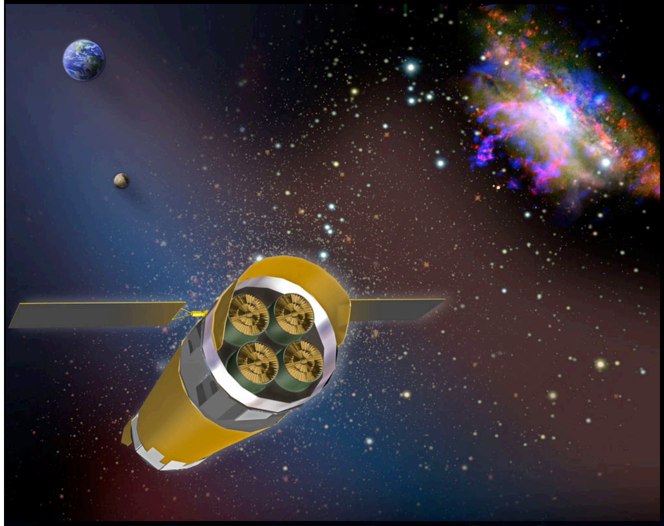
BEYOND EINSTEIN: From the Big Bang to Black Holes

Constellation X

The Constellation X-Ray Mission



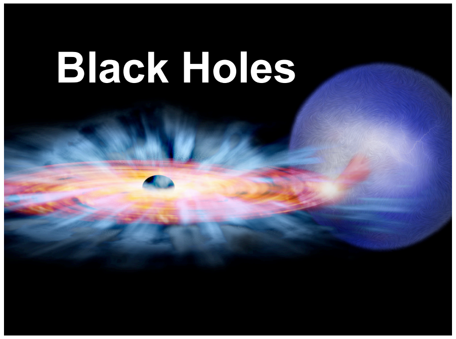
Going Beyond Einstein with Constellation-X

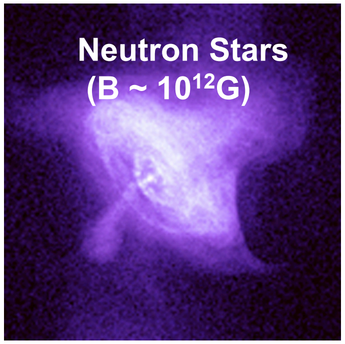
Nicholas White (NASA/GSFC)

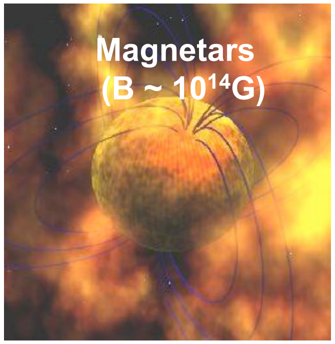
Project Scientist

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

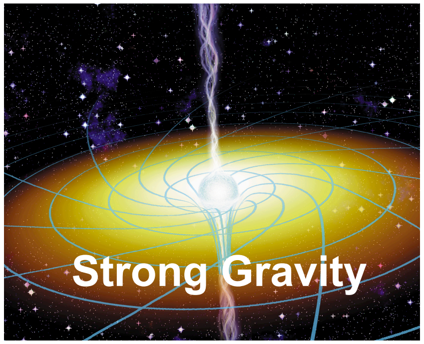
X-ray emission probes the physics of extreme processes, places and events

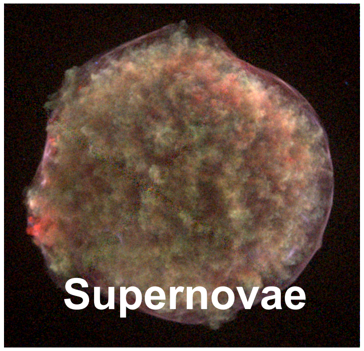

Black Holes


Neutron Stars (B ~ 10^{12}G)


Magnetars (B ~ 10^{14}G)


Dark Matter


Strong Gravity


Supernovae


Cosmic Accelerators


Dark Energy

- 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

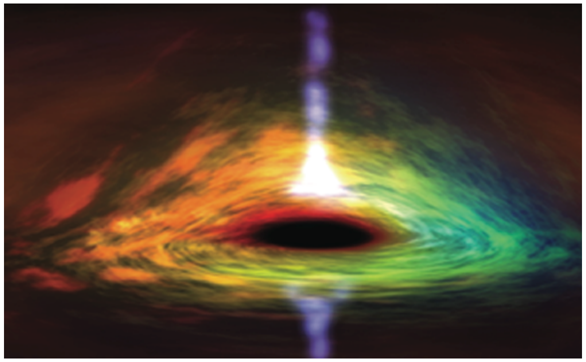
- Observe matter spiraling into Black Holes to test the predictions of strong field General Relativity
- Study distant/faint sources to trace the evolution of Black Holes with cosmic time

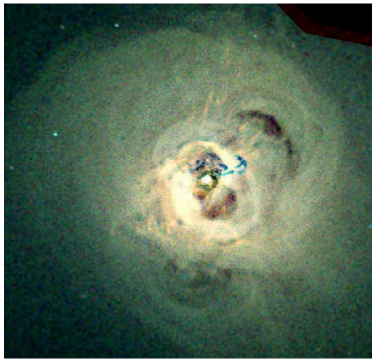
Dark Matter and Dark Energy

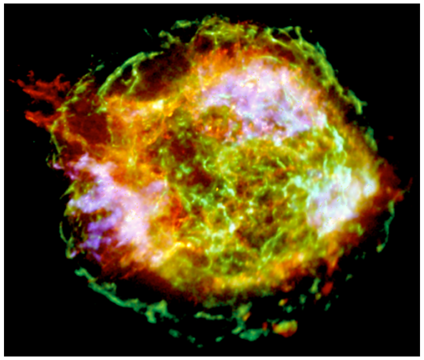
- Use Galaxy Clusters to trace dark matter and as probes for amount and evolution of dark energy

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

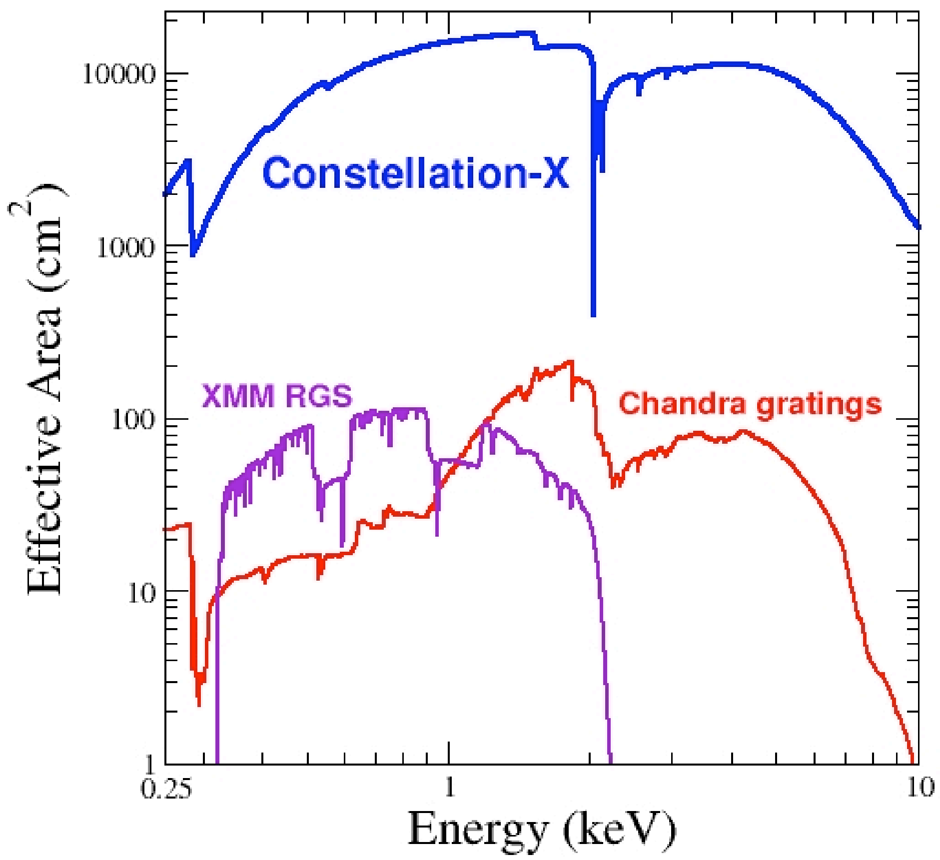






CONSTELLATION-X will open a new window on X-ray spectroscopy

Comparison of X-ray mission collecting areas

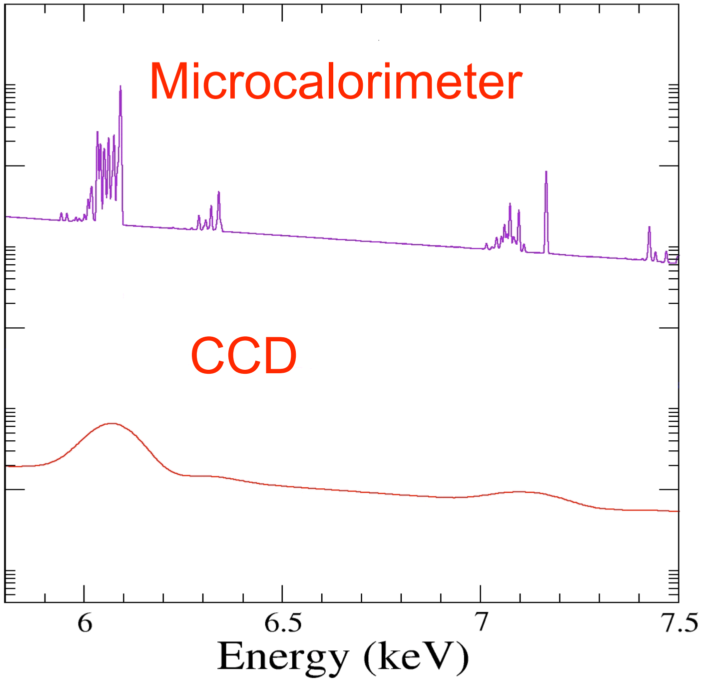


- **Spectral Resolution (E/ΔE): 1250 @ 0.3 – 1 keV and 2400 @ 6 keV to resolve crucial density, velocity and other diagnostics**
- **Two order of magnitude increased area for high resolution X-ray spectroscopy**
- Angular resolution requirement of 15 arc sec (goal of 5 arc sec HPD)
- Field of View 5 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

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

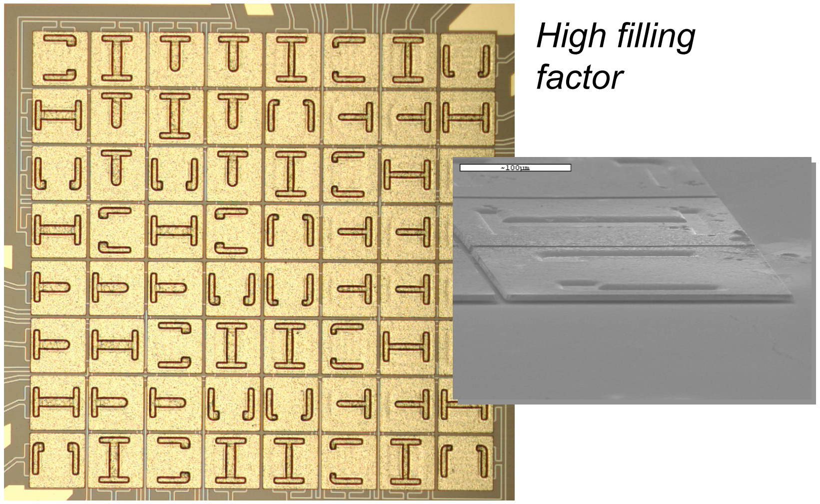
X-ray Micro-calorimeter Spectrometer (XMS)

