X-ray Interferometry

The Future of X-ray Astronomy

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Co-Investigators

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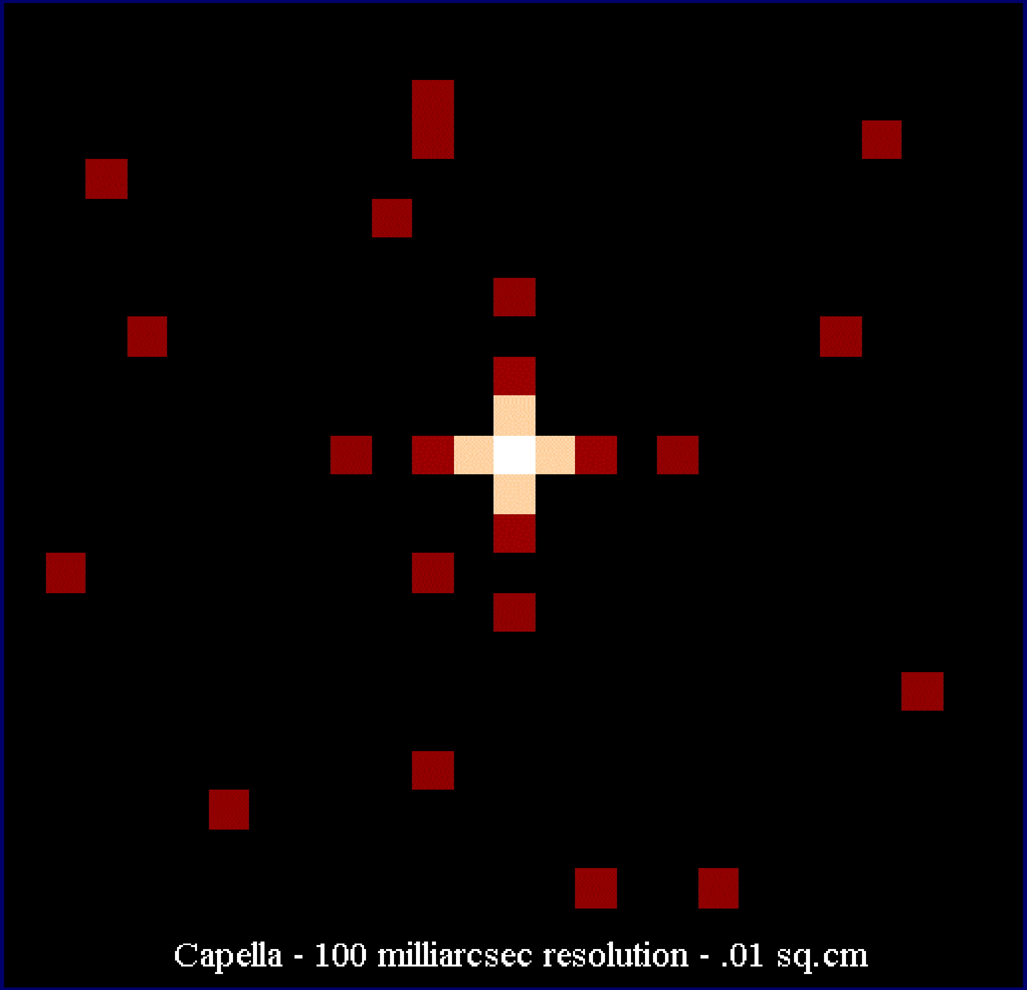
Outline of Presentation

- Science Potential
- How to Do It
- Laboratory Efforts
- Mission Design
- A Surprise Application
- Summary

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”



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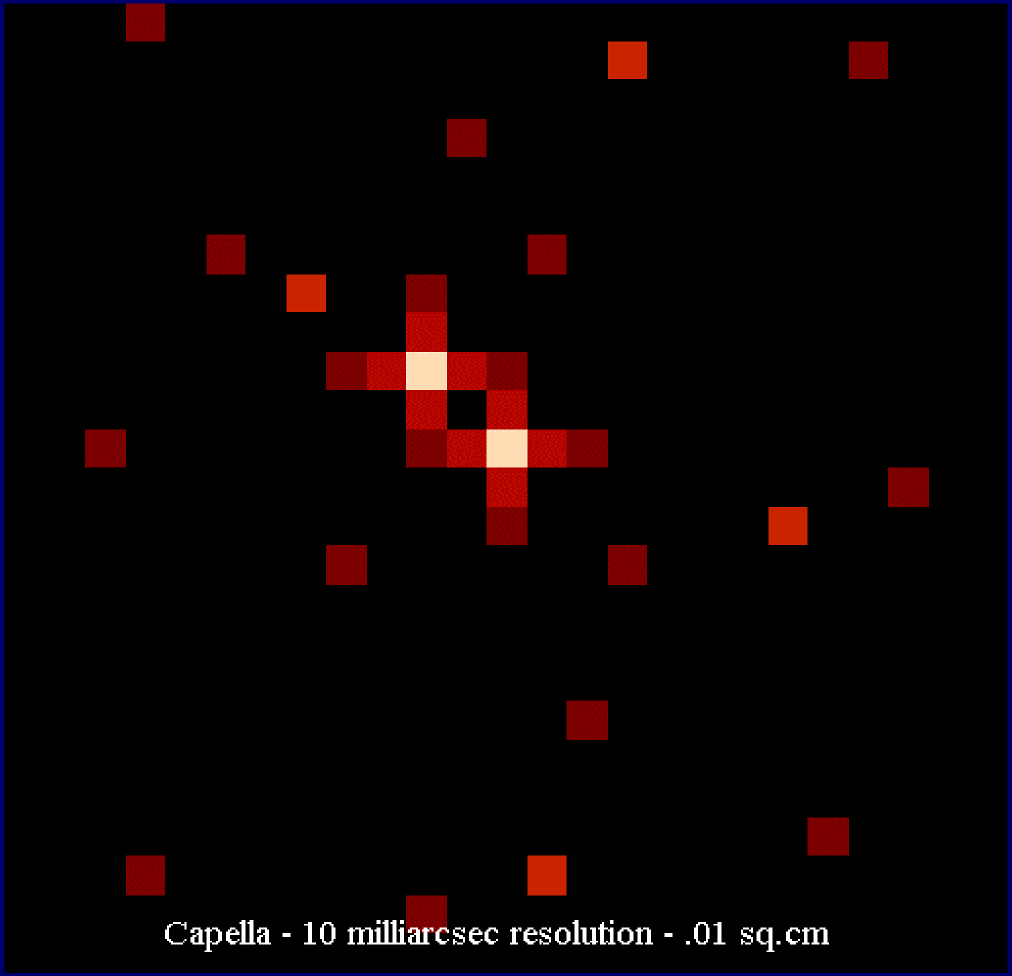

