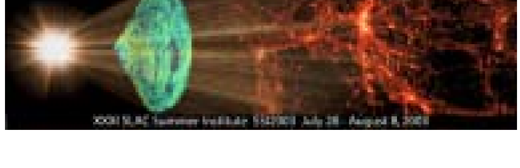
The Cosmic X-Ray Background

Steven M. Kahn

Kavli Institute for Particle Astrophysics and Cosmology

Stanford University



Outline of Lectures

Lecture I:

* Historical Introduction and General Characteristics of the CXB.
* Contributions from Discrete Source Classes
* Spectral Paradoxes

Lecture II:

* The CXB and Large Scale Structure
* The Diffuse Soft X-Ray Background
* The CXB and the Cosmic Web

IV. The Cosmic X-ray Background and Large-Scale Structure

The CXB and Large-Scale Structure

* As we saw in the last lecture, there is good reason to believe that the CXB is entirely made up of discrete sources.

* In addition, the spectral shape of the background, especially the peak at 30 keV is suggestive that the dominant contribution comes from obscured AGNs with strong reflection components.

* If this is true, then the most of the flux is originating at $z \sim 2$ or so. [100 keV/30 keV $\sim 1+z$].

* What can we learn about the structure of matter in the Universe from these results?

The CXB and Large-Scale Structure

* First, look at the absolute value of the intensity (Fabian and Iwasawa, 1999, MNRAS, 303, L34):

* In this picture, the flux at 30 keV is unabsorbed, and is produced by accretion onto BHs. The energy density in such "accretion radiation" is given by:

$$U_X = 4\pi I_X/c \sim 1.2 \times 10^{-15} \text{ ergs cm}^{-3} \text{ s}^{-1}$$

(with an appropriate bolometric correction)

* Accretion onto a BH is roughly 10% efficient. That means that the mass density which has been accreted is:

$$P_{acc} \sim 10(1+z)U_X/c^2 \sim 6 \times 10^5 \text{ M}_{sol} \text{ Mpc}^{-3}$$

* Essentially all of the accreted matter ends up in BHs. The mass estimate agrees "disturbingly" well with an independent estimate of the BH mass density derived by scaling from the bulges of nearby galaxies - i.e. the BHs we are seeing today produced the CXB when they formed at z > 2 or so.

* The total power in accretion is ~ 20% of that produced in stars! And roughly 85% of it is absorbed.

The CXB and Large-Scale Structure

* Fluctuations in the CXB:

* Even without knowing for sure what the sources of the CXB are, we can safely assume that they involve baryons and thus must trace the mass distribution in some way. Hence the fluctuations in the CXB on various angular scales can tell us something about the clustering of matter, and thus about the growth of perturbations.

* What makes the CXB interesting in this regard is that it arises at truly intermediate redshifts. At z ~ 2, 1^{o} corresponds to a scale length ~ few hundred Mpc. This is intermediate between the scales probed by the CMB (~ 1000 Mpc), and the scale probed by the available optical redshift surveys (~ 10 Mpc).

The CXB and Large-Scale Structure

* One of the simplest things to do is to search for clustering on the smaller scales by looking at the fluctuation distribution, P(D), below the detection limit.

* The width of P(D) contains essentially three contributions:
  – A "Poisson" term associated with counting statistics given the X-ray count rate.
  – A "Shot Noise" term associated with the fluctuations in the number of point sources in the beam, given a random orientation in those sources. This estimation of this term depends on the shape of the Log N - Log S relationship - but that can be extrapolated from brighter flux levels where it is directly measured.
  – A "Clustering" term associated with LSS in the parent source distribution.

* Another approach is to compute an autocorrelation function:

$$W(\theta) = \langle\delta(\phi+\theta)\delta(\phi)\rangle / \langle\delta^2\rangle$$

* Both forms of analyses have suggested that the sources responsible for the CXB are less clustered on Mpc scales than bright AGNs are. Their clustering looks more like that of normal galaxies.

The CXB and Large-Scale Structure

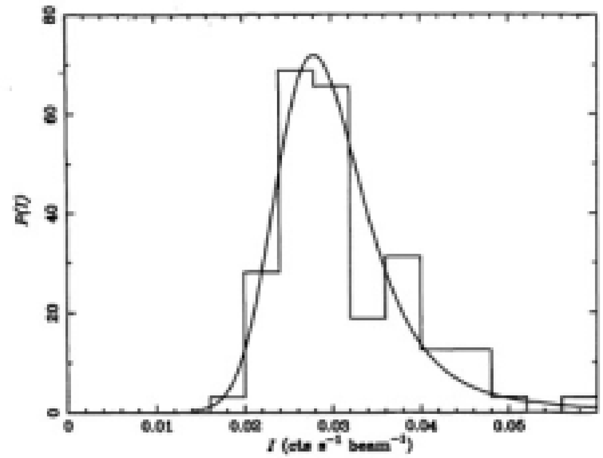


Figure 1. Histogram of the distribution of the XRB intensities for the large beam (see text). Also shown as a solid continuous line is the best fit $P(I)$ with $K = 55\ \mathrm{deg}^{-2}$, with no cluster contribution and the average $\Delta I_{\mathrm{noise}}$ (see text).

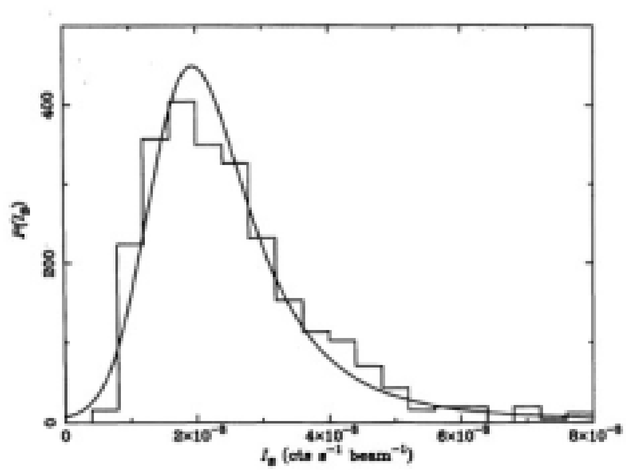


Figure 2. Histogram of the distribution of XRB intensities for the small beam (whole data set, see text). Also shown as a solid continuous line is the best fitting $P(I_s)$ with $K = 55\ \mathrm{deg}^{-2}$, with no cluster contribution and the average $\Delta I_{\mathrm{snoise}}$ (see text).

From Carrera, Fabian, and Barcons, 1997, MNRAS, 285, 820.

The CXB and Large-Scale Structure

* One can also carry out an analysis in terms of spherical harmonics, similar to what is done for the CMB. This can be used to convert a mass power density spectrum, predicted by CDM models, to a form which can be directly compared with the data. (See several papers by Lahav, Treyer et al.)

* To do this, you need to understand how the X-ray emitting sources "trace" the matter, and how their luminosity density evolves with z. Assuming constant "bias", linear growth of perturbations, and evolution of the form: $\rho(z) \sim (1+z)^q$, one gets:

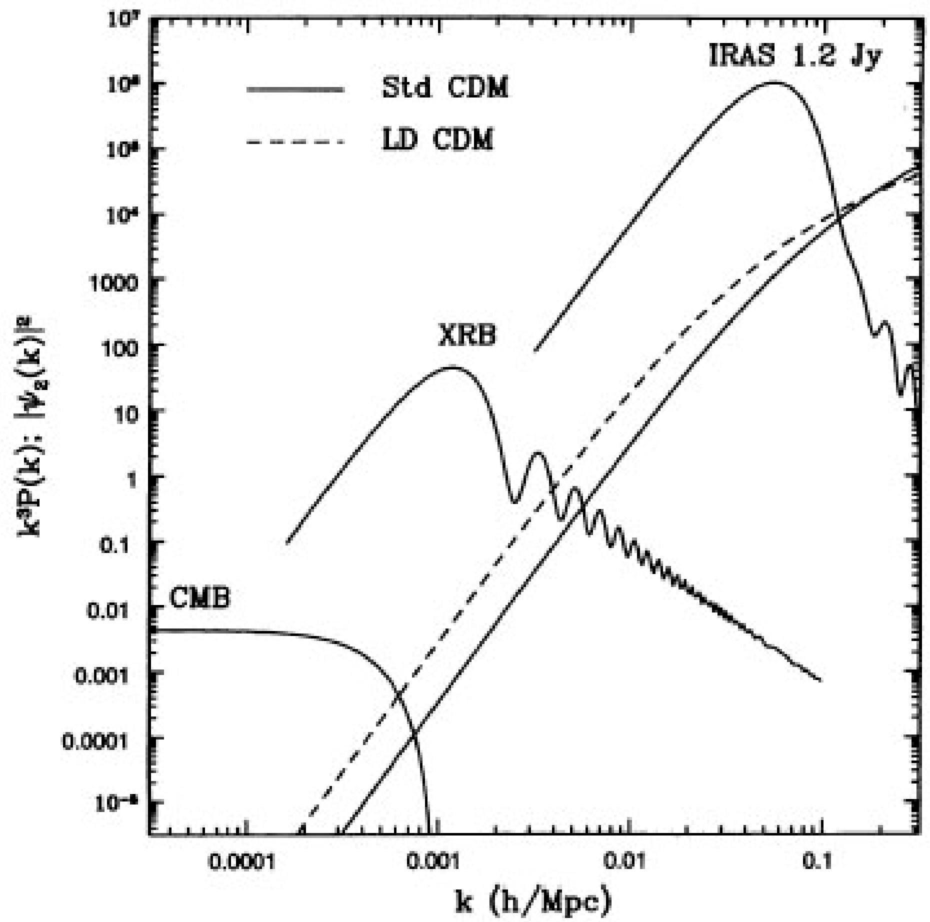
$$<|a_{lm}|^2> = \frac{1}{(2\pi)^3}\rho_{x0}^2 b_x^2 \left(\frac{c}{H_o}\right)^2 \int dk k^2 P(k) |\Psi_l(k)|^2$$

Where

$$\Psi_l(k) \approx \int_{z\,\min}^{z\,\max} dz (1+z)^{q-1-7/2} j_l(kr[z])$$

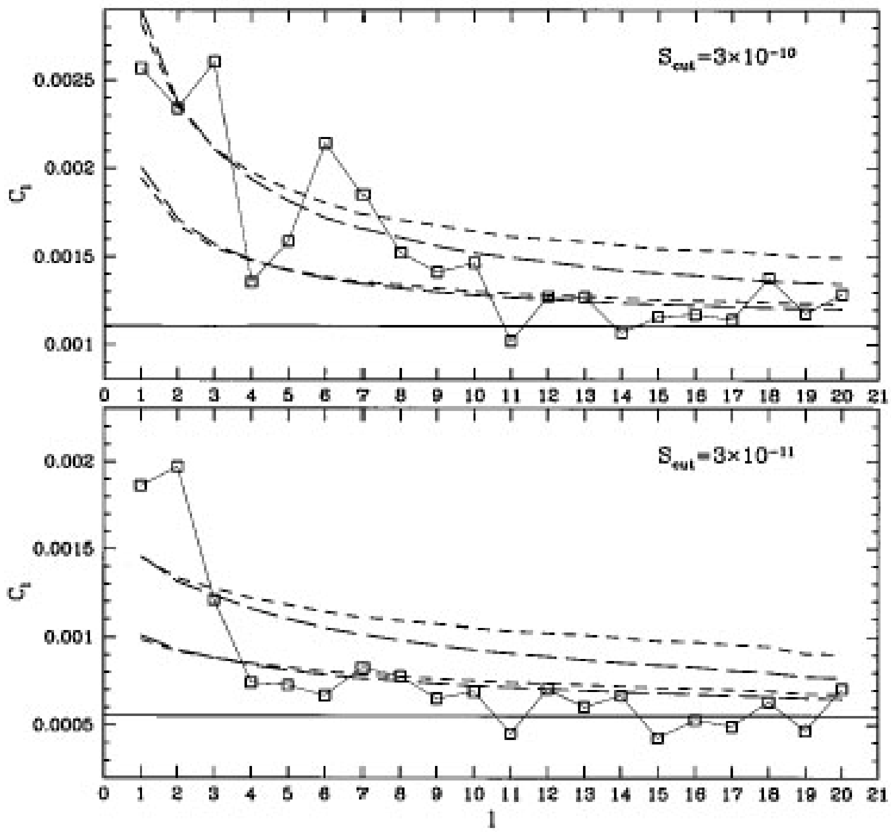
(Lahav, Piran, and Treyer, 1997, MNRAS, 284, 489.)

