The Warm & Hot Universe – May 2008

Constellation X

The Constellation X-ray Mission

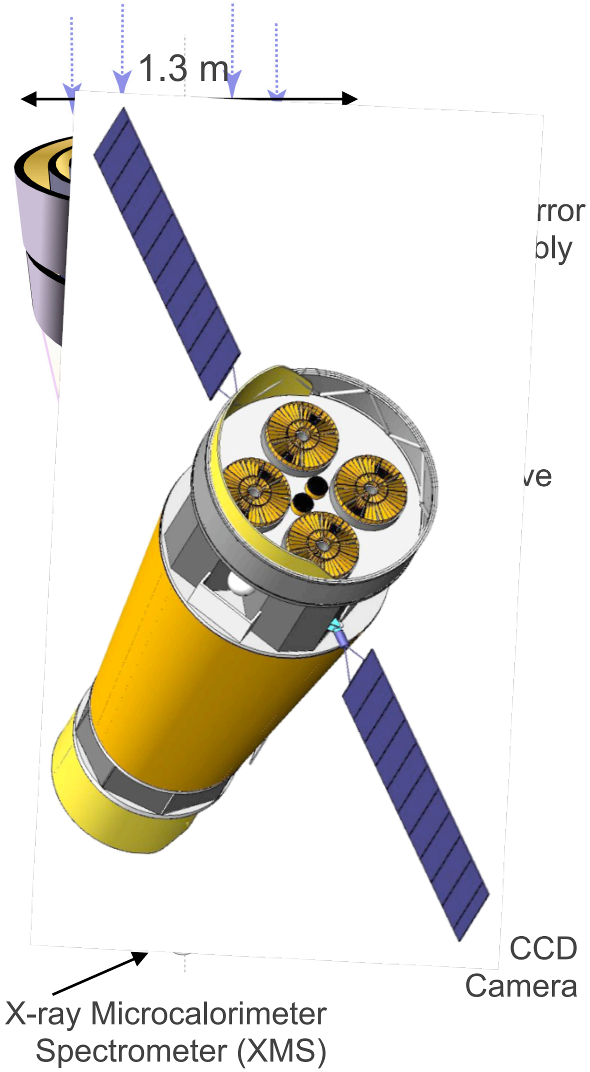
Observing the Warm-Hot Medium

Randall Smith

Constellation-X Mission Scientist – NASA/GSFC

Mission Implementation

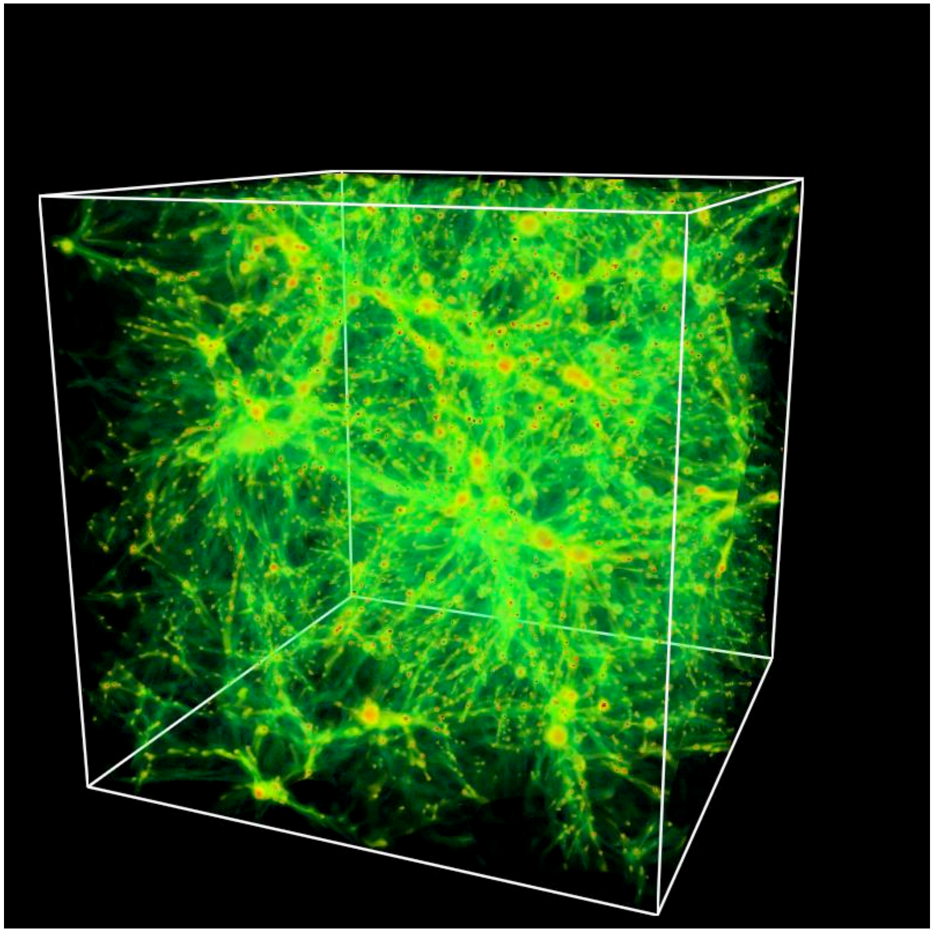
- 4 Spectroscopy X-ray Telescopes (SXTs) each consisting of a Flight Mirror Assembly and a X-ray Microcalorimeter Spectrometer (XMS)
  - Covers the band-pass from 0.6 to 10 keV
  - Angular resolution requirement of 15 arc sec (goal of 5 arc sec HPD)
  - Field of View 5 x 5 arc min (64x64 pixels, goal of 10 x 10 arc min FOV)
  - Count rates: 1/4 crab or 1,000 ct/sec/pixel
- Two additional systems extend the bandpass:
  - X-ray Grating Spectrometer (XGS) covers from 0.3 to 1 keV (included in one or two SXT's)
  - Hard X-ray Telescope (HXT) band-pass covers from 6 to 40 keV (not shown)
- All instruments operate **simultaneously**



Where are the Baryons: Searching in the UV and X-ray Bands

Many of the predicted baryons have **not** been detected in the local Universe

- Most are thought to reside in a hot 10^6 – 10^7 K intergalactic medium
- Major challenge is to detect this warm-hot intergalactic medium



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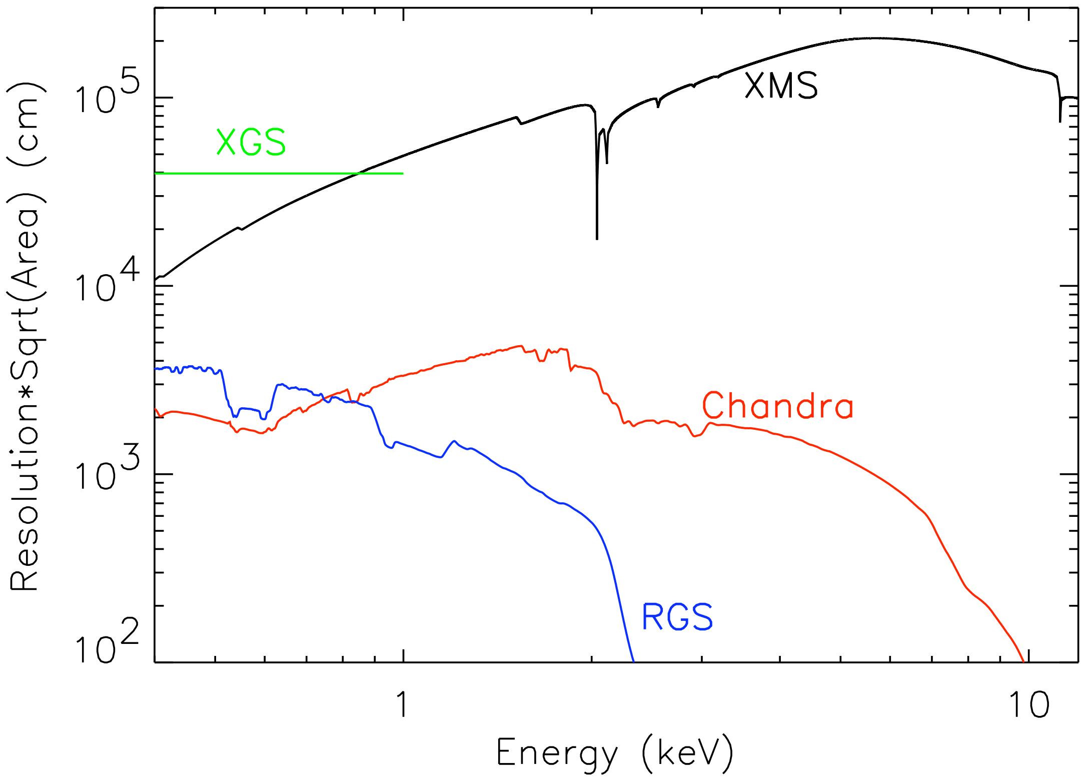
The Constellation-X Advantage:

- Large area (XMS)
- High resolution (XGS)
- >10x the line resolving power of Chandra and XMM-Newton



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Hubble Limit:

~15% of baryons detected from O VI absorption lines if $f_{O\ VI}/f_O = 0.2$ and Ab(O) = 0.1 solar

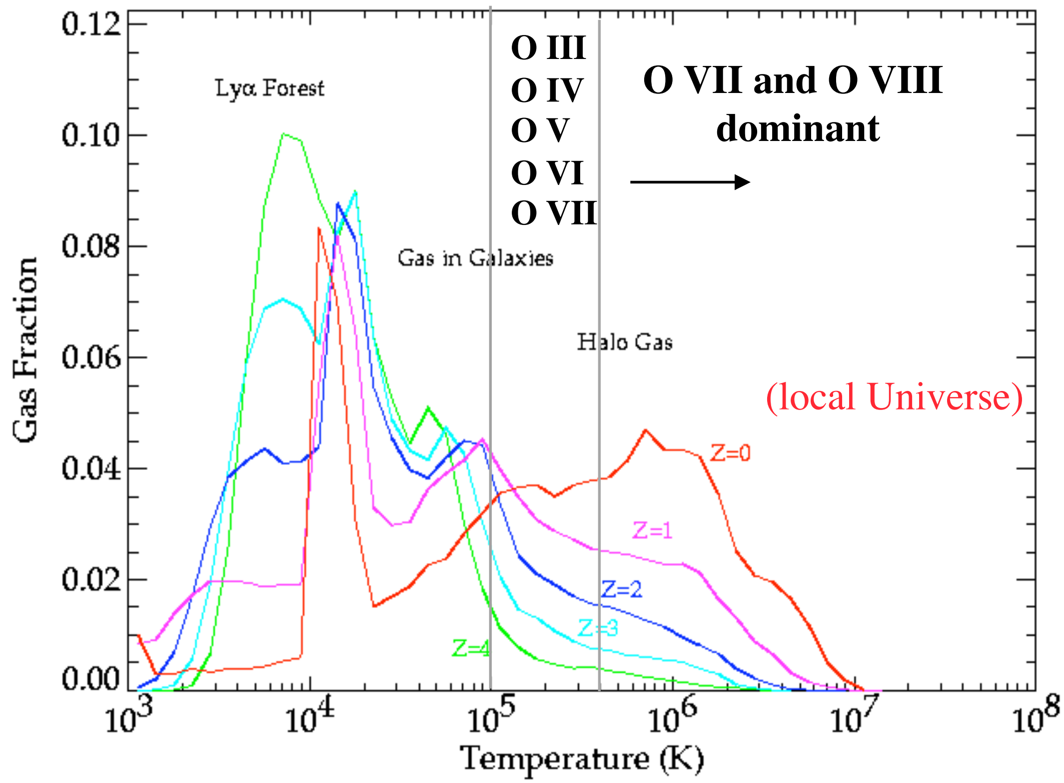
~ O VI line alone **does not uniquely constrain** the temperature or ionization fraction

Constellation-X Limit:

No assumption of ionization fraction needed!

