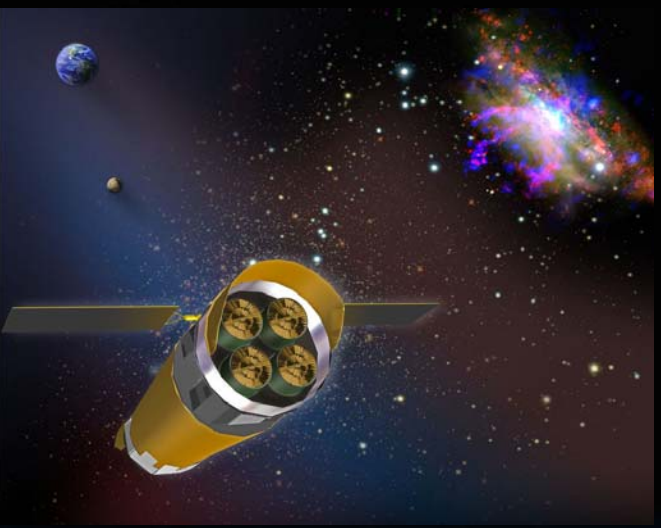
BEYOND EINSTEIN: From the Big Bang to Black Holes

Constellation-X

The Constellation X-Ray Mission

Going Beyond Einstein with Constellation-X

Nicholas White (NASA/GSFC)





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

Completing Einstein's Legacy

- Einstein's legacy is incomplete, his theory fails to explain the underlying physics of the very phenomena his work predicted

  → Unification of Quantum Mechanics and General Relativity

- **Dark Energy, Black Holes, Big Bang:** We are on the threshold of a breakthrough comparable to Einstein's discoveries one century ago . . .

Beyond Einstein is a series of NASA missions linked by powerful new technologies, and interlinked science goals to address:



What powered the Big Bang?

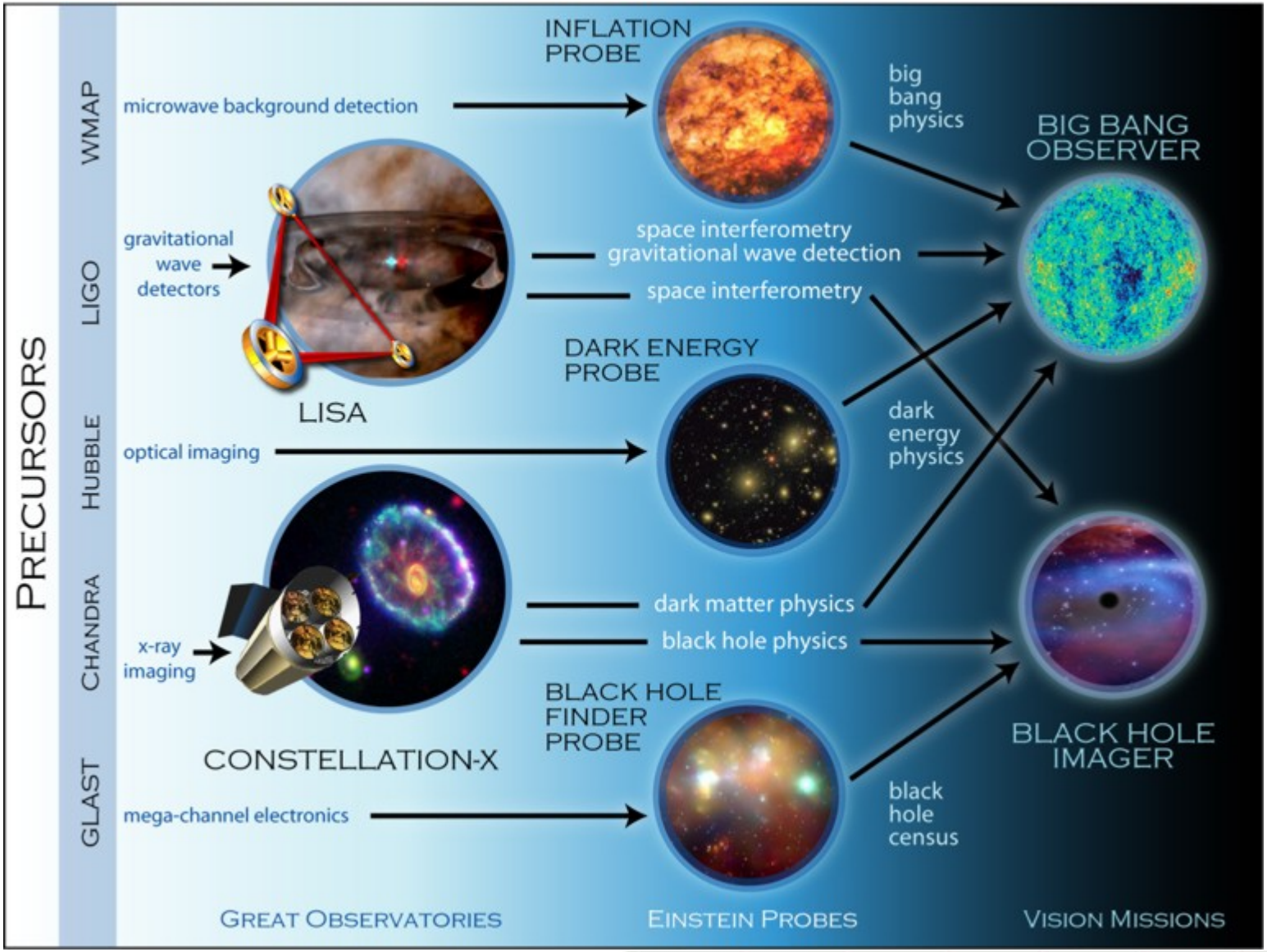


What happens at the edge of a Black Hole?



What is the mysterious Dark Energy pulling the Universe apart?

Beyond Einstein Program



Beyond Einstein Program Status

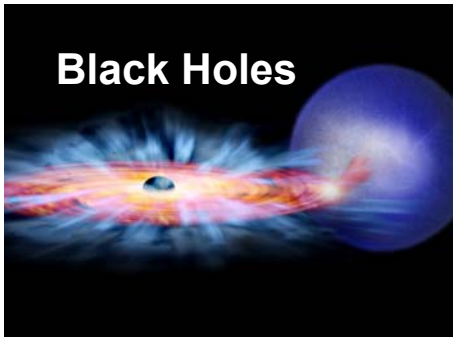
Challenges in overall NASA budget (Columbia loss, complete ISS, replace Shuttle, HST servicing delayed, etc) has slowed the start of Beyond Einstein

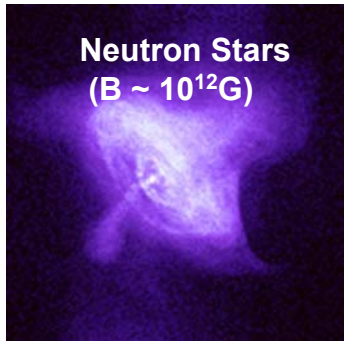
Beyond Einstein program consists of five missions: Constellation-X, LISA, Joint Dark Energy Mission (JDEM), Inflation Probe and Black Hole Finder

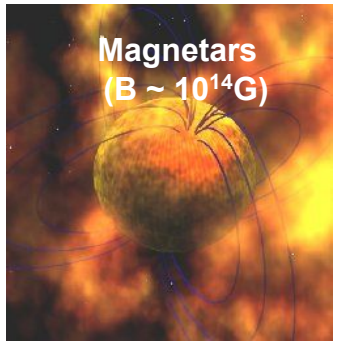
Decision to be made by Fall 2007 as to which the Beyond Einstein mission will be the first to start via a National Academy of Sciences Beyond Einstein Program Assessment Committee (BEPAC)

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

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

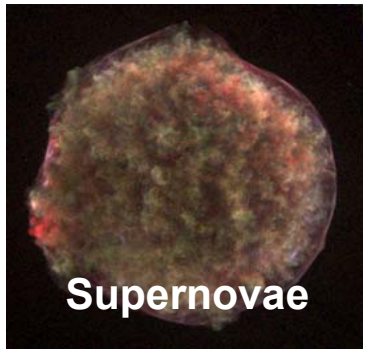
















- High temperatures, intense gravity, strong magnetic fields — explosions, collisions, shocks, and collapsed objects
- Conditions not achievable in earth-bound labs or accelerators
- X-ray observations can only be made from space

CONSTELLATION-X SCIENCE OBJECTIVES

Black Holes

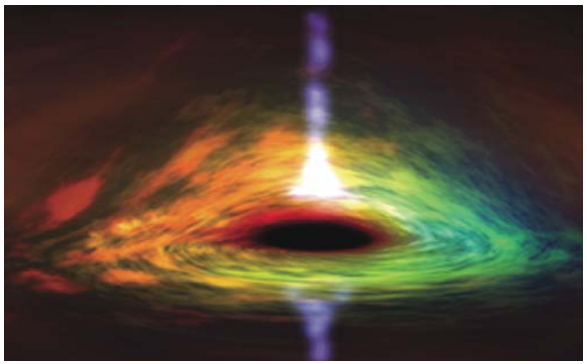
- Observe matter spiraling into Black Holes to test the predictions of strong field General Relativity
- Study distant/faint sources to trace the evolution of Black Holes with cosmic time

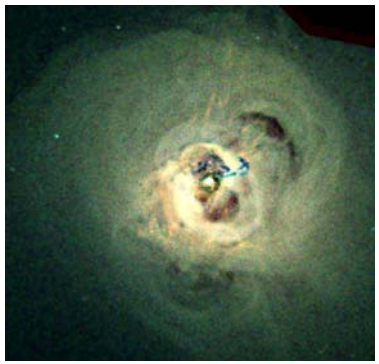
Dark Matter and Dark Energy

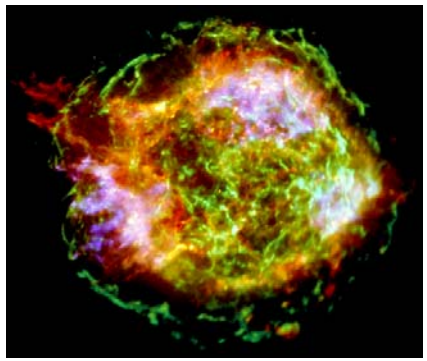
- Use Galaxy Clusters to trace dark matter and as probes for amount and evolution of dark energy

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

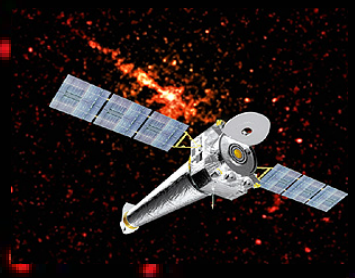


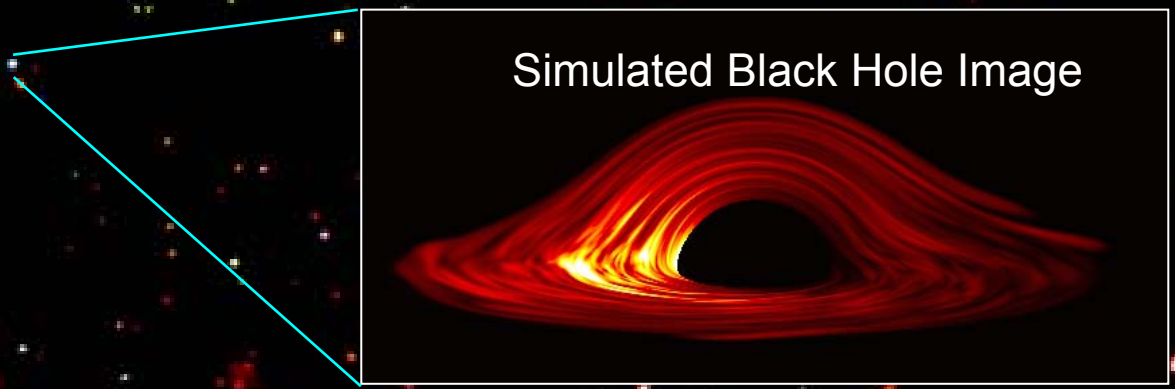




Exploring at the Edge of a Black Hole

The Chandra X-ray Deep Field





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

CHANDRA launched 1999 brought X-ray Astronomy to the forefront

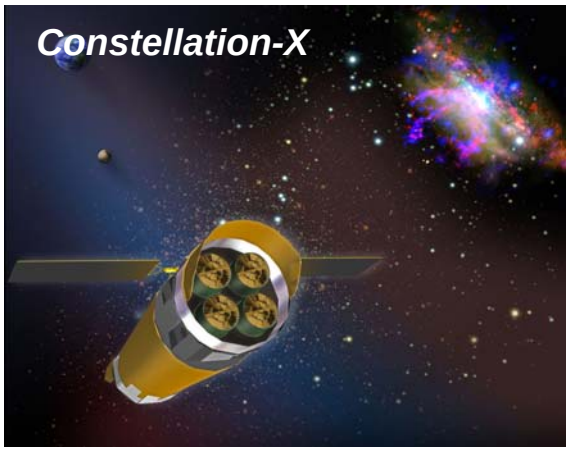


Chandra imaging 0.5" comparable to typical ground-based O/IR telescopes

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

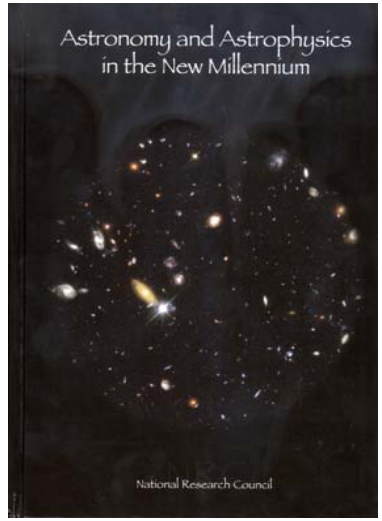
Constellation-X fills a critical gap required to address the Beyond Einstein science goals

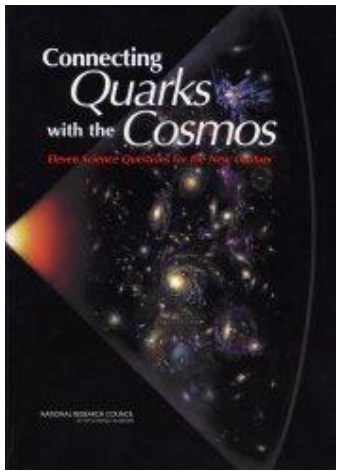
Science priority recognized by the 2000 *Astronomy and Astrophysics in the New Millennium decadal survey*, second only to JWST among major space initiatives

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

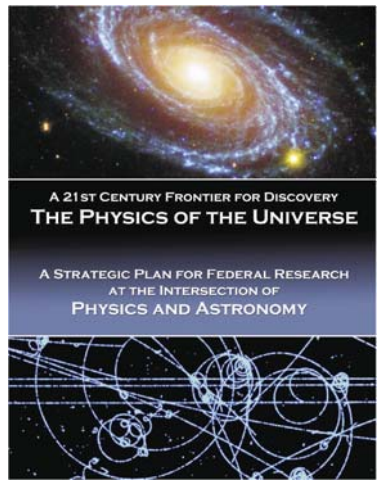
Science Priority

The Astronomy and Astrophysics in the New Millenium "decadal survey" ranked Constellation-X next priority to the JWST for large new space observatories *"The Constellation-X Observatory is a suite of four powerful x-ray telescopes…the premier instrument for studying the formation and evolution of black holes… Constellation-X will complement Chandra, much as Keck and Gemini complement HST… The technology issues are well in hand….."*





The National Academy Committee chaired by Michael Turner prepared a 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*"



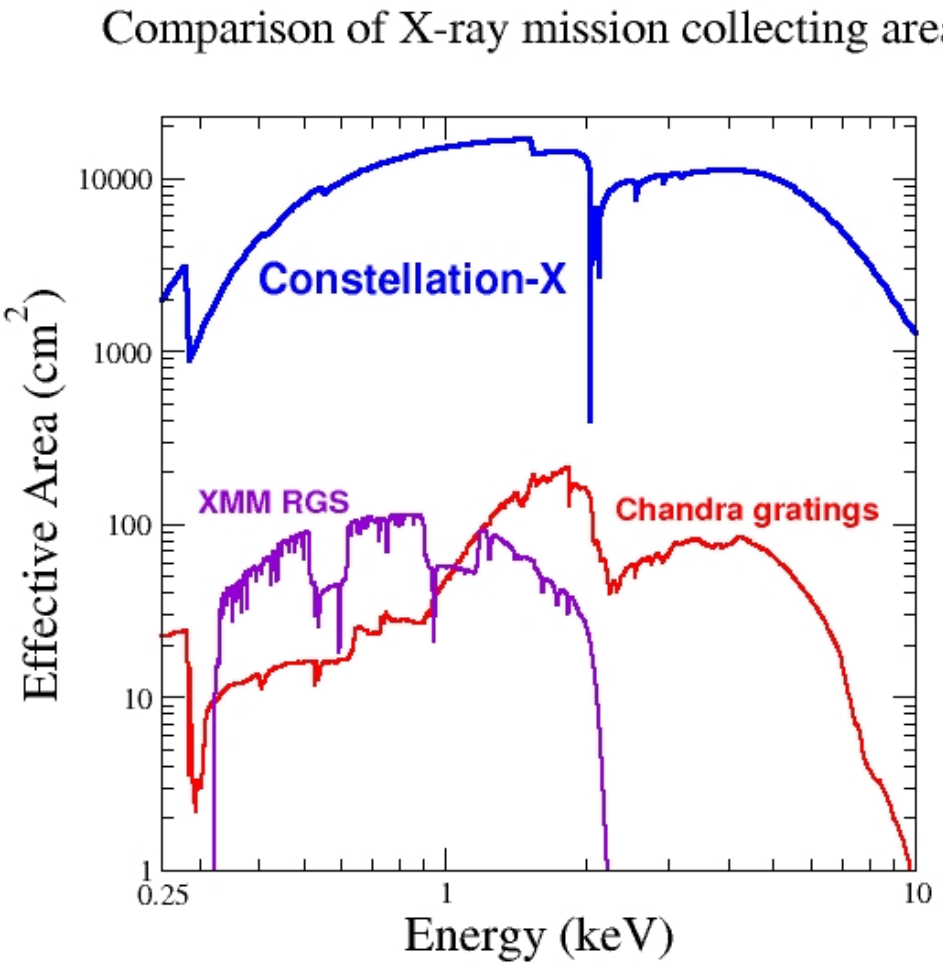
From the OSTP interagency Physics of the Universe Report: *"Another priority method to constrain Dark Energy will be to use Clusters of Galaxies by …. space-based X-ray observations."*

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 ♦

Key Constellation-X Capabilities



- 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

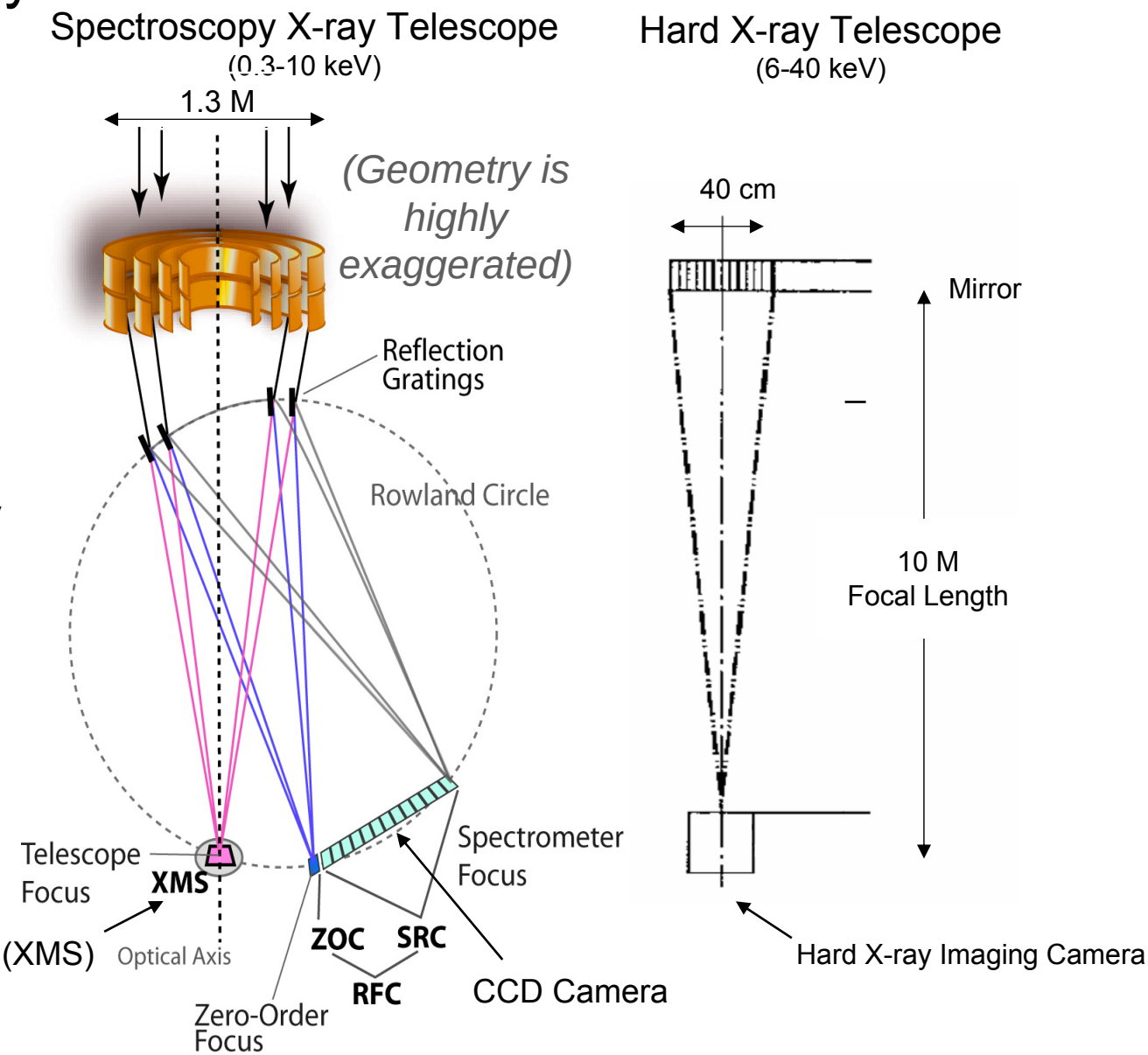
Constellation-X Payload

Configuration of 4 SXT and 1 or 2 HXT

All instruments operate simultaneously

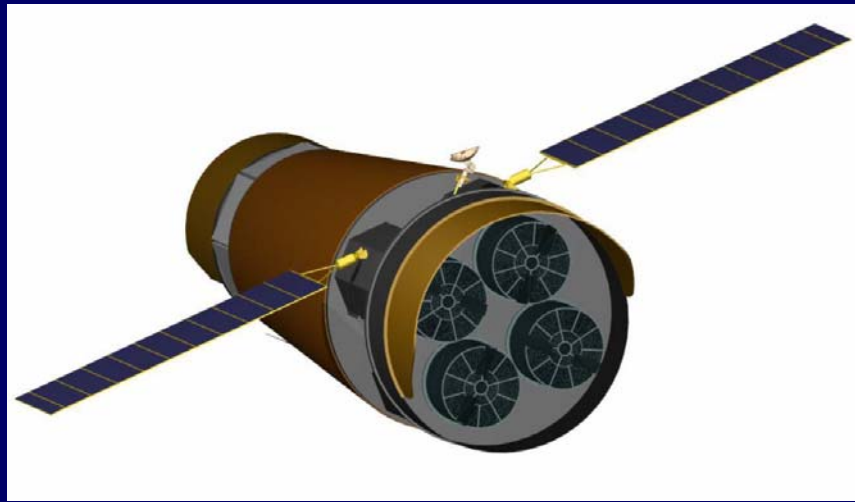
XMS is the workhorse instrument providing imaging and spectroscopy (0.3-10 keV)

