An Ultra-High Throughput X-ray Astronomy Observatory with a New Mission Architecture

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NIAC Annual Meeting, June 5, 6, 2001

X-Ray Astronomy

EM Band: 80 - 1 Angstroms or 0.15 to 12 keV

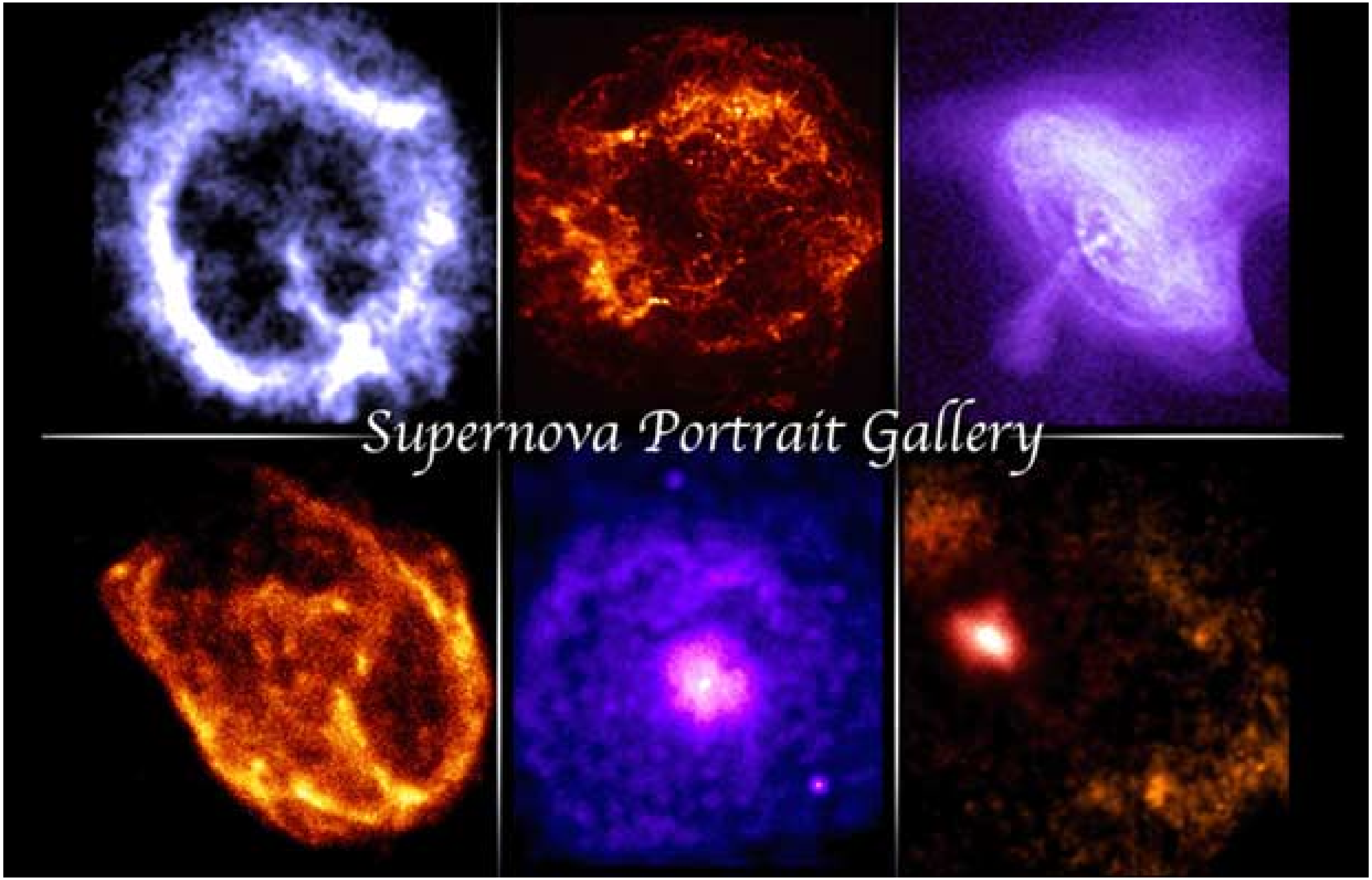
X-ray Emission Comes From Regions With One or More of the Following Conditions:

High Temperature, 1E06 to 100E06 K

High Energy Particles

High Magnetic Fields

Very Strong Gravity



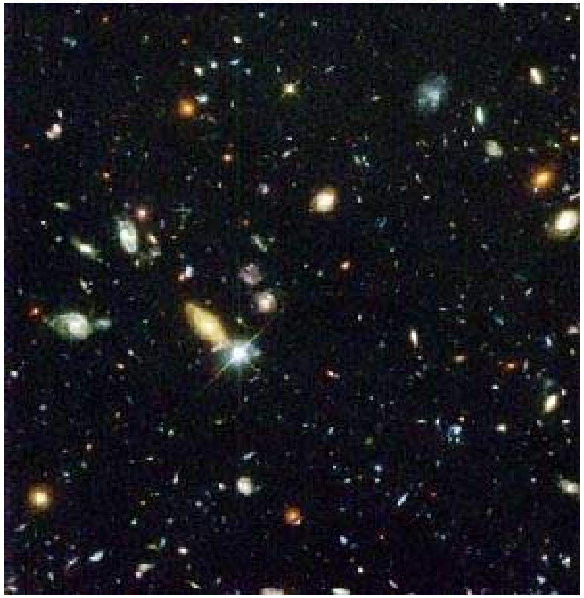
Ultra-High Throughput X-ray Observatory with a New Mission Architecture

Importance of X-ray Astronomy-Major Objectives

- **Detect Most Distant Objects, i.e. Youngest, in Universe**

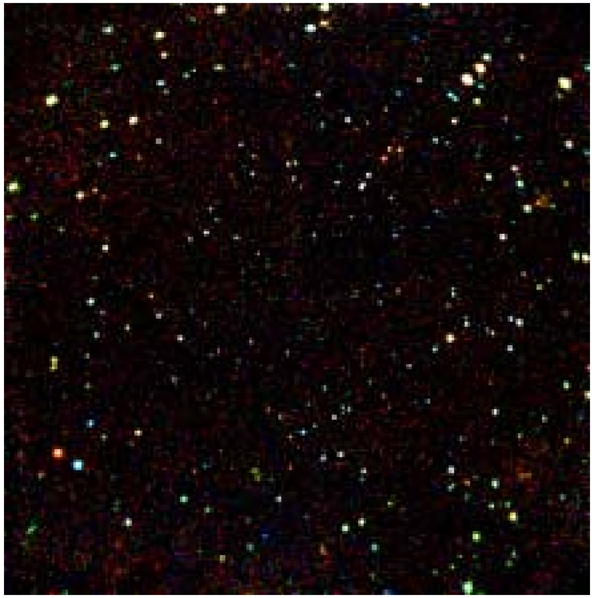
Hubble Deep Field

Galaxies



Chandra Deep Field

Black Holes

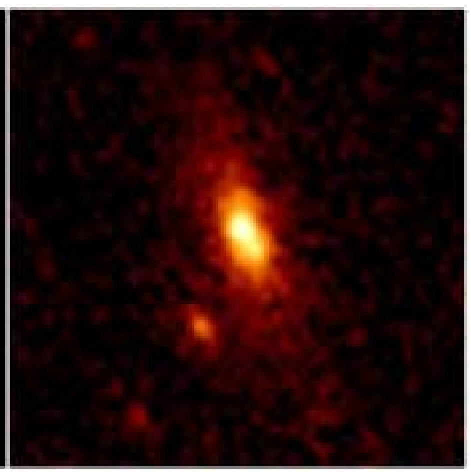


Importance of X-ray Astronomy-Major Objectives

- Detect Black Holes at the Centers of Active Galaxies

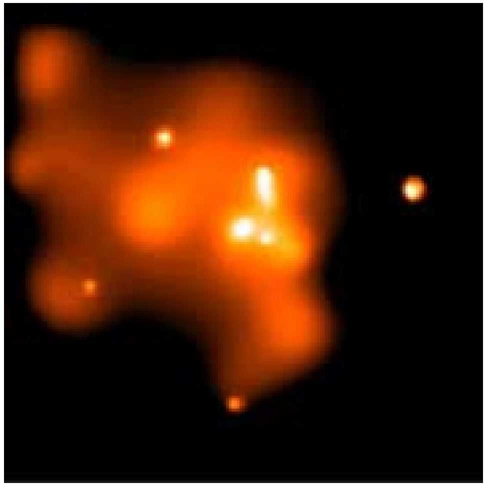
Type 2 Quasar

Chandra X-ray



HST Optical

Galactic Center

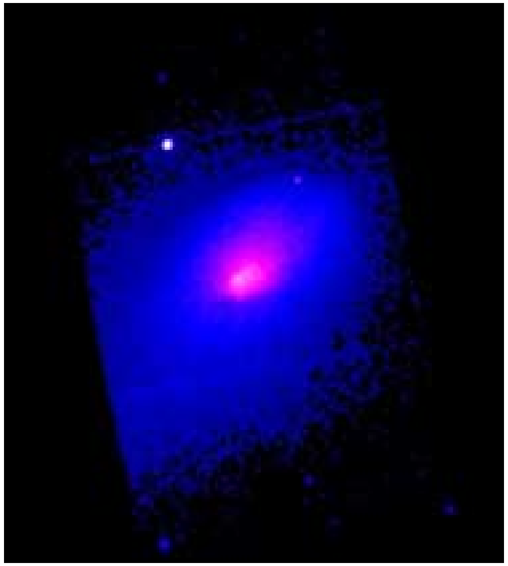


Chandra X-ray

Importance of X-ray Astronomy-Major Objectives

- Observe Evolution of Structure: Clusters of Galaxies

Abell 2142



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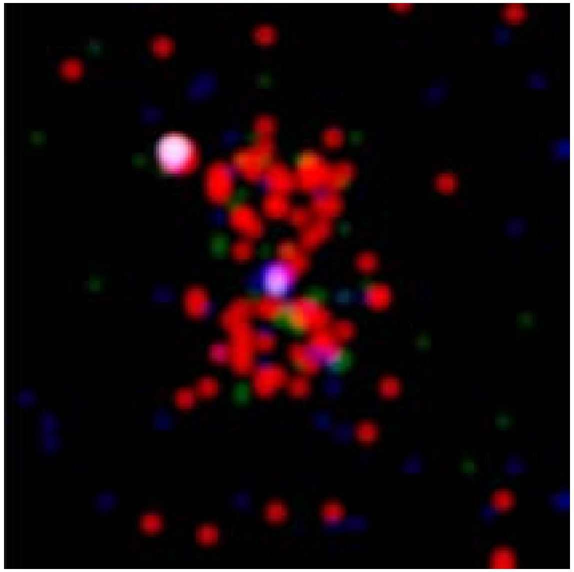
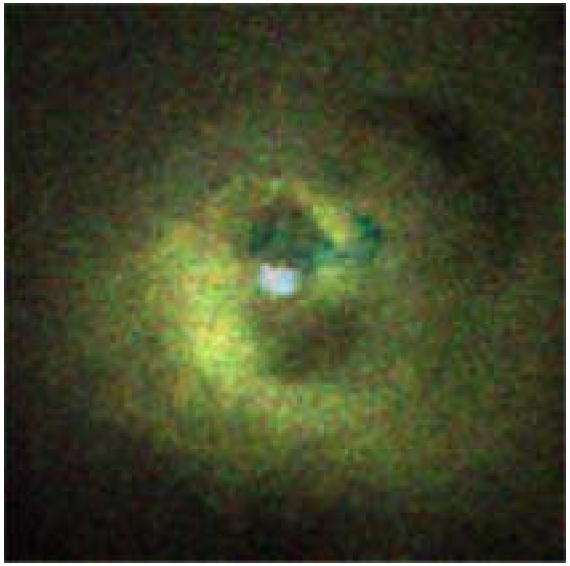


Perseus Cl. w. NGC1275

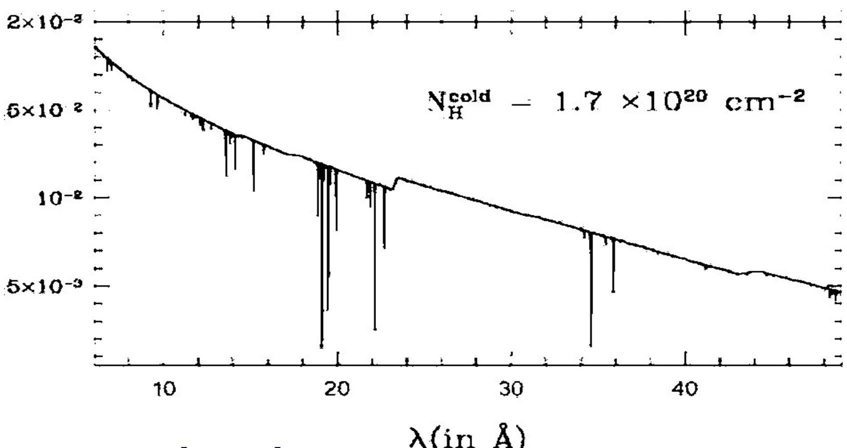


Markevich et al, 2000

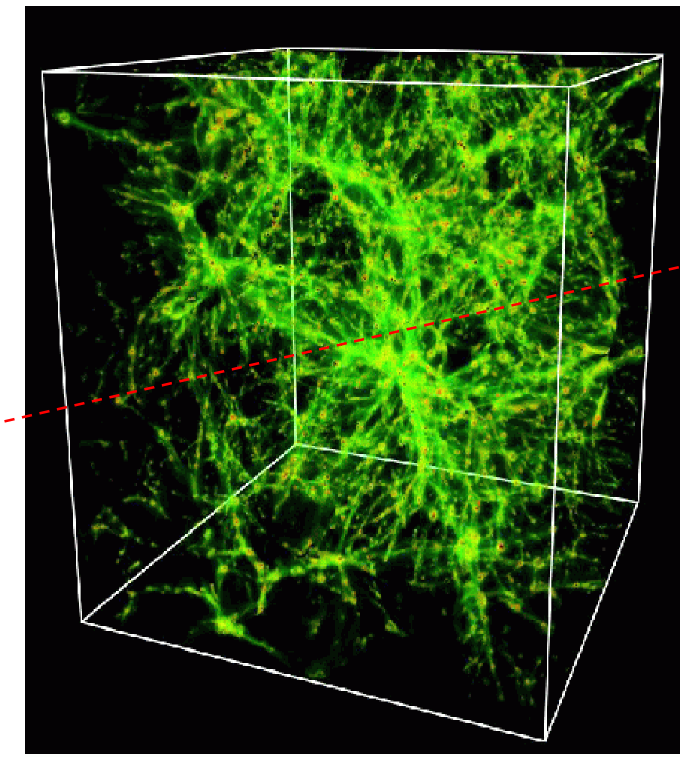
Importance of X-ray Astronomy-Major Objectives

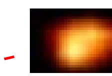
•Image the Major Component of Baryonic Matter in the Universe

Measure absorption lines from intergalactic medium in the spectra of quasars



F. Nicastro, Ph. D. thesis





Ultra-High Throughput X-ray Observatory with a New Mission Architecture

Team Finds Objects Older Than Light

In the Very Distant Universe, Objects Even Older Than Light

By JOHN NOBLE WILFORD

ATLANTA, Jan. 13 — In a discovery that could help explain the origin of the earliest galaxies, a new astronomy satellite has detected the first discrete objects in the mysterious glow of X-rays that pervades the distant universe.

Some of the faintest of the radiation sources, astronomers said, could be the most distant objects ever observed. They promise to be important clues to conditions

in the cosmic da[…] that began soo[…] Bang created t[…] lasted for perha[…] until the emerge[…] tu[…] stars tha[…] f[…]ment.

Many of the [X-]… coming from th[…] ies. These core[…] as they existed i[…] verse, were pr[…] sive black holes[…] nearly the speed[…] erating treme[…] Yet in many ca[…] not emit visibl[…] that they existe[…] the multitude o[…]

The discove[r]y today at a meeti[…] can Astronomical Society was hailed by scientists as the first major step in solving the mystery of the pervasive X-rays that form a backdrop throughout the universe. Until the launching of NASA's Chandra X-Ray Observatory five months ago, the mystery had defied explanation.

"We are all very excited by this finding," said Dr. Richard Mushotzky of the Goddard Space Flight Center in Greenbelt, Md., who was the leader of the discovery team. "These are signposts of the first things formed in the universe."

Other astronomers called it "a

Continued on Page A20

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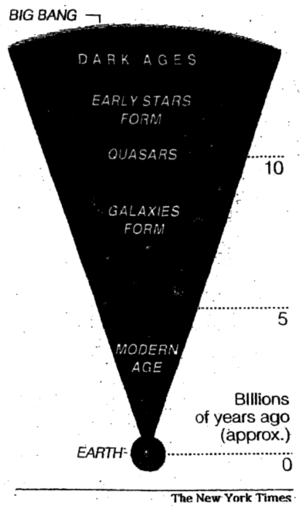
Early Mysteries



Continued From Page A1

major discovery" and said the data appeared to be impressive, although they wanted to see more observa-[…]

[…]swered questions in cosmology: How did matter created in the aftermath of the Big Bang, once all but uniformly smooth, get to be as lumpy as it is now in a universe of large-scale structures like galaxies and spreading clusters of galaxies?

Learning more about the X-ray objects, Dr. Trimble said, should give astronomers important insights into the transition, which must have occurred during the cosmic dark age, all but unobservable until now. The only earlier phenomenon previously observed was microwave background radiation (a relic of the Big Bang itself), which bears only the faintest traces of incipient galactic structure. After the dark age, which may have lasted one billion years or so, came the appearance of star-studded galaxies.

The new findings, however, along with other research reported at the astronomy meeting, suggest that relatively starless galaxies may have been emerging everywhere during the dark age.

In this interpretation, masses of gas and also dark matter, the exotic particles created by the Big Bang that are thought to be a major cosmic constituent, plumped together into proto-galaxies. At the cores of at least some, the mass was so great that it formed black holes, those awesome gravitational sinks so dense

> Perhaps the most distant objects ever observed.

that, by the rules of Einstein's general theory of relativity, nothing, not even light, can escape them. As ravenous black holes consumed more gas, they produced the X-rays now being observed and marking the locations of those galactic cores.

If this interpretation is correct, then the X-ray observations suggest that galaxy formation and black holes preceded the period of star formation, a possibility raised by theorists in recent years.