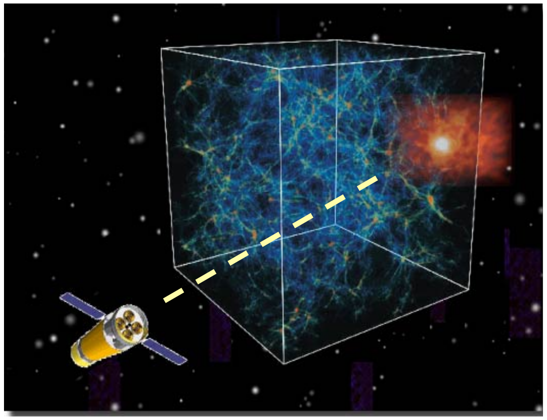
~70% of baryons detected using O VII and O VIII resonant absorption lines

Distribution of gas temperature at different Cosmic epochs



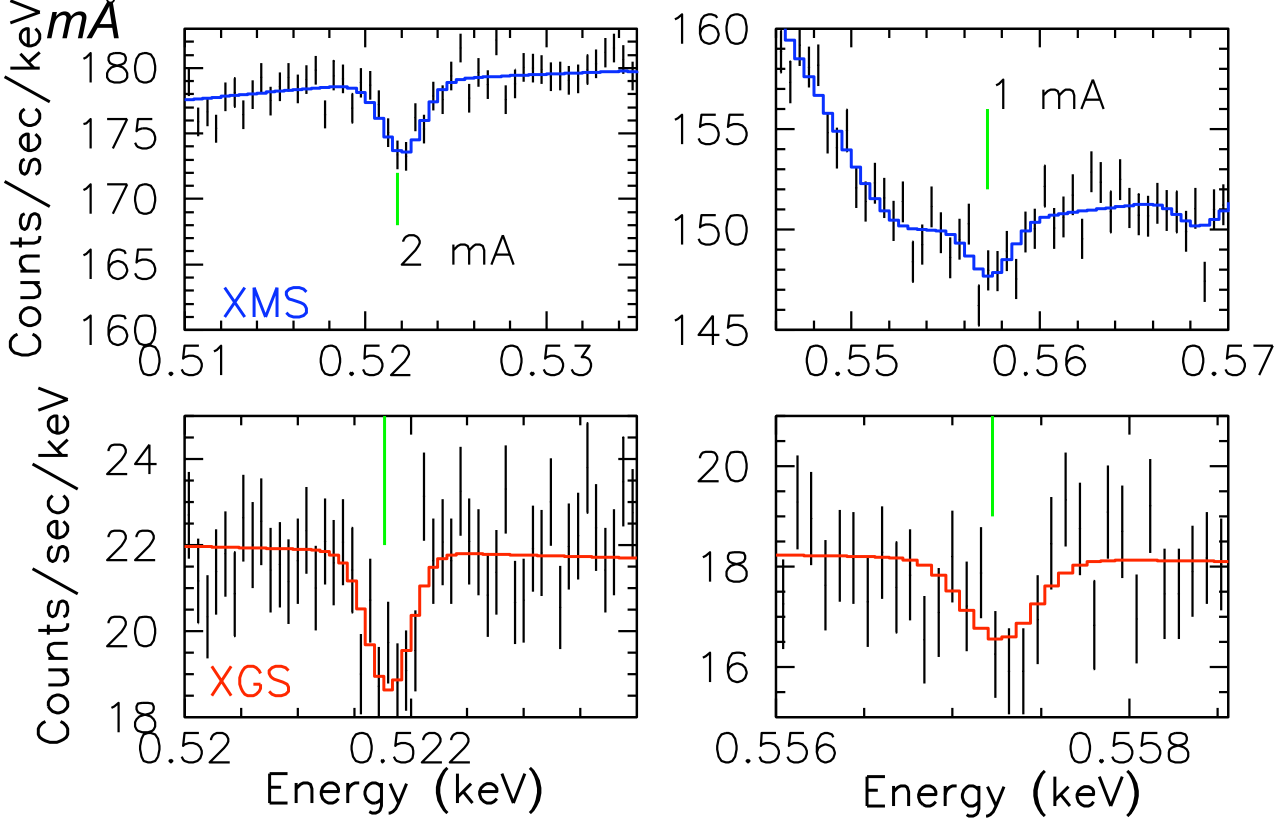
Together, UV and X-ray *completely constrain* the problem

Searching for the missing baryons trapped in the Cosmic Web



Detect ionized gas in the hot IGM medium via absorption lines in spectra of hundreds of background quasars

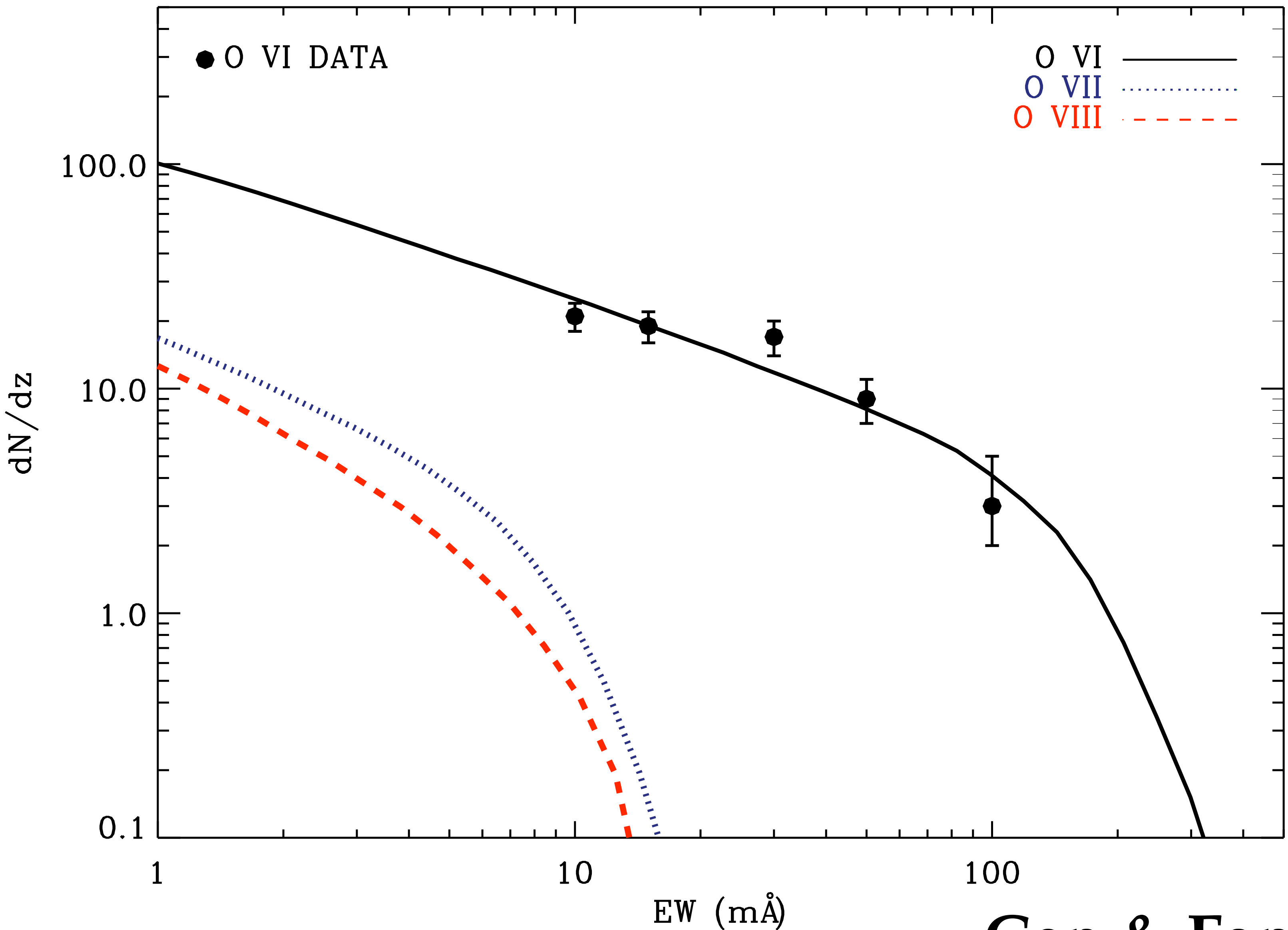
A typical bright (1.5×10^{-11} ergs/cm^2/s) AGN with two filaments at z=0.03 and 0.1 with EqW = 1mÅ and 2 mÅ



The large effective area of the calorimeter can detect absorption, but has limited sensitivity to position or width.

The high resolution of the gratings measures the velocity and possibly the width of any features.

How Many Filaments are There?



