energy resolved imaging in x-ray astrophysics

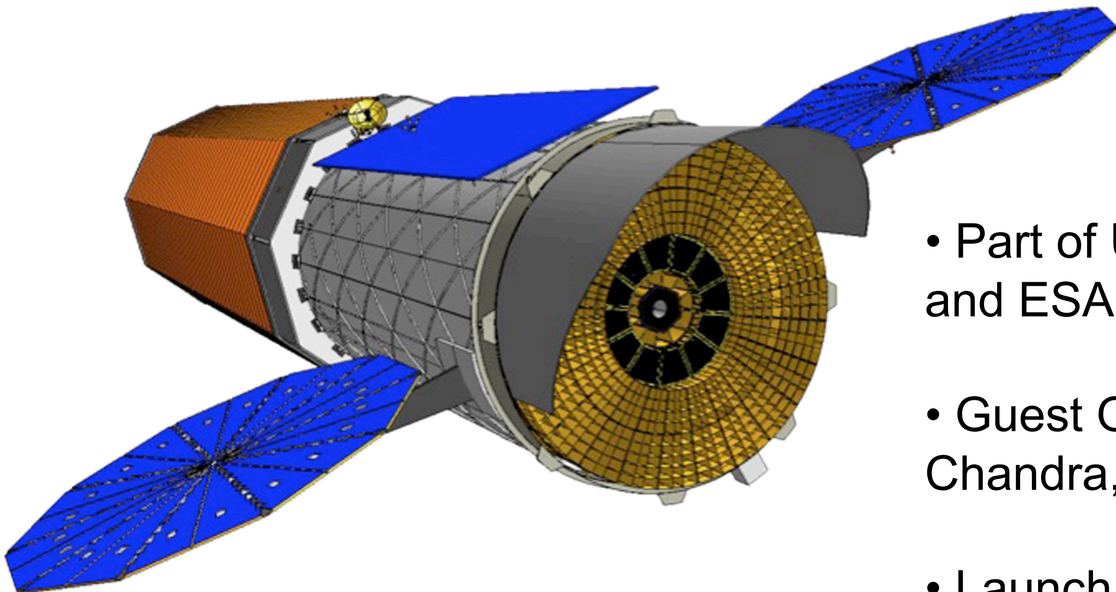
Peter Mao

Space Radiation Lab, Caltech

x-ray astrophysics in 2 minutes

- energy range: 0.1 to 100 keV (0.01-10 nm, 10^{16}-10^{19} Hz)
- sources: hot plasmas (shock heating, accretion), relativistic electrons (jets), nuclear decay lines (low energy gammas)
- environments: black holes, neutron stars, cosmic web, supernovae and supernova remnants
- topics: structure formation, heavy element production, physics in extreme environments
- today's imaging instruments
  - < 10 keV: Chandra, XMM-Newton, Suzaku (focusing, CCDs)
  - > 10 keV: Integral, Swift (coded mask, CdTe or CdZnTe)
- tomorrow's imaging instruments:
  - Astro-H, IXO, NuSTAR

the International X-ray Observatory



• Merger of ESA/JAXA XEUS and NASA's Constellation-X missions

• Part of US Astro2010 **Decadal Review** and ESA **Cosmic Visions**

• Guest Observatory, like Hubble, Chandra, Spitzer, Suzaku, Astro-H

• Launch: No Earlier Than ~2021

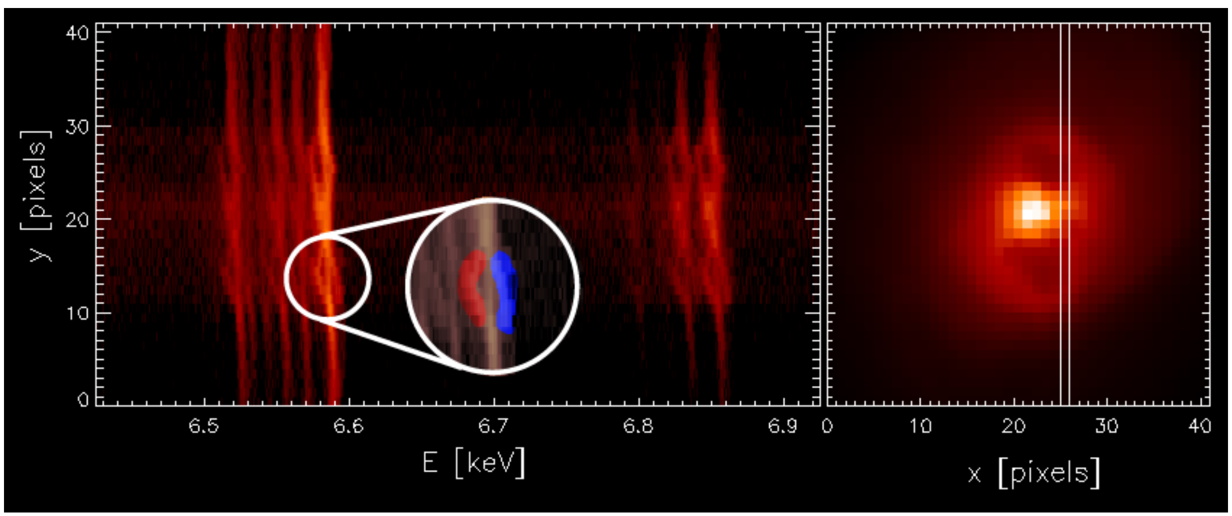
IXO material from N. White, X-ray Astronomy 2009 Conf., Bologna

