Non-thermal emission from clusters

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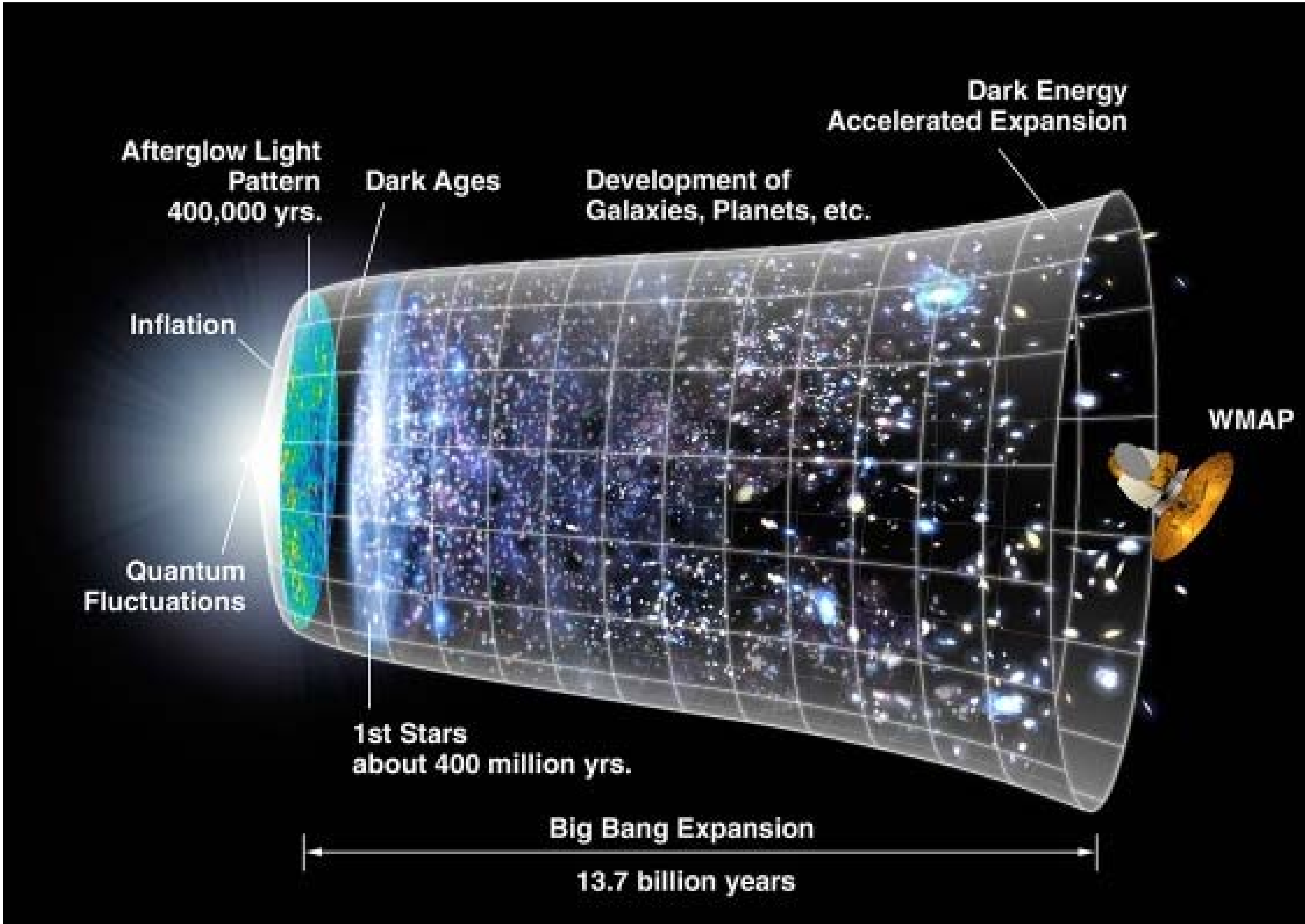
Outline:

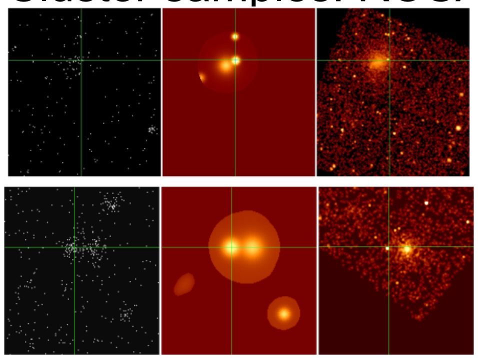
- Clusters and cosmology
- Clusters as diffuse light sources: Thermal X-rays but not only
- Non-thermal emission in radio, X-rays
- The case of Bullet Cluster: Suzaku observations
- Gamma-rays with Fermi
- Future hard X-ray observations: NuSTAR
  Astro-H's Hard X-ray Imager (HXI)

Clusters: why do we care?



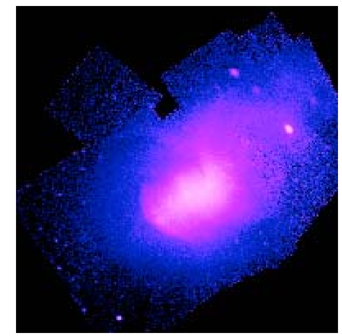
Tight constraints on cosmological parameters require well-determined masses

Cluster samples: ROSAT

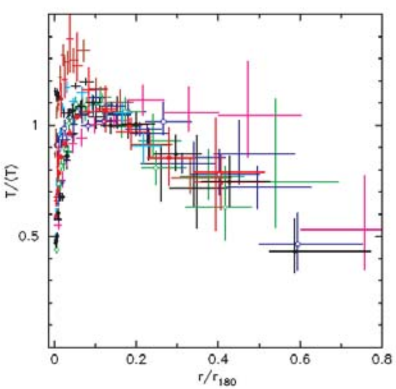


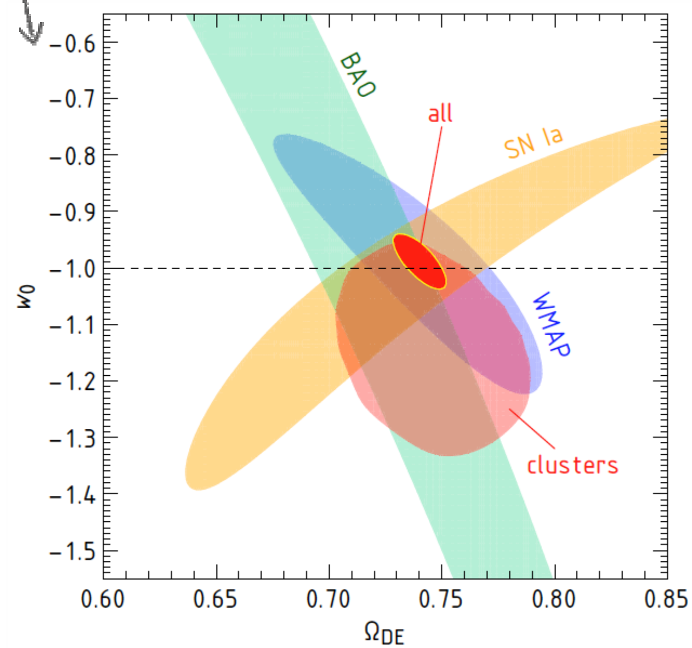
Dark Energy constraints

Cluster physics: Chandra & simulations



Detailed properties: Chandra & XMM



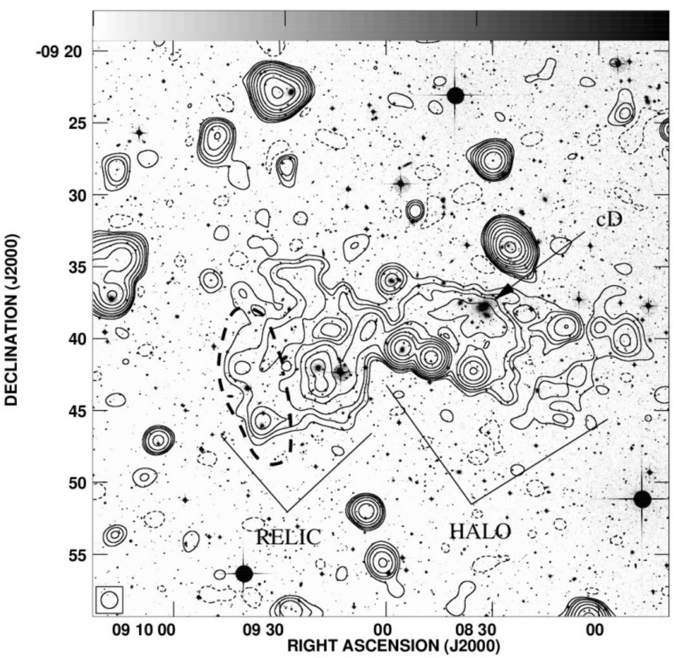


$w_0 = -0.99$
$\pm$ 0.045 (stat)
($\pm$ 0.067 w/o clusters)
* Systematic errors comparable

