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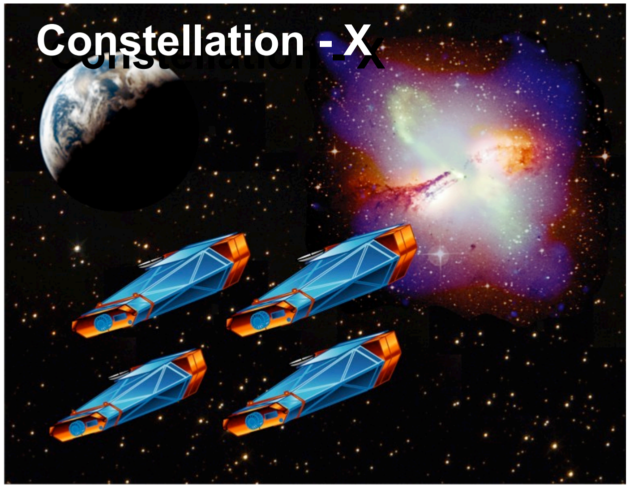
Constellation X-ray Mission:

Science and Prospects

Presented by Harvey Tananbaum (SAO) on behalf of the
Constellation-X Team
HEAD-AAS New Orleans September 9, 2004

Constellation-X Mission Overview



An X-ray VLT

Use X-ray spectroscopy to observe

- **Black holes: strong gravity & evolution**
- **Dark Matter throughout the Universe**
- **Dark Energy parameters**
- **Production and recycling of the elements**

Mission parameters

– **Telescope area:** 3 m^2 at 1 keV

25-100 times XMM/Chandra for high resolution spectroscopy

– **Spectral resolving power:** 300-1,500

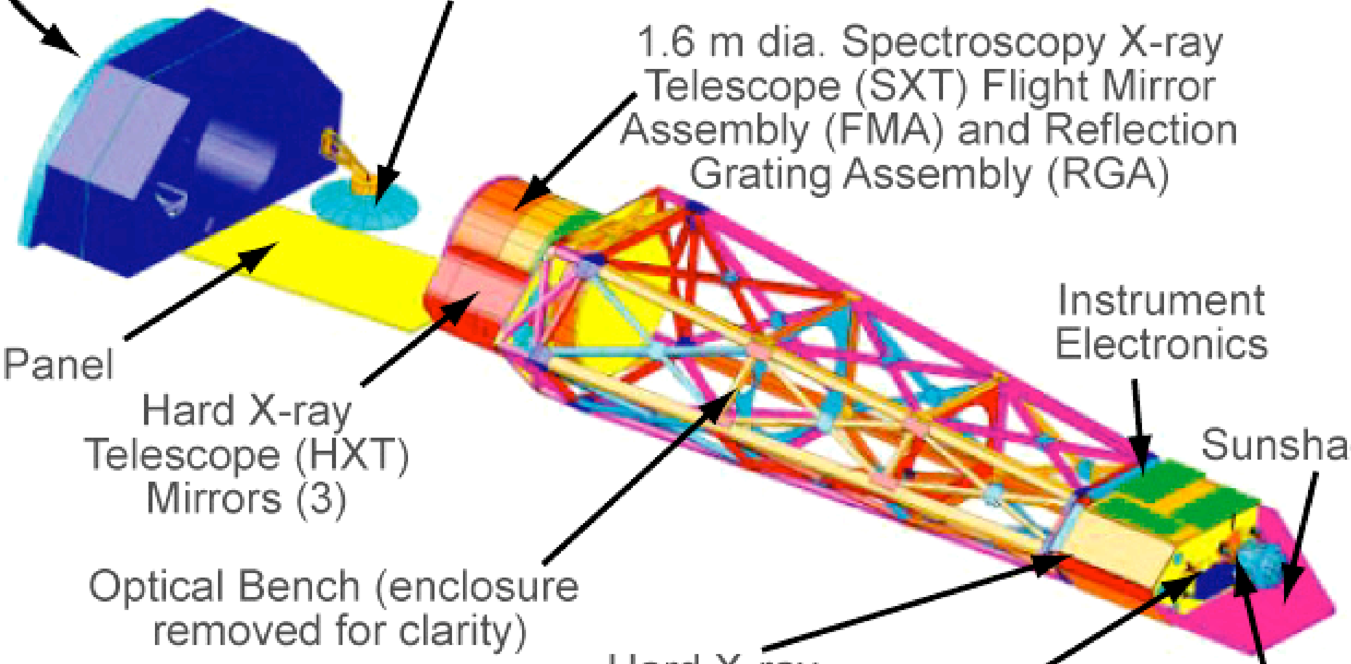
2-3 times better than Astro-E2 at 6 keV

– **Band pass:** 0.25 to 40 keV

100 times RXTE sensitivity at 40 keV

Enable high resolution spectroscopy of faint X-ray source populations

Exploded View of Constellation-X Observatory



Spacecraft Bus

Spacecraft Bus Component Compartments

High Gain Antenna

Solar Panel

Hard X-ray Telescope (HXT) Mirrors (3)

Optical Bench (enclosure removed for clarity)

Telescope Module

1.6 m dia. Spectroscopy X-ray Telescope (SXT) Flight Mirror Assembly (FMA) and Reflection Grating Assembly (RGA)

Instrument Electronics

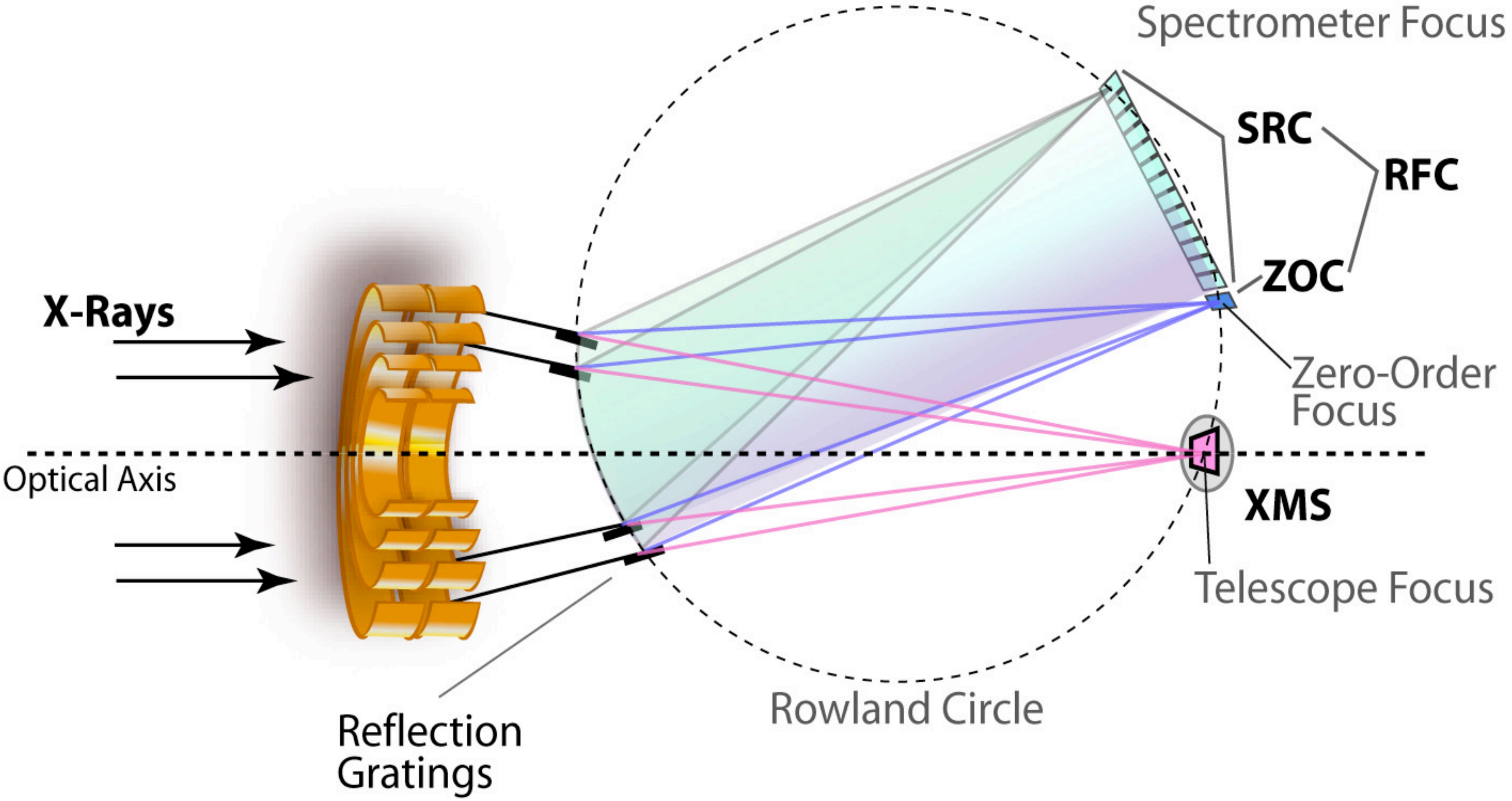
Sunshade

Hard X-ray Telescope (HXT) Detectors (3)

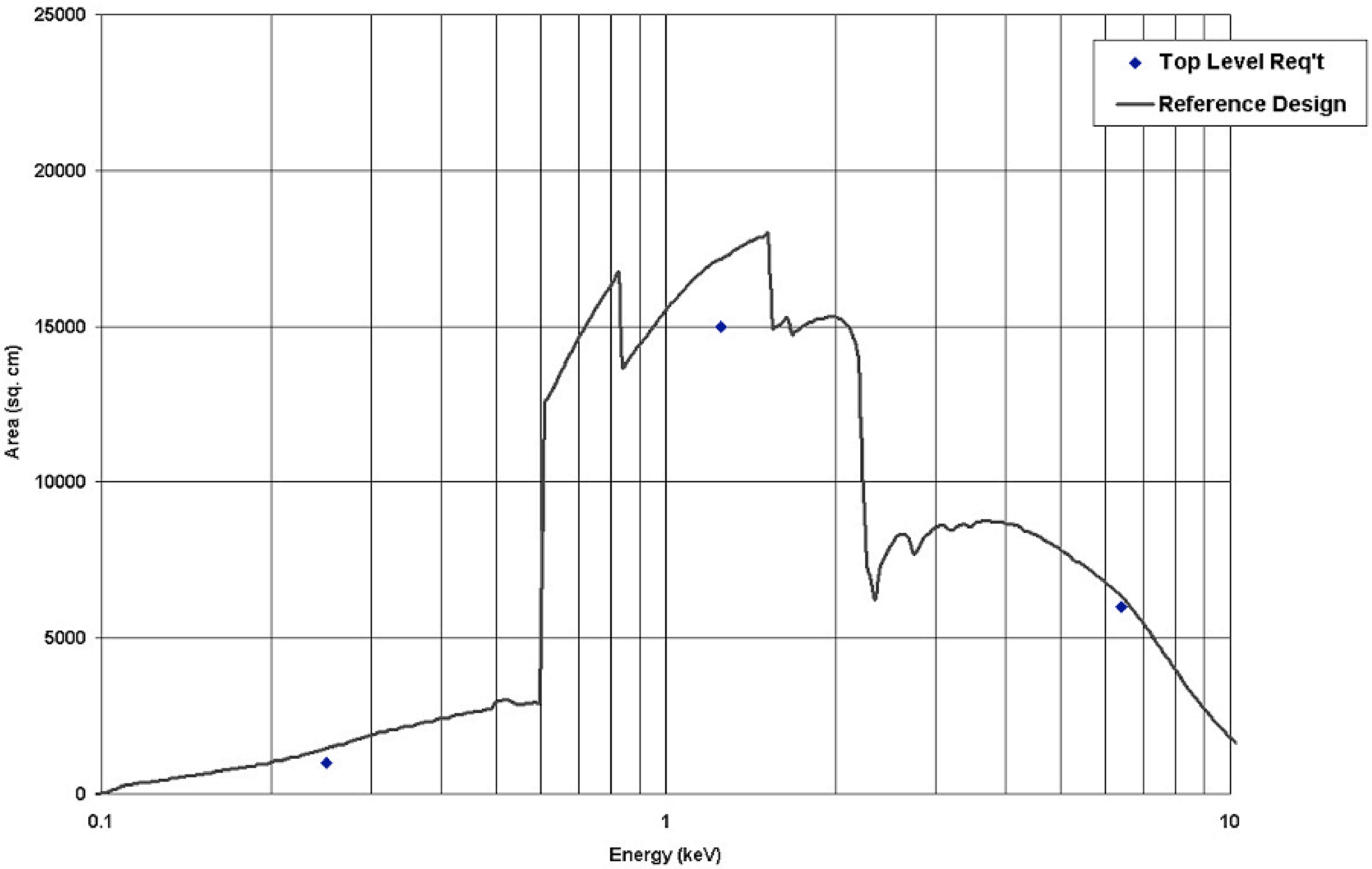
RGS Focalplane Camera (RFC)

X-ray Microcalorimeter Spectrometer (XMS)

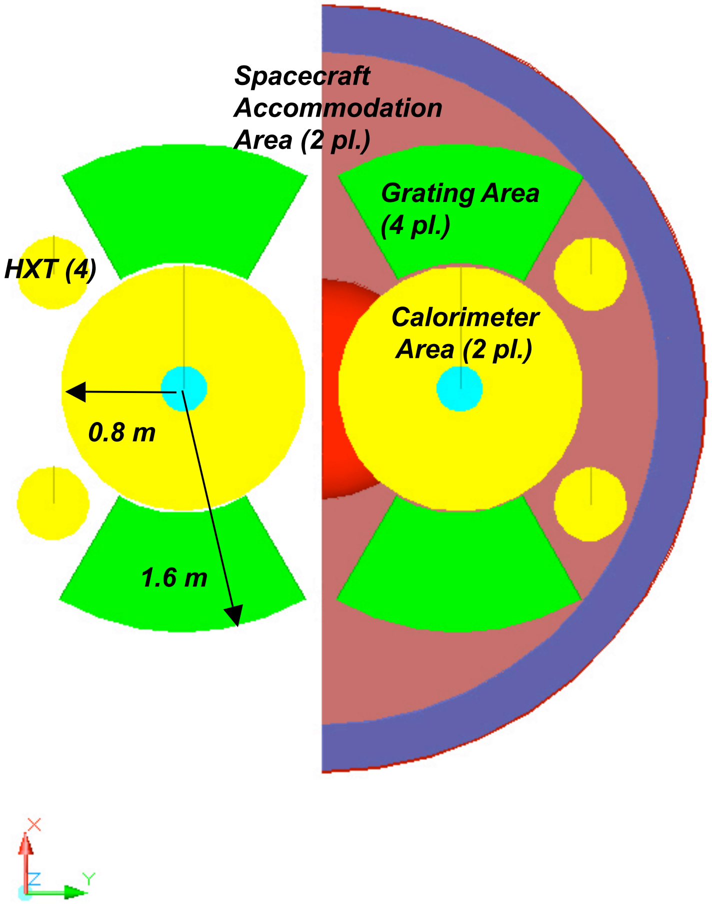
SXT Optical Path



SXT Effective Area



3.2m/1.6m x12m FL Configuration



2 Complete SXTs per launch

- **2 sets of detectors req'd.**

3.2m OD x (4) 60° wedges for gratings

(2) 1.6m Full Diameter Inner Tel.