Cen & Fang 2006

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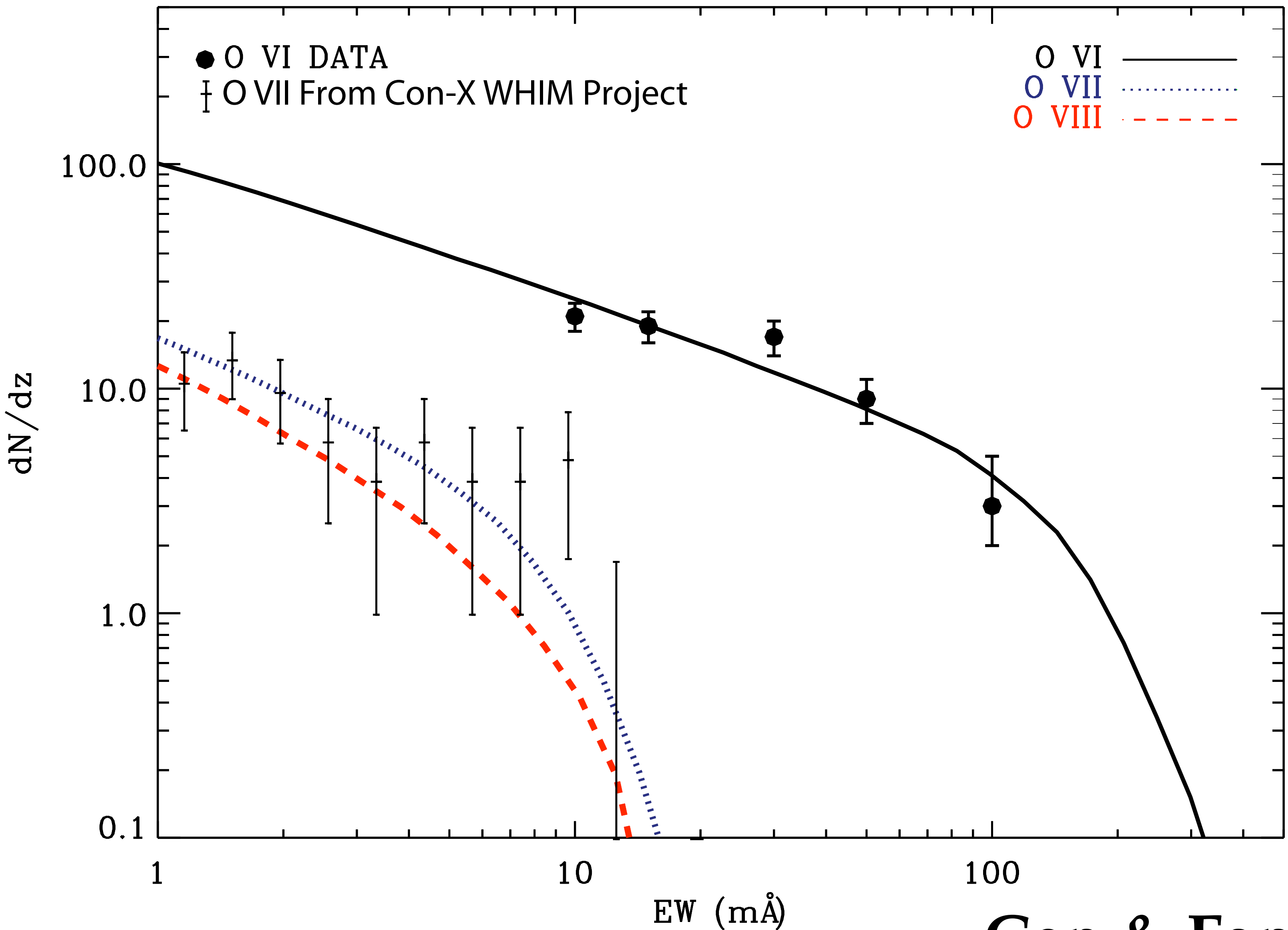
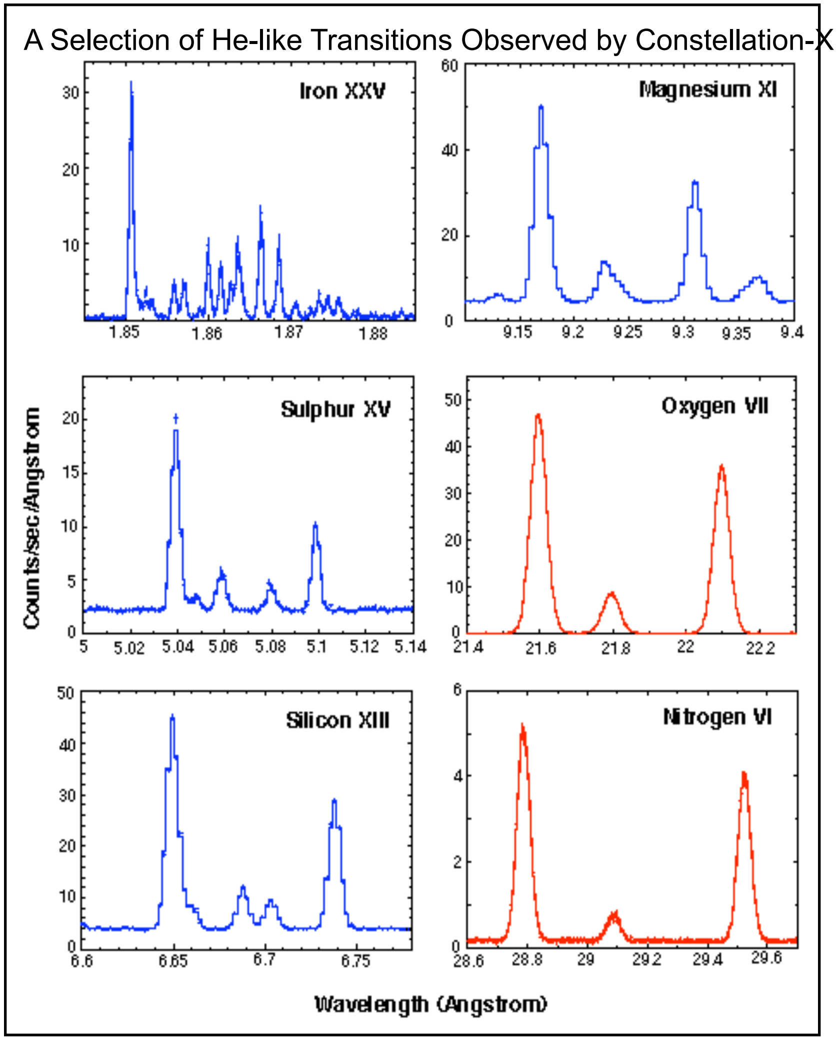


Cen & Fang 2006

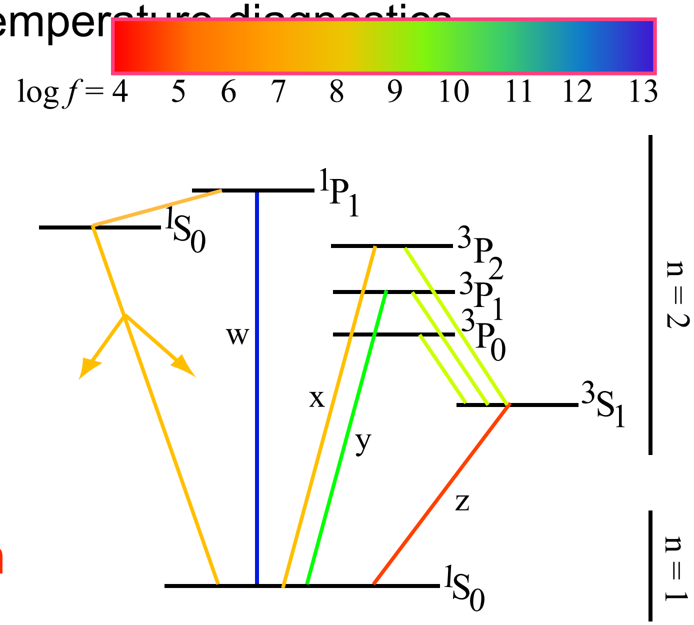
Plasma Diagnostics with Constellation-X



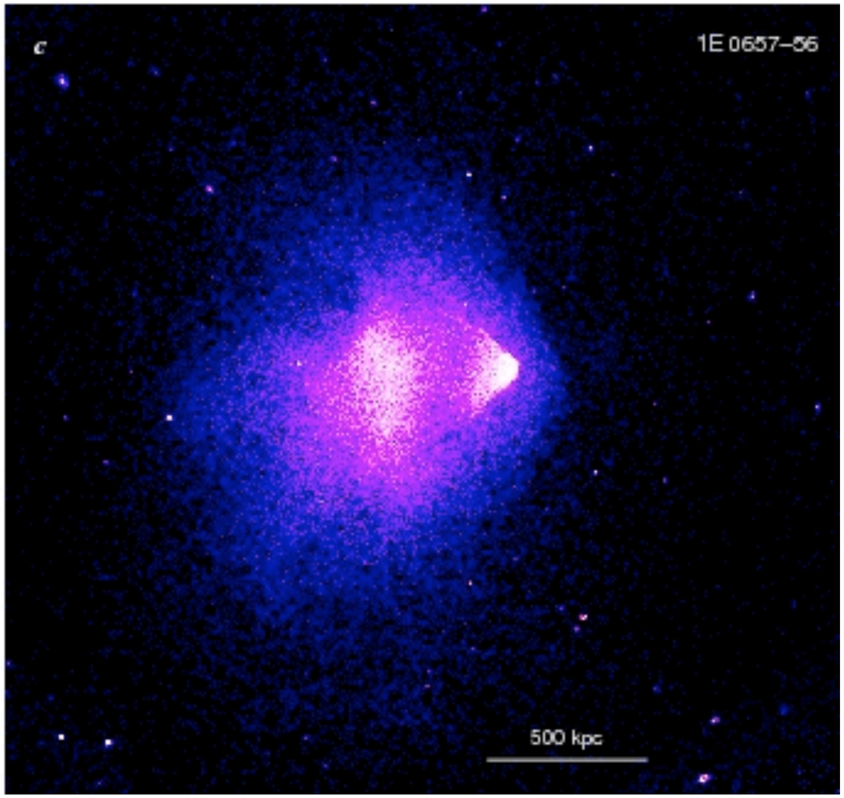
The Constellation-X energy band contains the K-line transitions of 25 elements allowing simultaneous direct abundance determinations using line-to-continuum ratios

X-ray spectroscopic workhorse: the He-like triplet
→ density and temperature diagnostics

The spectral resolution of Constellation-X is tuned to study the He-like density sensitive transitions of Carbon through Zinc



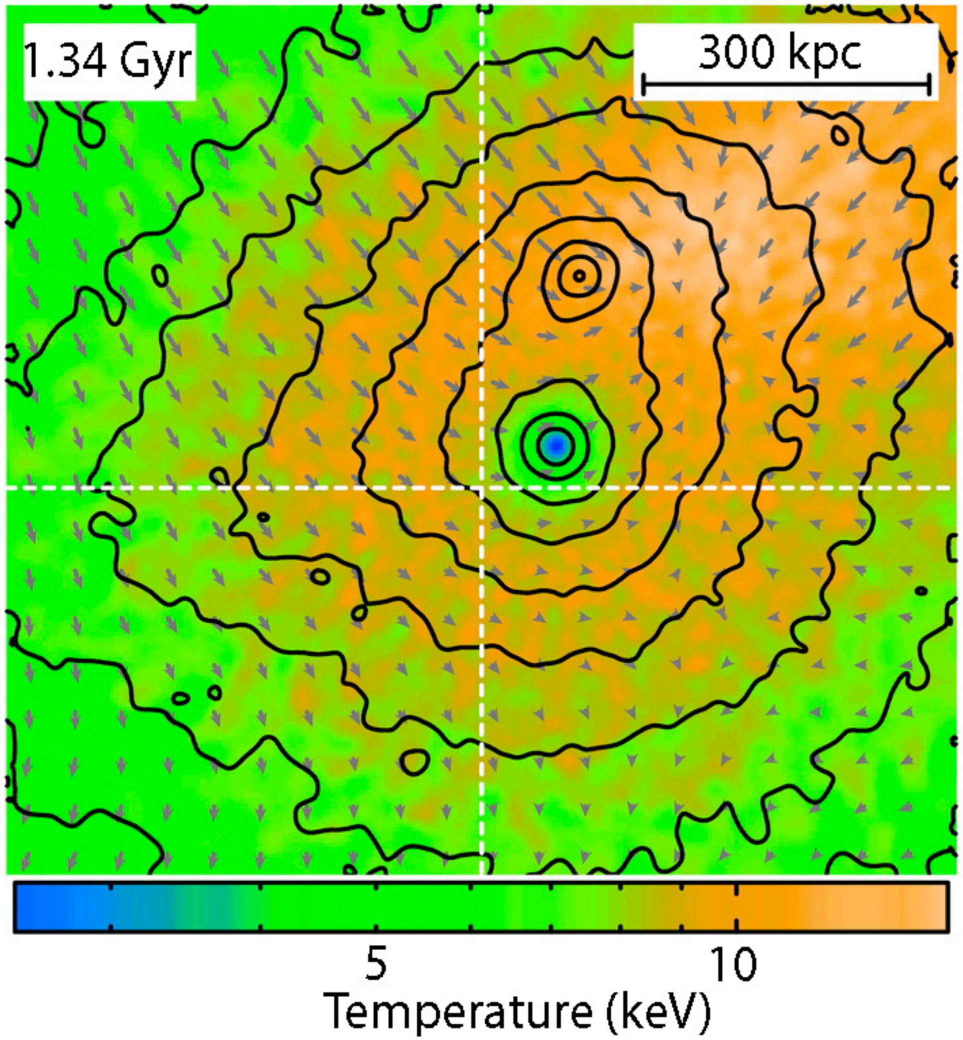
How do clusters form and grow?
(how is the gas heated and enriched in heavy elements?)



