Active X-ray Optics
For The Next High Resolution X-ray Observatory

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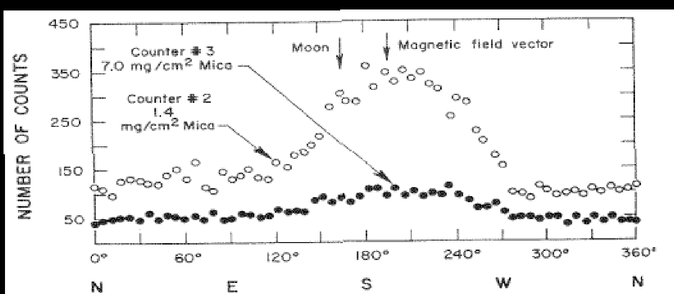
43 Years of X-ray Astronomy:

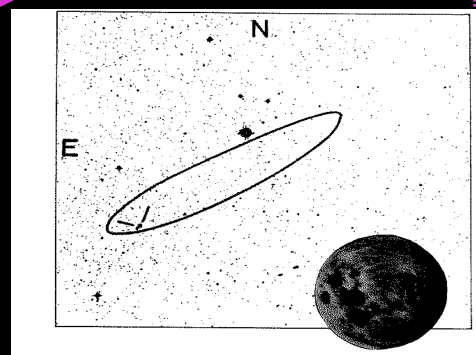
1 billion times more sensitive

Sco X-1



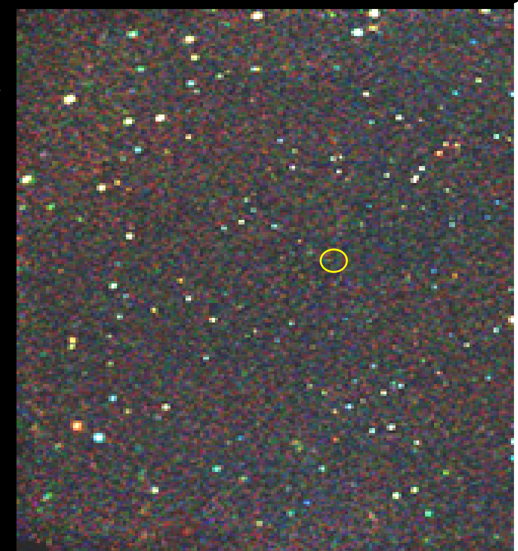
Good for 1 (one) Nobel Prize

1/10,000



good enough for my thesis

1/100,000



Detector Area,
Exposure time

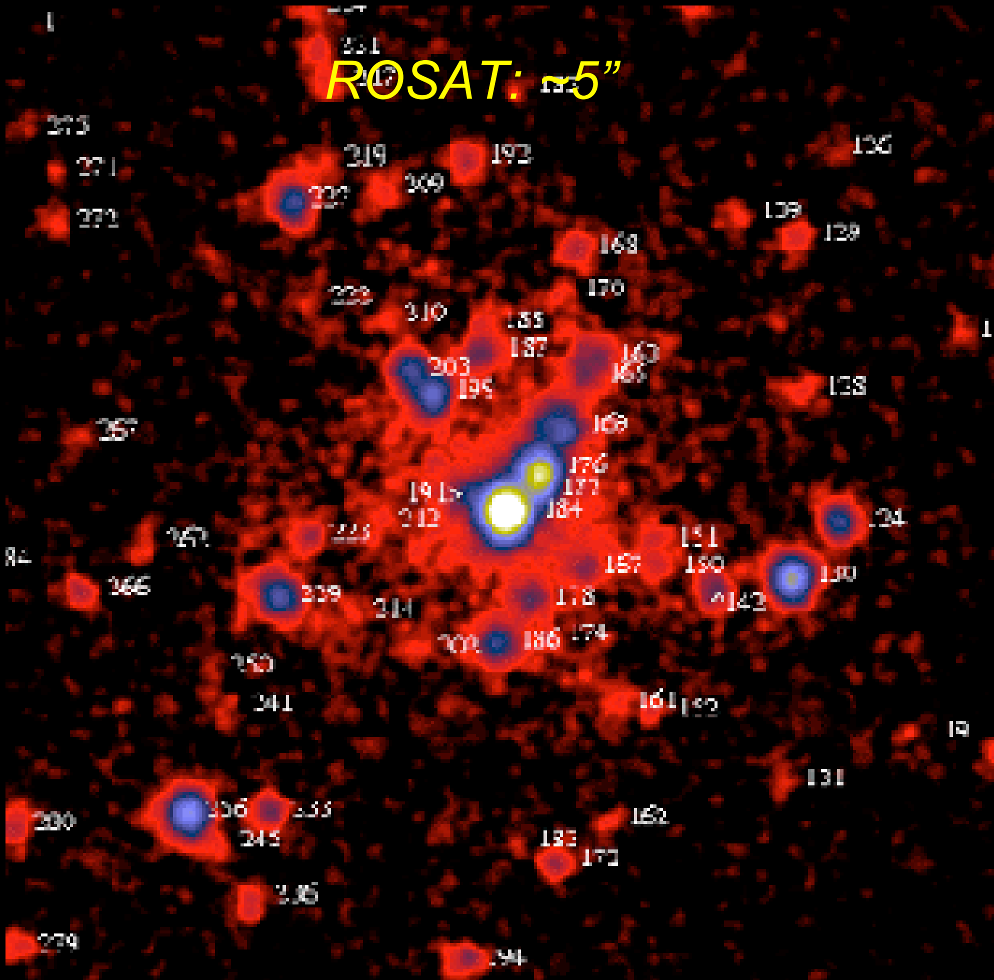
angular resolution

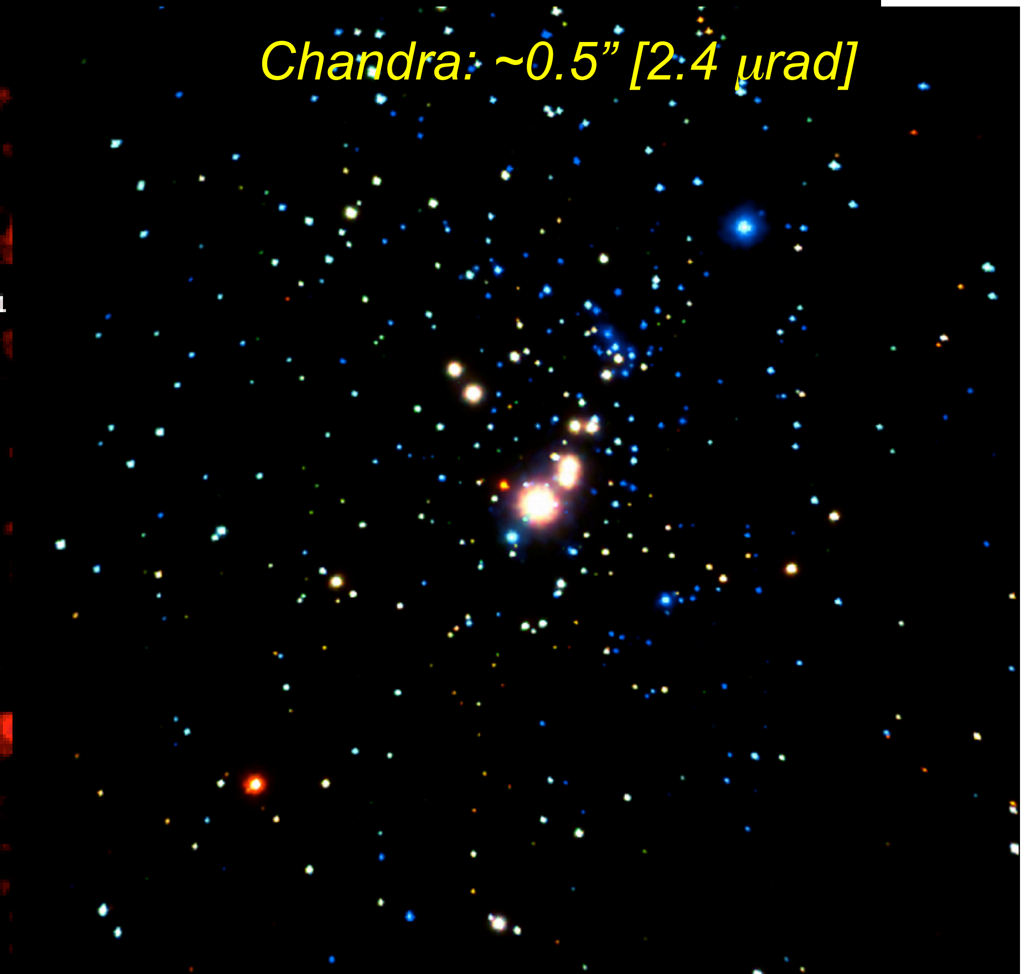
The Chandra X-ray Observatory

Launched by NASA 7 years ago: 23 July 1999
Has revolutionized X-ray astronomy
…and all of astronomy

The Chandra Revolution:

