SAHARA

Spectral Analysis with High Angular Resolution Astronomy

A mission concept for a soft X-ray optic with high spatial and spectral resolution over a wide field of view

Sahara- A High Spatial and Spectral Resolution Imaging Mission

Goal: A large fraction of the IXO science for <1/5th the Astro2010 cost which can be launched in <10yrs

Cost Drivers: complexity & mass

Reduce Complexity: 1 instrument, 1 telescope, 1 mode

Reduce Mass: Shorten Focal Length from 20 to 4m

Short focal length starts a *positive* chain reaction : better plate scale for calorimeters, lighter optics easier to assemble, smaller/thinner pixels (better energy resolution), larger collecting area per unit mass, lighter overall system allow smaller rocket, faster slew time etc etc........

Core IXO Science

"The key component of the IXO focal plane is an X-ray microcalorimeter spectrometer—a 40 x 40 array of transition-edge sensors covering several arcminutes of sky that measure X-ray energy with an accuracy of roughly 1 part per 1,000 (depending on energy)."

Questions:

1. collecting area?
2. FOV?
3. spectral resolution?
4. spatial resolution?
5. bandpass ?

Science Goals Set the Answers:

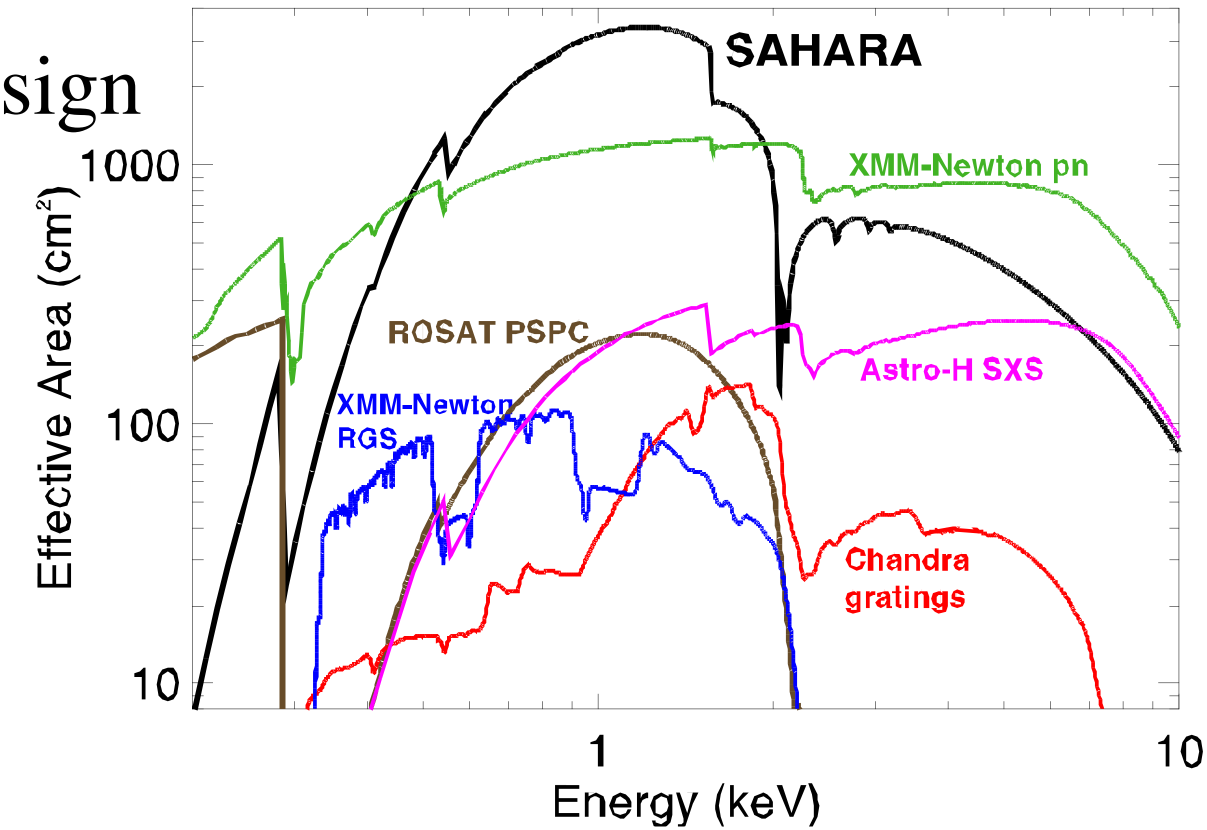
Imaging spectral goals-spatially resolving structures discovered by Chandra in SN, Clusters, nearby galaxies **with enough photons/angular bin to utilize high spectral resolution** in moderate (100 ksec) exposures

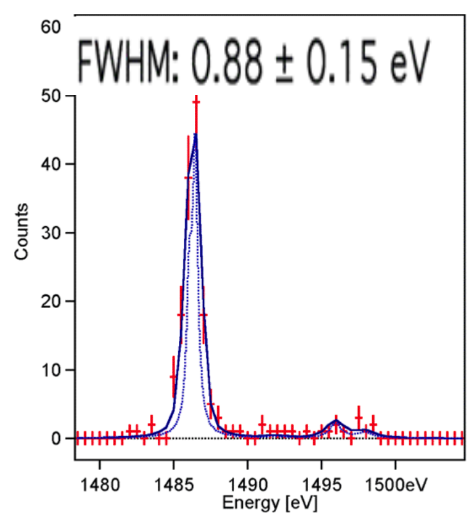
High enough area and spectral resolution to observe relativistic features in AGN

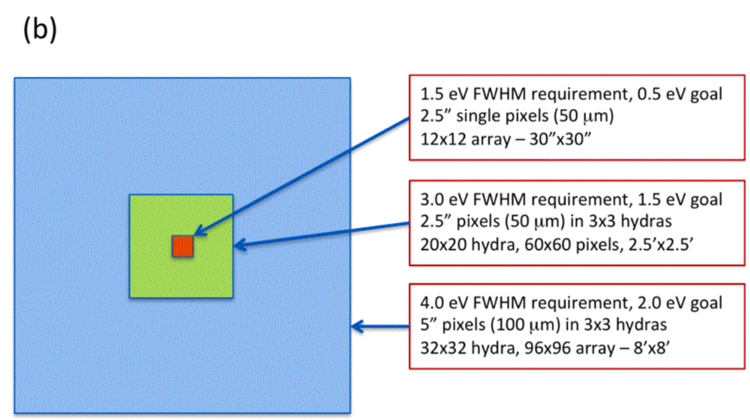
These determine the field of view, angular resolution, spectral resolution, collecting area.

Baseline Sahara Design

- Optics
  - Large (~3000 cm^2 @1keV) collecting area **optimized** for the 0.2-3 keV band
  - goal of <5" angular resolution
- Detectors
  - Moderate (8' diameter) FOV
  - Hierarchical array of calorimeters with $\delta E<2$ eV with 2.5" pixels
- Spacecraft
  - short focal length allows low mass, rapid slew in LEO- high efficiency







Sahara and IXO Science

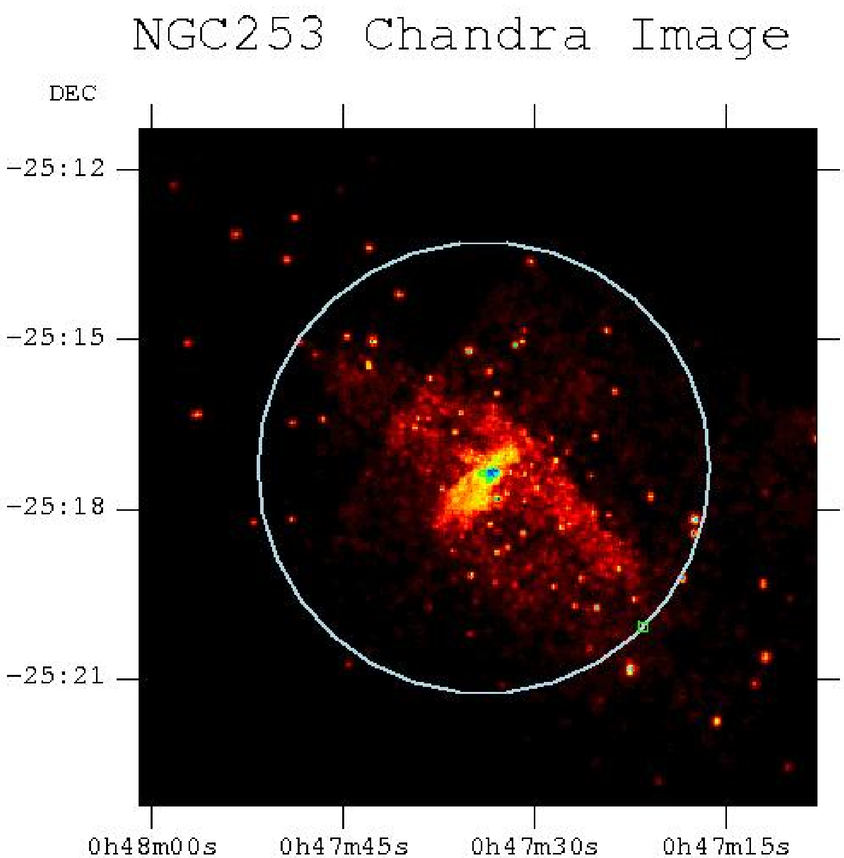
Question	Method
What happens close to a black hole?	Relativistic features in AGN at E<3 keV
When and how did SMBH grow?	High spectral resolution for ~ 1-3000 serendipitous AGN+detailed observations of many bright AGN
How does large scale structure evolve?	Observations of groups and clusters: dynamics, temperatures, etc to z>1 - physics of clusters, scaling laws for cosmology
What connects SMBH and LSS?	Direct measurements of effects of AGN feedback in clusters via spectral imaging
How does matter behave at very high density?	Resonance abs. lines in atmospheres of isolated neutron stars

