Webster Cash
University of Colorado

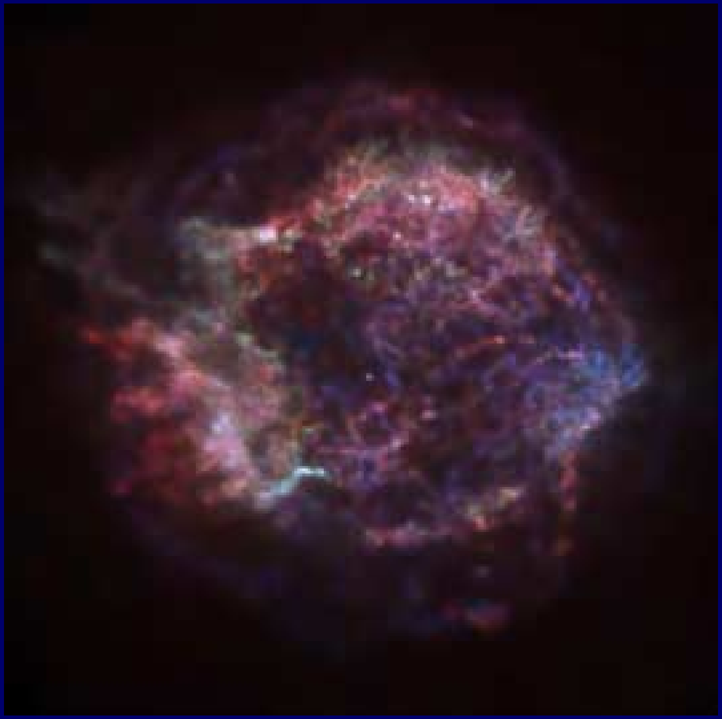
X-ray Interferometry

Ultimate Astronomical Imaging

Collaborators

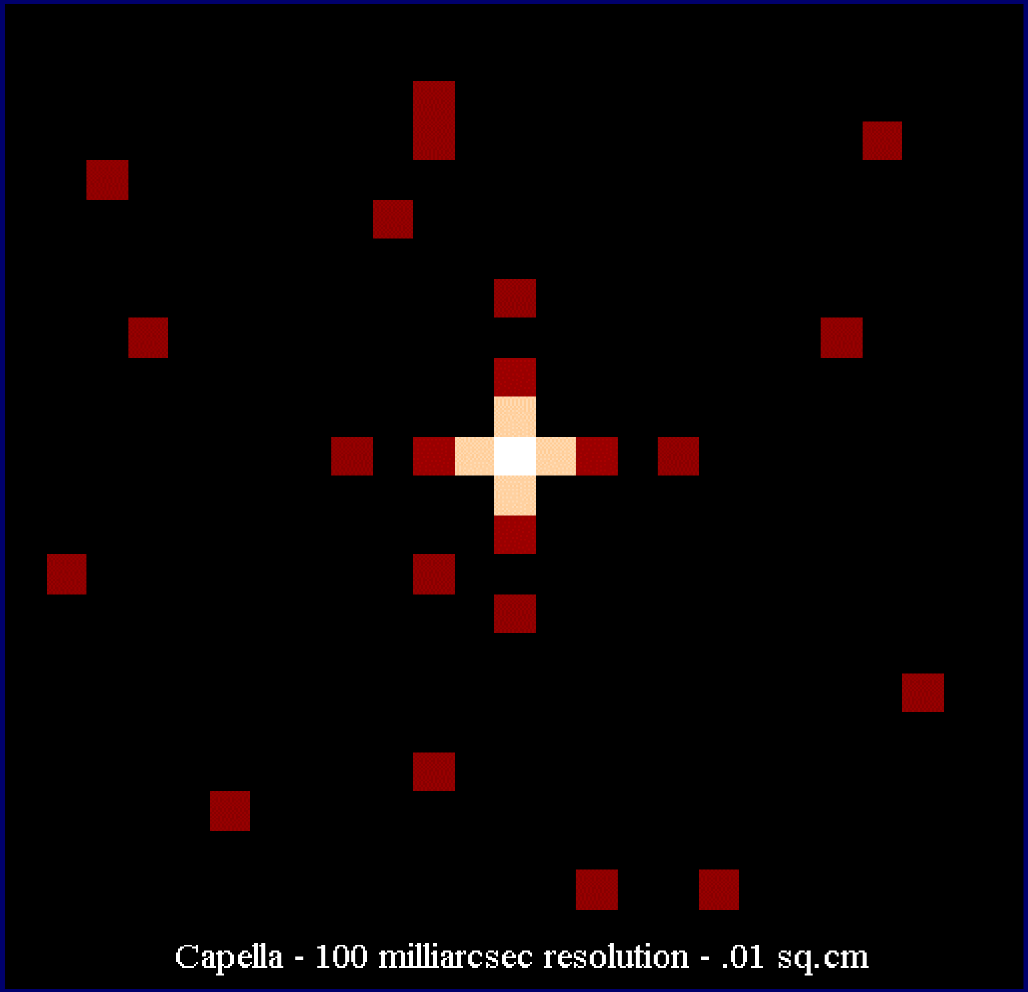
- Ann Shipley, Karen Doty, Randy McEntaffer, & Steve Osterman at CU
- Nick White – Goddard
- Marshall Joy – Marshall
- David Windt and Steve Kahn - Columbia
- Mark Schattenburg - MIT
- Dennis Gallagher – Ball Aerospace

X-ray Telescopes

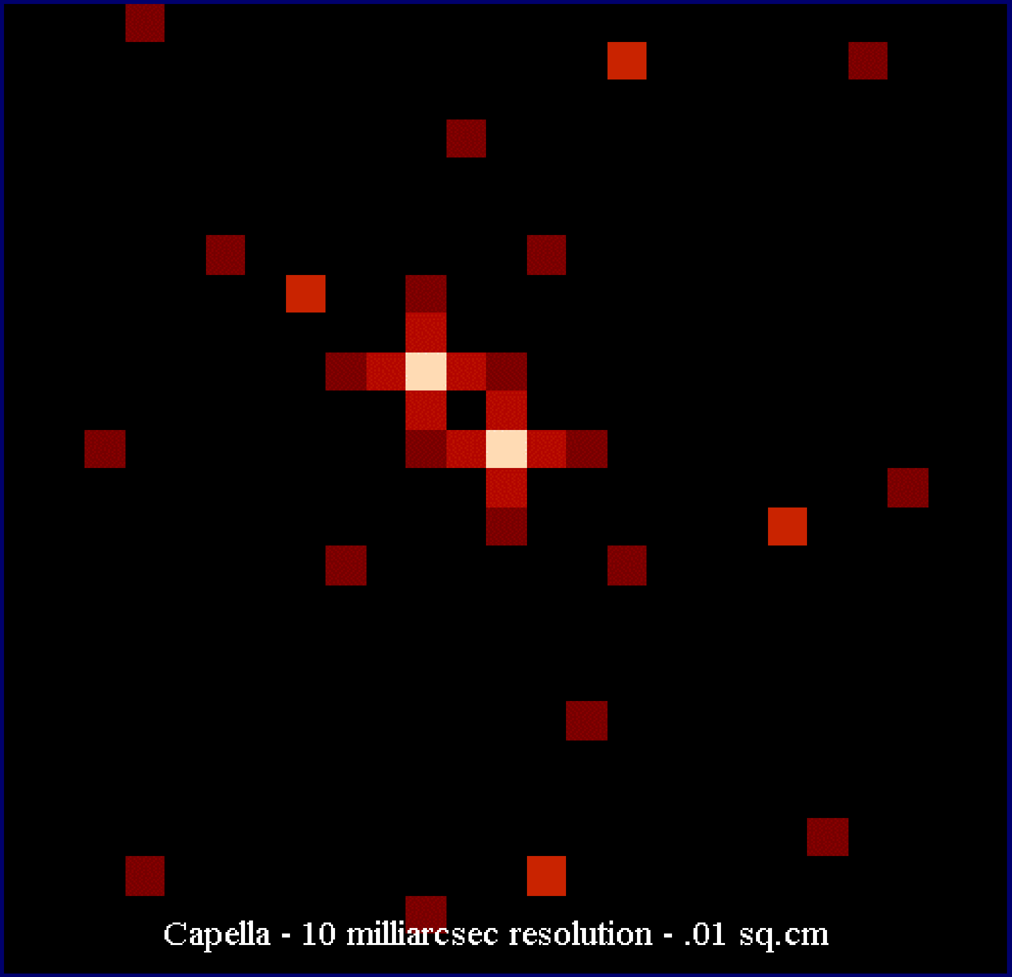


X-ray telescopes are sensitive to material at millions of degrees.

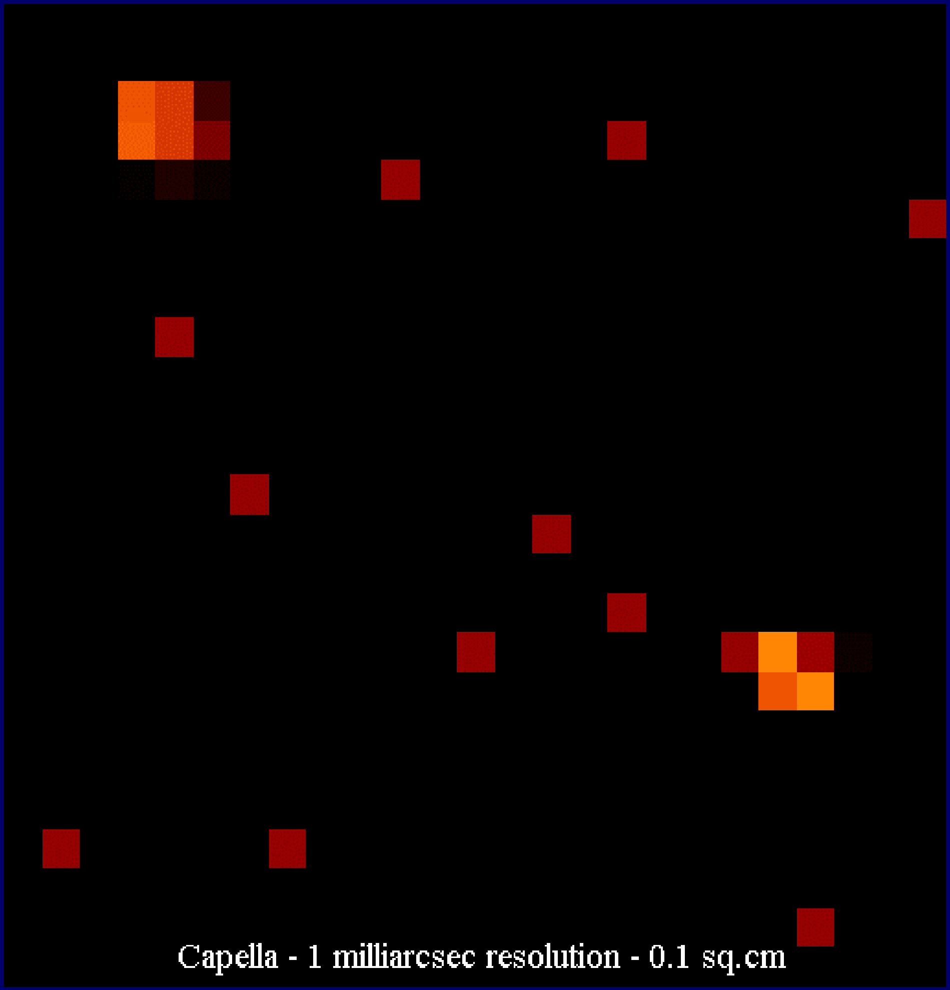
Capella 0.1”



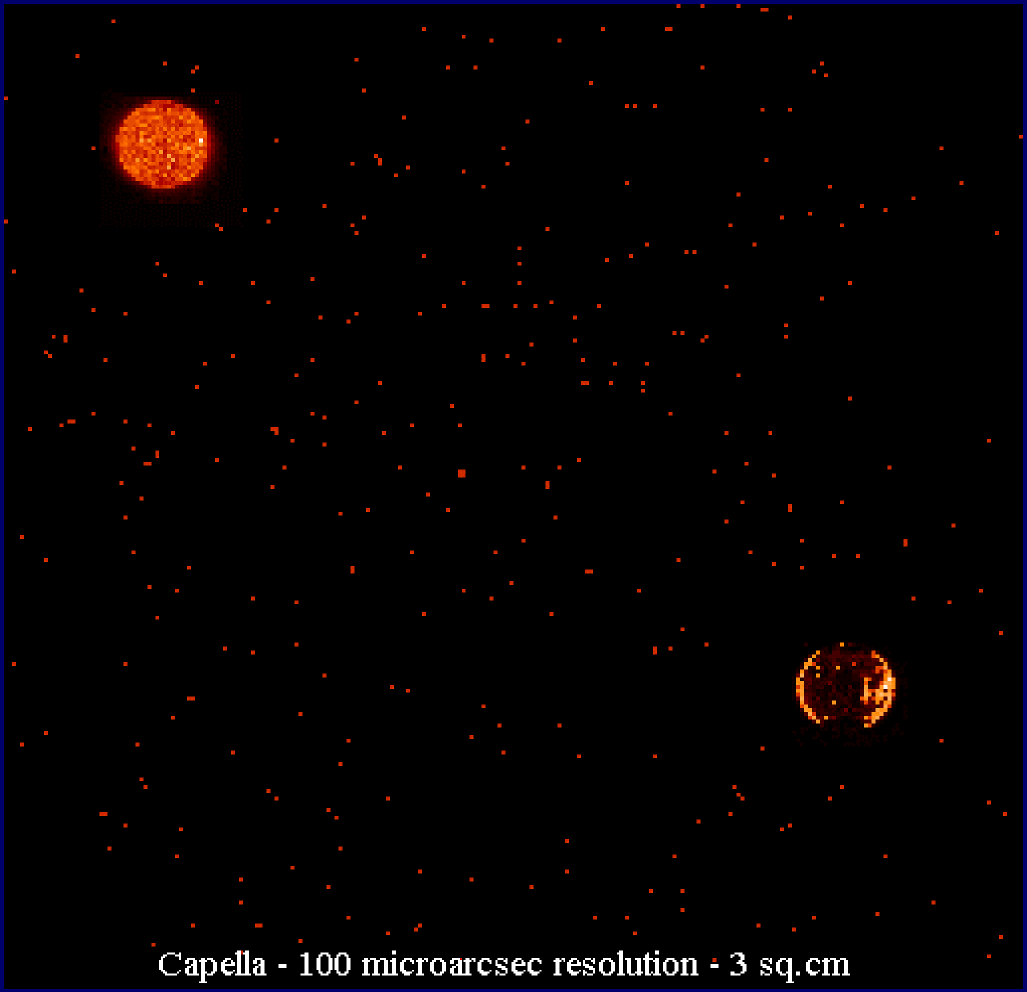
Capella 0.01"



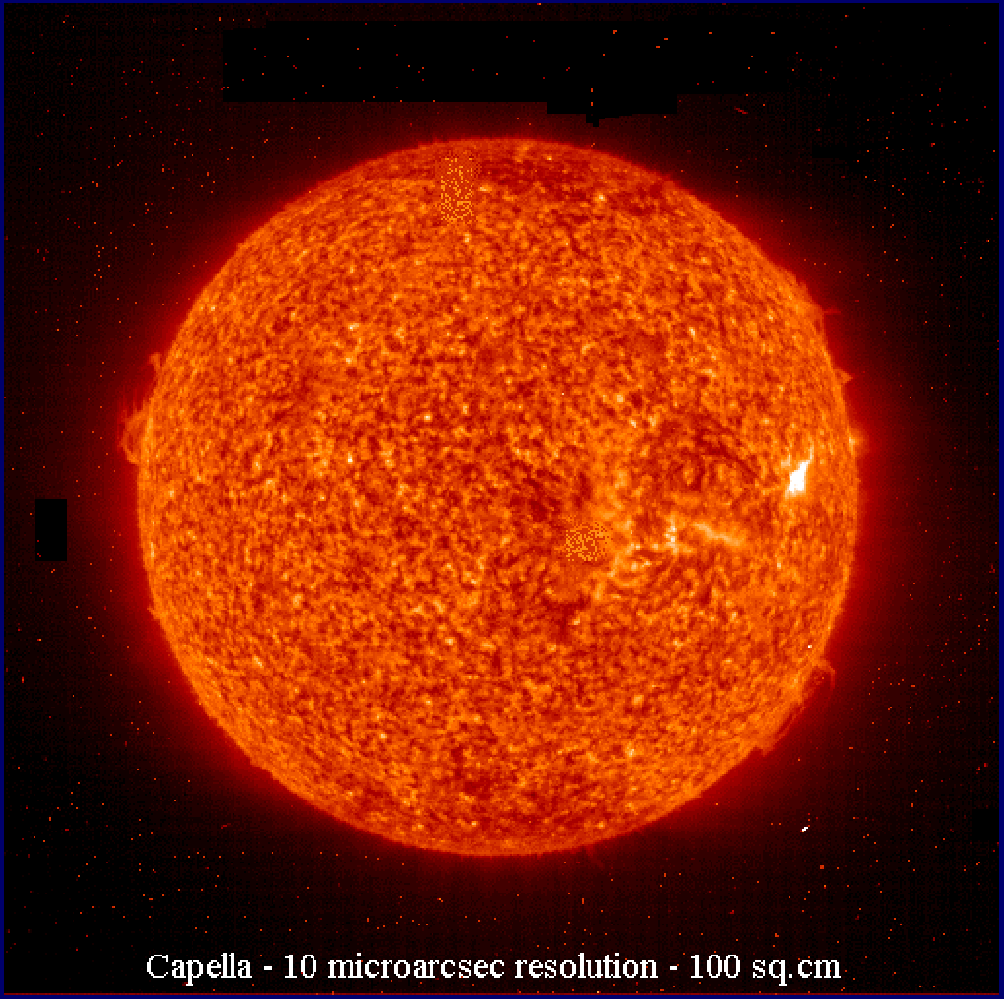
Capella 0.001"



