BEYOND EINSTEIN: From the Big Bang to Black Holes

Science Drivers for Con-X

Presented by

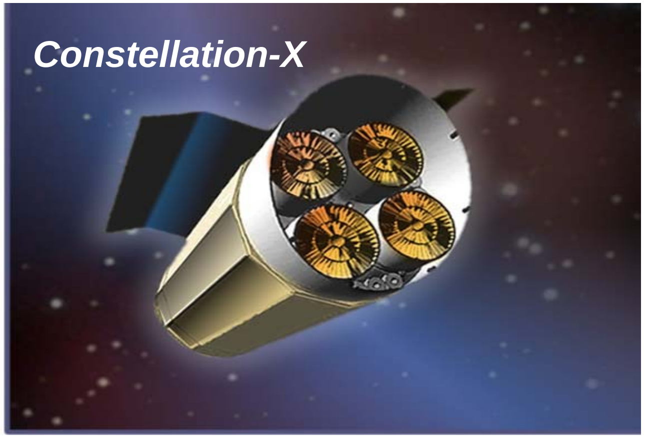
Michael Garcia (SAO Science Lead)

SPIE, May 29 2006

Why Con-X?

CHANDRA has brought X-ray Imaging to <1'' : on par with typical optical/IR imaging

But most X-ray SPECTRA are still 'colors' – typically F_X, N_H, kt, ala U/B/V – Except for the brightest sources, or VERY long exposures



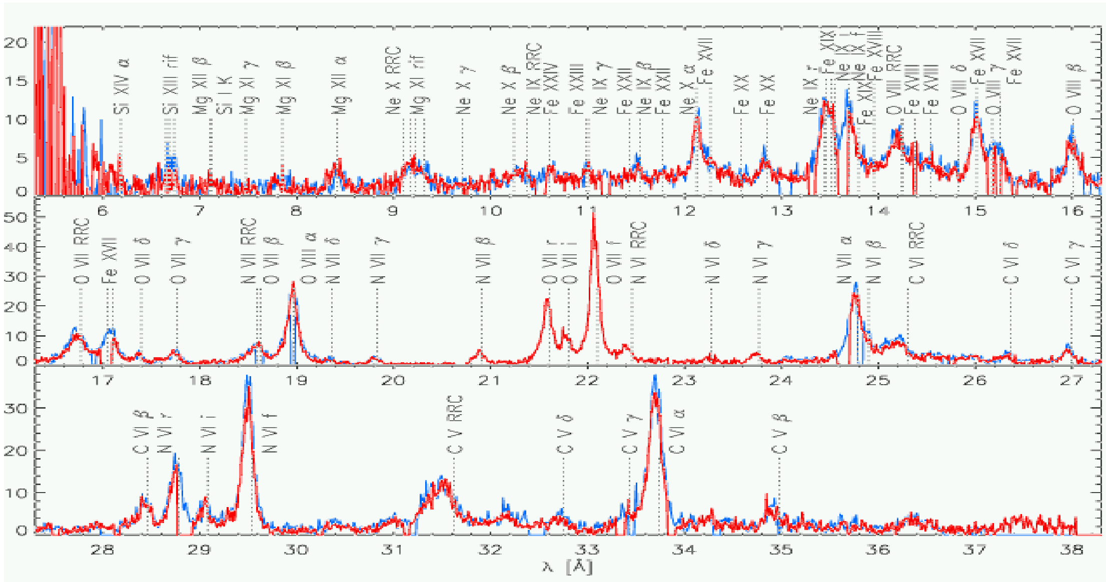
Constellation-X will change this – Routine spectra with 300<R<2000 for tens of thousands of sources – RASS/BSC $F_X \sim 10^{-15}$ ergs/cm^2/s (0.25-2keV)

100x Throughput for R>300, AREA alone 40x Chandra, 20x XMM at FeK (strongest E-line)

The PHYSICS is in the Spectra!

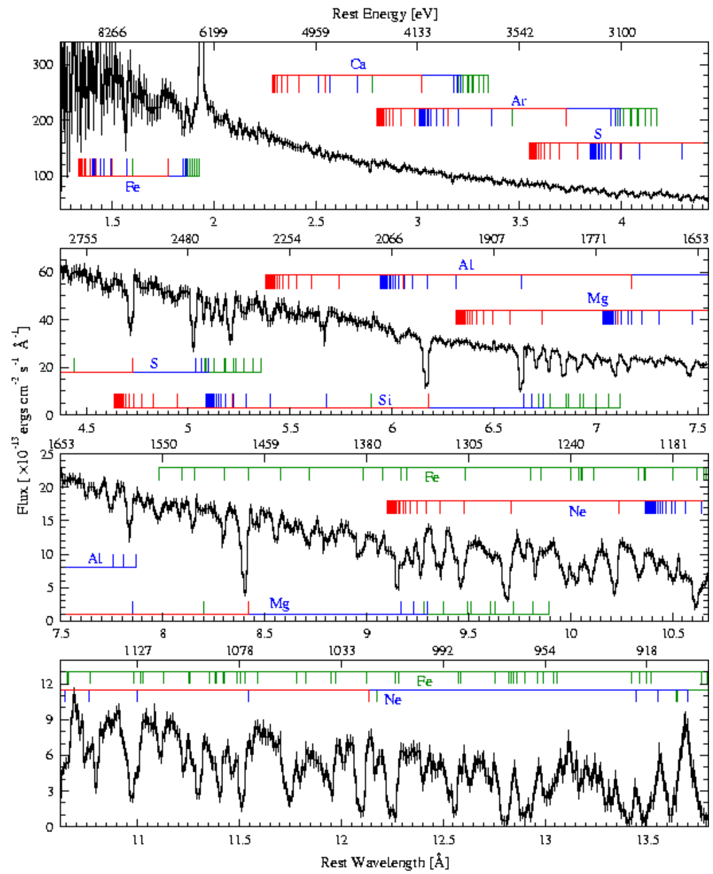
A Glimpse of the future

Heroic Grating observations from Chandra and XMM-Newton are providing the first glimpse of the power of X-ray Spectroscopy



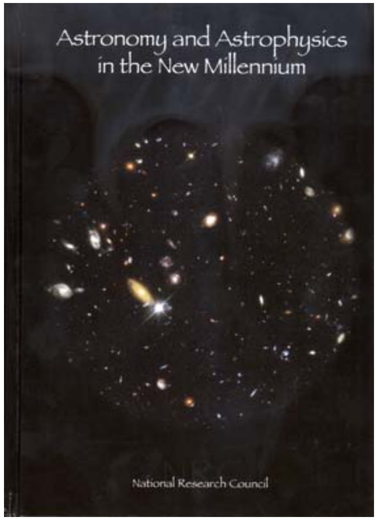
XMM RGS Spectrum of NGC1068 Kinkhabwala et al 2002

Constellation-X will be able to observe sources 100 times fainter to exploit these diagnostics on typical X-ray sources.

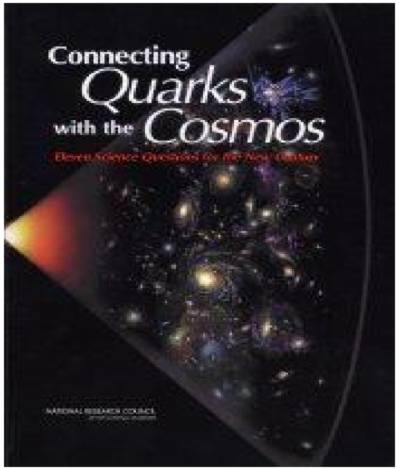


Chandra HETGS Spectrum of NGC3783 from Kaspi et al (2002)

Science Priority (reviews by National Academy)



The Astronomy and Astrophysics in the New Millennium (2000) decadal survey ranked Constellation-X priority next after JWST among large new space observatories



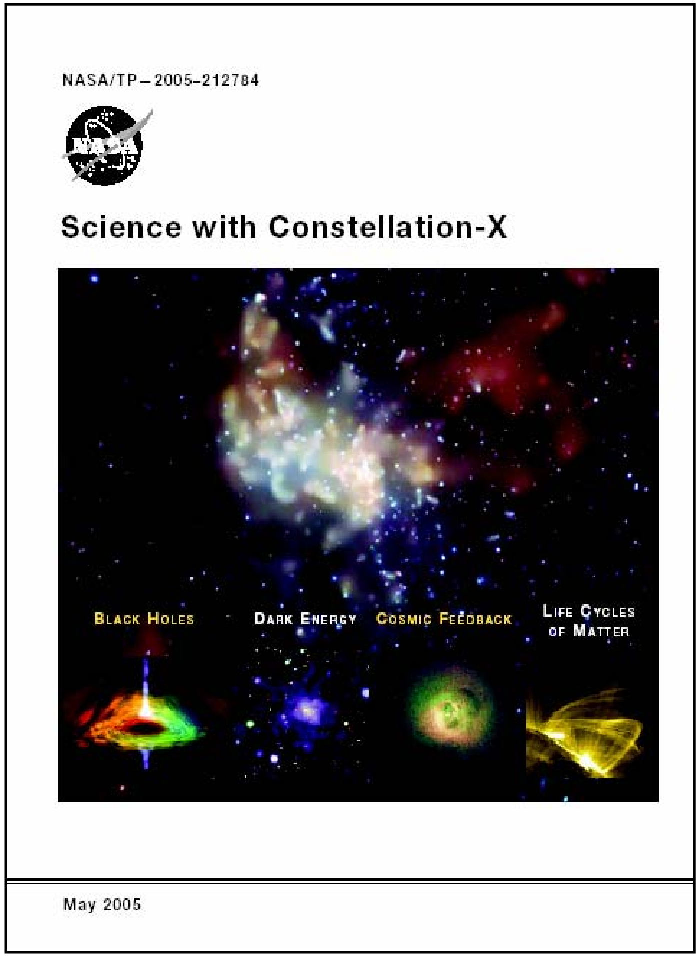
The National Academy Committee chaired by Michael Turner (2003) prepared a science assessment and strategy for research at the intersection of Physics and Astronomy strongly endorsed the Constellation-X mission

