BEYOND EINSTEIN: From the Big Bang to Black Holes

Constellation-X

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Deputy Project Scientist

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

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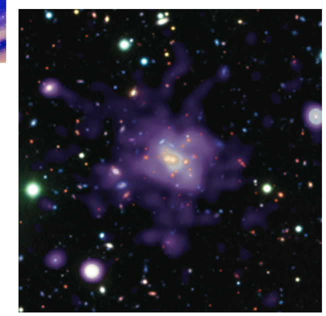
Driving Science Objectives

Black Holes

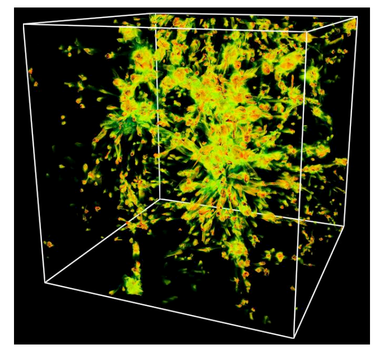
- Use black holes to test General Relativity and measure black hole spin

Dark Energy (and Dark Matter)



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

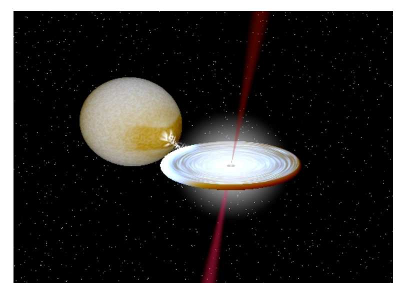
Missing Baryons



- 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



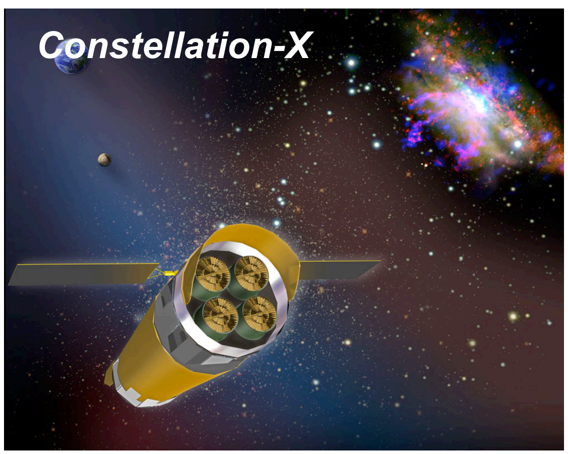
CHANDRA launched 1999 brought X-ray Astronomy to the forefront

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/ΔE < 30, insufficient for crucial plasma diagnostics

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



Resolution (E/ΔE): 300-1500

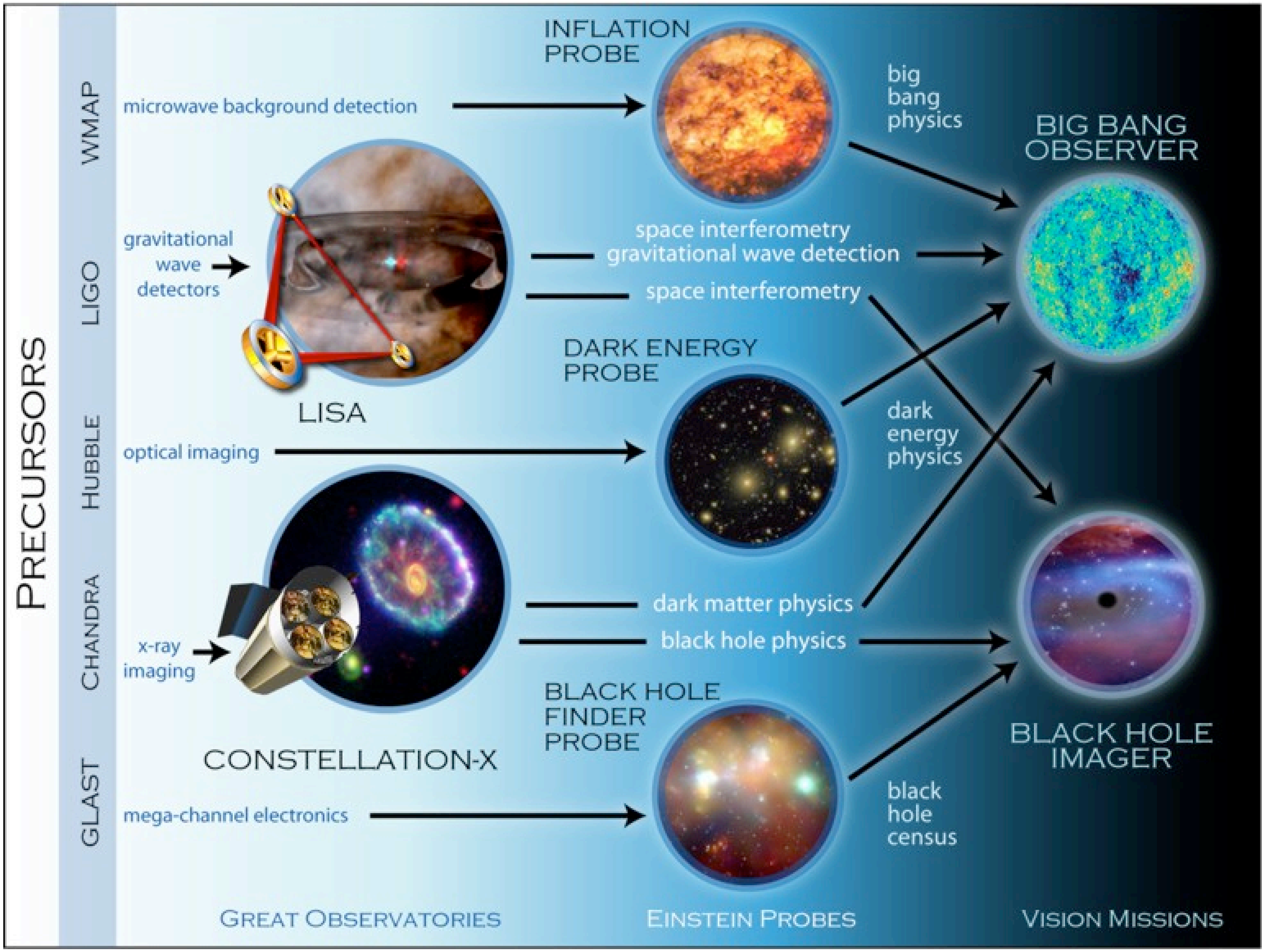
Effective area is a 50-100 gain over current missions

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

Beyond Einstein Program



Beyond Einstein Program Status

Challenges in overall NASA budget (Columbia loss, complete ISS, replace Shuttle, HST servicing delayed, etc) has slowed the start of Beyond Einstein

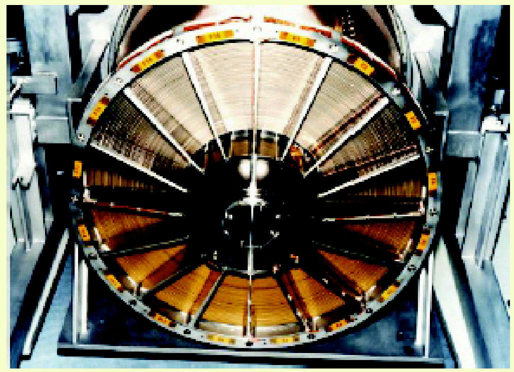
Beyond Einstein program consists of five missions: Constellation-X, LISA, Joint Dark Energy Mission (JDEM), Inflation Probe and Black Hole Finder

Decision to be made by Fall 2007 as to which the Beyond Einstein mission will be the first to start via a National Academy of Sciences Beyond Einstein Program Assessment Committee (BEPAC)

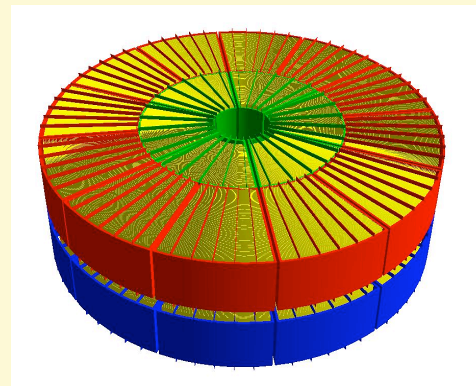
Funding wedge for new start in 2009, and if Constellation-X is selected allows a launch in mid-2017

A Quick Primer on X-ray Optics: *They are extremely heavy.*

CHANDRA
0.5”
18500 kg/m^2
A_{eff} @ 1 keV



XMM-NEWTON
14”
2300 kg/m^2
A_{eff} @ 1 keV

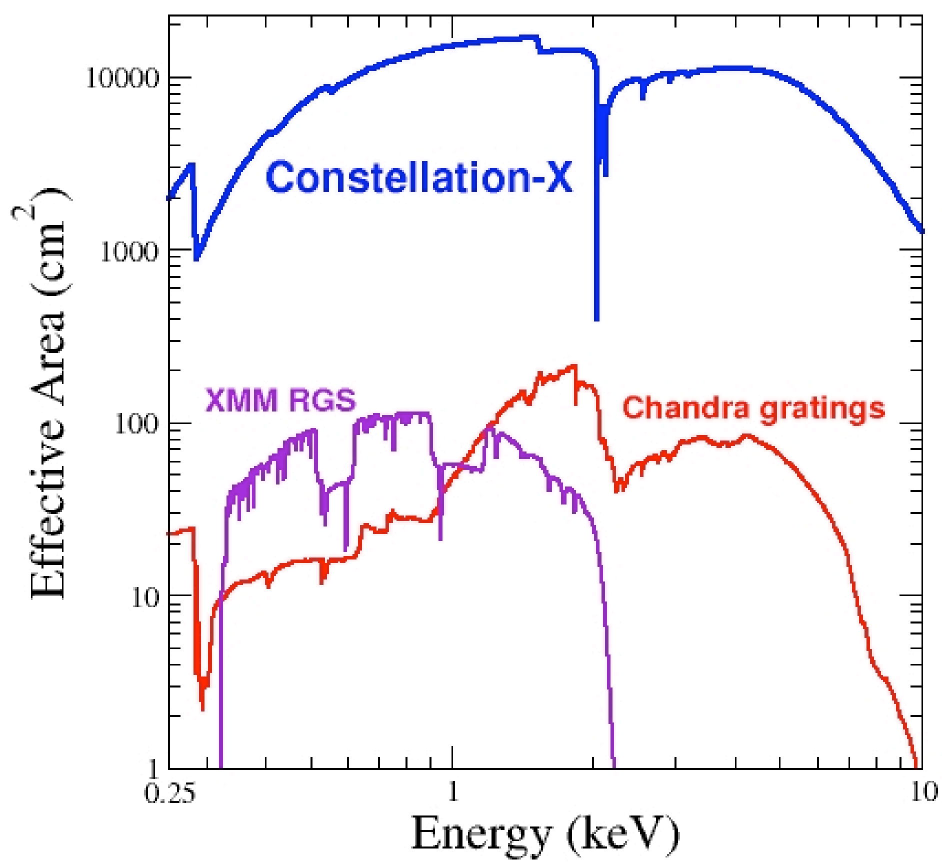


CON-X
5-15”
250 kg/m^2
A_{eff} @ 1 keV

credit: Marcos Bavdaz, ESA-XEUS team

Key Constellation-X Capabilities

Comparison of X-ray mission collecting areas



- A factor of ~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 5 x 5 arc min (goal of 10 x 10 arc min FOV)

