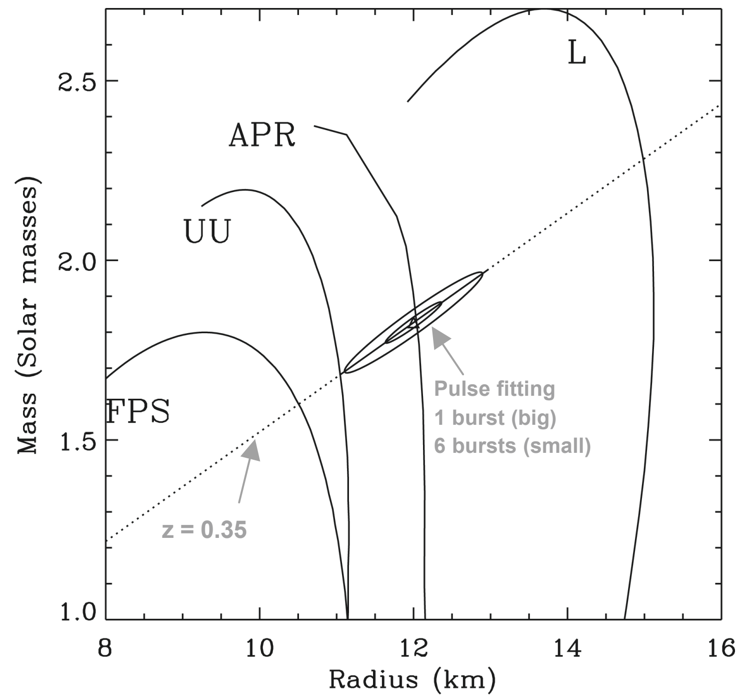


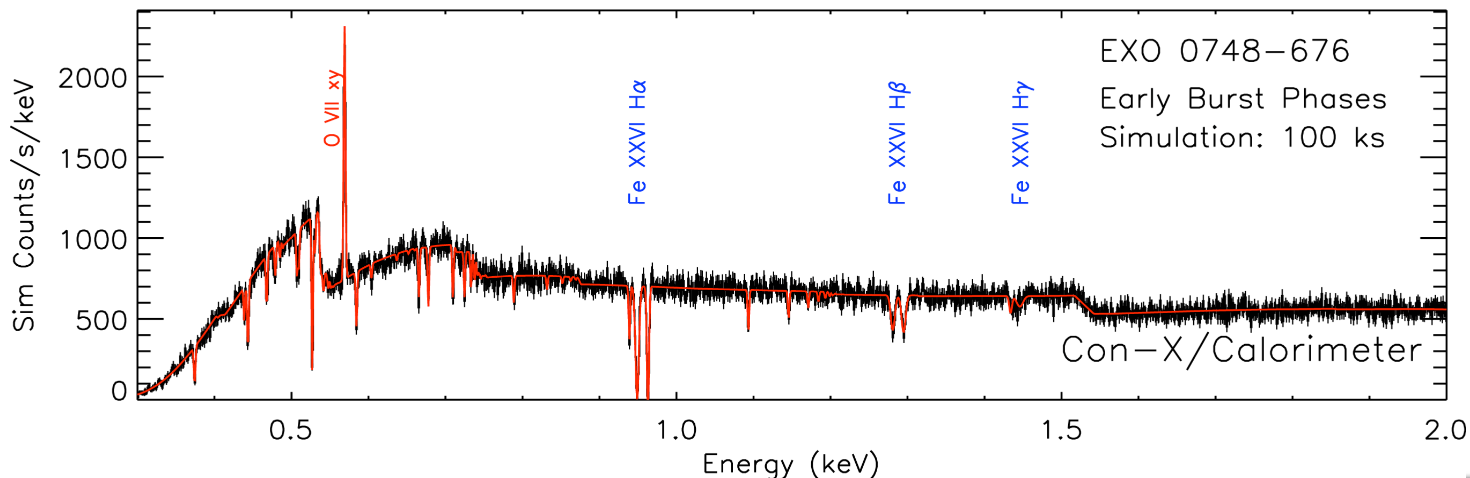


Constellation-X will determine the equation of state for nuclear matter at high density and low temperature

What is the Neutron Star Equation of State?

- Con-X will provide many high S/N measurements of X-ray burst absorption spectra:
  - Measure of gravitational red-shift at the surface of the star for multiple sources, constrains M/R
  - Absorption line widths constrain R to 5-10%.
  - Pulse shapes of coherent oscillations on the rise of the burst can provide an independent measure of mass and radius to a few percent





Constellation-X Requirements Flow Down

Science Goals

Black Holes:
Test Relativity
Mass, Spin vs redshift

Galaxy Clusters:
Dark Matter
Dark Energy

Cycles of Matter/Energy:
Neutron Stars
Supernovae
Black Hole Feedback
Missing Baryons

Measurement Capabilities

Effective area:

15,000 cm_ at 1 keV
6,000 cm_ at 6 keV

Band pass:

0.6 to 10 keV

Spectral resolving power (E/ΔE):

≥ 300	0.6-10.0 keV
≥ 1500	at 6 keV

System angular resolution and FOV:

<15 arc sec HPD
> 2.5 arc min

Engineering Implications

Effective area:
Light weight, highly nested, large diameter (Focal length 10 m)

Band pass:
Grazing incidence telescopes to cover energy range

Spectral resolving power:
Calorimeters
Allow high resolution, non-dispersive spectroscopy

System angular resolution and FOV:
Tight tolerances on telescope figure, surface finish, alignment

≥ 30 x 30 array for x-ray calorimeter (pixels ~5")

Cryocooler driven by array size and readout electronics

Key Technologies

Optics:
High performance replicated segments and shells
High strength/mass materials for optical surfaces
Replication
Mandrels
Metrology
Alignment and assembly