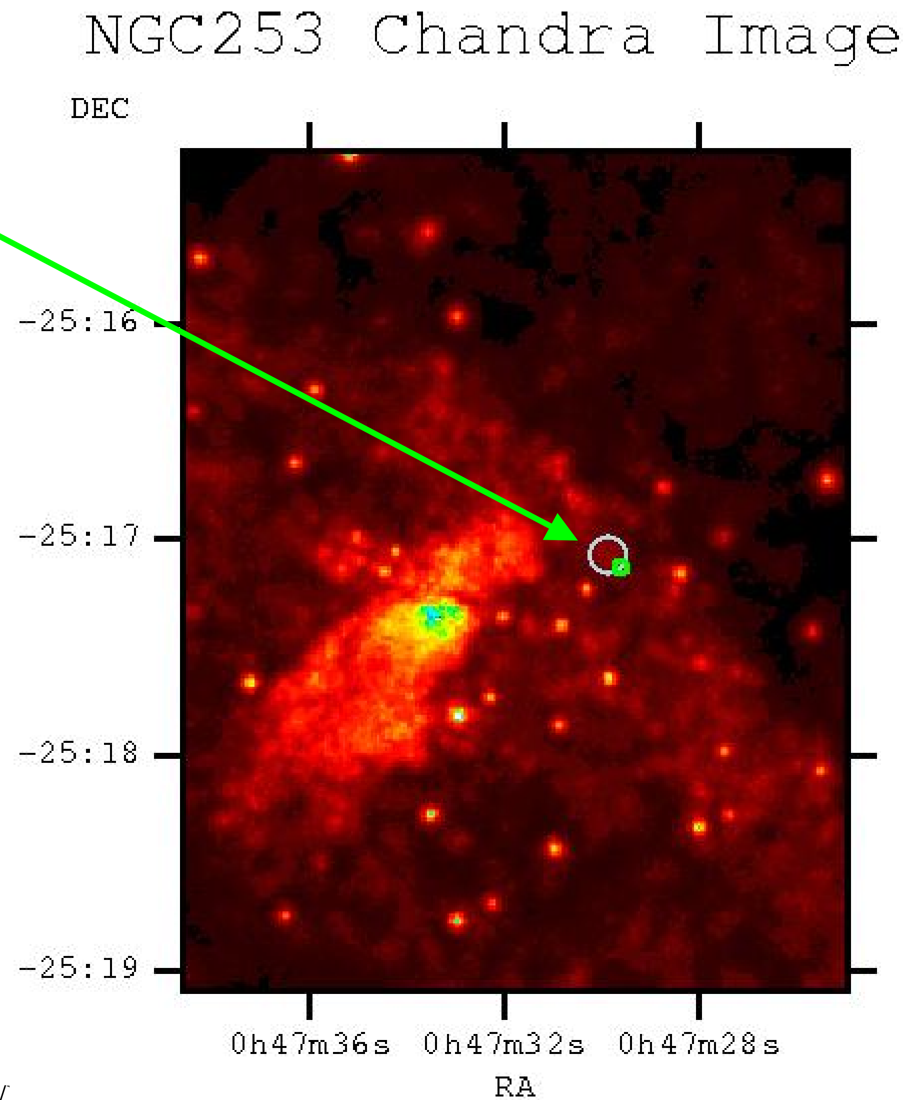
Sahara and IXO Science Requirements

Question	Requirement
What happens close to a black hole?	Large collecting area for time resolved, high resolution spectra of AGN
When and how did SMBH grow?	Large field of view to obtain reasonable number of serendipitous sources per exposure, large collecting area to get good S/N, high spectral resolution to detect winds, <5" angular resolution to detect weak sources.
How does large scale structure evolve?	Large field of view with low background to detect clusters to virial radius, high spectral resolution to measure turbulence in clusters, good sensitivity
What connects SMBH and LSS	Direct measurements of effects of AGN feedback in clusters via spectral imaging, <5" angular resolution to spectrally/spatially resolve feedback features in clusters/groups

Sahara Requirement
FOV and Angular Resolution to Study X-ray Binaries and Diffuse Emission in Nearby Galaxies

circles: Sahara angular resolution and FOV





Spatial and Spectral

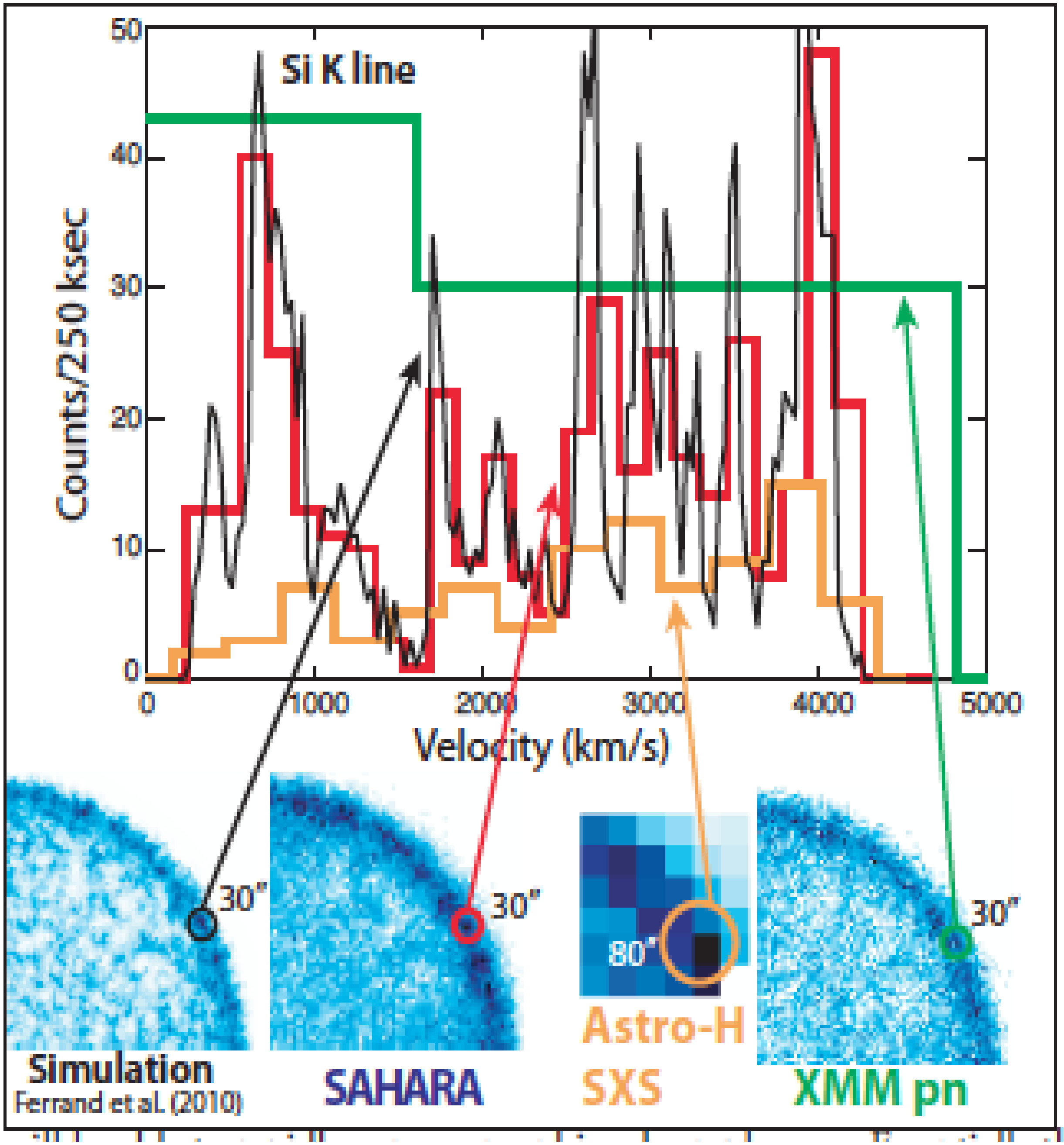
- Simulation of Tycho SNR

the SNR spatial and spectral resolution

of **Sahara**

Astro-H

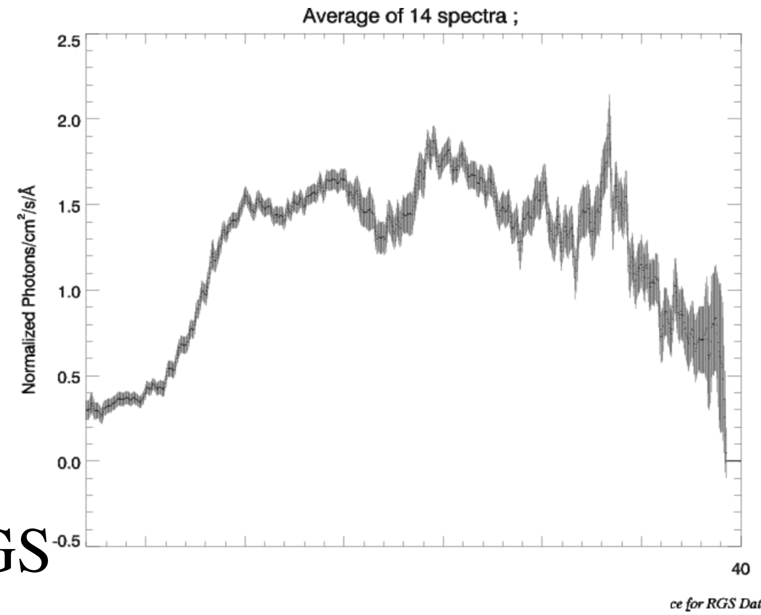
XMM PN

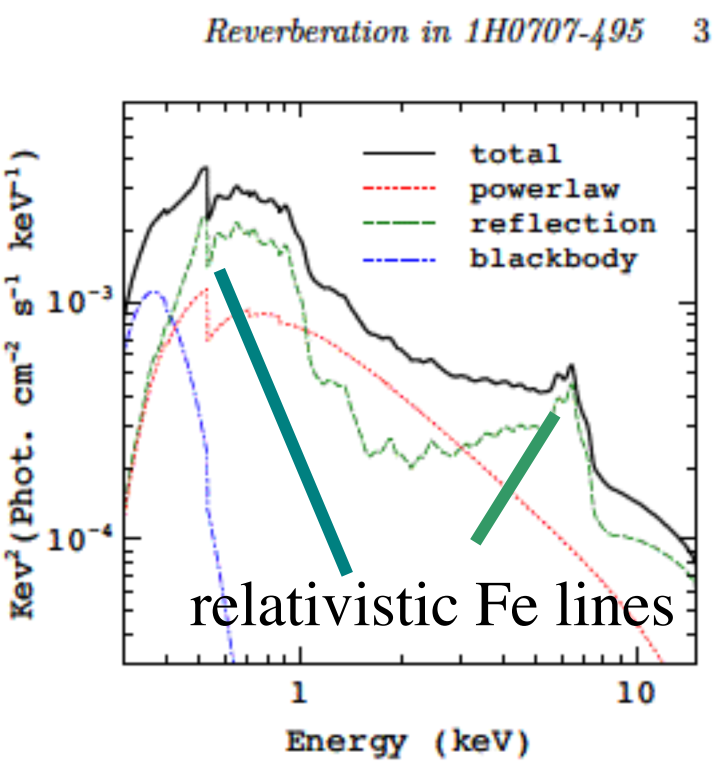


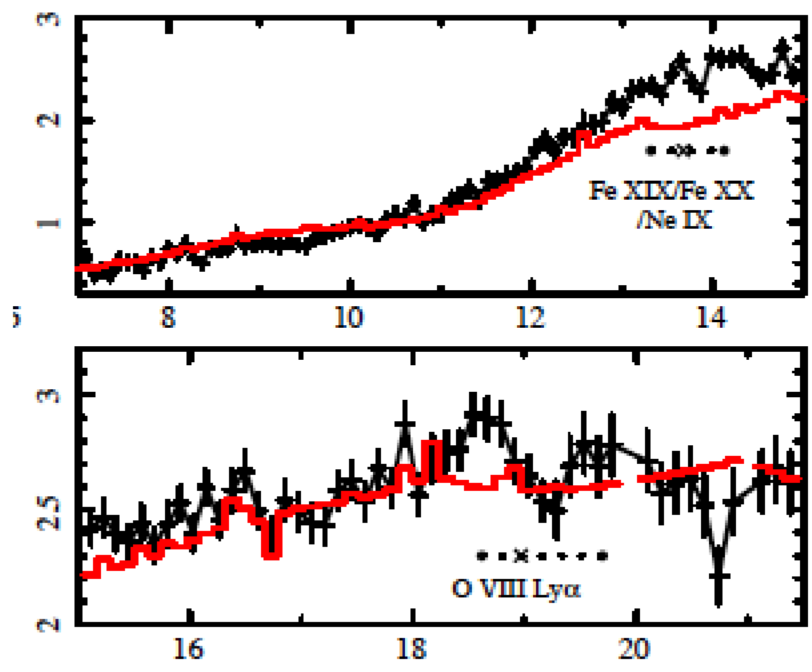
Relativistic Features in AGN

- IXO did this science with Fe Kα, the physics is the "same" at Fe L
- A 15 ksec observation with Sahara can trace all the spectra features on relevant time scales (Blustin and Fabian 2010) .