- 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



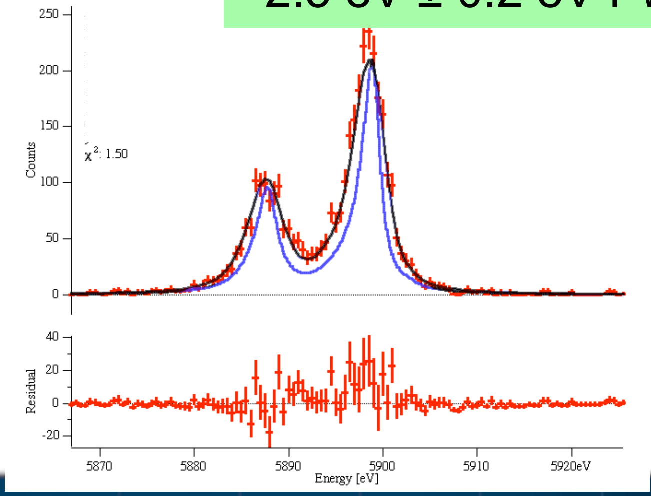
Con-X arrays under development and approaching goal of 2 eV at 6 keV.

High filling factor



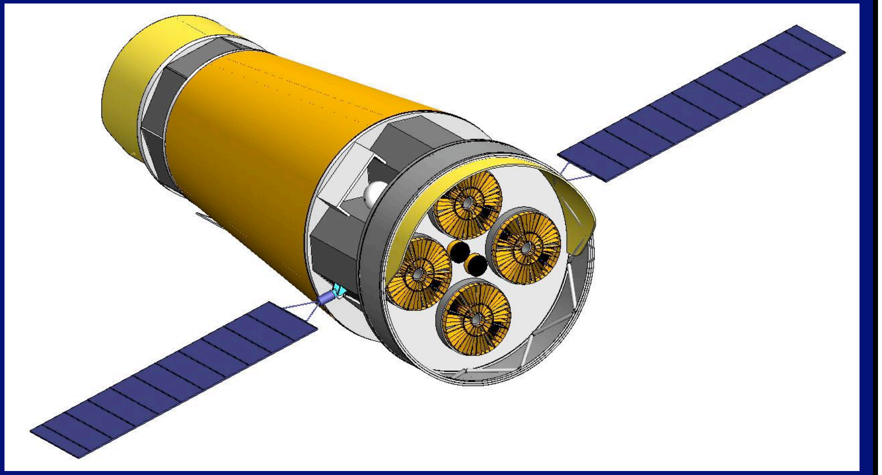
8x8 development Transition Edge Sensor array for Con-X with 250 μm pixels

2.5 eV ± 0.2 eV FWHM

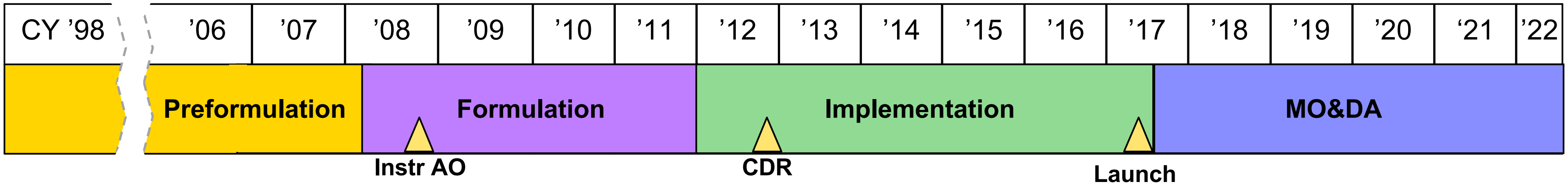


Mission Implementation Approach

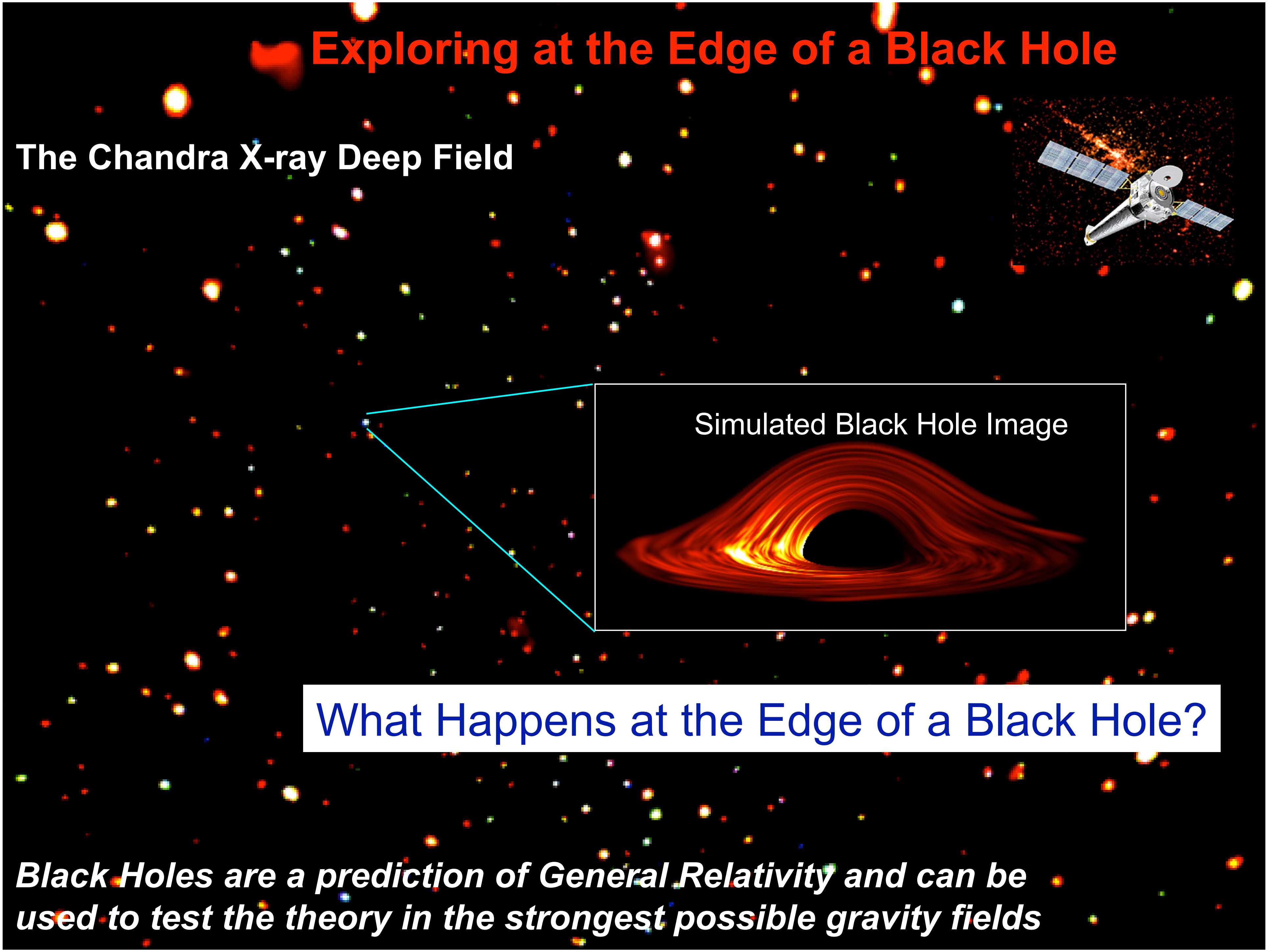
- **Four X-ray telescopes with common design, manufacture, assembly, and testing**
- **Manageable mirror dimensions and 10m focal length provide required area**
- **Single spacecraft with proven subsystems and single launch vehicle**
- **Mission success (via longer exposures) even with loss of one detector**



Approach Reduces Risk and Costs



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

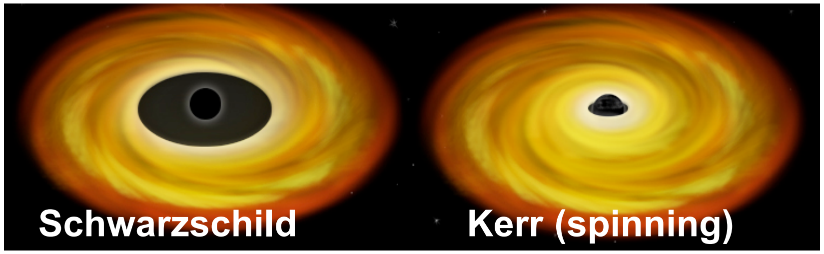
Nature is providing us with a new and direct probe of strong field General Relativity in the vicinity of Black Holes

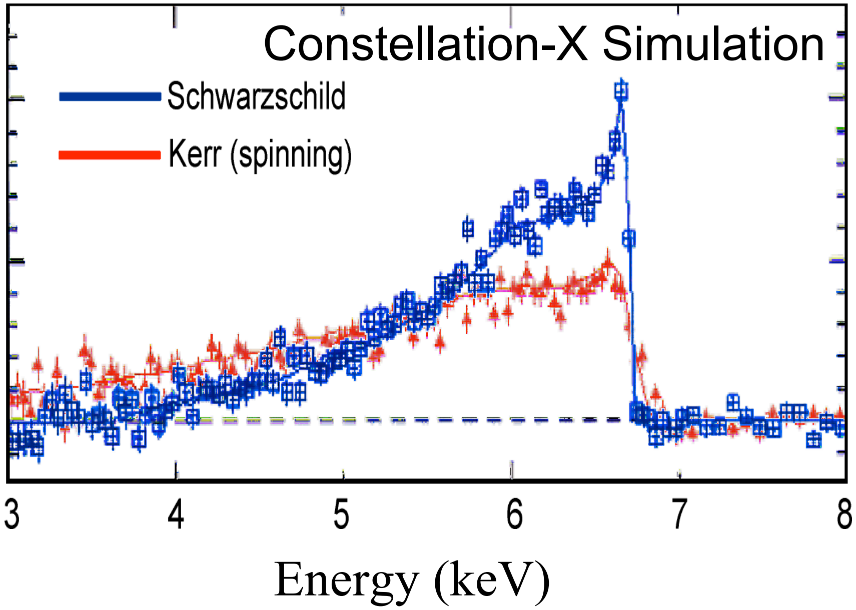
Relativistically broadened iron K lines have been detected from within 6 gravitational radii of Black Hole by ASCA, XMM-Newton, Chandra and Suzaku

