Relativity from Chandra to Constellation-X

MG11 - Saturday, July 29, 2006

- Michael Garcia, Smithsonian

SAO Con-X Science Lead

Black Holes, Gravity, Dark Energy ?

- Words from DETF – ‘It is not at present possible…to determine whether Λ, a dynamical fluid, or a modification to GR is correct explanation of the observed accelerating Universe …any observational evidence for modifications of GR… may point the way toward understanding DE…[and have] far reaching implications for other fields of physics..’
- Gravity as described by GR has yet to be tested in the Strong Field limit
- Observations of Black Holes = Strong Field Gravity
- Will Review Key Chandra Results and Way Forward with Constellation-X

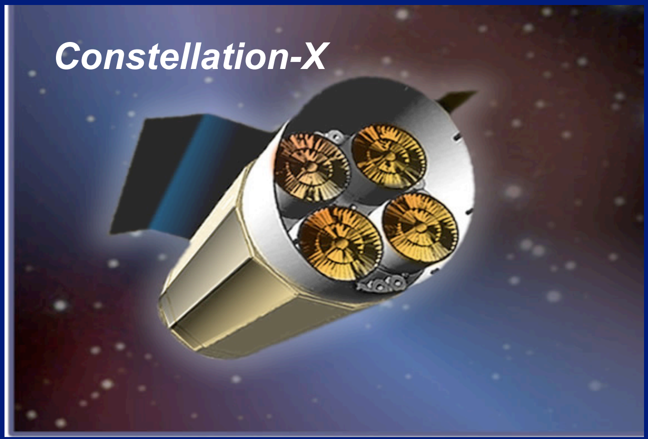
IAUS 230 Dublin 'Gravity Bar'

Constellation-X as the Successor to Chandra

CHANDRA has brought X-ray Imaging to <1''

Comparable with typical optical/IR telescopes

But most X-ray SPECTRA are still 'colors' typically N_H, Kt, equivalent of U/B/V – Except for the brightest sources with gratings, or VERY long exposures



Constellation-X will change this – Routine spectra with 300 < R < 3000 for tens of thousands of sources – $F_X \sim 10^{-15}$ ergs/cm^2/s (0.25-2keV)

100 times throughput for R>300, AREA alone 40x Chandra, 20x XMM at Fe-K (strongest emission line)

The PHYSICS is in the Spectra!

Example:

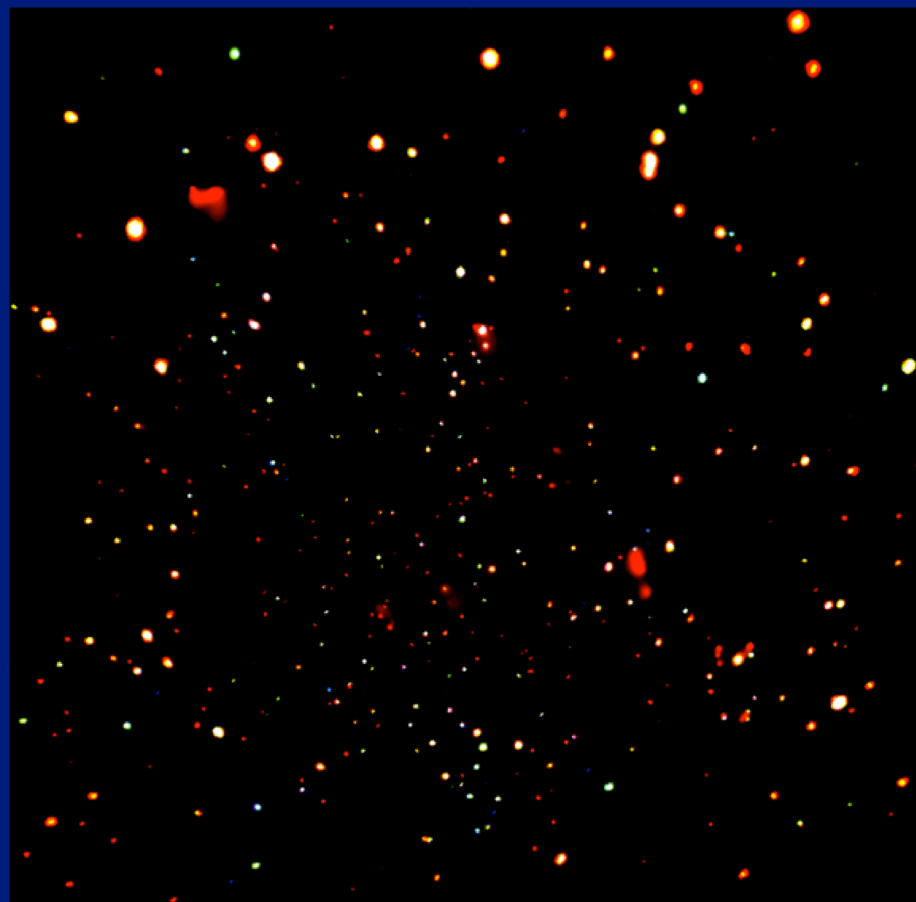
Chandra and Cosmic X-ray Background Black Holes

The Chandra Deep Fields

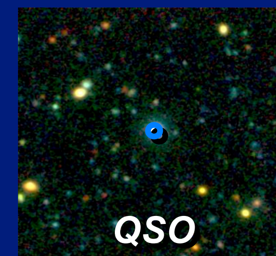
Chandra has resolved the X-ray background into active galactic nuclei (AGN) with a space density of a few thousand per sq deg

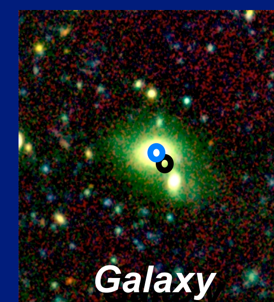
- Constellation-X will gather high-resolution X-ray spectra of the elusive optically faint black hole X-ray sources

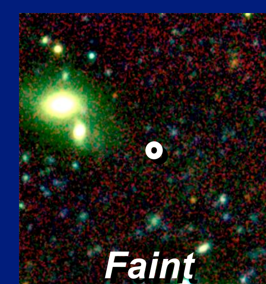
- Chandra deep surveys have the sensitivity to detect AGN up to z~8



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





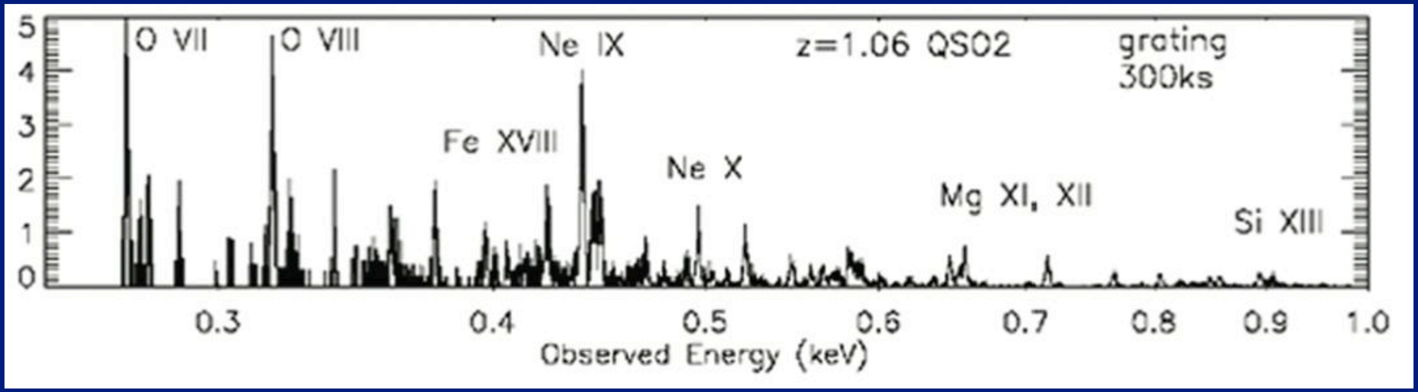


Chandra sources identified with mix of active galaxies and normal galaxies, many are optically faint and unidentified

Constellation-X Spectroscopic IDs of BHs

- 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
- 100ks at 2×10^{-15} erg cm^{-2} s^{-1}

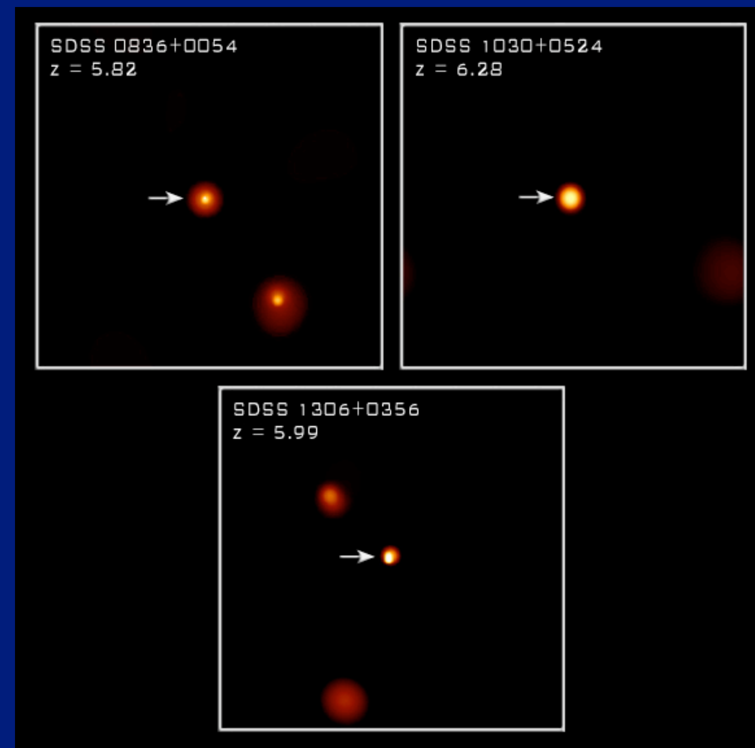
Con-X simulations of faint z=1.06 "Type II QSO"



Chandra BHs at high z

X-ray Detections of High Redshift QSOs

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



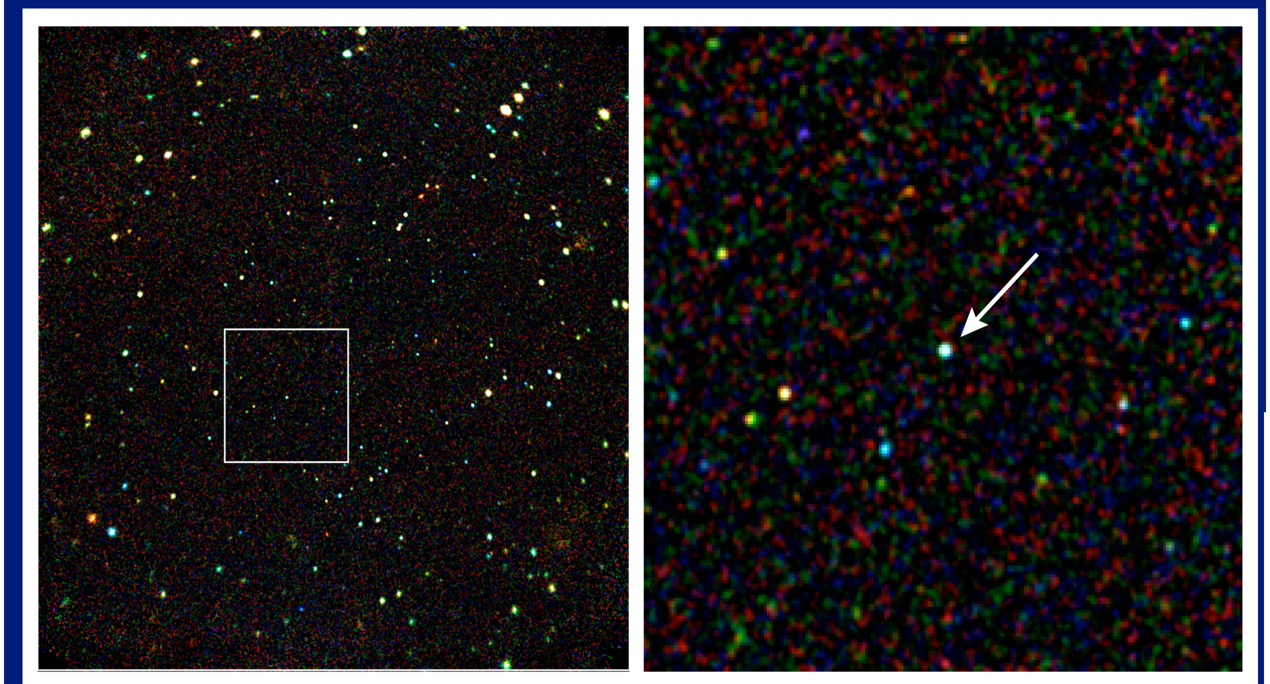
Flux of 2-10 x 10^{-15} erg cm^{-2} s^{-1} beyond grasp of XMM-Newton, Chandra or Astro-E2 high resolution spectrometers, but within the capabilities of Constellation-X to obtain high quality spectra