An article describing the X-ray discovery is to be published soon in the journal Nature by Dr. Mushotzky and his collaborators: Dr. Lennox Cowie and Dr. Amy Barger of the University of Hawaii and Dr. Keith Arnaud of the University of Maryland.

The Chandra observatory, a 12,000-pound spacecraft in earth orbit, was designed to examine X-ray sources much fainter and more distant than before. The newly described X-ray background was observed for almost 28 hours last month through use of the spacecraft's imaging spectrometer. The instrument was built for the National Aeronautics and Space Administration by the Massachusetts Institute of Technology and Pennsylvania State University.

Dr. Mushotzky's team looked at a small sector of the sky, a circle about one-fifth the size of a full moon. It was able to resolve about 80 percent of the X-ray glow in that region into specific light sources. Extrapolated across the entire sky, this would add up to about 70 million sources, most of which are galaxies.

In their report, the astronomers said that one-third of the detected sources were presumably proto-galaxies: their cores shone bright in X-rays, yet no visible light from them has been picked up by the Keck Observatory in Hawaii.

Another type of these sources emitted little or no visible light and appeared to be extremely faint even in X-rays, either because they are obscured by dust or because they are so far away that the light is absorbed by intervening matter on its long journey across space. These objects, Dr. Mushotzky said, may be as much as 14 billion light-years away and thus the earliest, most distant objects ever observed.

Whatever the ultimate interpretation of the discovery, Dr. Mushotzky said, "we're changing the demographics of black holes — their masses, distribution, how much matter they are eating."

Ultra-High Throughput X-ray Observatory with a New Mission Architecture

1980's

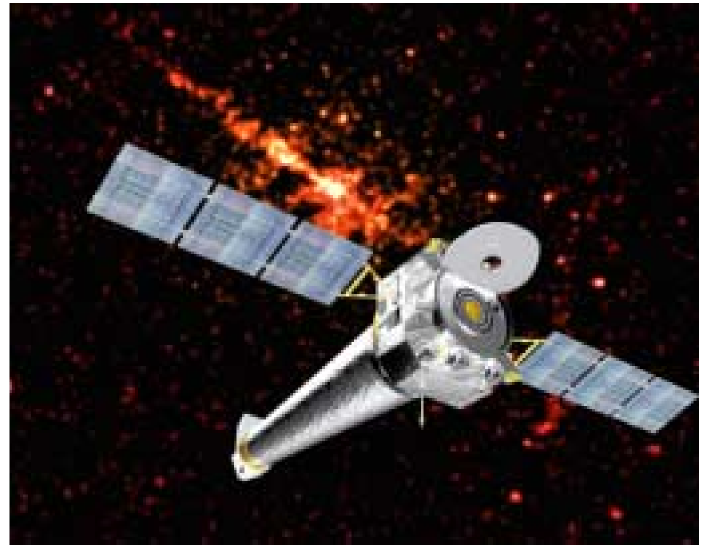
Einstein Observatory

1990's

ROSAT

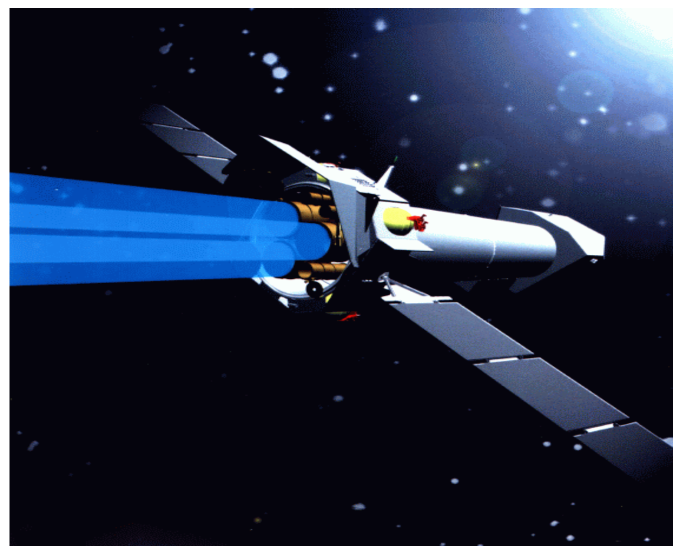
ASCA

2000's, Currently Operating



High Thoughput

Chandra



XMM-Newton

High Angular Resolution

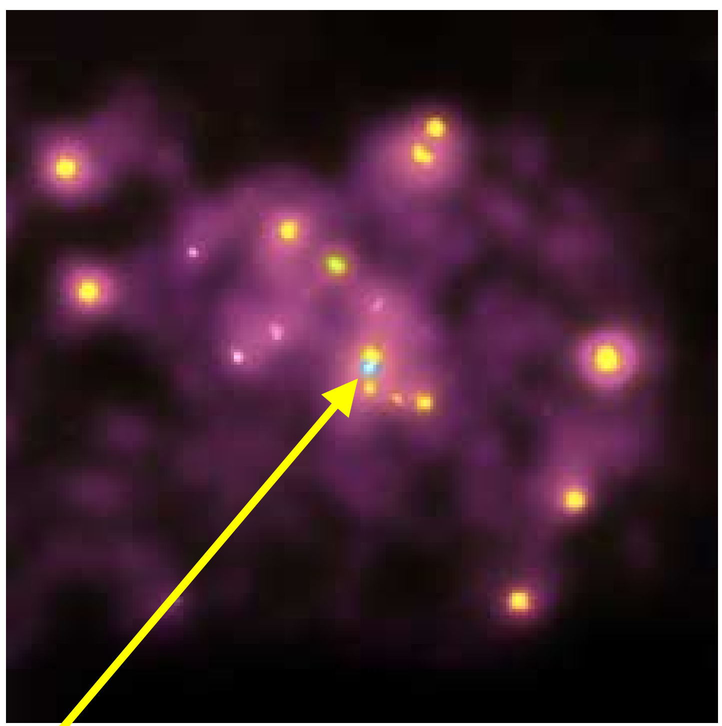
Performance Requirements Upon the "Generation-X" Ultra High Throughput X-ray Observatory

- Effective Area of 2 million sq. cm. at 1 keV
- Angular Resolution of the order of 1 arcsec to avoid source confusion and for imaging
- Accommodating unlimited number and large variety of detectors
- Replacing detectors that are exhausted, failed, or obsolete
- No long period of construction required prior to use
- Not dependent upon single launch for success
- Long life, at least 15 years
- Moderate cost, should not exceed current large space programs

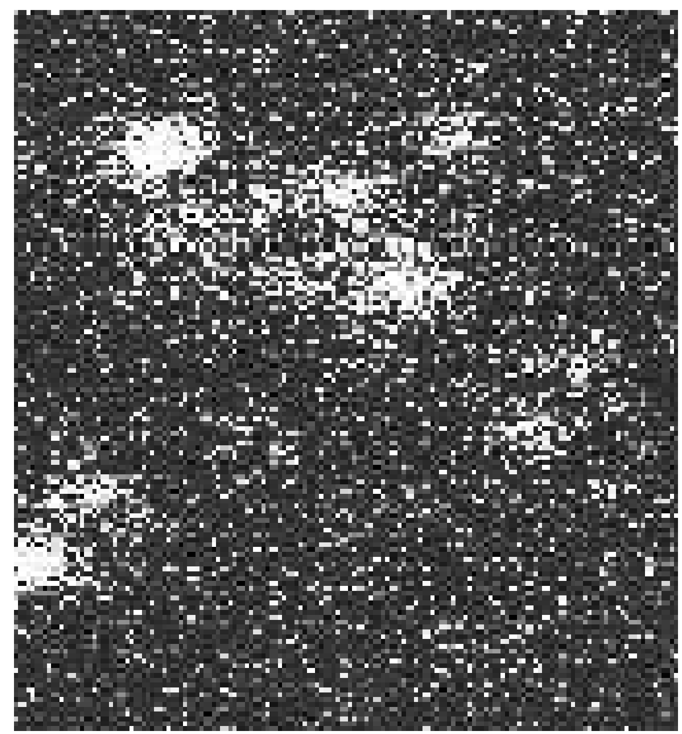
Importance of Better Angular Resolution

Central 1 arcmin region in M31 (Andromeda Galaxy)

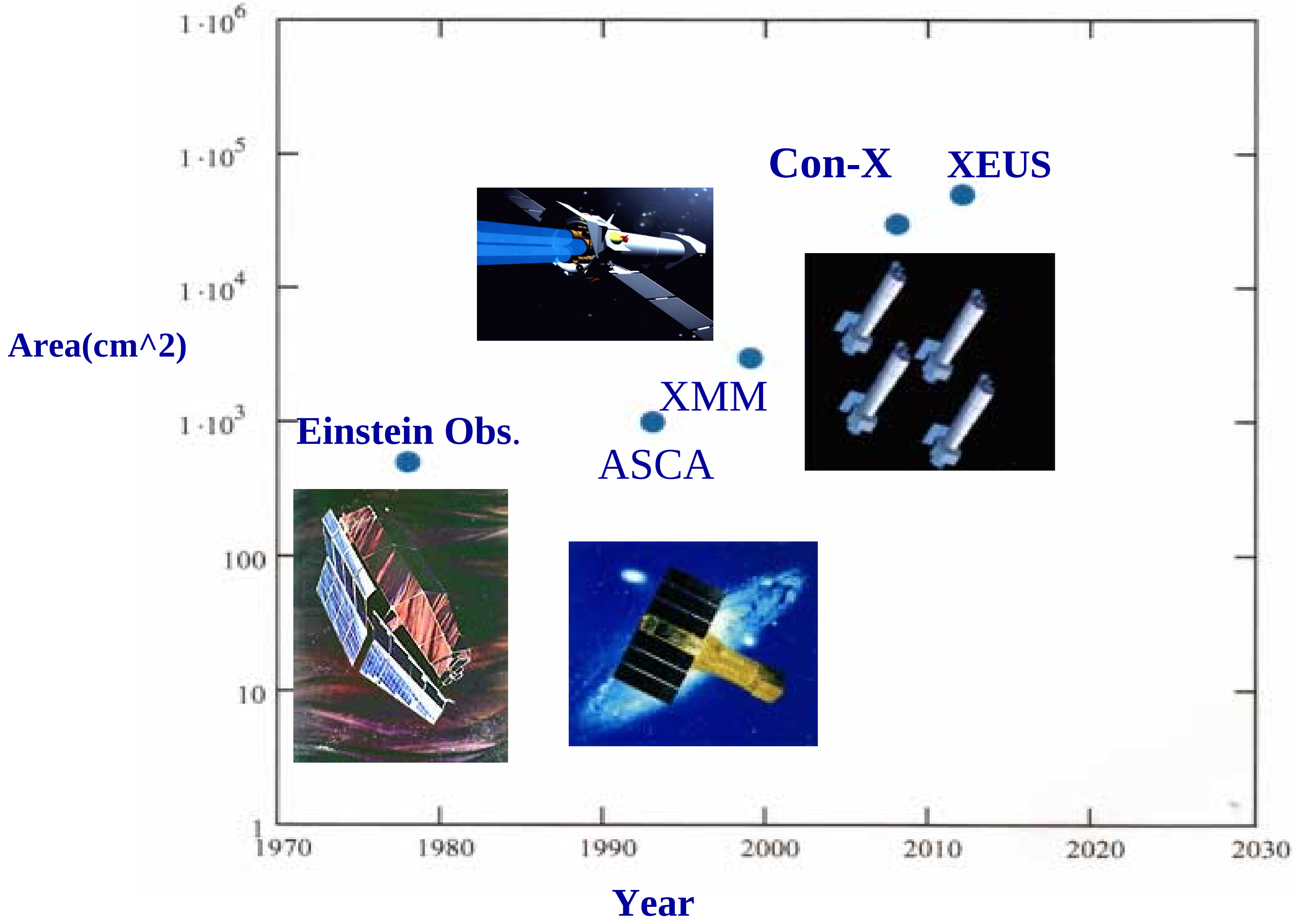
Chandra X-ray Observatory	**ROSAT**
< 1 arcsec	5 arcsec



Black Hole



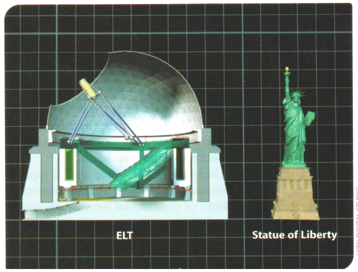
Evolution of High Throughput X-ray Telescopes



Ultra-High Throughput X-ray Observatory with a New Mission Architecture

Optical and Radio Astronomers are also Thinking Big

ELT



Square Kilometer Array

Program Objectives

Define the ultimate high throughput X-ray observatory

“Generation-X” and how it should be developed

- Type of optics
- Geometry of the optics
- Observatory architecture
- Site

Mission Architectures

Ones that Are Radically Different from Current Practice Are Needed to Achieve the Ultimate in:

- **High Throughput**

- **High Angular Resolution**

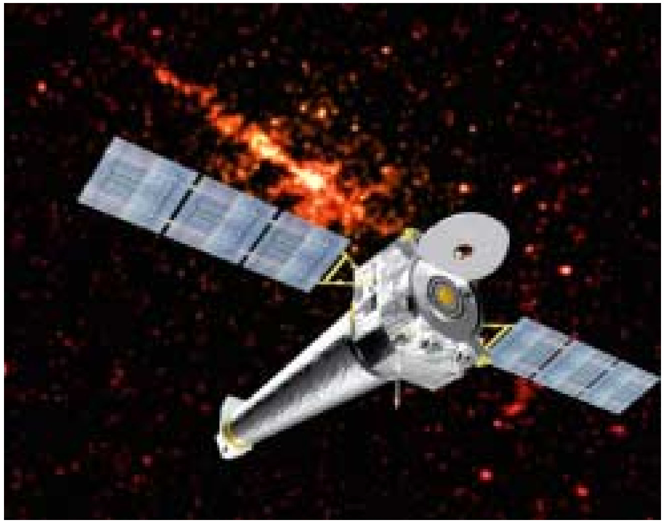
It is not likely that a single facility can provide the ultimate performance in both throughput and resolution. Each is a subject of a separate NIAC mission concept study.

Advantages of Being in Space

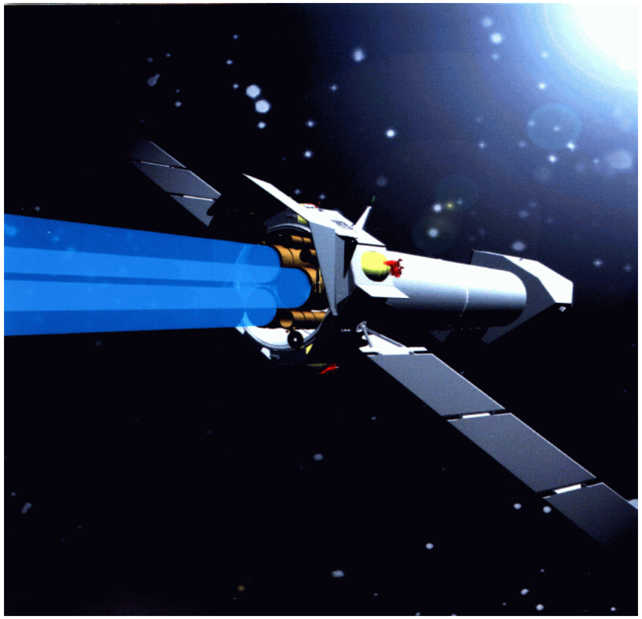
- Above the Absorption of the Atmosphere
- Zero Gravity (permits in situ construction)
- Err…Space (allows giant structures and very long focal lengths

All missions to date have utilized only the first property

The Chandra X-ray Observatory
High Angular Resolution



XMM-Newton
High Throughput



Their conventional spacecraft and mission architectures are inadequate for the future.

The next generation *Constellation X-ray Mission* with an order of magnitude higher throughput than XMM-Newton is a significant change in mission architecture by using multiple identical spacecraft. However it is not a model for future generations with another order of magnitude more throughput.

The Approach

- A new mission architecture where the telescope and each detector are abroad their own spacecraft and can be launched independently
- "Formation Flying" between between telescope and active detector and in some cases an intermediate wavelength dispersive grating
- Long, very long, or extremely long focal lengths, depending on the optics
- Telescope with 30 meter diameter or larger
- Telescope is:
    - Segmented into many modules equipped with angle and position controllers
    - Constructed in situ
    - Functional while under construction

Advantages of the New Mission Architectures

- One launch of a very large mass is replaced by multiple launches of smaller mass payloads
- Not dependent upon success of single launch
- Simpler integration of telescope with detectors
- Allows in situ construction of telescope and use by observers while under construction
- Allows unlimited number of detectors and their replacement
- Facilitates collaborations and participations by smaller institutions and cost sharing with other agencies

Five Options:Telescopes and Mission Architectures

- Familiar Wolter 1 Optics, (parabola + hyperbola), filled aperture, segmented into modules with controllers, **focal length of ~ 200m**
- Kirkpatrick-Baez Optics, (orthogonal parabolas) filled aperture, segmented into modules with controllers, **focal length of ~ 300m**
- Kirkpatrick-Baez Optics, sparse aperture, segmented into panels, **focal length of ~ 10 km**
- Fresnel Zone Plate + Fresnel Type Lens with correction for chromatic aberration and **focal length of ~ 1000 km**
- **Lunar Based Observatory for Wolter or KB filled aperture**

  focal length of ~ 200m

Physical Area of Grazing Incidence Telescopes

Telescope Diameter = 30 m

$$\text{Aperture} = 700\ \text{m}^2$$

$$\text{Graze Angle}\ \theta = 1.5\ \text{deg}$$

$$\text{Packing Fraction} = 0.6 \qquad \text{Reflectivity} = 0.6$$

$$\text{Efficiency} = \text{Reflectivity}^2 \cdot \text{Packing Fraction}$$

$$\text{Total Area} = \frac{2 \cdot \text{Aperture}}{\text{Sin}\,\theta \cdot \text{Efficiency}}$$

$$\text{Total Area} = 2.5 \times 10^5\ \text{m}^2$$

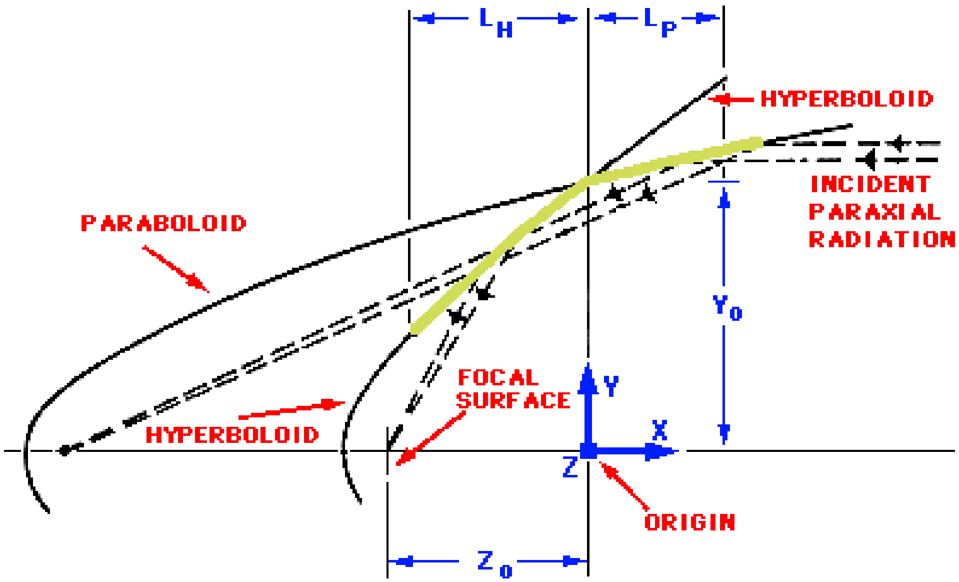
Total Reflector Area = 250,000 square meters

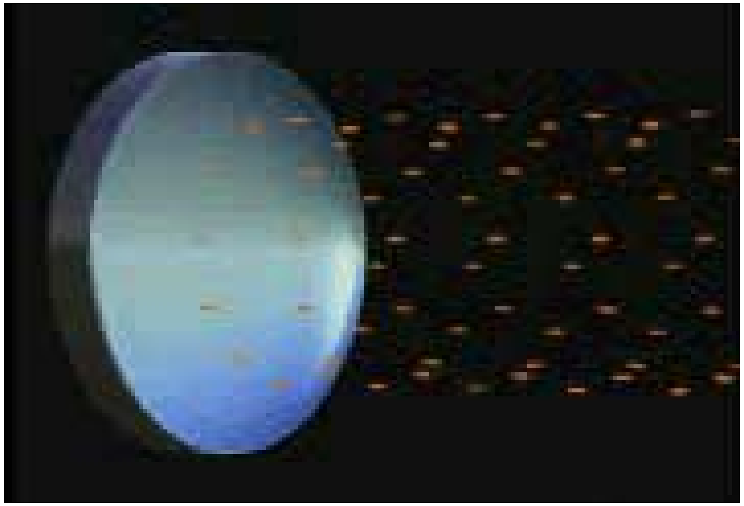
Lightest material may be 7 mil (175 micron) tensioned plastic

Density with framing to provide tension and slight curvature is estimated to be ~ 0.5 kg/sq. m.