- **0.3m ID**

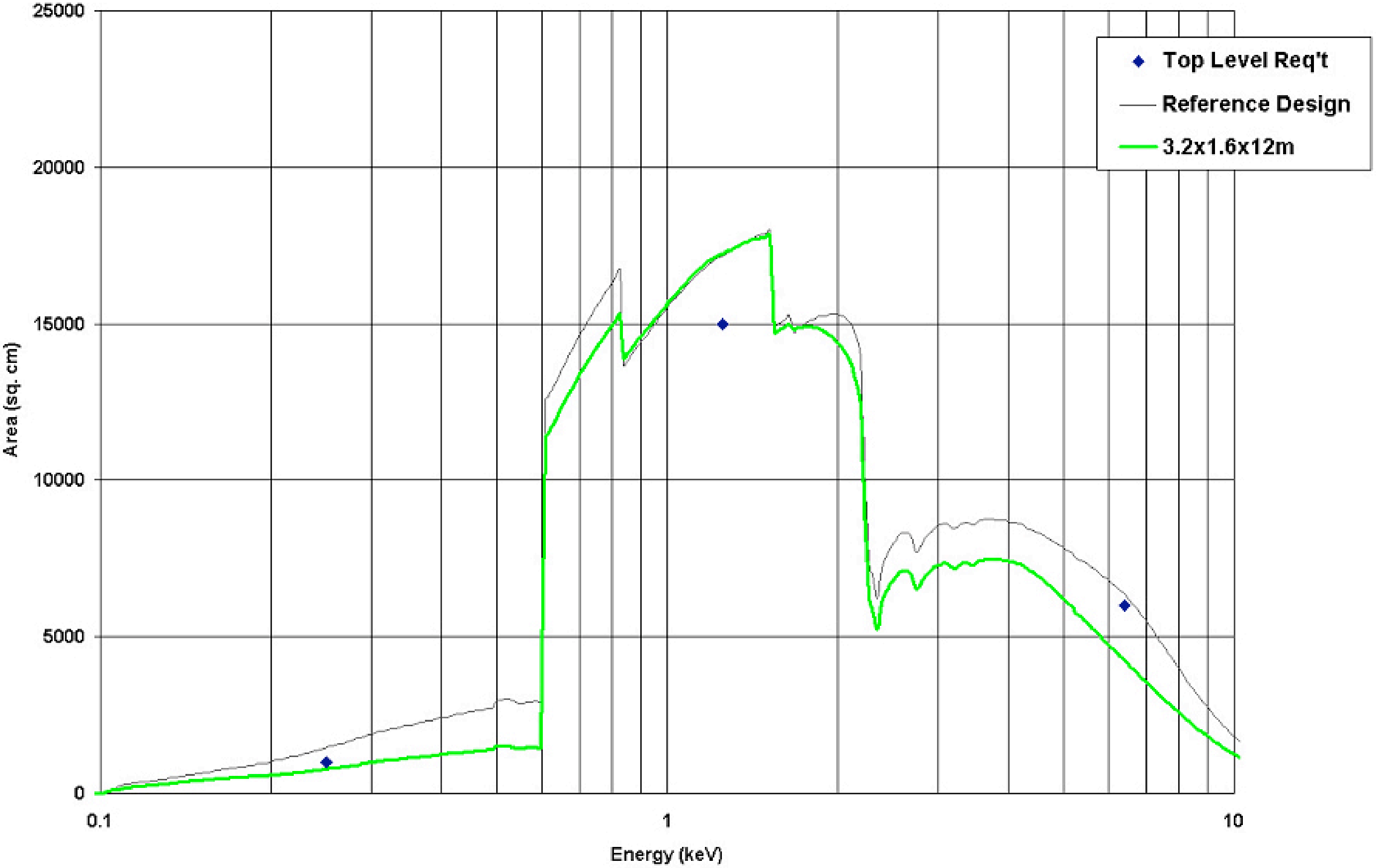
12m Focal Length

- **Can be accommodated in 19.1m fairing with *fixed* optical bench**

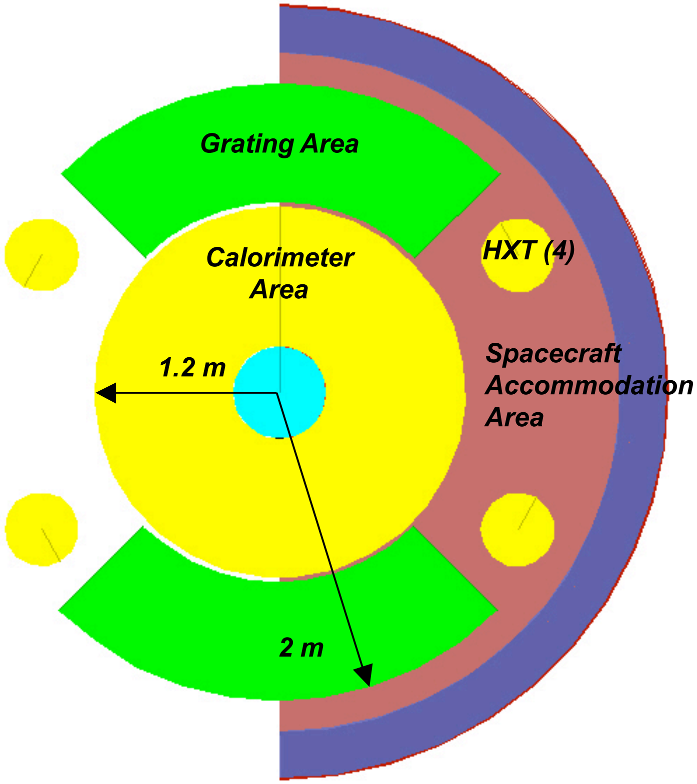
SXT raw glass weight ~850 kg

- **Should be OK for Delta-4H launch**

SXT Effective Area



4m/2.4m with 25m FL “Bowtie” configuration



4m OD x (2) 90º wedges

2.4m Full Diameter Optic

- 0.6m ID

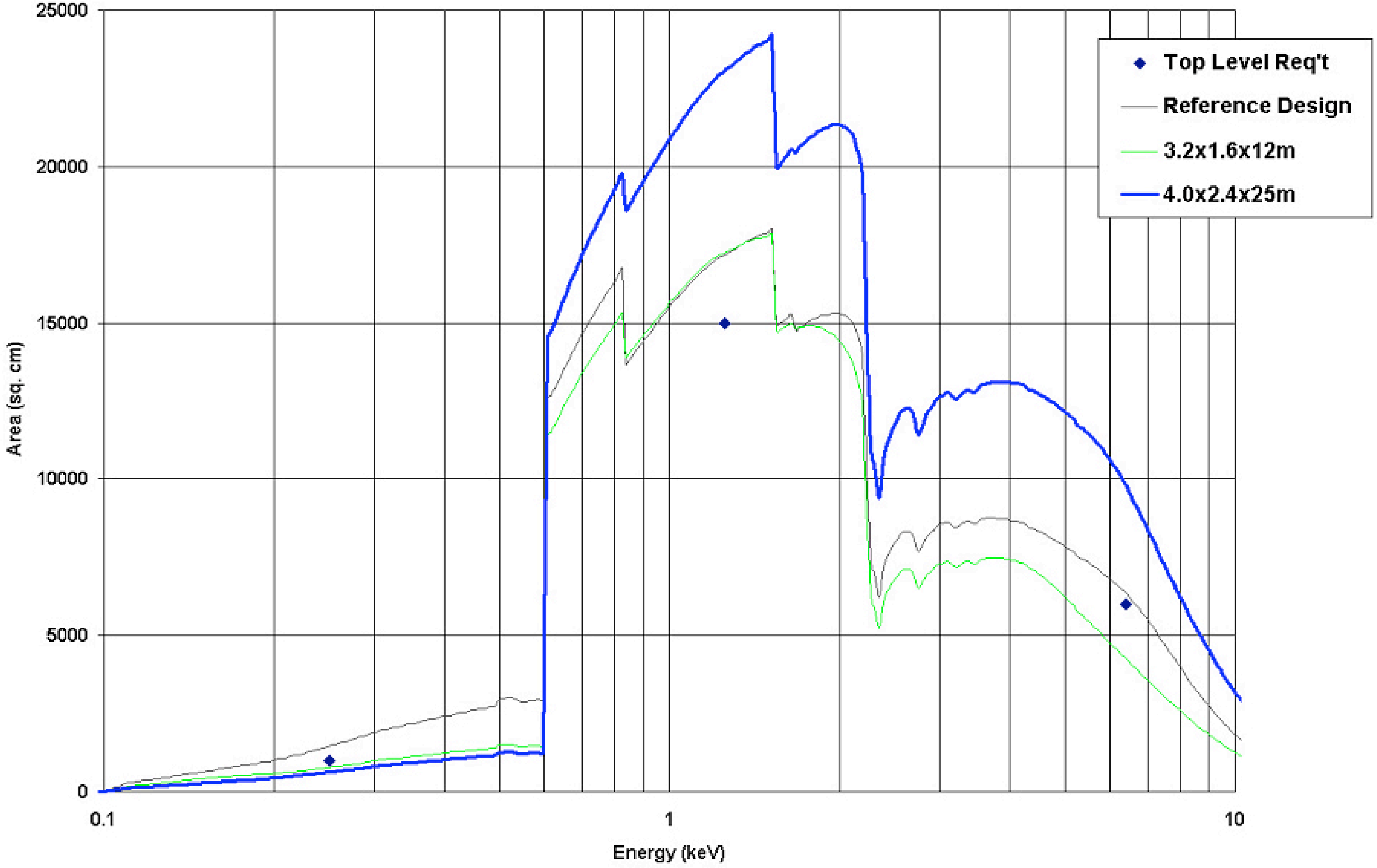
25m Focal Length

- Requires extendable bench or mast

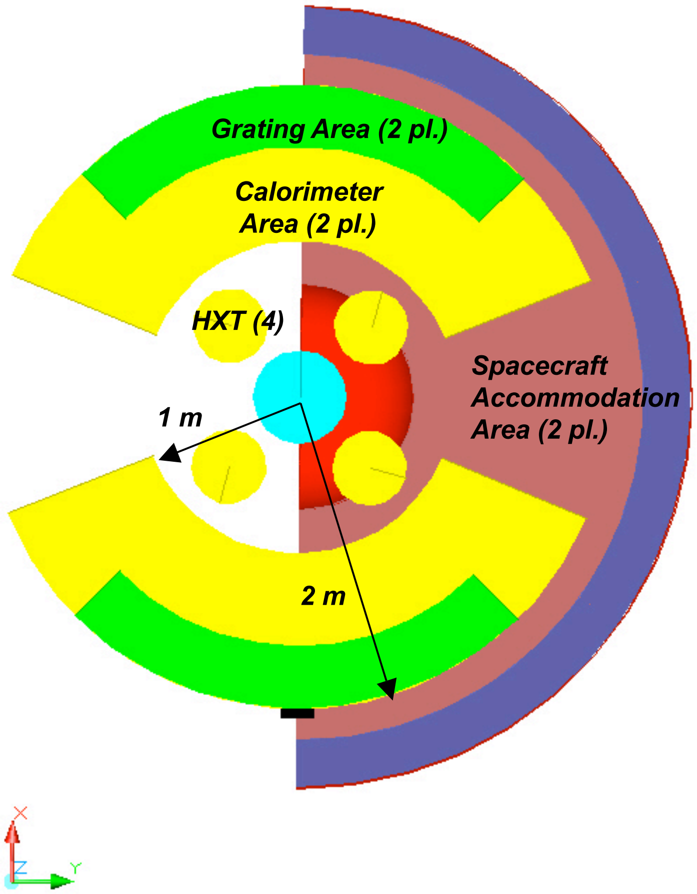
SXT raw glass weight of 1085 kg

- Should be OK for Delta 4H launch, depending on weight of extension hardware

SXT Effective Area



4m/2m 135º Wedge with 50m FL Configuration



4m OD x (2) 135º wedges

2m ID

Gratings cover (2) 90º arcs

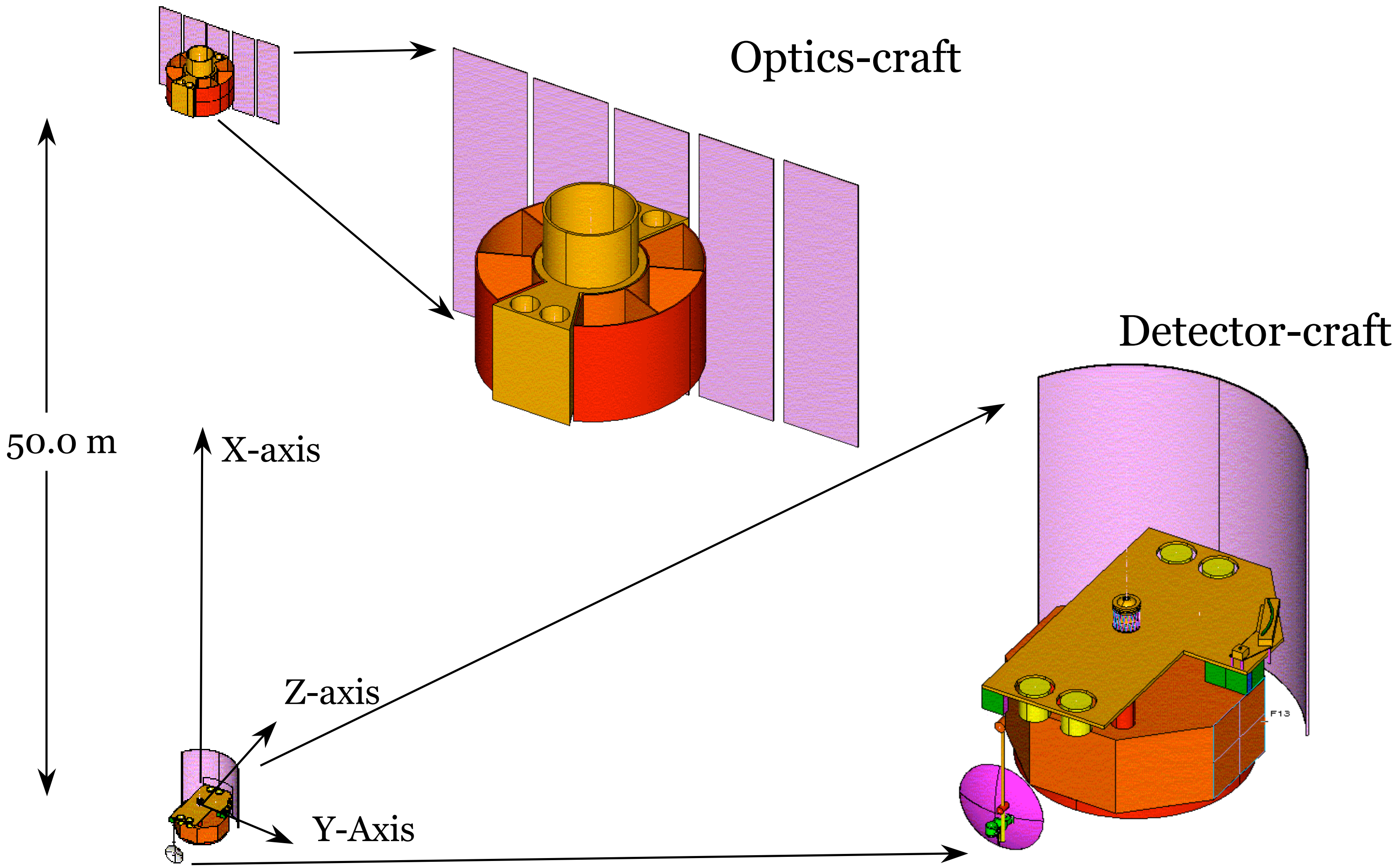