H0707-495 XMM RGS



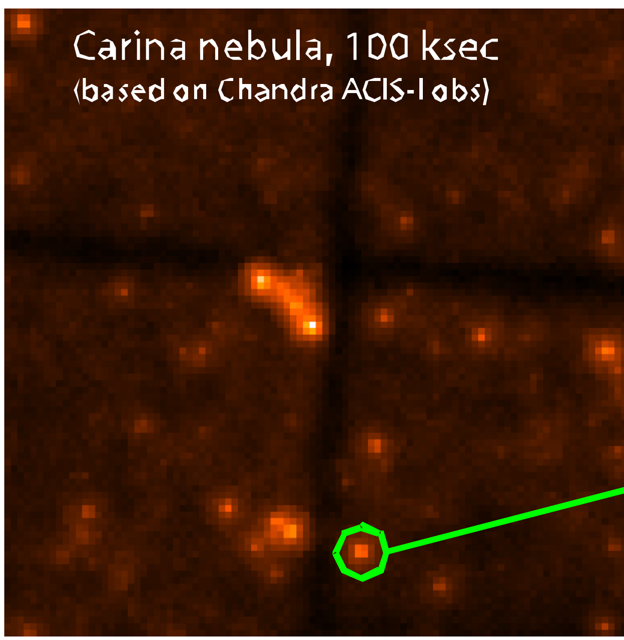


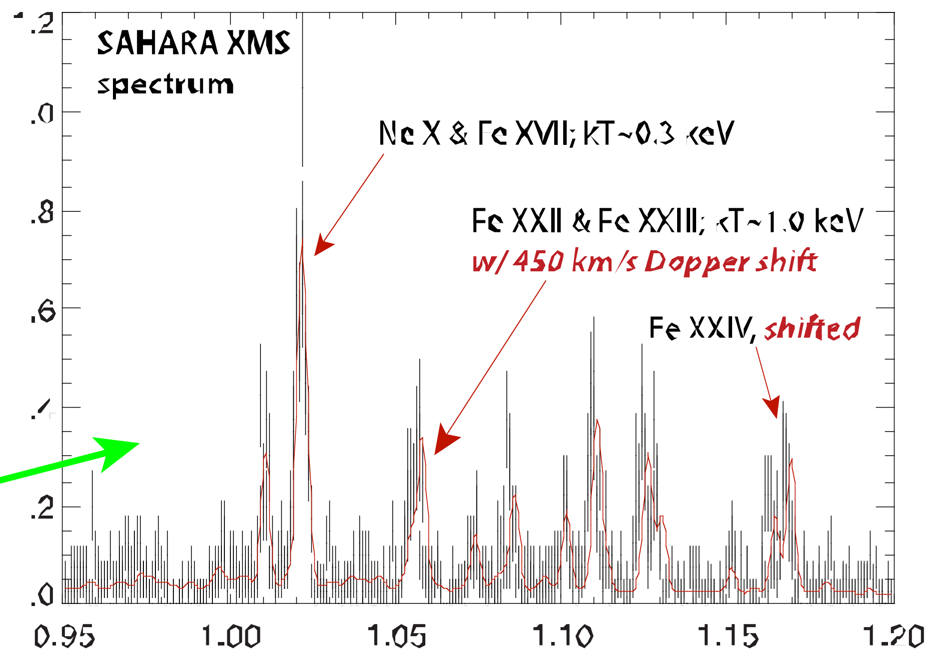


Additional Top Level IXO Science Enabled by Sahara

- How do stars form ?
- How does gas exchange in galaxies and the IGM?
- How do rotation and magnetic fields affect stars?
- How do massive stars and Type Ia SNe explode?

All these science areas (and more) are achievable with the Sahara technical requirements





The Warm Hot Intergalactic Medium

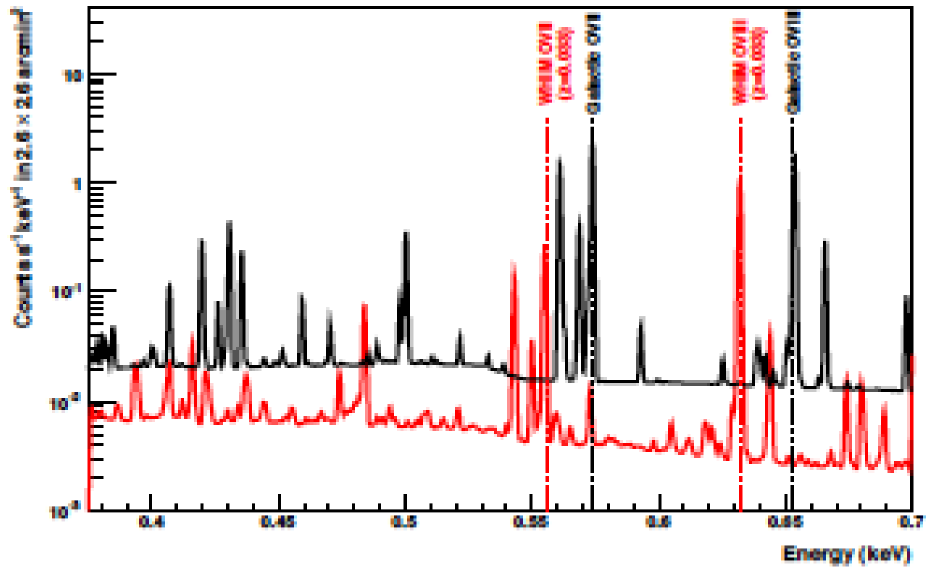
- Detecting the WHIM in emission kT = 0.1-0.3 keV
- Oxygen (OVII, OVIII) emission lines are the best signature
- Separation from the Galactic emission with redshift is necessary

<u>High resolution, low background, large solid angle essential</u>

Sensitivity required:

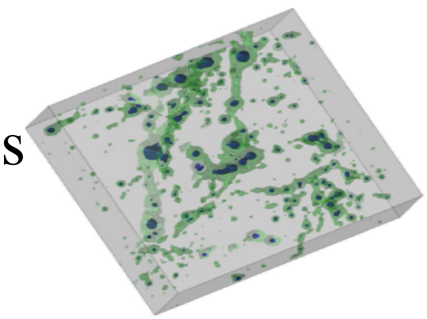
Sahara ΩxA=~0.05 of that assumed by Takei et al.

So Sahara will obtain ~1-10 filaments/FOV (- 200-2000/yr) depending crucially on accuracy of physics and length of exposures



Spectrum of WHIM +Galactic emission 1.5x1.5' FOV

5x5 deg simulations



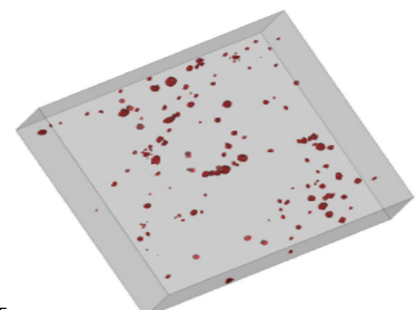
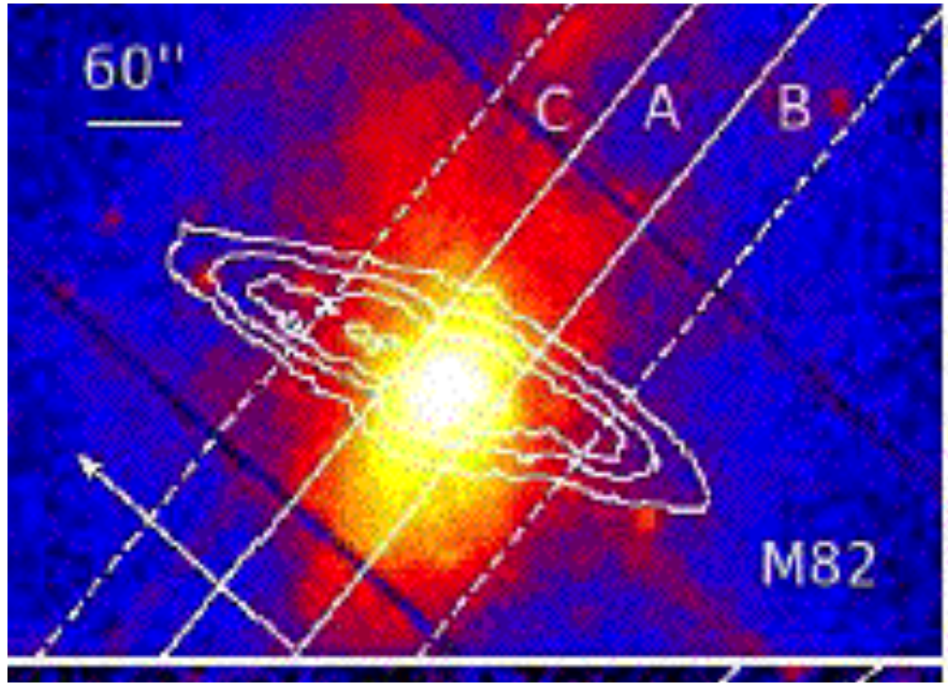
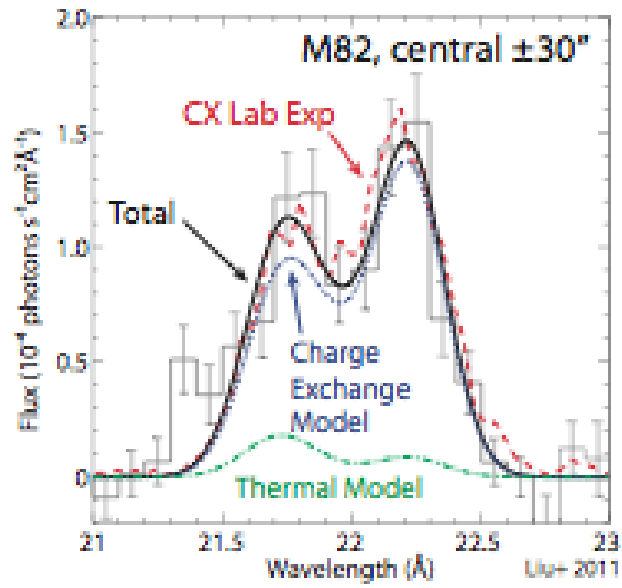


FIG. 8.— Same as Figure 7, but slice at $z = 0.0805 - 0.1004$, orresponding to comoving distance of 237–294h^{-1} Mpc. The field f view is 5.5° × 5.5°.

