NuSTAR

Bringing the High-Energy Universe into Focus

A report on the Phase A Concept Study
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Principal Investigator
Fiona Harrison (Caltech)

Presentation to the
RDC Seminar 5/25/04

Michael Pivovaroff for
William Craig

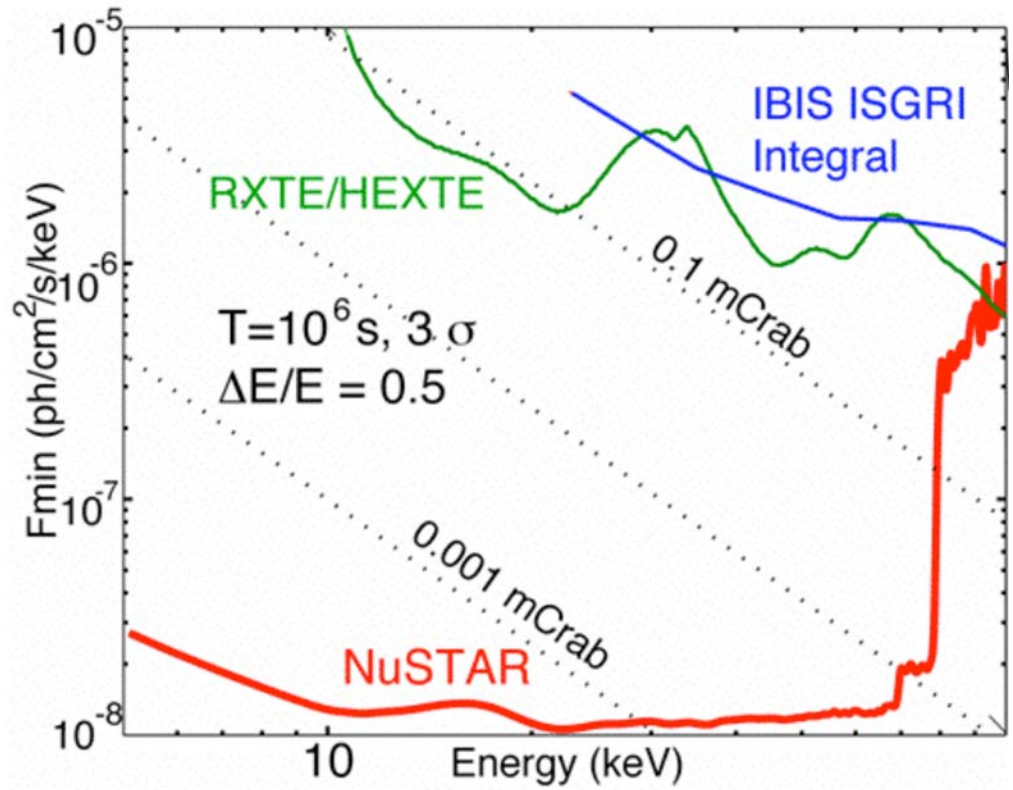
& the *NuSTAR* team

NuSTAR

NuSTAR
the first focusing mission above 10 keV

brings unparalleled
- sensitivity,
- angular resolution, and
- spectral resolution

to the hard X-ray band



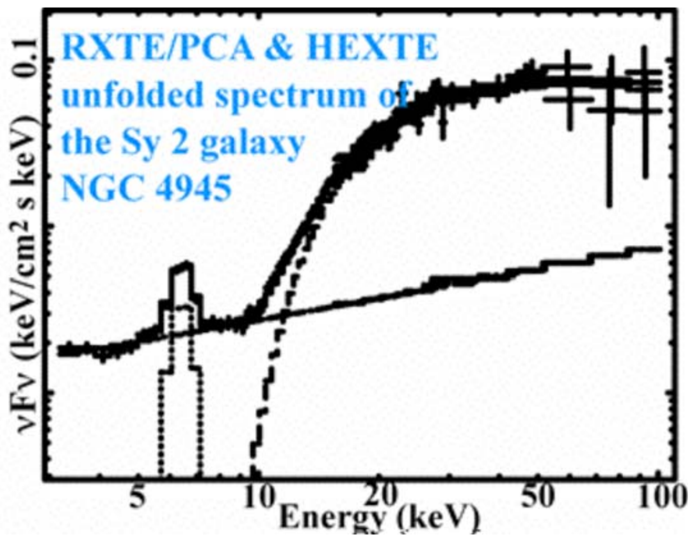
and opens an entirely new region of the electromagnetic spectrum for sensitive study. Will bring to hard X-ray astrophysics what *Einstein* brought to X-ray astronomy

Three primary science goals

1) NuSTAR will discover collapsed stars and black holes on all scales as a pathfinder for the Beyond Einstein missions

Census of massive black holes in the nuclei of galaxies

The penetrating power of high-energy X-rays means they provide a probe of dust-enshrouded sources.



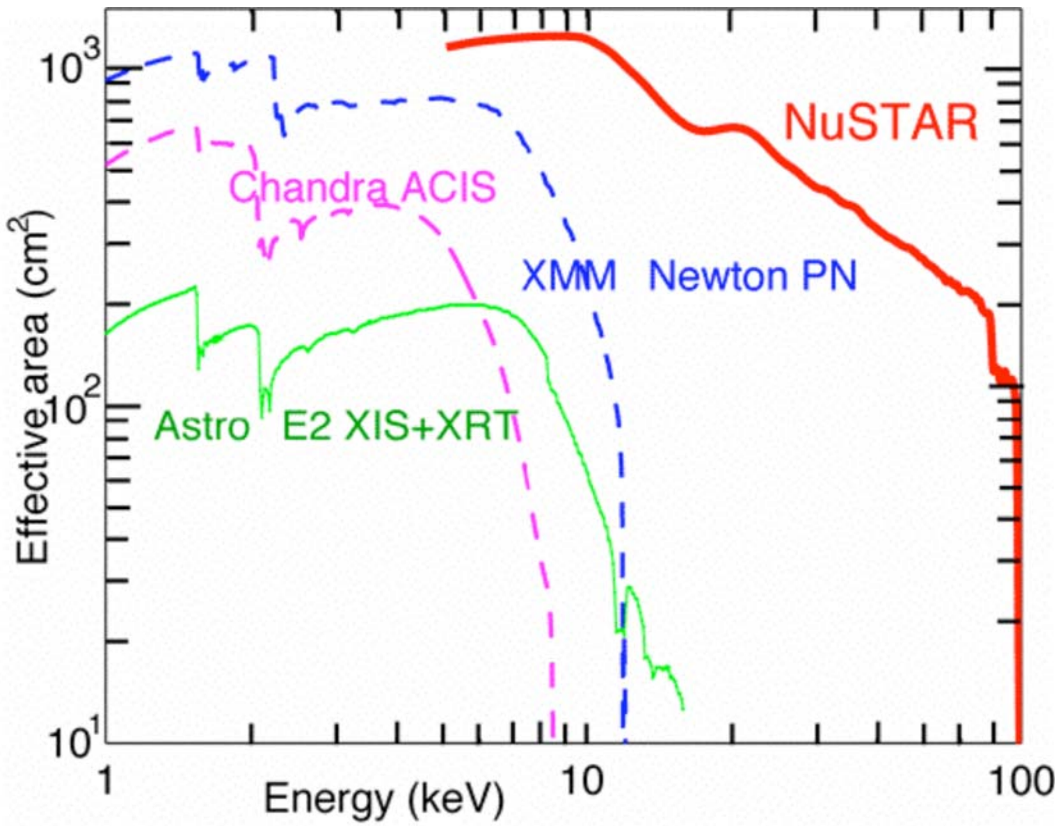
NuSTAR observes faint objects at 30 keV - the peak in the Diffuse Hard X-Ray Background

Combined with optical and *Spitzer* IR data, *NuSTAR* will measure the luminosity density in obscured accretion and its evolution over cosmic time.

