BEYOND EINSTEIN: From the Big Bang to Black Holes

High Resolution Spectroscopy with Constellation-X

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X-ray Grating Spectroscopy
Cambridge
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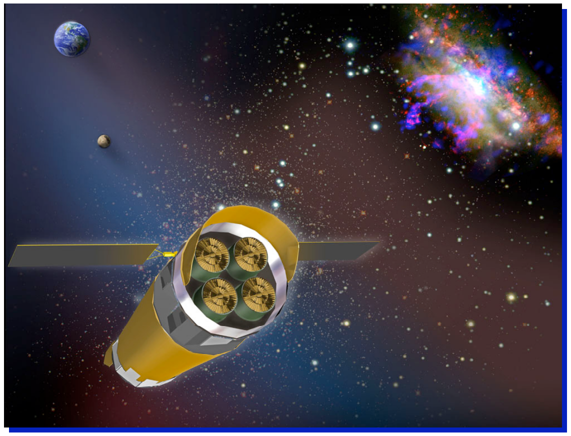
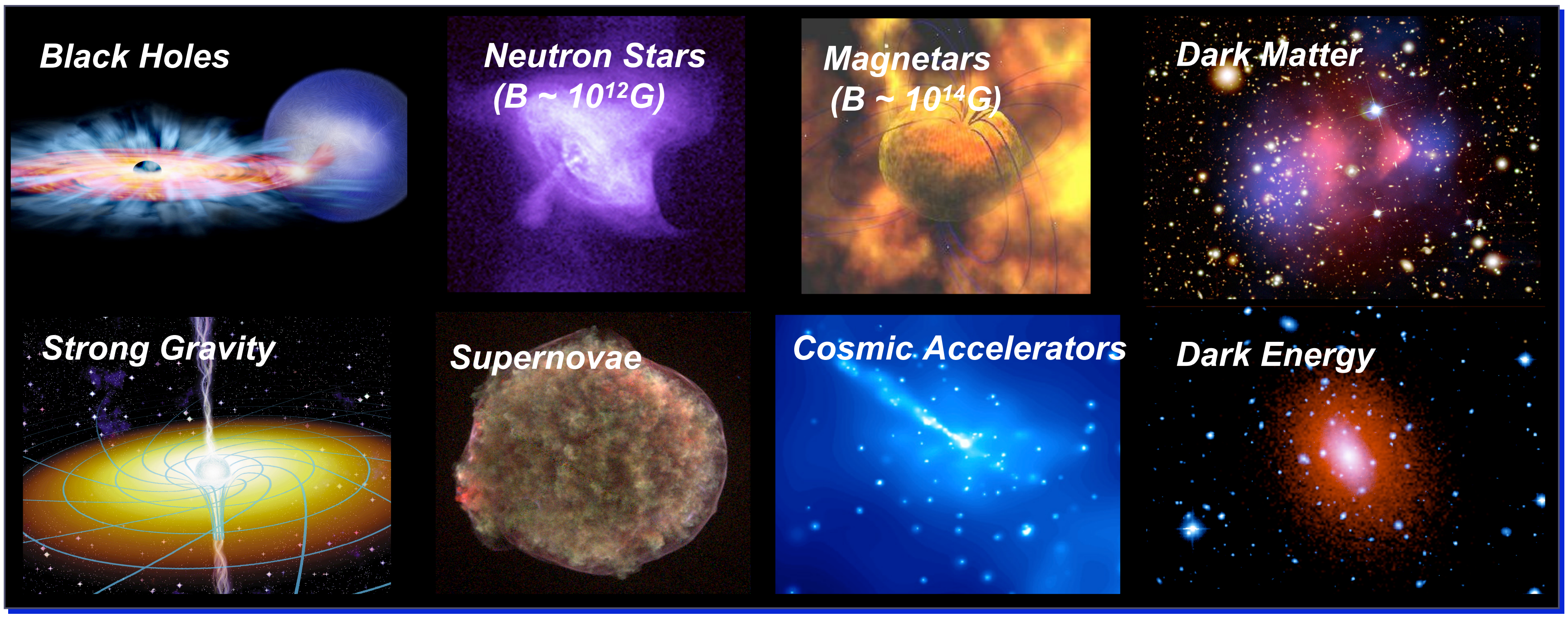
Constellation-X Will Open a New Window on X-ray Spectroscopy

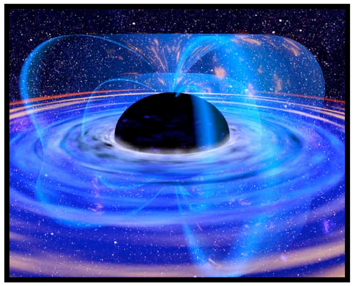


- X-ray emission probes the physics of extreme processes, places and events.
- Chandra and XMM-Newton brought x-ray astronomy to the forefront
- Con-X throughput for high resolution spectroscopy is 100 times higher than Chandra and XMM