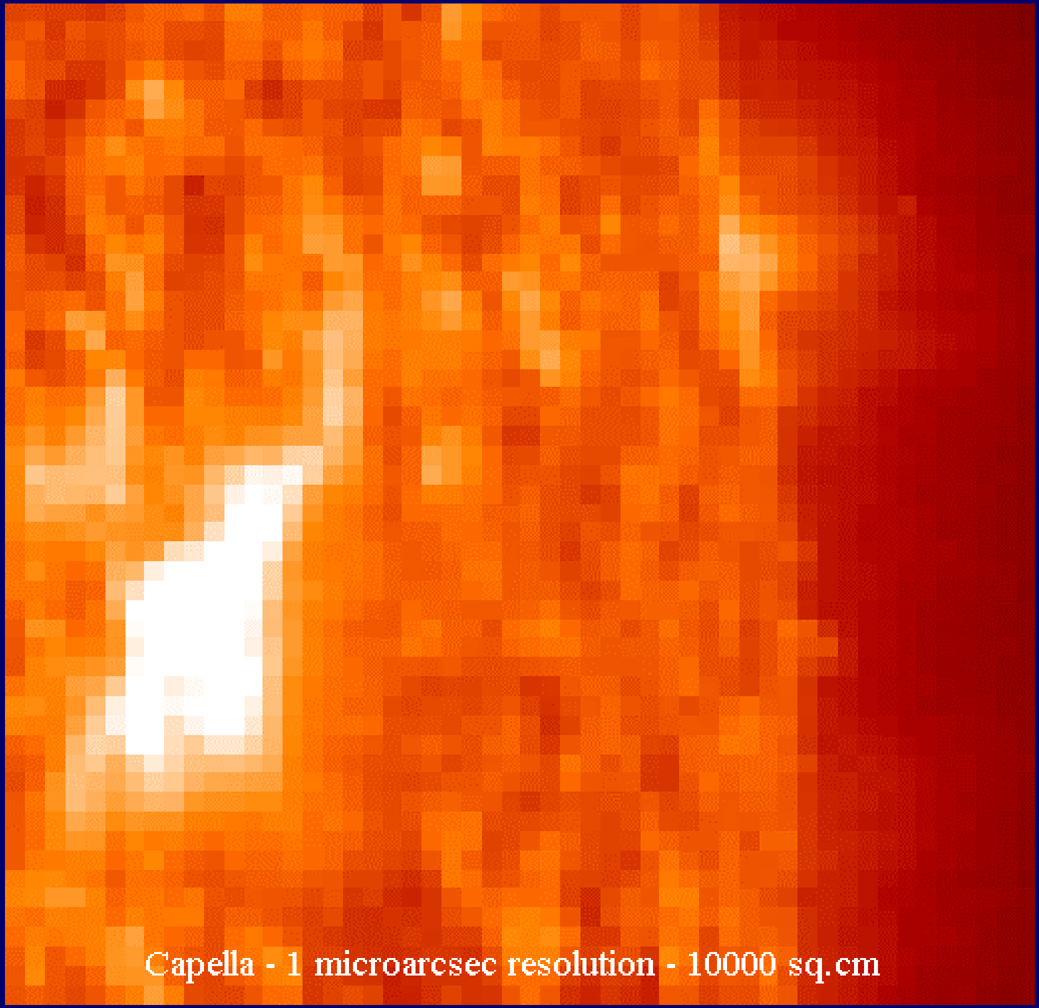
Capella 0.0001”



Capella 0.00001”

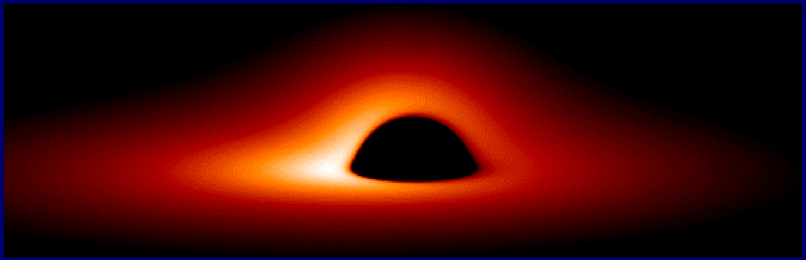


Capella 0.000001"

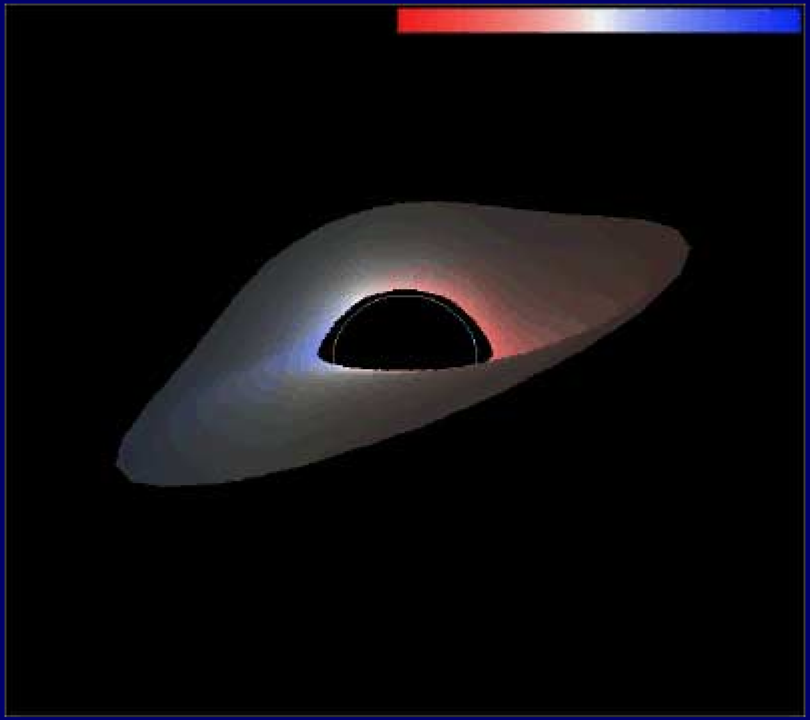


AR Lac
Simulation @ 100μas

AGN Accretion Disk Simulations @ 0.1μas



C. Reynolds, U. Colorado



M. Calvani, U. Padua

Need Resolution and Signal

If we are going to do this, we need to support two basic capabilities:

- **Signal**
- **Resolution**

X-ray Sources Are Super Bright

Example: Mass Transfer Binary

10^{37}ergs/s from 10^{9}cm object

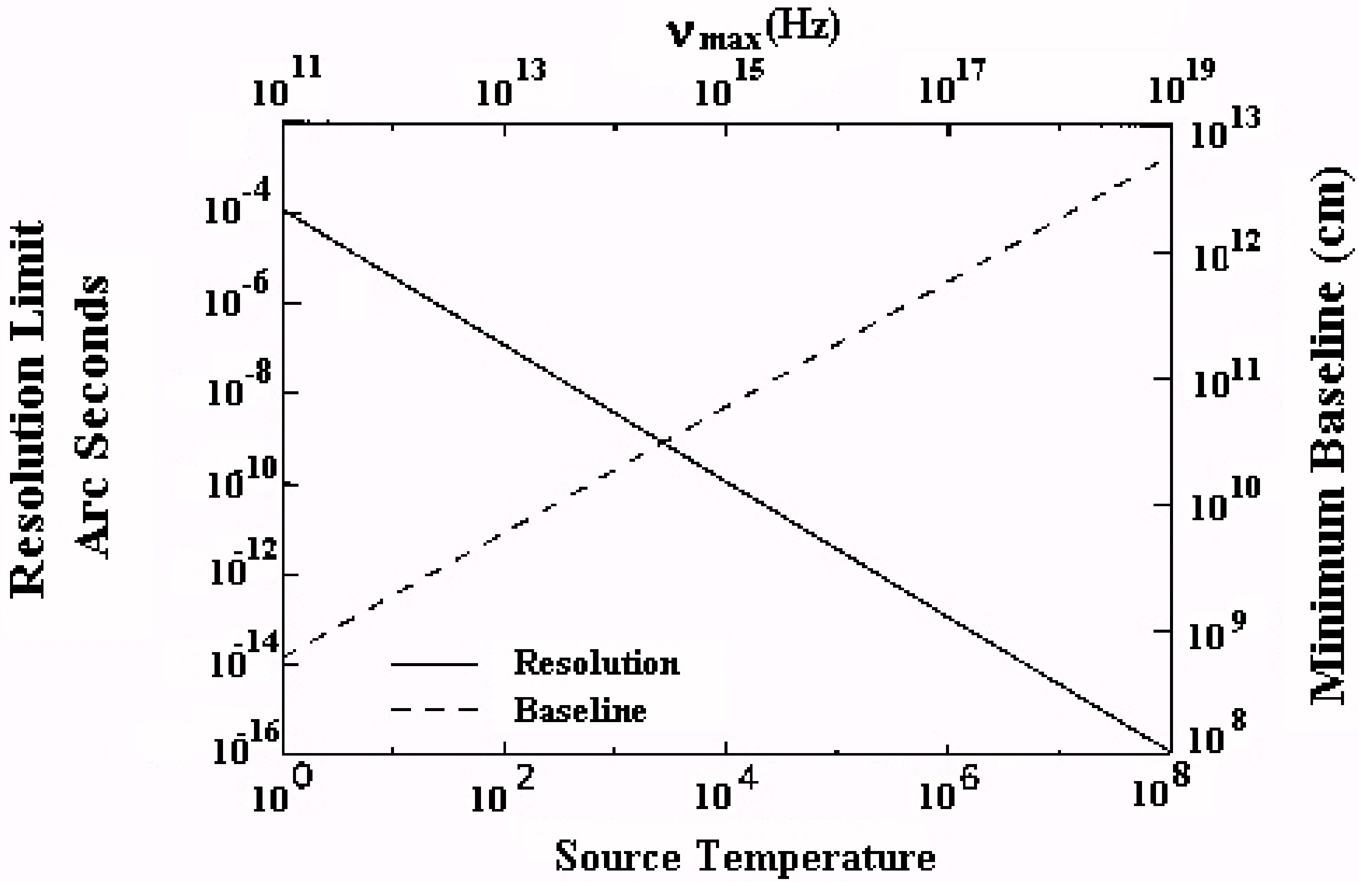
That is ~10,000$L_{\odot}$ from $10^{-4}A_{\odot}$ = $10^{8} B_{\odot}$

where $B_{\odot}$ is the solar brightness in ergs/cm^2/s/steradian

Brightness is a conserved quantity and is the measure of visibility for a resolved object

Note: Optically thin x-ray sources can have very low brightness and are inappropriate targets for interferometry.
Same is true in all parts of spectrum!

Minimum Resolution



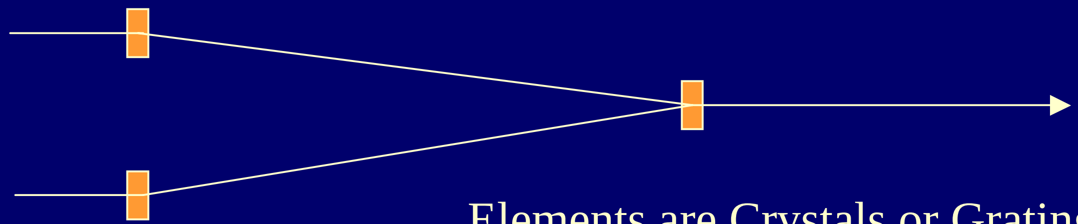
Status of X-ray Optics

- Modest Resolution
  - 0.5 arcsec telescopes
  - 0.5 micron microscopes
- Severe Scatter Problem
  - Mid-Frequency Ripple
- Extreme Cost
  - Millions of Dollars Each
  - Years to Fabricate

Need Easier Approach

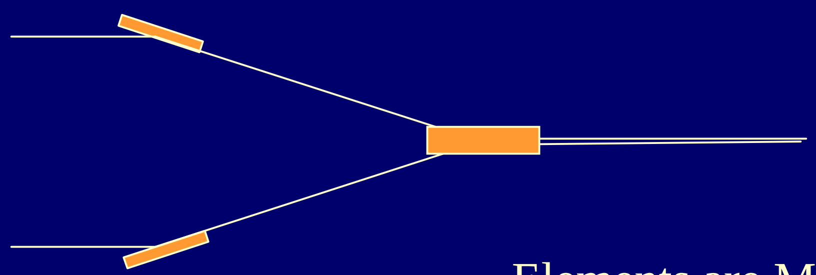
Classes of X-ray Interferometers

Dispersive



Elements are Crystals or Gratings

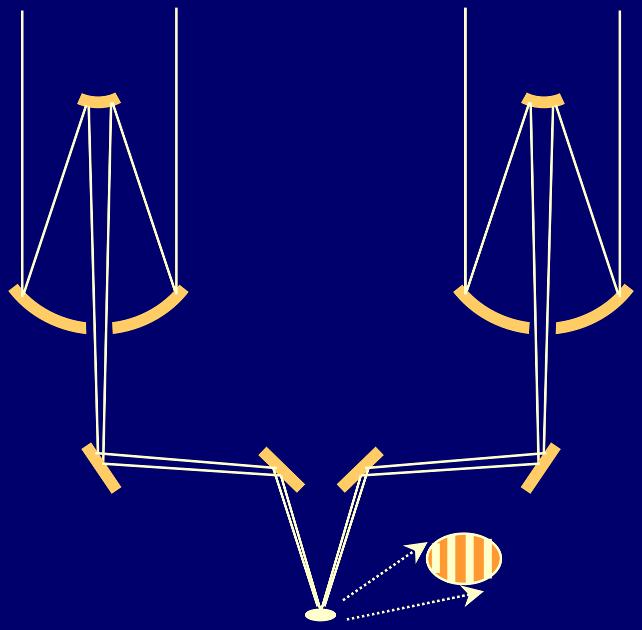
Non-Dispersive



Elements are Mirrors & Telescopes

Achieving High Resolution

Use Interferometry to Bypass Diffraction Limit



Michelson Stellar Interferometer

$$R = \lambda / 20000D$$

R in Arcsec

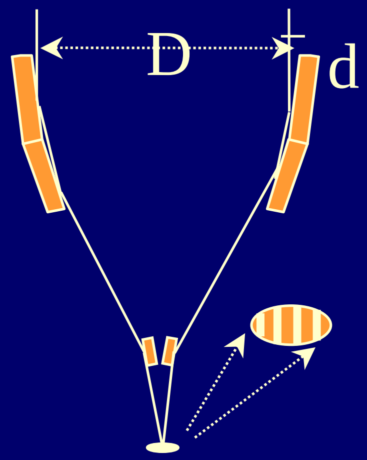
λ in Angstroms

D in Meters

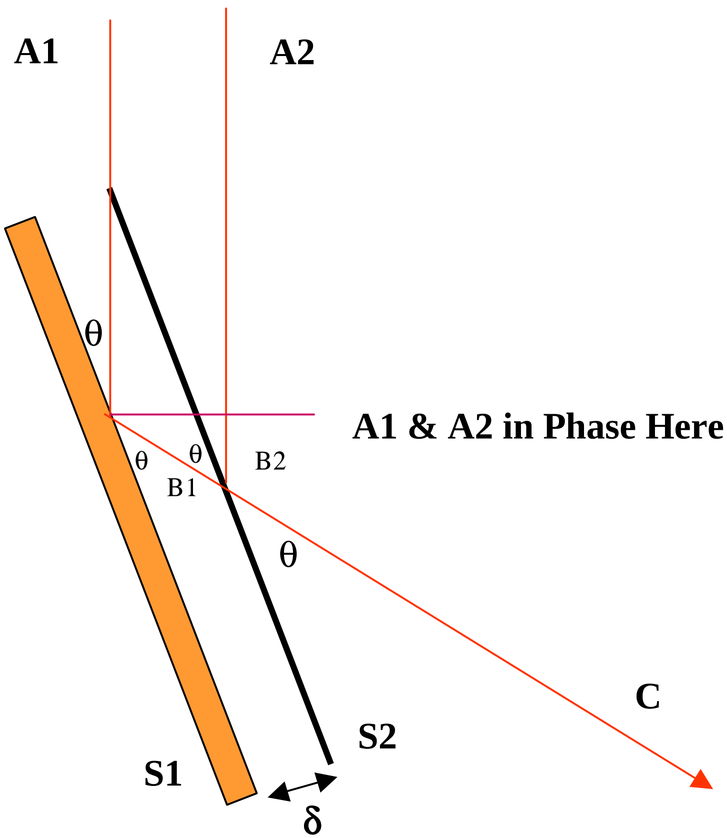
Creating Fringes

Requirements

- Path Lengths Nearly Equal
- Plate Scale Matched to Detector Pixels
- Adequate Stability
- Adequate Pointing
- Diffraction Limited Optics



Pathlength Tolerance Analysis at Grazing Incidence



$$B1 = \frac{\delta}{\sin\theta}$$

$$B2 = B1\cos(2\theta)$$

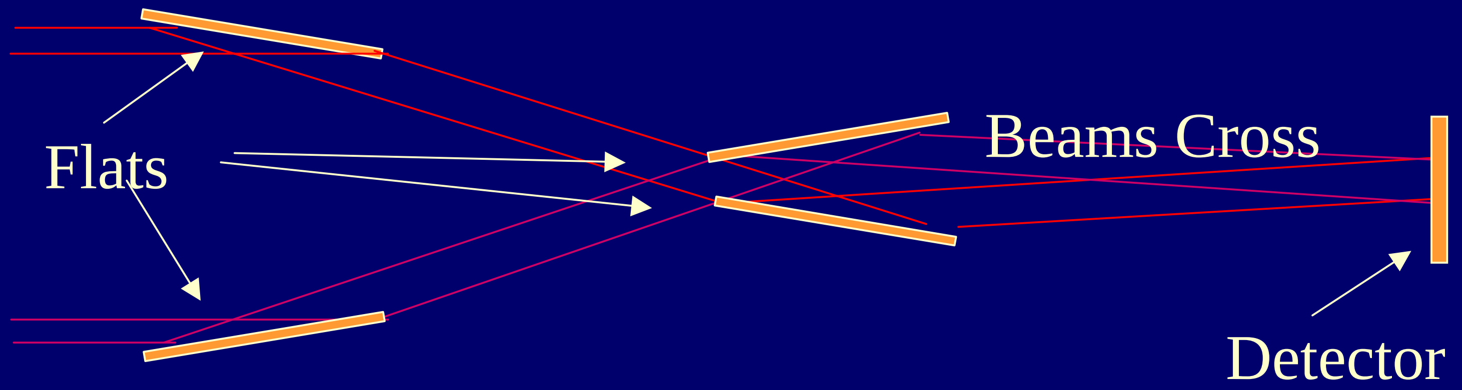
$$OPD = B1 - B2 = \frac{\delta[1 - \cos(2\theta)]}{\sin\theta} = 2\delta\sin\theta$$

If OPD to be < λ/10 then $\boxed{\delta < \frac{\lambda}{20\sin\theta}}$

$$d(Baseline) < \frac{\lambda}{20\sin\theta\cos\theta}$$

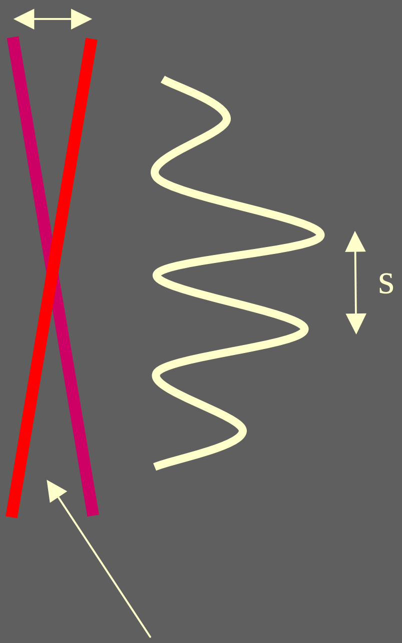
$$d(focal) < \frac{\lambda}{20\sin^2\theta}$$