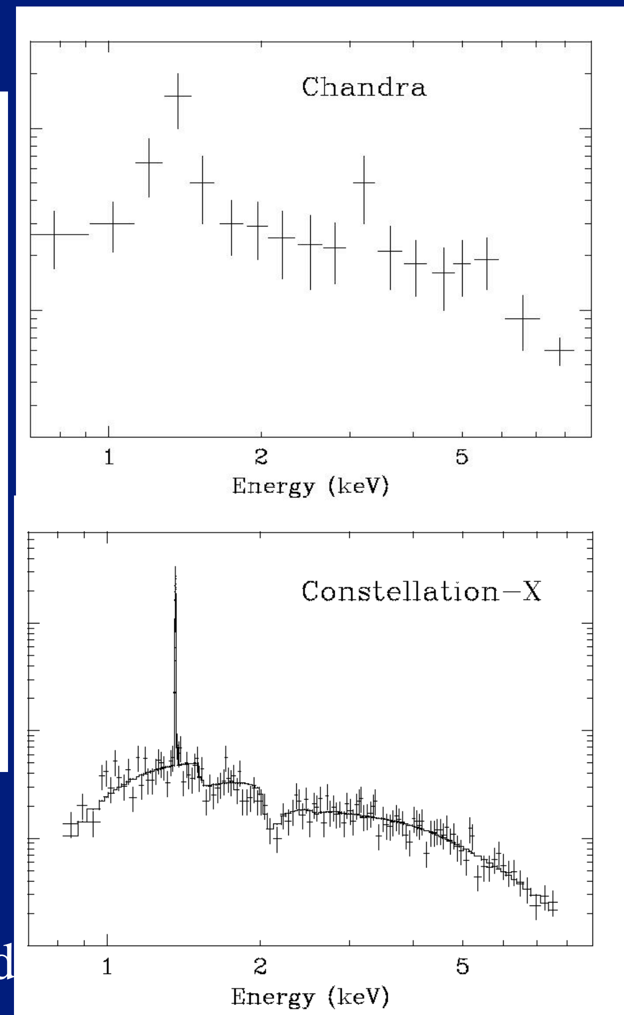
High resolution spectroscopy enables study of the evolution of black holes with redshift and probe the intergalactic medium of the early universe

Constellation-X Physics of high Z BHs

Constellation-X Identification of Faint Chandra Sources

The high redshift universe of AGN





Constellation-X will gather high quality spectra of these faintest X-rays sources that make up the X-ray background, like this z = 3.7 type II quasar discovered serendipitously by *Chandra*.

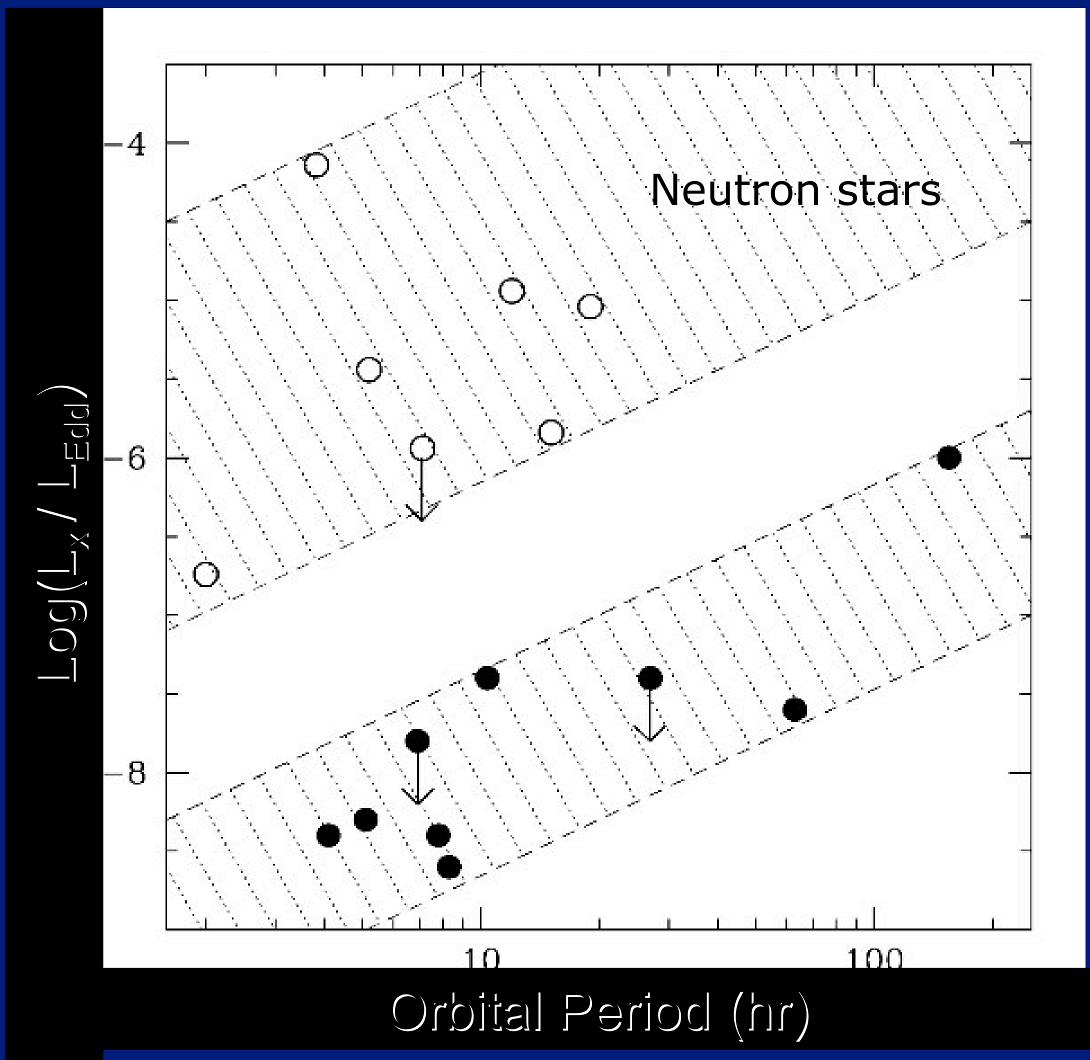
Black Holes – From Astrophysics to Physics

- Stage I – Identify BH Candidates
  - ASM -> Chandra Pos/Spectra -> optical f(m)
  - Resolve Cosmic X-ray Background
- Stage II – Confirm BH Candidates
  - Event Horizons (Chandra), Timing, Spectra
  - L / L_{Bondi} Radiatively inefficient flows
- Stage III – Measure Spin of BH
  - Spectra, Timing (Chandra, XMM, RXTE -> Con-X)
- Stage IV – Relate Spin to Penrose, BZ
  - Jets, Chandra, VLA, Con-X
- Stage V – Quantitative tests of Kerr Metric
  - Doppler Tomography, Reverb Mapping, $T<T_{ORB}$ Con-X