Signatures of Feedback

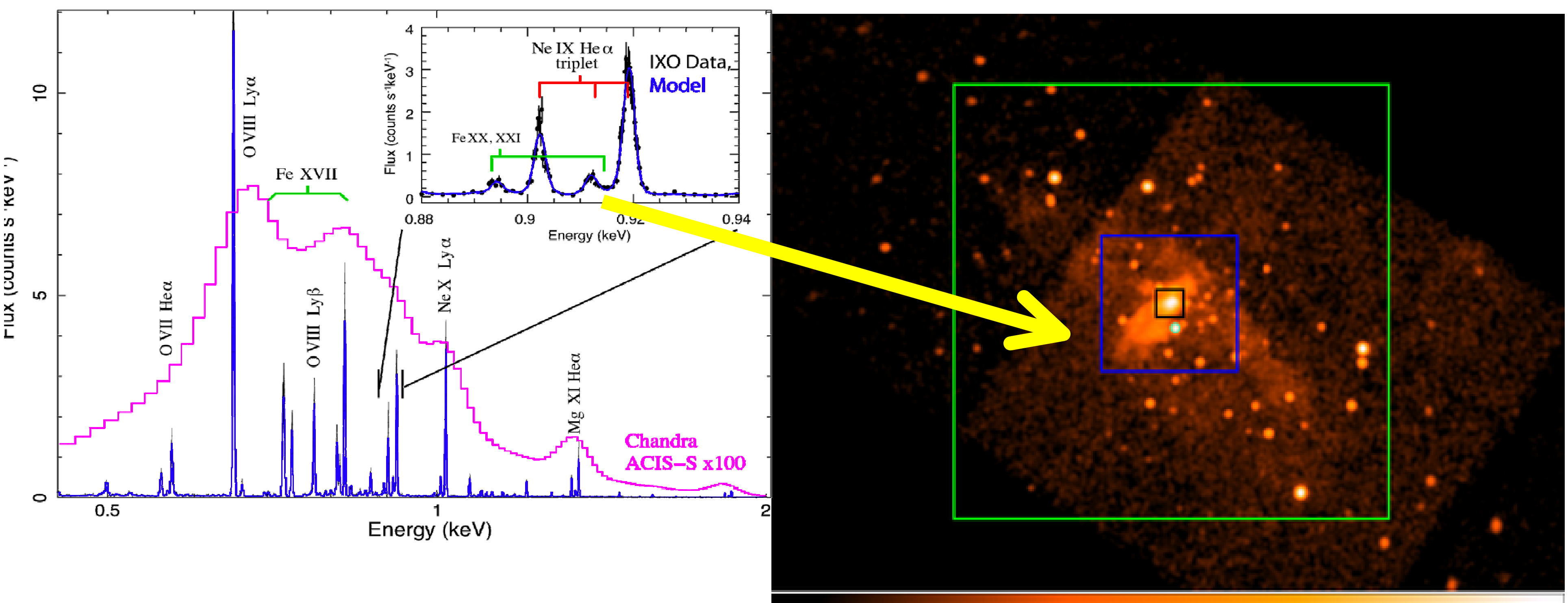


- Feedback- how galaxies and black holes influenced their environment and created the universe we see today
- A general feature is the transmission of (energy, momentum, heat, ionization) from the source (AGN, star formation) to the gas that can form stars- how, where and when is this occurring.
- General process- hot and/or fast and/or ionized gas interacts with cold gas - Charge exchange must happen and now has been detected in starburst galaxies (Q. Wang and team)
- Sahara gets ~ 30 photons/line/25sq arc secs in 30ks exposures - **complete map of velocity and mass in winds**



Starburst + Normal Galaxies

- Hot ISM
  - Detect velocity shifts and broadening due to superwinds
  - Map temperatures and abundances in nucleus, disk, and halo
- X-ray binaries
  - Measure detailed spectra including intrinsic and ISM absorption features
  - Variability



Absorption features in Isolated NS to Determine EOS?

- Several authors have detected absorption features in Isolated NS- the physical nature is not known
- but if interpreted as gravitational, redshifts are consistent
- Sahara has ~3x XMM PN and 25x the RGS collecting area at E<2 keV it can easily detect spectral features seen by RGS from several NS (similar resolution to RGS 1.7eV FWHM) .

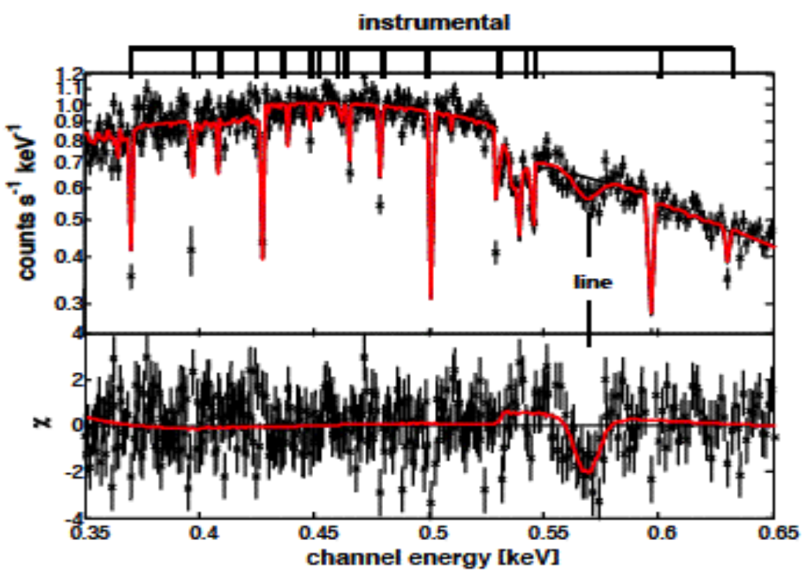


Figure 1. The co-added *RGS1* (first order) spectrum of RX J0720.4−3125 with a total exposure of 516 ks. The thin,

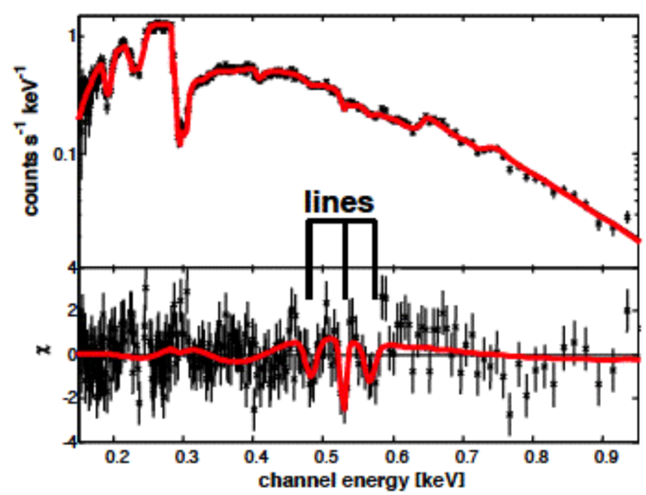


Figure 8. The co-added *Chandra HRC-S/LETG* spectrum of RX J0720.4−3125 with a total exposure of 429 ks. The black line

Hambaryan et al 2009, Hohle et al 2011

What is Sahara Missing Compared to IXO?

- Effective area at 6 keV similar to Astro-H reduces AGN and Cluster Fe K band science
  - much can be achieved with lower energy data
    - Cluster chemical abundances from resolution of Fe L complex + other elements
    - Relativistic broad lines are also seen at low energies
- Bright source spectral timing (x-ray binaries)
  - lack of high timing mode strongly limits bright source science- similar to Astro-H
  - But NS EOS maybe done with dimmer sources

•Grating instrument for R>600 at E<0.6 keV

- major impact : difficult to study WHIM in absorption

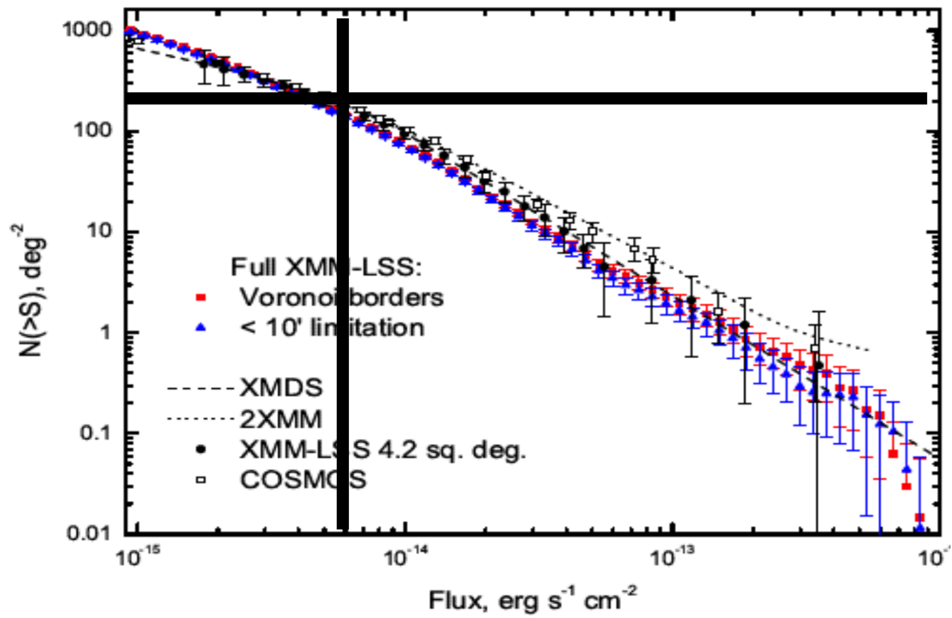
•Wide field of view 'CCD-like' imager for surveys

major impact is deep/wide x-ray surveys; high z universe

Derived Mission Parameters- Telescope Collecting Area

Effective area requirements are set by need to obtain:

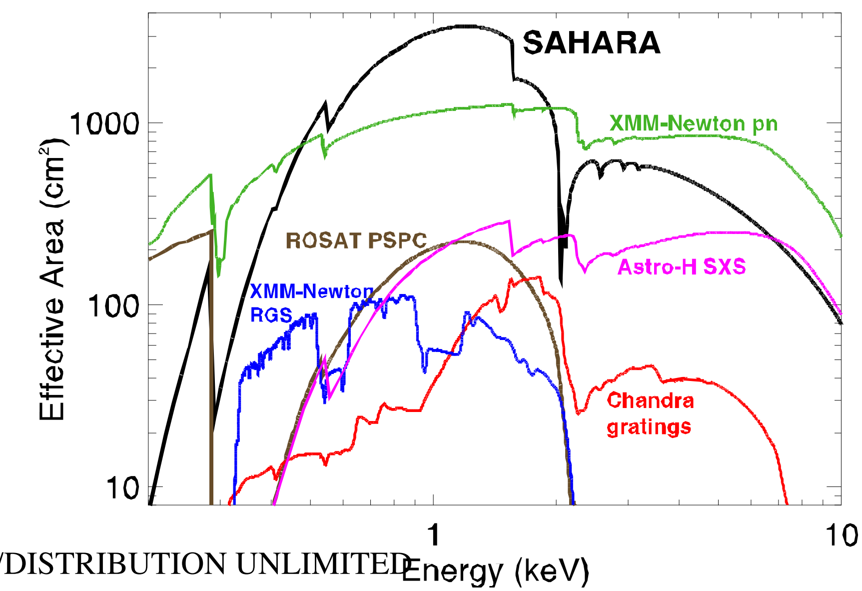
1. Good quality spectra with ~4000 cts/resolution element in 100 ksec for z<0.1 clusters.
2. Reasonable number (~3) serendipitous sources with ~1000 cts in each 100 ksec FOV.