Constellation X

The Constellation X-Ray Mission

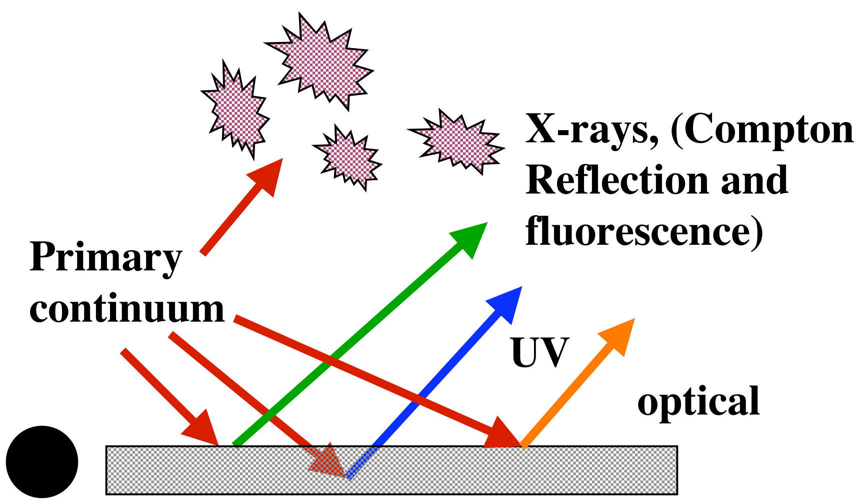
Science Objective #1:

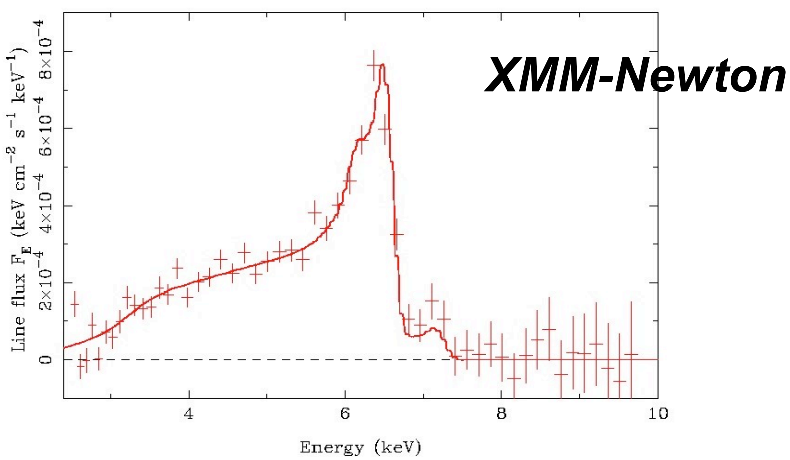
Black Holes

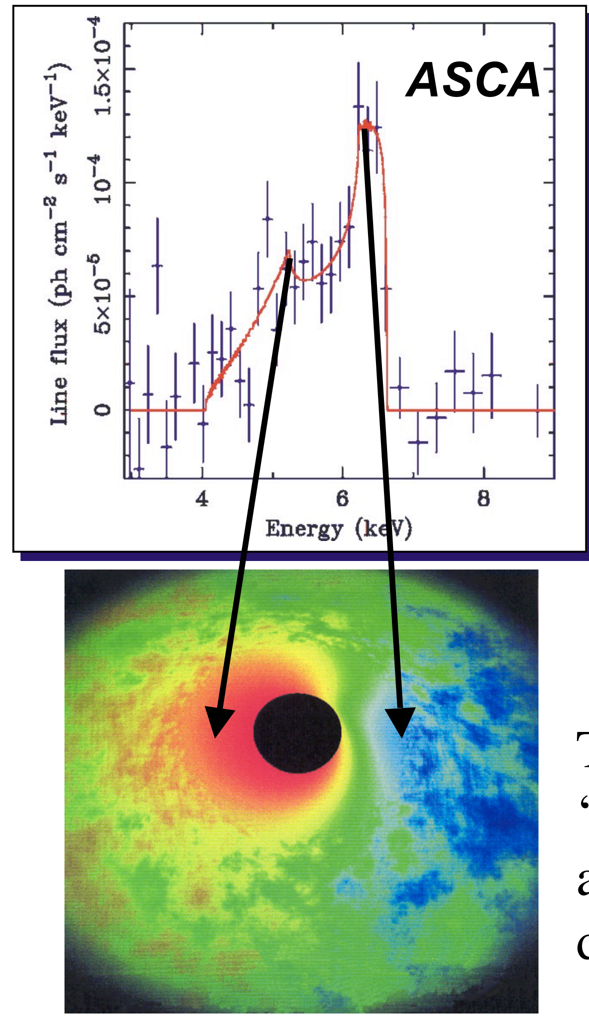
NASA

Black Holes: Accretion Disks and X-ray Reflection

The Iron fluorescence emission line is created when X-rays scatter and are absorbed in dense matter, close to the event horizon of the black hole.





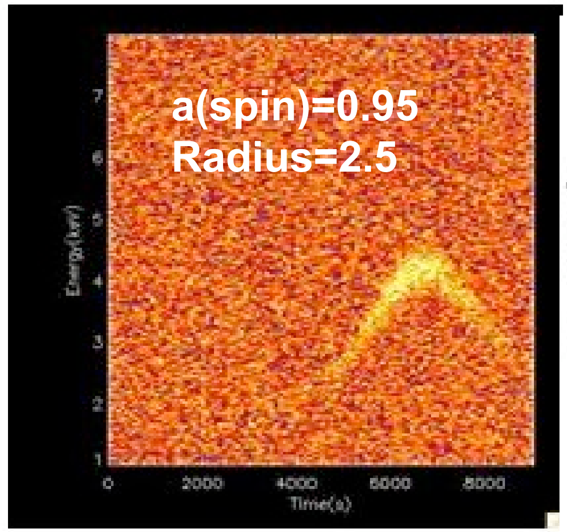


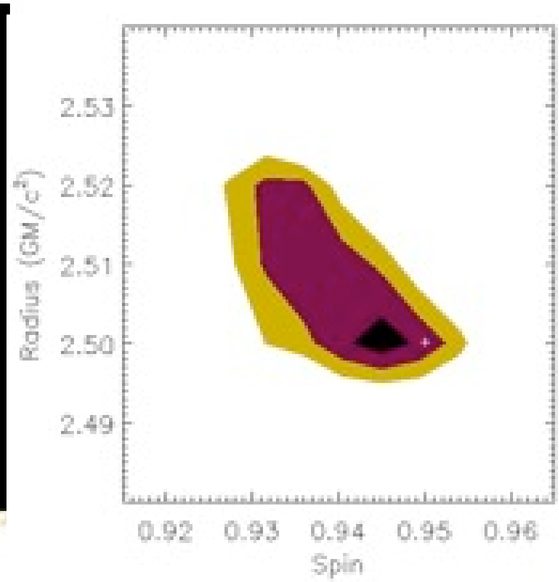
Theoretical 'image' of an accretion disk.

Black Holes:

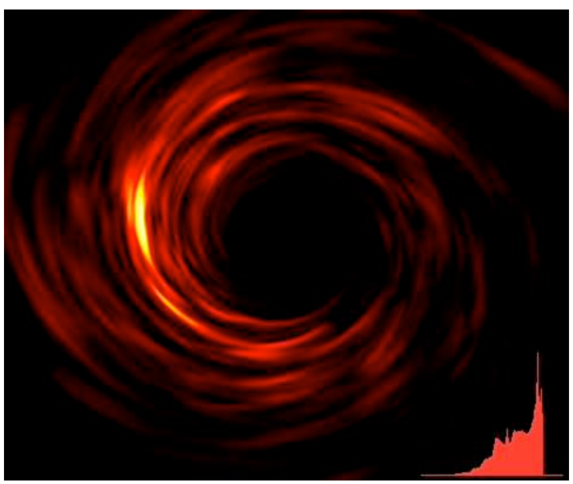
Use black holes to test General Relativity (GR) and measure black hole spin

- **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.**



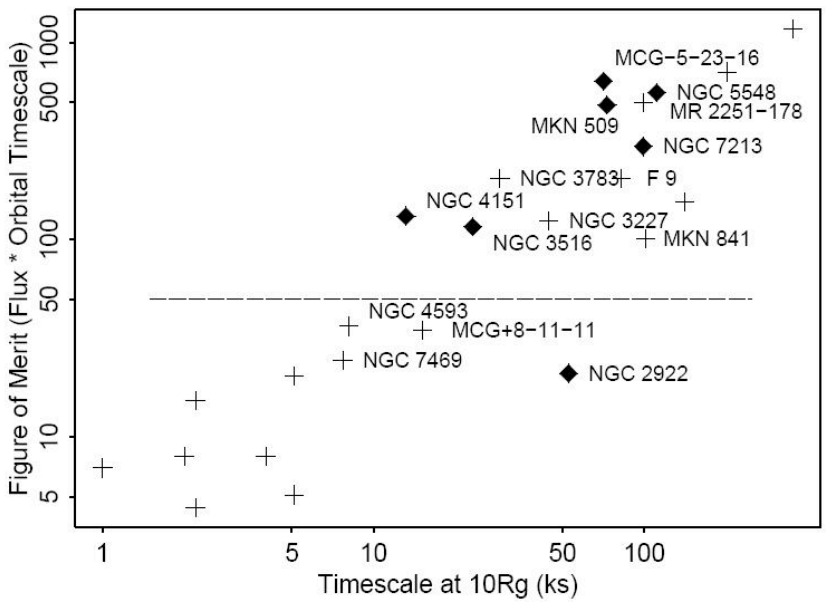


Detectability depends on X-ray flux, line intensity, and orbital timescale



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

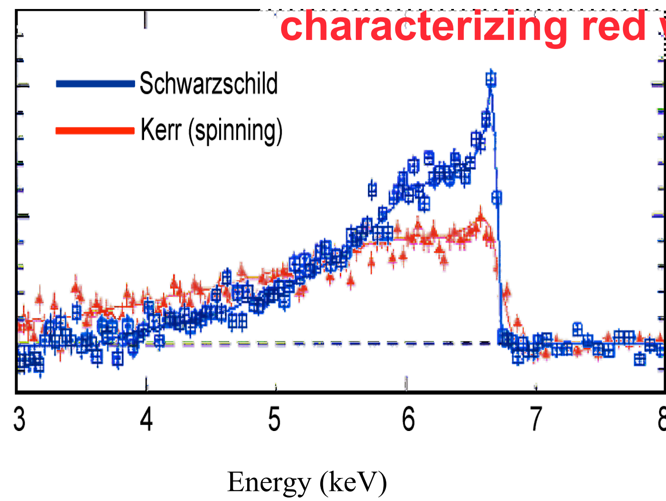
Black Holes: *Measurements*



ASCA X-ray sample of AGN

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



Time-variable Fe K measurements

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

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)