Total Mass = 125 Tons

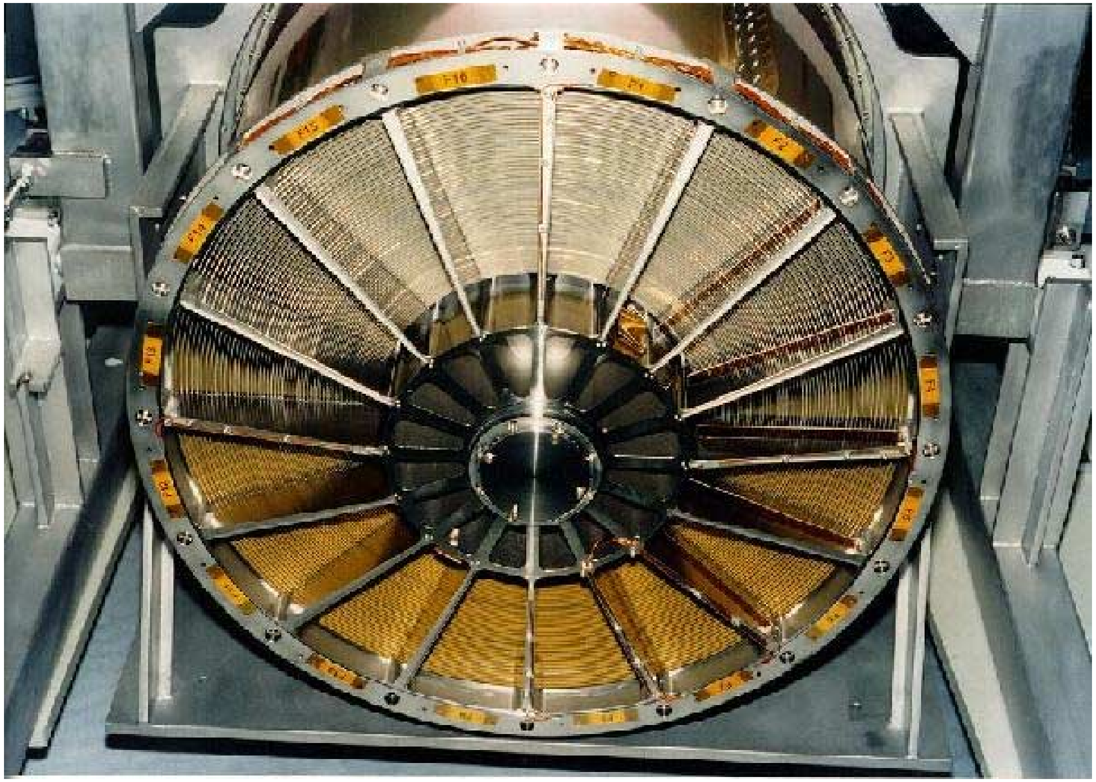
Wolter 1 Optics





Every X-ray telescope that has been or is now in orbit is a Wolter Type 1 optic.

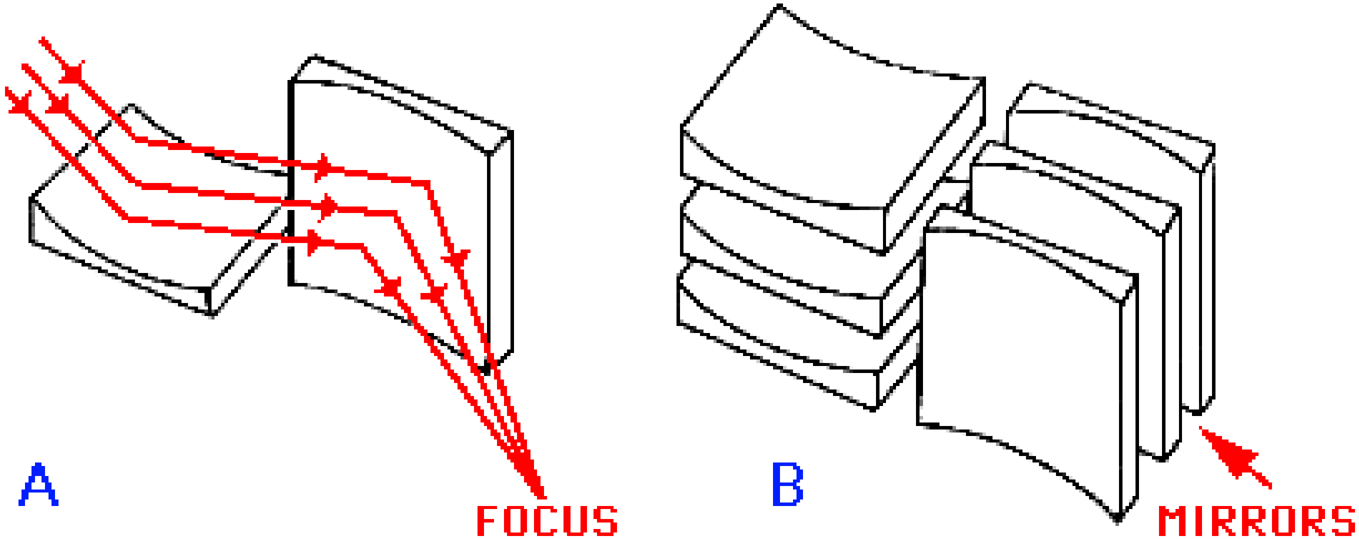
European Space Agency's XMM

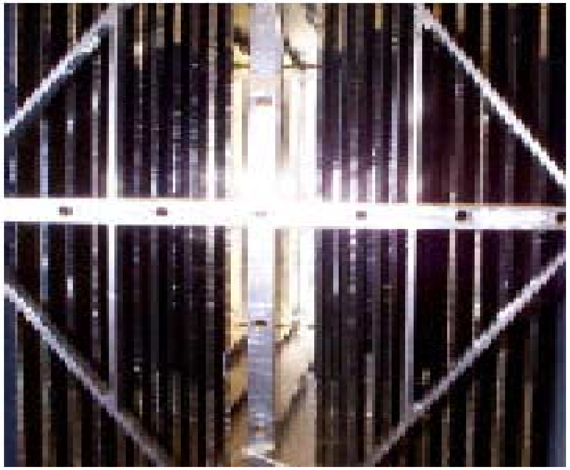


XMM Mirror (1 of 3)

300 Micron Gold Coated Nickel Foils, Media Lario, Italy For Segmented Filled Aperture Wolter Telescope

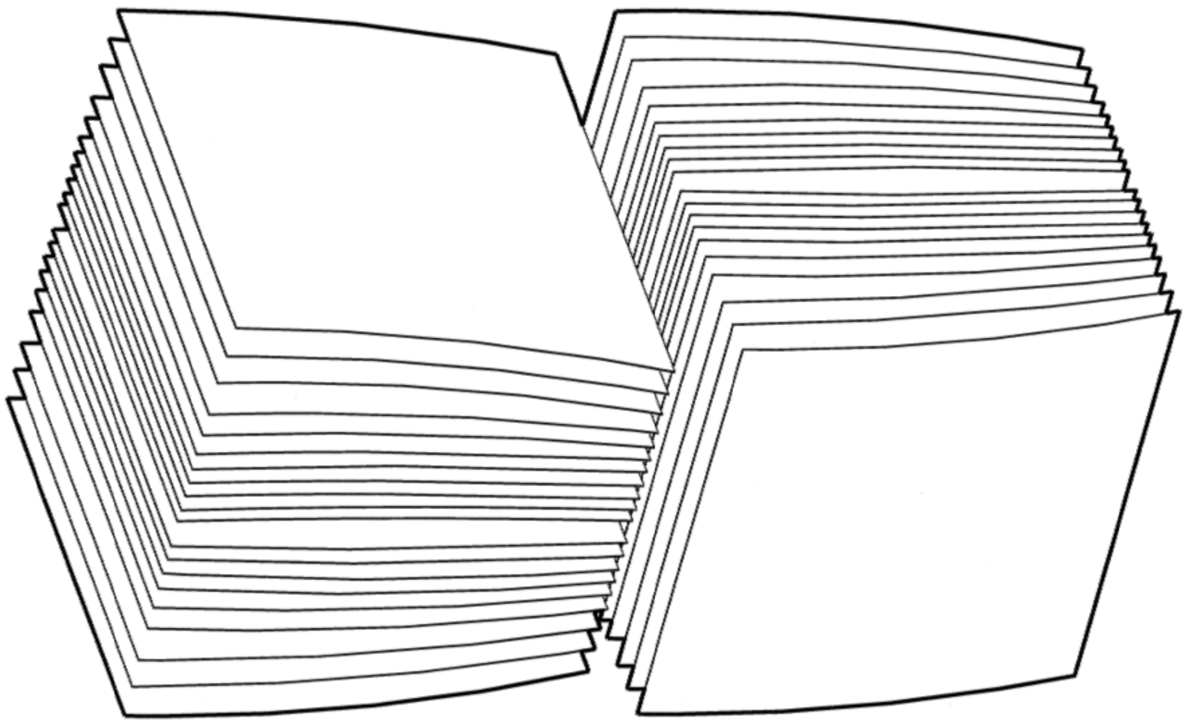
Kirkpatrick-Baez Optics, Orthogonal Parabolas