NuSTAR Hard X-rays enable BH study

- Intermediate-z AGN difficult to survey and measure luminosity in optical
  - Lower-luminosity than quasars → small ratio AGN activity/stellar luminosity: accretion luminosity difficult to measure in optical
  - Obscuration from dust surrounding the nucleus can 'hide' the central AGN in the optical ($N_H > 10^{22}$ cm^{-2})
  - Surveys in optical (narrow band to pick up prominent AGN lines) and radio miss large fraction of sources
  - Hard X-ray observations can detect heavily obscured (Compton thick) sources

NuSTAR Deep extragalactic surveys



NuSTAR will spend 6 months on two extragalactic survey fields:

NDWFS (wide - 9 deg^2)

VLA, *Spitzer*, optical

Chandra (5 ks)

F(2-10) = 3_10^{-14} erg/cm^2/s with

α = 1 detected 20 – 40 keV

>150 AGN detected 10 – 40 keV

GOODS (deep-500'^{2})

HST, *Chandra*, *Spitzer*

F(2-10) = 2_10^{-15} erg/cm^2/s

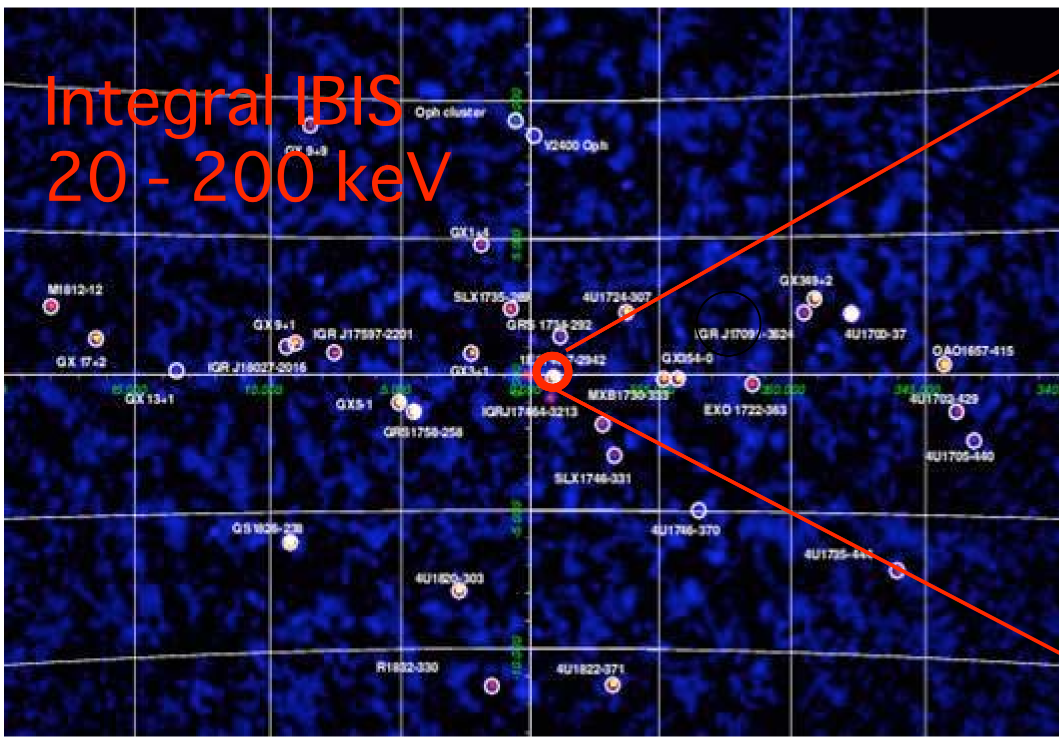
Detected 20–40 keV

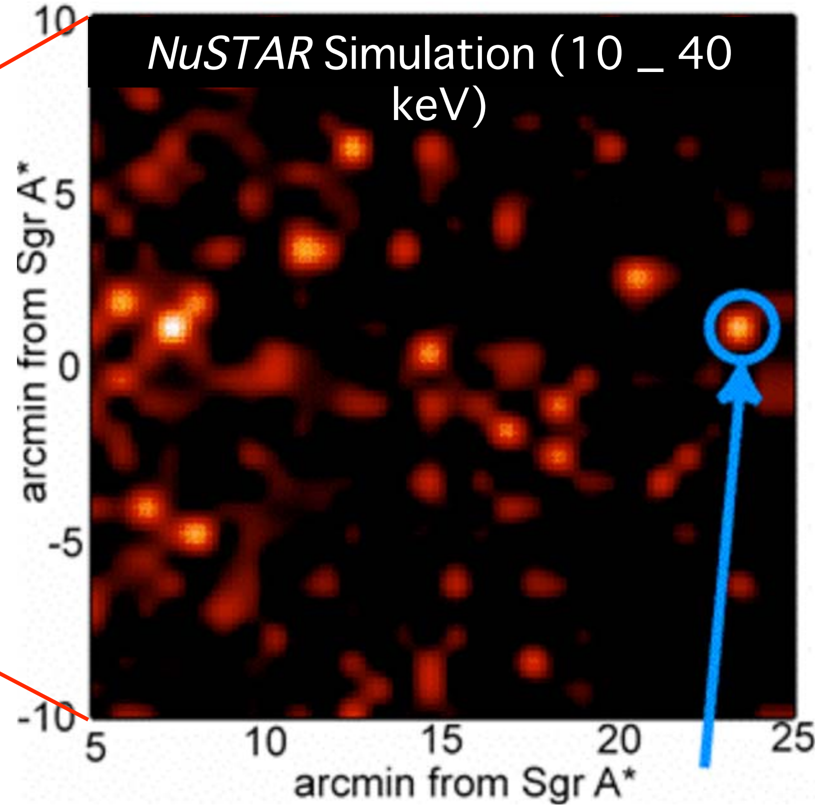
>170 AGN detected 10 – 40 keV

Obscured galactic sources

Discover the nature of the mysterious obscured Galactic sources

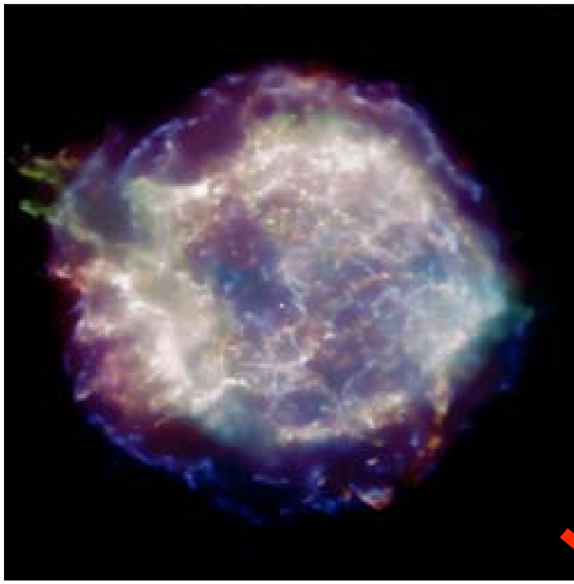
Chandra (near the GC) and *Integral* IBIS are discovering populations of hard and highly-obscured sources in the Galactic plane. *NuSTAR* will perform Galactic surveys to obtain localizations, spectra and help discover the nature of these new objects.

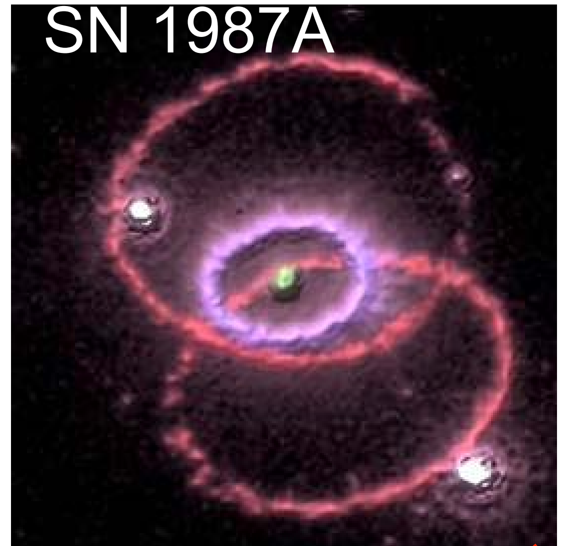




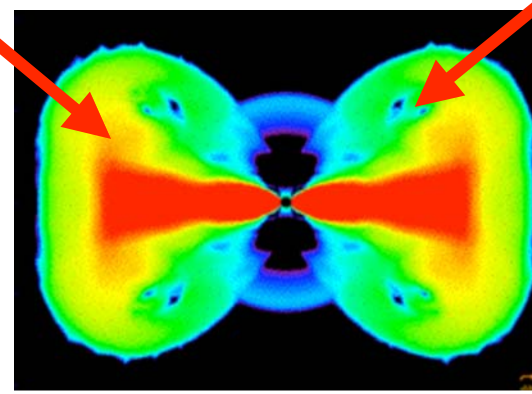
NuSTAR Supernova remnant science

2) NuSTAR will map the remnants of recent supernova explosions, testing theories of how stars explode, and of where the elements are born





By imaging radioactive material, *NuSTAR* looks into the heart of these explosions, putting theory to the ultimate test.