The CXB and Large-Scale Structure



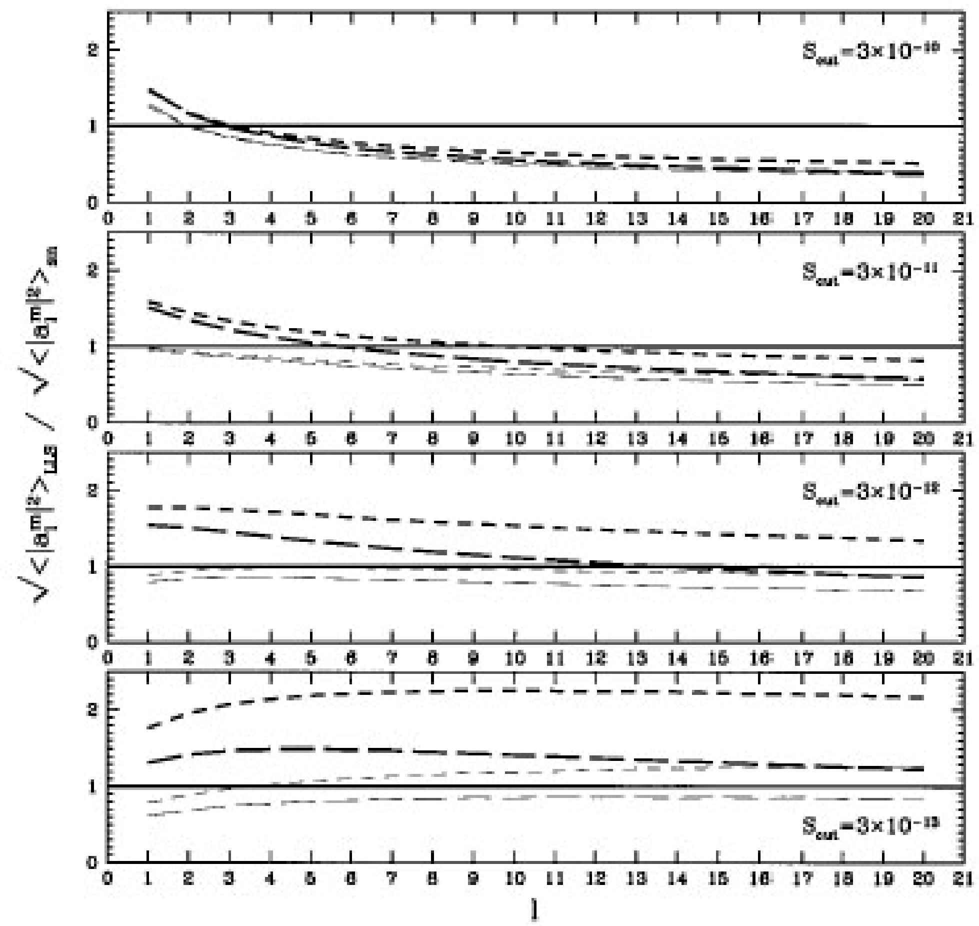
From Lahav, Piran, and Treyer, 1997, MNRAS, 284, 499.

The CXB and Large-Scale Structure



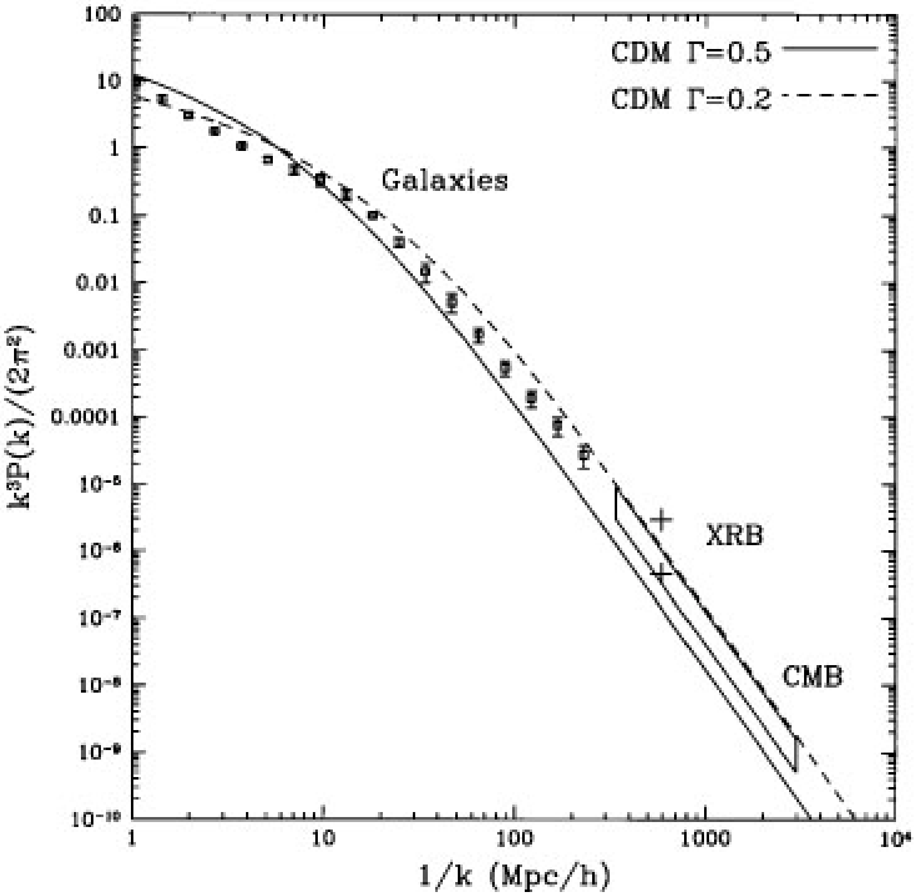
From Treyer et al., 1998, Ap. J., 509, 531.

The CXB and Large-Scale Structure



From Treyer et al., 1998, Ap. J., 509, 531.

The CXB and Large-Scale Structure



From Treyer et al., 1998, Ap. J., 509, 531.

The CXB and Large-Scale Structure

- The dipole term is interesting, because it also constrains local bulk velocity flows. The LPT analysis shows that this term is dominated by the matter distribution on the scale of 150 - 300 Mpc.

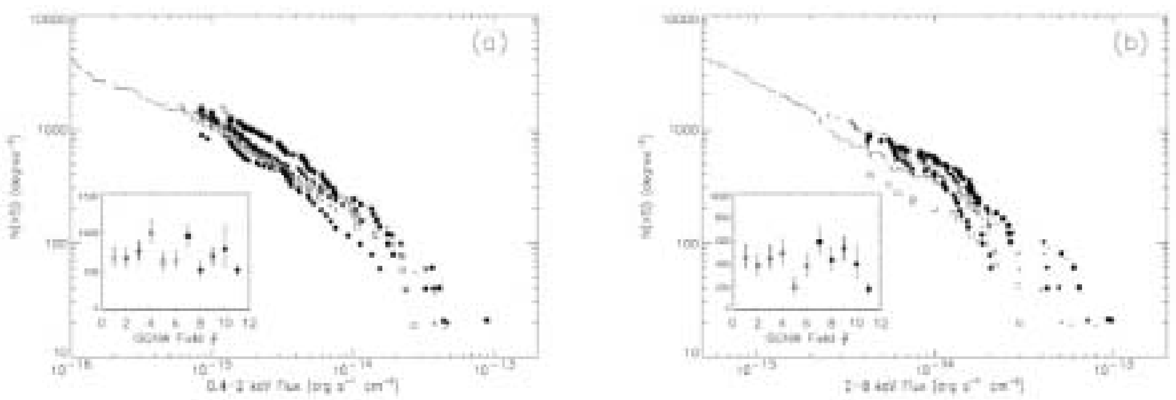
- But: $$\vec{D} \propto \int \frac{\delta}{r^2} dV \hat{r} \propto \vec{g}$$

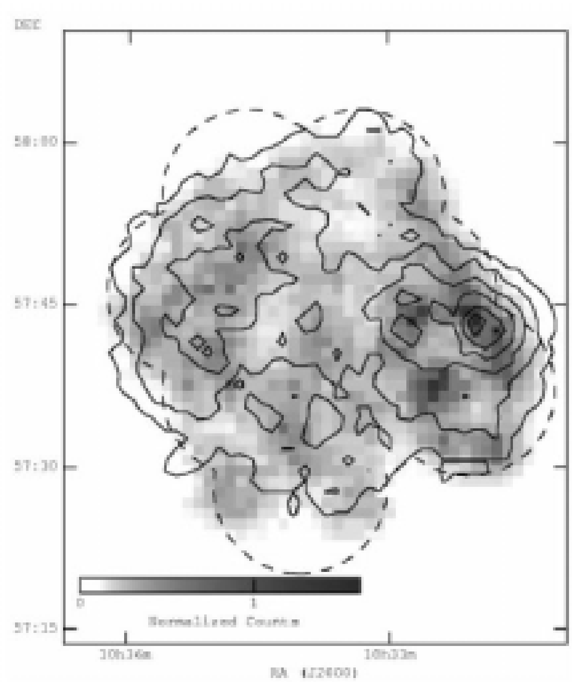
- In linear perturbation theory, the peculiar motion at any point in space is directly proportional to the local gravitational acceleration. So, the measured value of the X-ray dipole can yield an estimate of typical bulk velocities which can be compared with direct observations.

- The result yields an estimate of the bias parameter for the CXB sources - b ~ few.

The CXB and Large-Scale Structure

Chandra "direct" observations of LSS!





From Yang et al. 2003, Ap. J., 585, L85.