Cosmic Feedback

AGN feedback: regulates the growth of galaxies and clusters of galaxies

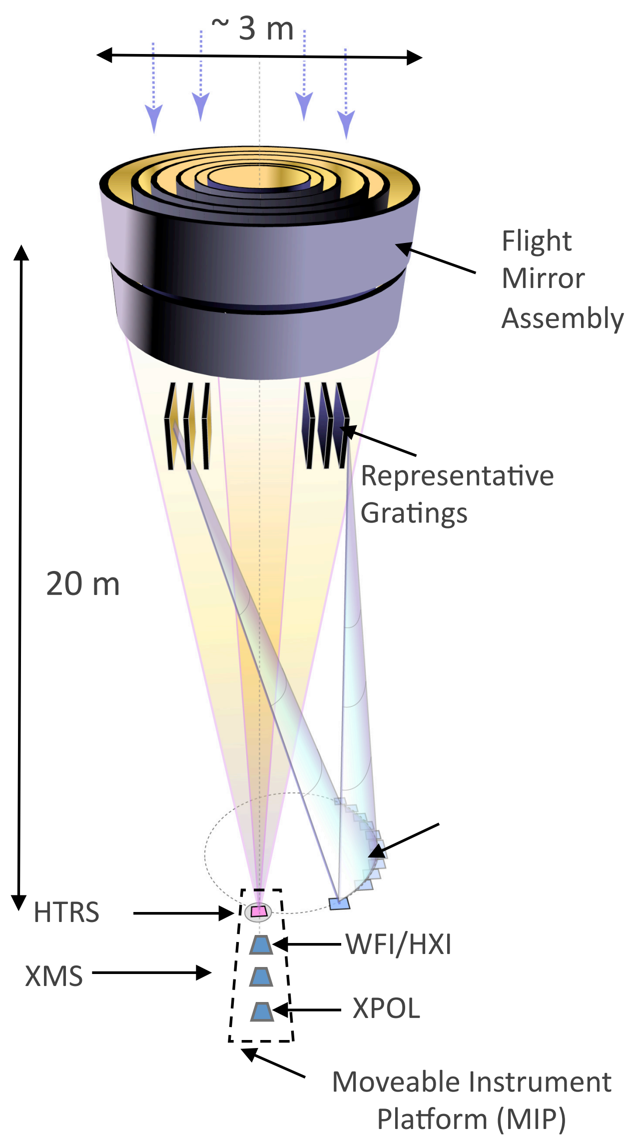
How is energy transferred from the nucleus to the galaxy/cluster (mechanical/radiative)?