⇒ X-ray astronomy becomes X-ray astrophysics

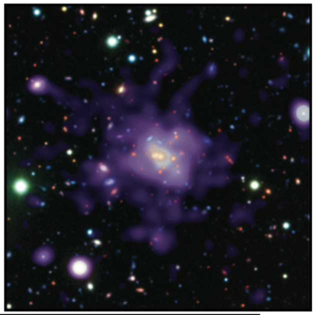


Driving Science Objectives



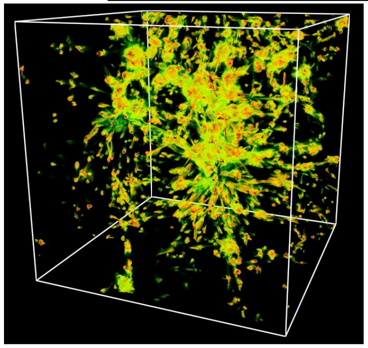
Black Holes

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



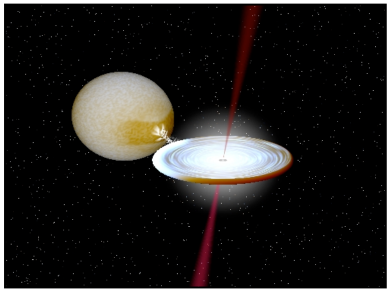
Dark Energy (and Dark Matter)

- 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



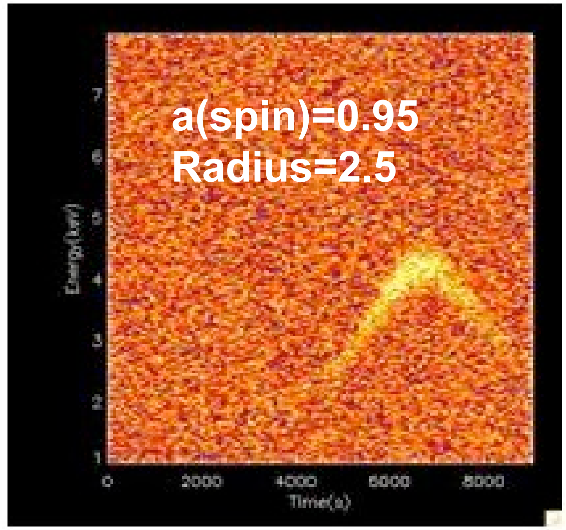
Neutron Star Equation of State

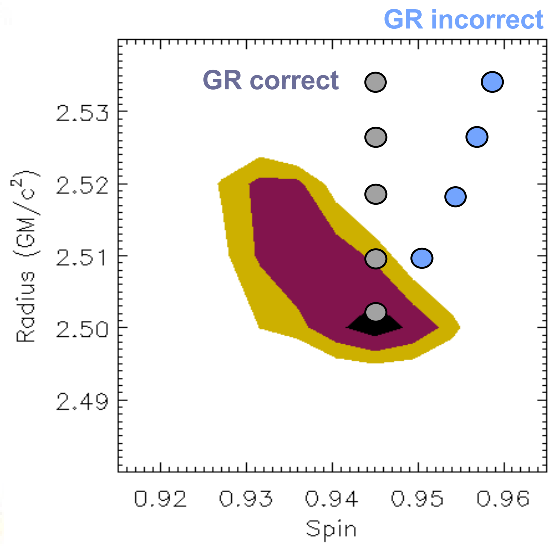
- Measuring the mass-radius relation of neutron stars to determine the Equation of State (EOS) of ultra-dense matter

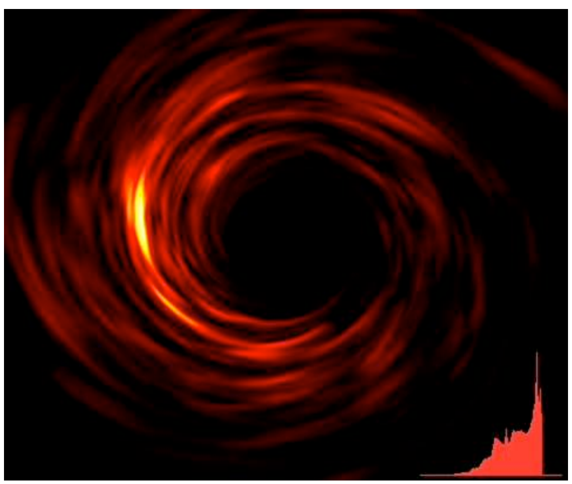
Black Holes

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 a function of radius in disk.**
  - **Spin measurements vs radius provide a powerful consistency check of GR in the strong gravity regime.**



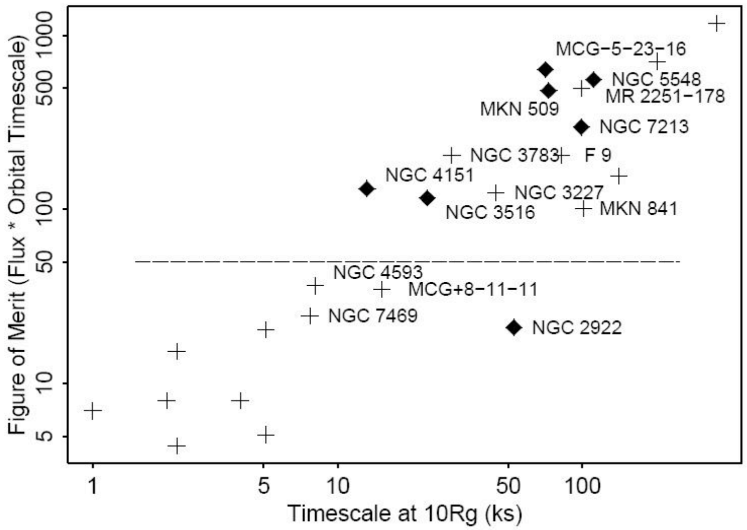




Detectability depends on X-ray flux, line intensity, and orbital timescale (FOM)