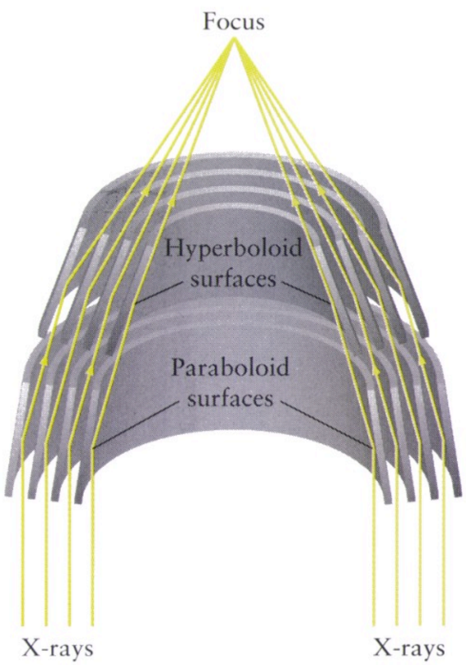
Detector:

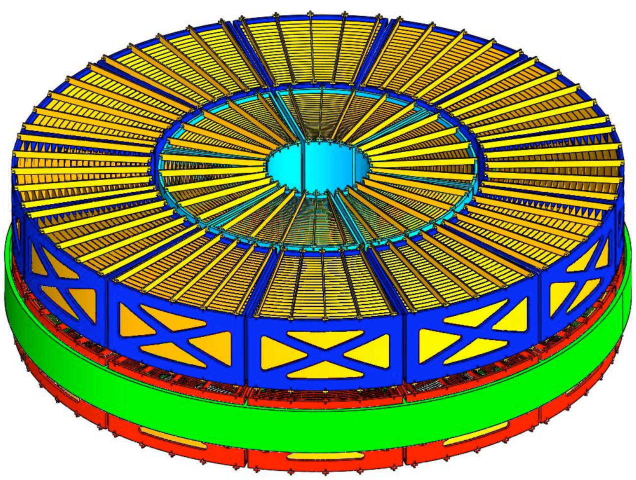
Filters
TES and other calorimeter arrays
SQUID multiplex readouts
Thermal and electrical staging
Anti-coincidence detectors
ADR
Mechanical Coolers

Constellation-X Facility Science Team (FST)

- ♣Science oversight, monitor technology progress and provide feedback
- ♣Responsible for developing and maintaining top level mission science requirements
- ♣Drawn from a broad based community representation with 59 scientists at 28 institutions
  - – Chair: Harvey Tananbaum SAO
- ♣In addition another ~50 scientists are involved in dedicated science topic teams that report to the FST

Enabling Technology: Thin, Segmented X-ray Mirrors





- ♣ Efficient X-ray imaging requires grazing incidence mirrors
  - – 300-700 more telescope surface area required over normal incidence for a given aperture
  - – Precisely figured hyperboloid/paraboloid surfaces
  - – **Trade-off between collecting area and angular resolution**
- ♣ The 0.5 arc sec angular resolution state of the art is *Chandra*
  - – Small number of thick, highly polished substrates leads to a very expensive and heavy mirror with modest area
- ♣ Constellation-X will have a collecting area ~10 times larger than *Chandra*. Combined with high quantum efficiency micro-calorimeters increases throughput by 50-100
  - – 15 arc sec angular resolution required to meet science objectives (5 arc sec is goal)
  - – Thin, replicated segments pioneered by ASCA and Suzaku provide high aperture filling factor and low 1 kg/m^2 areal density

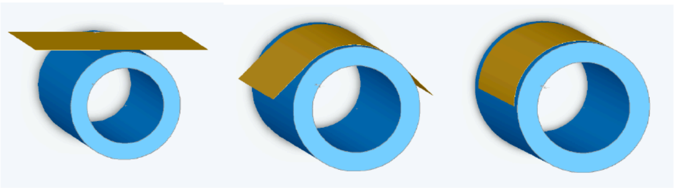
Enabling Technology: Segmented X-ray Mirrors

Highly nested segments with low mass and angular resolution of ≤15 arc sec Half Power Diameter

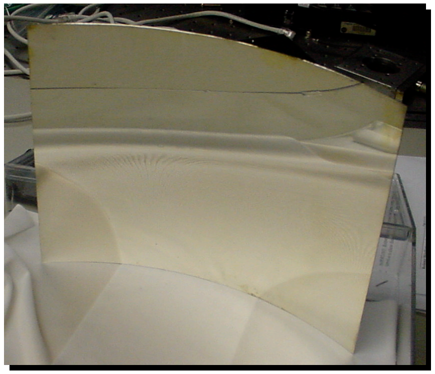
- ♣ Modular approach allows mass production and simplifies alignment
- ♣ Reflecting surface is shaped via thermal forming of 440 μm thick glass mirror segments on precise mandrels
- ♣ Iridium is deposited on each segment
- ♣ Mirror segments are individually aligned within a module

Heritage: Suzaku flight mirror (40 cm diameter)

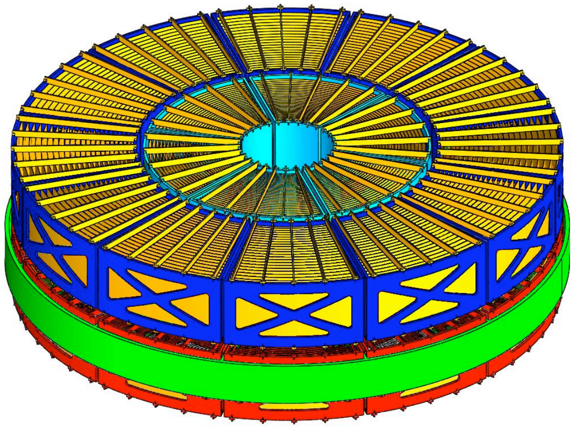
1.3 m diameter
10m focal length
Total mass 197 kg



Mirror segment is produced by thermal forming of a thin glass sheet on a precisely figured mandrel

