MAXIM
The Black Hole Imager

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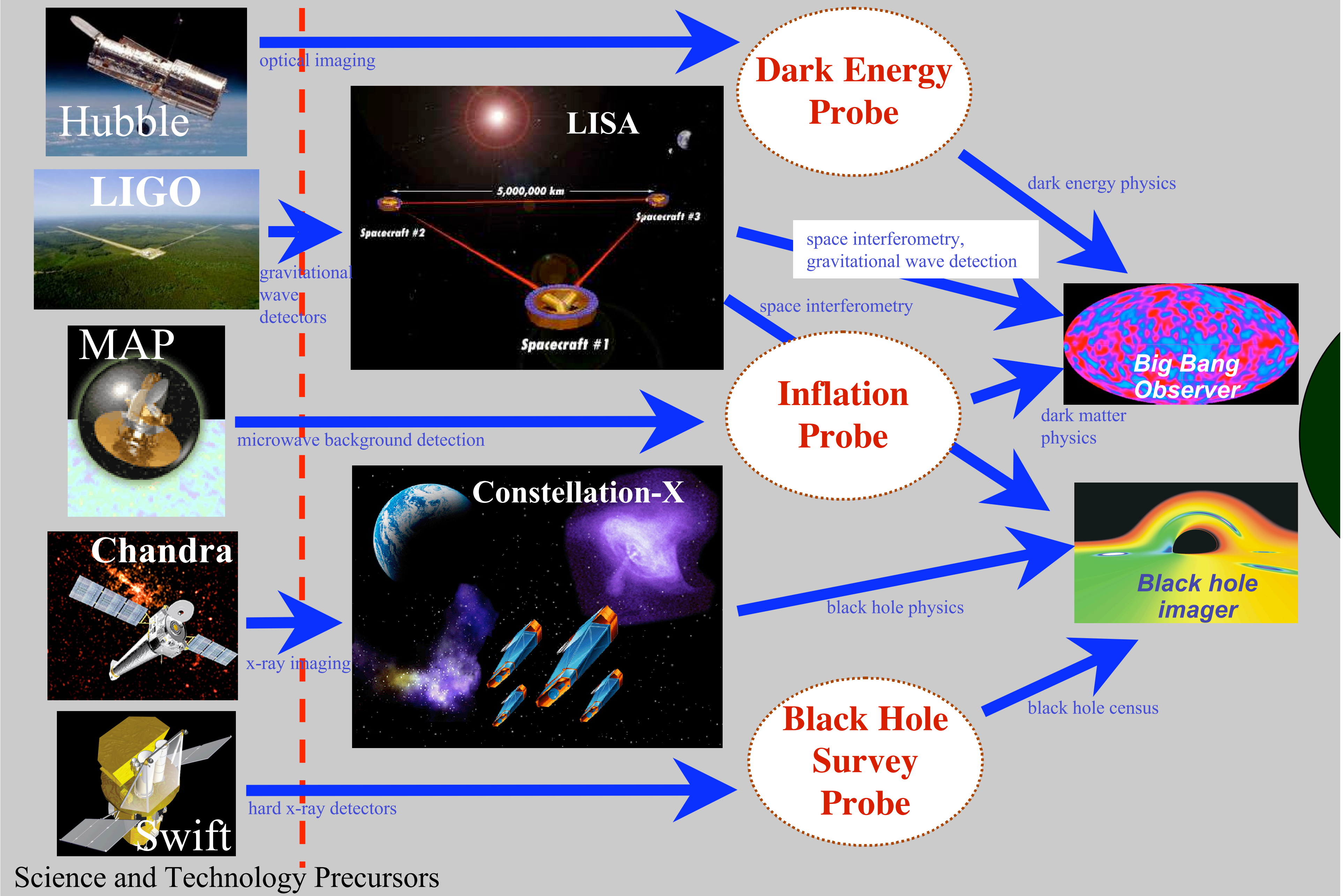
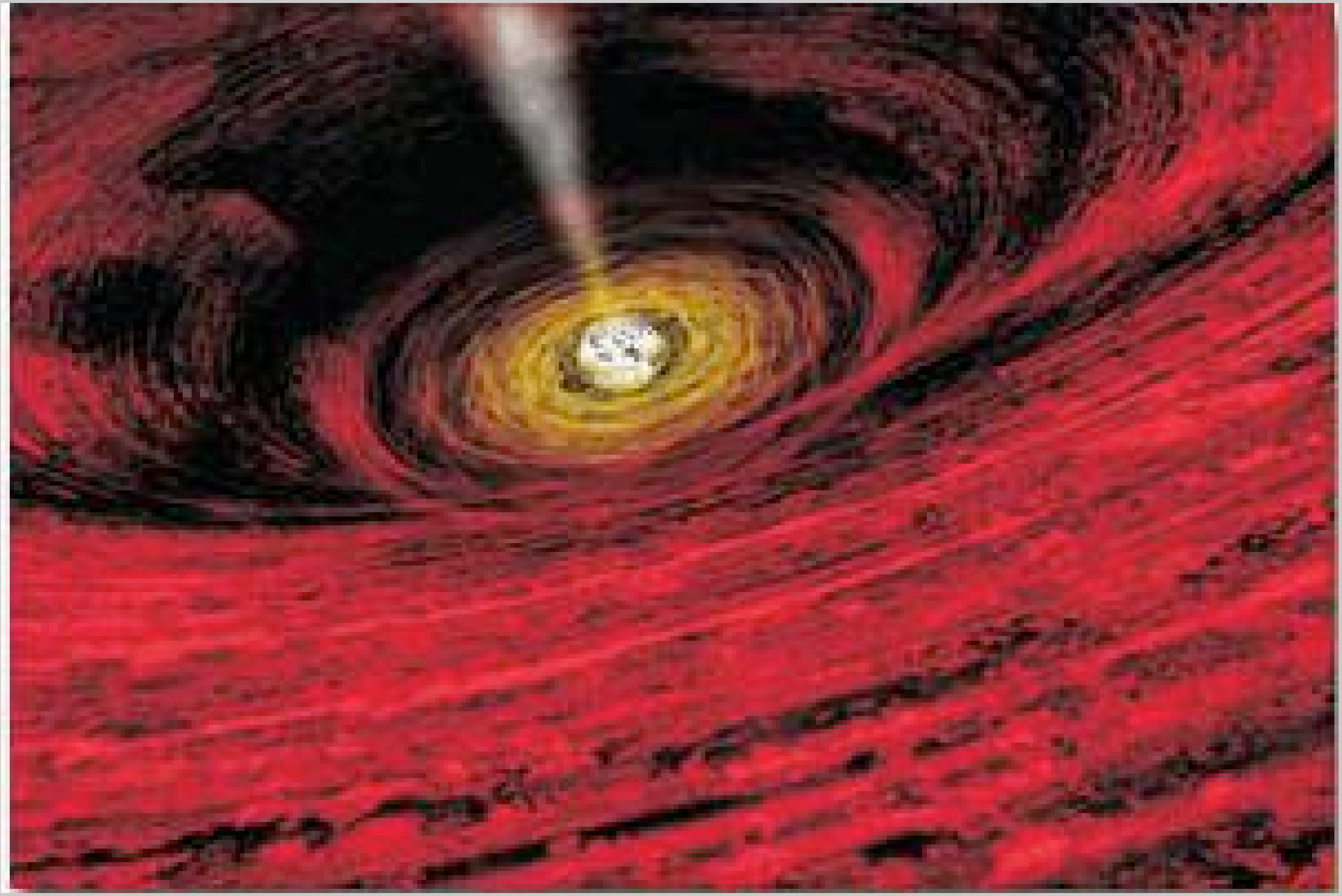
and