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

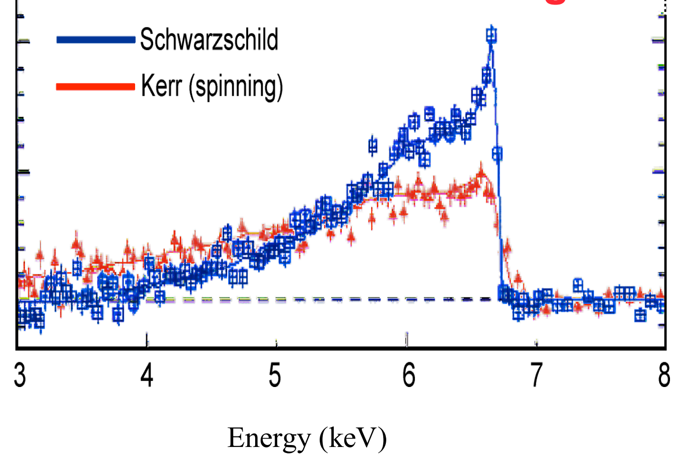
Black Holes: *Measurements*



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

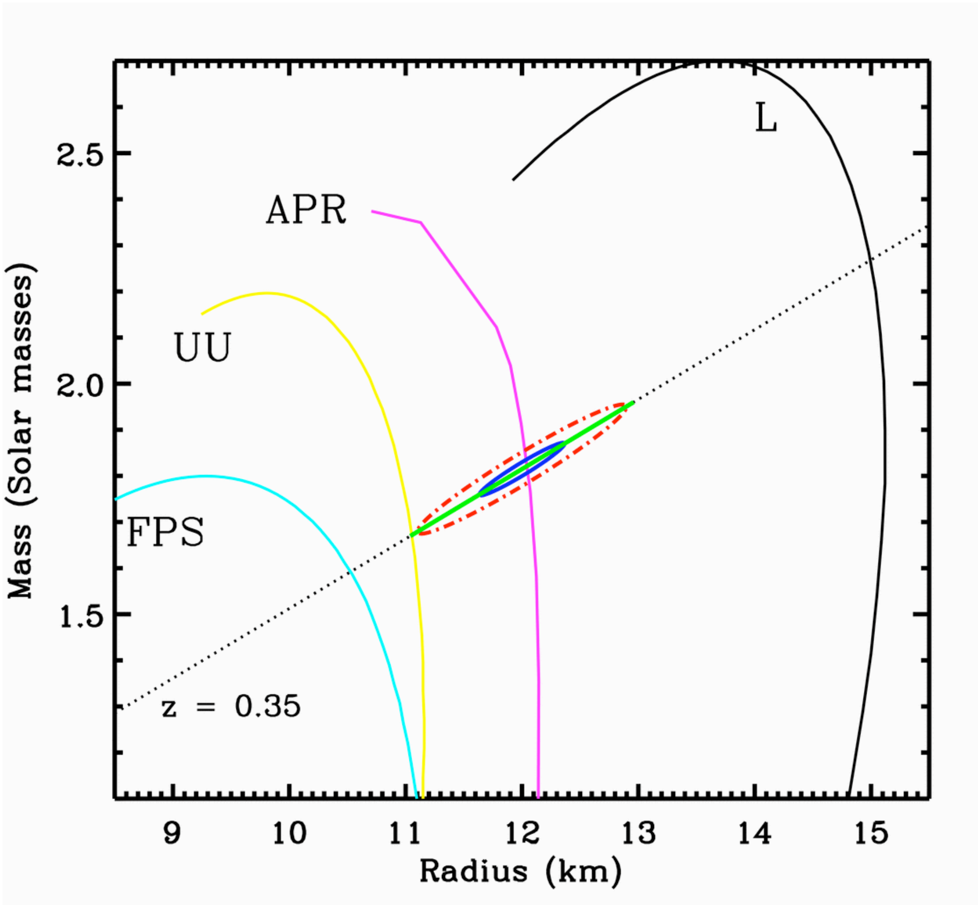
- **Target list for GR tests known and growing**
- **Single target sufficient to test GR under strong gravity**
- **Currently >dozen targets over FOM requirement**
- **Range of masses at least 1, perhaps 3 orders of magnitude**

