X-ray Interferometry

The Future of X-ray Astronomy

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University of Colorado

Co-Investigators

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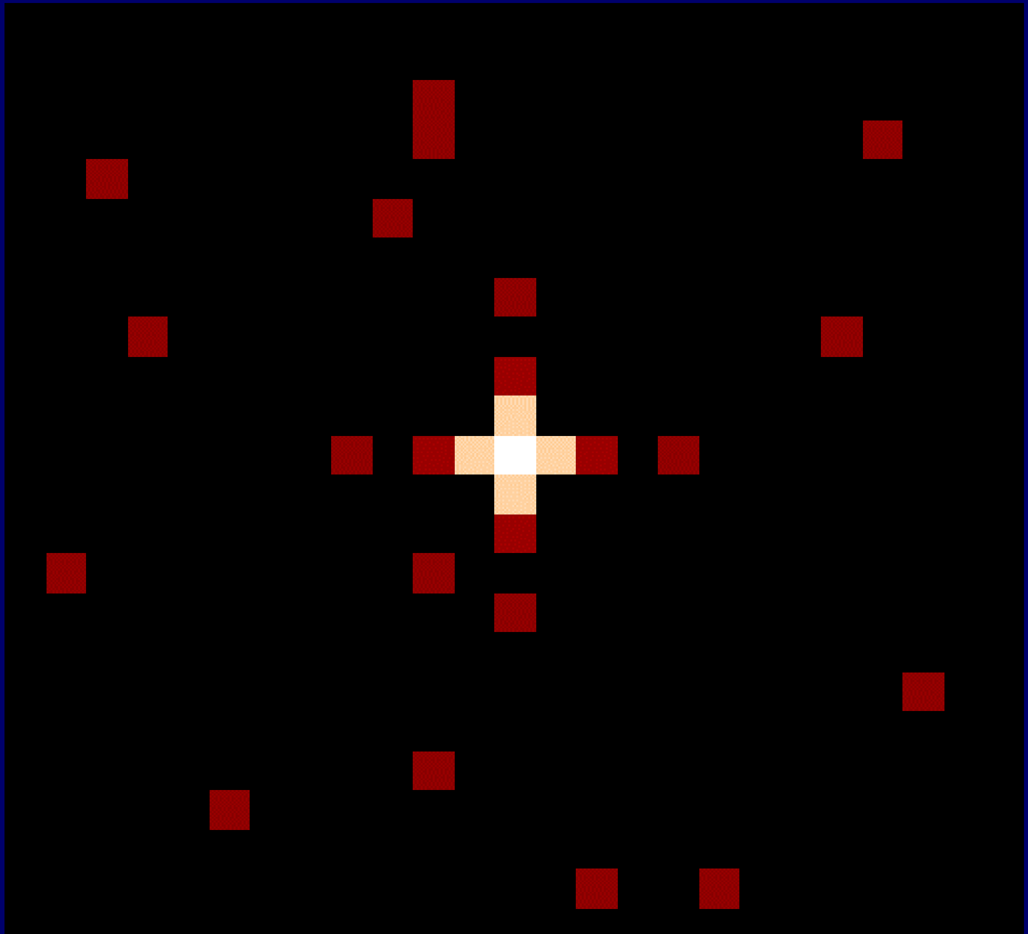
- Mark Schattenburg - MIT
- David Windt – Columbia University
- Dennis Gallagher – Ball Aerospace

A Sufficiently Good Image is Like a Visit

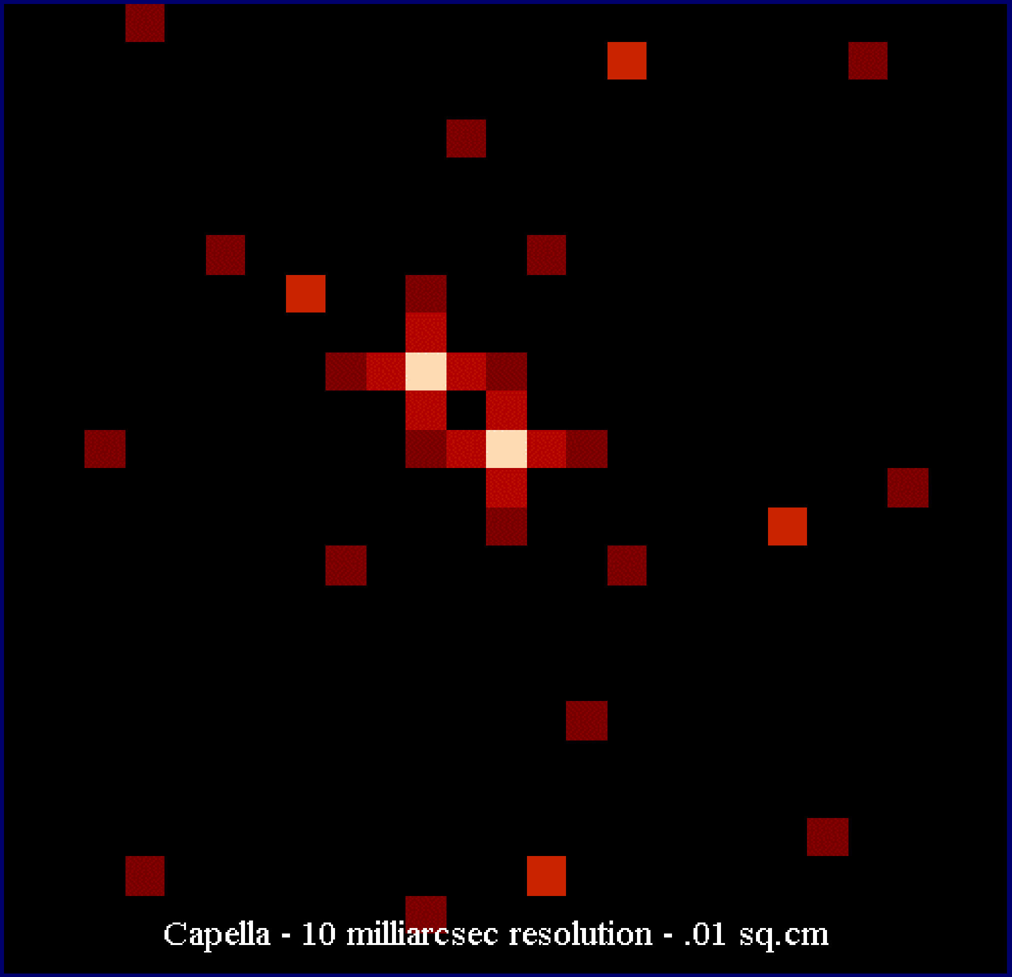
	Resolution (arcsec)	Log Improvement
Cavemen	100	--
Galileo	3	1.5
Palomar	1	2
HST	0.1	3
VLBA	.001	5
Voyager	10^{-5}	7
X-ray Int.	10^{-7}	9

Capella 0.1”

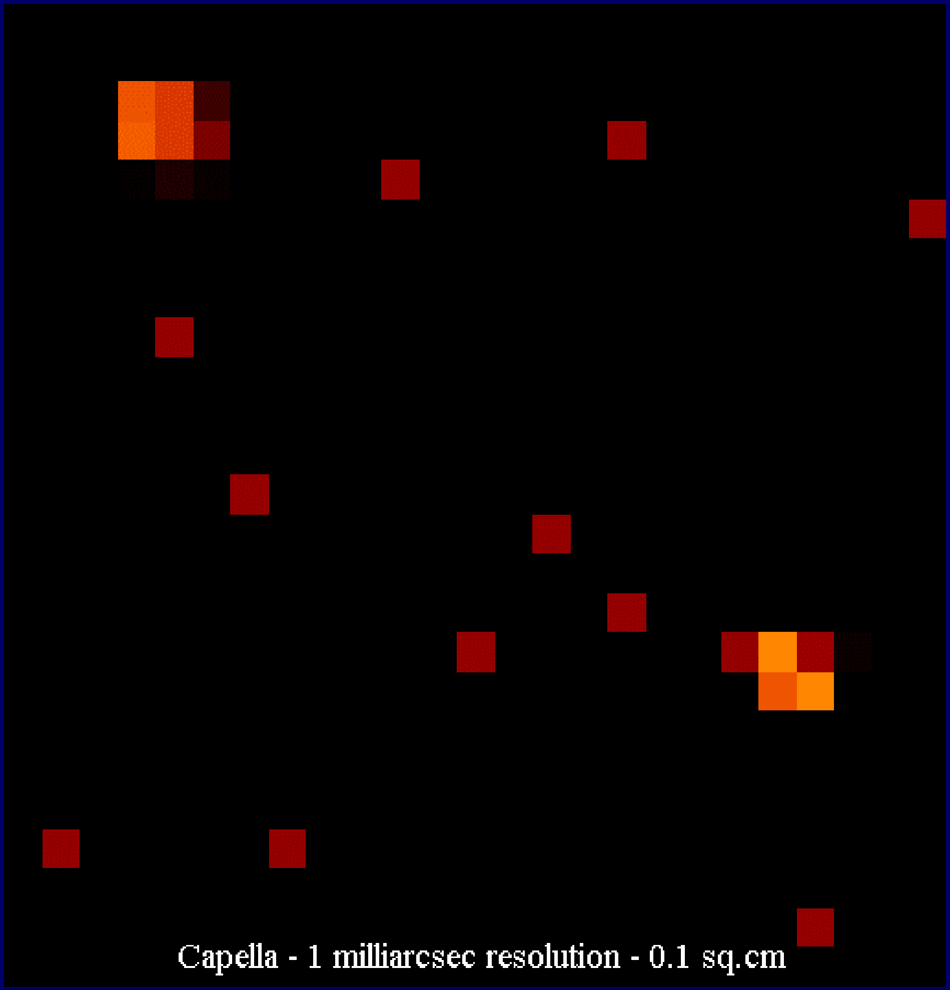


Capella - 100 milliarcsec resolution - .01 sq.cm

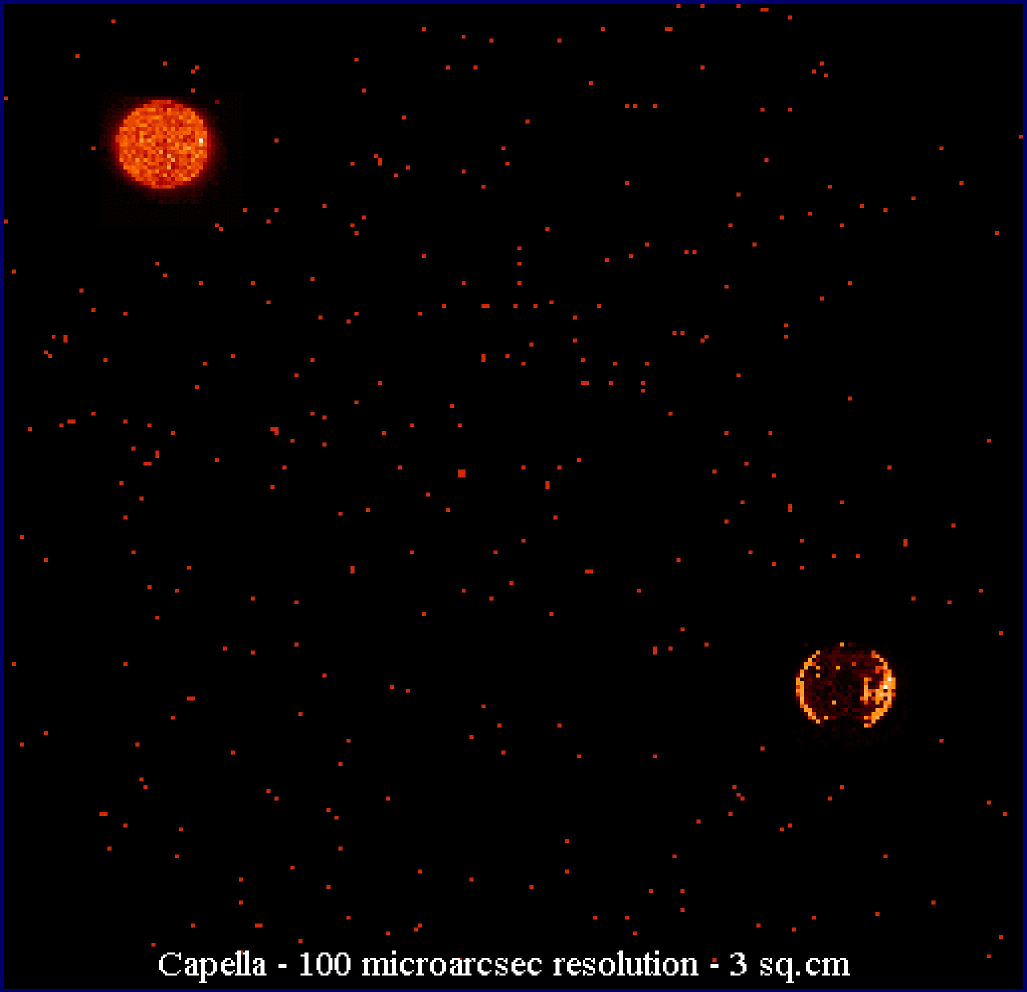
Capella 0.01"