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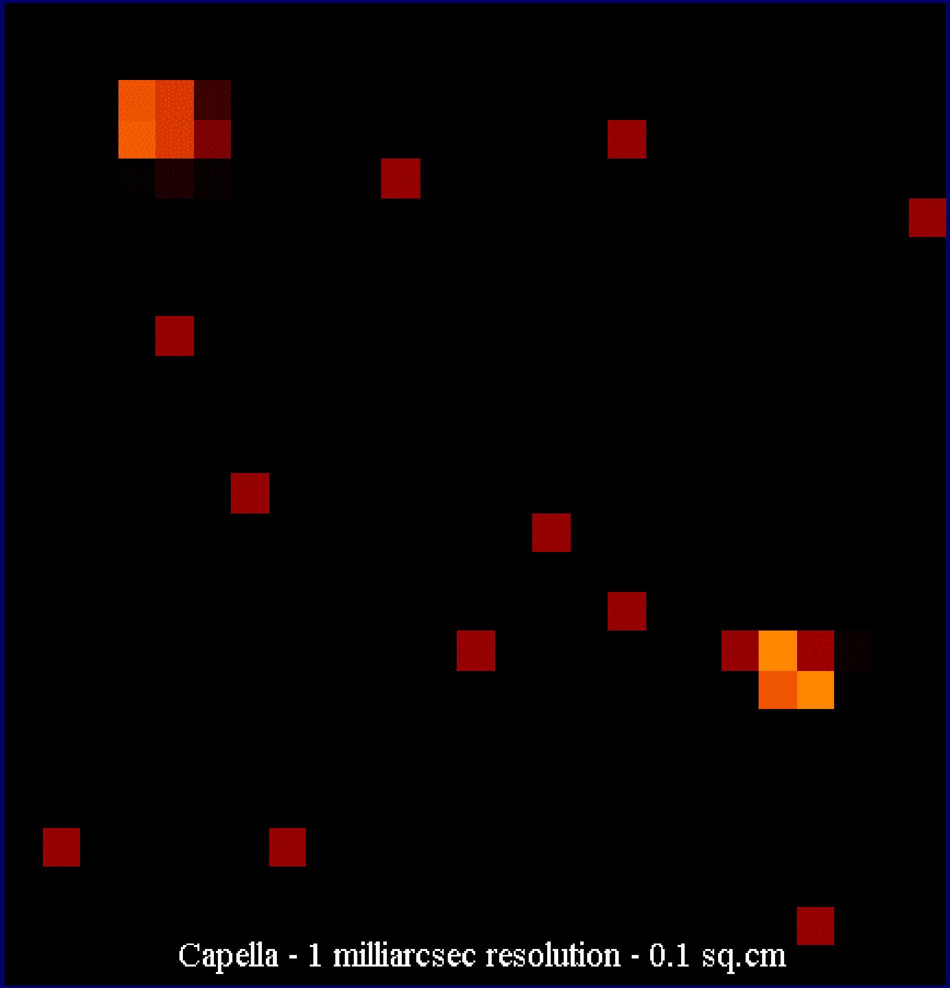
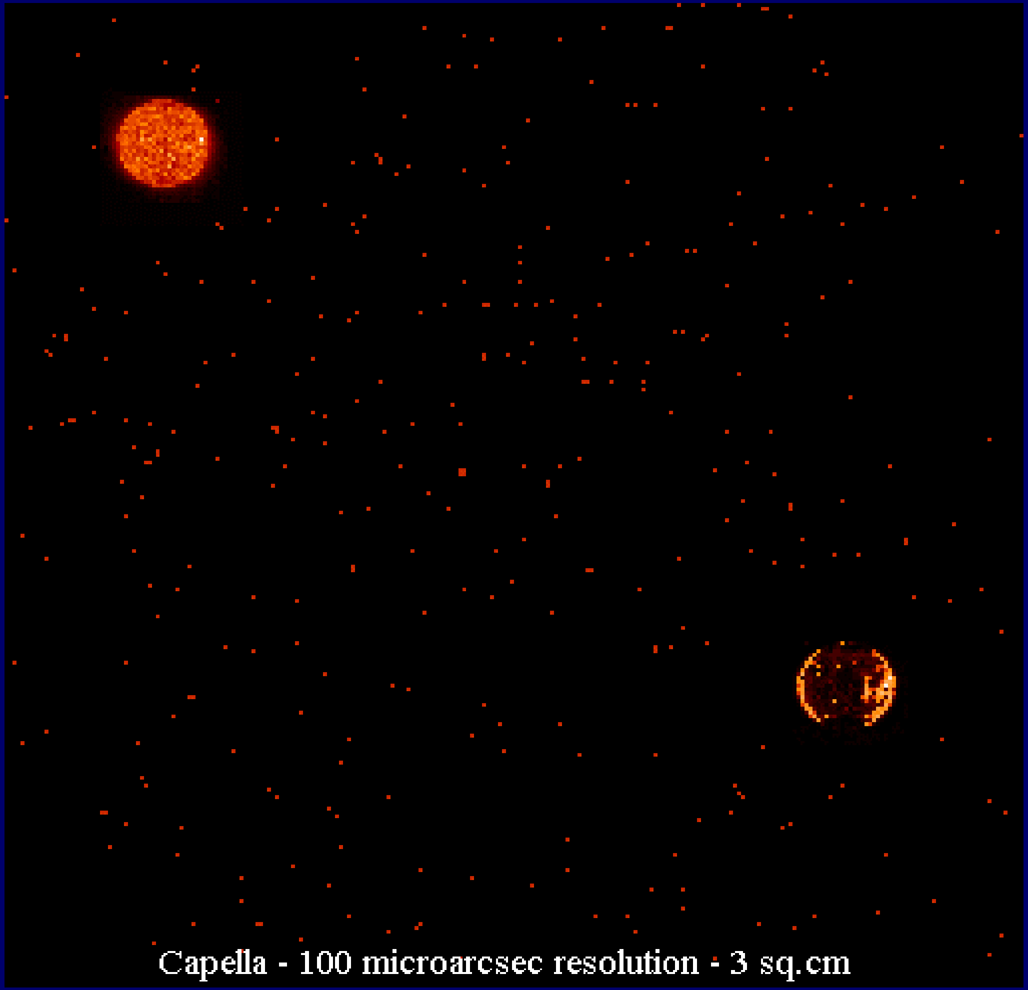
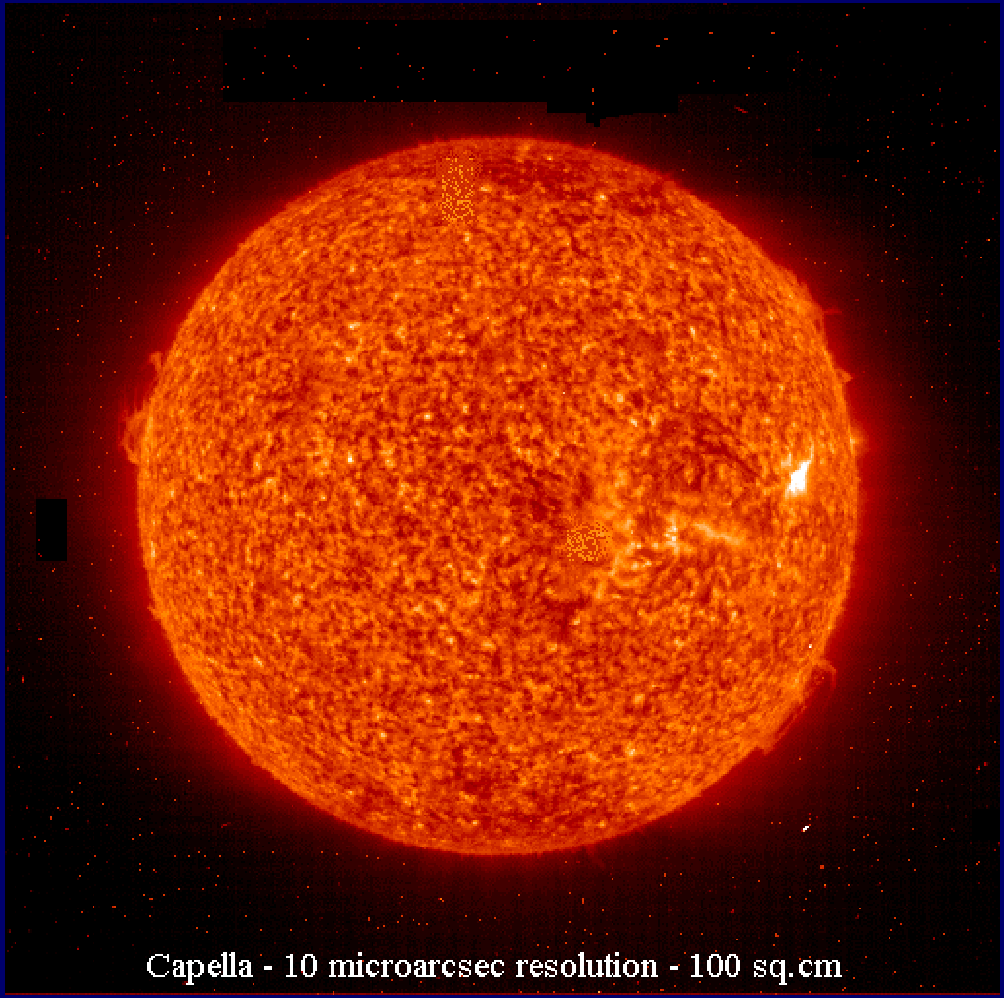


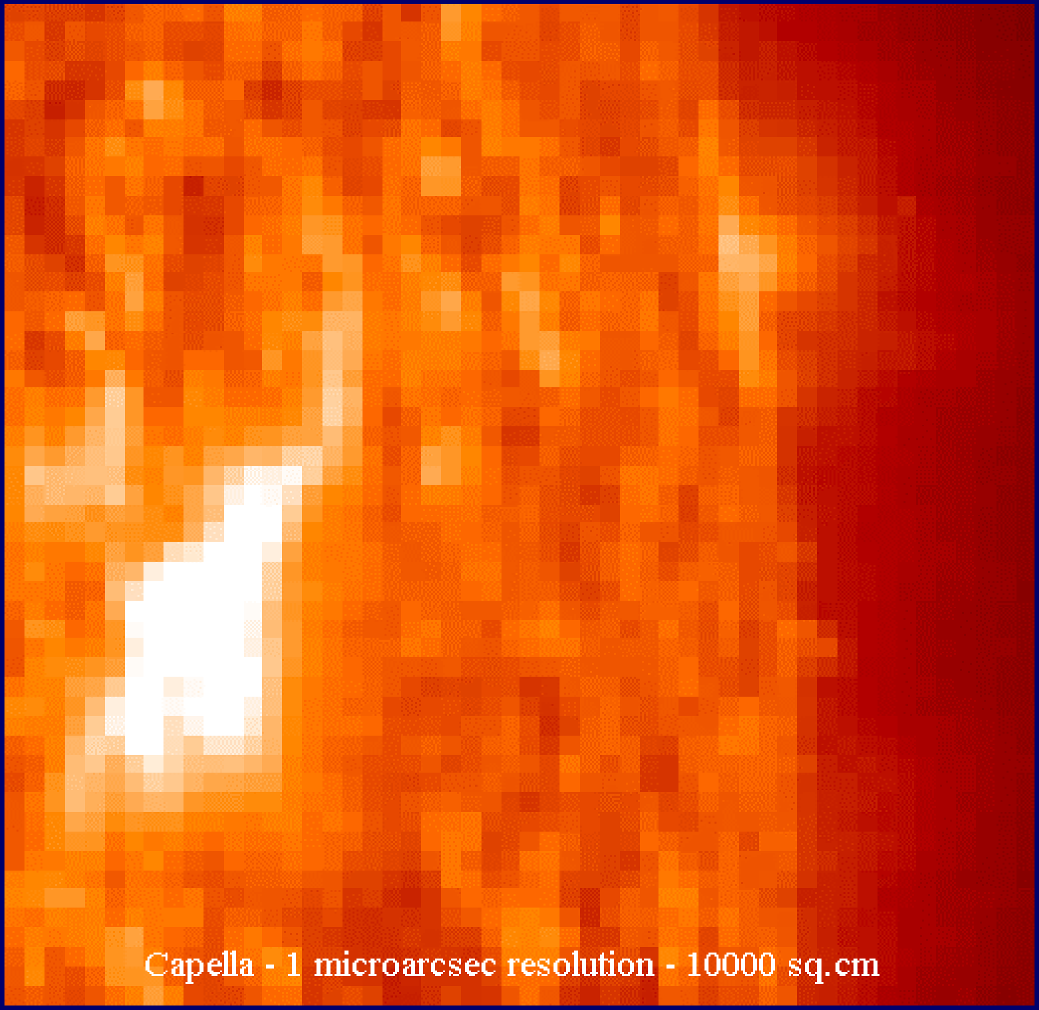
Capella 0.0001”