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)**

Neutron Stars

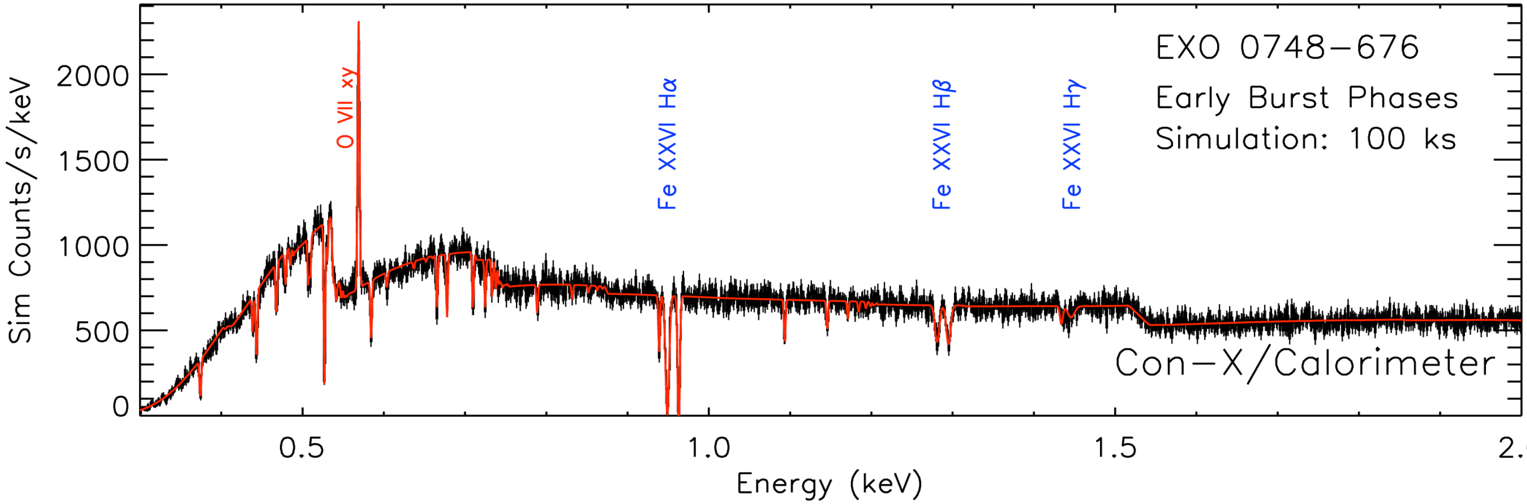
Measuring the mass-radius relation of neutron stars to determine the Equation of State (EOS) of ultra-dense matter



- NS 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 covering a range of masses.

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.**

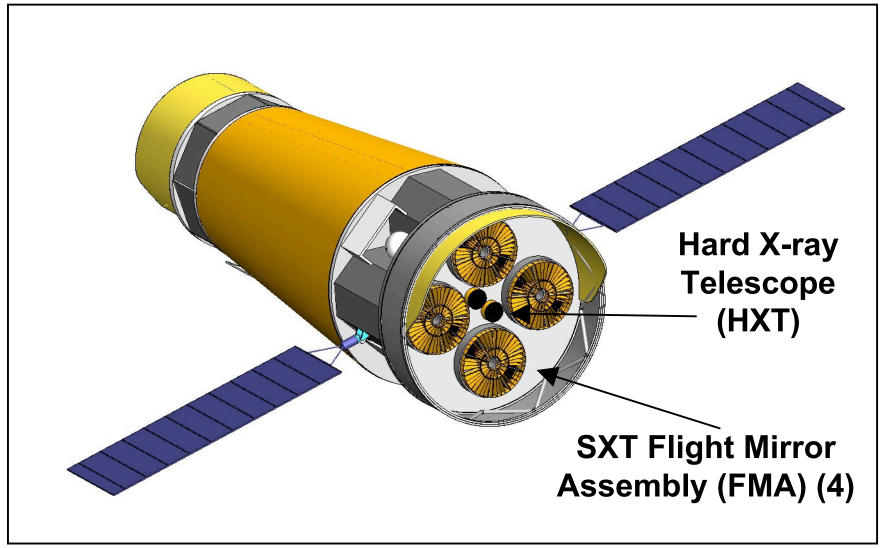
Science Objectives Flow Into Key Performance Requirements

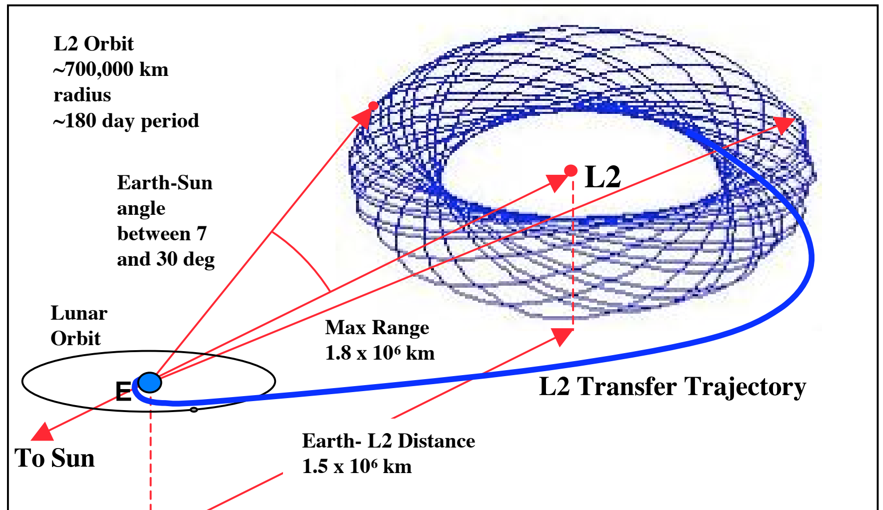
Bandpass:	0.3 – 40 keV
Effective Area:	15,000 cm^2 @ 1.25 keV 6,000 cm^2 @ 6 keV 150 cm^2 @ 40 keV
Spectral Resolution:	1250 @ 0.3 – 1 keV 2400 @ 6 keV
Angular Resolution	15 arcsec 0.3 – 7 keV (5 arcsec goal) 30 arcsec 7.0 – 40 keV
Field of View	5 x 5 arcmin