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



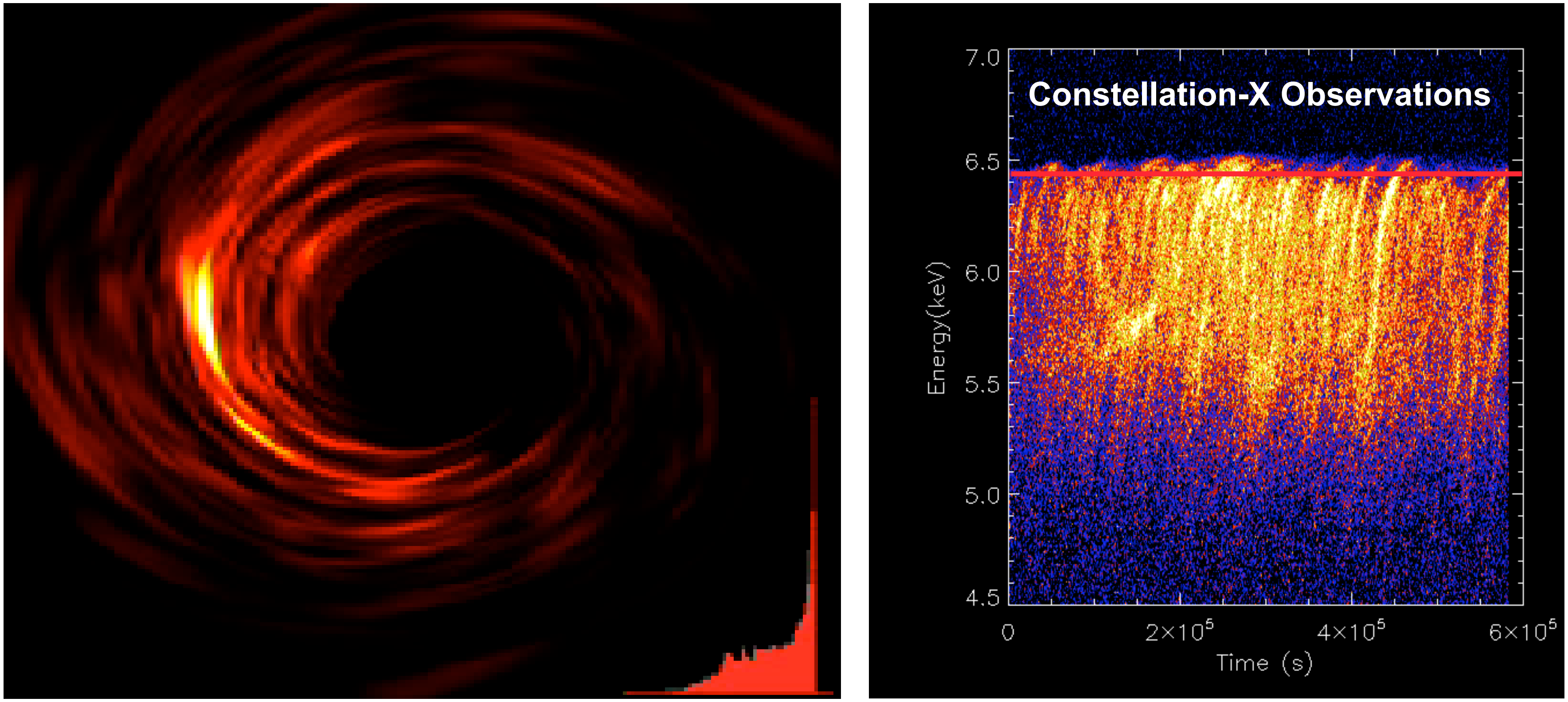


Very Broad Line = Spinning BH

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:

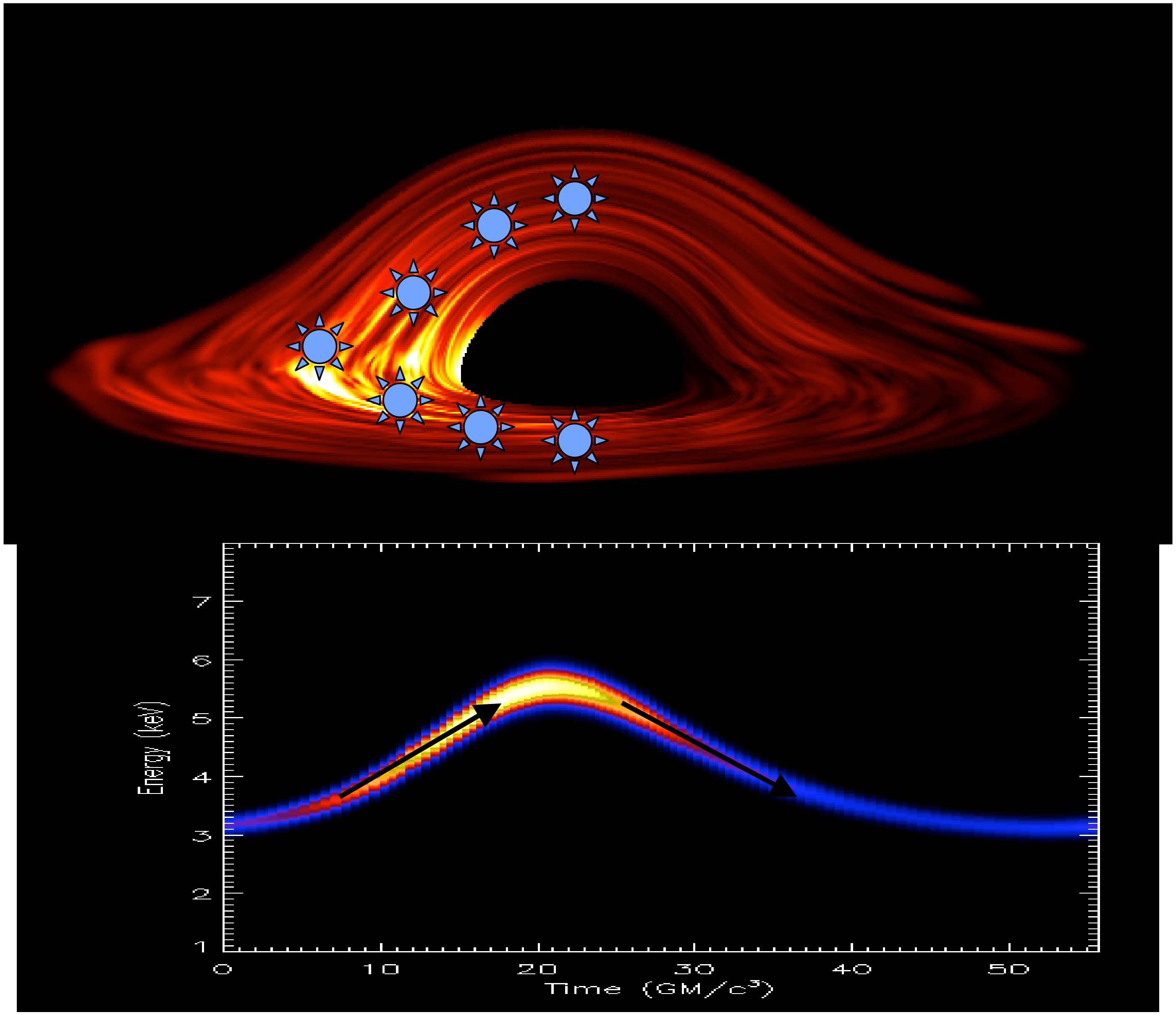
- Dynamics of individual “X-ray bright spots” in disk to determine mass and spin
- Quantitative measure of orbital dynamics: Test the Kerr metric



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

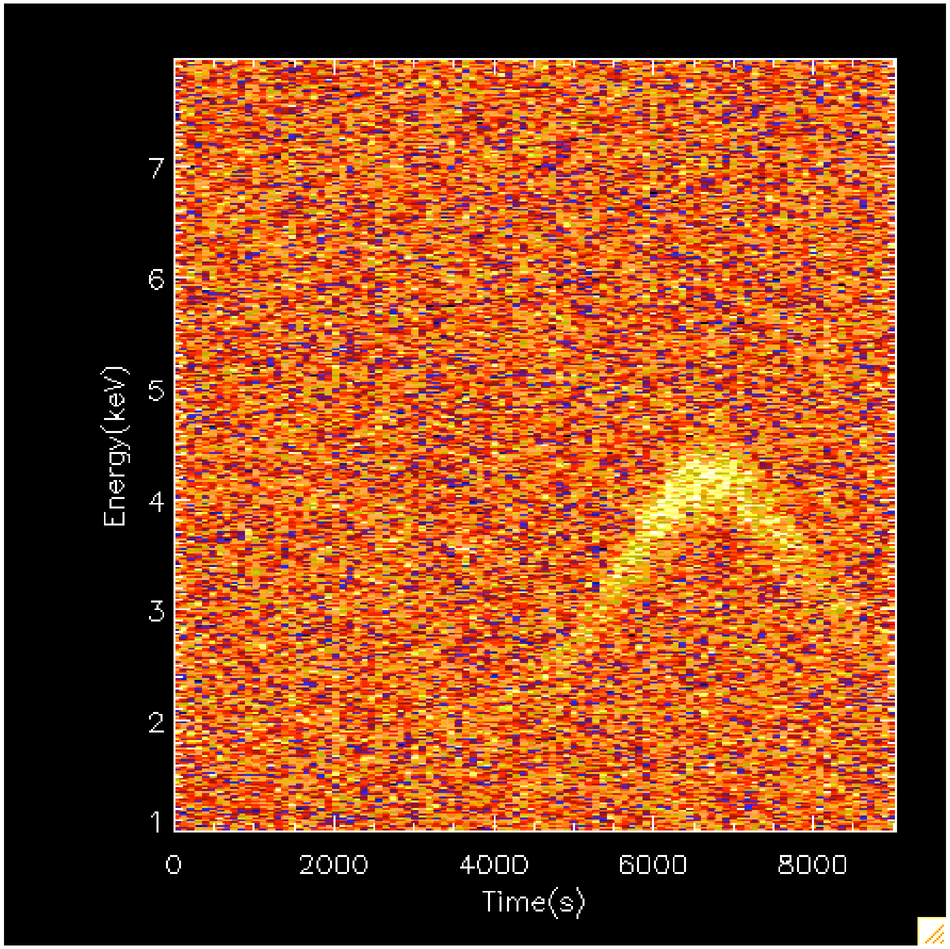
Predicted orbits of individual bright spots

a(spin)=0.98
Radius=3.0
Inclination=30



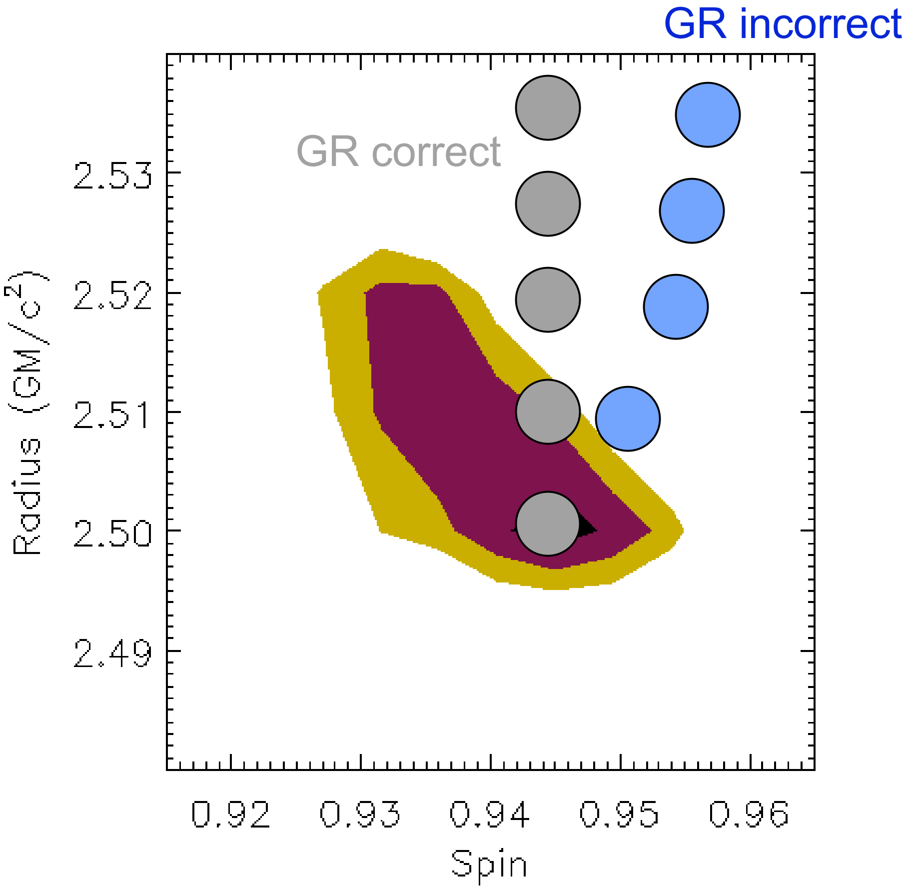
C. Reynolds University of Maryland

Testing GR via consistency of measurements



F=5×10^{-11} erg/s/cm2; EW=20eV; M=6×10^{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