IXO: Velocity measurements → bubble expansion and energy transfer

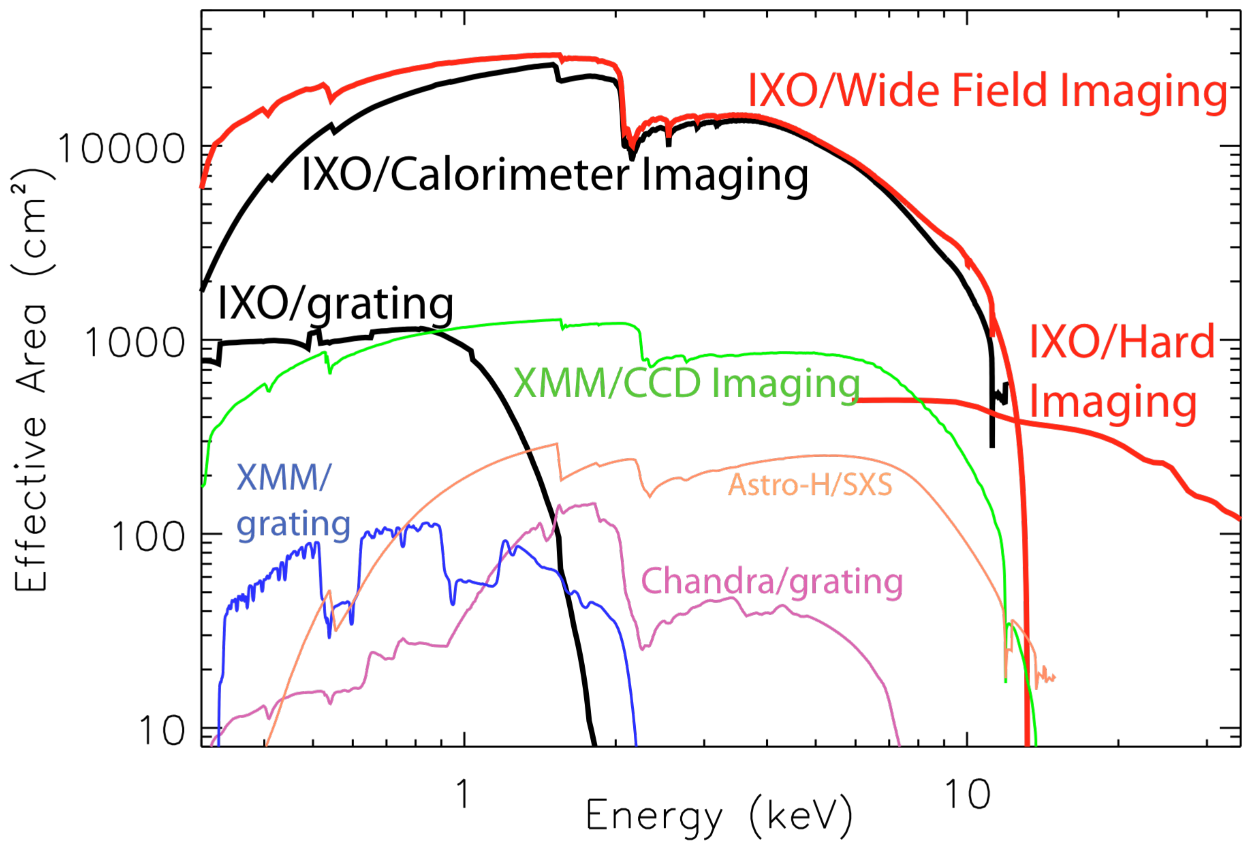


IXO Payload

- Flight Mirror Assembly (FMA)
  - Highly nested grazing incidence optics
  - 3 sq m @ 1.25 keV with a 5’’ PSF
- Instruments
  - X-ray Micro-calorimeter Spectrometer (XMS)
    - 2.5 eV with 5 arc min FOV
  - X-ray Grating Spectrometer (XGS)
    - R = 3000 with 1,000 sq cm
  - Wide Field Imager (WFI) and Hard X-ray Imager (HXI)
    - 18 arc min FOV with CCD-like resolution
    - 0.3 to 40 keV
  - X-ray Polarimeter (X-POL)
  - High Time Resolution Spectrometer (HTRS)



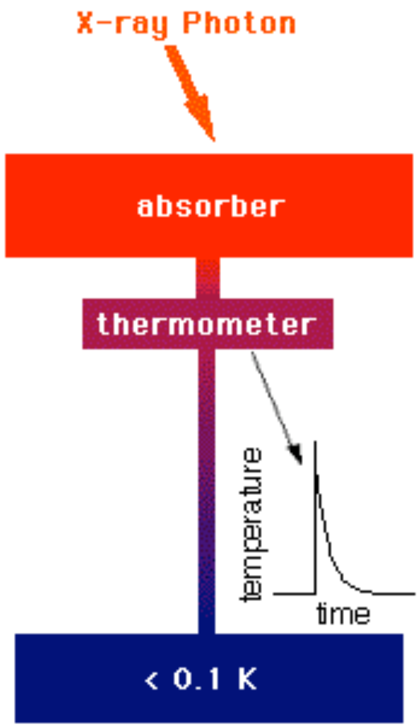
IXO is a Vast Improvement over Existing Missions