- Merger processes that form clusters have kinetic energies up to 10^{63} -10^{64} ergs and are the most energetic events since the Big Bang,
- Major mergers have variations in gas velocity and gas is hot (e.g., the Bullet cluster: 3000- 4000 km/s ; Markevitch et al. 2002)
- With high-throughput, spatially-resolved spectroscopy with the calorimeter, Con-X can determine subcluster velocities and:
    - Measure redshifts of subclusters from X-ray spectra (LOS velocity)
    - Measure velocity in plane of sky from shocks or density/temperature jumps across cold fronts

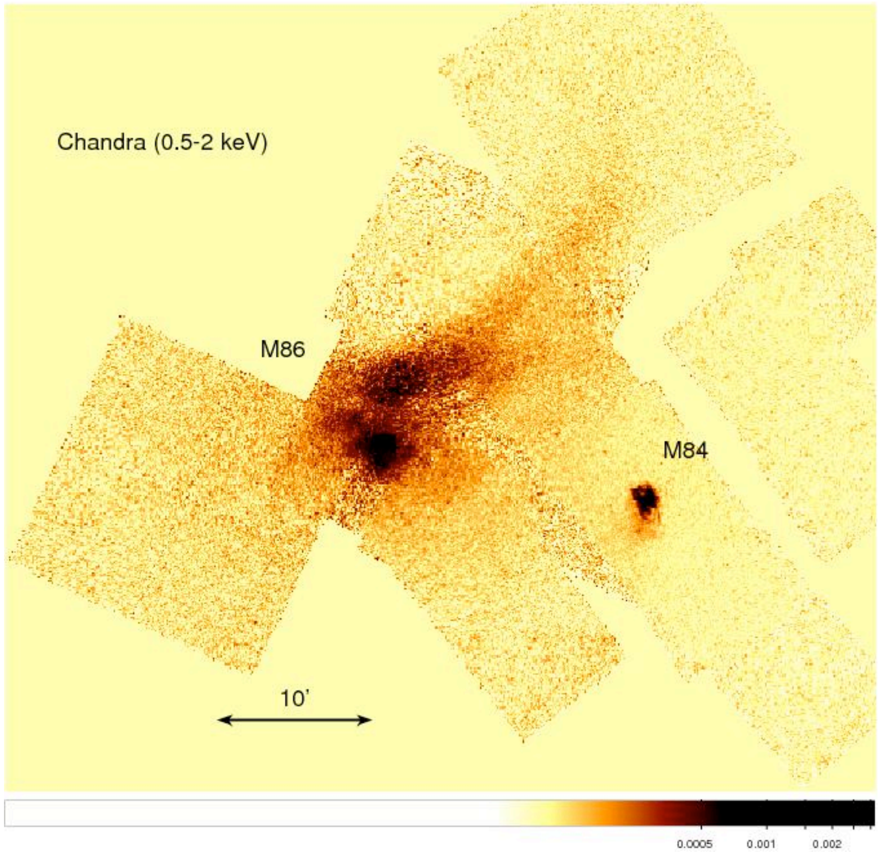
How do more typical minor cluster mergers proceed?

Temperature Map
Ascasibar & Markevitch (2006)

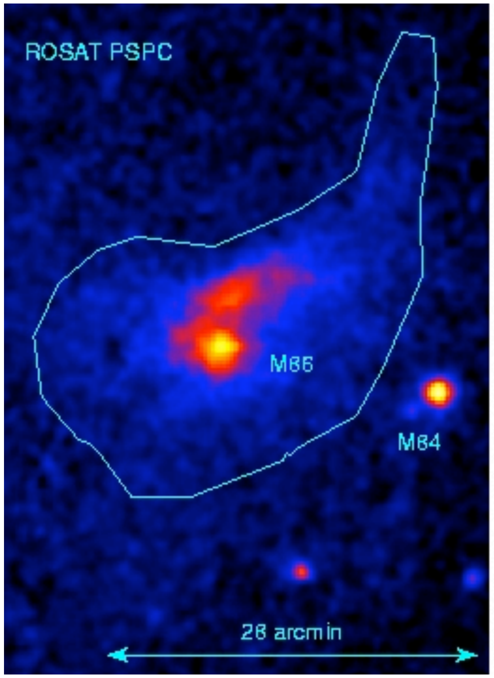


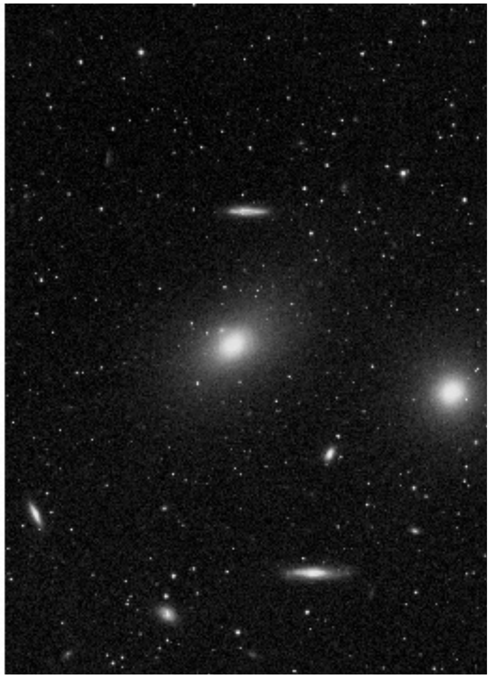
- Supersonic mergers like the Bullet cluster merger are relatively rare: more common are minor mergers
- Minor mergers cause “sloshing” and cold fronts.
- Con-X will observe velocity differences on the scale of ~200-300 km/s, which is the expected scale in these mergers – bringing observational tests to models of how structure is formed.

How are the gas and heavy elements stripped from galaxies and groups heated and incorporated into the hot ICM?



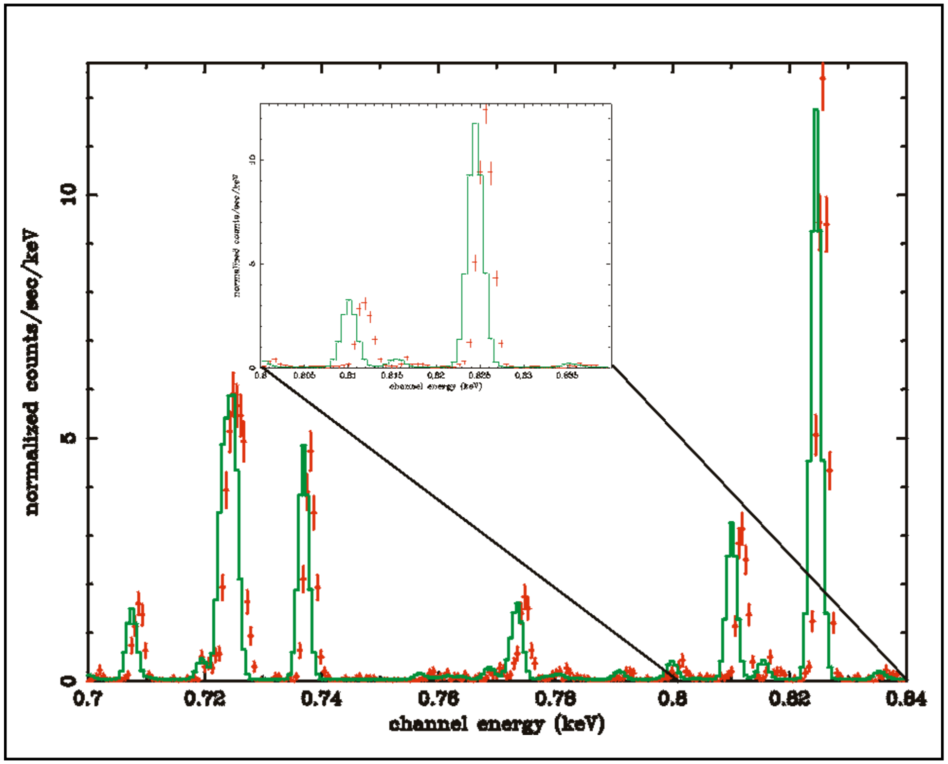
Determine abundances in galaxy core and along the stripped tail (M86 is shown as a prime candidate for study)





Dark Matter Distribution in Spiral Galaxies

- Rotation curves of cold gas and stars prove existence of dark matter halos. Since stars and gas are confined to the plane of the galaxy, the rotation curves probe only <u>2D distribution</u> of dark matter
- By measuring the T and r distribution of hot gas surrounding the galaxy, as well as its rotational velocity, the <u>3D distribution</u> of dark and luminous matter in the galaxy can be determined
- Expected rotation velocities are ~ 300 km s^{-1} - well within Constellation-X capabilities



A 50 ks simulated observation of the hot halo gas in the edge-on spiral galaxy NGC 891. The solid line shows 0.3 keV gas model shifted by 600 km/s (assuming halo circular velocity of 300 km/s based on disk measurements).

Credit: Diana Worrall

Does the metal-enriched gas in starburst superwinds escape?

The starburst galaxy M82 and its superwind as seen by the three Great Observatories.

Chandra ACIS-S thermal X-ray emission (blue); Spitzer 8μm (red); HST ACS Hα+[N II] (yellow); HST ACS B-band (cyan) [image credit: Hubble Heritage/NASA].

- Heavy elements created in stars & supernovae end up in hot, X-ray emitting, gas seen in superwinds (10^6 K < T < 10^8 K).