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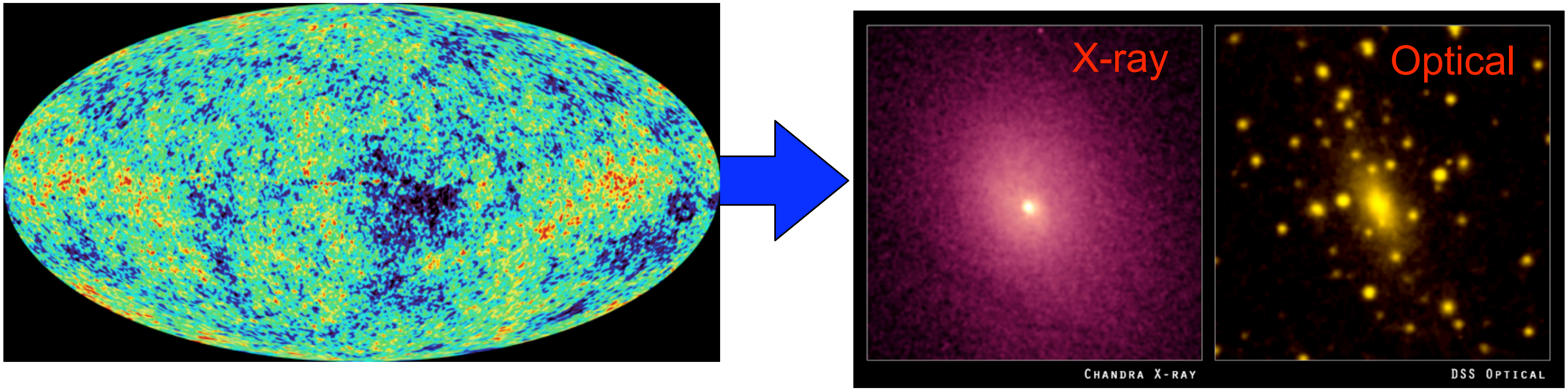
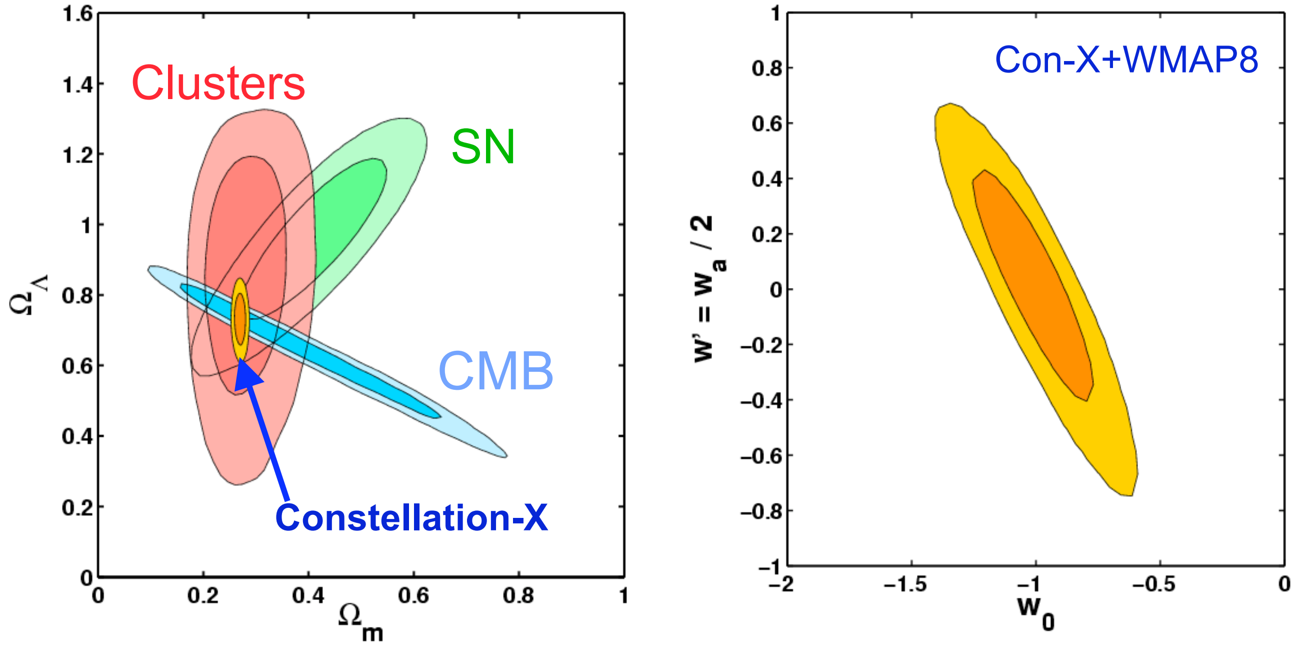
Clusters of Galaxies as Cosmological Probes

Clusters of galaxies are the largest objects in the Universe and grow from the initial fluctuations seen in the microwave background



Clusters of galaxies are the largest objects in the Universe and their properties and evolution are sensitive to the Cosmological parameters

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)

1. Using the gas mass fraction as a standard ruler measures f_{gas} to 5% (or better) for each of 500 galaxy clusters to give $\Omega_M=0.300\pm0.007$, $\Omega_\Lambda=0.700\pm0.047$
2. 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
3. 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)

Allowances for systematic uncertainties

The analysis includes a comprehensive and <u>conservative</u> treatment of potential sources of systematic uncertainty

1) The bias factor (calibration, simulation physics, gas clumping etc.)

$b(z)=b_0(1+a_b z)$: 10% Gaussian prior on b_0 (as before: modelling + calibration)
20% uniform prior on b_0 (simulation physics)
10% uniform prior on a_b (simulation physics)

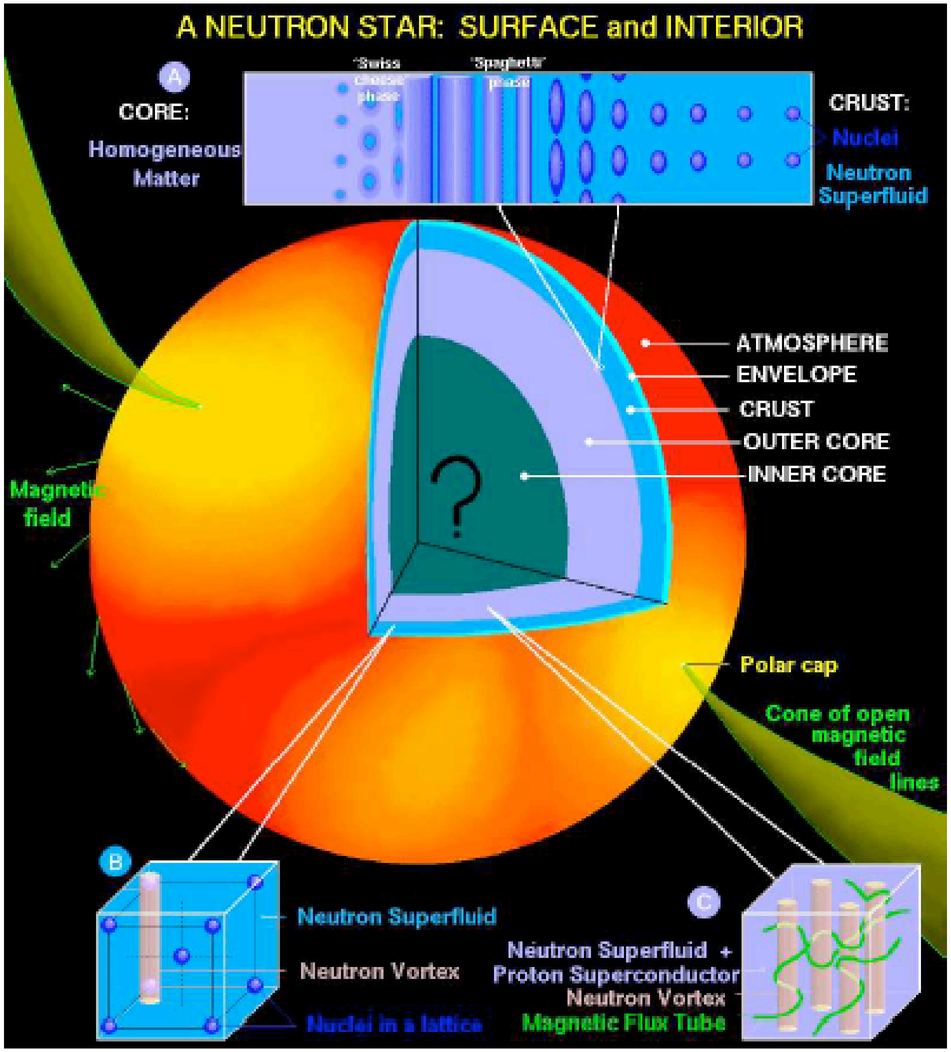
2) Baryonic mass in stars: define $s= f_{star}/f_{gas} =0.16h_{70}^{\ 0.5}$

$s(z)=s_0(1+a_s z)$: 30% Gaussian uncertainty in s_0 (observational uncertainty)
20% uniform prior on as (observational uncertainty)

3) Non-thermal pressure support in gas: (magnetic fields, bulk motions)