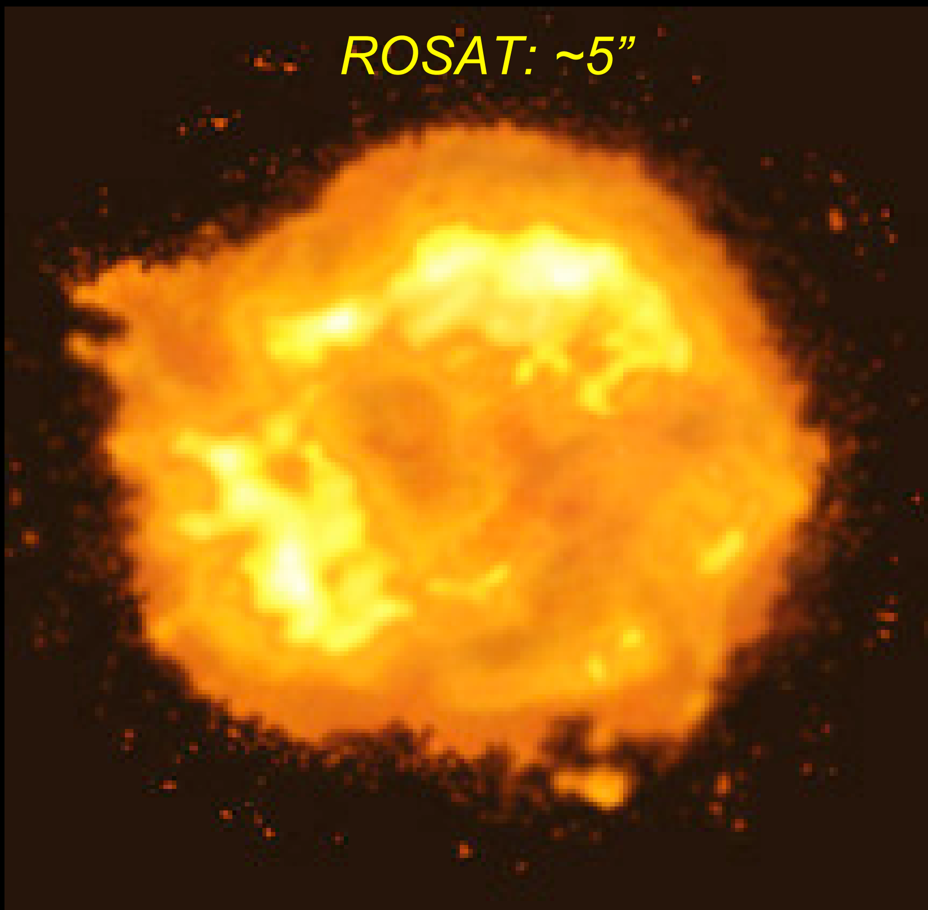
Quantitative : 70 to 1400 Sources



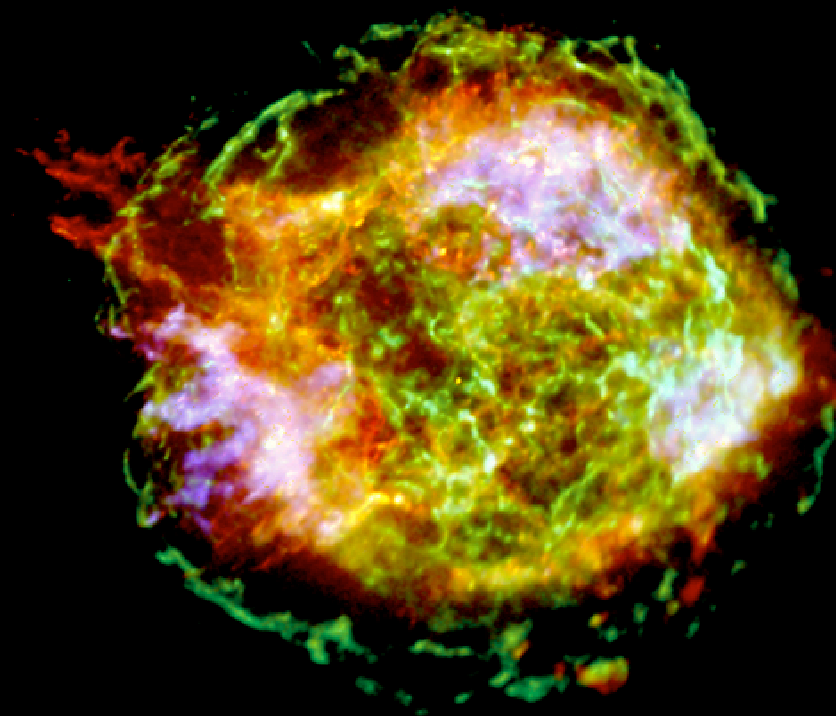


The Star Formation Region in Orion

The Chandra Revolution: qualitatively new structures

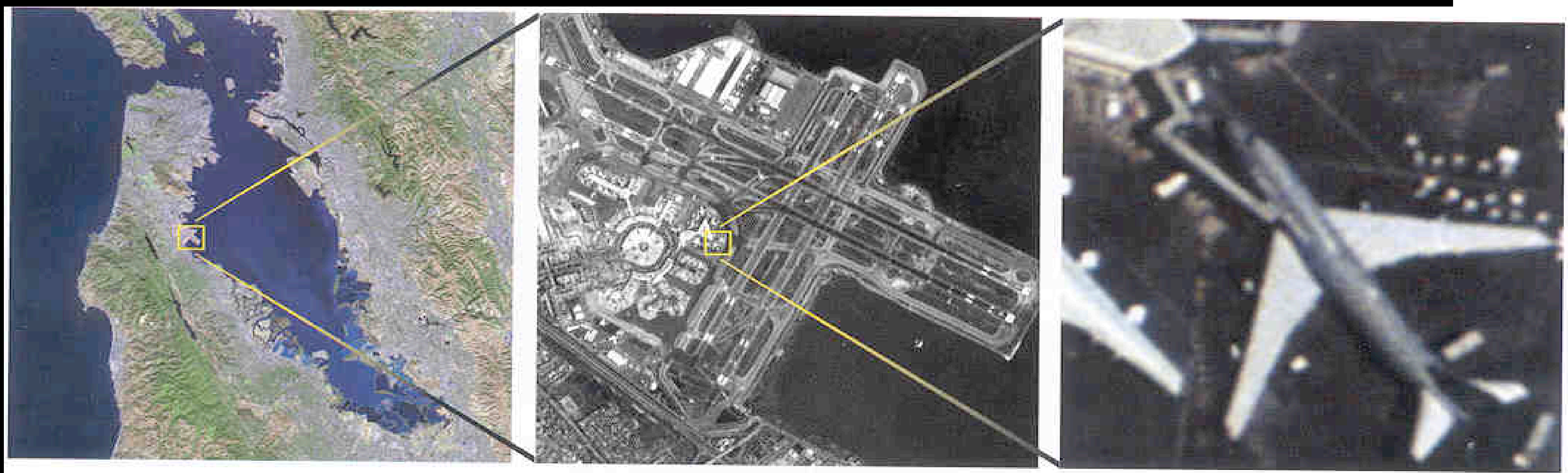


Chandra: ~0.5”



The Supernova Remnant Cassiopeia A

Chandra's High Resolution:
A Terrestrial Analog

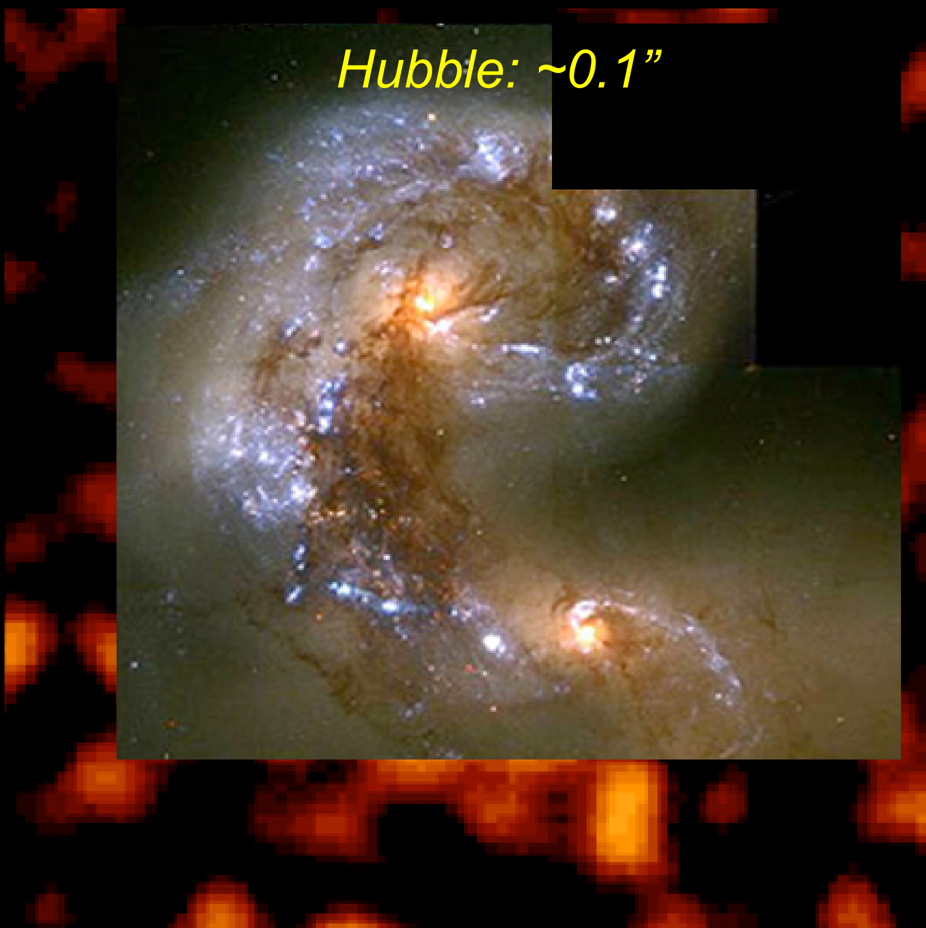


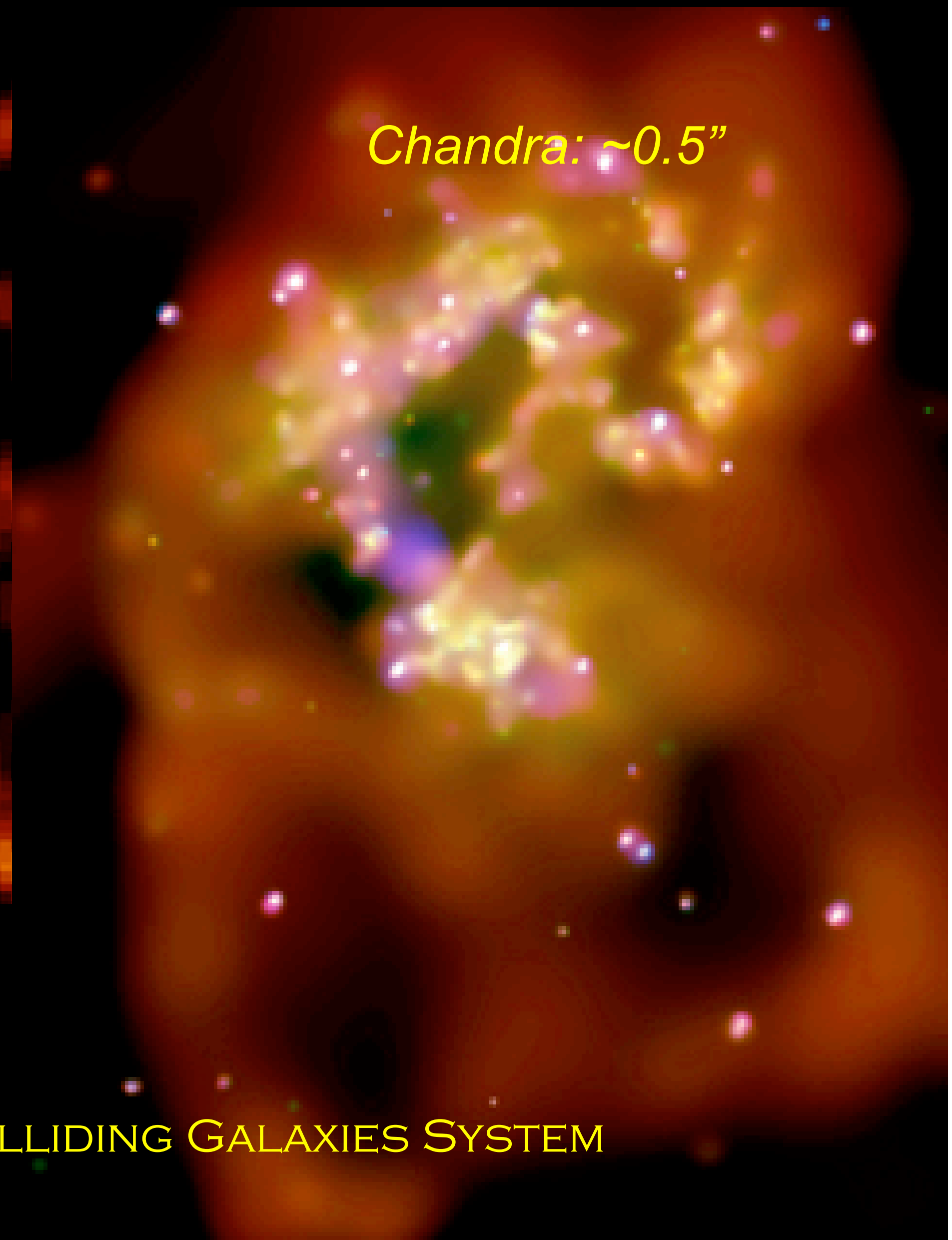
Any sign of life?

What's this odd thing?

I get it!