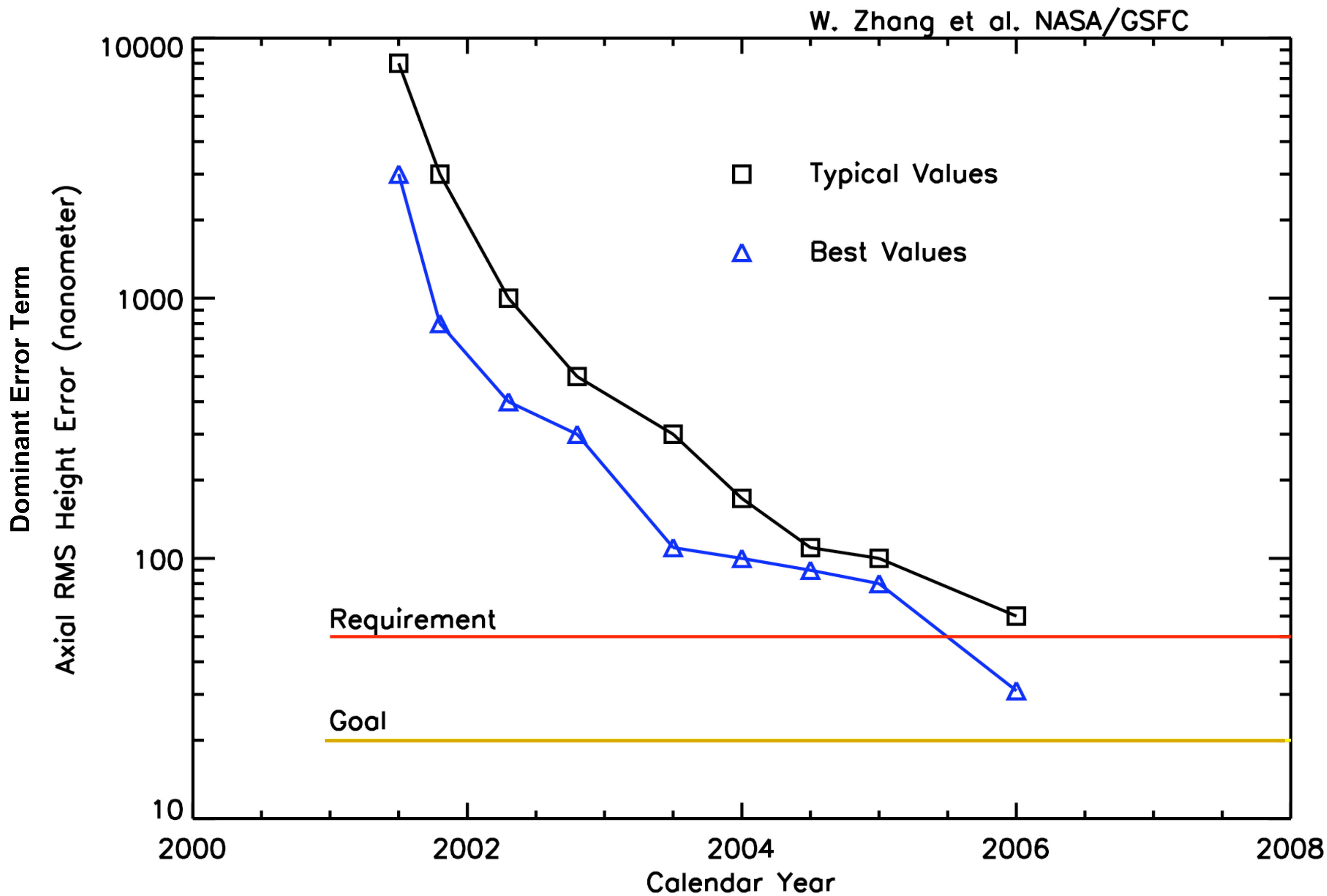


Formed 50 cm diameter glass mirror segment



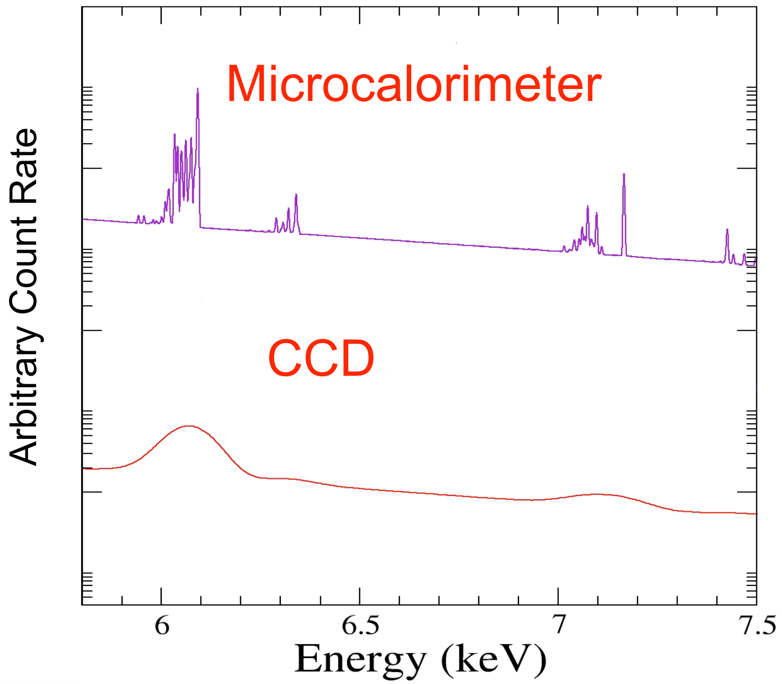
163 shells, 3660 mirror segments
5 inner modules, 10 outer modules