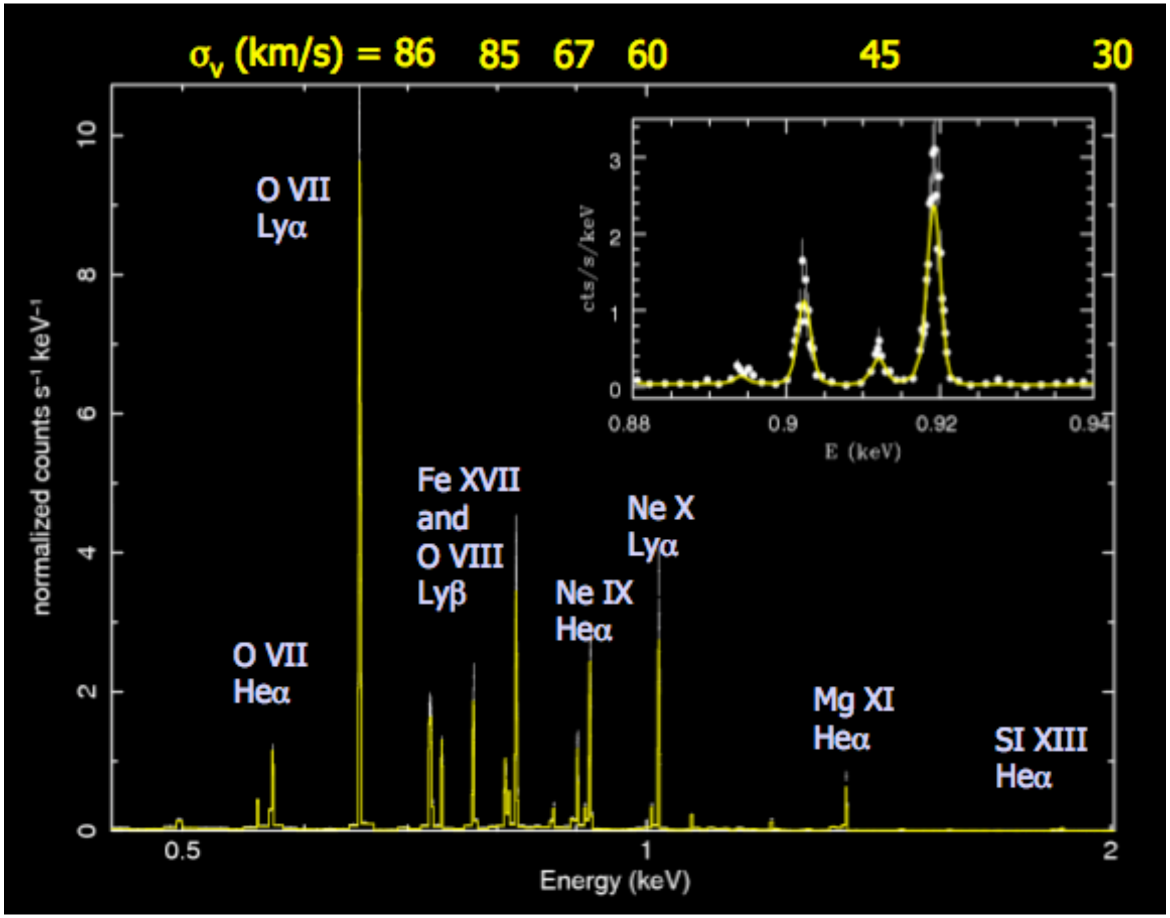
- Ejected metals may be the source for the metals of the Intergalactic Medium (IGM).

- **Proving that starburst superwinds can eject metals into the IGM requires measurements of the velocity of the hot metal-enriched gases**

- Con-X will measure gas velocities in superwinds. Current X-ray telescopes lack the necessary spectral resolution.

Velocity measurements in superwinds with Con-X

- Hydrodynamical simulations of superwinds predict soft X-ray emission from gas with 400 km/s < v < 2000 km/s
- Escape velocities for local superwind galaxies and Lyman Break Galaxies with $M_* > 10^{10}\ M_{sun}$ are in the range 300 – 700 km/s.
- In 100 ks exposures, in the faintest regions of currently-detected superwinds, the Con-X calorimeter will measure individual X-ray line redshifts
- Con-X will able to map the velocity as a function of position in nearby starbursts of different mass, allowing us to test whether $v_X > v_{escape}$ as a function of galaxy mass.



Simulated Con-X XMS spectrum of a small region within a superwind For any line with > 40 counts the line redshift can be determined to the accuracy shown above.

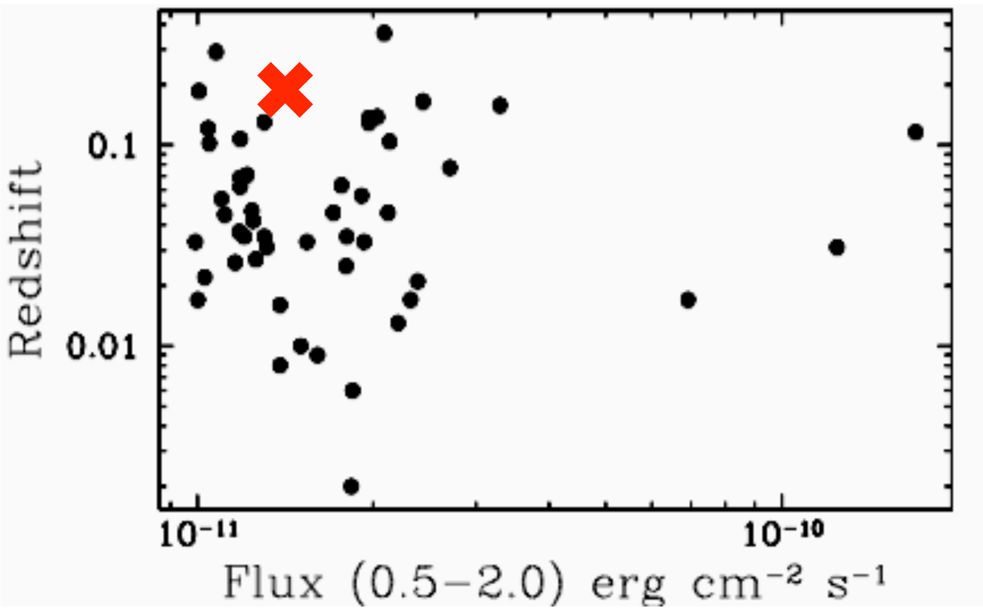
Summary

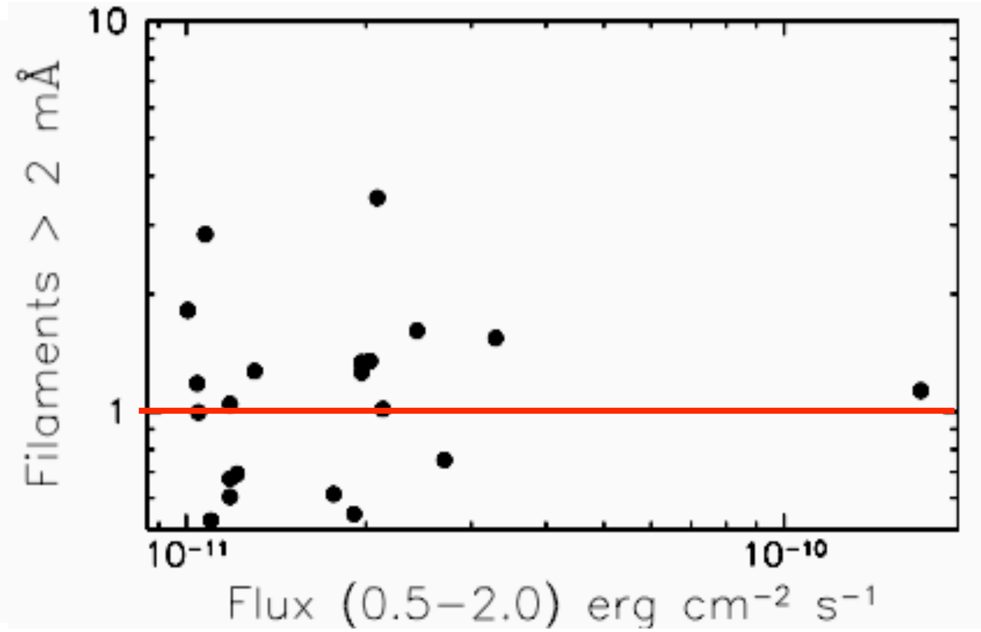
- Constellation-X is a facility class observatory that opens the window of X-ray spectroscopy with a two order of magnitude gain in capability that will make major advances in the study of virtually all classes of astrophysical objects, and will specifically:
  - Follow the formation of large scale structure through observations of clusters of galaxies and search the Cosmic Web to find the missing hot Baryons
  - Study the processes that drive Cosmic Feedback, the formation of the elements and their distribution throughout the Universe
  - Revolutionize our understanding of how Black Holes evolve with cosmic time, and observe matter orbiting close to the event horizon
- We are realizing the payoff from many years of well focused technology investments and mission implementation studies that demonstrate the mission is ready to proceed
- We are poised to make a robust case to the upcoming decadal survey that Constellation-X is the highest priority for the next large astrophysics observatory

http://constellation.gsfc.nasa.gov

Backup Material

Detecting the WHIM: Bright AGN and Dense Filaments





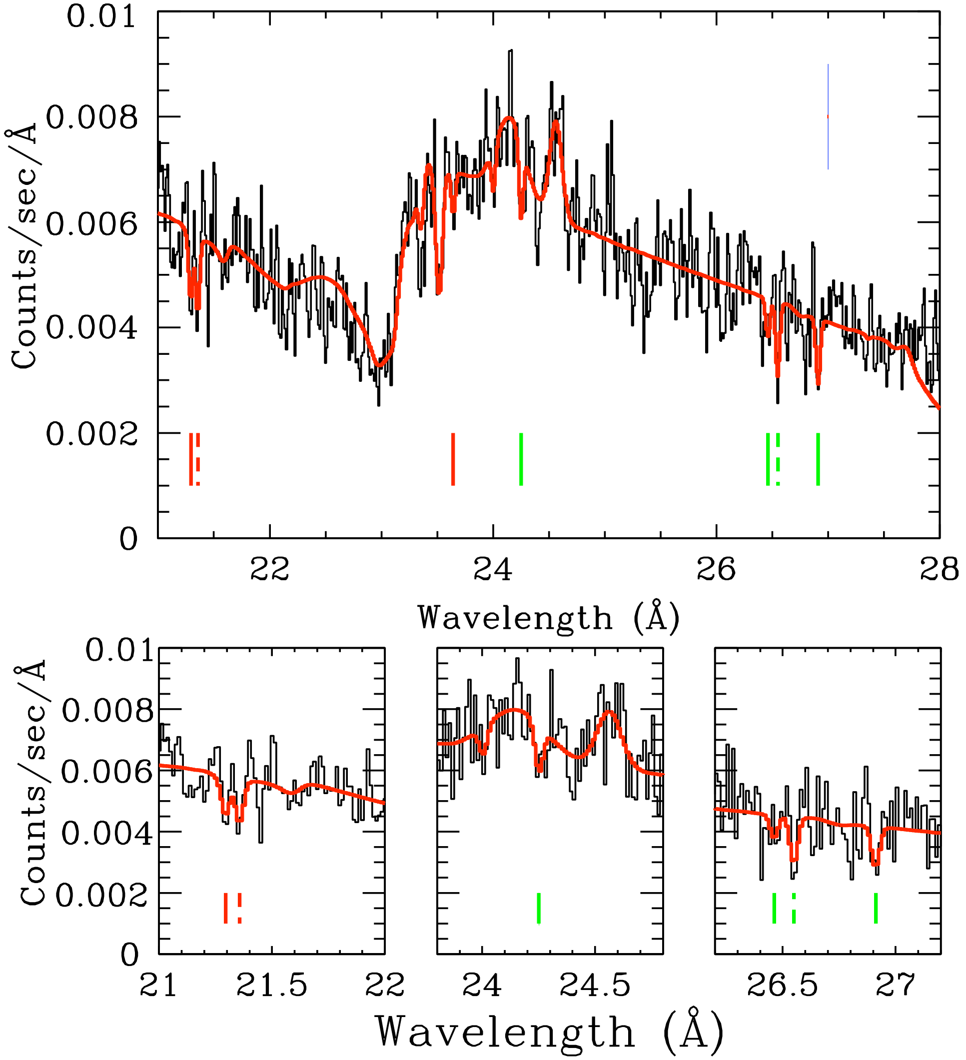
The Brightest 50 AGN – from the ROSAT Survey

- Nearby
- F_X(0.5-2 keV) > 10^{-11} erg/cm^2/s)

Unsurprisingly, dense filaments are rare – ~12/50 AGN will have EW > 2 mÅ

(Cen & Fang 2006)