V. The Diffuse Soft X-Ray Background

The Diffuse Soft X-Ray Background

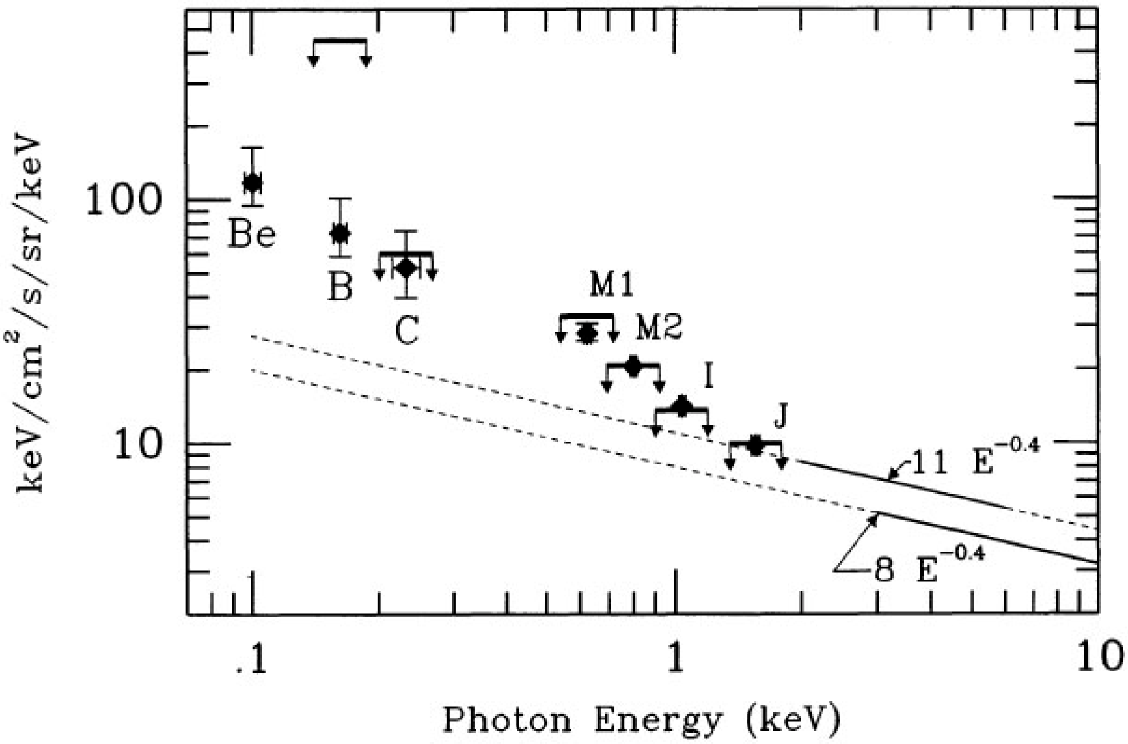
* As indicated in the first lecture, at energies below 1 keV, the CXB spectrum rises above the extrapolation of the extragalactic power law.

* In addition, the spatial distribution becomes comparatively highly structured. In particular, there is a clear correlation with galactic latitude.

* High, or even intermediate resolution spectroscopy of this emission is difficult, but what exists suggests that the flux is dominated by emission lines indicative of collisional excitation in gas with a characteristic temperature ~ 10^6 K.

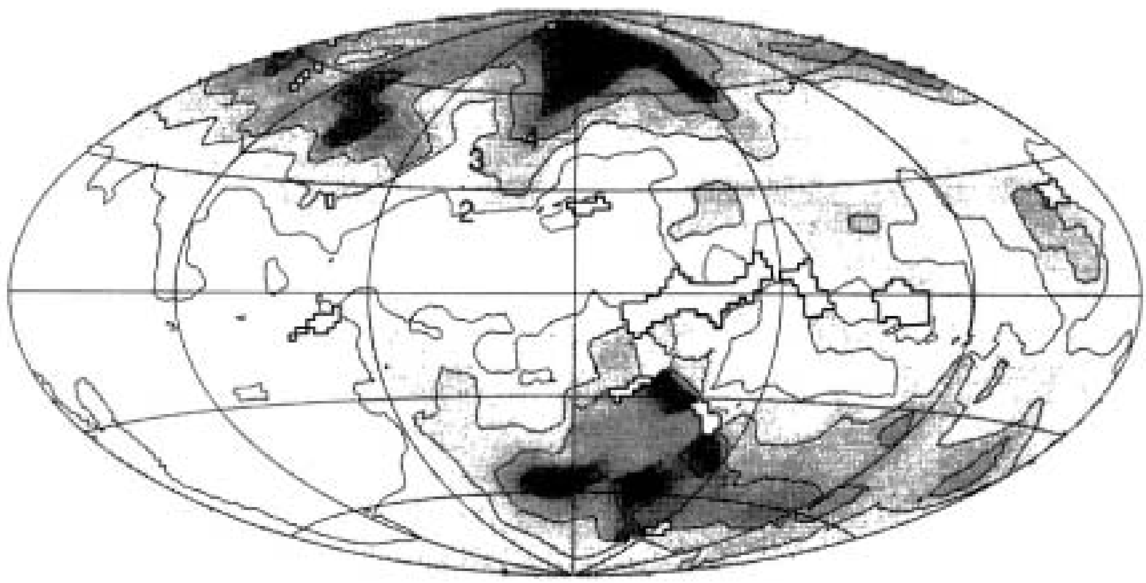
* This gas is thought to reside in the interstellar medium relatively close (~ 100 pc) to the solar system. There is known to be a cavity in the cooler components of the ISM on this scale, and the gas is thought to fill that cavity. This is the so-called "Local Bubble Model" (see McCammon and Sanders, 1990, ARAA, 28, 657.)

The Diffuse Soft X-Ray Background



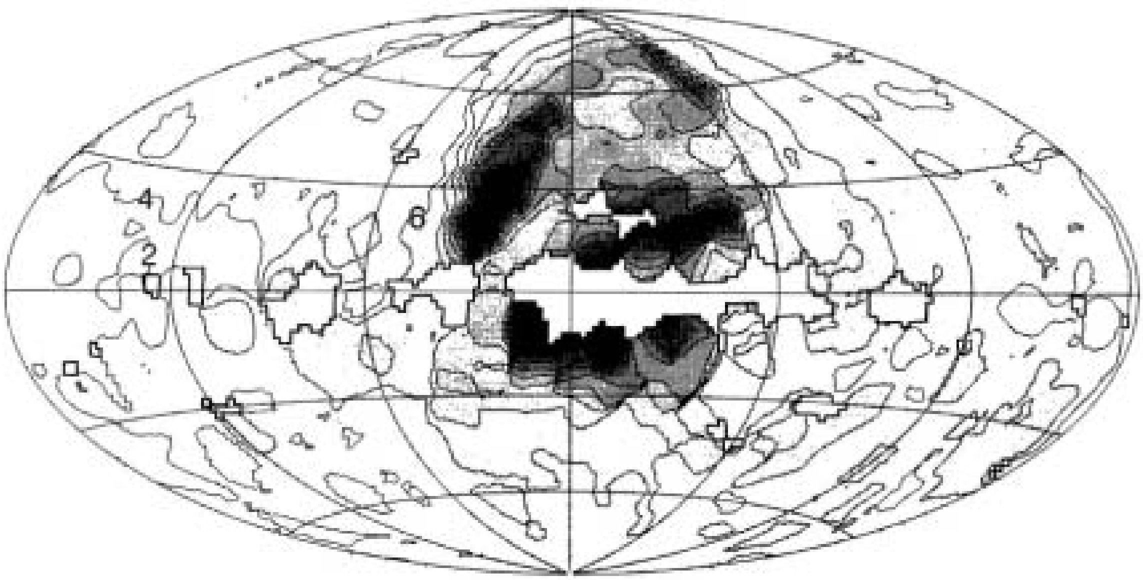
From McCammon & Sanders, 1990, ARAA, 28, 657.

The Diffuse Soft X-Ray Background



From McCammon & Sanders, 1990, ARAA, 28, 657

The Diffuse Soft X-Ray Background



From McCammon & Sanders, 1990, ARAA, 28, 657

The Diffuse Soft X-Ray Background

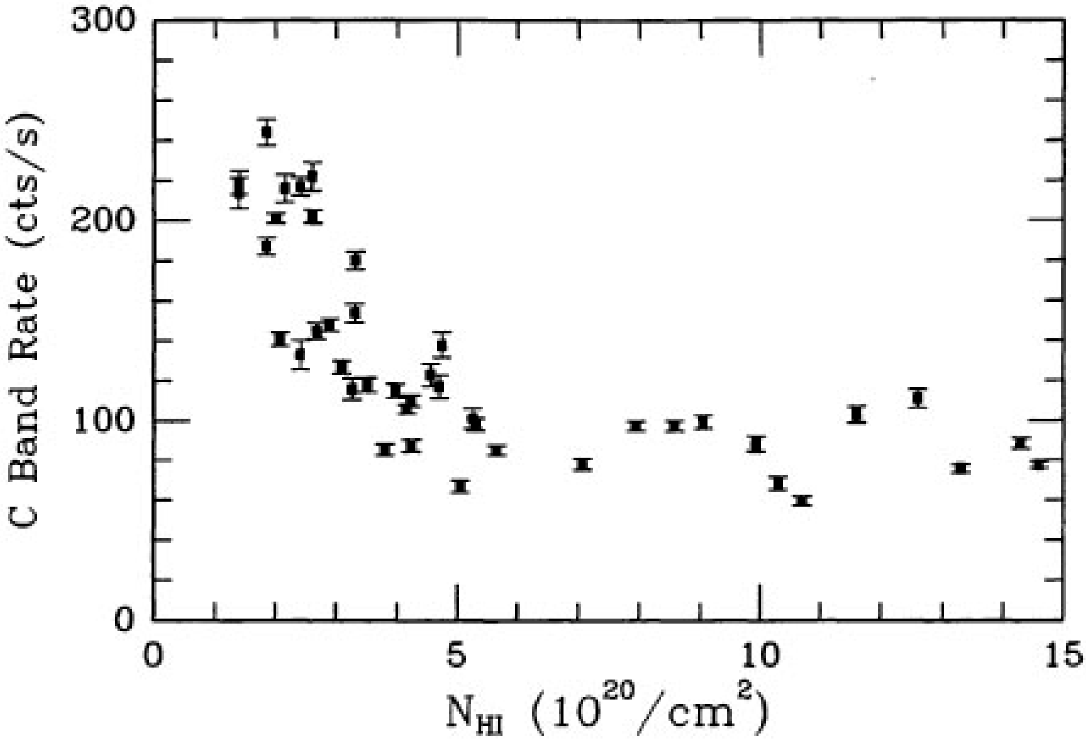
* However, there are some problems with this interpretation in the details:

* The softest fluxes (B, C bands) exhibit a clear anti-correlation with the column density of neutral hydrogen, N_H. One would expect such an anti-correlation due to absorption: $I \sim e^{-\sigma N_H}$. But the effective cross-section which is derived from the fits is much lower than one would expect for photoelectric absorption.

* Jakobsen and Kahn (1986) first suggested that this could result from “embedding”, i.e. since the absorbing “clouds” are embedded in the emitting medium, the attenuation is reduced. This would require roughly equal scale heights for the both the hot and cold gas, inconsistent with naïve expectations from hydrostatic equilibrium.