Slide shamelessly stolen from C. Jones;
plot from Vikhlinin et al. 2009

Radio emission in clusters

Clusters formed from galaxies – shocks expected
Excellent site for acceleration of particles to high energies
First confirmed in radio band, now at least 50 clusters known w/radio emission



Abell 754 (Fusco-Femiano et al. 2003)

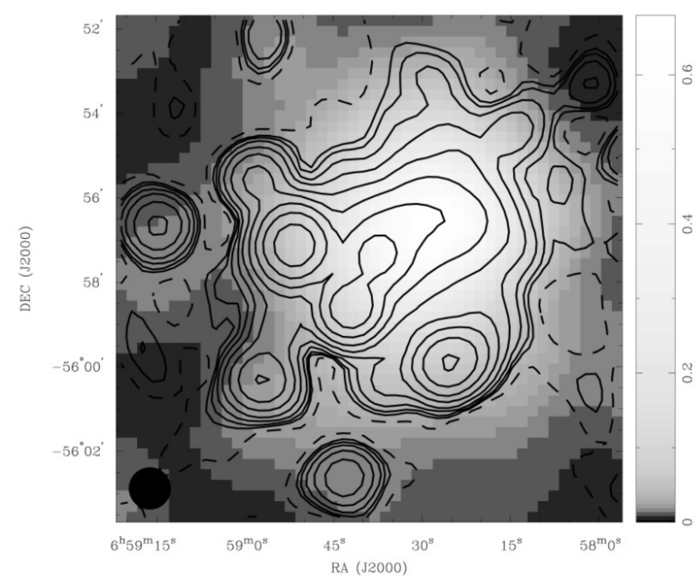


FIG. 3.—Low-resolution radio images overlaid on gray scale PSPC hard-band (0.5–2.0 keV) image smoothed with a 50″ Gaussian: (*a*) MOST contour image at 843 MHz smoothed to a beam size of 60″, the beam shown is the original beam before smoothing; (*b*–*e*) ATCA contour images with a 60″ beam at 1.3, 2.4, 4.9, 5.9, and 8.8 GHz, respectively; only the shortest spacings ($< 3600\lambda$) are used. Contour levels are $(-3, 3, 6, 12, 24, 48, 96, 192, 384) \times \sigma$, where rms noise are $\sigma \sim 1100, 51, 110, 56, 65, 56\ \mu\text{Jy beam}^{-1}$ for frequencies of 0.8, 1.3, 2.4, 4.9, 5.9, and 8.8 GHz, respectively.

Bullet cluster: ROSAT PSPC (gray scale)
with low-freq. radio (contours) (Liang et al. 2000)

Radio emission is polarized -> synchrotron process

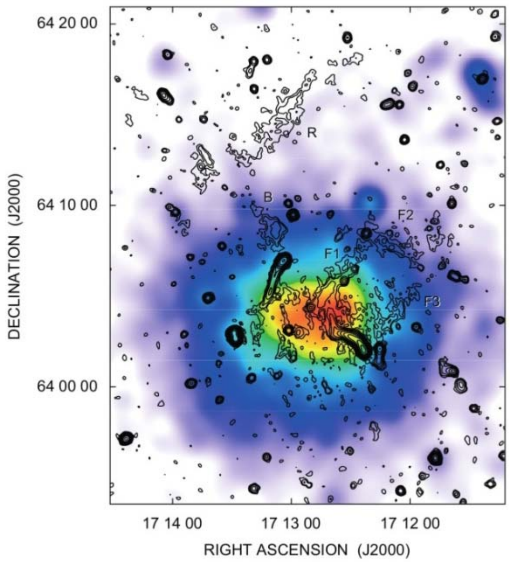
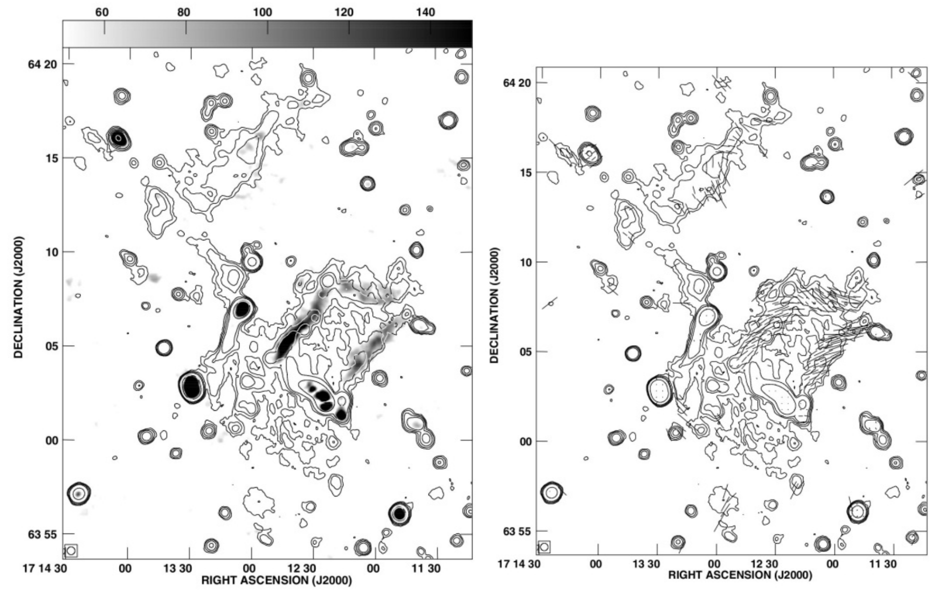


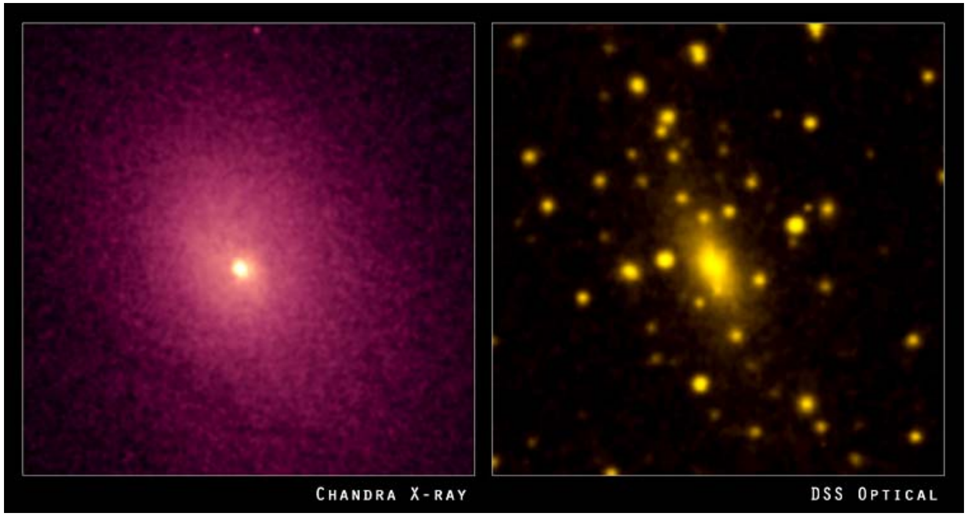
Fig. 1. Radio contours of the cluster A2255 overlaid on the Rosat X-ray image (colors). The radio image is at 1.4 GHz and has a *FWHM* of $15'' \times 15''$ (uniform weighting). The sensitivity (1σ) is 16 μJy/beam and the dynamic range is $\simeq$6300. Contour levels are: 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.8, 25.6, 51.2 mJy/beam. No primary beam correction has been applied to the image.



One example: Abell 2255 (Taylor et al.)