Serendipitous sources:

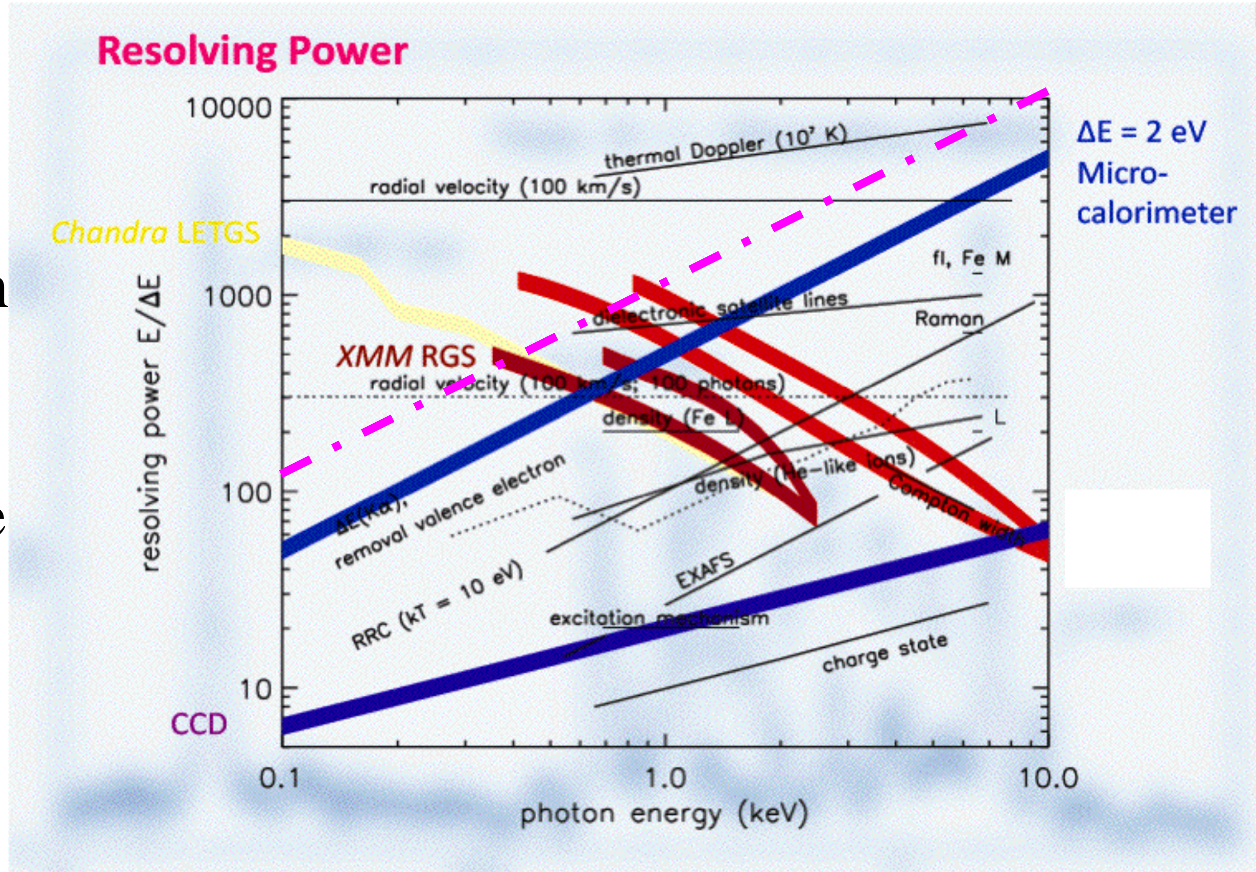
F(x)=7x10^{-15} erg/cm^2/sec-200/sq deg ➔ ~3 per Sahara FOV or ~600/yr in which one can:

- Detect 30 eV physical width (10^4 km/sec)
- Absorption lines at 1 keV (6 σ)
- Doppler shifts with ±1500 km/sec errors

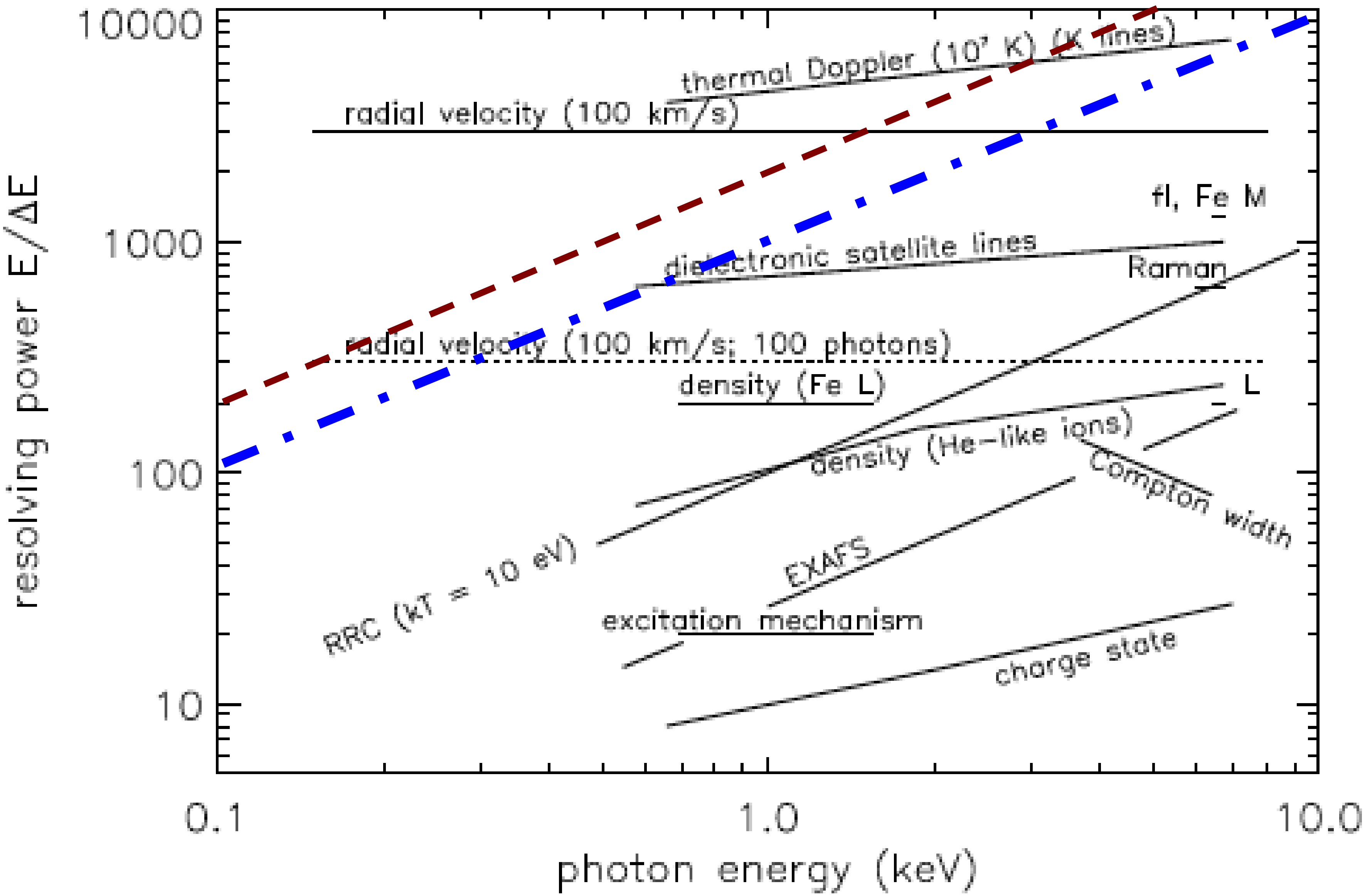


Derived Mission Parameters-Spectral Resolution/Area

- **All the plasma diagnostics** (Paerels 2003)
- Derive velocities with ~4000 ct spectra: ±35 km/s errors in a 200km/sec turbulence in a 1 keV plasma – cooling flow clusters, ellipticals and SNR
- Abundances of O and Fe can be determined, on a 5x5 sq. arcsec (!) basis with errors of ~30% (assuming CIE)

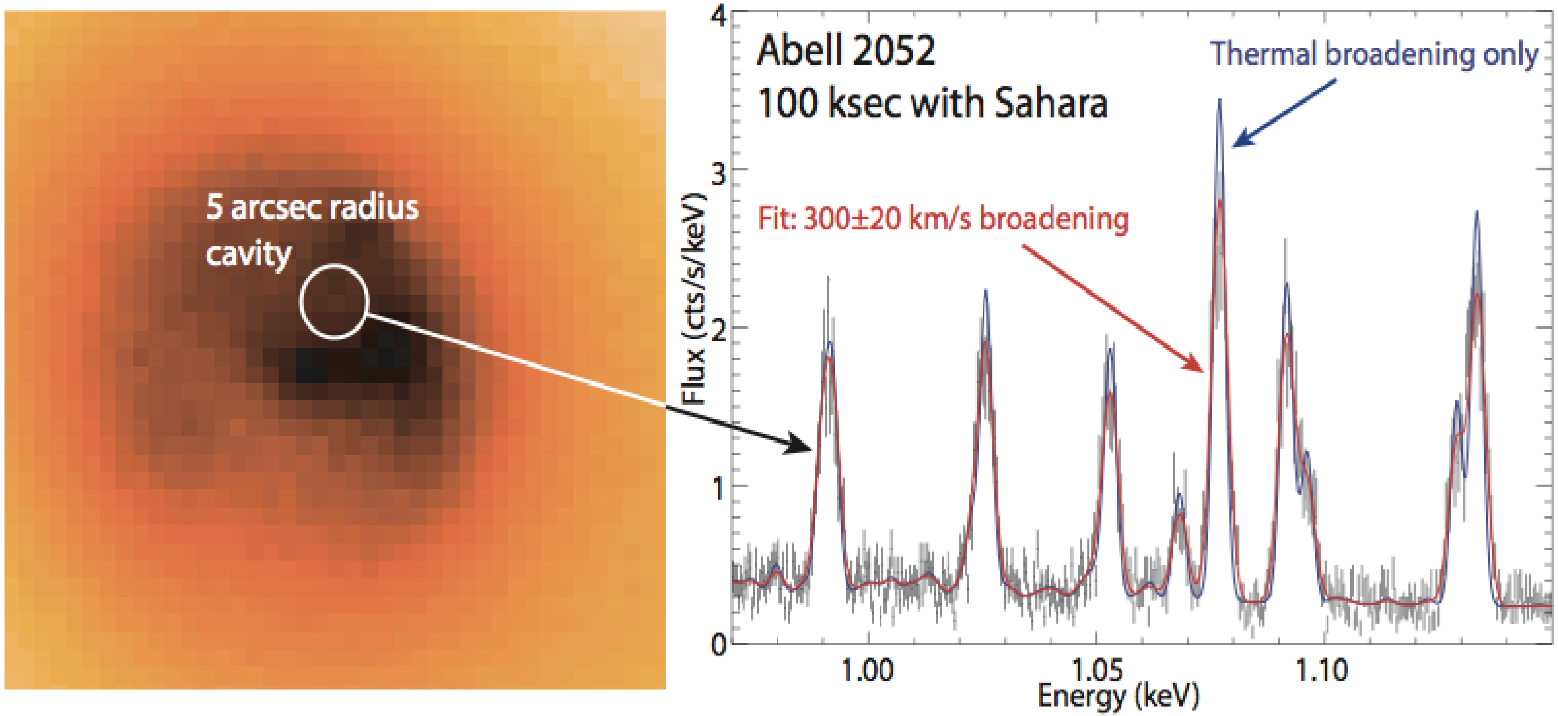


Obtain plasma diagnostics for ALL abundant metals



10000
1000
100
10
0.1
1.0
10.0
photon energy (keV)
resolving power E/ΔE
thermal Doppler (10⁷ K) (K lines)
radial velocity (100 km/s)
fl, Fe M
dielectronic satellite lines
Raman
radial velocity (100 km/s; 100 photons)
density (Fe L)
L
density (He-like ions)
Compton width
RRC (kT = 10 eV)
EXAFS
excitation mechanism
charge state