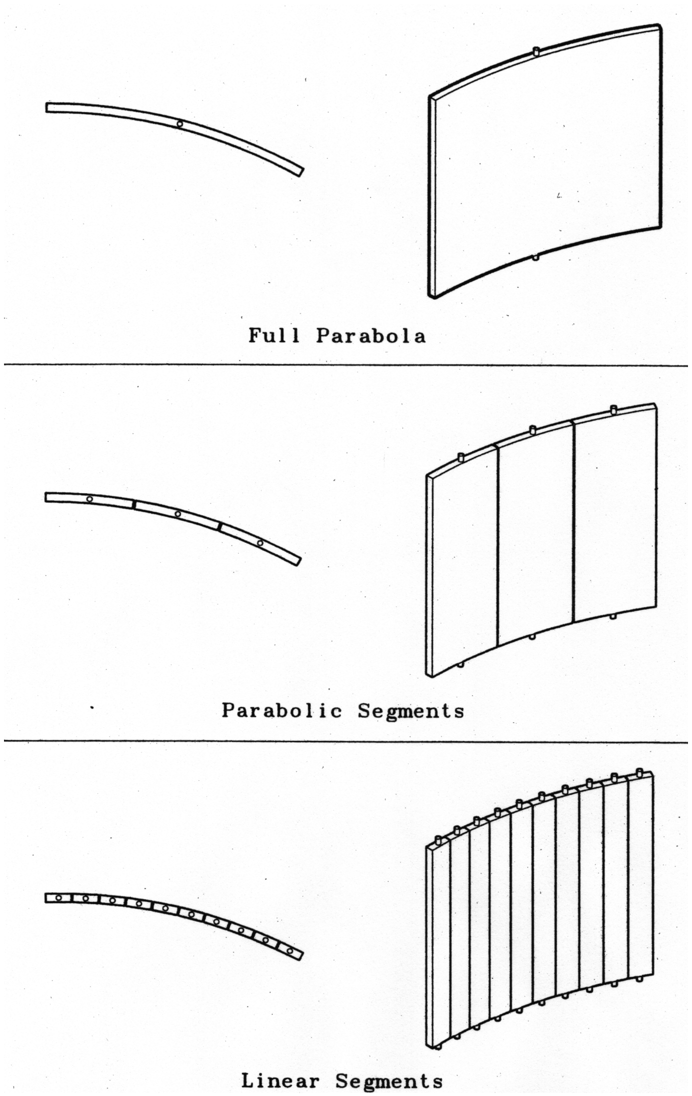


Ultra-High Throughput X-ray Observatory with a New Mission Architecture

Kirkpatrick-Baez Mirror, Orthogonal Parabolas, Single Module or Entire Array



Linear Segment Approximation to Parabola

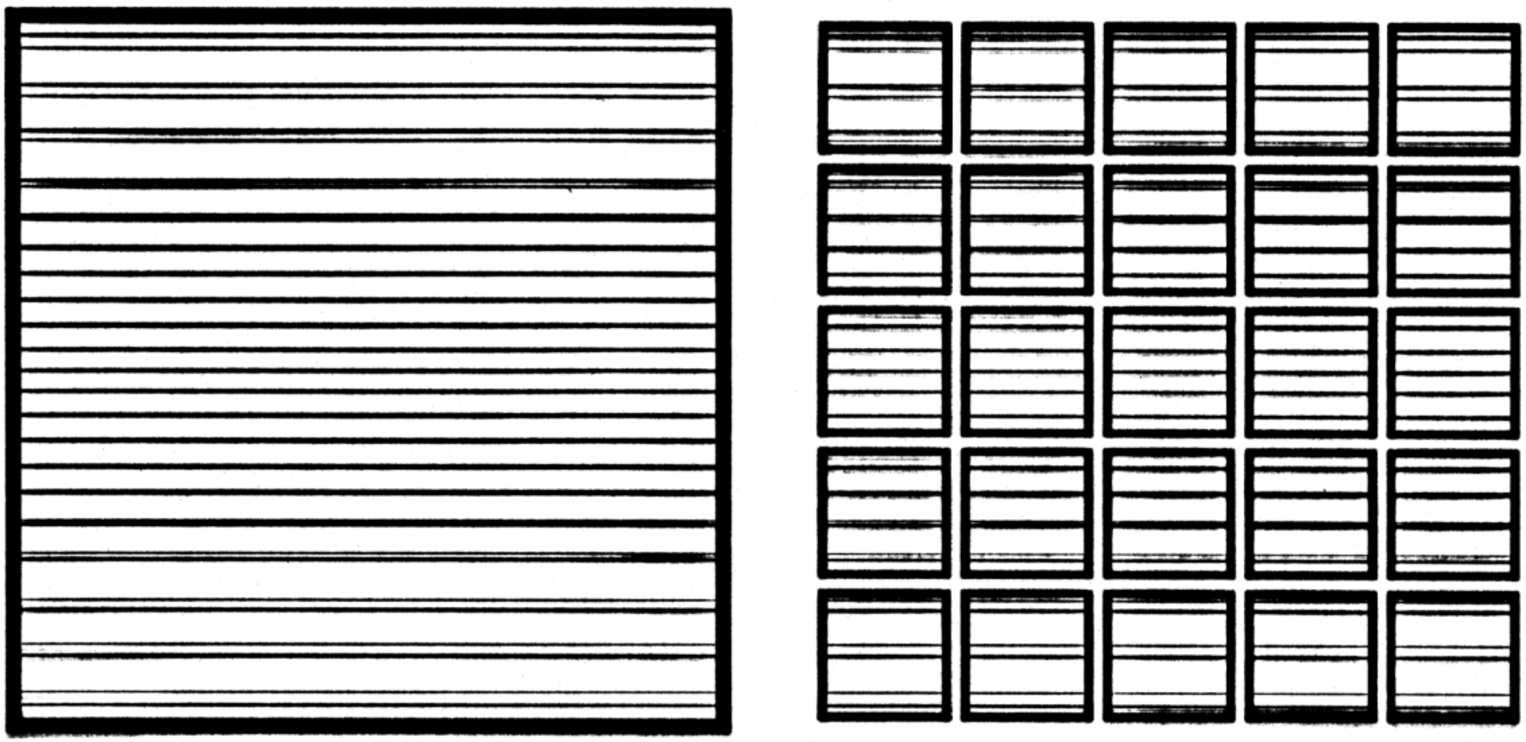


Single Parabola

A Few Curved Segments

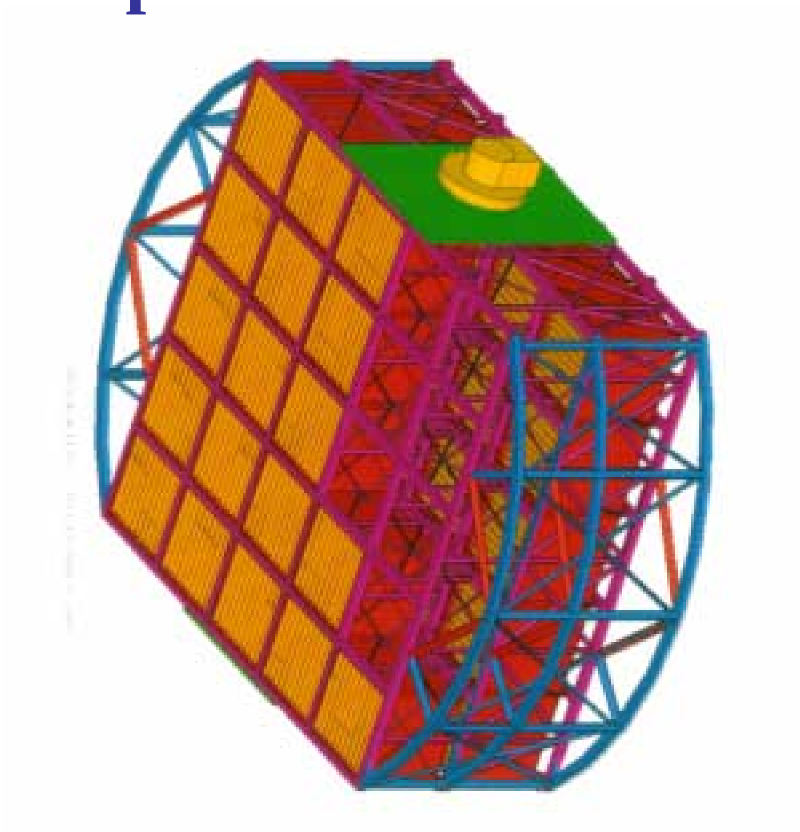
More Linear Segments

Segmenting a KB Mirror Into Equal Size Modules

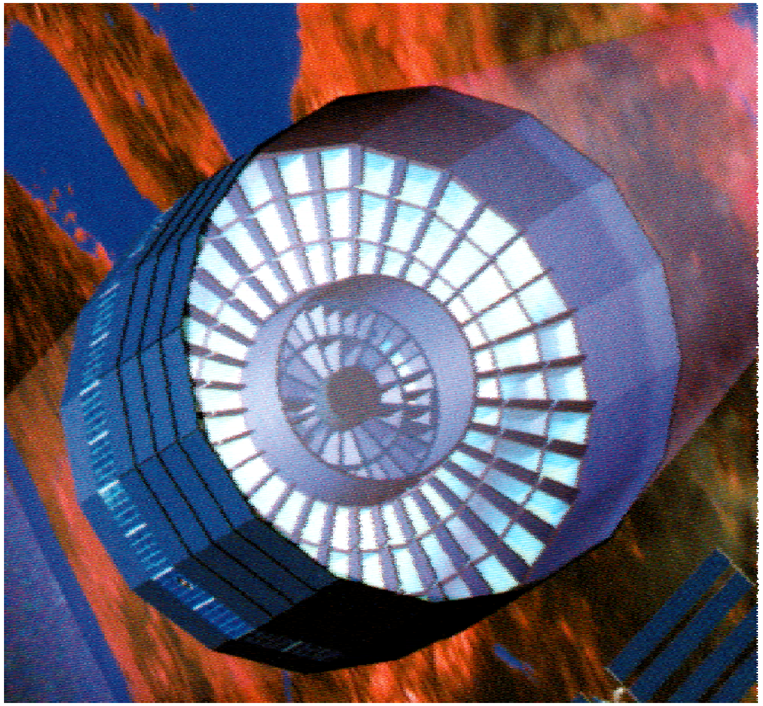


Filled Aperture Segmented Telescopes with Controllers for Aligning Angle and Position

Kirkpatrick-Baez



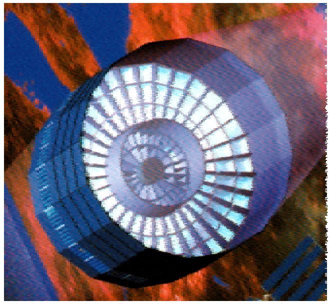
Wolter



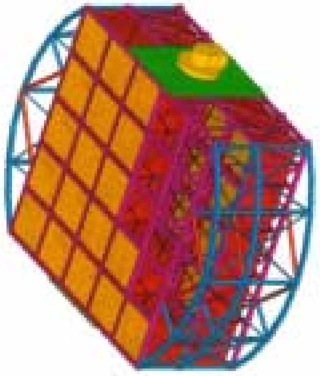
XEUS Mirror (ESA)

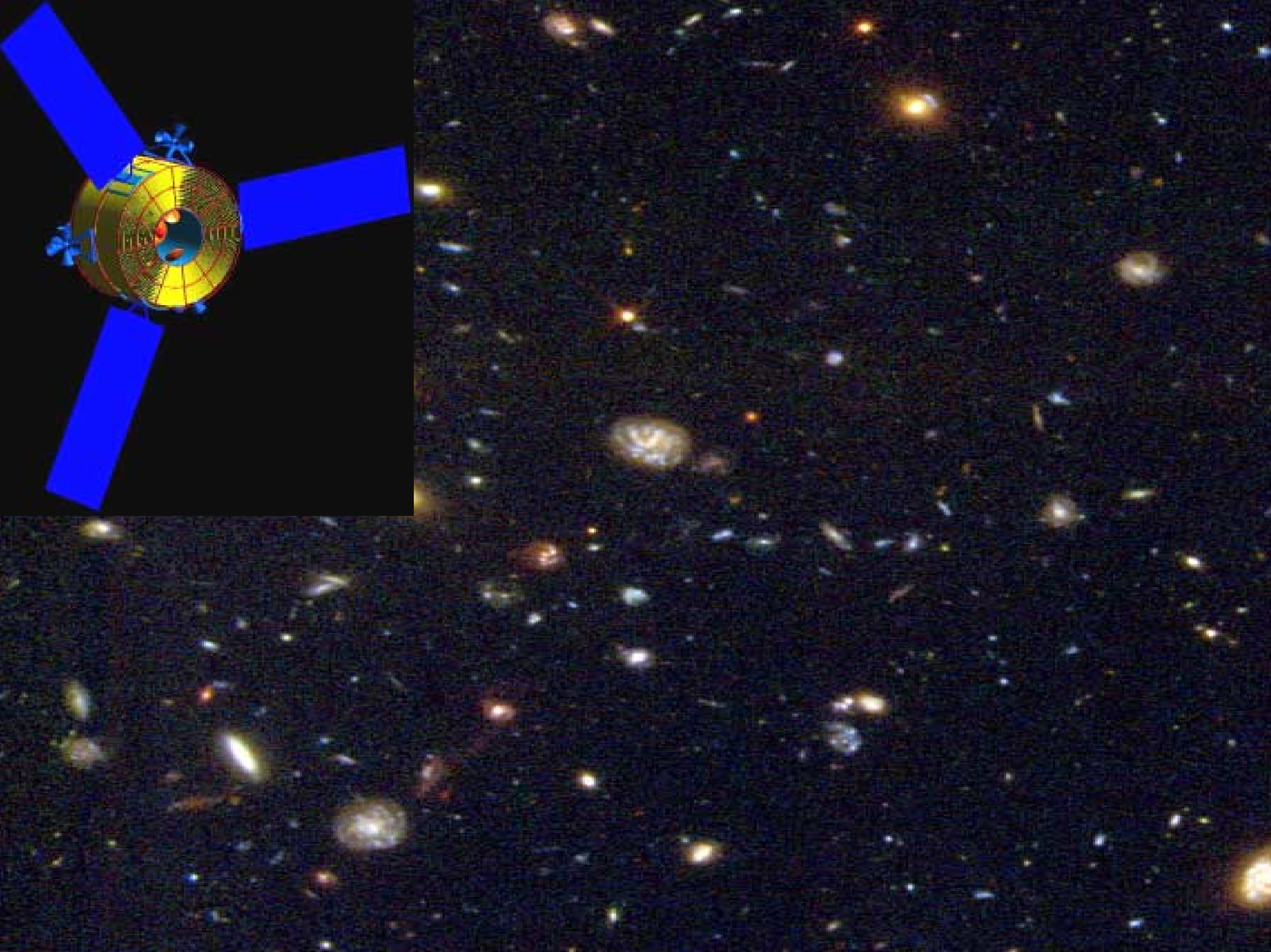
Comparison of Wolter and KB Segmented Optics

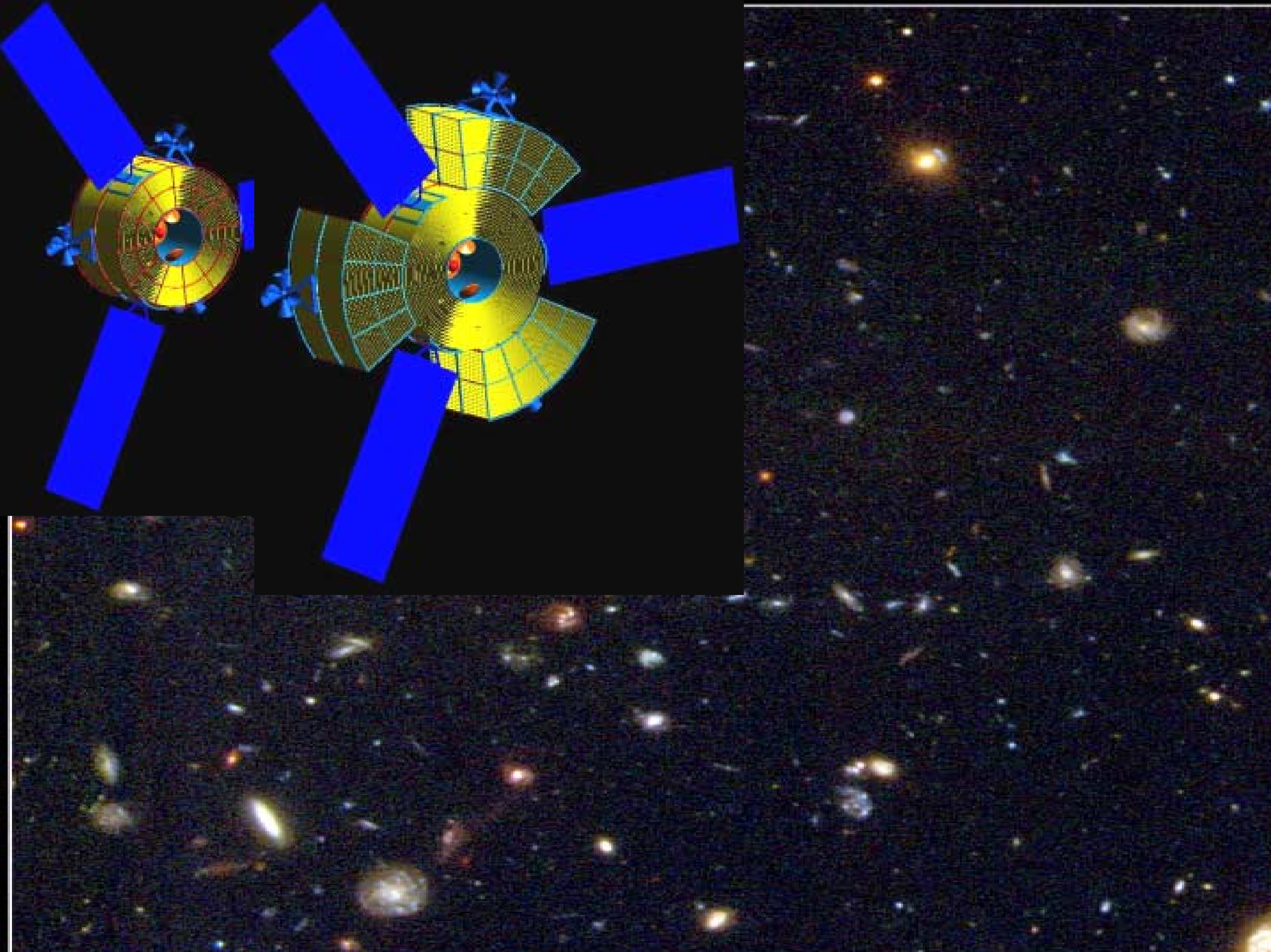
- There is more experience with the Wolter and Con-X will add to it
- The theoretical resolution of the Wolter is superior, especially off axis
- The Wolter optic has a superior geometric efficiency

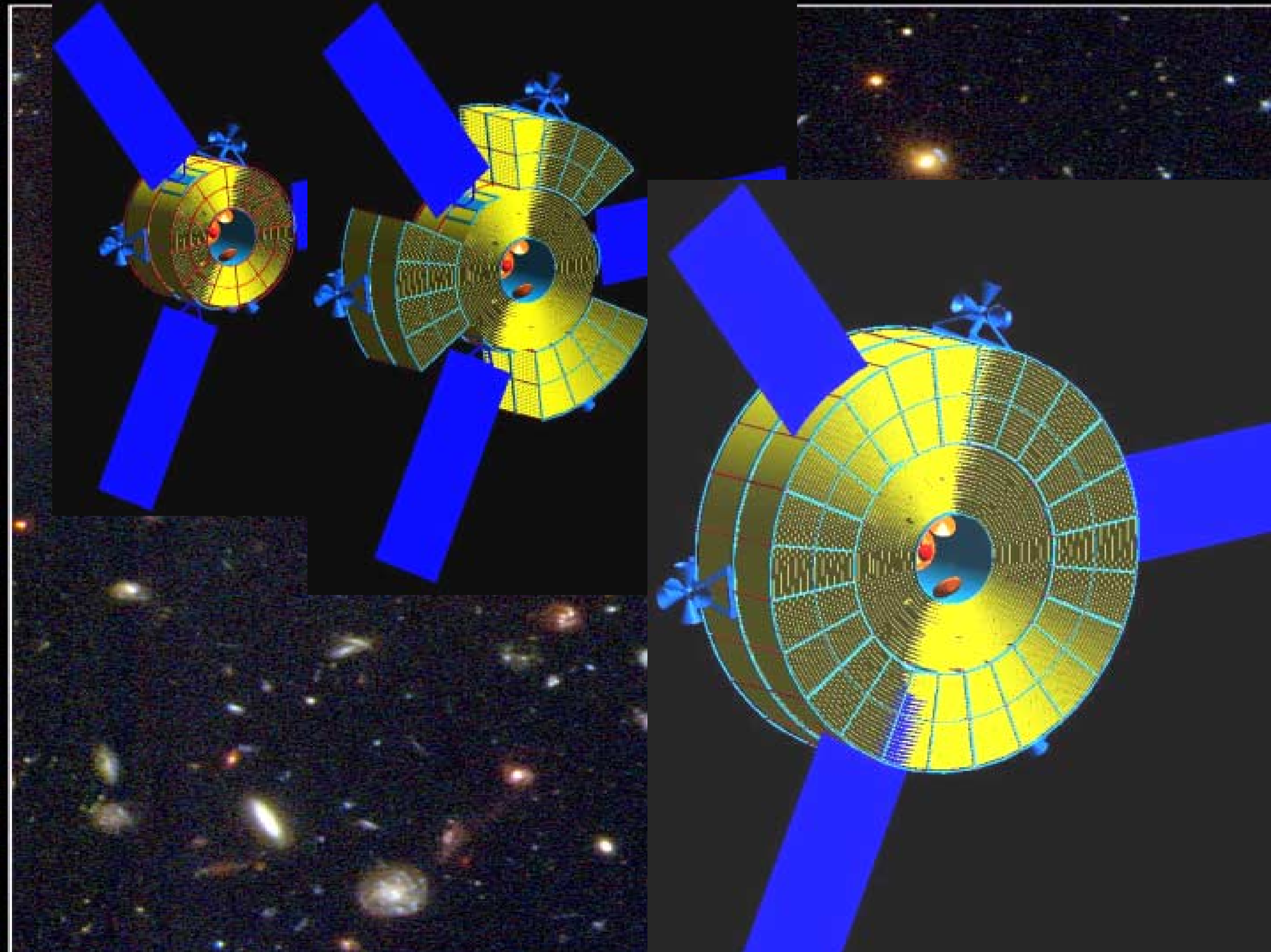


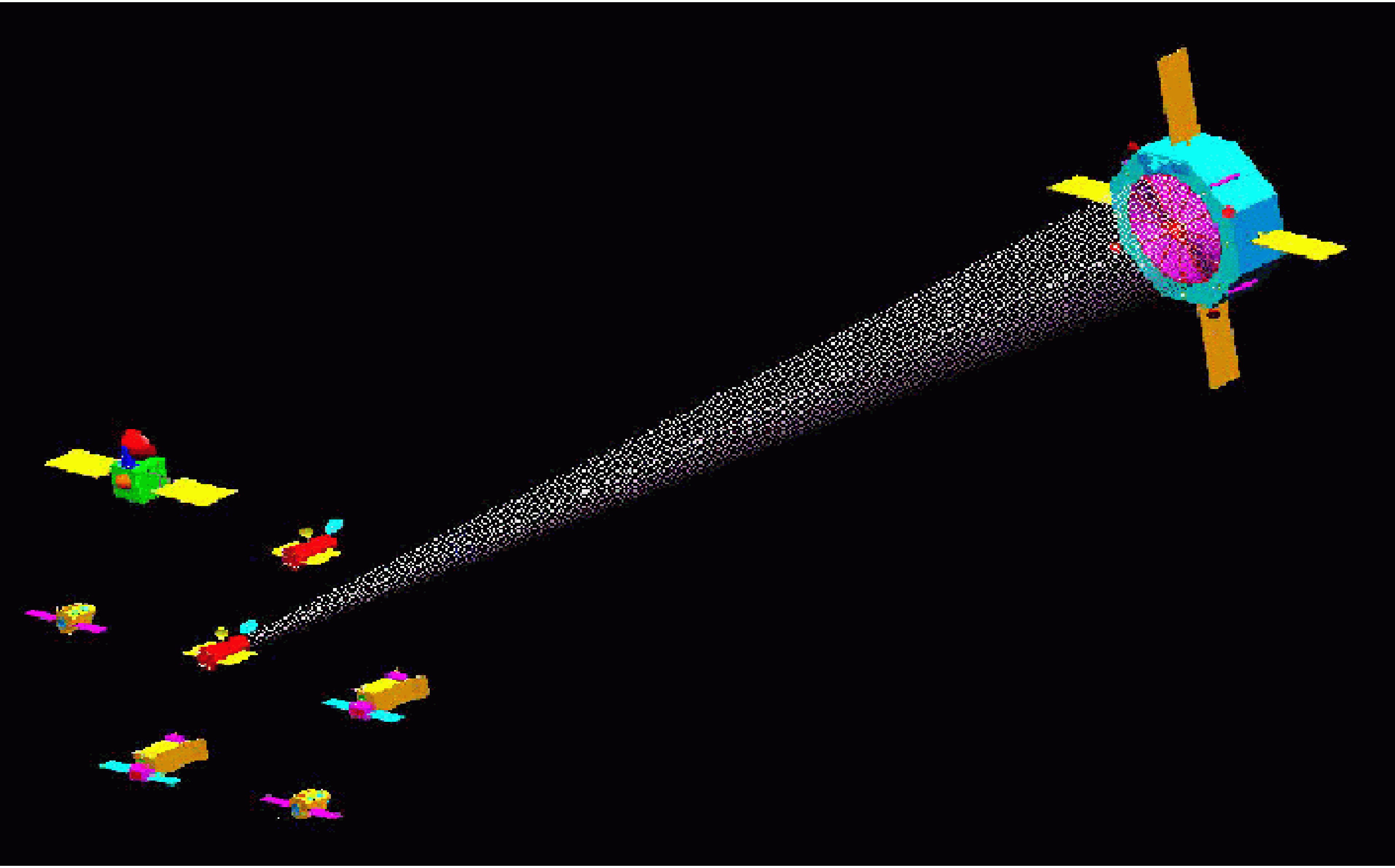
- The KB can be made of flats or near flats which may result in better angular resolution in practice
- Segments of a KB are rectangular and can have identical exterior dimensions resulting in fewer parts