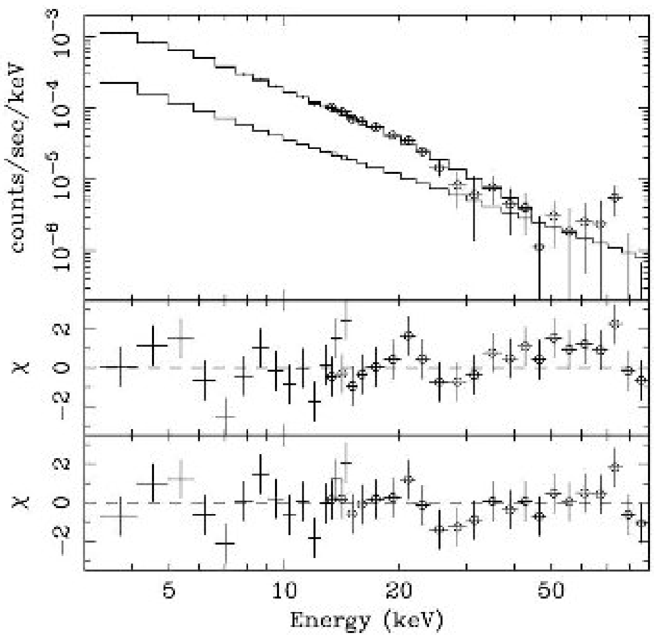
- Radio emission is a convolution of *B* and $N(\gamma)$ of relativistic electrons
- Those provide pressure -> affect hydrostatic equilibrium
- Need another tool to break the degeneracy
- Inverse Compton emission against the CMB photons –
  -> Emission expected in the X-ray band

* CMB energy density at z=0 is ~ the same as $B = 3\ \mu$G

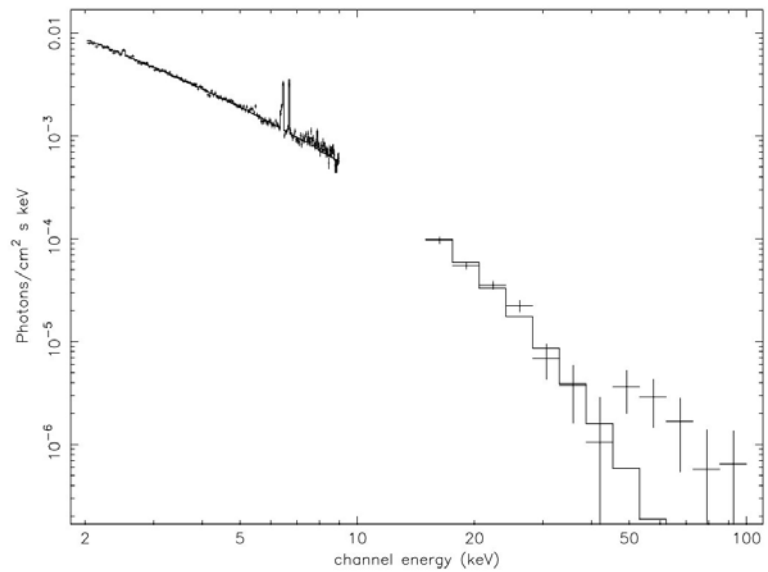


Where to look?

But clusters are strong *thermal* X-ray emitters – need to account for it in the search for non-thermal component
Hard X-ray regime most promising
Searches / detections controversial…



Abell 2163 RXTE (Gruber, Rephaeli)



Abell 754 BeppoSAX (Fusco-Femiano)

Coma has been particularly controversial…

- Hard X-ray instruments are collimated detectors – background is large
- Beppo-SAX – detection, non-detection…
- RXTE – tentative detection
- Suzaku probably most sensitive, detection – yes,
  but systematics of the NXB subtraction (Wik, Sarazin, + 2009)

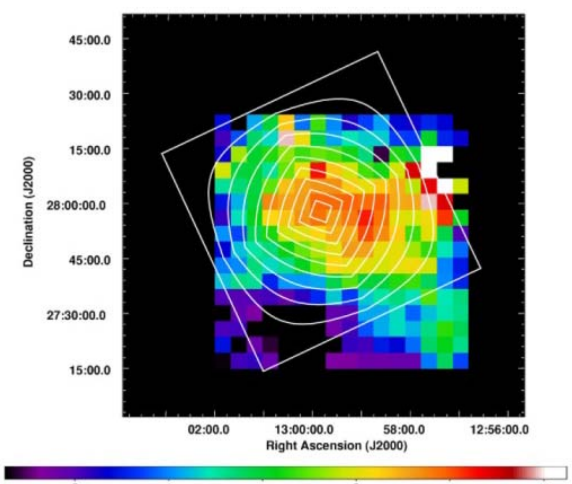


Figure 7. *XMM-Newton* temperature map across Coma with HXD-PIN contours of constant PIN effective area overlaid at 10% intervals. The *XMM-Newton* spectra were fit in square spatial regions 4!3 on a side. The temperatures, given in keV by the color bar, are accurate to either a few tenths of a keV (in the center) or 1–2 keV in lower surface brightness regions. Temperatures shown here were determined from fits to the 0.5–14 keV spectrum in each region.

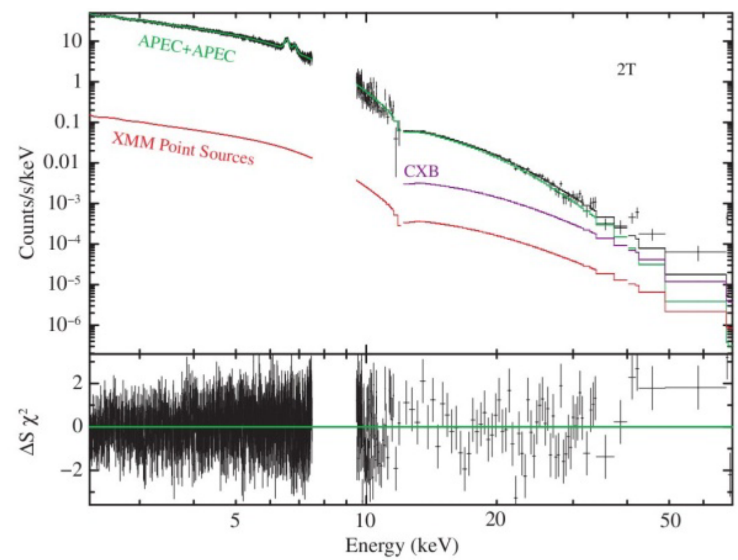


Figure 6. *Suzaku* HXD-PIN spectrum ($E > 12$ keV) and the combined *XMM* spectrum ($E < 12$ keV) corresponding to the spatial sensitivity of the PIN. Shown as solid lines are the best-fit models for a 2-T thermal component. The thermal model ("APEC+APEC," green) is nearly coincident with the data, though falling below it at higher energies. The other two components are

Coded mask imaging helps a little: Swift BAT

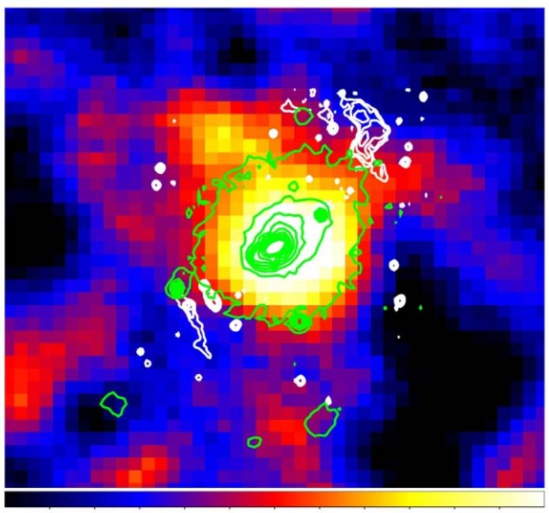


Figure 13. BAT significance map of A3667 with superimposed X-ray contours from the *ROSAT*-PSPC (green) and radio 843 MHz SUMSS contours (white).

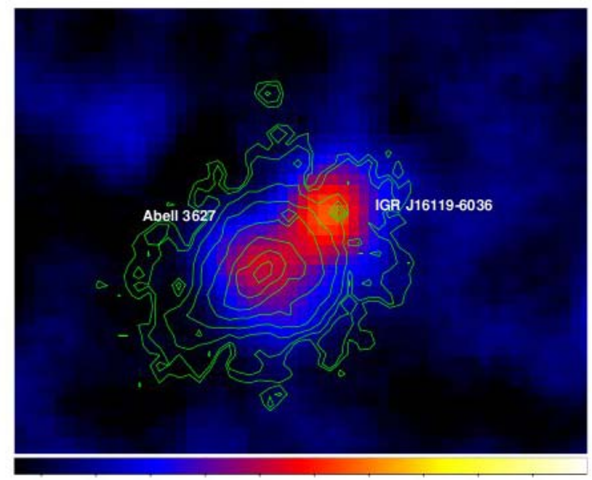


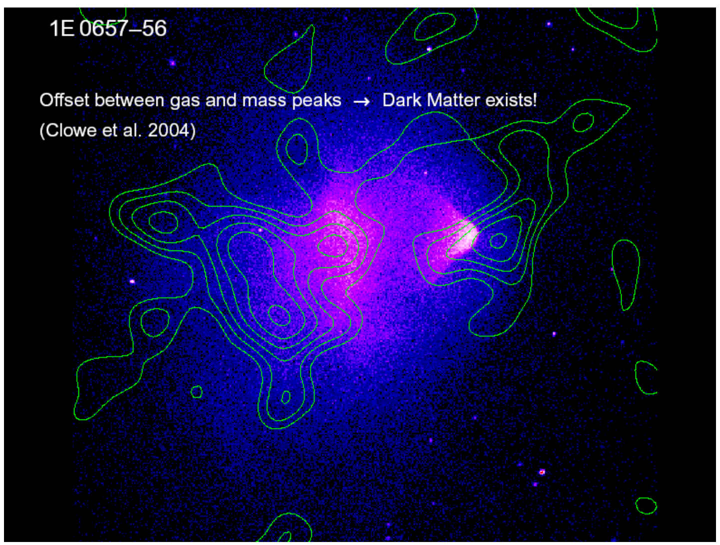
Figure 10. Contours of the surface brightness of the Norma cluster, as derived from *ROSAT*-PSPC observations, superimposed on the *Swift*/BAT significance map. (A color version of this figure is available in the online journal.)