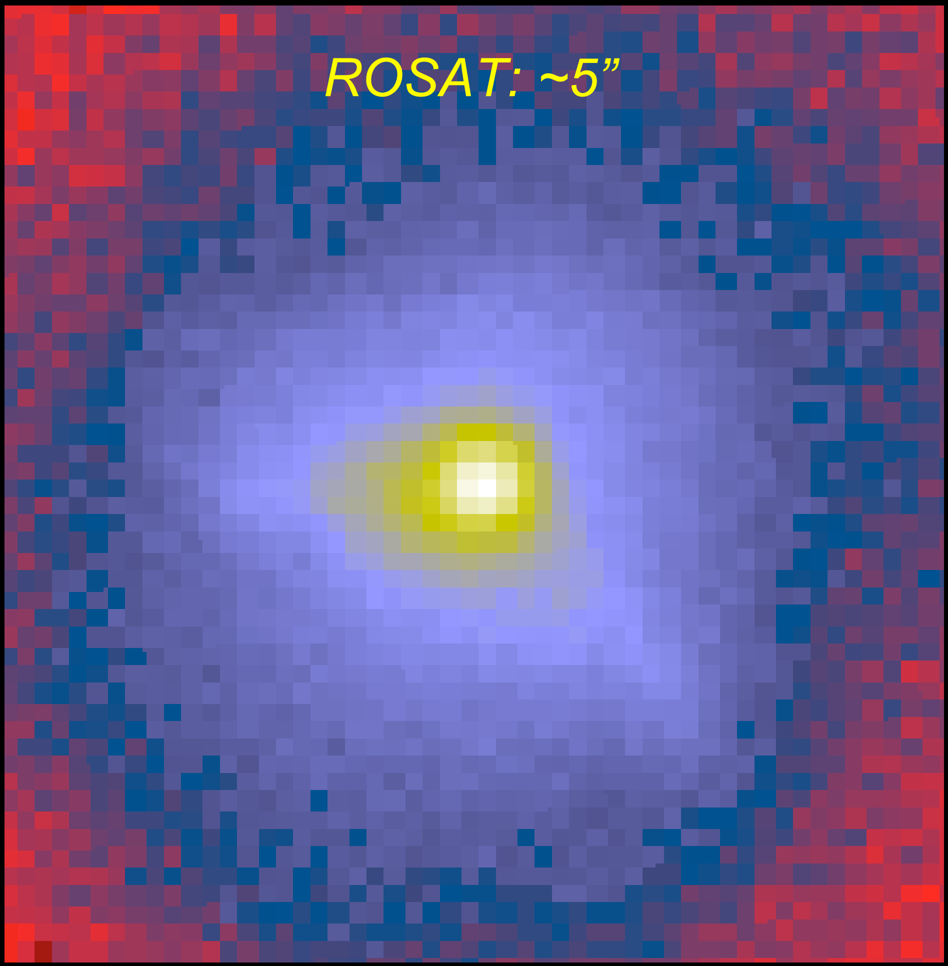
Chandra's 1/2" Does not Tell All

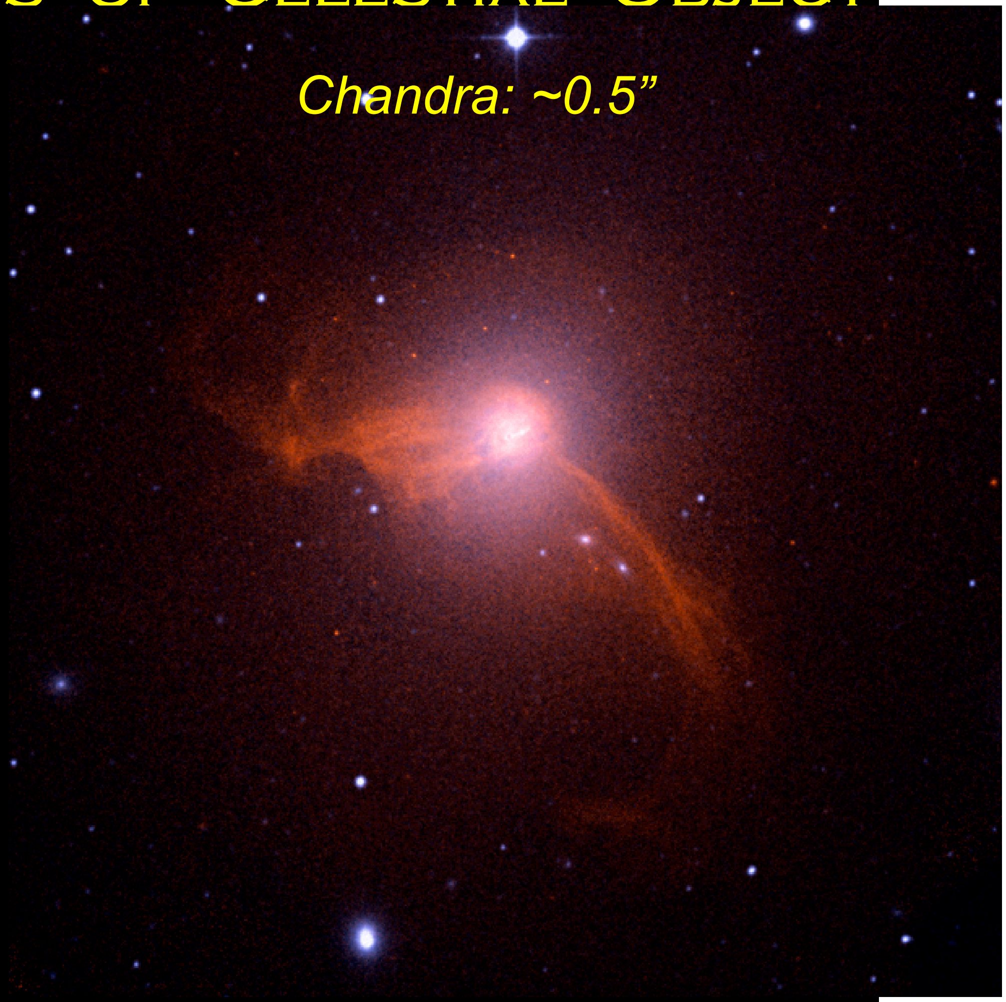




The Antennae Colliding Galaxies System

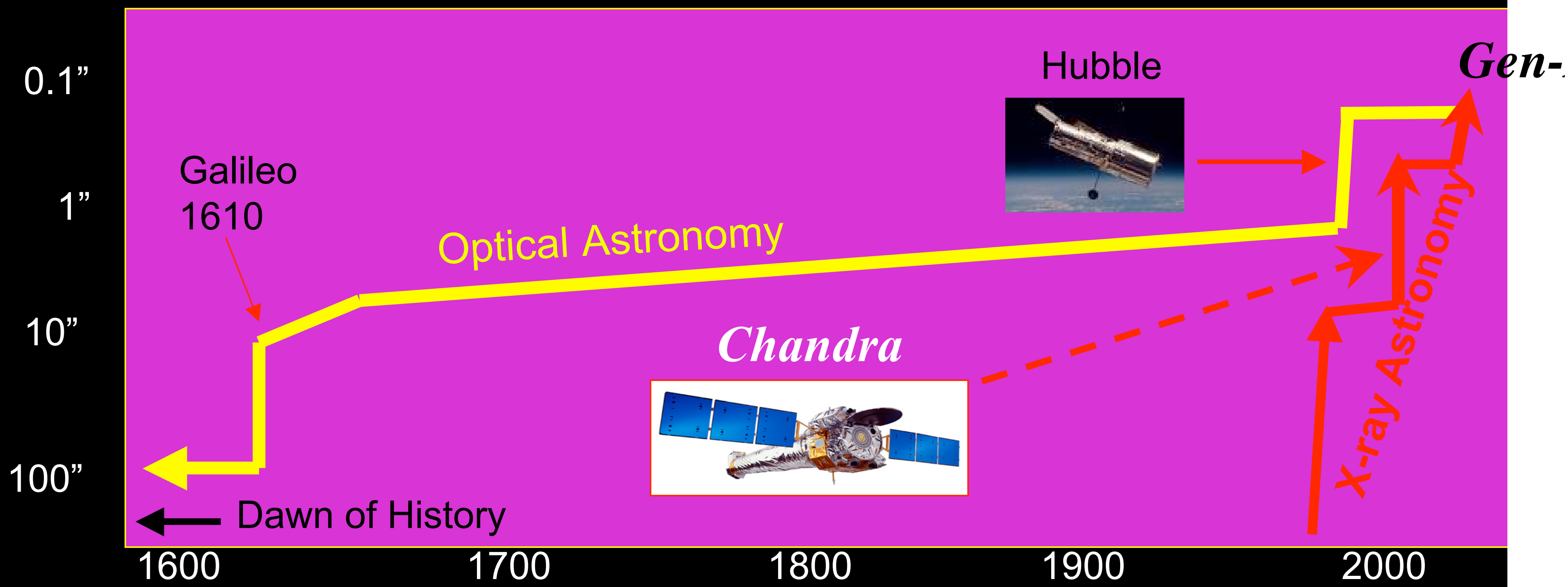
Chandra only gives this Detail on the nearest of each Class of Celestial Object





The Giant Galaxy M87 in the Virgo Cluster

Chandra took X-ray Astronomy from a 'Galileo' era to a 'Palomar' era



X-ray Astronomy needs to move into its 'Hubble' era

A High Resolution X-ray Successor to Chandra is Obviously Needed

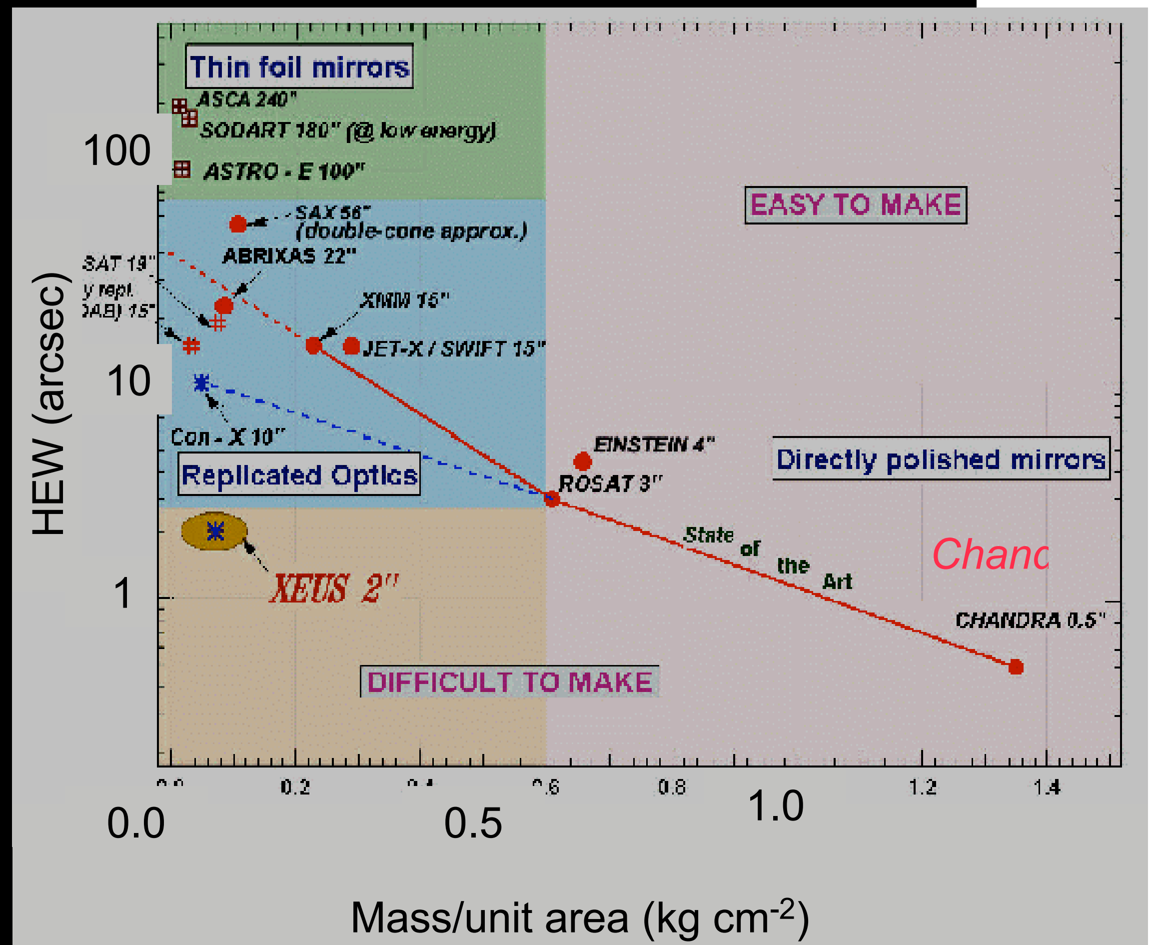
- Chandra mirrors are heavy
  - 1.5 cm thick glass cylinders
- No current plans for a Chandra-class - sub-arcsec - mission - world-wide
- No space agency developing high resolution X-ray mirrors
- Planned missions revert to pre-Chandra image quality:
  - *Constellation-X* (NASA) **HEW=15", 75μrad** (5" goal); concentrates on area and spectral resolution
  - *XEUS* (ESA) **HEW = 5", 25 μrad** (2" goal)