X-ray Grating Spectrometer (XGS) provides ~1250 resolution between 0.3 and 1keV with either a transmission or reflection design

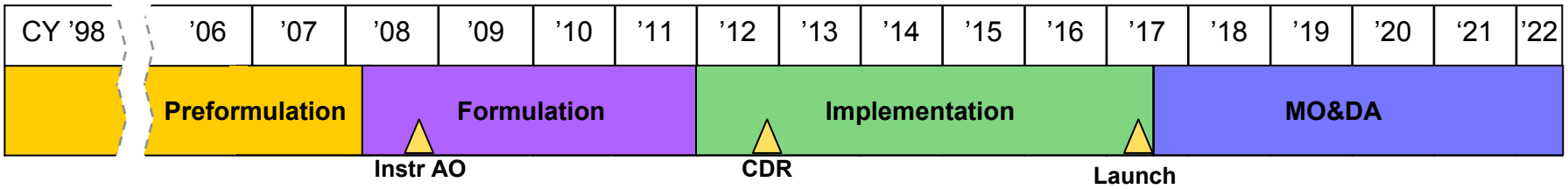


Mission Implementation Approach

- 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

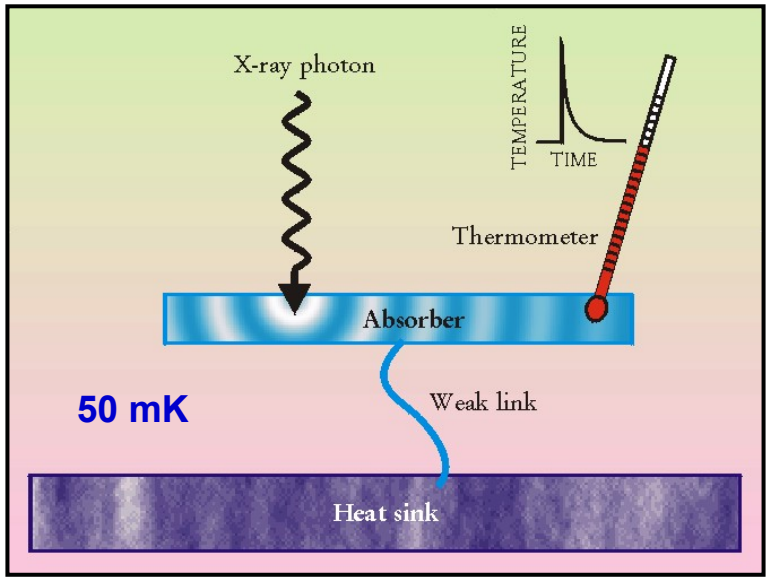


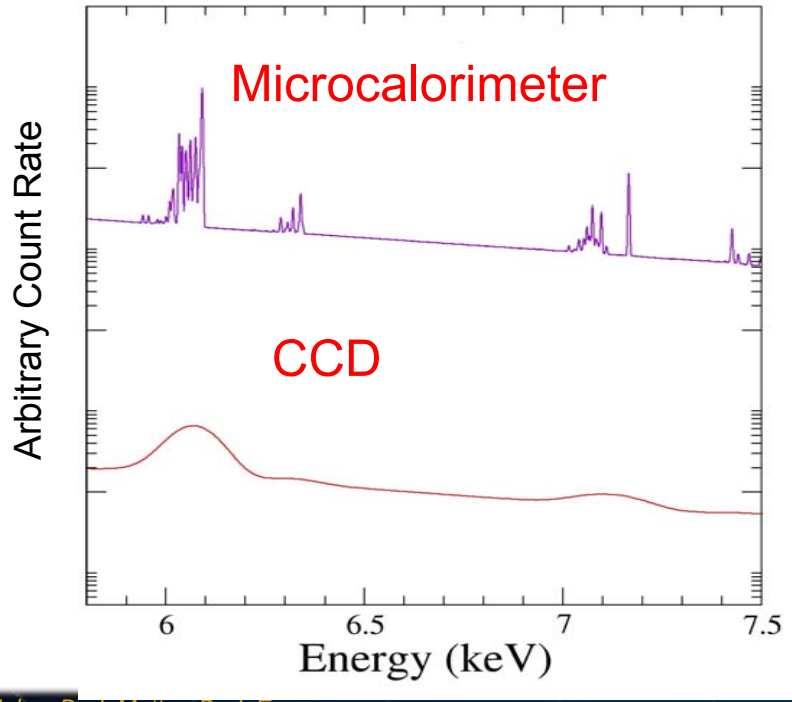
Approach Reduces Risk and Costs



Enabling Technology: X-Ray Microcalorimeters

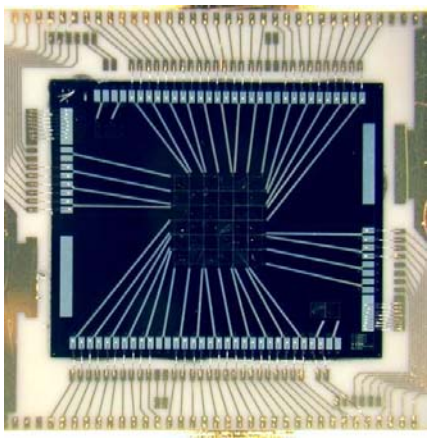
- X-ray microcalorimeter: thermal detection of individual X-ray photons
  - High spectral resolution
  - ΔE very nearly constant with E
  - High intrinsic quantum efficiency
  - Non-dispersive — spectral resolution not affected by source angular size





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

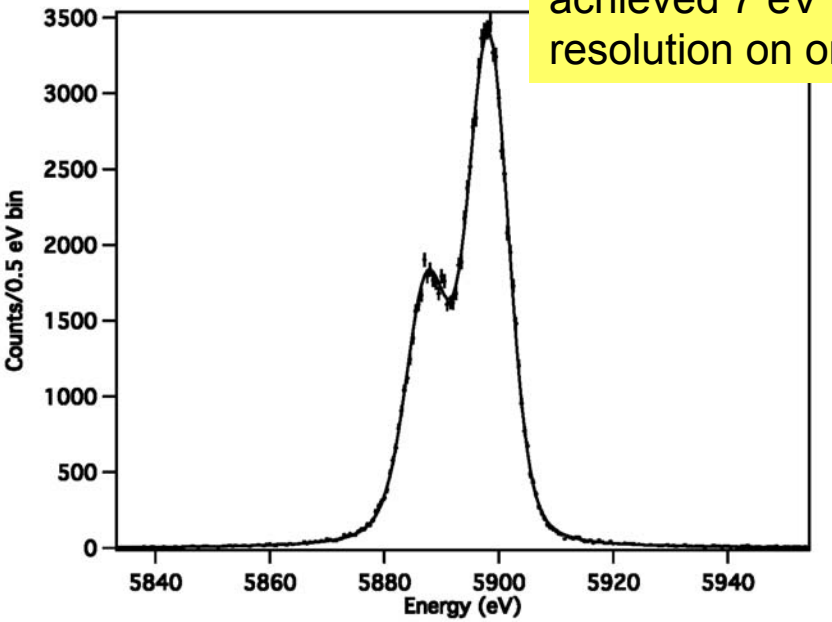
X-ray Micro-calorimeter Spectrometer (XMS)



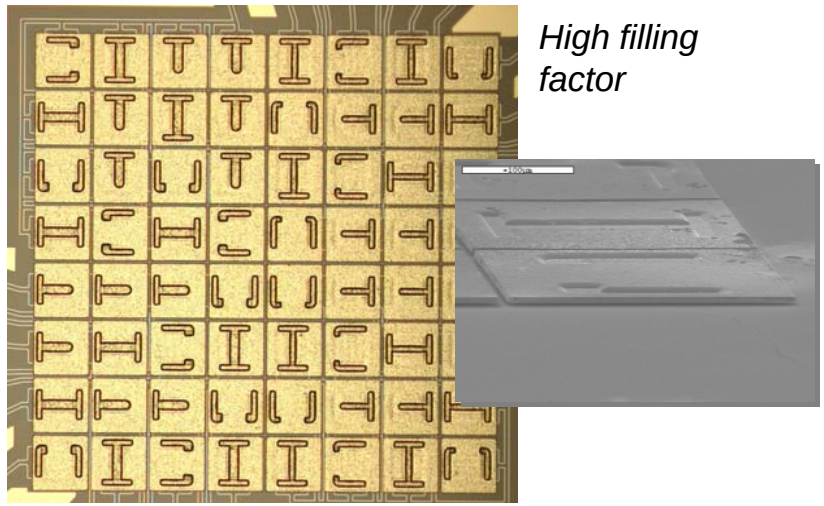
Arrays have been demonstrated on sounding rockets and *Suzaku*

Suzaku array with
32 x 640 μm pixels

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



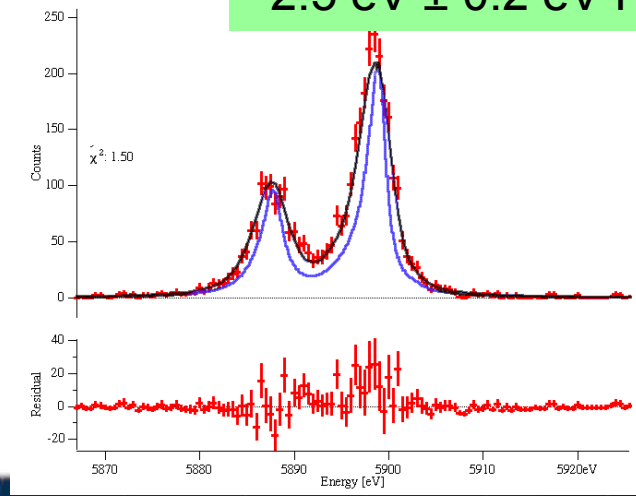
Con-X arrays under development and approaching goal of 2 eV at 6 keV.



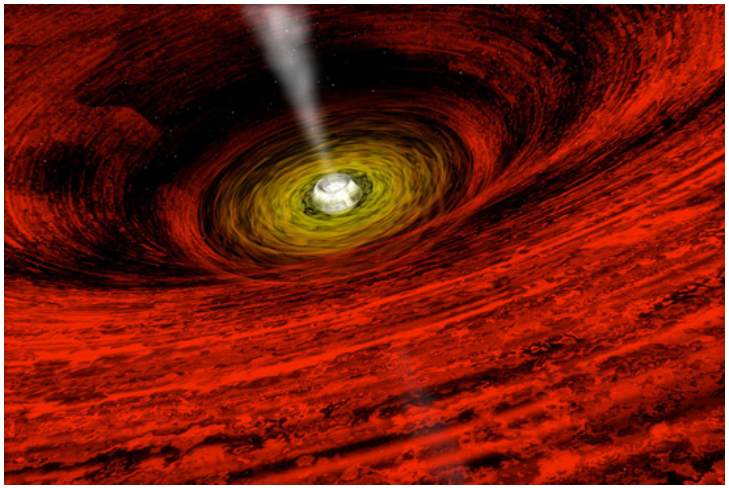
High filling factor

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

2.5 eV ± 0.2 eV FWHM



Black Holes: A Gateway to New Physics?



Black Holes may be the key

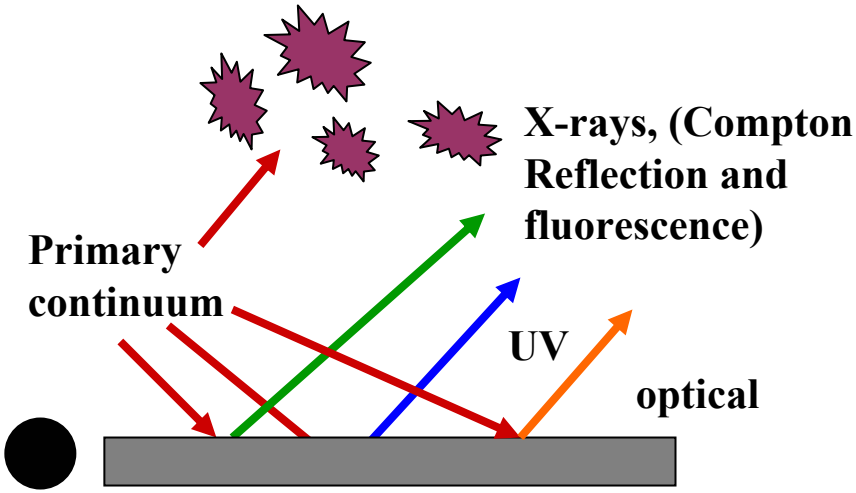
- ***The most extreme gravitational fields known***
- ***A place where space and time cease to exist***
- ***Very simple objects with just mass, spin & charge***

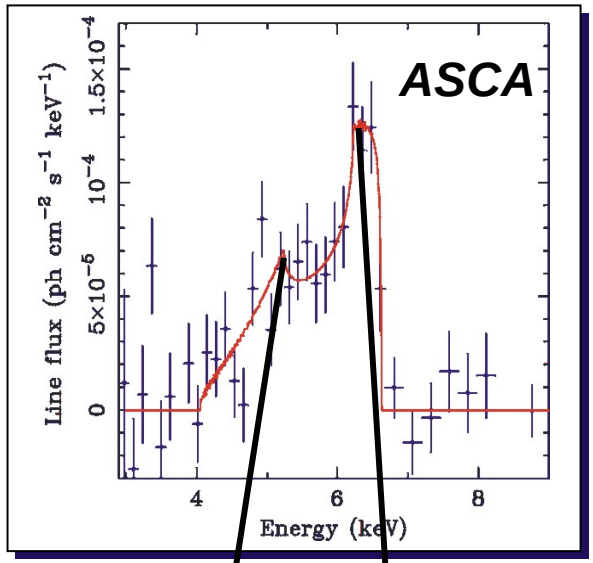
Observations of black holes can be used to

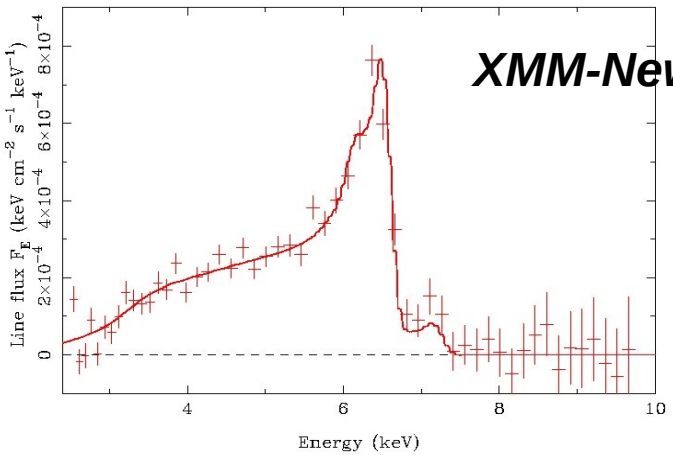
- **Test the predictions of general relativity in the strong field limit**
- **Determine the process that accelerates cosmic jets to close to the speed of light**
- **Investigate the energy release process in an accretion disk, one of the most efficient energy sources we know**
- **Search for exotic and unexpected phenomena**

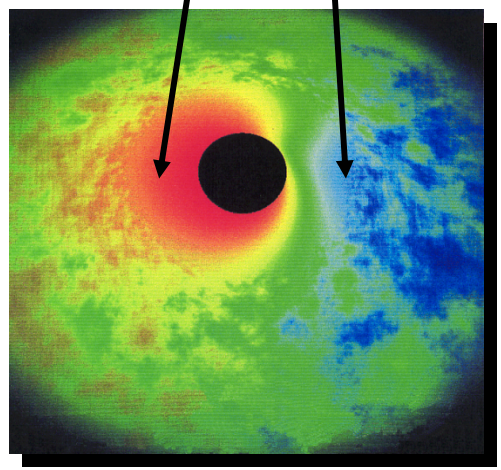
Black Holes, Accretion Disks and X-ray Reflection

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.





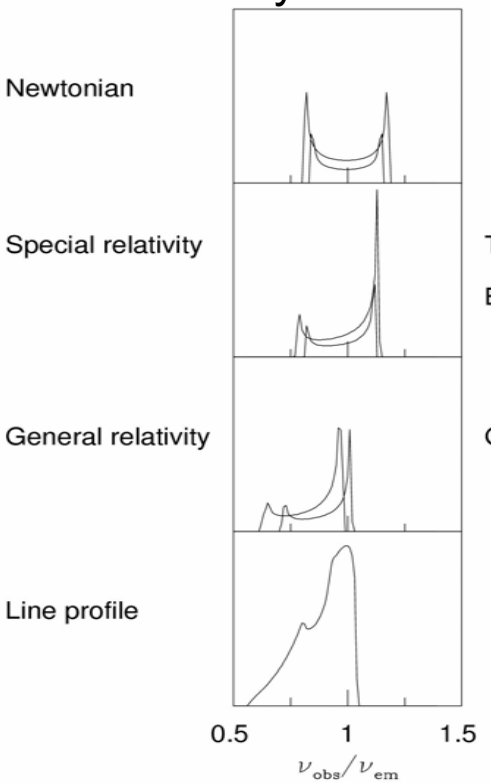


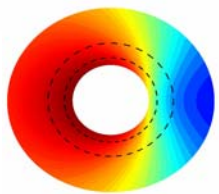


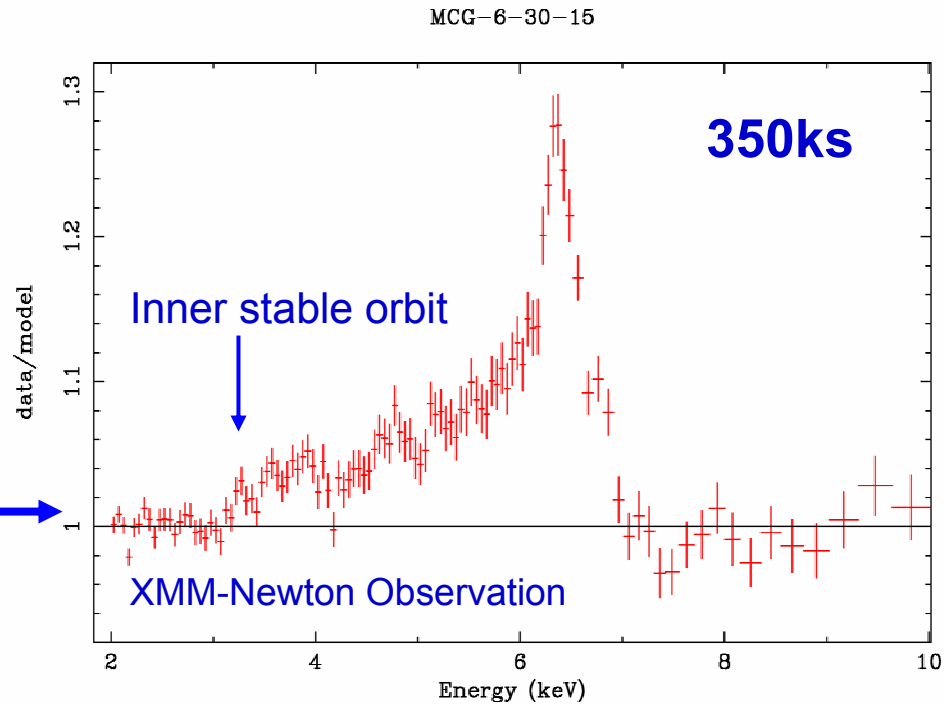
Theoretical ‘image’ of an accretion disk.