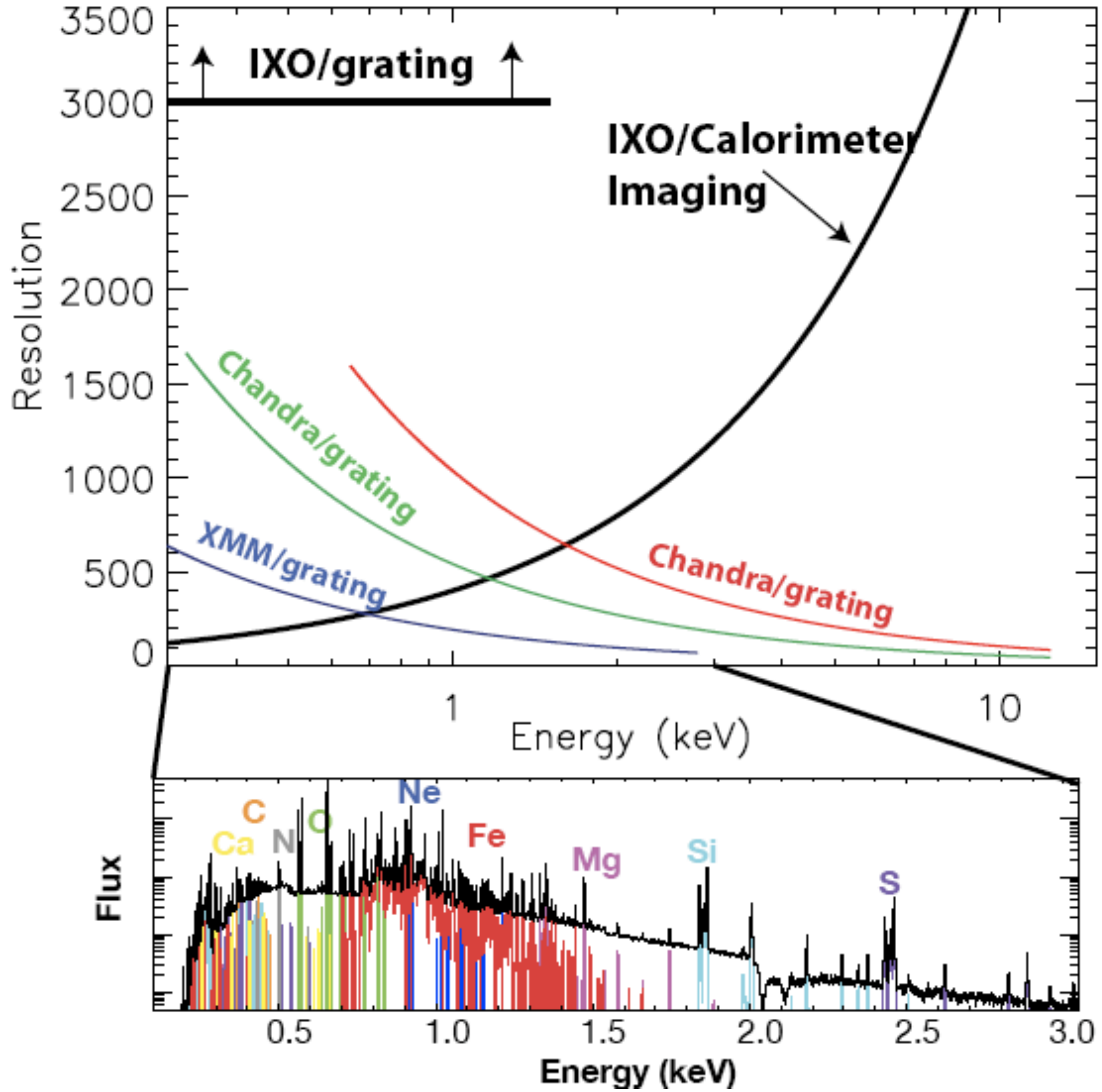


Effective area a factor of >10x of current missions
Spectroscopy capabilities >100x of current missions

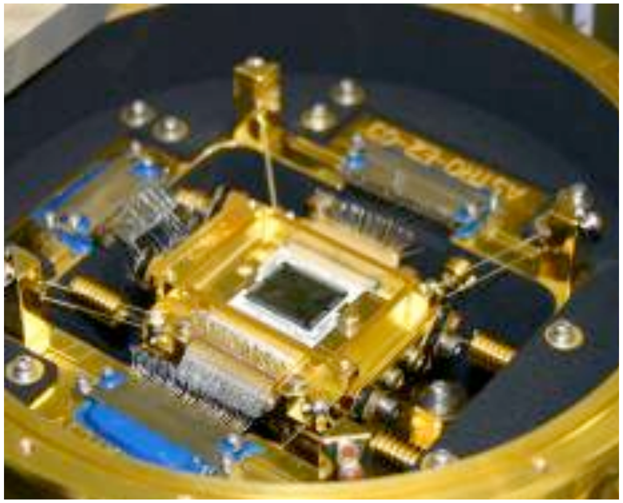
spectral capability of microcalorimeter vs. grating

- gratings: wavelength dispersive
- microcal: energy dispersive
- present microcals use thermistor
- future designs will use TES
    - allow multiplexing
    - faster response time



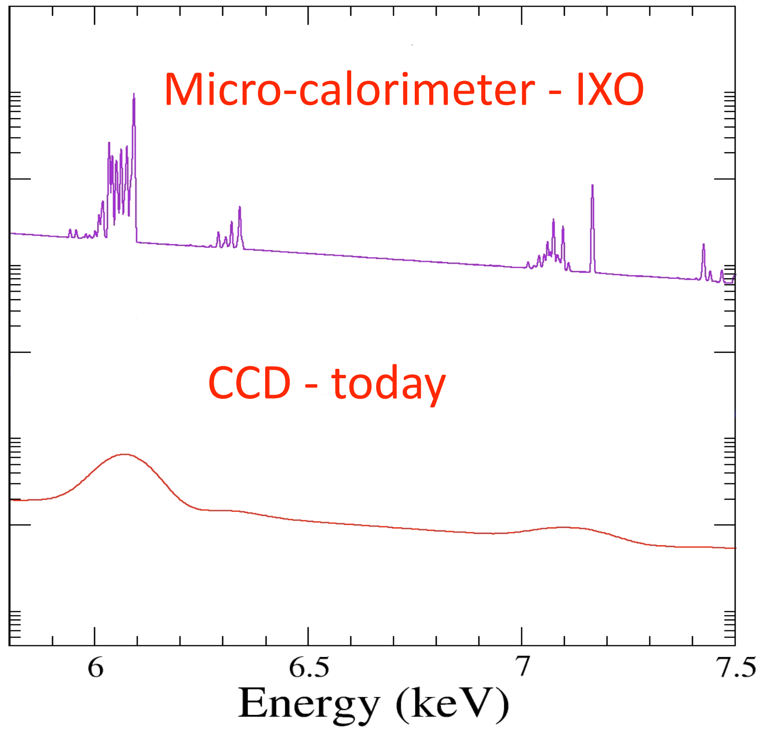


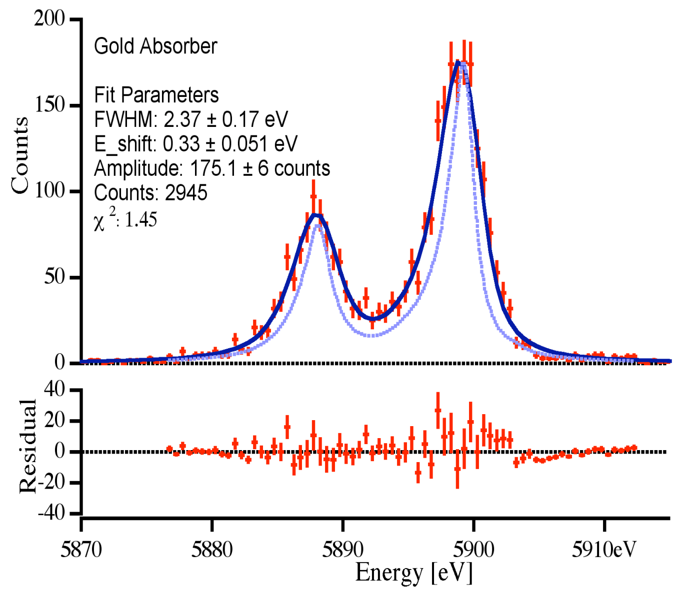
Example of Next Generation Instrument Capability
X-ray Micro-calorimeter Spectrometer (XMS)