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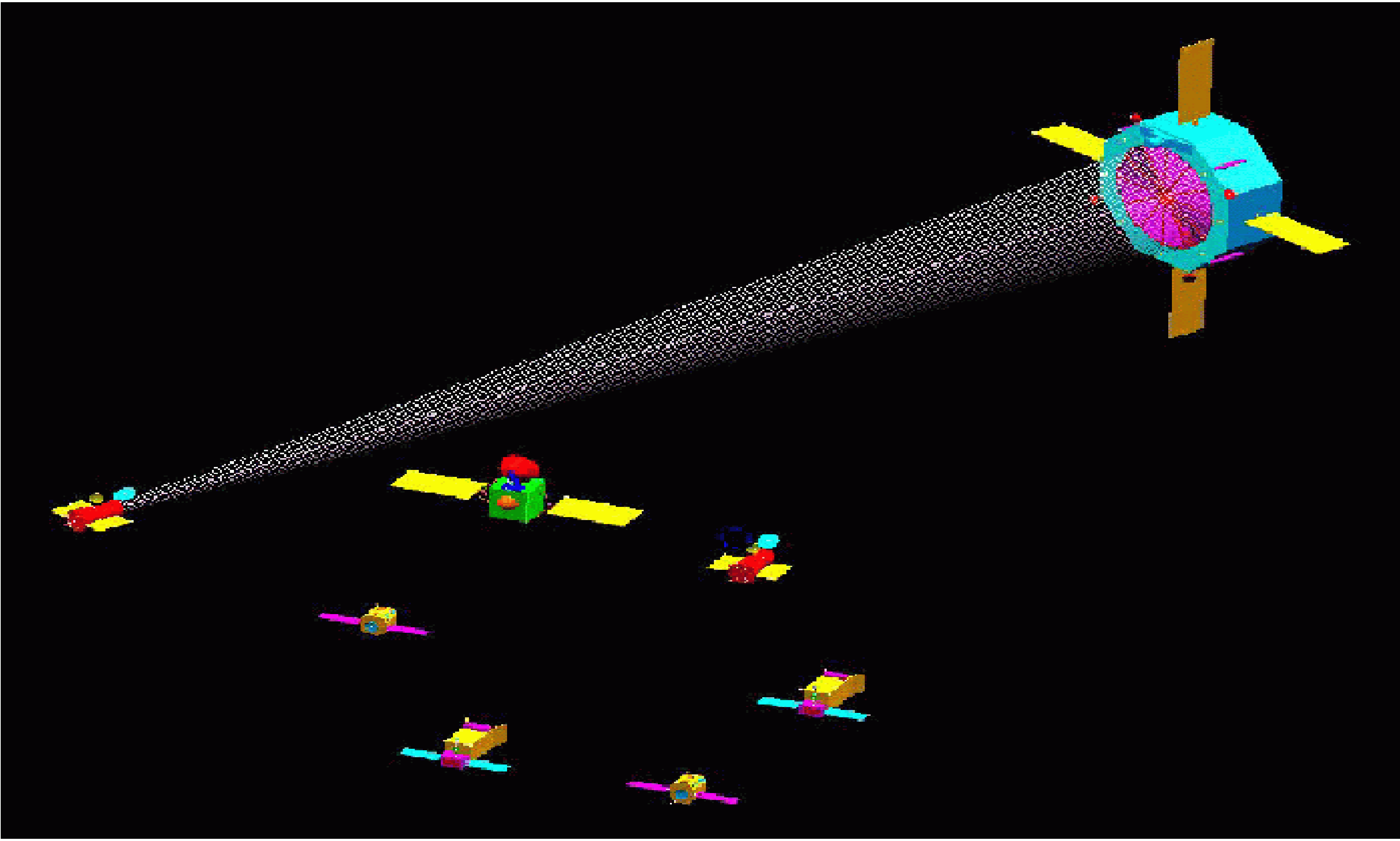

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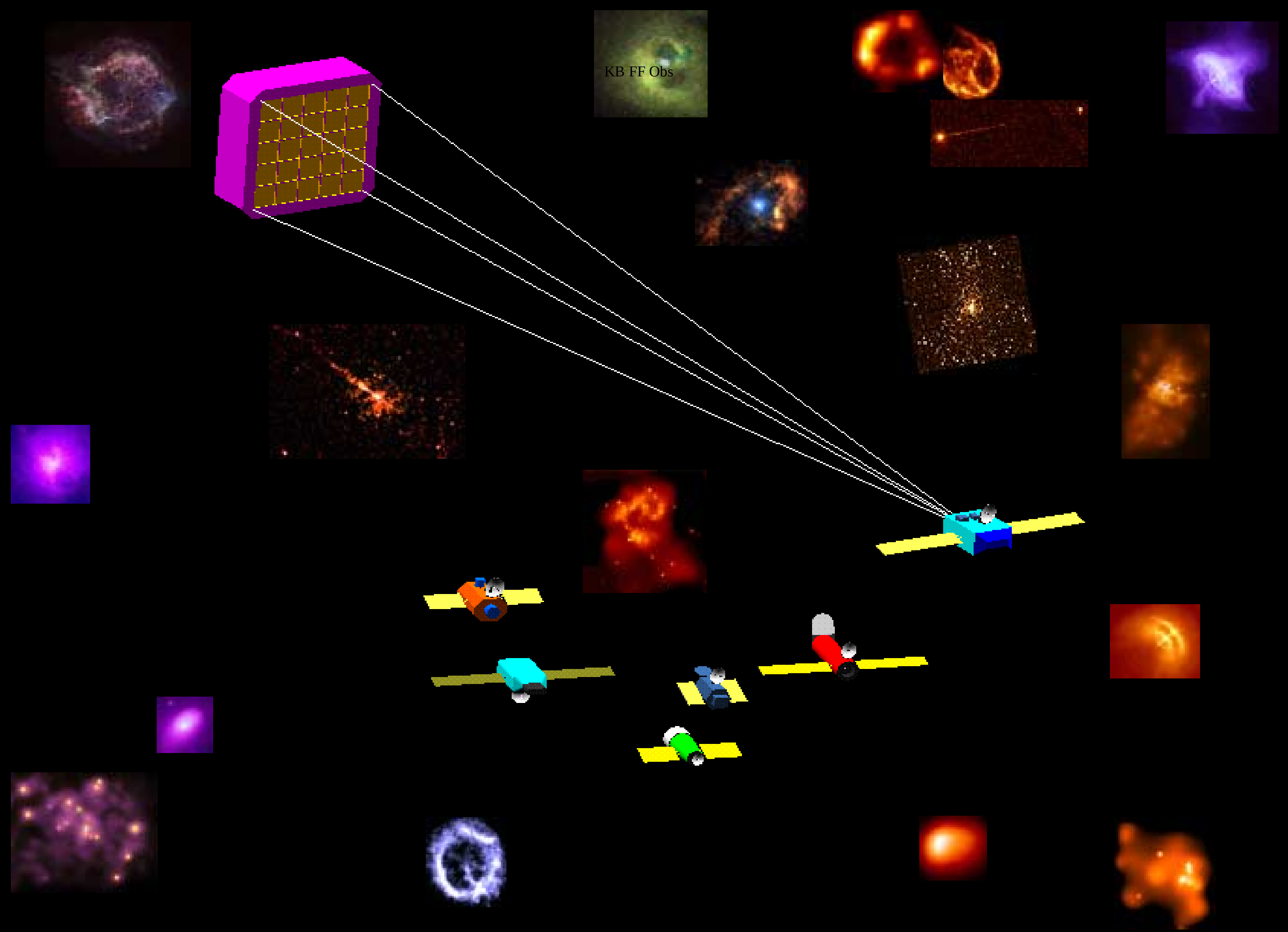
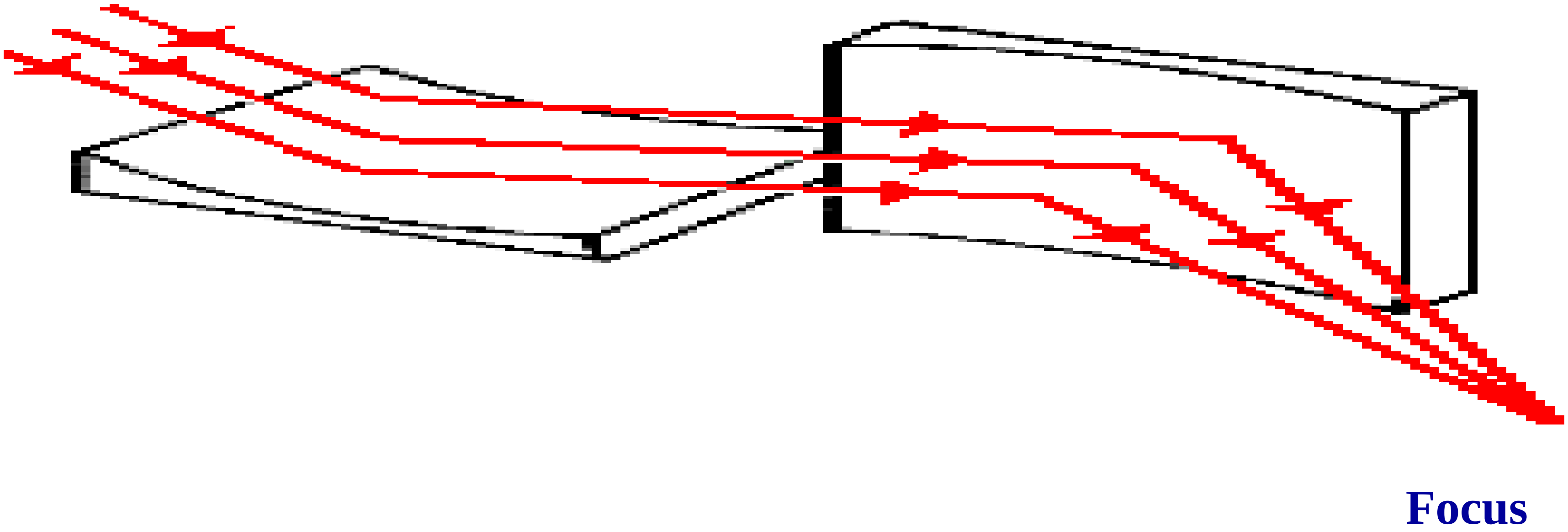
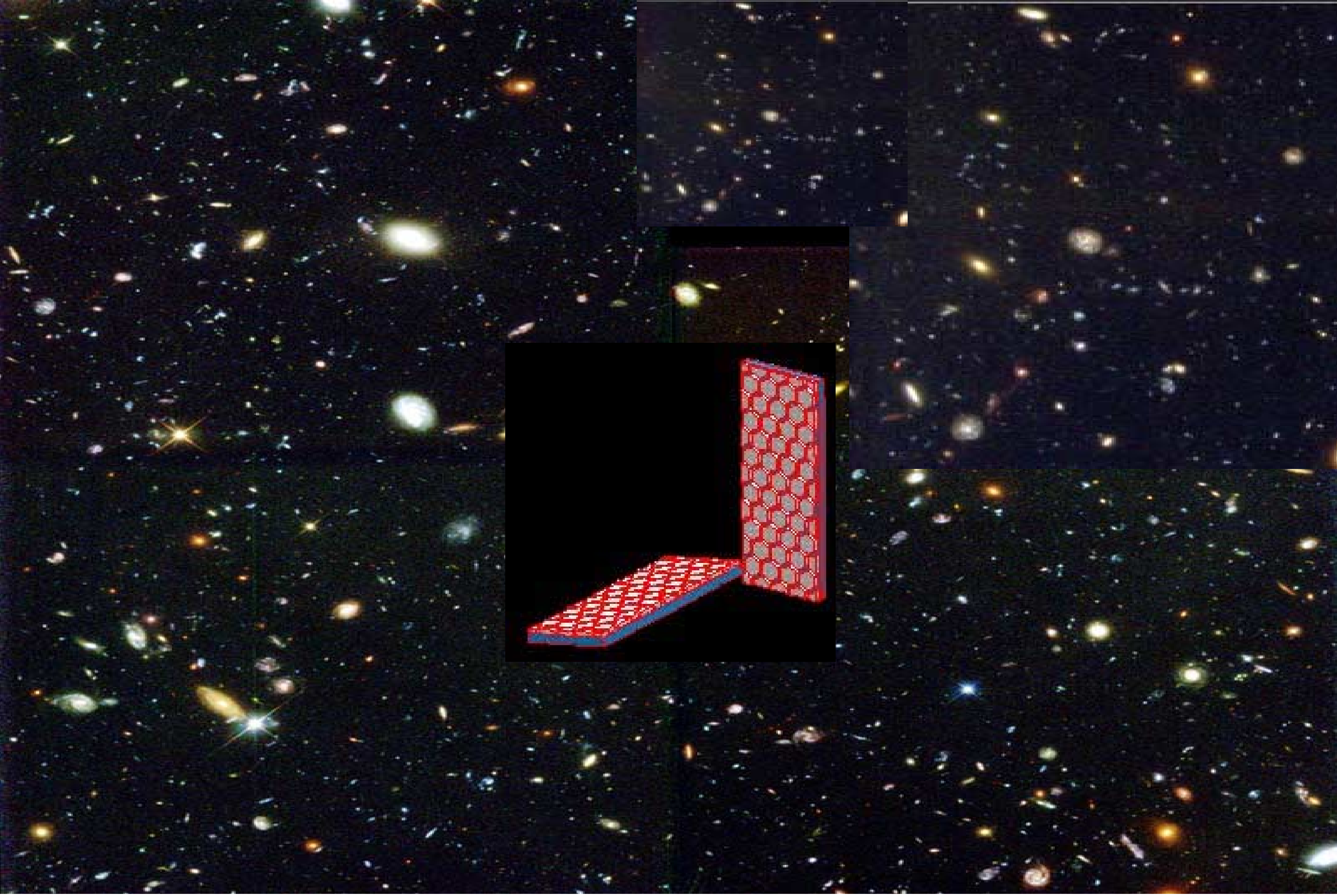

KB FF Obs

Sparse Aperture KB Telescope





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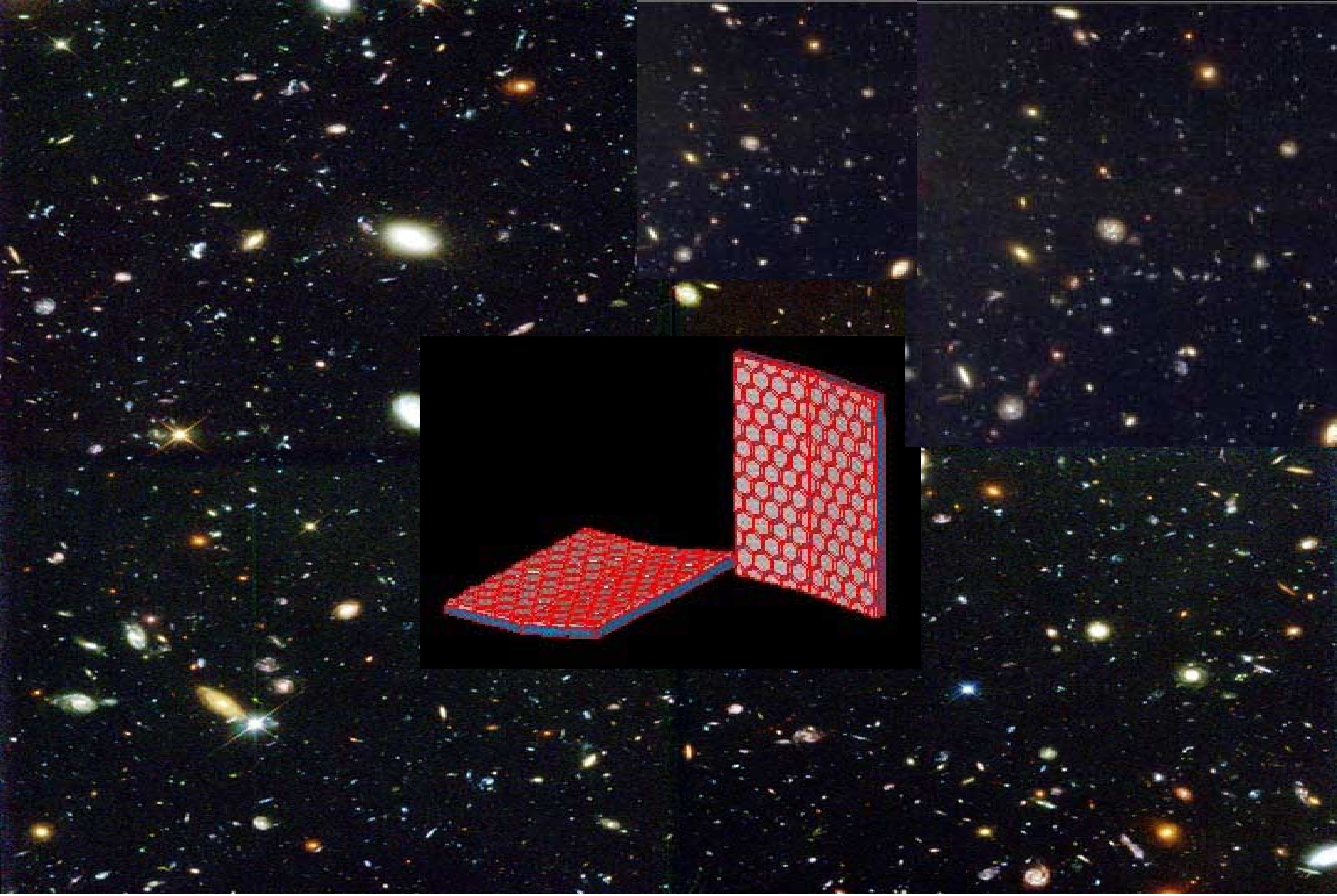