50m Focal Length

- •Requires 2 spacecraft formation flying

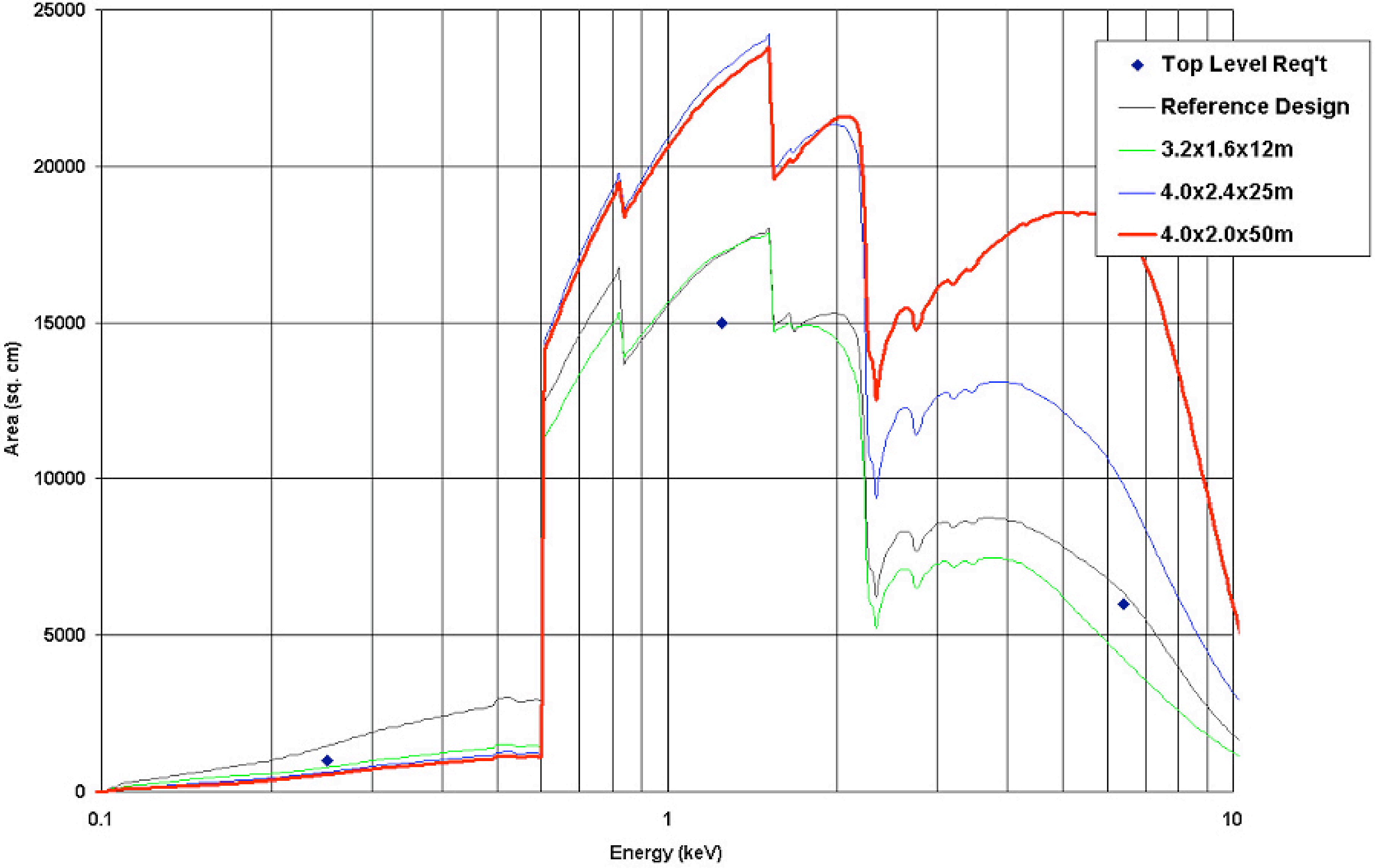
SXT raw glass weight ~1304 kg

- •May stress launch capabilities of Delta 4H, depending on SXT structural weight, and propulsion requirements

Orbit configuration for 50m focal length separated s/c



SXT Effective Area



This talk will concentrate on the Constellation-X Science Goals in three Beyond Einstein Topics:

1. What happens close to a Black Hole?

   (thanks to Jon Miller, Chris Reynolds, Paul Nandra)

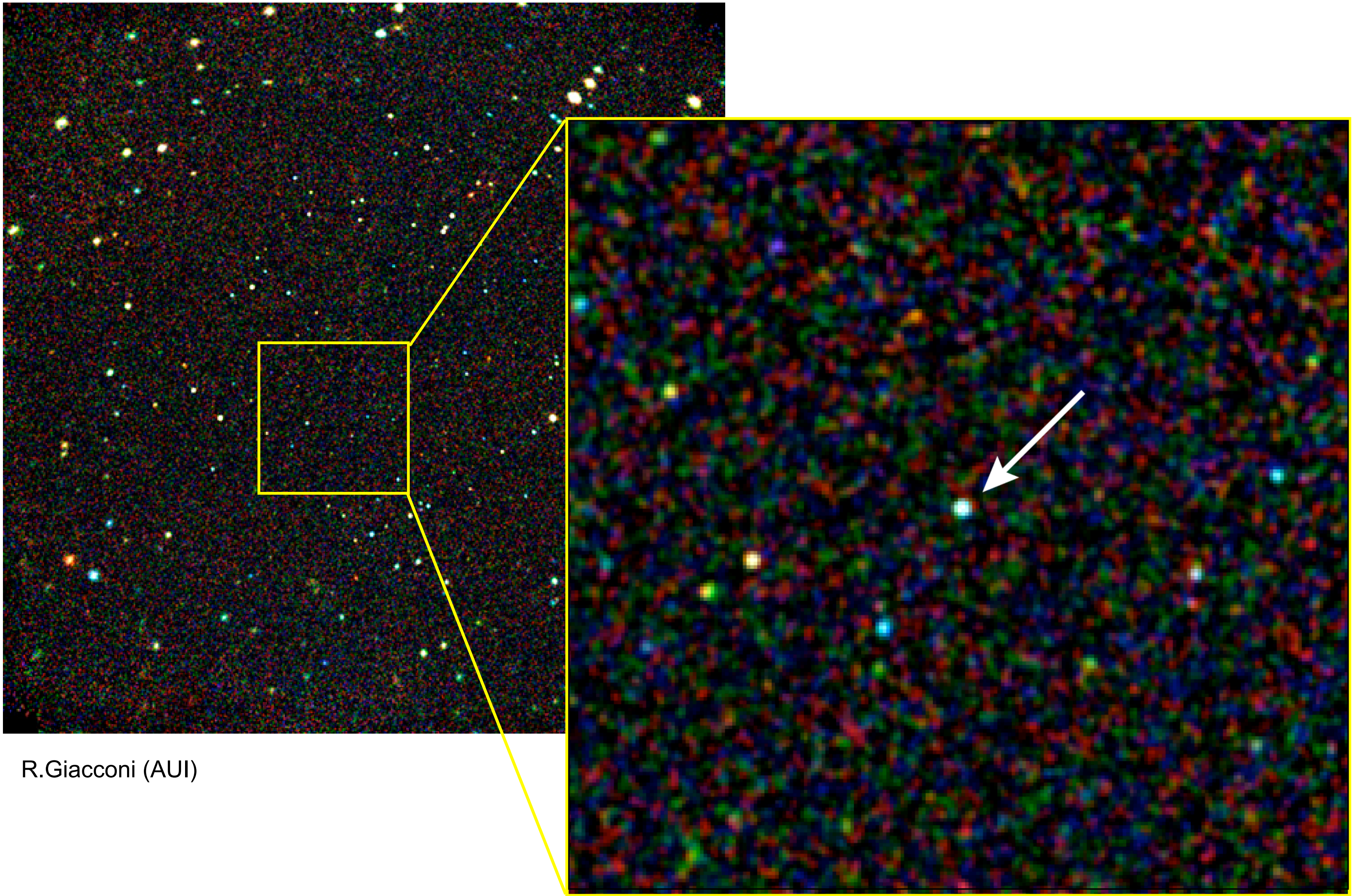
2. What is Dark Energy?

   (thanks to Steve Allen, Richard Mushotzky)

3. What is the Equation of State of Neutron Star?

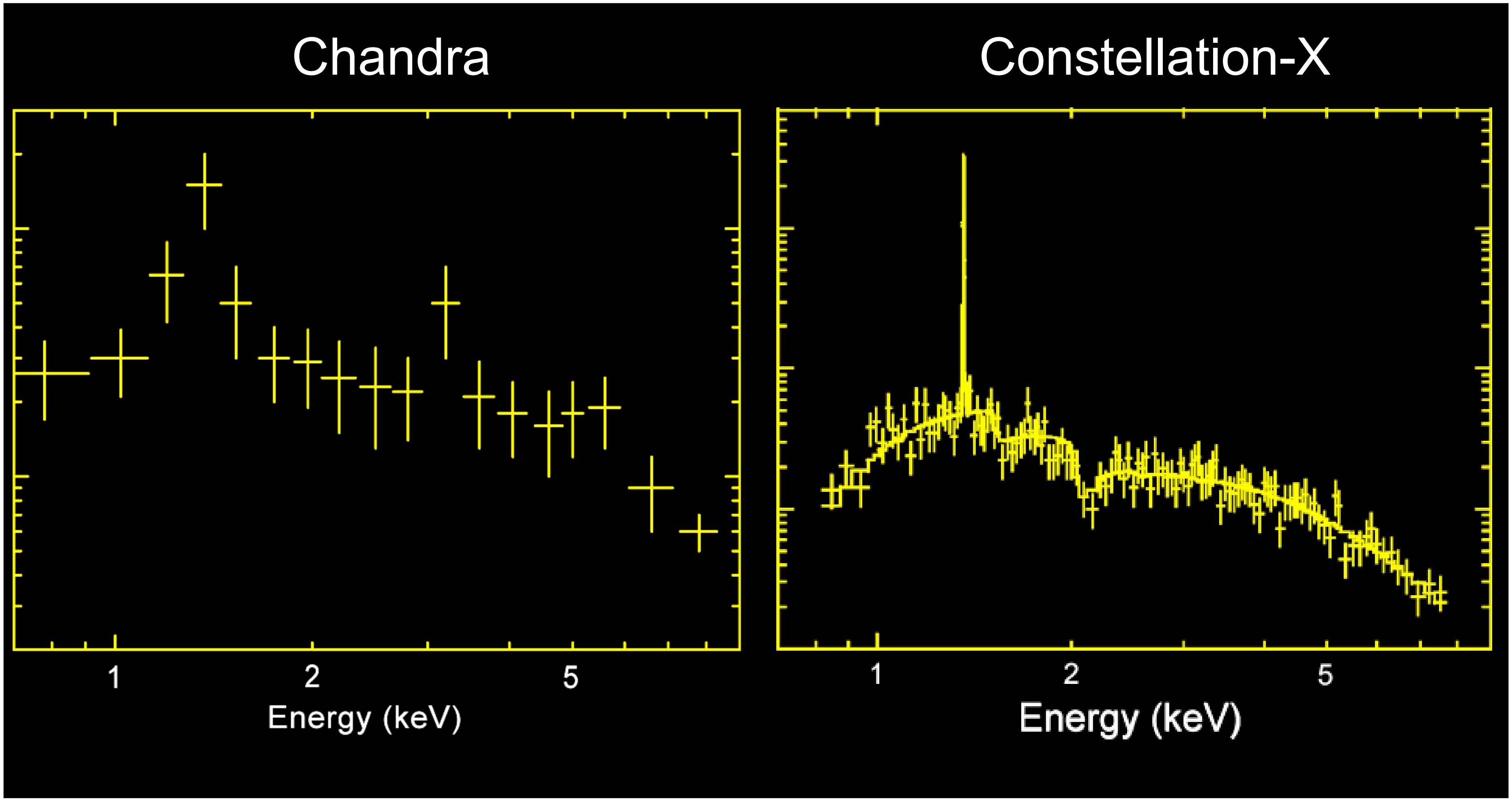
   (thanks to Tod Strohmayer, Jean Cottam)

Chandra Deep Field South



R.Giacconi (AUI)