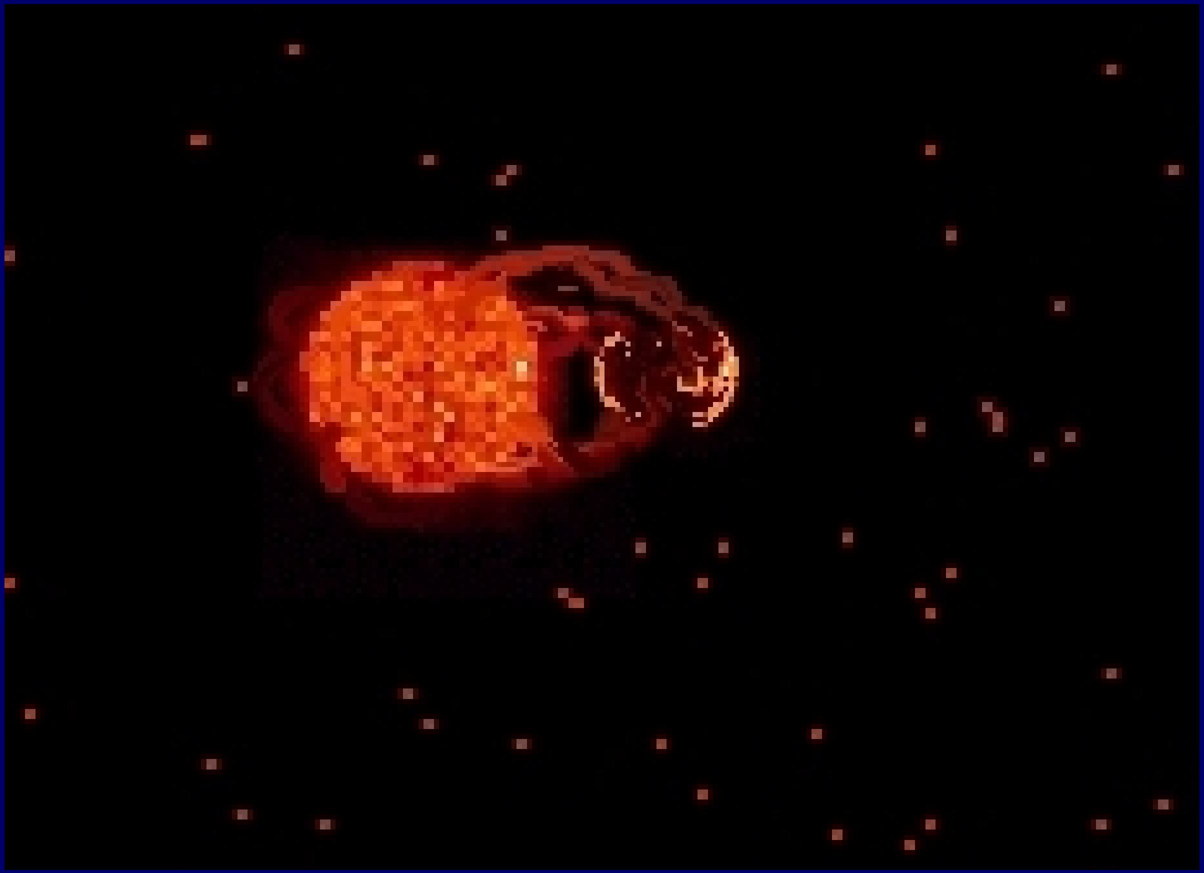
Capella 0.00001"



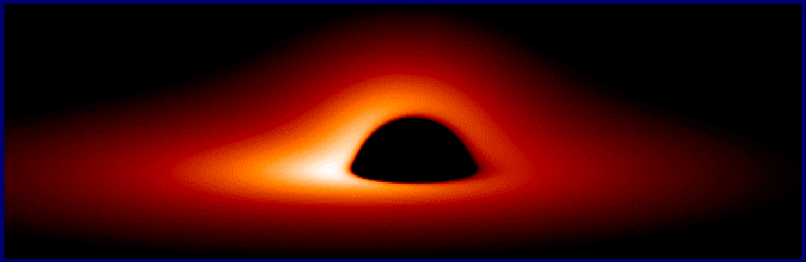
Capella 0.000001"



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 Source Brightness

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A more important [requirement] is astronomical and is critical:
one needs at least one x-ray photon per resolution element to do
interferometry.    There are not that many x-ray photons around.
This makes the proposal, though revolutionary, unrealizable.

Anonymous Referee
October, 19[illegible]
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WRONG!!

Some X-ray sources are the brightest in the universe.
We can actually see much smaller structures in the x-ray.

Optically Thick Sources

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!

Why X-ray Sources are Brighter

The peak frequency of emission from a blackbody of temperature T is given by:

$$\nu_{\max} = 10^{11} T$$

The number of photons detected in an instrument is given by:

$$N = \frac{1.8x10^{-5}}{h\nu_{\max}} G\theta^2 T^4$$

Where N is in photons/cm^2/s/ster.
Requiring N to be 100 photons and grasp G to be $10^{10} cm^2 s$, we find:

$$\theta_{\min} = 6x10^{-10} T^{-1.5}$$

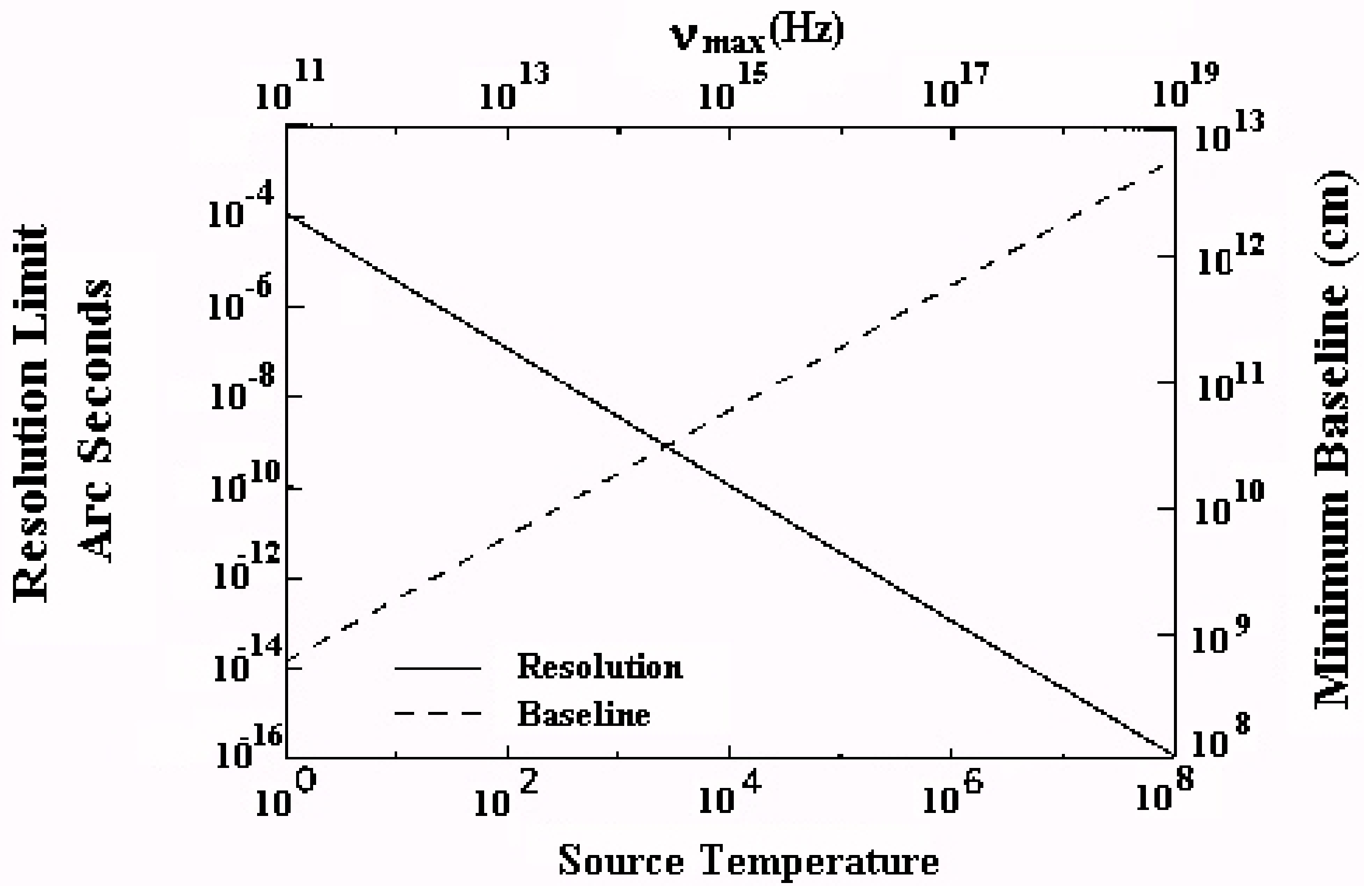
where θ_{min} is the minimum detectable angular feature in radians.

The baseline required to resolve θ_{min} is:

$$L = \frac{c}{\nu_{\max}\theta_{\min}} = 5.8x10^8 T^{1/2}$$

where L is the baseline in centimeters

Minimum Resolution

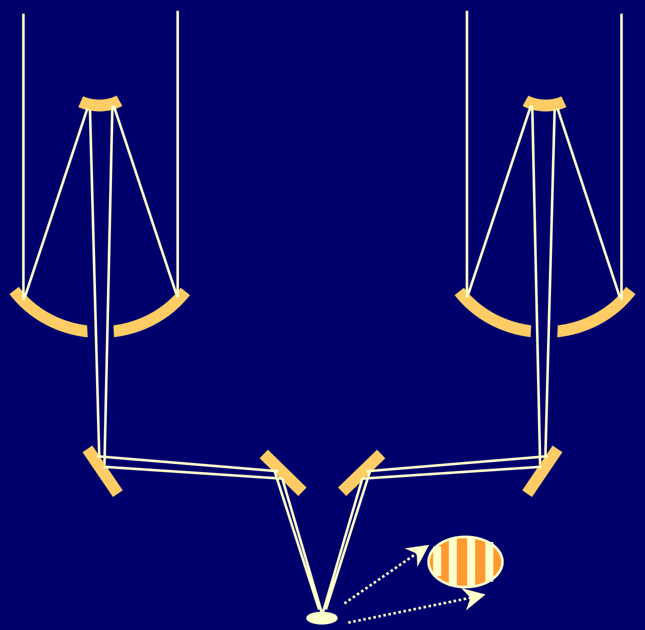


Status of X-ray Optics

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

Achieving High Resolution

Use Interferometry to Bypass Diffraction Limit



Michelson Stellar Interferometer

$$R = \lambda / 20000D$$

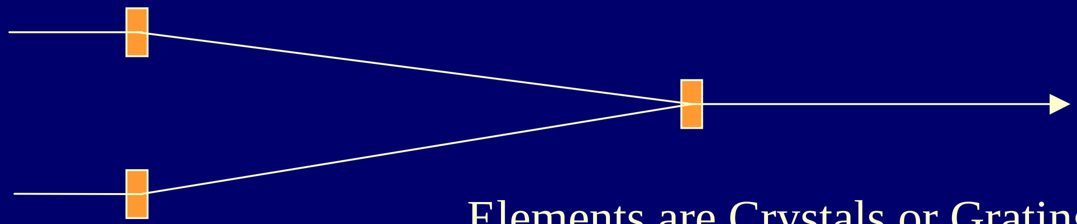
R in Arcsec

λ in Angstroms

D in Meters

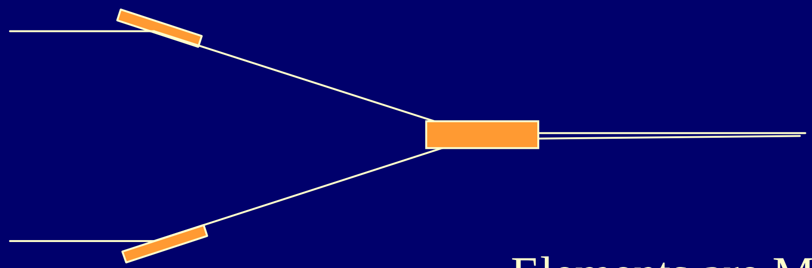
Classes of X-ray Interferometers

Dispersive



Elements are Crystals or Gratings

Non-Dispersive

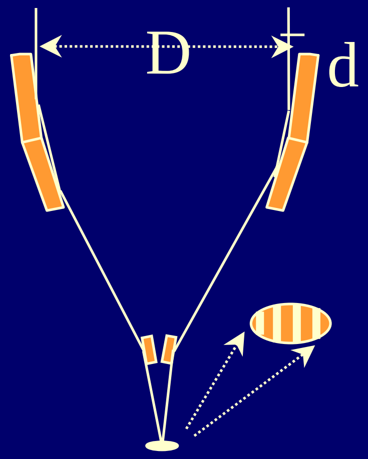


Elements are Mirrors & Telescopes

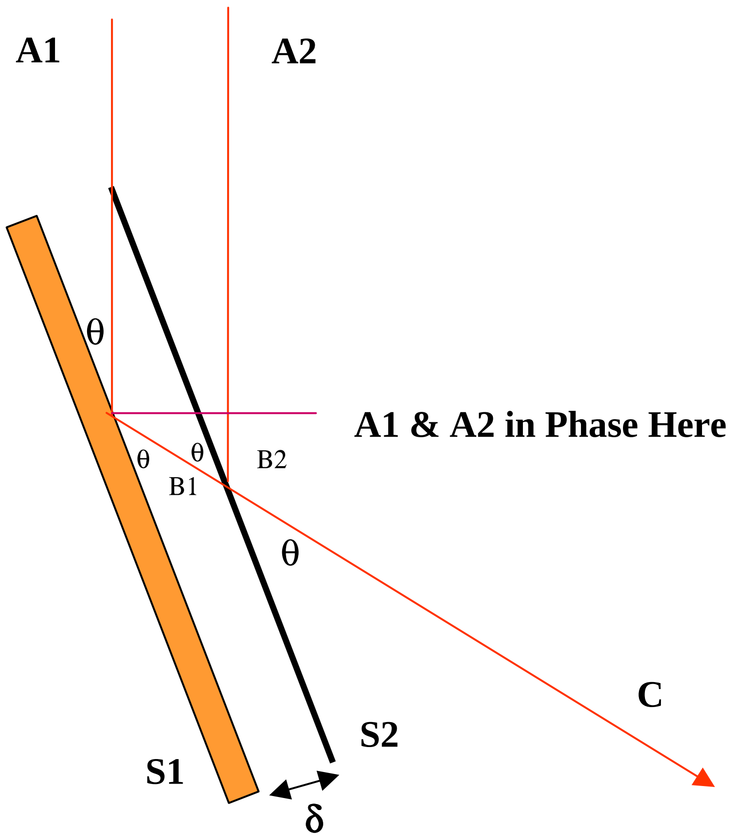
Creating Fringes

Requirements

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



Pathlength Tolerance Analysis at Grazing Incidence



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

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

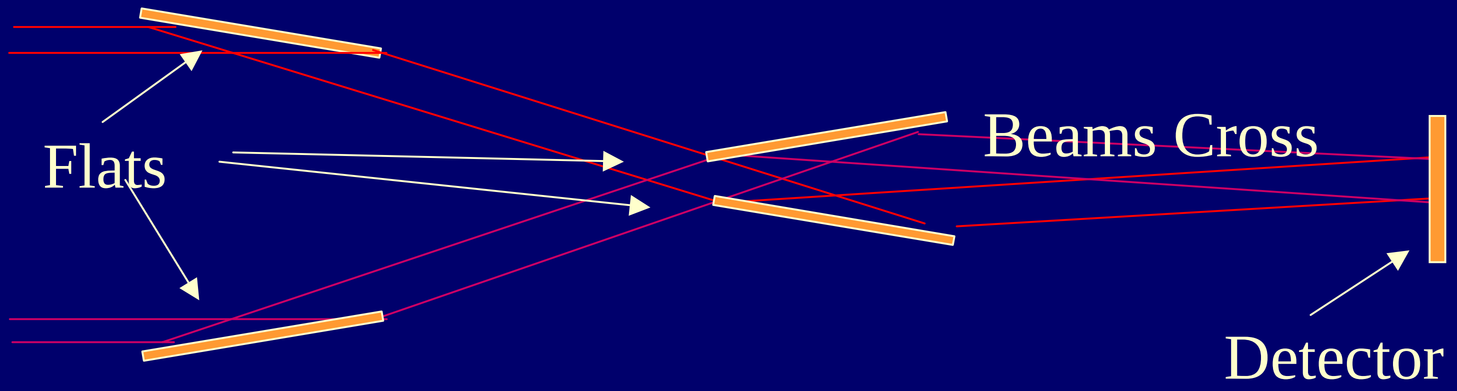
$$OPD = B1 - B2 = \frac{\delta[1-\cos(2\theta)]}{\sin\theta} = 2\delta\sin\theta$$

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

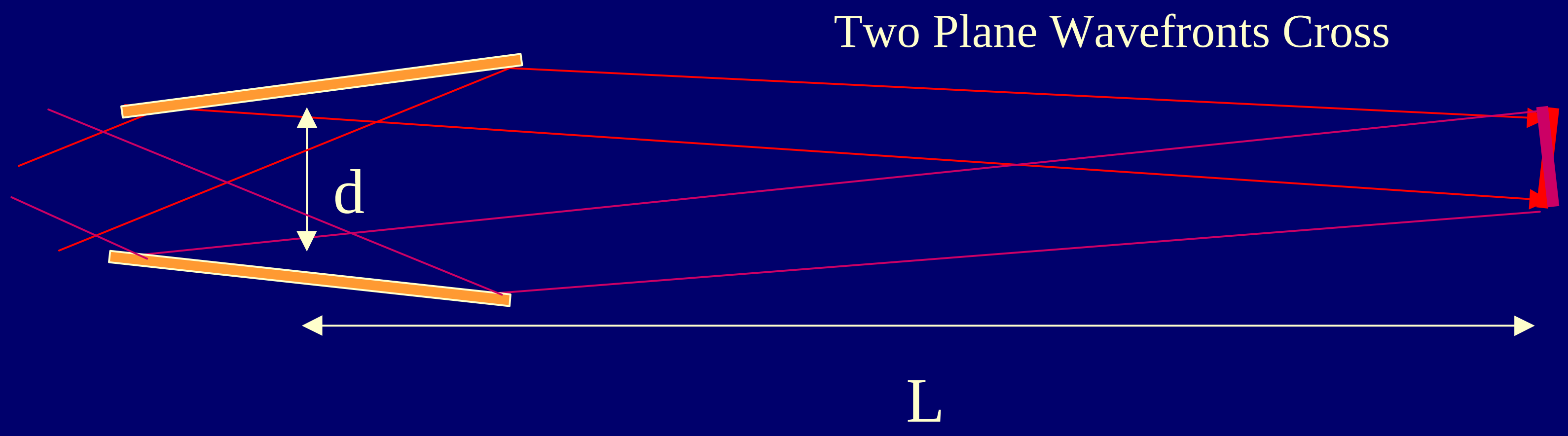
$$d(Baseline) < \frac{\lambda}{20\sin\theta\cos\theta}$$

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

A Simple X-ray Interferometer

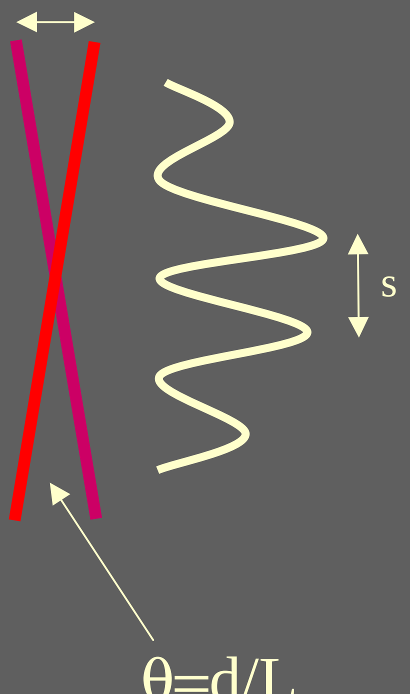


Beams Cross to Form Fringes



Wavefront Interference

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



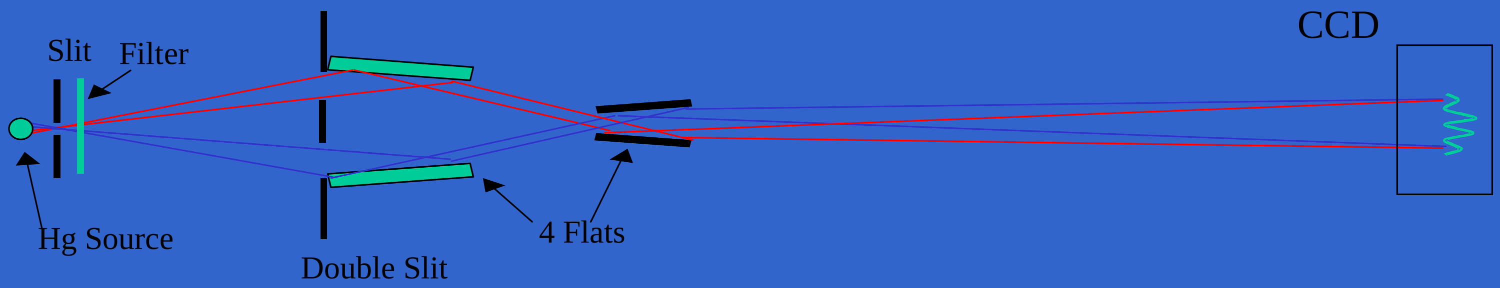
$$s = \frac{L\,\lambda}{d}$$

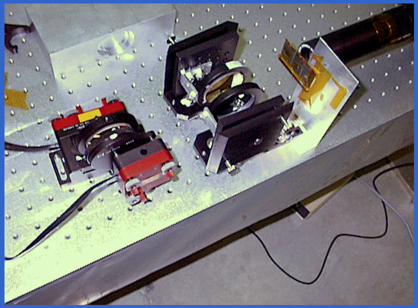
Beam Combiner

- 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

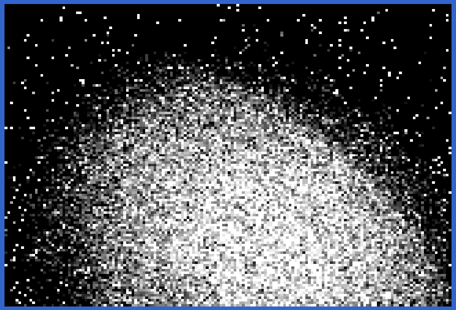
    - Grazing Incidence Mirrors Only
    - Flats OK
    - No
        - Partially Silvered Mirrors
        - Diffraction Gratings
        - Paraboloids
        - Windows or Filters
    - Diffraction Limited Optics OK