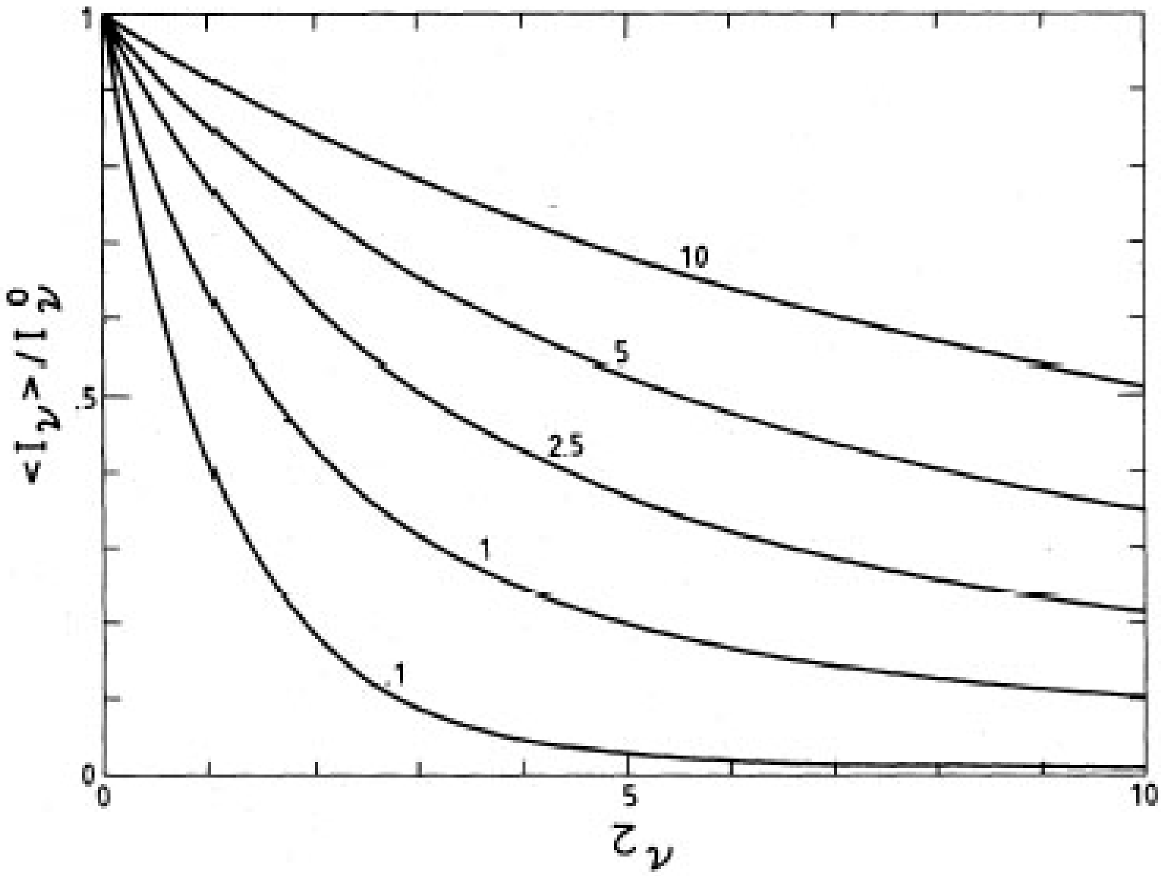
* The relative constancy of the band ratios is even more constraining.

The Diffuse Soft X-Ray Background



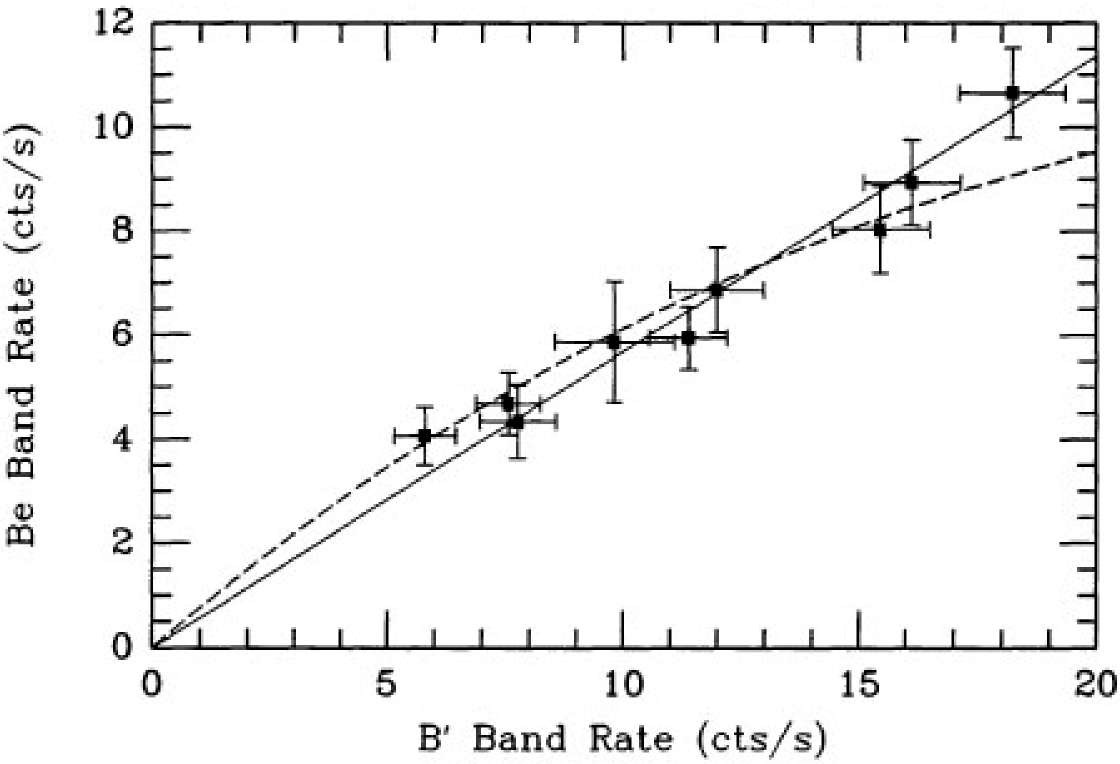
From McCammon & Sanders, 1990, ARAA, 28, 657

The Diffuse Soft X-Ray Background



From Jakobsen & Kahn, 1986, Ap. J., 309, 628.

The Diffuse Soft X-Ray Background



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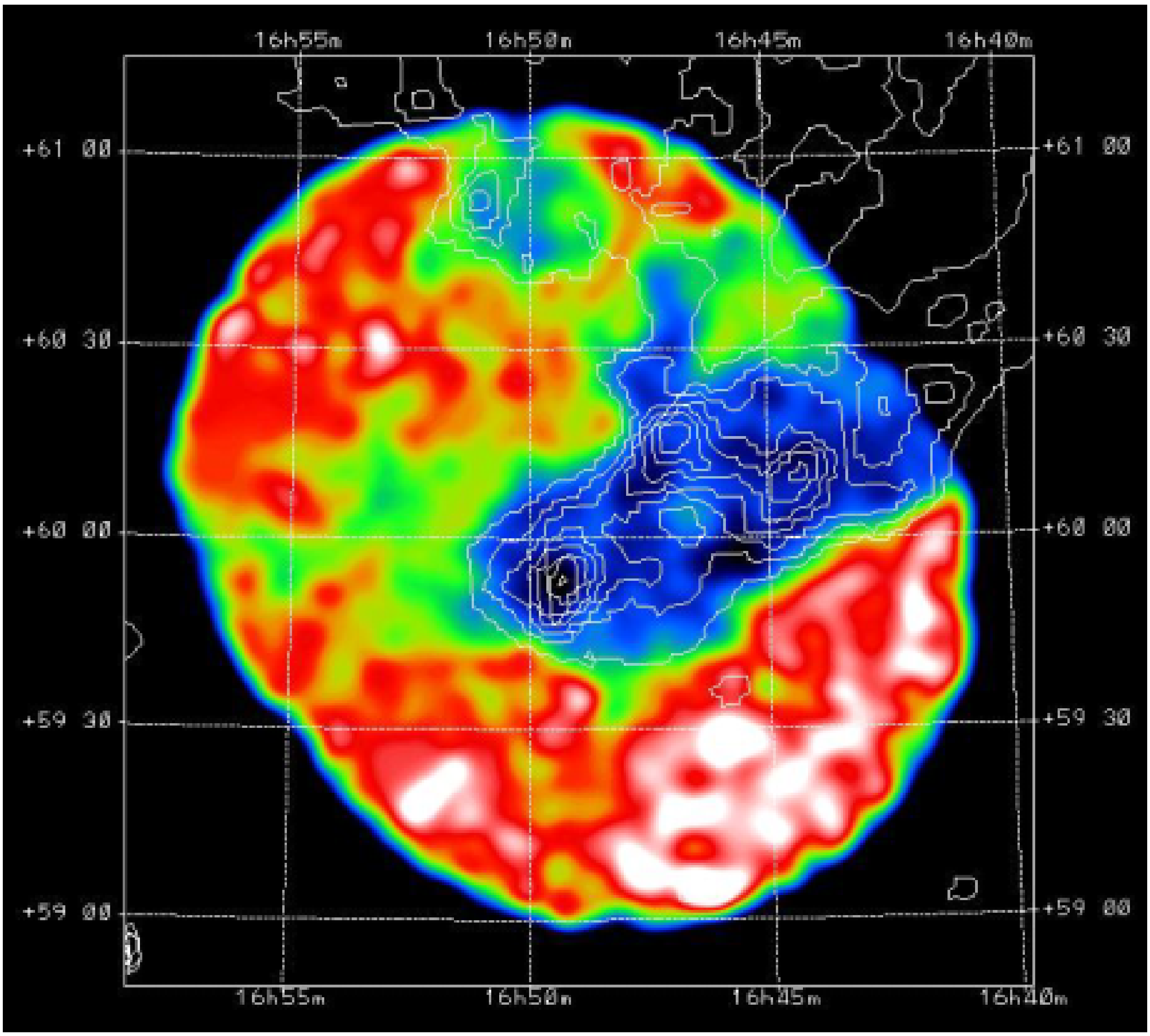


The Diffuse Soft X-Ray Background

* The shadowing results suggest that at least some significant fraction of the soft background is coming from larger distances, > few hundred parsec.

* This could be from the within the halo of our galaxy, or it could be a larger medium associated with the Local Group. (More on this later.)

* However, the present data are still confusing in this regard because the inferred distant component appears to vary considerably from field to field where shadowing has been observed.

* Thus, the exact nature of the soft CXB remains unresolved.

The Diffuse Soft X-Ray Background

* Spectrum of the Soft CXB:

* The spectrum of the soft CXB is difficult to measure because the resolving power of the available nondispersive detectors gets poor in this band. For example, for a proportional counter: $\Delta E/E \sim 0.4\ (E_{keV})^{-1/2}$. In addition, one cannot use gratings in an objective configuration because of the blurring due to the source extent.