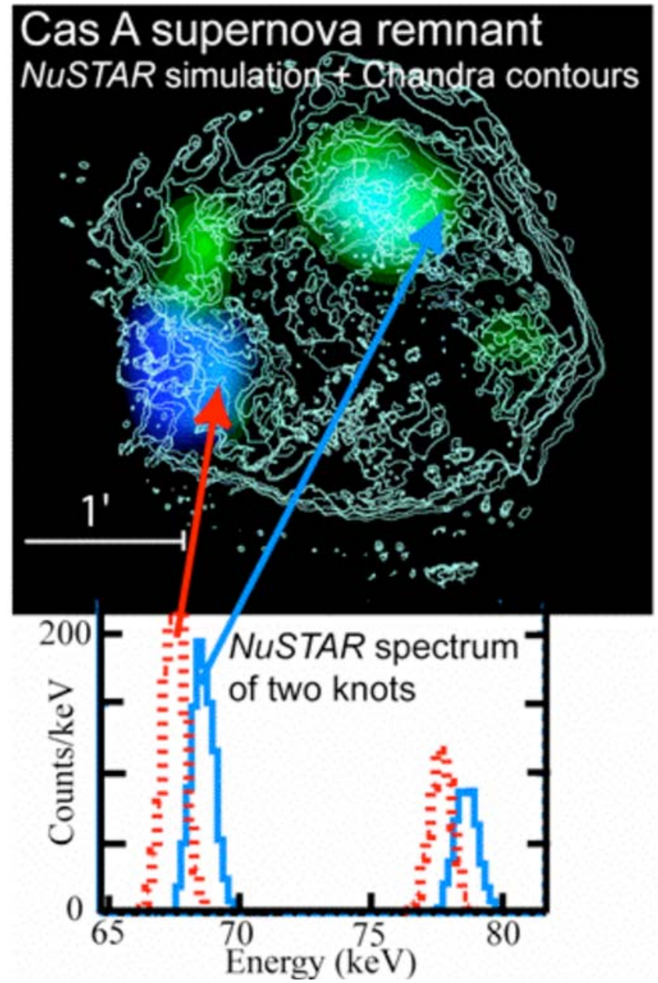
Sensitive ^{44}Ti surveys

Line flux sensitivity: ~2_10^{-7} ph/cm^2/s (10^6 s)

Map 3 young remnants
Measure asymmetry, velocity distribution
Clumpyness

Measure flux from SN1987a

Remnant	**Age (yr)**	**Dist (kpc)**	**Size (')**	**67.9 keV flux (_ 10^{-6} ph/cm^2/s)**
SN 1987a	20	50	0	2.5
Cas A	327	3.4	3.6	15
Kepler	403	2.9	3.5	8.4 (?)
Tycho	435	2.3	8x5	9.2



NuSTAR Type Ia supernovae studies

- SNe Ia widely believed to result from thermonuclear incineration of an accreting C/O white dwarf. We don't know:

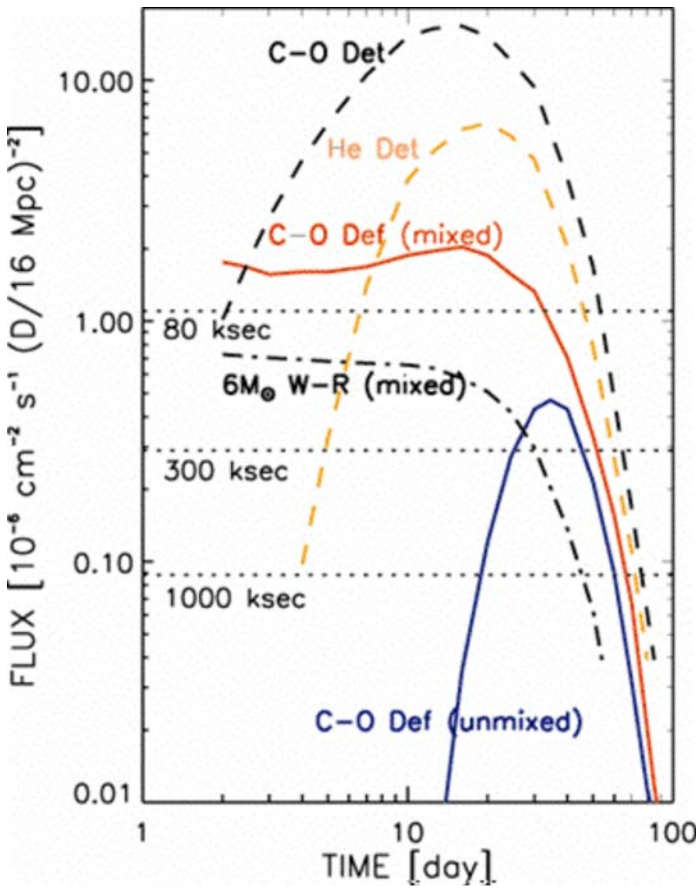
- Nature and evolution of the progenitor system
  - mass of dwarf at ignition
  - physics of subsequent nuclear burning
  - reason for the (empirical) width-optical luminosity relation

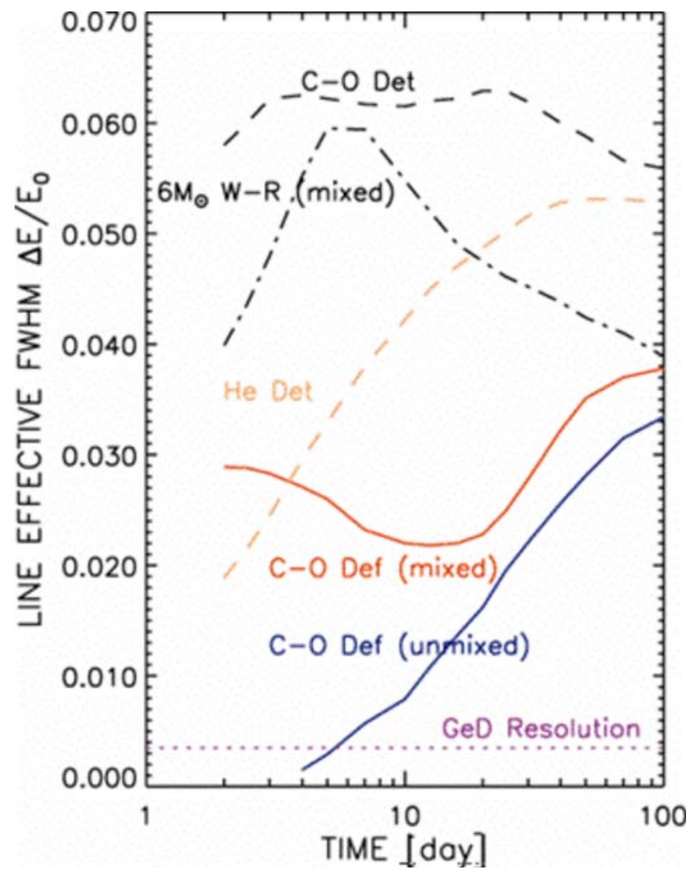
- The lightcurve is believed to be powered by the decay of ^{56}Ni
  - A SN Ia has never been seen in the X-ray/gamma-ray

- Observations of the time evolution of the ^{56}Ni line (158 keV) would provide important constraints on the explosion mechanism and dynamics

SN-Ia diagnostics

Prompt Decay of ^{56}Ni in Type Ia SNe



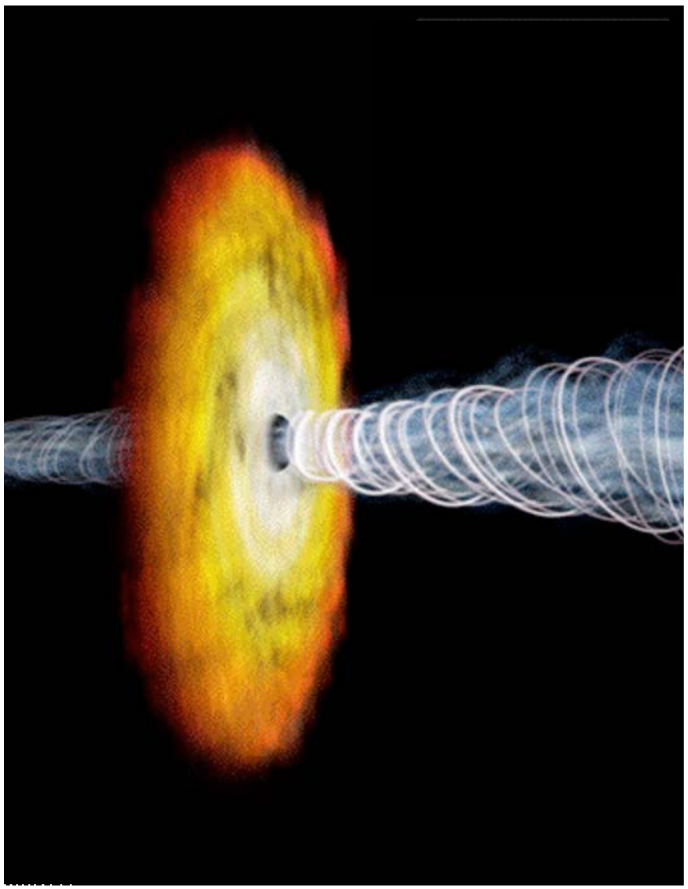


Evolution of the ^{56}Ni in Type Ia SNe is sensitive to the explosion mechanism and mixing. For example, M_{ch} and sub-M_{ch} models can be easily distinguished. *NuSTAR* can measure evolution of down-scattered HXR photons to Virgo.