Black 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

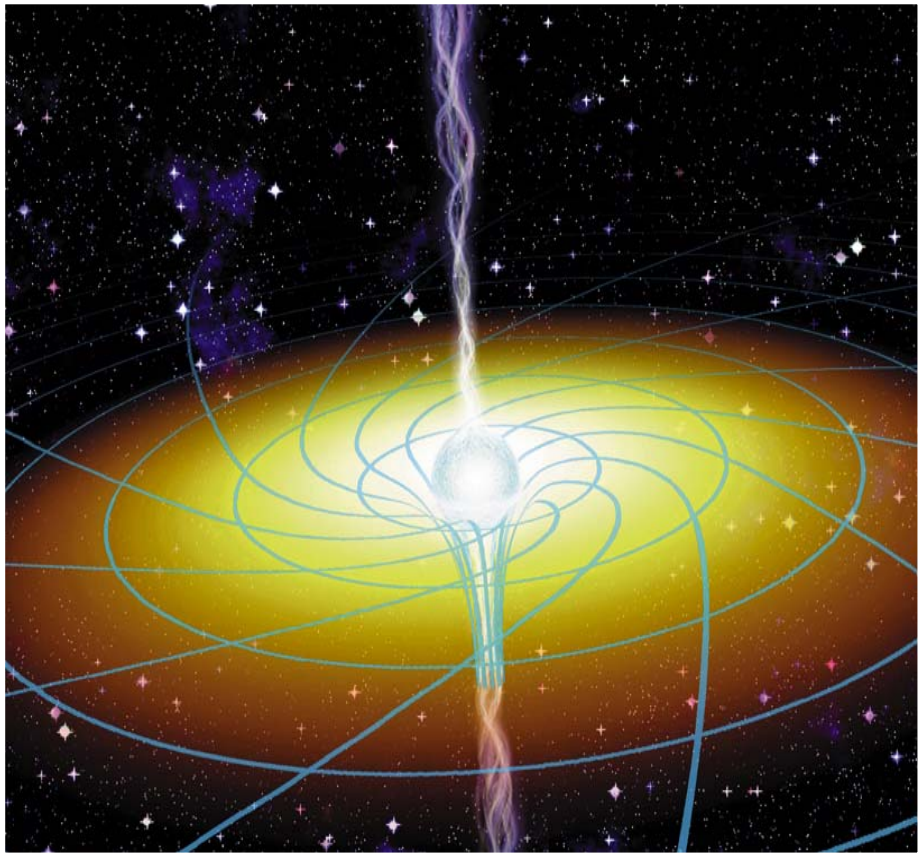


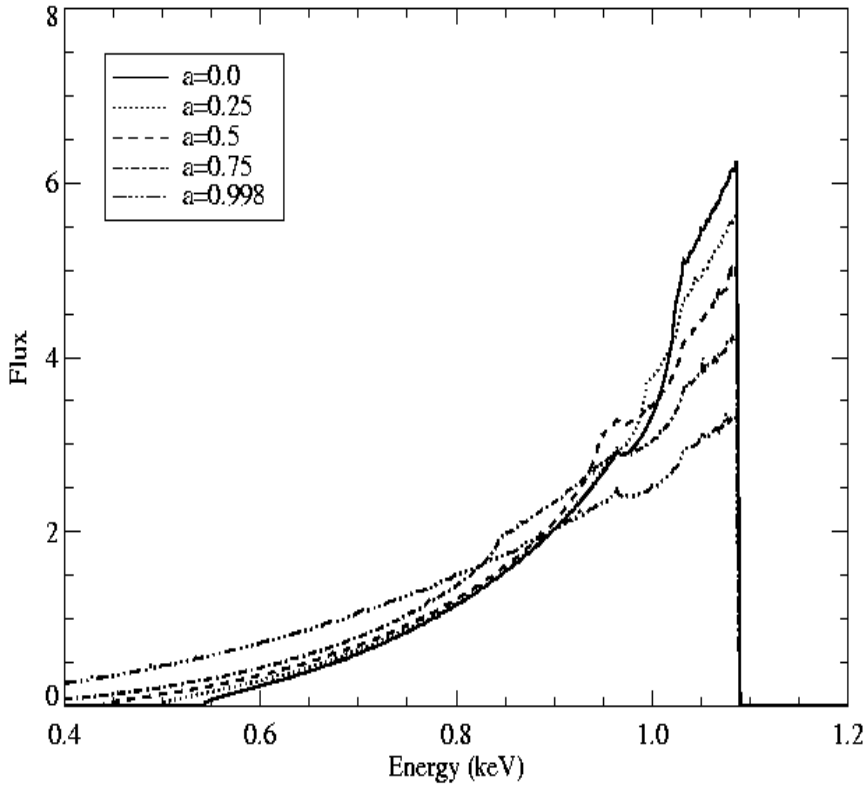




Fabian 1989, Laor 1990, Dovciak 2004, Beckwith & Done 2005

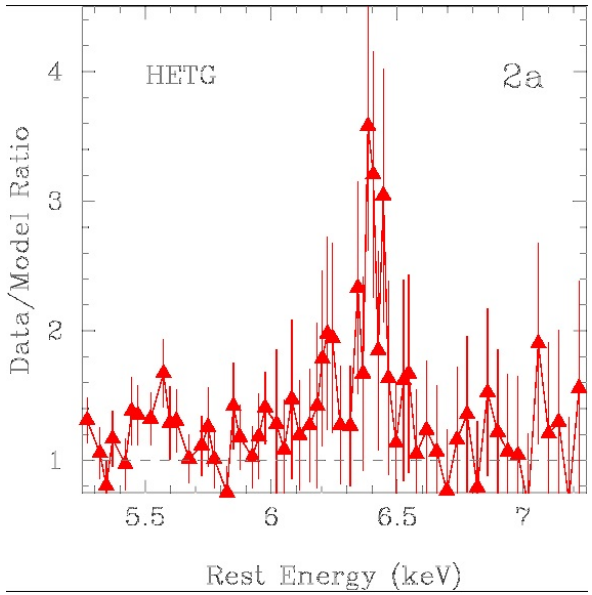
Probing Black Hole Spin



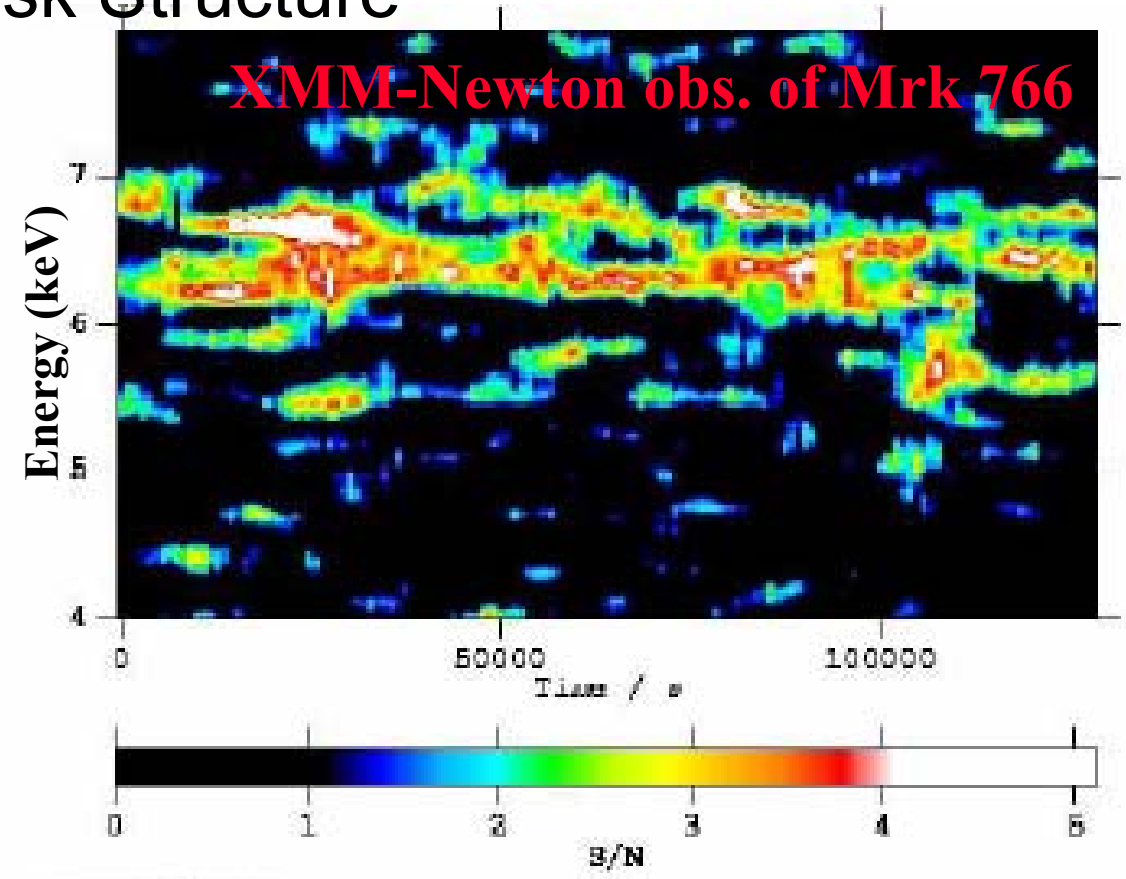


Fe Kα: Accretion Disk Structure

- Fe K fluorescence from surface layers of thin, Keplerian accretion disk
- Chandra/XMM → beginning to probe structure on orbital/sub-orbital timescales in outskirts of accretion disk



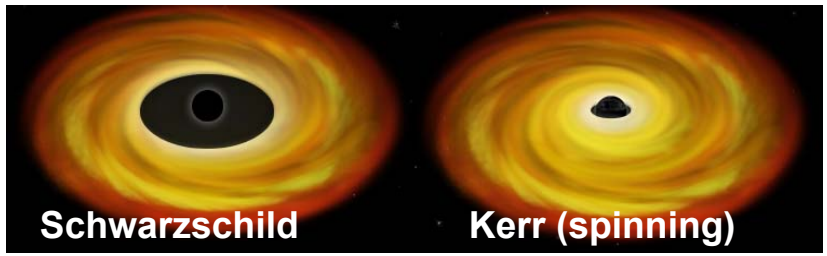
Chandra-HETG data on NGC3516 (Turner et al. 2002)

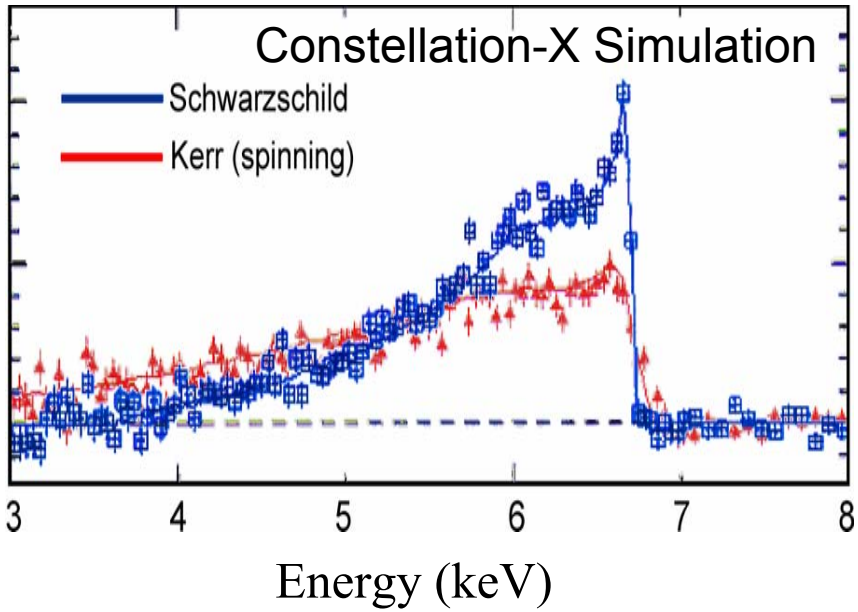


Evidence for non-axisymmetric structure may already have been seen by Chandra and XMM-Newton… Constellation-X area needed to confirm and utilize as GR probes

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





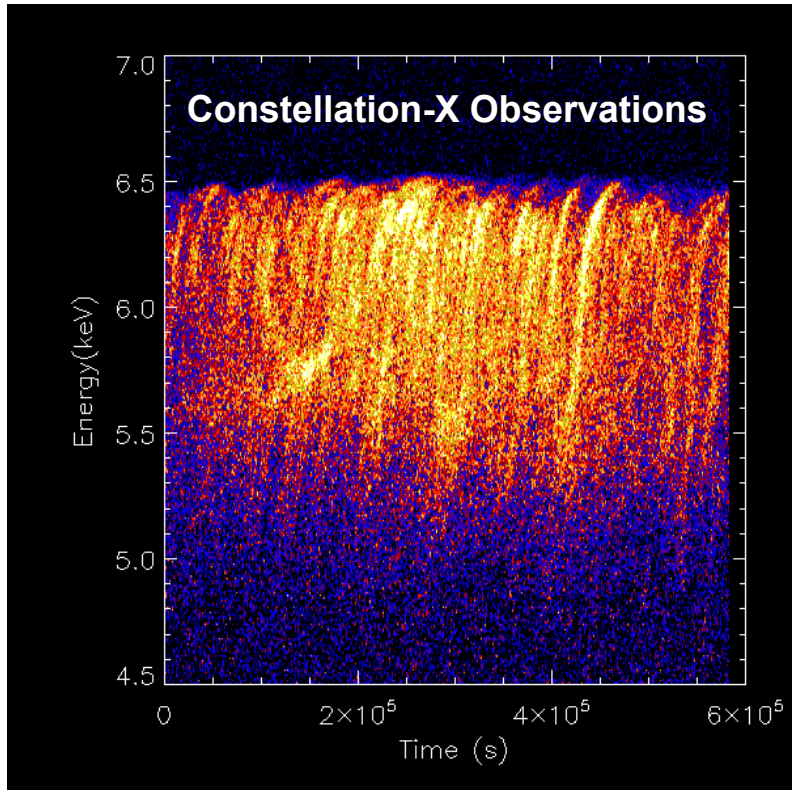
Very Broad Line = Spinning BH

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:

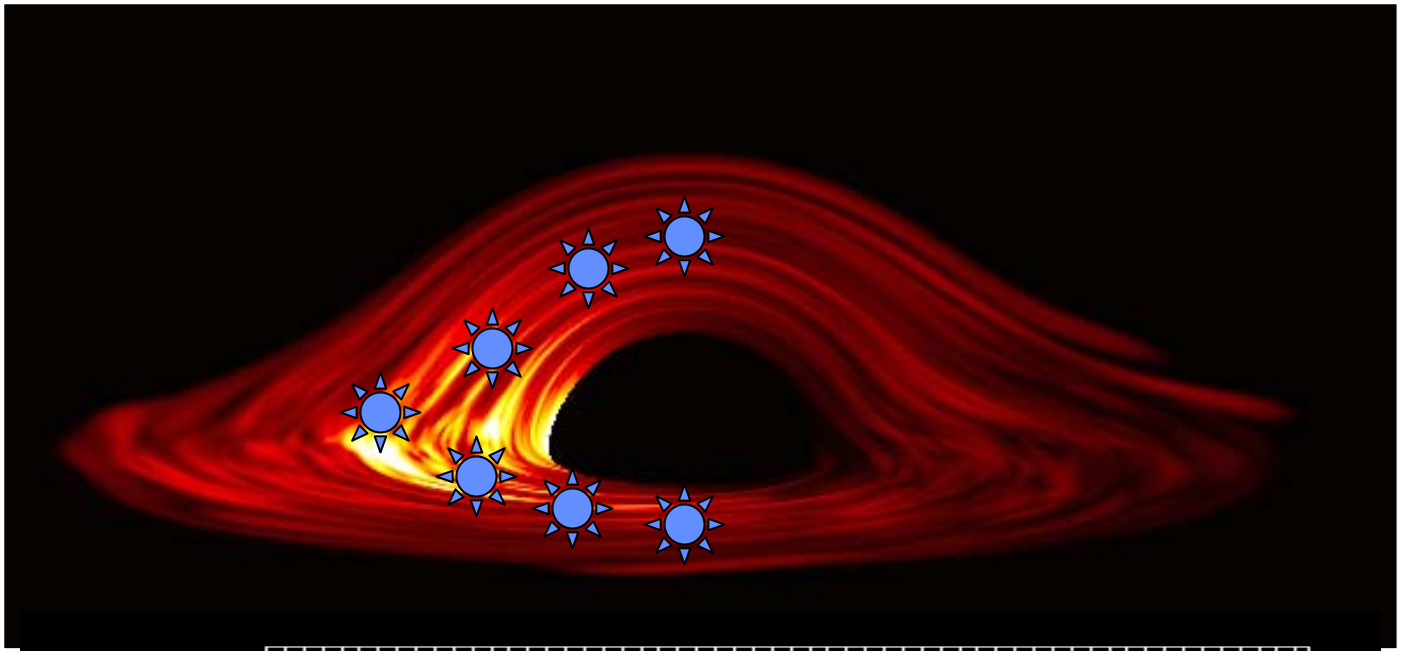
- ✓ Dynamics of individual "X-ray bright spots" in disk to determine mass and spin
- ✓ Quantitative measure of orbital dynamics: Test the Kerr metric

are needed to see this picture.

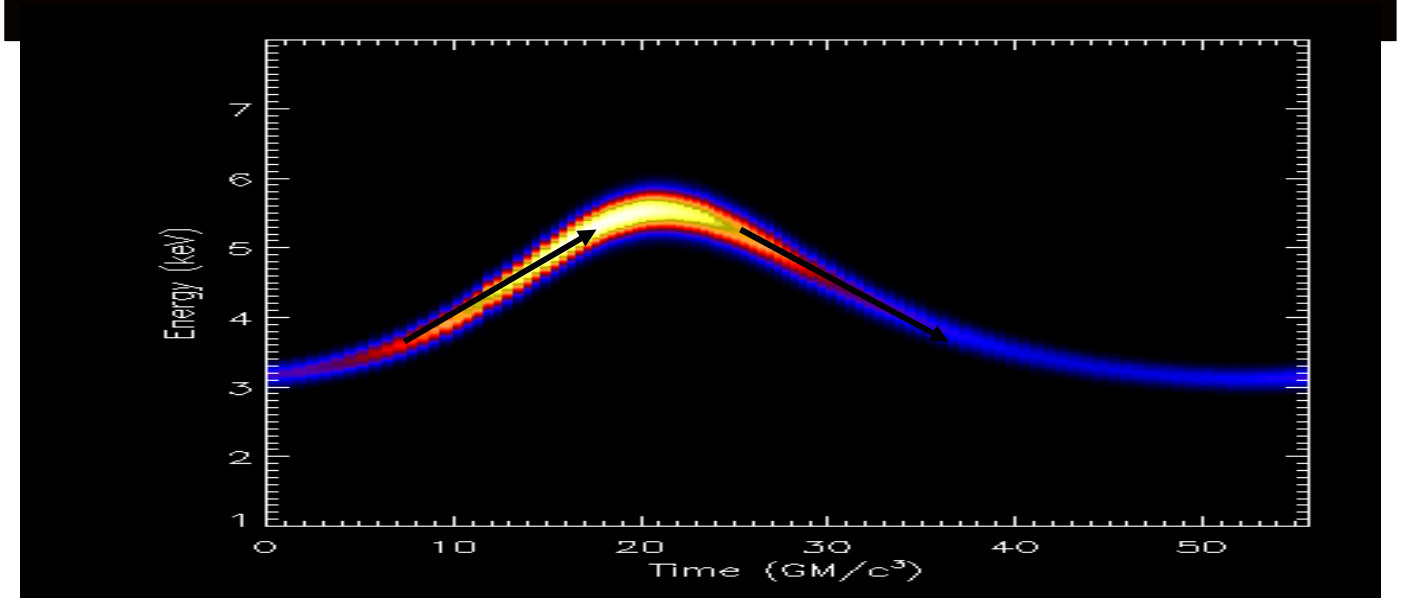


Magneto-hydro-dynamic simulations of accretion disk surrounding a Black Hole (Armitage & Reynolds 2003)

Predicted orbits of individual bright spots

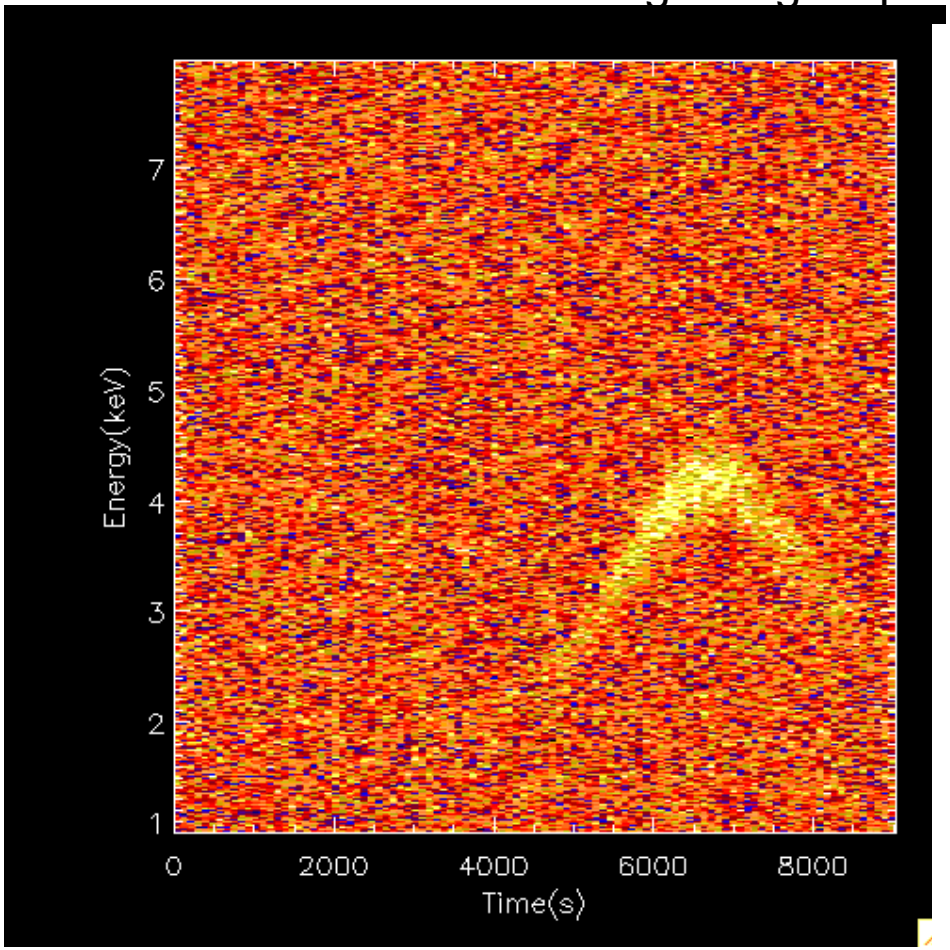


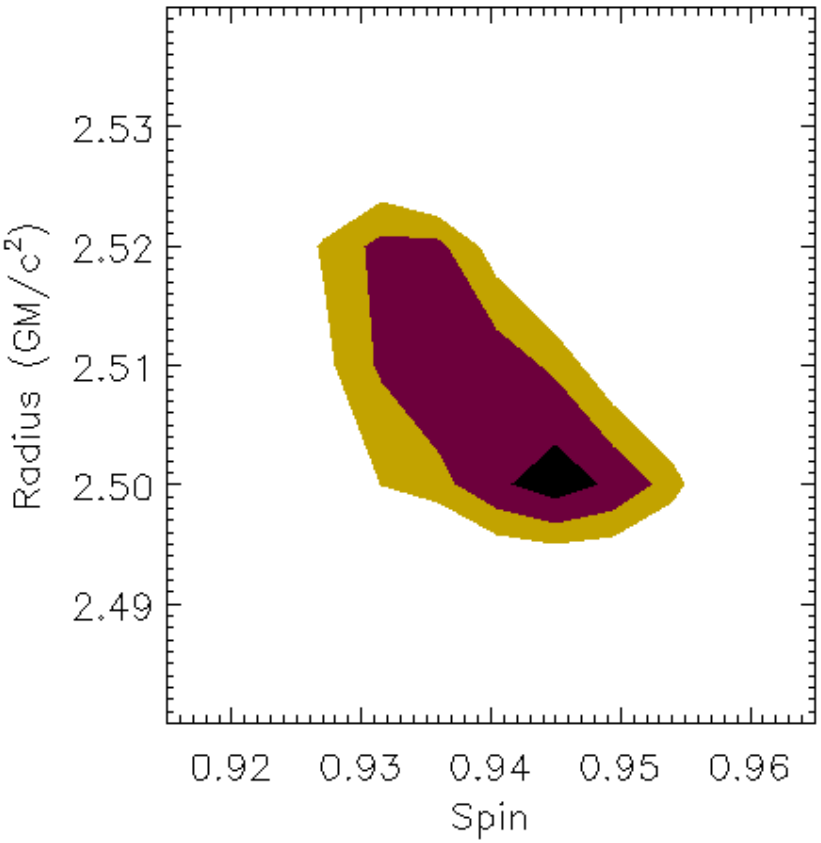
a(spin)=0.98
Radius=3.0
Inclination=30



C. Reynolds University of Maryland

Con-X simulation of single bright spots



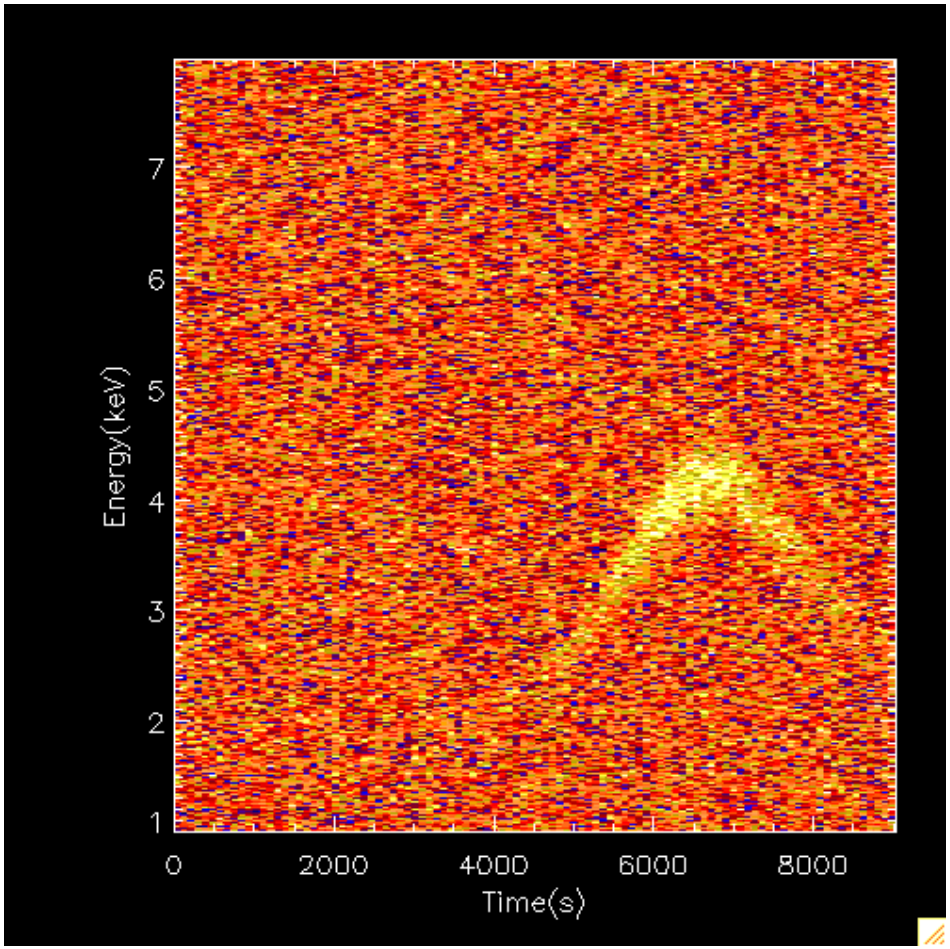


F=5×10^{-11} erg/s/cm2; EW=20eV; M=6×10^{7}
r=2.5 ; a=0.95 ; i=30 degrees

High precision measurements of spin, radius of bright spot (and other parameters e.g. mass of Black Hole)