* On the other hand, for temperatures of ~ 10^6 K, which are characteristic of this component, the emission line spectrum is exceedingly rich in this band. It includes the K-shell transitions of C, N, and O, the L-shell transitions of Ne - Ar, and the M-shell transtions of Fe.

* The best one can hope for is a highly blended spectrum that still shows distinctive "features".

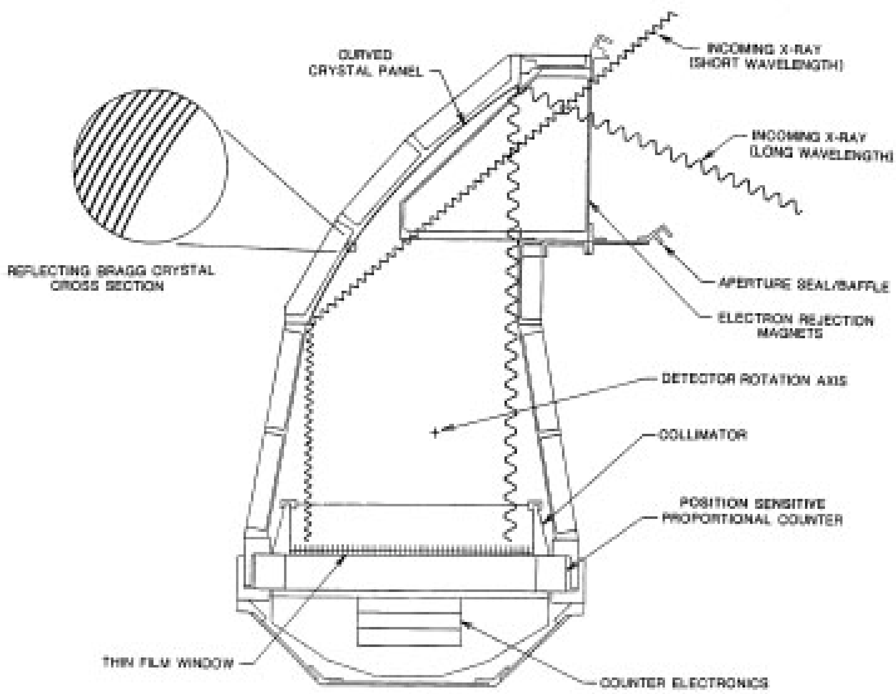
The Diffuse Soft X-Ray Background

* There have been two significant measurement to date, both coming from the same group at Wisconsin.

* The first involved a large Bragg crystal experiment flown as an attached payload on the Space Shuttle (Sanders et al., 2001, Ap. J., 554, 694).

* The second involved a rocket measurement using a novel X-ray calorimeter detector (McCammon et al., 2002, Ap. J., 576, 188).

The Diffuse Soft X-Ray Background



From Sanders et al., 2001, Ap. J., 554, 694.

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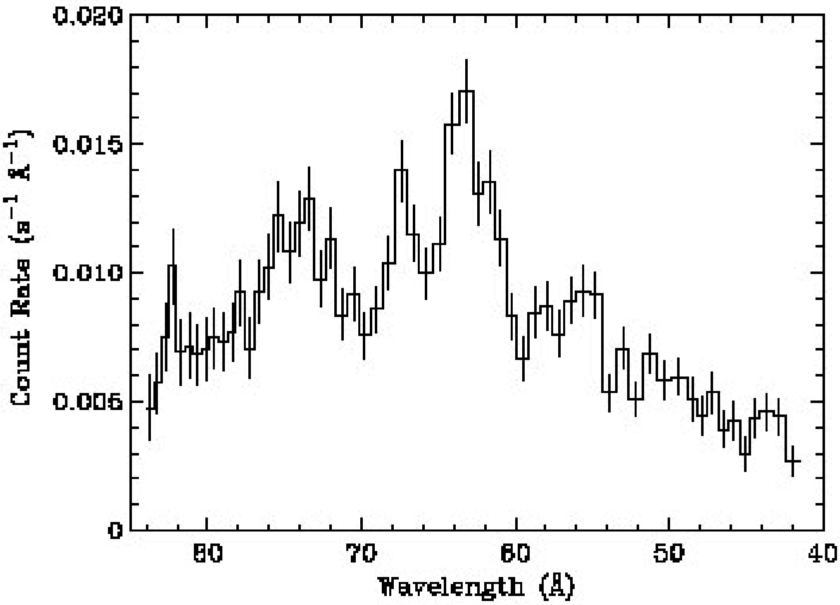

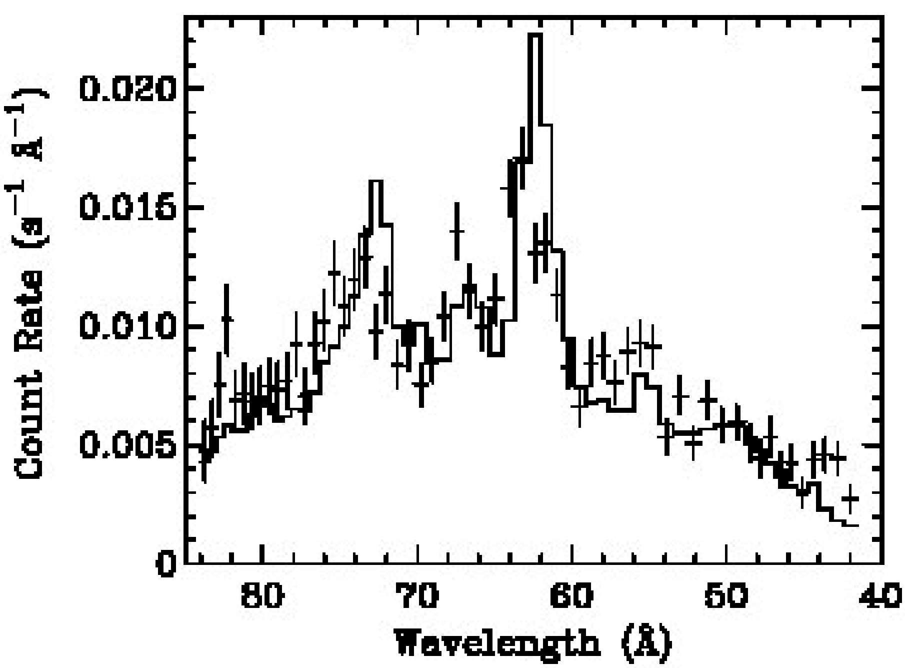

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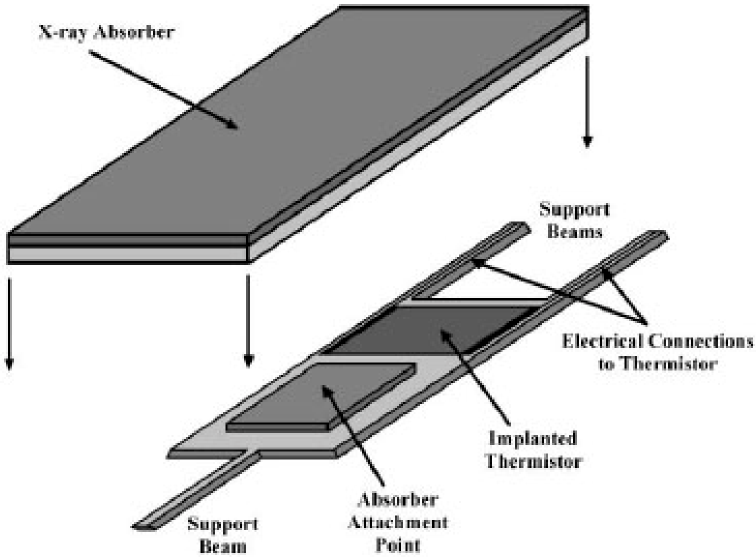
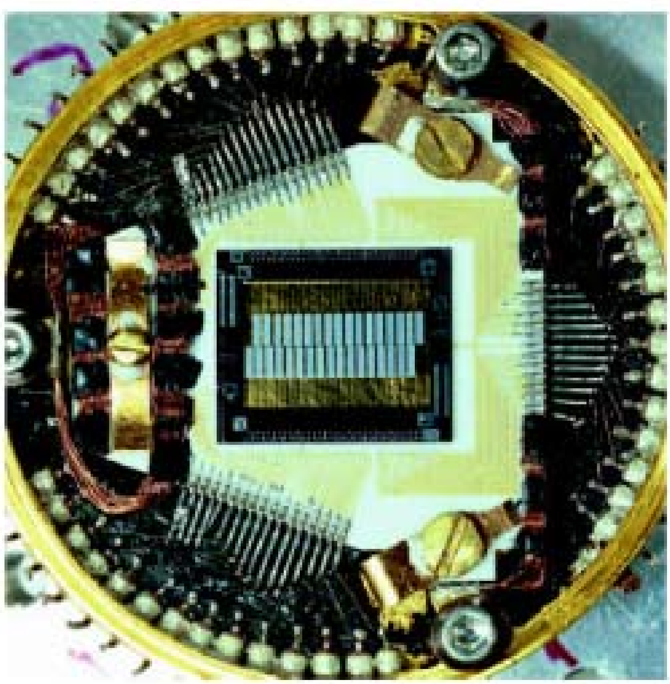
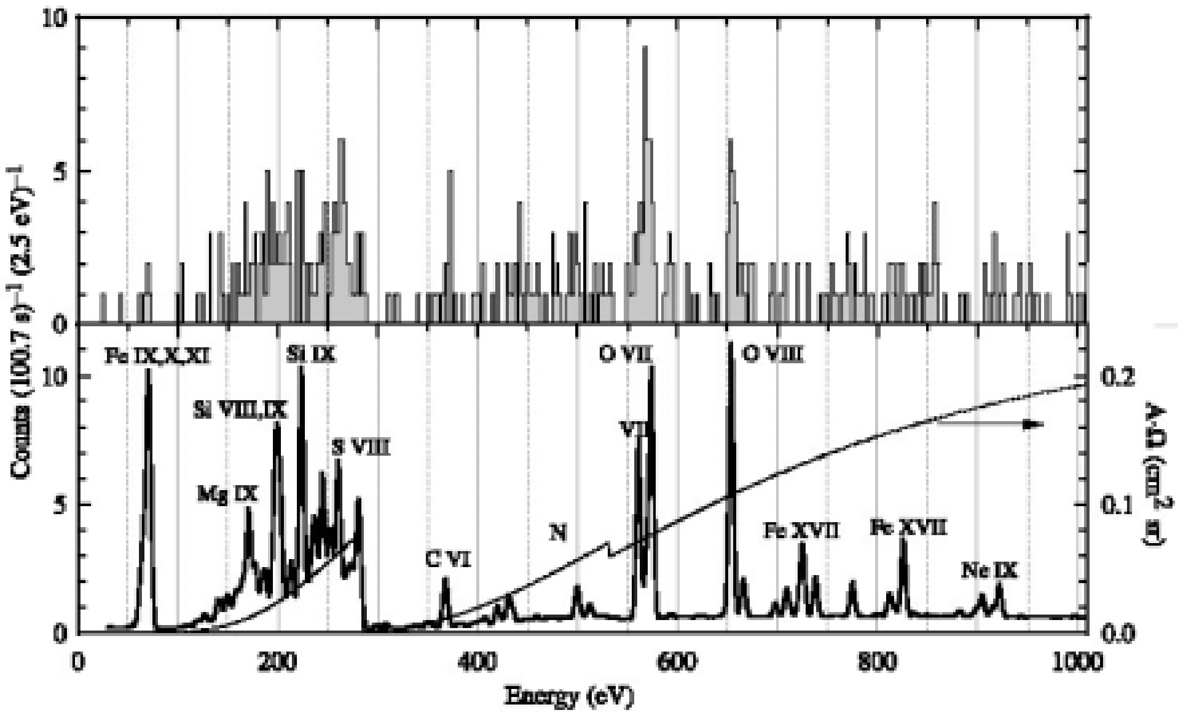




From McCammon et al., 2002, Ap. J., 576, 188.