Fringes with Visible Light

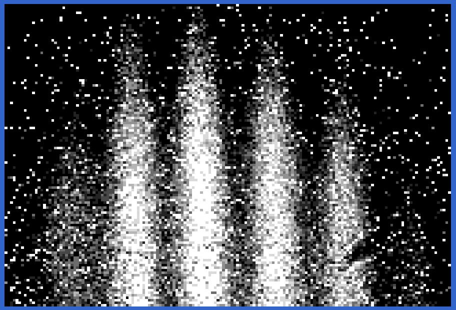




Picture of Interferometer

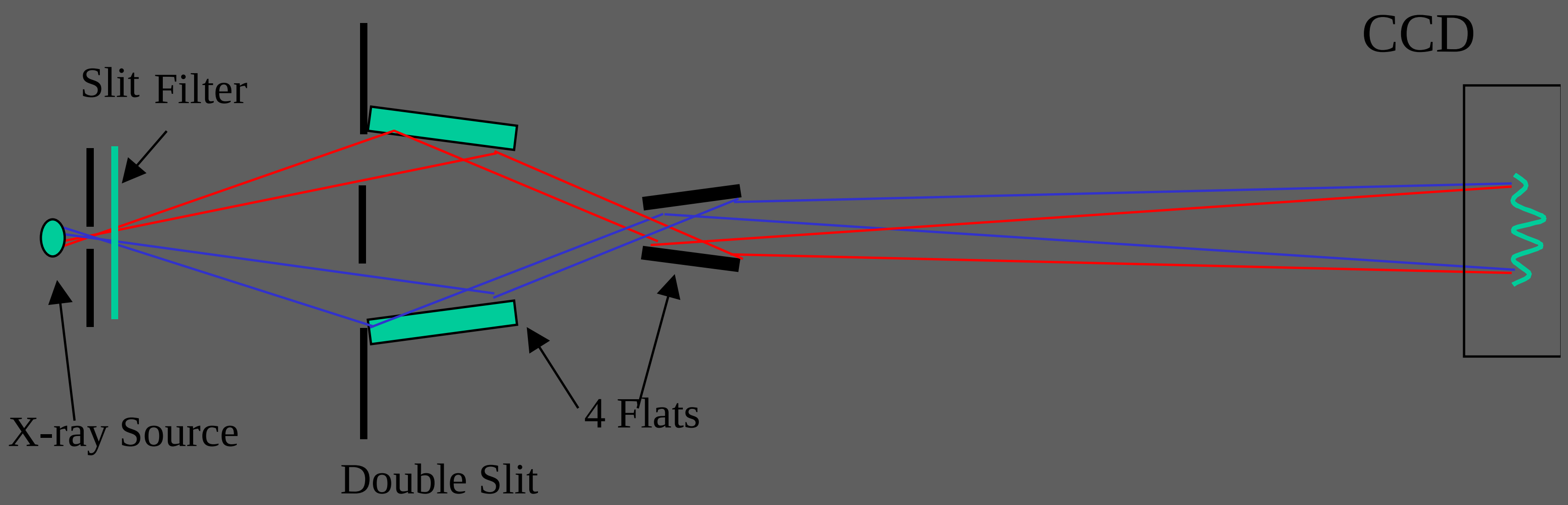


One Channel Blocked

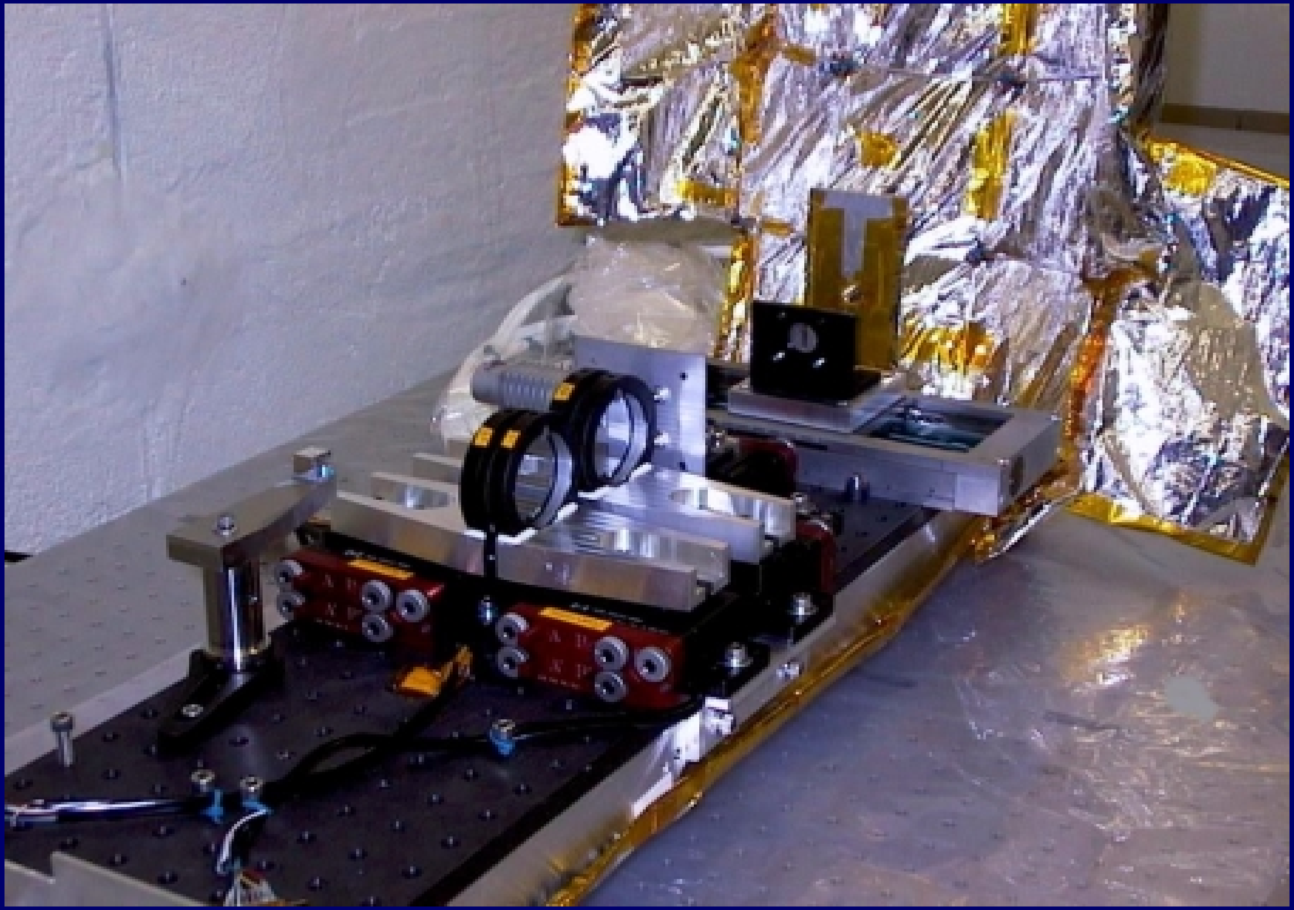


Both Channel Open

Schematic of X-ray Interferometer

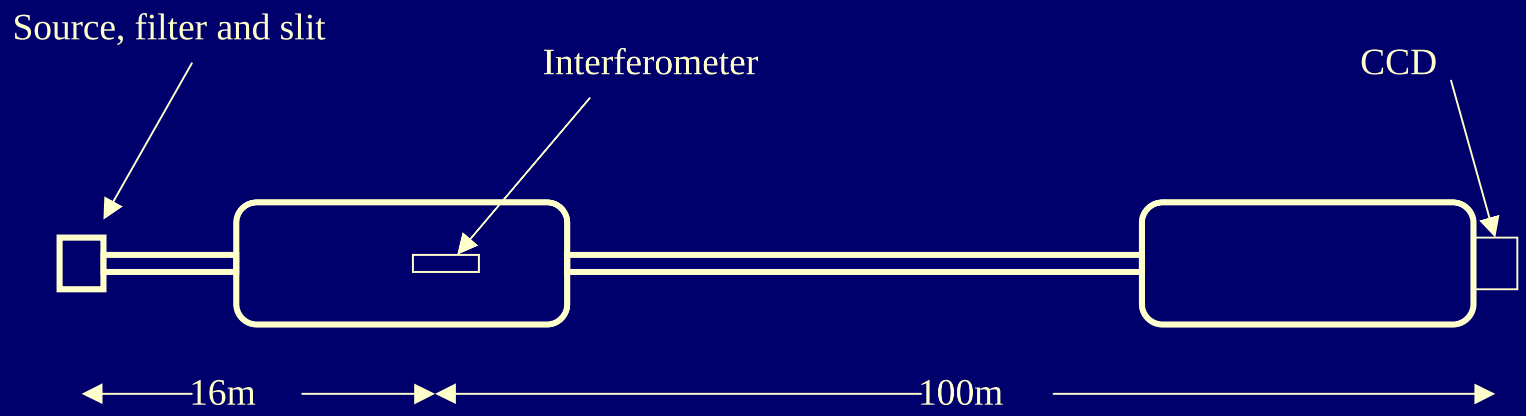


Optics



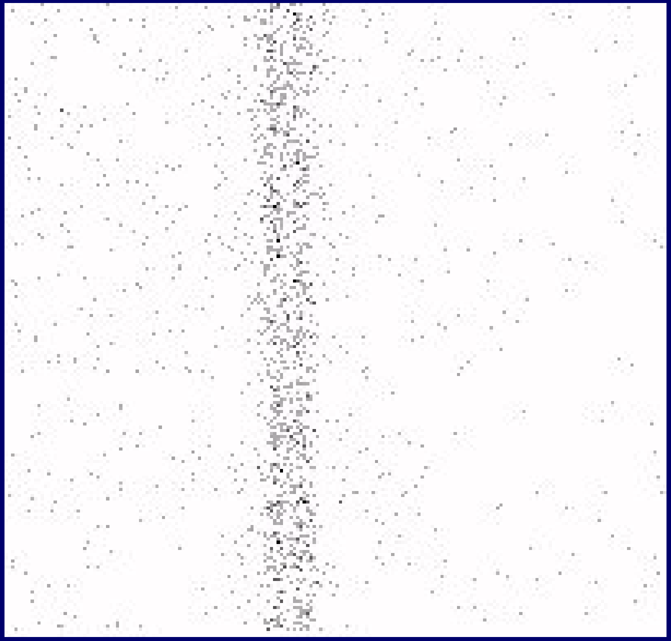
Each Mirror Was Adjustable
From Outside Vacuum
System was covered by thermal shroud