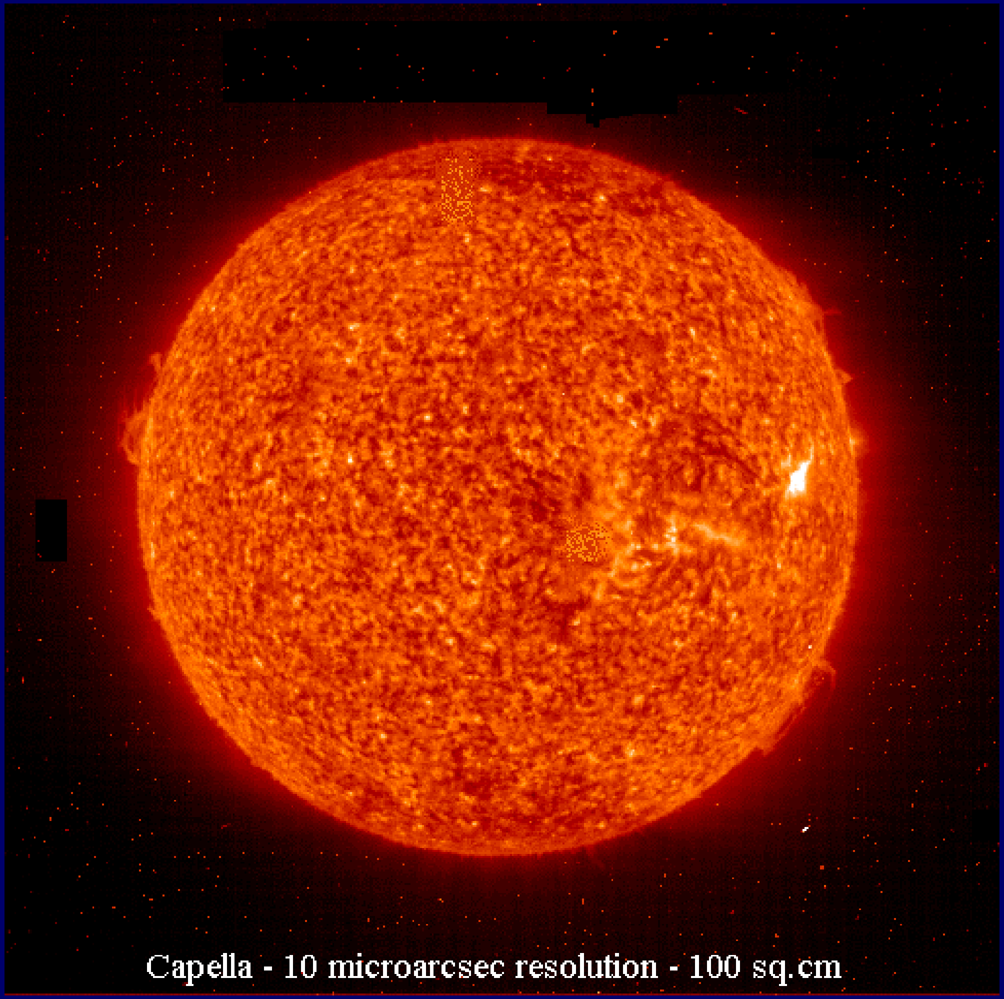
Capella 0.001"



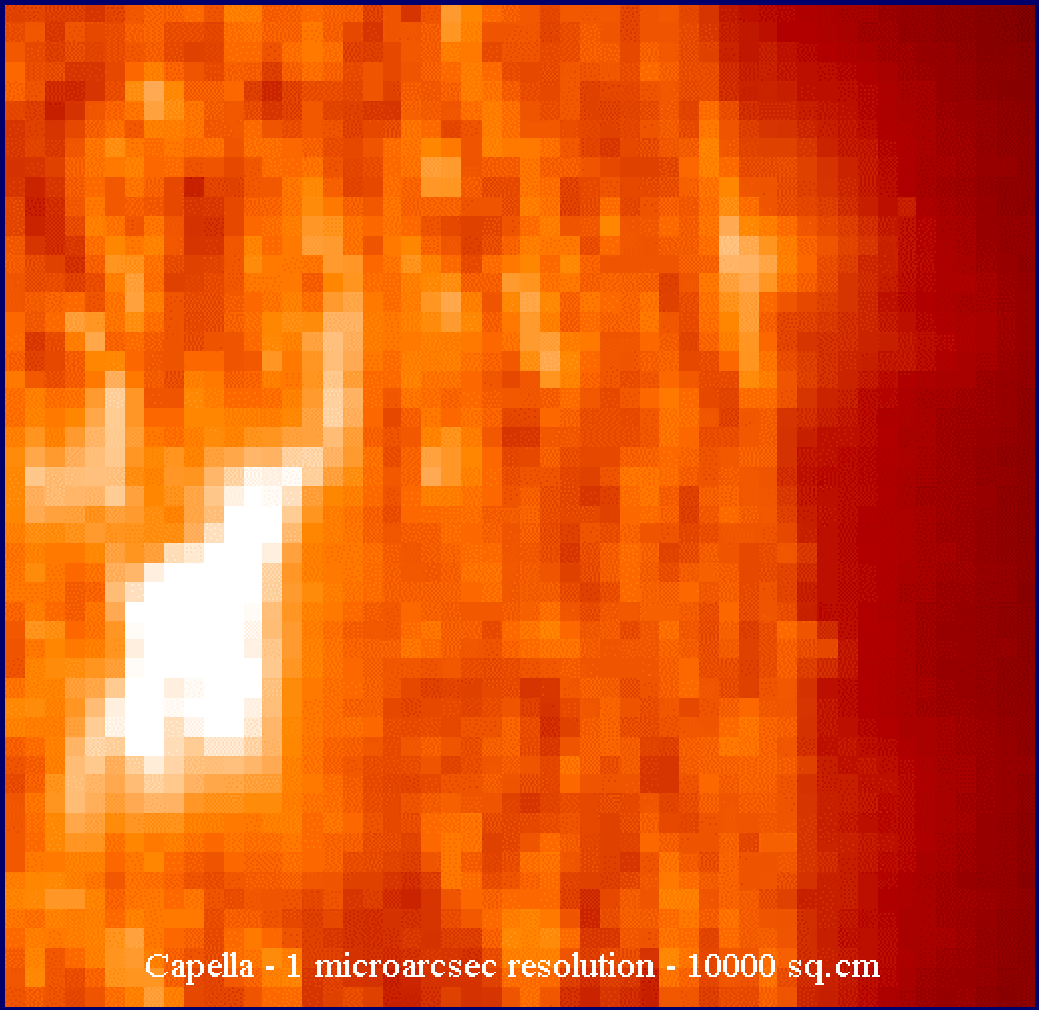
Capella 0.0001"



Capella 0.00001"

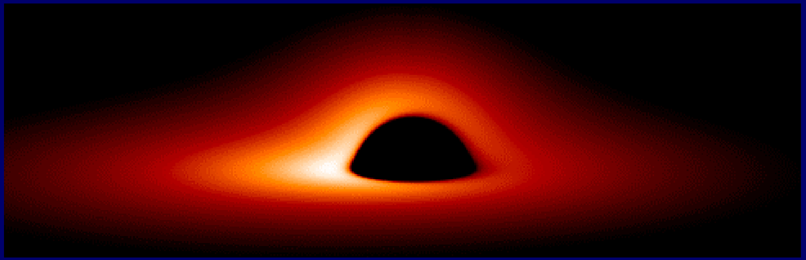


Capella 0.000001”



AR Lac
Simulation @ 100μas

AGN Accretion Disk Simulation @ 0.1μas
(Chris Reynolds)



Seeing the Strong Field Limit
Is Believing

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

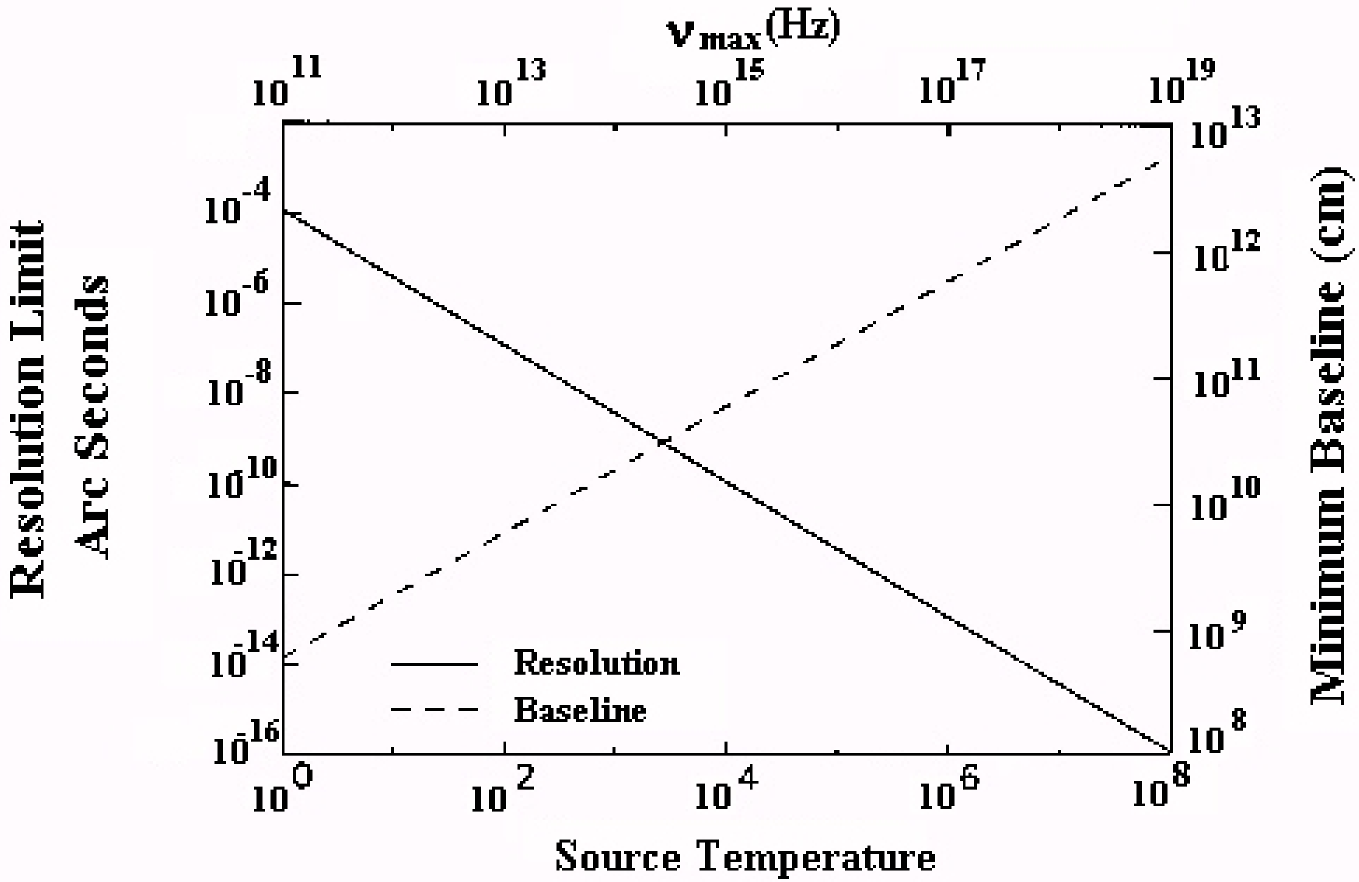
That is ~10,000$L_{\odot}$ from $10^{-4}A_{\odot}$ = $10^{8}B_{\odot}$