Derived Mission Parameters- Spatial resolution



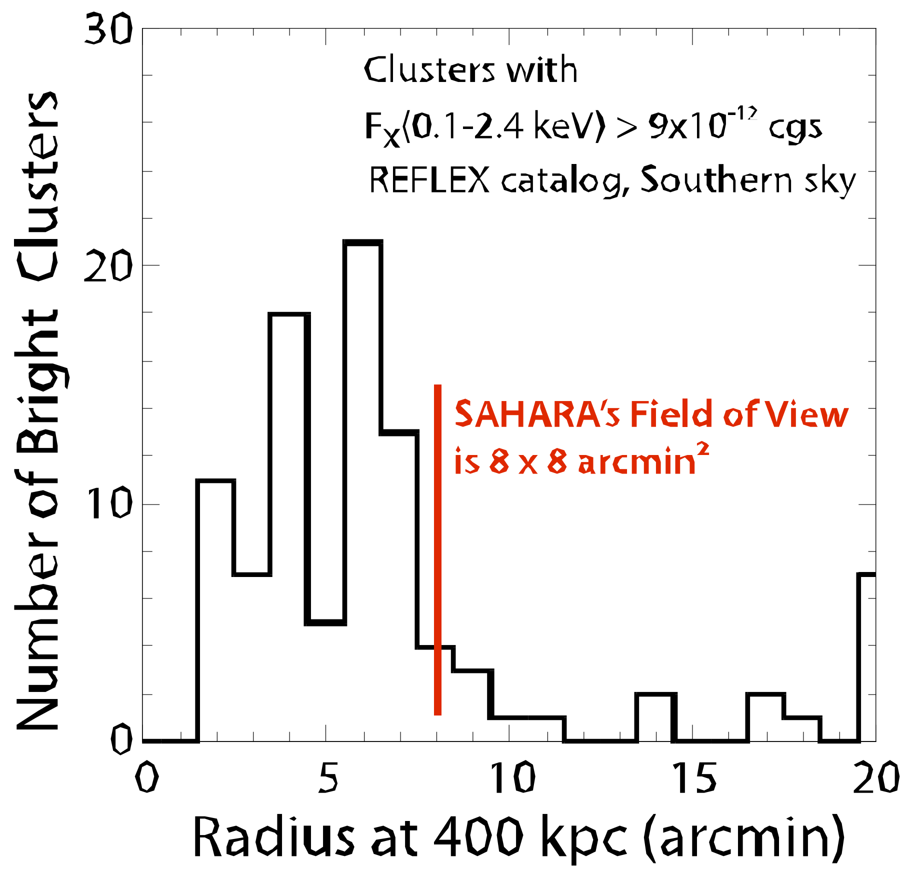
Set by

- surface brightness of clusters, SNR ellipticals etc
- resolve spatial structure in cluster feedback, SNR
- isolate and identify serendipitous sources

Derived Mission Parameters- FOV

- Choose 8' diameter to encompass r_{500} of M~$5x10^{14}$M cluster at z=0.2.
- Full size of almost all galaxies (except local group)
- Full size of >75 Galactic SNR
- Get >3 serendipitous sources/field with>1000 cts in 10^5 sec exposures

- FOV commensurate with technical requirements of calorimeter array with 'reasonable' number of pixels and sampling of 1/2 PSF/pixel



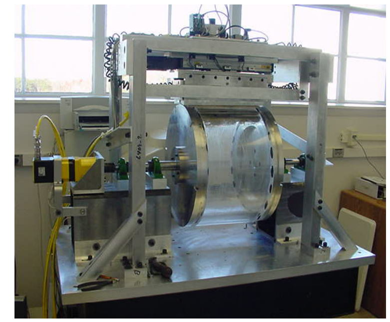
Meeting the Technical Requirements: Optics

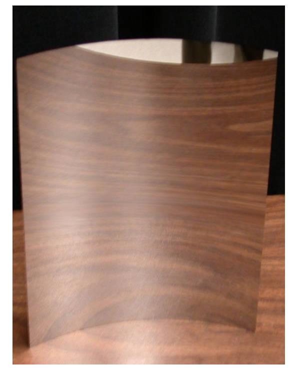
- Design constraint : maximum area in 0.2-3 keV band consistent with Taurus fairing and launch mass into low earth orbit with <5" HPD
  - no extendible bench
  - one mirror
  - 'high' TRL consistent with launch in <10yrs (TRL-5 for 10" in less than 2 yrs TRL-5 for 5" in less than 4 yrs.)

Meeting the Technical Requirements: Optics

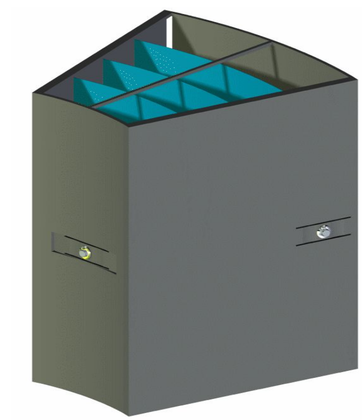
- Mirror assembly design- lighter, cheaper, simpler, easier
  - Focal length 4m (cf. IXO’s 20m)
  - 93 shells (cf. IXO’s 360)
  - 250 kg (cf. IXO’s 1800 kg)
- Implementation
  - Segmented design with two radial rings
  - Inner ring: 12 modules
  - Out ring: 24 modules
- Technical Readiness
  - TRL-4 for 10” requirement
  - TRL-3 for 3” goal

186 Forming Mandrels

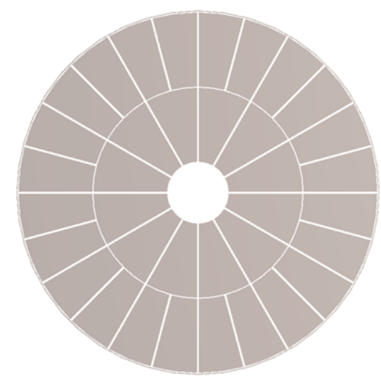




3,192 Mirror Segments



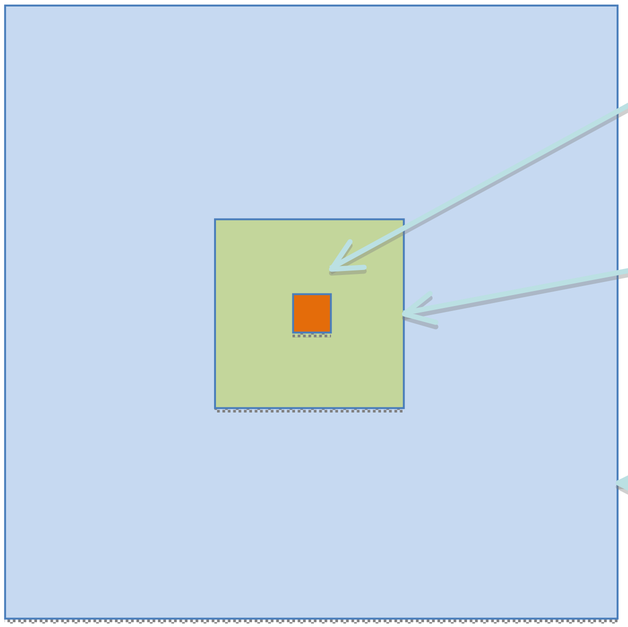
36 Mirror Modules



1 Mirror Assembly

Detectors

Test results



1.5 eV FWHM requirement, 0.5 eV goal
2.5” single pixels (50 μm)
12x12 array – 30”x30”

~ 1 eV up to 3 keV
~ 4 eV at 6 keV
- data

3.0 eV FWHM requirement, 1.5 eV goal
2.5” pixels (50 μm) in 3x3 hydras
20x20 hydra, 60x60 pixels, 2.5’x2.5’

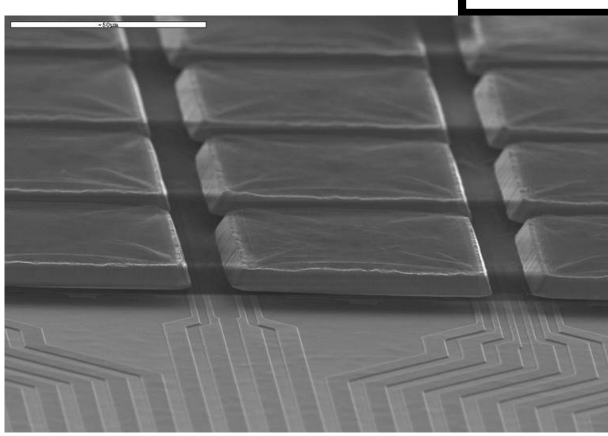
~ 2 eV for all energies up to 7 keV
- estimate

4.0 eV FWHM requirement, 2.0 eV goal
5” pixels (100 μm) in 3x3 hydras
32x32 hydra, 96x96 array – 8’x8’

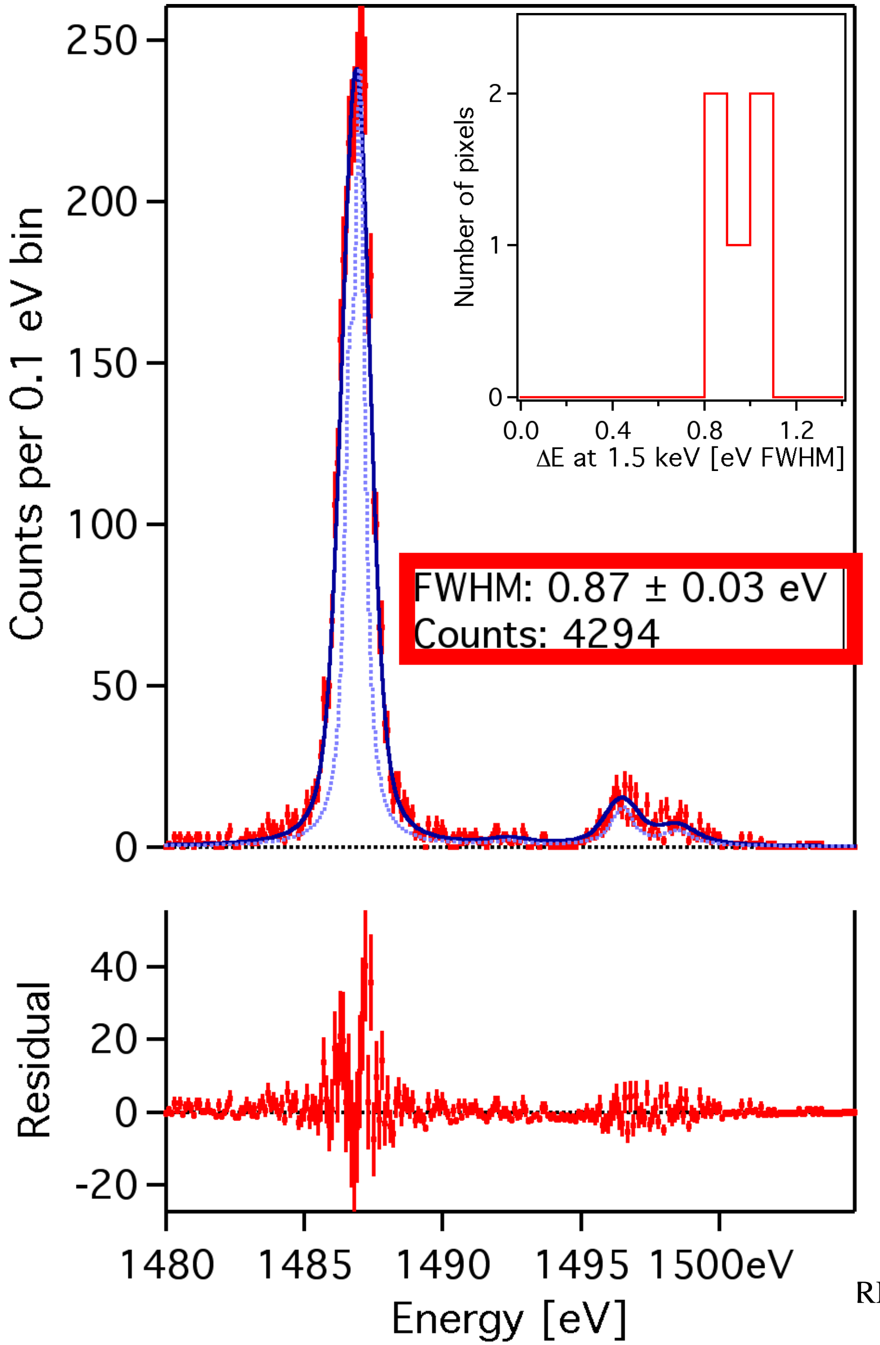
~ 3 eV for all energies up to 7 keV
- data