NuSTAR

Exploring the extreme Universe

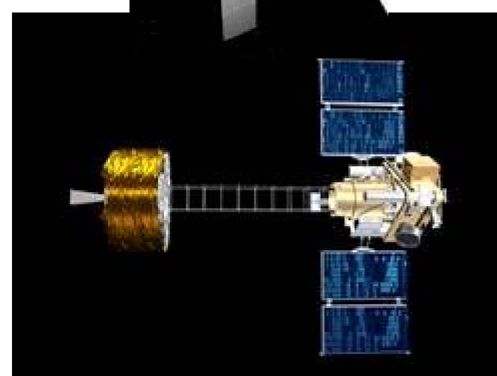
3) NuSTAR will explore the most extreme physical environments in the Universe. Teaming with GLAST and TeV telescopes NuSTAR fills in an essental part of the puzzle in understanding how giant particle accelerators in massive black holes work.



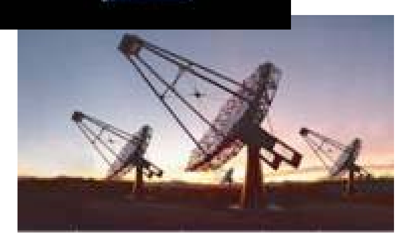
Simultaneous observations with

GLAST

NuSTAR



TeV telescopes

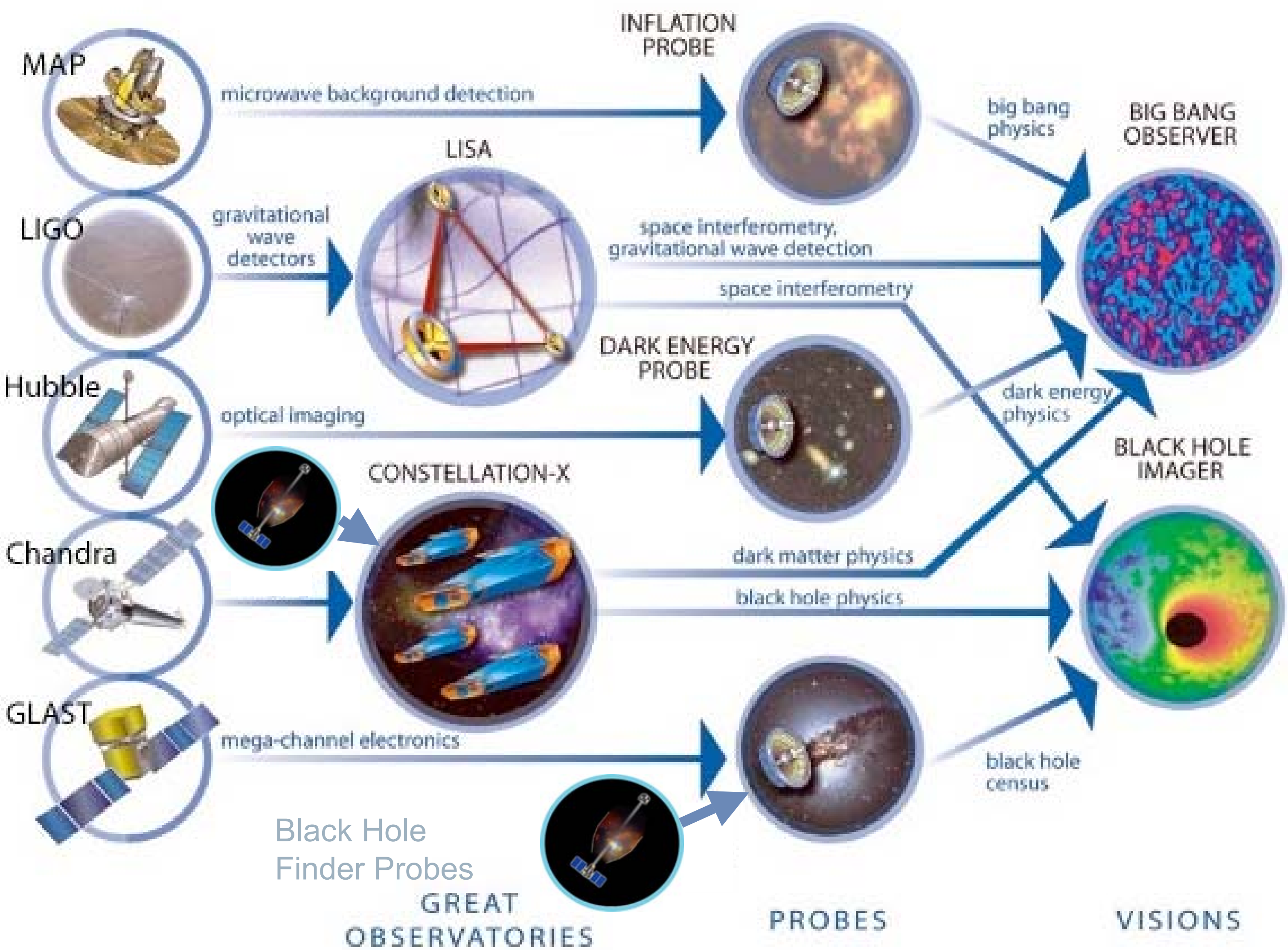


NuSTAR Aligned with NASA roadmaps

- *NuSTAR* is a timely partner for large roadmap missions:
  - *NuSTAR* will provide important followup for *Spitzer,* testing correlations between dusty obscured AGN and mid-IR sources
  - *NuSTAR* will team with *GLAST*, making simultaneous observations that will greatly enhance *GLAST's* science return
  - *NuSTAR* will act as a key pathfinder for *Constellation-X,* building an AGN catalog that will help *Con-X* to address its primary goals
- *NuSTAR* is an important part of the SEU roadmap, achieving goals that will be met by no other mission:
  - *NuSTAR* is a vital step in the Beyond Einstein program
    - *NuSTAR's* black hole census requires wide-field surveys impractical *Con-X,* and sensitivity to complement the all-sky *Black Hole Finder* probe
  - *NuSTAR* addresses critical elements of the Cycles of Matter and Energy program
    - *NuSTAR's* nucleosynthesis study, a key focus of Cycles, requires spectral coverage unplanned for any other mission
    - *NuSTAR's* AGN studies, exploring the formation of cosmic jets and the behavior of matter in extreme environments, require simultaneous observations by *NuSTAR* and *GLAST*

NuSTAR

The Beyond Einstein roadmap



NuSTAR A new era in X-ray astronomy

- The recently-launched *Chandra* and *XMM* satellites have brought dramatic improvements in sensitivity, imaging, and spectral resolution in the 0.1 – 10 keV X-ray band

$\Delta\theta$ ~ 1 arcsec, E/ΔE ~ 1000, thousands of objects

- Still a sharp contrast to the high-energy X-ray band (10 – few 100 keV)

$\Delta\theta$ ~ 20 arcmin, E/ΔE ~ 10, dozens of objects

The next revolution in X-ray astronomy will be the first imaging telescopes in the high-energy band