- 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 (64x64 pixels, goal of 10 x 10 arc min FOV)
- Ability to handle 1,000 ct/sec/pixel required for studies of nearby black holes and neutron stars

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



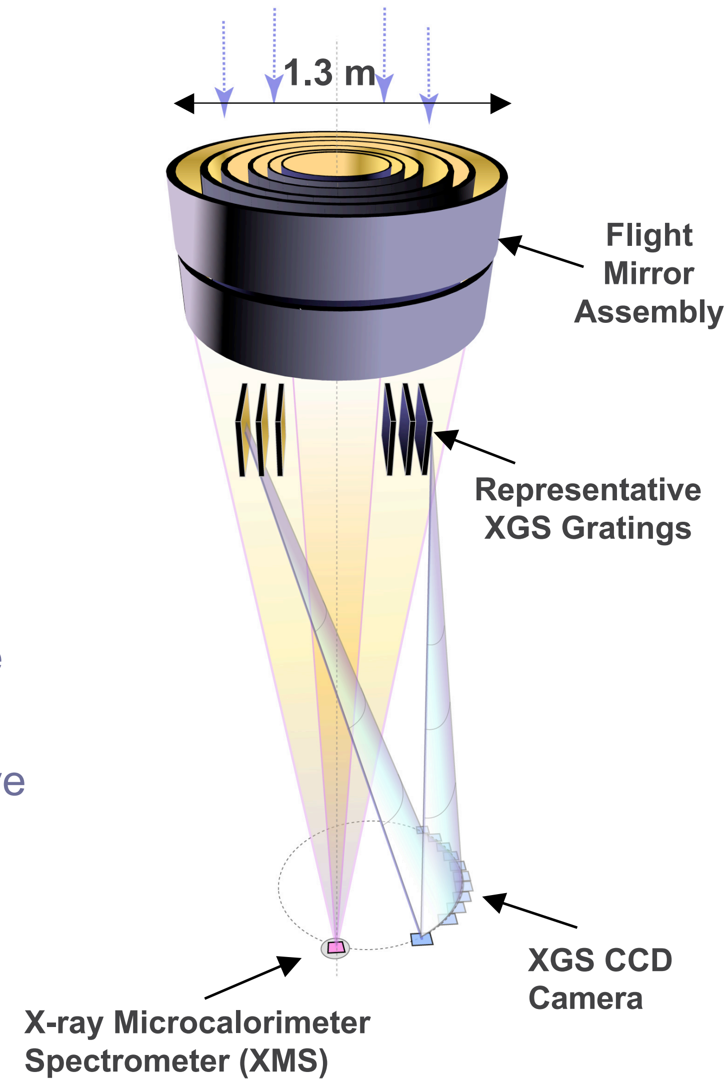


Courtesy - JWST

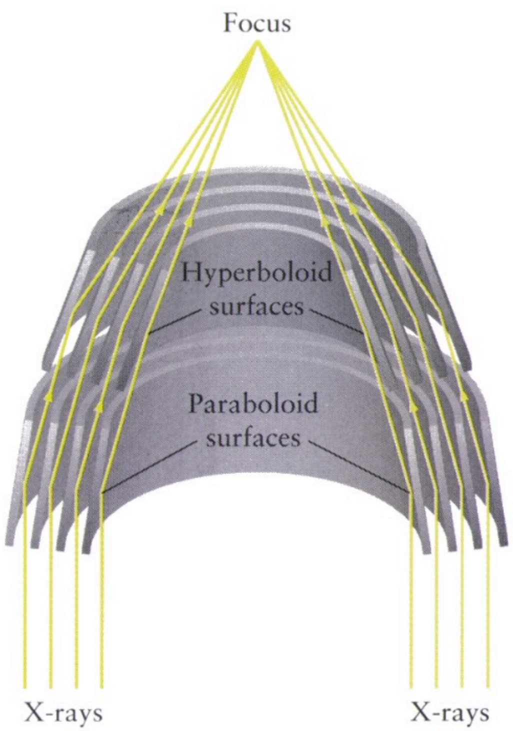
Mission Implementation

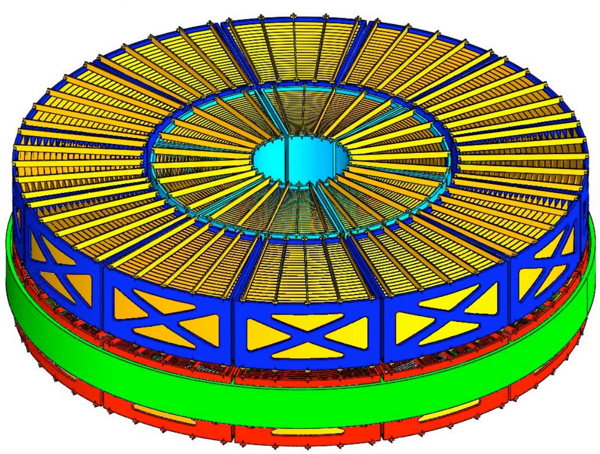
- To meet the requirements, our technical implementation consists of:
  - 4 SXTs each consisting of a Flight Mirror Assembly (FMA) and a X-ray Microcalorimeter Spectrometer (XMS)
    - Covers the bandpass from 0.6 to 10 keV
  - Two additional systems extend the bandpass:
    - X-ray Grating Spectrometer (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

4 Spectroscopy X-ray Telescopes



Spectroscopy X-ray Telescope (SXT)

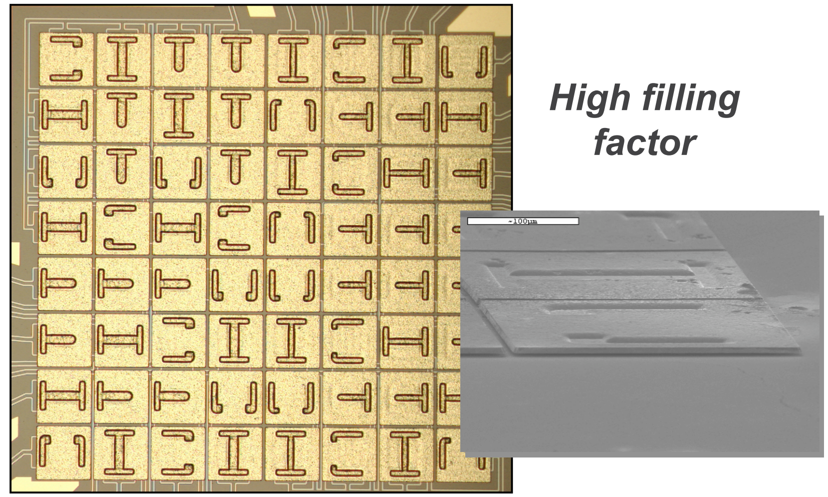




- **Trade-off between collecting area and angular resolution**
- The 0.5 arcsec angular resolution state of the art is *Chandra*