The National Academy Mid-Course Review (2005) Endorsed Decadal plan

The Con-X Science Case Review (internal)

- October 2004 through January 2005,
  >60 scientists met in small groups and produced
  13 white papers (100 pages of text)
- Goal: Reassess the Constellation-X science case given progress by Chandra and XMM-Newton over past 5 years
  - Team leaders in this effort:
    - David Alexander (IoA)
    - Jean Cottam (GSFC)
    - Jeremy Drake (CfA)
    - Jack Hughes (Rutgers)
    - Casey Lisse (U Md)
    - Jon Miller (U Mich)
    - Michael Muno (UCLA)
    - Richard Mushotzky (GSFC)
    - Frits Paerels (Columbia)
    - Chris Reynolds (U Md)
    - Gordon Richards (JHU)
    - Michael Shull (Colorado)
    - Randall Smith (JHU/GSFC)
    - David Strickland (JHU)
    - Tod Strohmayer (GSFC)

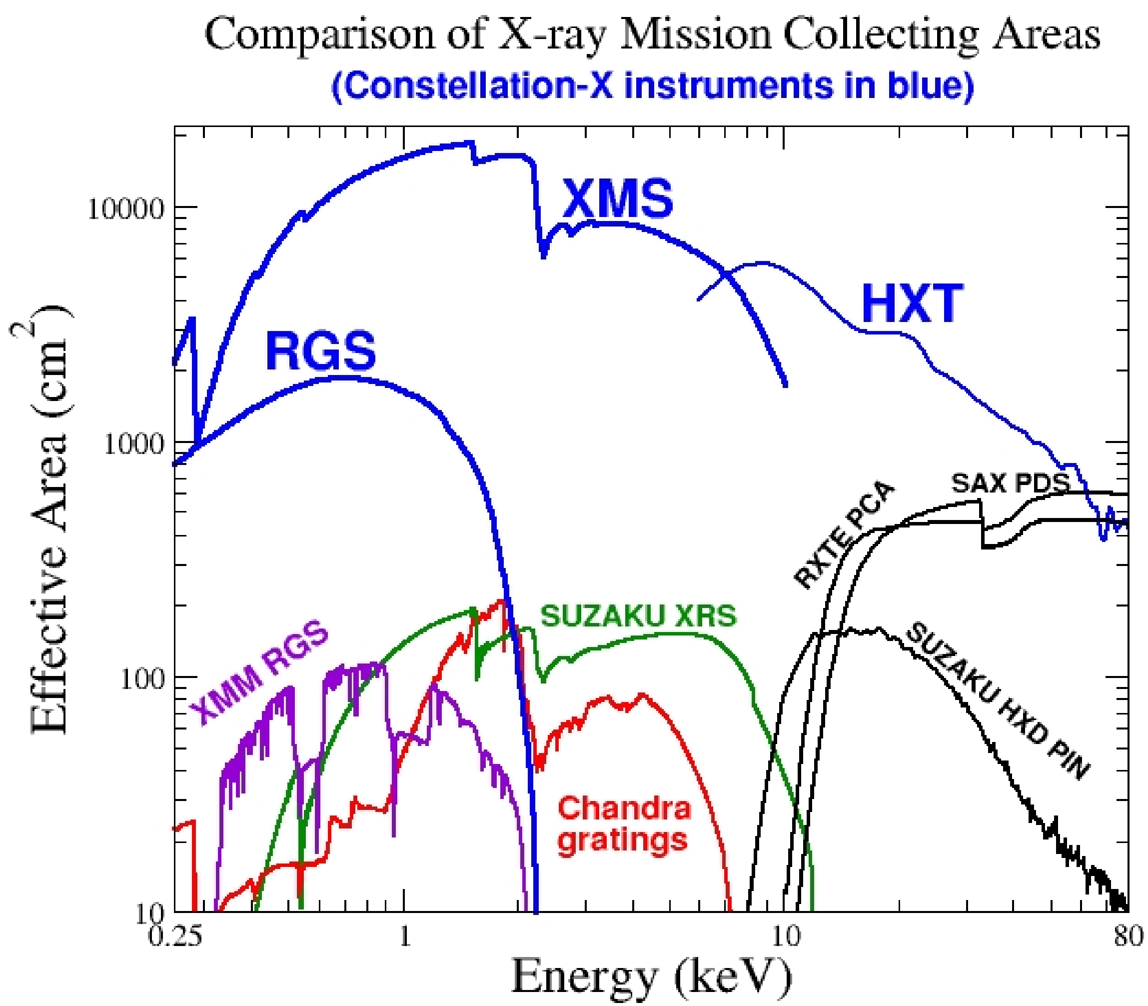
Result of the Process:
“Science with Constellation-X” booklet
(May 2005)


NASA/TP–2005–212784

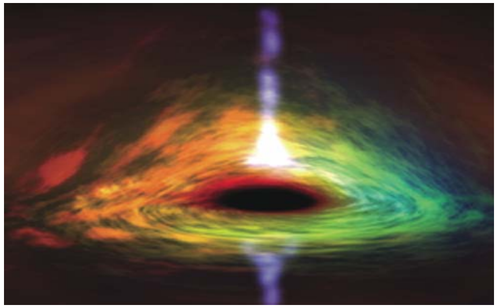
Science with Constellation-X

May 2005

Comparison of collecting area



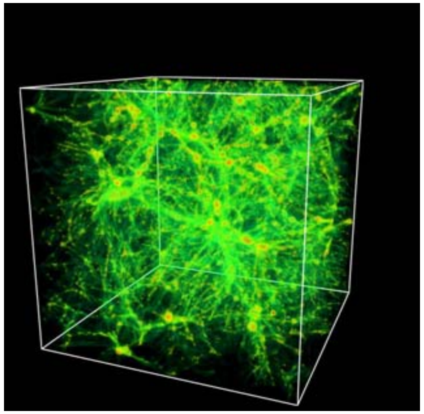
Constellation-X Science Objectives



Black Holes

Observe hot matter spiraling into **Black Holes** to test the effects of General Relativity

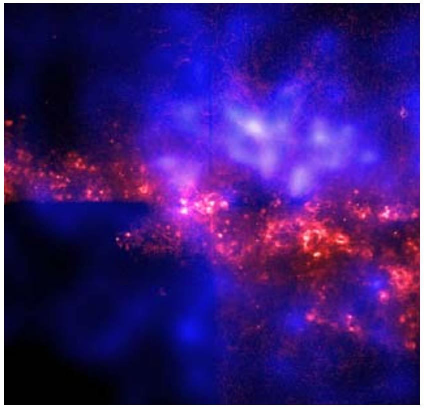
Trace their **evolution with cosmic time**, their contribution to the energy output of the Universe and their effect on galaxy formation



Dark Matter and Dark Energy

Use clusters of galaxies to trace the locations of **Dark Matter** and as independent probes to constrain the amount and evolution of **Dark Energy**