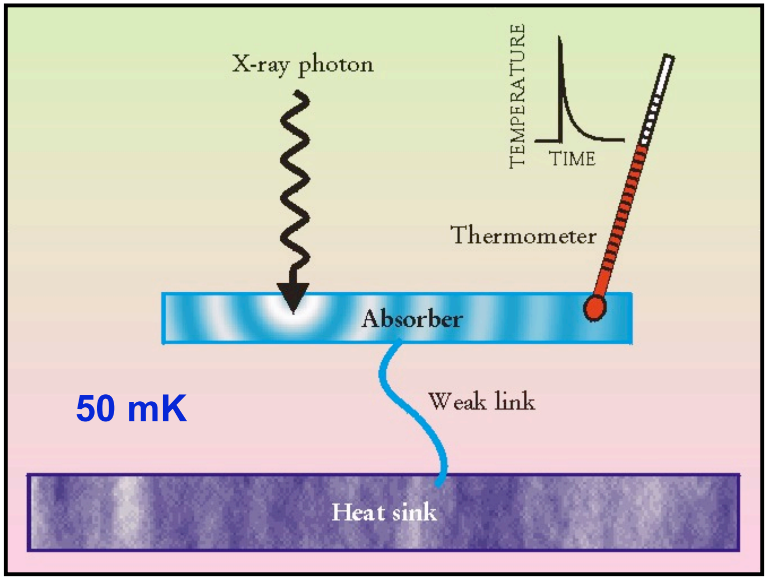
SXT MIRROR SEGMENT PROGRESS



Enabling Technology: X-Ray Microcalorimeters

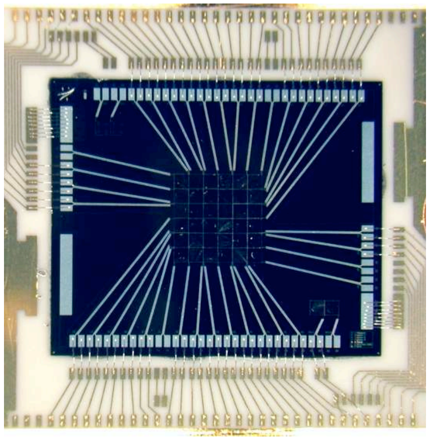
- X-ray microcalorimeter: thermal detection of individual X-ray photons
  - High spectral resolution
  - ΔE very nearly constant with E
  - High intrinsic quantum efficiency
  - Non-dispersive — spectral resolution not affected by source angular size





X-ray micro-calorimeters can image extended sources such as supernova remnants and galaxy clusters (as well as point sources) with 20-40 times improved energy resolution over CCD arrays, and factor of 5-10 better quantum efficiency than gratings

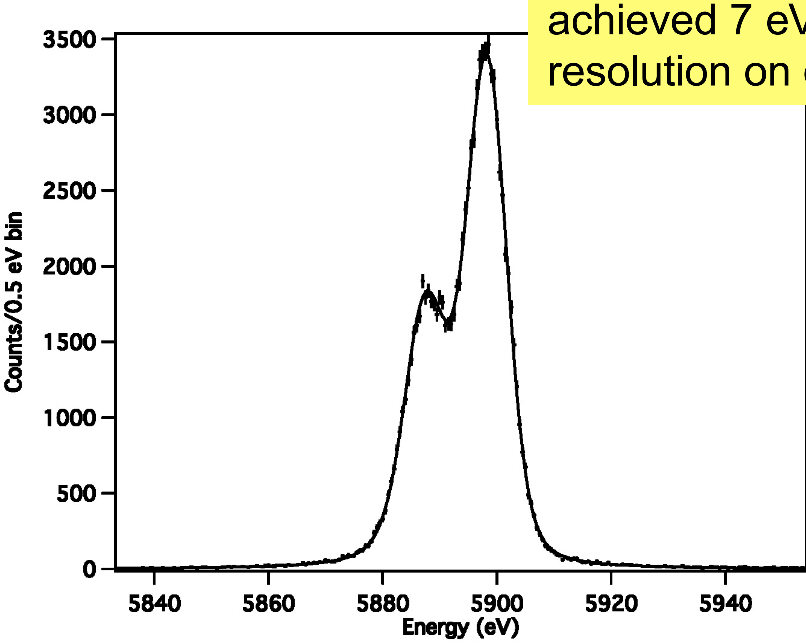
X-ray Micro-calorimeter Spectrometer (XMS)



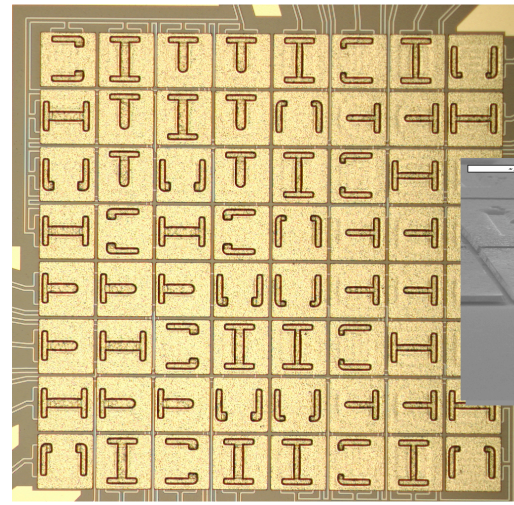
Arrays have been demonstrated on sounding rockets and *Suzaku*

Suzaku array with 32 x 640 μm pixels

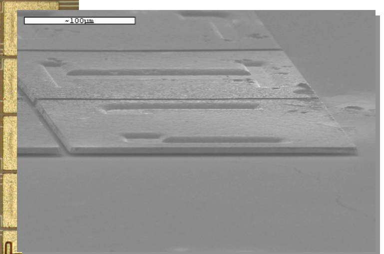
Suzaku X-ray calorimeter array achieved 7 eV resolution on orbit



Con-X arrays under development and approaching goal of 2 eV at 6 keV.