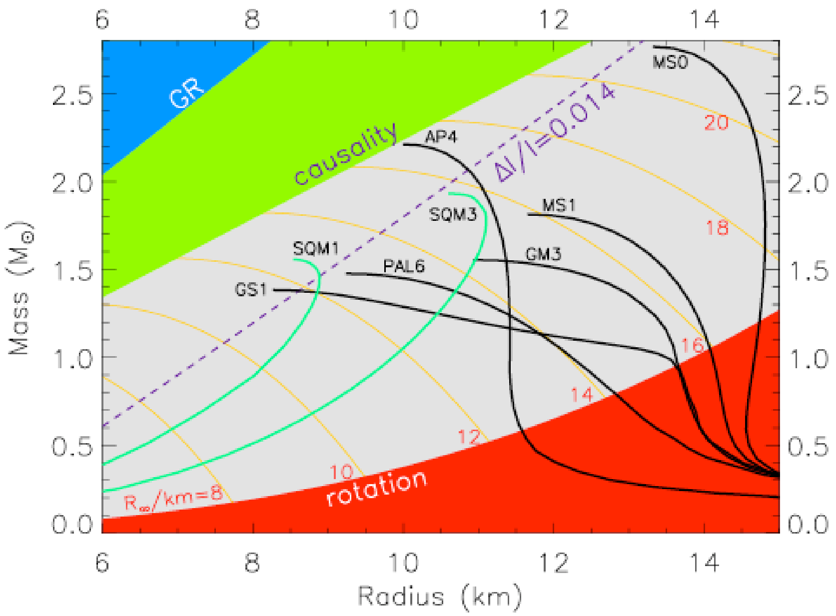
$\gamma = M_{true}/M_{X\text{-}ray}$: 10% uniform prior $1 < \gamma < 1.1$ (e.g. Nagai et al 2006)

Inside Neutron Stars……



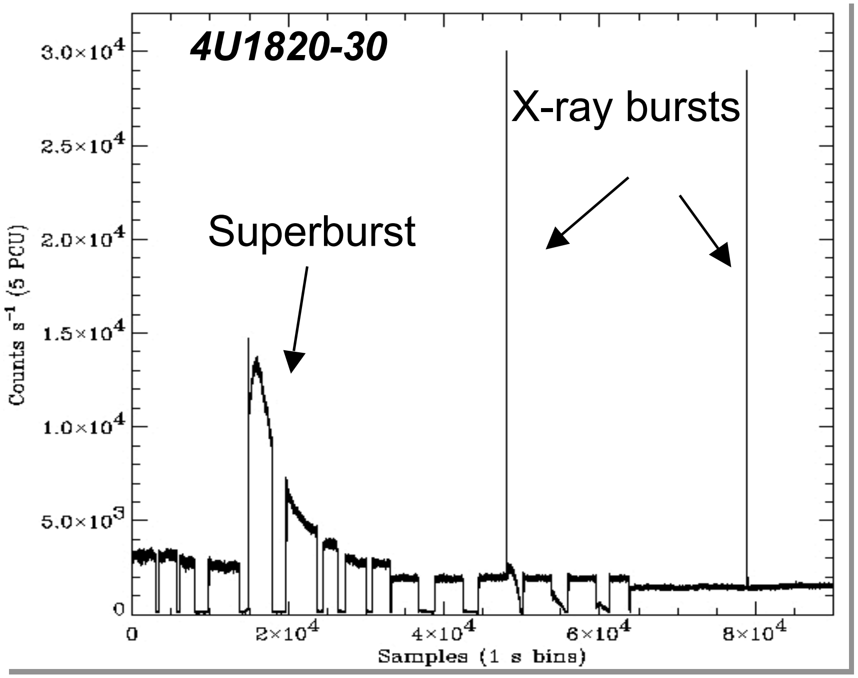
The physical constituents and equation of state of neutron stars remain a mystery after 40 years

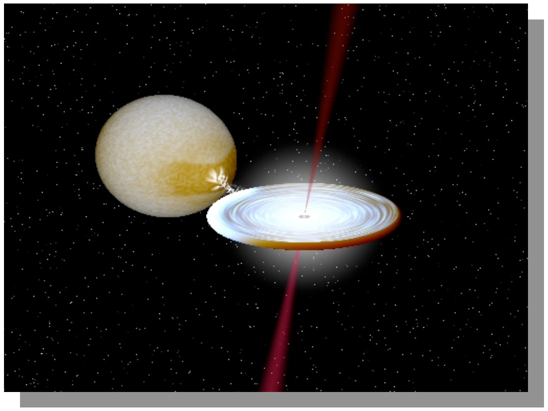
Constellation-X may finally provide answers….



Neutron Star Equation of State

RXTE





Accretion supplies metals to Neutron Star atmosphere which favors the formation of spectral lines

Thermonuclear burning of accreted matter produces X-ray bursts

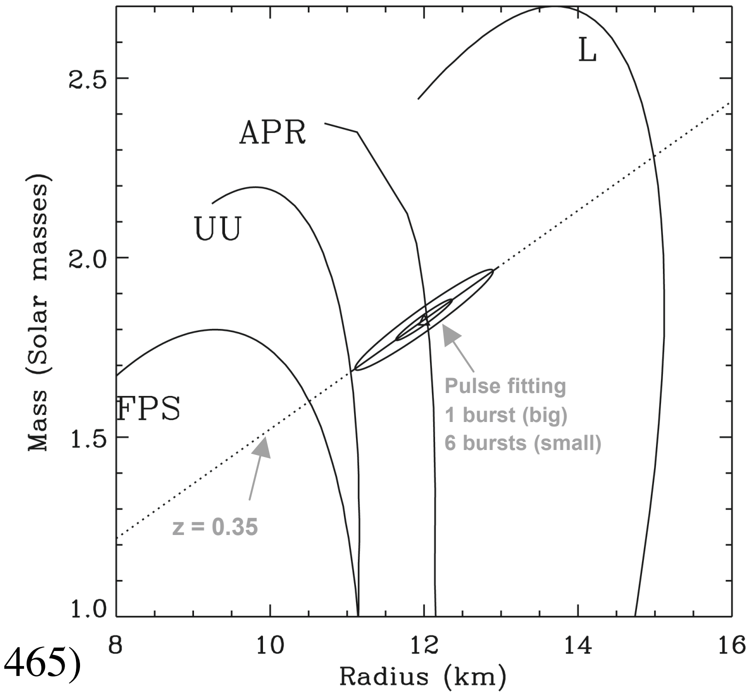
Neutron Star surface shines brightly during X-ray bursts and X-ray observations provide an opportunity to determine mass radius relation

Current observatories are pointing the way to the future capabilities required to make the required precision measurements I.e. the Constellation-X high throughput combined with high spectral resolution and timing capability

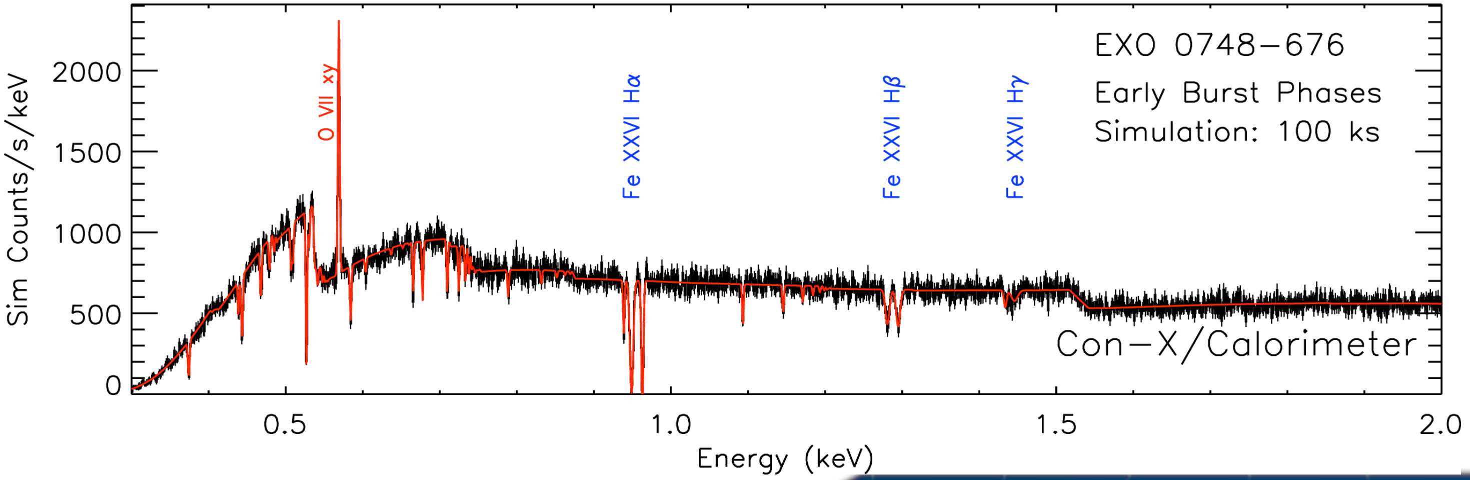
Neutron Star Equation of State

Constellation-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

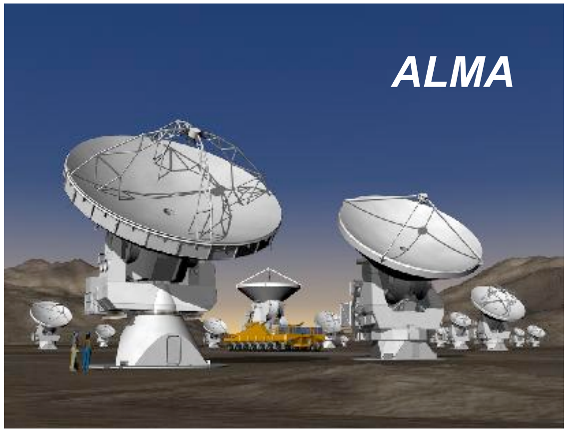


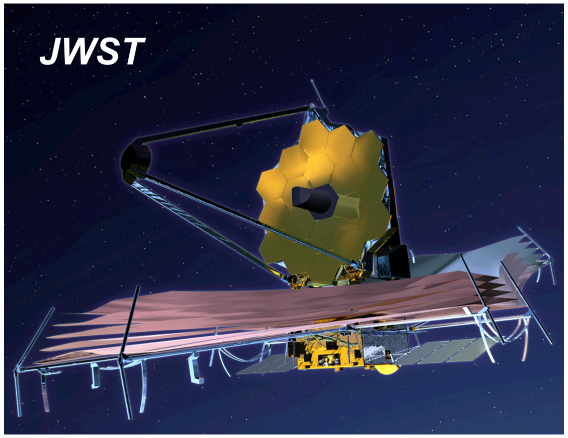
Cottam et al (astro-ph/0211126), Strohmayer (astro-ph/0401465)



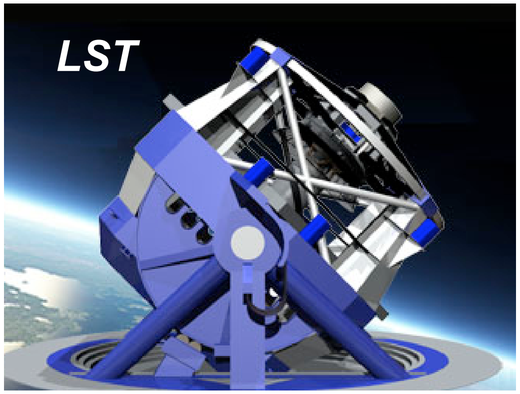
Constellation-X: A future astrophysics great observatory