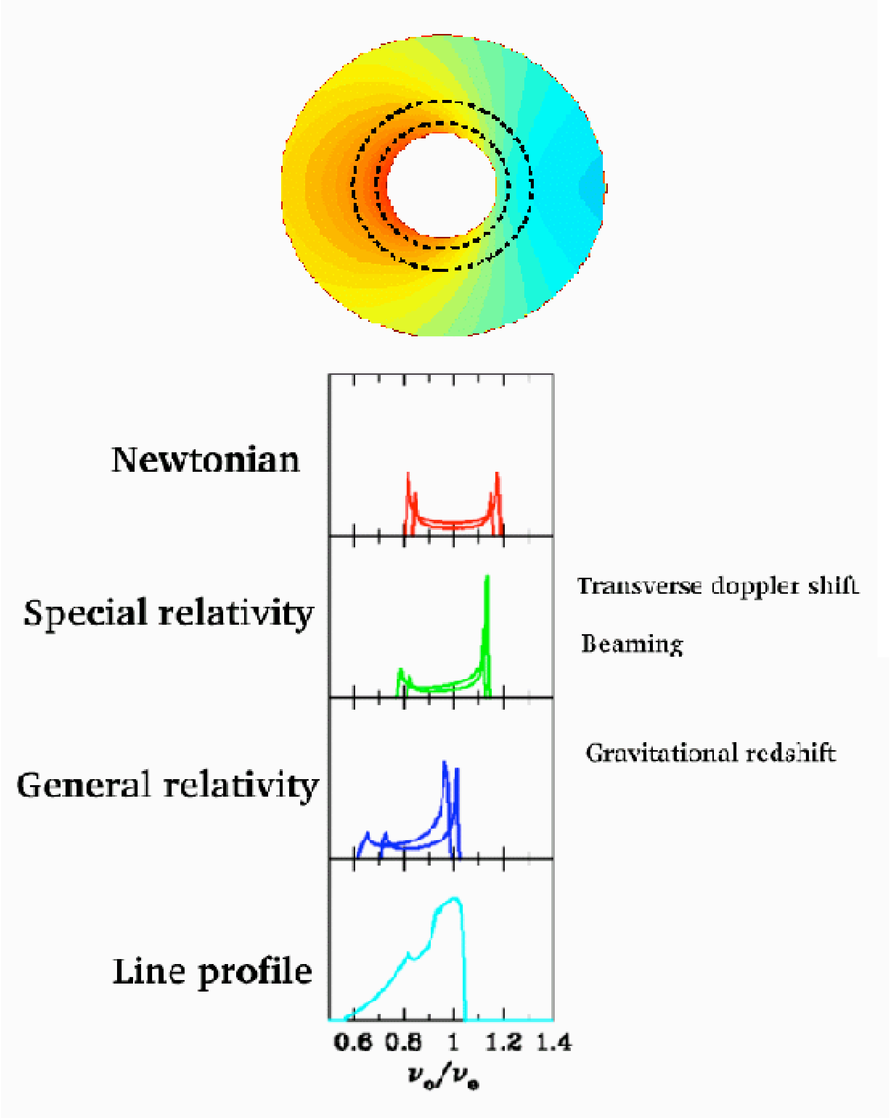
Type 2 Quasar at z = 3.7

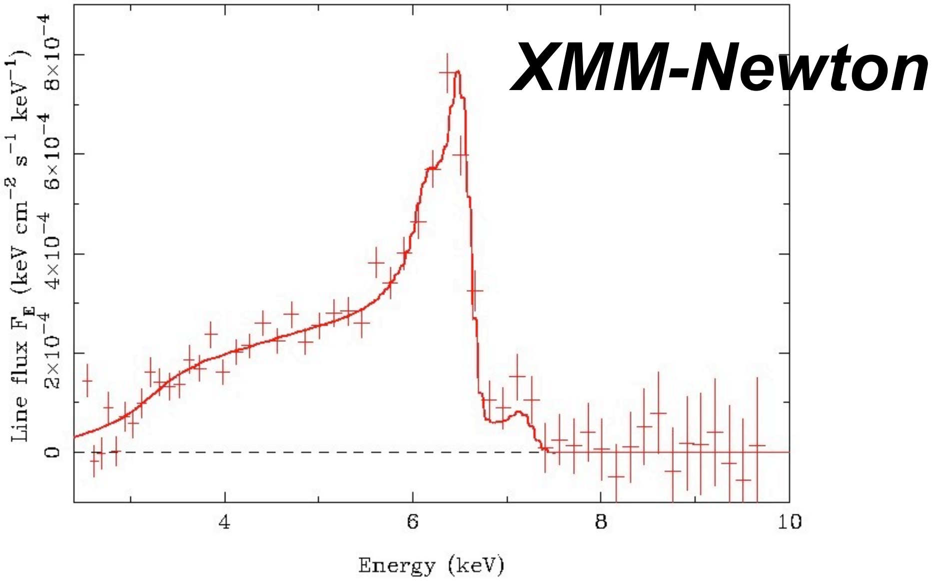


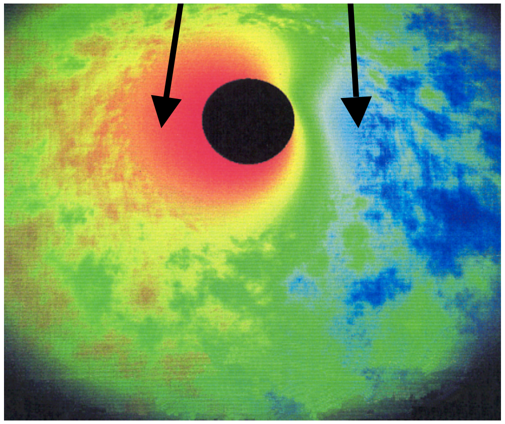
C.Norman (STScI)

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.

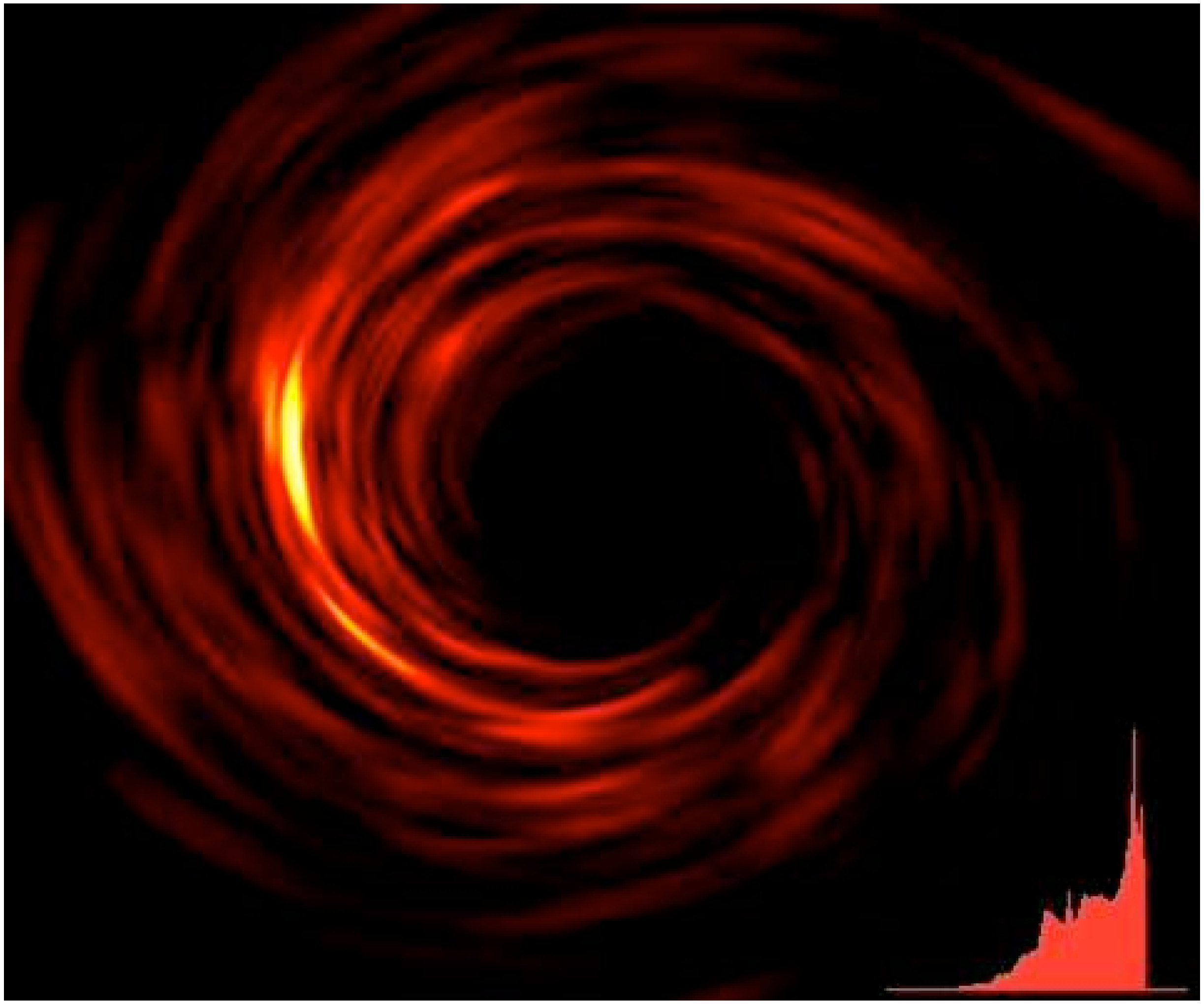






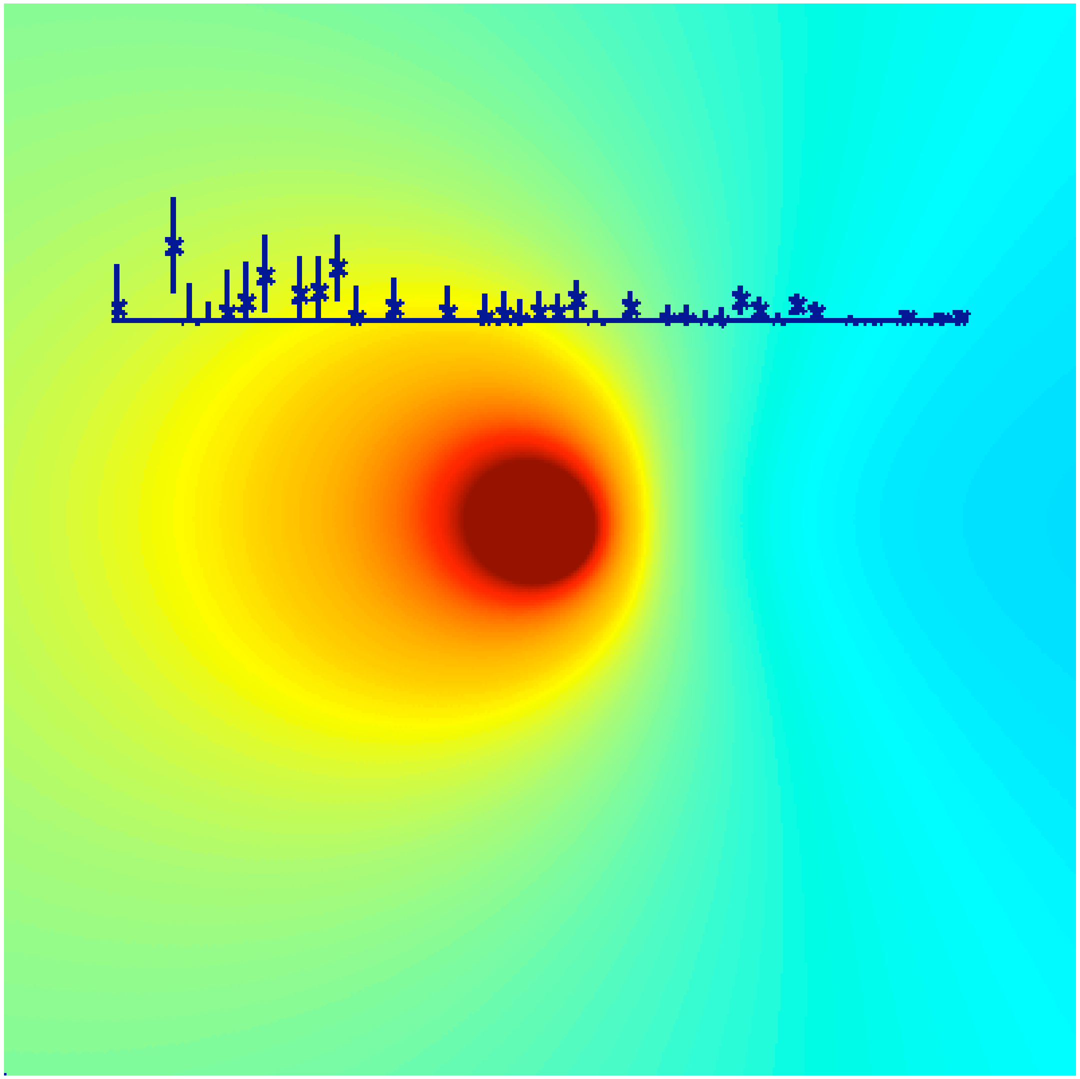
Theoretical ‘image’ of an accretion disk.

MHD Simulations of Accretion Disk and Relativistic Iron Line Emission



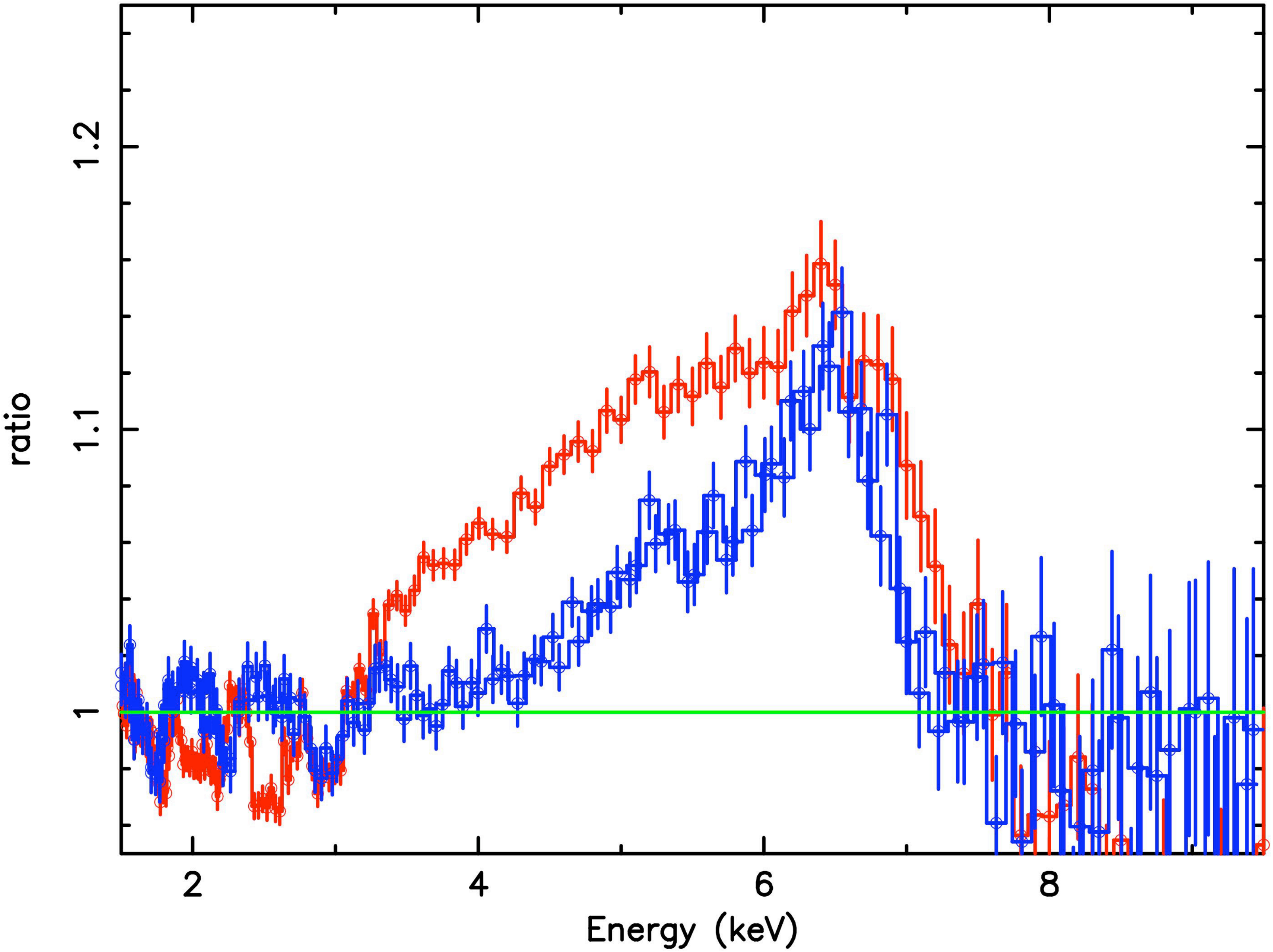
C.Reynolds (U Md)