The Diffuse Soft X-Ray Background



From McCammon et al., 2002, Ap. J., 576, 188.

The Diffuse Soft X-Ray Background

* The DXS and XQC data clearly show that the soft X-ray background is dominated by thermal emission from hot gas.

* However, the spectra are not well-described by simple collisional thermal models. This is not really unexpected because there can be a number of complicating effects:
  - Embedded absorption
  - Non-equilibrium ionization
  - Multi-temperature emission

* It does indicate though that the interstellar foreground is difficult to estimate reliably in this band!

VI. The CXB and the Cosmic Web

The CXB and the Cosmic Web

* Cosmic nucleosynthesis requires that $\Omega_b \sim 0.039$. This also agrees well with the fits to the WMAP data, giving us strong confidence in the results.

* Only a small fraction of these baryons can be in stars. However, at $z \sim 2$, the amount of H and He inferred from the absorption lines in the Lyα forest can easily account for the rest.

* The same is not true at $z = 0$. If we add up all the know constituents, we get:

$$\Omega_* + \Omega_{HI} + \Omega_{HII} + \Omega_{cl} \sim 0.0068$$

* Where are the missing baryons in the low redshift Universe?

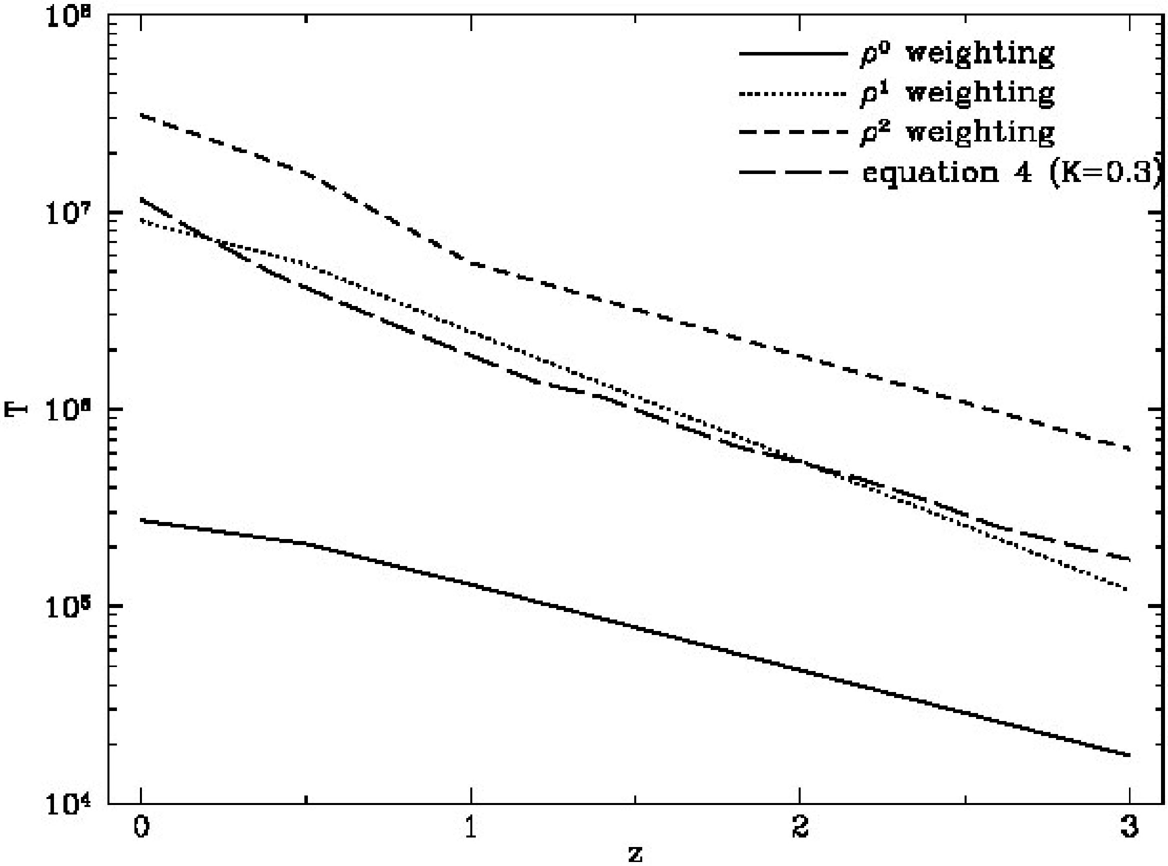
The CXB and the Cosmic Web

* A simple argument suggests that they should be mostly in the form of warm/hot gas distributed in the filaments near and between clusters and groups.

* Structures beginning to collapse non-linearly now have characteristic scales L ~ 8 Mpc. The velocity at collapse should be of order v ~ L/t ~ HL ~ few hundred km s^{-1}. As a collapsing perturbation attempts to cross another, a shock will form with a sound speed c ~ v. The corresponding temperature behind the shock is then ~ 10^6 - 10^7 K. This should give rise to a diffuse component of thermal X-rays that may be "hidden" in the CXB.

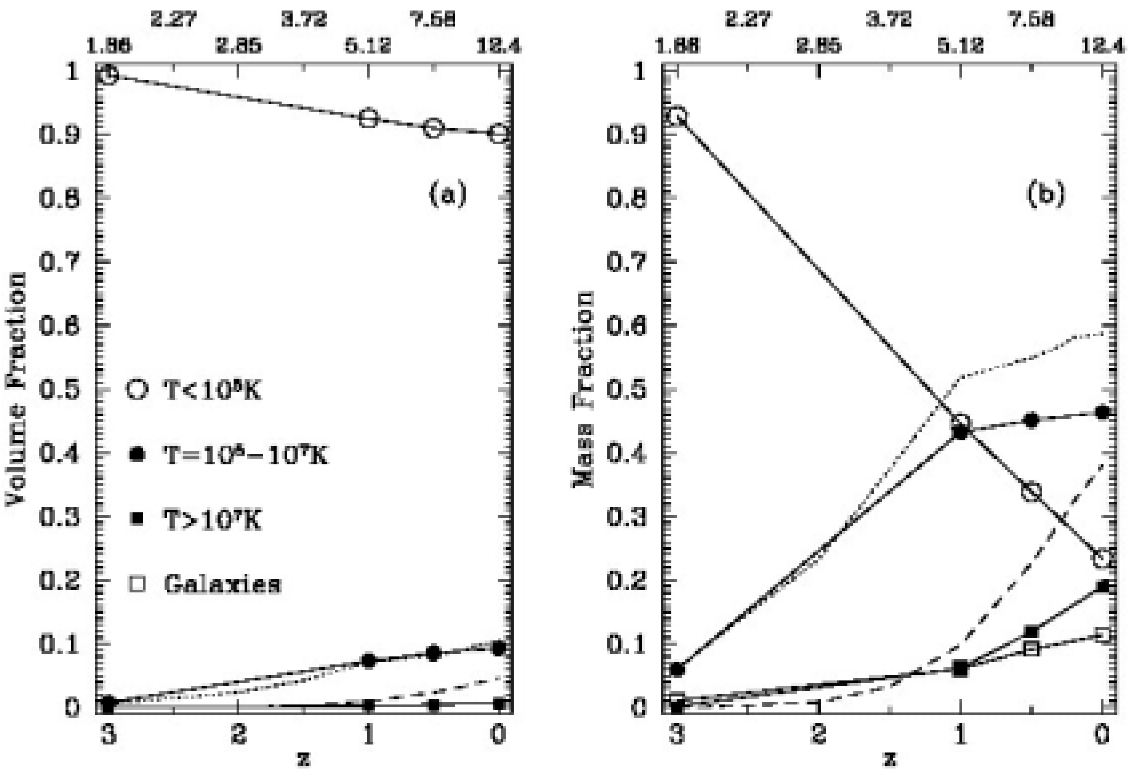
* Indeed, hydrodynamic simulations seem to verify these simple expectations. They suggest that in the present era, ~ 50% of the baryonic mass may be in this diffuse intergalactic medium.

The CXB and the Cosmic Web



From Cen & Ostriker, 1999, Ap. J., 514, 1.