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



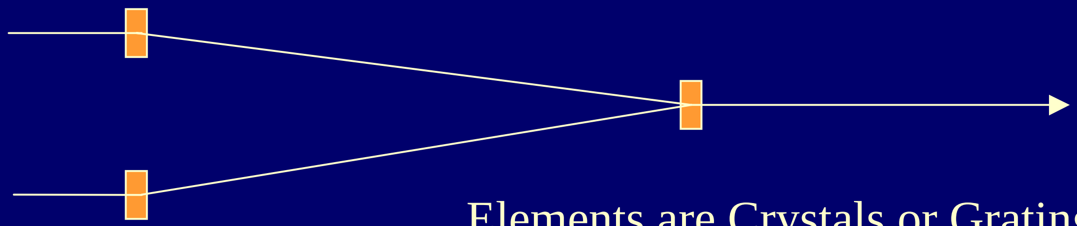
Status of X-ray Optics

- 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

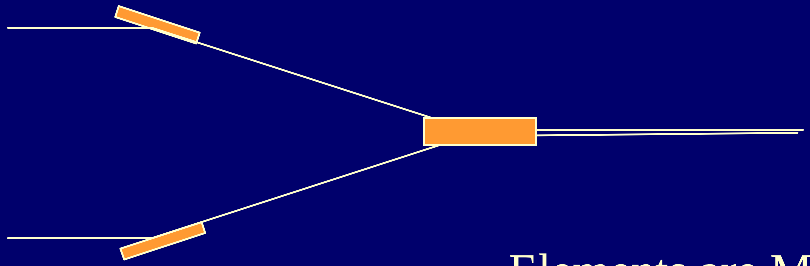
Classes of X-ray Interferometers

Dispersive



Elements are Crystals or Gratings

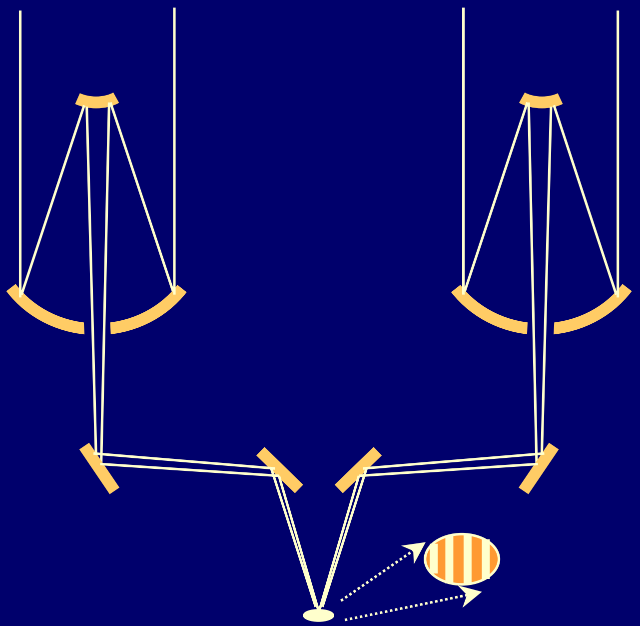
Non-Dispersive



Elements are Mirrors & Telescopes

Achieving High Resolution

Use Interferometry to Bypass Diffraction Limit



Michelson Stellar Interferometer

$$R = \lambda / 20000D$$

R in Arcsec

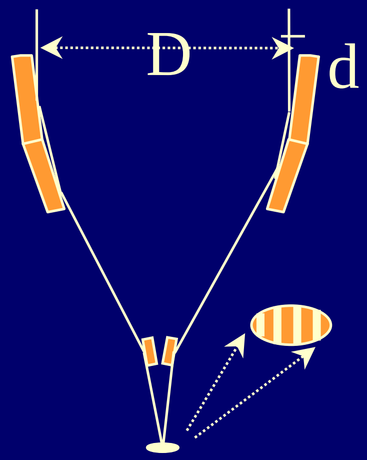
λ in Angstroms

D in Meters

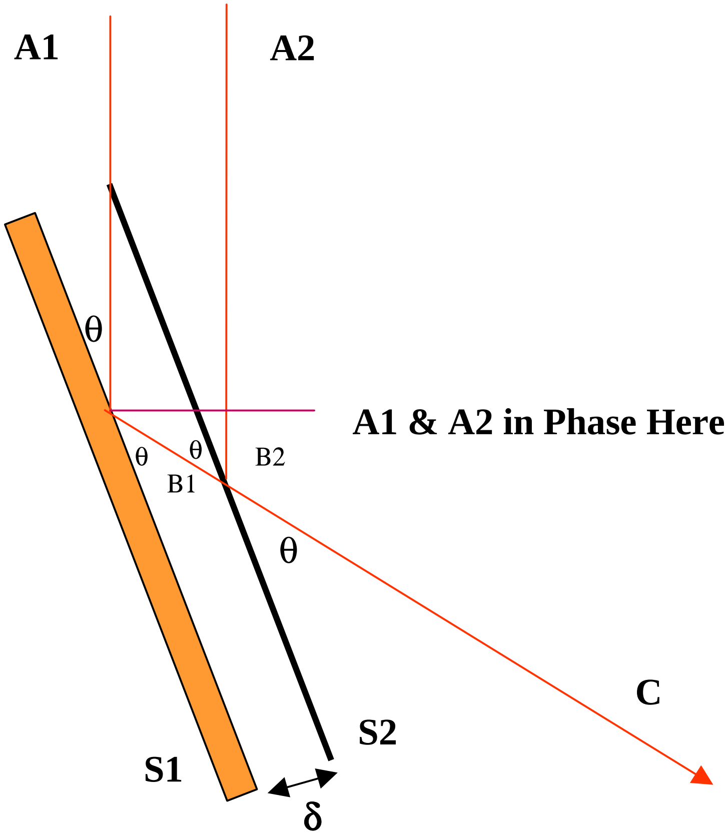
Creating Fringes

Requirements

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



Pathlength Tolerance Analysis at Grazing Incidence



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

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

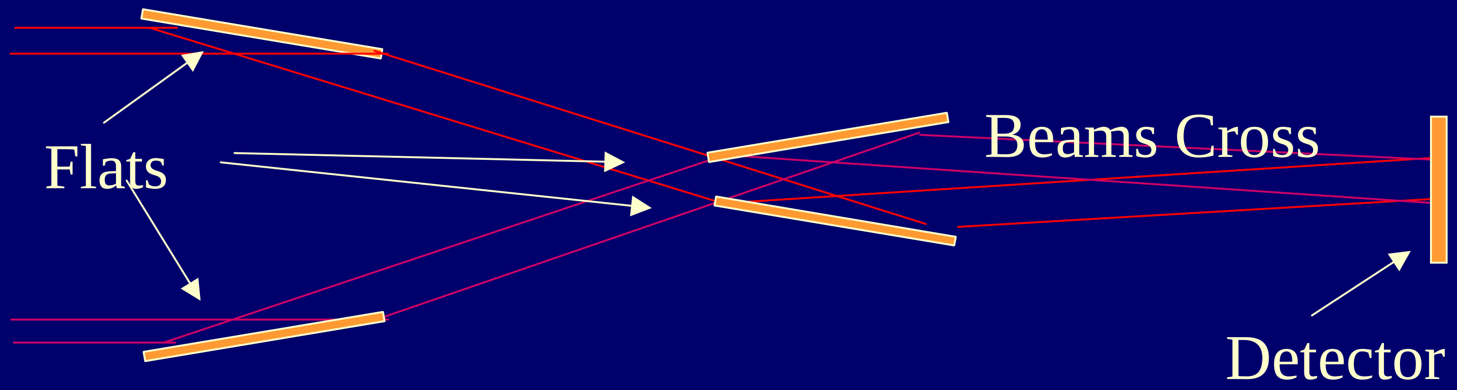
$$OPD = B1 - B2 = \frac{\delta[1-\cos(2\theta)]}{\sin\theta} = 2\delta\sin\theta$$

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

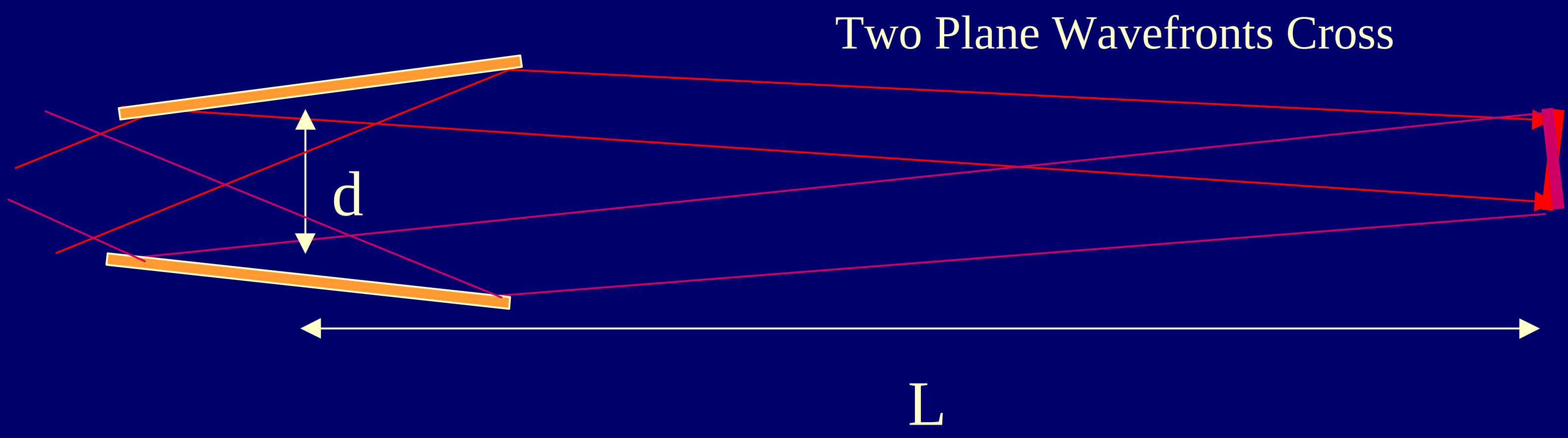
$$d(Baseline) < \frac{\lambda}{20\sin\theta\cos\theta}$$

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

A Simple X-ray Interferometer

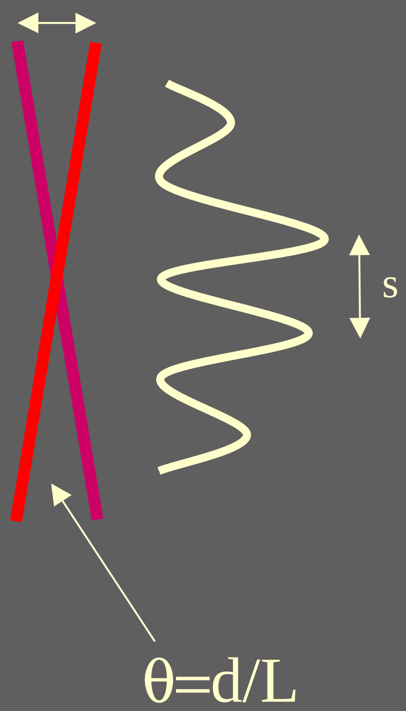


Beams Cross to Form Fringes



Wavefront Interference

λ=θs (where s is fringe spacing)



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

Beam Combiner

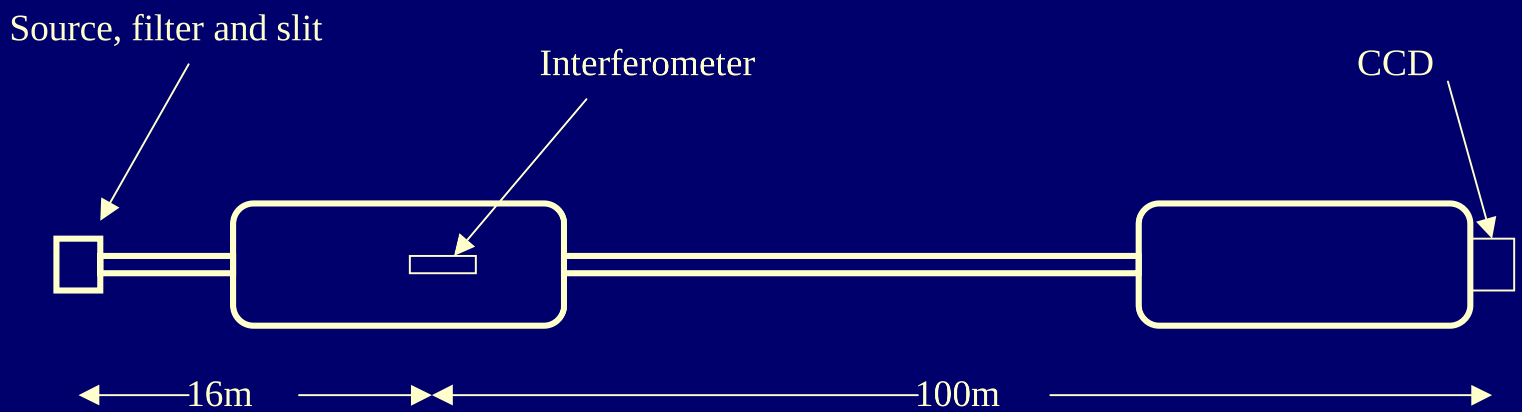
- Just use two grazing incidence flats to steer two beams together.
- Beats will occur, even if not focused
- Fringe is spacing function of beam crossing angle

  - Grazing Incidence Mirrors Only
  - Flats OK
  - No
    - Partially Silvered Mirrors
    - Diffraction Gratings
    - Paraboloids
    - Windows or Filters
  - Diffraction Limited Optics OK

Optics

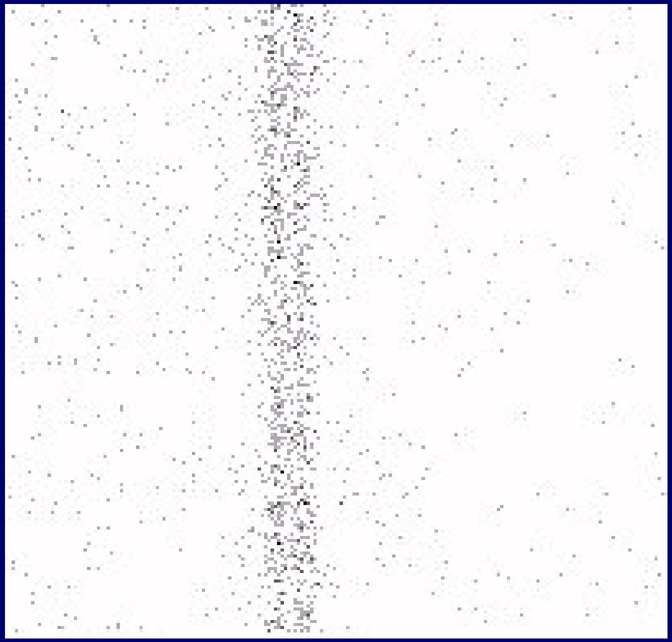
Each Mirror Was Adjustable
From Outside Vacuum
System was covered by thermal shroud