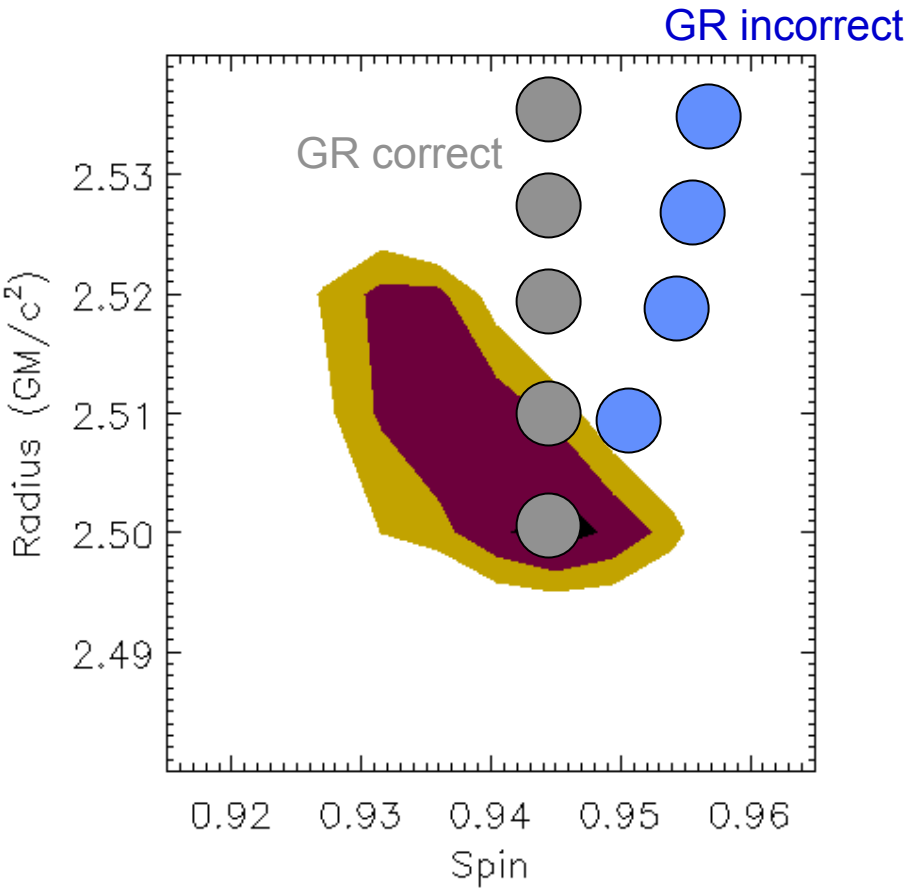
C. Reynolds University of Maryland

Testing GR via consistency of measurements



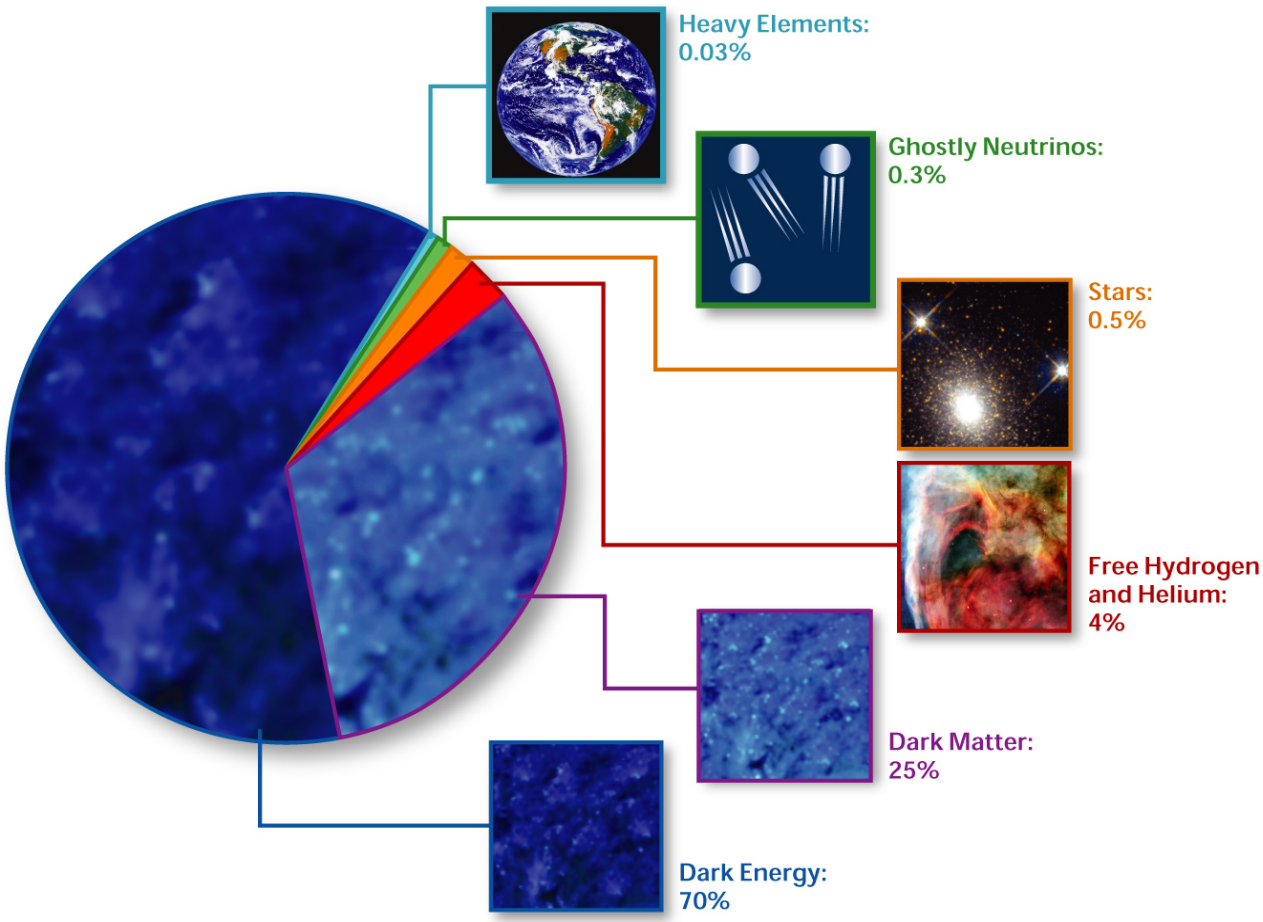
F=5×10^{-11} erg/s/cm2; EW=20eV; M=6×10^{7}
r=2.5 ; a=0.95 ; i=30 degrees

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



C. Reynolds University of Maryland

What is Dark Energy?



We do not know what 95% of the universe is made of!

Solving this mystery may fundamentally change our view of the Universe and also may impact the standard model of particle physics!

What is Dark Energy?

In the standard cosmological framework the acceleration of the expansion of the Universe is caused by dark energy that makes up 70% of mass-energy density of the Universe *in the current epoch*

Several Possibilities:

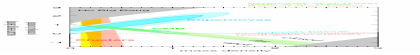
- Dark Energy constant in space & time (Einstein's Λ)
- Dark Energy varies with time
- GR or standard cosmological model incorrect
- Or something new and completely unexpected….

There are no leading theoretical explanations for Dark Energy, to help guide us as to the right experiment to perform

Multiple approaches to measure the expansion of the universe are vital to look for inconsistencies

→ **the answer may be where we least expect it!**

Constraining Dark Energy and Dark Matter



Ω_Λ

You are here

Ω_m

The constraints from different techniques on the mass content of the universe - notice that different techniques are "orthogonal" in this diagram

Need several precision techniques relatively free from systematic error or whose errors can be measured and quantified

The breakthrough may come from increased precision for each technique and disagreement between them!

Dark Energy Experimental Approaches

The origin of cosmic acceleration (dark energy) is widely viewed as the biggest current question in physics.

Many observational routes are being pursued to study it

CMB (WMAP, Planck), SNIa (LSST, JDEM), BAO (LSST, SKA, JDEM), weak lensing (LSST, SKA, JDEM), cluster counts (X-ray, LSST)
+ distance measurements to galaxy clusters (Con-X ---- space only).

These methods have different strengths/weaknesses and are sensitive to dark energy in essentially two different ways:

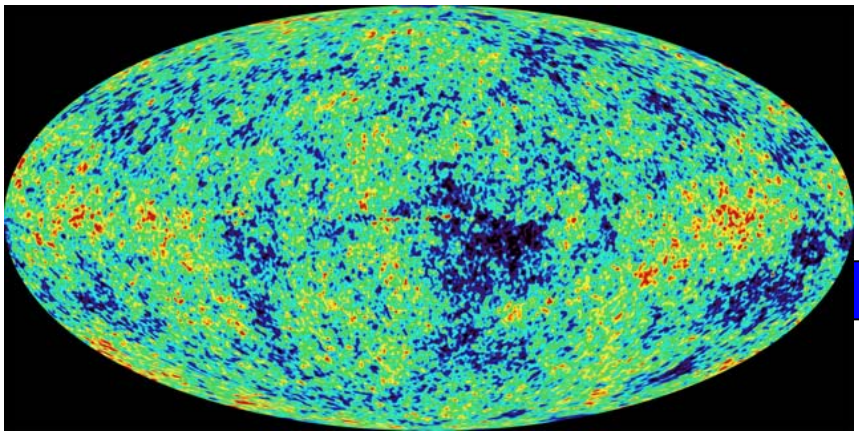
1) Absolute distances/expansion history (CMB, SN1a, BAO, clusters)
2) Growth of structure (weak lensing, cluster counts)

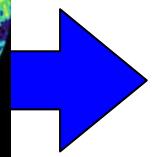
Differences between these two approaches may point to problems with GR on large scales

From Steve Allen Kipac/SLAC

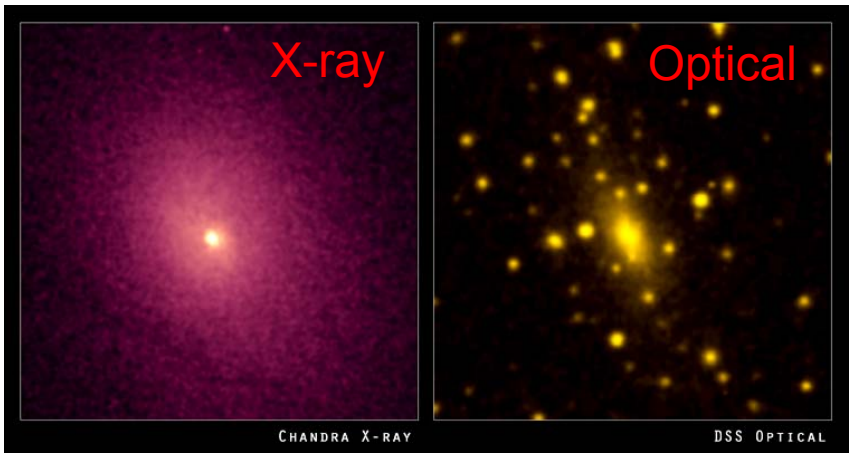
Clusters of Galaxies as Cosmological Probes

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



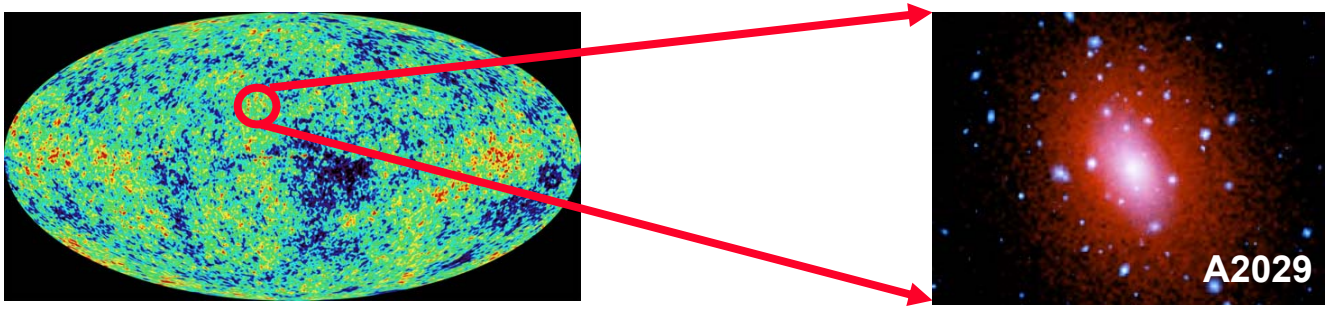


QuickTime™ and a
Cinepak decompressor
are needed to see this picture.



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

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

Dark Matter and Dark Energy

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

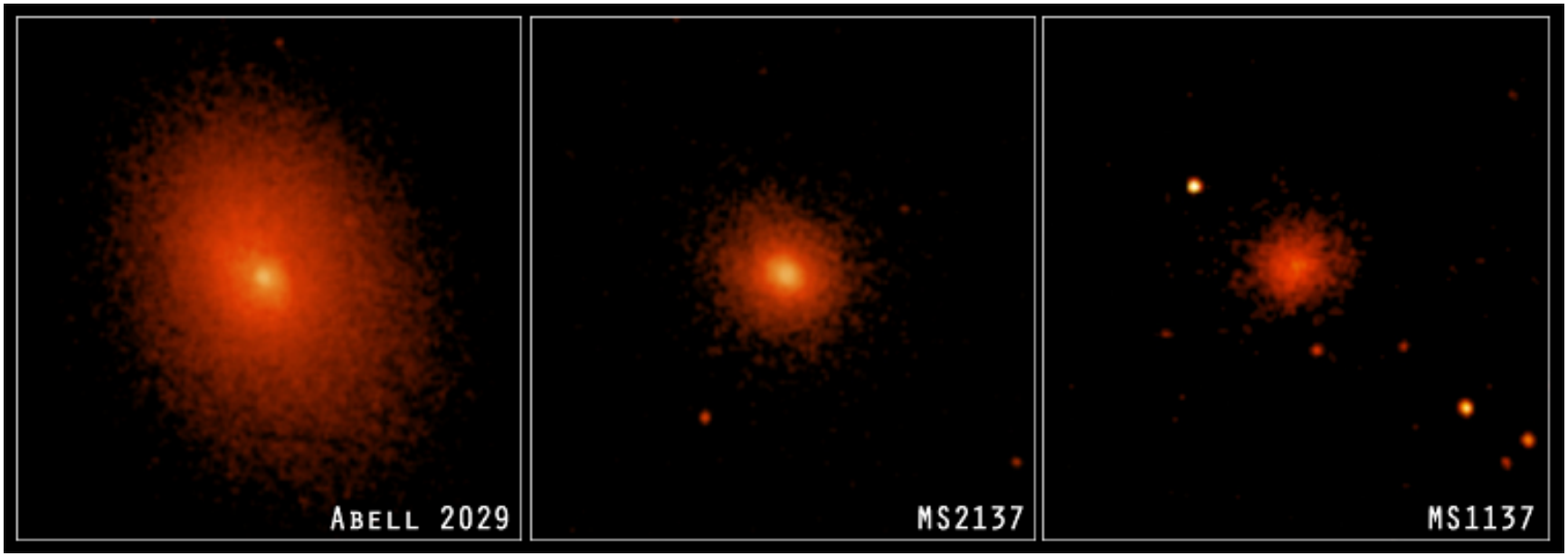
1. Using the gas mass fraction in clusters as a “standard candle”

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)

1 and 2 are ‘distance rule’ techniques (ala SNIa), 3 is a “growth of structure” technique which depends on GR

Chandra data on Clusters



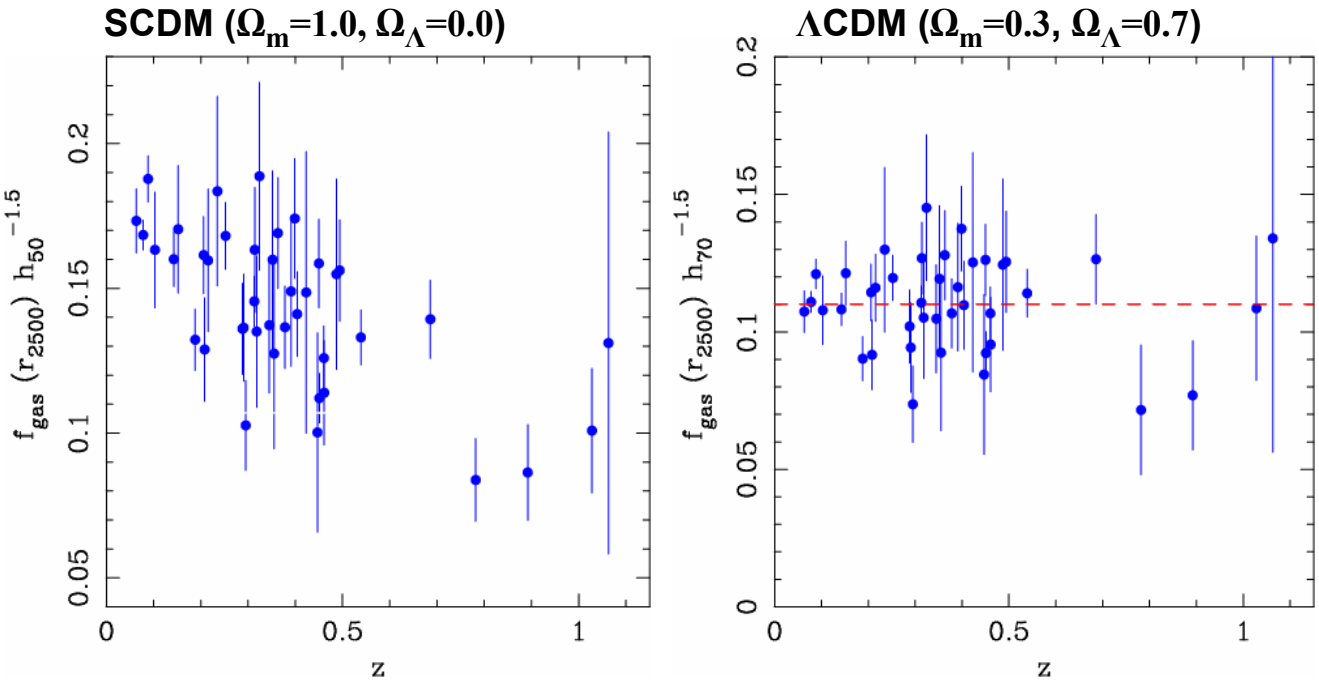
The most dynamically relaxed, highly X-ray luminous clusters spanning the redshift range 0<z<1.1 (look back time of 8Gyr)

From Steve Allen Kipac/SLAC

Gas Fraction Technique

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

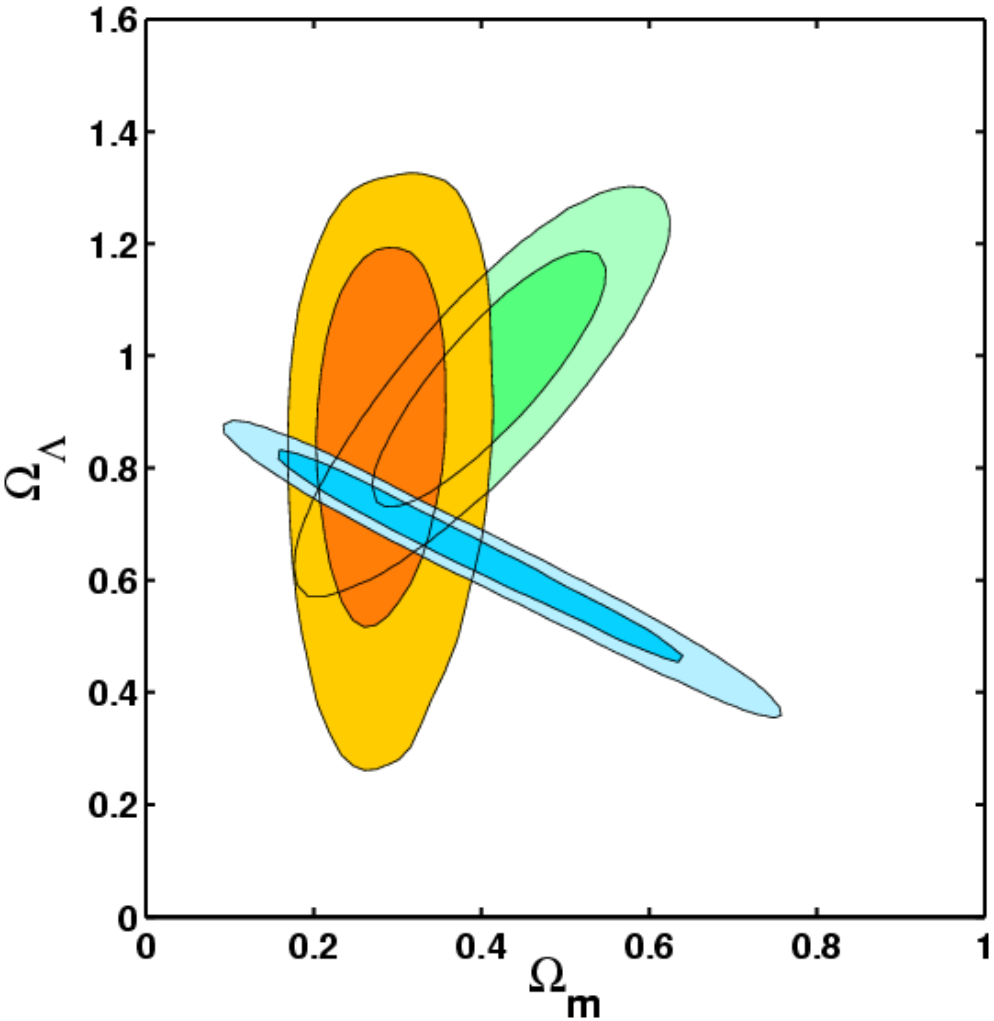
The X-ray measured $f_{gas}(z)$ values depend upon assumed distances to clusters $\boldsymbol{f_{gas} \propto d^{1.5}}$ which introduces apparent systematic variations in $f_{gas}(z)$ depending on the differences between the reference cosmology and the true cosmology



ΛCDM clearly favoured over SCDM cosmology

From Steve Allen KIPAC/SLAC

Comparison of independent constraints (ΛCDM)



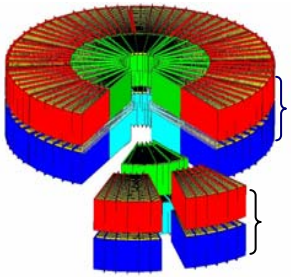
$F_{gas}(z)$ analysis: 42 clusters including standard $\Omega_b h^2$, and h priors and full systematic allowances

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)

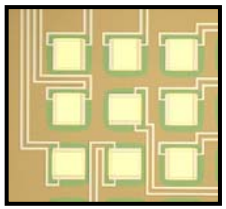
From Steve Allen Kipac/SLAC

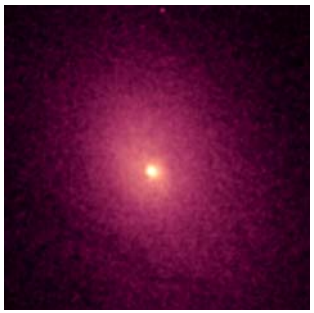
Precision Cosmology with Constellation-X



Constellation-X provides the required capabilities with large telescope area and 2-4 eV micro-calorimeter spectrometers

This combination is ideal to observe clusters of galaxies!