The CXB and the Cosmic Web



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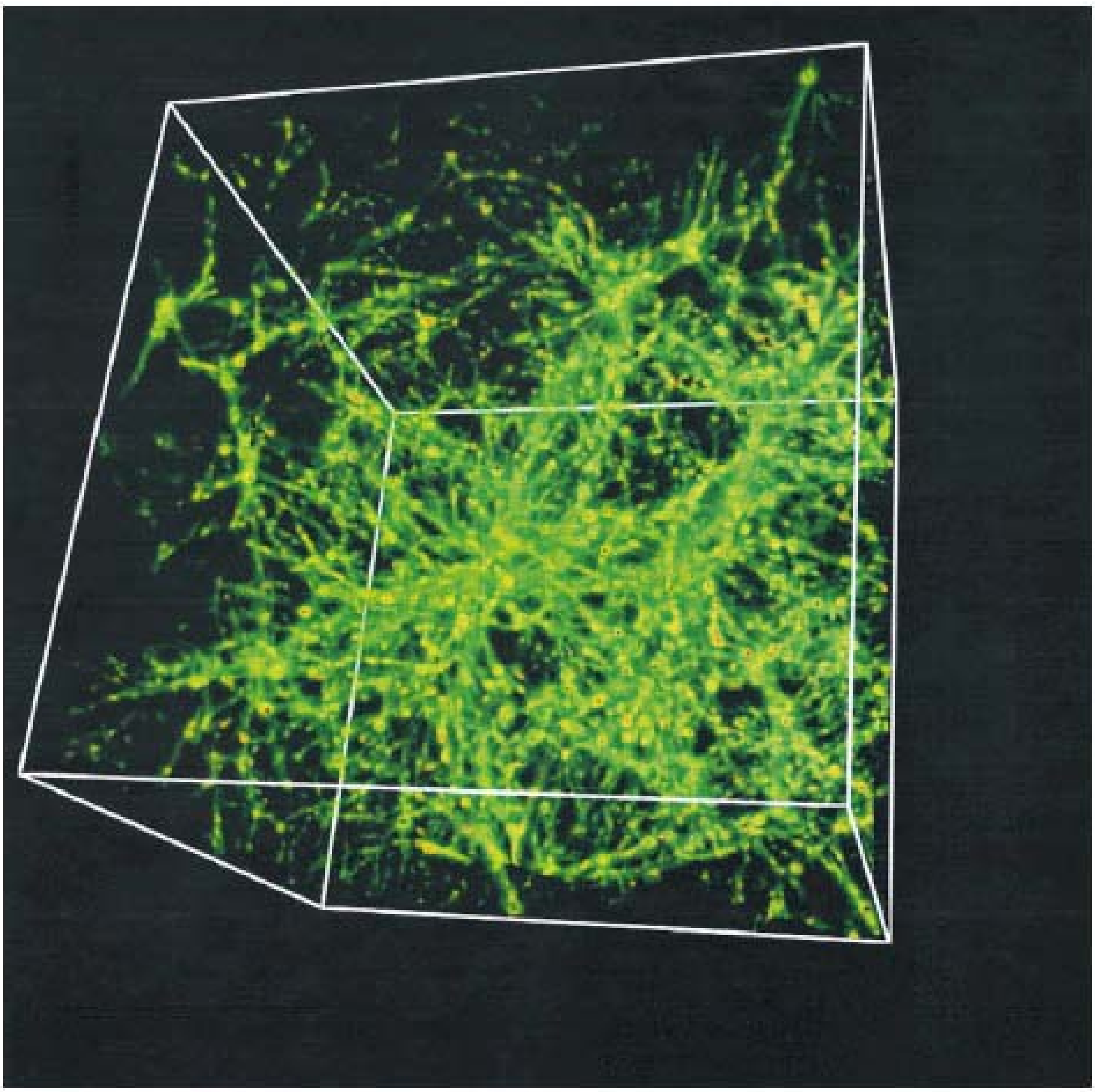
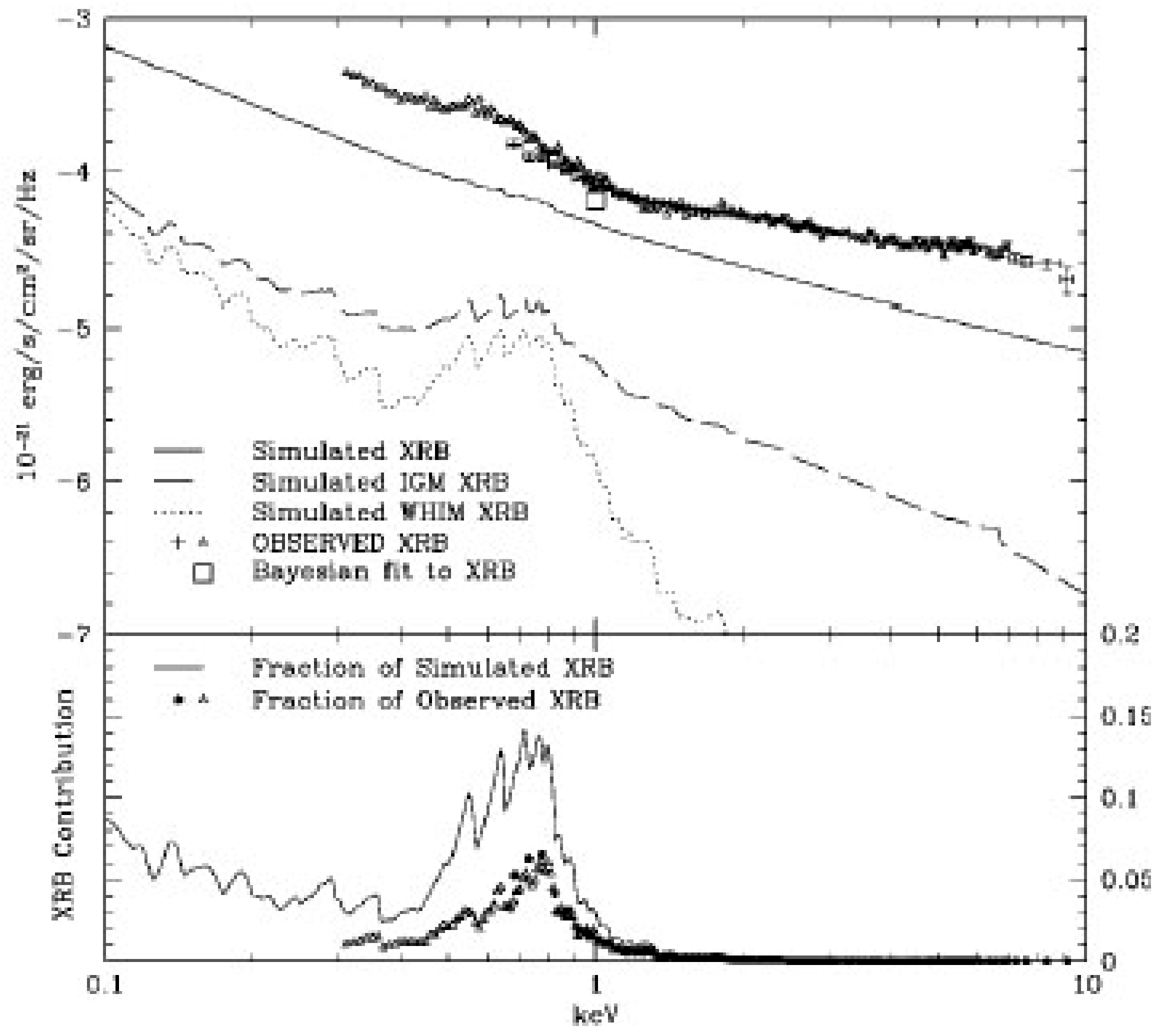
The CXB and the Cosmic Web



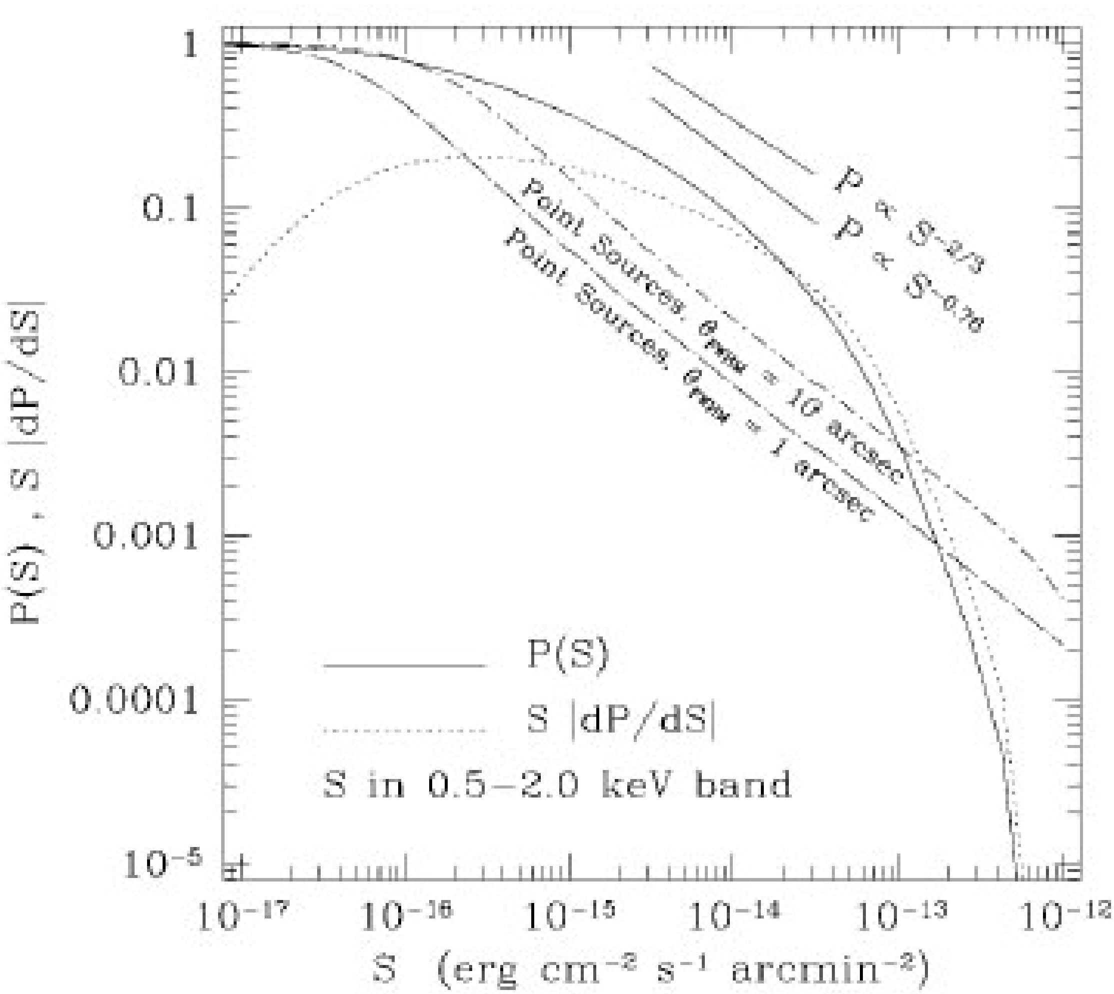
The CXB and the Cosmic Web



From Phillips et al., 2001, Ap. J., 554, L9.