Stray Light Facility MSFC

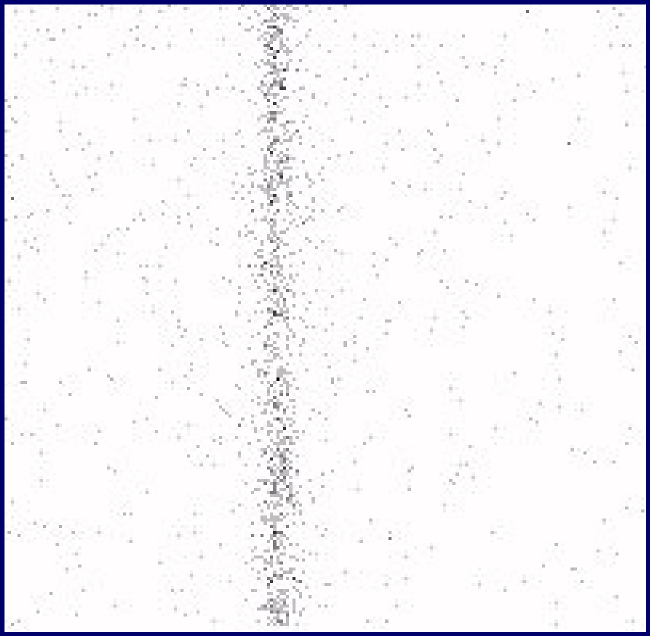


Used Long Distance To
Maximize Fringe Spacing

CCD Image @ 1.25keV

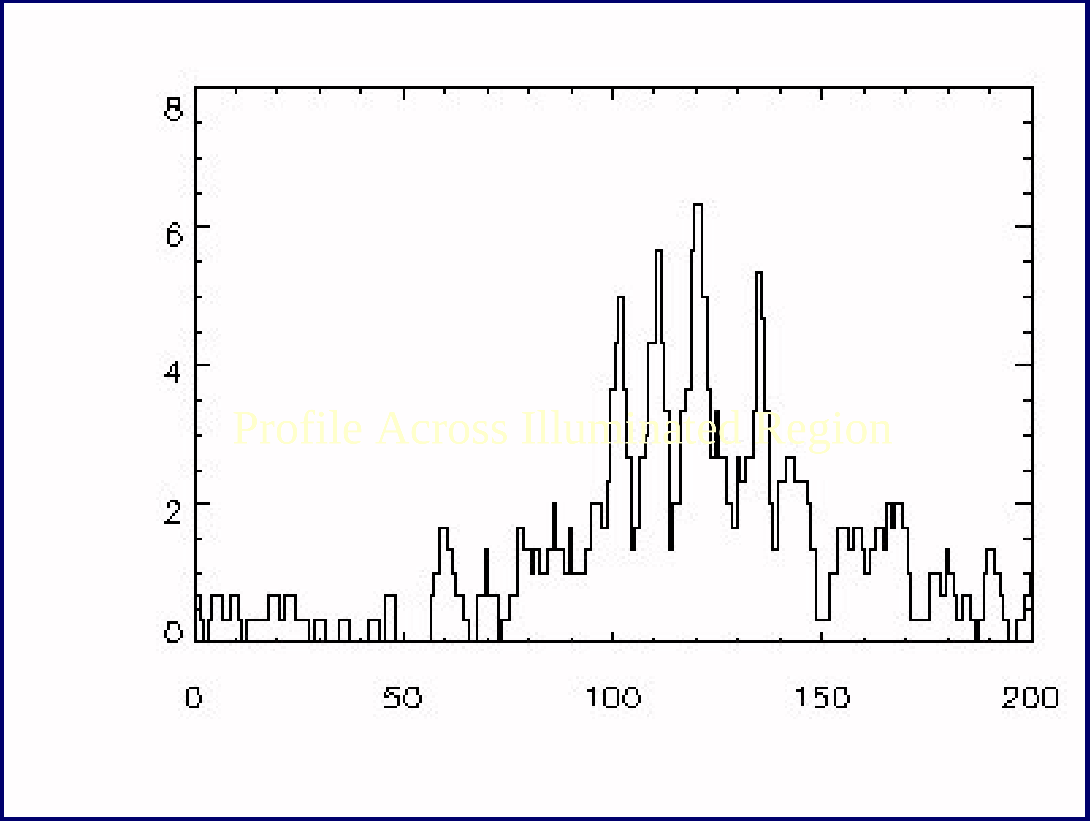


2 Beams Separate



2 Beams Superimposed

Fringes at 1.25keV



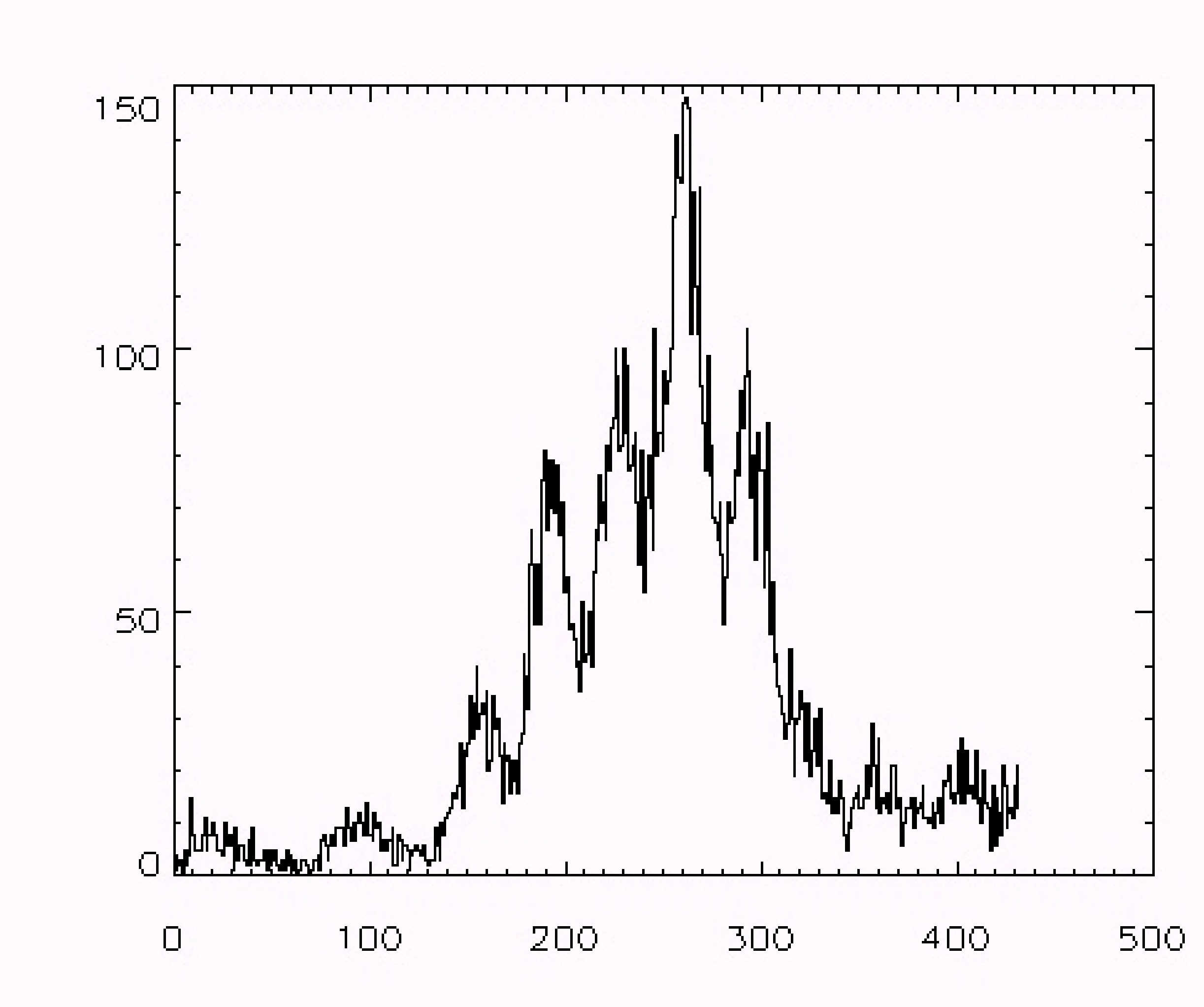
Test Chamber at CU

Ten Meter Long Vacuum Chamber for Testing

Came on-line early May

EUV results good
Upgrade to x-ray next

Helium II 304Å



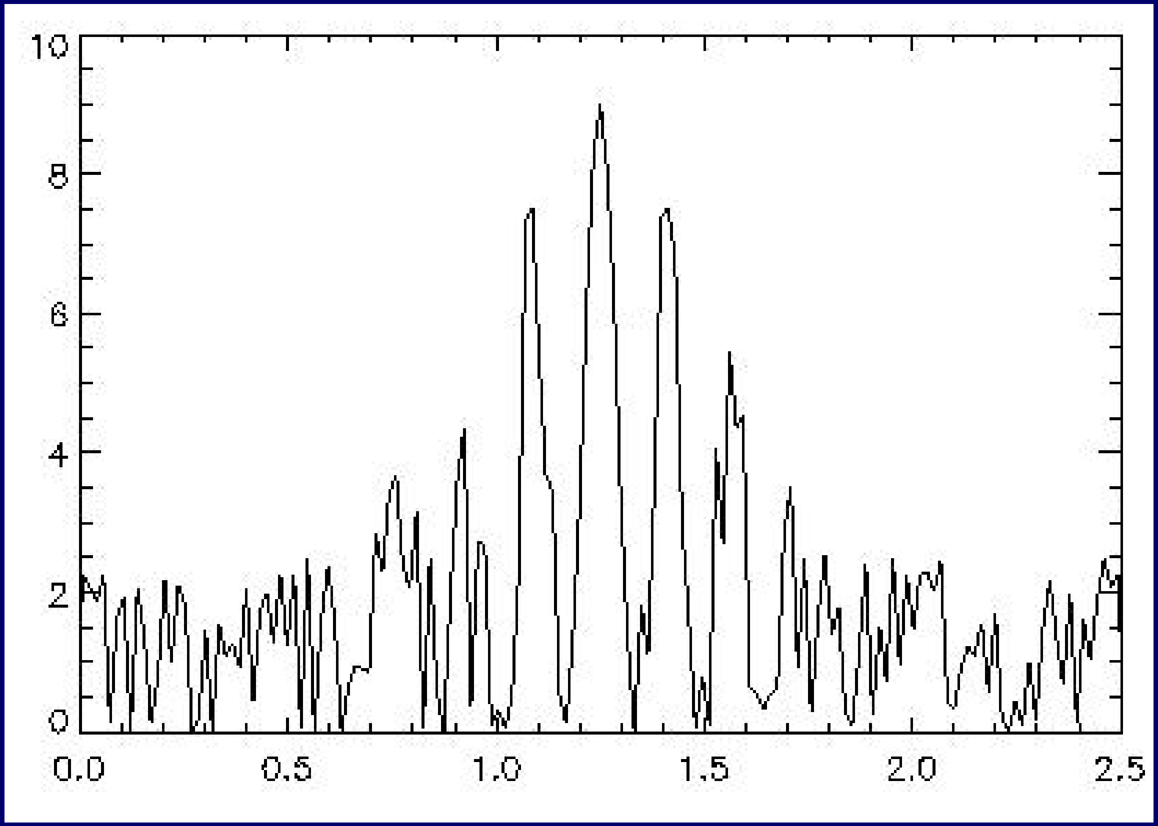
Simulation of Fringes

An approximate theoretical fringe pattern for our experimental geometry can be obtained by numerically superimposing a series of partial wave amplitudes,

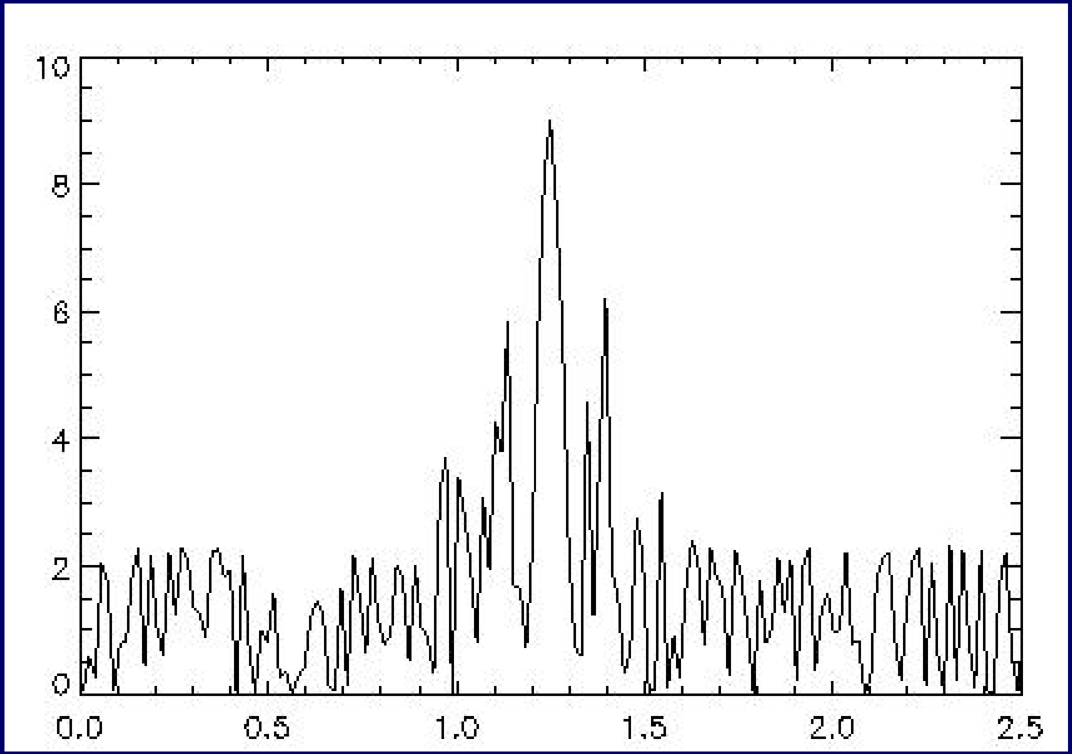
$$A = \Sigma_j \, e^{-i(\omega t - kx_j)}$$

where the intensity is obtained from the square of the summed amplitudes. The fringe intensity simulations shown next correspond to a superposition of partial waves with 50% of the flux in the Mg Kα line and 50% in the underlying x-ray continuum; the partial wave analysis also incorporates random phase errors with standard deviations of 0.002, 0.005, and 0.01 wavelengths.

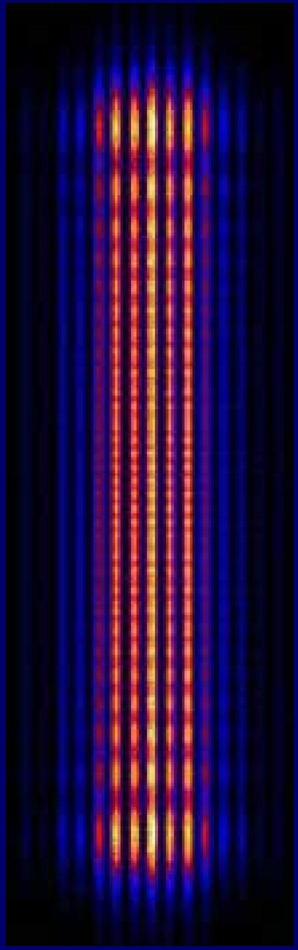
Phase Errors of .005λ

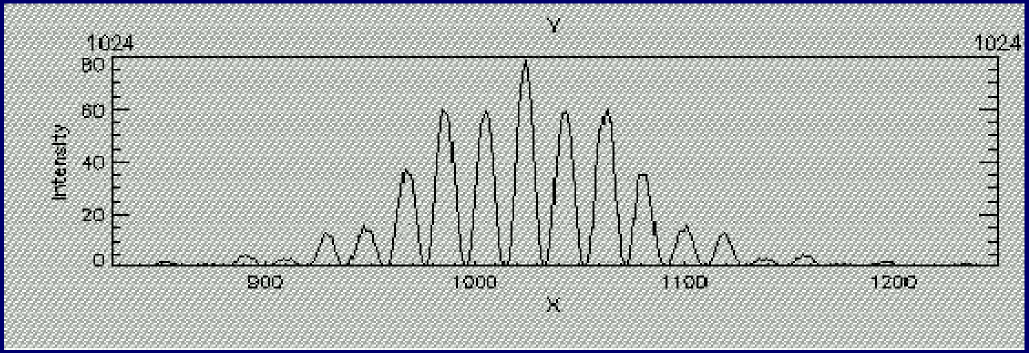


Phase Errors of .01λ



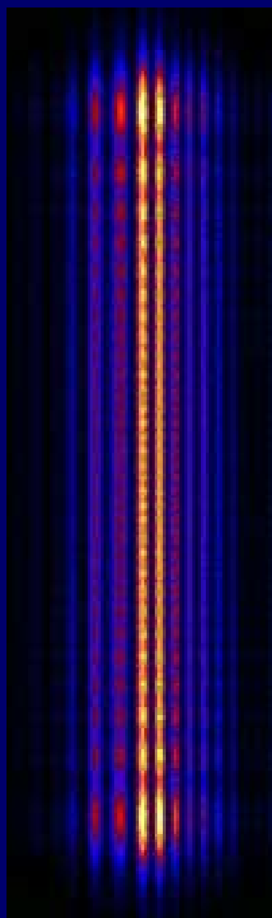
Theoretically Perfect Mirrors

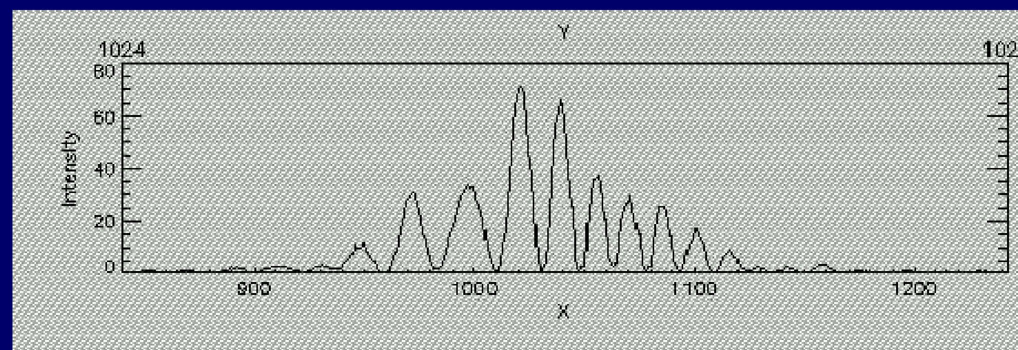




A monochromatic 1.24 keV x-ray beam

With Imperfections





$\lambda_{6328Å}$/12 RMS surface figure

Technology Summary

- X-ray Interferometers Can be Built
- Results Can be Modeled Effectively
- Provides Basis for Design of Next Generations of X-ray Interferometers