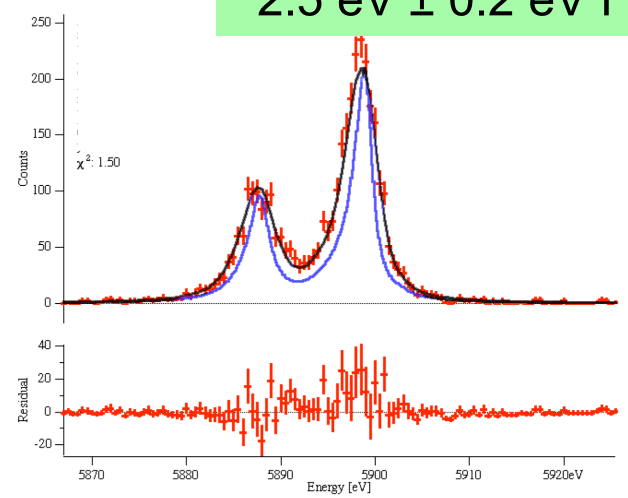


High filling factor

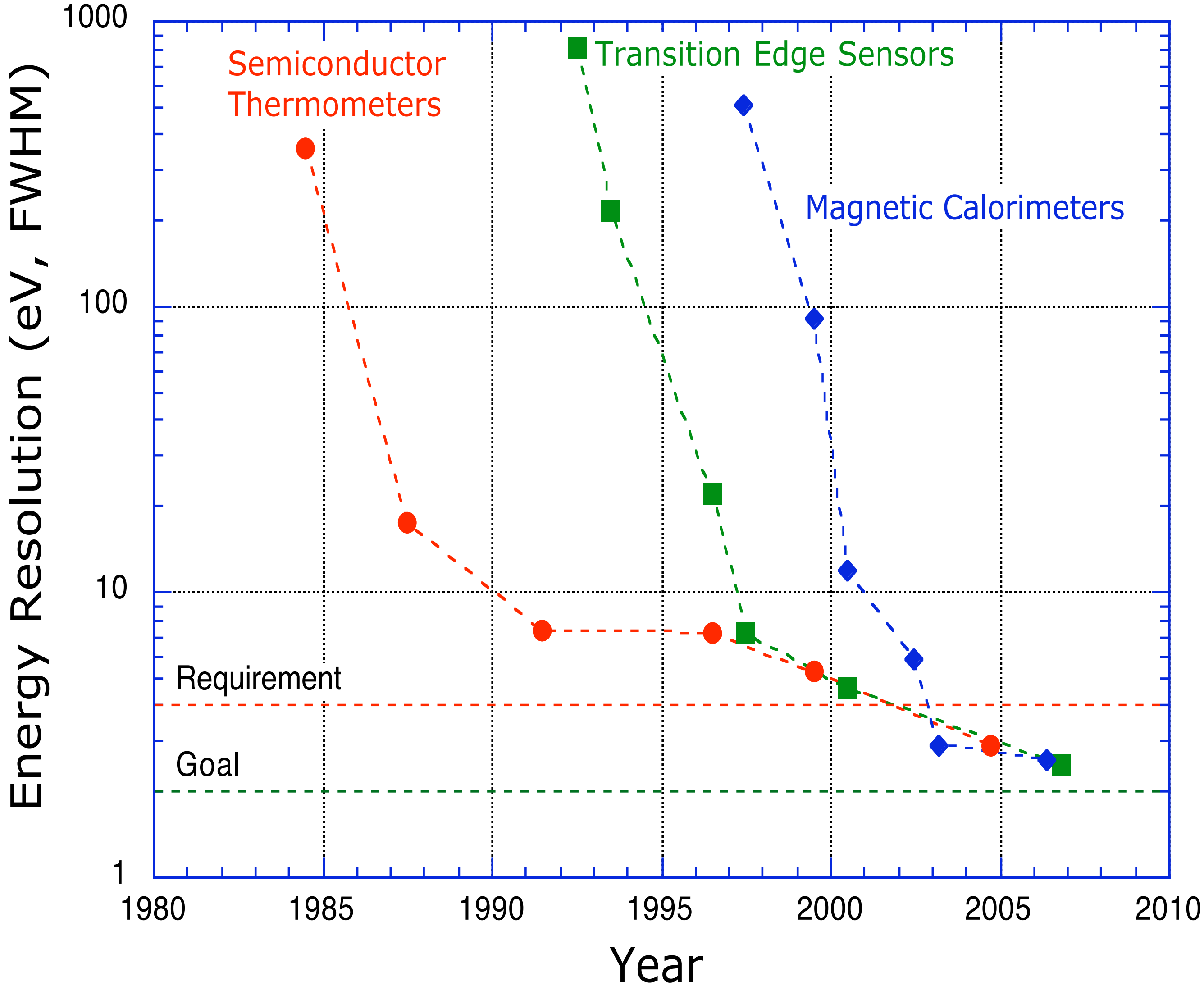


8x8 development Transition Edge Sensor array for Con-X with 250 μm pixels

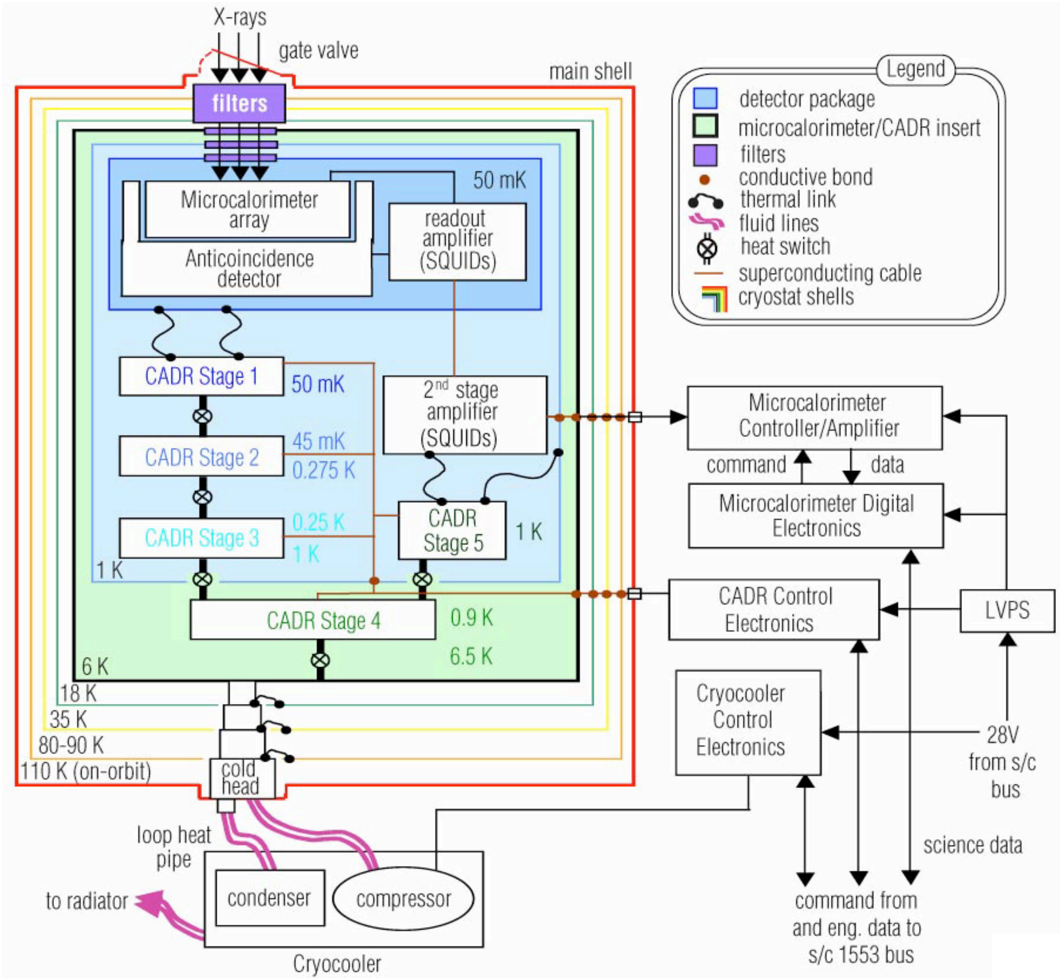
2.5 eV ± 0.2 eV FWHM

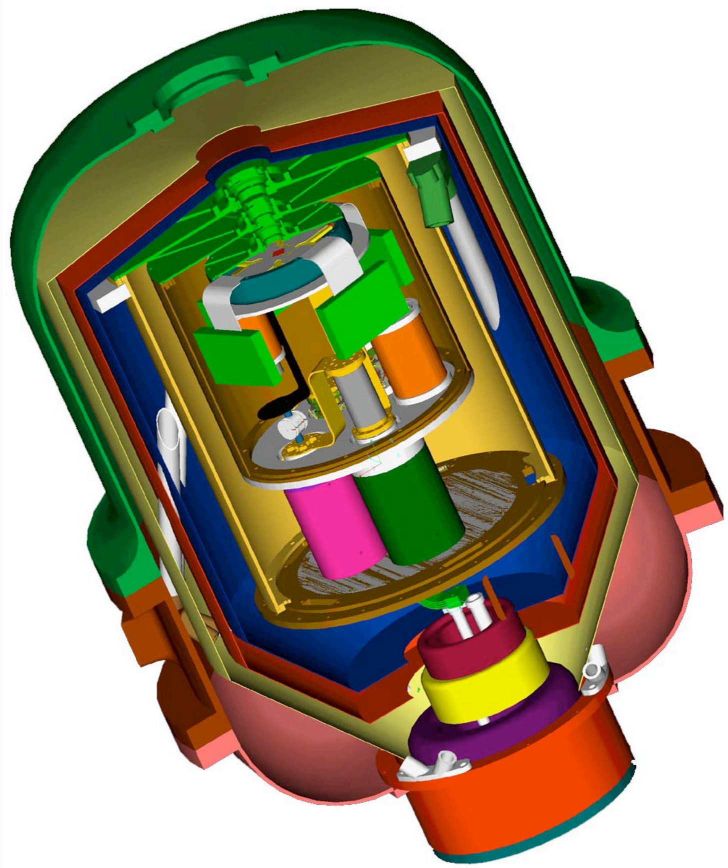


TECHNOLOGY PROGRESS:
Micro-calorimeter resolution E/ΔE at 6 keV



Instrument Block Diagram and Conceptual Implementation for TES X-Ray Microcalorimeter Spectrometer (XMS)





Size ~ 50 x 75 cm
Mass ~ 150 kg, including electronics

Technology Status & Challenges

A total of 14 critical milestones for the telescope and microcalorimeter technologies have been achieved over past 7 yrs (6 remaining)

Current funding profile supports reaching TRL 6 at component level by 2009

- additional funding in FY2007/2008 would enable acceleration of the schedule and launch in 2016