Science Objective #2:

Dark Energy & Dark Matter

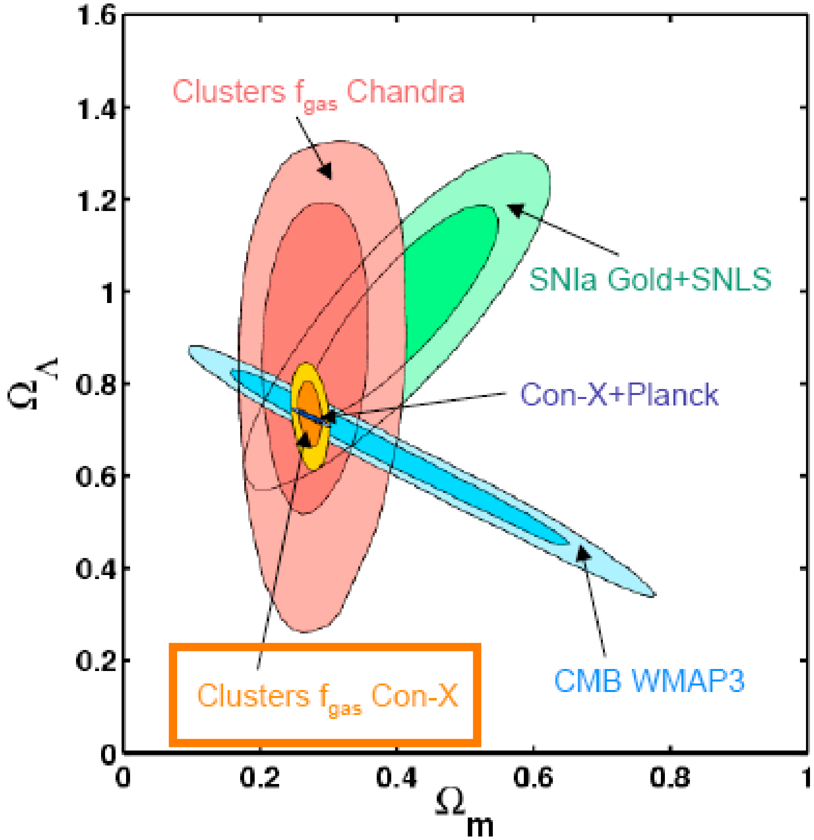
Dark Energy:

X-ray Emission from Clusters of Galaxies

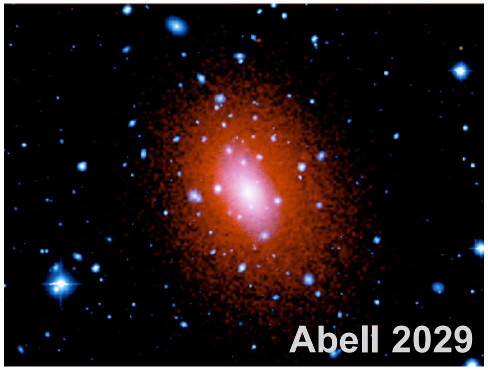
Largest gravitationally bound structures in the Universe, most of the normal, baryonic matter lies in the hot X-ray emitting gas (10^6 - 10^8 K)

Dark Energy:

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



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

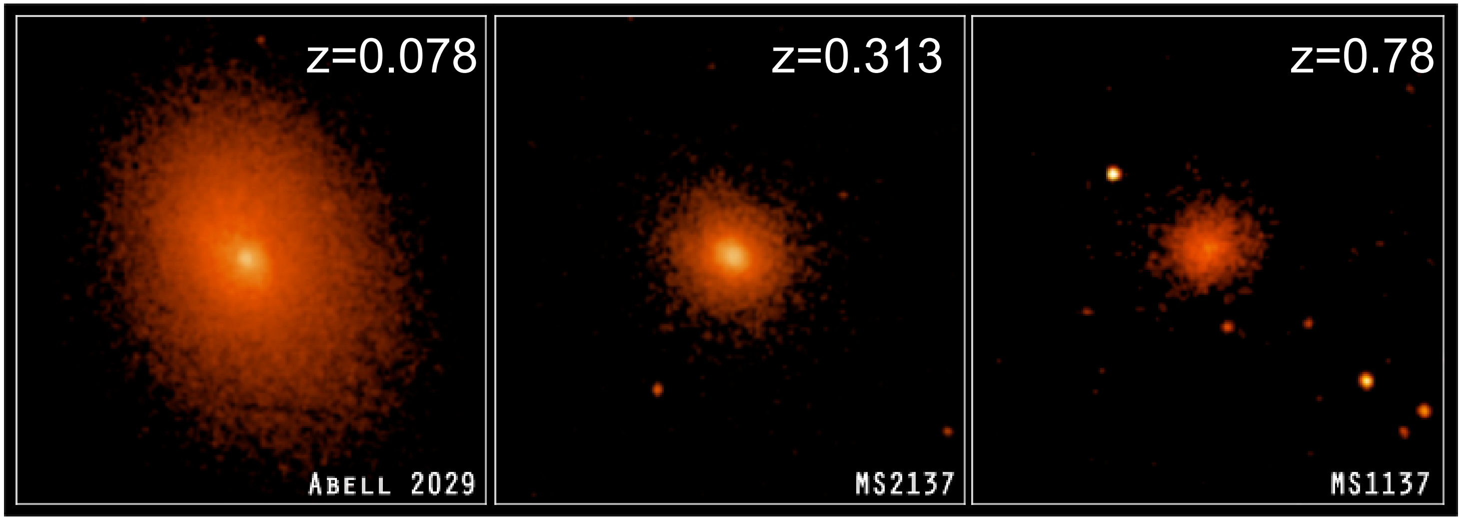


- **Largest gravitationally bound structures in the Universe, most of the normal, baryonic matter lies in the hot X-ray emitting gas (10^6 - 10^8 K)**
- **Measurement #1 (Geometric):** **Use clusters to measure distance based on gas mass fraction.**
- **Measurement #2 (Growth of structure): Use clusters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

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

Science Objective #3:

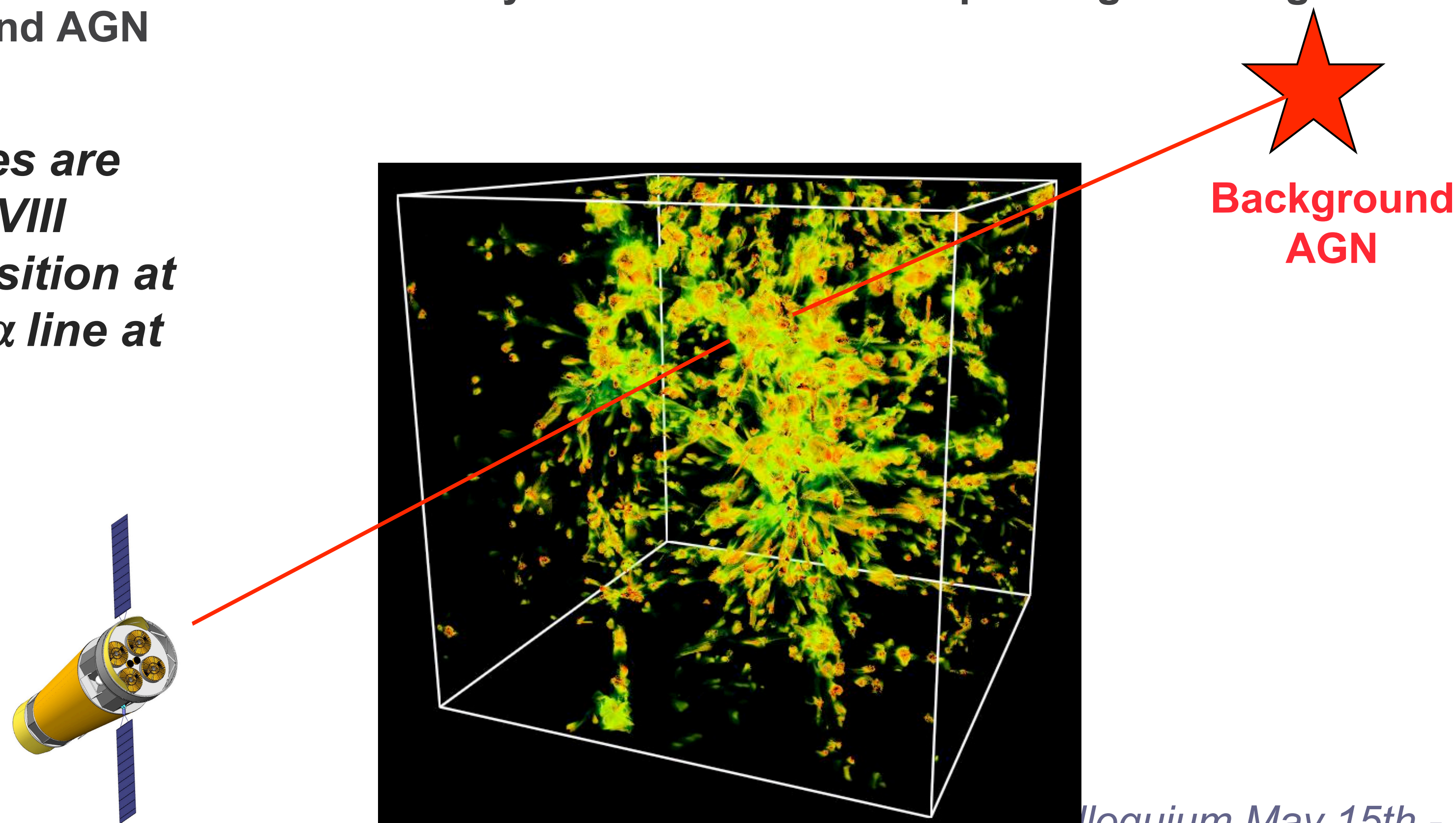
Missing Baryons

Missing Baryons:

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

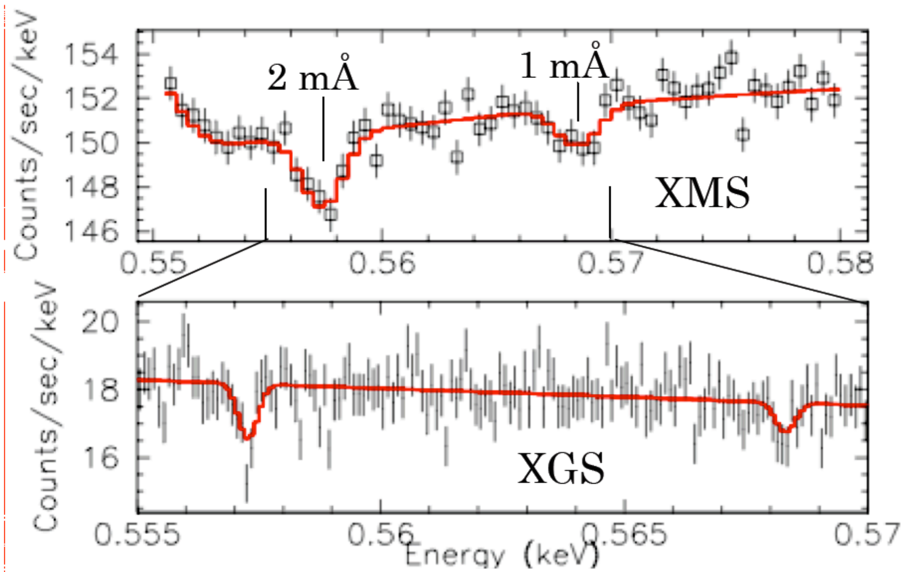
- ~ 60% of the baryonic matter at $z < 2$ is largely undetected.
- Theoretical simulations agree that it resides in filaments of hot (10^5 -$10^{7.5}$ K) gas
- Filaments of this "cosmic web" may be observed in absorption against bright background AGN

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

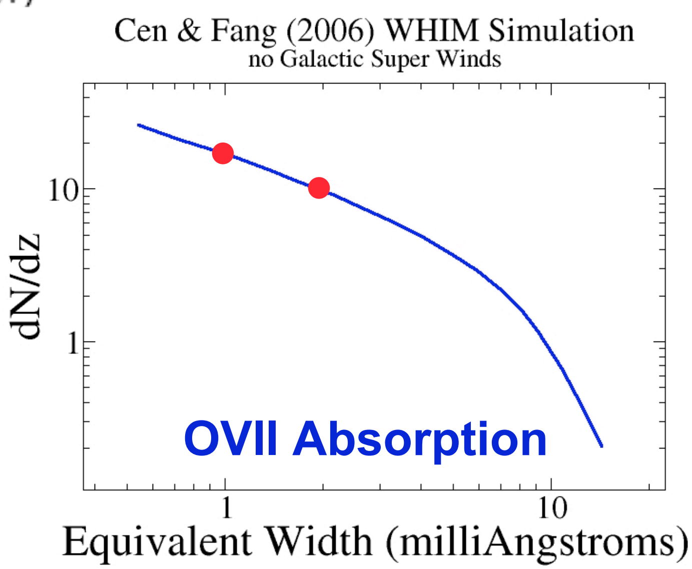


- **Sensitivity for WHIM measurements can be characterized in terms of equivalent width of relevant absorption features**
- **Benchmark measurement: 30 brightest AGN in ROSAT survey (typical redshifts z~0.2-0.3)**

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.**

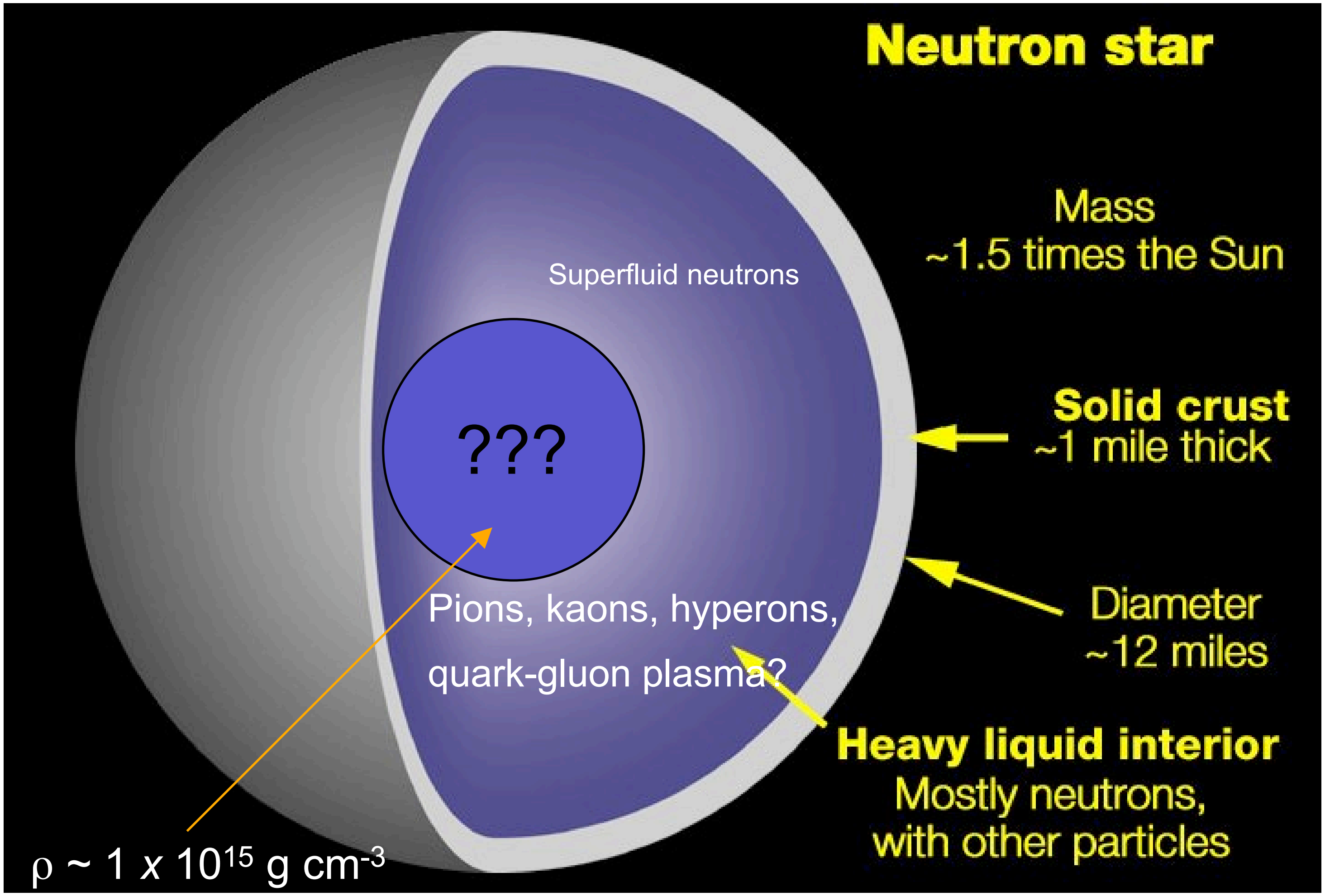
Science Objective #4:

Neutron Star Equation of State

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

Inside a Neutron Star

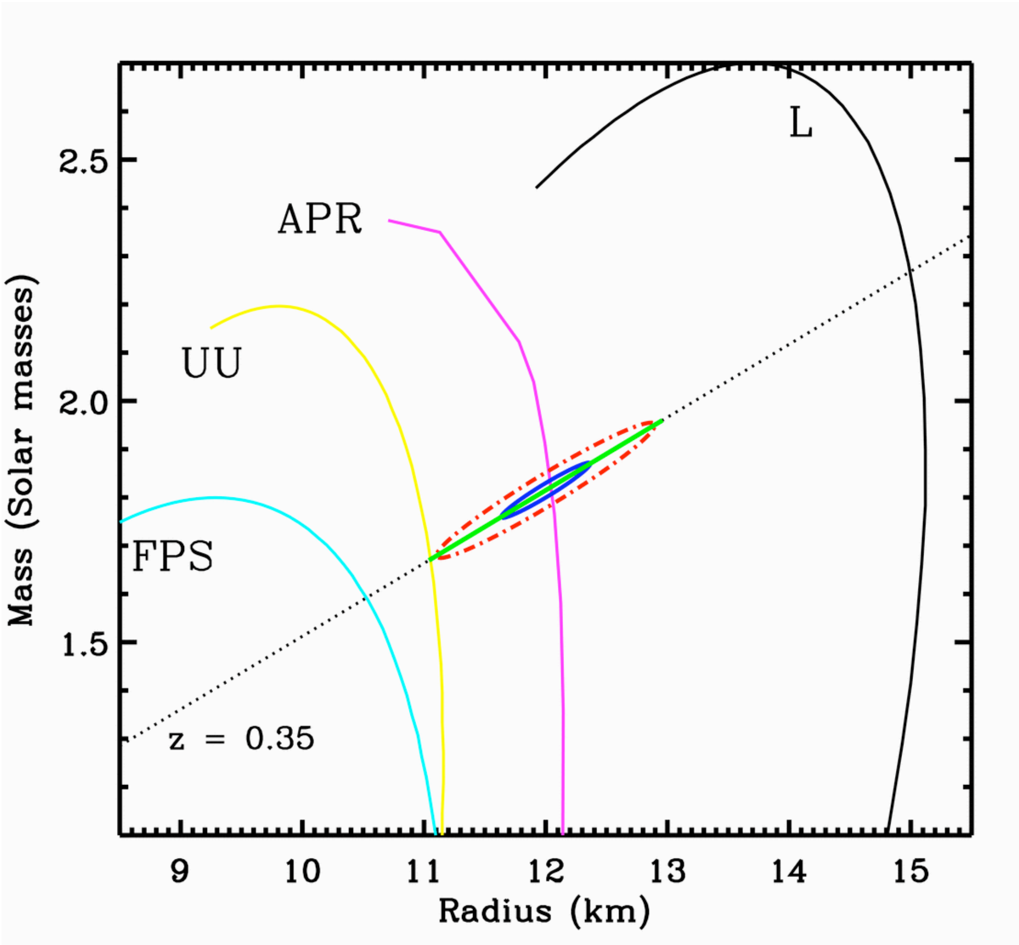
The physical constituents of neutron star interiors remain a mystery.



Constellation-X may finally provide the answers by determining the neutron star equation of state.