Black Hole Flare



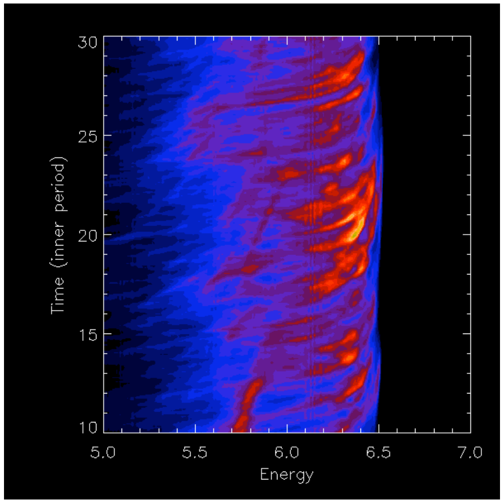
C.Reynolds (U Md)

GX 339-4



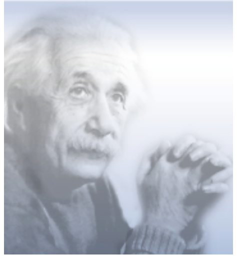
J.Miller (CfA)

Con-X and Strong Gravity

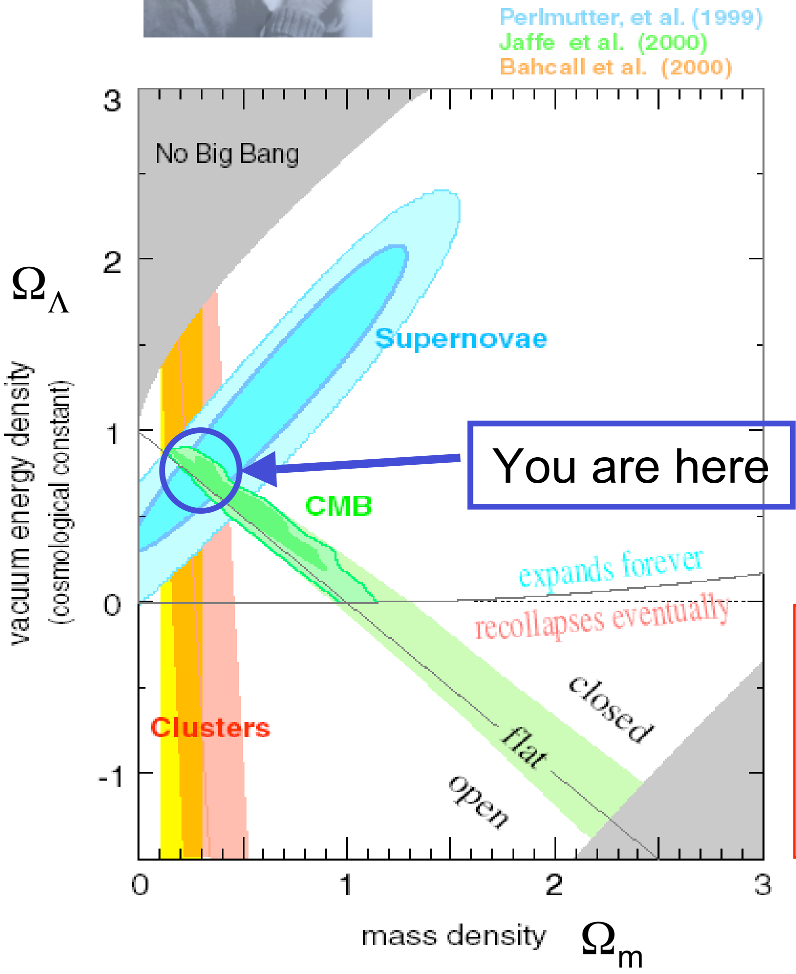


- Con-X observations of broad iron line AGN
  - **Variability of the broad iron line**
  - Can “see” non-axisymmetric orbiting structures
    - ⇒Direct measure of particle orbits close to BH
  - Line reverberation as flares sweep across disk
    - ⇒Direct probe of photon orbits close to BH
  - Check for consistency with GR predictions (Kerr)
    - If OK, can measure BH masses and spins!
    - Otherwise, can constrain alternative space-time metric
    - Basic analysis technique does not rely on validity of GR or any other particular theory (no template fitting needed to extract signal).
- Comparison of AGN and Galactic Black Hole Binaries
  - **Examine nature of gravity across 5-6 orders of magnitude in mass (using time-averaged line profiles)**
  - GR predicts scale-independence… do we see that?
- Con-X observations of neutron star absorption lines
  - **Redshifts of NS emission lines are probe of the strong gravity**
  - Constrains “RHS” of Field Equations, i.e., coupling of matter/fields to spacetime curvature (modulo e-o-s uncertainties)

Dark Energy and Dark Matter



A major challenge to physics is that there is no “unique natural” candidate for dark matter and no physical theory accounts for the dark energy.



You are here

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!

The Baryonic Fraction “Standard Candle”

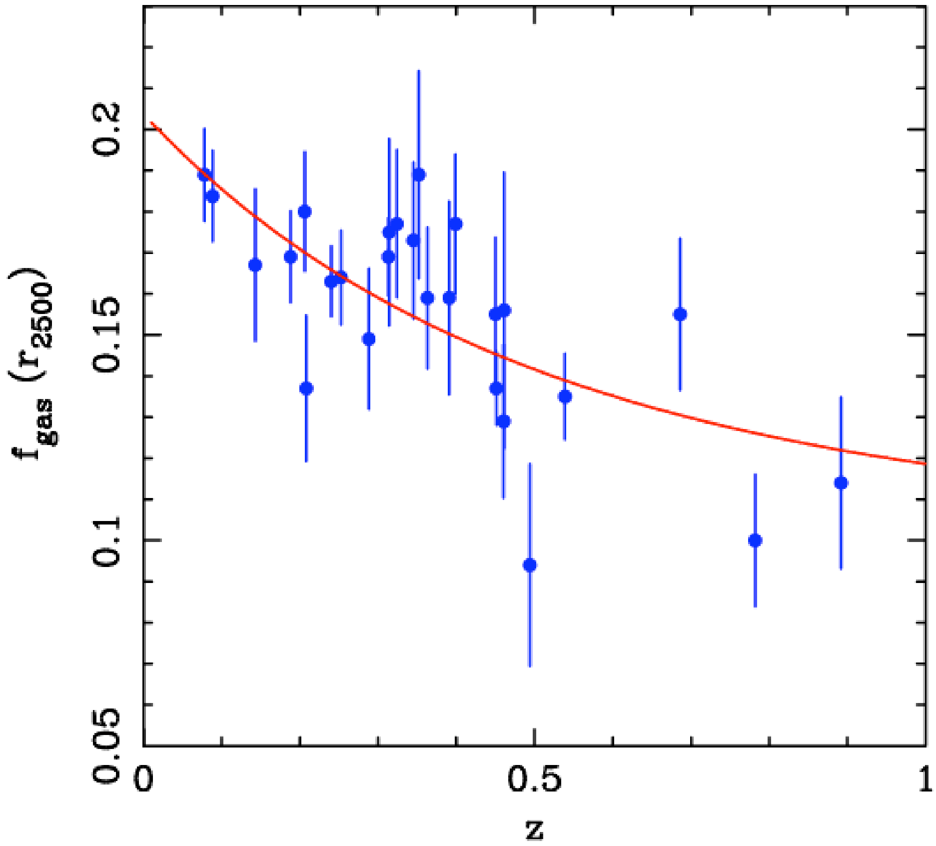
Clusters of Galaxies are the largest objects in the Universe and the relative amounts of dark and baryonic matter ($f_{gas} = \Omega_b/\Omega_m$) should be constant.

This translates to a determination of the angular diameter distance.

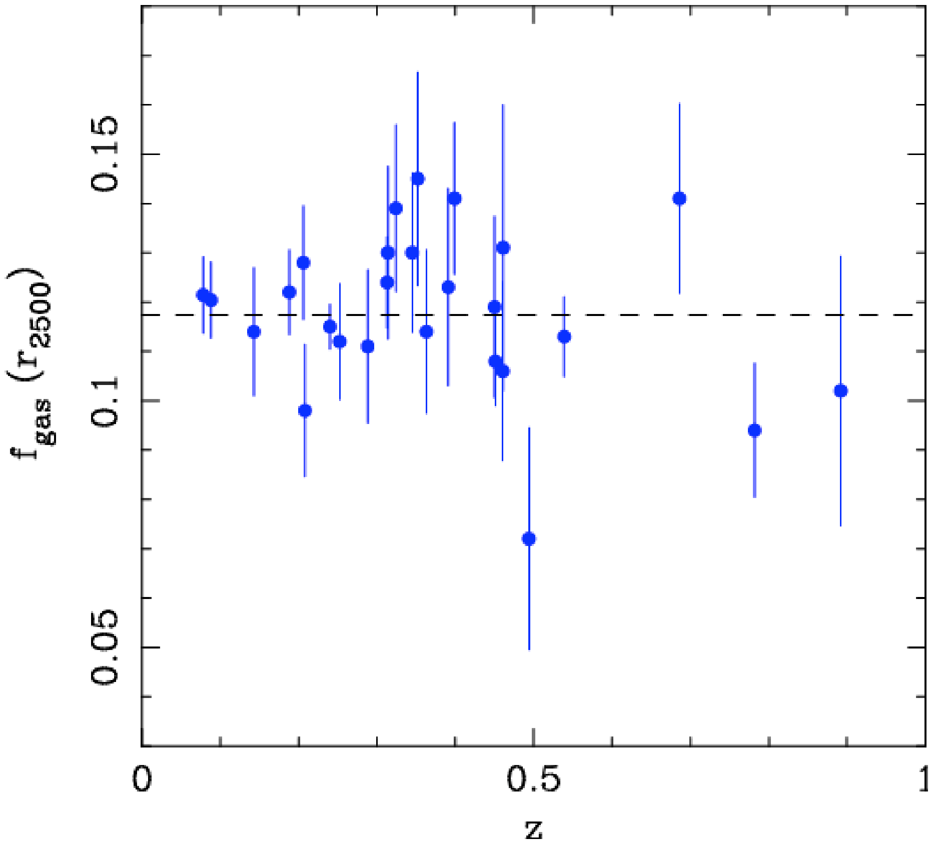
A major strength of the method is that it gives precise constraints on Ω_m as well as Dark Energy, thereby breaking a key degeneracy affecting other methods.

The combination of f_{gas} plus the CMB removes the need for external priors.