Search for the **missing baryonic matter** in the Cosmic Web



Cycles of Matter and Energy

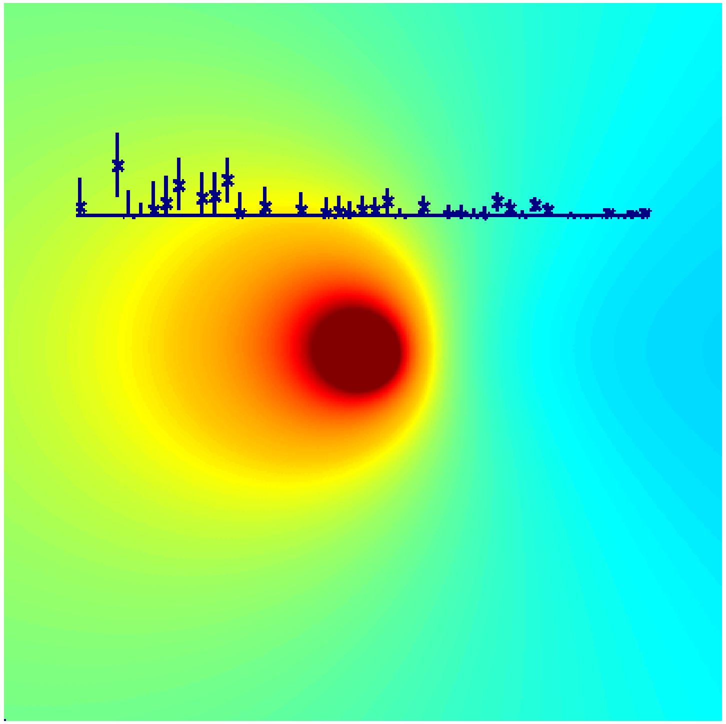
Study dynamics of **Cosmic Feedback**

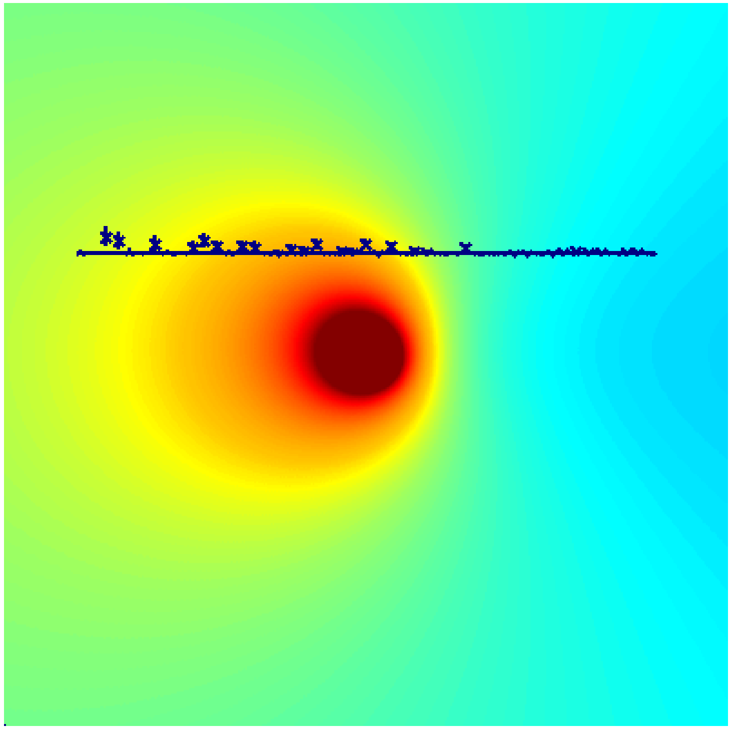
Creation of the elements in **supernovae**, The equation of state of **neutron stars, Stellar activity, proto-planetary systems** and X-rays from **solar system objects**

DRIVERS are a sub-set that define telescope requirements

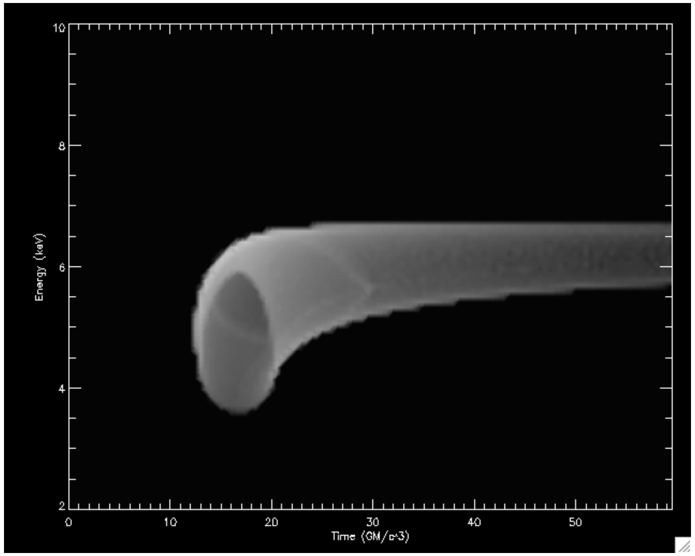
Iron Line Reverberation Mapping (handful of AGN)

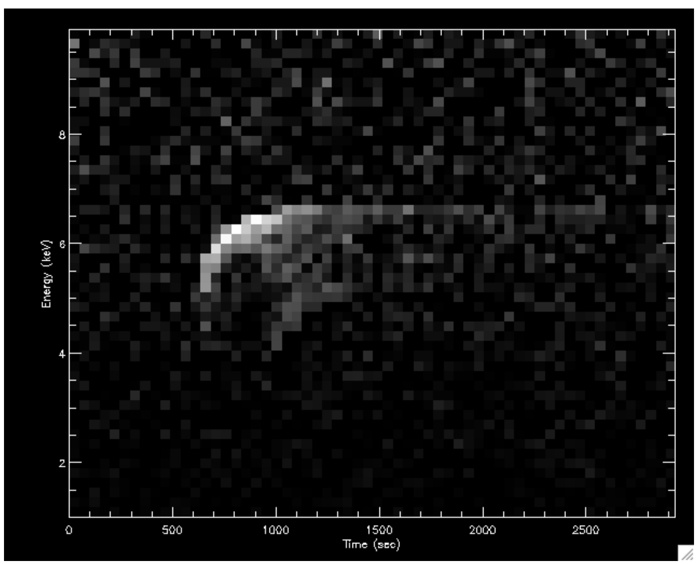
Courtesy Chris Reynolds (UMD)



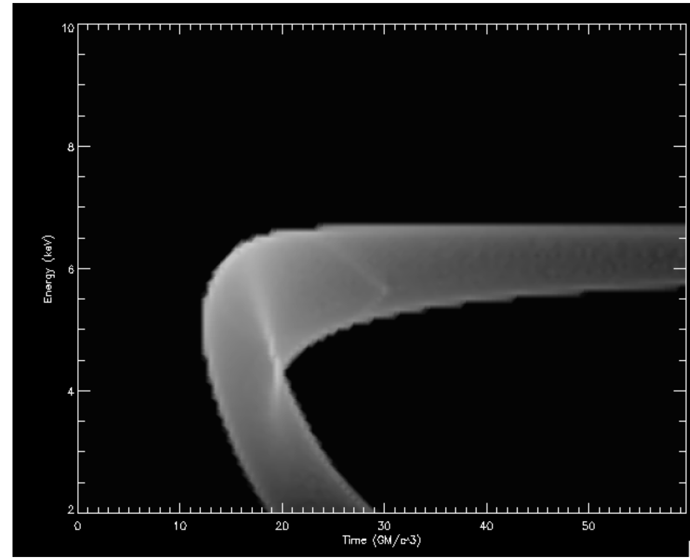


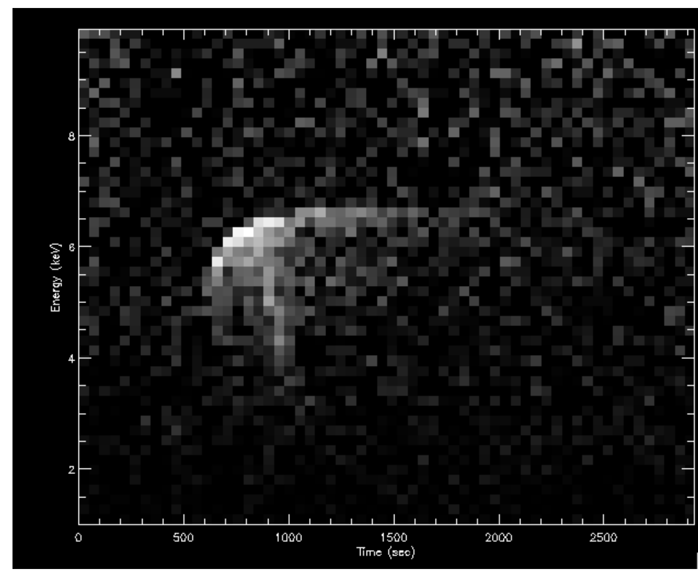
Strong Gravity tests. ‘Snapshot’ of Geometry - Derive: Mass, Spin, Geometry – F_X ~$5x10^{-11}$ ergs/cm2/s(2-10)