MAXIM

The Micro Arcsecond X-ray Imaging Mission

Webster Cash	Colorado
Nicholas White	Goddard
Marshall Joy	Marshall

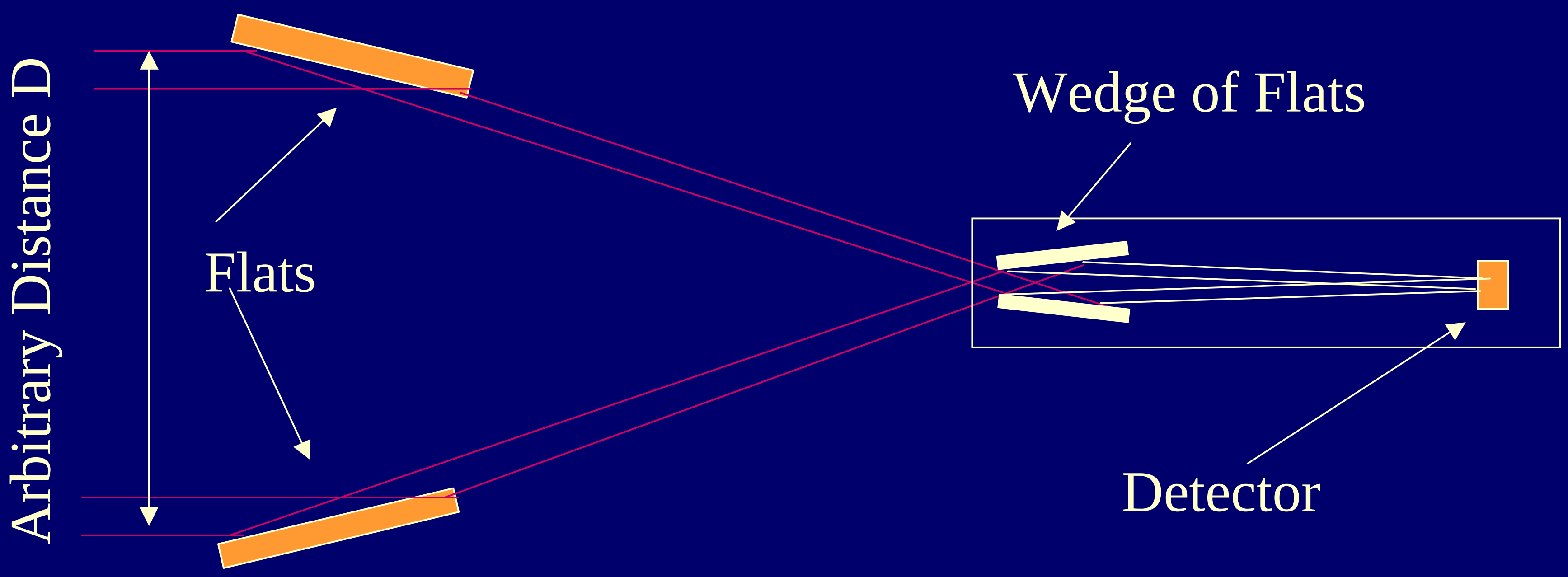
PLUS Contributions from the Maxim Team

http://maxim.gsfc.nasa.gov

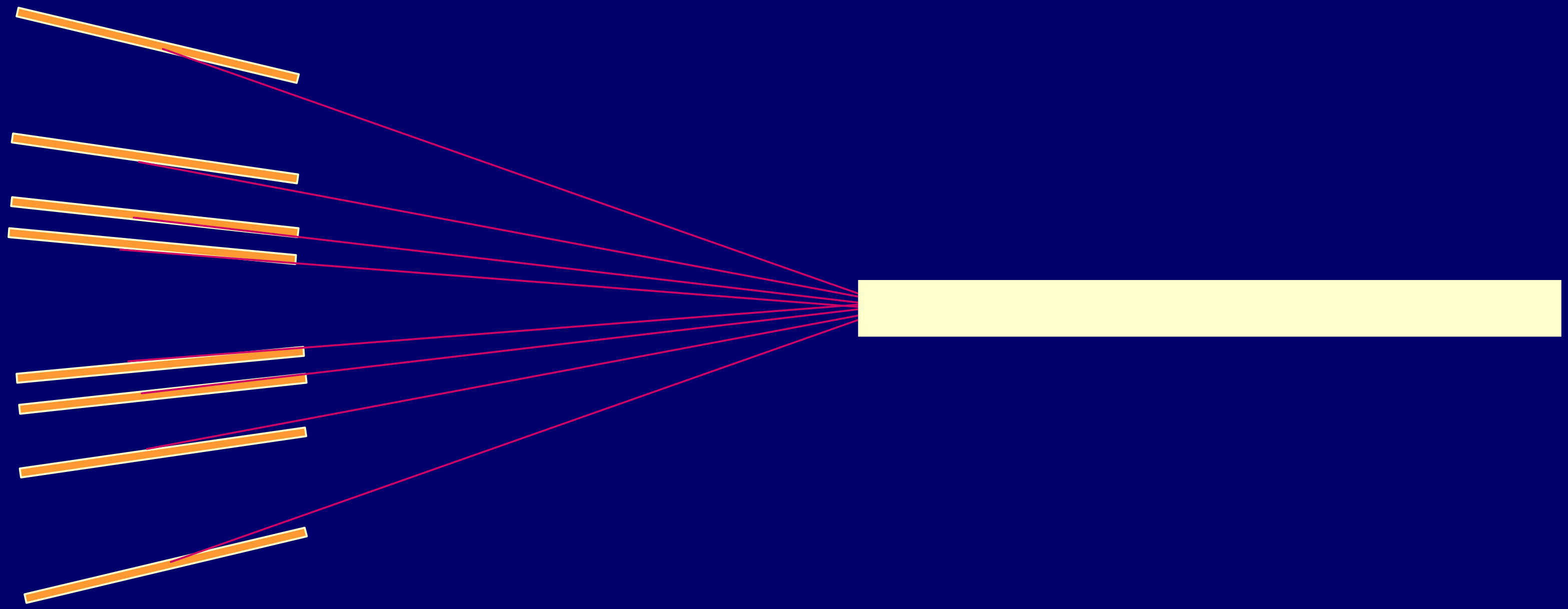
Maxim: A Few Science Goals

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*

Observatory Design



Observatory Design



Multiple Spacings and Rotation Angles Needed Simultaneously to Sample UV Plane

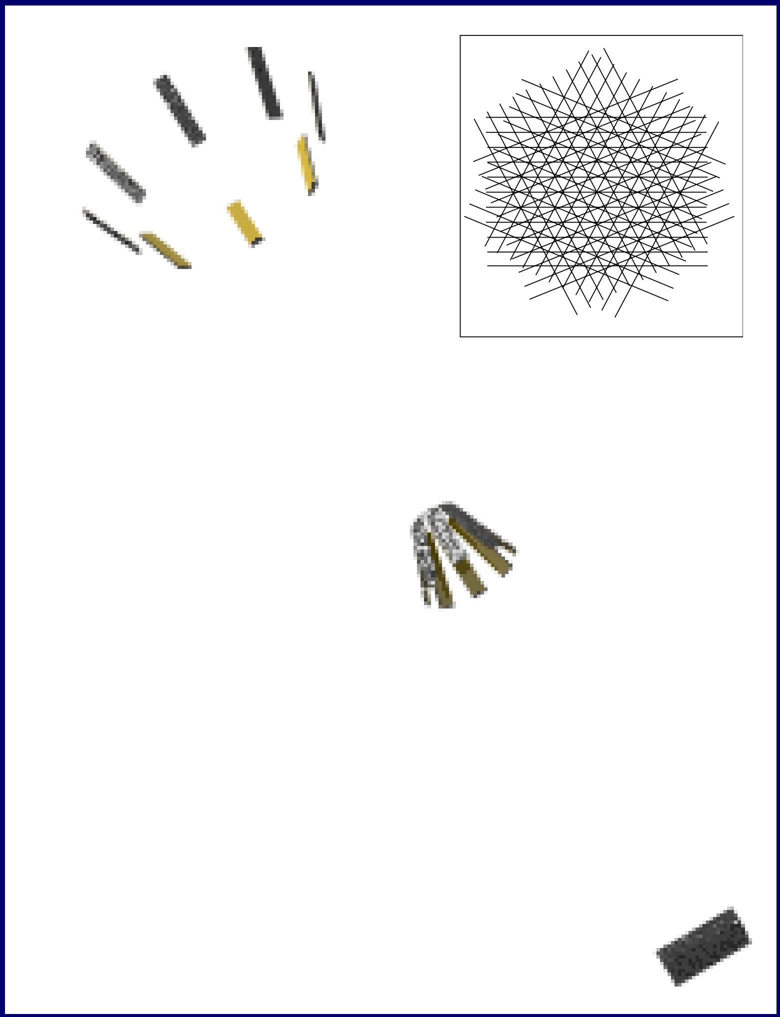
Tolerance Table

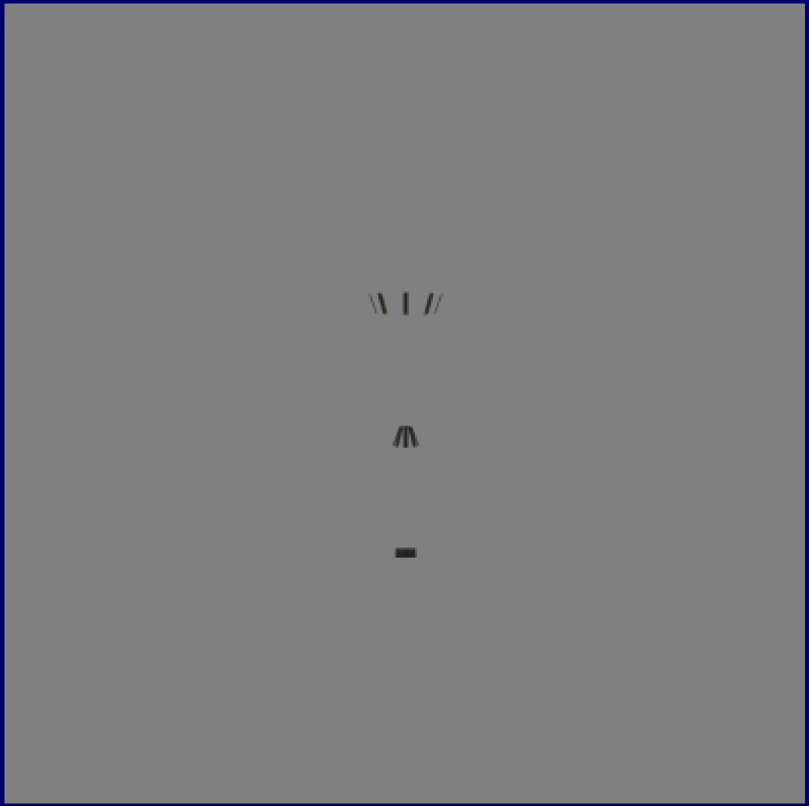
Resolution Arcseconds	**10^{-4}**	**10^{-5}**	**10^{-6}**	**10^{-7}**
Baseline (m)	1	10	100	1000
Mirror Size (cm)	3x100	3x100	3x100	3x100
Position Stability (nm)	20	20	20	20
Angular Stability (arcsec)	10^{-3}	10^{-3}	10^{-3}	10^{-3}
Figure	$\lambda/100$	$\lambda/200$	$\lambda/200$	$\lambda/200$
Polish (Å rms)	20	20	20	20
Angular Knowledge (as)	3×10^{-5}	3×10^{-6}	3×10^{-7}	3×10^{-8}
Position Knowledge (nm)	2	2	2	2
Field of View (Pixels)	20x20	20x20	1000x1000	1000x1000
E/ΔE Detector	20	20	1000	1000

Notes:

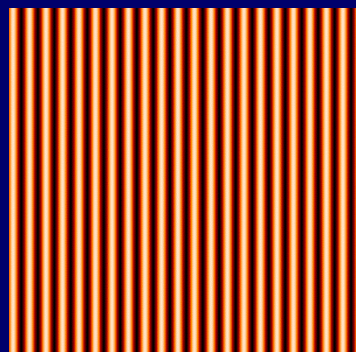
- Angular stability is for individual mirrors relative to target direction.
- Only the Angular Knowledge requirement grows tighter with baseline, but this is achieved by a (fixed) 2nm relative position knowledge over a longer baseline.
- Absolute positioning remains constant as interferometer grows, but does not get tighter!