A Simple X-ray Interferometer



Wavefront Interference

$\lambda=\theta s$ (where s is fringe spacing)



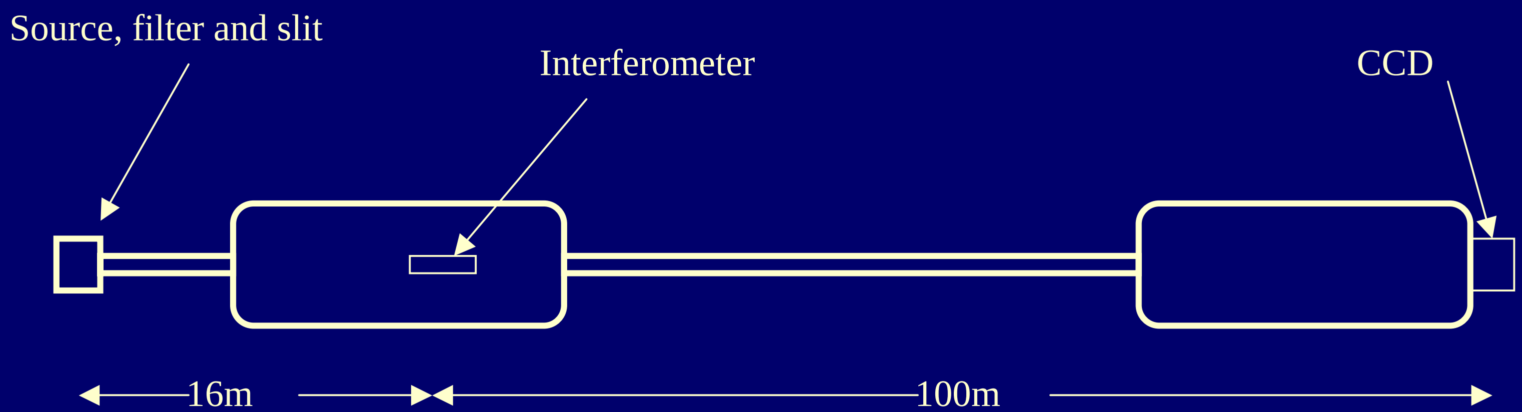
$\theta=d/L$

$$s = \frac{L\,\lambda}{d}$$

Optics

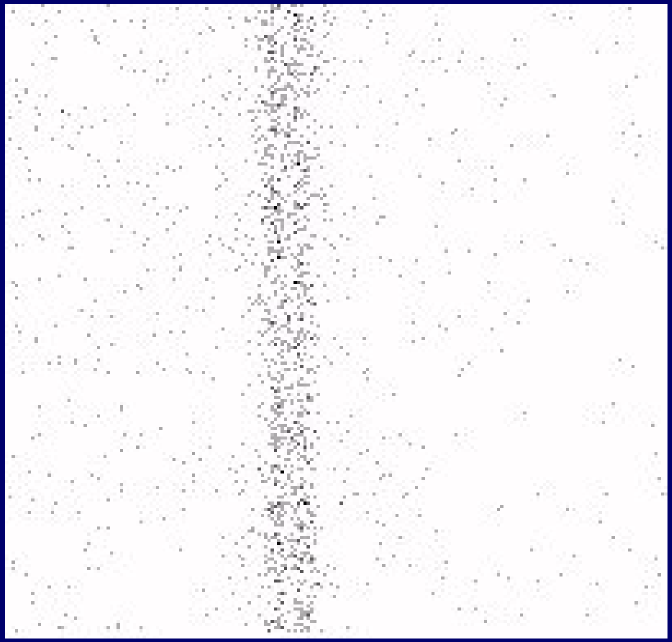
Each Mirror Was Adjustable
From Outside Vacuum
System was covered by thermal shroud

Stray Light Facility MSFC

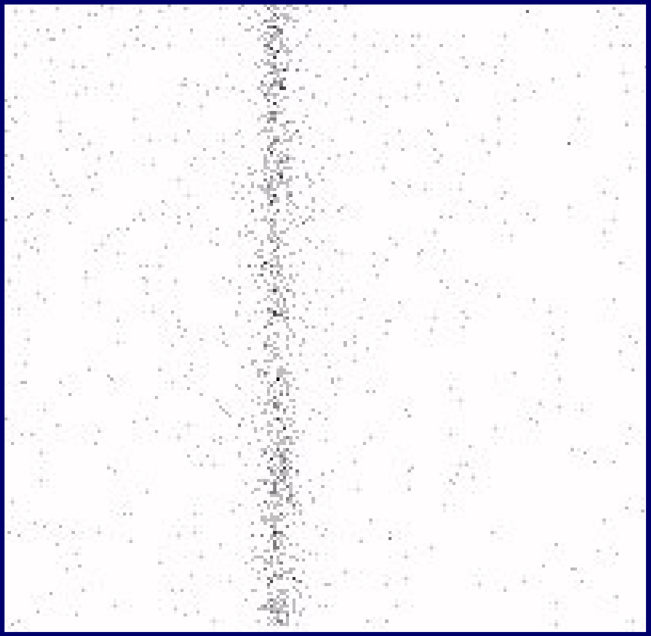


Used Long Distance To
Maximize Fringe Spacing

CCD Image @ 1.25keV

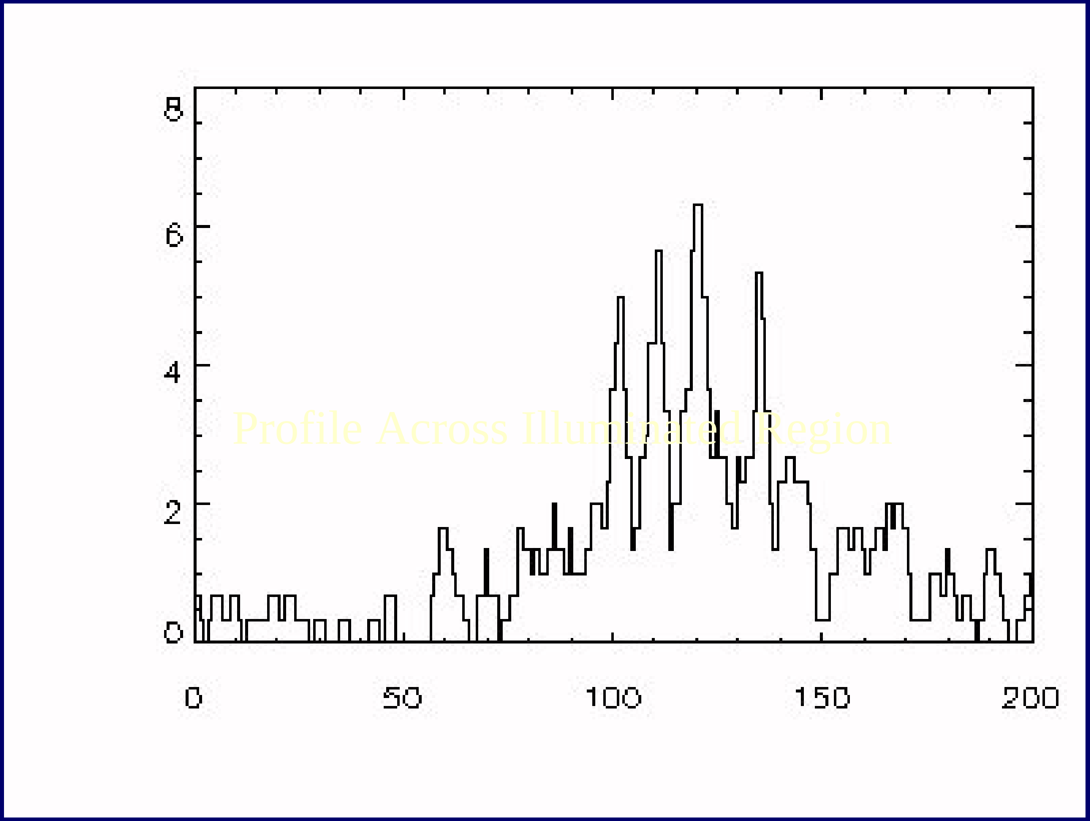


2 Beams Separate



2 Beams Superimposed

Fringes at 1.25keV



Test Chamber at CU

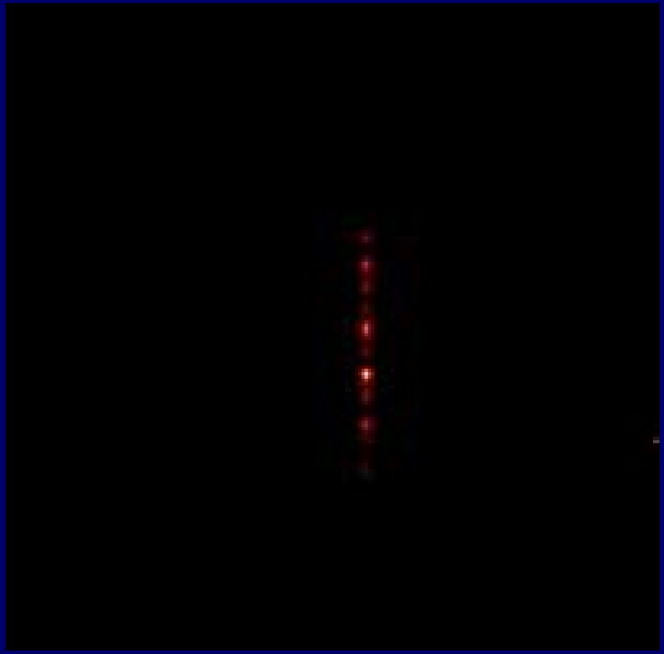
Ten Meter Long Vacuum Chamber for Testing

Came on-line early May

EUV results good
Upgrade to x-ray next

Actual Image at 30.4nm

Image of Slit
Reconstructed from 4 azimuths



MAXIM

The Micro Arcsecond X-ray Imaging Mission

Webster Cash	Colorado
Nicholas White	Goddard
Marshall Joy	Marshall

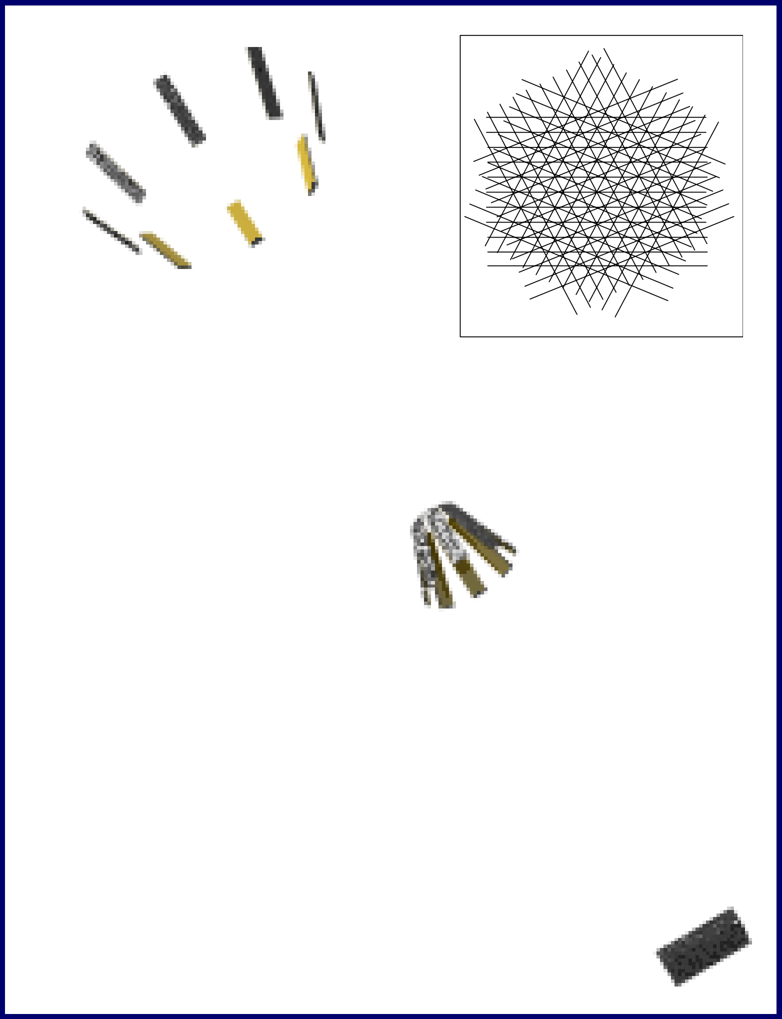
PLUS Contributions from the Maxim Team

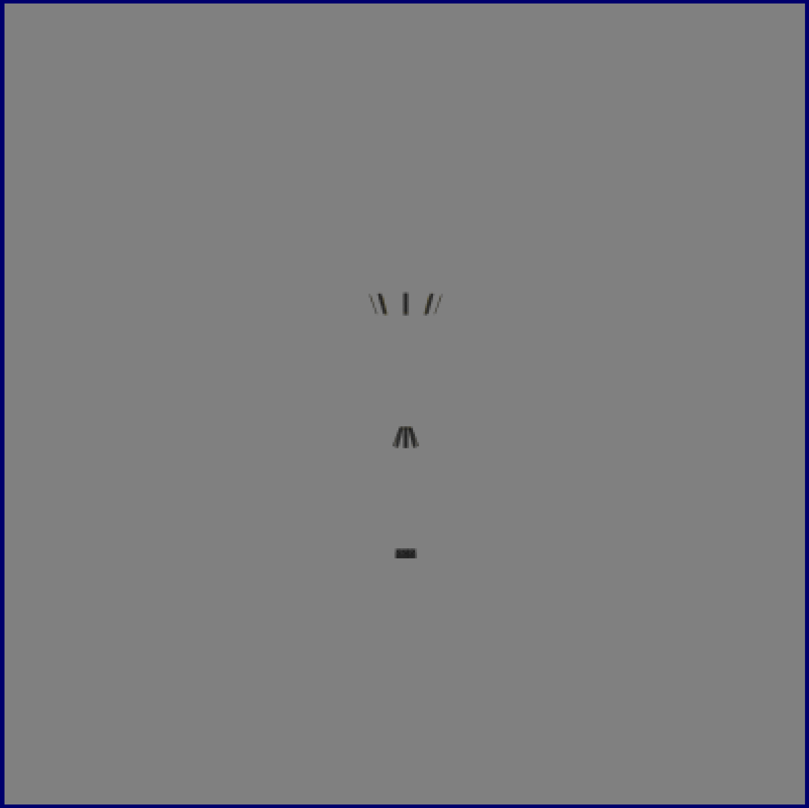
http://maxim.gsfc.nasa.gov

Maxim:
A Few Science Goals

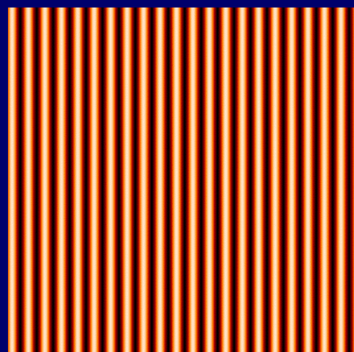
Target Class	**Goal**
Resolve the corona of nearby stars:	*Are other coronal structures like the solar corona?*
Resolve the winds of OB stars:	*What kind of shocks drive the x-ray emission?*
Resolve pre-main sequence stars:	*How does coronal activity interact with disk?*
Image of center of Milky Way:	*Detect and resolve accretion disk?*
Detailed images of LMC, SMC, M31:	*Supernova morphology and star formation in other settings*
Image jets, outflows and BLR from AGN:	*Follow jet structure, search for scattered emission from BLR*
Detailed view of starbursts:	*Resolve supernovae and outflows*
Map center of cooling flows in clusters:	*Resolve star formation regions?*
Detailed maps of clusters at high redshift:	*Cluster evolution, cooling flows*
Image Event Horizons in AGNS:	*Probe Extreme Gravity Limit*

Flats Held in Phase Sample Many Frequencies





As More Flats Are Used Pattern Approaches Image



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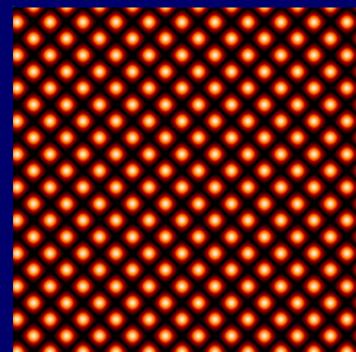

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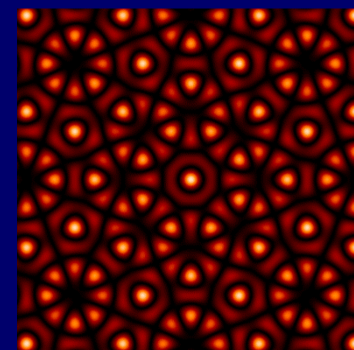

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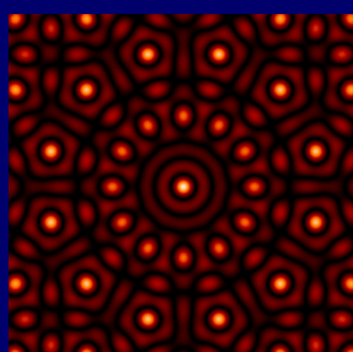

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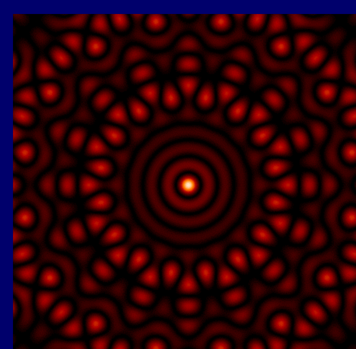

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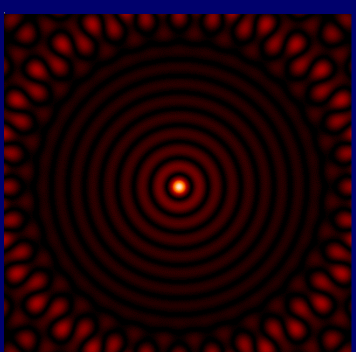