J McClintock

Chandra: Confirming Black Hole Candidates

Soft X-ray Novae in Quiescence



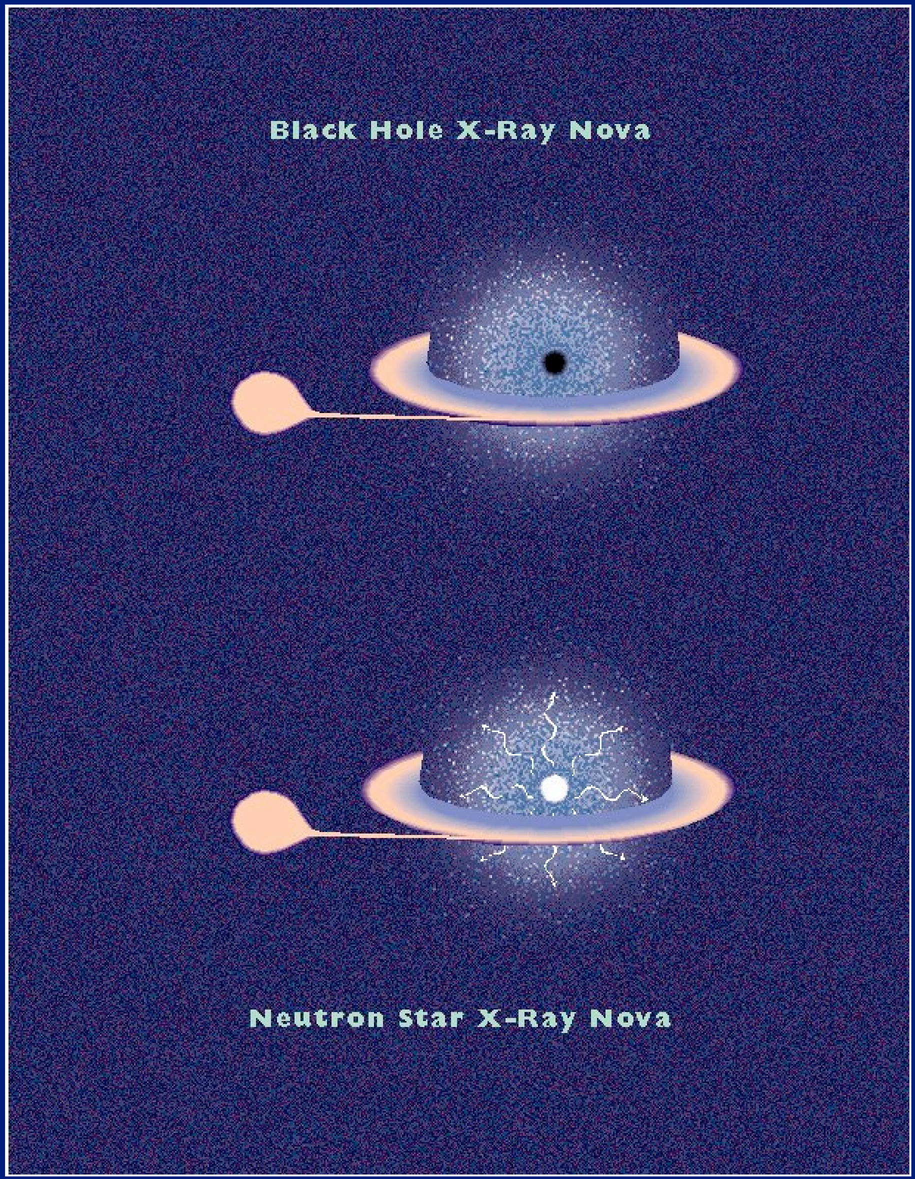
Quiescence

Neutron Stars

Black Holes

Narayan et al. 1997
Garcia et al. 2001

Event Horizons: Theory and Interpretation



Bondi Accretion Rates in Nearby SMBH

Severe constraints

Secure accretion rate

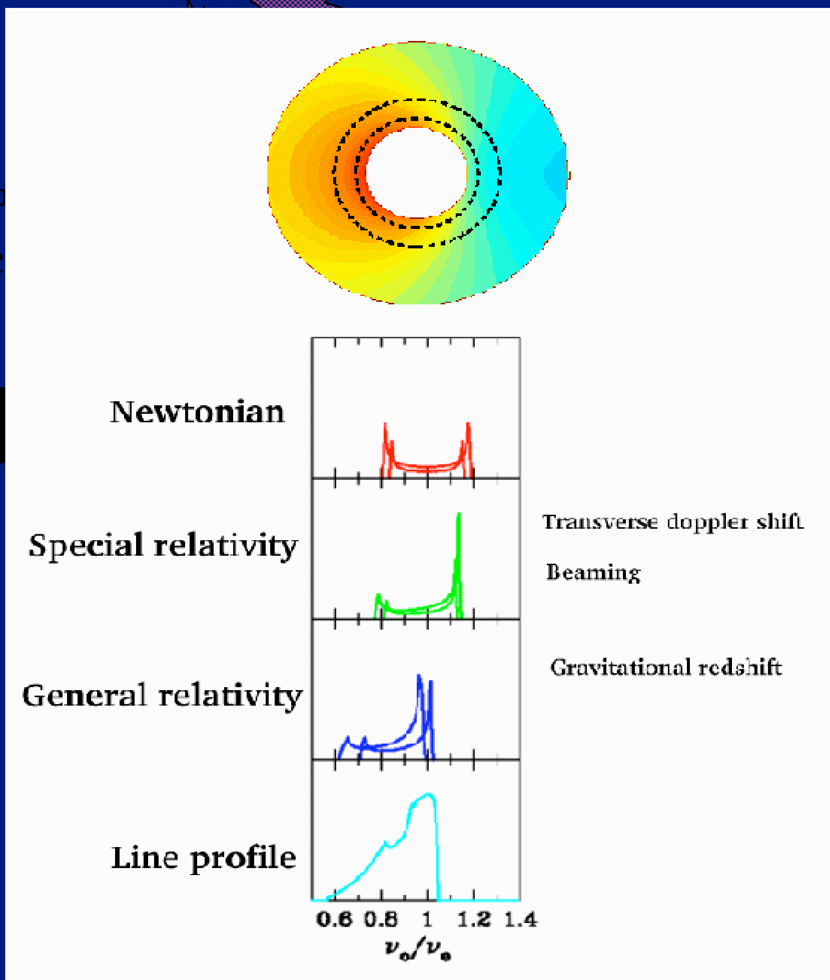
- When R_{Bondi} resolved, accretion rate known

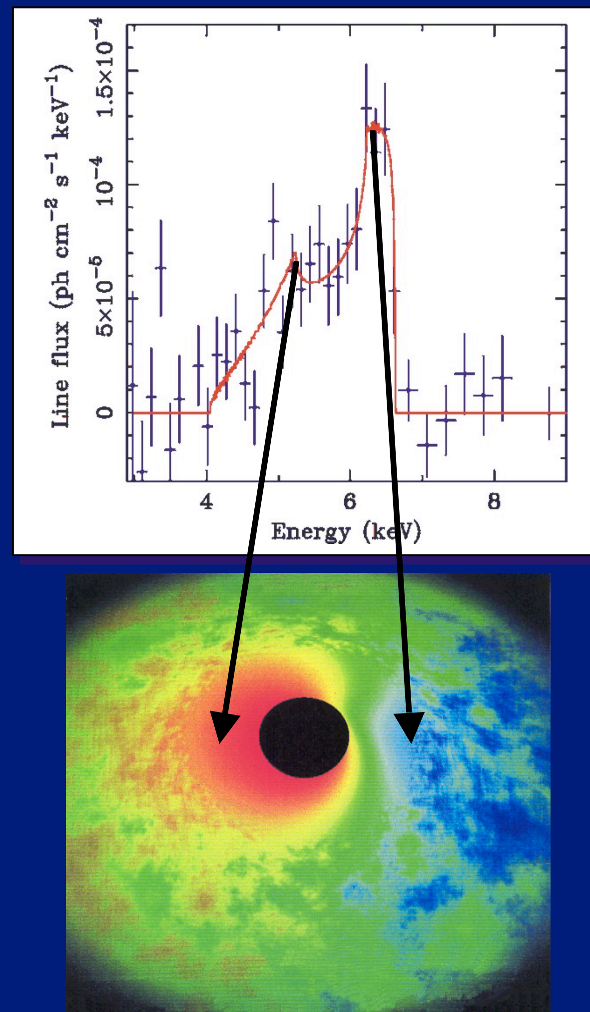
Chandra resolves in several nearby galaxies

Accretion must be radiatively innefficient – ADAF, CDAF, RIAF – all with event horizon

SgrA – Baganoff etal
M31 – Garcia etal

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.





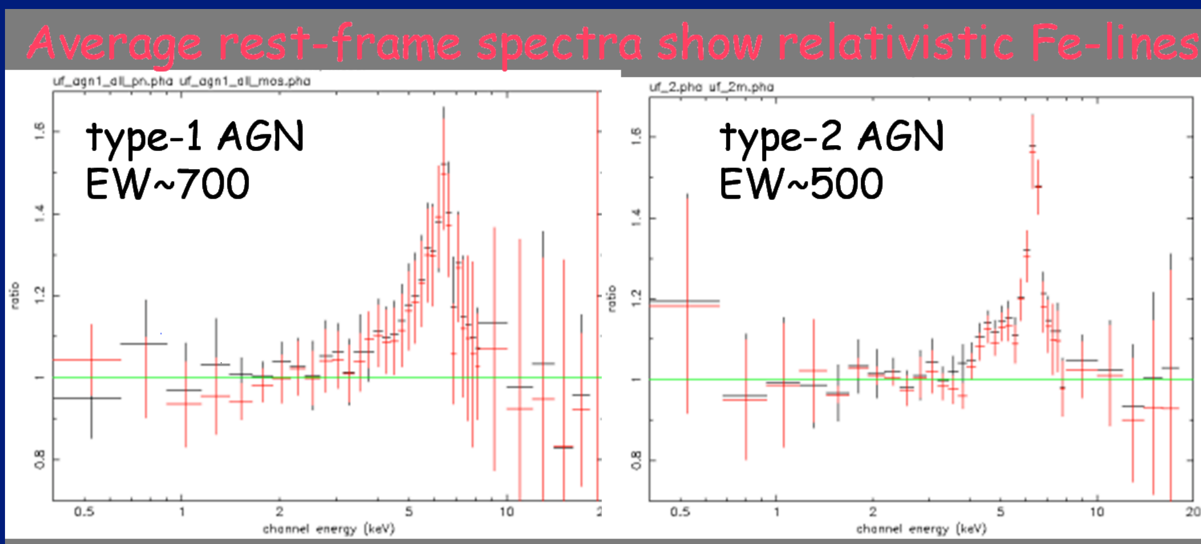
Theoretical 'image' of an accretion disk.

RELATAVISTIC Fe Lines in Stellar and SMBH

J. Miller MG10

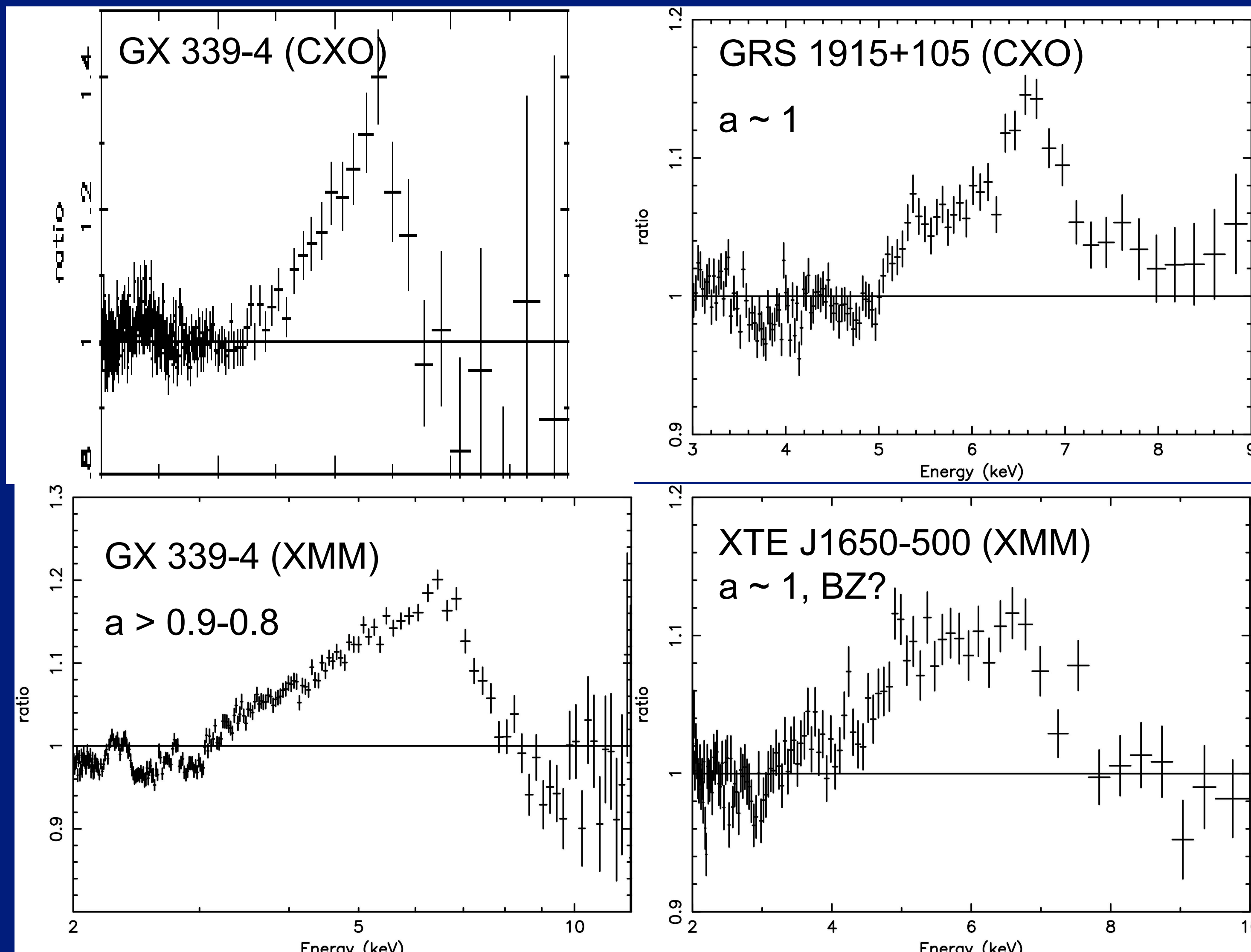
- <u>Prior to 1999</u>
- GX 339-4
- Cygnus X-1
- V404 Cyg ??