Shorter focal length + high angular resolution => Small pixels =>

- *Excellent microcalorimeter energy resolution*
  - for single pixels and for Hydras
- *Use of all-gold absorbers*
  - great for reliable fast thermalization
- *Solid substrate design*
  - great for heat-sinking/low cross-talk
- *Use of multiple designs on a single silicon chip*
  - no variation in back-etching / fabrication
  - less complex focal plane assembly design
- *Less sensitive to stray power* – very uniform



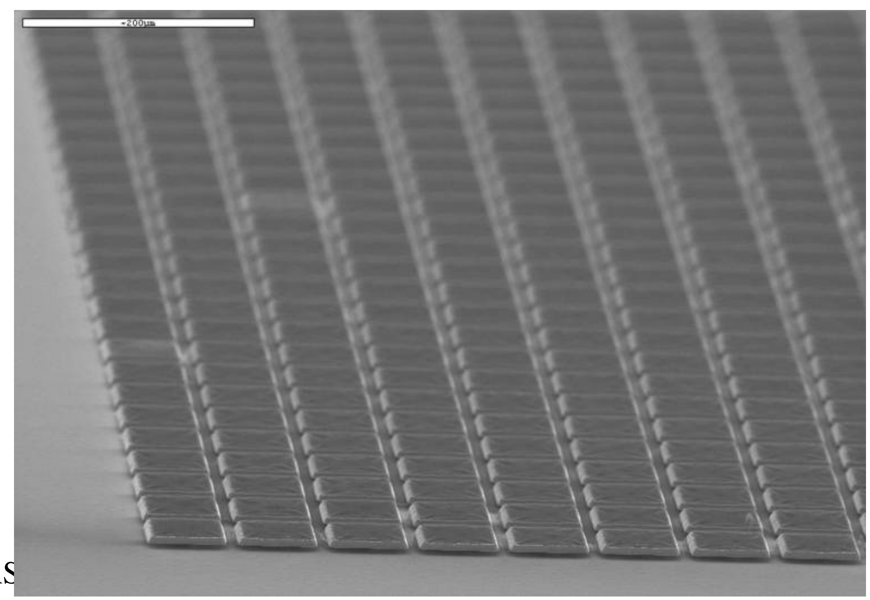
Meeting the Technical Requirements: Detectors



The first close-packed arrays have been fabricated and tested

TES on 75 micron pitch
Absorber: 65μm x 65μm x 5μm

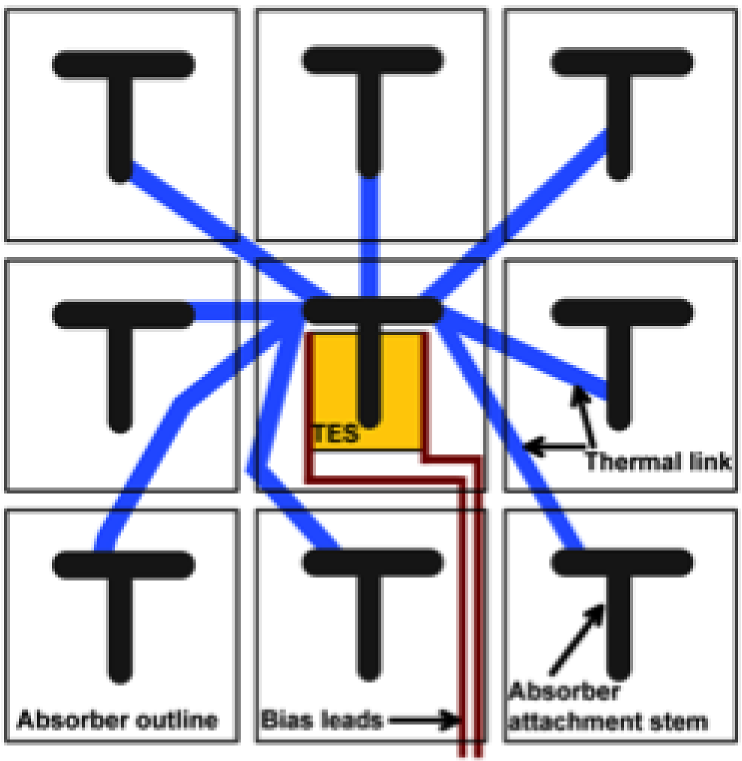
Design has 1.6 ms decay times
⇒Regular TDM MUXing could be sufficient and easier than for IXO/AXSIO
⇒Count rate capability of a few 10's per second

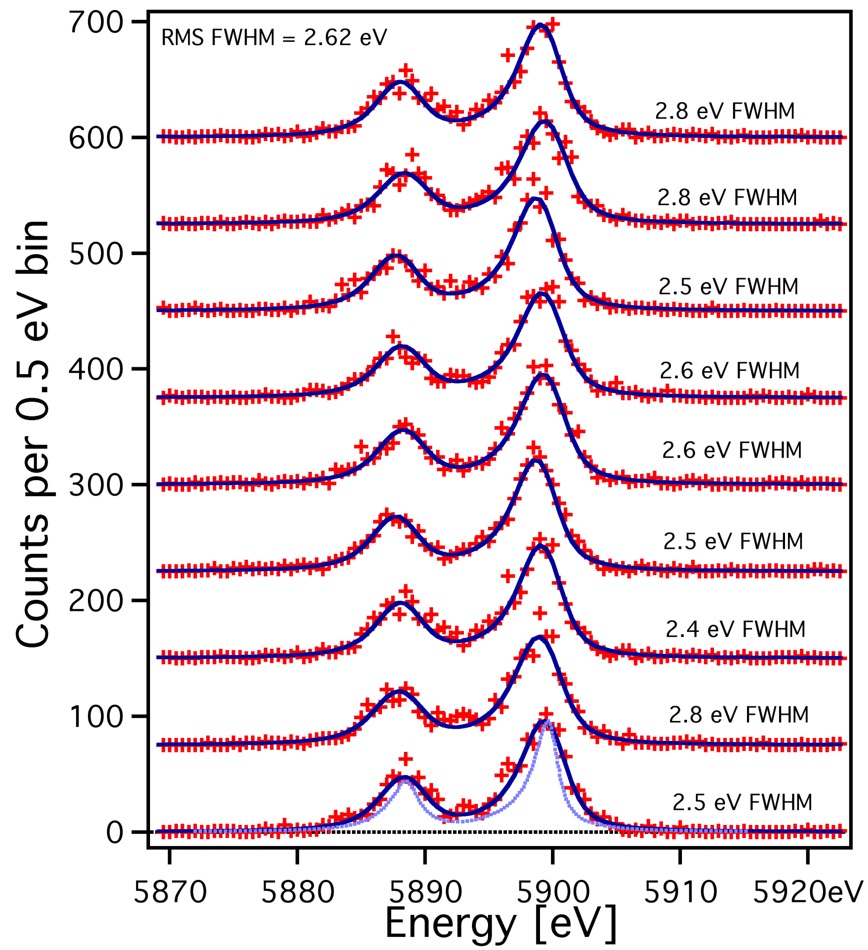


RELEAS

Meeting the Technical Requirements: Detectors

Hydras – increase field of view for a fixed number of read-out channels
< ΔE> =2.6 eV @6 keV 3x3 Hydra- small dispersion in ΔE





Result is for 3x3 array of 65 μm absorbers, 5 μm thick.
Sahara outer array has 95 μm absorbers, 3 μm thick – similar heat capacity/energy resolution

Conclusions

- Sahara can achieve a large fraction of the IXO science goals and can also be a general purpose observatory
- The cost and risk should be much less than IXO
- All of the components are under development and achievement of the technical requirements is within sight.
- ***Can build and launch in < 10 years for <1/5th IXO cost– meet decadal recommendations and fit in NASA budget envelope.***

Our team is **completely** open and we welcome participation

We Want You

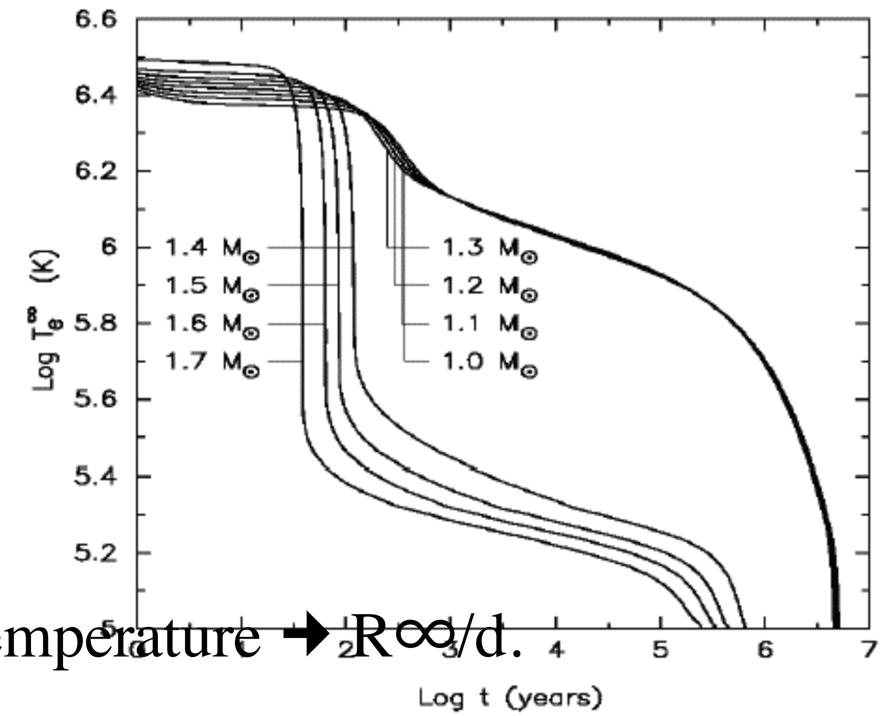
To Join the Sahara Team-

lets get a mission going in < 10 years!