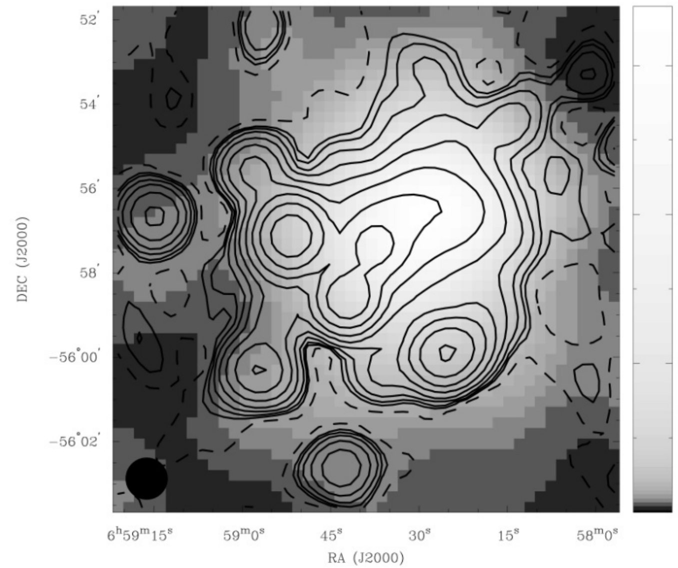
Abell 3667 with BAT (colors), radio (white contours), and PSPC (green contours) – from Ajello et al.)

Same for Norma cluster

Bullet Cluster and non-thermal emission

Poster child for merging activity
One sub-cluster traveling through another sub-cluster
Angle of the cone gives a Mach number of the shock
Non-thermal radio emission detected
Beautiful S-Z data (shown in later talks?)
Very massive - ~ 10^{15} Solar masses? Gonzalez et al.





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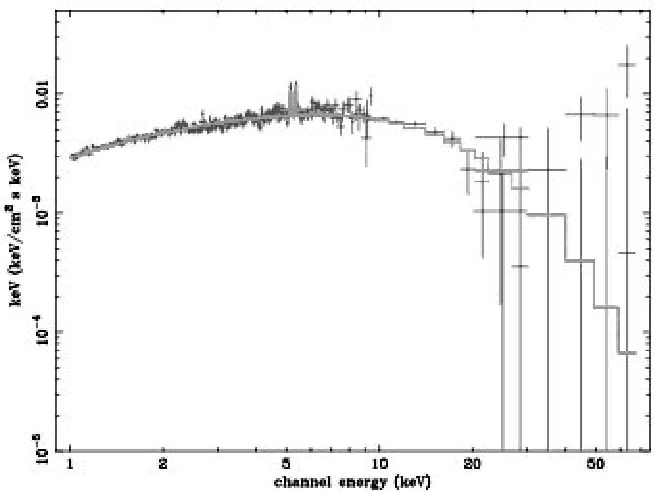
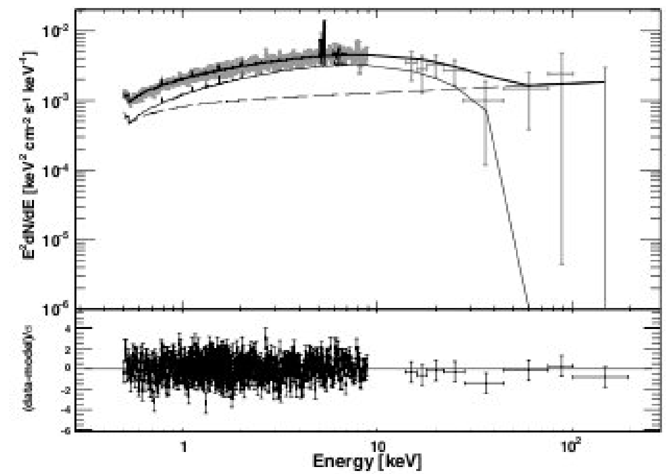
Chandra image, with the green contours indicating mass distribution inferred from gravitational lensing (Markevitch+, Clowe+, Bradac+)

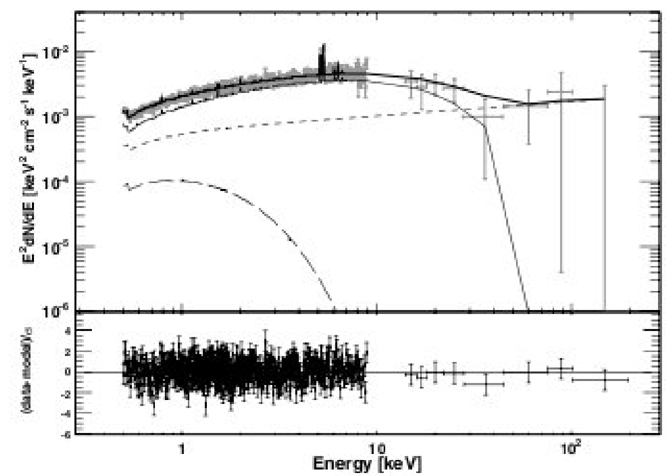
**Radio emission (contours)
Overlaid on X-ray gray scale map
(Liang et al)**

Hard X-rays from the Bullet Cluster

RXTE data (PCA, HEXTE) suggests
non-thermal emission at the ~ 2.5 σ
level (Petrosian, GM, Luli)
Extends to ~ 100 keV, 20-100 keV;
flux ~ 5 x 10^{-12} erg/cm^2/s
Confirmed by Swift BAT observations

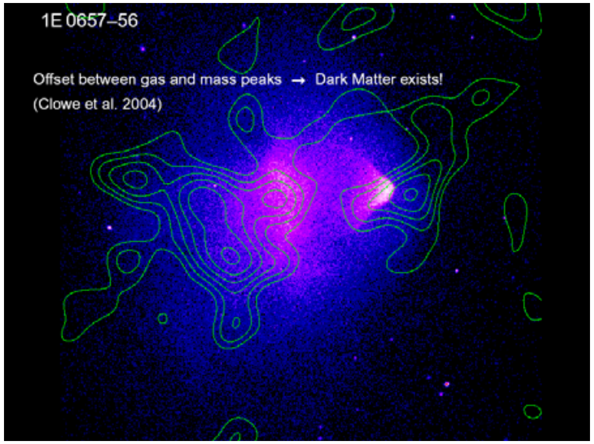






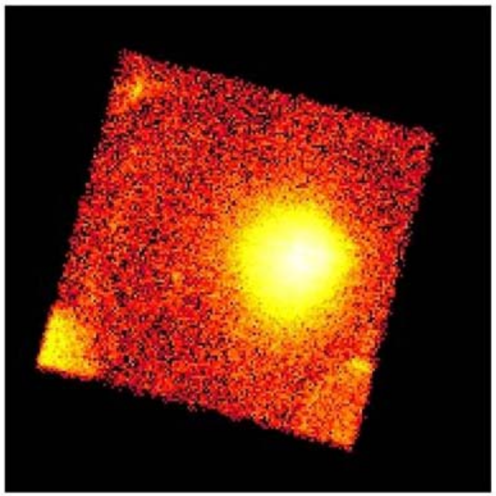
- Spectrum of the bullet cluster obtained with RXTE (left, Petrosian et al.) and Swift BAT (right, Ajello et al.)