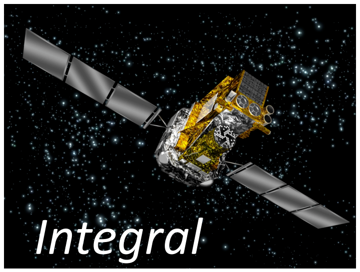
- mature technology: Astro-E, Suzaku, Astro-H all did or will fly an XMS
- major limitation: scaling up the number of pixels – solvable with TES?
- Astro-H will have an 6x6 array w/ thermistors

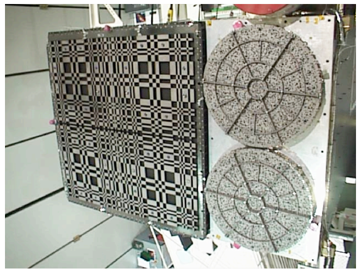
Suzaku's 32 pixel microcalorimeter



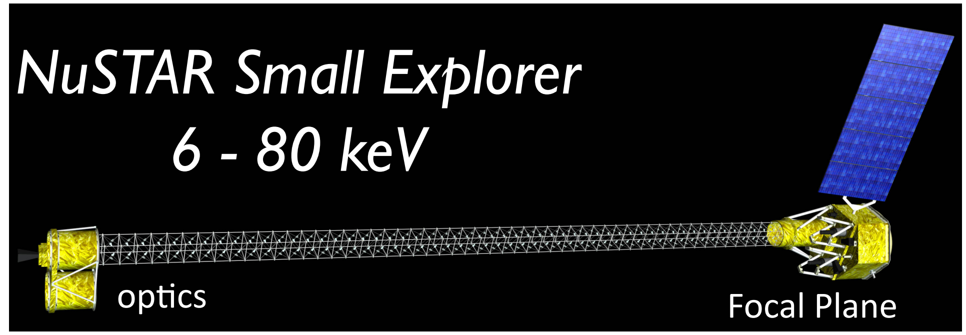


NuSTAR Mission





Coded Aperture



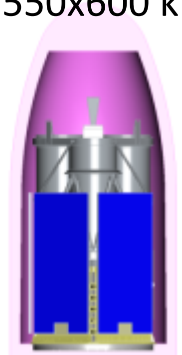
Focusing Telescope

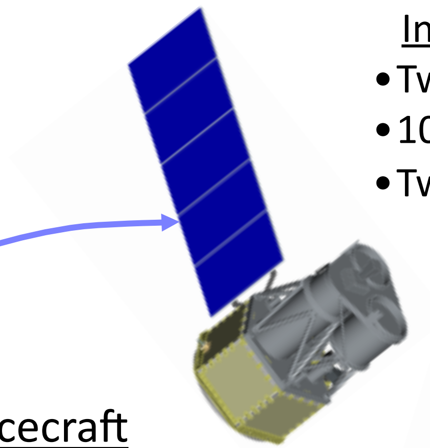
Scheduled to be launch in February 2012

Pegasus XL launch

6º inclination

550x600 km orbit



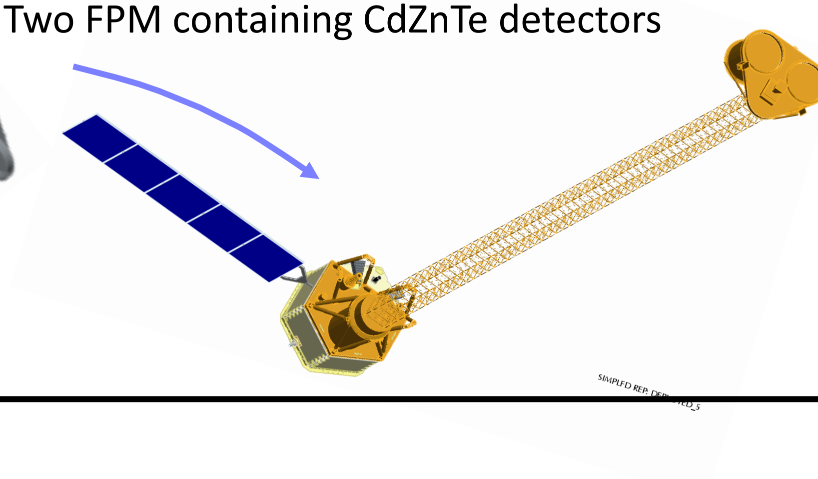