a=0, M=10^7, A=0.6m^2

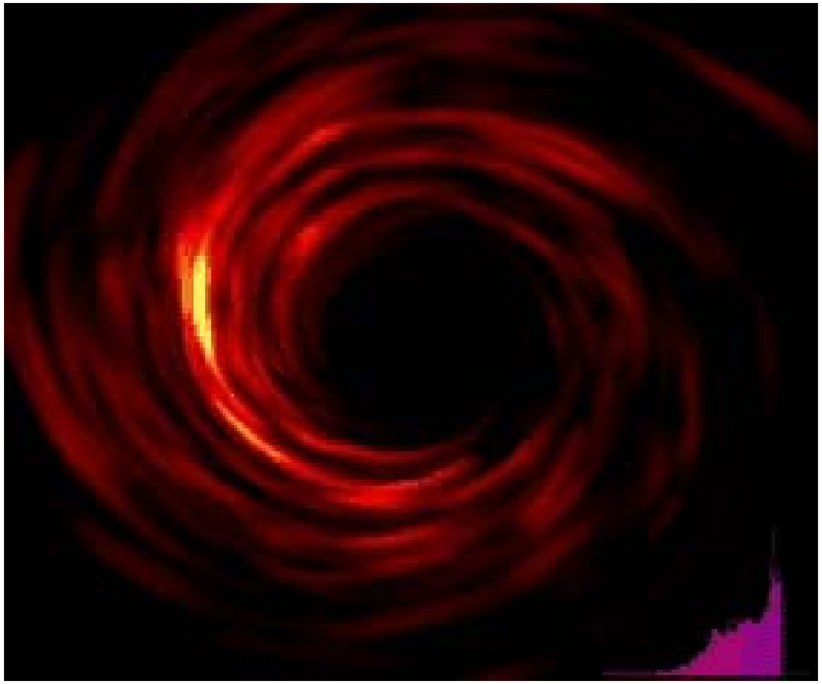


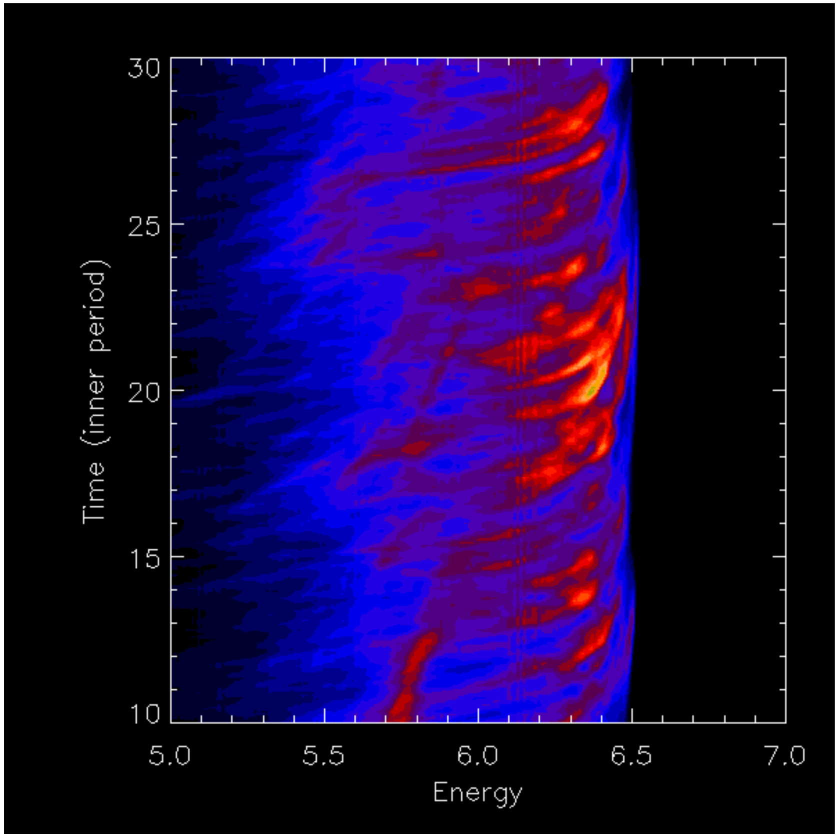


a=1, M=10^7, A=0.6m^2

Iron Line Doppler Tomography (100s+ AGN)

- Orbital Time scale 10x Reverb Mapping: $F_X \sim 5\mathrm{x}10^{-12}$ ergs/cm2/s(2-10)
- Follow dynamics of individual blobs in disk
- Quantitative test of orbital dynamics in strong gravity regime





Armitage & Reynolds (2003)

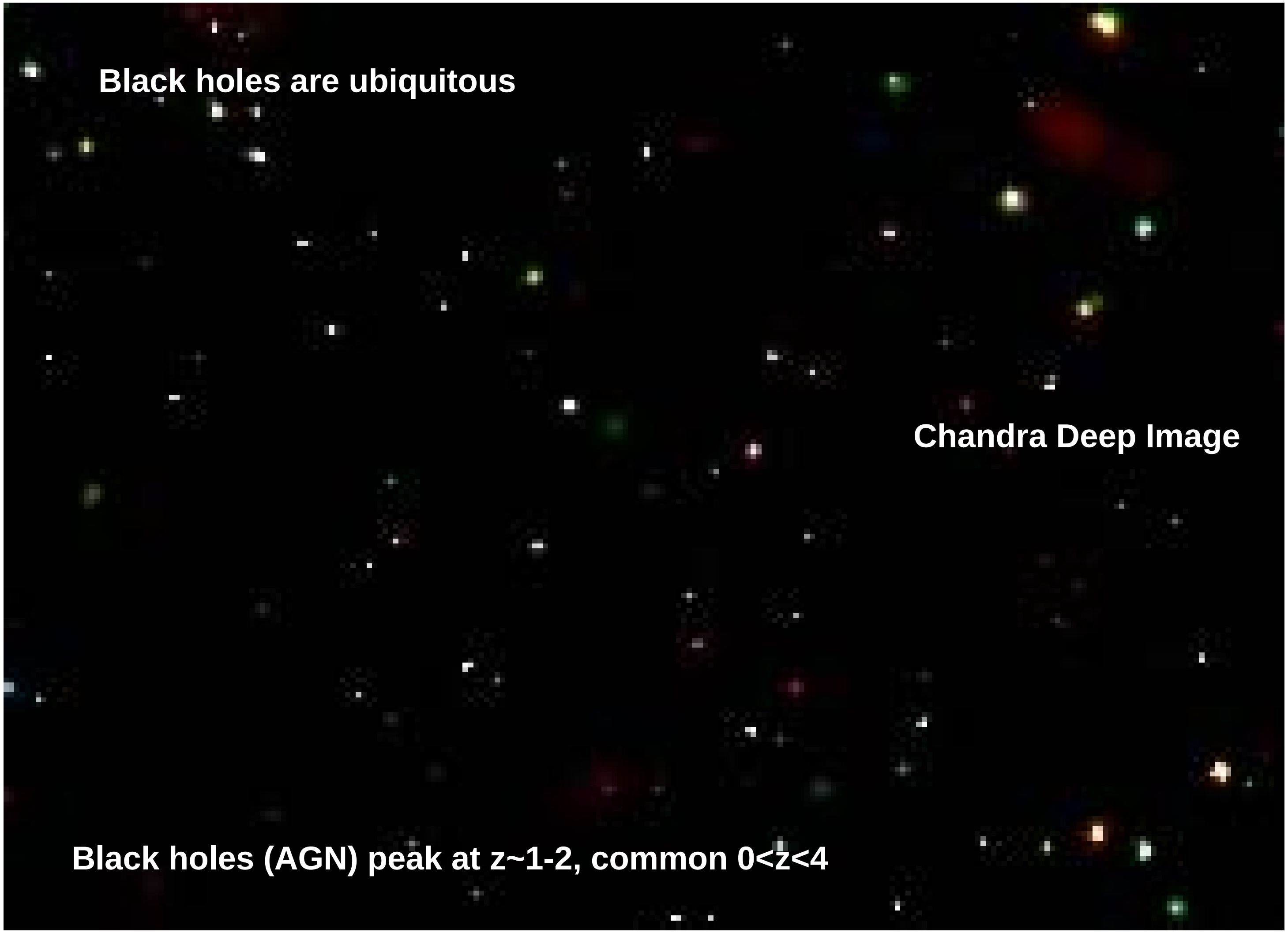
Strong Gravity Time domain largely untested – most test utilize FFTs, time averaged line profiles.

Fe Line GR tests - Science Requirements:

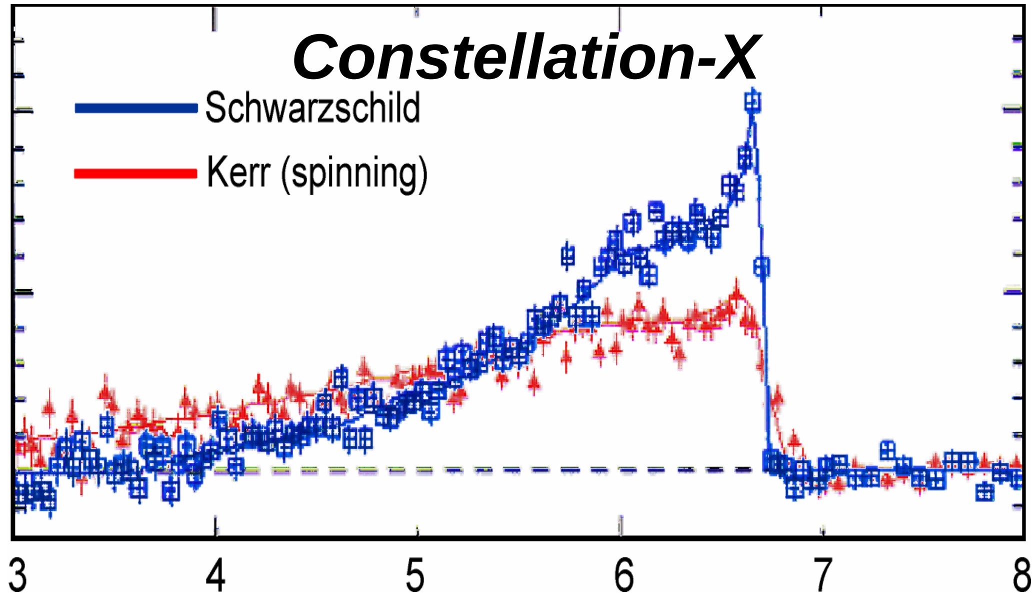
- Reverberation Mapping
- Band: 0.25 keV - 40 keV
  - 6.4/6.7 critical, but redshifted Fe line, soft absorption, reflection continuum
- Sensitivity, Area: $0.6m^2$ @ 6keV
  - $5x10^{-11}$ ergs/cm^2/s, handful of sources, 3σ in 200s FeK-line
- Spectral Resolution: 1500 @ 6keV
  - Fe Kα1 Δ~13eV, Kα2 Δ~3eV
  - 1500 = 4eV
  - Chandra, XMM-Newton show complex absorption (emission?)
- Angular Resolution: N/A
  - Degree sufficient
- FOV: N/A
- Other: N/A