A High Resolution Successor to Chandra: Desiderata

- **A_{eff} > 1 m^2** (10x Chandra)
  - 10 - 100 m^2 preferred
  - Can't use integral shells
    ⇨ segments
- **HEW < 0.25"** (<0.5 Chandra)
  - HEW ~< 0.1" preferred
- Mirror mass < 1000 kg
  - Launcher capability, cost

Requires <1/10 M/A_{eff} of Chandra

i.e. New Technology

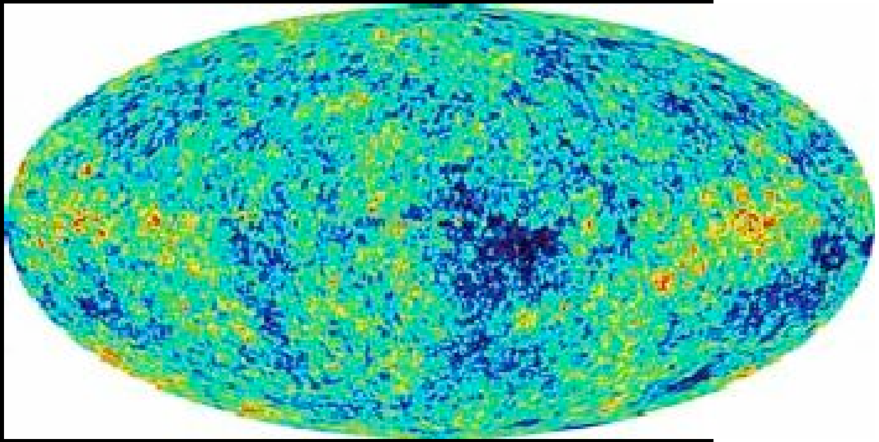


Citterio et al.199x [Brera]

Science Goals for a Next Generation High Resolution X-ray Observatory

Sensitivity: X-rays are a channel to the epoch of the first stars and black holes

- Strong X-ray emission expected from early universe (z~10) objects
  - ❖ Collapse of first overdensities
  - ❖ Growth of first black holes
    - must grow at maximum [Eddington] rate to make quasars by z=6
    - Affect re-ionization? Madau et al. 2004 ApJ 604, 484
  - ❖ Gamma-ray Bursts probe to z=10?



WMAP Cosmic Microwave Background fluctuations map

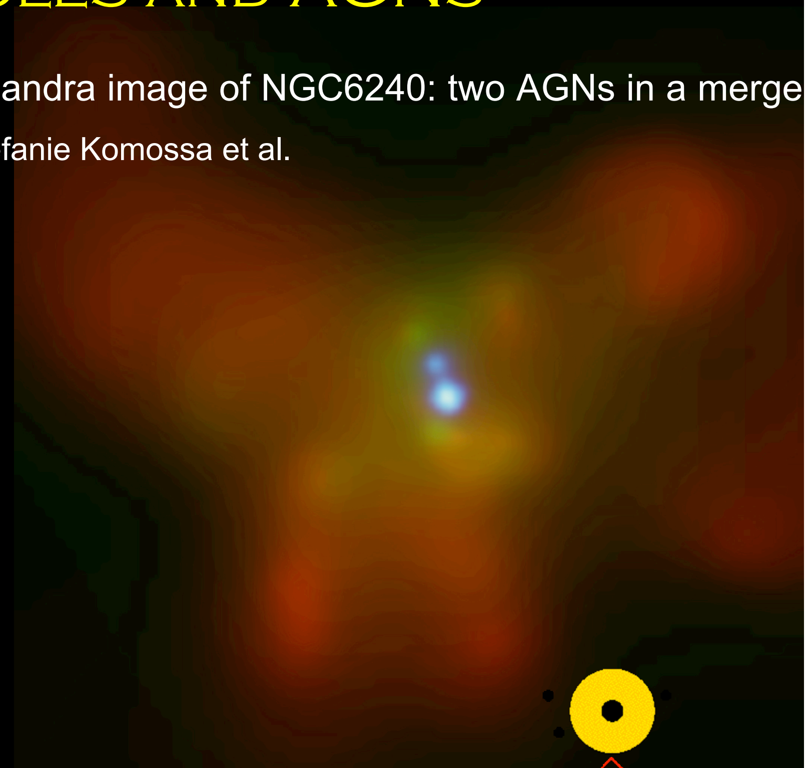
- Probes of z=10?
  - ❖ Optical, UV not available *HI absorption*
  - ❖ FIR, mm limited by lack of molecules at high z
  - ❖ Radio has HI 21 cm line ⇨ *<140 MHz*
  - ❖ Near-IR and X-ray have atomic features: *1-10μm*, *0.1-1.0 keV*

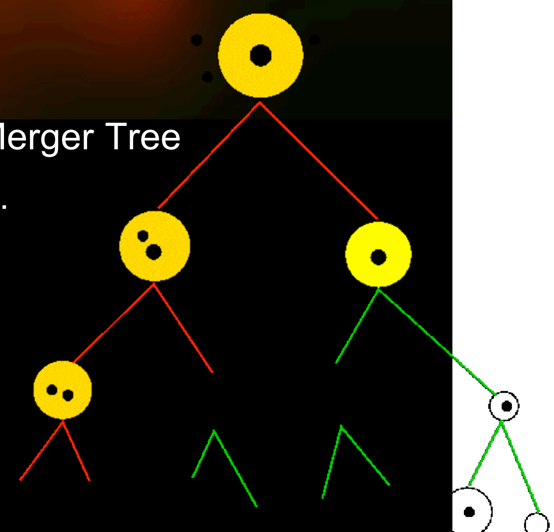
Imaging:
Merging Black Holes and AGNs

- Merging black holes give insight into merger tree vs. redshift
- Tests models of galaxy formation
- But early quasars may be heavily dust enshrouded
- X-rays can see through a factor 10^{20} optical obscuration
  - 10keV rest frame
- Needs high angular resolution
  - 2 kpc at z=1 is 0.25"
    - (~0.1 galaxy dia.)
  - Higher z does *not* need higher angular resolution

Chandra image of NGC6240: two AGNs in a merge

Stefanie Komossa et al.





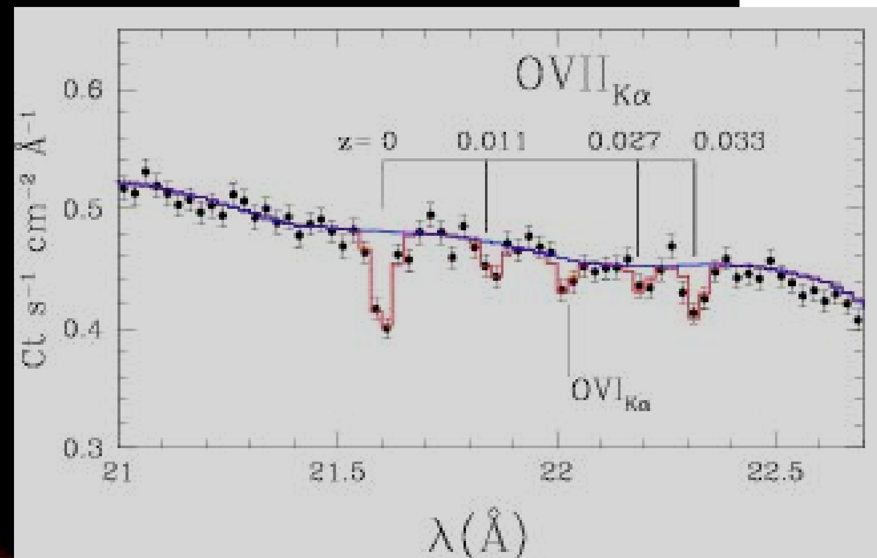
Schematic Black Hole Merger Tree

Marta Volonteri, priv. Comm.

Spectroscopy:
Warm-Hot Intergalactic Medium

- Chandra detected the Warm-Hot Intergalactic Medium -

  where most of the baryons reside in the local universe (z<1)
- X-rays can measure heating and enrichment of IGM
- Needs R=3000
  - Resolve thermal widths of lines
  - R=400 with Chandra
  - Set by HEW of mirror
  - Need HEW <0.1"



Chandra Spectrum of the lo
WHIM toward MKN 421

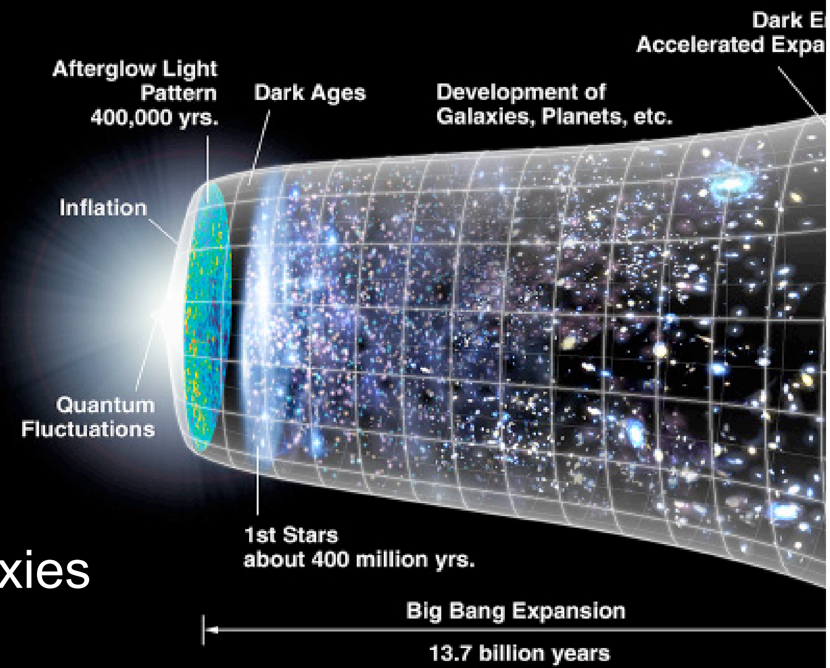
Nicastro et al. 2005 Nature

X-rays at z~10

Age = 480 Myr (3.5%)