Spacecraft

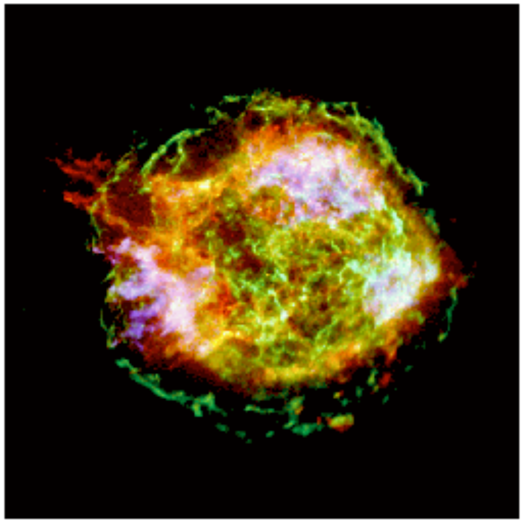
- Three-axis attitude control

Instruments

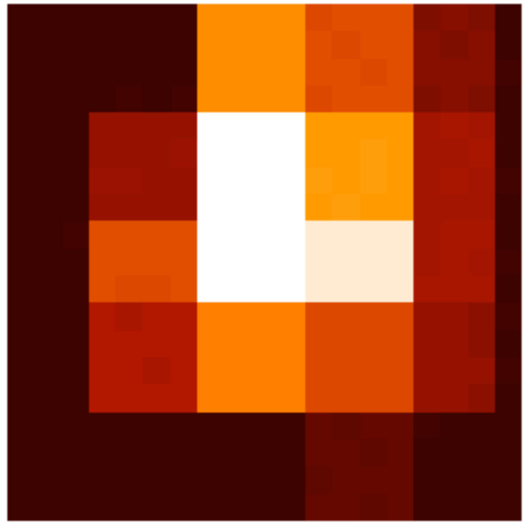
- Two hard x-ray telescopes (6-80 keV)
- 10 meter focal length
- Two FPM containing CdZnTe detectors



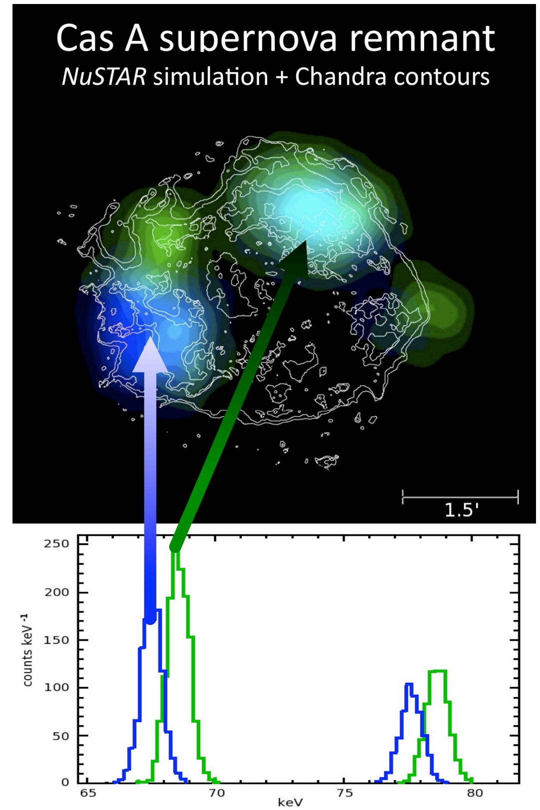
Cassiopeia A



Low–energy X–ray (Chandra)



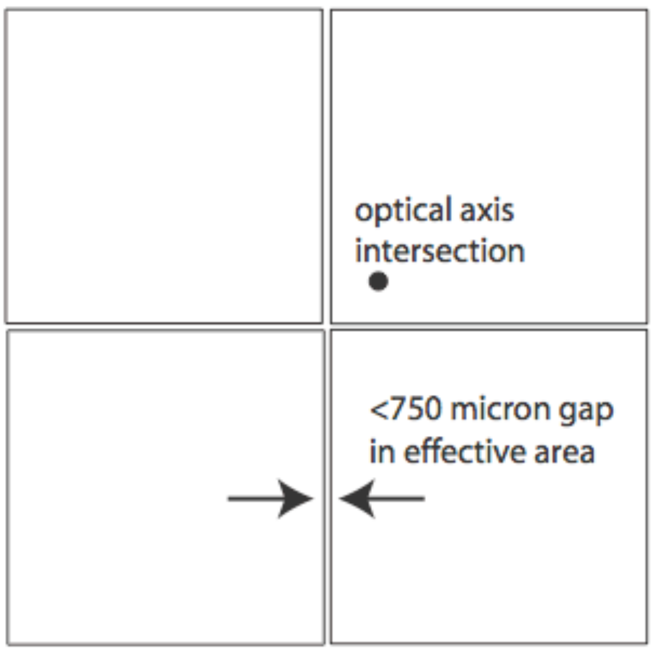
High–energy X–ray (Integral)

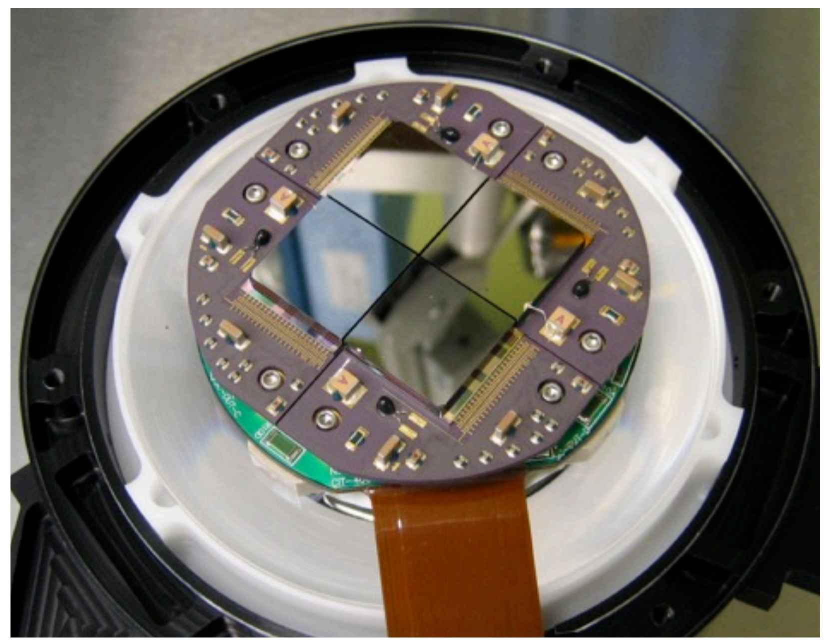


- ^{44}Ti decay (68 keV)– mass cut between infall and ejecta
- NuSTAR is a major step forward in hard x-ray angular resolution, energy resolution and photon sensitivity
- Cas A max ejecta velocity ~.03c