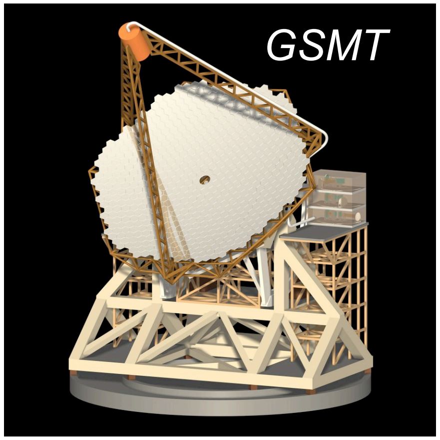
Sub-mm

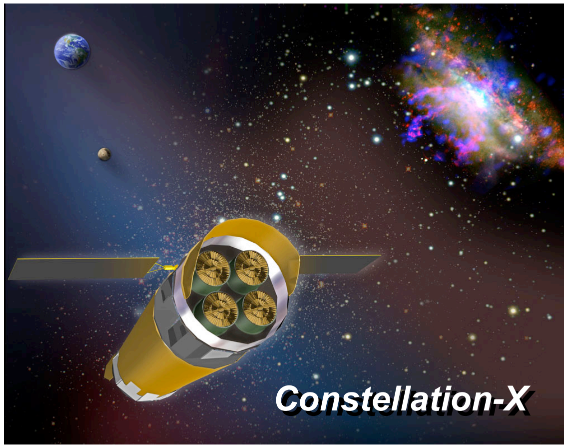




IR







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 the next decade

Summary

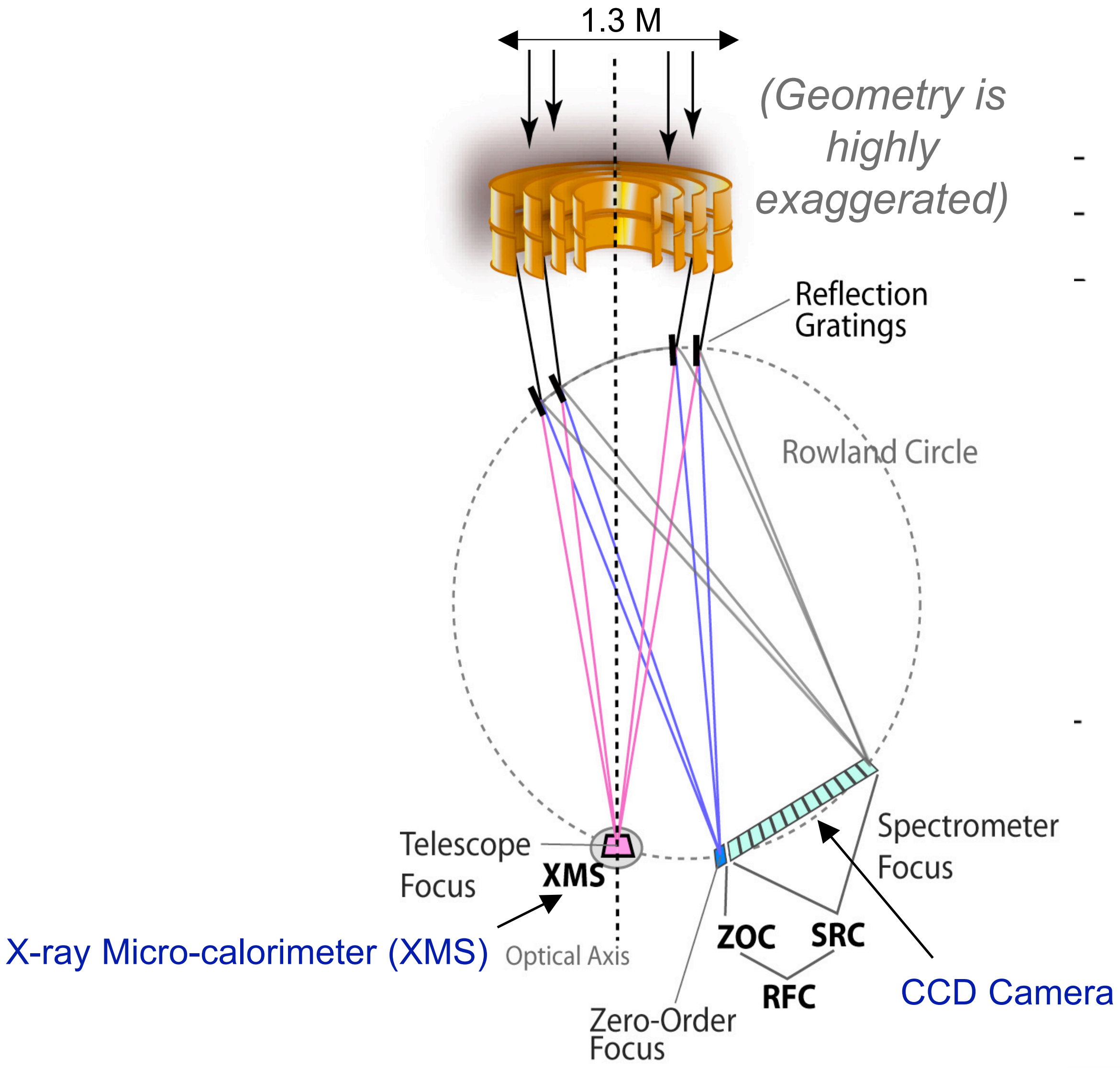
- ♣ Constellation-X opens the window of X-ray spectroscopy with a two order of magnitude gain in capability over current missions
- ♣ The science goals driving the need for this new capability are:
  - – Black Holes: tests of GR in the strong field limit and determination of Black Hole spin in a large sample
  - – Dark Energy: precision Cosmology using clusters of galaxies to tightly constrain Dark Energy parameters using both distance and growth of structure
  - – Equation of State: observations of neutron stars to determine mass-radius relation of a large selection of neutron stars
- ♣ 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

Constellation-X Payload

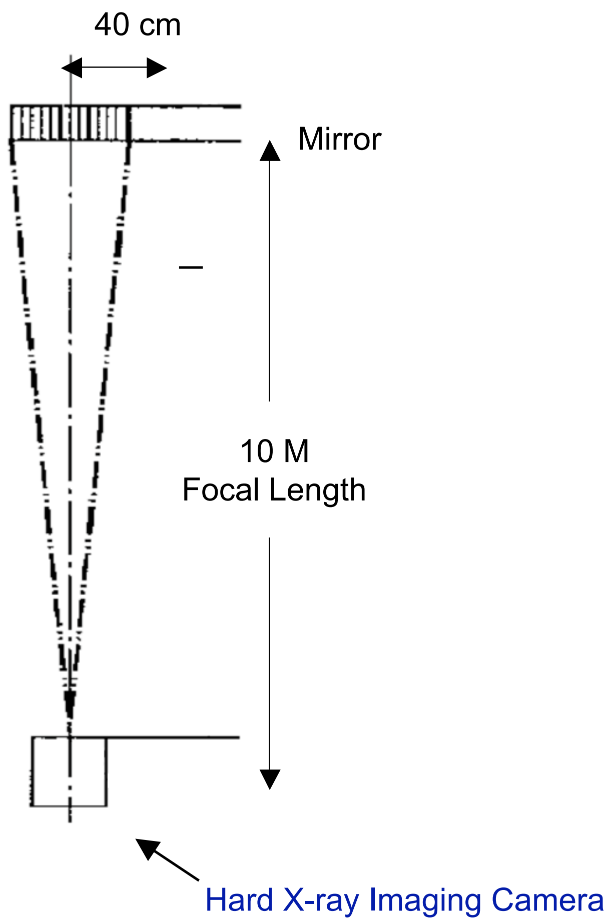
4 Spectroscopy X-ray Telescope (SXT)

(0.3-10 keV)



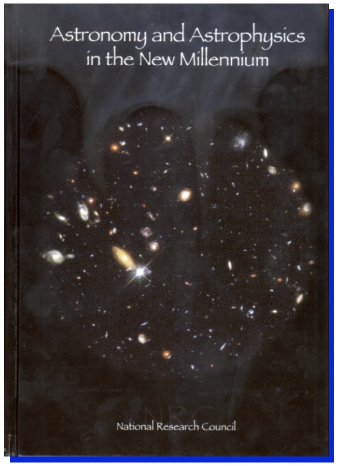
2 Hard X-ray Telescope (HXT)

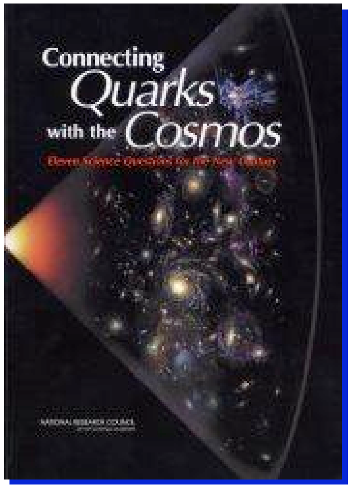
(6-40 keV)



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

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

Constellation-X critical to addressing the Beyond Einstein science goals

Dark Matter and Dark Energy

Constellation-X will derive cosmological parameters using (at least) three different galaxy cluster techniques:

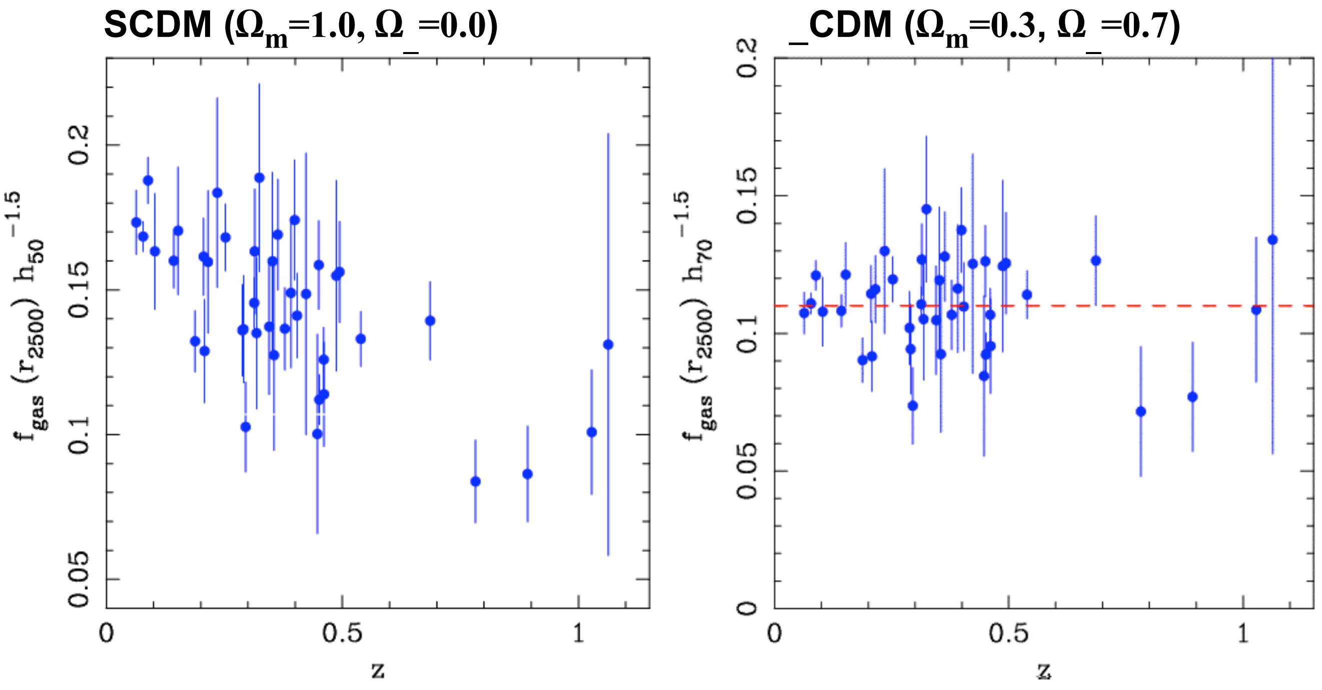
1. Using the gas mass fraction in clusters is a "standard candle" that depends on redshift as $d^{3/2}$
2. in combination with microwave background measurements the Sunyaev-Zeldovich technique to measure absolute distances
3. Measuring the evolution of the cluster parameters and mass function with redshift (=growth of structure) calibrating mass measurement for other cluster surveys