Key remaining technical challenges:

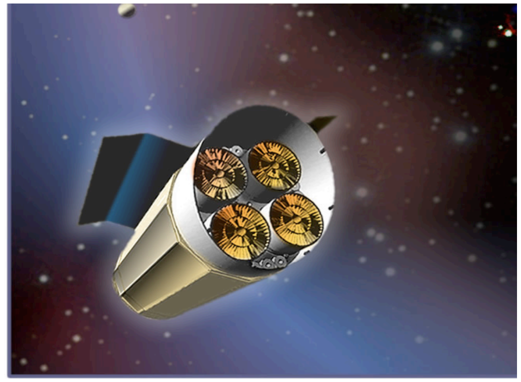
- Replicating segments with 1 kg/m^2 areal density beyond the 15" required angular resolution towards the 5" goal
- Fabrication and alignment/assembly of segments
- Development of microcalorimeter arrays larger than 32x32 (5x5" elements) to cover larger field of view (5x5' goal) with 2-4 eV spectral resolution (in the central region)

Constellation-X Mission Configuration Evolution

2000-2004

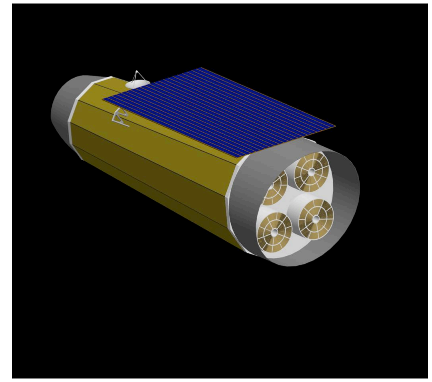
Two ATLAS V 551

2005



Delta IV H

2006



ATLAS V 551

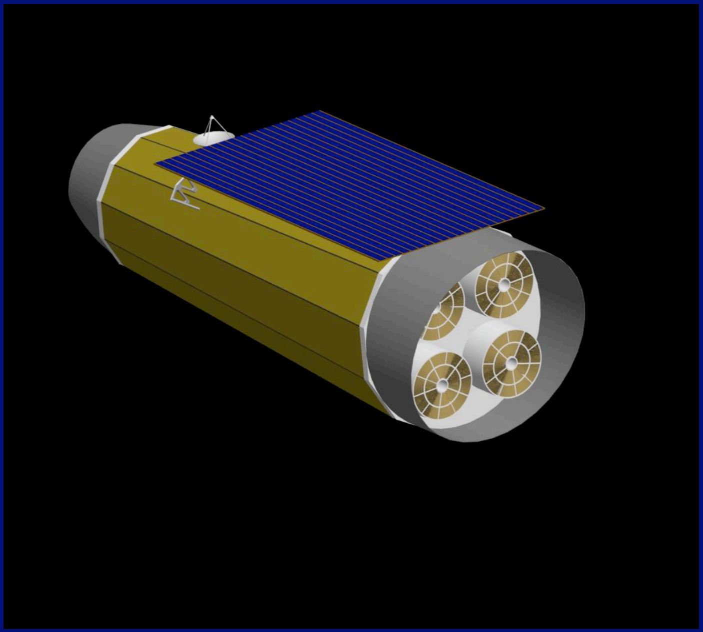
The Constellation-X design has evolved as pre-phase A mission studies have matured and in response to increased costs in the launcher market - *while at the same time maintaining the core science capabilities*