- Doppler Tomography
- Band: 0.25 keV - 40 keV
  - Redshifted Fe line, complex absorption, reflection continuum
- Sensitivity, Area: $0.6m^2$ @ 6 keV
  - $5x10^{-12}$ ergs/cm^2/s, 100s of sources, 2000s orbital timescale
- Spectral Resolution: 1500 @ 6keV
  - Fe Kα1 Δ~13eV, Kα2 Δ~3eV
  - 1500 = 4eV
  - Chandra, XMM-Newton show complex absorption (emission?)
- Angular Resolution: N/A
  - Degree sufficient
- FOV: N/A
- Other: N/A

Black Hole Evolution with Cosmic Time:



Black Holes Evolution with Cosmic Time



Energy (keV)

Constellation-X will probe close to the event horizon with 100 times better sensitivity to:

- ✓ Observe iron profile from the vicinity of the event horizon where strong gravity effects of General Relativity can be observed
- ✓ Use Line profile to determine black hole spin (*a* to 10%)
- ✓ Investigate evolution of black hole properties (spin and mass) over a wide range of luminosity (F_X 10^{-11} – 10^{-14})and redshift (0<z<4)

Black Hole Evolution: Science Requirements

- Band: 0.25 keV - 40 keV
  - 6.4/6.7 critical, but redshifted Fe line, soft absorption, reflection continuum
- Sensitivity, Area: 1.5m^2 @ 1.25keV, 0.6m^2 @ 6keV
  - 10^{-11} - 10^{-14} ergs/cm^2/s, >5000 cts in 100ks, *a*~10%
- Spectral Resolution: 500 @ 2keV, 1500 @ 6keV, 10 @ 40keV
  - Fe Kα1 Δ~13eV, Kα2 Δ~3eV, 1500 = 4eV @ 6keV
  - @ z=2.5, FeK=2keV, Fe Kα1 Δ~4eV, 500=4eV @ 2keV
  - Reflection continuum peak ~ 30 keV, R=10 sufficient
- Angular Resolution: 15''
  - Arc-min Avoids confusion, ~0.05 AGN/sq-arc-min @ 10^{-14}
  - But must subtract BG (FOV and PSF coupled)
- FOV: 2.5'
  - FOV > 3 x 90% ECF to allow good BG subtraction
- Other: N/A

Dark Matter and Dark Energy

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

1. In combination with microwave background measurements the Sunyaev-Zeldovich technique to measure absolute distances

2. Using the gas mass fraction in clusters as a "standard candle"

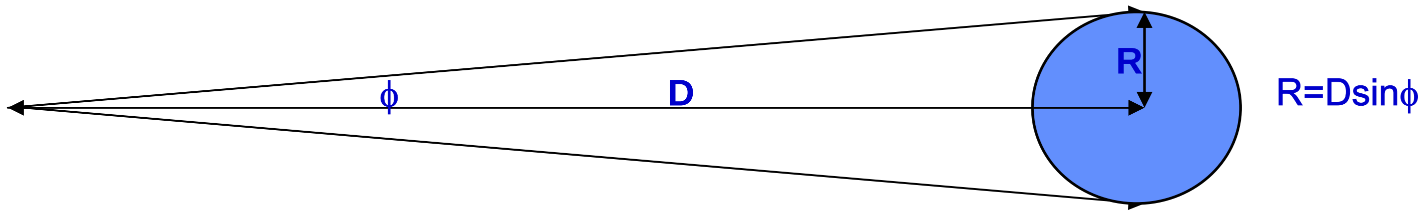
3. Measuring the evolution of the cluster parameters and mass function with redshift (=growth of structure)

1 and 2 are 'distance' techniques (ala SNIa), 3 is very different

Cosmology (=Distances) with fgas

Assume: Virial Theorem (must select 'relaxed' clusters)
Radiating (=baryonic)/Dark Matter constant and representative
Then: Can measure relative D (~DE) and knowing fgas, absolute D (~DM)
because x-ray measurements of fgas ~ $D^{3/2}$

Measure T, F_X, ϕ
Compute R, M_T, M_B



$GM_T/R = ½\, kT$ — virial theorem – includes Dark Matter — $M_T = 1/2\, kTR/G \sim D$

$F_X = \text{const}\, T^{1/2}\, n_e^2\, R$ — Bremsstrahlung Equation

$n_e\ (\sim n_B) = Fx/(\text{const}\, T^{1/2}\, D\sin\phi)]^{1/2}$ — non-X-ray baryons fixed $\sim 1/6 n_B$ — $M_B = 4/3 \pi n_e R^3 \sim D^{-1/2} D^3$

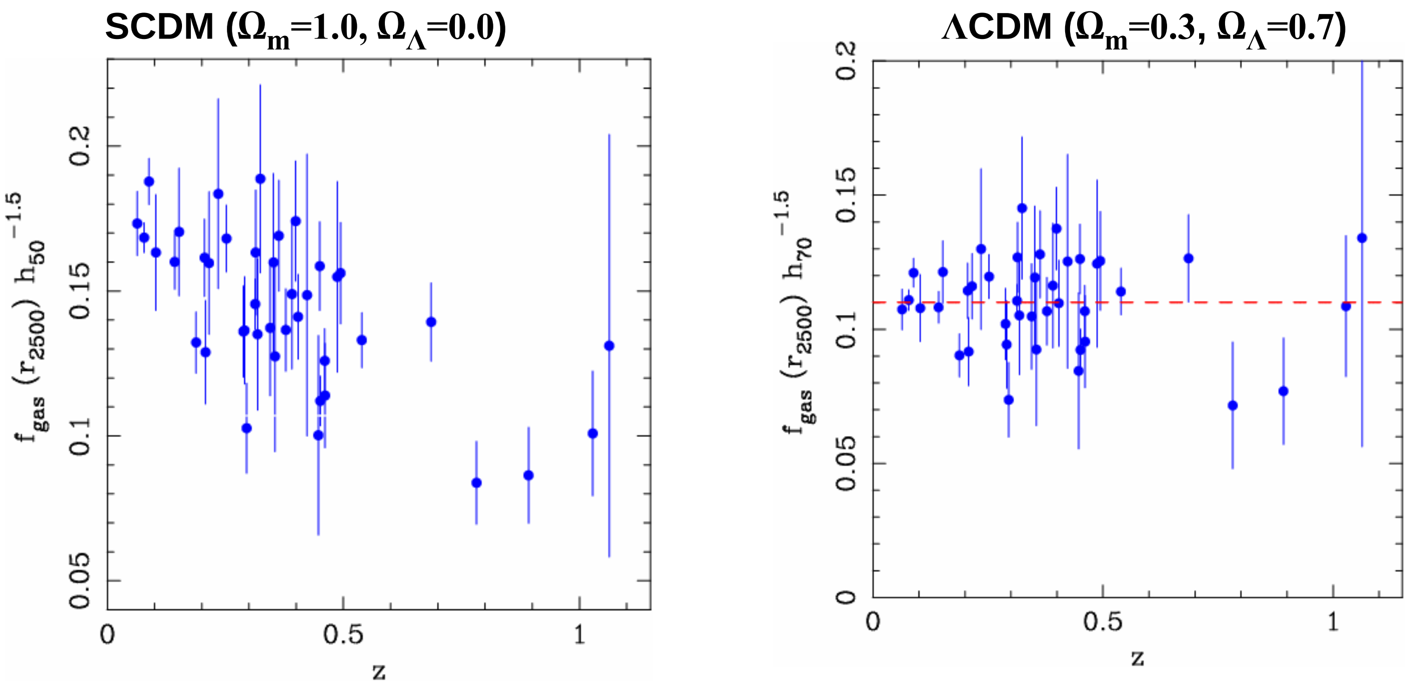
$n_e \sim D^{-1/2}$ — $M_B \sim D^{5/2}$

$f(gas) \sim M_B/M_T \sim D^{3/2}$ — measure fgas vs z(d) — IF fgas not constant – z(d) diff
diff z(d) = Dark Energy

Abs[fgas] = Dark Matter

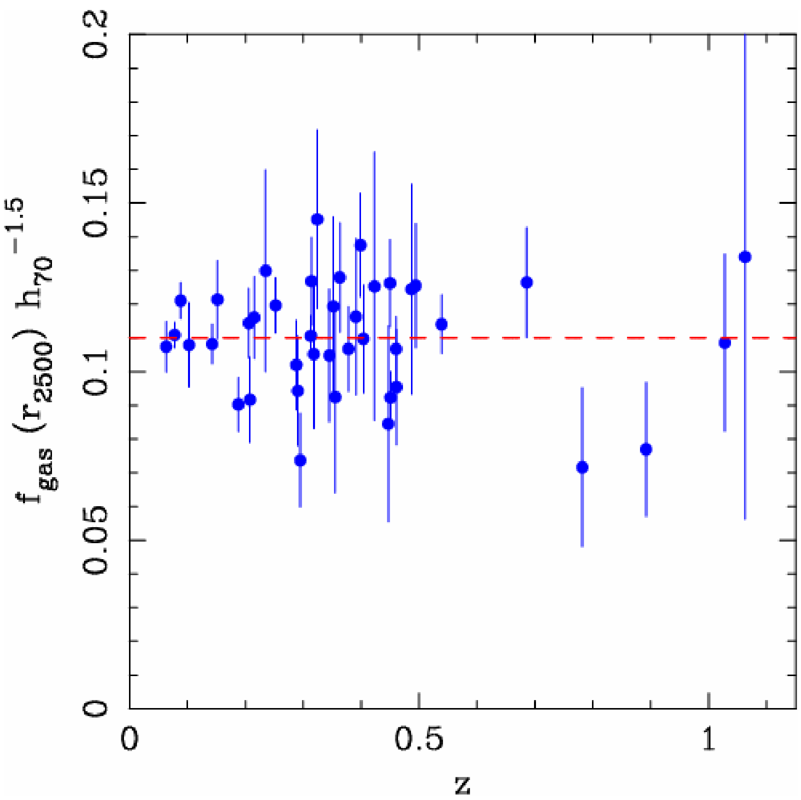
Courtesy Steve Allen (2006, Kavli/SLAC)

We expect true *f*gas(z) values to be approximately constant with redshift. However, measured *f*gas(z) values depend upon assumed distances to clusters ***fgas*** $\propto$ ***d*** $^{1.5}$. This introduces apparent systematic variations in *f*gas(z) depending on the differences between the reference cosmology and the true cosmology.