NuSTAR CZT Focal Plane Architecture

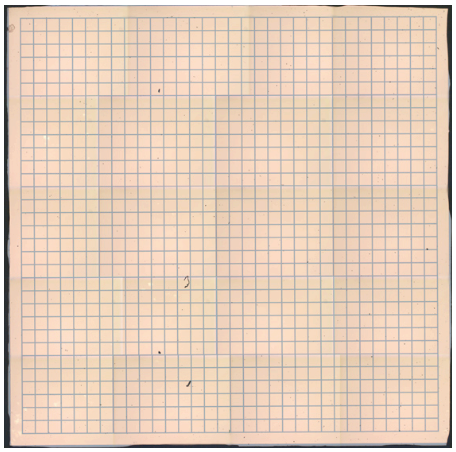
- Focal Plane: 2 x 2 array of CdZnTe hybrid pixel detectors
- Small physical gap between the hybrids
- Hybrids mounted on ceramic carrier boards
- Individual hybrids are replaceable



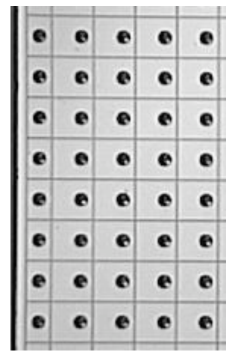


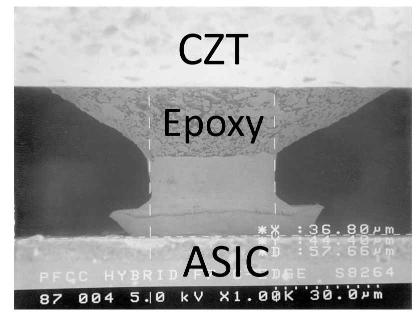
Hybrid Architecture

CdZnTe - eV Products, 2mm thick, 2.1 x 2.1 cm
Anode segmented into 32 x 32 pixel array
Guard ring surrounds pixel array

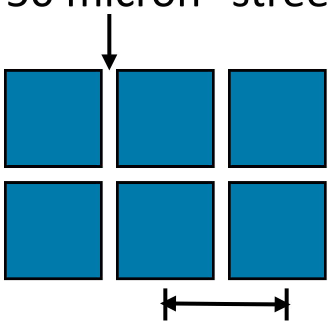


ASIC-CZT low-capacitance interconnect
Conductive epoxy - 50 micron high gold stud



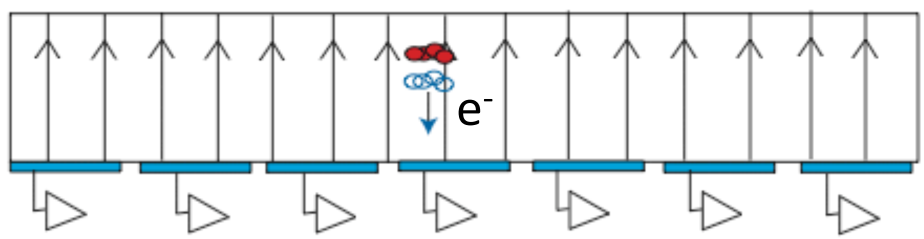


50 micron “streets”



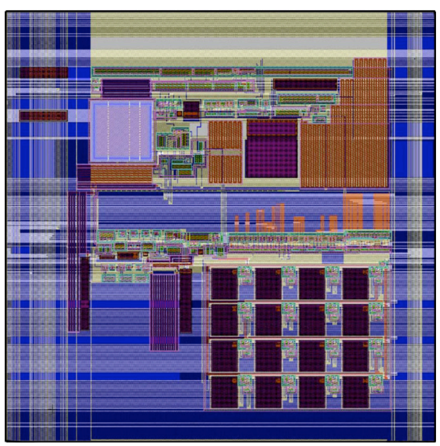
0.605 mm

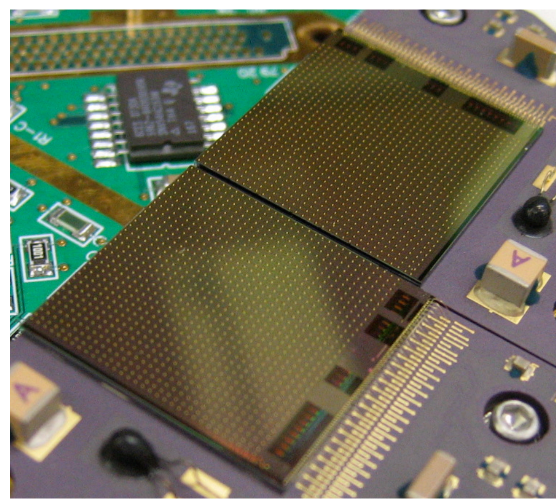
CdZnTe sensor bonded to custom low-noise ASIC