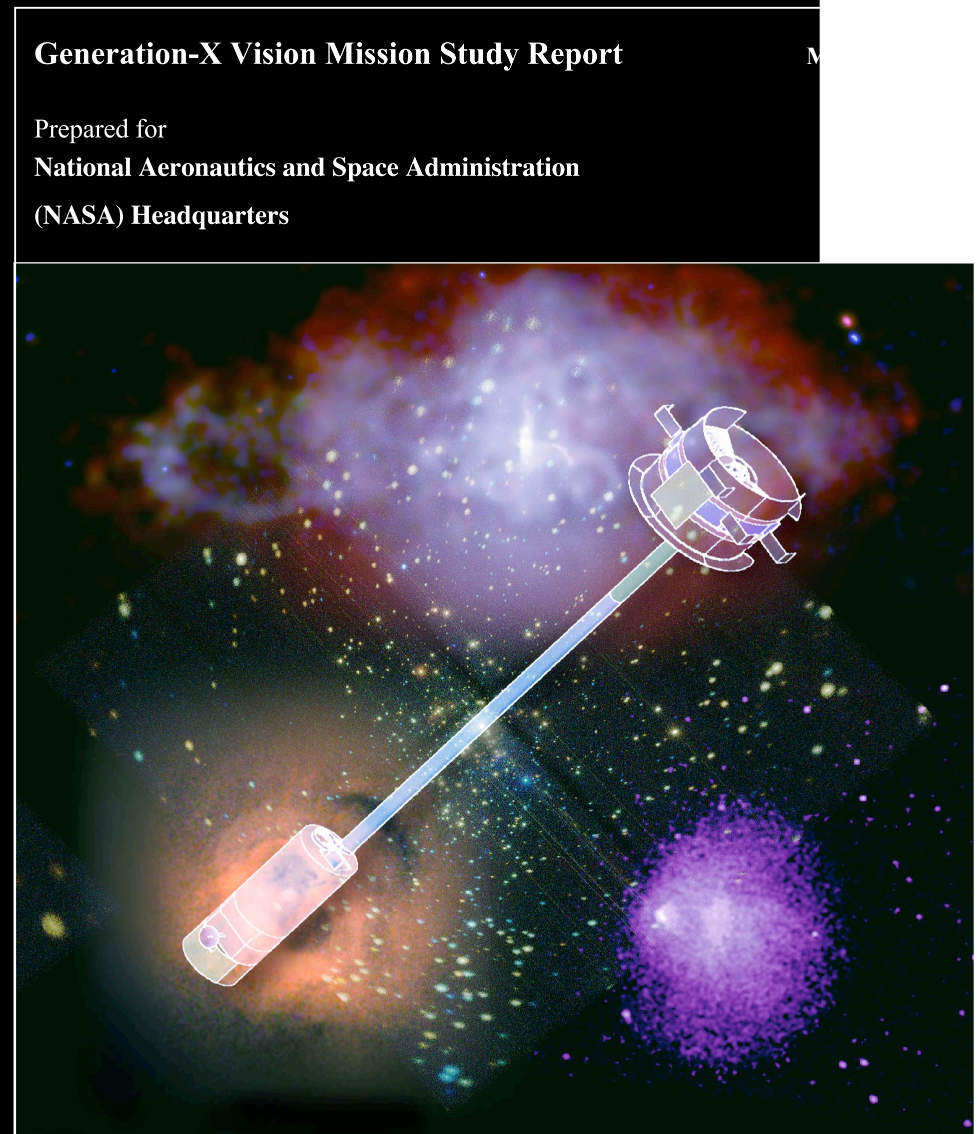
- Faint: 1st BH fluxes: ~10^{-3} of Deepest *Chandra* surveys
- Large area, A_{eff} ~ 100 m^2
- High angular resolution
  - HEW ~ 0.1”, 0.5μrad
  - Reduce background
  - Discriminate from foreground z=3 galaxies
- 0.1-10 keV band
  - spectra kT~10keV / (1+z) ~1 keV
- Defines next generation high resolution large X-ray Observatory:

Generation-X



Generation-X Vision Mission Study

- Gen-X selected as NASA Vision Mission study in 2003
- Large, high resolution X-ray Observatory to follow *Chandra*, *XMM-Newton* and *Constellation-X*
- Nominal Launch date ~ 2020
- Mission concept studies
  - JPL 'Team-X' : formation flying
  - GSFC 'IMDC': single spacecraft
- Mirror studies: SAO, GSFC
- Detector studies: SAO, MIT
- Presented to NASA committees



Generation-X Vision Mission Study Team

- Roger Brissenden (PI) SAO
- Martin Elvis
- Pepi Fabbiano
- Paul Gorenstein
- Paul Reid
- Dan Schwartz
- Harvey Tananbaum

- Rob Petre GSFC
- Richard Mushotzky
- Nick White
- Will Zhang

- Mark Bautz MIT
- Claude Canizares
- Enectali Figueroa-Feliciano David Miller
- Mark Schattenburg

- Webster Cash Colorad
- Martin Weisskopf MSFC
- Mel Ulmer Northwe
- Niel Brandt PSU
- Robert Cameron Stanford
- Steve Kahn
- Rogier Windhorst ASU

and collaborators

75 People, 14 Institutions,
5 Industry Partners,
2 NASA Centers

Gen-X Study Options: 1

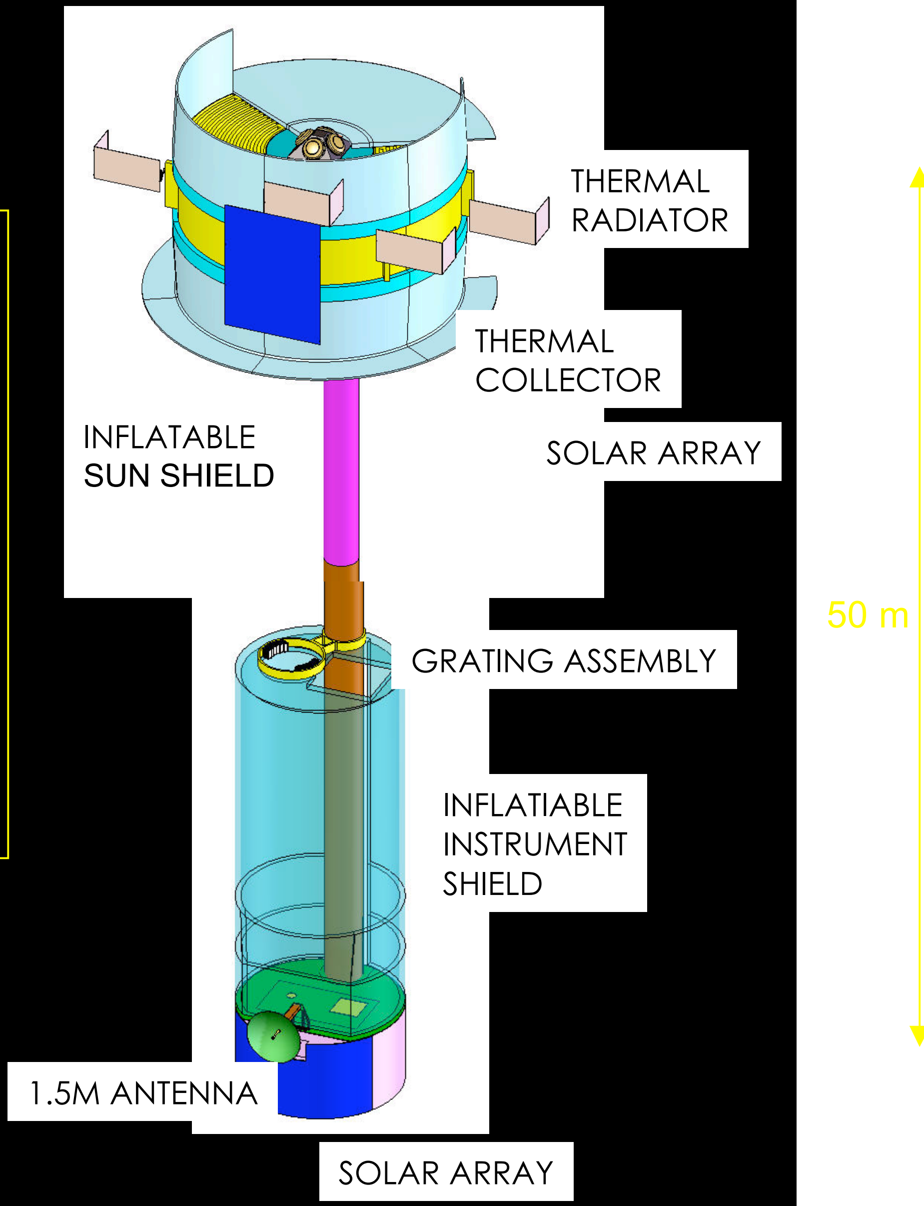
Option 1: GSFC IMDC

Six identical spacecraft, 8m dia mirrors

2/3 filling factor: 60^{o} segments:

50 meter focal length

- Thermal mirror control feasible
- Optical bench tolerances OK



Gen-X Study Options: 2

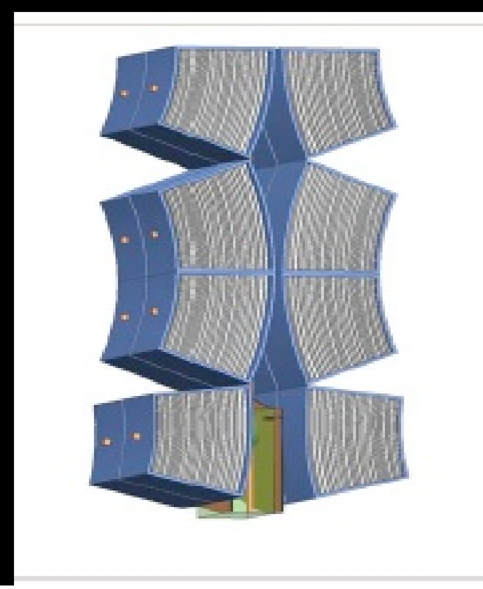
Option 2: JPL Team X

Separate mirror, detector spacecraft.
formation flying.

20m dia. Mirror; 125 meter focal length
(same f-ratio as option 1)

- ✚ Single instrument suite
- ✚ Able to change instrument spacecraft
- • Main Challenge: maintaining s/c separation

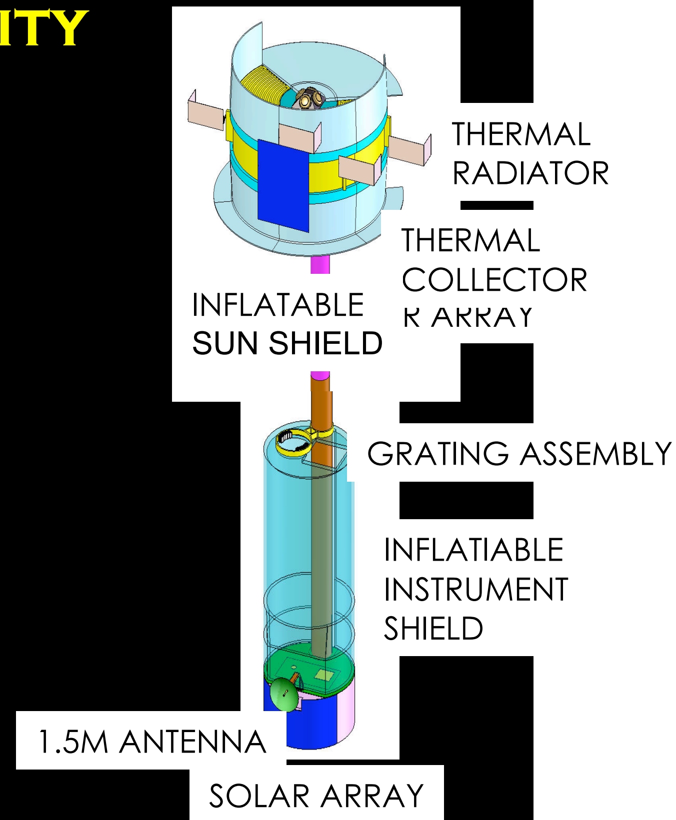
20 m Diameter, Folded Mirror

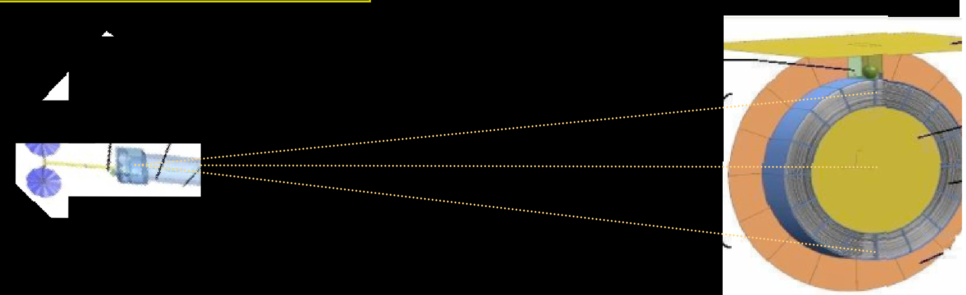


Gen-X Study: Feasibility

Both options:

- ***No show stoppers***
  - Launch capability to Sun-Earth L2 OK
  - Power budget OK
- **Main Challenge: *Mirror technology***
  - Need 1/100 Chandra mass/area
  - Yet 10 x better angular resolution





High Resolution X-ray Optics for Astronomy: Challenging Requirements

- High angular resolution, large area ➪ thin shells
- Axial figure errors comparable to Chandra
- Azimuthal figure errors substantially better

➪ *On-orbit adjustment of figure?*

Advantages

- Reduced ground calibration
- Reduced launch stability requirements
- Can operate away from room temperature
- Slow adjustments ~10^{-5} Hz high orbit

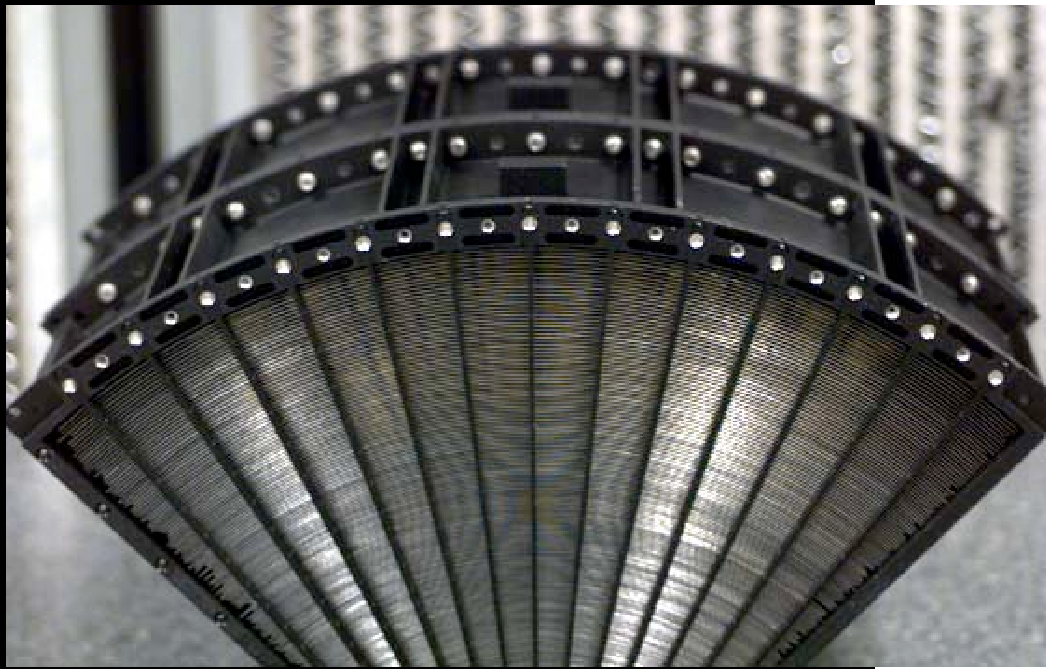
  C.f. 10 Hz on ground-based telescopes

Challenges

- Optical path clearance
- Sensing misalignments
- Calculating adjustmen
- Applying corrections
- Stable actuators

X-ray Telescopes vs. Synchrotrons

- Low rates: 10 ct s^{-1} m^{-2} is bright
- ⇨ Nested shells Giacconi & Rossi 1962 to build up collecting area
- Thin substrates: few 100 mm
- No blockage of optical path allowed
- Parabola - Hyperbola mirror pairs
- Energy range:
  - E > 0.1 keV Galaxy absorption
  - E < 10 keV Area, focal length limits
- Incoherent
  - 1” [5μrad] is good
  - Diffraction limit 25 mas on Chandra
    - C.f. 500 mas achieved
  - **0.1” [0.5μrad] goal**



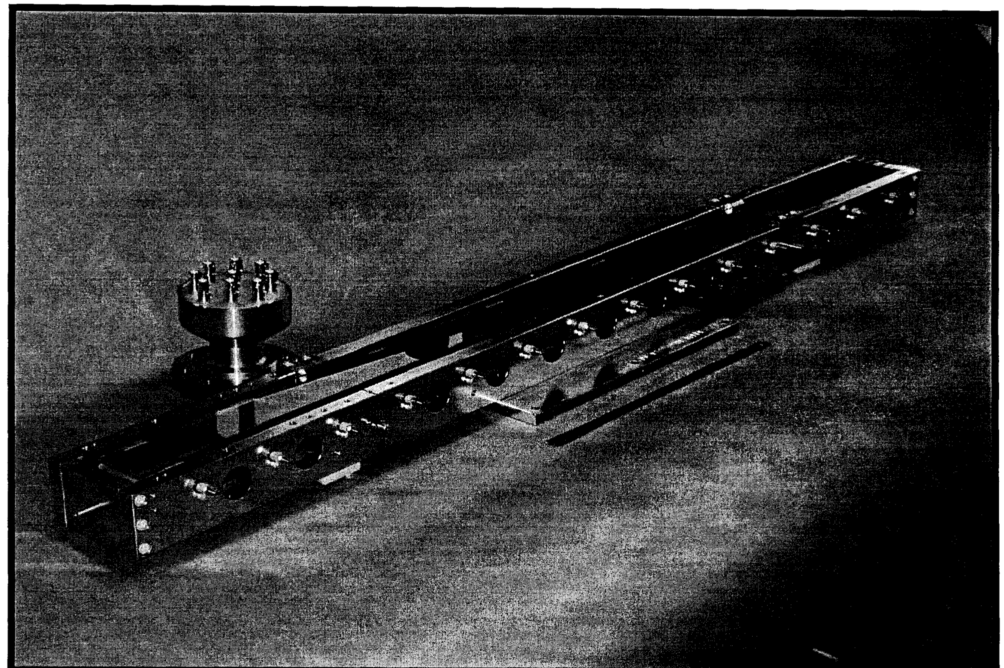
Suzaku Mirror segment

- Jitter removed via star camera
  - Photon counting - correct each photon position
- Space mirrors are expensive

Piezoelectric Bi-morph (PBM) Active X-ray Optics

- Working at Synchrotrons
  - *news to astronomers*
- 10 year program by Signorato et al.
- Operational
  - 16-, 32- element
  - ~1 m long optics
  - 2 cm sized actuators
- Kirkpatrick-Baez configuration

@ APS 16-element PBM



Signorato et al.,2004, SPIE *Photo courtesy of SESO*

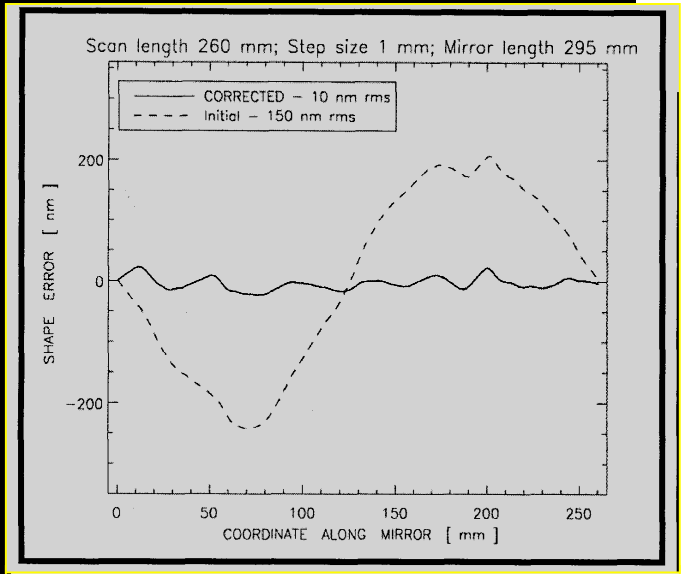
Piezoelectric Bi-morph Mirrors (PBM):

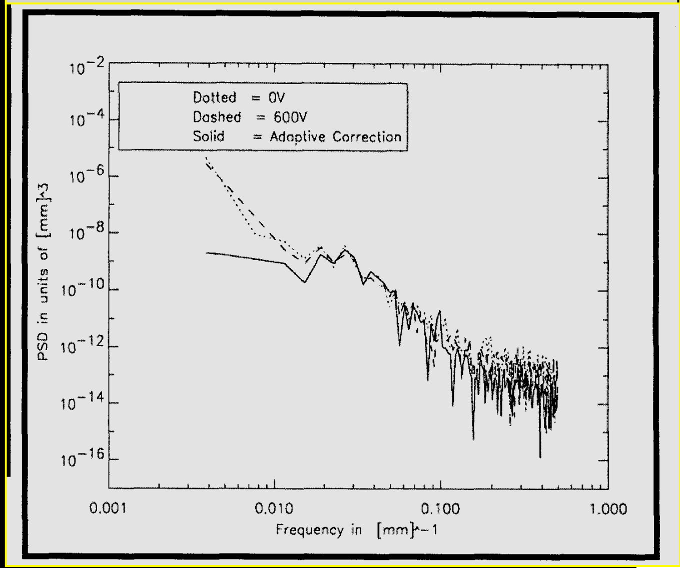
Good Properties for Astronomy II

- Piezos parallel to mirror surface
- Reduce amplitude of errors by factor 15
    - From 150 nm to 10 nm
    - Factor 100 more improvement possible
- C.f. mechanical actuators:

No -

- Optical path blockage
- lubricants
- hysterisis
- backlash

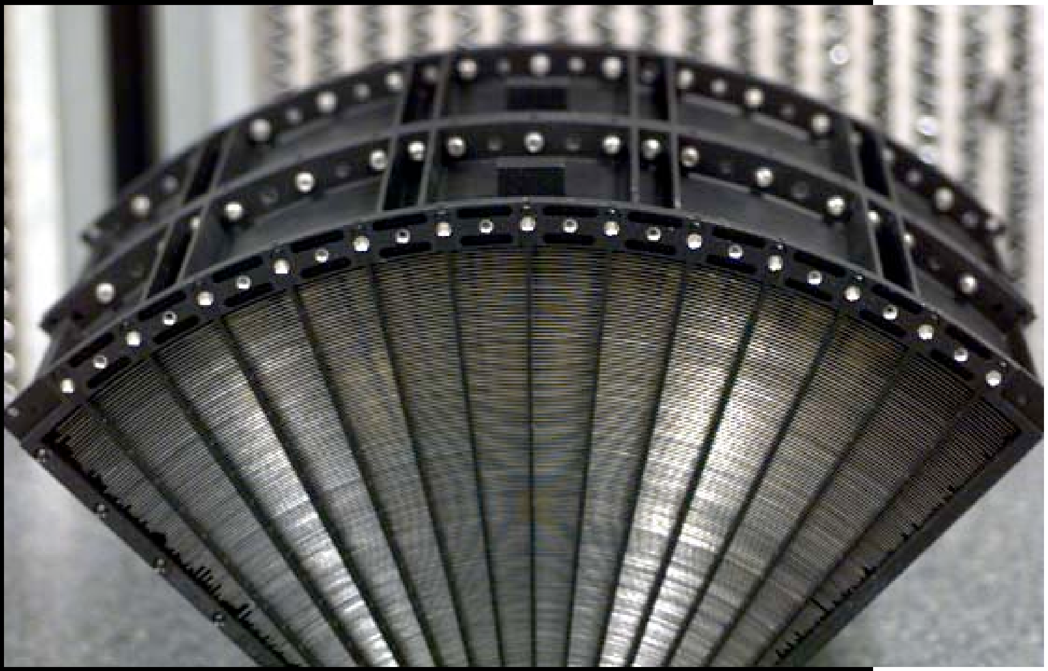




Piezoelectric Bi-morph Mirrors (PBM):