Inspection clearly favours ΛCDM over SCDM cosmology.

Courtesy Steve Allen (2006, Kavli/SLAC)



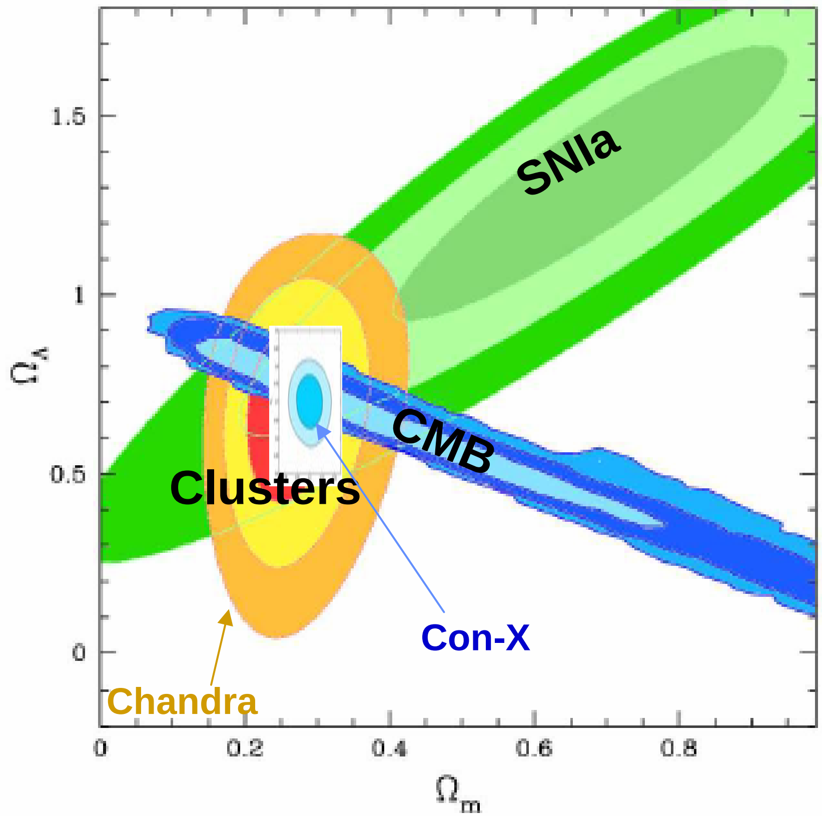
The scatter in the current Chandra fgas data for 41 clusters is LOW.

The weighted mean scatter about the best-fitting model is only 12%, which translates to only 8% in distance (comparable to SNIa).

No sign as yet of systematic scatter with acceptable χ^2. Method offers the prospect to probe cosmic acceleration with high precision (Con-X/XEUS)

Cosmological Parameters with Constellation-X

(Allen et al. 2004)

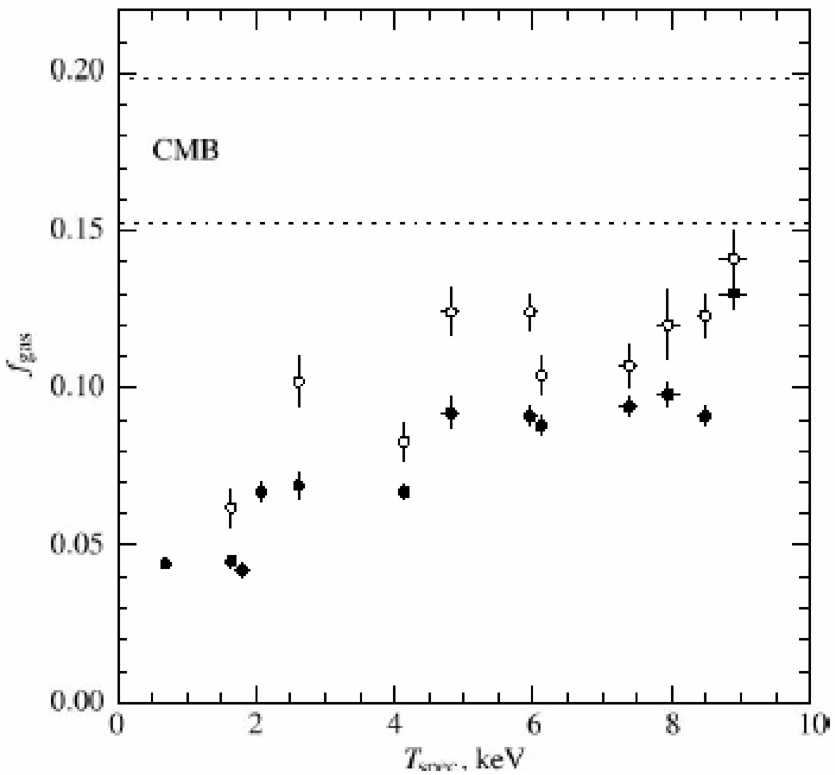


- Clusters CAN be used as 'standard' candles – kT, Fx, size -> Distance, 26 Chandra clusters 2004 MNRAS
- A large snapshot survey followed by deeper spectroscopic observations of relaxed clusters will achieve f_{gas} measurements to better than 5% for individual clusters:
  - Corresponds to Ω_M=0.300±0.007, Ω_Λ=0.700±0.047
  - For flat evolving DE model,

    w_0 = -1.00±0.15, w' = 0.00±0.27

SNIa DISTANCES systematics at ~7% (statistical = 13% Riess etal 2004 'gold' 157, zmax=1.8) Clusters show NO systematics (yet) at ~8% levels

Systematics? Vikhlinin etal 2006



- T correlates with fgas
- Different set of clusters… but need to understand systematics – Con-X, with R=1500 @ 6keV, can do this – identify non-virial motions (mergers?)

Cluster fgas Science Requirements

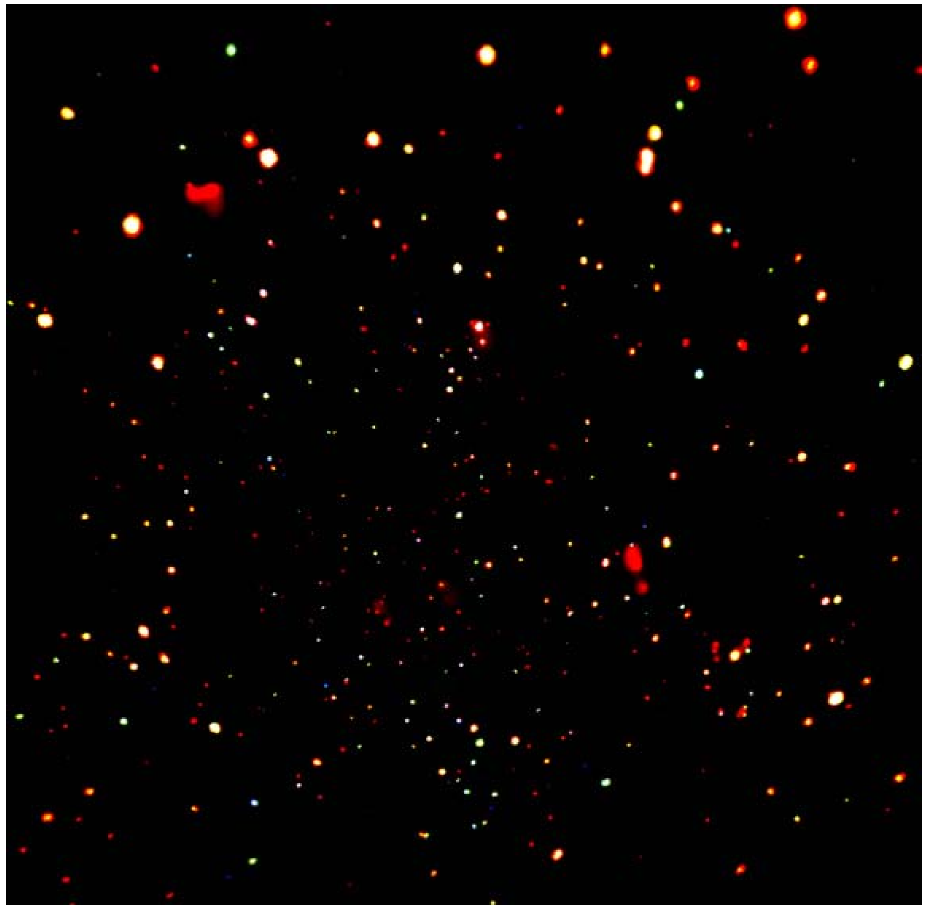
- Band: 1.0 keV – 15 keV
  - Cluster temps 2 keV – 10 keV
- Sensitivity, Area: 1.5m^2 @ 1.25keV, 0.6m^2 @ 6keV
  - Surface brightness of 3 x 10^{-16} ergs/cm^2/s/sq-arc-min in 50ks
  - Typical of luminous cluster at virial radius at moderate redshift
- Spectral Resolution: ~100 @ 6keV
  - CCD-like resolution sufficient to measure T, fgas
  - 4eV @ 6keV HIGHLY advantageous to measure non-virial flows (200km/s resolution, 20km/s absolute centroiding) over full FOV
- Angular Resolution: ~5'', perhaps 10''
  - Depends on PSF Wings, simulations needed.
  - Must move beyond baseline 15'' towards goal of 5''
- FOV: 2.5'
  - Mosaicing may be needed for nearby clusters
- Other:
  - detector BG must be low, ~ 4 x 10^{-3} c/s/keV/cm^2 at 1 keV, documented vs. F ratio, FL in Mark Bautz memo