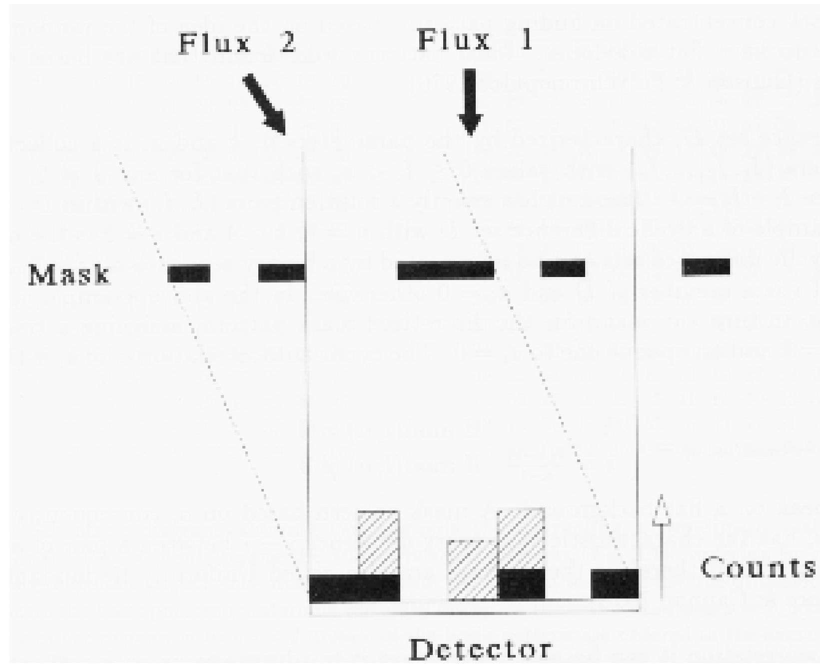
NuSTAR Hard X-ray is the new frontier

- Soft X-ray band dominated by thermal emission (10^6 – 10^7 K)
  - hard X-ray band dominated by non-thermal processes
  - many sources (Galactic and extragalactic) have intrinsic absorption, hard X-rays can penetrate
- A sensitive hard X-ray mission is a timely complement to other high-energy experiments
  - *Swift* (2004 launch) and *Integral* will perform the first all-sky and Galactic imaging HXR sky surveys at moderate sensitivity and low resolution.
  - *GLAST* (2007 launch) will study some of the most extreme AGN and GRBs - hard X-ray observations are an important real-time complement

NuSTAR Coded apertures lack sensitivity

- Wide field survey missions rely on coded aperture imaging.
- Coded aperture imaging is an indirect modulation technique
- Information from source coded on entire detector area

  $(A_{detector} \approx A_{collecting})$
- Background = entire detector background, or diffuse flux from entire FOV



Coded apertures: spatial modulation records source position information

Focusing is required for sensitive studies.

NuSTAR *HEFT* program provides heritage

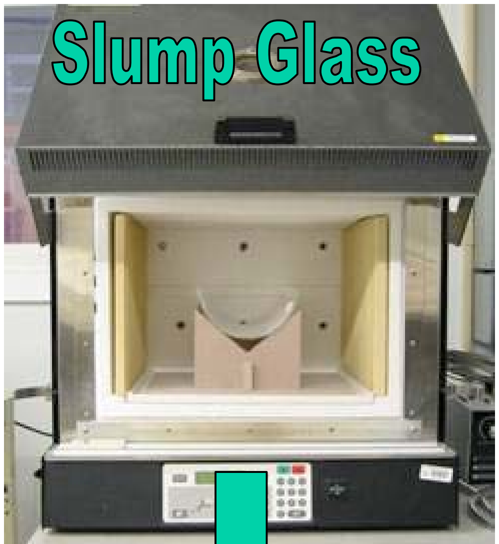
- *HEFT* Flight Units (HF-1, -2, -3)
- *Constellation-X* Prototypes (ConX-0, -1, -2)

HF1

HF2

HF3

Optics production overview



Flat microsheet glass is:

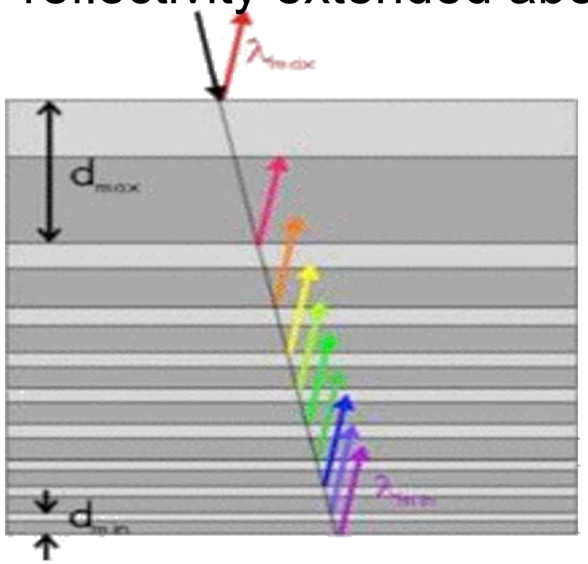
- received, inspected, cut, slumped
- laser scanned, cut, inspected
- shipped, cleaned, inspected
- coated, inspected
- mounted and verified mechanically and with X-ray measurements

NuSTAR

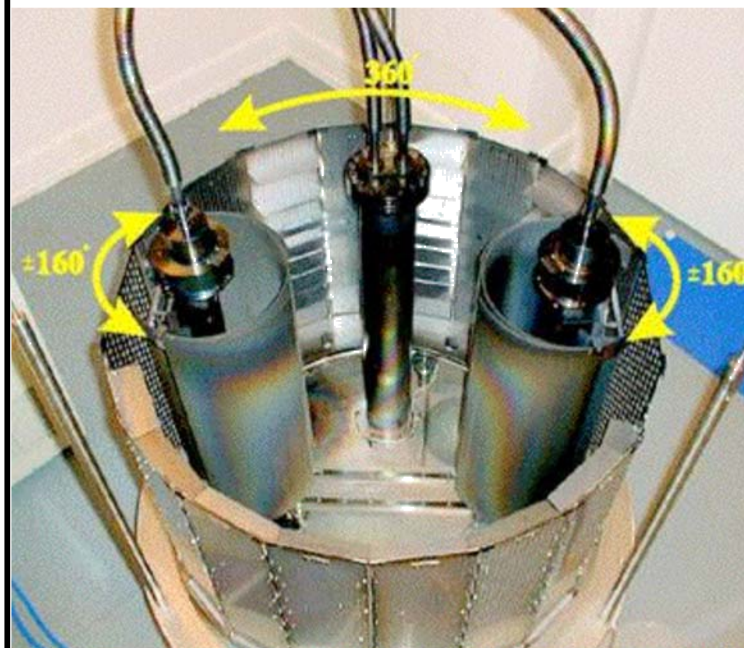
Depth-graded multilayers

Normally, α_{Crit} ~ 1/Energy
However, coherent reflections possible for
$2d \sin \alpha = m\lambda$ (Bragg condition)
→Reflections for $\alpha > \alpha_{Crit}$

- Good reflectivity for E < 70 keV using W/aSi for the first HEFT modules
- Pt/C based for subsequent modules – reflectivity extended above 80 keV



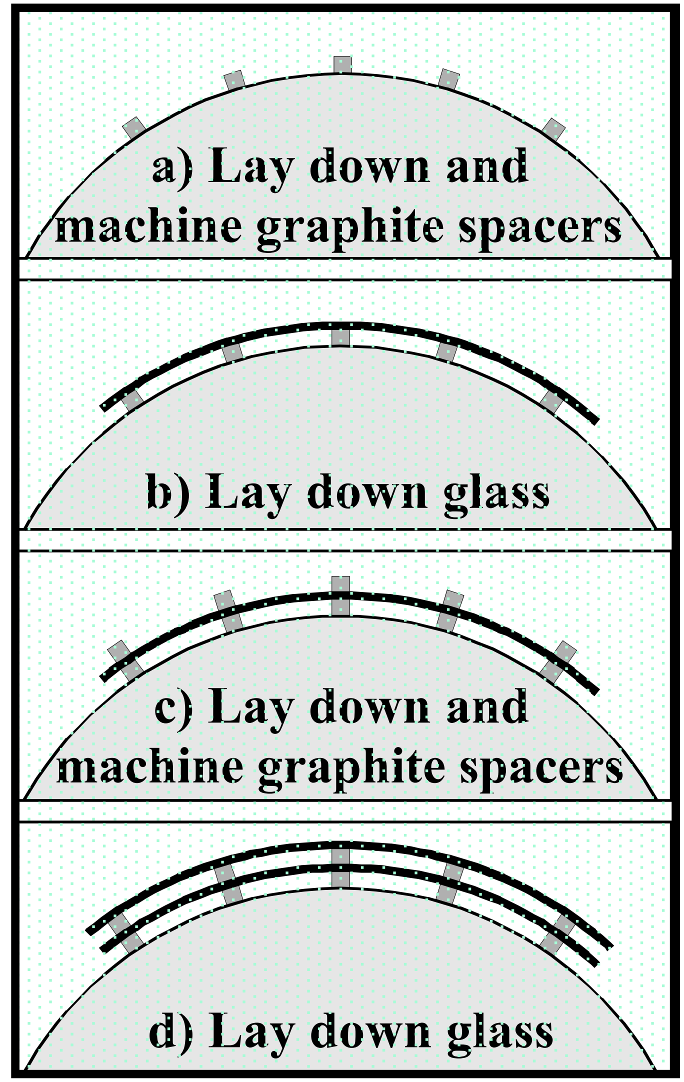
High throughput at DSRI coating facility