  - Small number of thick, highly polished substrates leads to a very expensive and heavy mirror with modest area
- Constellation-X collecting area (~10 times larger than *Chandra*) combined with high efficiency microcalorimeters increases throughput for high resolution spectroscopy by a factor of 100
  - 15 arcsec angular resolution required to meet science objectives (5 arcsec is goal)
  - Thin, replicated segments pioneered by ASCA and Suzaku provide high aperture filling factor and low 1 kg/m^2 areal density

X-ray Microcalorimeter Spectrometer (XMS)

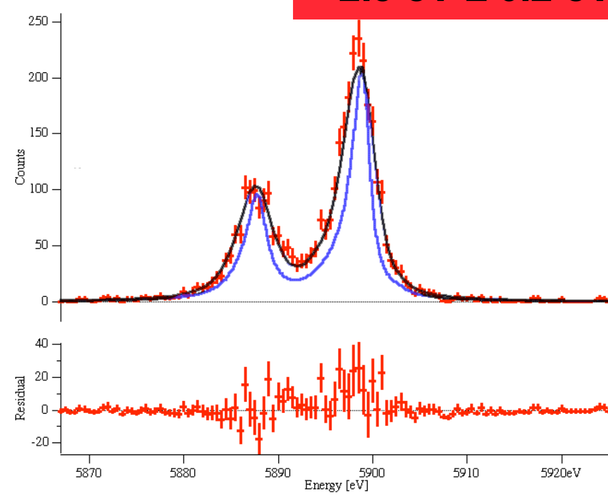
- X-ray Microcalorimeter: thermal detection of individual X-ray photons
  - **High spectral resolution**
  - **ΔE very nearly constant with E**
  - **High intrinsic quantum efficiency**
  - **Non-dispersive — spectral resolution not affected by source angular size**
- Transition Edge Sensor (TES), NTD/Ge and magnetic microcalorimeter technologies under development