Chandra Observations of Missing Baryons

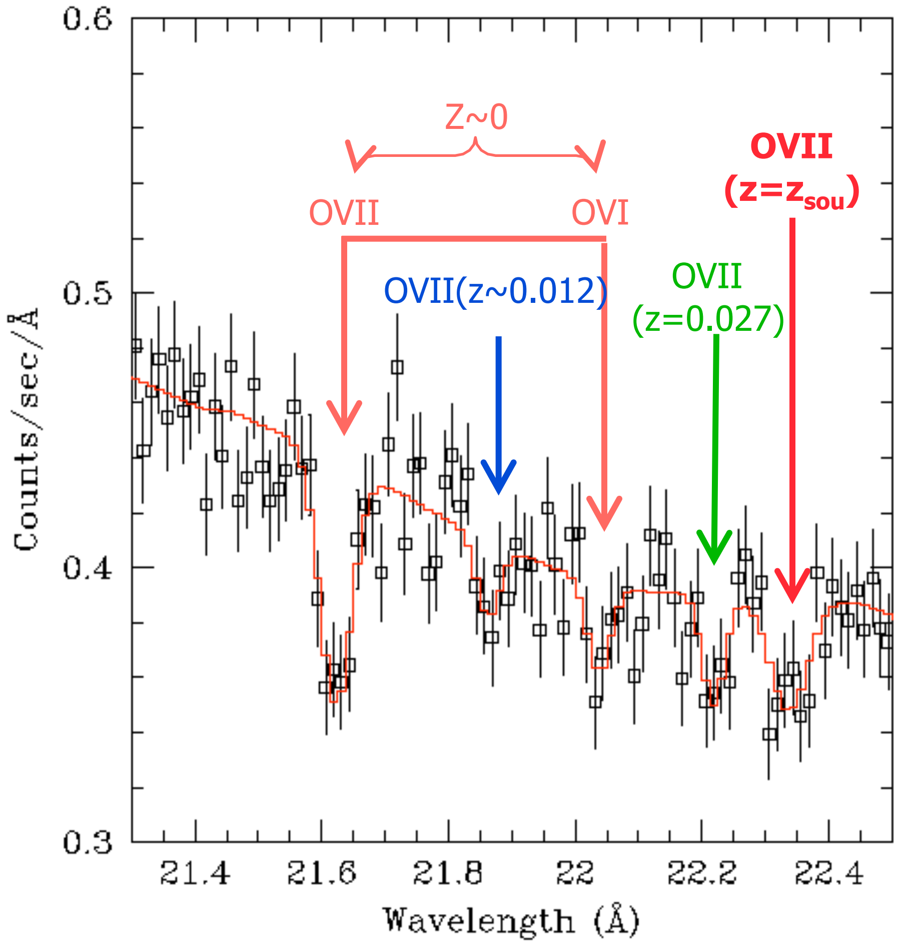


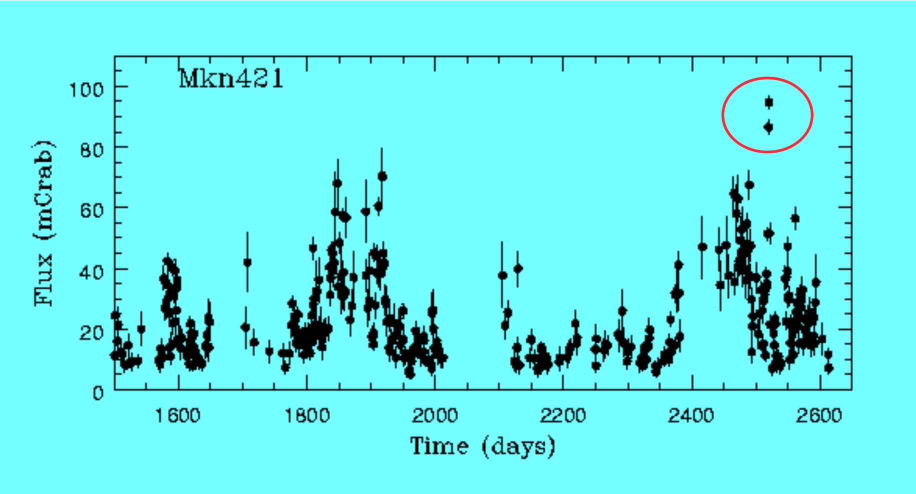
Mathur et al (2003)

- 500ks Observation of H1821+643 with Chandra
- FUSE has detected OVI features in UV spectrum - provides a marker to search for X-ray features
- Solid tick marks: Weak features (95% confidence) correspond to OVII (green) and OVIII (red) systems at expected wavelength from FUSE detection of OVI.
- Dashed tick marks: Candidate new lines
- Evidence that most of oxygen in web is highly ionized
- But requires confirmation from longer Chandra observation, and eventually Constellation-X.

The OVII Forest

Chandra observation of MKN 421 timed to catch the source in a bright state





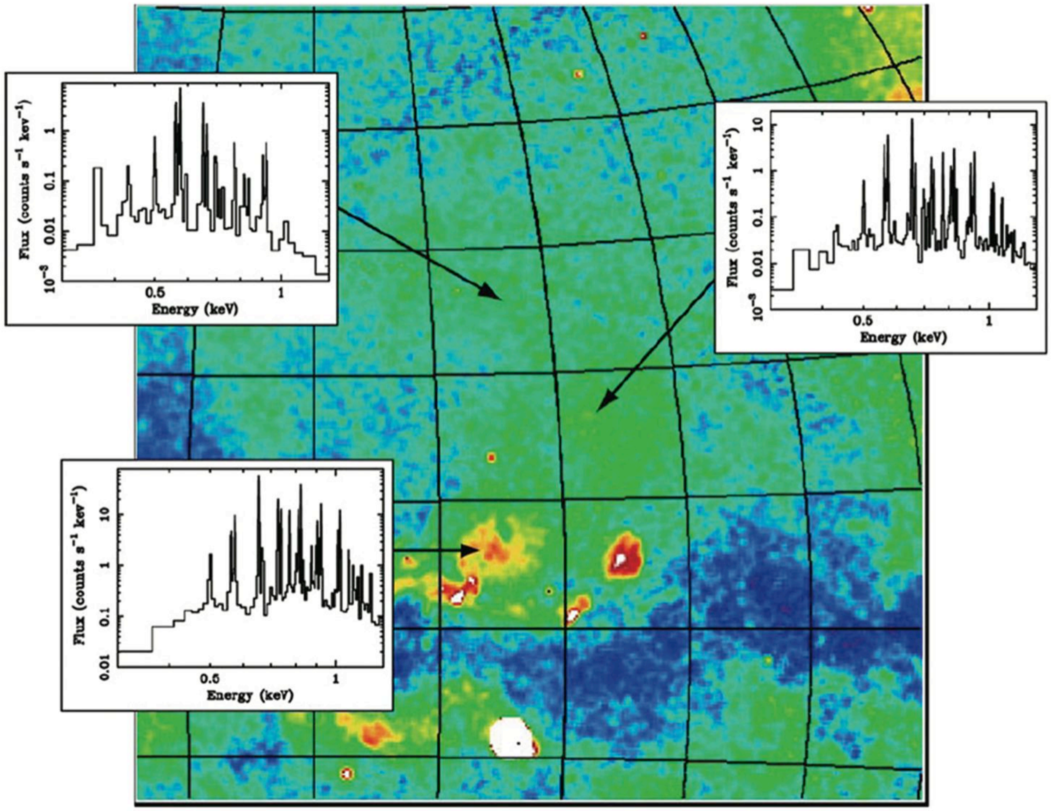
Nicastro et al (2003)