- <u>After 1999</u>
- *GS 1354-645*
- *4U 1543-475*
- XTE J1550-564
- XTE J1650-500
- GRO J1655-40
- GX 339-4
- SAX J1711.6-3808
- *XTE J1720-318*
- *XTE J1748-288*
- V4641 Sgr
- XTE J1859+226
- XTE J1908+094
- GRS 1915+105
- Cygnus X-1
- XTE J2012+381



Streblyanskaya et al 2004
XMM Lockman Hole 0.8Ms

Spin via Fe Line Profile in BH Binaries

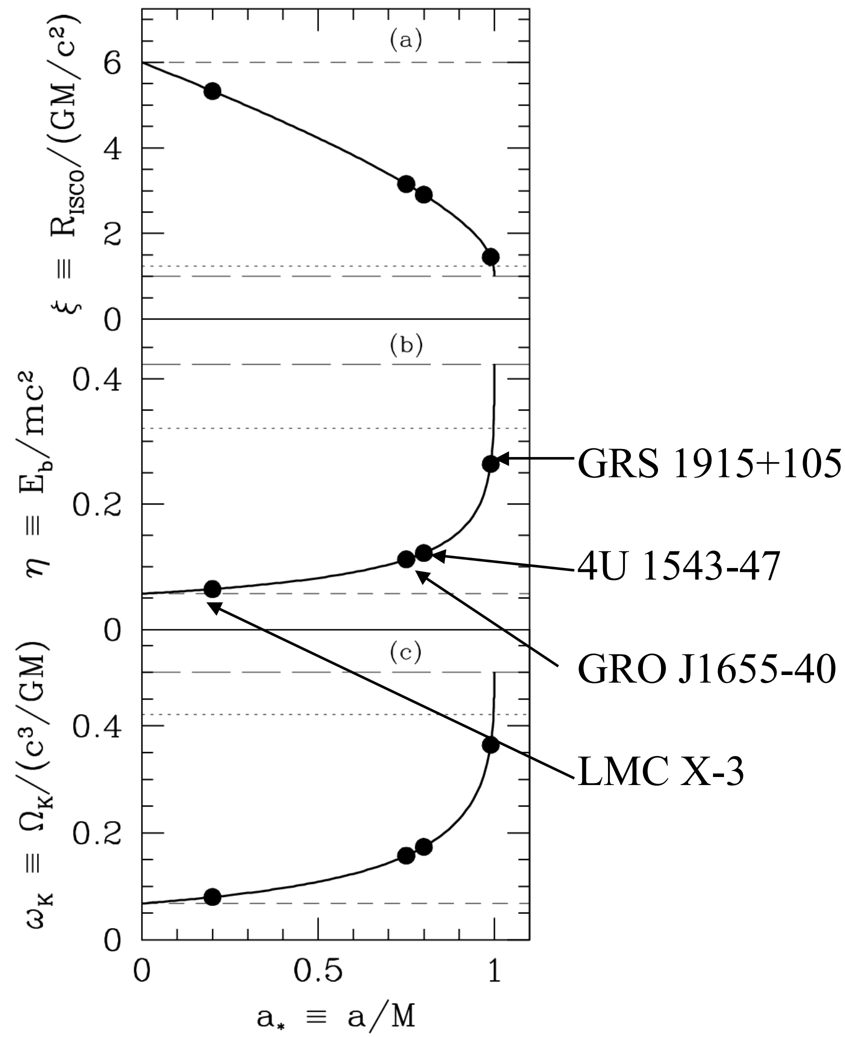


• Spin Changes the Geometry of BH

Radius
ISCO

Binding
Energy

Frequency

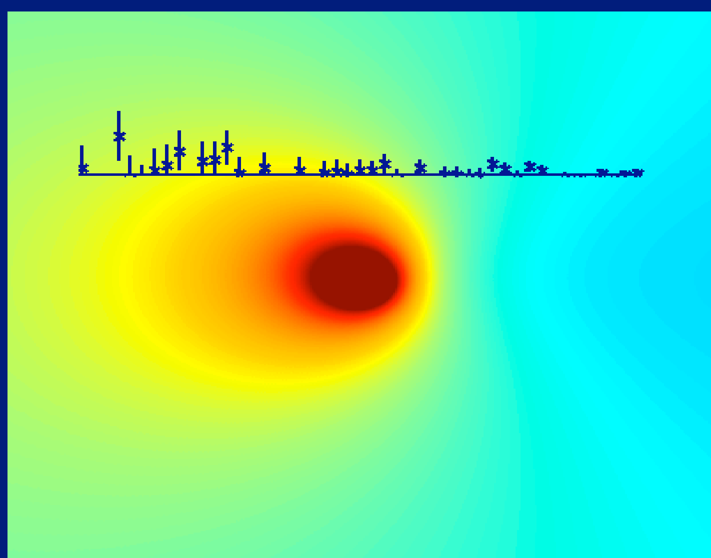


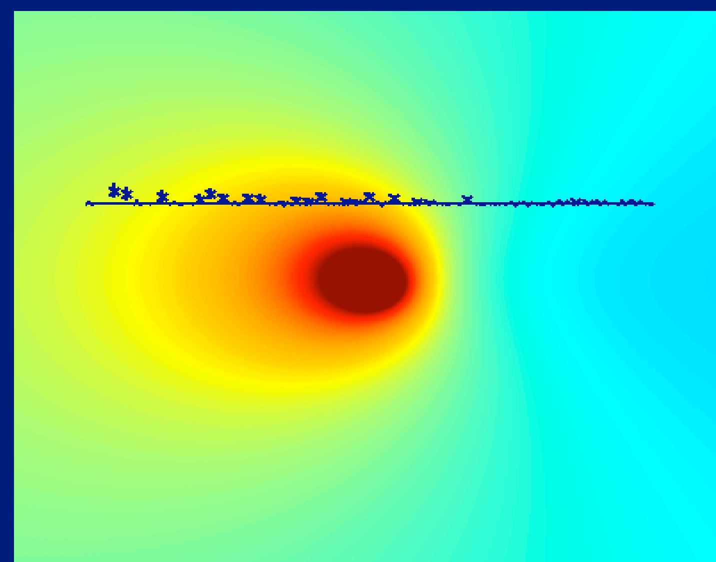
J. McClintock

Constellation-X: Reverberation Mapping

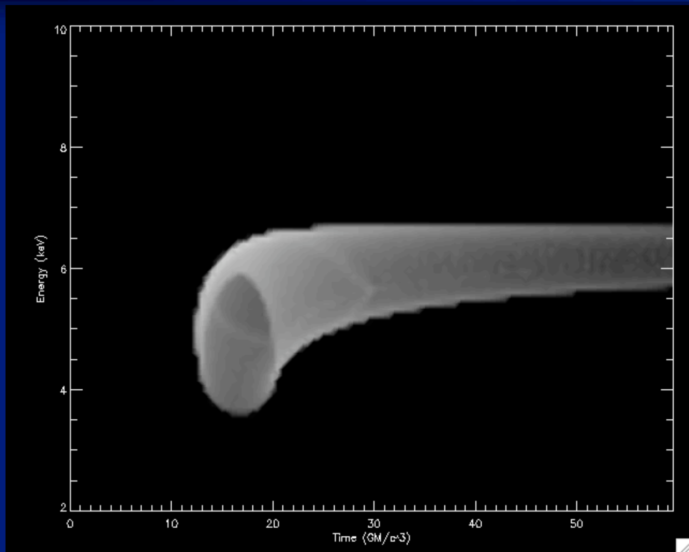
Probes Stage III, IV, and V

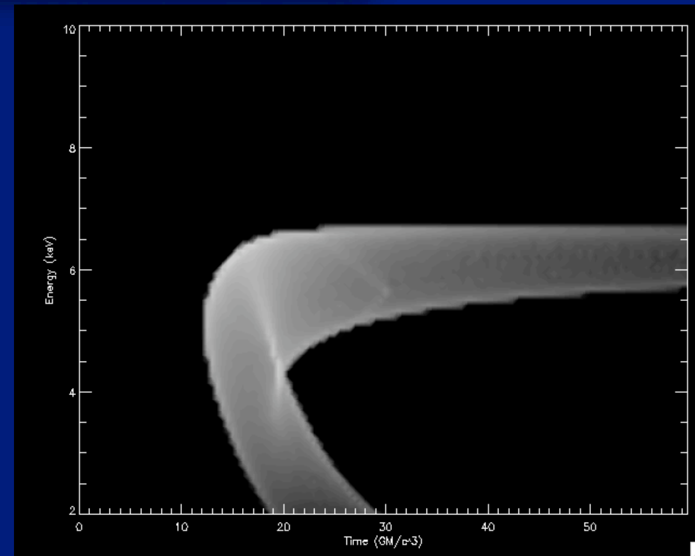
Courtesy Chris Reynolds (UMD)

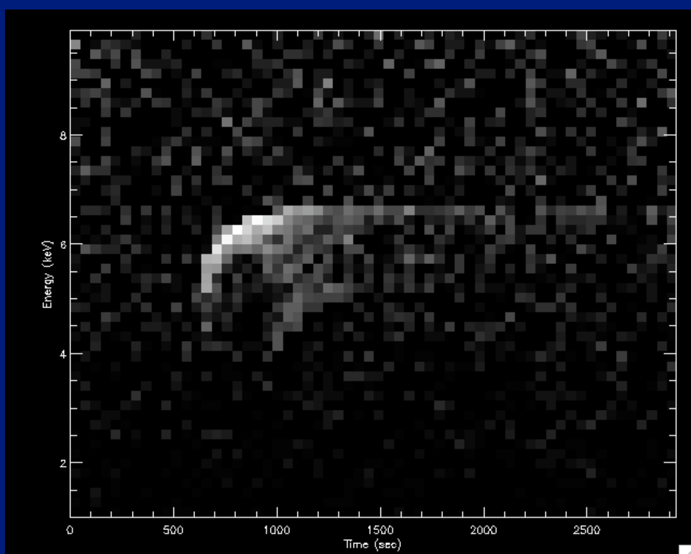


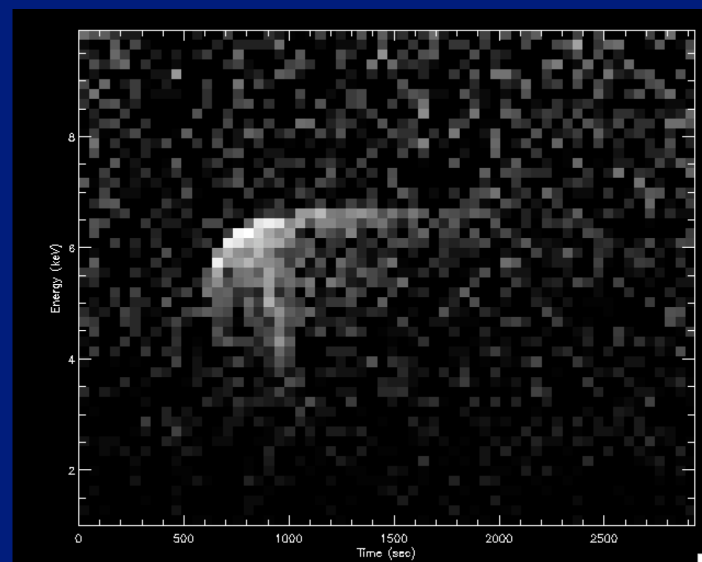


Strong Field GR tests. 'Snapshot' of Geometry - Derive: Mass, Spin, Geometry – F_X ~5x10^{-11} ergs/cm2/s(2-10) GR well tested in weak field – but not all of applicable parameter space. Technique used in OPTICAL at many R_S to estimate black hole mass