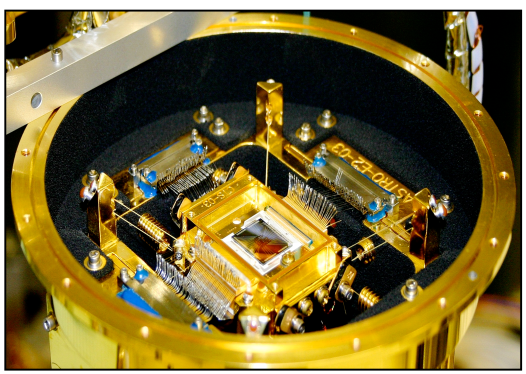


High filling factor

8 x8 development Transition Edge Sensor array: 250 μm pixels

2.5 eV ± 0.2 eV FWHM

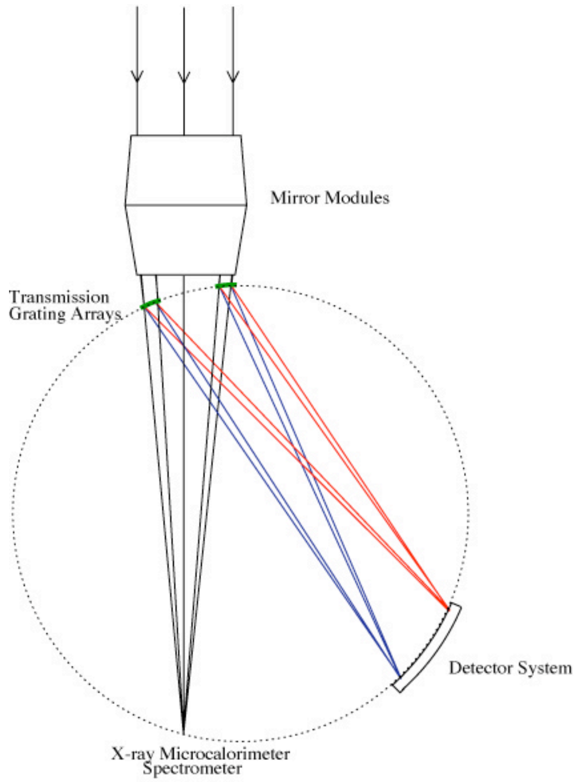


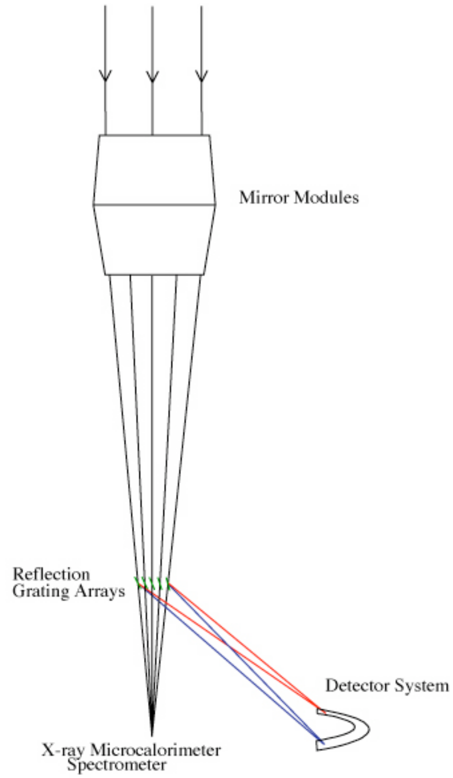


Suzaku X-ray calorimeter array achieved 7 eV resolution on orbit

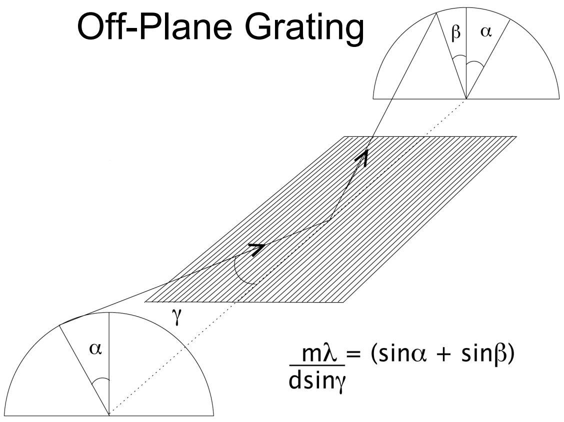
X-ray Grating Spectrometer (XGS)

- 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
  - CAT grating
  - Off-plane reflection grating