Chandra Results



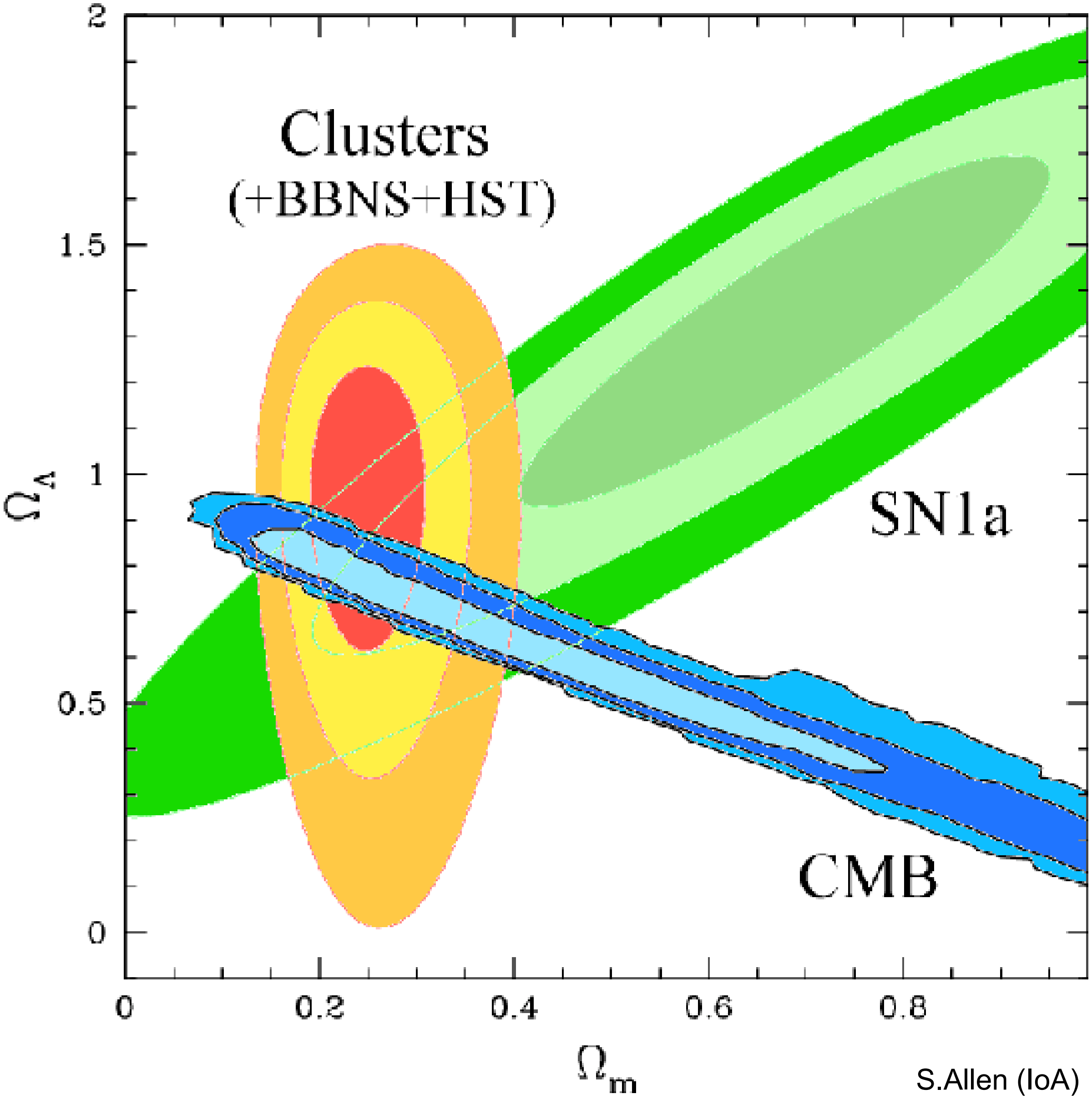
SCDM Cosmology



ΛCDM Cosmology

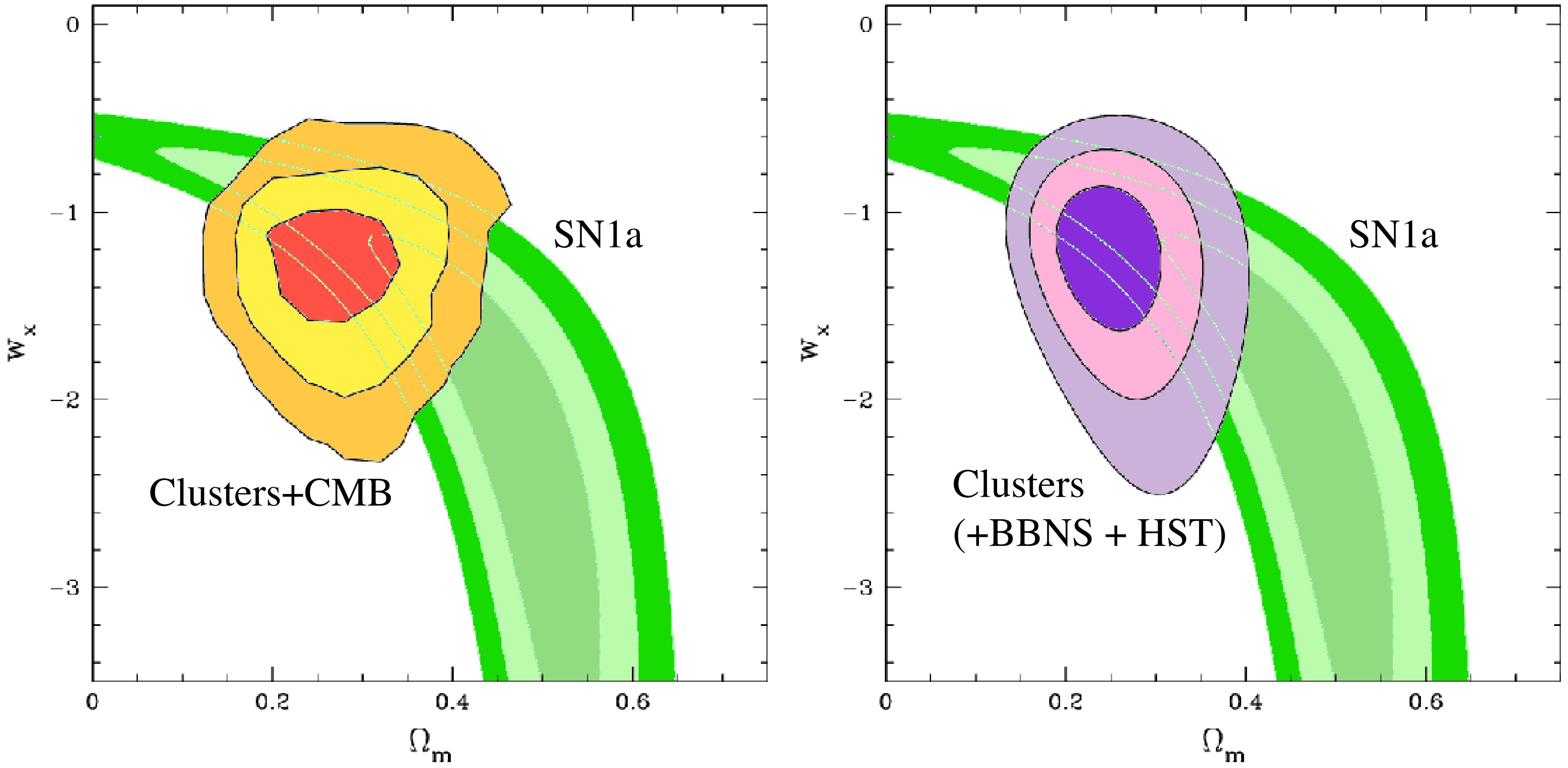
S.Allen (IoA)

Cosmological Parameters



S.Allen (IoA)

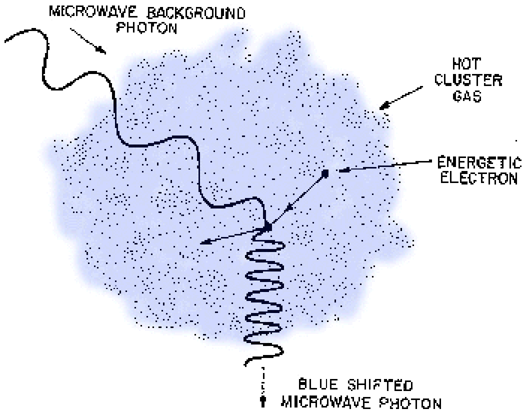
Dark Energy Parameter

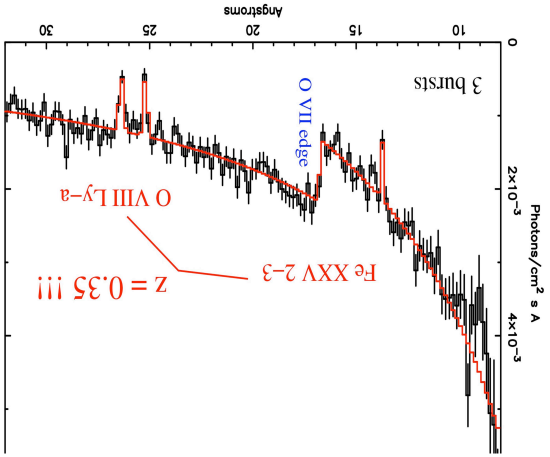


S.Allen (IoA)

Cosmology with Sunyaev-Zeldovich Distance Measure

$$\Delta T \propto g(\nu) \int dz\, n_e(\mathbf{r})\, T_e(\mathbf{r}). \quad H_0 \propto \left(\frac{T_e}{\Delta T_{SZ}}\right)^2 \theta S_X \frac{\ell_\perp}{\ell_\parallel}, \quad D_A \propto \frac{(\Delta T_0)^2 \Lambda_{eH0}}{S_{x0} T_{e0}^2} \frac{1}{\theta_c},$$





All the required quantities are directly measurable with an X-ray image + spectrum and a S-Z microwave image

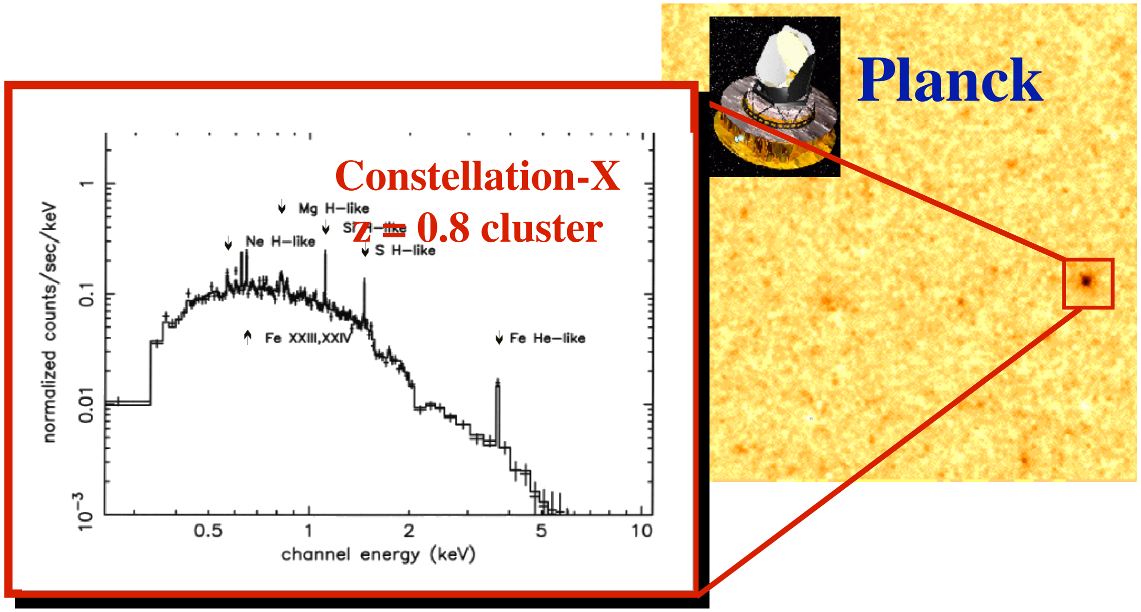
Sensitivity to cosmological parameters due to Ω_m, H_0 and $w(\Omega_E)$ dependence on the transformation from redshift to distance

- Present estimates from 41 S-Z clusters (e.g. Reese et al 2002) give $H_0 = 61$ +/- 3, a statistical error similar to WMAP
- Current systematic errors of +/- 18 in H_0 dominates due to too few objects to average out geometry effects

Improved SZE measurements combined with 500 Con-X clusters will provide the required precision

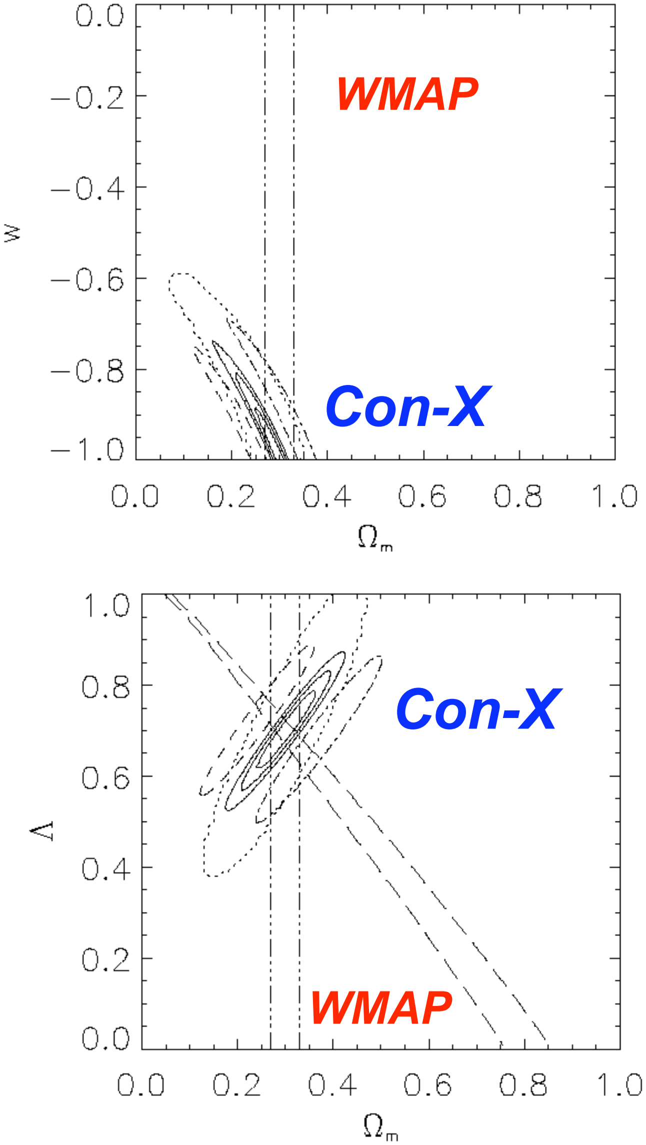
SZE Cosmology with Clusters of Galaxies

SZE and X-ray surveys will find many thousands of clusters, Constellation-X required to follow up ~500 most massive high redshift clusters with detailed spectroscopy



Cosmological parameters Ω_{m}, H_0 and $w(\Omega_E)$, will be determined via Con-X observations of most distant clusters combined with SZE data

The SZE constraints are orthogonal to those from the microwave background constraints



SZE derived cosmological parameters using 500 clusters Molnar et al (2002)

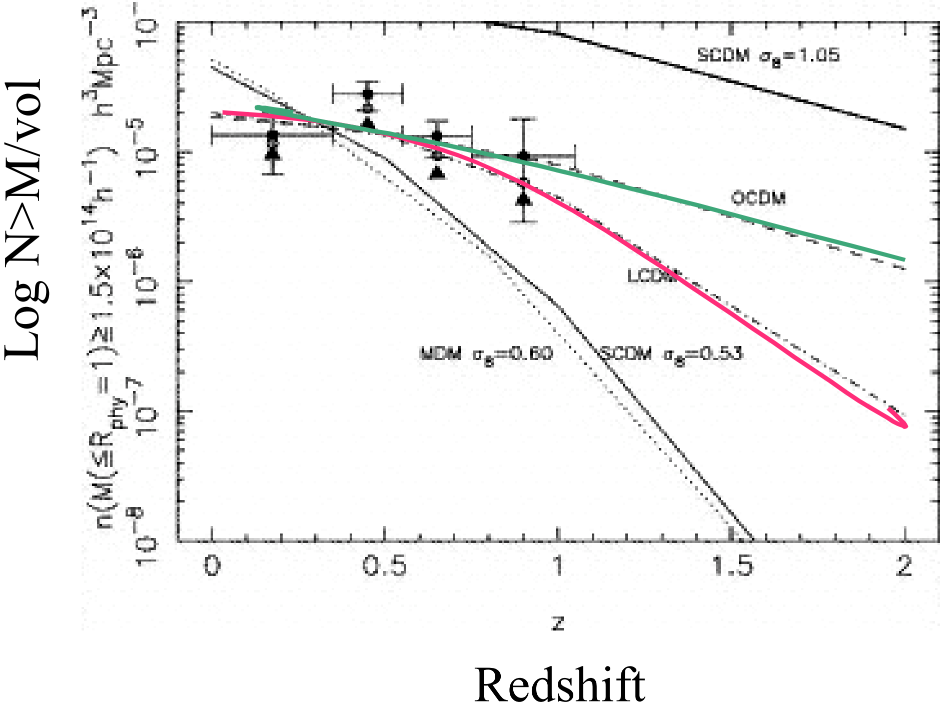
Cosmology Using Cluster X-ray Mass Function