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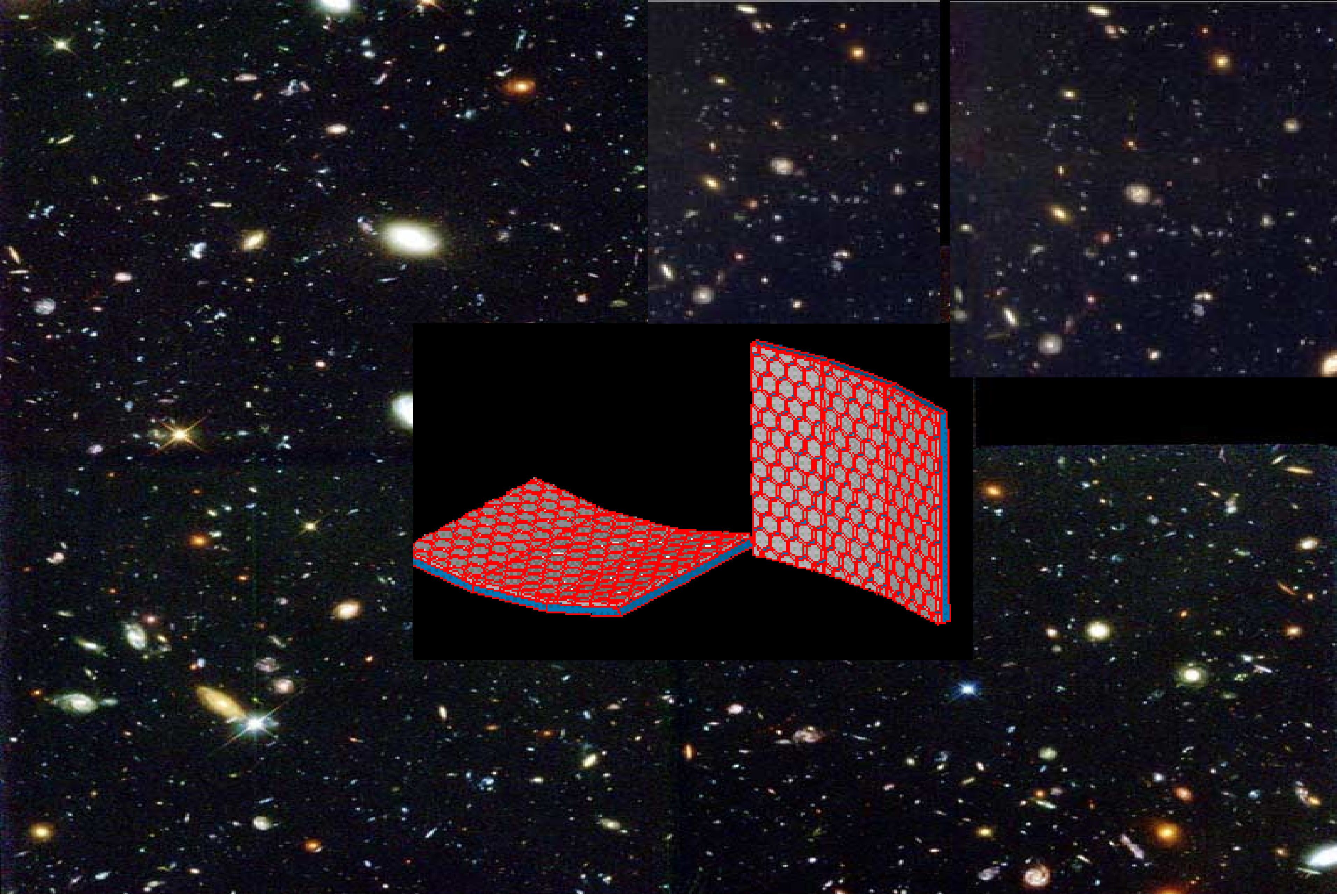

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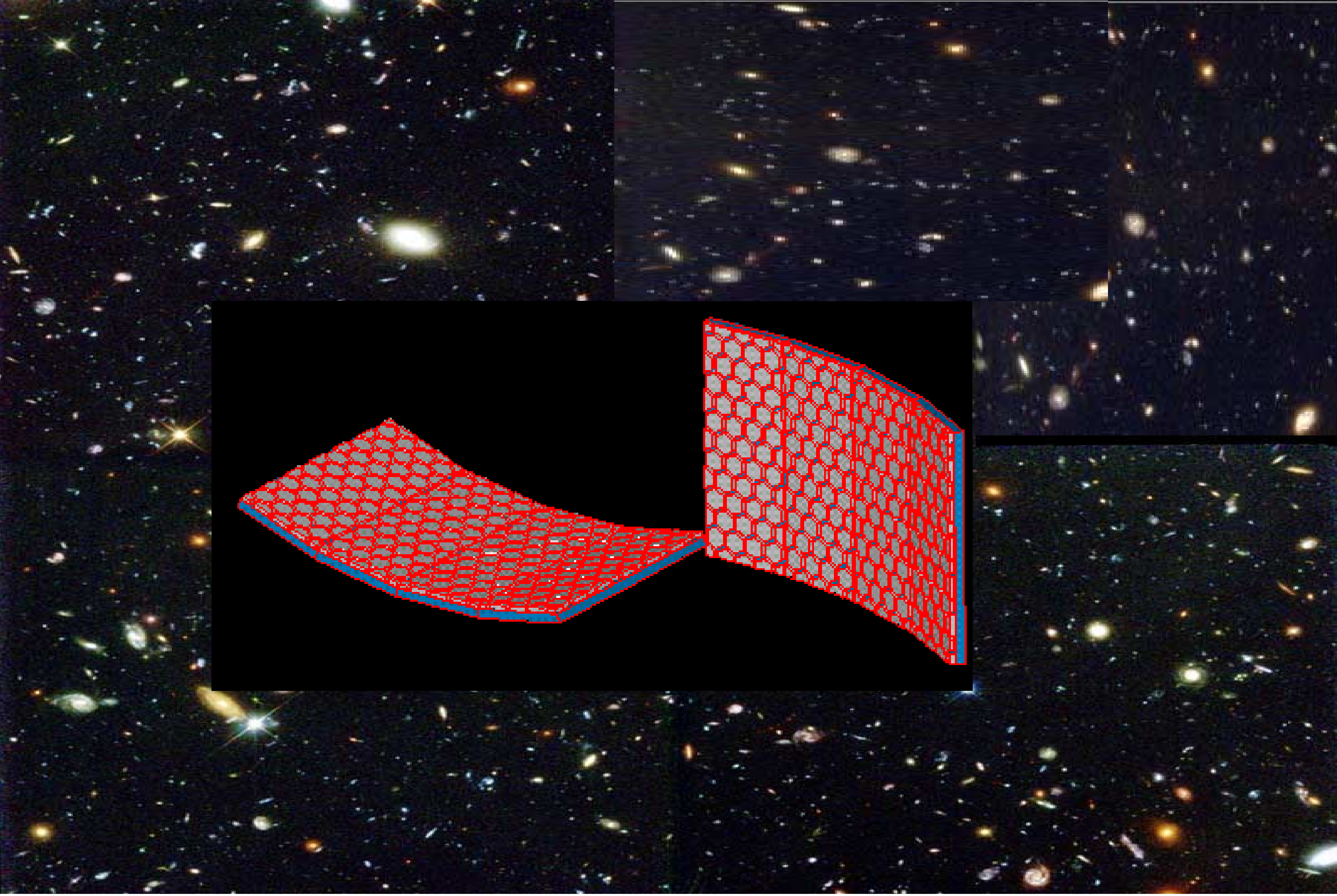


Ultra-High Throughput X-ray Observatory with a New Mission Architecture

Steward Obs. (U. of A.) Tensioned Membranes For Sparse Aperture K-B Telescope

The Flat Membrane Telescope Concept

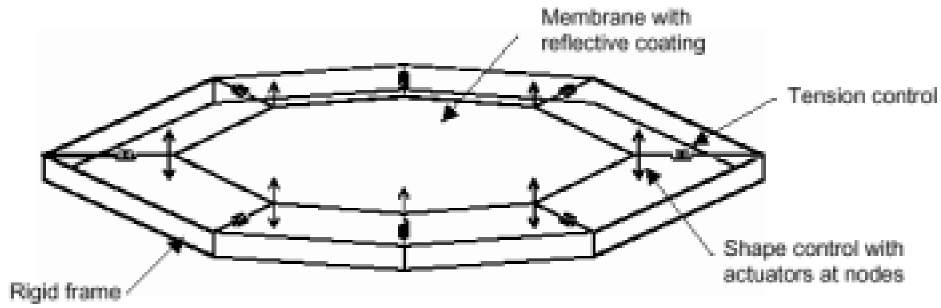
Very Large Optics for the Study of Extra-solar Terrestrial Planets

N. Woolf, R. Angel, J. Burge, W. Hoffmann and P.Strittmatter
Steward Observatory, University of Arizona

Stretched membrane with electrostatic curvature (SMEC): A new technology for ultra-lightweight space telescopes

Roger Angel, James Burge, Keith Hege, Matthew Kenworthy and Neville Woolf

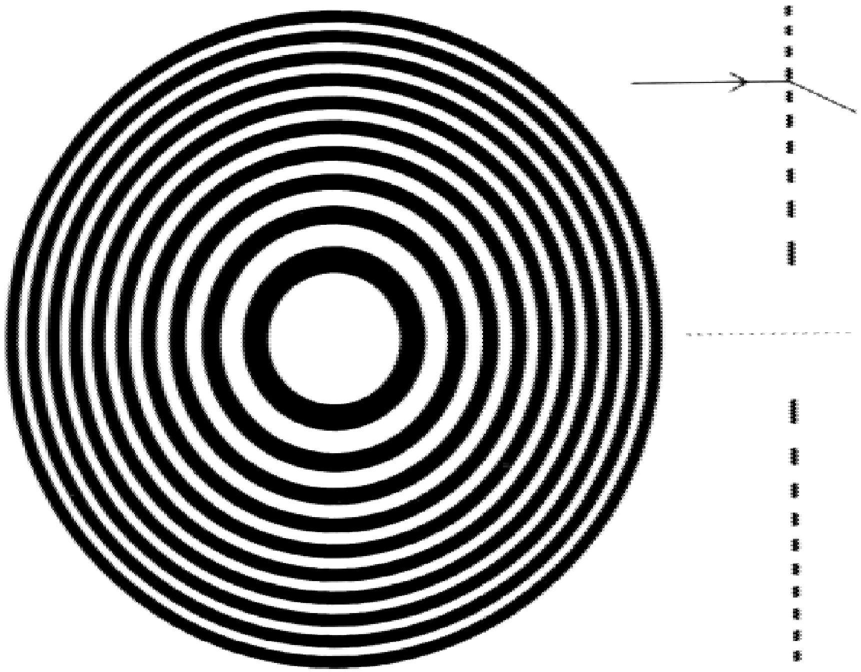
Steward Observatory, The University of Arizona, Tucson, AZ 85721



Fresnel Zone Plate and Fresnel Telescope

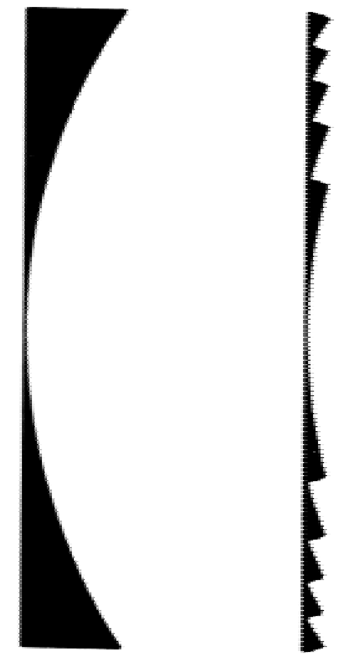
Diffractive

All energies



Refractive

> 3 keV

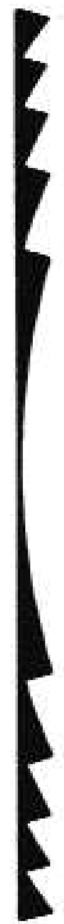


Converging Lenses

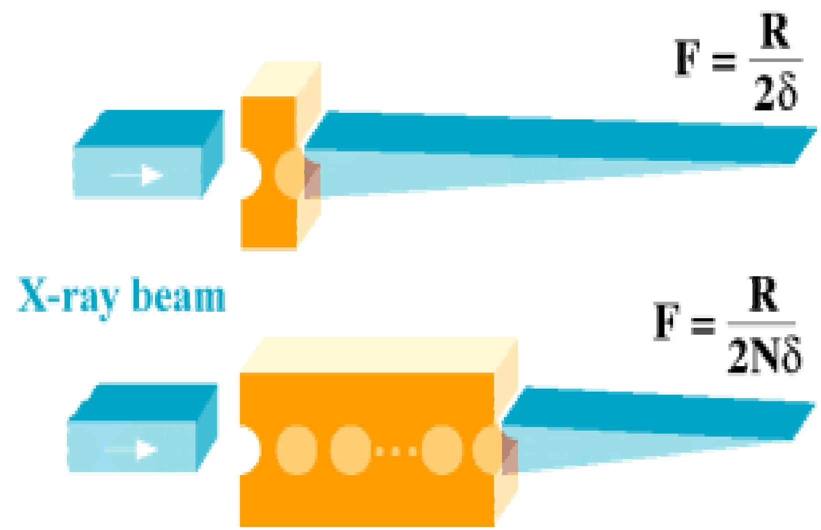
Refractive X-ray Lenses

Converging Lens

Fresnel Equivalent



Compound Lens (1D)

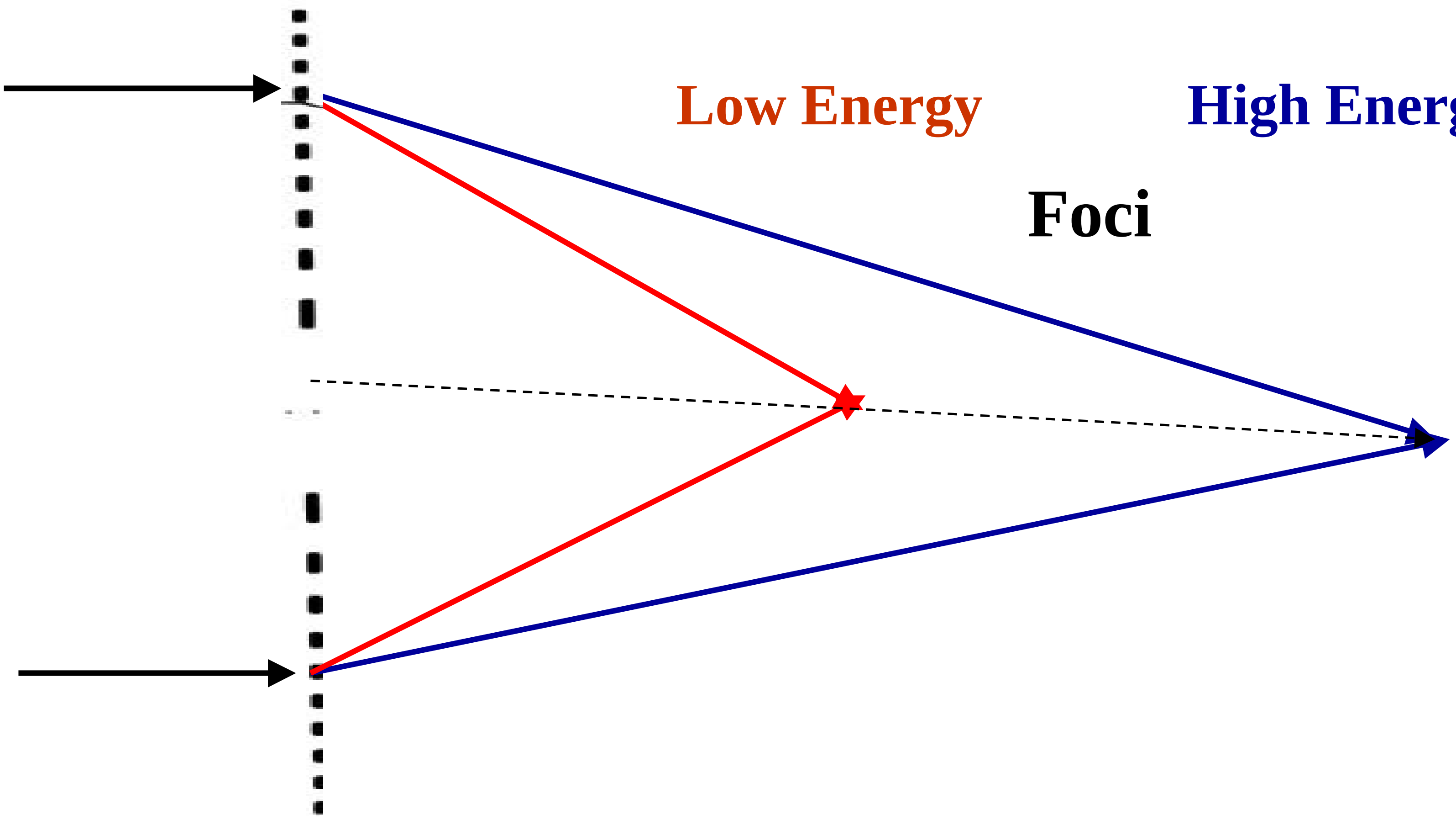


Advantages of the Fresnel Zone Plate /Lens

- **Focuses by selective transmission rather than reflection**
  - **Surface condition and figure fidelity are not critical**
  - **Need not be perfectly flat**
  - **No polishing required**
- **Normal incidence**
  - **Physical area is the actual aperture area**
  - **Material need only thick enough to absorb X-rays**
  - **Relatively low mass, ~ 1 ton as compared to ~ 100 tons**
- **Small volume, can be folded or rolled for launch**

Extreme Chromatic Aberration of Fresnel Zone Plate and Fresnel Lens

Focal Length: ~ E for Zone Plate, (~ E^2 for Lens)