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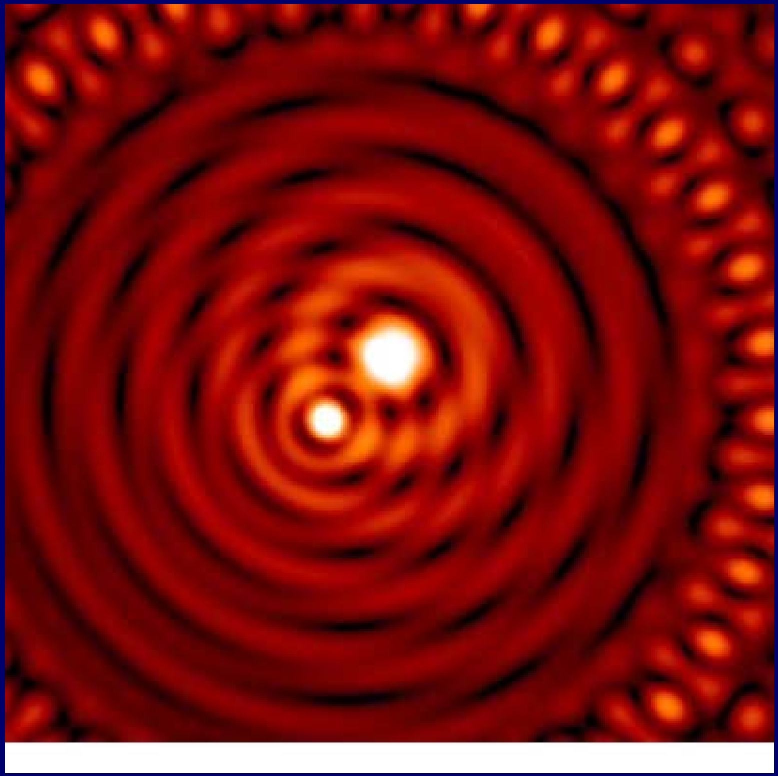
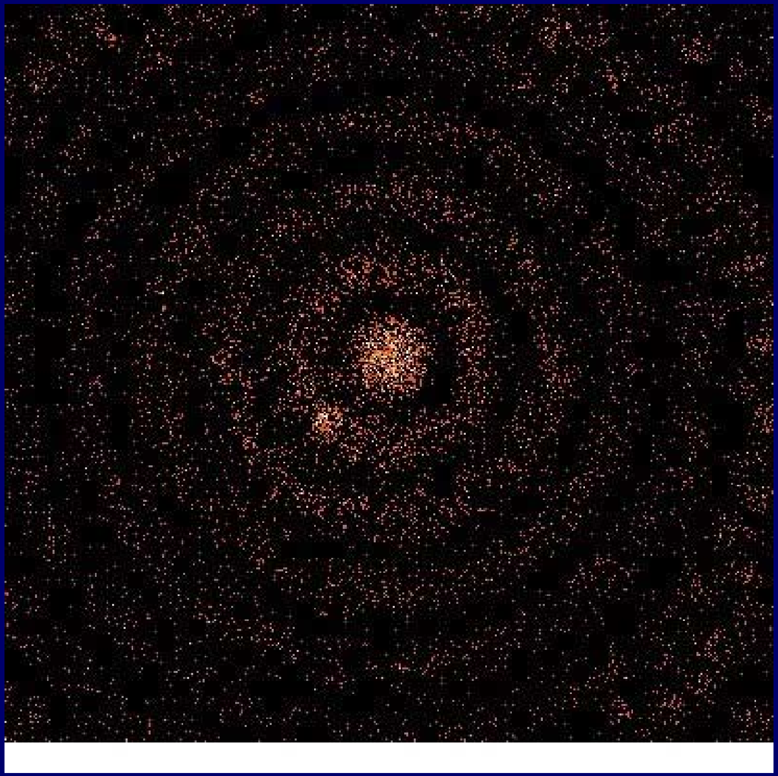
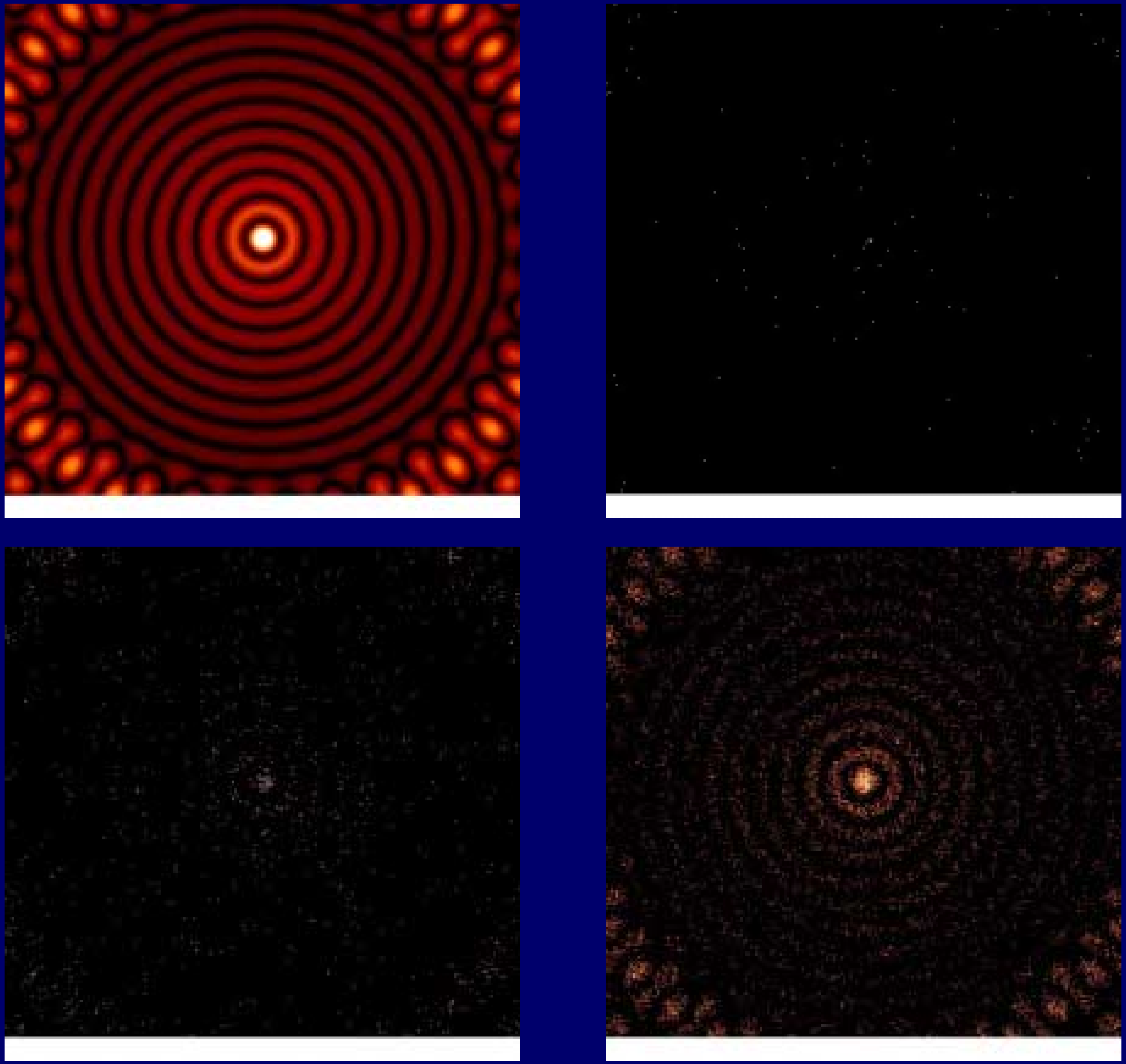
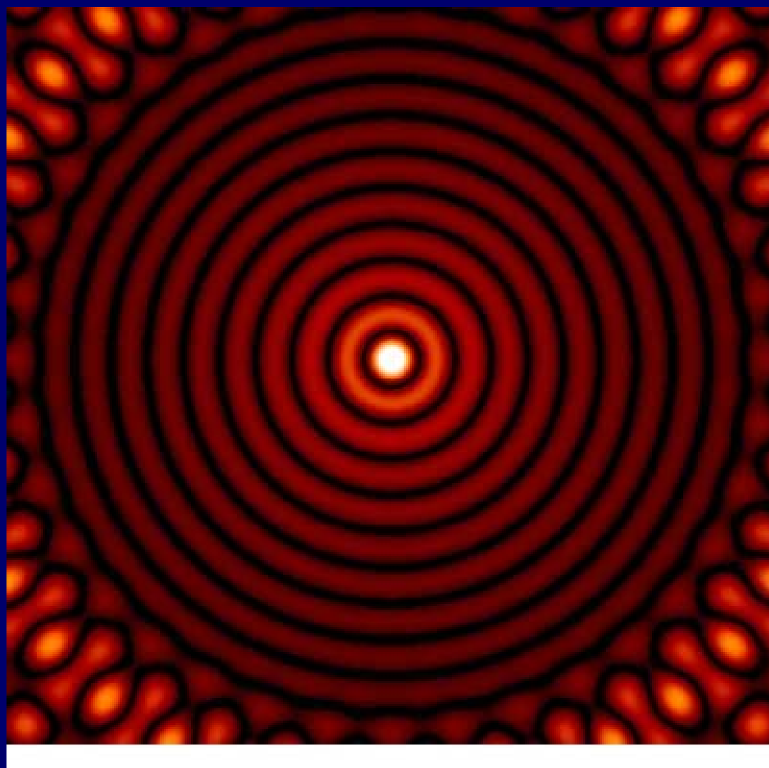




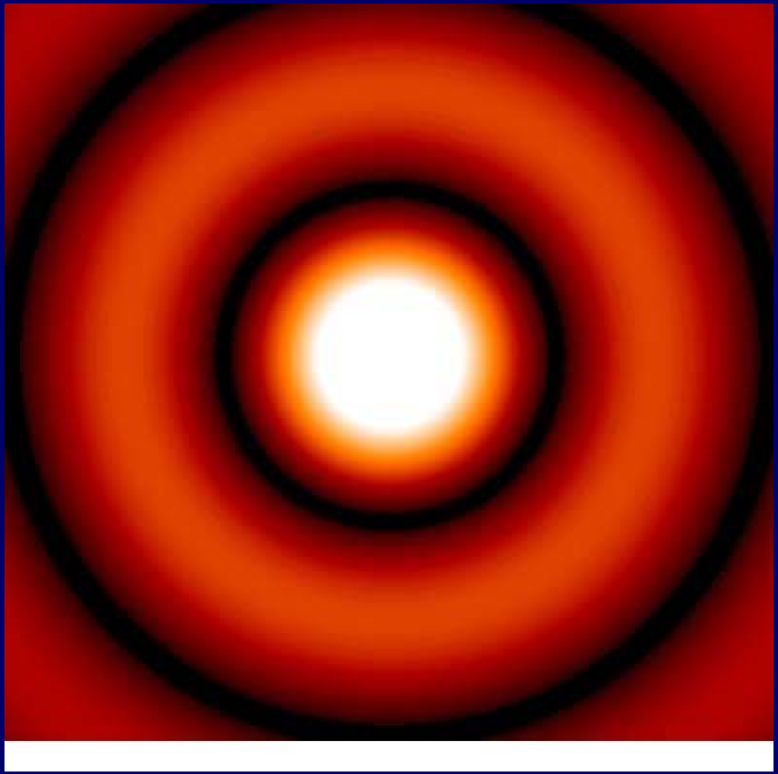
On the left is the probability distribution function for two sources in the same field of view. The central source has an energy half that of the source that is displaced to the lower left. The image on the right shows 9000 total events for this system with the lower energy source having twice the intensity of the higher energy source. Even though the higher energy source is in the first maxima of the other, the two can still be easily distinguished.

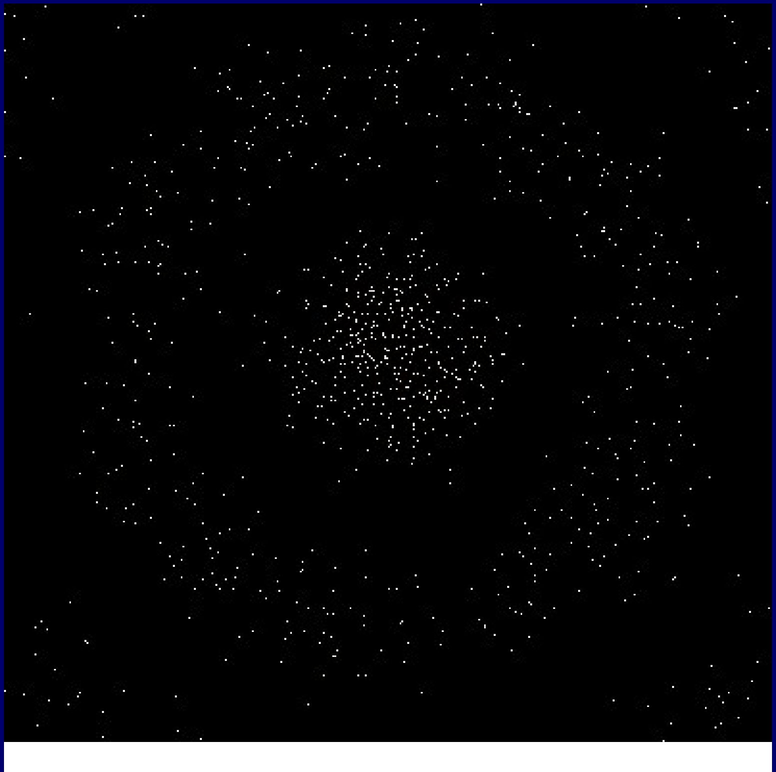


Clockwise from upper left: Probability distribution; 100 photons randomly plotted; 9000 photons; and 5000 photons.

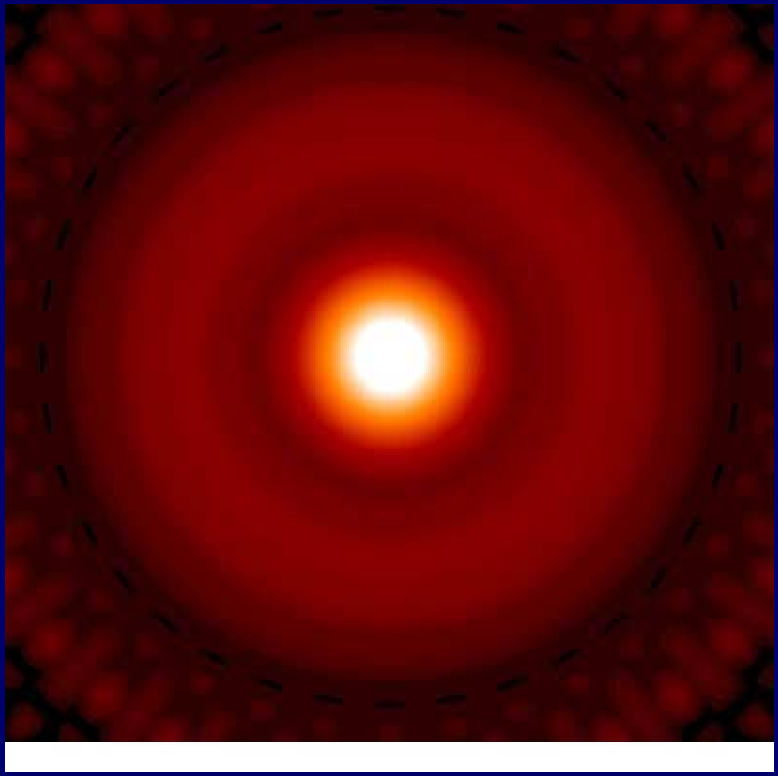
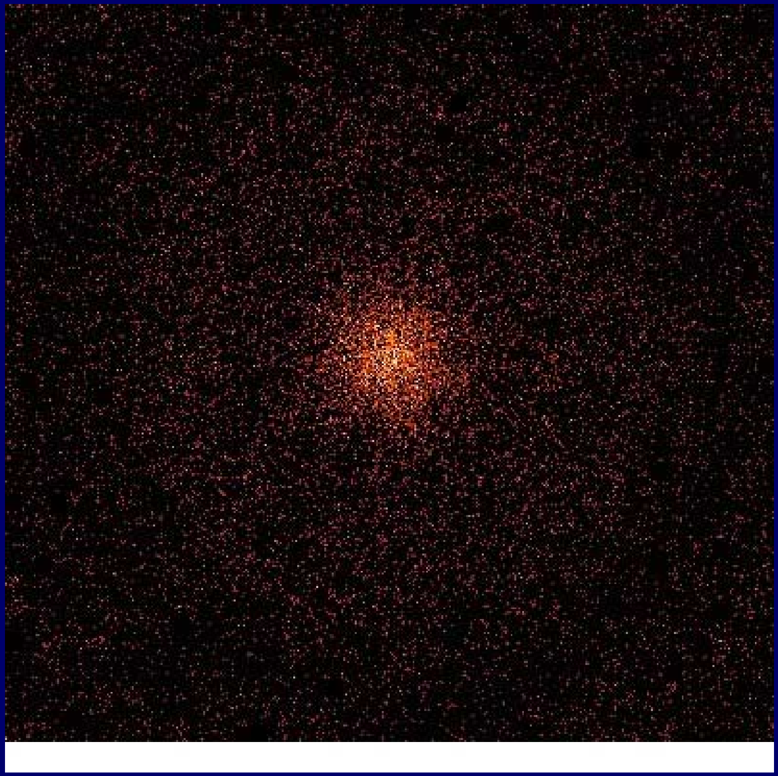


These figures show the probability distribution for the 6keV portion of the continuum and the contribution of photons with energies between 5-6keV to the data simulation.



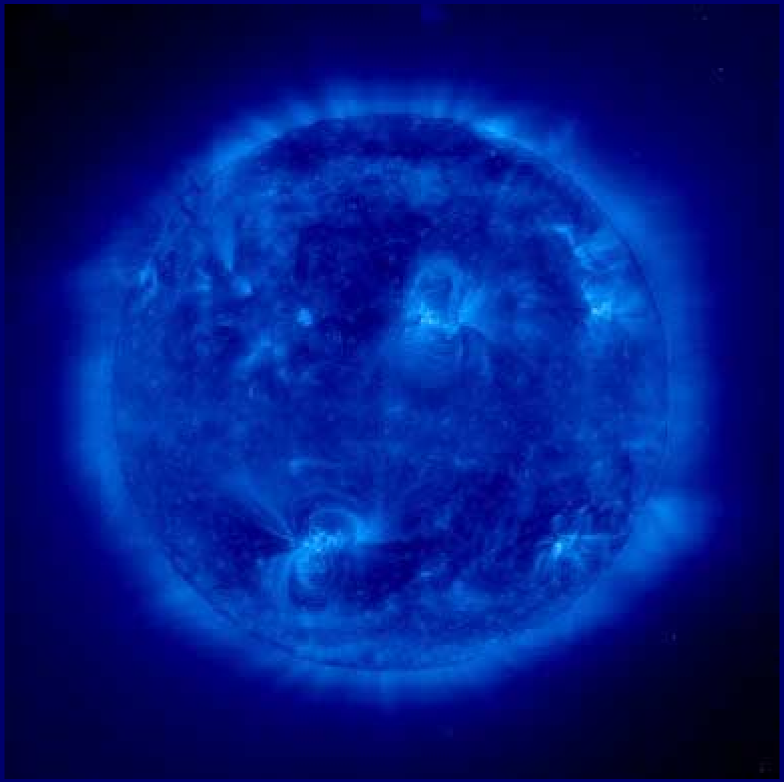


These figures show the probability distribution for the 1keV portion of the continuum and the contribution of photons with energies between 0-1keV to the data simulation.