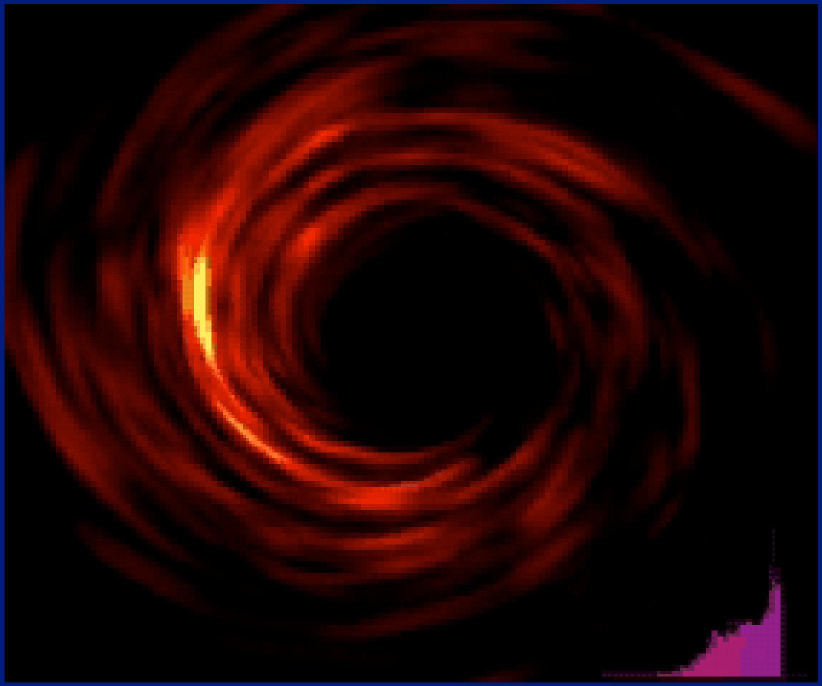


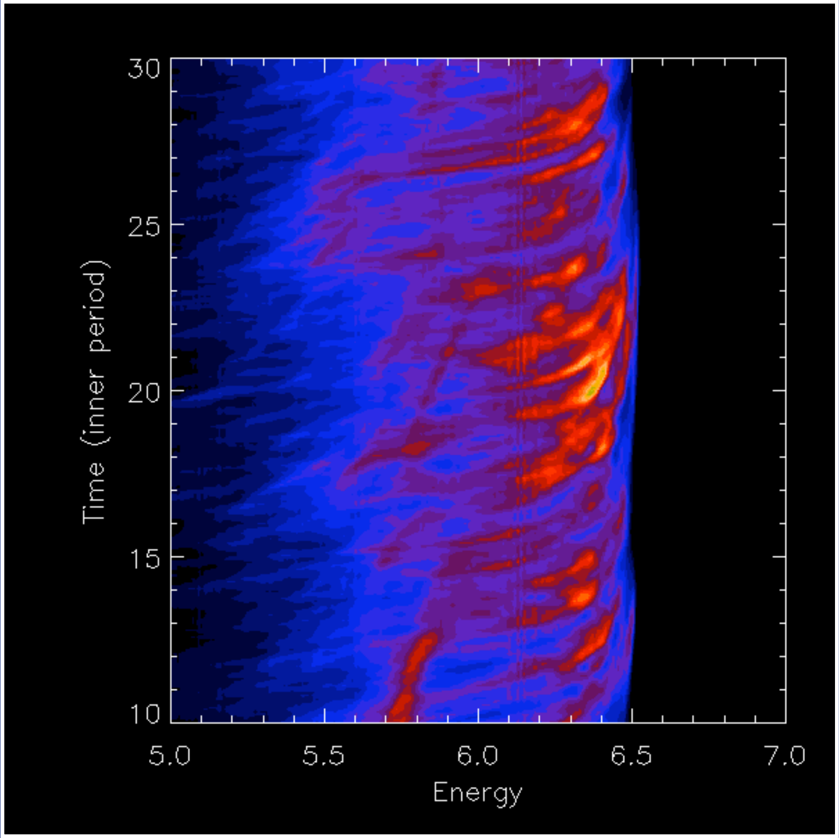
a=0, M=10^7, A=0.6m^2

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

Con-X: Spin via Doppler Tomography

- Orbital Time scale 10x Reverb Mapping: $F_X \sim 5\times10^{-12}$ ergs/cm2/s(2-10)
- Follow dynamics of individual blobs in disk
- Quantitative test of orbital dynamics in strong field regime (STAGE V)



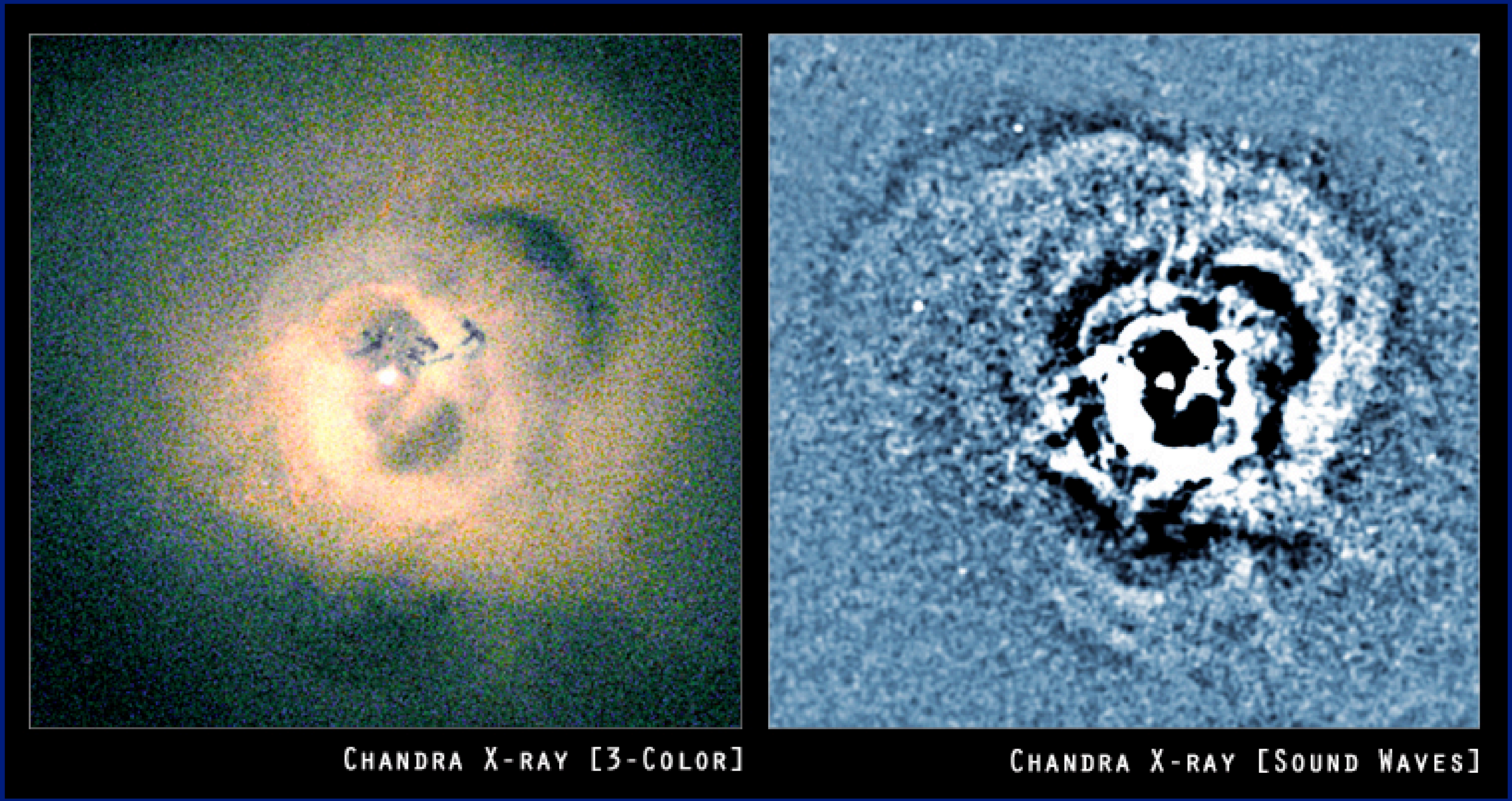


Armitage & Reynolds (2003)

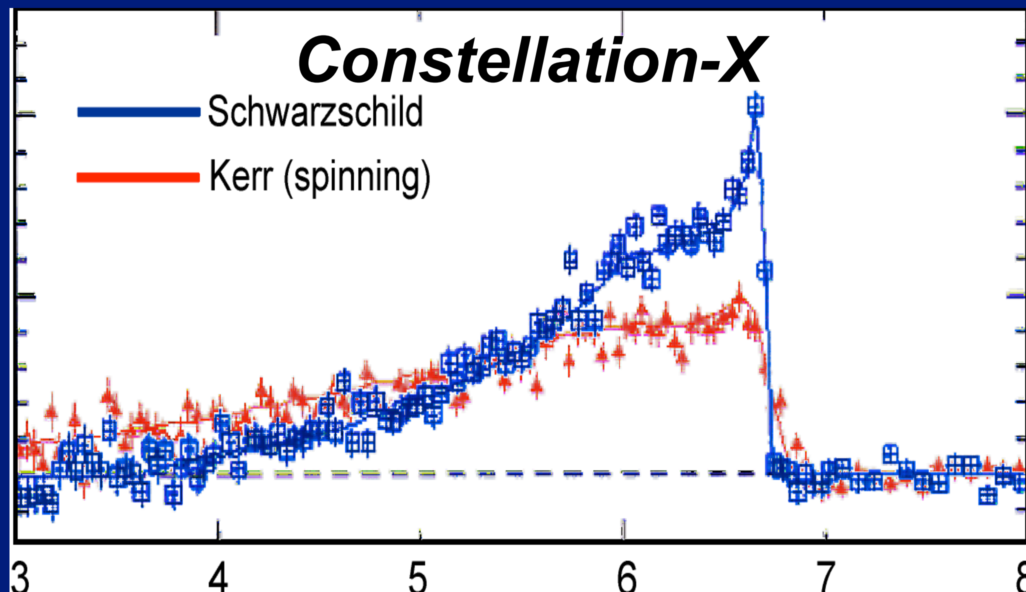
Strong Field domain largely untested – most test utilize FFTs, time averaged line profiles.

Stage IV: Spin, Jet, AGN, Galaxy Coupling

- Black Holes clearly effect their environment: Feedback (jets, B-Z effect), M-σ – what are BH properties vs z?



Stage IV: Spin, Jet, AGN, Galaxy Coupling



Energy (keV)

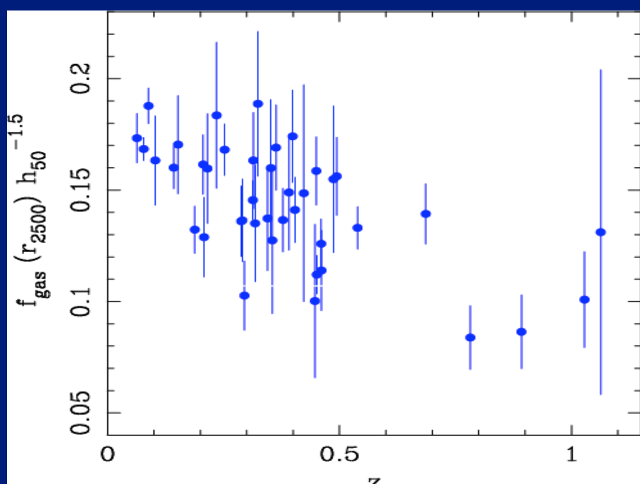
Black Holes (AGN) peak at z~1.5, common 0<z<4

- ✓Time averaged Fe profiles, calibrated by time-resolved, will allow:
- ✓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)
- ✓Use Line profile to determine black hole spin (*a* to 10%)

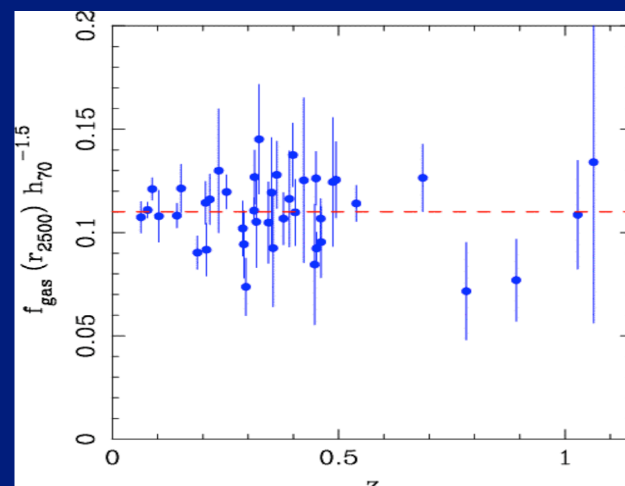
Cosmology (DE) with X-ray Obs of Clusters of Galaxies