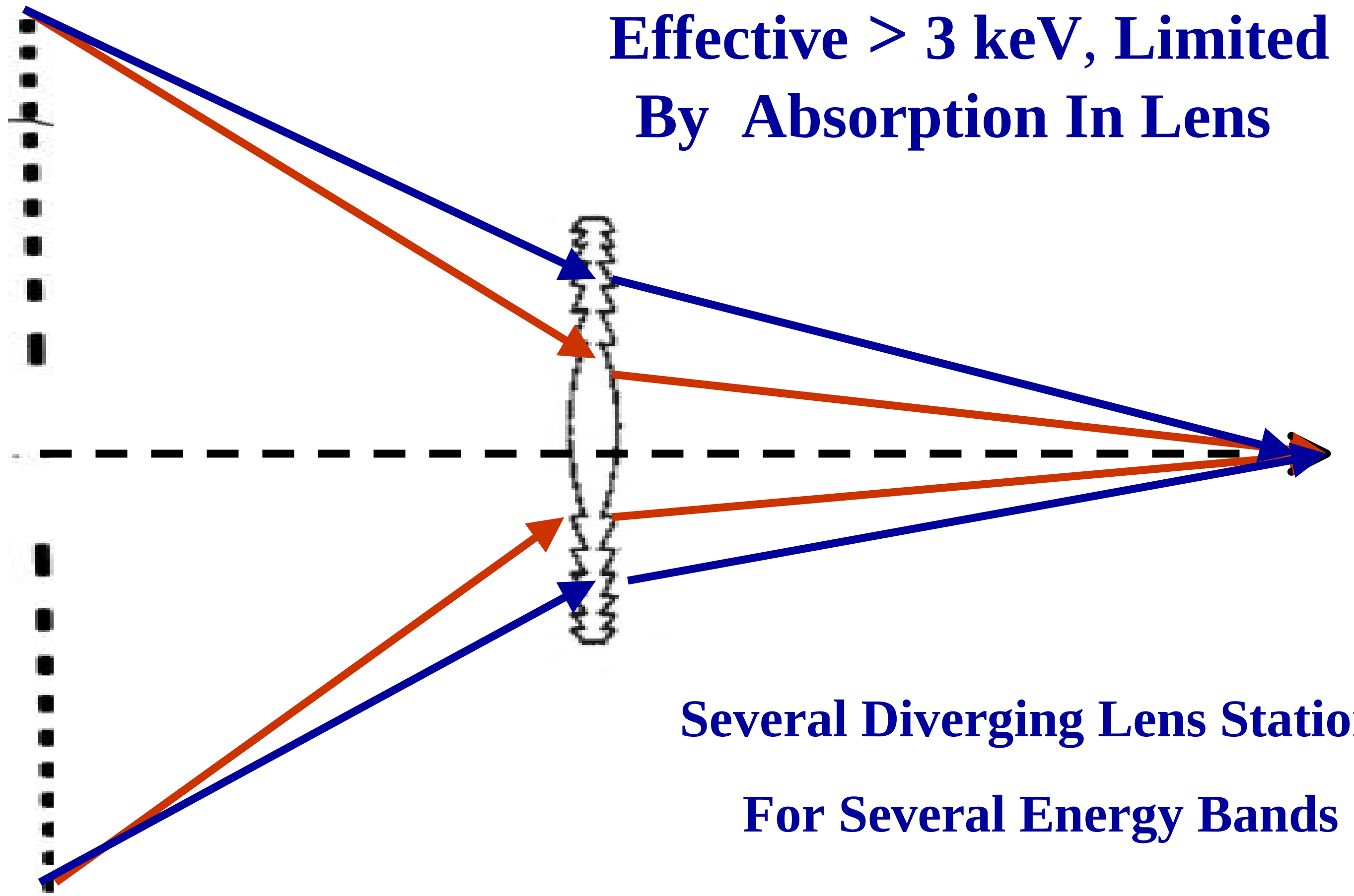


Strategies for Coping with the Fresnel Lens/Zone Plate Chromatic Aberration

Each of the following is effective only in a narrow band of wavelength. However the total bandwidth can be increased by applying each multiple times and simultaneously at various distances from the telescope.

A. For Imaging and Source Detection: Combine Convergent Fresnel Zone Plate and Divergent Fresnel Lens (L. Van Speybroeck)

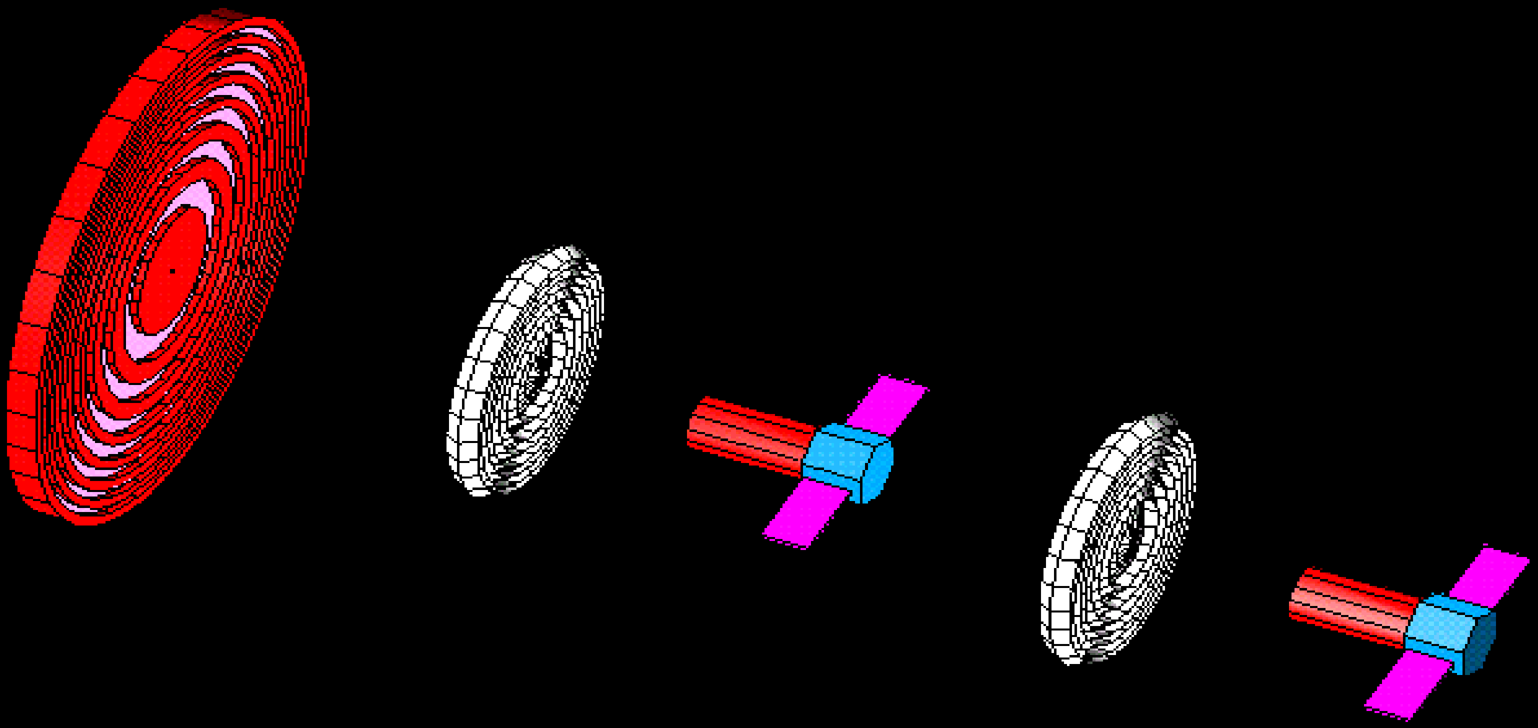
Correcting Chromatic Aberration In Finite Band of Wavelength By Combining Converging Zone Plate and Diverging Lens



Effective > 3 keV, Limited By Absorption In Lens

Several Diverging Lens Stations

For Several Energy Bands



Ultra-High Throughput X-ray Observatory with a New Mission Architecture

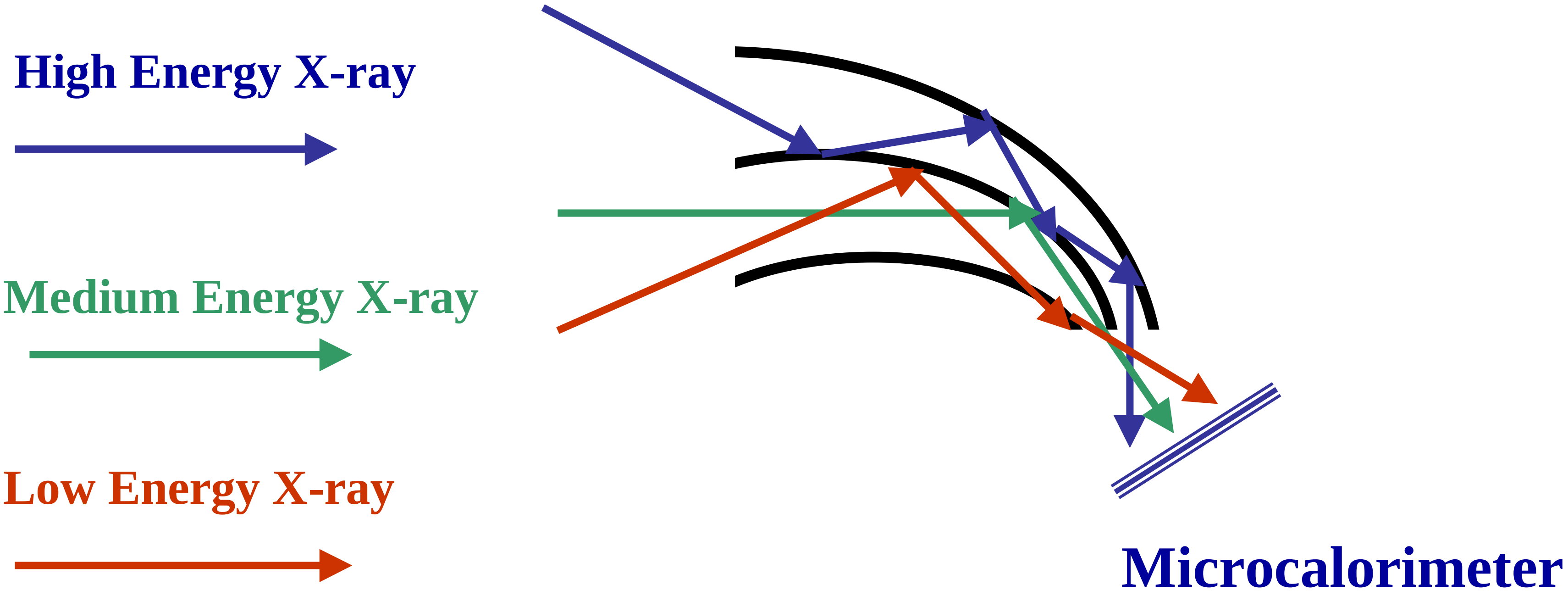
Strategies for Coping with the Fresnel Lens/Zone Plate Chromatic Aberration

Each of the following is effective only in a narrow band of wavelength. However the total bandwidth can be increased by applying each multiple times and simultaneously at various distances from the telescope.

A. **For Imaging and Source Detection: Combine Convergent Zone Plate and Divergent Fresnel Lens (L. Van Speybroeck**

B. **For Non-Dispersive Moderate Resolution Spectroscopy (~2 eV) : Non-Imaging Concentrator with Microcalorimeter at the Focus**

Non-Dispersive Moderate Resolution Spectroscopy with Wide Field Non-Imaging Concentrator, "Waveguide" + Polycapillaries



Strategies for Coping with the Fresnel Lens/Zone Plate Chromatic Aberration

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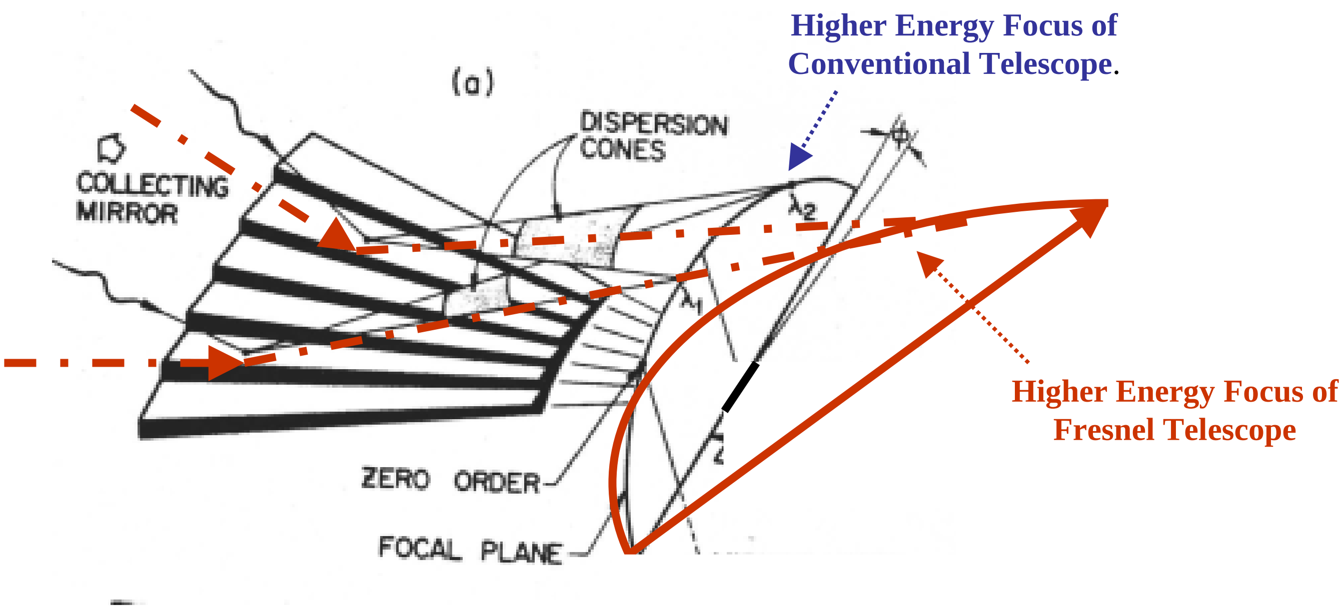
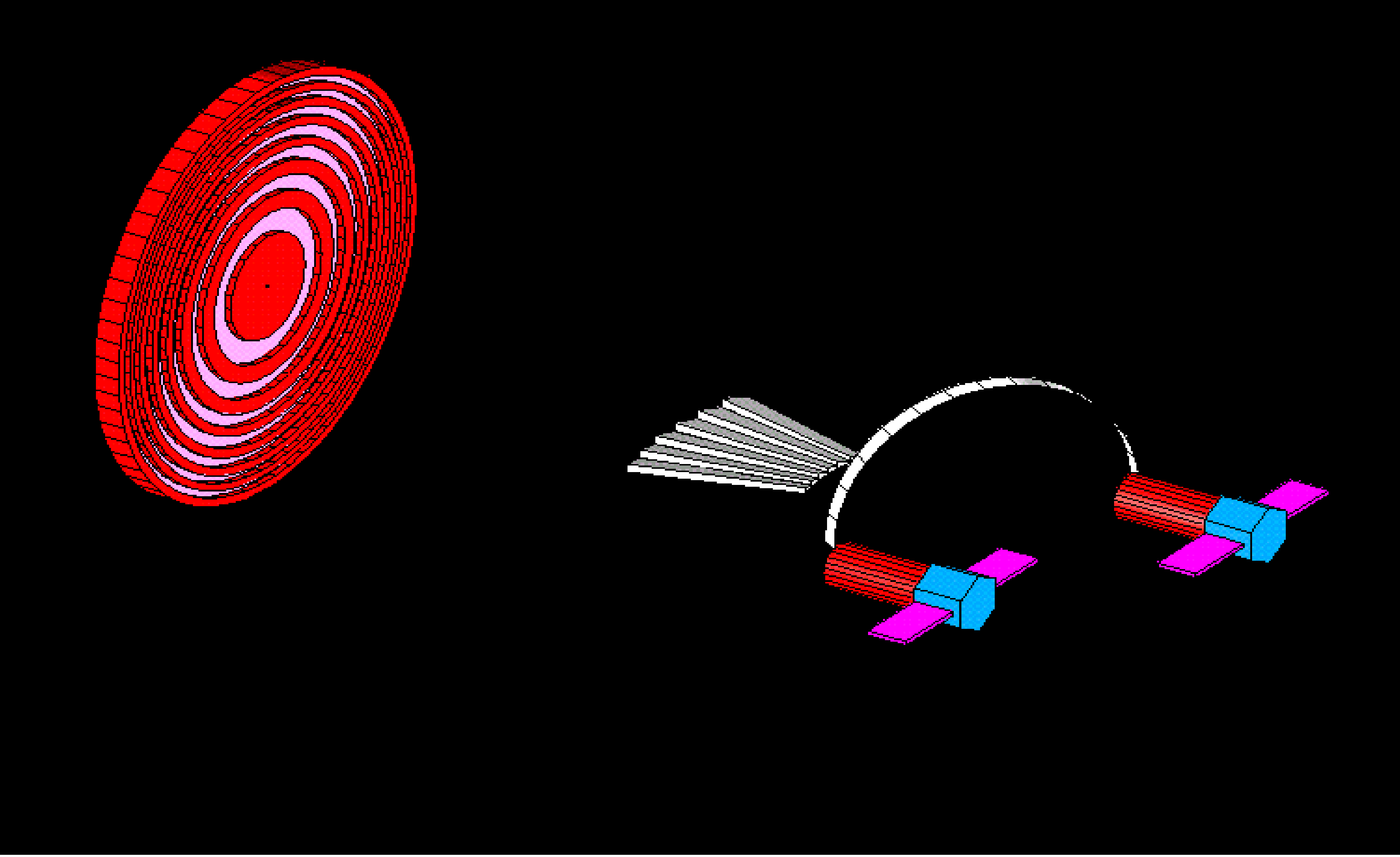
B. **For Non-Dispersive Moderate Resolution Spectroscopy (~2 eV) : Non-Imaging Concentrator with Microcalorimeter at the Focus**

C. **For Dispersive High Resolution Spectroscopy (~0.1 eV) : Variable Space Reflection Grating , In-Plane or Out of Plane, Between the Fresnel Zone Plate and Detector**



Dispersion Plane Is Rotated When Fresnel Zone Plate Replaces Grazing Incidence Telescope



Ultra-High Throughput X-ray Observatory with a New Mission Architecture

Summary

Strategies for Coping with the Fresnel Lens/Zone Plate Chromatic Aberration

Each of the following is effective only in a narrow band of wavelength. However the total bandwidth can be increased by applying each multiple times and simultaneously at various distances from the telescope.