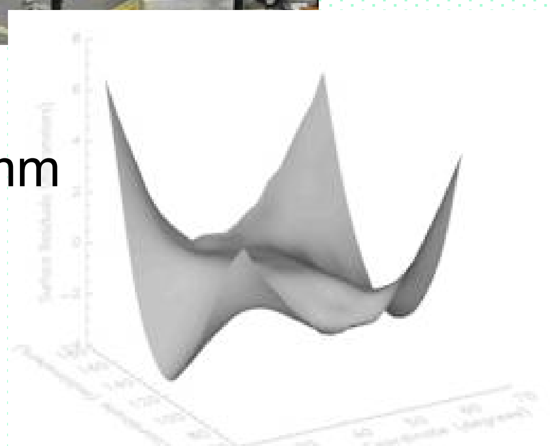
Bilayer Thickness: 2 – 30 nm
Grazing Angles: 1.7 – 5.0 mrad
Energy Range: 20 – 70 keV

NuSTAR Optic assembly

- Each spacer layer is individually machined to the precise radius and angle
- X-ray mirror segments are constrained to spacers and then bonded with epoxy

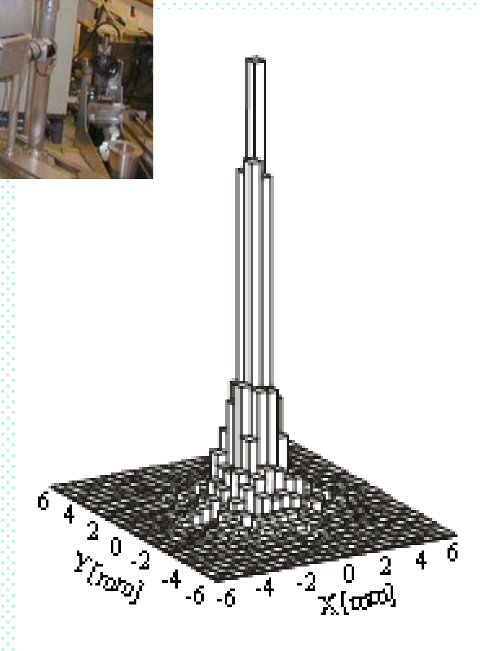


Metrology verifies performance



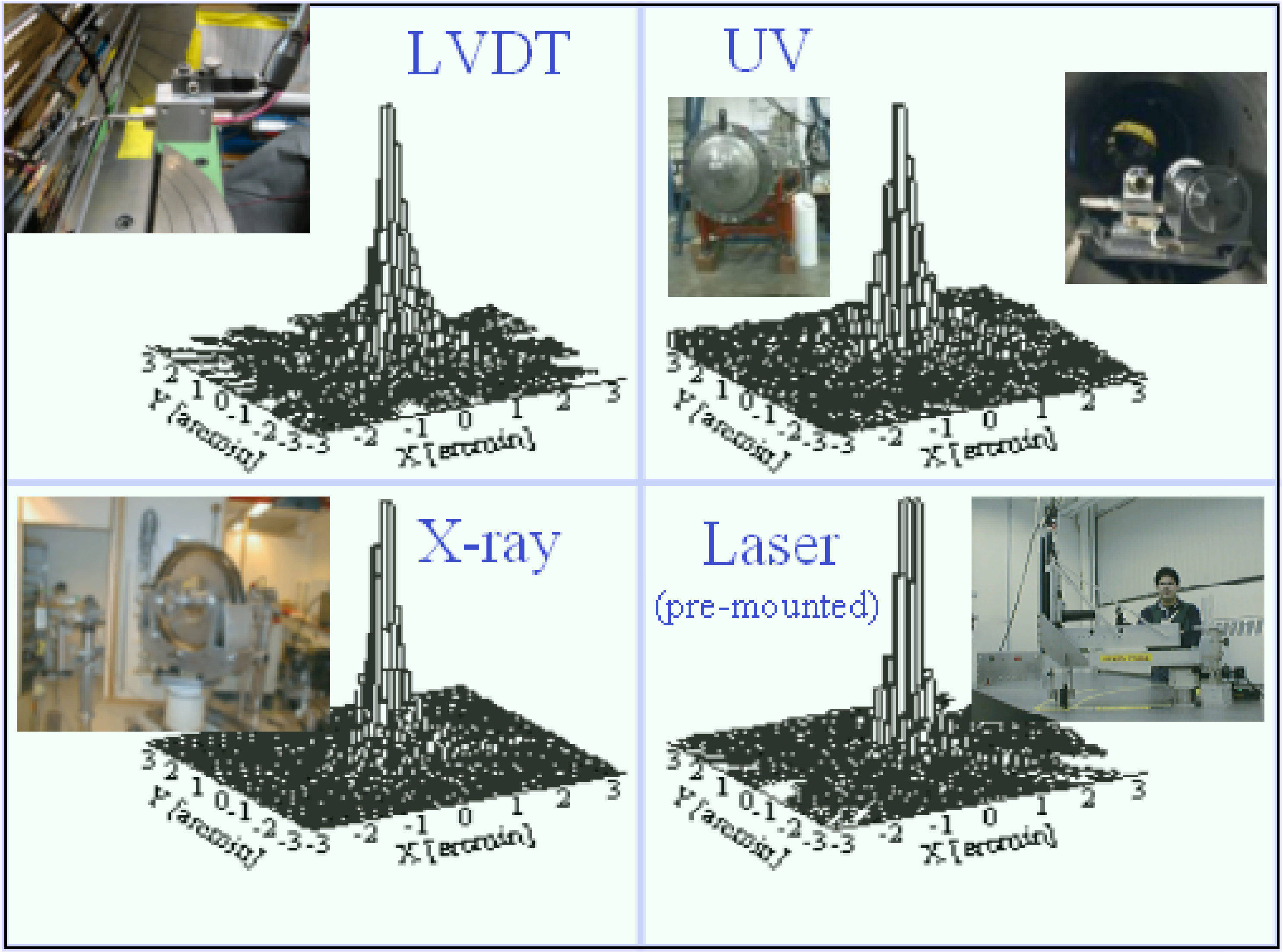
35″ 0.2mm
AF45

Laser scanner probes unmounted shells

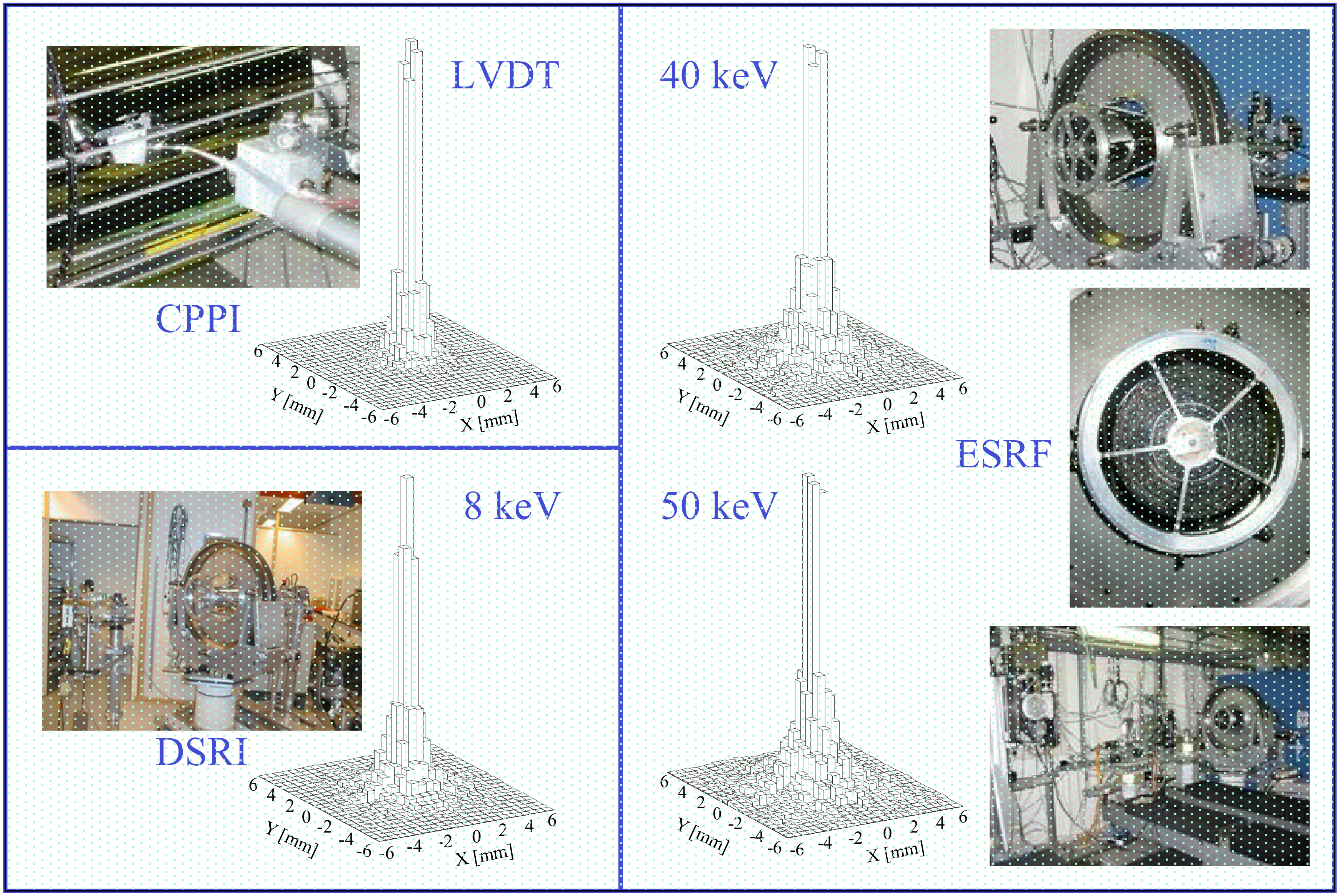


8 keV X-ray measurements provide final confirmation

Performance validation



Metrology tracks X-ray results



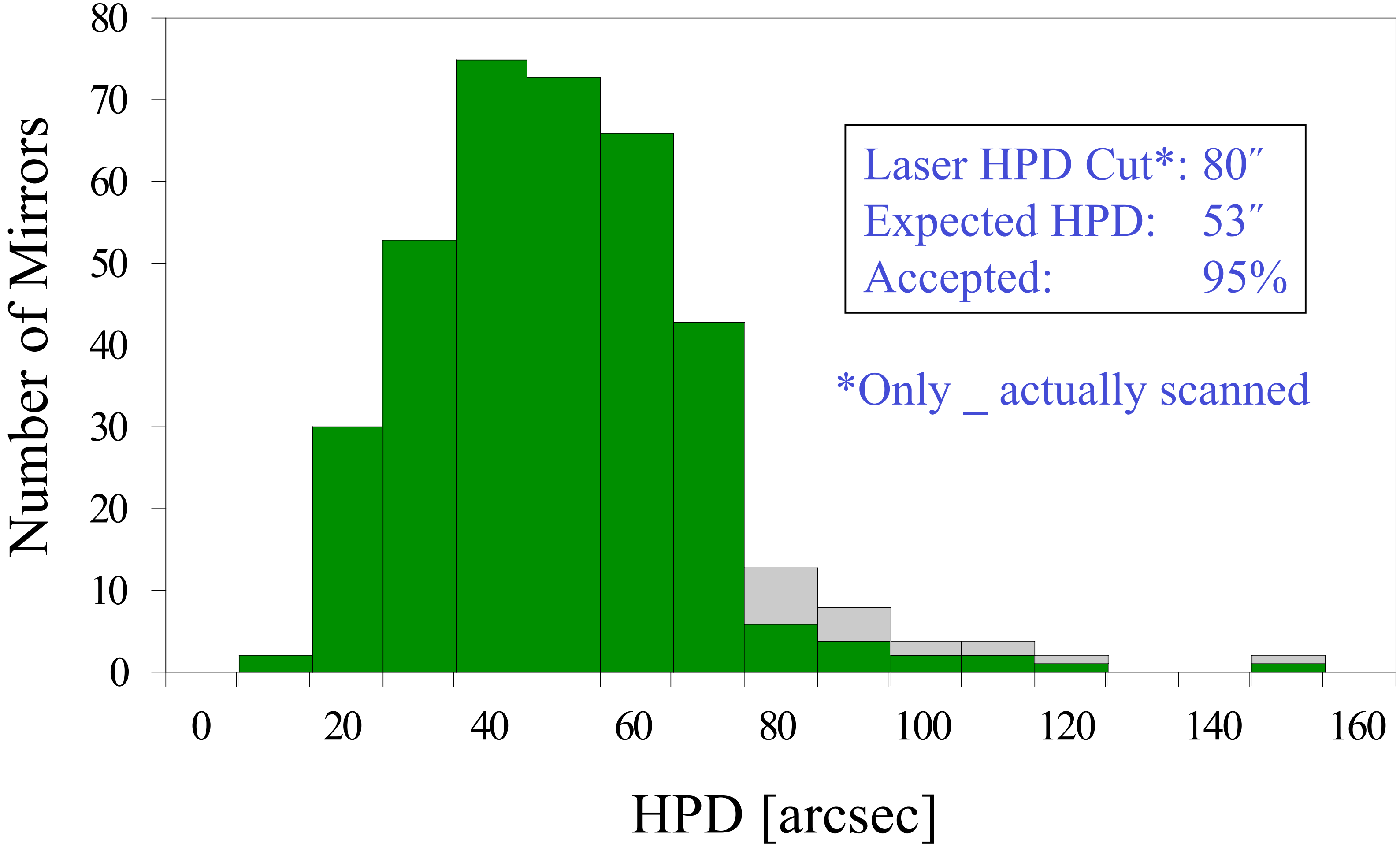
Performance summary