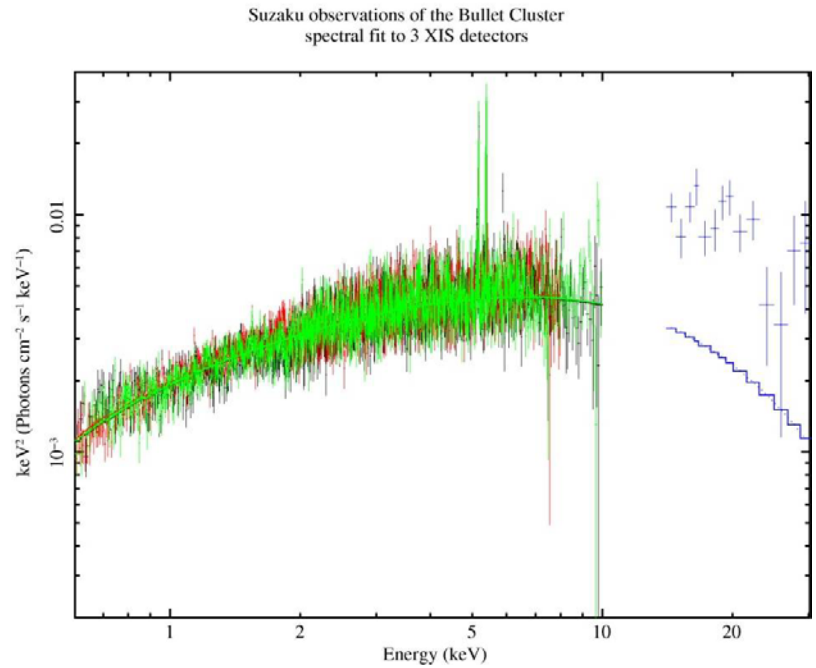
Bullet Cluster with Suzaku



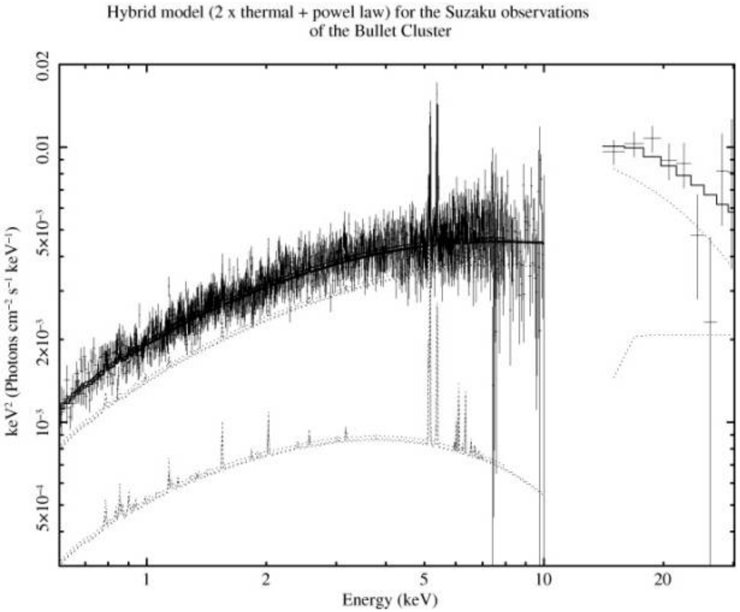
Chandra image

Suzaku image





- Observed with Suzaku for 100 ks, XIS: beautiful detection, low background
- Suzaku XIS spectrum fits adequately with a single T ~ 12 keV,
  but multi-temperature structure slightly preferred (not new – seen in Chandra by Markevitch et al.; XMM-Newton by Andersson, Peterson, GM), T range 9 – 15+ keV
- Hard X-ray spectrum (HXD PIN data) not on the extrapolation of the XIS data
- But - note that PIN subtends larger Ω (0.34 deg.sq) than the XIS image (cluster: ~0.02 deg sq)



Bullet Cluster: the nature of the hard X-ray component – work in progress

<- Swift BAT detection level

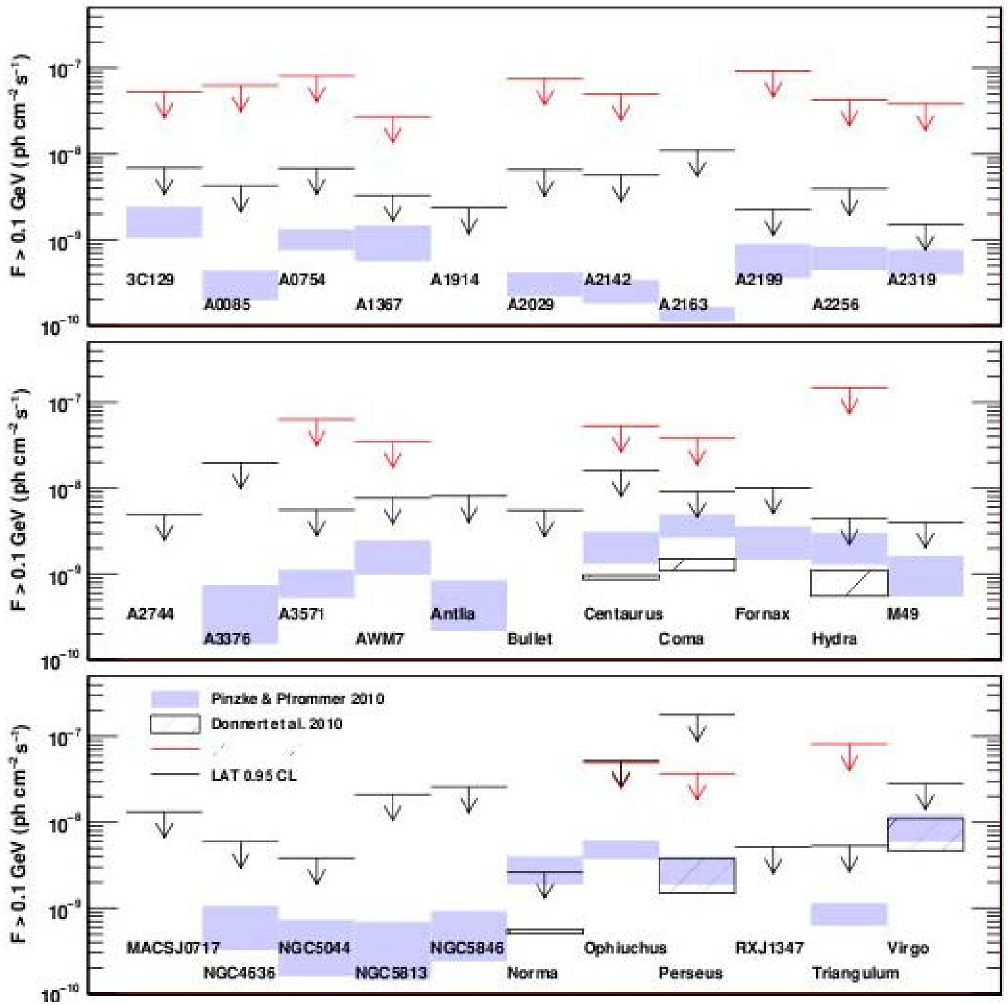
- What is the origin of the hard component seen in the Suzaku HXD/PIN data?
- Could be potentially a result of imprecise subtraction of the particle background –
  - Inclusion of the systematic errors makes it only a ~ 2σ detection, but systematics of NXB in the PIN observations – 3% nominal - are probably an overestimate
- Two possibilities: it could be a power-law-like component, but then:
  - (1) if all of it is at the flux level seen in the HXD, it has to cut off sharply between the XIS & PIN – not too attractive…
  - (2) Swift BAT flux at 20-30 keV is much lower than seen in in the HXD PIN
- More likely possibility: a hybrid scenario:

  includes a PL component at the BAT flux level, modest cut-off

  \+ a low surface brightness, but significantly more extended and somewhat hotter thermal component (RXTE PCA normalization closer to the HXD PIN value!)

* Robust total emission / mass determinations require studies to and beyond the virial radius

Another handle on non-thermal emission: γ-rays

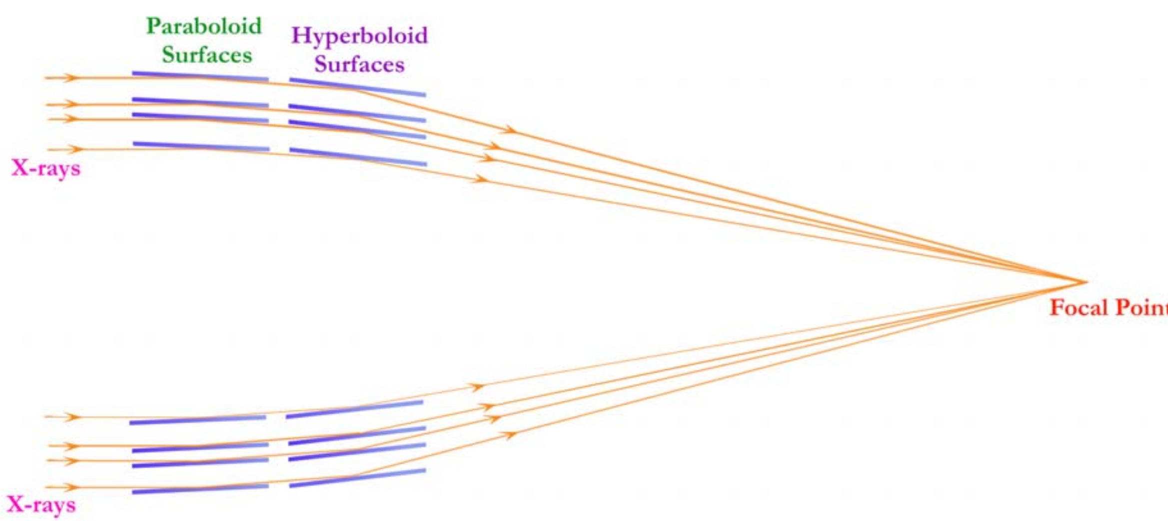


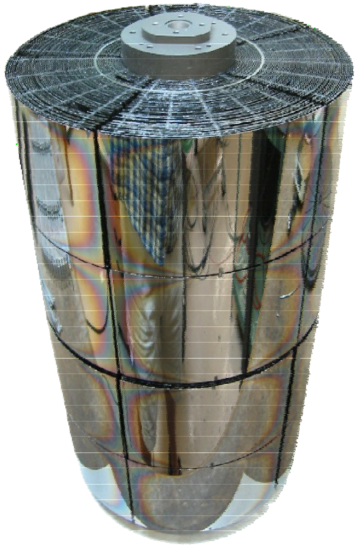
Upper limits for γ-ray emission for clusters measured by Fermi (Abdo, …, Bechtol 2011)