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

SCDM (Ω_m=1.0, Ω_=0.0)



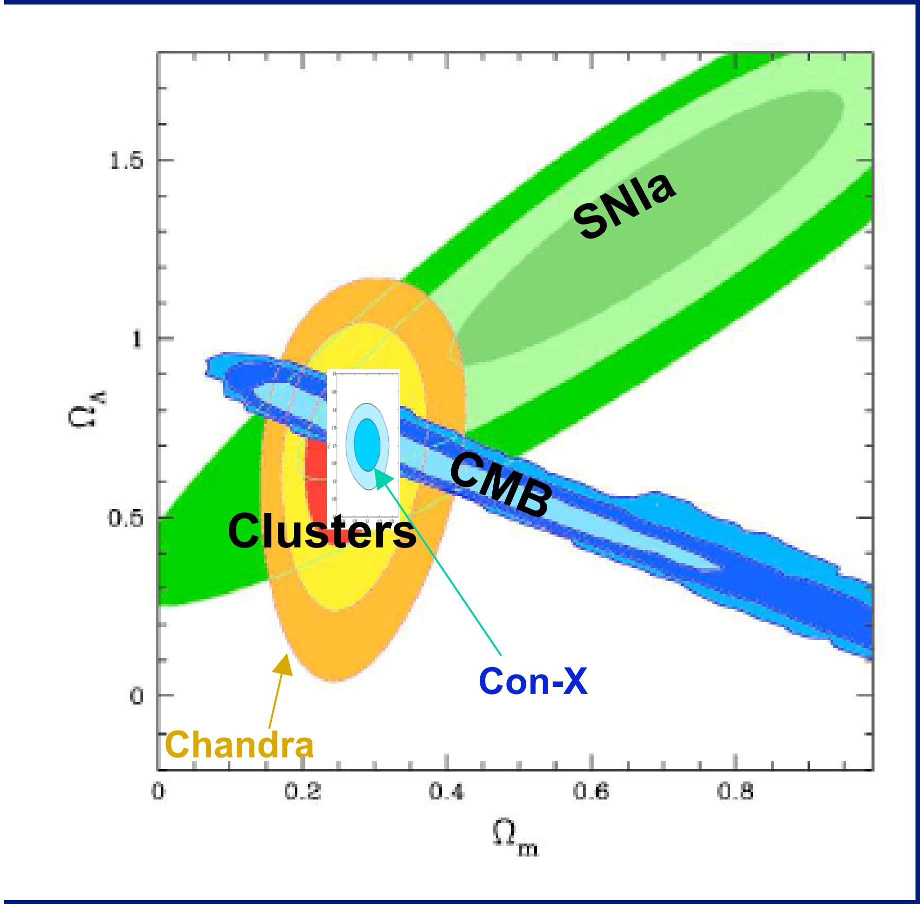
CDM (Ω_m=0.3, Ω=0.7)



Inspection clearly favours _CDM over SCDM cosmology.

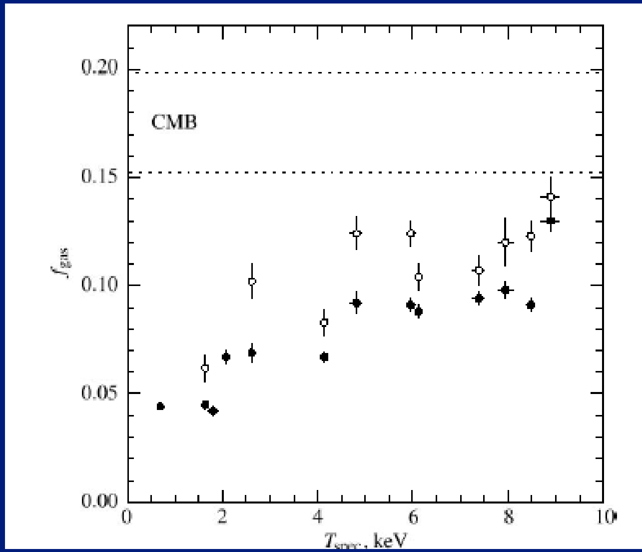
Steve Allen et al

X-ray Obs of Clusters of Galaxies: It works!

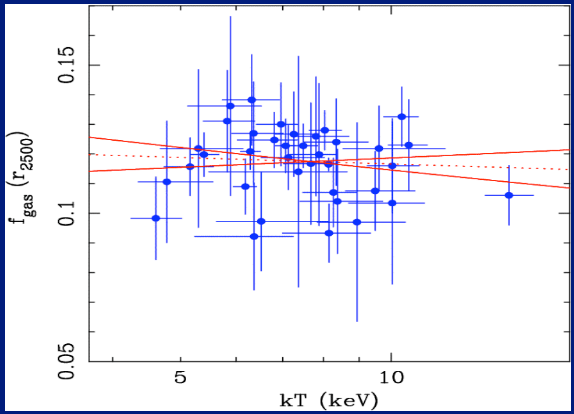


- Clusters CAN be used as 'standard' candles – kT, Fx, size -> Distance, 26 Chandra clusters Allen etal 2004 MNRAS
- SNIa distance systematics at ~7% (statistical = 13%, Riess etal 2004 gold sample 157 SN, z<1.8) Chandra clusters show NO systematics (yet) at 10% (or 5% gold) level.
- A large Con-X snapshot 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

- Vikhlinin etal 2006
- T correlates with fgas
- Different set of clusters…
- Trend not obvious for T>5keV



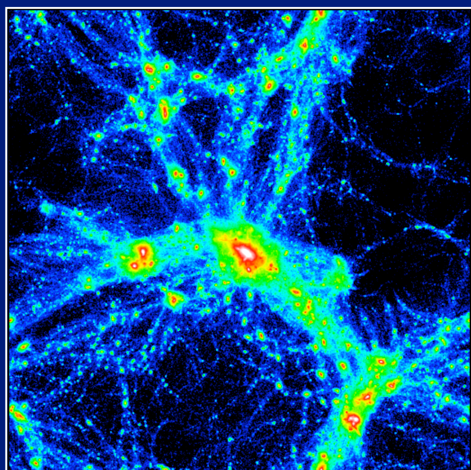
- Allen etal 2006 in prep
- NO correlation of T with fgas
- Best fitting power-law model is consistent with a constant at 1σ
- **Must select hot (>5keV), luminous(>10^{45}) clusters**



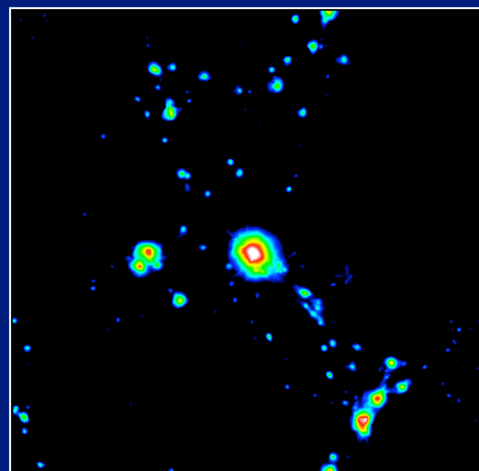
Must select against systematics – ConX with R=1500 at 6keV, can do this by detecting non-virial motions (mergers, shocks), accurate T, mass measurements.

X-ray Obs of Clusters of Galaxies: It works!

Dark Matter



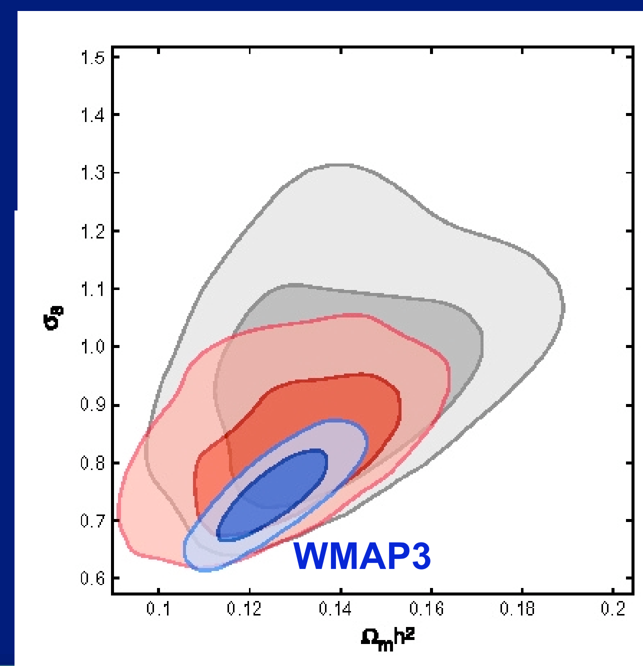
Hot Gas



X-ray emission is an excellent tracer of dark matter over a wide range of masses and redshift

Evolution of massive clusters with redshift is very sensitive to Cosmological parameters

The sources are luminous and relatively bright X-ray sources, easily found in wide field surveys (20-40 per sq deg at Con-X flux limits)

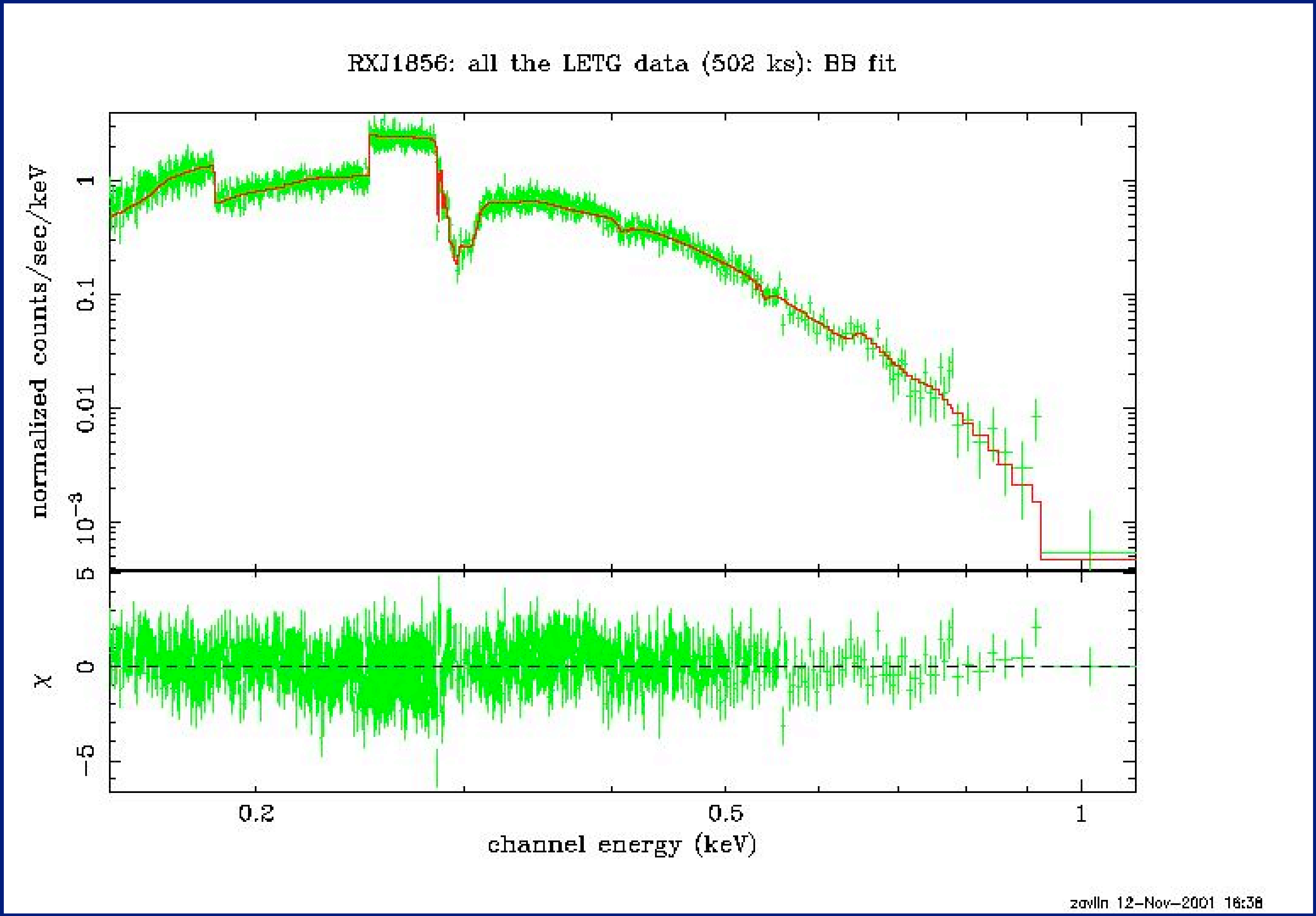


Provides precise Cosmological parameters, e.g. contours in the Ω_m and σ_8 space from Allen et al (2003):