Backup

NS EOS

Neutron star cooling is sensitive to the EOS of NS- Sahara will get exquisite physical temperatures of old NS



Spectroscopy:

Solid angle from flux and effective temperature ➔ R_∞/d.

Cooling ? Internal structure.

Redshifted photospheric lines ➔ M/R, potentially M/R^2 and/or °spin R sin i.

Spectral line profile ➔ M-R.

Observing thermal spectra from neutron stars yields the surface temperature AND the emitting area and thus its radius Becker (2010)

Cost Trades Leo vs HEO

- I use the analysis done in 2005 for Con-X
- LEO advantages-
  - more mass available to solve technical problems
  - cheaper rocket (big difference for Taurus vs Atlas-V)
  - easier communications
- LEO disadvantages for Con-X
  - Decreased observing efficiency at LEO: **- less true for Sahara (fast slews- Swift gets 72% efficiency, SAA takes 15% of time)**
  - Science Operations: **more complicated at LEO**
    - slightly true, but use cheap ground stations rather than DSN- cost savings; can be very cheap (RXTE)
  - Mission Operations: **more complicated at LEO**
    - yes, but we have done this for decades, no big deal can be very cheap (RXTE)
  - End-of-life disposal- seems no longer to be an issue
  - Harder to cool calorimeter- yes, but solved for Astro-H, Akari, HST etc
  - ACS Subsystem is more complex but another problem solved for 30 years and can use magnetic torquers.

other trades

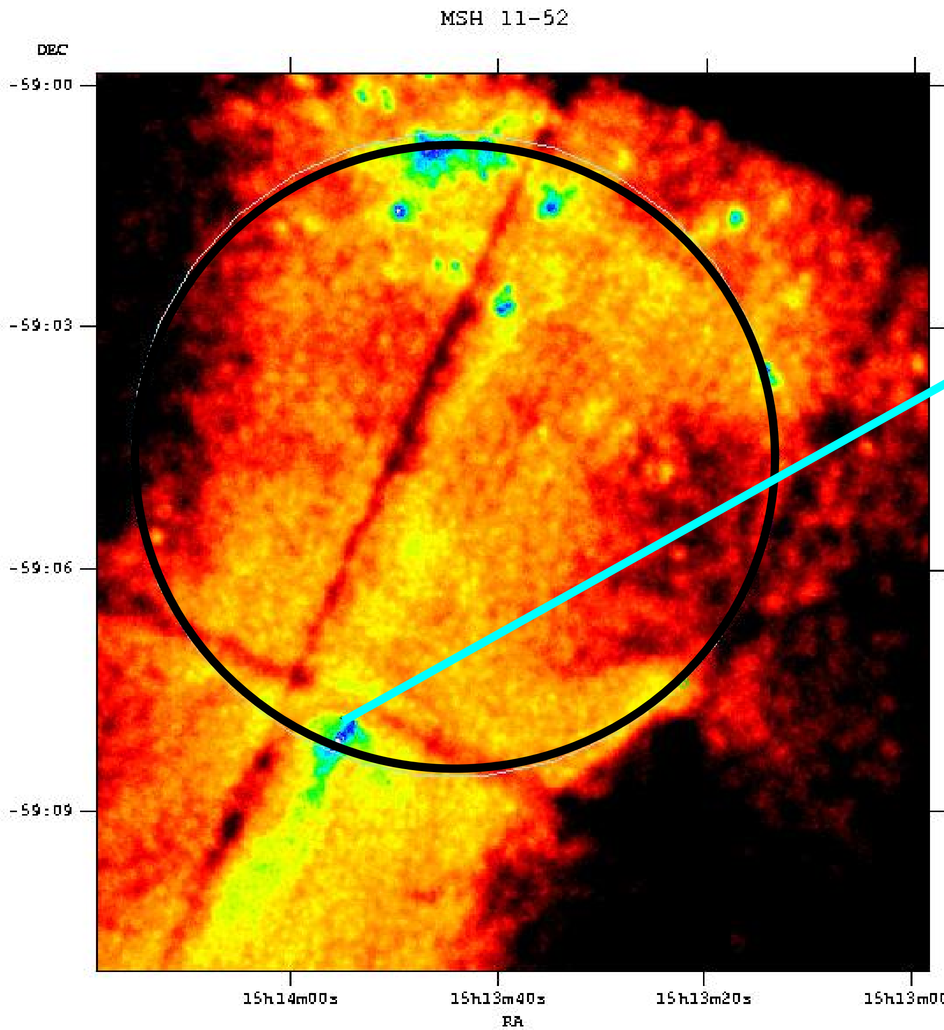
- Reducing the counting rate requirement allows an increase in the multiplexing scale, which enables a larger array and combined with the shorter focal length a much larger field of view (cluster, galaxy, survey science) and for a given field of view fewer pixels.

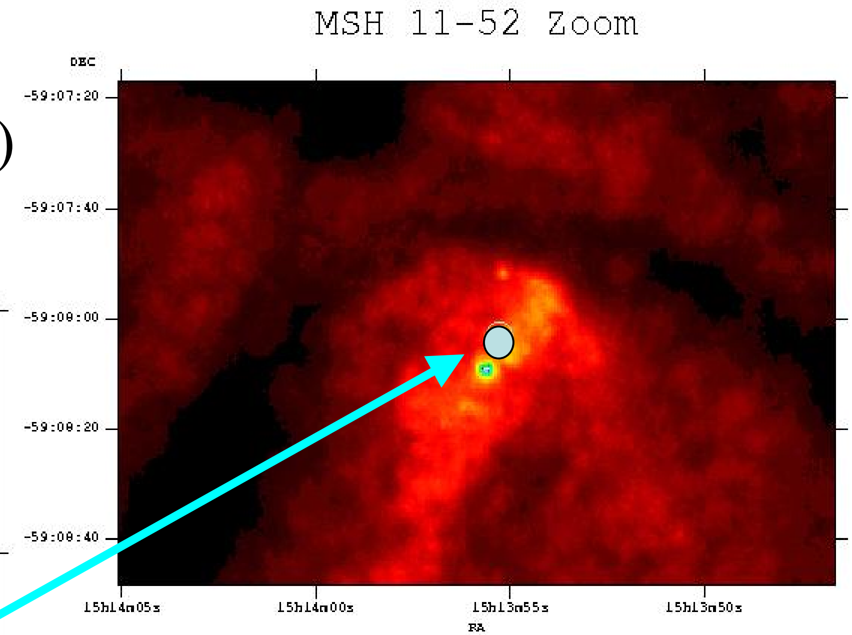
- Shorter focal length and lower energy prime science allows much smaller heat capacity pixels- factor of ~2-5 better energy resolution

- Shorter focal length allows lighter mirror, smaller spacecraft, rapid slewing.

Sahara Requirements for Science

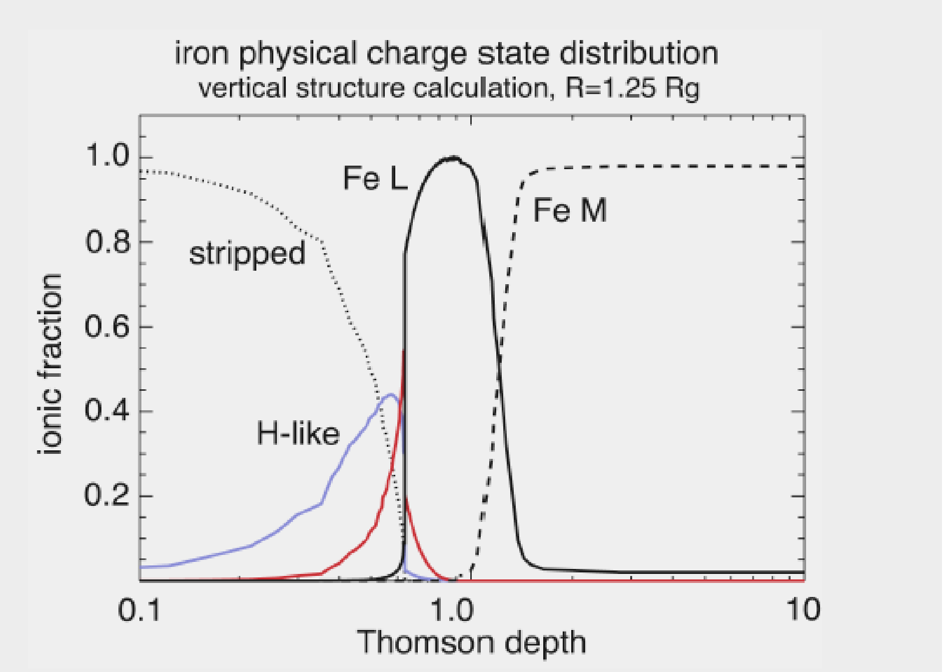
- Angular resolution and FOV
  (Chandra data for SNR MSH11-52)



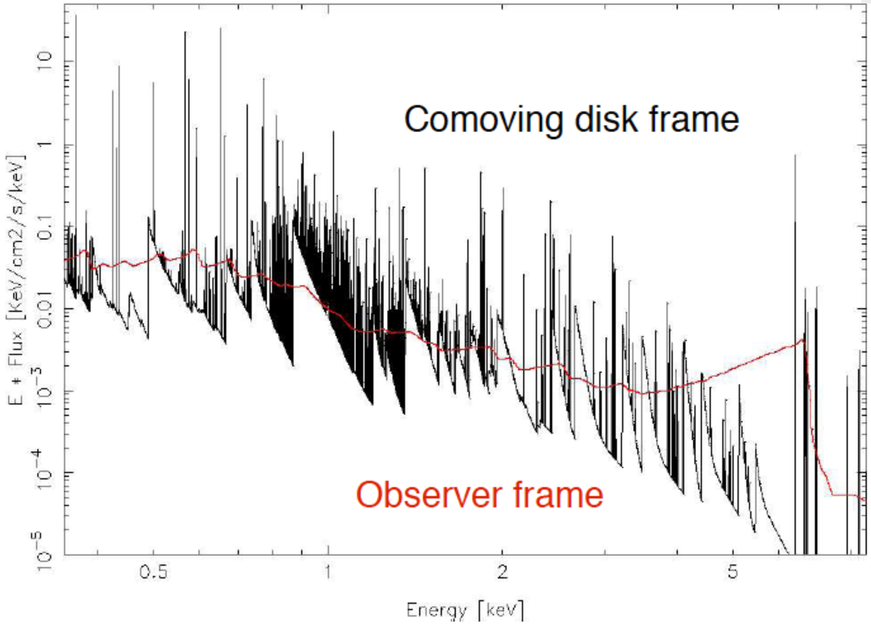


circles: Sahara angular resolution and FOV

•characteristic size of cluster cool cores ~100kpc is 12” at z=1
•virial radius of a massive cluster at z=1 is ~1.5 Mpc (4')



Calculation by Mario Jimenez-Garate; figure provided by Chris Mauche



APPROV 2004 Mario Jimenez-Garate(MIT) D

- NGXO- 1994 response to the NRA
- 3 telescope concept; Sahara is essentially one of them
- In 1995 cost estimated at $500M