Future observations

- **Traditional, collimated hard X-ray instruments probably reached their ultimate sensitivity, ~ 0.5 x 10^{11} erg/cm^2/s (say 10-50 keV)**
- **Any advances will need focussing optics**
- **Advantages: much lower background, and of course imaging**
- **Easier to do below 10 keV, more difficult above 10 keV (cannot use standard reflection from grazing incidence)**
- **Major breakthrough: multi-layered optics allows focussing to 80 keV and possibly beyond; proven in balloon flights**

*** Examples: NuSTAR (2012), Astro-H (2014)**





NuSTAR: What is it?

* NuSTAR will be the first satellite-based focusing X-ray telescope operating in the hard X-ray band, 5 – 80 keV

* Leading institution is Caltech (Fiona Harrison, PI)

* It is scheduled for launch in February of 2012 into a low-Earth, nearly equatorial orbit -> low background

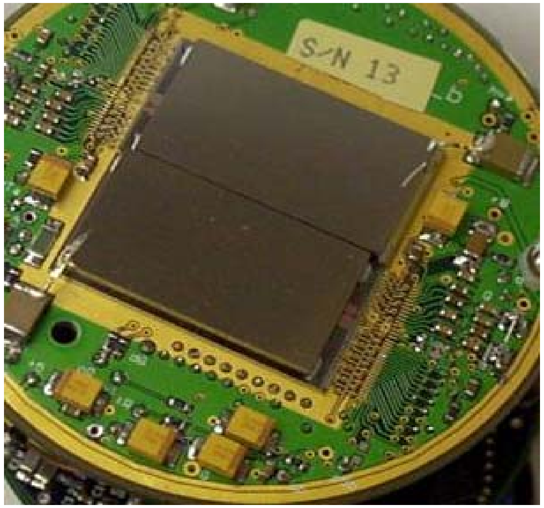
• It is a part of NASA's Small Explorer program

NuSTAR will feature three key novel technologies:

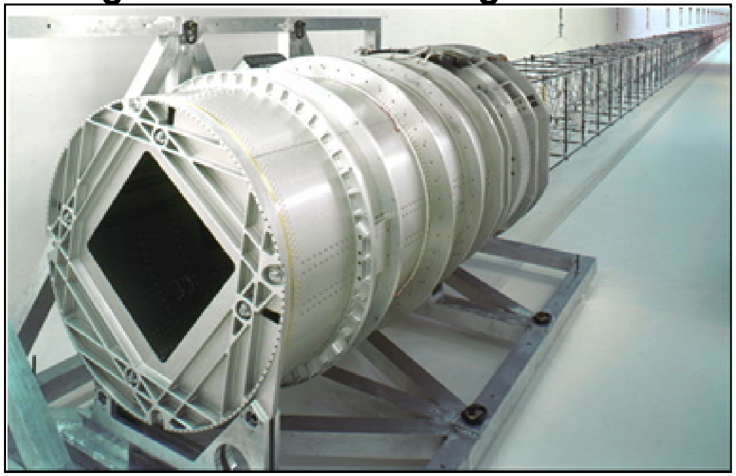
• Co-aligned multi-coated focusing hard X-ray telescopes: excellent angular resolution will allow surveys at unprecedented sensitivity

• Pixellated CdZnTe detectors: broad bandpass well matched to the telescope reflectivity

• Deployable mast, enabling the ~ 10 m focal length



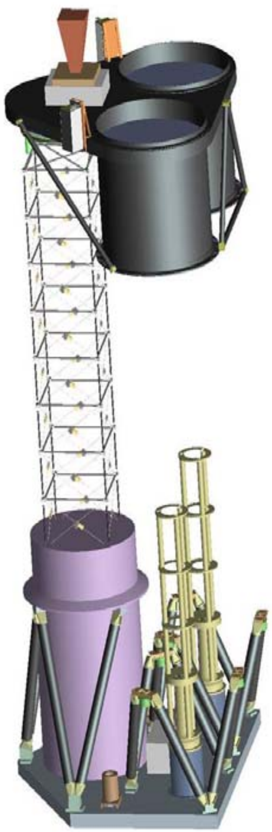
CdZnTe detectors:
pixel size 0.6 mm (~ 12")
Max. count rate: 300 cts/s
HEFT heritage

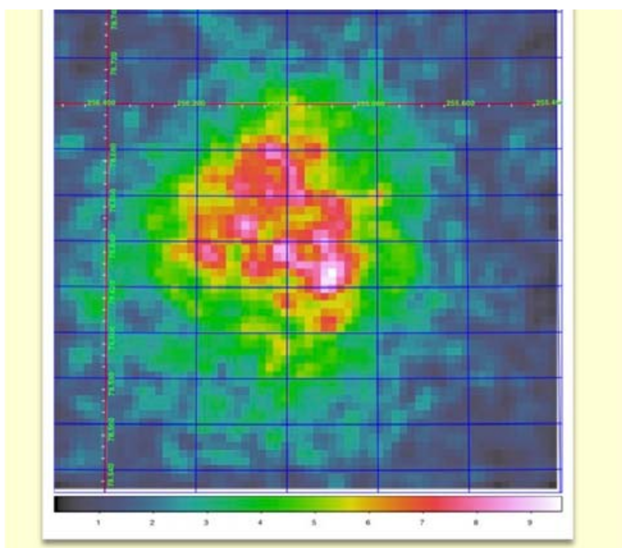


NuSTAR: key parameters

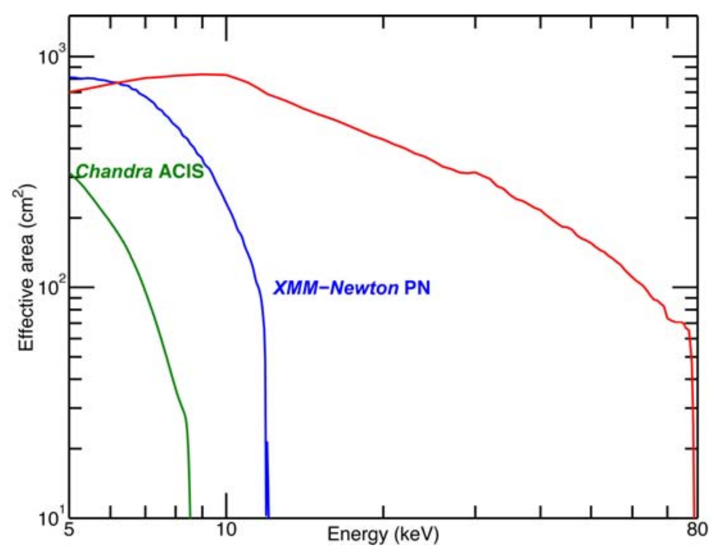
Energy range	5 – 80 keV
Angular resolution	43” Half Power Diameter, 7.5” FWHM
Field of View	13 arc min x 13 arc min @ 10 keV
Spectral resolution	1.2 keV at 68 keV
Sensitivity (3σ, 10^6 Sec)	2×10^{-15} erg/cm^2/s (6-10 keV) 1×10^{-14} erg/cm^2/s (10-30 keV)
Timing resolution	0.1 millisecond
ToO response	< 48 hour
Launch date	February 2012
Orbit	6° inclination, 550 x 600 km
Mission lifetime	2 years baseline
Orbit lifetime	> 7 years