- ***HEFT*** **Flight 1: 72″**
- ***HEFT*** **Flight 2: 72″**
- ***HEFT*** **Flight 3: 57″**
- **All** ***HEFT*** **units are quintant geometry**

- **Con-X0: 45″**
- **Con-X1: 45″**
- **Con-X2: 58″**
- **NuSTAR-1: 40 – 48″**
- **All** ***Con-X*** **and** ***NuSTAR*** **prototypes are octant geometry**

Technique has steadily improved, as has our ability to predict performance

NuSTAR Performance set by shell selection



NuSTAR *HEFT* & *NuSTAR* optics production

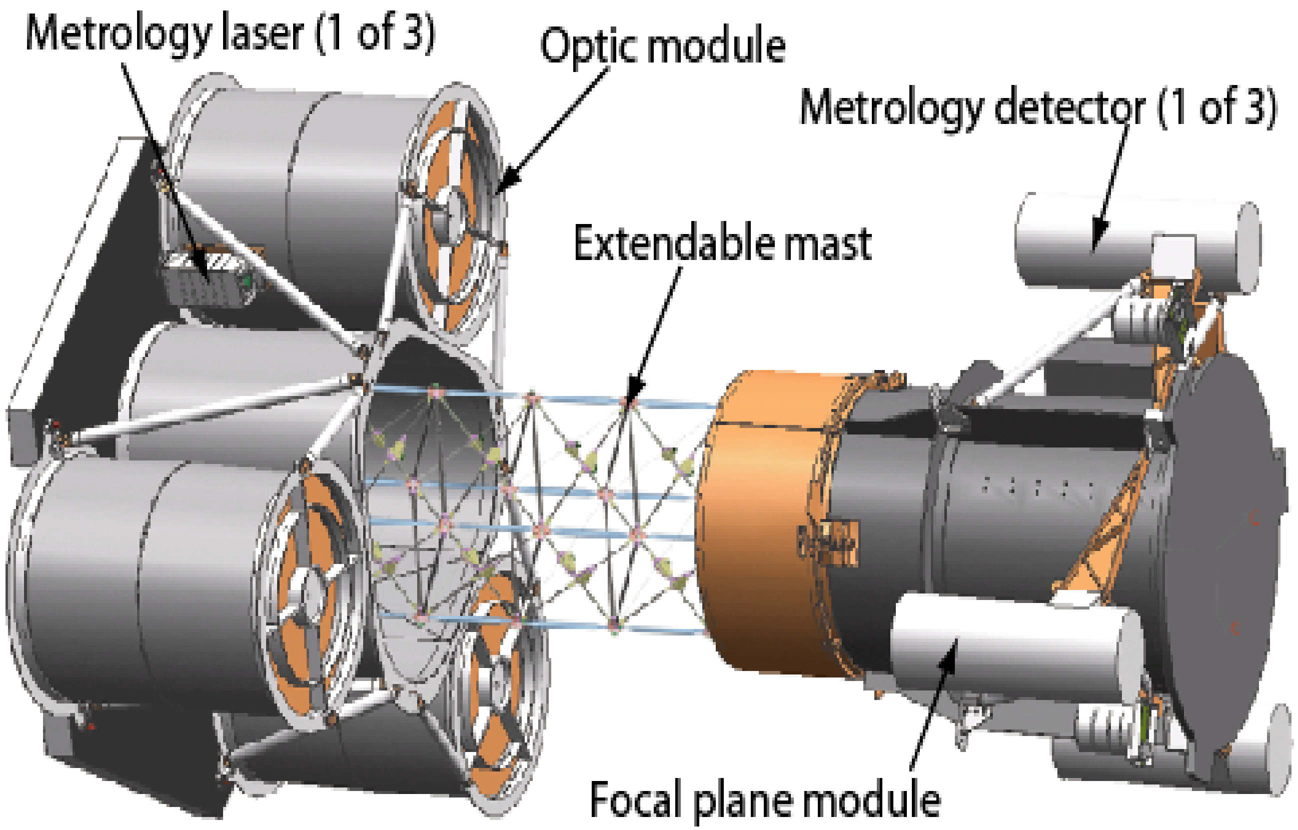
HEFT

- **0.3 mm AF-45 and D-263**
- **72 layers per telescope**
- **Quintent geometry**
- **20 shells per layer**
- **4400 shells laid to date**
- **Cut shells by hand scribe**
- **1.5 mm graphite spacers**