Neutron Stars:

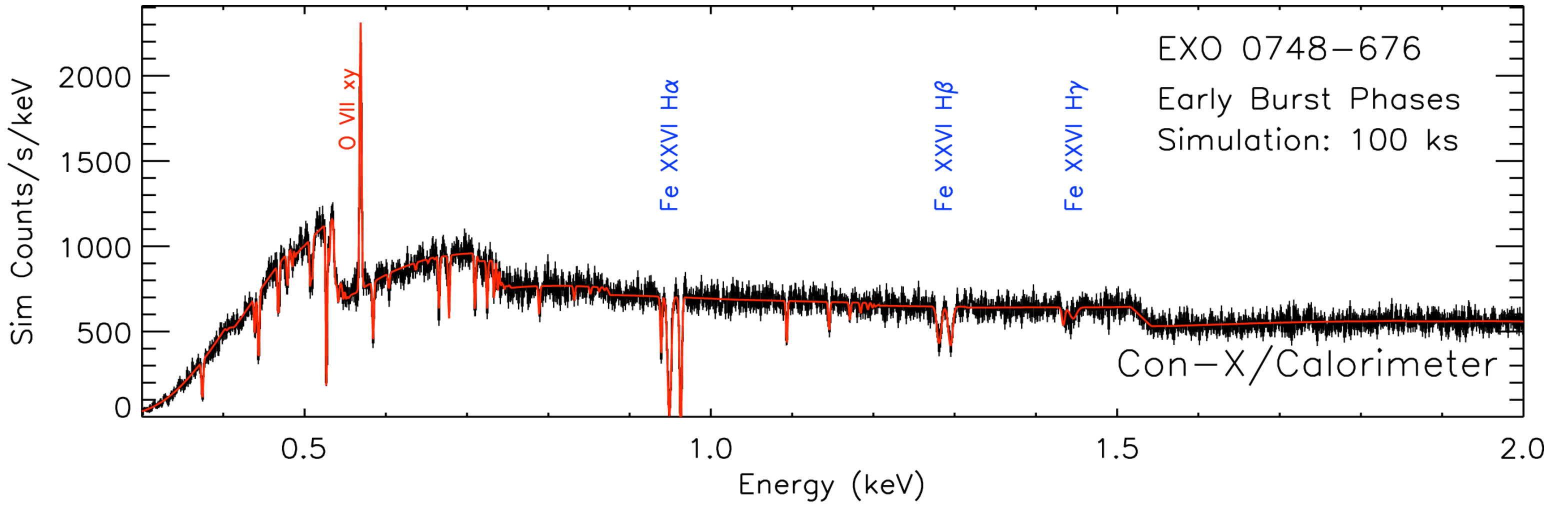
Measuring the mass-radius relation of neutron stars to determine the Equation of State (EOS) of ultra-dense matter



- **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:

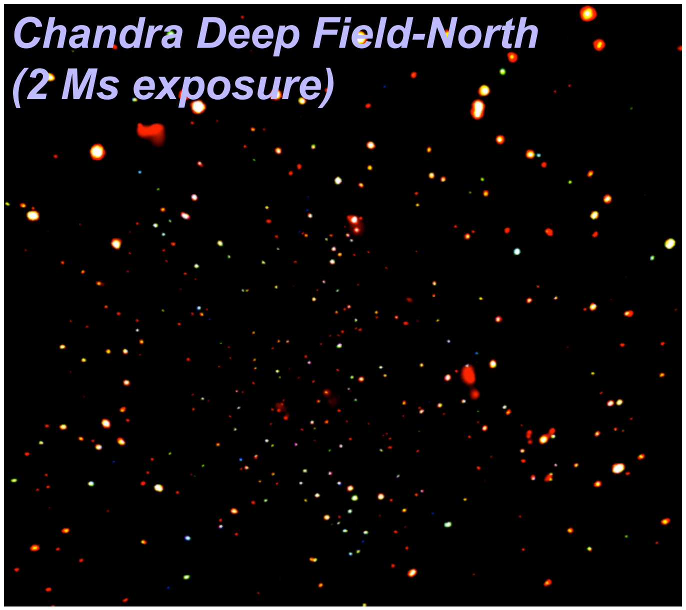
- **Absorption spectra provide a direct measure of gravitational redshift at surface of the star ($z \propto M/R$).**
- **The measured widths of the lines constrains the NS radius to 5-10% (compare to best present constraints: 9.5-15 km for EXO 0748-676)**

Measurement #2 – Burst oscillations:

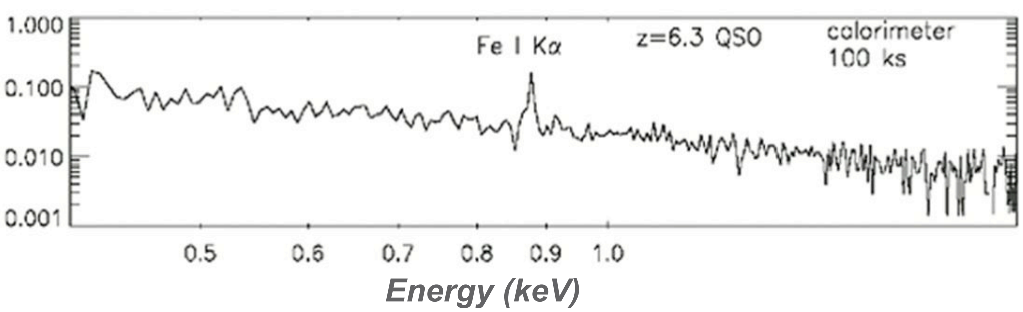
- **Pulse shapes of burst oscillations can provide an independent measure of the mass and radius to a few percent. Requires 100 microsec timing and ability to handle count rates up to 0.25 Crab.**

Beyond the 4 Driving Objectives...