1 and 2 are 'distance rule' techniques (ala SNIa), 3 is a "growth of structure" technique which depends on GR

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



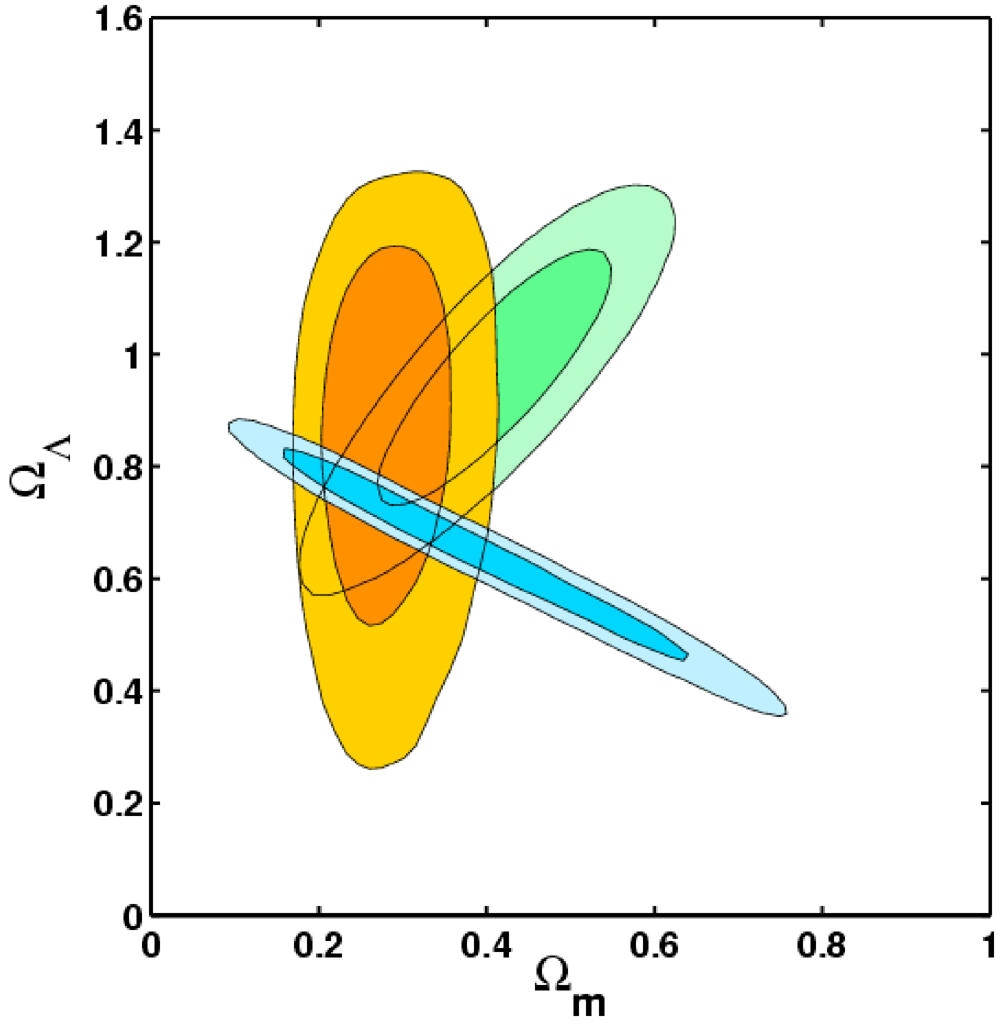
SCDM (Ω_m=1.0, Ω_=0.0)

CDM (Ω_m=0.3, Ω=0.7)

_CDM clearly favoured over SCDM cosmology

From Steve Allen KIPAC/SLAC

Comparison of independent constraints (_CDM)



Gas mass fraction analysis: 42 clusters including standard $\Omega_b h^2$, and h priors and full systematic allowances

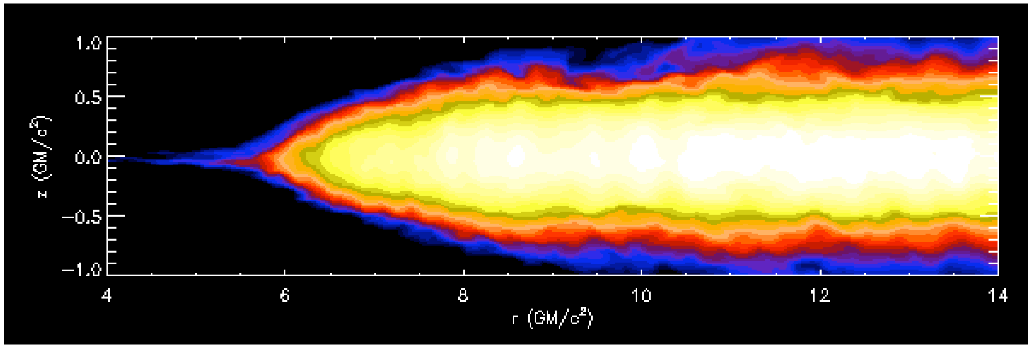
CMB data (WMAP3 + prior 0.4<h<2.0)

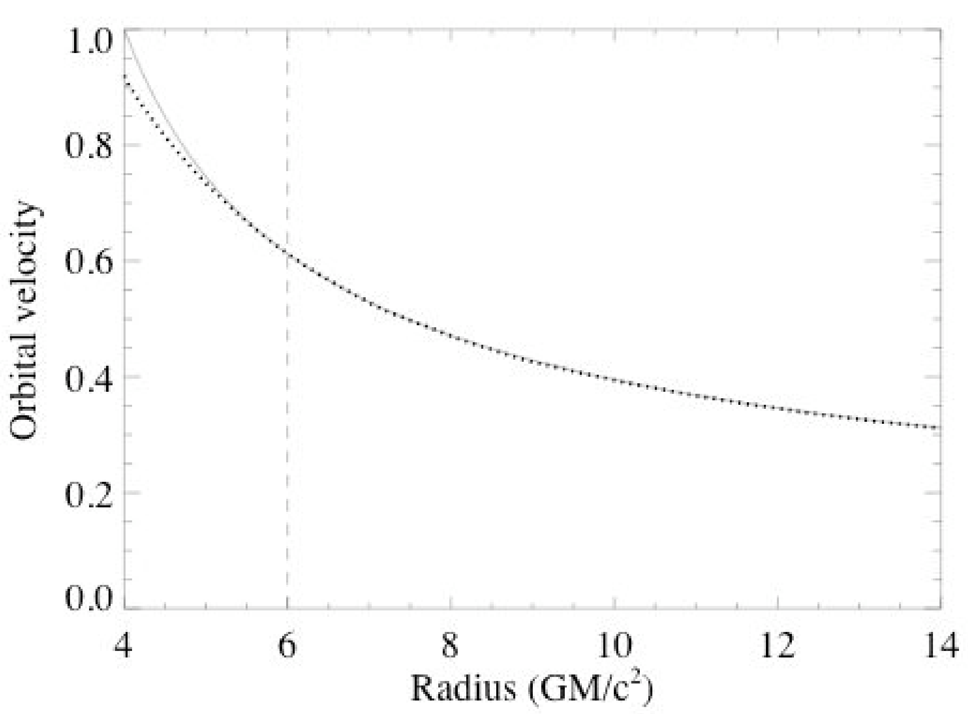
Supernovae data from Riess et al. ’04 (Gold sample) and Astier et al ’05 (235 SNIa total)

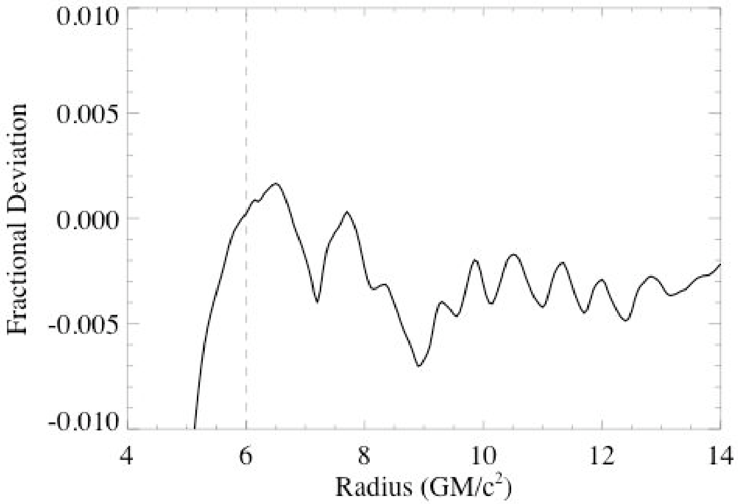
From Steve Allen Kipac/SLAC

Comparison of simulated accretion flow with test-particle orbits…

3-d MHD simulations of thin accretion disks for pseudo-Newtonian disk with h/r=0.05





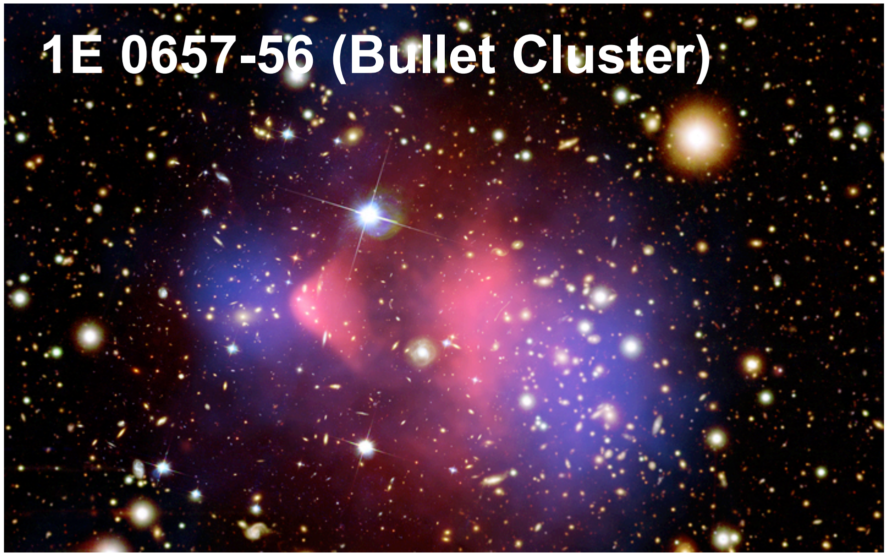


Outside of the inner stable orbit the gas velocity traces test-particle orbits to an accuracy of 1% or less