A stream-lined Single S/C Atlas V Configuration

- Retain effective area over 0.6-10.0 keV band
- Reduce mass and envelope to fit within single Atlas V
  - removes previous versions of reflection gratings and hard x-ray telescopes
  - allocation of 100kg of mass and $100M budget for simplified approaches
  - community solicitation underway with inputs due 11/13/06
- Significant cost reductions - $700 Million RY$ less than dual launch four satellite configuration
- Estimated end to end cost - $2.0B RY
  - one quarter of budget is Mission Operations & Data Analysis covering pre-launch and five year prime mission
- Launch in 2017 - possibly 2016 with increase in early year $$

Mission Implementation Approach

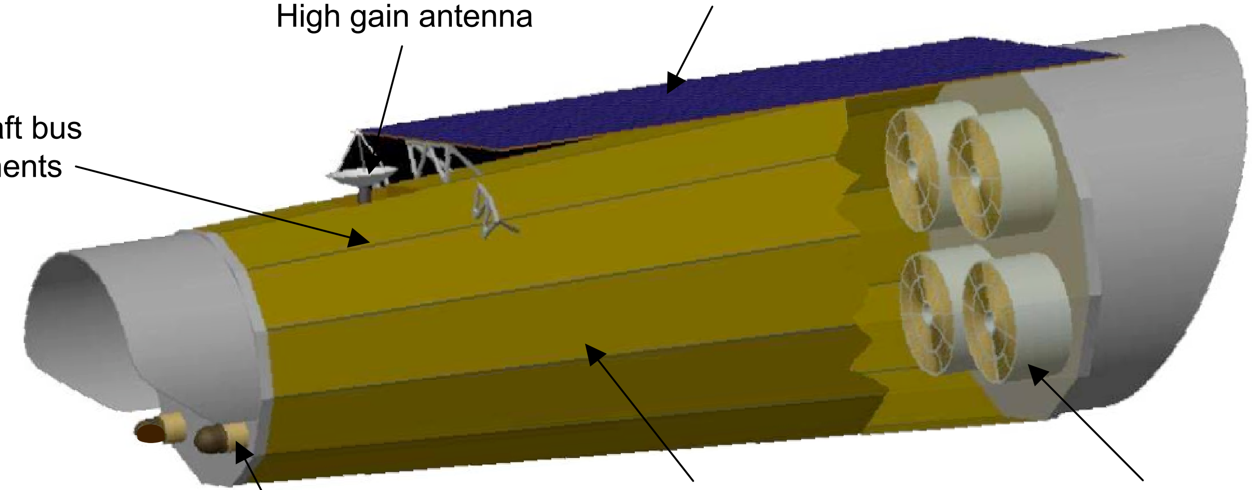
- Four X-ray telescopes with common design, manufacture, assembly, and testing
- Manageable mirror dimensions and 10m focal length provide required area
- Proven spacecraft subsystems and launch vehicles
- Mission success (via longer exposures) even with loss of one detector



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					

Con-X Atlas V Single Launch Mission Configuration

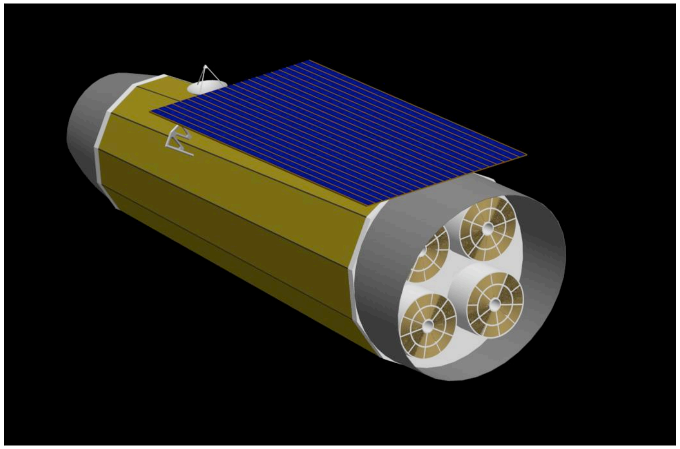


Atlas V 551
Launch Configuration

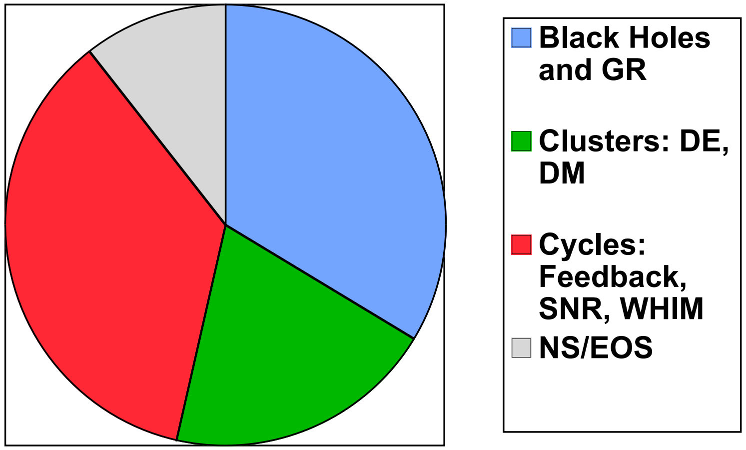
Orbit	**Direct insertion to L2 700,000 km halo orbit**
Reliability	**No performance degradation w/ single point failure**
Operational Efficiency	**~85%, when averaged over the mission life**
Field of Regard	**Pitch: +/- 20° off Sunline, Yaw: +/- 180°**
XMS Shell Temperature	**150 ºK, achieved w/ sunshade + passive radiators maintain**
Attitude Knowledge (3_)	**Pitch and Yaw: 3 arcsec**
Propulsion	**Hydrazine bipropellant (N2O4/N2H4)**
RF Comm	**Ka band High Gain Antenna (40 Mbps) to DSN S band Omni antennas, 2 kbps**