Low instrumental background due to focussing optics, equatorial orbit



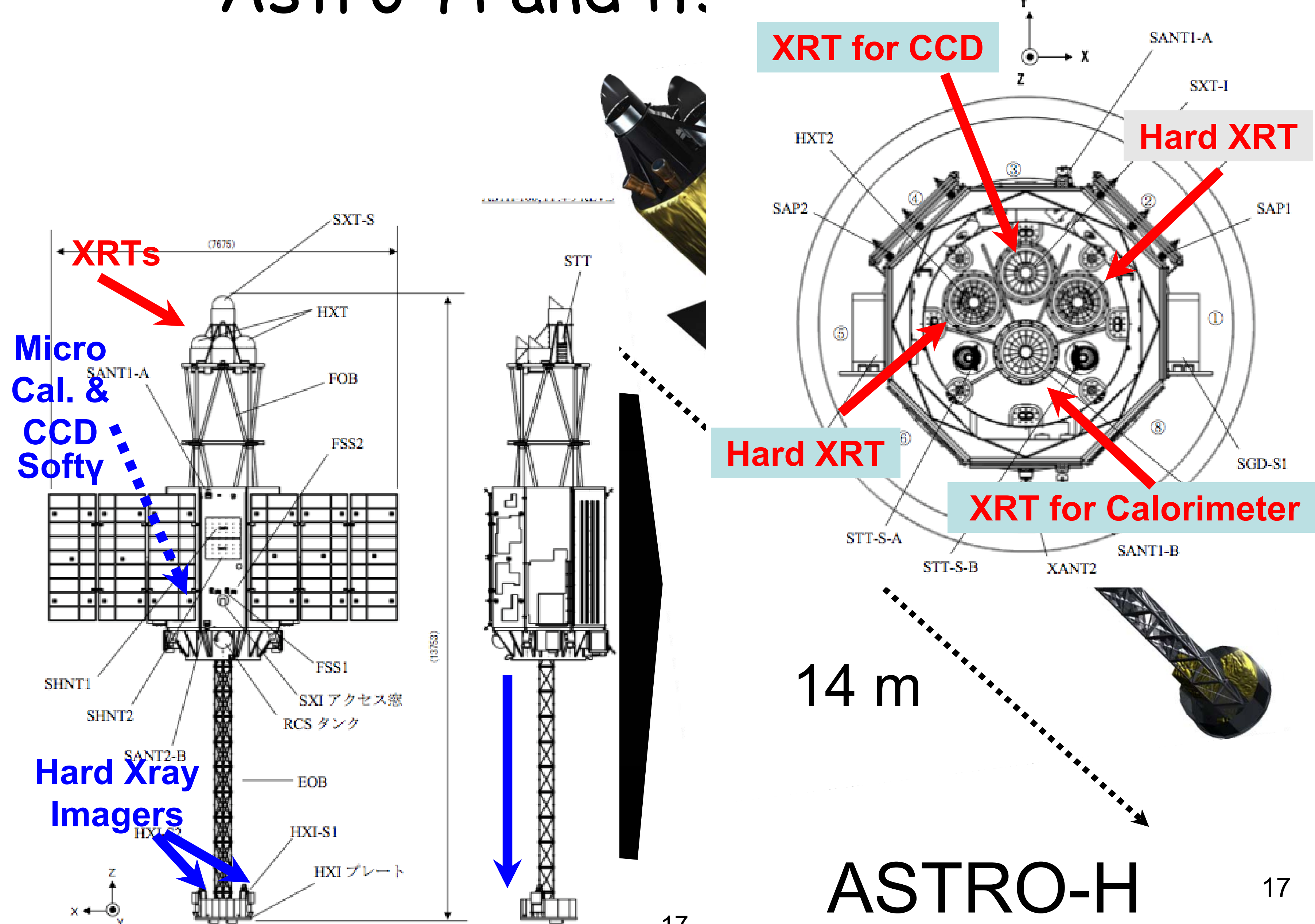


Simulated NuSTAR 200 ks observation of Abell 2256



NuSTAR effective area

Astro-H and its instruments



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Astro-H and its instruments

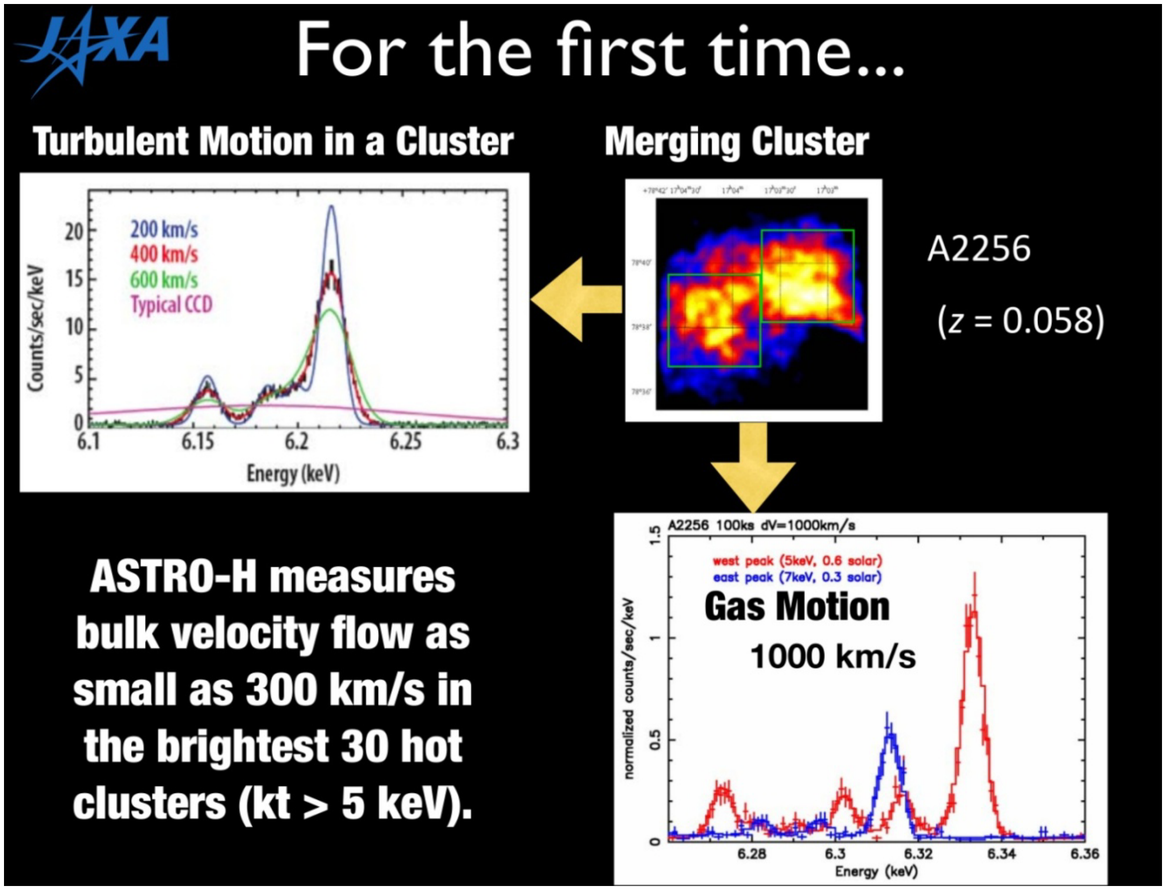
- **Three instruments will feature X-ray focussing optics**
- **Fourth, the Soft Gamma-ray Detector, will use Compton kinematics + passive collimation**

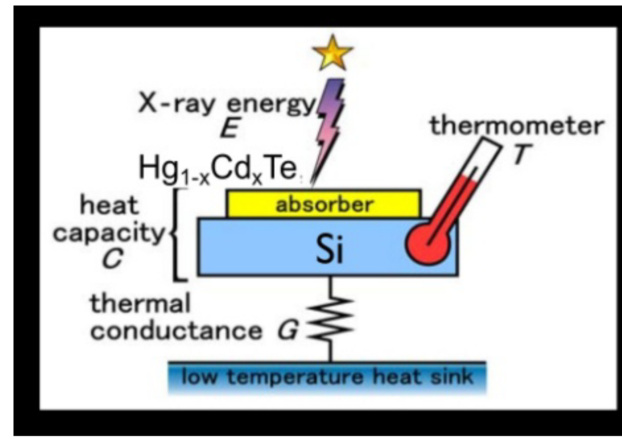
Design Parameters of Instruments

	Specifications **(Requirement)**
Hard X-ray Imaging System (HXT+HXI) 5-80 keV	Effective area : 300 cm^2 (@30 keV) Spatial resolution : 1.7 arcmin (HPD) Energy resolution : 2 keV Field of view : 9 $arcmin^2$ @30 keV
Soft X-ray Spectrometer System (SXT-S+SXS) 0.3-10 keV	Energy resolution : 7 eV Spatial resolution : 1.7 arcmin (HPD) Effective area : 210 cm^2 (@6 keV) Field of view : 3 $arcmin^2$ @6 keV
Soft X-ray Imaging System (SXT-I+SXI) 0.5-12 keV	Spatial resolution : 1.7 arcmin (HPD) Effective area : 360 cm^2 @6 keV Energy resolution : 150 eV Field of view : 38 $arcmin^2$ @6 keV
Soft γ-ray detector (SGD) 10-600 keV	Effective area : 100cm^2 @100 keV Energy resolution : 2 keV @40 keV Astrometric accuracy : <0.6 arcdeg (E<150 keV)