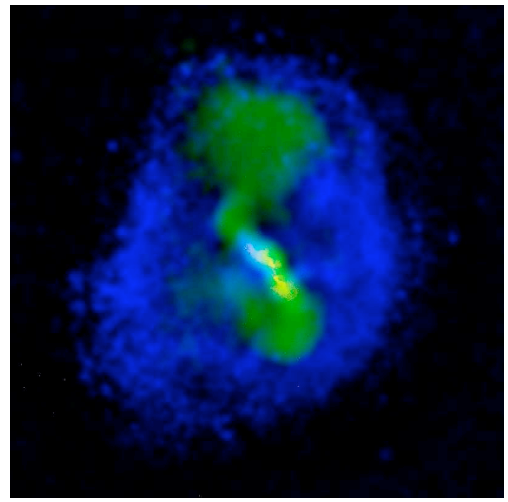
Evolution Of Black Holes



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



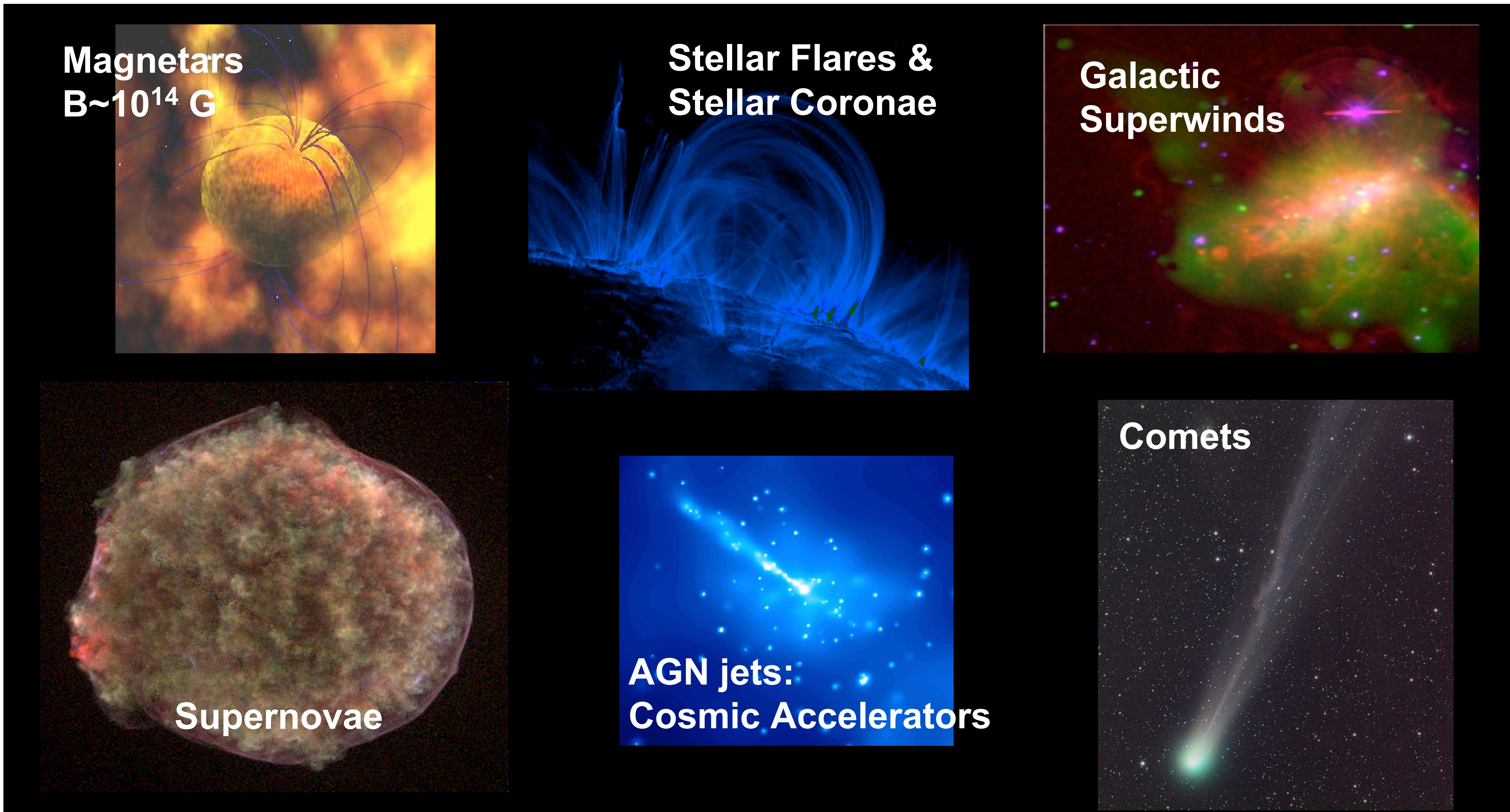
Wise et al. 2006
Hydra A

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

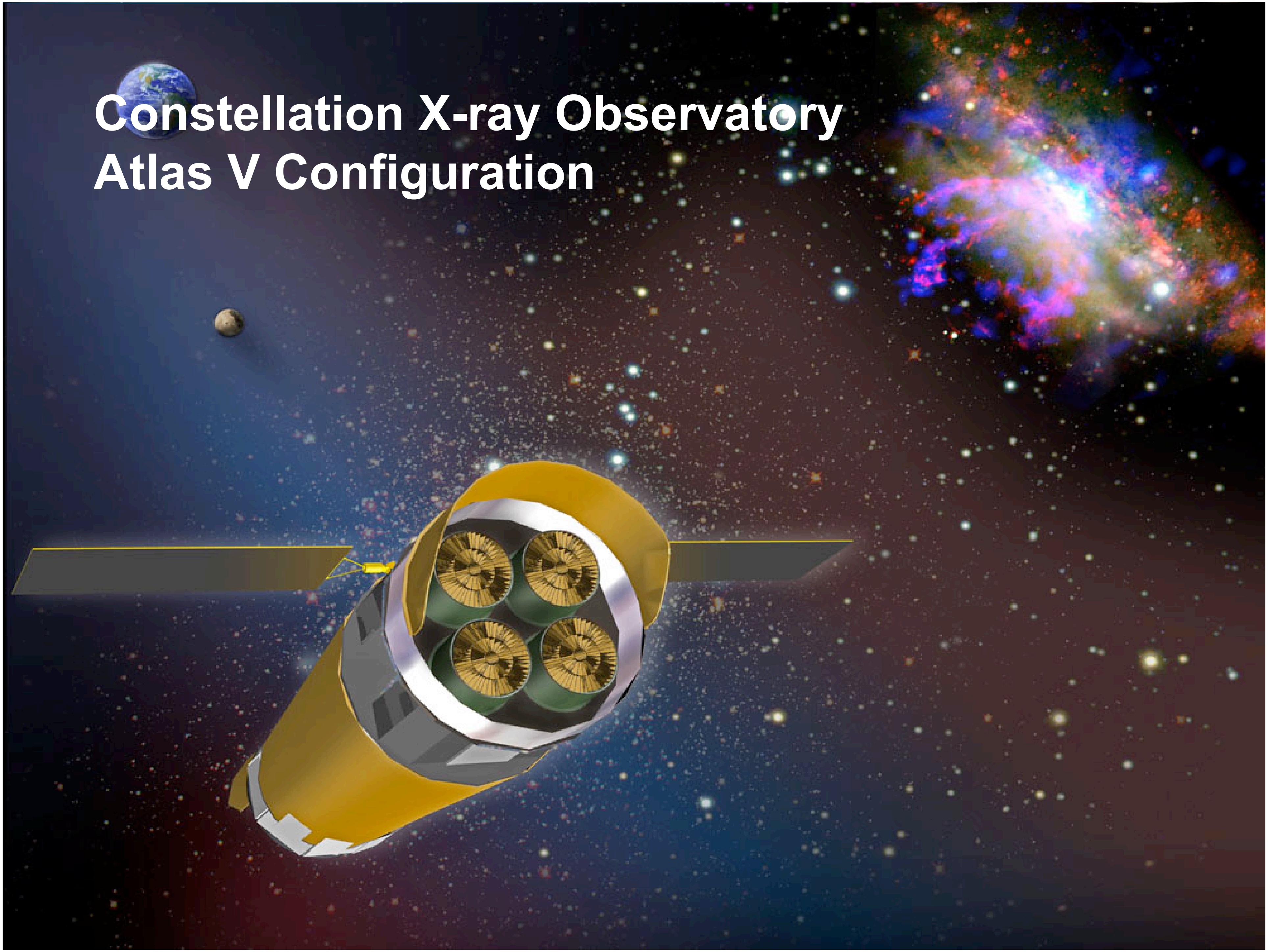
- Con-X enables a large range of science
- A broad scientific community will utilize this facility



Science Objectives Flow Into Key Performance Requirements

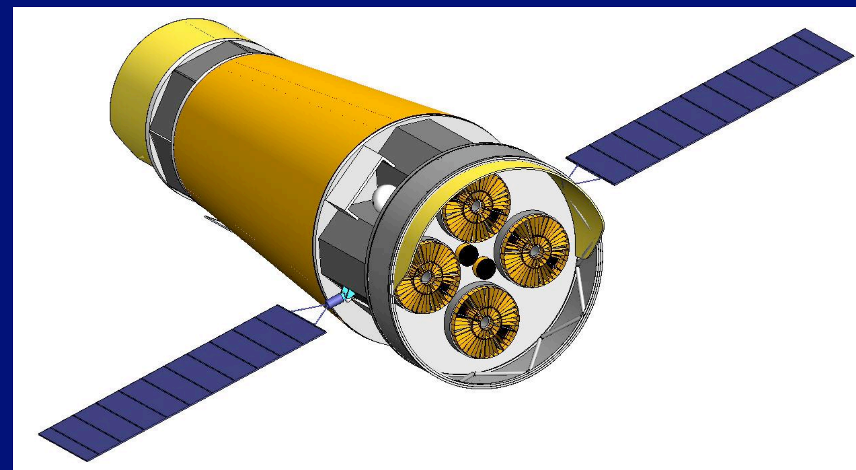
Effective Area:	15,000 cm^2 @1.25 keV 6,000 cm^2 @6 keV 150 cm^2 @40 keV
Bandpass:	0.3 – 40 keV
Spectral Resolution:	1250 @0.3 – 1 keV 2400 @6 keV
Angular Resolution	15 arcsec 0.3 – 7 keV 30 arcsec 0.7 – 40 keV
Field of View	5 x 5 arcmin

Constellation X-ray Observatory
Atlas V Configuration



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

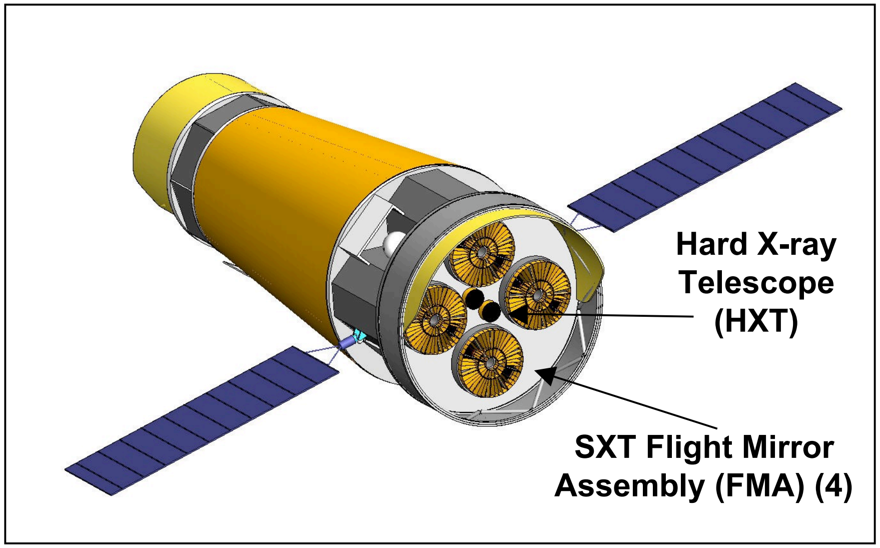


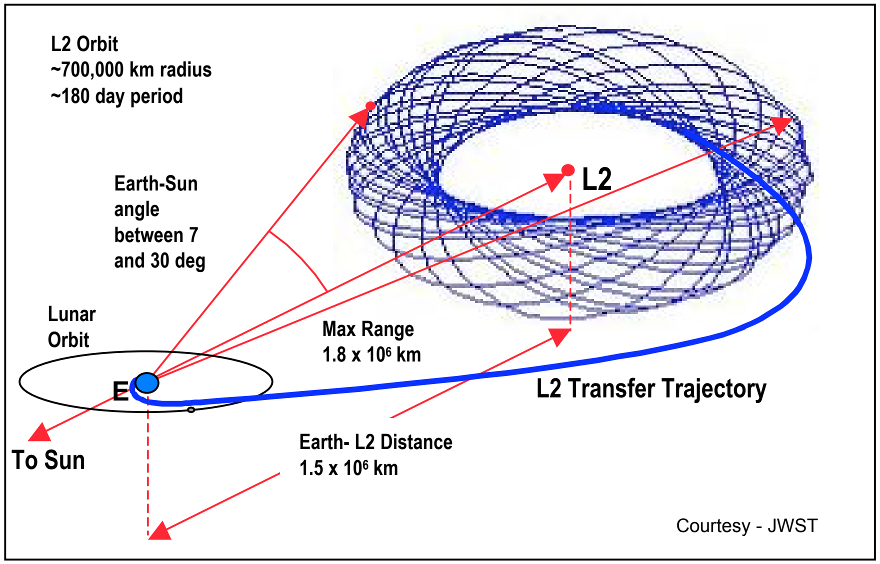
Approach Reduces Risk and Costs

CY '98	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16	'17	'18	'19	'20	'21	'2
Preformulation			Formulation				Implementation						MO&DA				
			Instr AO				CDR					Launch					

Mission Approach

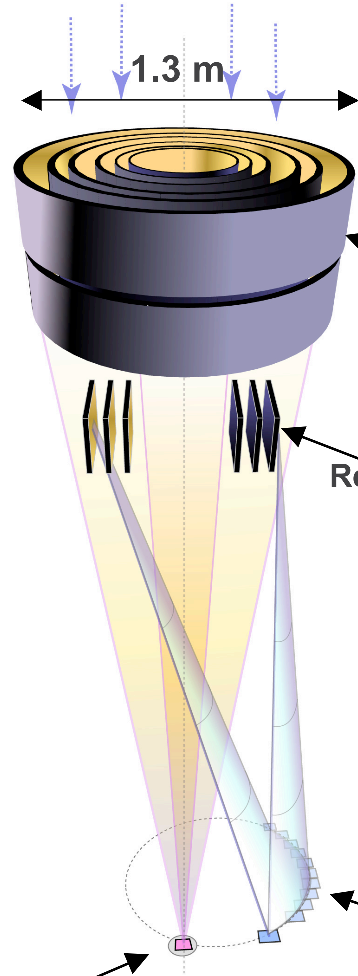
- High throughput achieved with 4 telescope systems on a single satellite
  - Complemented by low and high energy instruments
- L2 Orbit; 700,000 km radius halo orbit
  - High operational efficiency
  - Uninterrupted viewing
  - Stable temperature
- Field of regard allows full sky coverage every 180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