NuSTAR

- **0.2 mm D-263 (baseline)**
- **130 layers per telescope**
- **Octant geometry**
- **32 shells per layer**
- **~170,00 shells required**
- **Cut shells by hot wire**
- **1.0 mm graphite spacers**

NuSTAR mission concept

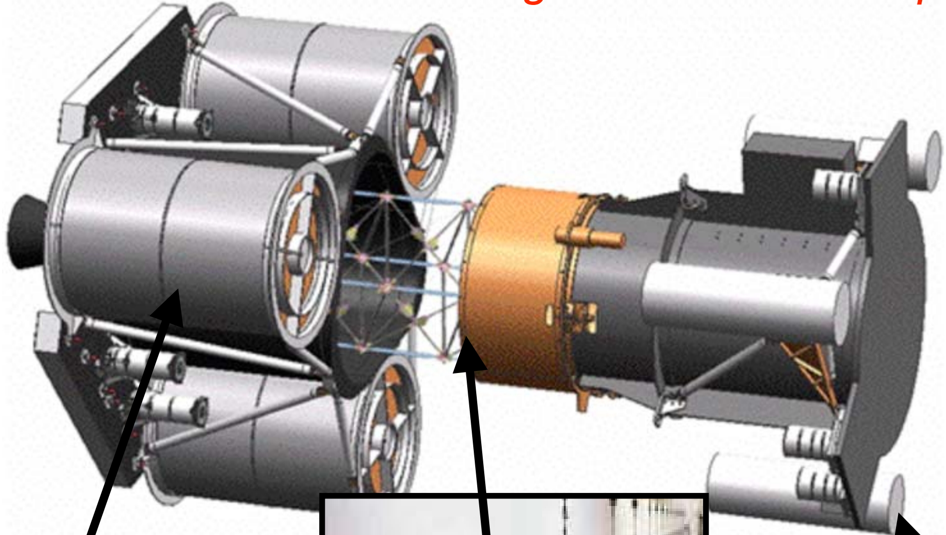


NuSTAR instrument (shown partially deployed)

NuSTAR employs a 10-meter extendable mast to separate hard X-ray optics from CZT detector modules

NuSTAR

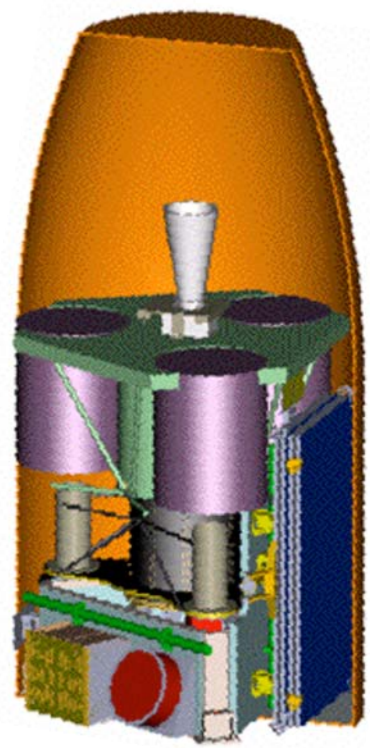
NuSTAR is based on existing hardware developed in the 9 year HEFT program



The three *NuSTAR* telescopes have direct heritage to the completed *HEFT* flight optics.

The 10-m *NuSTAR* mast is a direct adaptation of the 60-m mast successfully flown on *SRTM.*

NuSTAR detector modules are the *HEFT* flight units.



Based on the Spectrum Astro SA200-S bus, the *NuSTAR* spacecraft has extensive heritage. *NuSTAR* will be launched into an equatorial orbit from Kwajalein.

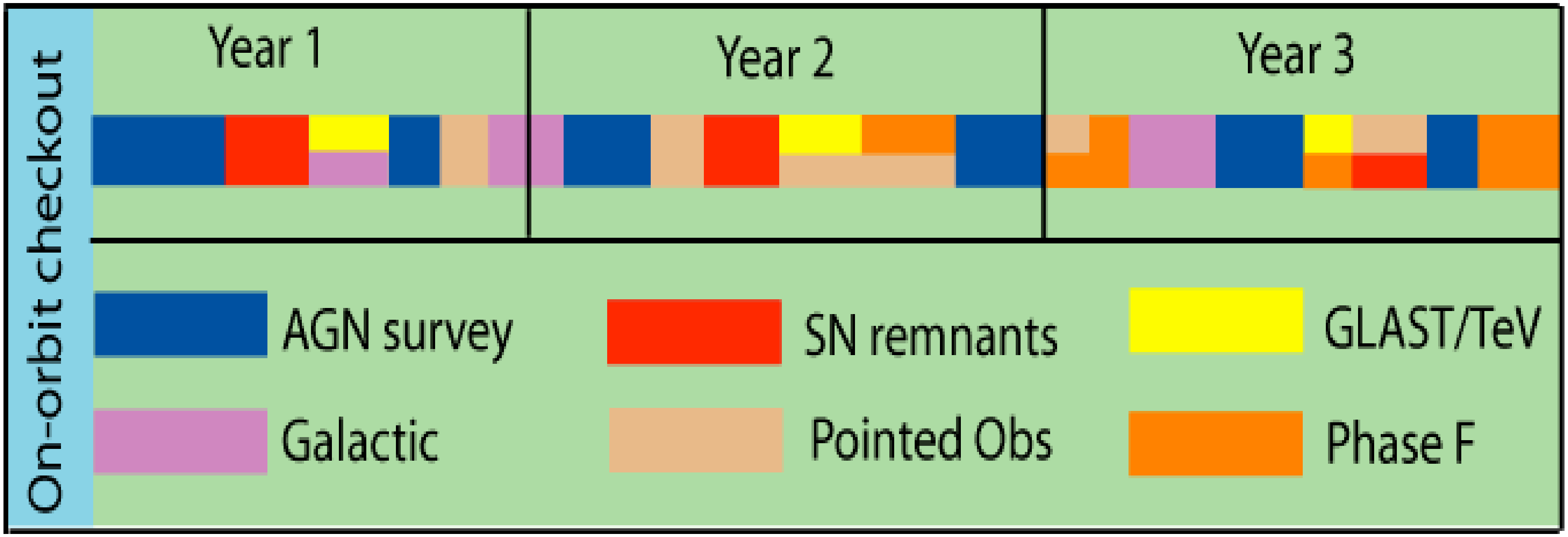
Orbit	525 km 0°
Inclination Launch vehicle	Pegasus XL
Launch date	late 2007
Mission lifetime	3 years
Coverage	Full sky

NuSTAR

NuSTAR capabilities

Energy range	6 – 80 keV
Angular resolution (HPD)	40 arcseconds
FOV (20 keV)	10 arcminutes (mean)
Strong/weak src positioning	4.8 arcsec/12 arcsec
Spectral resolution	1 keV @ 60 keV
Timing resolution	1 ms UTC
Mission lifetime	3 years
Orbit	Near-Earth equatorial
ToO response	< 24 hours
Solar angle constraint	none
Observing efficiency (typical)	65%

Mission timeline



Long pointed survey and pointed observations complete the minimum science mission in 18 months.

Phase F (Guest Investigator) program will be proposed as result of community involvement during Phase A study.

NuSTAR status

- Concept study report in preparation.
- Prototype optics in test now, 40″ – 48″ performance validated.
- Concept Study completed June 18.
- Site visit in August ’04, downselection in November ’04.
- Launch November 2007

Hard X-ray optics are the enabling technology…
from concept to space-ready in less than 10 years.