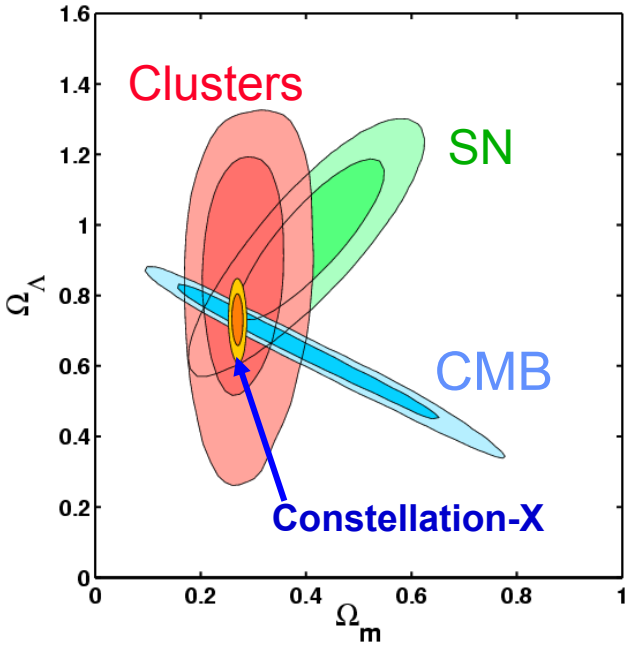


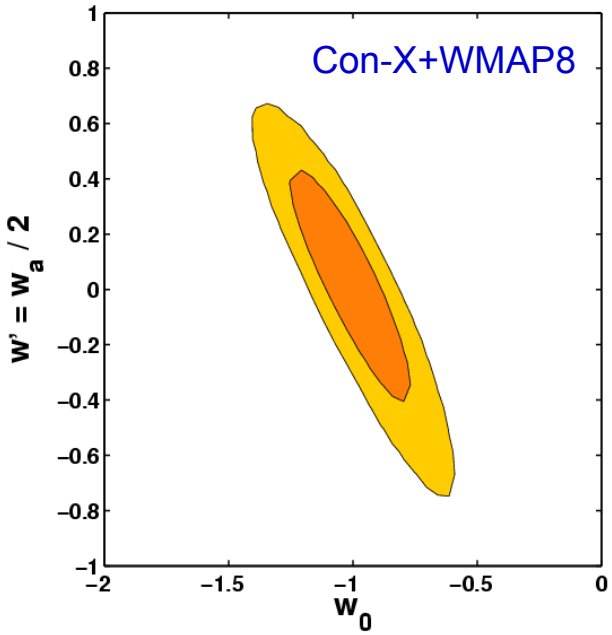
X-ray observables are:

- X-ray temperature and luminosity to give cluster mass
- Gas mass fraction (ratio of baryons to total cluster mass)
- Velocity structure of the cluster

Constellation-X will be able to measure the mass of <u>any</u> cluster of galaxies in the Universe >10^{14} solar masses - resulting in a sample of ~500 clusters

Dark Energy Cosmology with Constellation-X





Factor of ten improvement

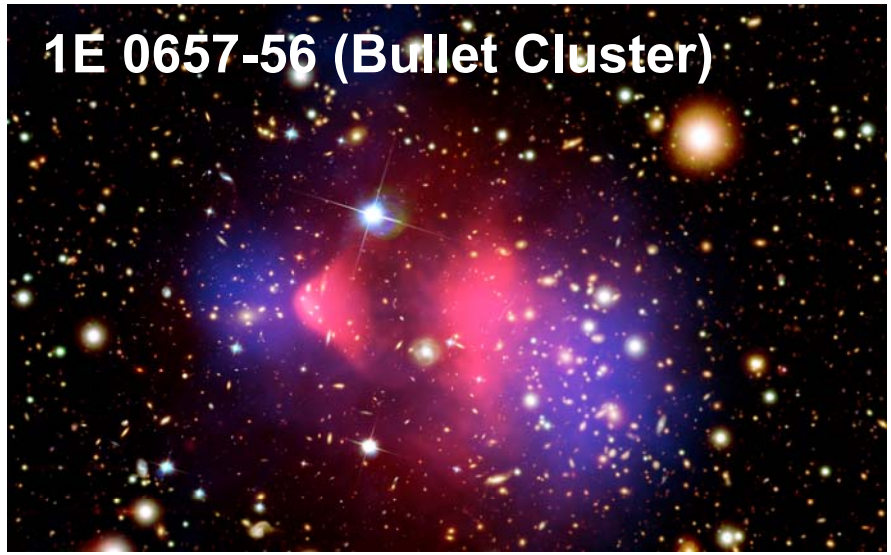
In the terms of the Dark Energy Task Force Figure of Merit this is a Stage IV result

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

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

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

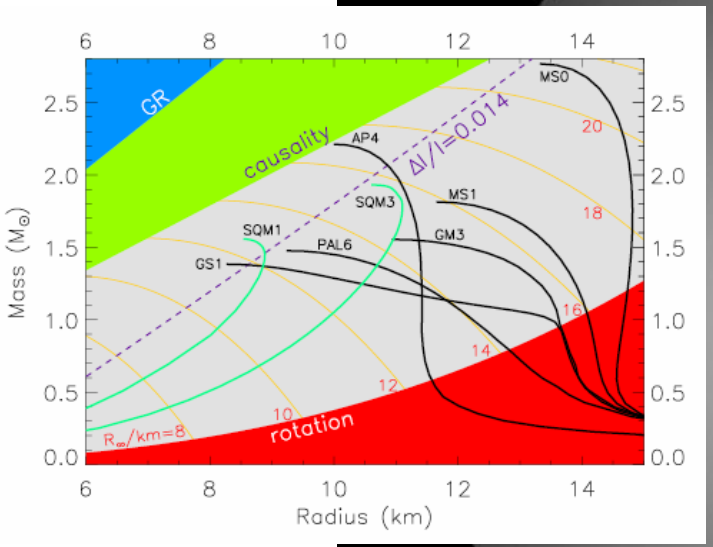


Chandra X-ray Observations of a merging Cluster where the dark matter in the clusters (blue) is clearly separate from the normal matter (pink), directly ruling out modified gravity models (Markevitch et al 2006)

- **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

The physical constituents of neutron star interiors remain a mystery.

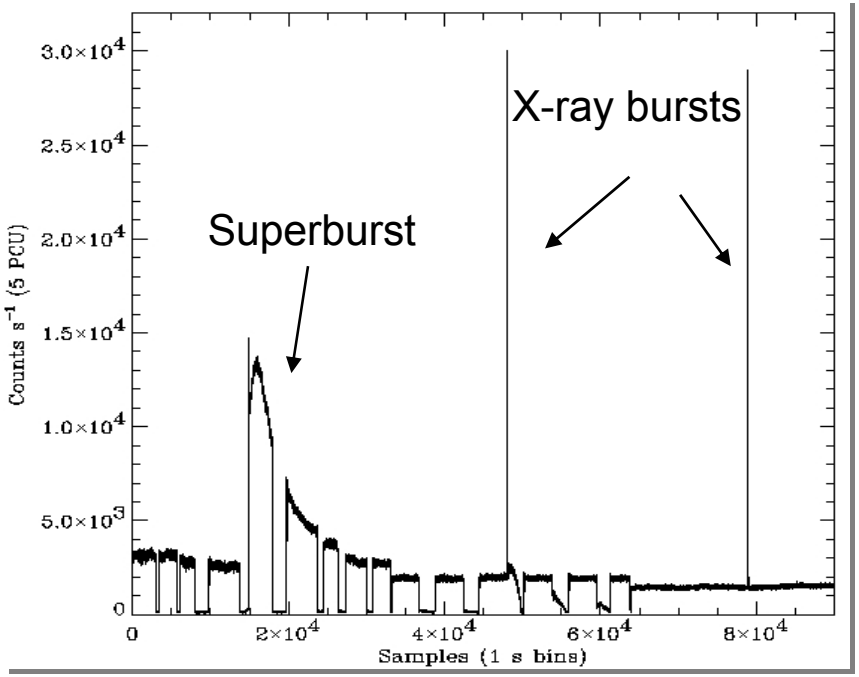


Constellation-X may finally provide the answers by determining the neutron star equation of state.

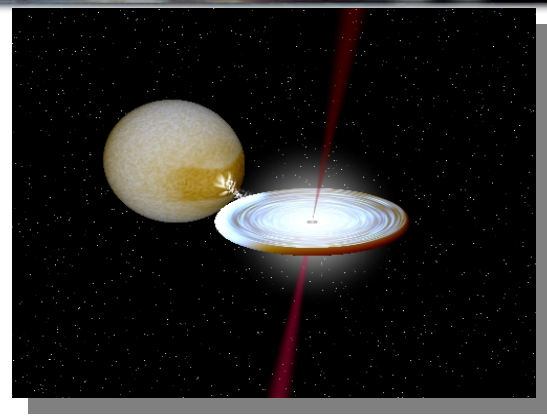
Accreting Neutron Stars

RXTE

4U1820-30







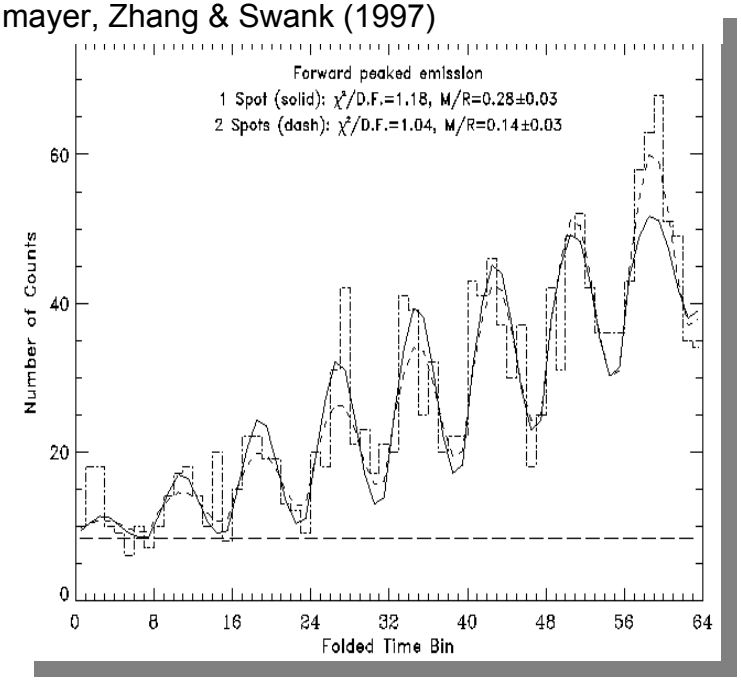
Accretion supplies metals to Neutron Star atmosphere which favors the formation of spectral lines.

Thermonuclear burning of accreted matter produces X-ray bursts.

Neutron Star surface shines brightly during X-ray bursts.

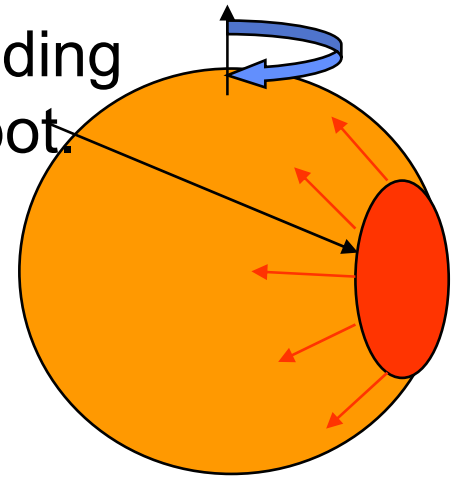
Using Burst Oscillations to Probe the EOS of Neutron Stars

Strohmayer, Zhang & Swank (1997)



QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

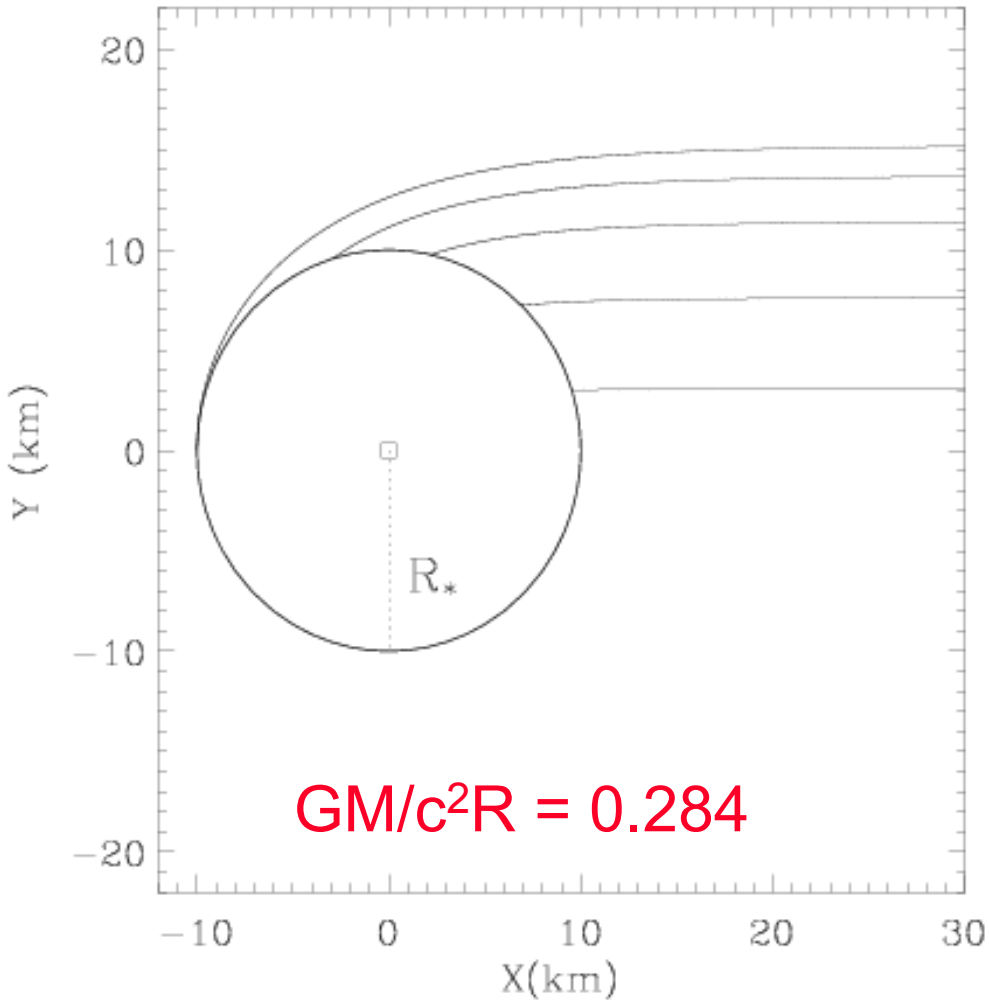
Spreading hot spot.



Credit: Anatoly Spitkovsky (2003)

- 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

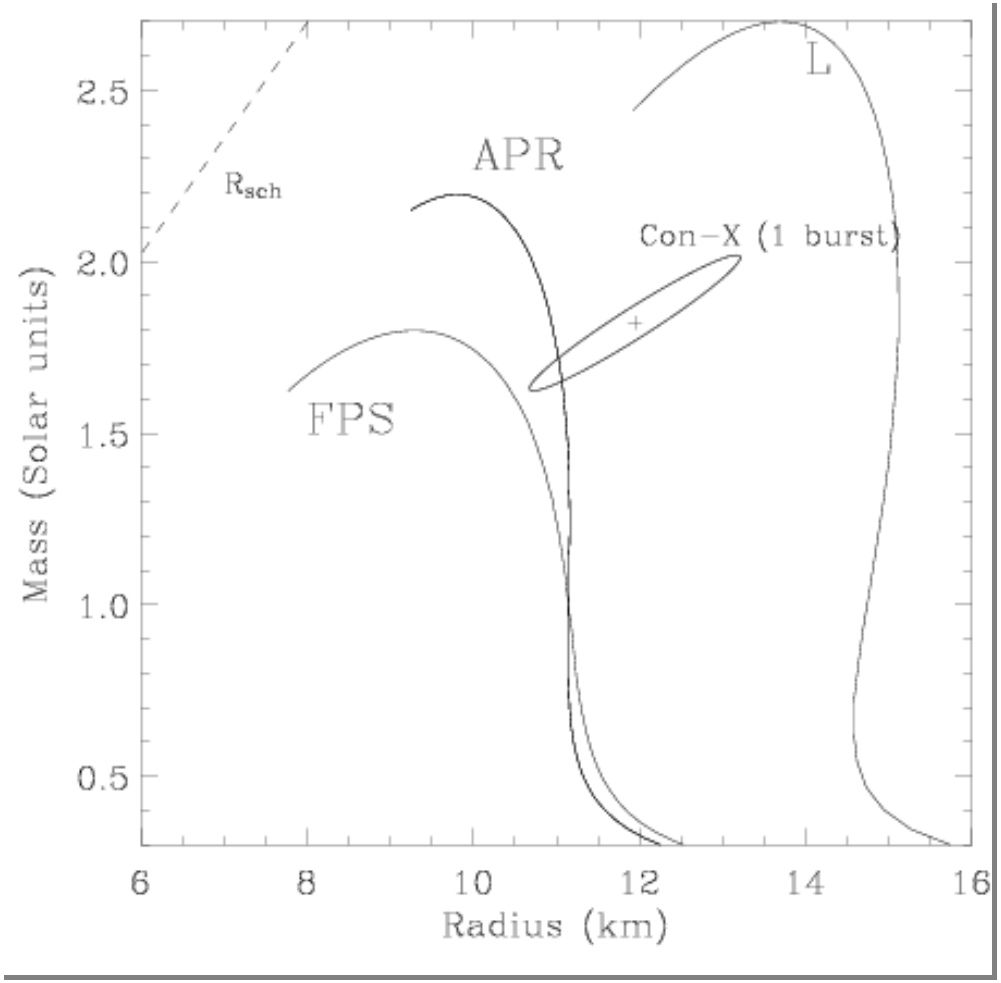
Rotational Modulation of Neutron Star Emission: The Model



- 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.

Equation of State Constraints from Burst Oscillations with Con-X



Strohmayer (2003)

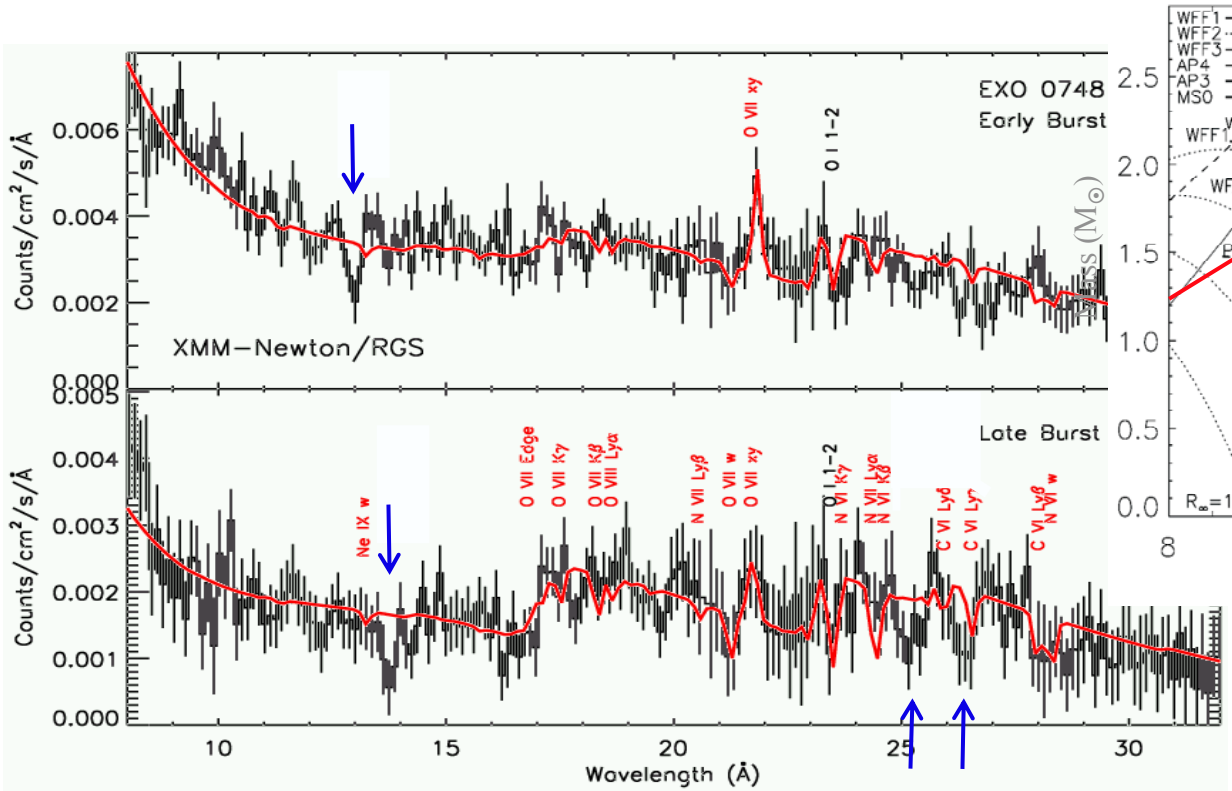
Pulse shapes of burst oscillations encode information on the neutron star mass and radius.

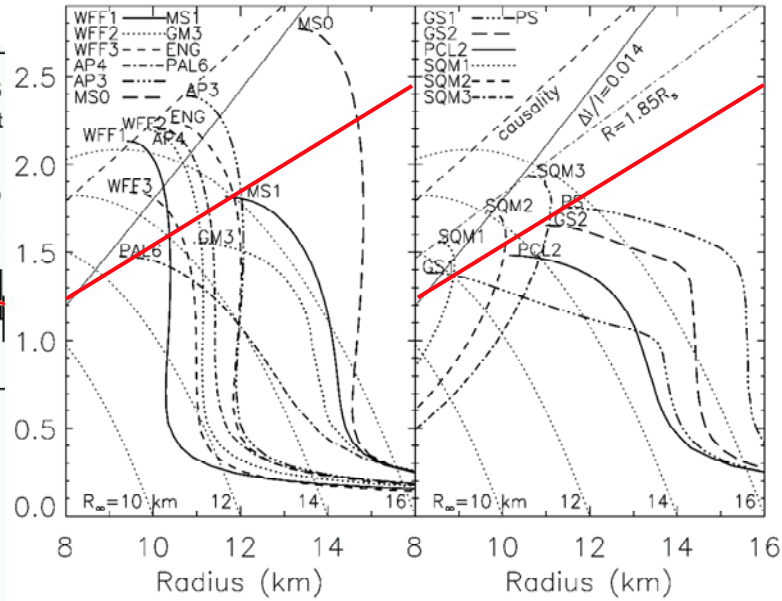
- Modulation amplitude sensitive to compactness, M/R.
- Pulse sharpness (harmonic content) sensitive to surface velocity, and hence radius for known spin frequency.