Flats Held in Phase
Sample Many Frequencies





As More Flats Are Used
Pattern Approaches Image



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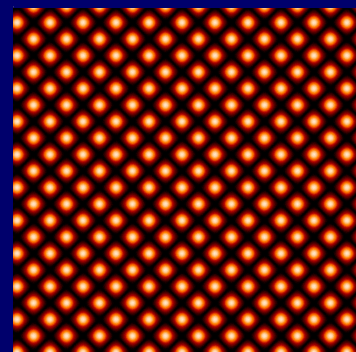

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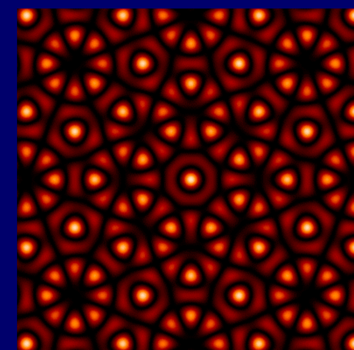

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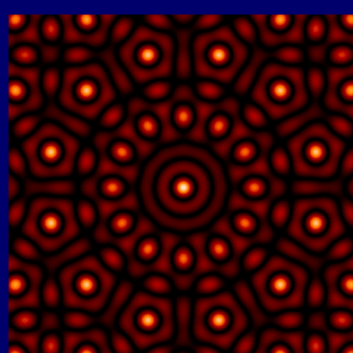

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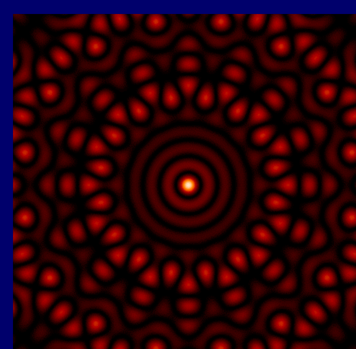

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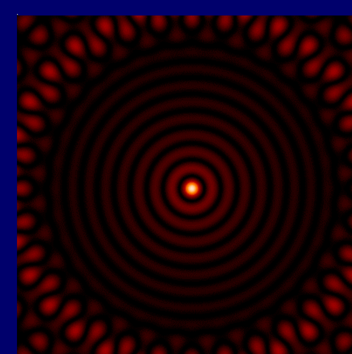

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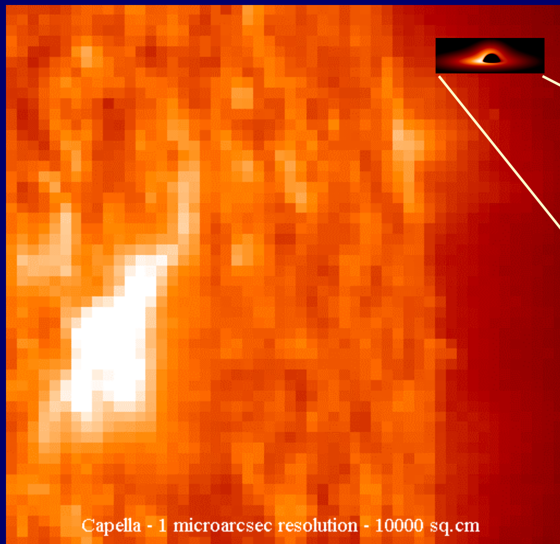
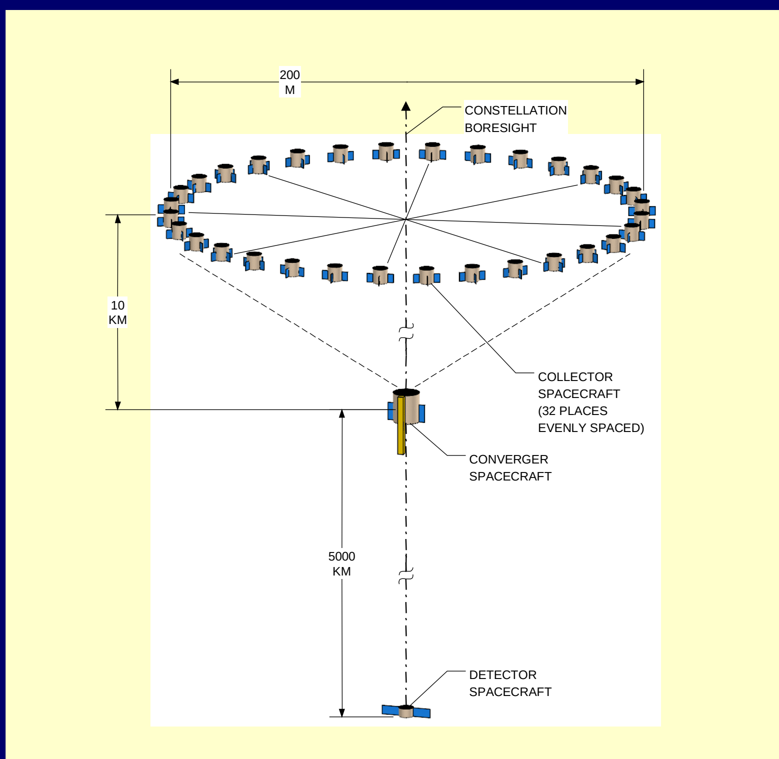
Four Difficult Areas

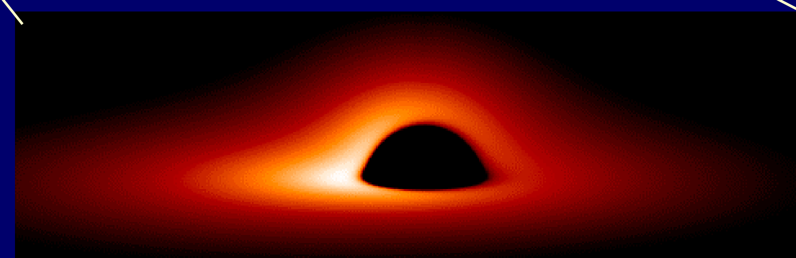
- *Fabrication of Interferometer*
- *Internal Metrology*
  - Hold Mirrors Flat and In Position
- *Formation Flying*
  - Hold Detector Craft in Position
- *Pointing*
  - Hold Interferometer on Target

Maxim

"The Black Hole Imager"







0.1μas Resolution

10,000cm^2 Effective Area

0.4-7.0 keV

Maxim Pathfinder

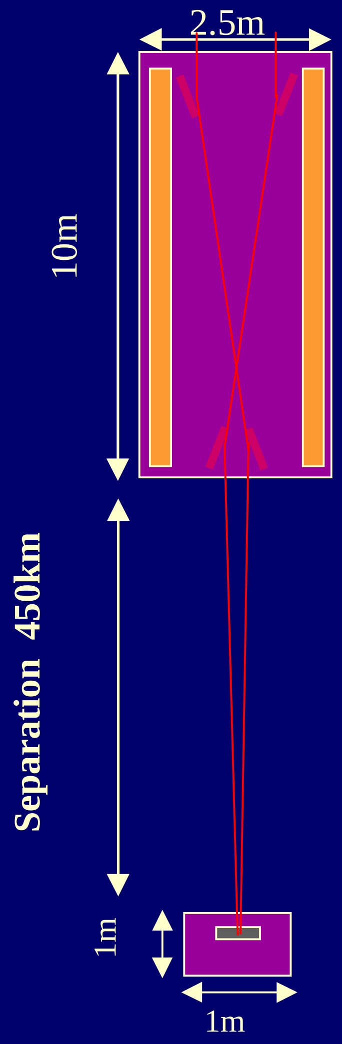
100μas Resolution
100cm^2 Effective Area
0.4-2.0keV + 6keV

Two Spacecraft
Formation Flying at
450km Separation

Maxim Pathfinder Performance Requirements

Angular Resolution	100µas
Baseline	1.4 meters
Collecting Area	100cm^2
Field of View	10 mas
Bandpass	0.5-2keV + 6keV
Pointing	30µas
Spectral Resolution (E/δE)	20
Size	Single Launch
Orbit	High Earth or Drift Away

Maxim Pathfinder Mission Concept



Optics Spacecraft

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

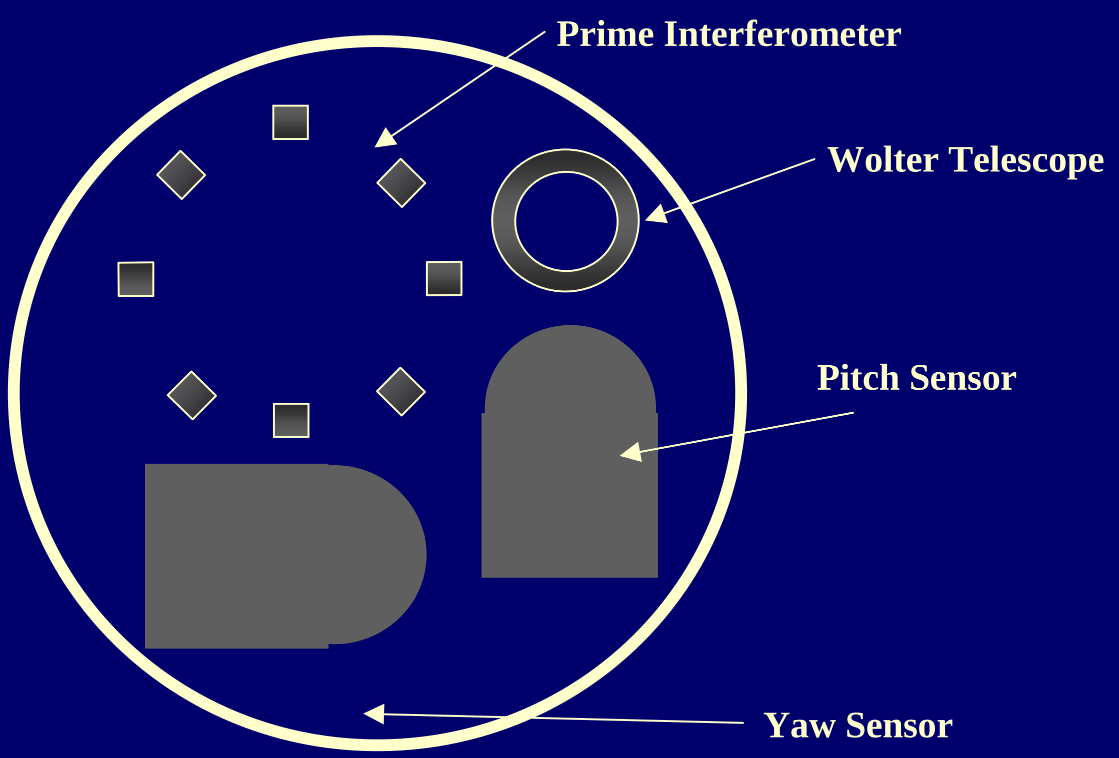
Size:	**2.5x2.5x10m**
Pitch&Yaw Stability:	**$3x10^{-4}$ arcsec**
Pitch&Yaw Knowledge:	**$3x10^{-5}$ arcsec**
Roll Stability:	**20 arcsec**
Position Stability:	**-----**

Detector Spacecraft

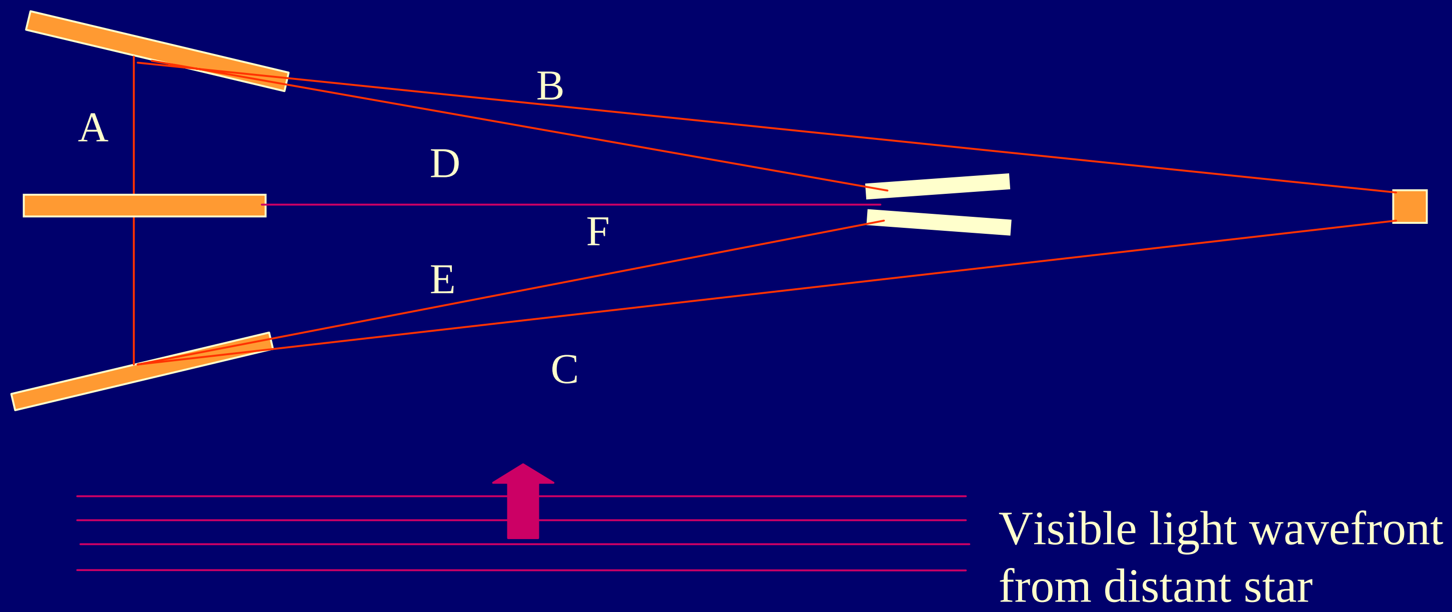
Carries: X-ray Detector Array
Laser Retro Reflectors
Precision Thrusters

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

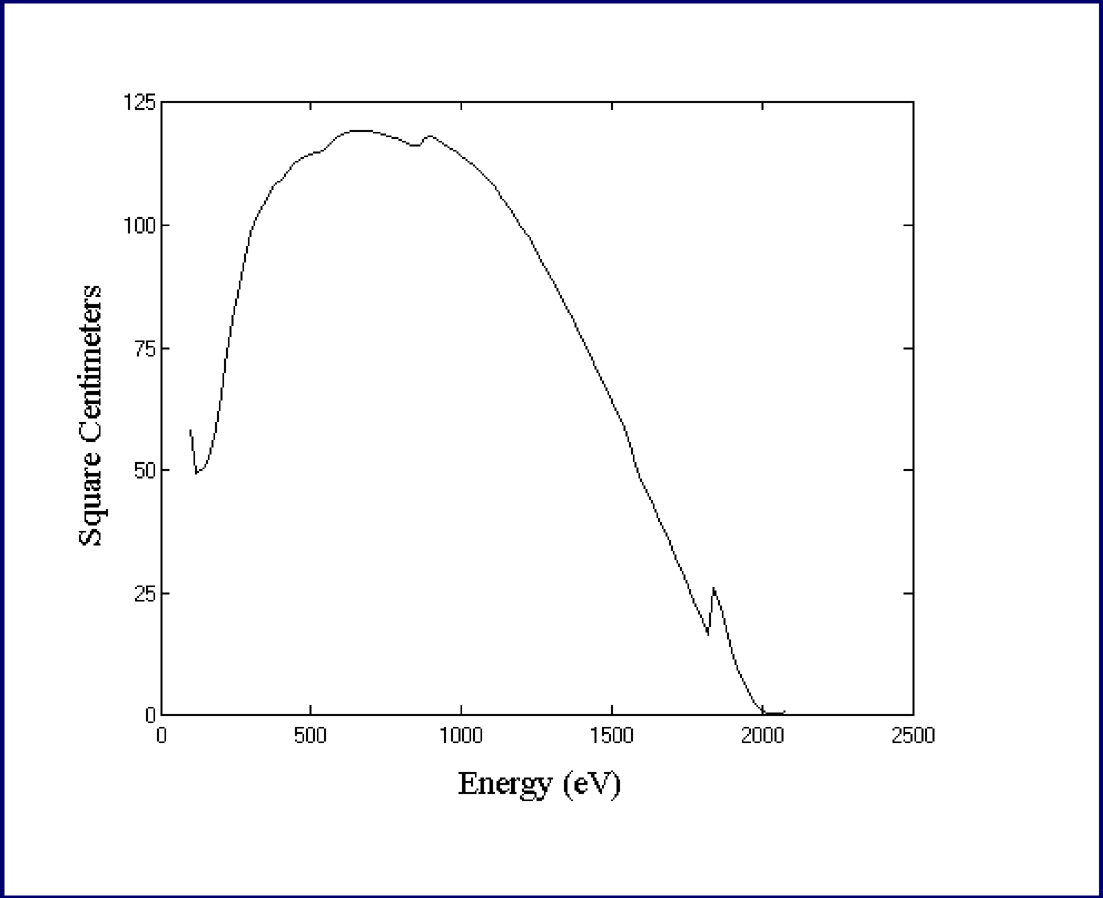


Consider, instead, line F.
Mount the visible light interferometer on structures at the ends of line F. They then maintain 1nm precision wrt to guide star that lies perpendicular to F. This defines pointing AND maintains lateral position of convergers.
(40pm not needed in D and E after all.)
A, B, C,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