A. **For Imaging and Source Detection: Combine Convergent Fresnel Zone Plate and Divergent Fresnel Lens (L. Van Speybroeck)**

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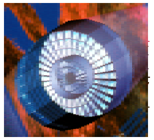
Conclusions on the Telescope 1

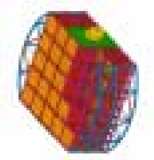
Filled Aperture Wolter



Will be extremely difficult to satisfy the 1arcsec requirement. Best so far is 15arcsec by XMM with substrates that are complete cylinders of revolution, whereas UHT large diameter requires the substrates to be segmented, which are inherently much less stiff

Best hope is that research for Con-X and ESA's XEUS will provide solution

Filled Aperture KB



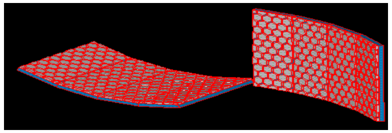
Prospects are possibly better because the substrates can be all flat or nearly so

However approximating a parabola adequately requires an extremely large number of them

Packing efficiency is less than the Wolter

Conclusions on the Telescope 2

Sparse Aperture KB



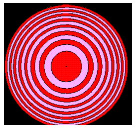
Appears to have better chance of satisfying the 1arcsec requirement.

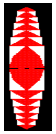
Without nesting, reflectors there are no limits on thickness of rear support frame

Long focal length allows larger and fewer reflectors to make a good linear approximation to a parabola.

Flat mirror technology developed for TPF by Steward Observatory applicable here

Fresnel Zone Plate/Refractive Lens





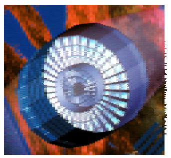
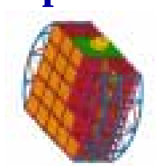
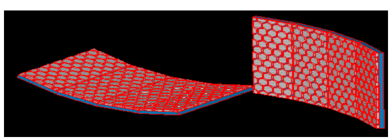
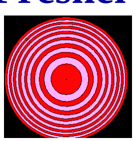
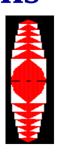
Possibly the most interesting optic but least studied option

Relatively low mass, relatively easy to fabricate and deploy

Can satisfy angular resolution and throughput requirements but only in one narrow wavelength band at a time. However, can operate in multiple bands simultaneously

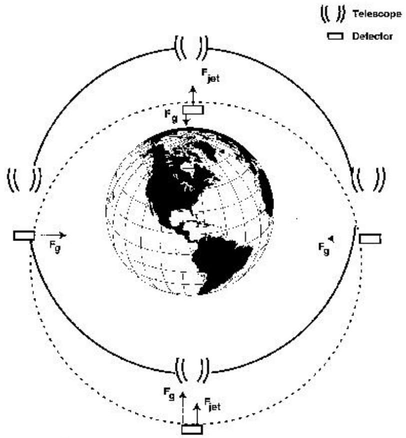
Focal Length is extremely long, resulting in the most complex operations

Rating the Optics, Qualitatively

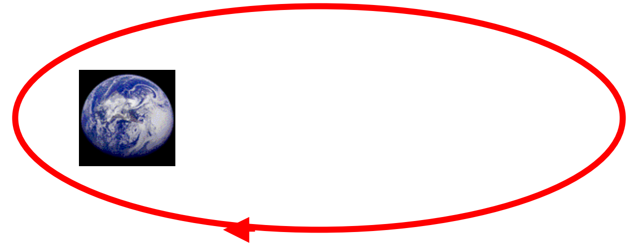
Optic	Mass	Fabrication Difficulty	Eff. Area	Ang. Res.	Field Size	Launch, Deploy	Average Rating
Filled Apert. Wolter 	D	C	A	C	A	C	C+
Filled Aperture, KB 	D	C	B	C	A	C	C+
Sparse Aperture, KB 	C	C	B	B	C	C	C+
Fresnel ZP F. Lens  	A	B	D	A	D	B	B-

Sites for the Ultra-High Throughput X-ray Observatory

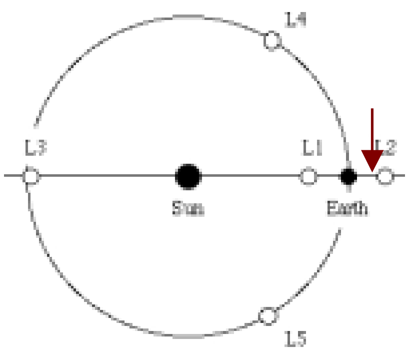
LEO



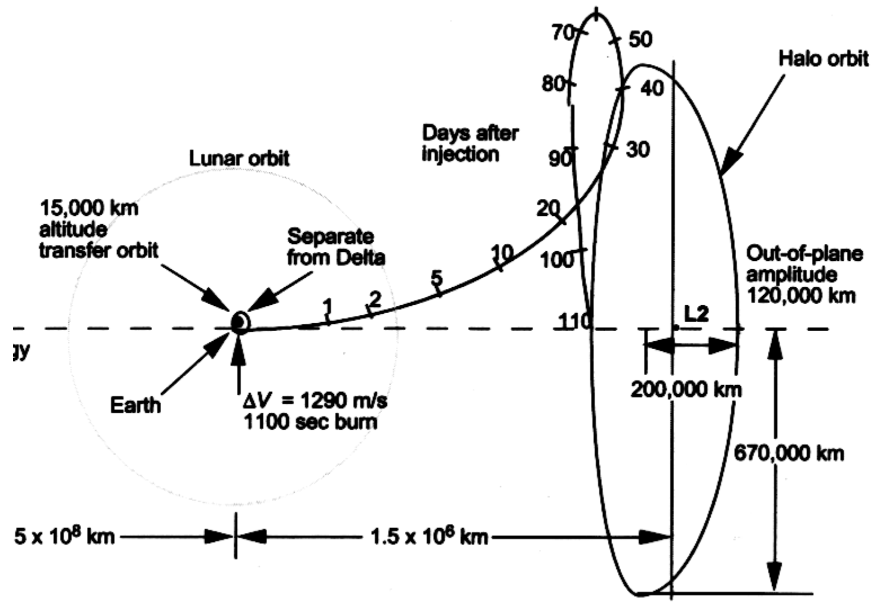
HEO



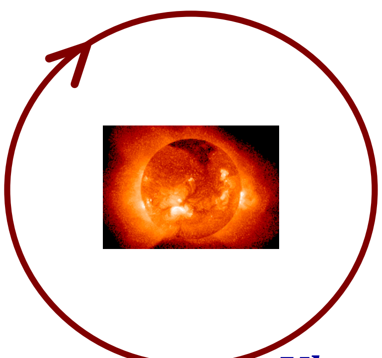
L2



L2
Halo



Helio-
centric



Moon

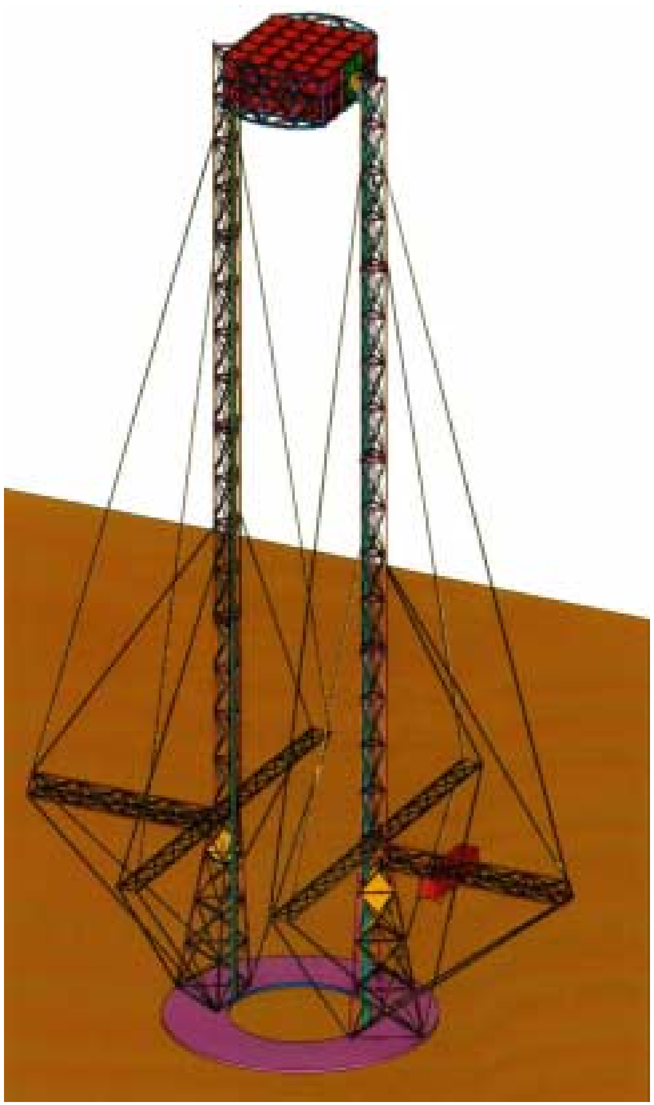
Moon As a Site for the Ultra-High Throughput X-ray Observatory

The Moon is desirable or at least competitive with other sites only if a lunar base is established for other purposes and there is an infrastructure which provides power and construction services plus a reliable mode of transportation from the Earth for bringing the telescope modules and detectors.

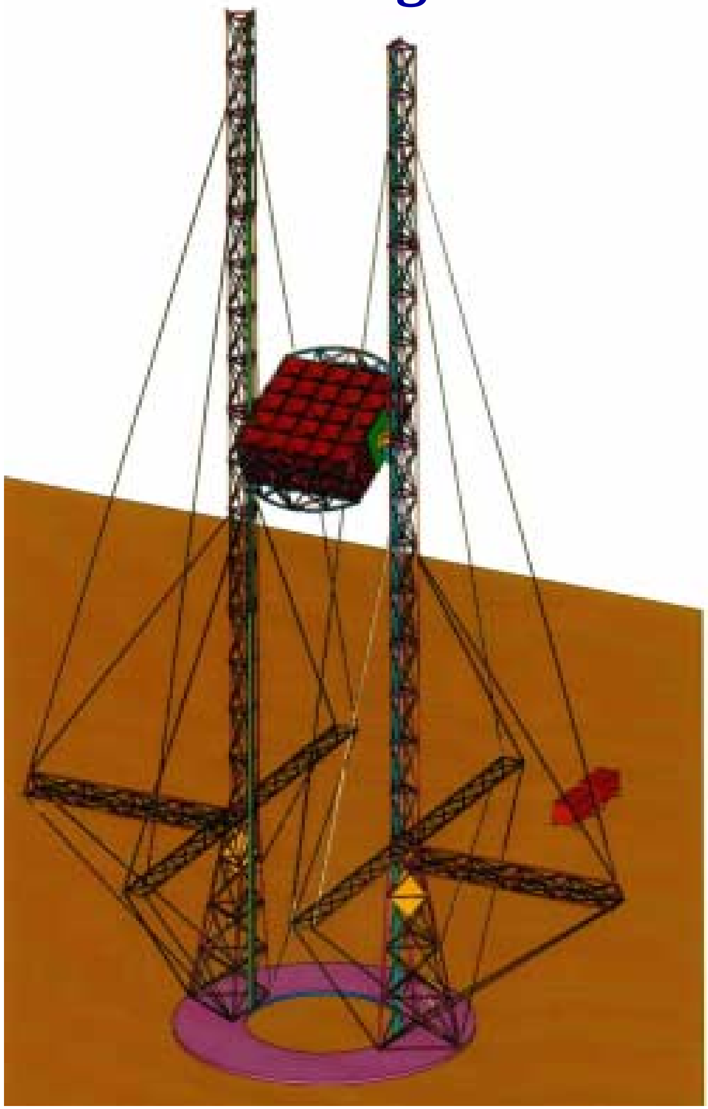
Otherwise, the Moon is at a disadvantage because:

- Soft landing an instrument on the Moon requires more energy than placing it at the other sites.
- Lack of power during lunar night
- High temperatures during lunar day
- Severe thermal cycling between lunar day and night

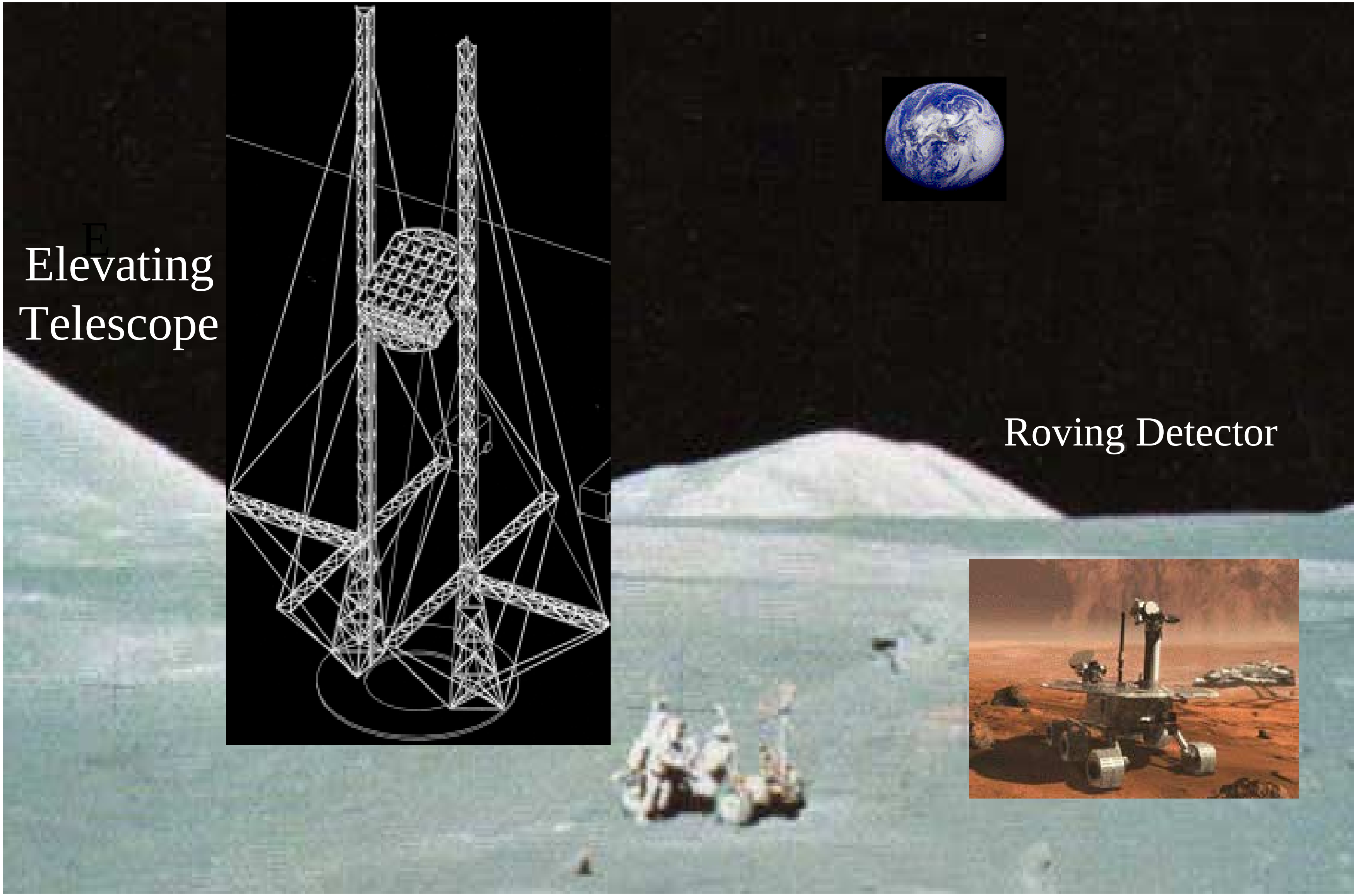
Higher Target Elevation



Lower Target Elevation

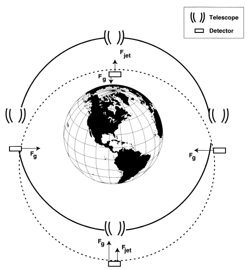
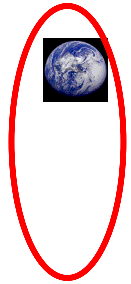
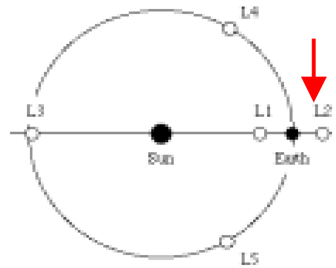
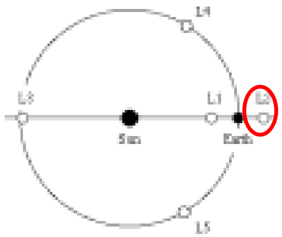
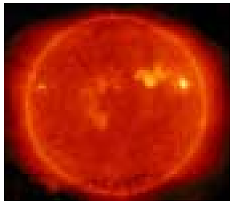


Ultra-High Throughput X-ray Observatory with a New Mission Architecture



Ultra-High Throughput X-ray Observatory with a New Mission Architecture

Compatibility of the Various Optics Architectures with Several Possible Sites

Optic	LEO	HEO	Sun-Earth L2	L2 Halo	Helio-Centric	Moon
						
Filled Apert. Wolter	Yes	No	Yes	Yes	Yes	Yes
Filled Apert. KB	Yes	No	Yes	Yes	Yes	Yes
Sparse Apert. KB	No	No	Yes	Yes	Yes	No
Fresnel ZP/Lens	No	No	Yes	?	Yes	No

Propulsion Requirements of the Ultra-High Throughput X-ray Observatory

- Launch of the telescope segments and multiple detector spacecraft into low Earth orbit (LEO)
- Transport from LEO to Sun-Earth L2
- Navigation to and rendezvous with the observatory site
- Station keeping and traffic control at L2 of telescope spacecraft and multiple detector spacecraft
- Formation flying between the telescope spacecraft and the selected detector spacecraft which is at the focus
- Changing targets: which requires a rotation of the telescope axis to the new pointing position while simultaneously a detector spacecraft is displaced to its new position
- Attitude Control of the telescope pointing direction to better than one arcminute and the detector orientation to 10 arcminutes