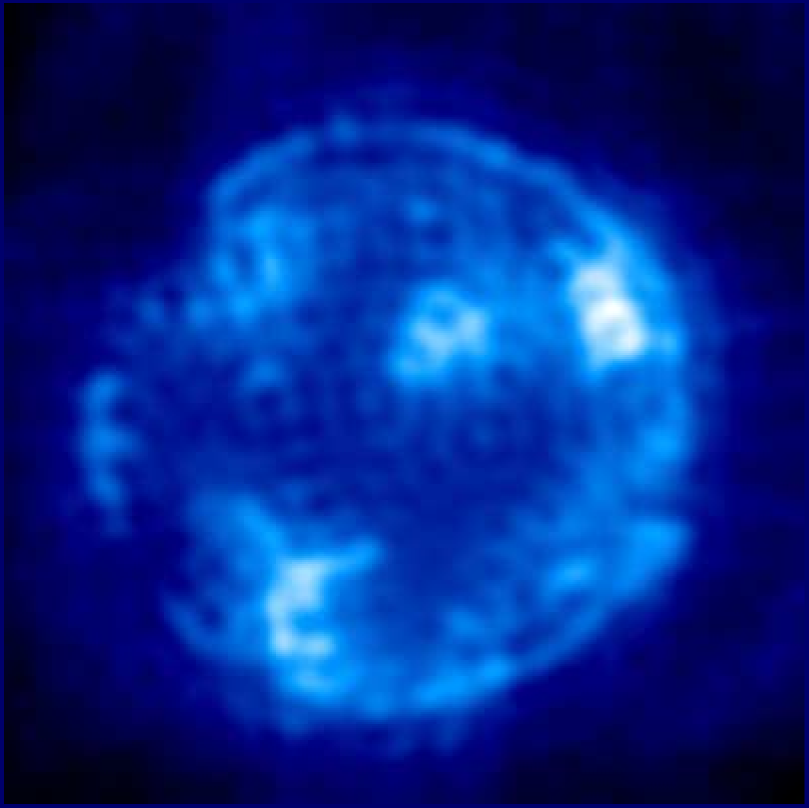
The probability distribution on the left represents a continuum of energies between 1keV and 6keV. In the right figure, 16000 random events were recorded according to this distribution.

Stars

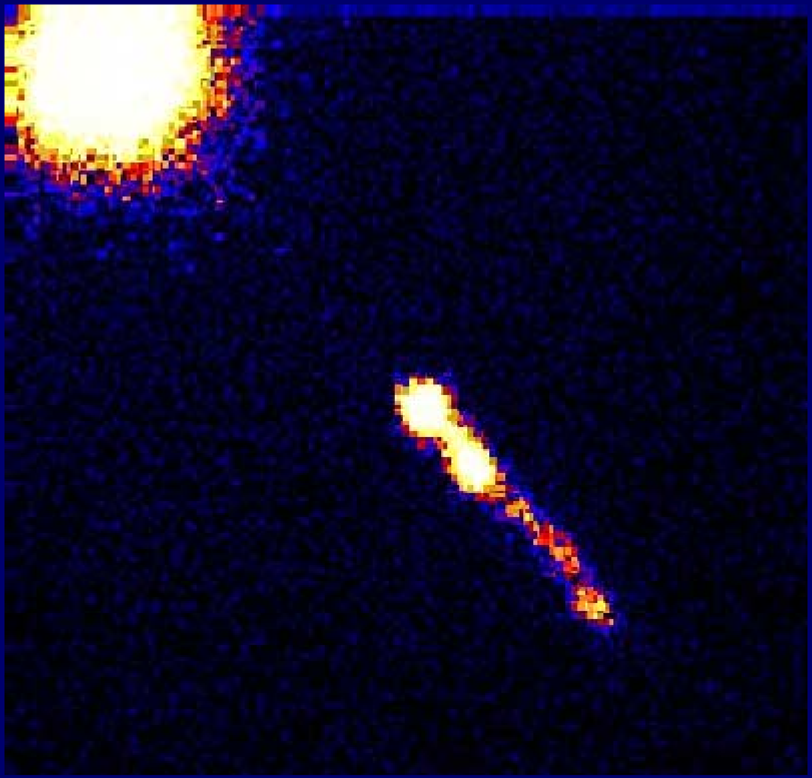


Sun with SOHO

Simulation with Interferometer

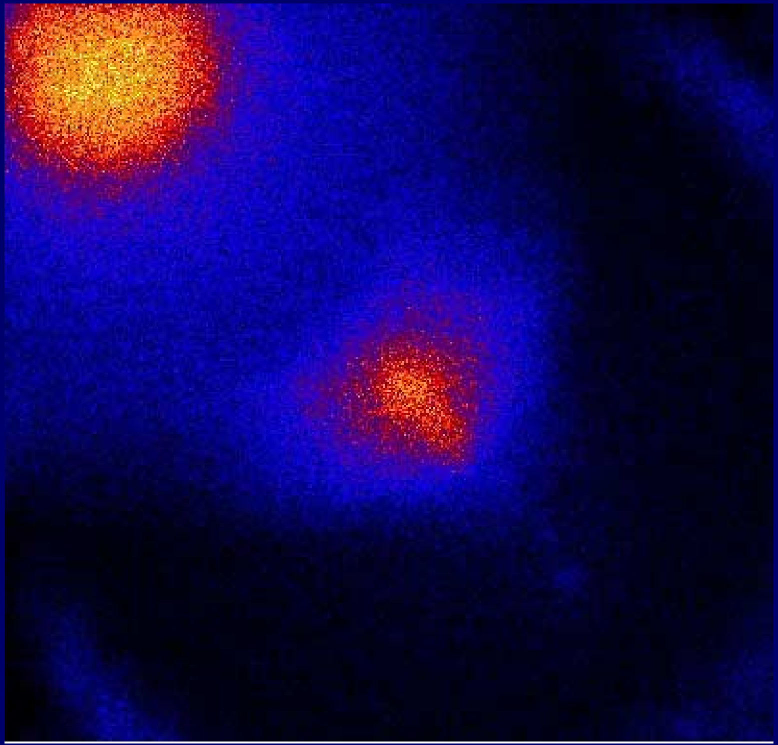


AGN with Jet



3C273 with Chandra

Simulation with Interferometer

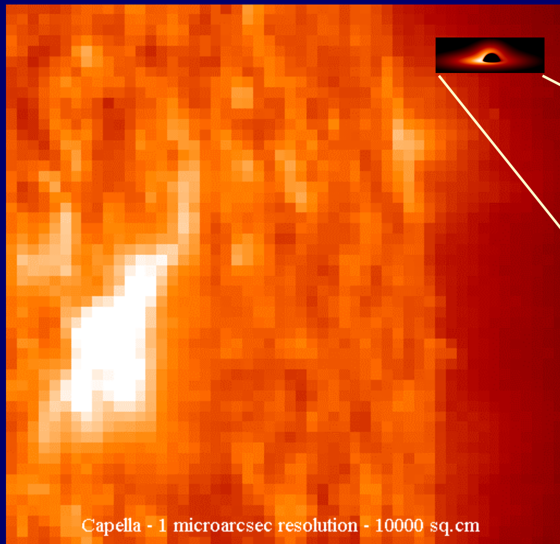


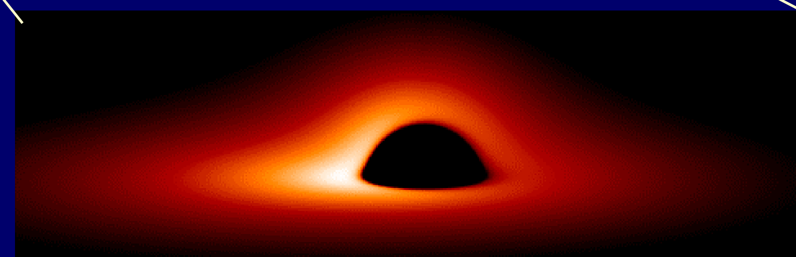
Four Difficult Areas

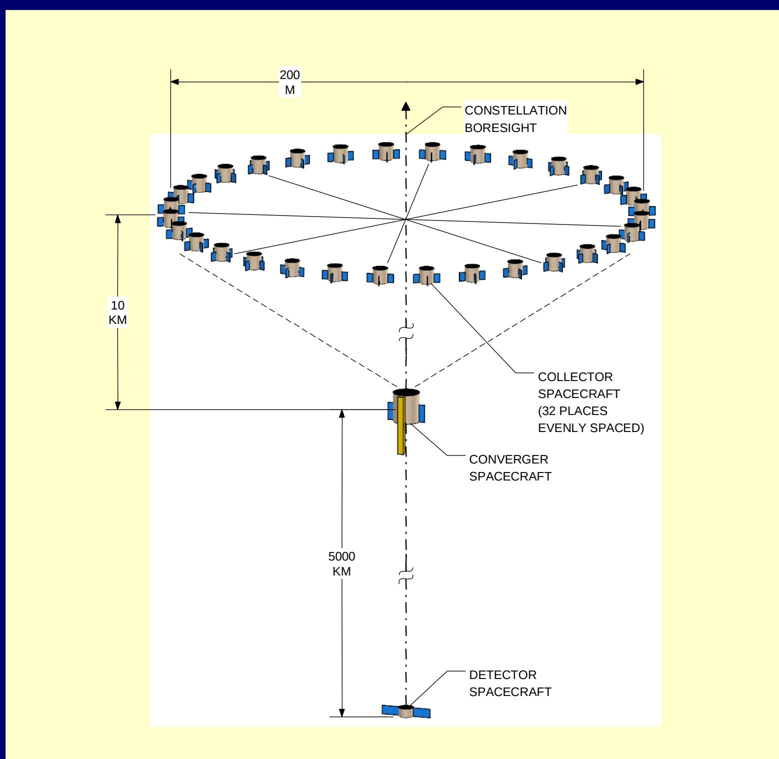
- *Fabrication of Interferometer*
    - *Internal Metrology*
        - Hold Mirrors Flat and In Position
    - *Formation Flying*
        - Hold Detector Craft in Position
    - *Pointing*
        - Hold Interferometer on Target

Maxim

"The Black Hole Imager"







0.1μas Resolution

10,000cm^2 Effective Area

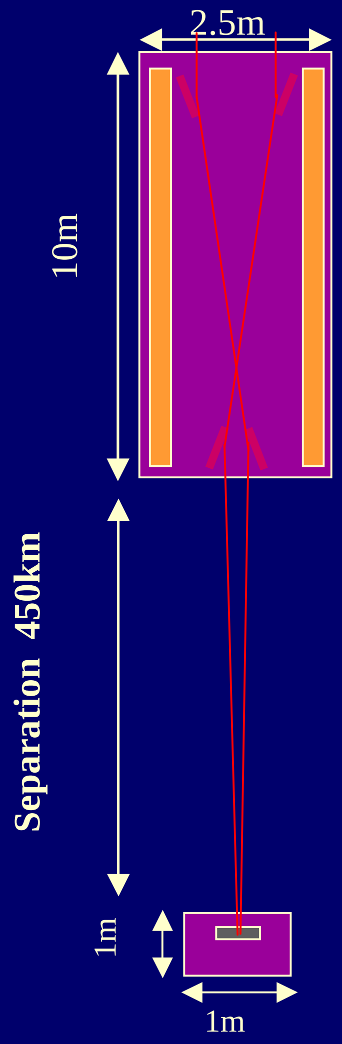
0.4-7.0 keV

Maxim Pathfinder

100μas Resolution
100cm^2 Effective Area
0.4-2.0keV + 6keV

Two Spacecraft
Formation Flying at
450km Separation

Maxim Pathfinder Mission Concept



Optics Spacecraft

Carries: X-ray Interferometers
Finder X-ray Telescopes
2 Visible Light Interferometers
Laser Ranging System

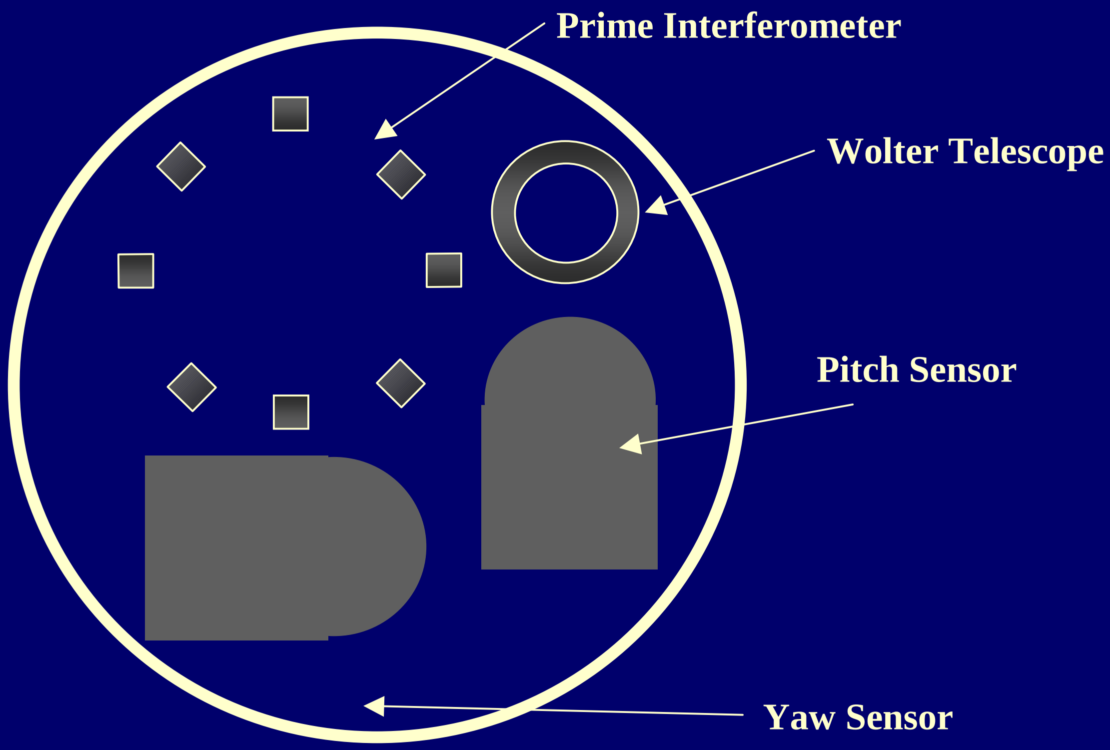
Size:	**2.5x2.5x10m**
Pitch&Yaw Stability:	**3×10^{-4} arcsec**
Pitch&Yaw Knowledge:	**3×10^{-5} arcsec**
Roll Stability:	**20 arcsec**
Position Stability:	**-----**

Detector Spacecraft

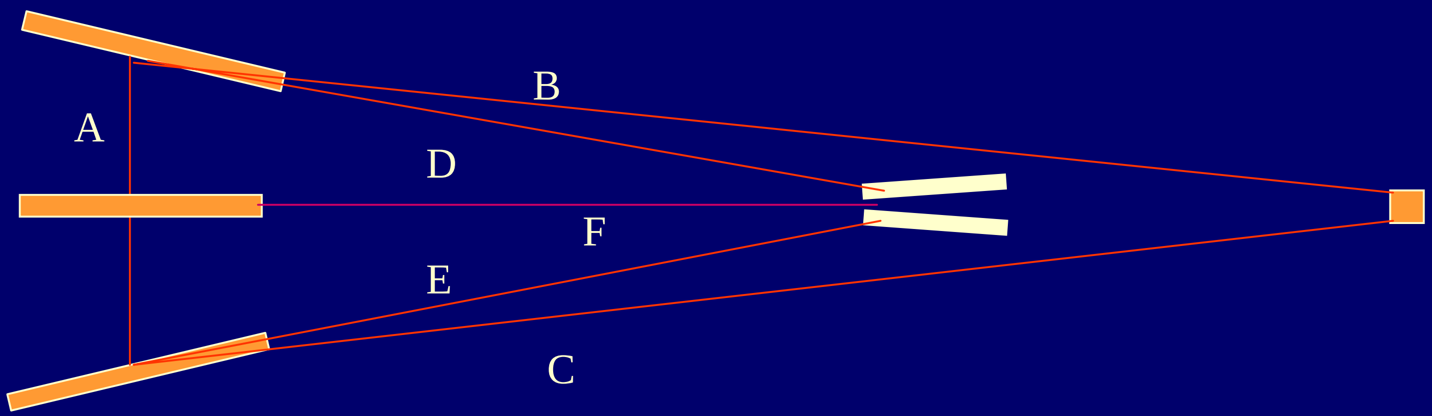
Carries: X-ray Detector Array
Laser Retro Reflectors
Precision Thrusters

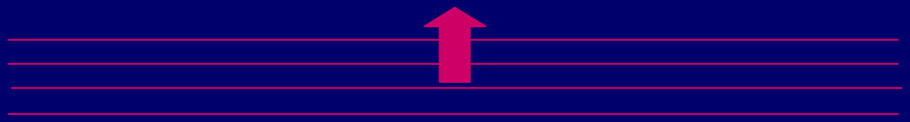
Size:	**1x1x1m**
Pitch&Yaw Stability:	**20 arcsec**
Roll Stability:	**20 arcsec**
Lateral Stability:	**5mm**
Lateral Knowledge:	**50 microns**
Focal Stability:	**10 meters**

Optics Craft
Front View



Solution to Pointing Problem





Visible light wavefront from distant star

Consider, instead, line F.
Mount the visible light interferometer on structures at the ends of line F. They then maintain 1nm precision wrt to guide star that lies perpendicular to F. This defines pointing AND maintains lateral position of convergers.
(40pm not needed in D and E after all.)
A, B, C, D and E all maintain position relative to F.