Effective Collecting Area



Metrology

Tightest Tolerance is Separation of Entrance Apertures

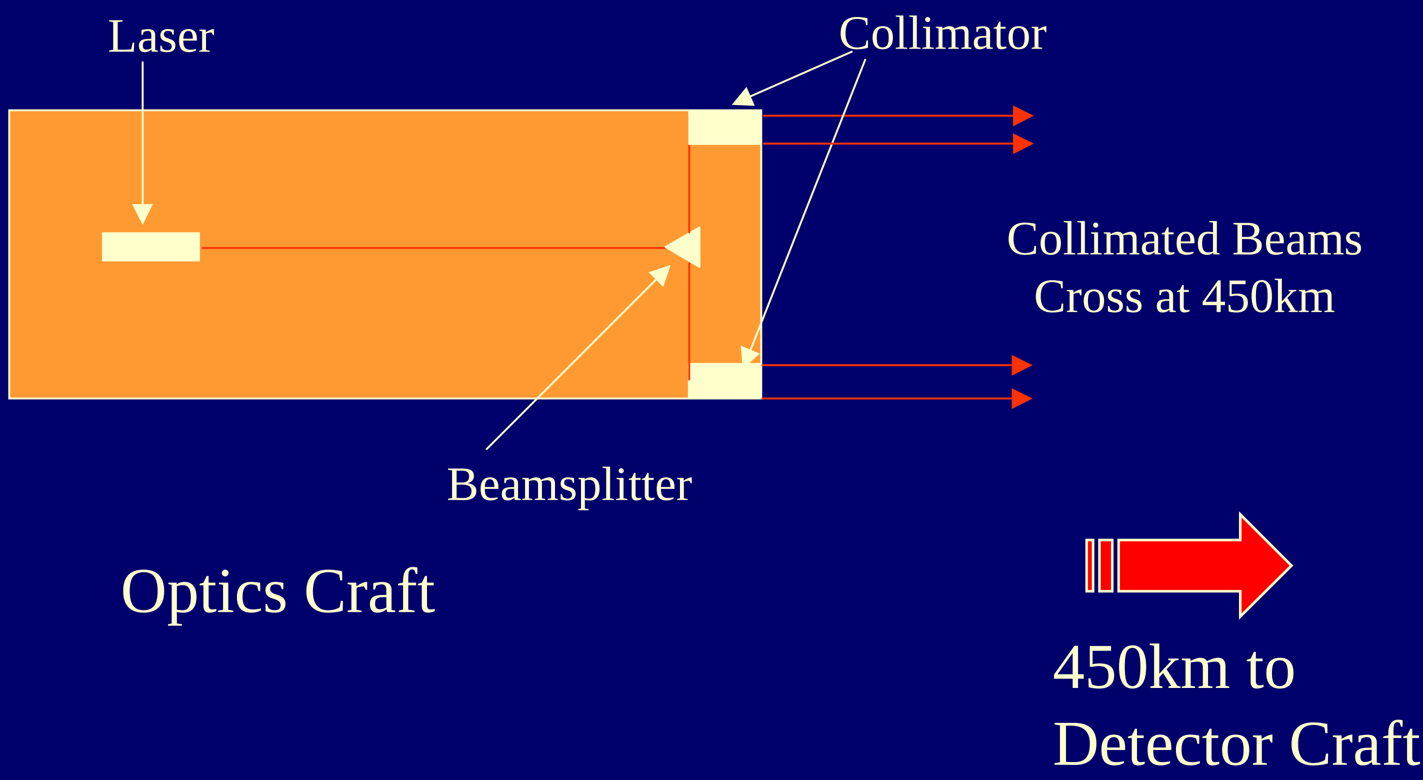
$d = \lambda/20\theta$ for tenth fringe stability

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

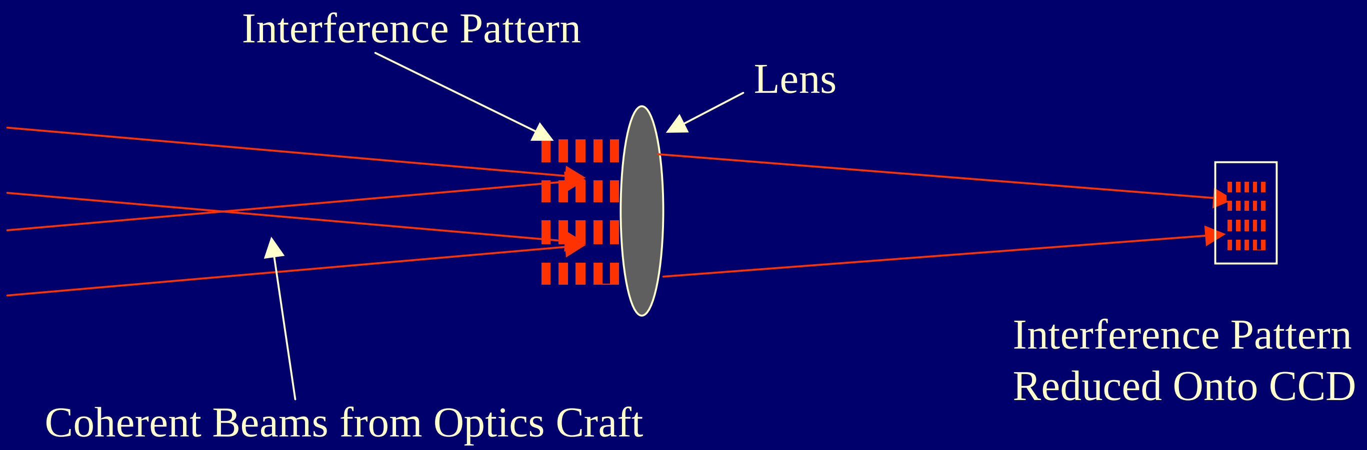
Requires active thermal control and internal alignment