Statistical limits from Constellation-X for even just a single burst will provide meaningful constraints on EOS.

XMM-Newton Observations of EXO 0748-676

- **EXO 0748-676 was observed with XMM-Newton during commissioning and calibration of the observatory for a total exposure with the Reflection Grating Spectrometer (RGS) of 335,000 s. A total of 28 X-ray bursts were observed.**
- **In addition to circumstellar features, the summed burst spectra show unidentified residual absorption features early in the bursts at 13.0 Å and late in the bursts at 13.75 Å, 25.2 Å and 26.4 Å. These are consistent with Fe and O absorption with a surface red-shift z = 0.35.**

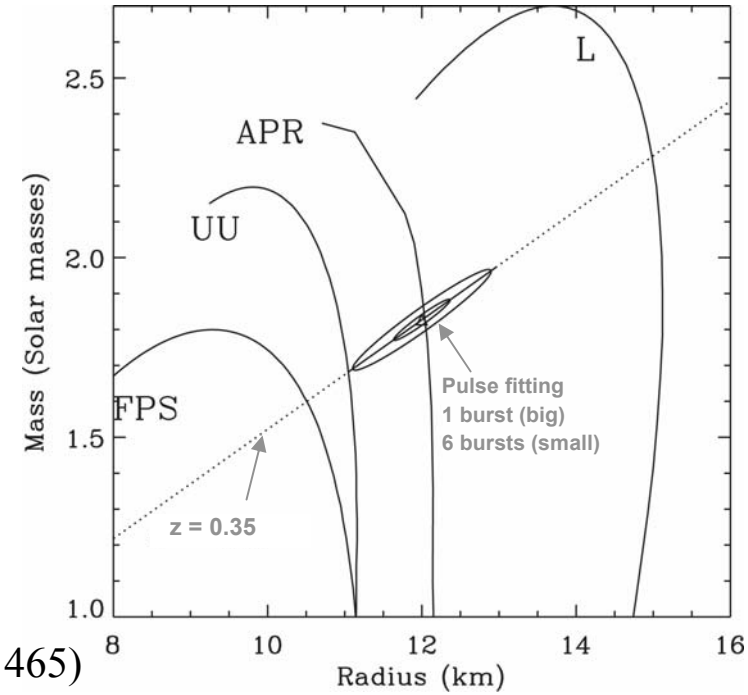




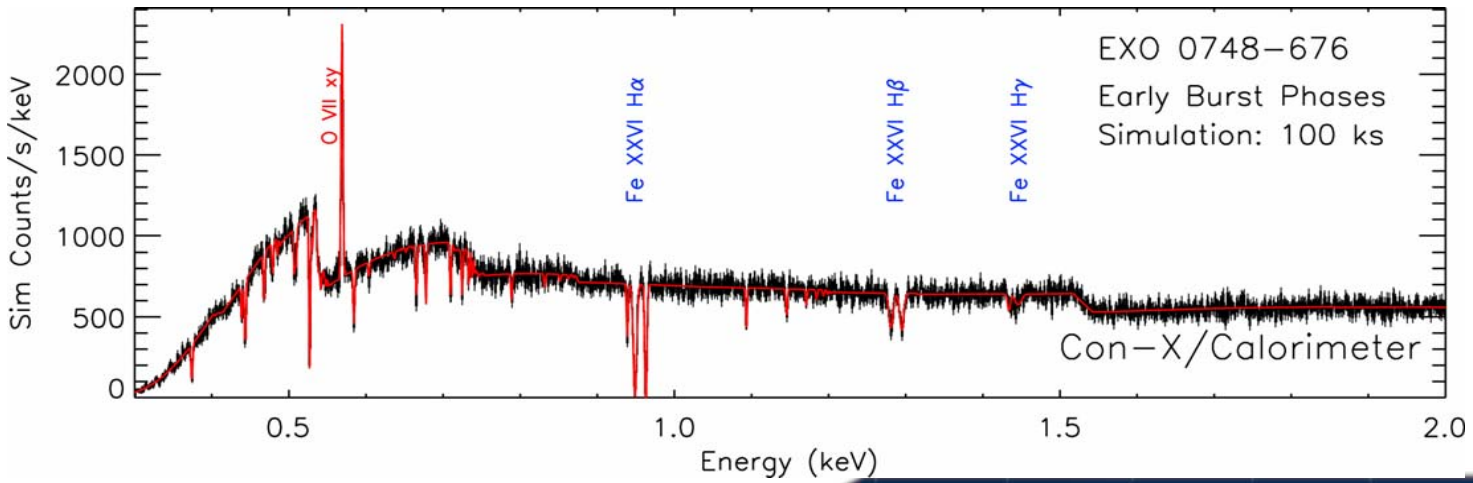
Cottam, Paerels, & Mendez (2002)

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



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

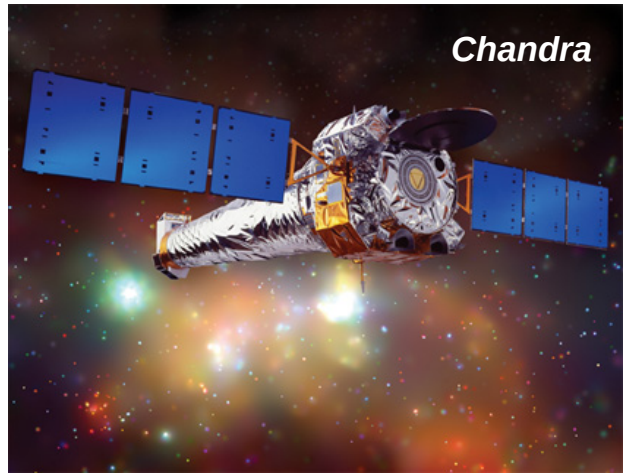


A new facility for high throughput X-ray spectroscopy



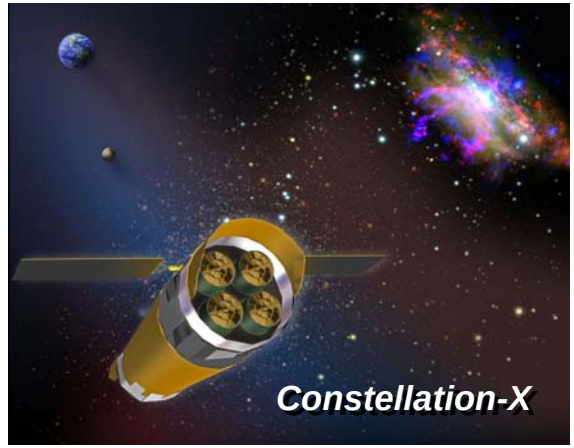
Constellation-X provides high throughput, high spectral resolution, & broad energy bandpass

Large sample sizes of key astrophysical objects





The spectroscopy of Constellation-X compliments the superb imaging of Chandra, in a manner similar to the way the Keck and Gemini compliment HST



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

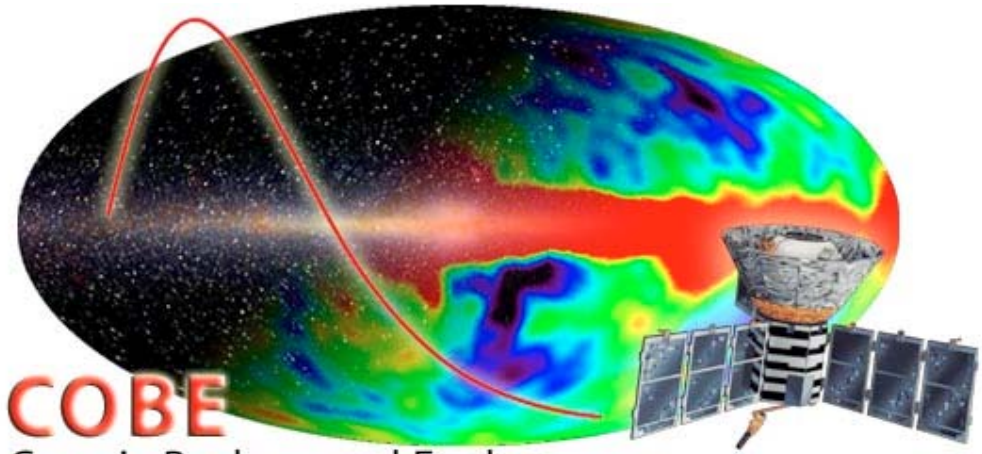
http://constellation.gsfc.nasa.gov

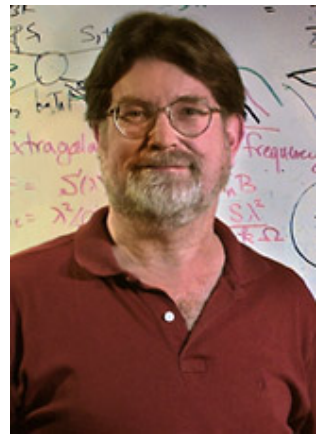
Beyond Einstein: Nobel Prize Science

2006 Nobel Prize in Physics awarded to John Mather (NASA/GSFC) and George Smoot (University of California Berkeley) for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation



John Mather



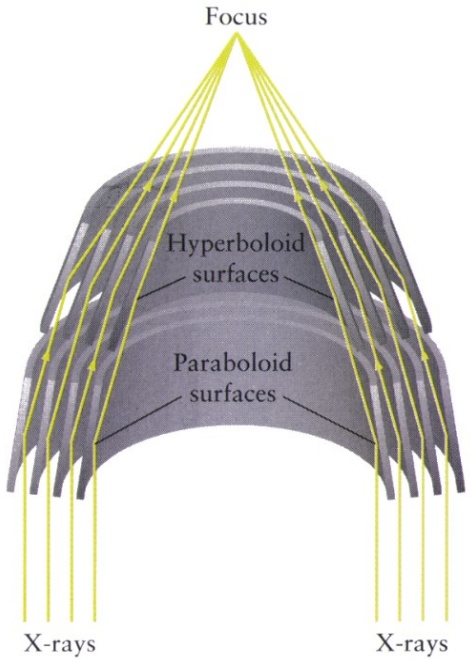


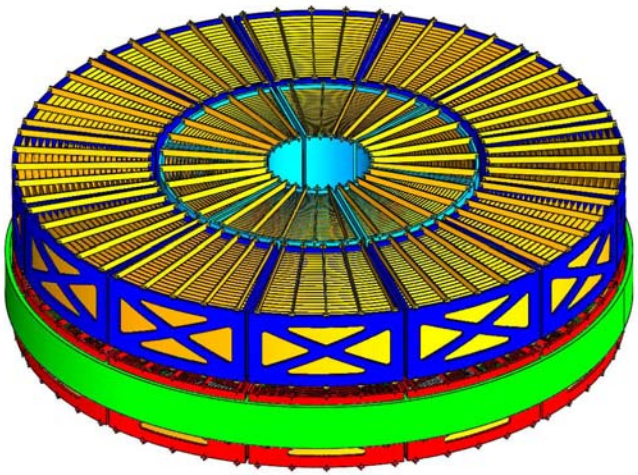
George Smoot



Other relevant Nobels: Giaconni (2002); Hulse & Taylor (1993); Fowler & Chandrasekhar (1983); Penzias & Wilson (1978); Hewish (1974); Hess (1936); Einstein (1921)

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

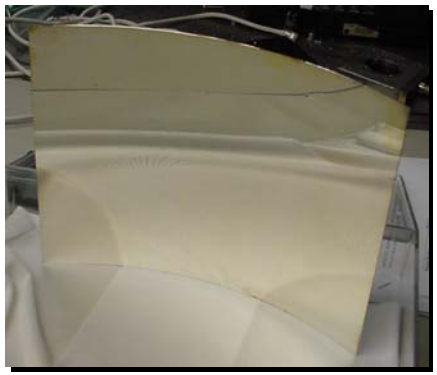


Heritage: Suzaku flight mirror (40 cm diameter)

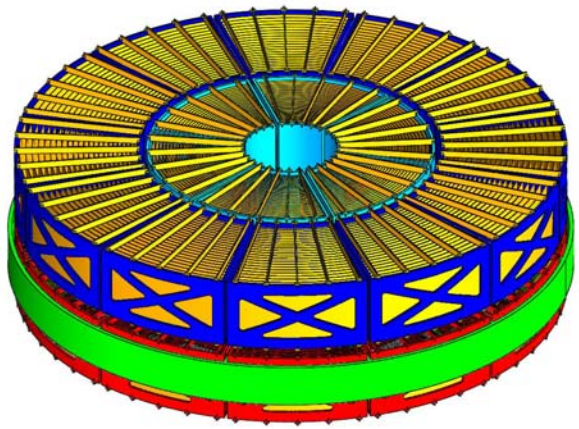
1.3 m diameter
10m focal length
Total mass 197 kg



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

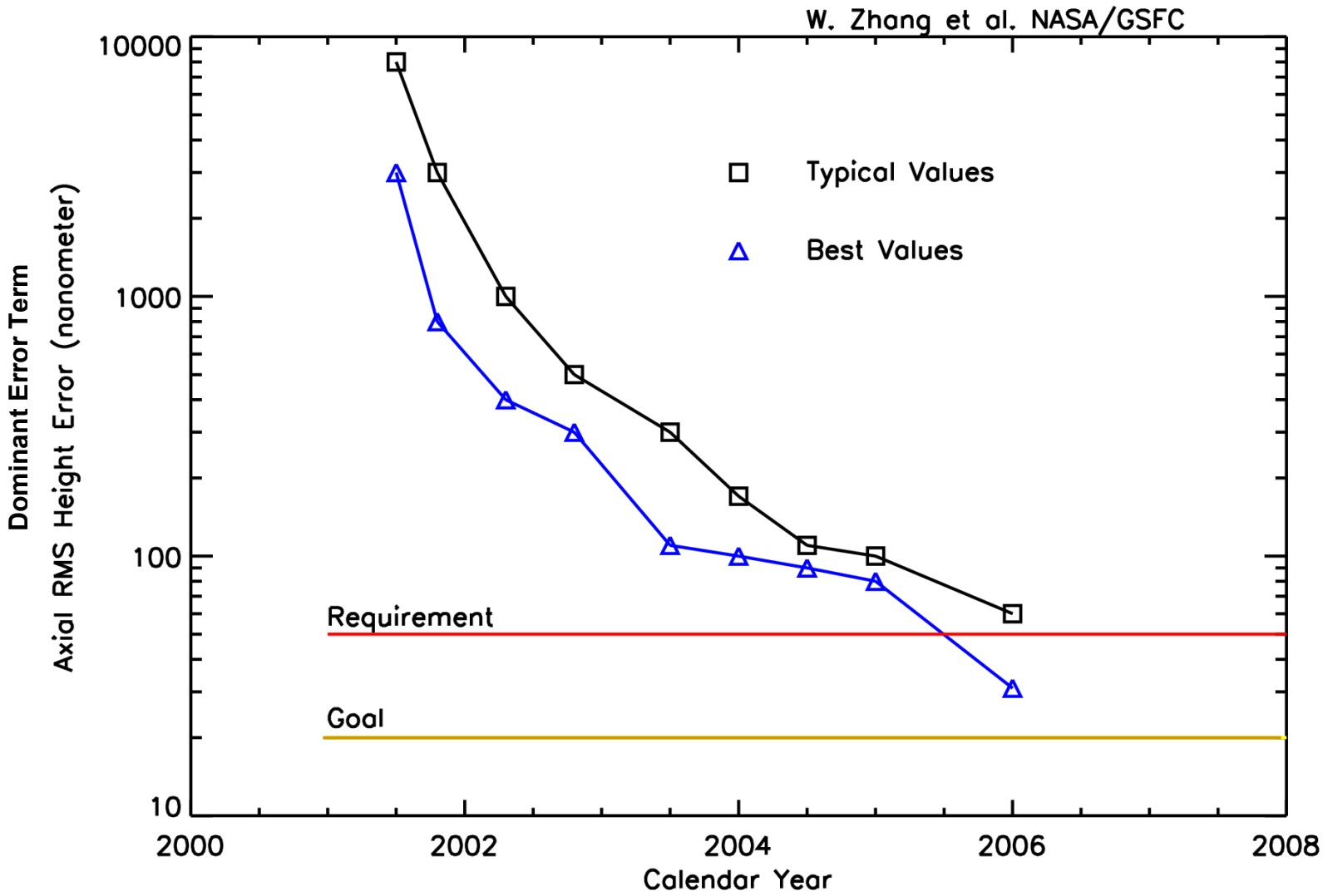


Formed 50 cm diameter glass mirror segment

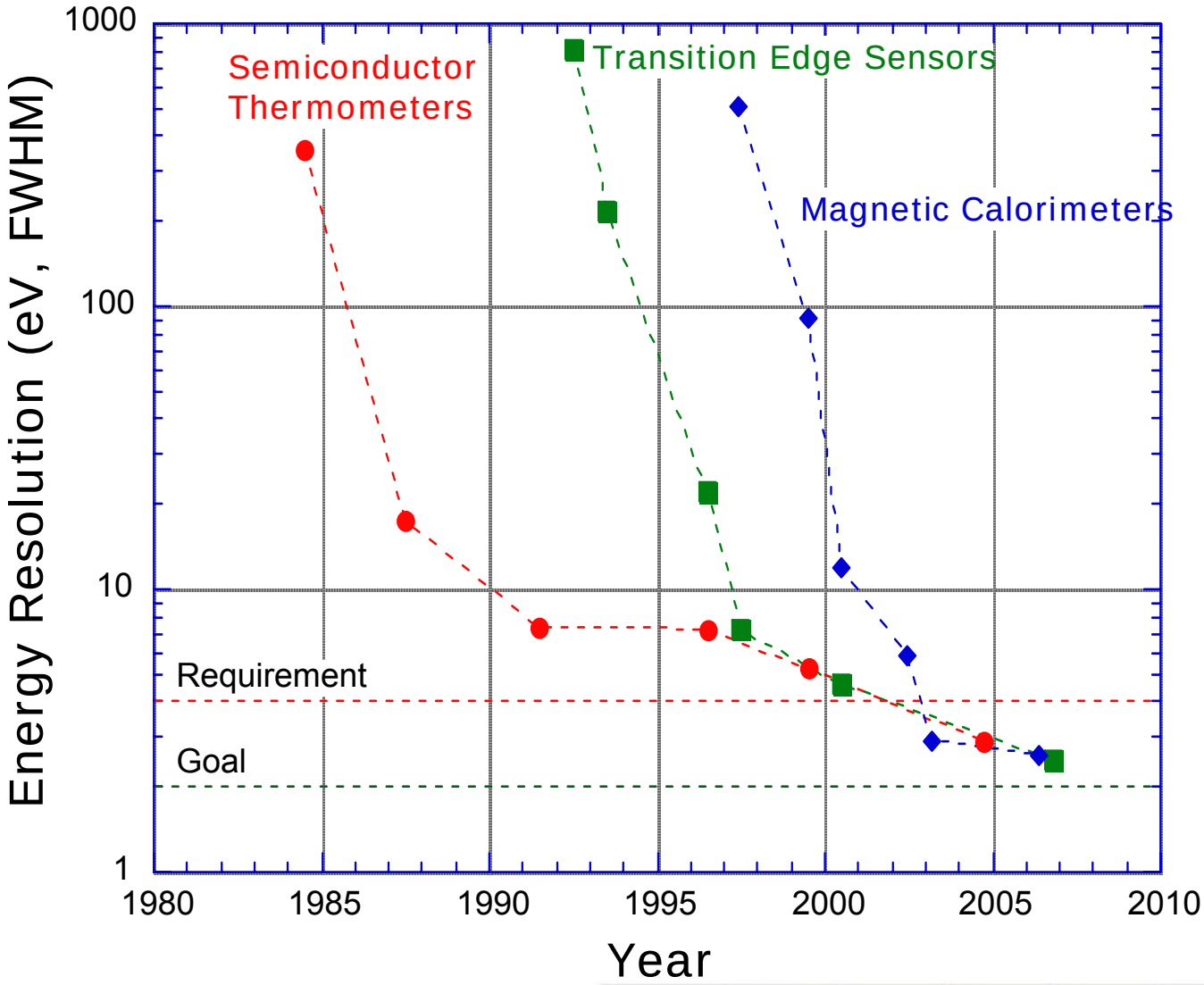


***163 shells, 3660 mirror segments
5 inner modules, 10 outer modules***

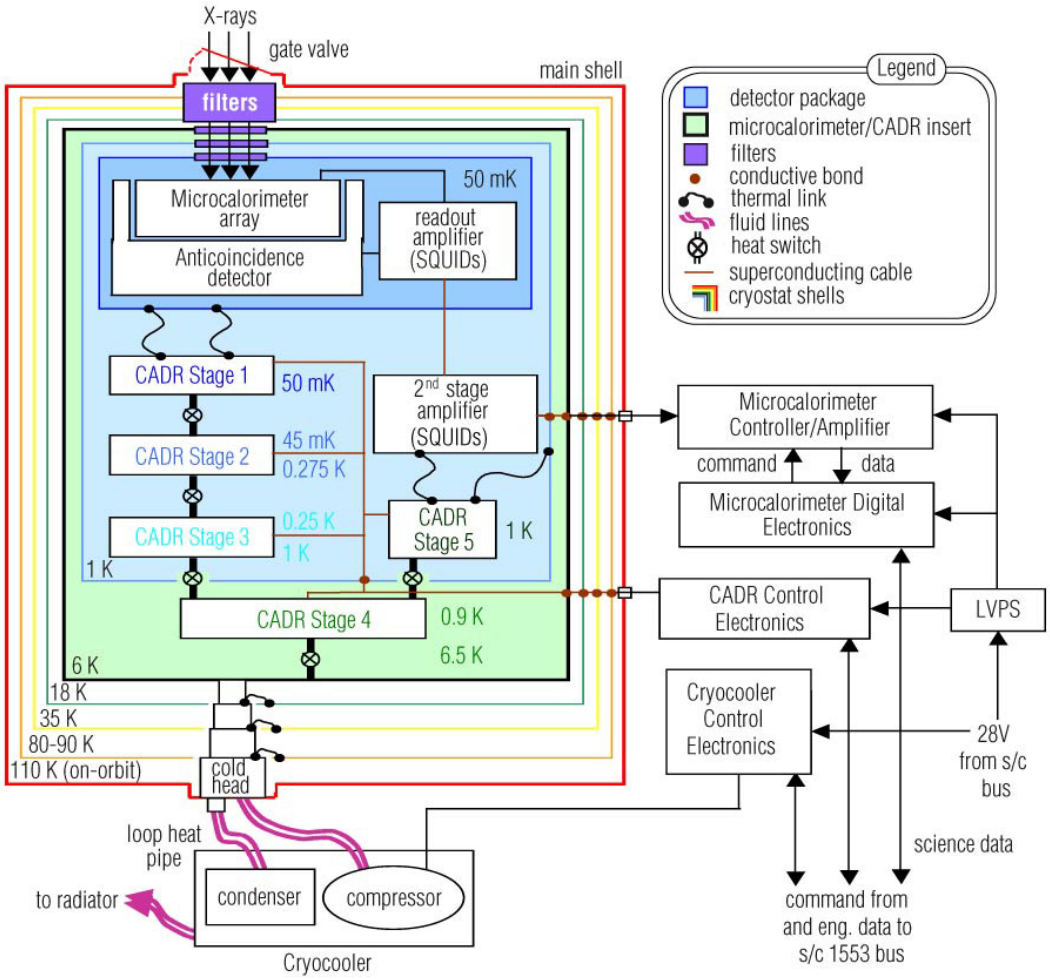
SXT MIRROR SEGMENT PROGRESS

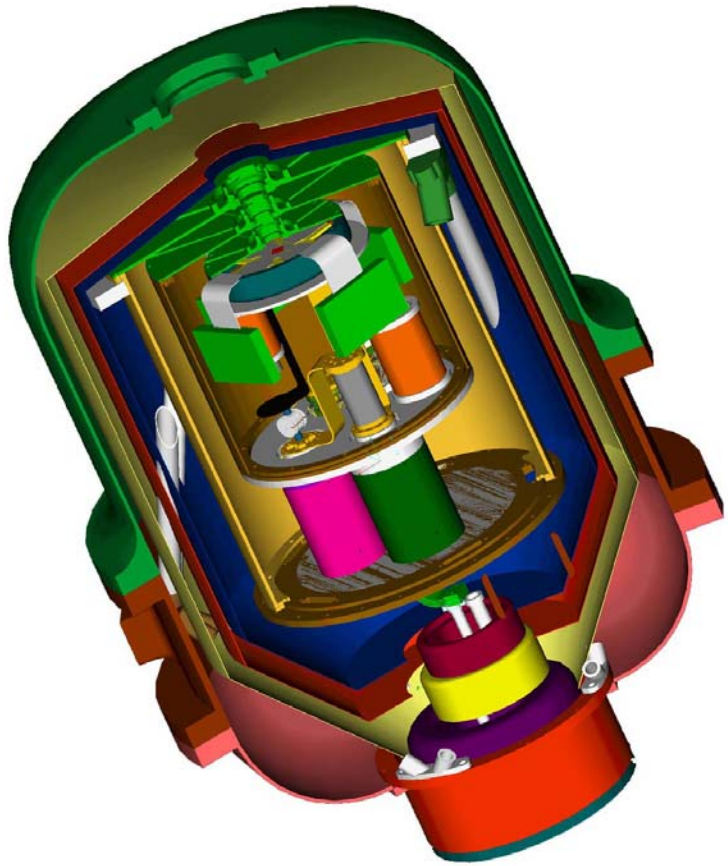


TECHNOLOGY PROGRESS:
Micro-calorimeter resolution ΔE at 6 keV



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:

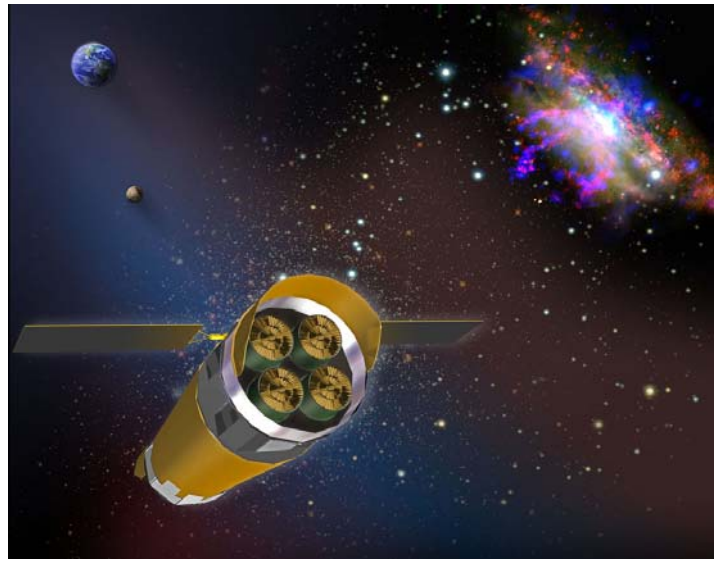
- Replicating segments with 1 kg/m^2 areal density beyond the 15" required angular resolution towards the 5" goal
- Fabrication and alignment/assembly of segments
- Development of microcalorimeter arrays larger than 32x32 (5x5" elements) to cover larger field of view (5x5' goal) with 2-4 eV spectral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

A stream-lined Single S/C Atlas V Configuration

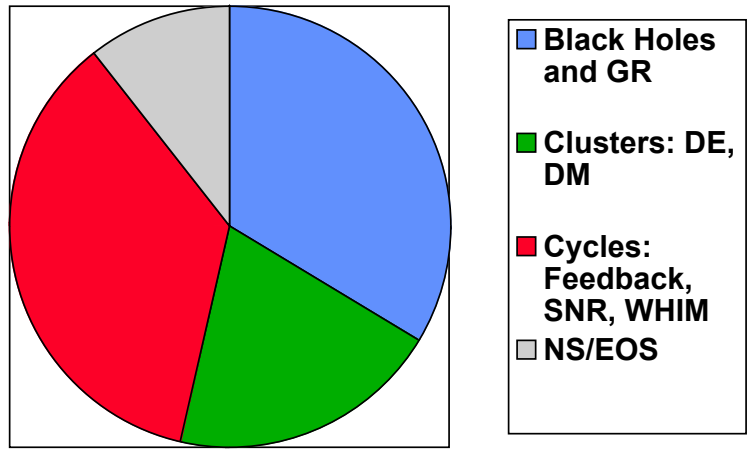
- Retain effective area over 0.6-10.0 keV band
- Reduce mass and envelope to fit within single Atlas V
  - removes previous versions of reflection gratings and hard x-ray telescopes
  - allocation of 100kg of mass and $100M budget for simplified approaches
  - community solicitation underway with inputs 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 $$

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



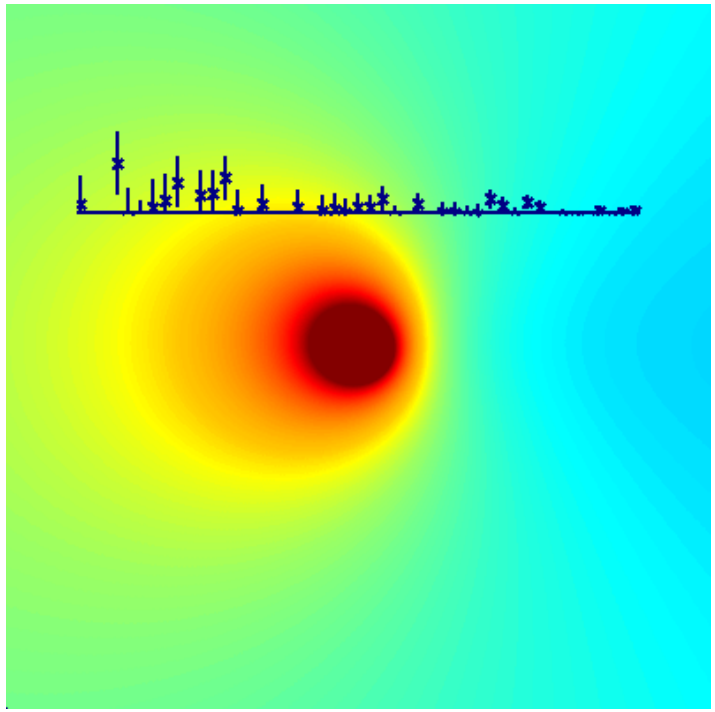
Estimated Division of Observation time by science objective





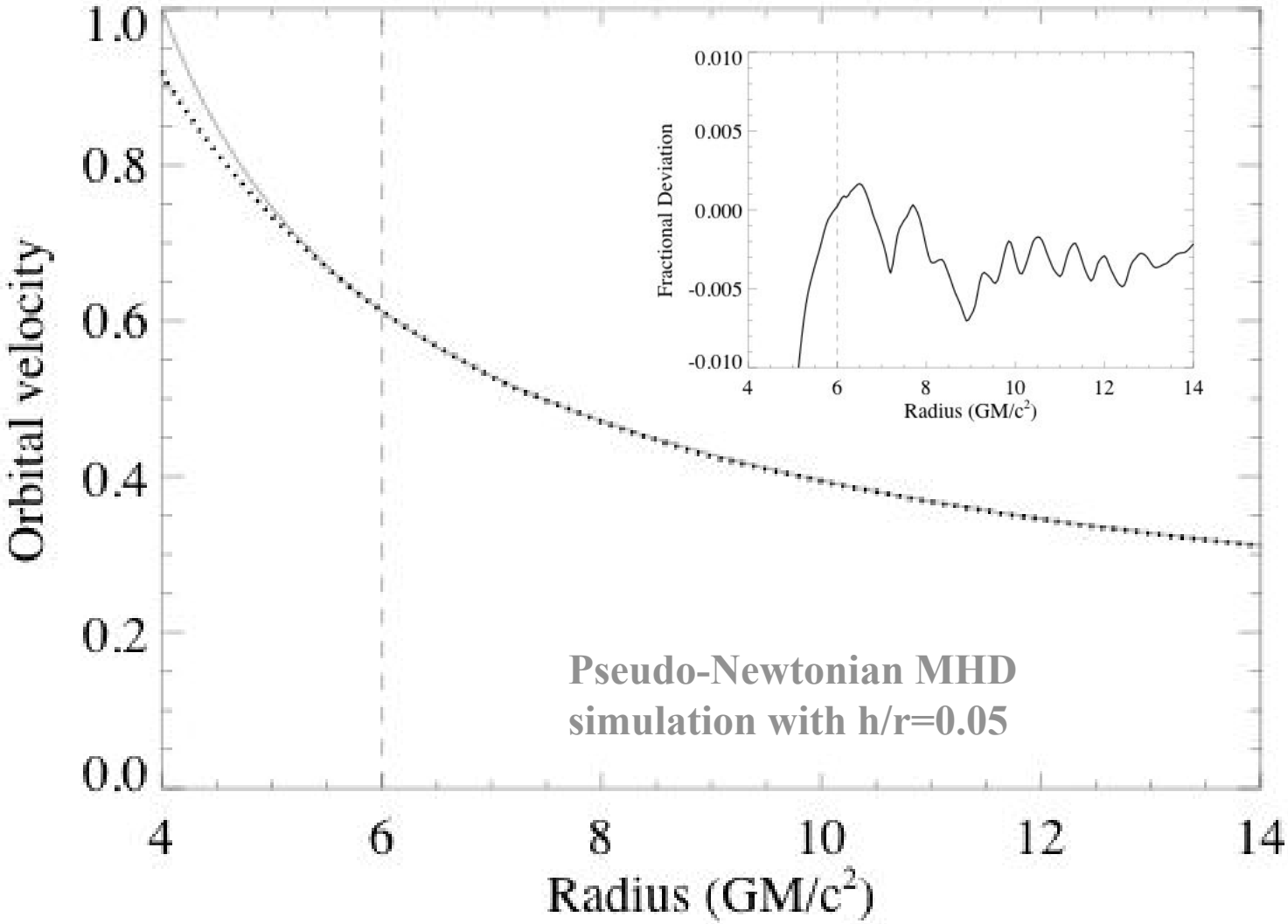
Iron line profiles changes in response to the echo of a rapid X-ray flare across the disk surface

"Relativistic iron line reverberation"



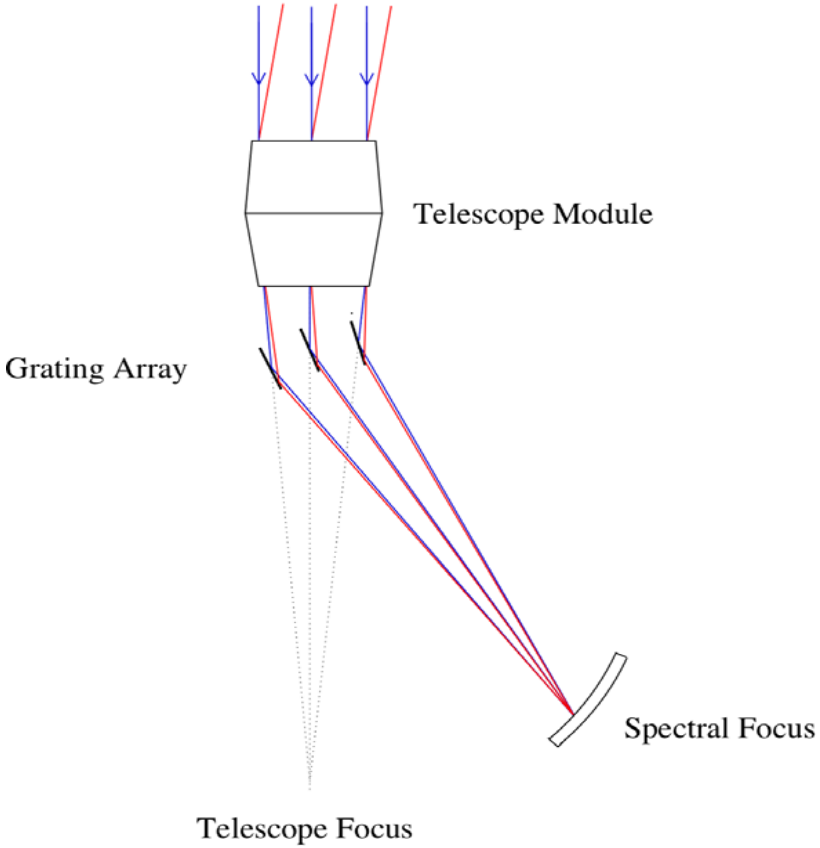
Reynolds et al. (1999)
Young & Reynolds (2000)

Comparison of simulated accretion flow with test-particle orbits…

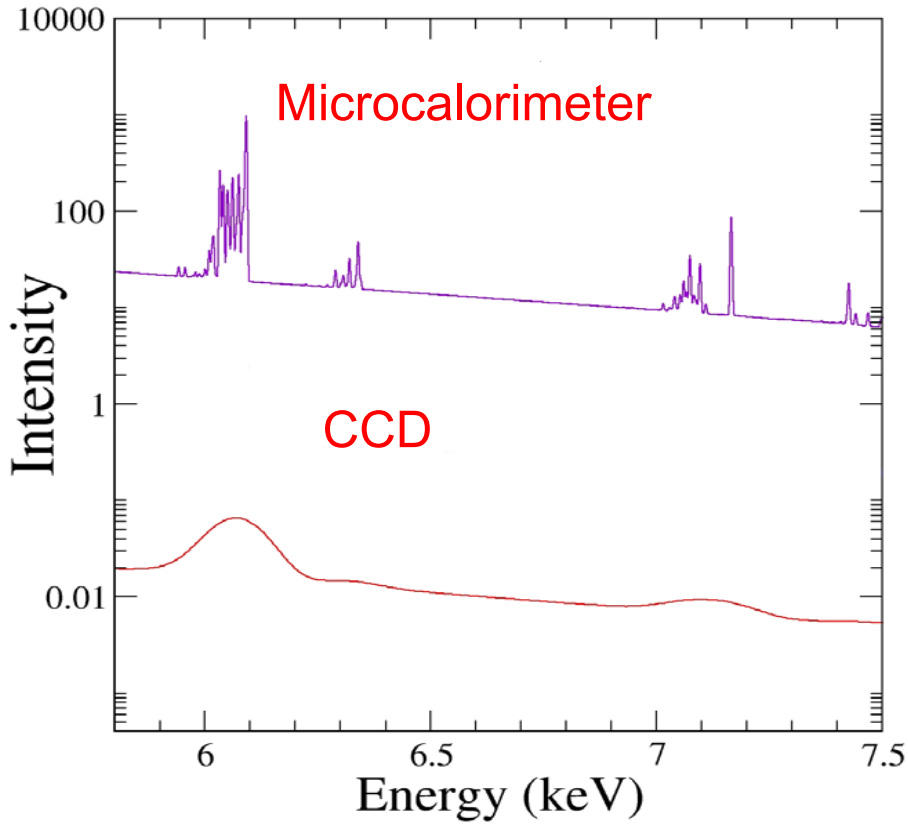


X-ray Spectroscopy Techniques

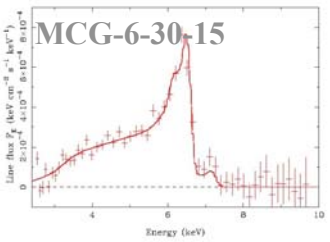
Dispersive spectrometers (e.g., gratings) have very high resolution at low energies, but degrades with increasing energy. Lower Efficiency (up to 20%) and not well-suited for extended sources.

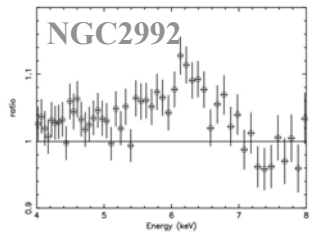


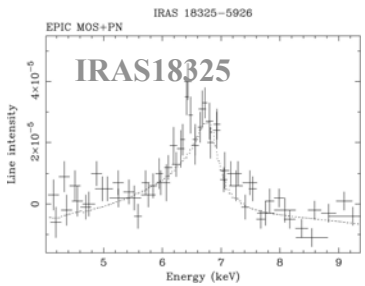
X-ray CCDs are excellent for imaging over large fields of view, but have comparatively low spectral resolution. X-ray micro-calorimeters provide high efficiency, 2-4 eV resolution and imaging of extended sources

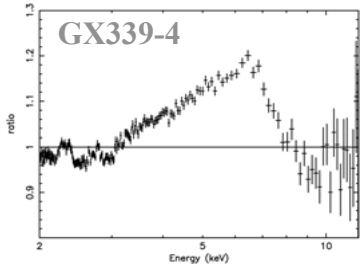


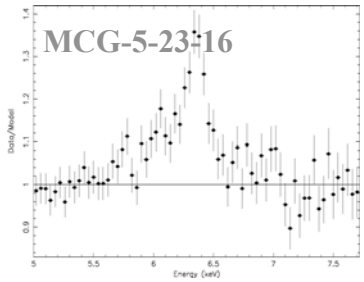
XMM-Newton and Chandra have confirmed relativistic broad iron lines are common

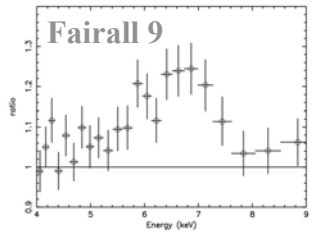


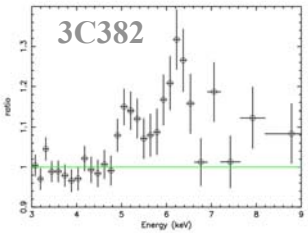


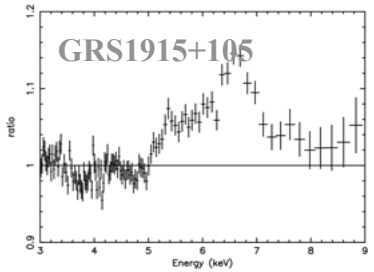


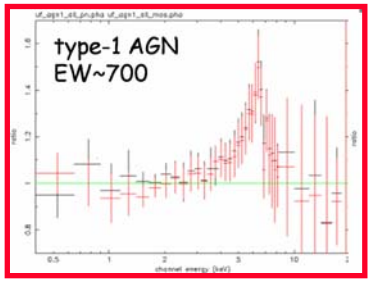


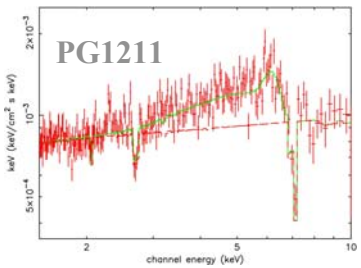


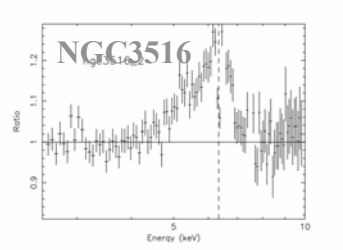


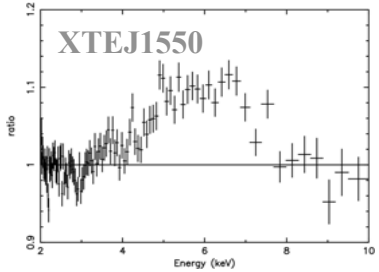


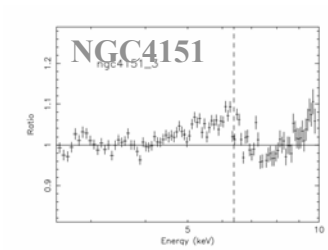


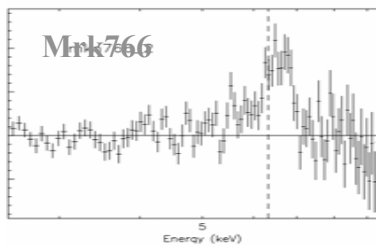




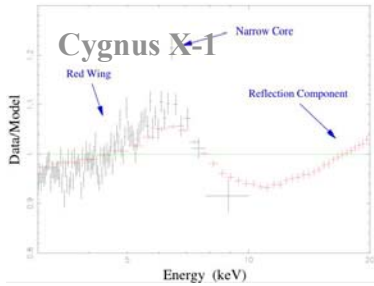


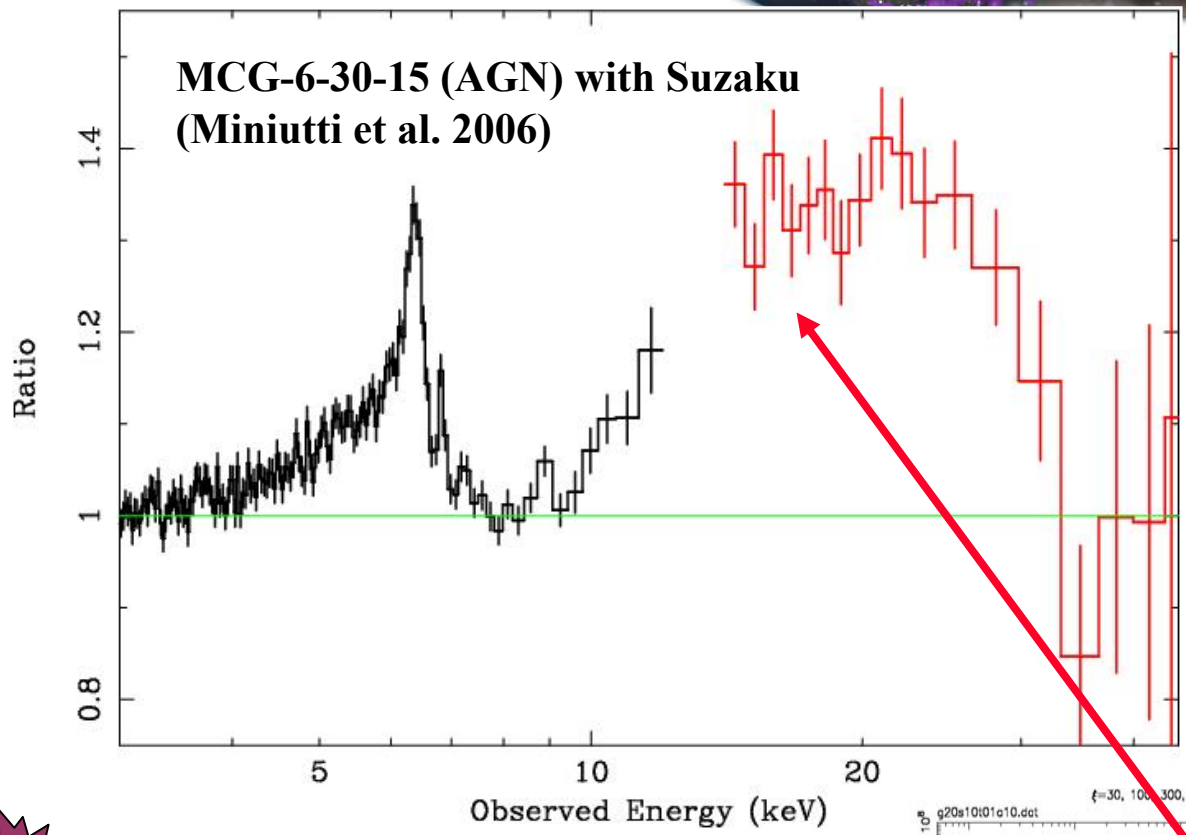


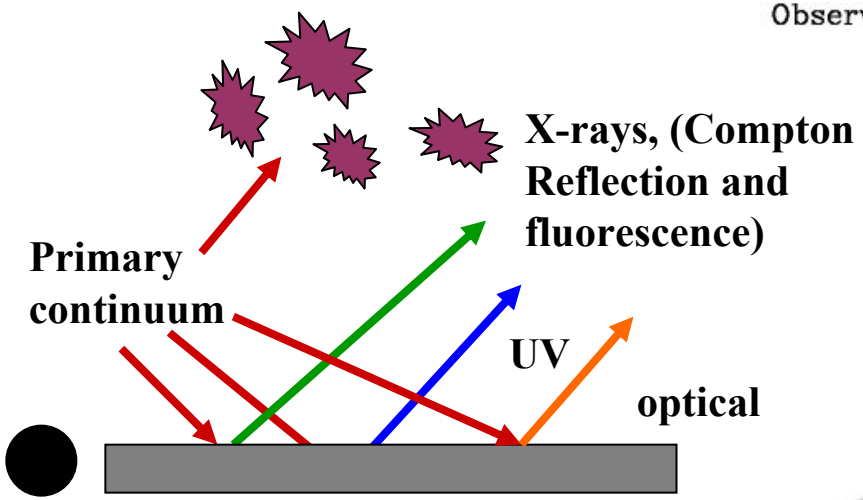


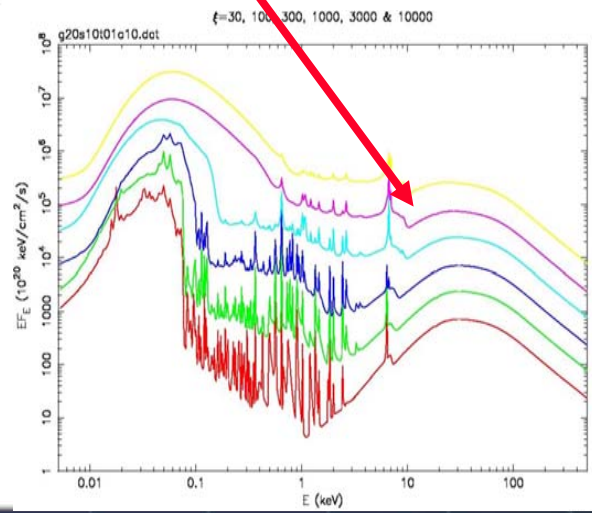


Similar line profiles from stellar-mass and super-massive black hole systems… demonstrates insensitivity of line profile to mass