Astro-H – Soft X-ray Spectrometer: Scientific objectives for the instrument

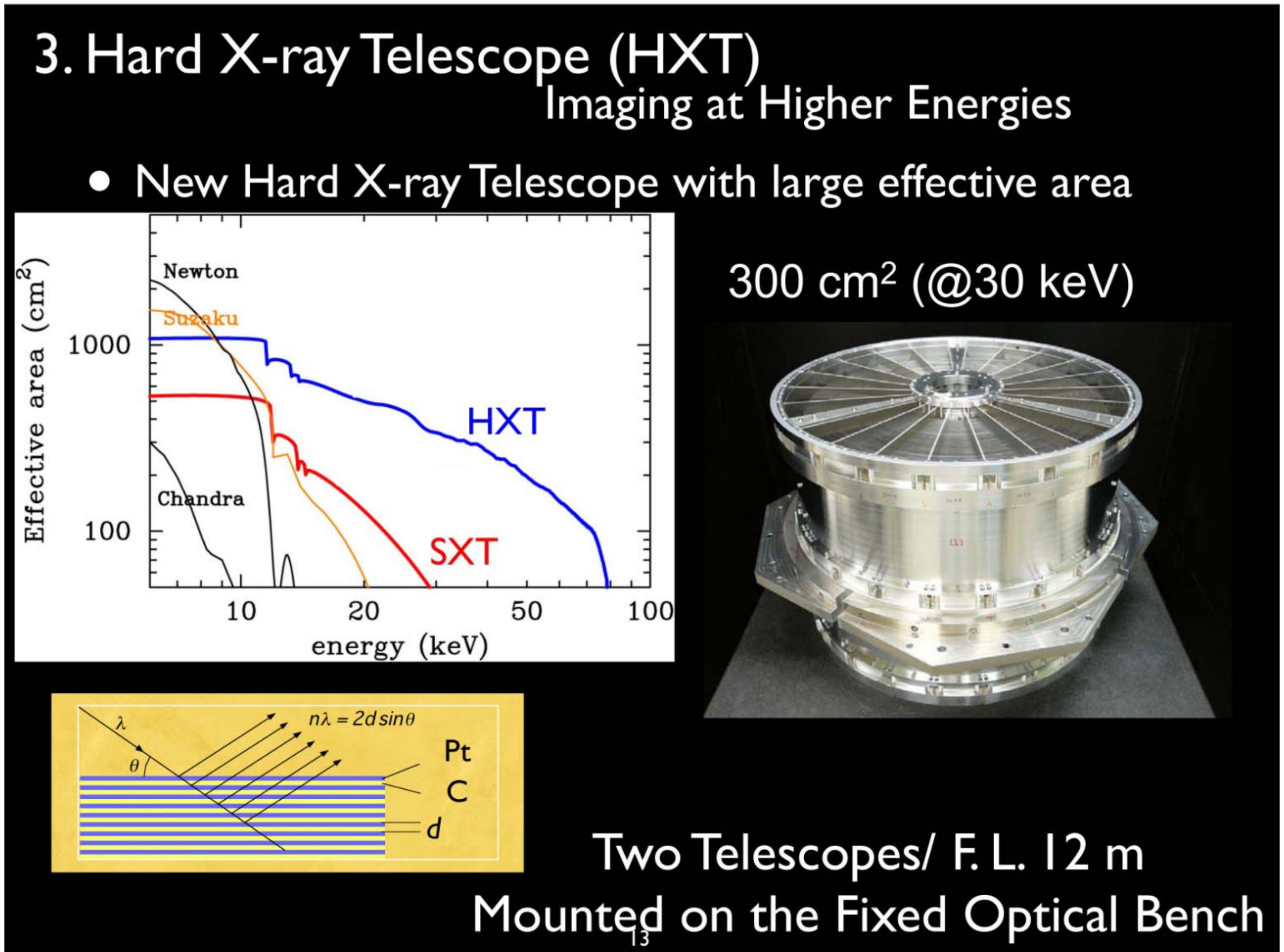
- **High resolution X-ray spectroscopy is crucial in understanding physical conditions in astrophysical sources**





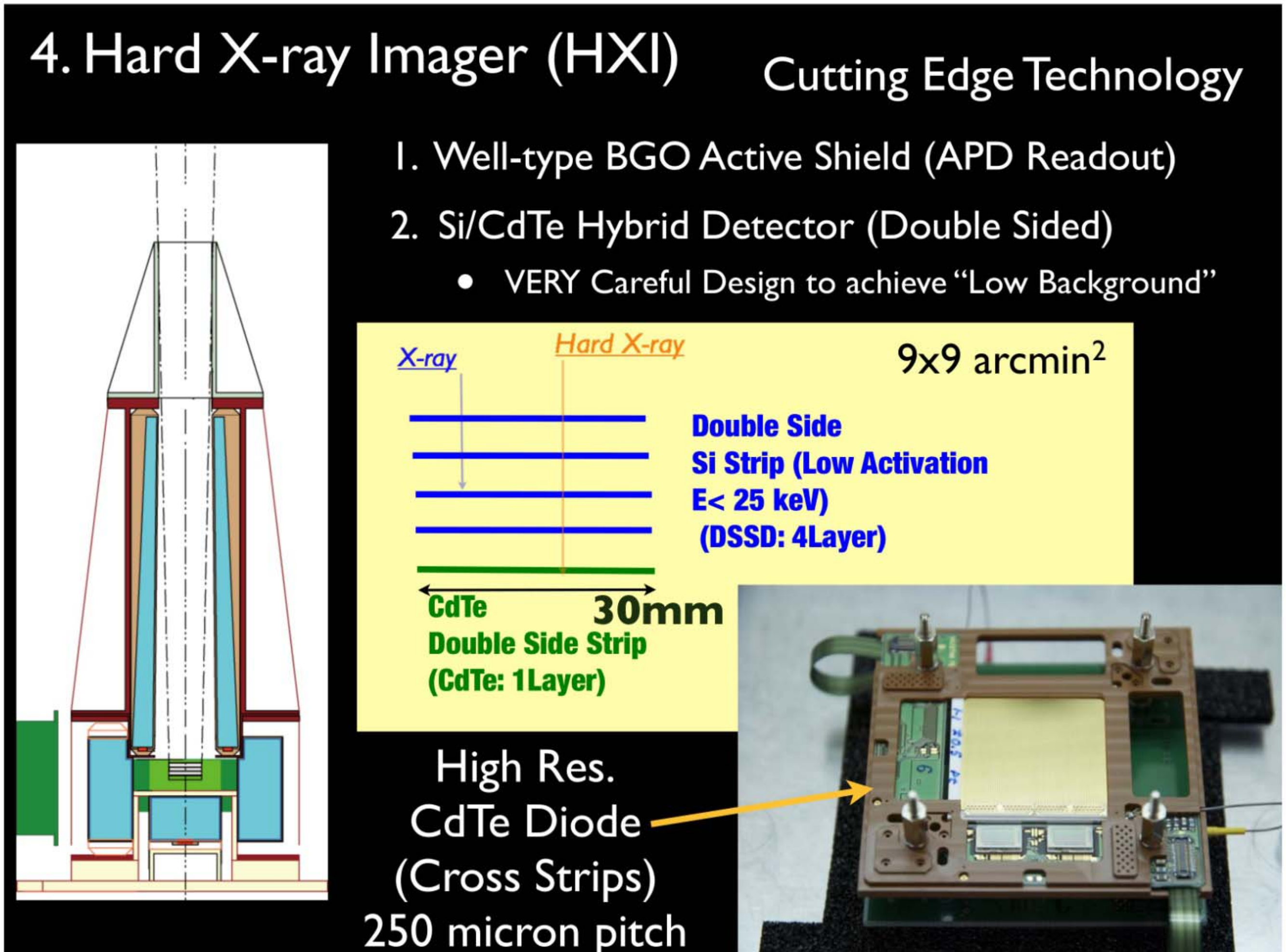
Astro-H – Hard X-ray Imager: novel telescopes and detectors

- Novel multi-layer technology allows for focussing of X-rays up to ~ 80 keV
- Requires long focal length (> 10 meters)



Astro-H – Hard X-ray Imager: novel telescopes and detectors

- Detectors for the Hard X-ray Imager need to be sensitive up to ~ 100 keV, with very low background, but pixellated – to allow for imaging



Next few years will bring major breakthroughs in understanding non-thermal emission / processes in clusters