Good Properties for Astronomy I

- Thin: no optical path blockage
- Natural match to thin reflectors
    - 0.2 mm
- Low power, weight
- Existing synchrotron K-B mirrors comparable size to telescope segments
- Pairs of oppositely directed piezos remove T dependence
- Stable over days, months
- No anticlastic effect ('saddling')

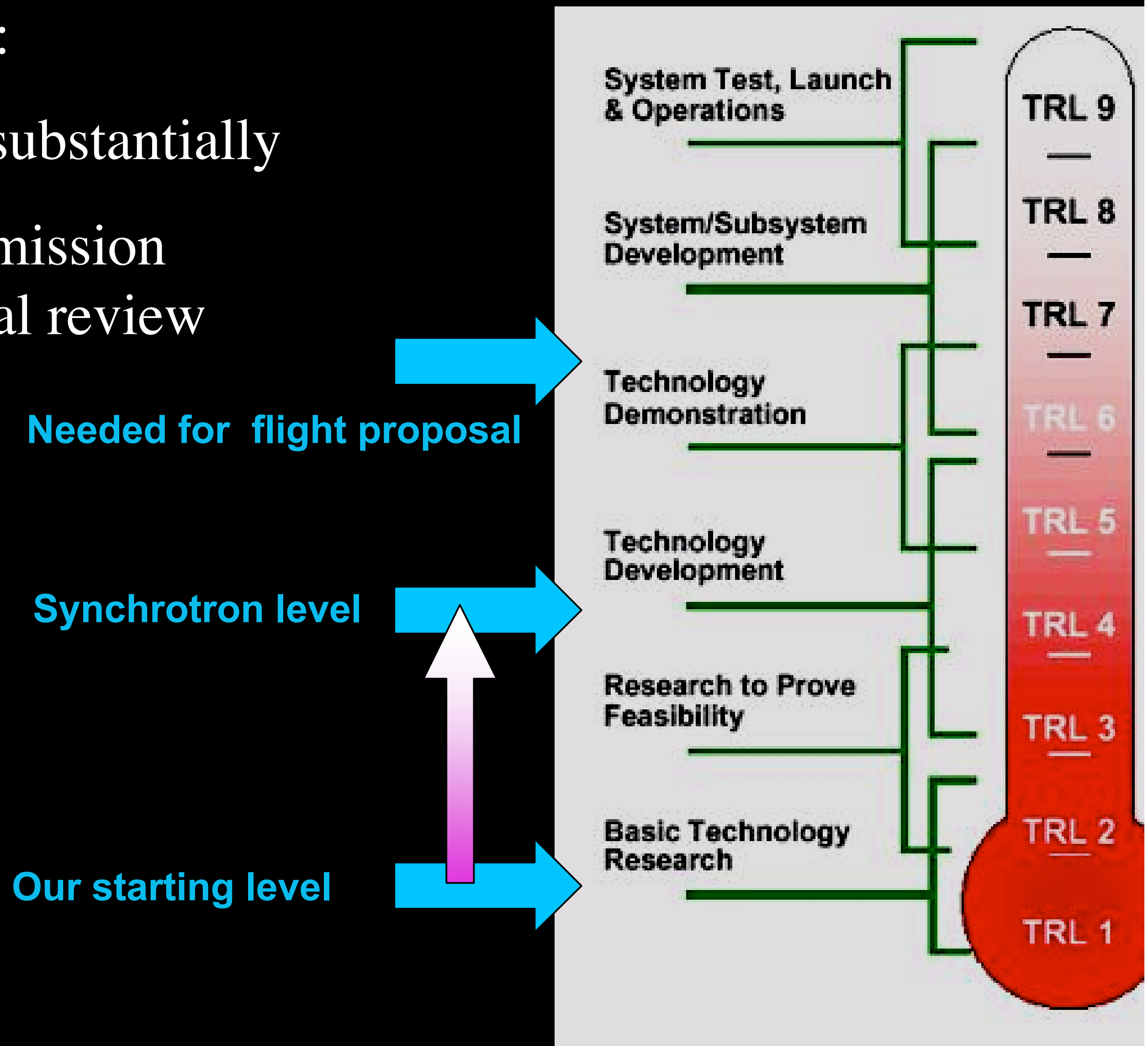


Suzaku Mirror segment

Active X-ray Optics for Astronomy and PBM

Synchrotron PBM work:

- Raises Gen-X TRL substantially
- Makes 'pathfinder' mission candidate for Decadal review (2007-2009)



Active Optics: CfA/Argonne Partnership

- **Argonne National Labs:**
  - *Center for Nanoscale Materials*
    Director: Eric Isaacs
  - piezo materials
    - Rad. Hard
    - 2-D deflections
    - power
- **Harvard-Smithsonian CfA:**
  - *Center for X-ray Technology*
    Director: Steve Murray
  - Forming substrates via replication
  - PBM metrology, ray tracing
  - Calibration: optics, computing

Argonne NATIONAL LABORATORY

Harvard-Smithsonian Center for Astrophysics

PBM Development needed for X-ray Astronomy

- Thin replica substrates - bonding PBM
- 2-D Wolter geometry
  - axial + azimuthal curvature
- Radiation hard piezo materials
- Cold operation piezos
- getting the wires out
- Mass production: 100 m^2 A_{eff}
  ⇨ 10^4 m^2 polished area
  - Cost
  - Speed - ~3 year production
- ~2×10^5 (2 cm actuators)/m^2 A_{eff} :
  - Calibration
  - Calculation problem -
    - closed loop essential in orbit

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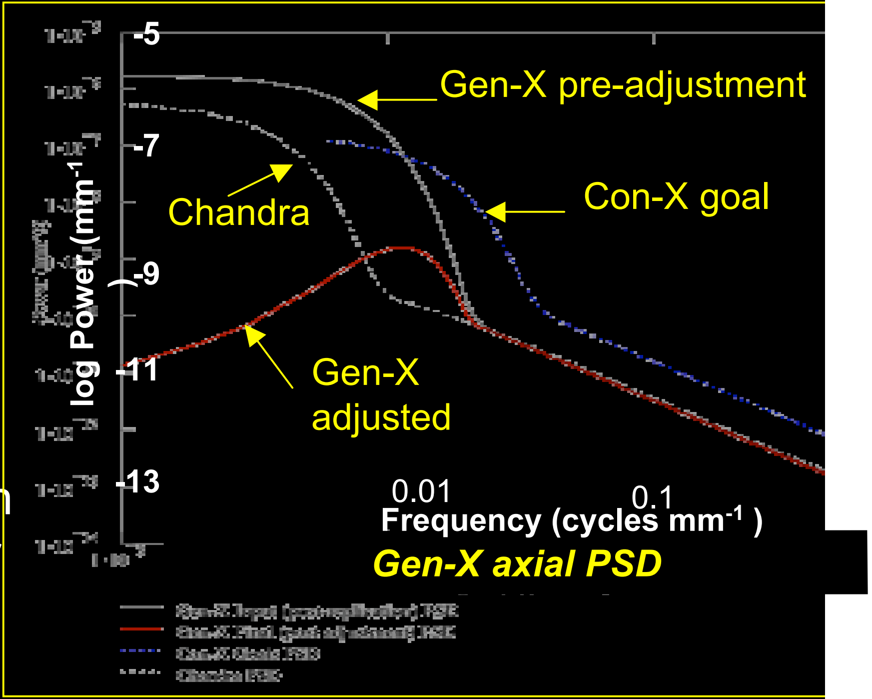
ACTIVE X-RAY OPTICS:

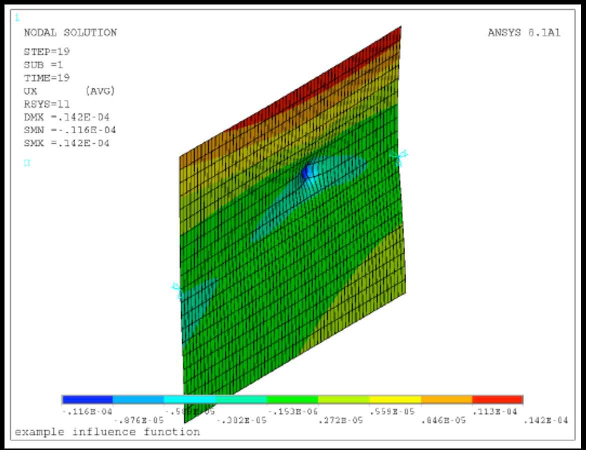
FIGURE IMPROVEMENT

- Need factor ~100 correction:
  - ~400 nm errors to ~4 nm
- Finite element analysis shows feasibility of control - *in principle!*
  - Begin with Con-X optic goal,
  - 2 cm axial actuators give figure correction $\nu < 0.025$ mm^{-1} I.e. Fourier low pass filter
  - Correct to:
    - 6.5 nm rms $0.001<\nu<0.01$ mm^{-1}

      ~ 2 times Con-X goal
    - 1.6 nm rms $0.01<\nu<0.1$ mm^{-1}

      ~ 10 times Con-X goal





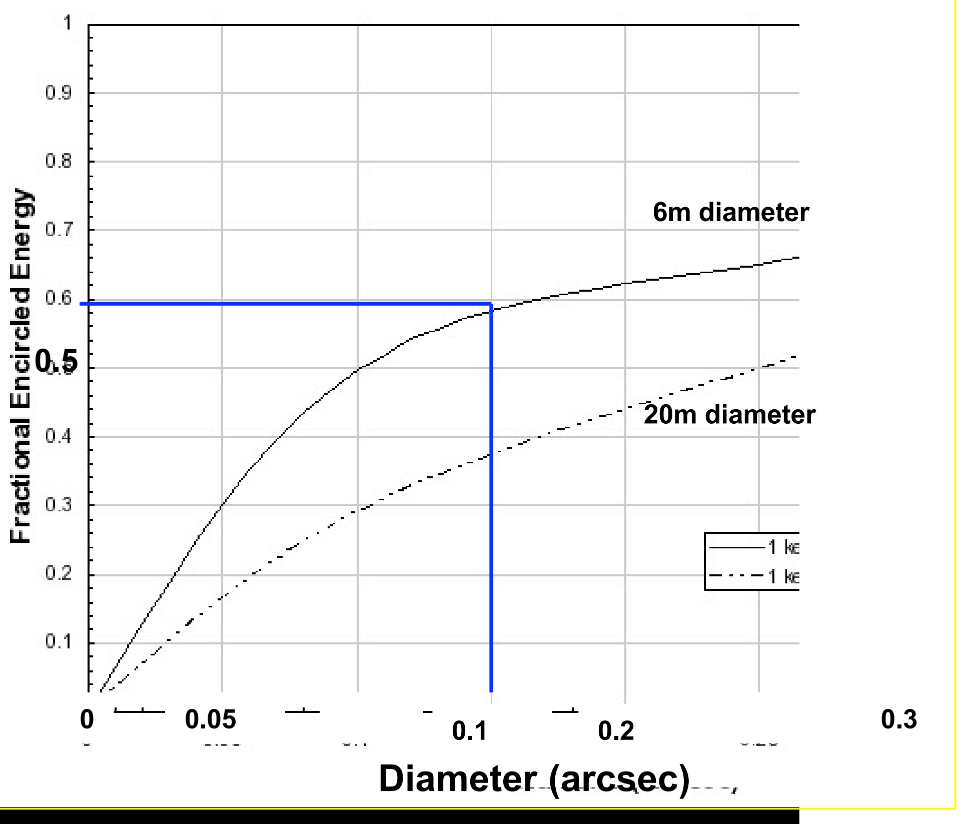
Active X-ray Optics :