Detector

- Energy Resolution Necessary for Fringe Inversion
- CCD is adequate
- To get large field of view use imaging quantum calorimeter

Metrology

Tightest Tolerance is Separation of Entrance Apertures

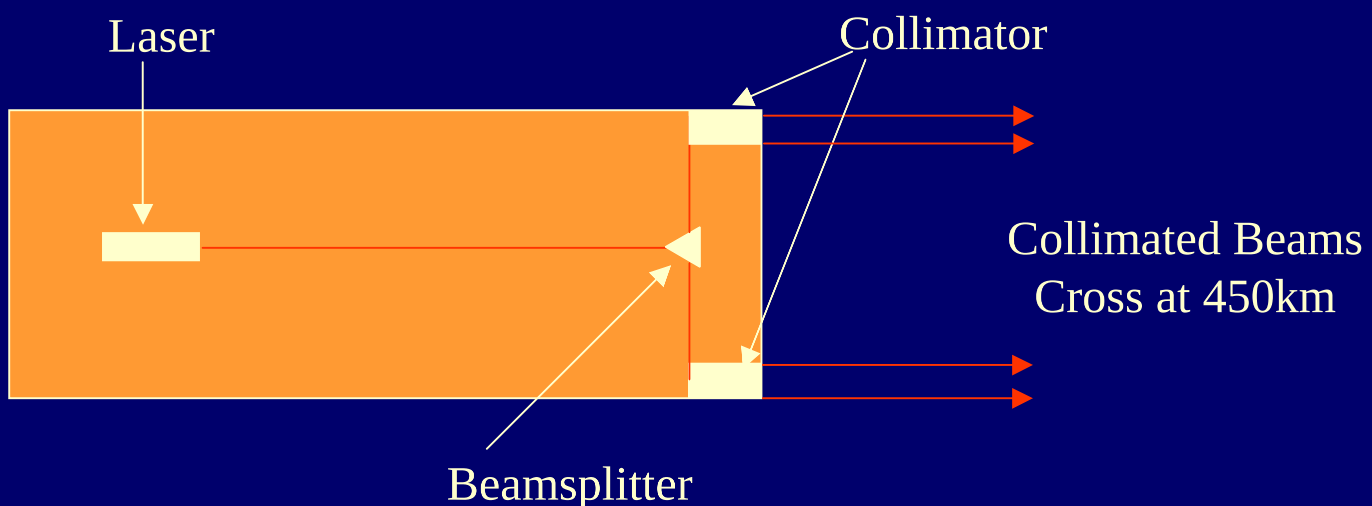
$d = \lambda/20\theta$ for tenth fringe stability

At 1keV and 2deg, d=1.7nm
At 6keV and 0.5deg, d=1.1nm

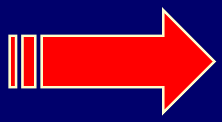
Requires active thermal control and internal alignment

Laser Beam

Split and Collimated

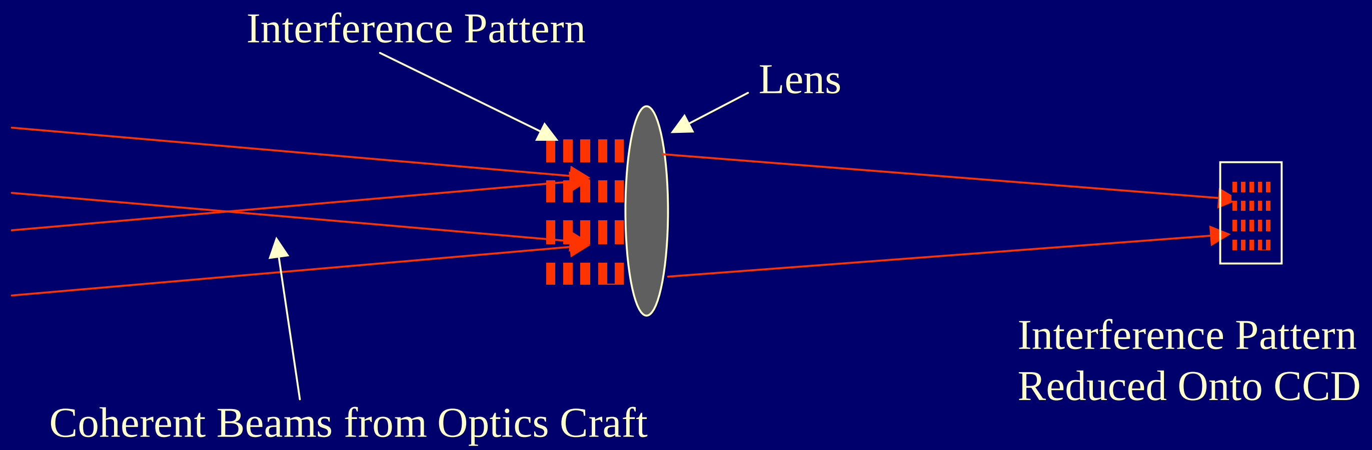


Optics Craft



450km to
Detector Craft

Detection of Pattern
at Detector Craft



Fringes have 14cm period at 450km

Pointing

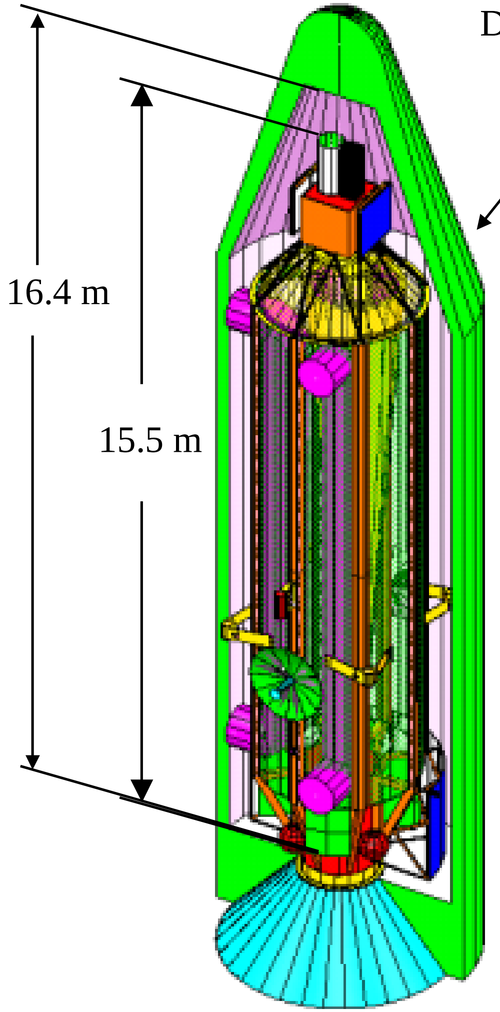
Need stability and information wrt to the celestial sphere at level of required resolution.

L2 or Fly-away orbit probably necessary

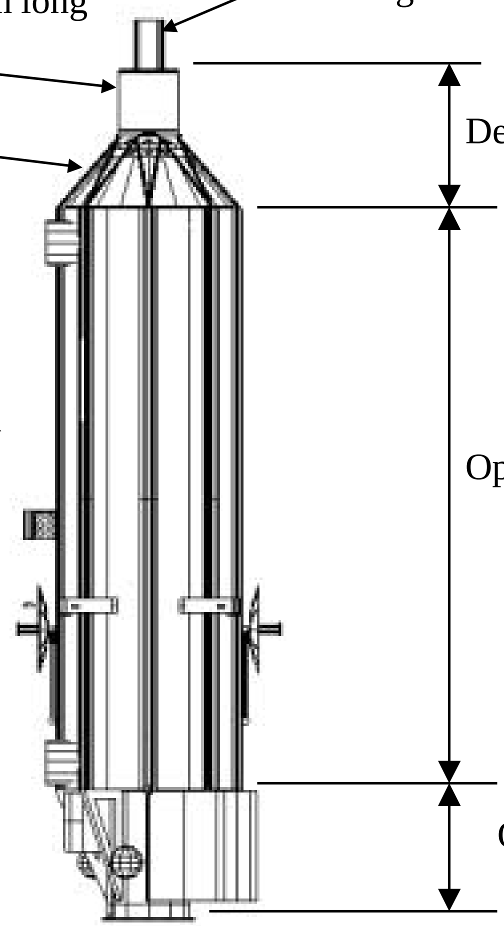
Baseline design calls for two stellar interferometers.

- One each for pitch and yaw
- SIM class interferometers more than adequate

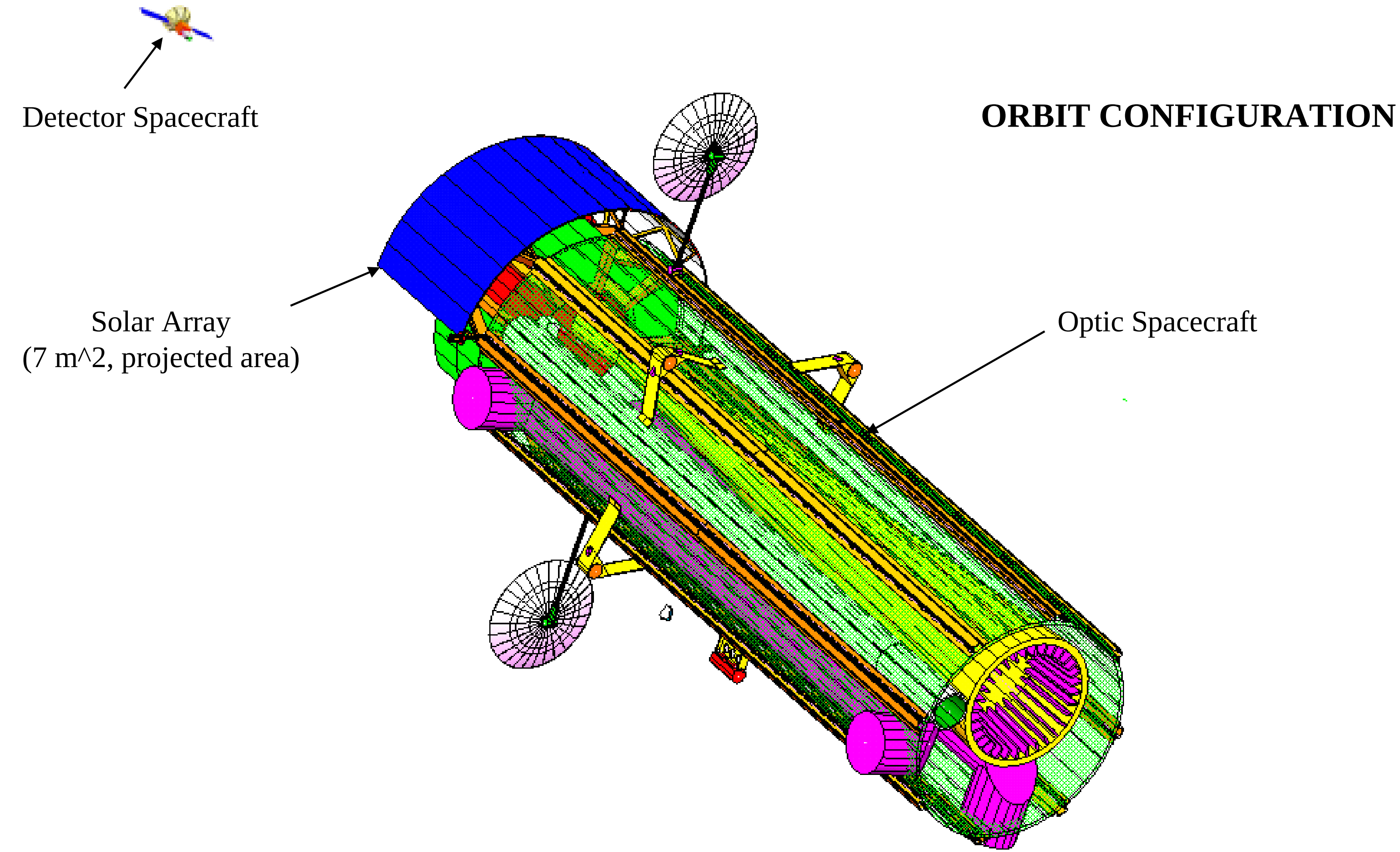
MAXIM



LAUNCH CONFIGURATION

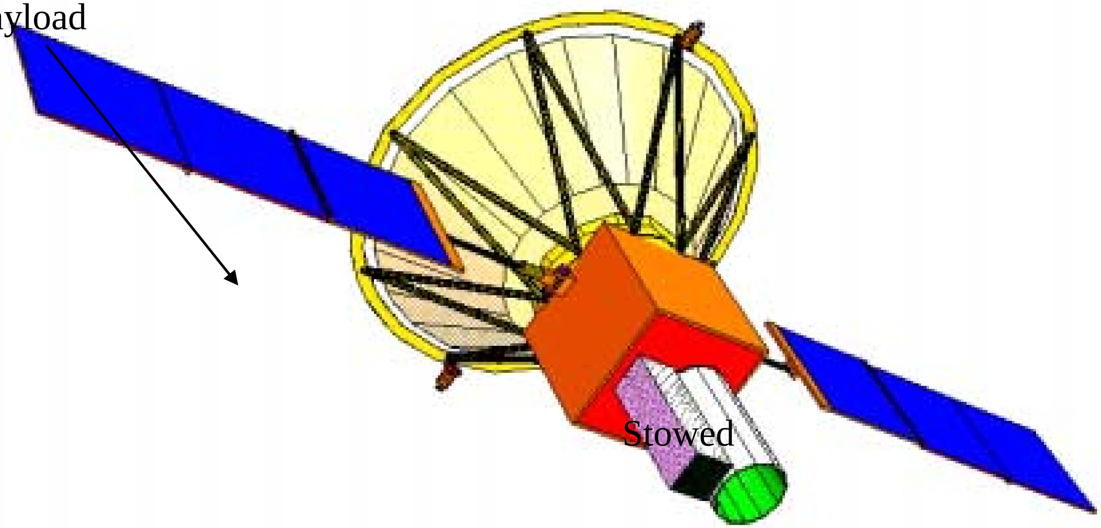


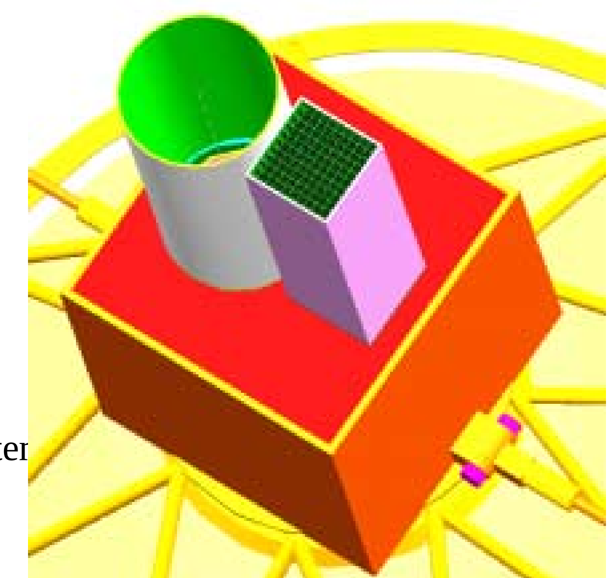
MAXIM


Detector Spacecraft
ORBIT CONFIGURATION
Solar Array
(7 m^2, projected area)
Optic Spacecraft