Laser Beam

Split and Collimated

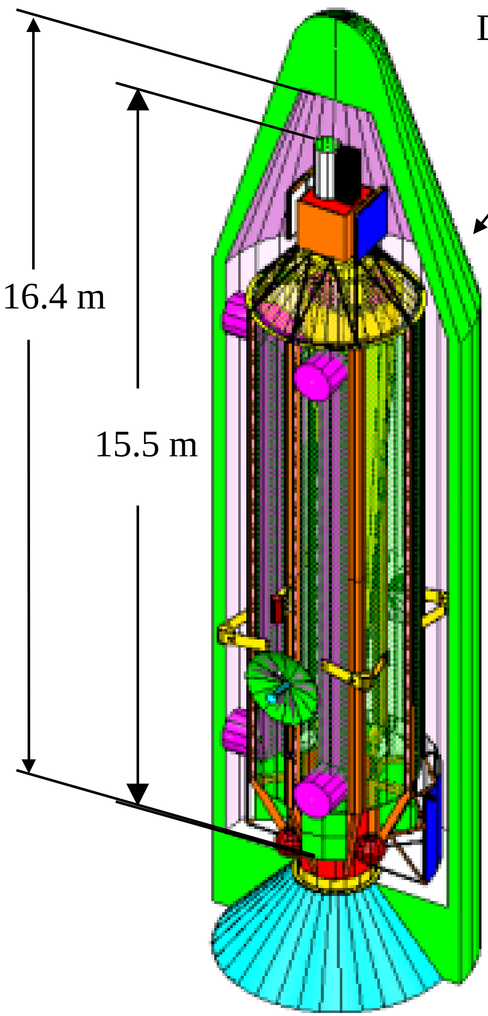


Detection of Pattern
at Detector Craft

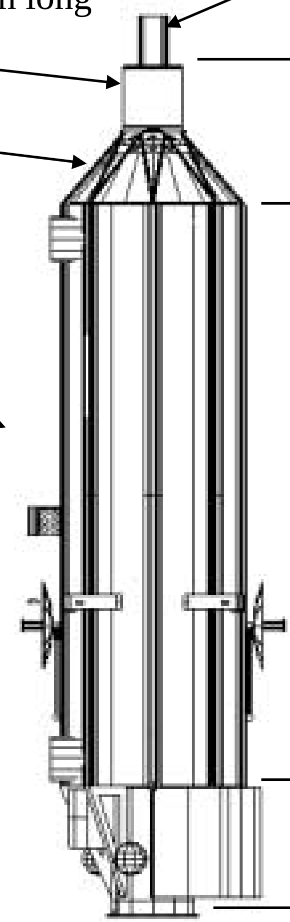


Fringes have 14cm period at 450km

MAXIM

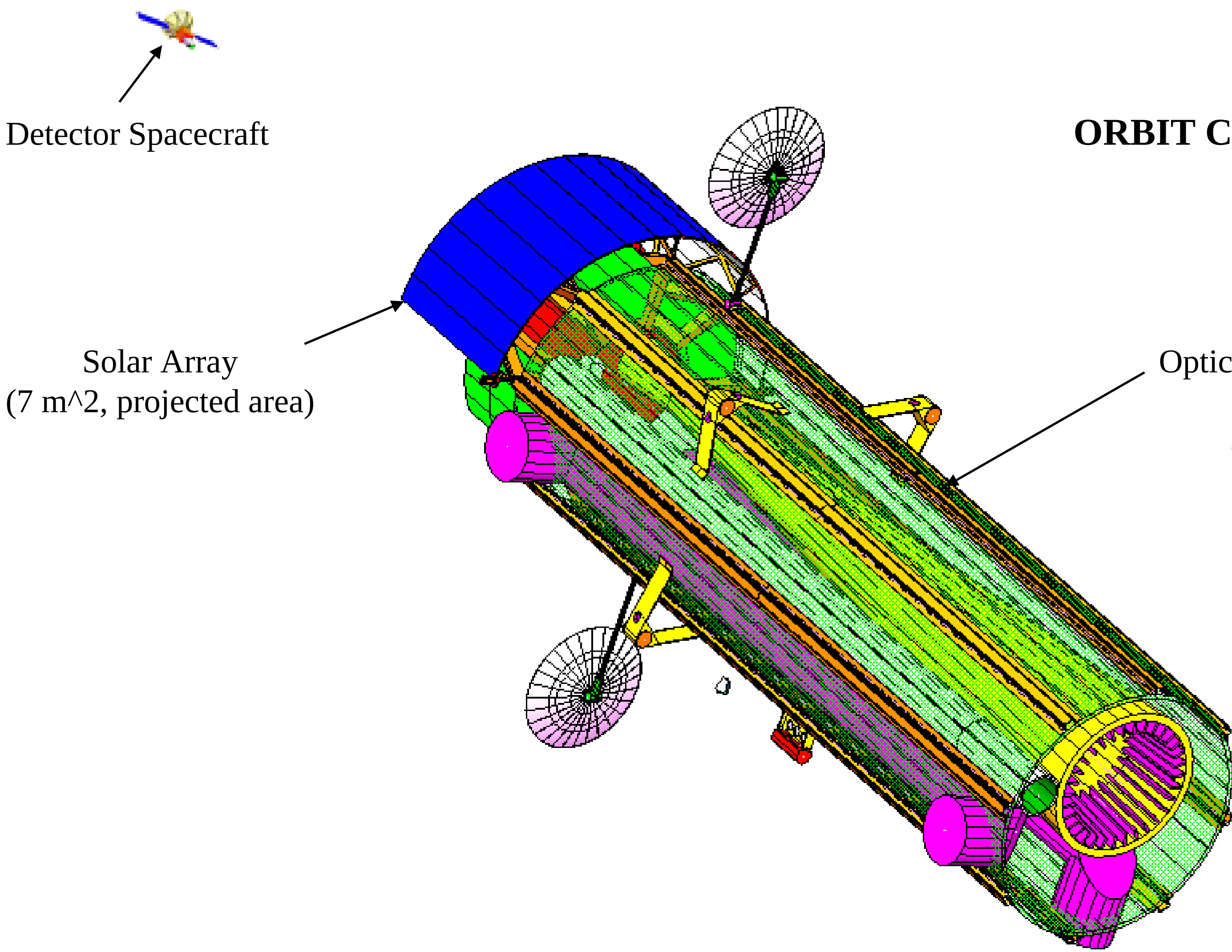


LAUNCH CONFIGURATION



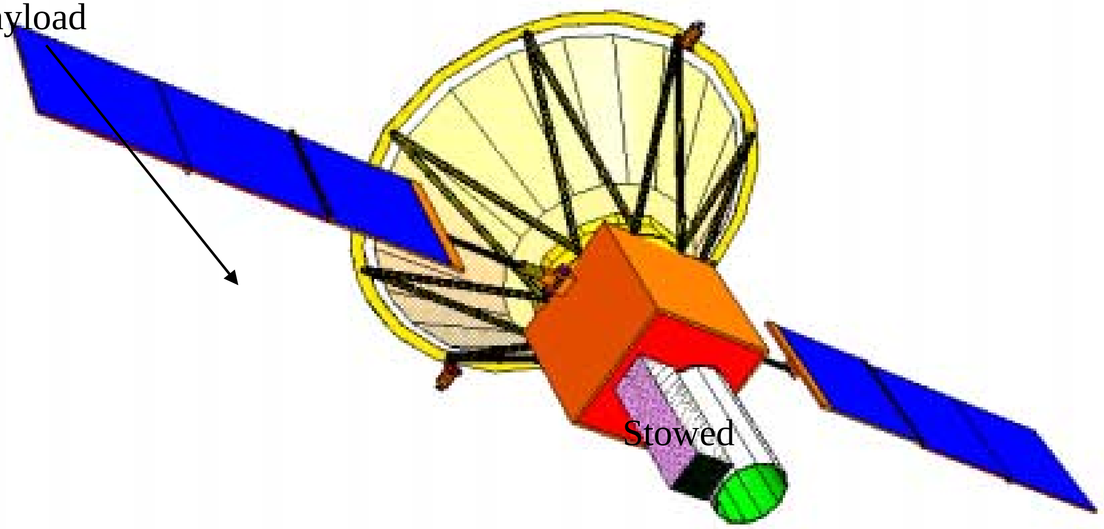
MAXIM

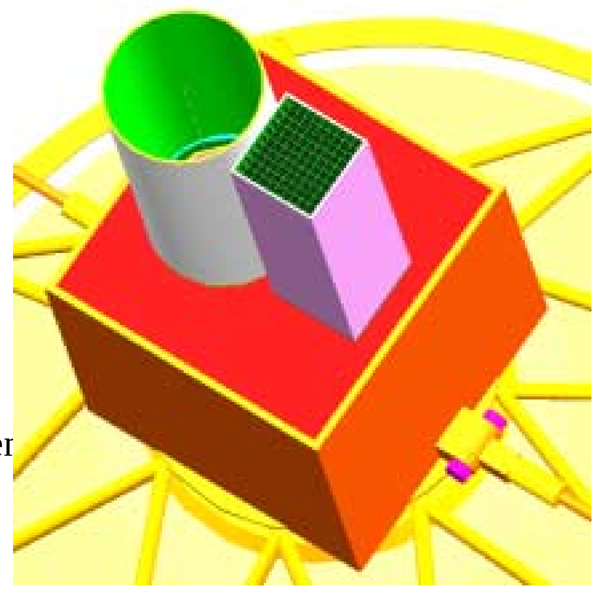
ORBIT CONFIGURATION



MAXIM

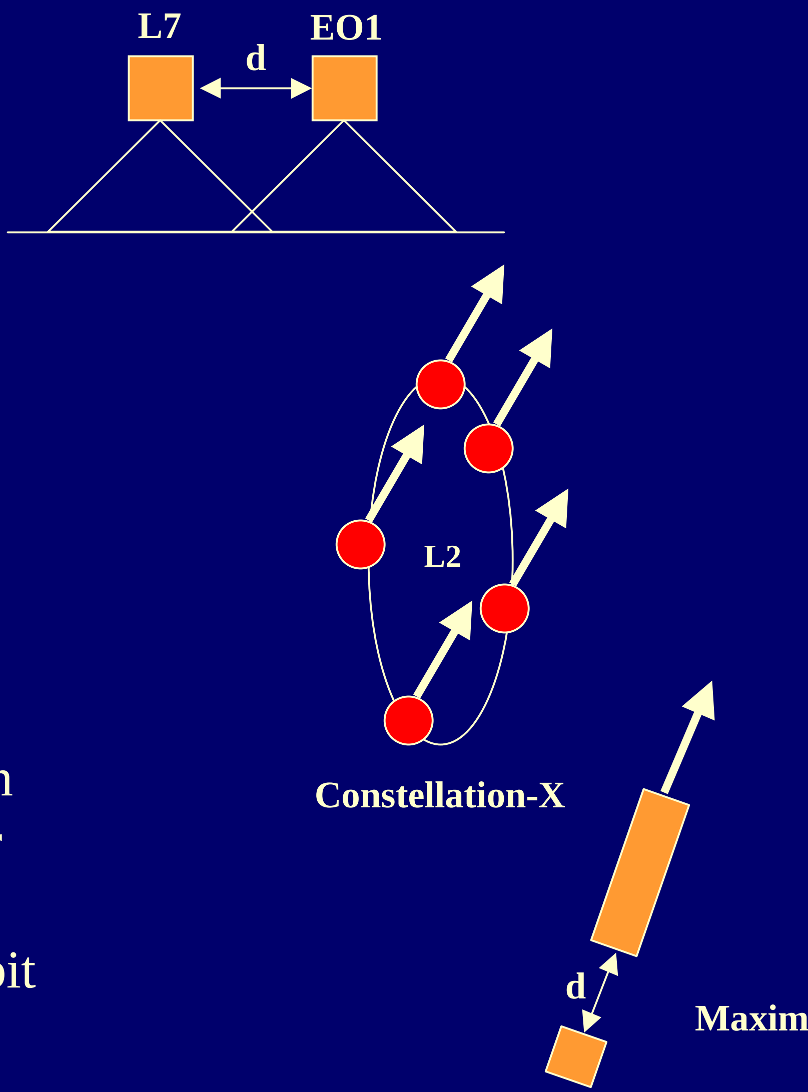
DETECTOR SPACECRAFT



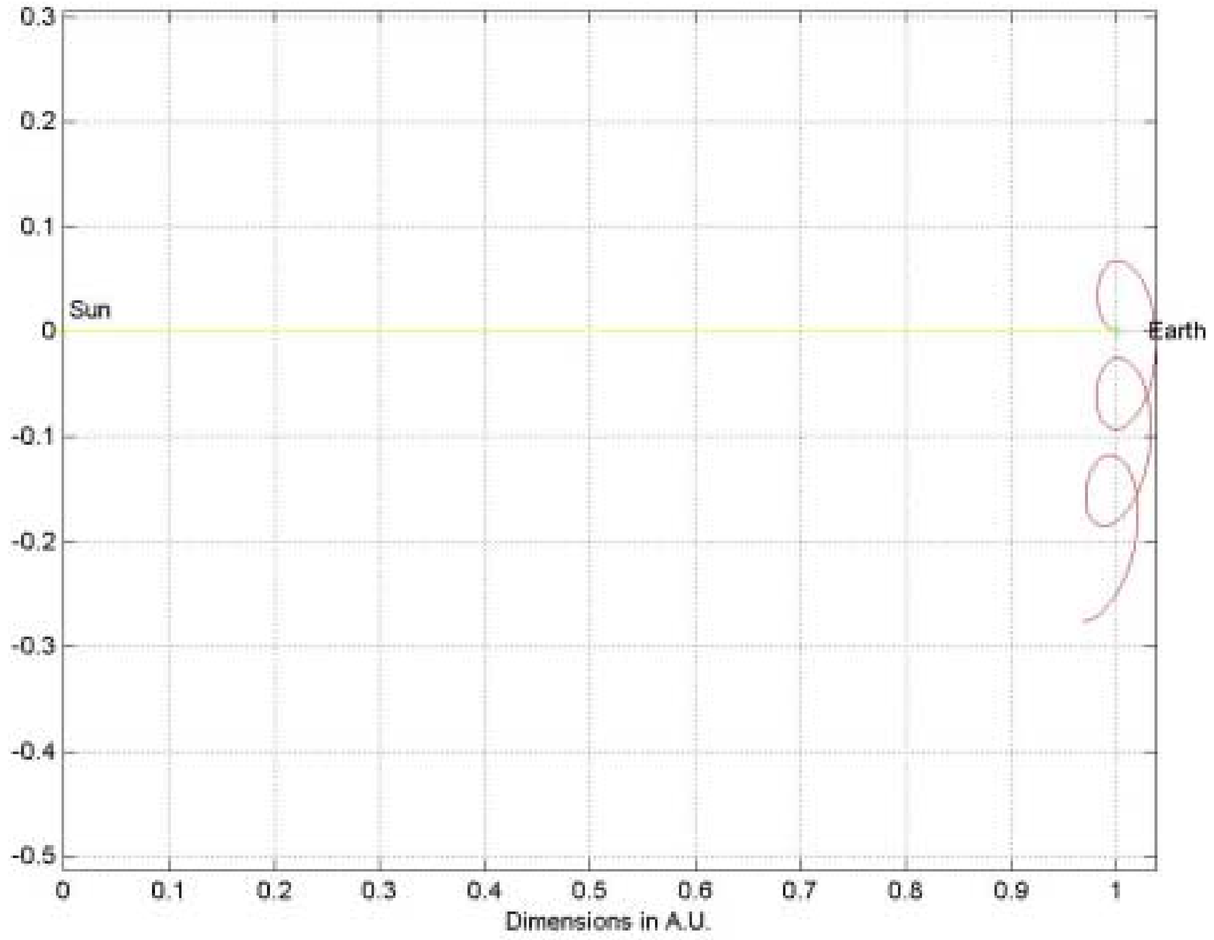


Formation Flying Challenge

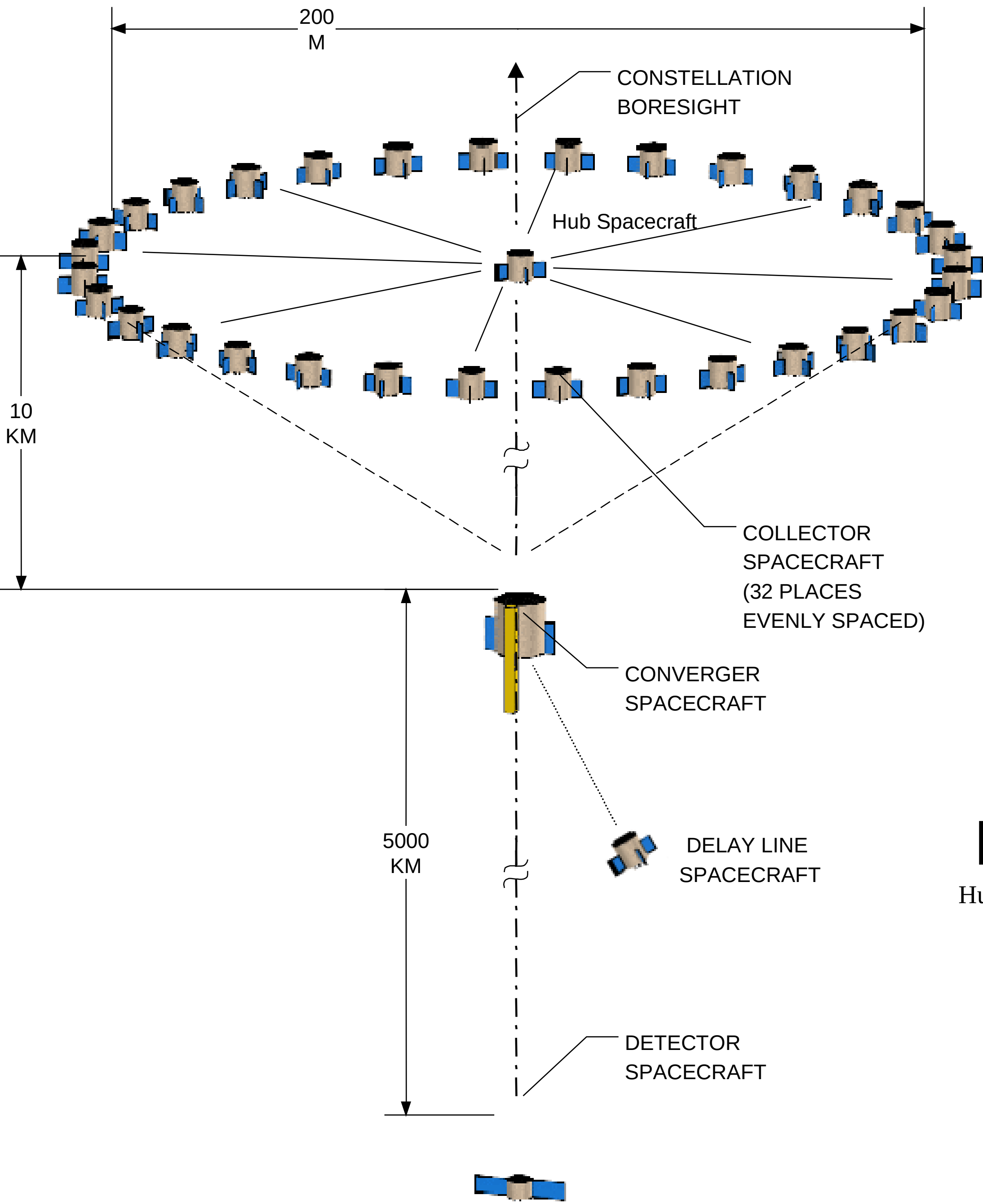
- The MAXIM formation flying concept is new - combination of previous implementations with a wrinkle
- Landsat-7 and EO-1 maintain a constant distance between each other in the same orbit while imaging the earth - image comparison is achieved because of close distance between s/c
- Constellation-X utilizes multiple s/c to observe the same target without any restriction on relative position
- MAXIM combines both constant separation and constant attitude/pointing. The detector s/c must 'fly' around the optics s/c continuously during an observation - its orbit will continually change.

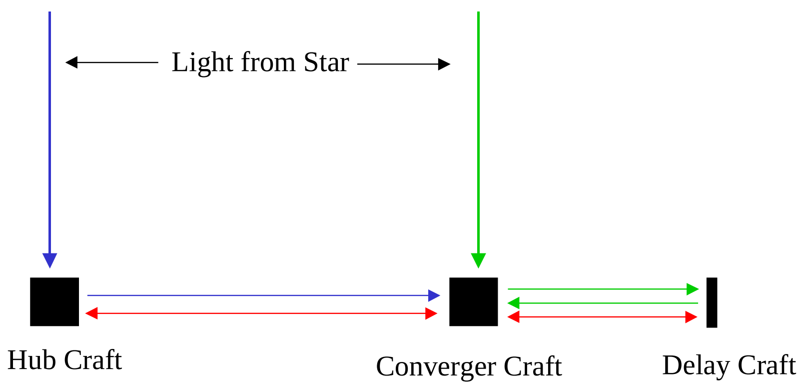


MAXIM Trajectory in Solar Rotating Coordinates



Maxim Design





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

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

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

In Conclusion

- In Last 2 Years
  - Demonstrated Feasibility of Optics
  - Developed Preliminary Mission Concepts
  - Raised Interest and Respect in the Community
  - Inserted X-ray Interferometry into NASA Plans
- In NIAC Phase II
  - More Detailed Study of Missions
  - Spread the Word

This Is Showing Signs of Happening!