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

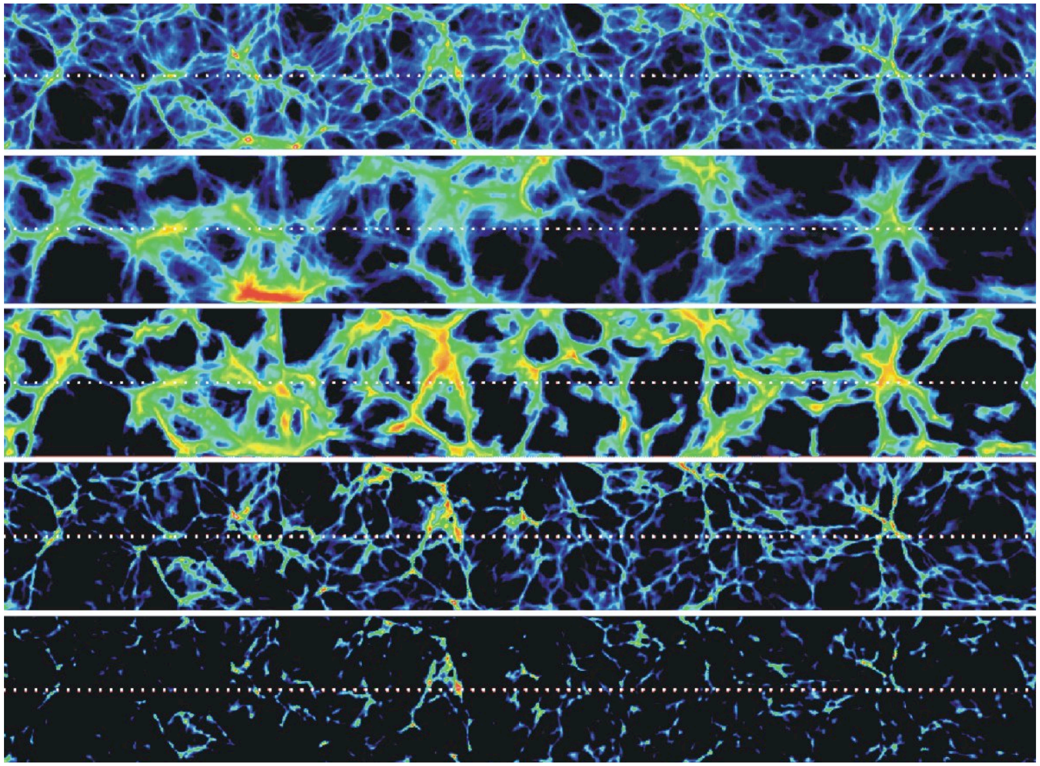
The distinction between models grows dramatically at higher redshift > 0.5 and for the highest cluster mass

XMM and Chandra provide CCD quality spectra to z ~ 0.8

Cluster evolution vs redshift at constant mass in 4 different cosmologies



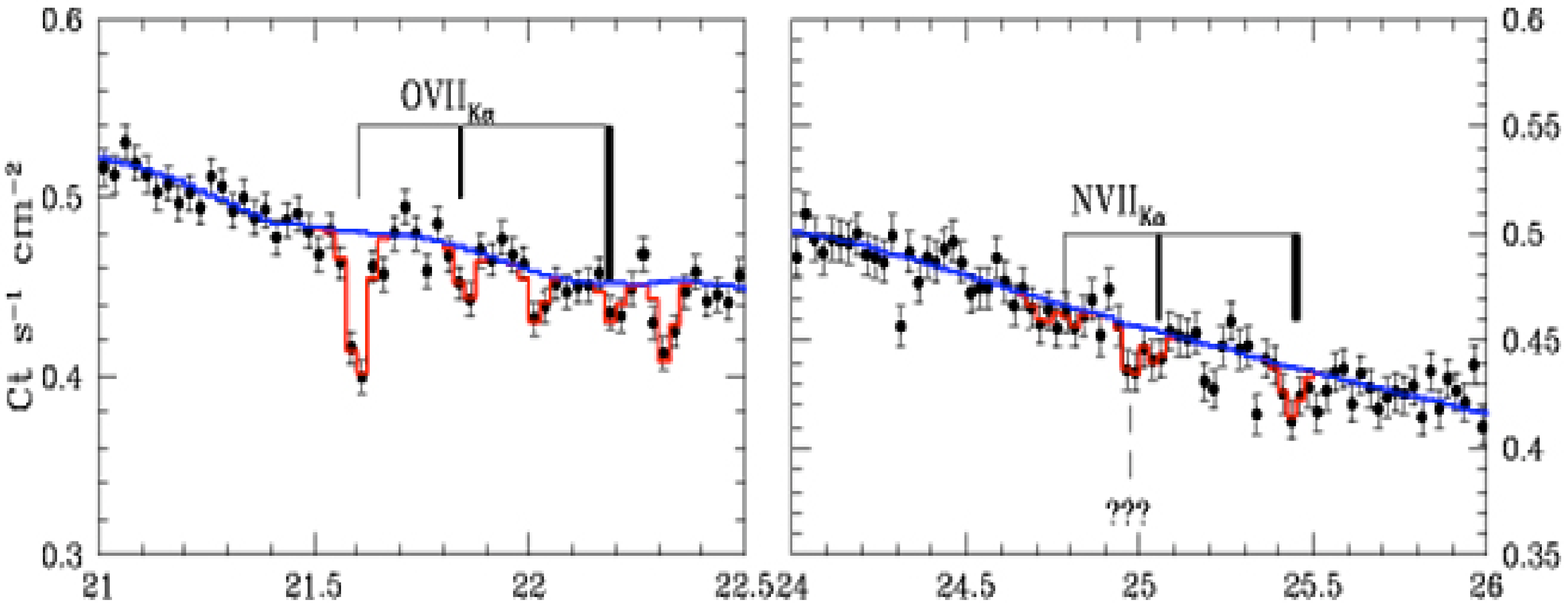
Missing Baryons And Cosmic Web



U.Hellsten et al (1998)

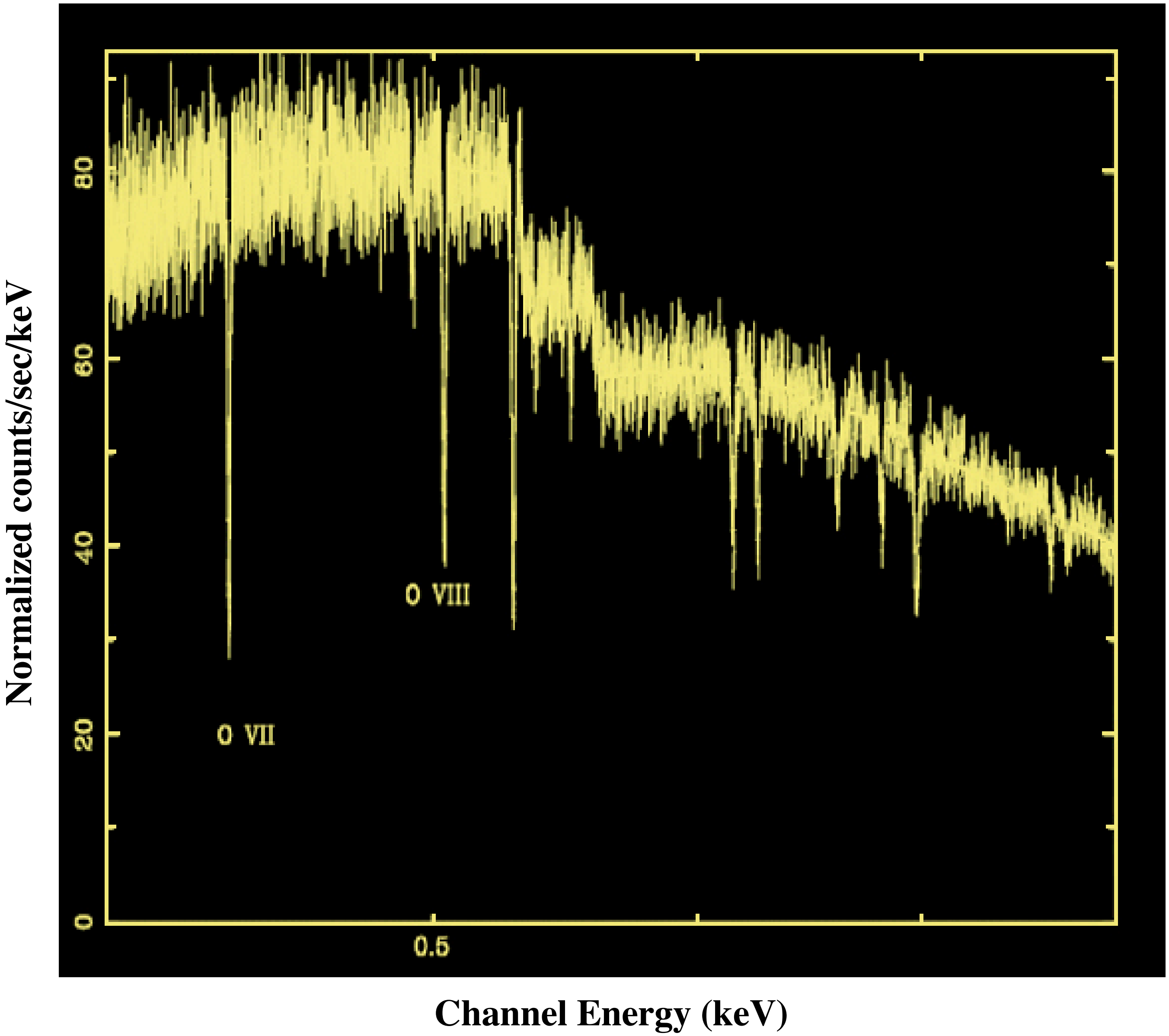
- Baryon content of Universe calculated by Big Bang nucleosynthesis — agrees with observations at high redshift
- Local Universe (z<~1) deficient — where is this matter?
- Not in stars or galaxies
- Probably in warm/hot gas filaments spread throughout the Intergalactic Medium
- Use distant quasars as light beams and search for missing baryons via absorption when web intercepts beam

Absorption by WHIM Baryons in Mkn 421 Spectrum



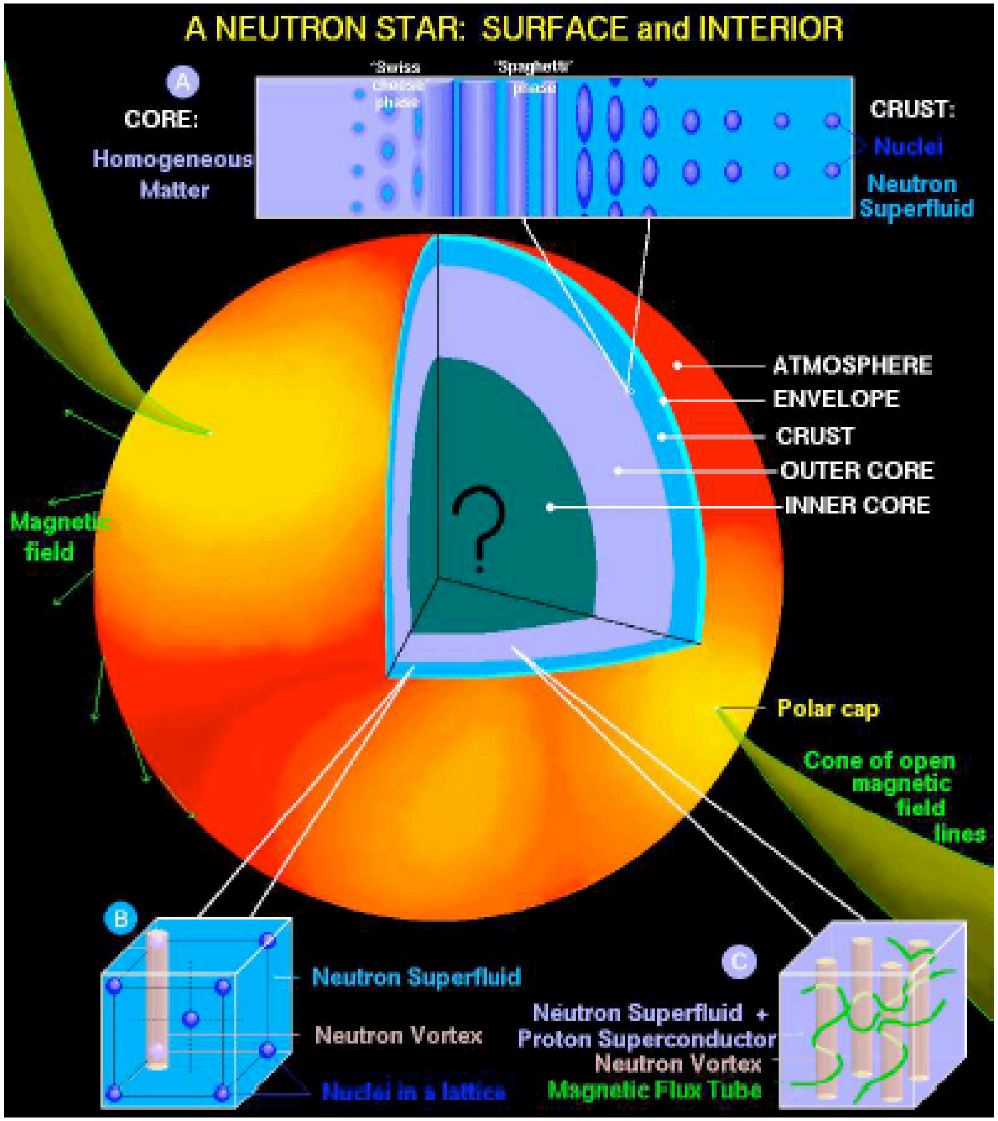
F.Nicastro (SAO)

Missing Baryons - Con-X Simulation



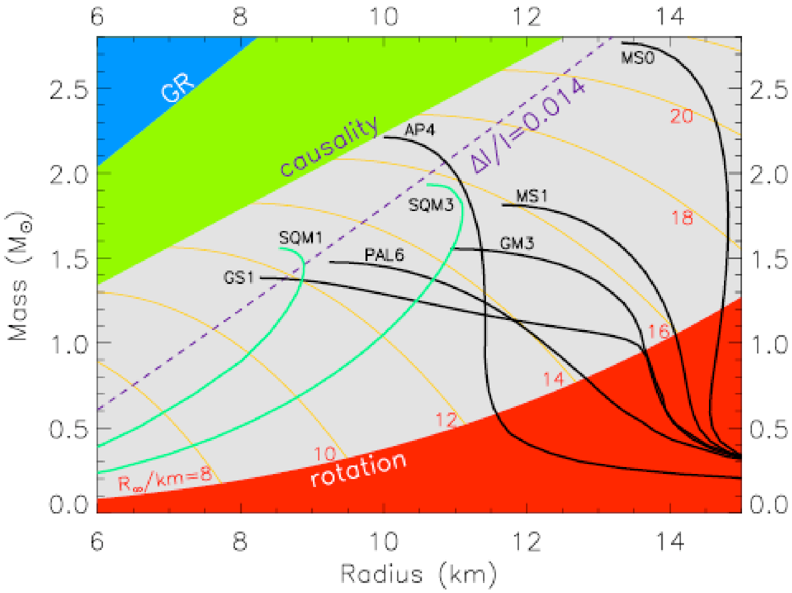
- Simulated 100ks Constellation-X RGS Observation
- OVII and OVIII absorption features easily seen
- Map absorption due to cosmic web all the way
  to source
- Map absorption in many different directions
- Determine global abundance of oxygen
  and other key elements
  in cosmic web

Inside Neutron Stars…



The physical constituents and equation of state of neutron stars remain a mystery after 35 years

Constellation-X may provide answers….