- ROSAT+Chandra z<0.5 luminosity function (blue)
- Galaxy counts plus WMAP1 (black)
- WMAP1 alone (yellow orange)

The ~0.75 value of σ_8 recently confirmed with WMAP3

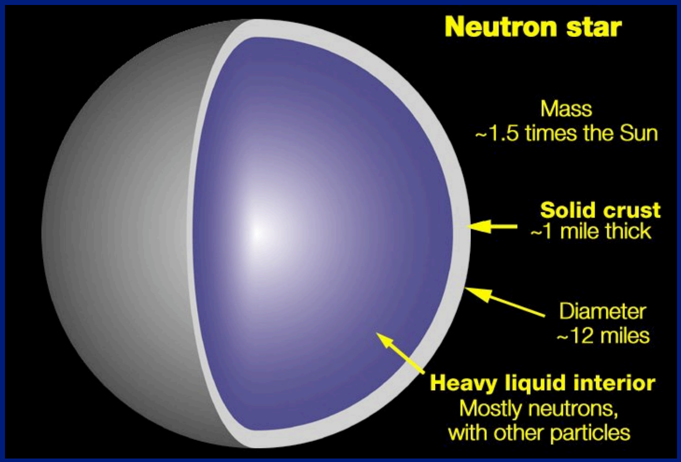
Chandra: The Puzzling Case of RX J1856.5-3754

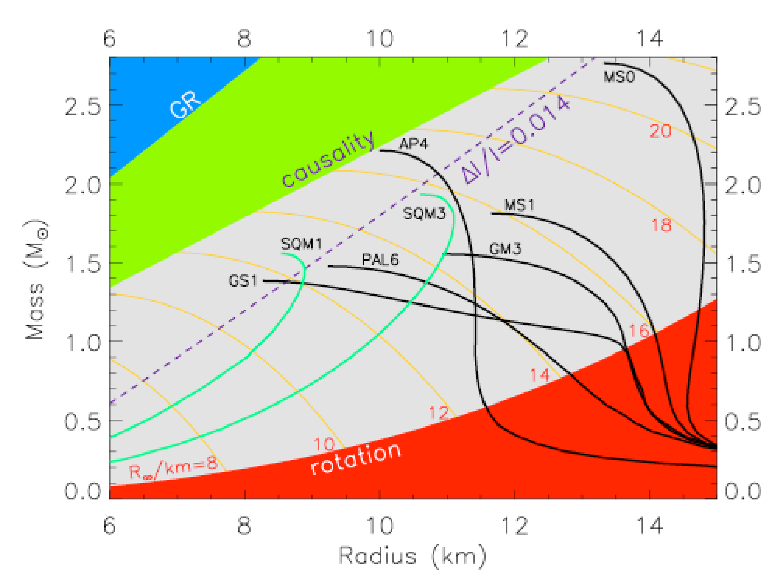


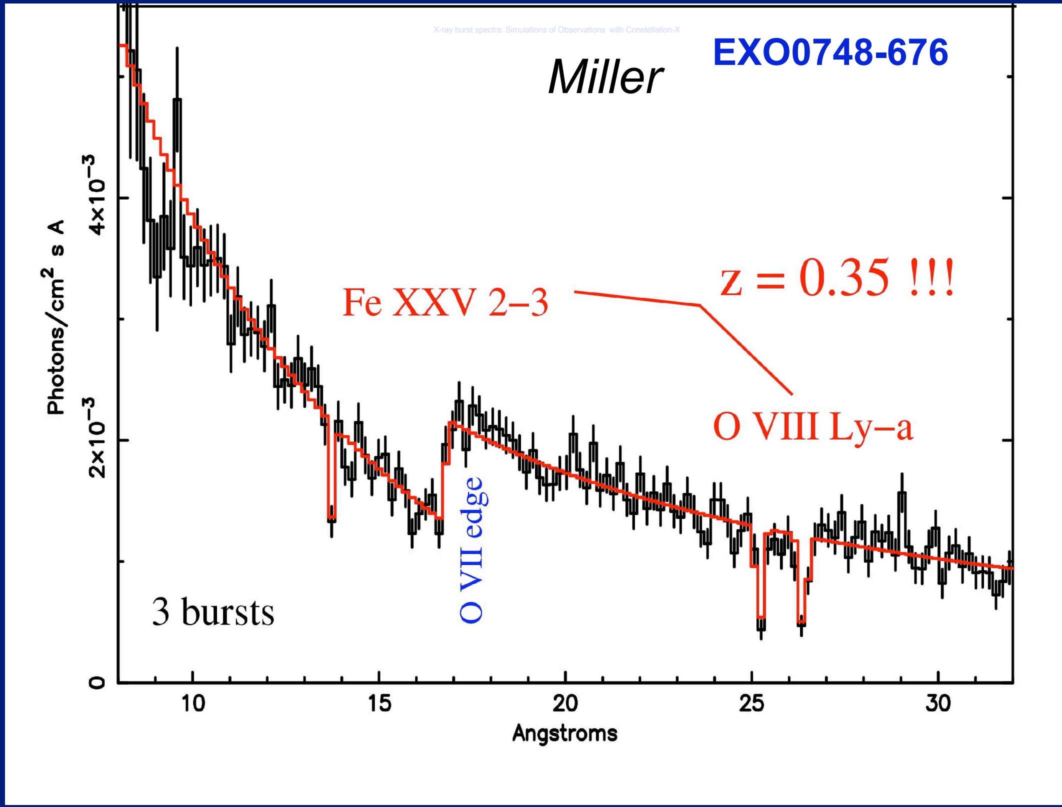
Burwitz et al. 2003

Constellation-X: Equation of State of Neutron Stars

The physical constituents of neutron star interiors remain a mystery. Constellation-X will finally provide the answers by determining the equation of state using multiple techniques: spectra and timing



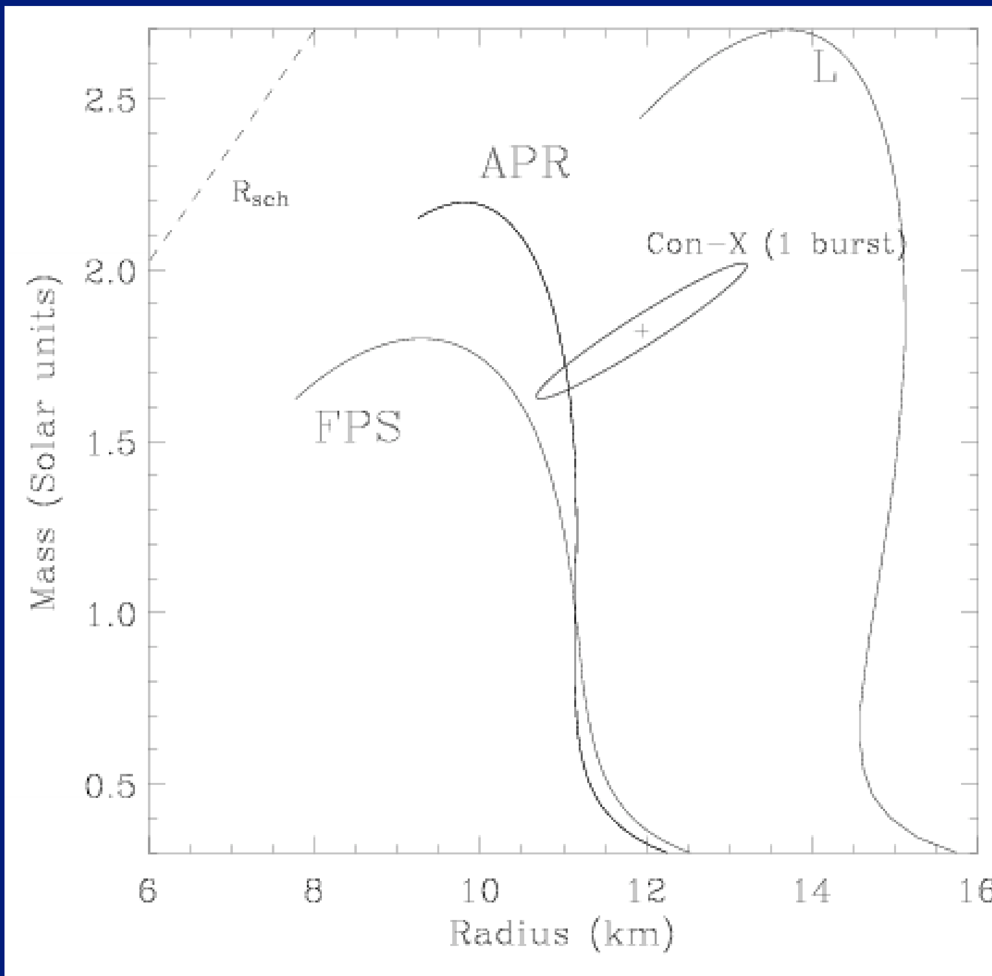




10 eV EW absorption lines can be detected with Con-X in single bursts.

Constellation-X: Equation of State of Neutron Stars

Equation of State Constraints from Burst Oscillations with Con-X



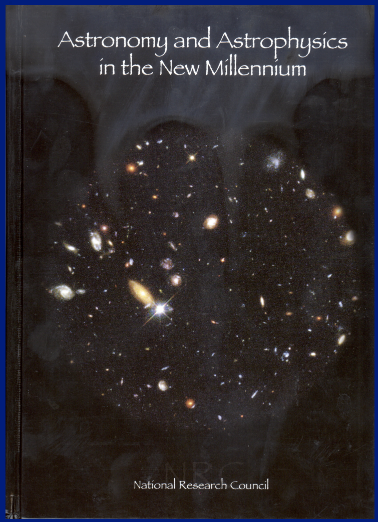
Strohmayer (2003)

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

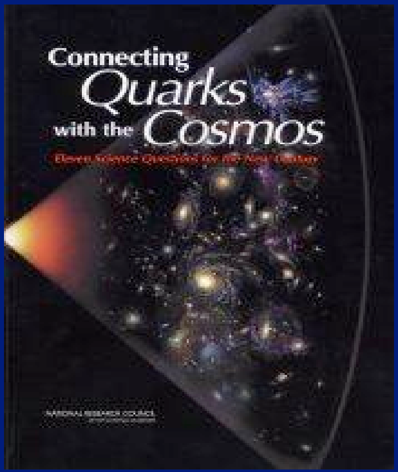
- Modulation amplitude sensitive to compactness, M/R.
- Pulse sharpness (harmonic content) sensitive to surface velocity, and hence radius for known spin frequency.