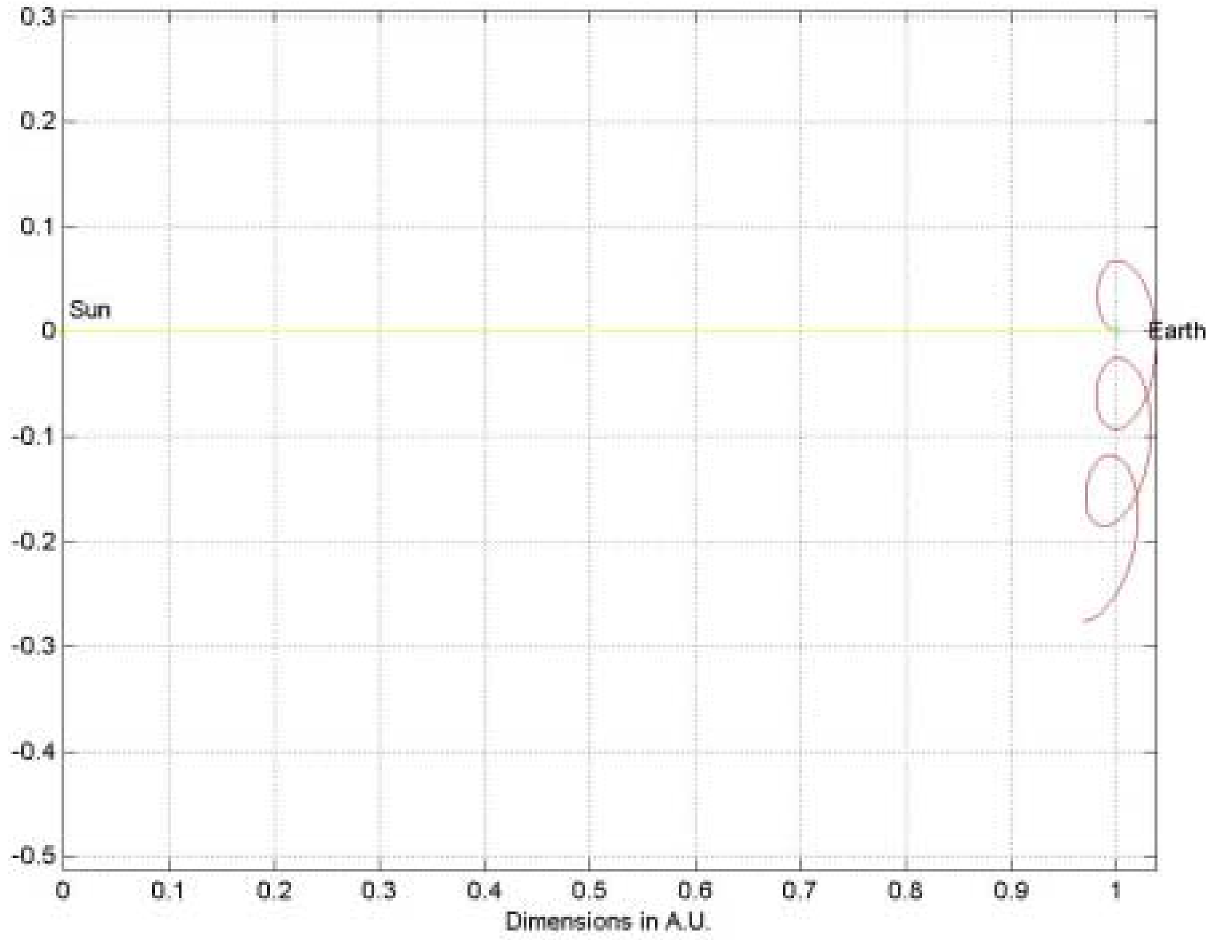
MAXIM

DETECTOR SPACECRAFT



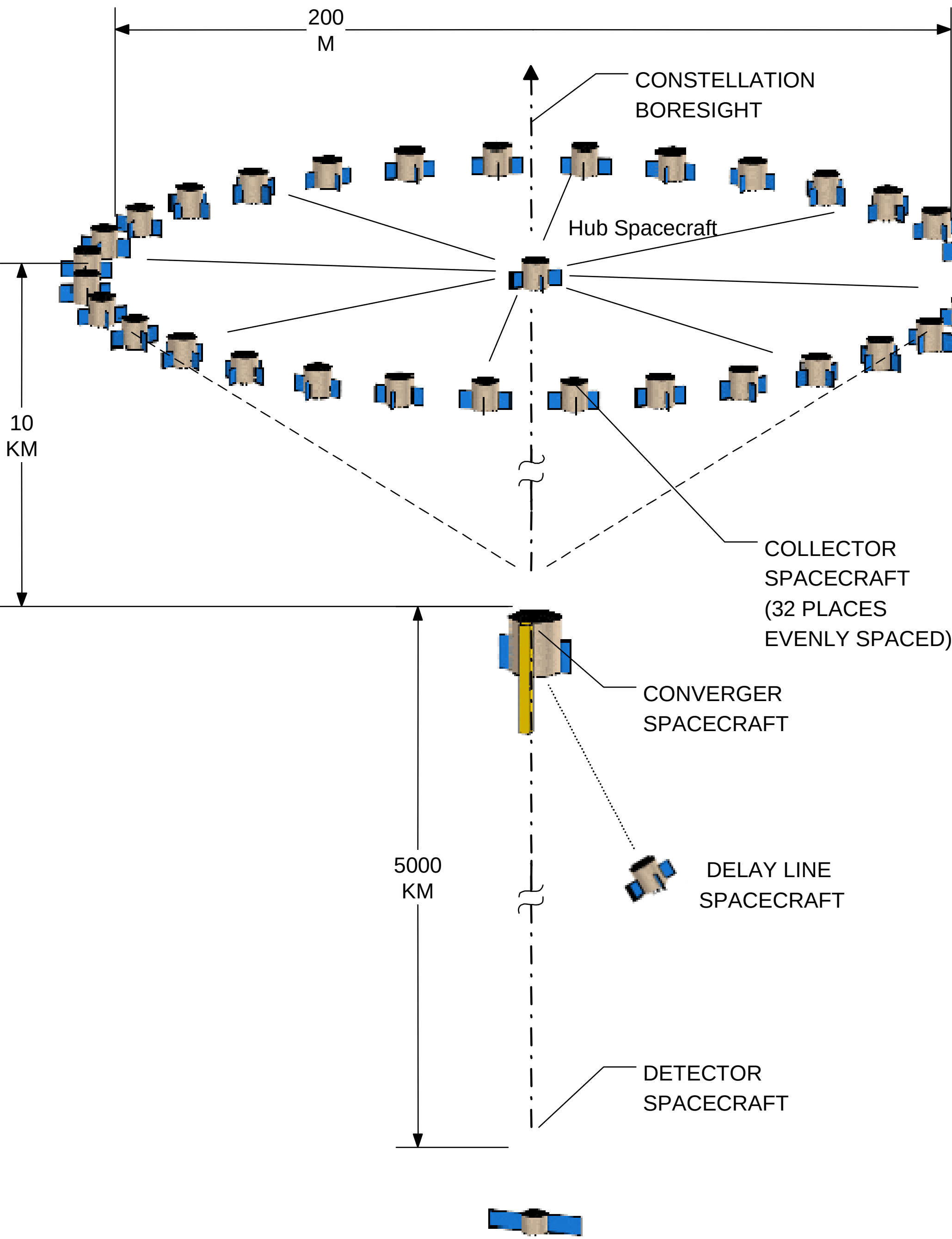


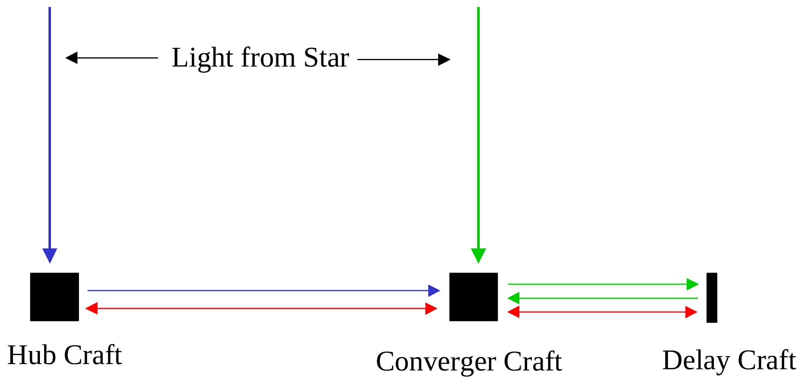
MAXIM Trajectory in Solar Rotating Coordinates



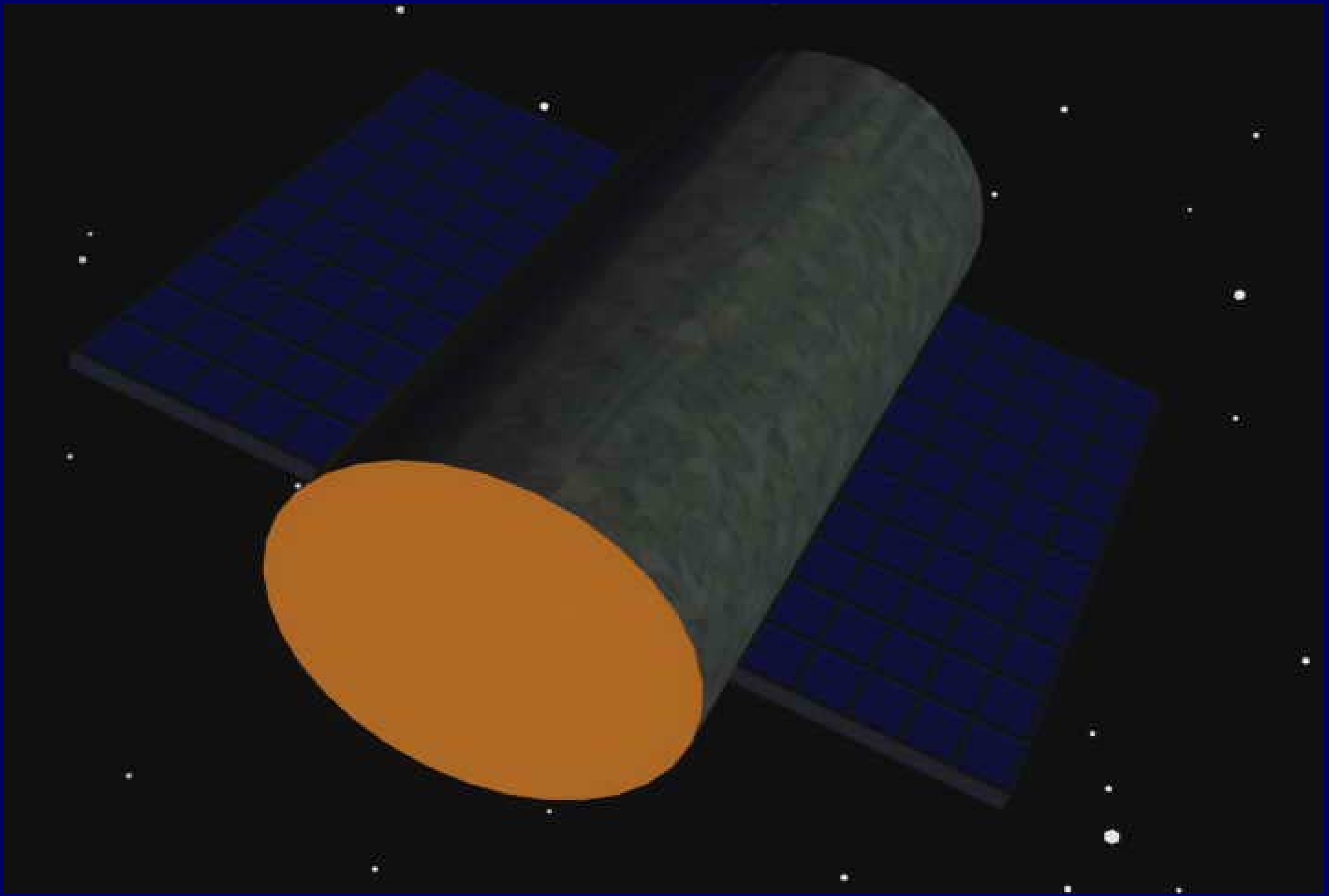
Maxim Pathfinder

Maxim Design





Full Maxim



Maxim Limitations

- If primary flats are on separate spacecraft then they can be flown farther apart. Resolution increases.
- Limited by visible light aspect from stars
  - They’re all resolved at 30nano-arcsec!
    - Find non-thermal visible sources
    - Use x-ray interferometry for aspect too.
- Solve aspect problem and reach 10^{-9} arcsec

Integrated System Modeling

Ball Aerospace Technologies Corporation

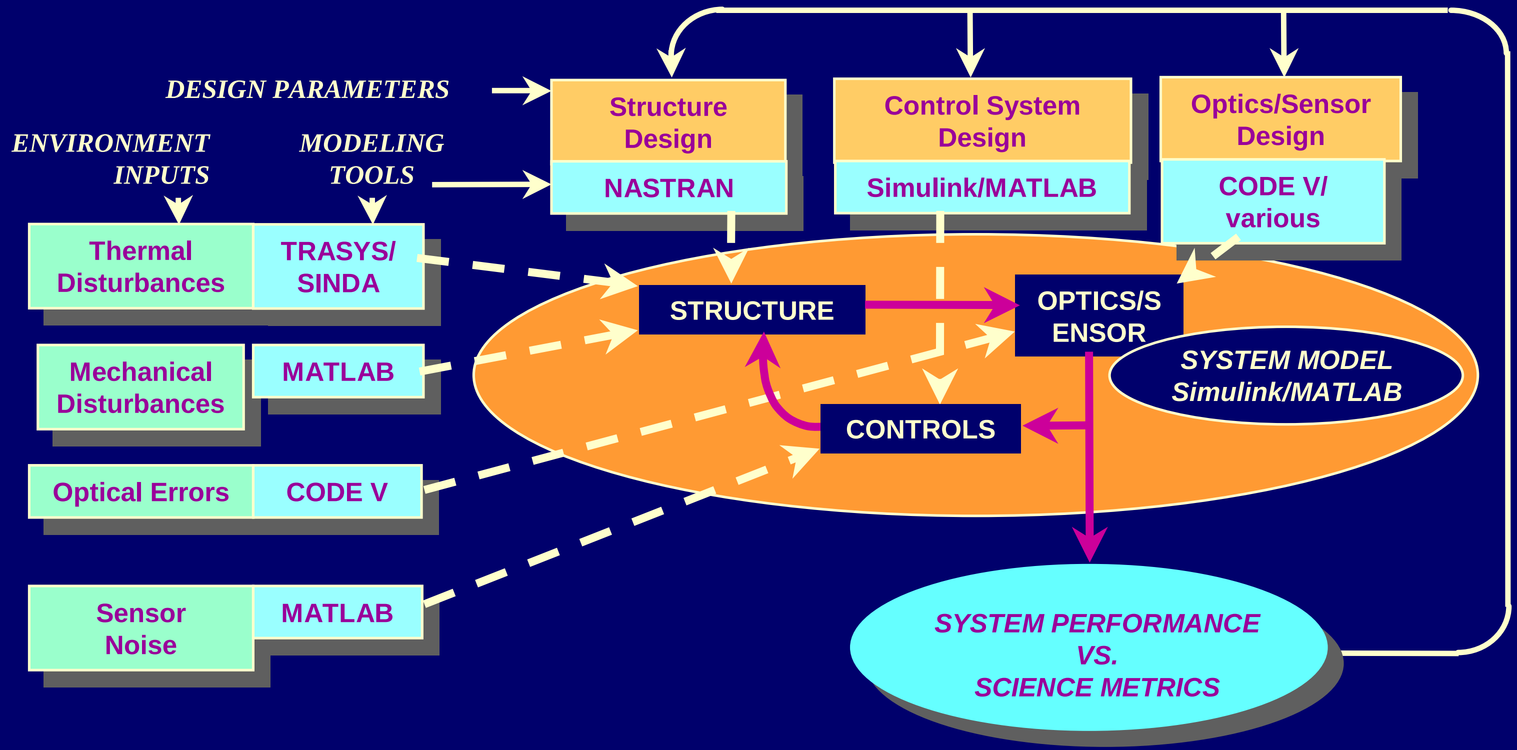
M. Lieber

D. Gallagher

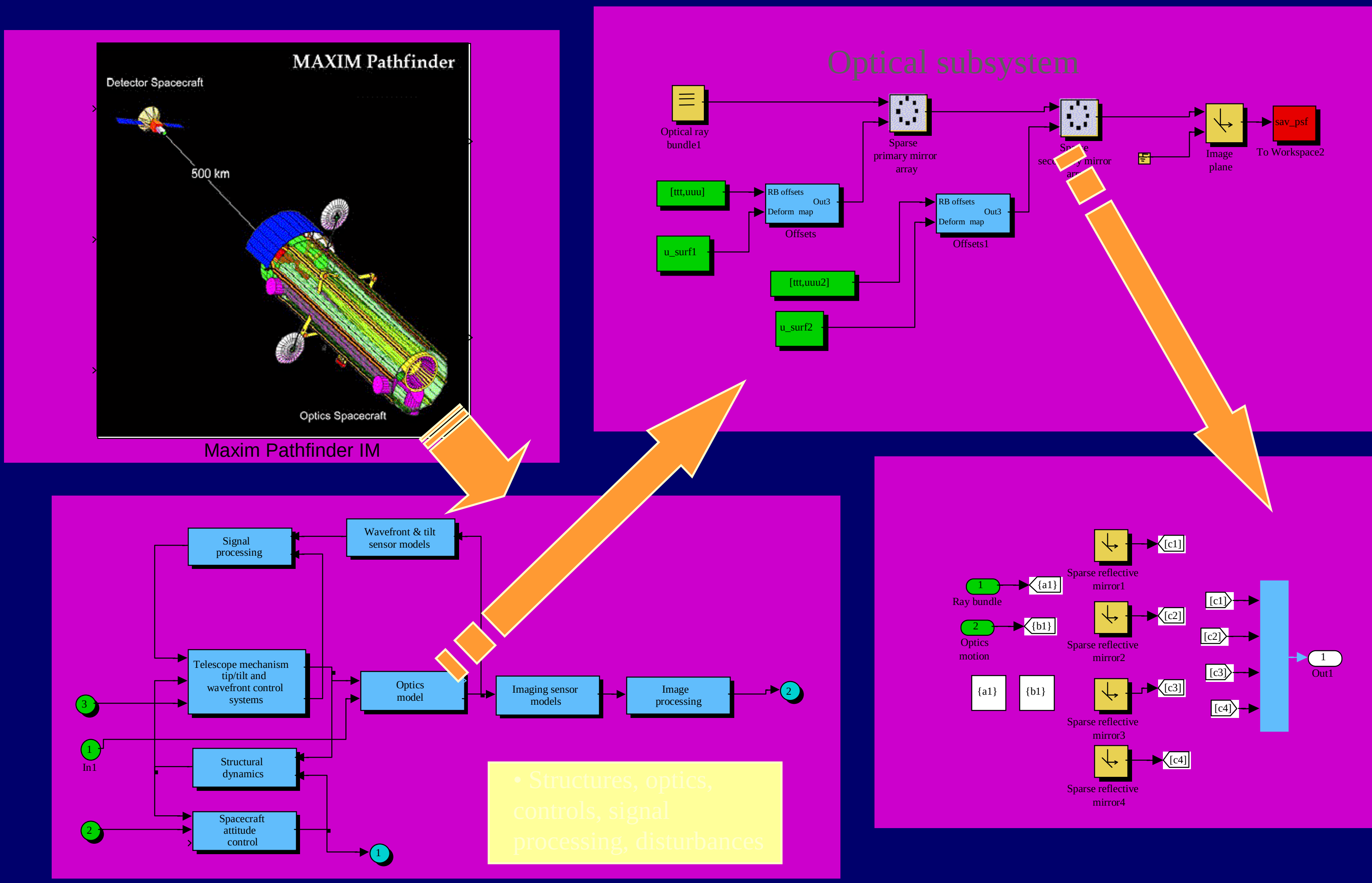
Will lead to single most important tool in development and definition of x-ray interferometry

Integrated End-to-End Modeling Environment

- Integrated modeling seamlessly combines the subsystem models from well established software tools.
- Allows one to rapidly study parameter interaction of disparate variables from different disciplines. Integrated models facilitate GUI development - muliti-user system tool.
- Standard interfaces minimizes errors and miscommunications between disciplines

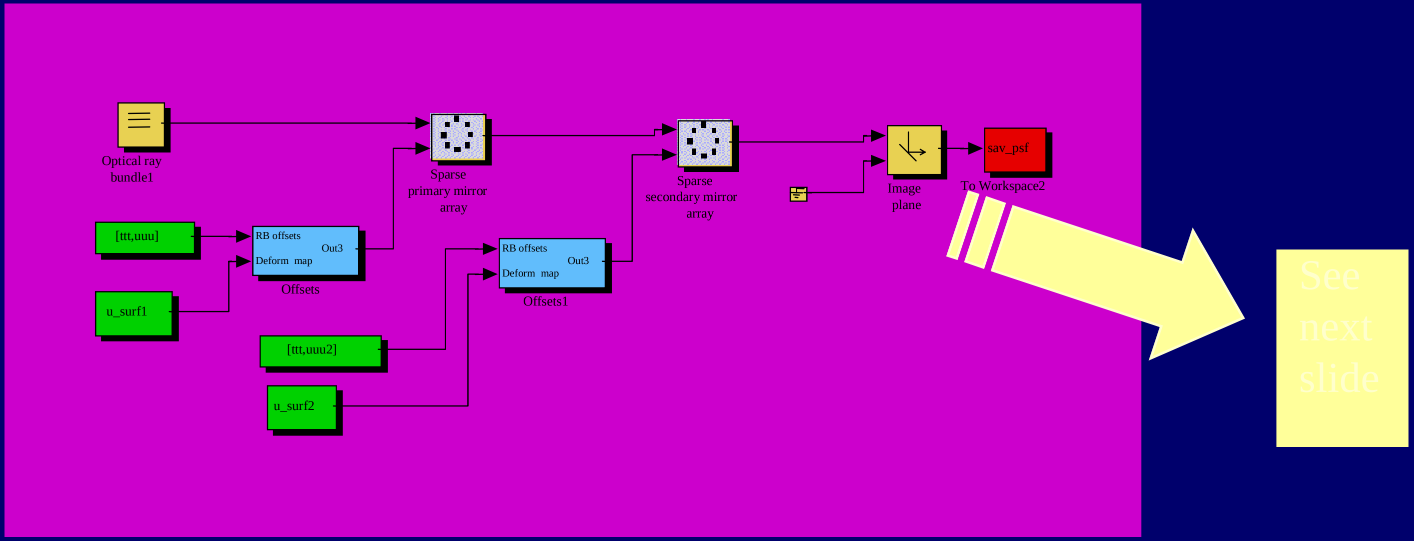


Example of MAXIM Pathfinder



Optical Toolbox: Key Element of Optical Performance Modeling

- Geometric ray trace
- Diffraction analysis (PSF outputs)
- Easy introduction of mirror distortions from thermal or vibration
- Optics tied to NASTRAN structural model
- Active control modeling of metrology system and active optics
- Interfaces with imaging and detection modules