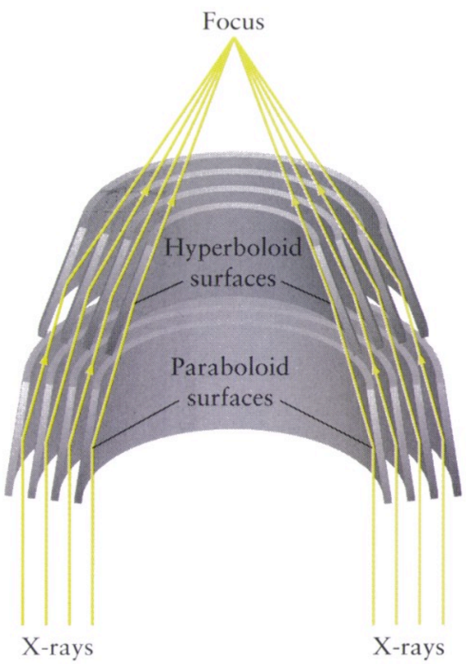


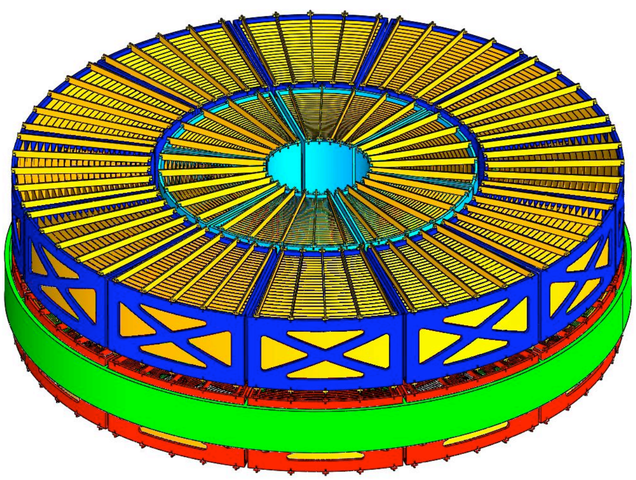
Mission Implementation

- 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



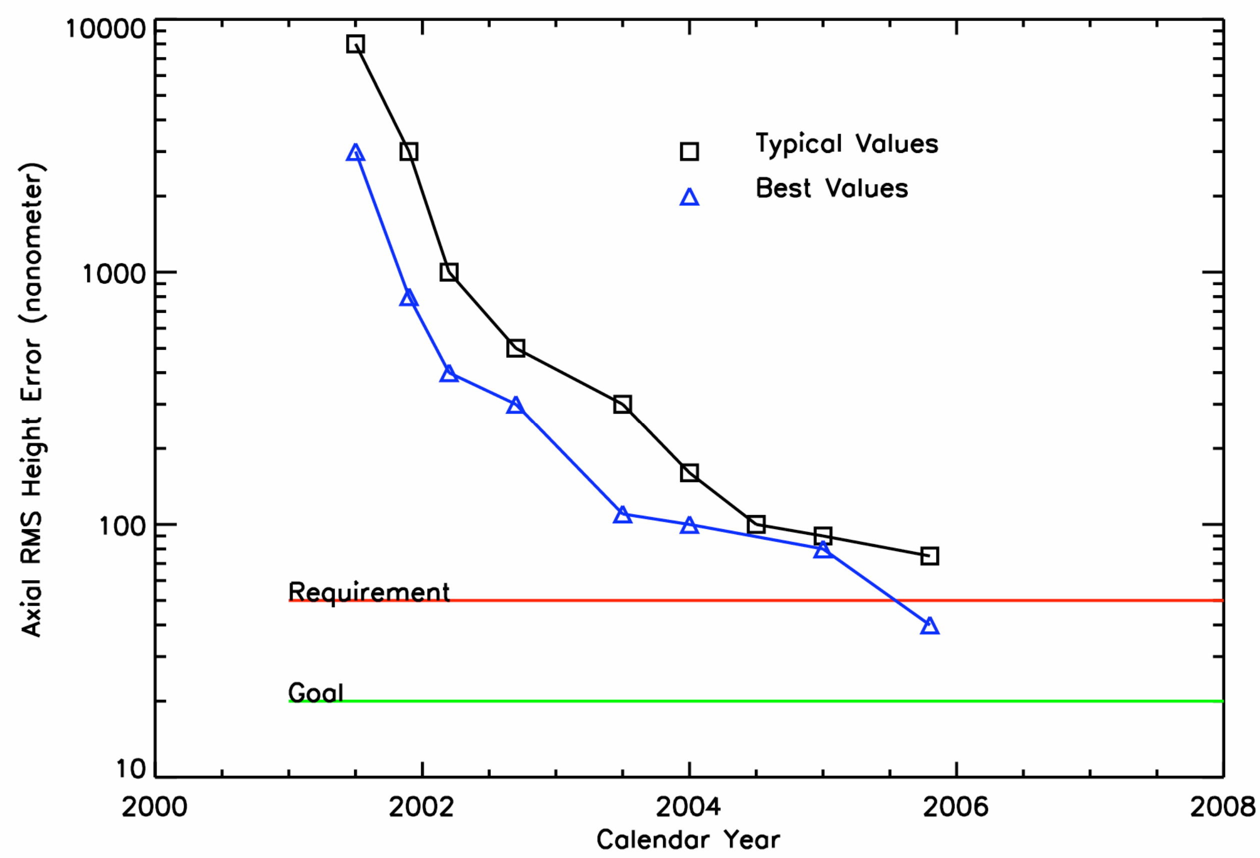
Enabling Technology: Thin, Segmented X-ray Mirrors





- **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**

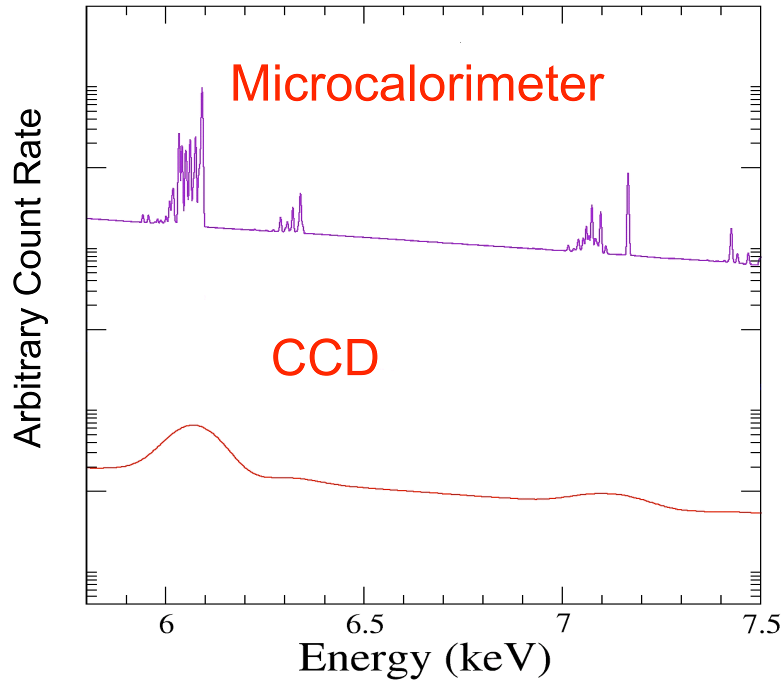
Mirror Segment Fabrication Progress

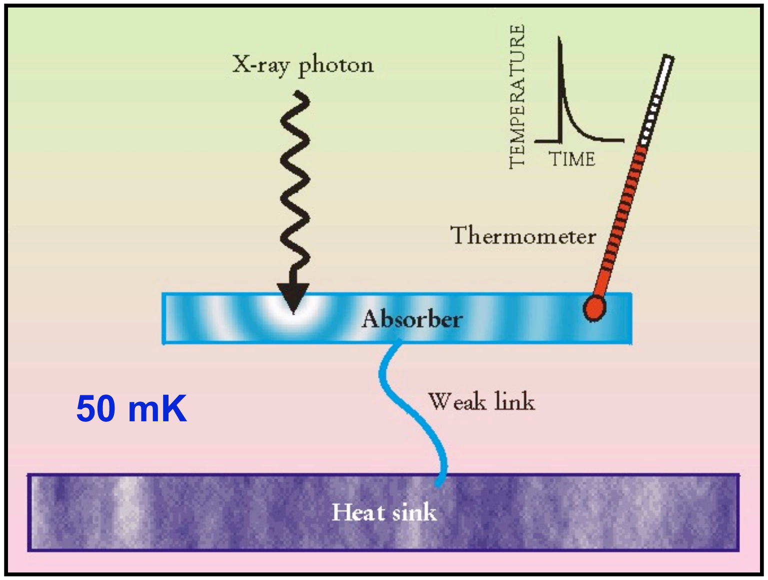


- RMS amplitude has improved to ~ required level
- Angular resolution improved by ~ 50% within year to within ~ 30% of requirements

Enabling Technology: X-Ray Microcalorimeters

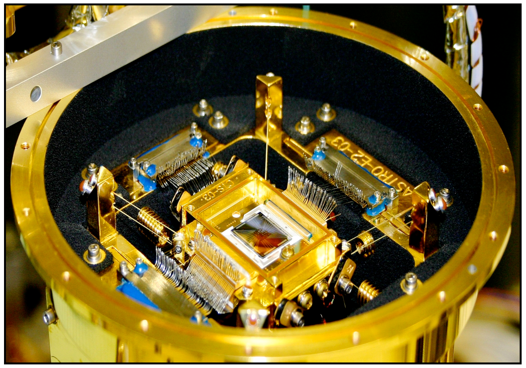
- X-ray microcalorimeter: thermal detection of individual X-ray photons
  - High spectral resolution
  - ΔE very nearly constant with E
  - High intrinsic quantum efficiency
  - Non-dispersive — spectral resolution not affected by source angular size





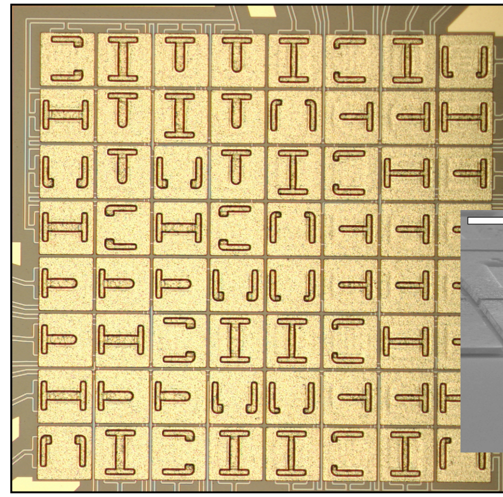
X-ray micro-calorimeters can image extended sources such as supernova remnants and galaxy clusters (as well as point sources) with 20-40 times improved energy resolution over CCD arrays, and factor of 5-10 better quantum efficiency than gratings

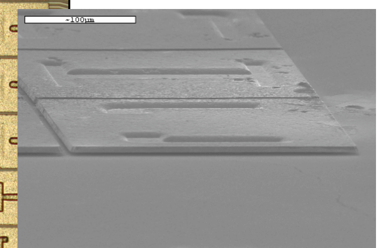
X-ray Microcalorimeter Spectrometer (XMS)