Neutron Star Mass and Radius Measurements

- Some neutron star masses are known very accurately (binary pulsars), but radii are extremely difficult to measure. Essentially no simultaneous M and R measurements.
- A number of different methods can be used; timing, continuum spectroscopy, cooling curves, but none at present sufficiently accurate.
- Most powerful method (in theory) is high resolution X-ray spectroscopy (Constellation-X).

A spectral line emitted at energy E_0 at the neutron star surface is redshifted by GR to energy $E_{obs} = E_0 (1 - 2GM/c^2R)^{1/2}$. Depends on the ratio M/R.

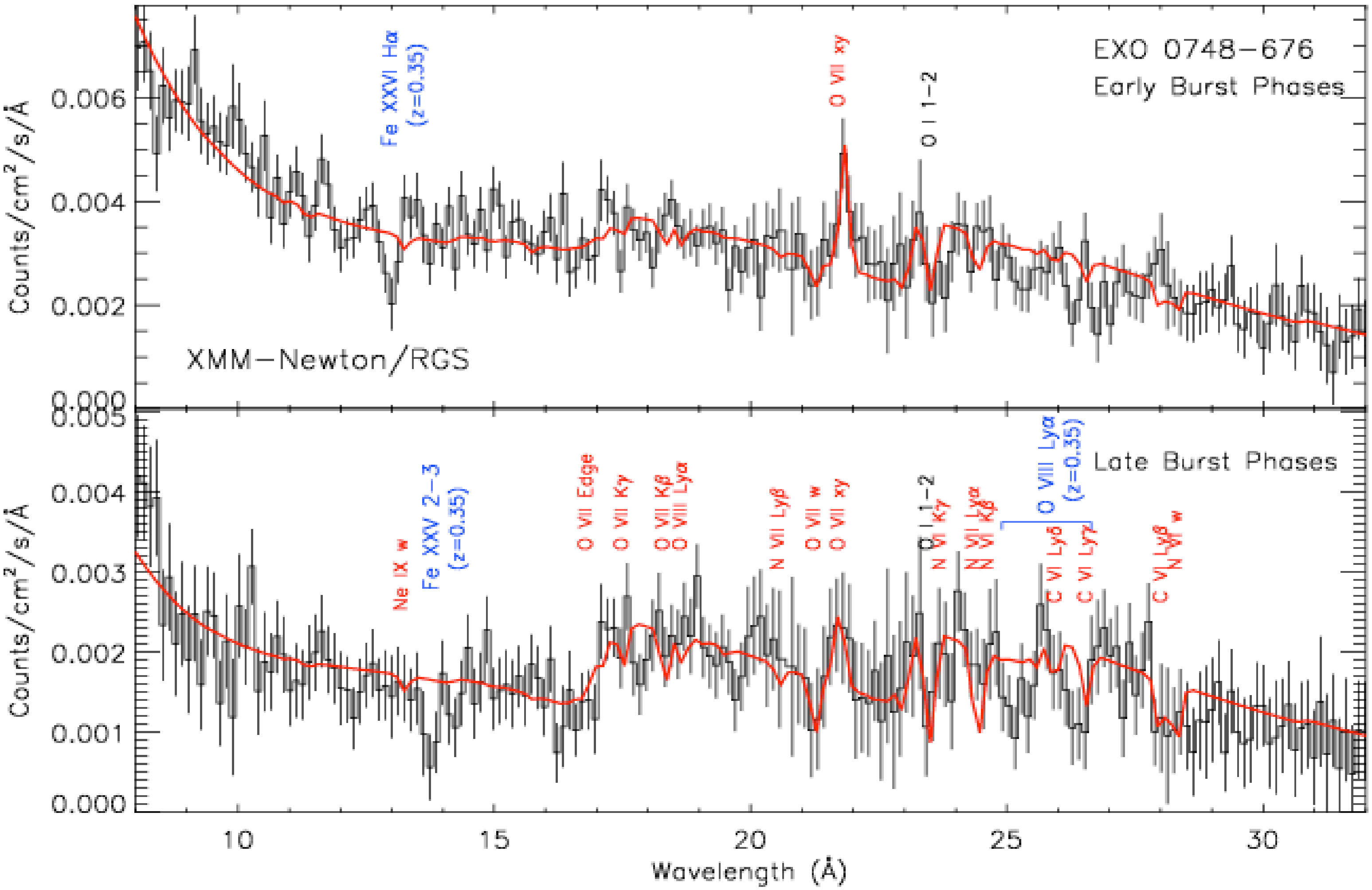
Widths of lines depend on surface gravity M/R^2 (Stark effect broadening), and rotational velocity (depends on R for known spin frequency).

Measurement, and correct physical interpretation, of both line energies and widths will determine both M and R.

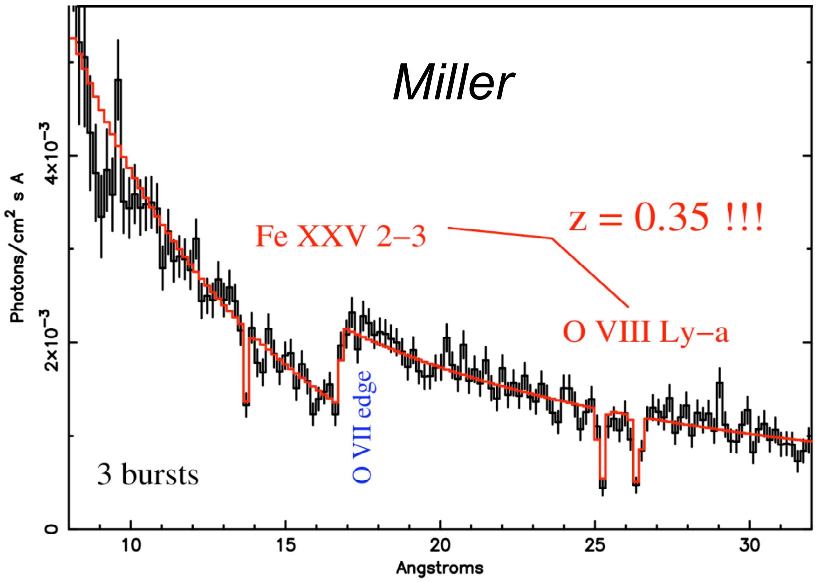
X-ray Spectroscopy of Neutron Stars: Recent Results

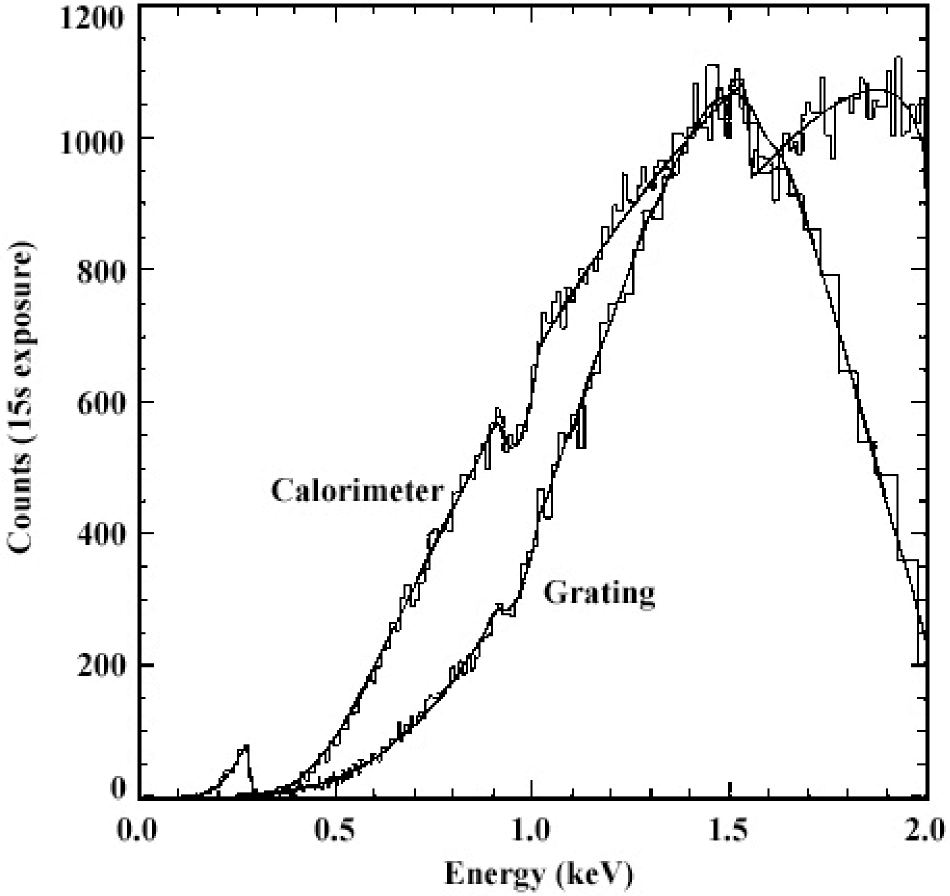
- **Recent observations with Chandra, XMM, and RXTE have provided strong evidence for line features from some neutron stars.**

XMM/Newton grating observations of X-ray bursts from an accreting neutron star (EXO 0748-676); Cottam, Paerels, & Mendez (2002); Nature



EXO 0748-676 Observed with Constellation-X

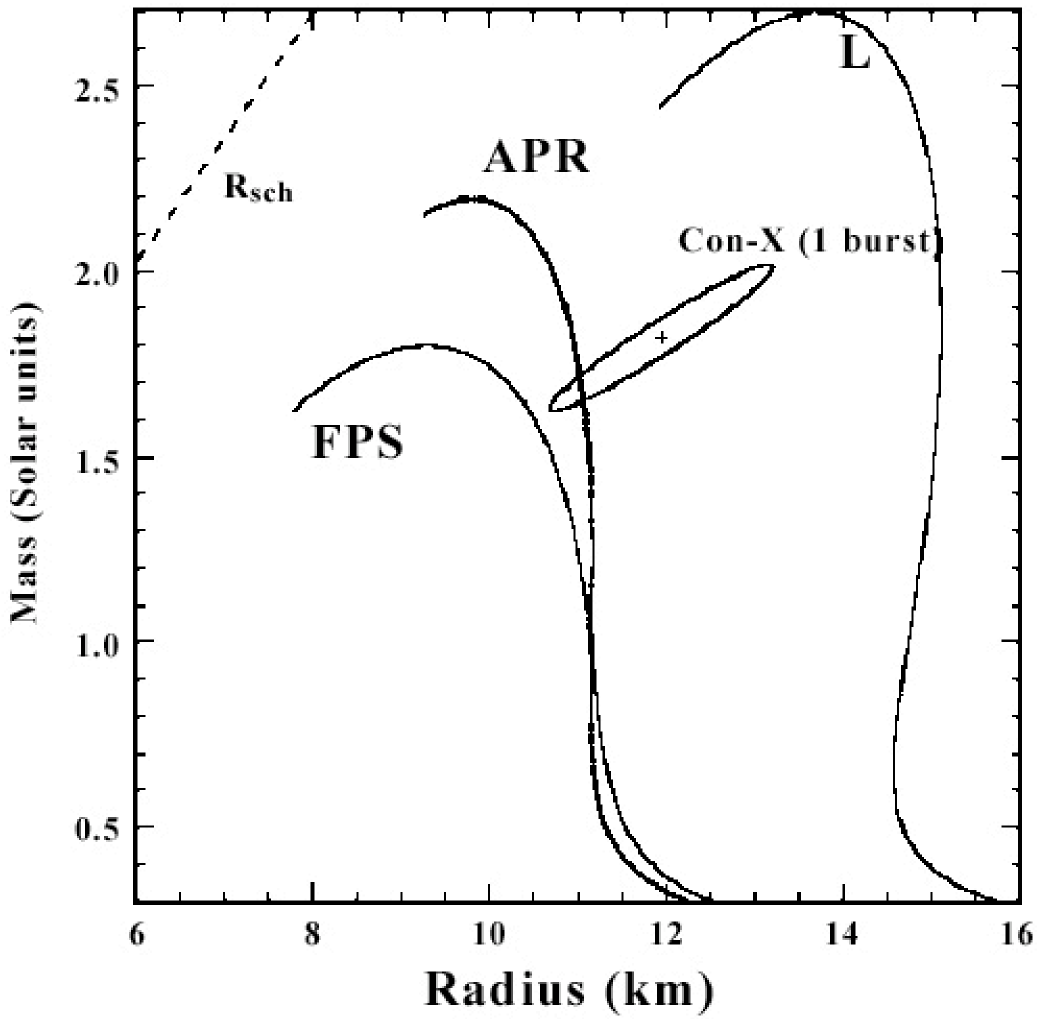




R = 12 km, ν_{spin} = 200 Hz

10 eV EW absorption lines detected by Con-X in single bursts

Equation of State Constraints from Burst Oscillations with Con-X



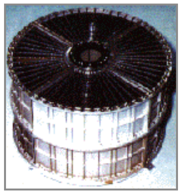
Pulse shapes of burst oscillations encode information on the neutron star mass and radius

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

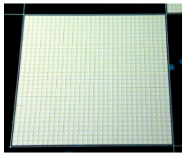
Statistical limits from Constellation-X for even just a single burst will provide meaningful constraints on EOS

Strohmayer (2003)

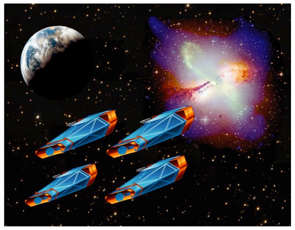
Overall Summary

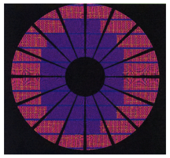


X-ray Mirrors



Micro-calorimeters





Grating/CCD

Hard X-ray Telescope

- Science case is compelling and central to Beyond Einstein program objectives:
  - Strong gravity close to black hole event horizon
  - Dark Energy using Clusters of Galaxies
  - Opens up X-ray spectroscopy to address pressing science questions e.g. Equation of State of neutron star
- Science goals high priority/strongly endorsed by independent National Academy Reviews
- Constellation-X proposed in 1995 and in pre-formulation since 1998
  - Mission extends existing technologies and technology, with substantial progress in all areas.
  - Focused technology continuing towards critical milestones, launch could be as soon as 2013
  - Approved mission FY04 budget as part of Beyond Einstein program
  - NASA FY05 budget delays mission to NET 2016