Stray Light Facility MSFC

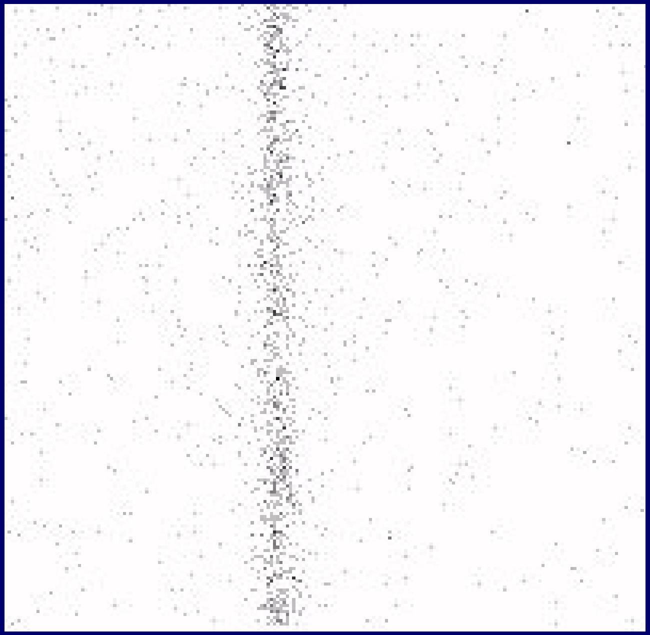


Used Long Distance To
Maximize Fringe Spacing

CCD Image @ 1.25keV

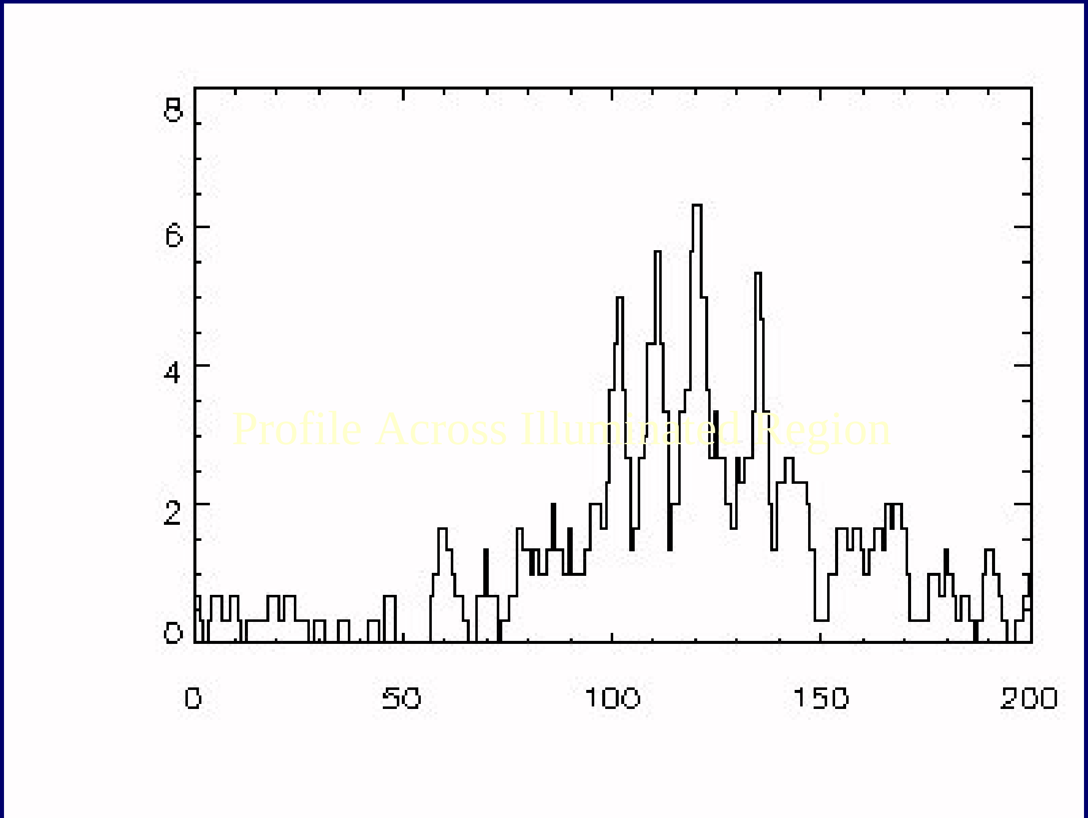


2 Beams Separate

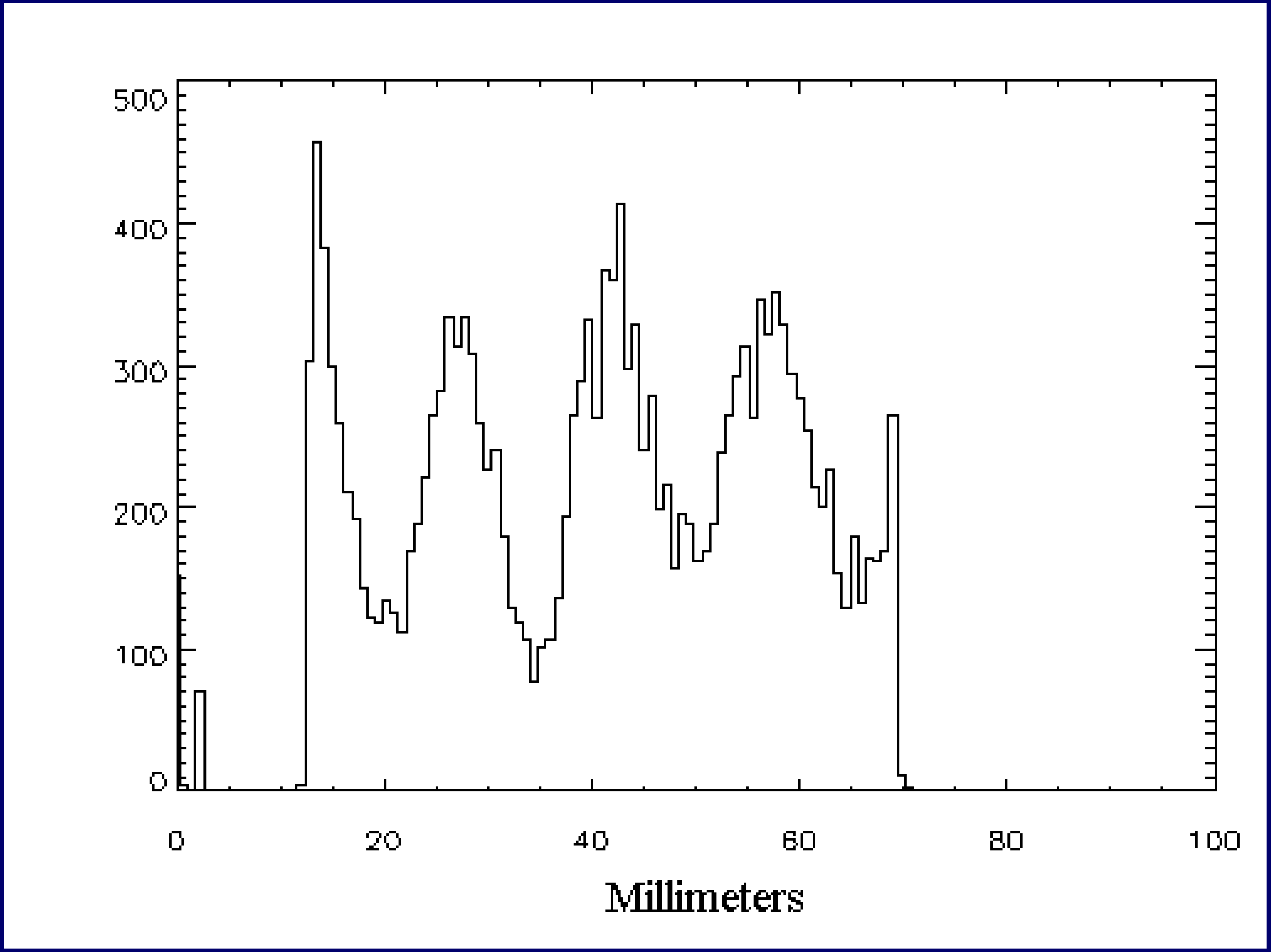


2 Beams Superimposed

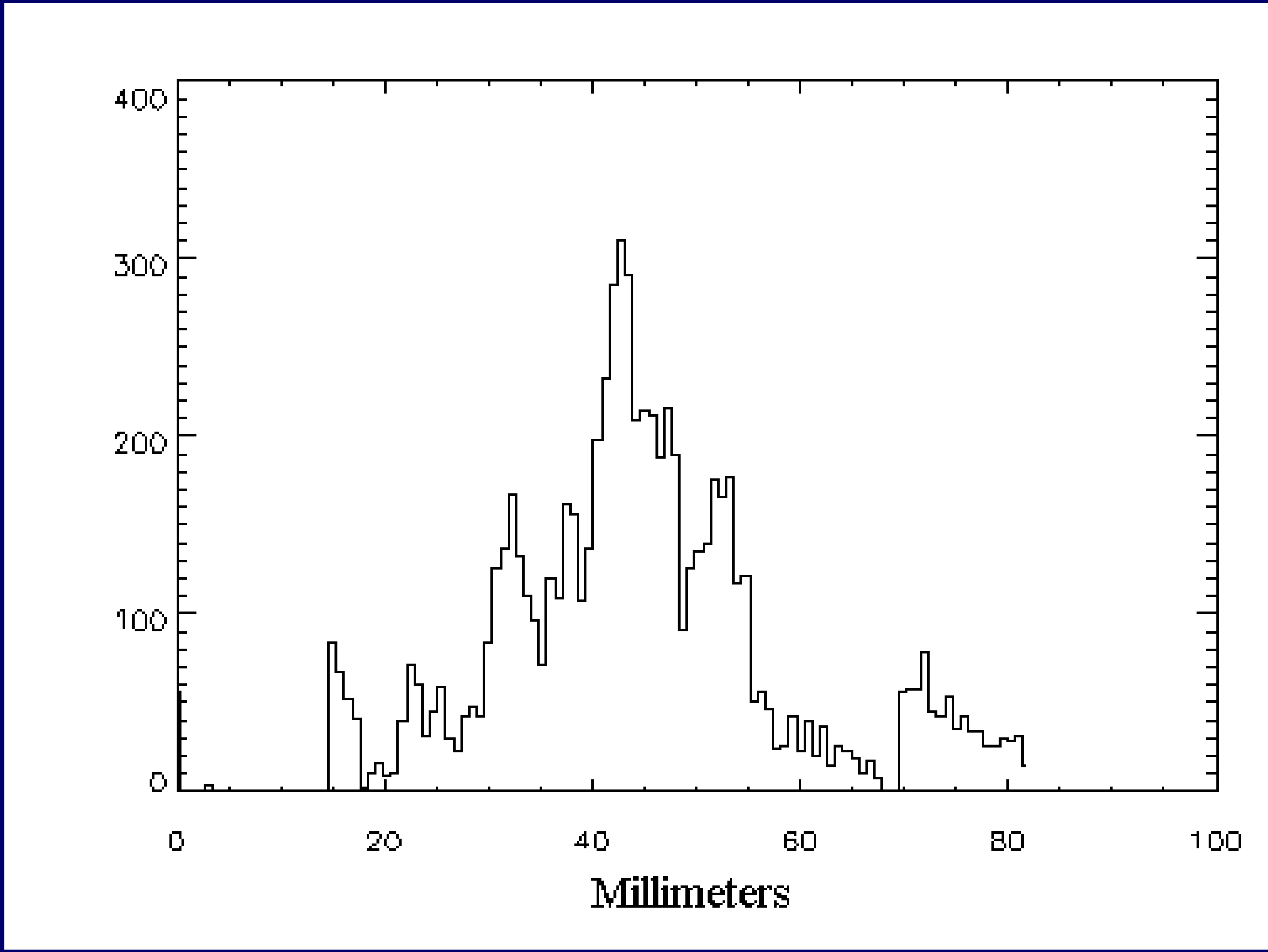
Fringes at 1.25keV



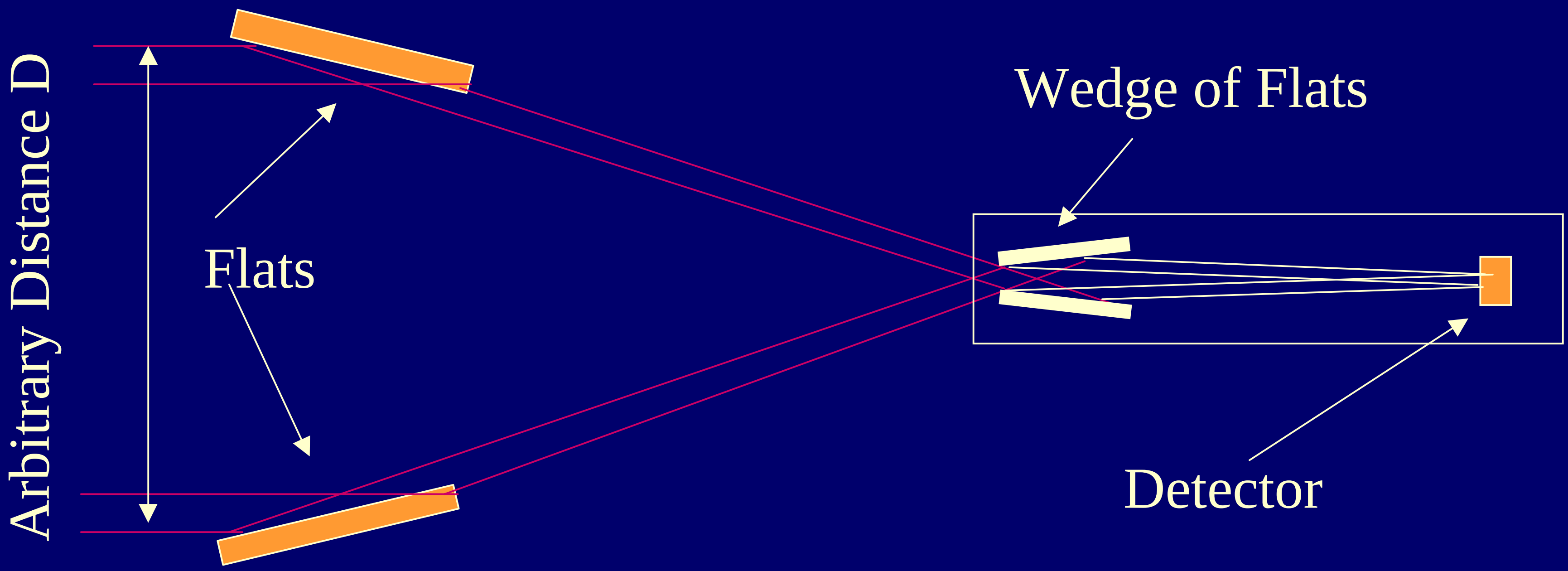
Argon 900-1000Å



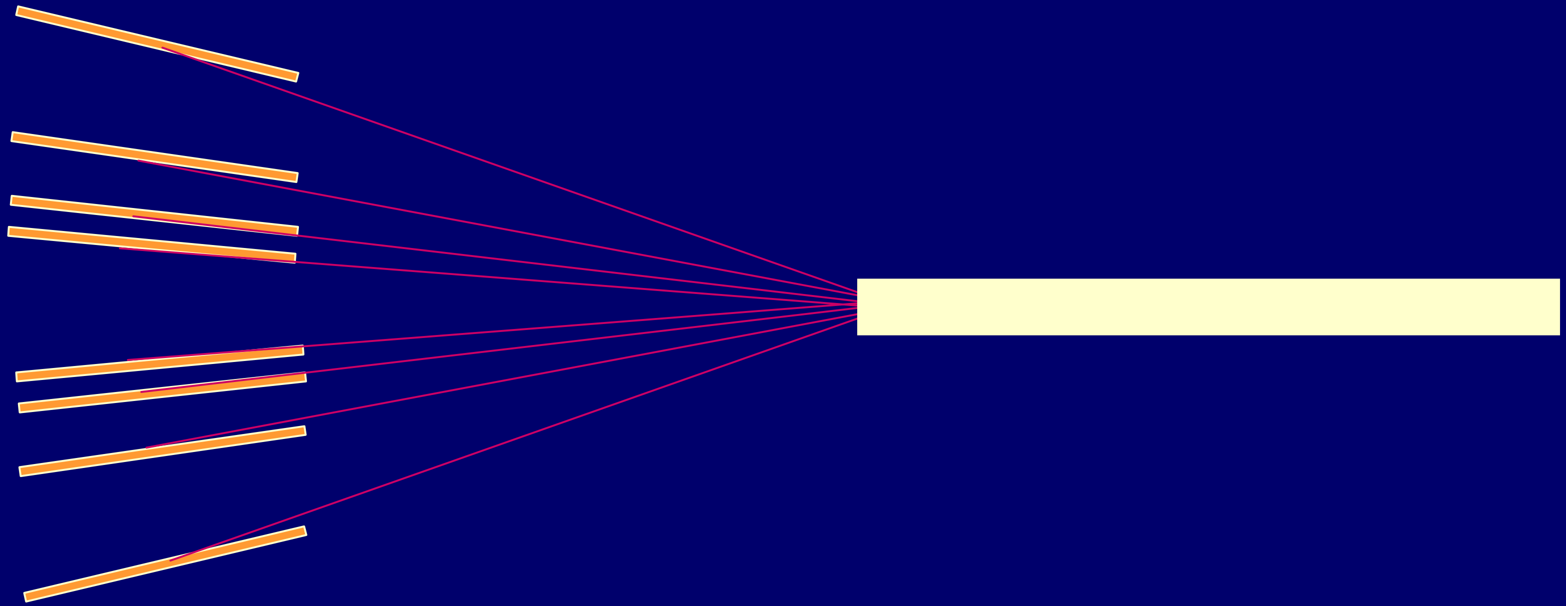
Helium 304 & 584Å



Observatory Design



Observatory Design



Multiple Spacings and Rotation Angles Needed Simultaneously to Sample UV Plan

Observatory Parameters

(Example)

4 Mirrors 300x100cm at 2degree graze makes 10x100cm beam
Effective Area ~1000cm^2 at 1.2keV (λ=1nm)
Spacing (d) of combiner mirrors - 20cm
Distance to Detector (L) - 1000km (Separate Spacecraft)
Fringe Spacing (s) - 5mm (across 100mm at λ=1nm)
Detector E/δE - 20 (100mm/5mm)