MCG-6-30-15 (AGN) with Suzaku
(Miniutti et al. 2006)
Ratio
0.8
1
1.2
1.4
5
10
20
Observed Energy (keV)


X-rays, (Compton Reflection and fluorescence)
Primary continuum
UV
optical


g20s10t01q10.dat
0.01
0.1
1
10
100
E (keV)

Scheme for testing GR

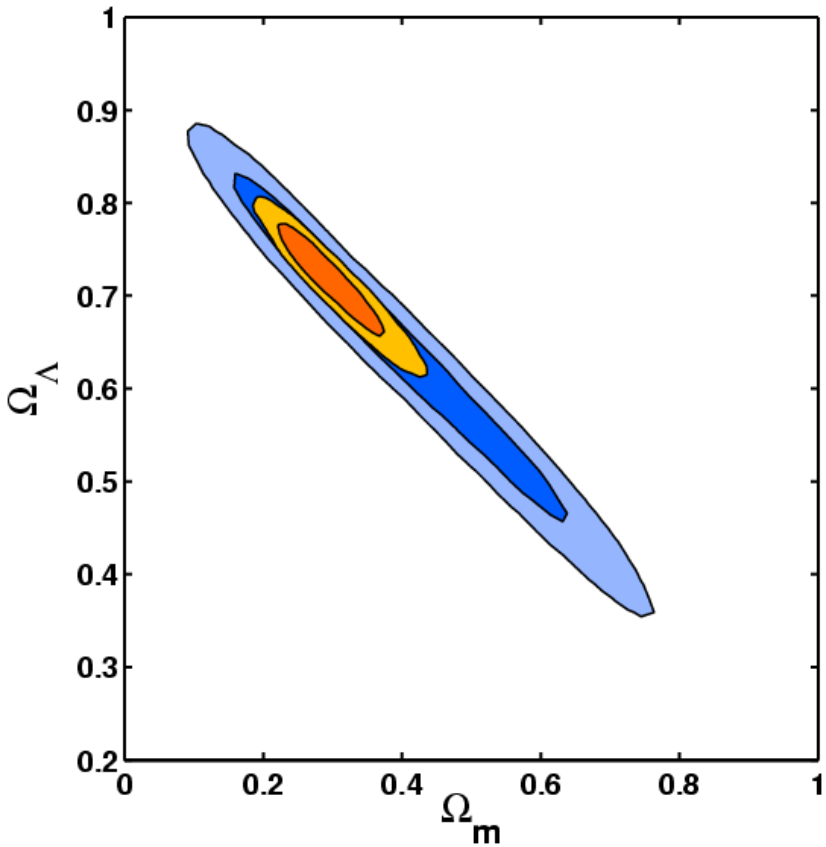
- Spin measurements are fundamentally measuring aspects of the spacetime metric

$$ds^2 = -\left(1 - \frac{2Mr}{\Sigma}\right) dt^2 - \frac{4aMr\sin^2\theta}{\Sigma} dt\, d\phi + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 + \left(r^2 + a^2 + \frac{2a^2 Mr \sin^2\theta}{\Sigma}\right) \sin^2\theta d\phi^2$$

- From iron line tracks, we can measure a spin at a number of different radii (assuming GR)…
  - Powerful consistency check… inferred spin had better be independent of radius
  - Many deviations from GR would produce a radial dependence on the inferred spin

Constraints from combination with other data

The combination of CMB+$f_{gas}(z)$ data breaks key parameter degeneracy



A) $\Omega_{\square}$ vs. Ω_m (non-flat)

68.3 and 95.4% confidence:

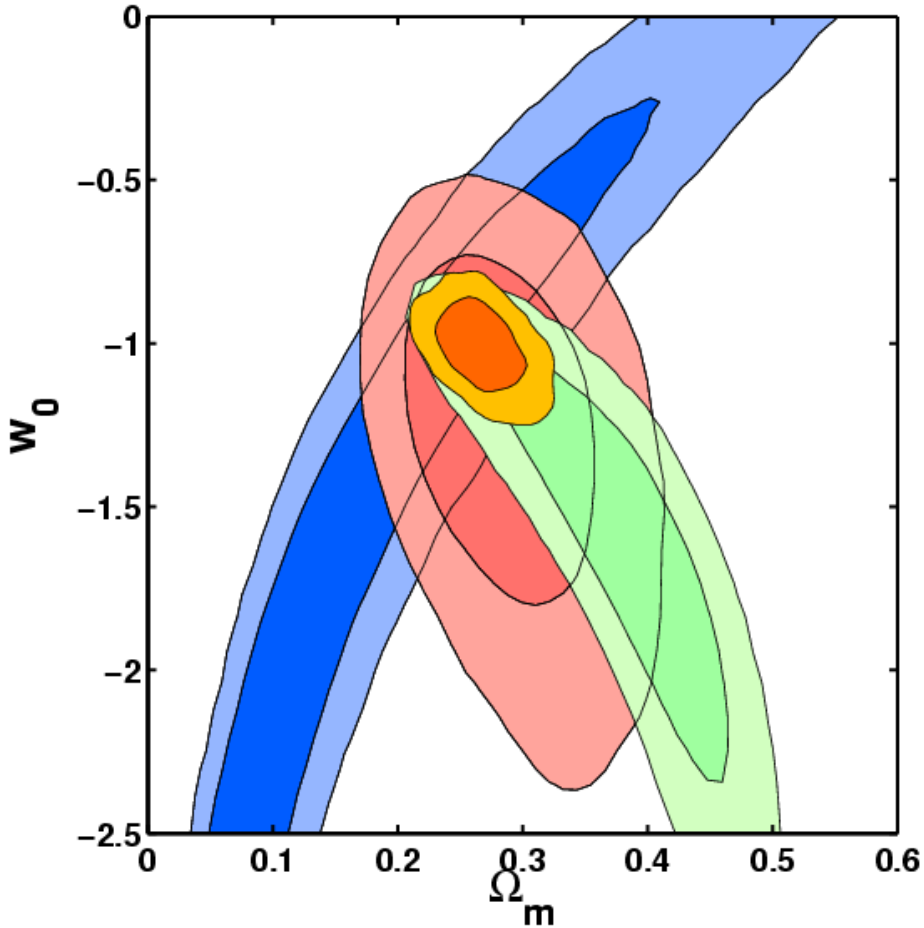
Blue: CMB only (0.4<h<2.0)
Red: $f_{gas}(z)$+CMB data

Marginalized results:

$\Omega_{DE} = 0.73 \pm 0.05$
$\Omega_M = 0.27 \pm 0.05$

Combination with CMB data removes need for $\Omega_b h^2$, h and flatness priors!

Dark energy equation of state



Analysis assumes flat prior

68.3, 95.4% confidence limits for all three parameter pairs consistent with each other

Combined constraints (68%)

$\Omega_m = 0.267 \pm 0.022$
$w_0 = -1.01 \pm 0.09$

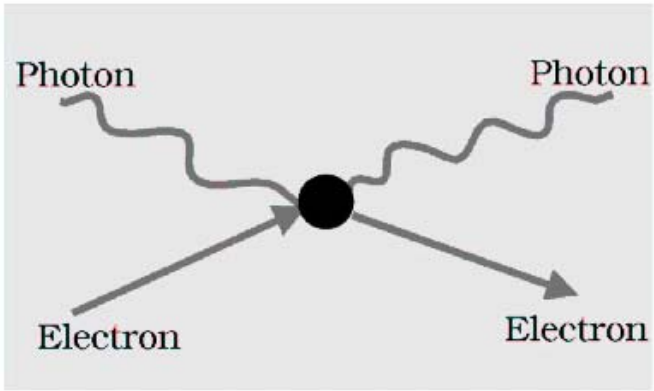
Pink: clusters only
Blue: CMB only
Green: SNIa only
Red/Orange: combined.

From Steve Allen Kipac/SLAC

Absolute distances from combined X-ray + SZ studies

The observed SZ flux (radio/sub-mm data) can be expressed in terms of the Compton y-parameter. For a given reference cosmology, the same parameter can also be predicted from X-ray data.

For correct reference cosmology observed and predicted SZ flux should agree.



$$y_{ref} \propto \int n_e T dl$$

$$y_{ref} = y_{obs} k(z) \left[\frac{d_{ref}}{d_{\mathrm{mod}}} \right]^{1/2}$$

Combined cal.+ systematic uncertainties $k(z)=k_0(1+\alpha_k z)$

To date, experiment only used to constrain H_0 (e.g. Bonamente et al '06)

Intrinsically less powerful than fgas experiment but provides important complementary information and, in combination with fgas data, allows us to minimize the need for priors in the analysis (important)

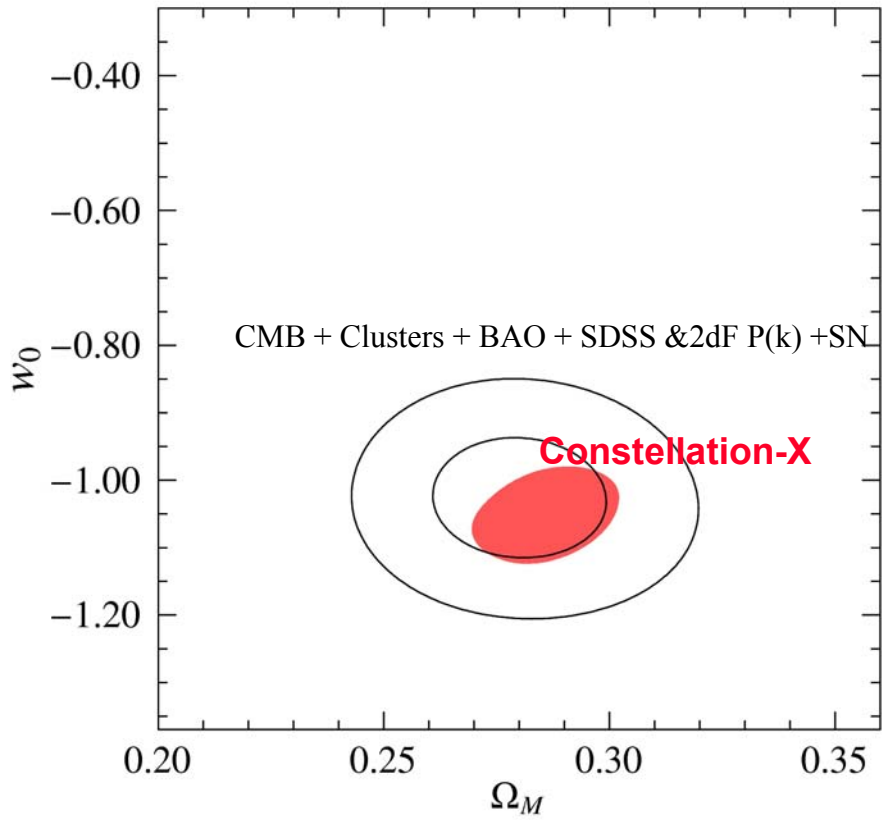
Cosmology using Cluster X-ray Mass Function

There are many surveys planned or ongoing from sub-mm surveys and X-ray surveys that will detect many thousands of massive Galaxy Clusters

Precision measurement of Cosmological parameters comes from the extreme sensitivity of the number of massive objects as a function of cosmic time and cosmological volume element

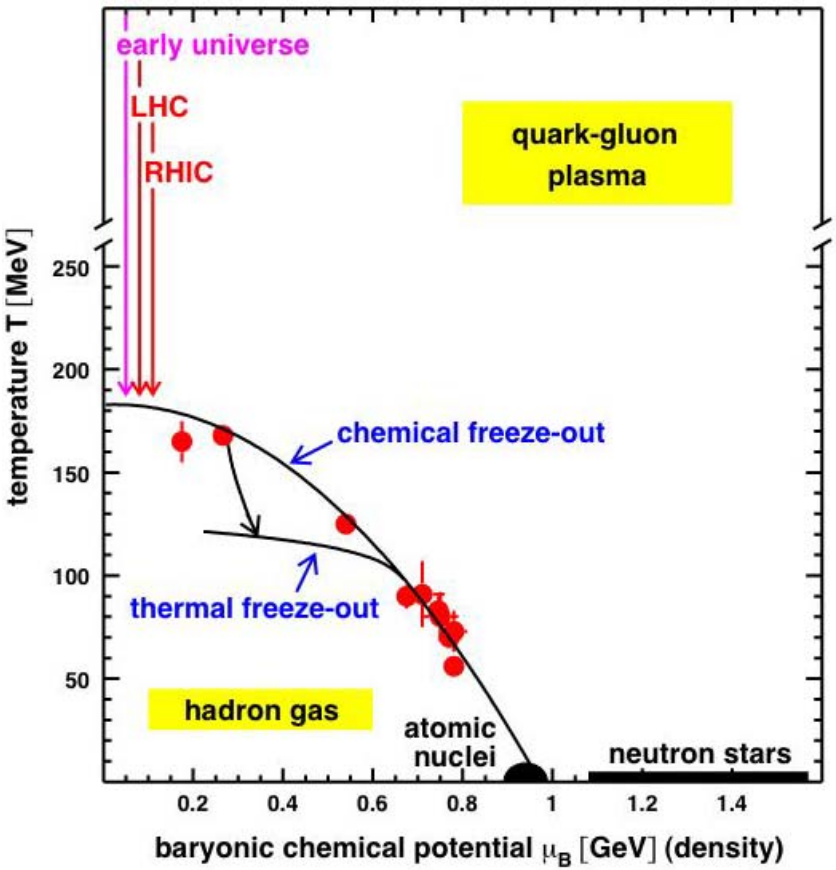
The distinction between models grows dramatically at higher redshift > 0.5 and for the highest cluster mass

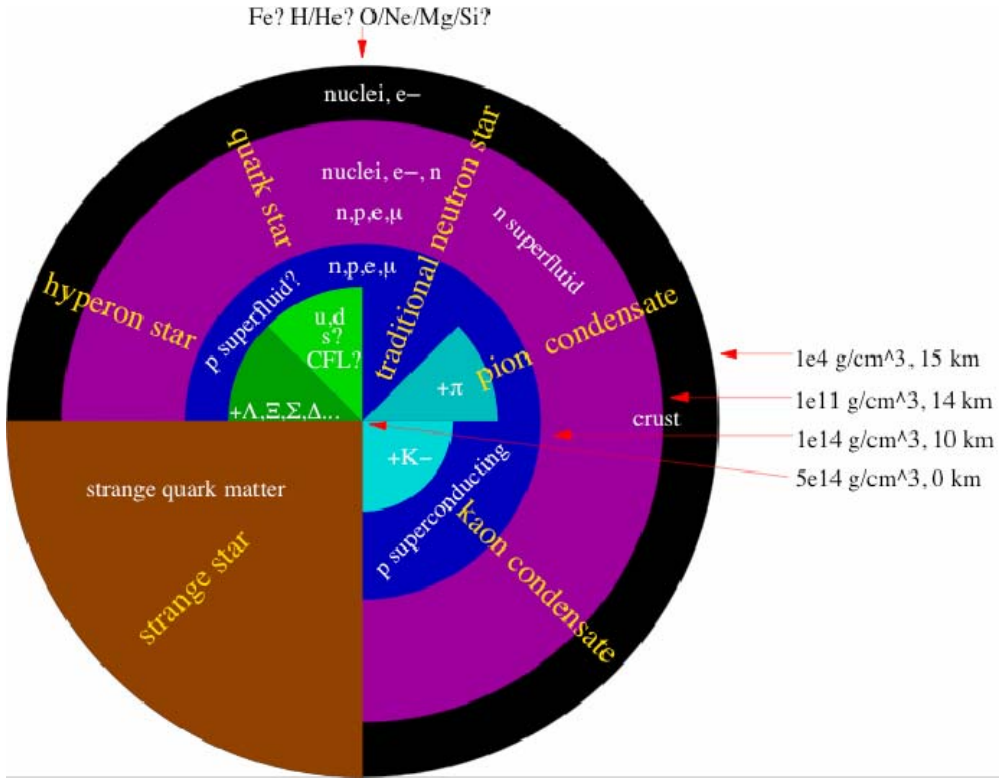
X-ray measurements required to calibrate X-ray temperature to Cluster mass, current missions can only go to a z of 0.8



Constellation-X will accurately calibrate the mass-luminosity-temperature relationship of large samples of high (z > 0.8) redshift clusters to significantly reduce errors and enable precision Dark Energy Measurements

Inside a Neutron Star





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

Constraining Ω_m with f_{gas} measurements

BASIC IDEA (White & Frenk 1991): Galaxy clusters are so large that their matter content should provide a fair sample of matter content of Universe.

For relaxed clusters: X-ray data → precise total mass measurements and (very) precise X-ray gas mass measurements

If we define:

$$f_{gas} = \frac{\text{X-ray gas mass}}{\text{total cluster mass}} \qquad f_{star} = 0.16 h_{70}^{0.5} f_{gas}$$

e.g. Lin & Mohr 04
Fukugita et al '98

Then:

$$f_{baryon} = f_{star} + f_{gas} = f_{gas}(1 + 0.16 h_{70}^{0.5})$$

Since clusters provide ~ fair sample of Universe $f_{baryon} = b\Omega_b/\Omega_m$

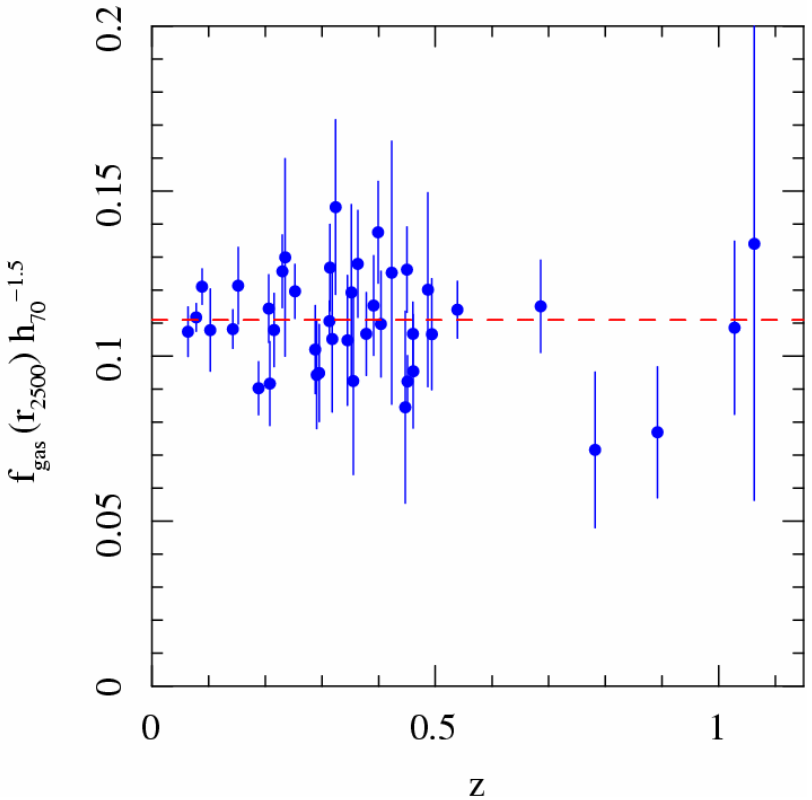
$$\Omega_m = \frac{b\Omega_b}{f_{baryon}} = \frac{b\Omega_b}{f_{gas}(1+0.16 h_{70}^{0.5})}$$

From Steve Allen Kipac/SLAC

Chandra Results on Dark Energy

Model:

$$f_{gas}(z) = \frac{\gamma b(z)\Omega_b}{(1+s(z))\Omega_m}\left[\frac{d_A^{LCDM}(z)}{d_A^{model}(z)}\right]^{1.5}$$



For ΛCDM

Full allowance for systematics + standard priors: ($\Omega_b h^2$=0.0214±0.0020, h=0.72±0.08, b=0.83±0.09)

Best-fit parameters (ΛCDM):

Ω_m=0.28±0.05, Ω_Λ=0.86±0.22

Acceptable □hi^2 even though rms scatter about the best-fit model is only 10% in fgas, corresponding to only 6.6% in distance

Weighted mean scatter only 5% in fgas (3.3% distance). For SNIa, systematic scatter is detected at ~7% level (distance)

No sign as yet of systematic scatter in $f_{gas}(z)$ data. Simulations of Crain et al (2006) suggest scatter should be at few % level in fgas method - this demonstrates power of method to probe Dark Energy to high precision and is pathfinder for its use with Con-X

From Steve Allen Kipac/SLAC