The Chandra Deep Fields

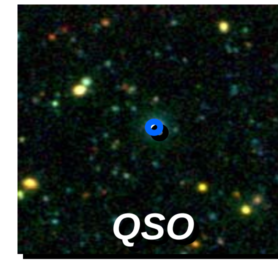
Chandra has resolved the X-ray background into active galactic nuclei (AGN) with a space density of a few thousand per sq deg

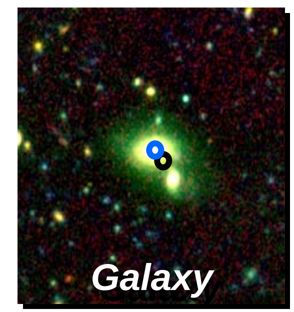
- Constellation-X will gather high-resolution X-ray spectra of the elusive optically faint X-ray sources

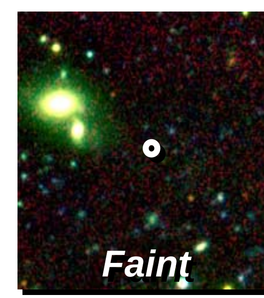
- Chandra deep surveys have the sensitivity to detect AGN up to z~8



2 Megasecond Observation of the CDF-N
(Alexander et al. 2003)





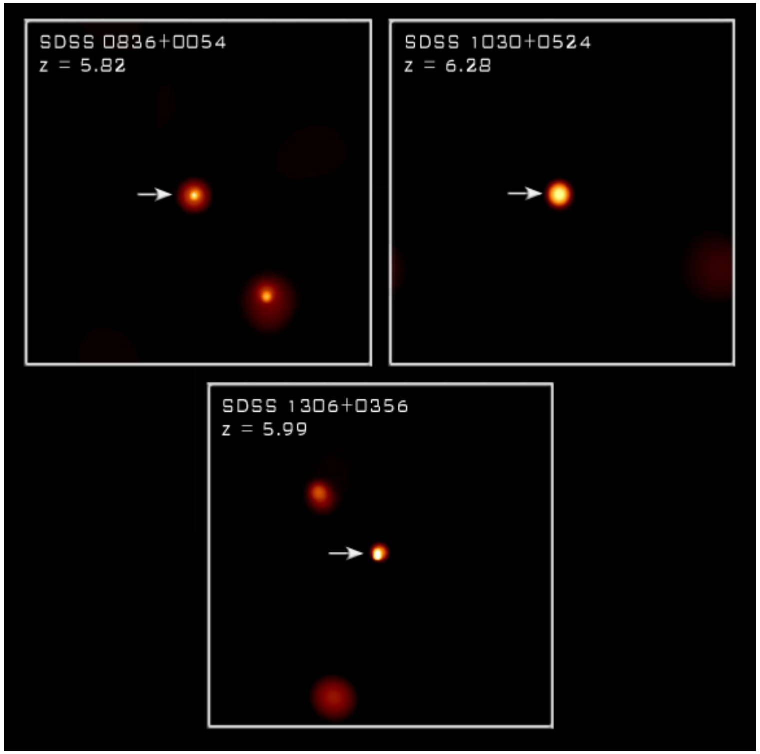


Chandra sources identified with mix of active galaxies and normal galaxies, many are optically faint and unidentified

X-ray Detections of High Redshift QSOs

Chandra has detected X-ray emission from three high redshift quasars at $z \sim 6$ found in the Sloan Digital Sky survey

Flux of 2-10 x 10^{-15} erg cm^{-2} s^{-1} beyond grasp of XMM-Newton, Chandra or Astro-E2 high resolution spectrometers, but within the capabilities of Constellation-X to obtain high quality spectra

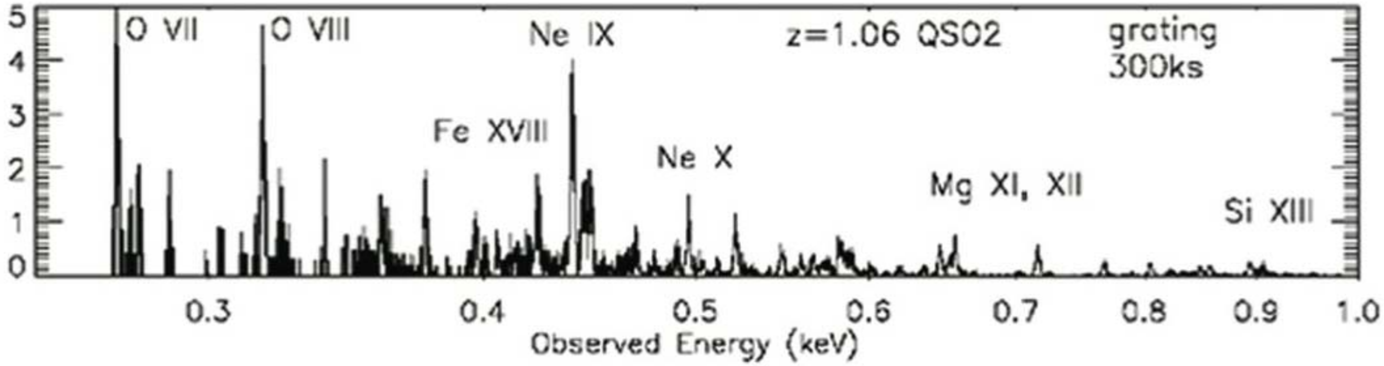


High resolution spectroscopy enables study of the evolution of black holes with redshift and probe the intergalactic medium of the early universe

Black Holes and the Cosmic X-ray Background

- Large fraction of the background identified with moderate-redshift ($1 < z < 3$) AGN (e.g., Barger et al. 2003)
- Constellation-X will provide detailed spectroscopic IDs

Con-X simulations of faint z=1.06 "Type II QSO"



- Near the background peak energy (20-50 keV) only 3% is resolved (Krivonos et al. 2005)
- Constellation-X will have unprecedented imaging capability at 10-40 keV will resolve a significant fraction of the hard X-ray background

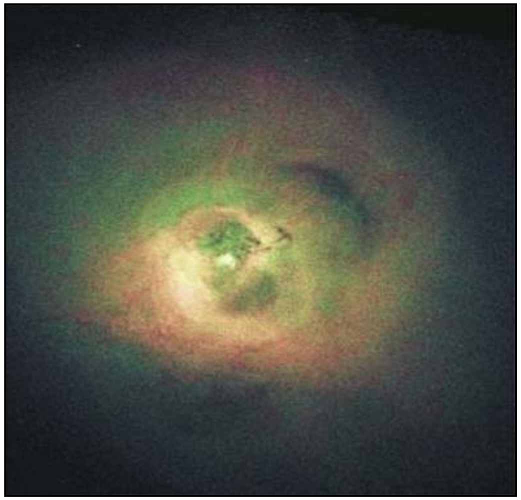
Black Holes, QSOs, Cosmic X-ray Background

- Band: 0.25-40.0
  - High redshifts, obscured sources
- Sensitivity, Area: 1.5m^2 @ 1.25keV, 0.6m^2 @ 6keV, 0.15m^2 @ 40keV,
  - Fluxes 10^{-14} to 10^{-17}, >100 cts in 1Ms
  - Obscured sources
- Spectral Resolution: 300 @ 0.6keV, 1500 @ 6keV, 10 @ 40keV
  - Spectroscopic IDs, redshifts
  - 1000 cts at 10^{-15} in 100ks
- Angular Resolution: 15’’
  - Faintest sources may require moving towards goal of 5’’
- FOV: 2.5’
  - 5 x PSF for BG subtraction
  - Desirable: 5’x5’, CCD-like resolution for 1Ms+ observations
- Other: N/A