Constellation-X Operations Concept

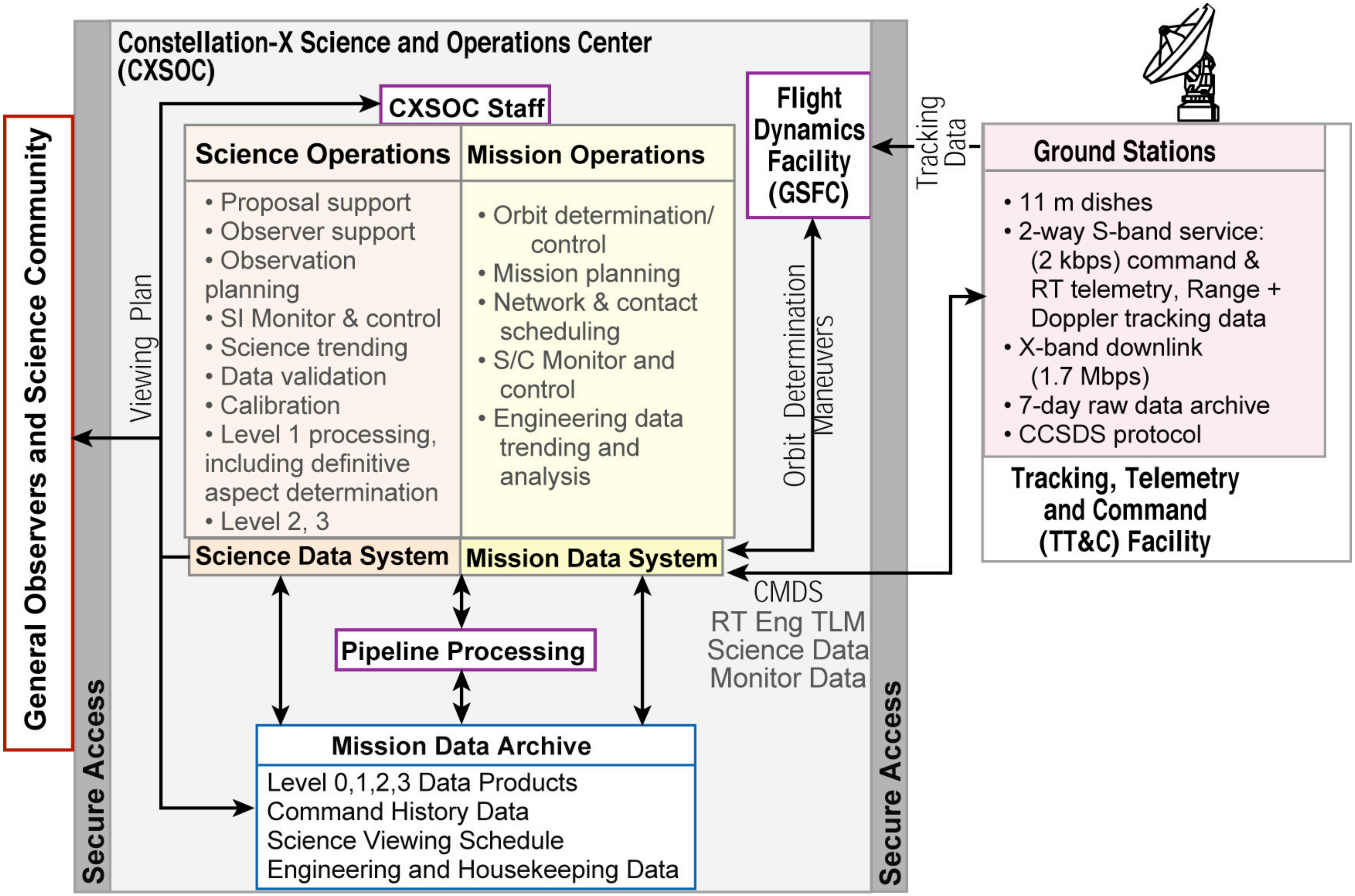
- Constellation-X will be a facility class observatory with programs selected via competitive Peer Review
- Based on Chandra and XMM-Newton anticipate 700-1000 proposals per year with perhaps 200 selections
- Constellation-X operates as a queue-scheduled observatory, pointing at selected targets in the most time efficient way consistent with science and observatory constraints
- Time on a target ranges from a few 1000 to several million seconds. Observations may be carried out over several pointing intervals
- Schedule may be interrupted to accommodate Targets of Opportunity (TOOs) pre-selected by Peer Review or approved as Director's Discretionary Time
- Present baseline operates all instruments simultaneously with power, telemetry, and other resources sized accordingly



Estimated Division of Observation time by science objective



Operations Concept Architecture



Constellation-X is low risk and ready to proceed

- High throughput, high spectral resolution X-ray spectroscopy is essential to accomplish Beyond Einstein science
- The technology development is proceeding on schedule and is on track to achieve the required Technology Readiness Level (TRL6) by 2009
- No technology breakthroughs or test flights required
- The mission utilizes extensions of flight proven technology — the Chandra and Suzaku X-ray optics and Suzaku microcalorimeter, standard spacecraft, operations and data analysis
- Experienced science and management team comprised of world leaders in field — have built and flown many successful instruments and missions

Constellation-X starts Beyond Einstein with a Bang!

- ♣ High science per dollar — Mission addresses 8 of the 11 Quarks to Cosmos Questions, with the focus on Black Holes as tests of GR, Dark Matter and Dark Energy, and matter under extreme conditions
- ♣ Opens the window of X-ray spectroscopy — a powerful tool transforming X-ray Astronomy into X-ray Astrophysics
- ♣ Science success guaranteed — hundreds of thousands of known targets with measured count rates and directly observable signals
- ♣ Engages a large community — Astrophysicists, Cosmologists, and Physicists through an open General Observer Program

http://constellation.gsfc.nasa.gov