$$dN_{OVII}^{predicted}(z<0.03, EW>3.1mA)=1.2$$

$$dN_{OVII}^{observed}(z<0.03, EW>3.1mA)=2$$

$$\boxed{dN/dz = 35\text{-}70}$$

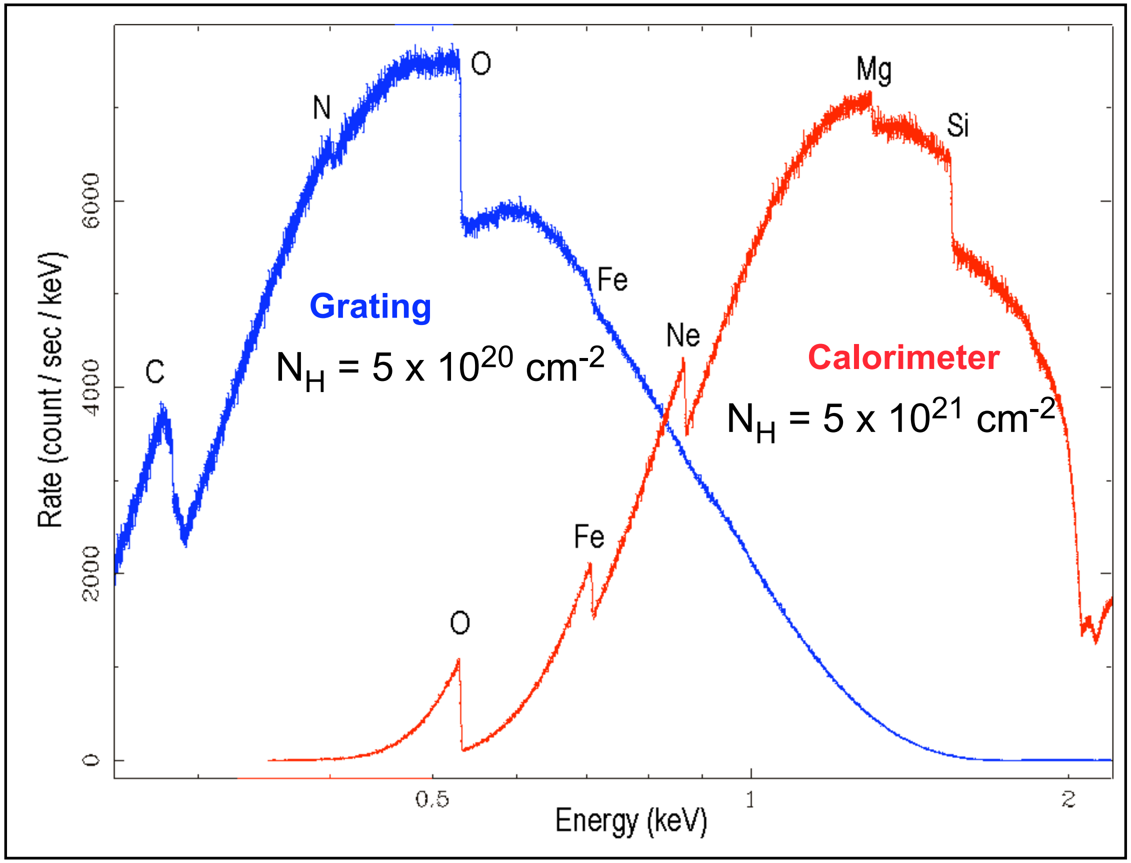
Interstellar Medium of our Galaxy



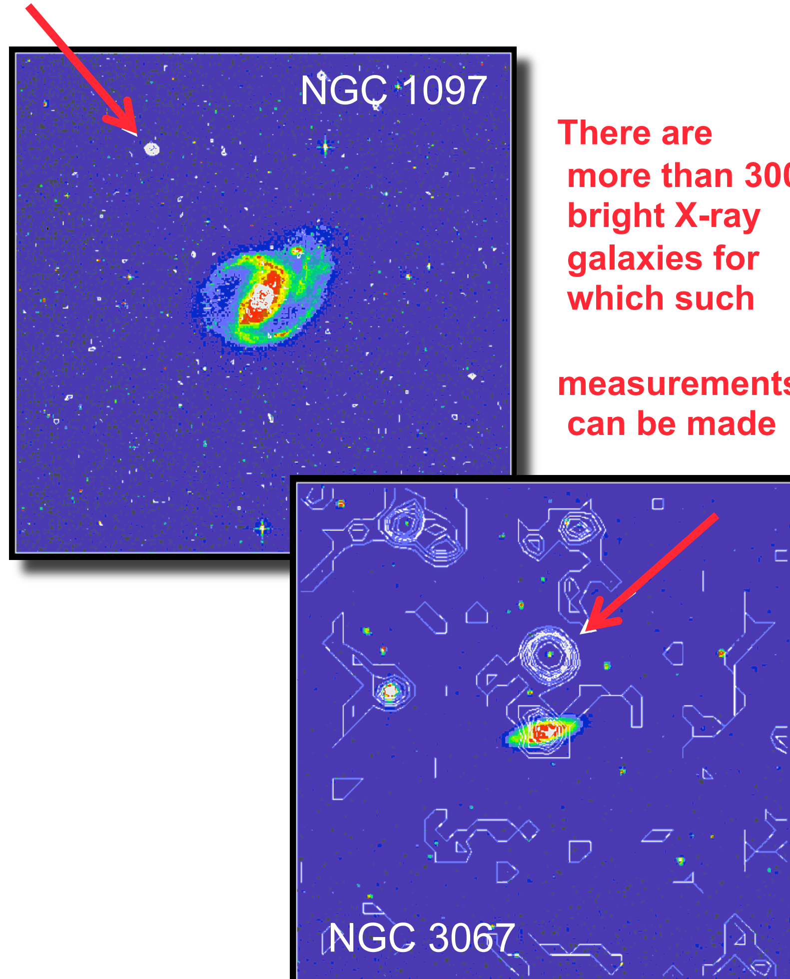
- Chimneys connecting the galactic plane to the halo in spiral galaxies provide a mechanism for hot plasma with enhanced abundances to escape the disk
- Such plasma, the result of supernovae and the winds of massive stars, heat and enrich the halo
- This figure shows a possible example of such a chimney in the Milky Way, with a trail of enhanced X-ray emission from a number of energetic regions in the plane to a plume into the lower halo
- Model Constellation-X spectra from three points in the chimney show cooling of the plasma as it progresses out of the disk can clearly be seen by the shifting of the emission to lower energies
- Constellation-X observations will allow a much deeper study than can currently be achieved with a considerably greater sensitivity to changes in ionization structure and abundances

Galactic Halos

The composition and state of the tenuous hot halos of Galaxies can be accurately measured via K or L shell absorption of X-rays against background quasars



Spectra of two typical quasars absorbed through two different hydrogen column densities in the ISM



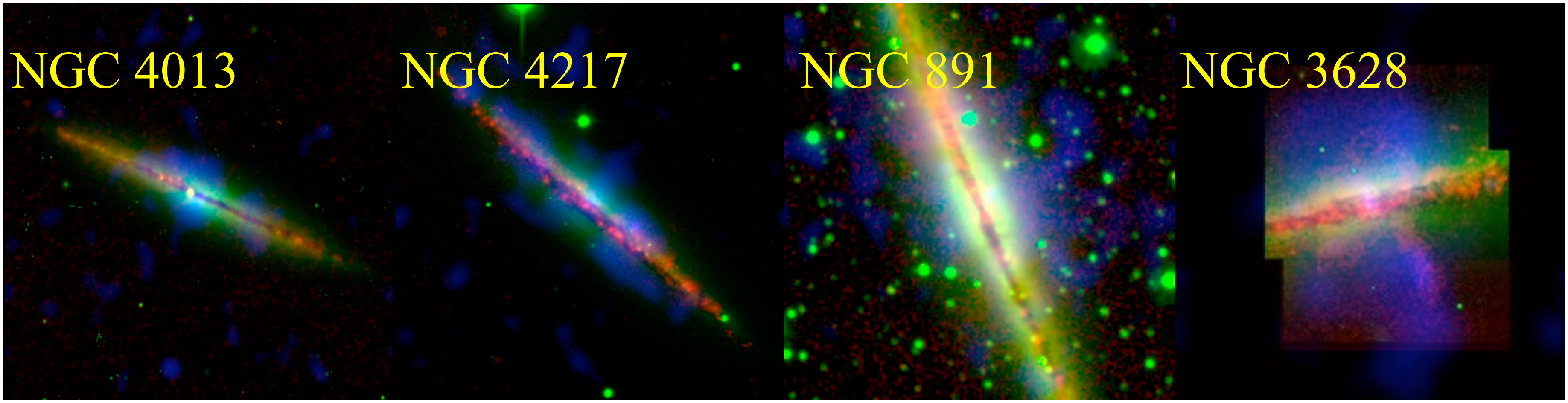
There are more than 300 bright X-ray galaxies for which such measurements can be made

Hot gas around normal disk galaxies

courtesy of D. Strickland (JHU)

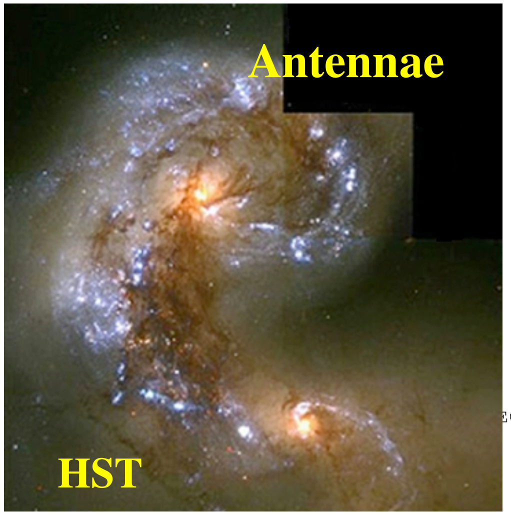
Normal spiral galaxies

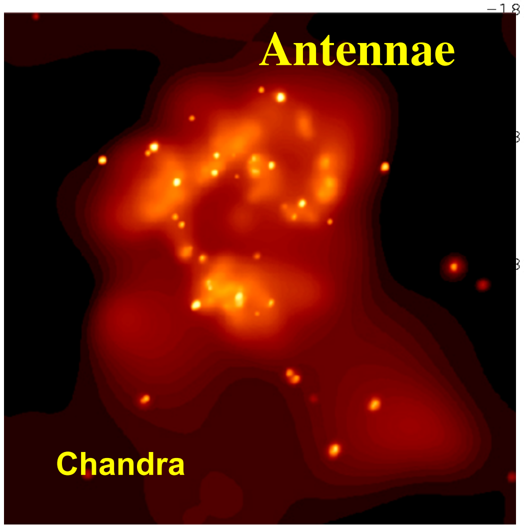
Example starburst galaxy with superwind



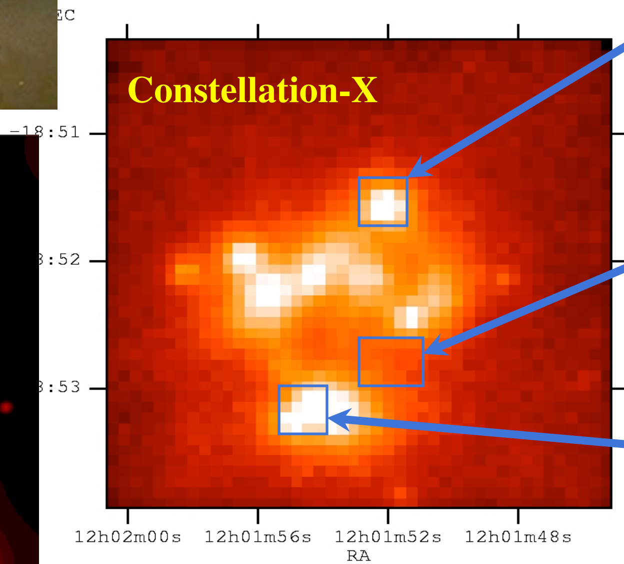
Red: H-alpha (WIM), Green: R-band (starlight), Blue: Diffuse soft X-ray (3 million deg gas).
The region covered by each image is 20 x 20 kpc. Intensity scale in square-root.

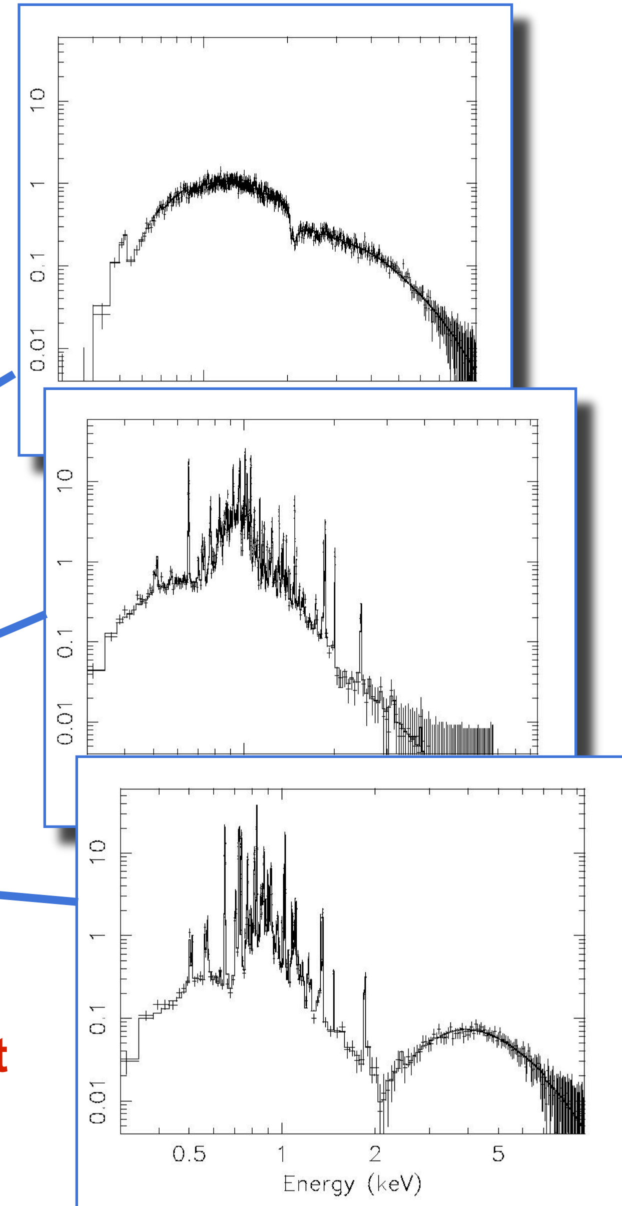
Hot ISM in Spiral Galaxies: The Antennae





Constellation-X needed to map the hot IGM in the Antennae to determine the plasma parameters (density, abundance, velocities, ionization state) of the hot ISM