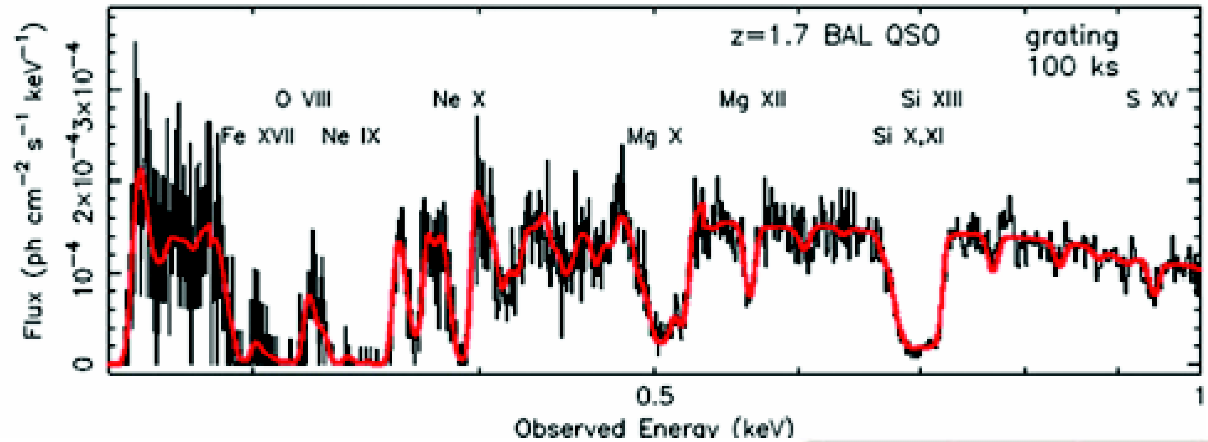
Black Holes and AGN Feedback

- Large scale-structure simulations require AGN feedback to regulate the growth of massive galaxies (e.g., Di Matteo et al. 2005, Croton et al. 2005)
- Constellation-X non-dispersive X-ray spectroscopy is needed to probe hot plasma in cluster cores (Begelman et al. 2003, 2005)
- Constellation-X will finally reach the powerful AGN outflows in the quasar epoch (1<z<4) with its large collecting area optics

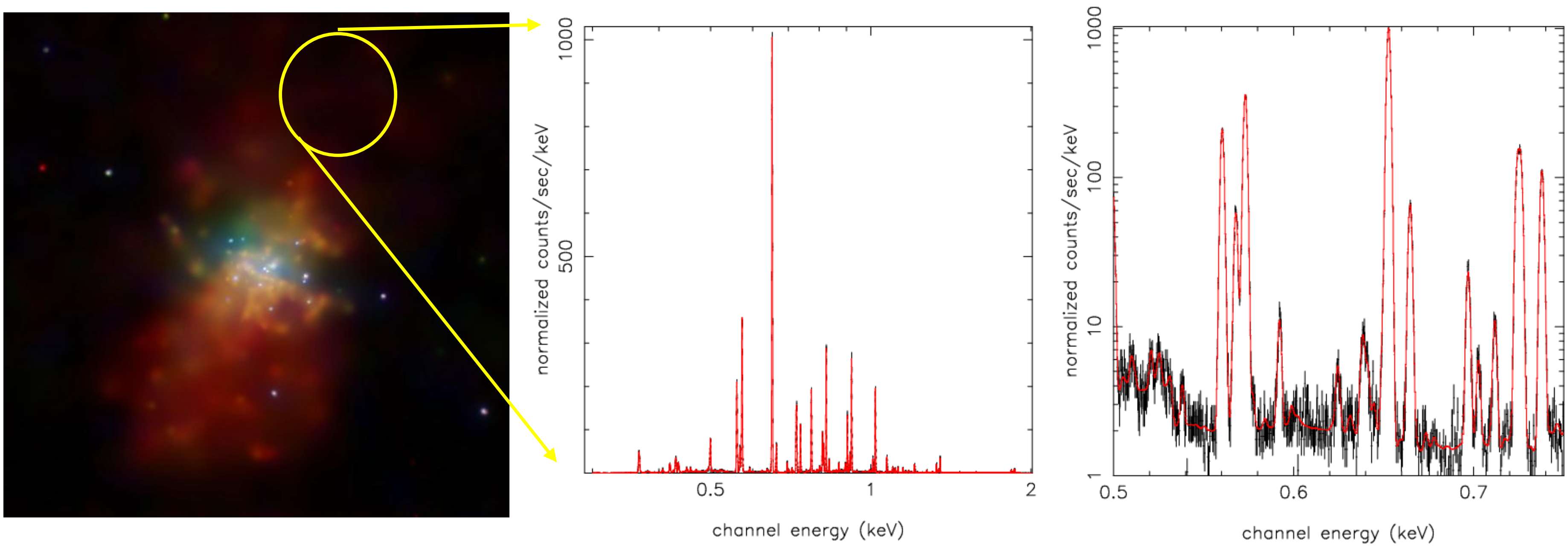
Perseus Cluster of Galaxies (Chandra image)



Con-X simulation of BAL QSO (S.Gallagher, UCLA)



Supernova (Stellar) feedback Wind plasma diagnostics (D. Strickland, JHU)



M82 Chandra central 5x5 kpc
0.3-1.1 keV
1.1-2.8 keV
2.8-9.0 keV

Simulated 20 ks Constellation-X northern halo observation, 0.3-2.0 keV

O VII and O VIII region. Well resolved triplet, high S/N in continuum.

With calorimeter ~2-eV resolution at 1keV we can determine temperatures, densities, and metallicities accurately in many extended winds (not just M82)

AGN Outflows, Starburst Winds

- Band: 0.25-40.0
  - High redshifts, obscured sources
- Sensitivity, Area: 0.1m^2 @ 0.25keV, 1.5m^2 @ 1.25keV, 0.3m^2 @ 6keV
  - Fluxes 10^{-14} to 10^{-12}, S/N>10 in OVIII, Fe, MgX, etc. lines in <100ks
- Spectral Resolution: 1000 @ 0.5keV, 1000 @ 6keV, 10 @ 40keV
  - Resolving Kα lines of OVIII, Fe, Mg, etc. at different ionization states
  - 1000 @ 0.5keV ~equal to baseline grating design
- Angular Resolution: 15''
  - Fainter sources in confused starbursts may require moving towards goal of 5''
- FOV: 2.5'
  - 5 x PSF for BG subtraction
- Other: N/A

Some Additional Topics, DRIVERS Highlighted

- Neutron Star EOS
  - m/r, m and r, tests of GR, matter under super-nuclear densities
  - Requires ToOs within 1 day, high rates achievable with baseline mission
- WHIM (Warm Hot Intergalactic Medium)
  - Where is the missing 50% of the 4% of the universe we understand?
  - R~1000 at ~0.5keV, to separate OVII, NeX, Kα lines at different ionizations
- SNR and SNIa
  - 'peeling the onion' of SNR, first images with few eV resolution
  - Understanding the progenitor and explosion of SNIa
  - Largest SNR doable with 15'', but moving towards goal of 5'' important
- Coronal Heating and Flares
  - High S/N spectra of corona for entire classes of stars
- Formation of young stars, planets
  - Reverberation mapping of planetary disks can ID 'gaps' where planets form

Top Level Requirements (TLR) to Science Requirements (SRD)

- TLRD stable since drafted in 2000
- SRD needed for Phase A
- Typically changes after Instrument AO – becomes SI specific, more detail
- Currently SRD in draft – expect first complete draft (public, circulating) by end of summer. Ahead of NASA requirements
- Based on TLRD, Science Booklet, and original HTXS, LAXS mission proposals, 2005 White Papers

The Constellation-X Mission

Science Goals:

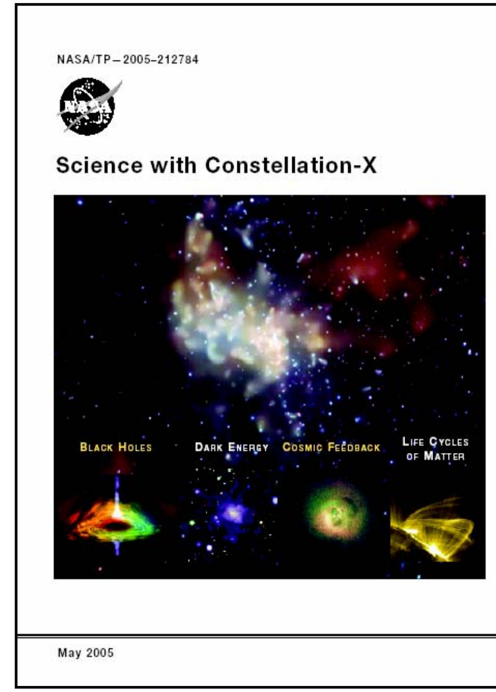
- ***Black Holes***
  - Probing strong gravity
  - Evolution & effects on galaxy formation
- ***Dark Matter and Dark Energy***
  - Cosmology using clusters of galaxies
  - Missing Baryons (WHIM)
- ***Cycles of Matter and Energy***
  - Cosmic feedback, extreme states of matter, stellar coronae, supernovae, planets, etc..

A Constellation of X-ray telescopes for high resolution spectroscopy:

- 25-100 times gain in throughput over current missions
- Major facility that will open a new window for X-ray spectroscopy
- Four SXT, x3 HXT telescopes orbiting around the L2 point, pointing at the same target with the data combined on the ground

Key Constellation-X Capabilities

- A factor of 25-100 increased collecting area for $E/\Delta E \sim 300$ to 1500 spectroscopy
- Routine spectroscopy to a flux of 4×10^{-15} ergs cm^{-2} s^{-1} (0.25 to 10.0 keV), with 1000 counts in 100,000s
- Factor ~100 increased sensitivity in 10 to 40 keV band
- New velocity diagnostics that with a ΔE of 4 eV at 6 keV gives a bulk velocity of 200 km/s & centroiding to an absolute velocity of 20 km/s
- SXT angular resolution requirement of 15 arc sec HPD, 5 arc sec goal
- Field of View 2.5 x 2.5 arc min with 32 x 32 pixels
- Ability to handle 1,000 ct/sec/pixel


NASA/TP—2005–212784

Science with Constellation-X

May 2005