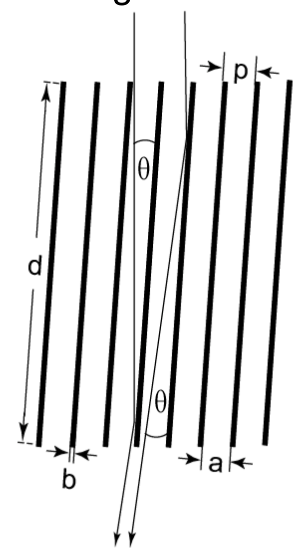


Off-Plane Grating

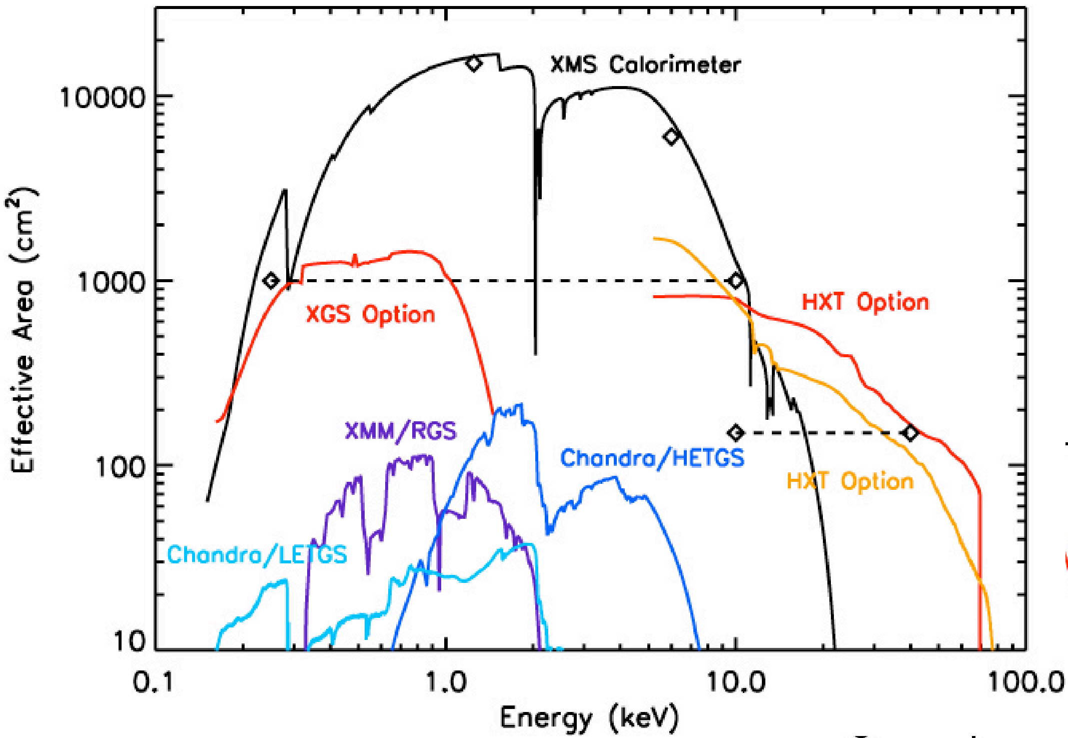


$$\frac{m\lambda}{d\sin\gamma} = (\sin\alpha + \sin\beta)$$

CAT Grating

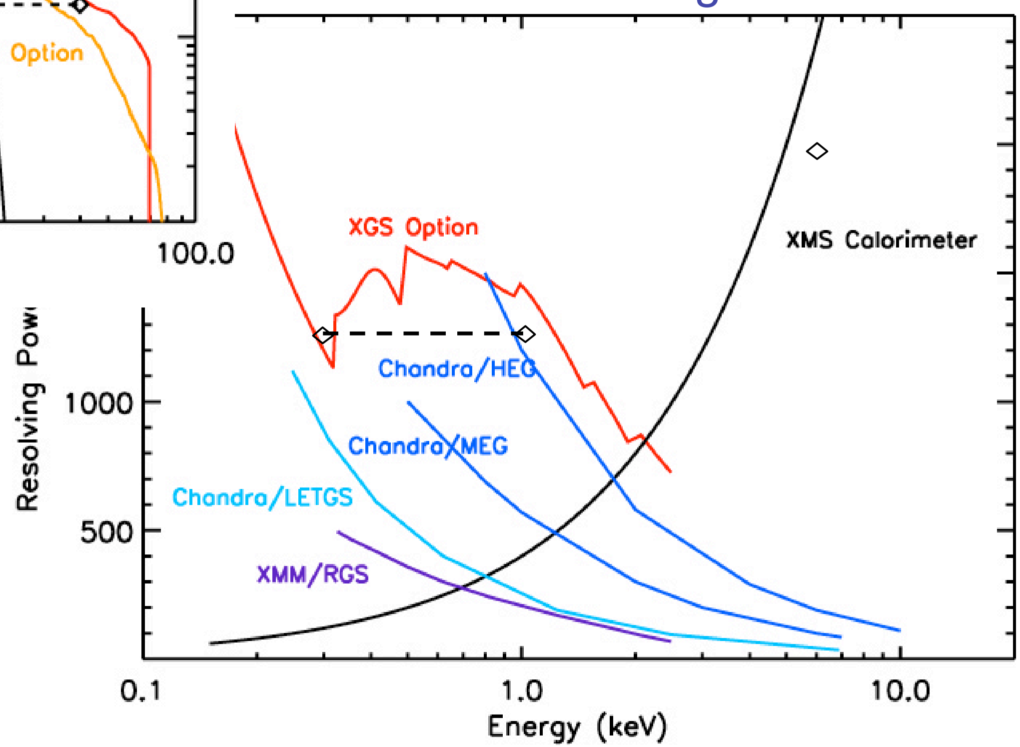


Projected Performance



Con-X Effective Area

Con-X Resolving Power



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
- Two 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
  - Neutron Stars: Precision measurements of the mass-radius relation of neutron stars to determine the Equation of State (EOS) of ultra-dense matter
- Constellation-X based on extensions of flight proven optics and instruments
- 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