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

Con-X test arrays achieve 2.5 eV at 6 keV



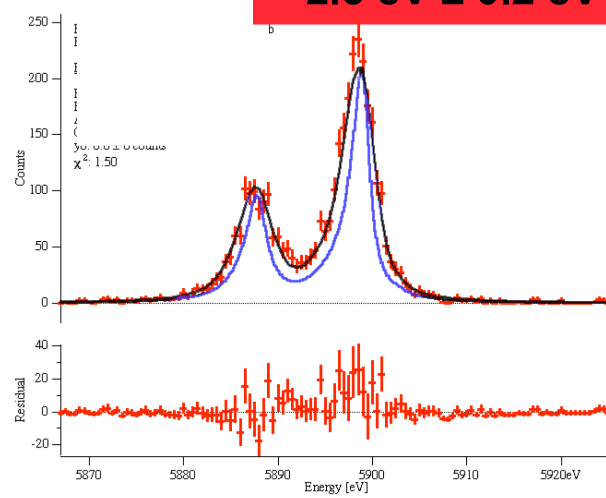


High filling factor

8 x8 development Transition Edge Sensor array: 250 μm pixels

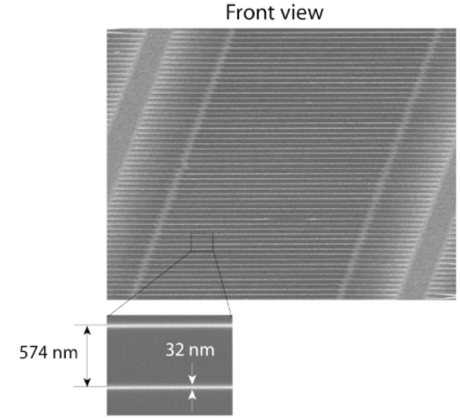
- **XMS key requirements:**
  - **Bandpass: 0.6 to 10 keV**
  - **Field of view:**
    - **5 arcmin x 5 arcmin via extended position sensitive microcalorimeters**
  - **Spectral resolving power:**
    - **2.5 eV in core array (2.5 x 2.5 arcmin)**
    - **8 eV for outer array**
- **Transition Edge Sensor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

2.5 eV ± 0.2 eV FWHM

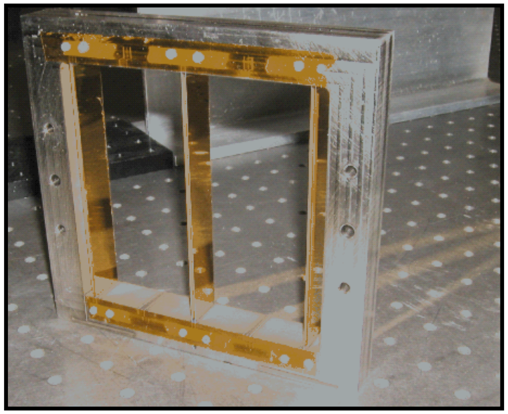


X-ray Grating Spectrometer (XGS)

- 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



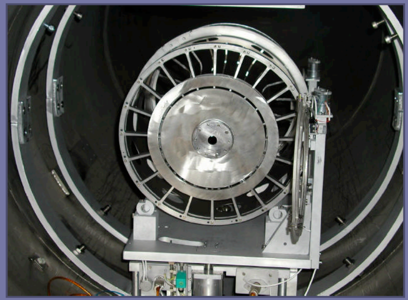
Three mounted off-plane gratings for sounding rocket

Hard X-ray Telescope (HXT)

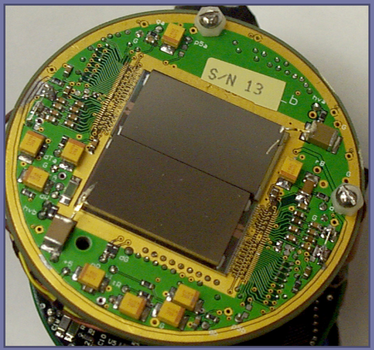
- HXT key requirements:
  - Effective area of 150 cm^2 from 6 to 40 keV
  - Spectral resolving power 10 over full band
  - 30 arcsec HPD
- Two potential technologies for the mirrors
  - Nickel Shell & Glass Segment
  - Highly nested optics with multilayer coatings
  - X-ray tests show 30 – 40 arcsec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

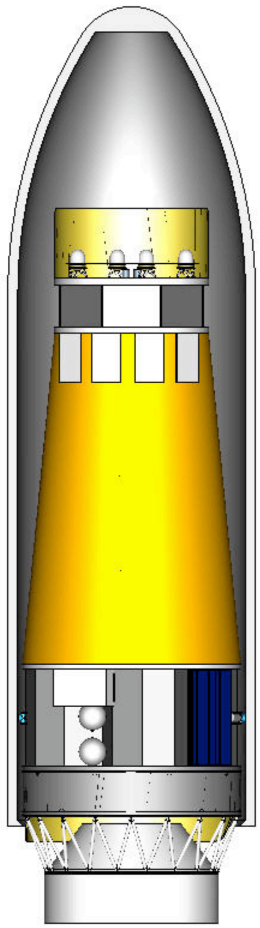


CdZnTe hybrid pixel detector

CdZnTe vibration test

Launch and Mass Summary

Atlas 551
Long Fairing



Atlas Payload
Adapter Fitting

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**

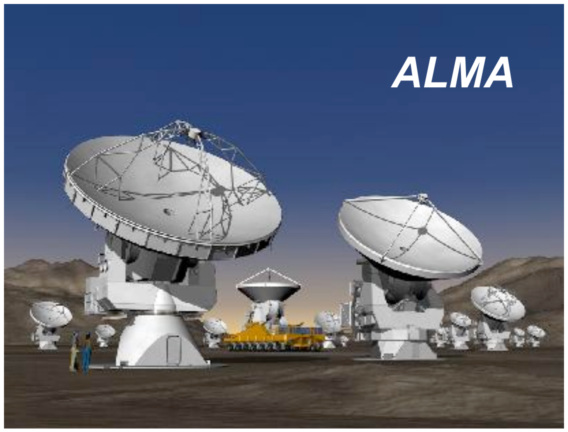
6217 kg Wet Mass

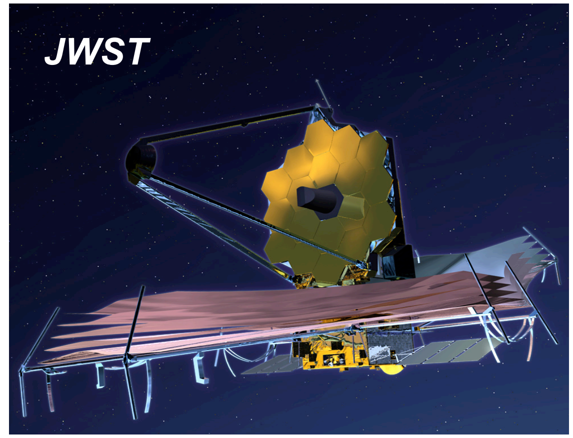
88 kg Margin

30% overall contingency

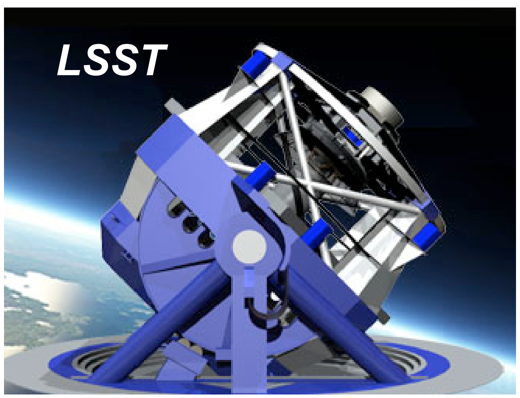
Constellation-X will complement other planned space and ground-based missions in a manner similar

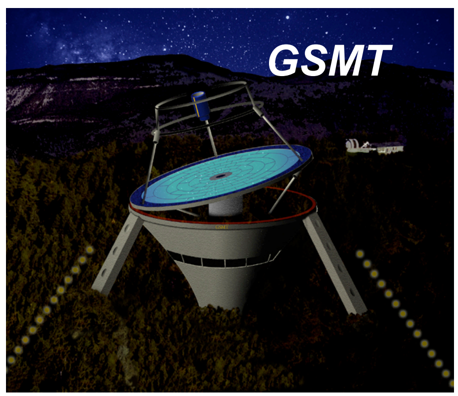
Sub-mm

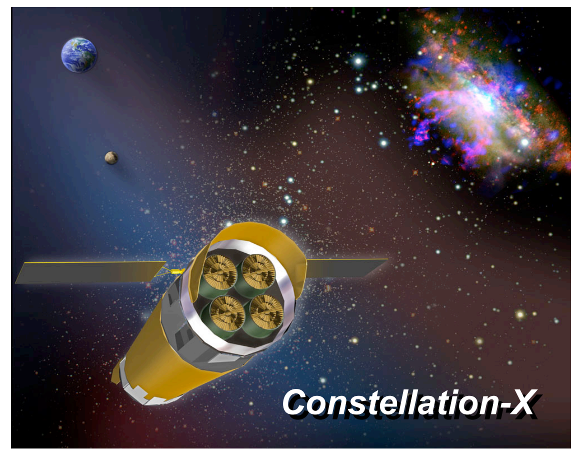




IR





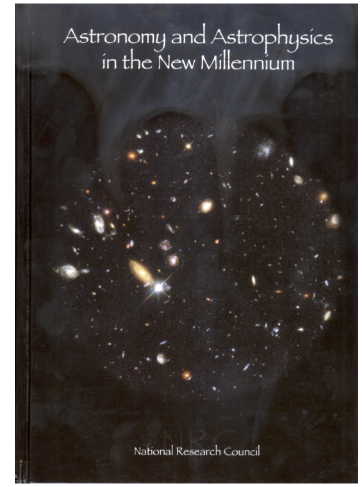


X-ray

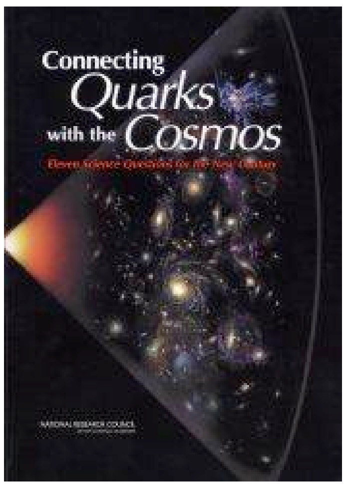
Optical

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

Science Reach – Previous Academy Reports



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



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"*

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