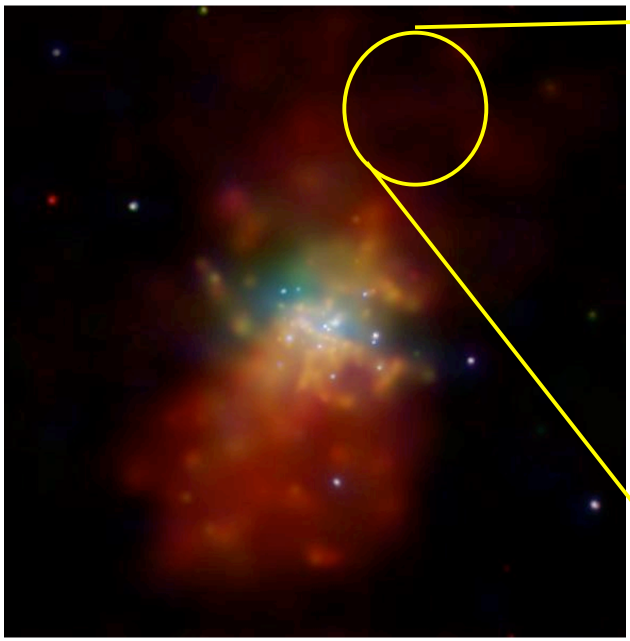




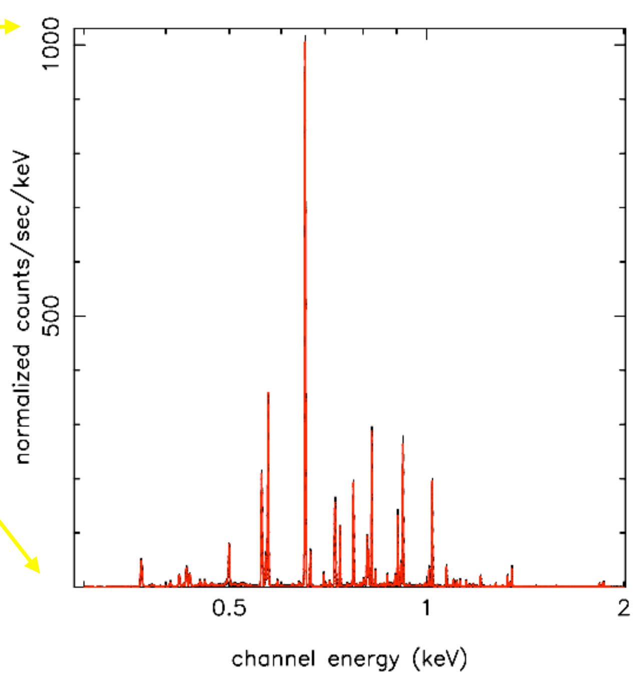
Constellation-X will complement Chandra by giving 900 high resolution spectra across the galaxy in one observation

Supernova (Stellar) feedback

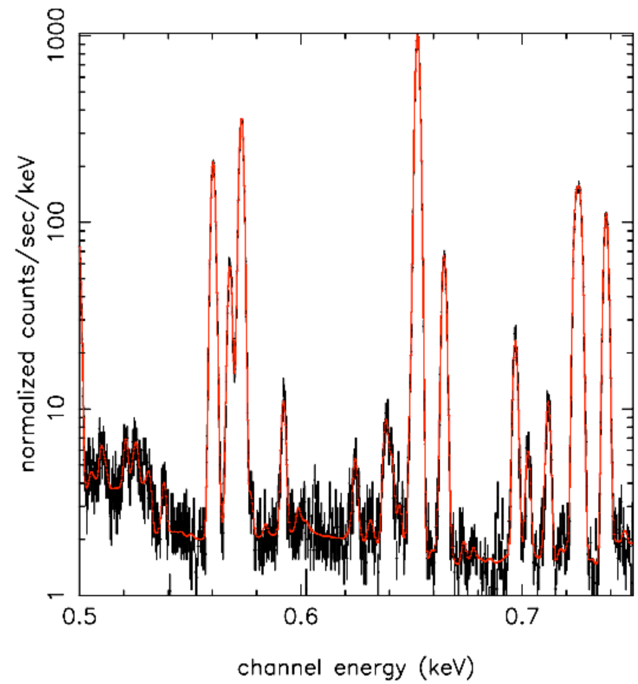
Wind plasma diagnostics (D. Strickland, JHU)



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



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

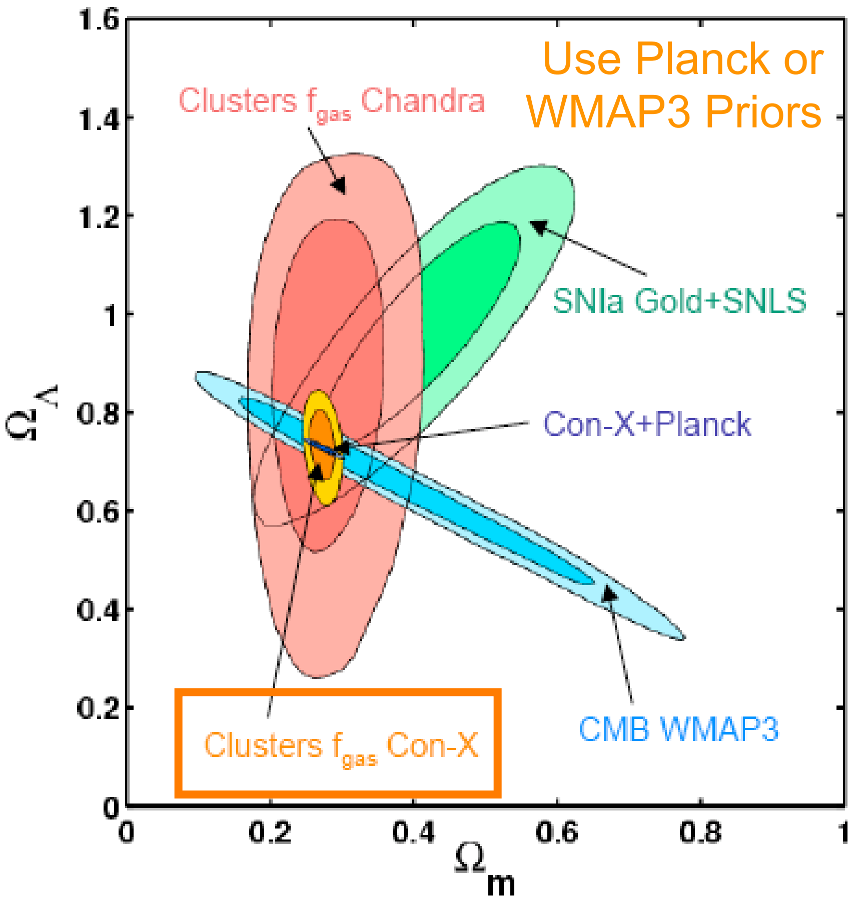


O VII and O VIII region. Well resolved triplet, high S/N in continuum.

With calorimeter ~2-eV resolution we can determine T, $n_e t$, [Z/H], v_{HOT} accurately in many extended winds (not just M82).

Dark Energy:

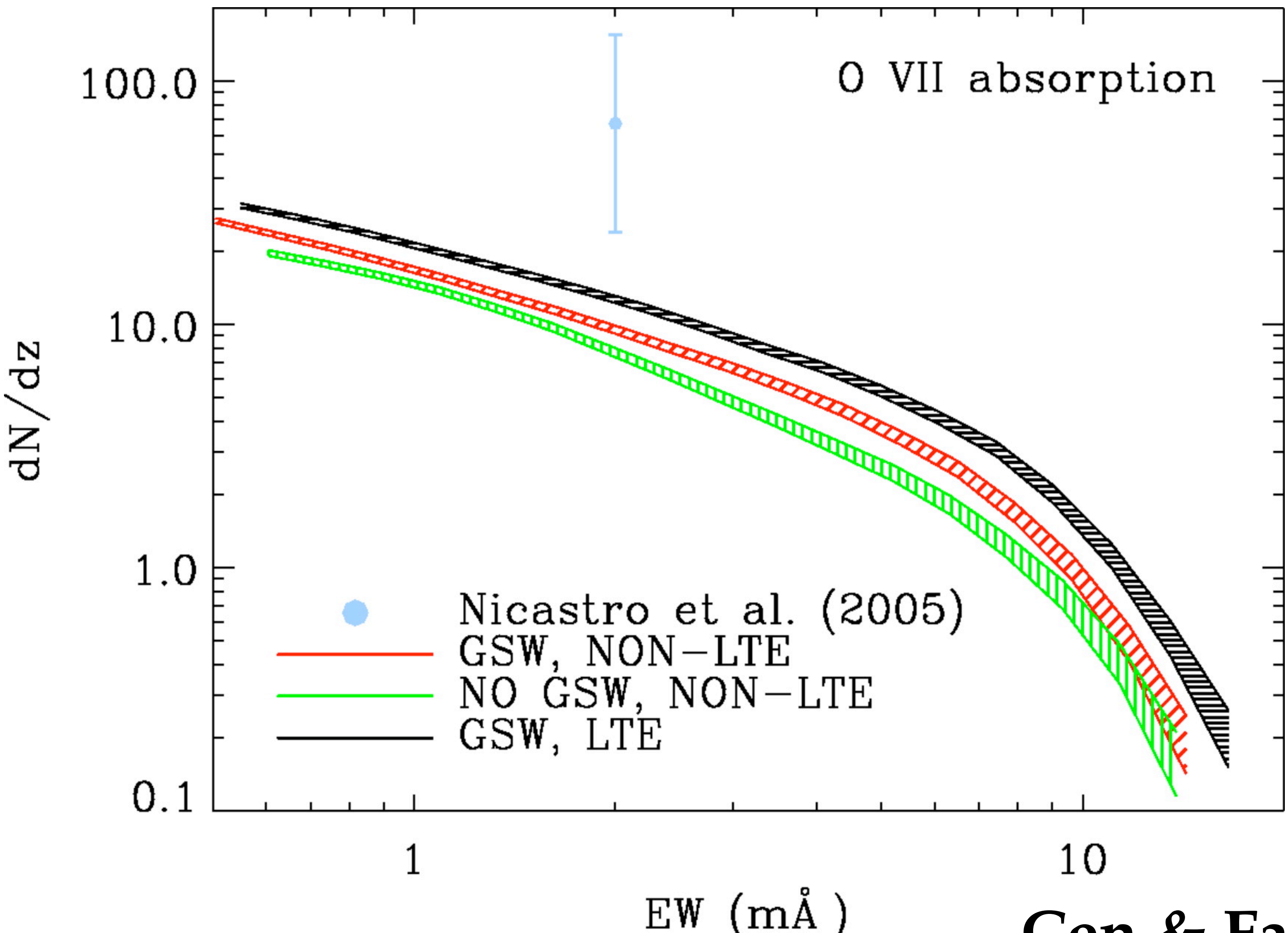
Improving the constraints on the key Dark Energy (DE) parameters by a factor of ten



Con-X will provide competitive and complementary DE parameter constraints to other methods planned for 2017

- **Largest gravitationally bound structures in the Universe, most of the normal, baryonic matter lies in the hot X-ray emitting gas (10^6 - 10^8 K)**
- **Measurement #1 (Geometric):** **Matter in clusters is "fair sample of the Universe" (constant baryonic mass fractions) to constrain *d(z)***
- **Measurement #2 (Growth of structure):** **Use clusters as probe of density perturbation growth in the Universe via cluster mass function vs *z* measurement *(samples from X-ray & submillimeter surveys)***

How Many Filaments are There?



Cen & Fang 2006