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

Constellation X-ray Mission Science Priority



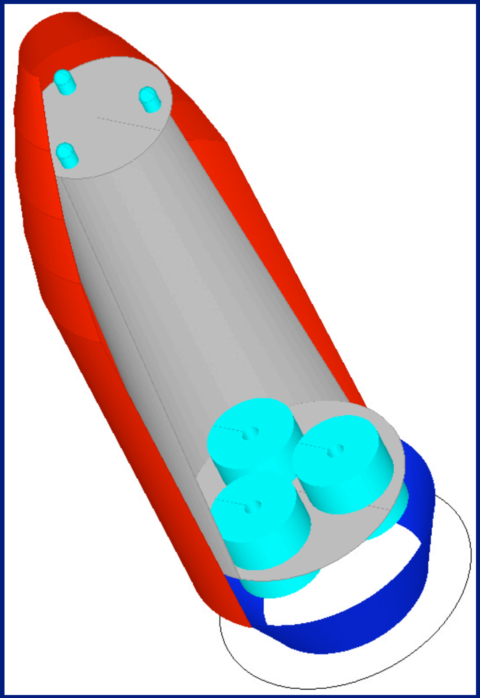
The Astronomy and Astrophysics in the New Millennium (2000) decadal survey ranked Constellation-X priority next after JWST among large new space observatories



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

Con-X can be Gracefully (re)-Scaled

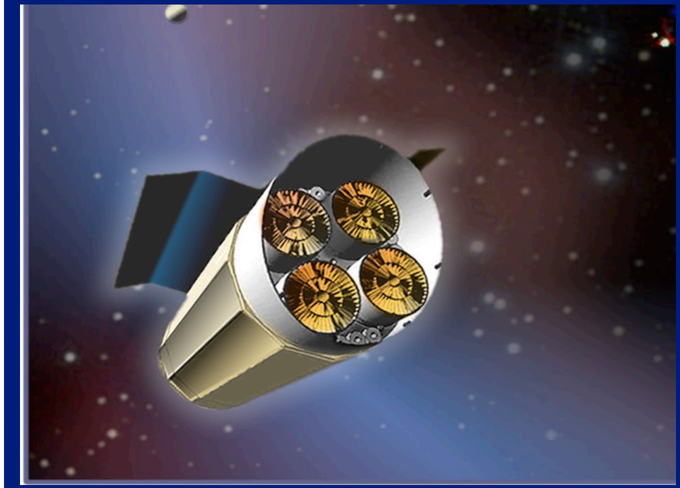


- Con-X 'Lite'
- 3 Telescopes meet Area Requirements
- Grating Spectrometer -> Low-E/Hybrid Calorimeter, Innovative Grating?
- Hard X-ray Telescopes -> Multilayers?
- 100 kg, $0.1B for science enhancement
- Savings of $0.5B

Savings of $0.5B vs 4 + 12 Tele + Gratins single s/c version

Minimum possible mission

Summary: Relativity from Chandra to Constellation-X



Chandra has brought X-ray imaging on par with that at optical wavelengths.

Constellation-X will do the same for X-ray spectroscopy.

X-ray Background:
- Chandra Resolves, ~2/3 unknown
- Con-X will give X-ray IDs, z, spin, BZ
- Stage III, IV, V

Dark Energy/Matter:
- Chandra measures Ω_M, Ω_Λ
- Con-X will measure w, w'

Coeval growth of BH and Galaxies:
- Chandra explains Cooling Flows
- Con-X will measure outflows, spin, mass, abundance, vs z, cosmic feedback?
- Stage III, IV, V

- Backup/extra slides follow

X-RAY ASTRONOMY ROADMAP

Chandra

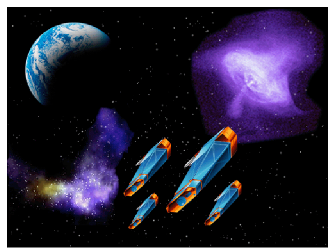
XMM-Newton

Astro-E2

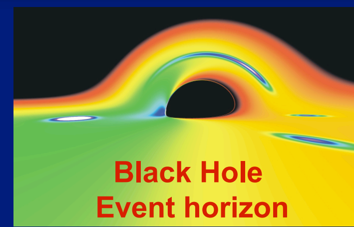
0.1-0.35 m^2
0.5-90 arc sec

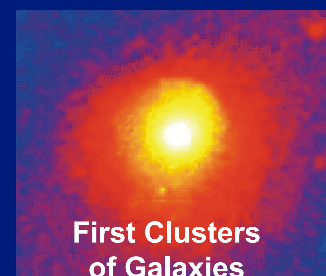
Constellation-X

20-100 times increased sensitivity for spectroscopy



3 m^2
5-15 arc sec





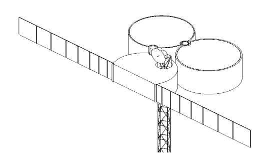
MAXIM

10 Million times finer imaging

0.1-1.0 m^2
0.1 micro arc sec

Generation-X

1000 times deeper X-ray imaging

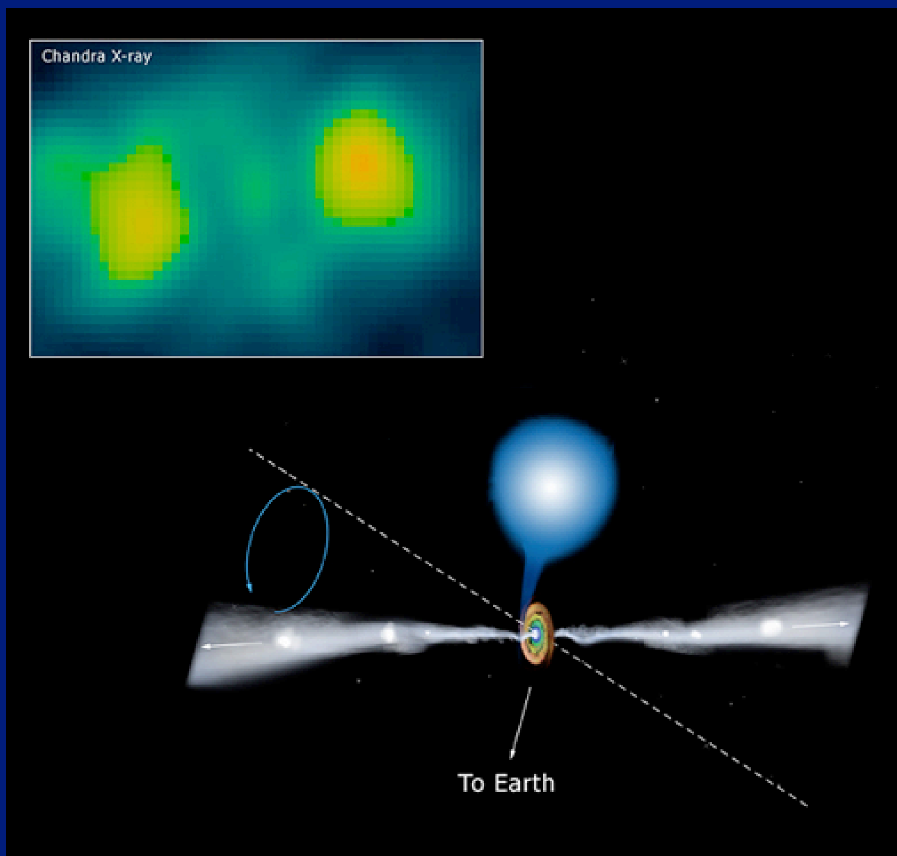


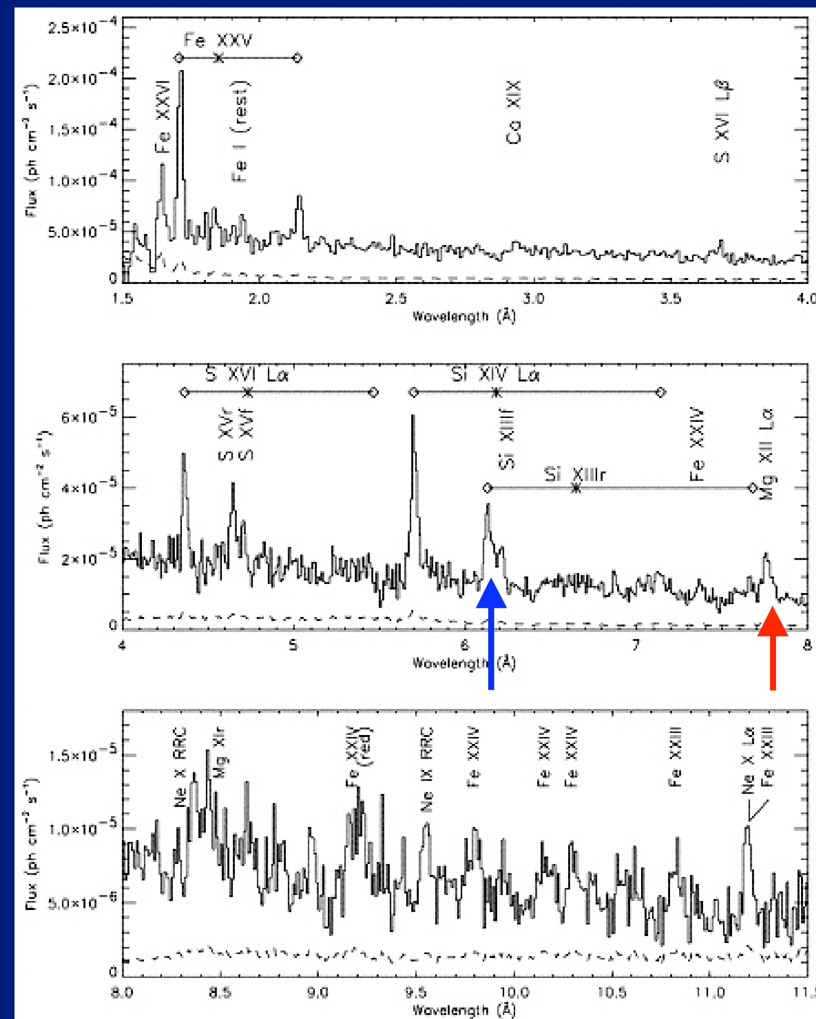
50-150 m^2
0.1-1 arc sec

Constellation-X endorsed by NAS McKee-Taylor Survey & Q2C report as high priority mission for this decade

SS 433

6''



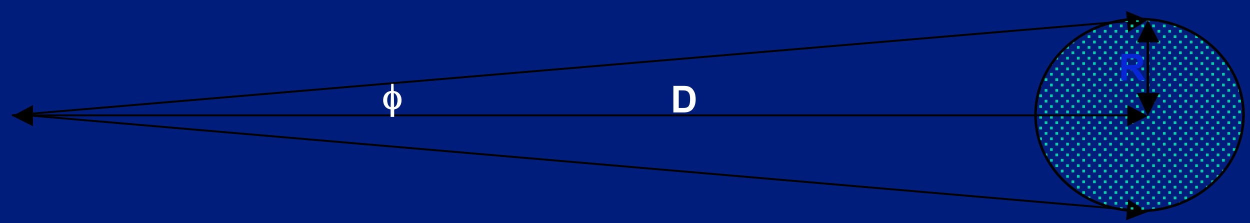


Marshall, Canizares, and Schulz 2002, Migliari et al. 2003

F_{gas} from First Principles

Assume: Hydrostatic Equilibrium (must select virialized, 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



$R = D\sin\phi$

GM_T/R = _ kT	hydro equilb – includes Dark Matter	M_T=1/2 kTR/G ~ D
F_X=const $T^{1/2}\, n_e^2\, R$	Bremsstrahlung Equation	
$n_e\ (\sim n_B) = Fx/(\mathrm{const}\ T^{1/2}\ D\sin\phi))]^{1/2}$	non-X-ray baryons fixed ~$1/6n_B$	$M_B = 4/3\pi n_e R^3 \sim D^{-1/2} D^3$
$n_e \sim D^{-1/2}$		$M_B \sim D^{5/2}$
f(gas) ~ $M_B/M_T \sim D^{3/2}$	measure fgas vs z(d)	IF fgas not constant – z(d) diff diff z(d) = Dark Energy

Abs[fgas] = Dark Matter