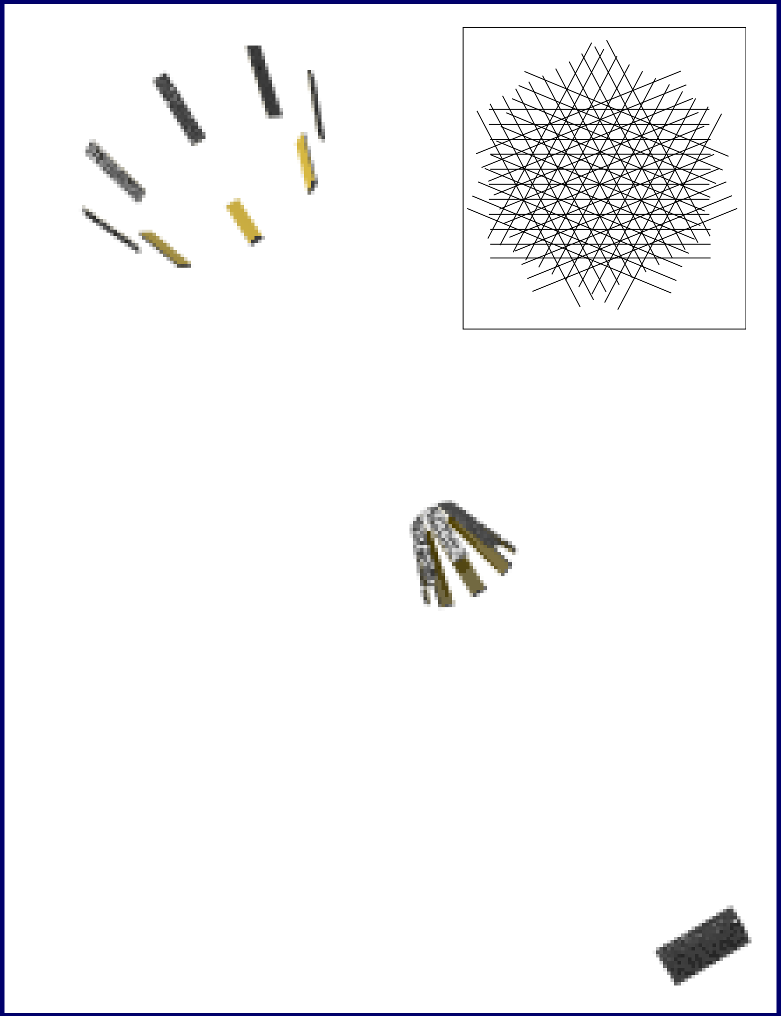
Resolution:	D (m)	Arcseconds
	60cm	3×10^{-4}
	600m	3×10^{-7}
	600km	3×10^{-10}
	600,000km	3×10^{-13}

Tolerance Table

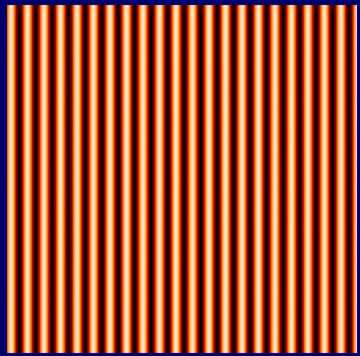
Resolution Arcseconds	$\mathbf{10^{-4}}$	$\mathbf{10^{-5}}$	$\mathbf{10^{-6}}$	$\mathbf{10^{-7}}$
Baseline (m)	1	10	100	1000
Mirror Size (cm)	3x100	3x100	3x100	3x100
Position Stability (nm)	20	20	20	20
Angular Stability (arcsec)	10^{-3}	10^{-3}	10^{-3}	10^{-3}
Figure	$\lambda/100$	$\lambda/200$	$\lambda/200$	$\lambda/200$
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
$E/\Delta E$ 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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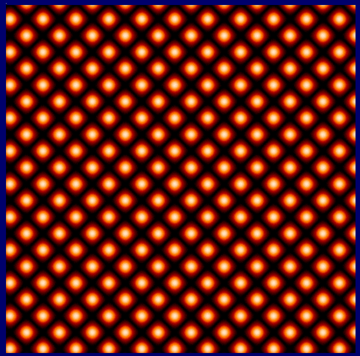

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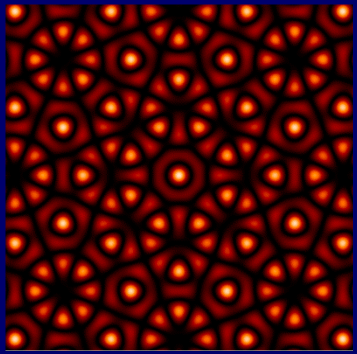

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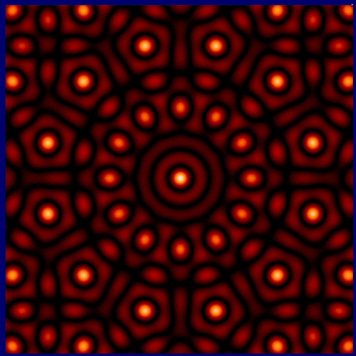

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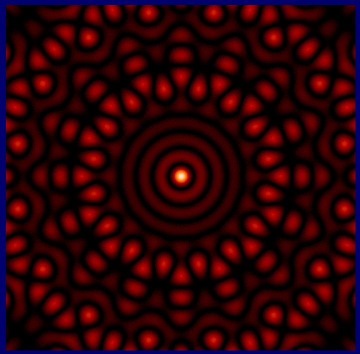

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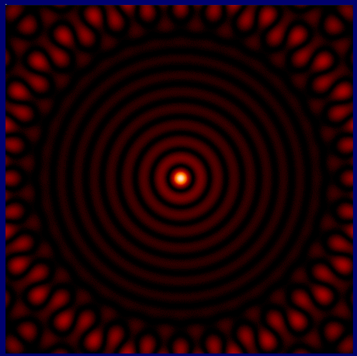

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Metrology

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

Remains Constant No Matter the Baseline!

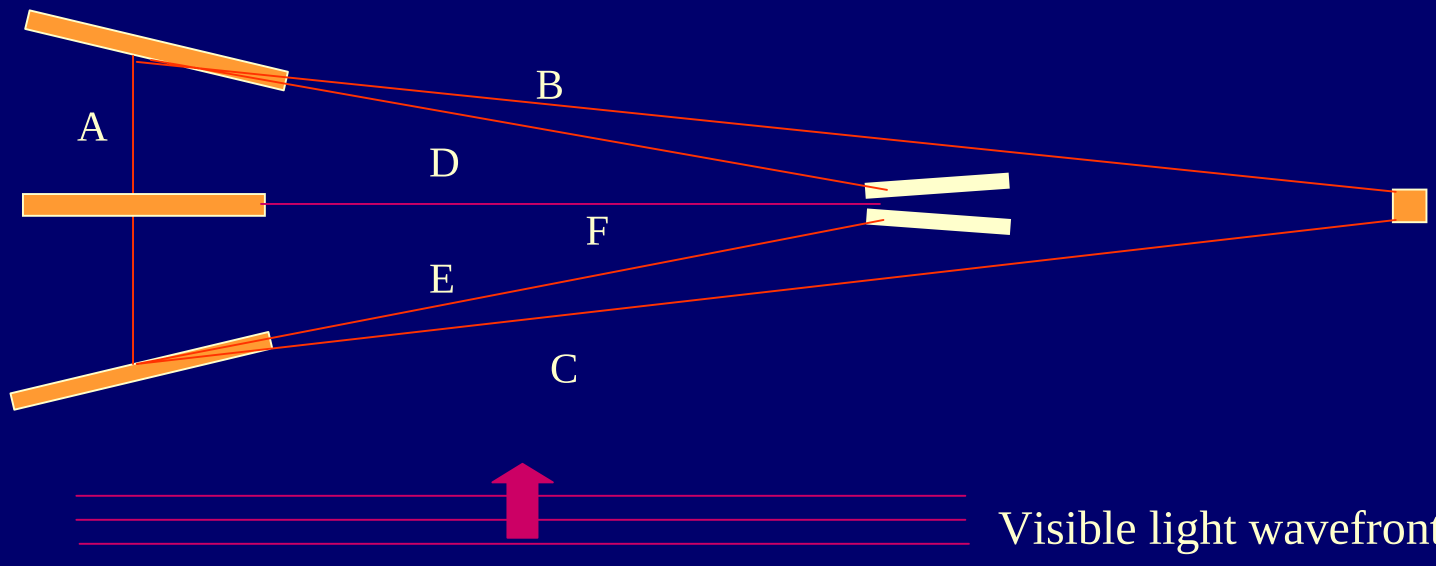
Pointing

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

L2 or Fly-away orbit probably necessary

Pointing Angle Constraint is Positional Accuracy With Respect To Celestial Sphere

Pointing Solves 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.

High Contrast Astronomy

- Search for Planets
- Problem: Close to Bright Stars
- Diffraction and Scatter are Severe
- Never Yet Been Done at Needed Level

Grazing incidence may play a role!

Terrestrial Planet Finder

Has A Problem!

10

Progress Toward Astronomical Nulling

INTRODUCTION

Perhaps the most difficult and unusual challenge of finding planets around nearby stars is that of rejecting the light of the parent star. The traditional approach on a filled aperture telescope is to use a coronagraph to enable faint objects to be found beyond a few diffraction widths of a bright object. As demonstrated on the Hubble Space Telescope (HST), coronagraphic rejection 0.5″ from a bright star can be as great as 10^4 (Schneider *et al.* 1998). A number of techniques have been suggested to combine a coronagraph with active optics that might work orders of magnitude better than a simple coronagraph (Malbet, Yu, and Shao 1995; Angel and Woolf 1997; Trauger *et al.* 1998). However, the level of rejection needed to detect an Earth-like planet 10 pc away at visible wavelengths, a factor of $1\text{-}10\times10^9$, implies wavefront and amplitude control of ~0.1 nm over an entire 8 m aperture and lies many years in the future. As described in Chapter 6, the approach that appears technologically most feasible within the next decade is an interferometric one using destructive interference, or nulling, to remove the on-axis light from a parent star. This chapter describes techniques for nulling, highlights the present state of the art in experiments in the laboratory and at the telescope, and presents a road map for continued progress.

Two experiments made in the last six months lead to the important conclusion that nulling is not just a theoretical construct:

1. Images of the dust cloud around Betelgeuse (α Ori) have been made by nulling the central star (Hinz *et al.* 1998a,b,c) to a modest factor of 24:1.
2. A laboratory nulling experiment has demonstrated at visible wavelengths a null depth of 25,000:1 (Serabyn *et al.* 1999).

These experiments have demonstrated the basic technique of nulling in the laboratory and at the telescope more than six years in advance of the start of the TPF project. A NASA-funded program of technology development using laboratory experiments and astronomical tests (Keck Interferometer, the Large Binocular Telescope, and the Space

Alternate Approach to TPF

$$Scatter \propto \left(\frac{\sigma \sin \theta}{\lambda} \right)^2$$

- We have been assuming $\sin\theta=1$ and σ must be made small
- Use grazing incidence: at $\sin\theta=.01$, the scatter is reduced a factor of 10,000 !!

Grazing Incidence Planetary Telescope

- Tolerances similar to those needed for x-ray interferometry
- Flats still attractive
- Build arrays of flats to suppress diffraction

NIAC Program

- Tolerances and Tradeoffs
- Ball Aerospace Subcontract
  - Find Solution to Mission Problem
  - Discover Limitations
- Simulation Code
- Investigate Planetary Options

Summary

- Science Will Be Outstanding -
  - Much Like Exploring
- Resolution and Collecting are Achievable
- Have Taken First Steps in the Lab
- Mission Design Appear Feasible
- May Have Application to Planet Imaging
- Program Underway