Angular Resolution

- Meets 0.1 arcsec HPD goal at 1 keV
- Easier with shorter focal length

  due to larger graze angles -

  hence less diffraction

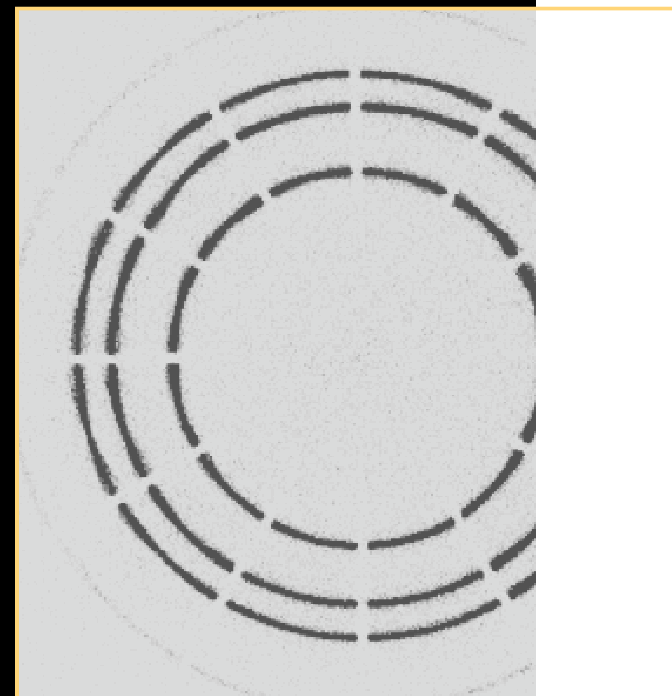


Parameter	Model Value
Primary Cone Angle	1 degree
Secondary Cone Angle	3 degrees
Primary Aft Radius (m)	10
Secondary Forward Radius (m)	10
Reflector Axial Length (m)	1.009
Reflector Azimuthal Width (m)	1.020
Reflector Thickness (mm)	0.2
Piezo Thickness (mm)	0.1 or 0.04
Piezo Cell Axial Length (mm)	15
Piezo Cell Azimuthal Width (mm)	50
Gap Between Cells (mm)	1

Active X-ray Optics Alignment:
Signal & Compute Challenges

- 10^5 actuators! How to sense adjustments?
- Form image ~2% forward of focus

⇨ Separate images of each shell, and azimuthal sector of parabola-hyperbola pair
  - c.f. Chandra 'Ring Focus'
- Factorizes calculation into small parallel steps
  - Each shell segment P-H pair is independent
  - Separate P, H via finite focus source?
- Example: 20m dia mirror, 10cm actuators
  - Annular images 400 μm thick: 20 resolved elements with 20 μm pixels

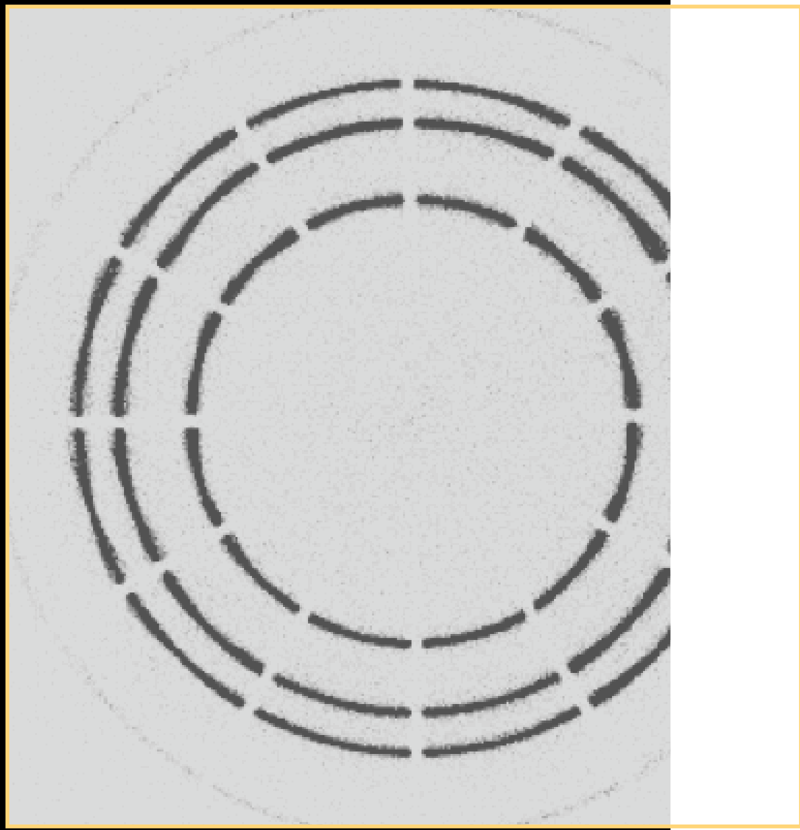


Chandra Ring Focus Test

Active Optics Alignment:
Computation

- Need 10^9 photons for 3% precision in each of 10^6 elements [1000 ct/element]
- Sco X-1 counts 10^7 ct/s/100m^2
- I.e. 10^9 counts at 10^{-2} Hz
  - Many iterations in 1 day 10^{-5} Hz
  - Low duty cycle in ~months
- Keck adjusts 349 actuators at 10 Hz
  van Dam et al. 2004

⇨ 3×10^5 corrections at processing current Keck rate



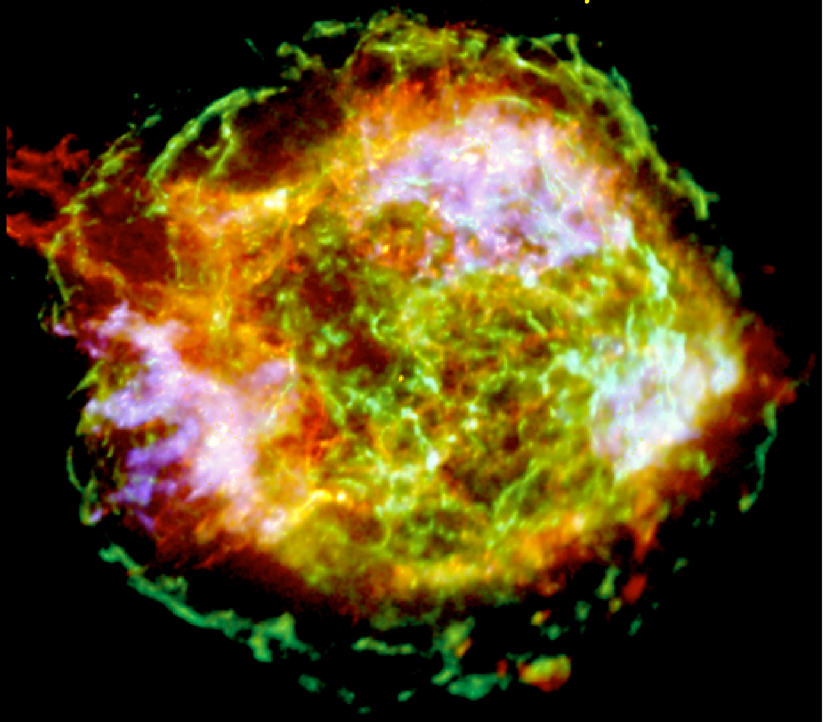
Chandra Ring Focus Test

Active X-ray Optics:

A More Immediate Flight Goal

- Need flight demonstration: e.g.
  - >=5 x Chandra Area
  - >=2 x Chandra resolution
  - 0.5 m^2 A_{eff} = 50 m^2 polished area
  - ~10^5 actuators
  - Focal length = 9 m [same as Chandra]
  - Outer dia. = 1.4 m [same as Chandra]
- Probe Class Mission?
  - 'Decadal Survey'
    - Committees formed 2007
    - reports 2009

Chandra: ~0.5", 2.5μrad



The Supernova Remnant Cassiopeia A

Active X-ray Optics: Short Term Goals

- Primary: Demonstrate 1 meter-sized Wolter mirror segment in laboratory to Chandra HEW specs
- Needed soon for 'Decadal Survey' begins 2007, reports 2009
- Secondary: space-qualified PBM materials; compute problem; wiring; …

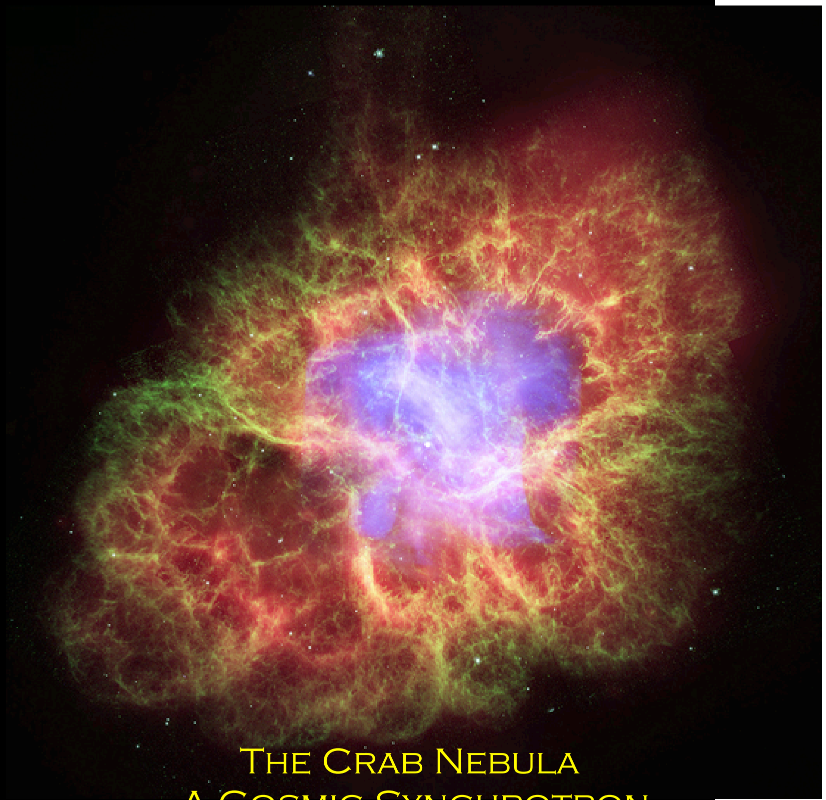
Harvard-Smithsonian Center for Astrophysics

Active X-ray Optics
For The Next High Resolution X-ray Observatory

Argonne NATIONAL LABORATORY

Harvard-Smithsonian Center for Astrophysics

- PBMs address biggest technical challenge
  - Low optical path blockage
  - 0.1 arcsec achievable with PBMs
  - Good match to weight/power/stability requirements
  - In operation at synchrotrons
  - Raised TRL substantially
- Major development needed for telescope use
- *Rapid development program could further all imaging X-ray astronomy missions*
- *Interested in partnerships*



The Crab Nebula
A Cosmic Synchrotron