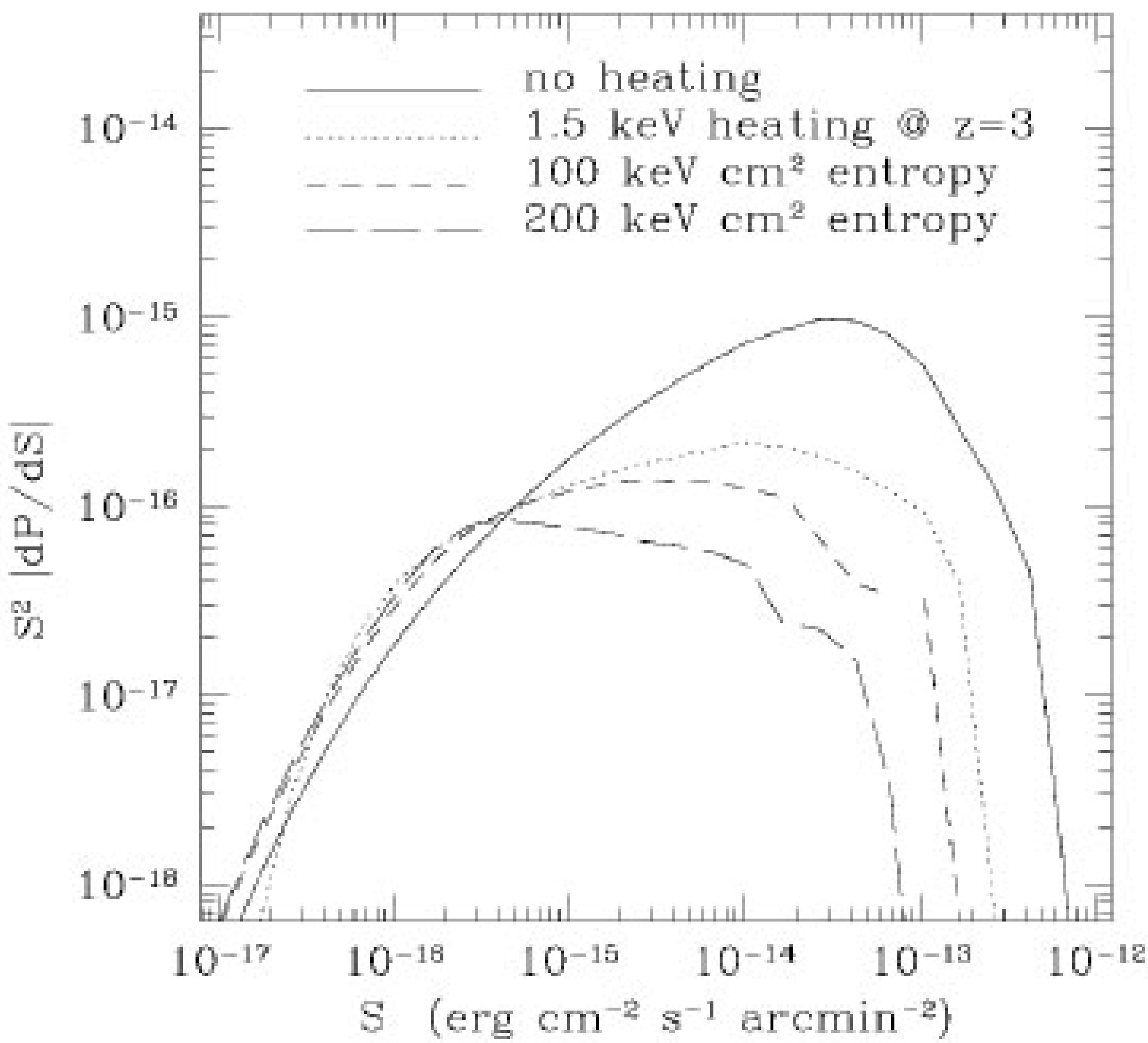
The CXB and the Cosmic Web

But not all simulations give the same answer!



From Voit & Bryan, 2001, Ap. J., 551, L139.

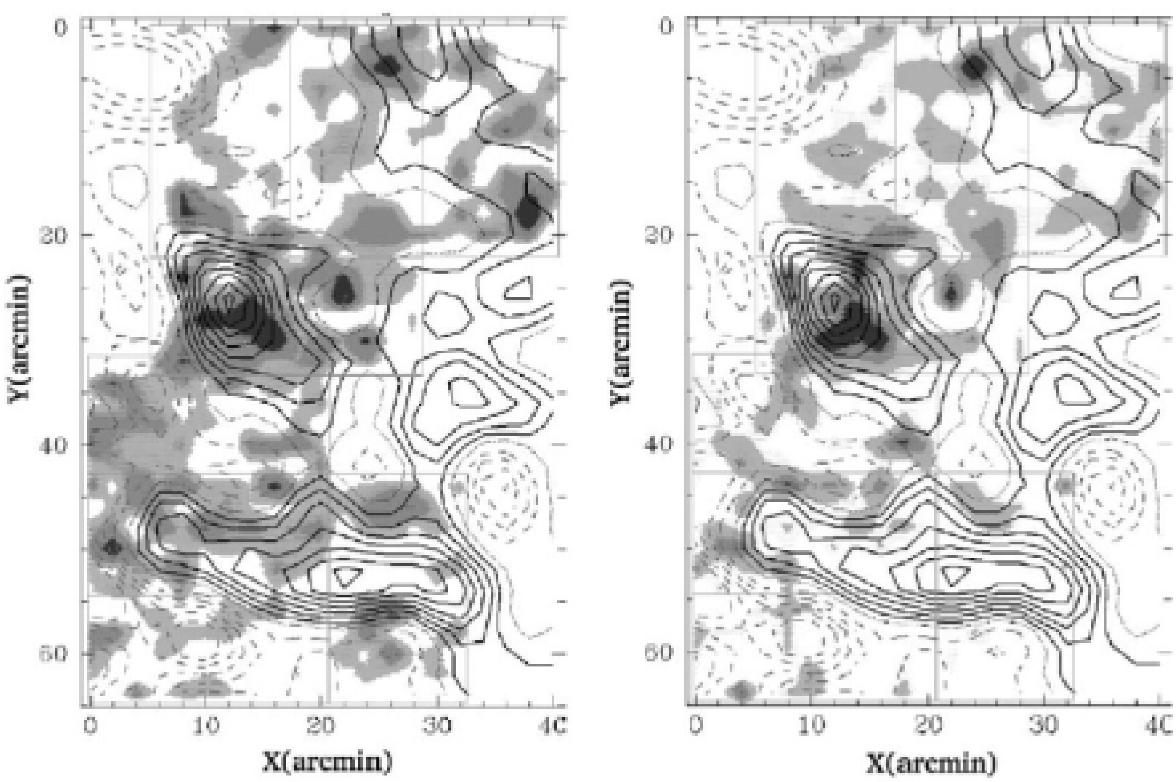
The CXB and the Cosmic Web



From Voit & Bryan, 2001, Ap. J., 551, L139.

The CXB and the Cosmic Web

Has it been seen?



From Zappacosta et al., 2002, A&A, 394, 7.

The CXB and the Cosmic Web

* Is it possible to make a map of this stuff?

* Answer: It is awfully hard! The flux is probably only 10% or less of the interstellar emission, which has a similar spectrum.

* The only hope is to use the fact that we should see it redshifted. But even that is tough, because the soft X-ray band is rife with weak features from many diverse charge states, and we still have no good model of its spectrum.

* Possible approach is to use the X-ray "water hole" between O VII and O VIII. This would give coverage out to $z \sim 0.15$. We would need a detector with high spectral resolution, good angular resolution, and large $A\Omega$. Best bet is an X-ray calorimeter array sitting behind a grazing incidence focus. But in this configuration, $A\Omega$ is proportional to the physical detector area, and it is difficult to get larger area with calorimeter arrays!

The CXB and the Cosmic Web

* An alternate approach just to see if the stuff is there is to look for it in line absorption against bright background sources.

* The optimal sensitivitity is in O VII and O VIII resonance lines where the predicted optical depth is ~ a few tenths.

* This has now been seen with both Chandra and XMM-Newton using very long calibration observations of bright continuum sources.

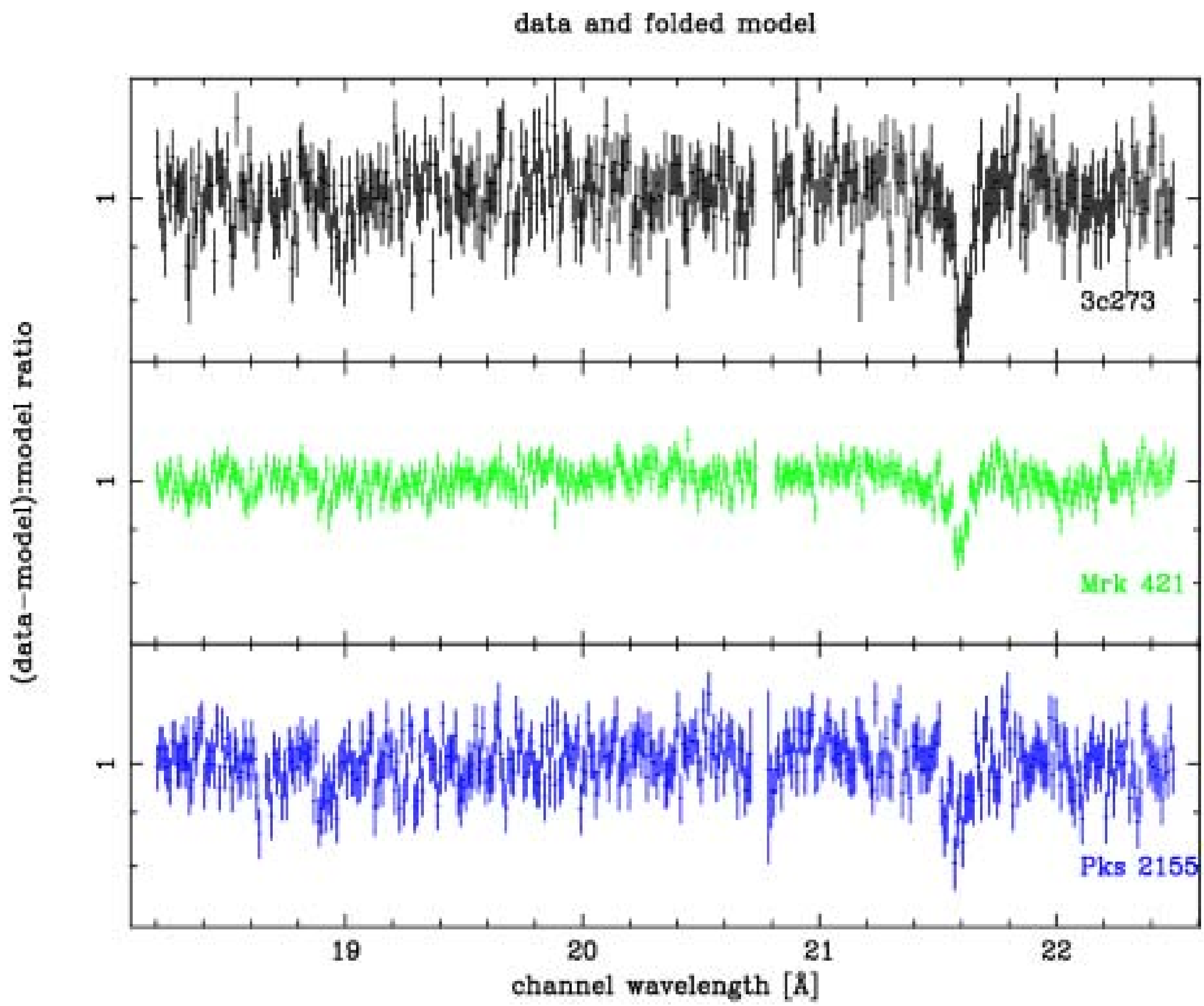
* The detected lines are at zero redshift. However, we know they are extragalactic by the following argument:

$$\tau \sim n_i\, d$$

$$I_{em} \sim n_e n_i d$$

* We have either an upper limit on I_{ext} from the XQC rocket data. This yields an upper limit on n_e and thus a lower limit on d. One finds d > 100 kpc, indicating that the absorbing gas is in the halo of the Local Group.

The CXB and the Cosmic Web



Summary and Conclusions

* The CXB is a prominent component of the total background radiation in the Universe.

* The emission in the hard X-ray band is most likely due to point sources at z ~ 1 - 5. Analysis of the spectrum suggests that these are mostly Type 2 AGNs, with significant reflection components.

* The analysis of fluctuations in the CXB can place useful constraints on the mass power spectrum on interesting length scales - intermediate between those probed by the CMB and those probed by redshift surveys in the local Universe.

* At the softest X-ray energies, the CXB exhibits a prominent thermal component which is almost certainly produced locally in the ISM of our galaxy. However, the detailed spectrum of this component has defied simple interpretation.

* Most of the baryons in the local Universe should reside in a warm/hot intergalactic medium, which may also contribute to the CXB. A measurement of the structure of this medium would be very exciting, but it will not be easy!