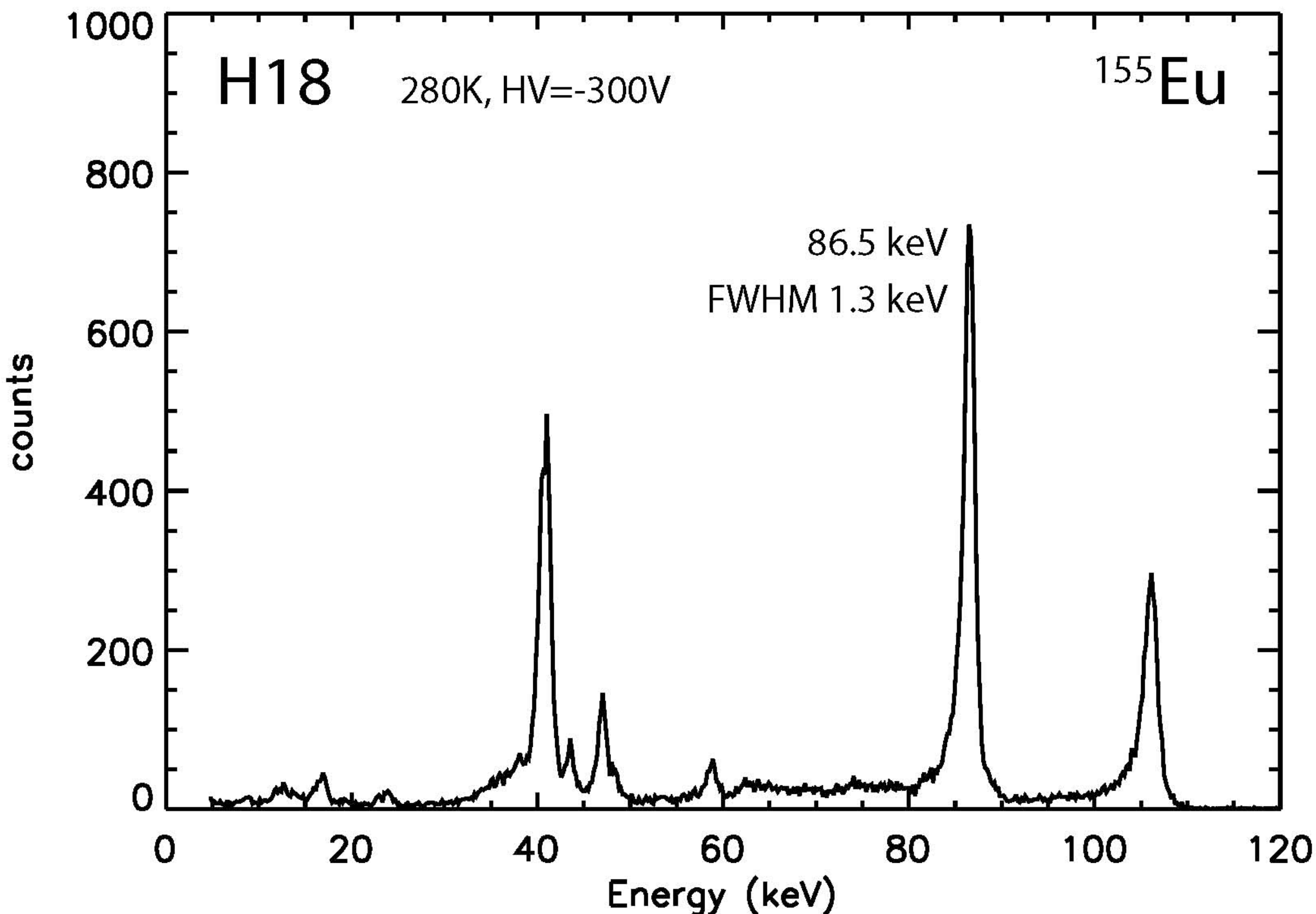
Custom Low-noise Readout

- Custom ASIC - Caltech design/layout
  - Originally developed for HEFT balloon program, upgraded for DNDO and NuSTAR (“DB ASIC”).
- Key features
  - “Normal mode”: leakage current up to 10 nA per pixel => room temp operation for easy of hybrid testing/instrument functional testing
  - “Charge pump” mode: leakage currents up to 300 pA per pixel and provides very low electronic noise
  - On-chip 12 bit ADC
  - Bipolar sensitivity allows for an interaction depth measurement.





Spectral Performance



Summary/state of the art

	microcalorimeter w/ thermistor	**CdZnTe**
number of pixels	6x6, limited by readout geometry	32x32, area limited by material (need better crystal growth)
pixel size	0.8 mm, tradeoff between FOV and spatial resolution	0.5 mm, limited by readout electronics
max event rate	~500 ev/s, tradeoff w/ energy resolution	200-1000 ph/s
energy resolution	~ 5 ev, tradeoff with event rate	<1.5 keV @ 80 keV
thermal constraints	requires cyrogenic cooling	requires stable temp ~ 0C

wishlist for focusing telescopes:

- field of view: O(1-10 mrad [degree])
- spatial resolution: O(1-10 urad [arcsec])
- energy resolution: E/dE > 3000 (~100 km/s doppler shift)
- timing: millisecond timing resolution
- event rate: O(100-1000 ph/s)
- near unity quantum efficiency