C. Reynolds University of Maryland

Dark Matter with Constellation-X

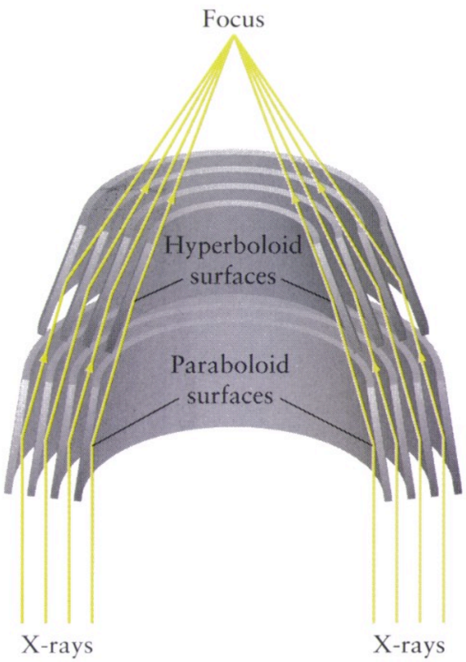
- **Tracing Dark Matter:** Constellation-X will enable the first mapping of the velocity field of Galaxy Clusters to ~100 km/s
  - Measure turbulence, mass motion, Black Hole heating and feedback, cluster mergers, detailed abundances, and ionization mechanisms
  - Provides a precise mapping of the Dark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

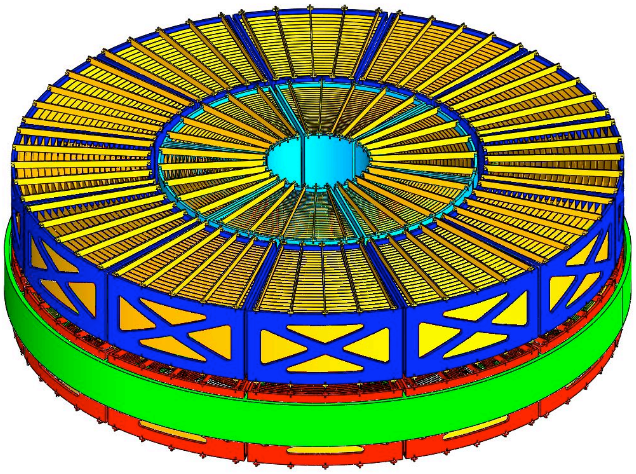


Chandra X-ray Observations of a merging Cluster where the dark matter in the clusters (blue) is clearly separate from the normal matter (pink), directly ruling out modified gravity models (Markevitch et al 2006)

- **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

Enabling Technology: Thin, Segmented X-ray Mirrors

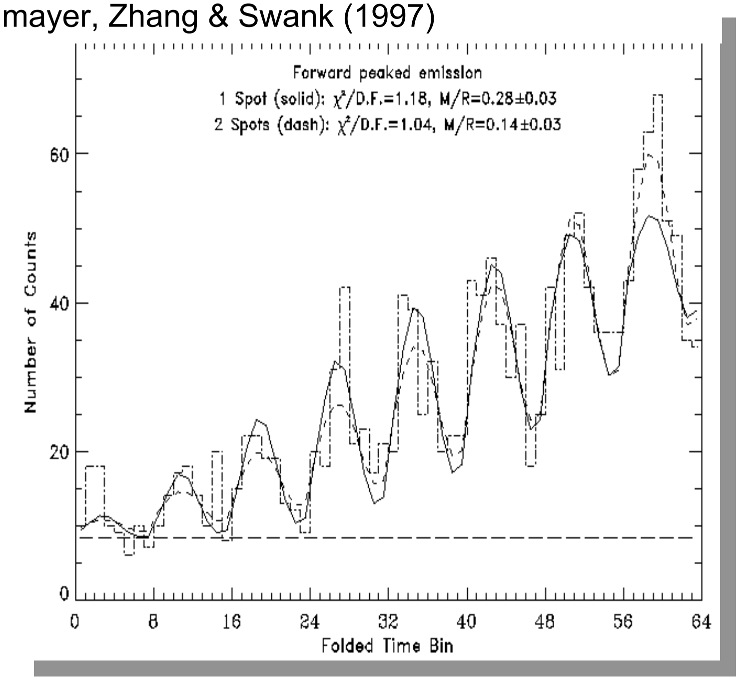


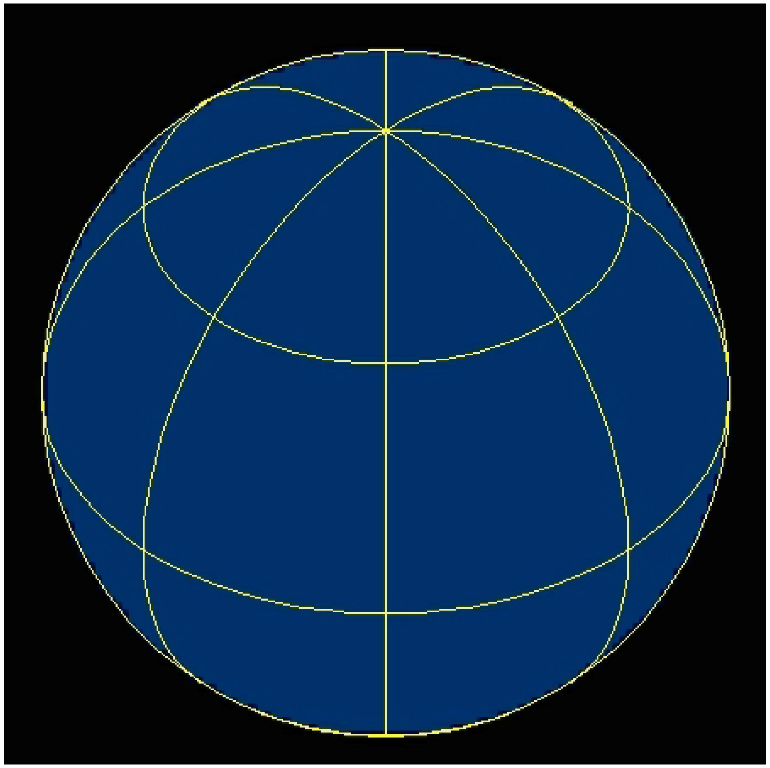


- ♣ Efficient X-ray imaging requires grazing incidence mirrors
  - 300-700 more telescope surface area required over normal incidence for a given aperture
  - Precisely figured hyperboloid/paraboloid surfaces
  - **Trade-off between collecting area and angular resolution**
- ♣ The 0.5 arc sec angular 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

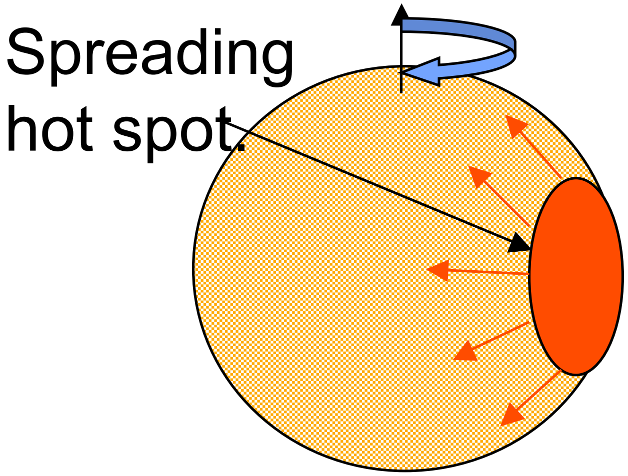
Using Burst Oscillations to Probe the EOS of Neutron Stars

Strohmayer, Zhang & Swank (1997)





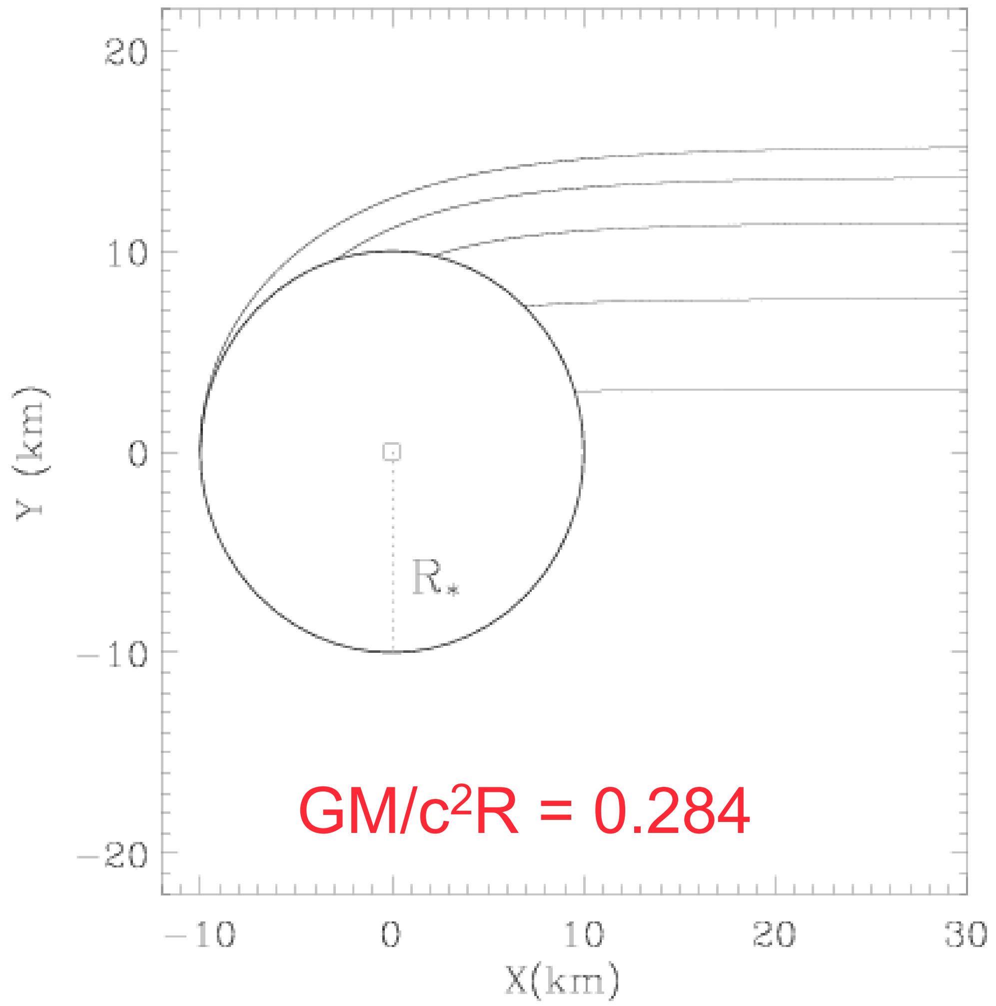
Credit: Anatoly Spitkovsky (2003)



Spreading hot spot

- Oscillations caused by hot spot on rotating neutron star
- Modulation amplitude drops as spot grows
- Spectra track increasing size of X-ray emitting area on star

Rotational Modulation of Neutron Star Emission: The Model



- Gravitational Light Deflection: Schwarzschild metric.
- Gravitational redshift.
- Rotational doppler shifts and aberration of the intensity.
- "Beaming" of intensity in NS rest frame.
- Arbitrary geometry of emission regions.
- Observed response using various detector response matrices.

Miller, Bhatacharya, Muno, Ozel, Psaltis, Braje, Romani, Nath, Chang, Cadeau, Morsink, etc.