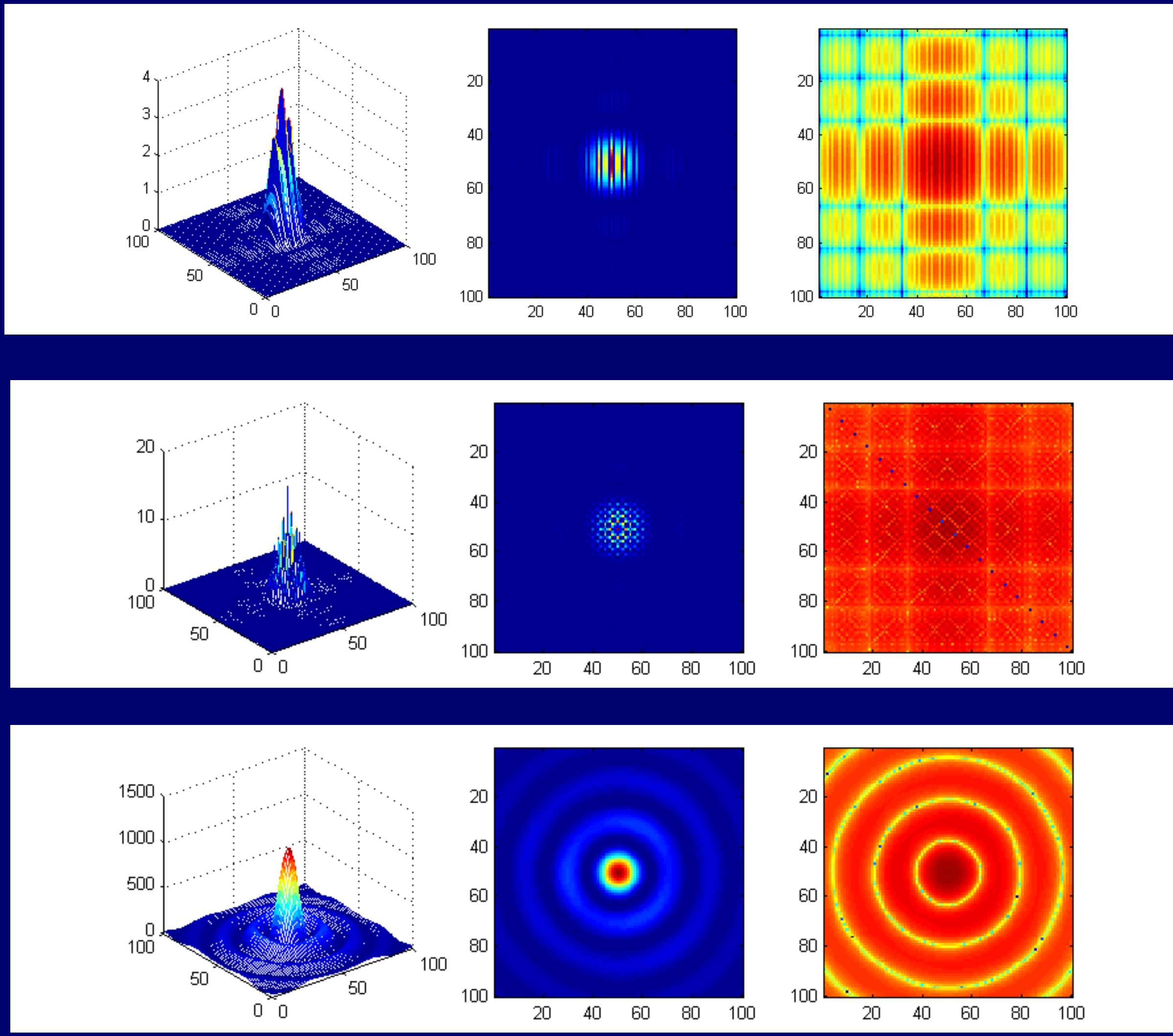
MAXIM Pathfinder PSFs with Different Number of Optical Elements

PSF | Image | Log image

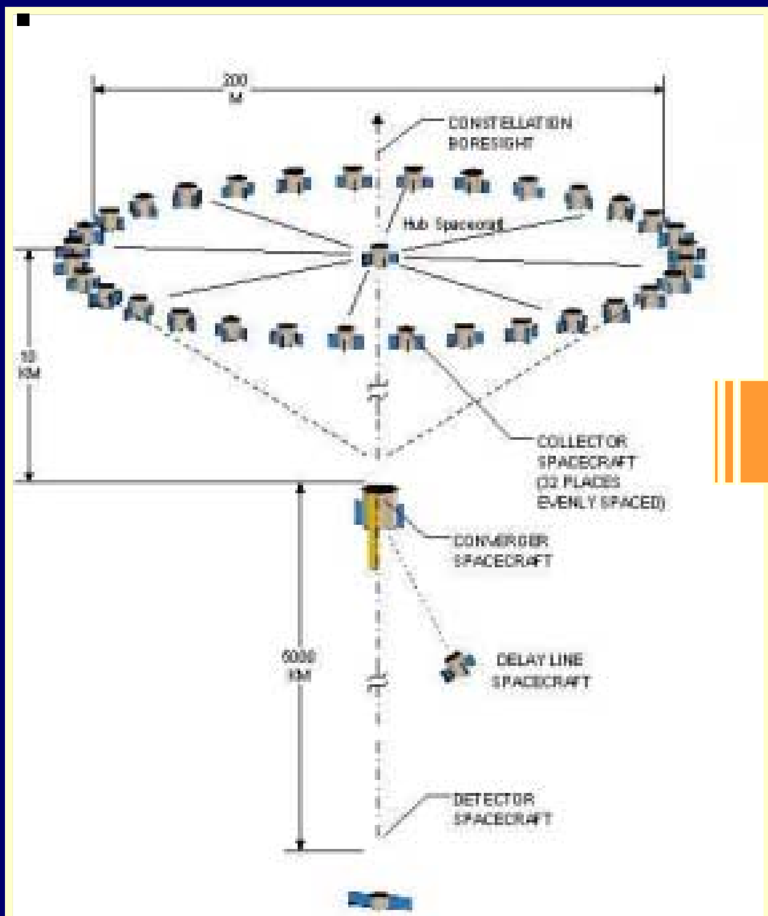
2 segments

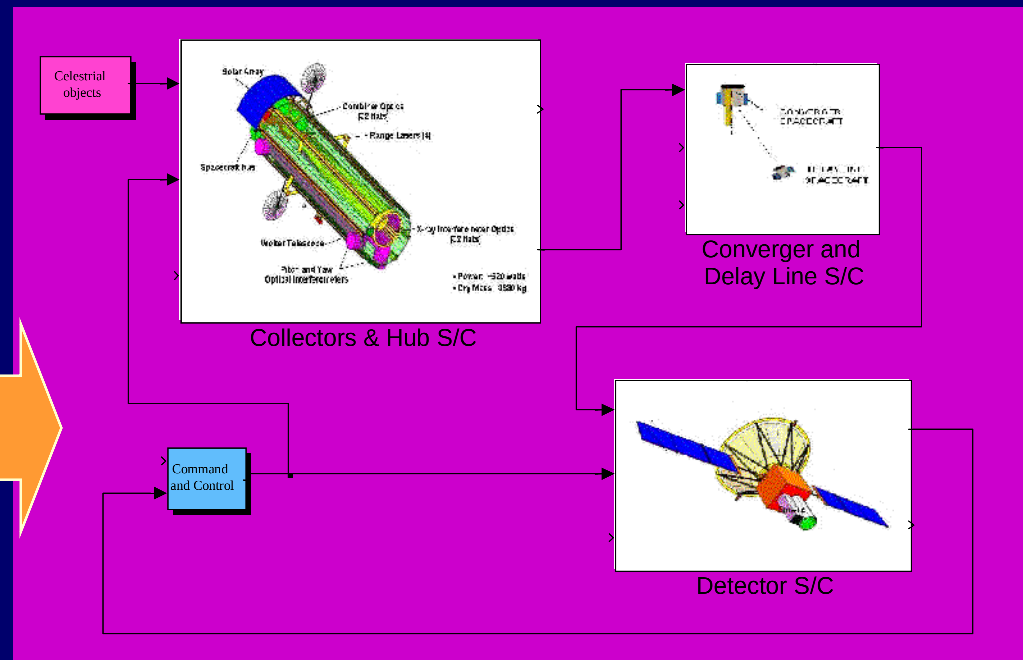
4 segments

32 segments



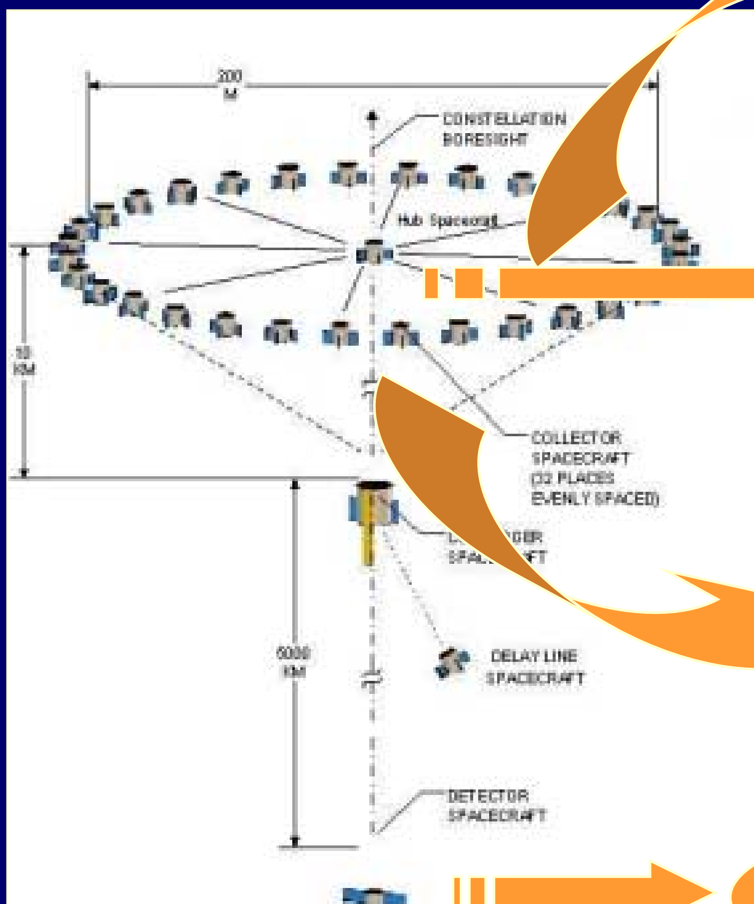
MAXIM Physical Model





MAXIM Integrated Model

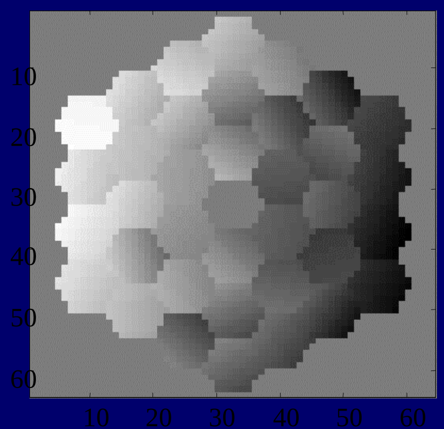
MAXIM System Modeling Leveraged From NASA and Other Programs

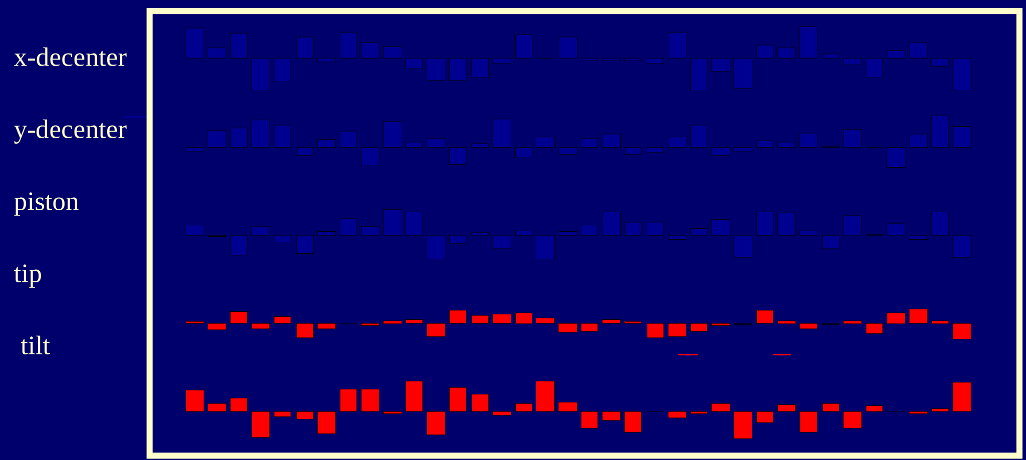


- GSFC - Expertise and models for formation flying - FF lab
- Optical metrology - Ball/GSFC Cross Enterprise contract, Ball/JPL Starlight program
- Integrated modeling environment and MATLAB/Simulink toolset - NGST, TPF, VLT
- Wavefront control - see next slide

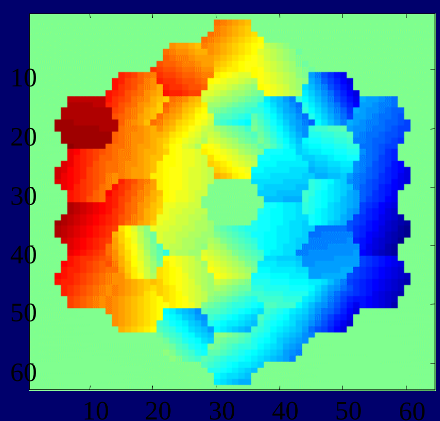
Example Wavefront Control Modeling - Initial Phase Map of NGST

- Wavefront control tools from NGST program and extensive work on phase retrieval by JPL



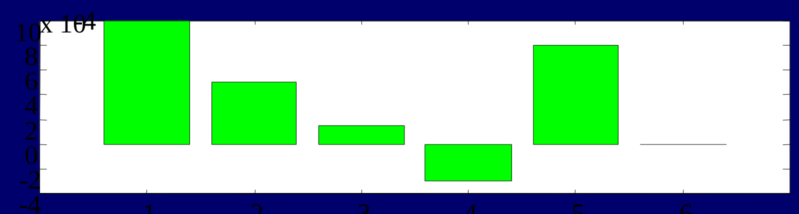


Random errors for 36 segments



- **<u>RMS</u> random segments = primary [1e-4 1e-4 4e-5 1e-5 1e-4 0]**

[x-decenter y-decenter piston tip tilt clocking]



- **Secondary = offsets [1e-3 5e-4 1.5e-5 -3e-5 8e-4 0]**

[x-decenter y-decenter piston tip tilt clocking]

Status: X-ray Interferometry in NASA Planning

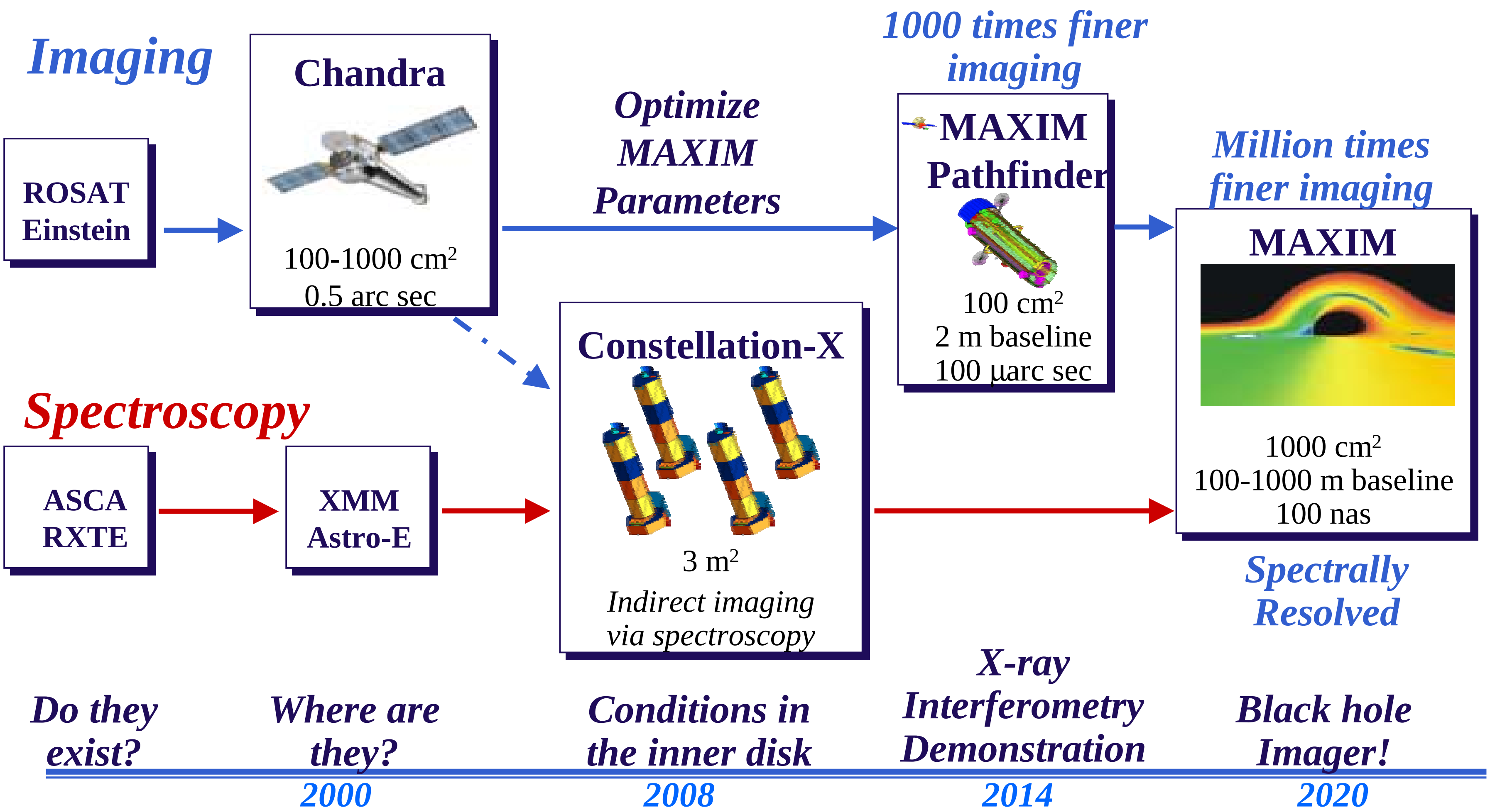
Structure and Evolution of the Universe (SEU) Roadmap

- Maxim Pathfinder Appears as Mid-Term Mission
  - Candidate Mission for 2008-2013
- Maxim Appears as Vision Mission
  - Candidate Mission for >2014

McKee-Taylor Report

- National Academy Decadal Review of Astronomy
- Released May 19, 2000
- Prominently Recommends Technology Development
  - Money for X-ray Interferometry

“X-ray Roadmap” to Image a Black Hole



Plan

- Technology Development
  - Start with NIAC and SR&T Funding
  - Mission Specific Funding
- Maxim Pathfinder
  - New Start 2008
  - Develop & Test Technology for Maxim
- MAXIM
  - Five Years after Pathfinder

The Black Hole

Disney, 1979

We have already found this black hole and will have these pictures before 2020.