The Maxim Team

The Beyond Einstein Program

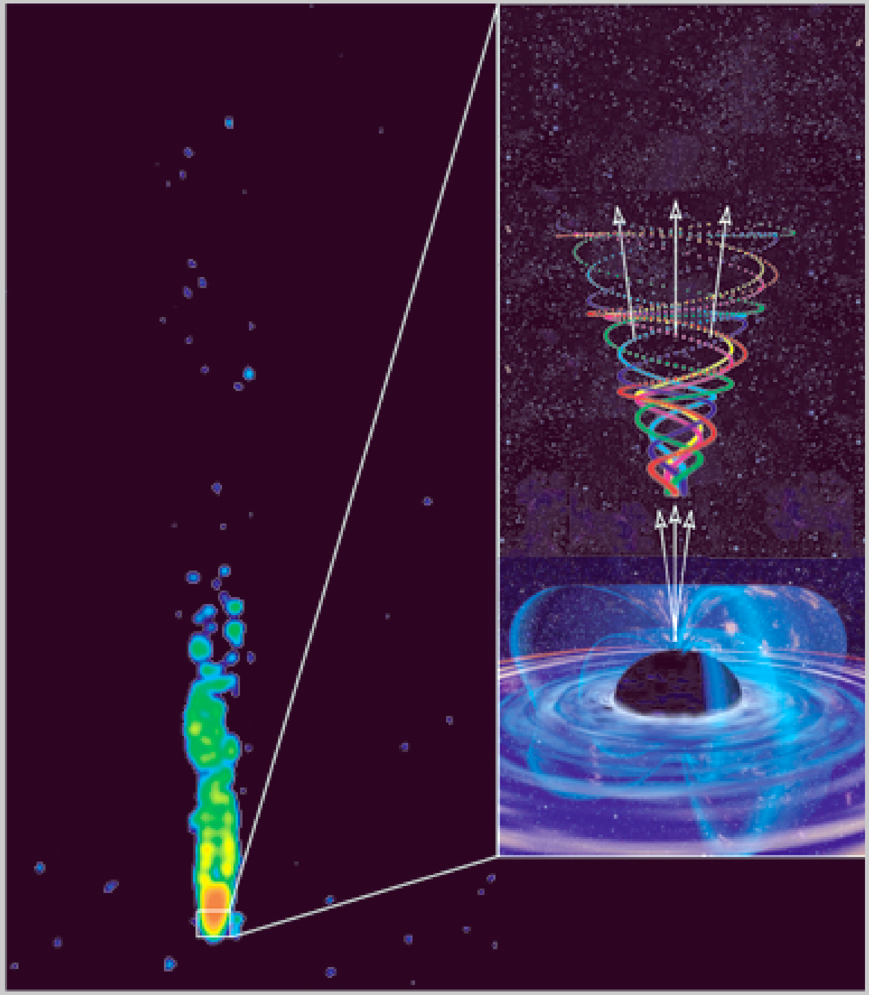


Science Objectives for the Black Hole Imager (1)



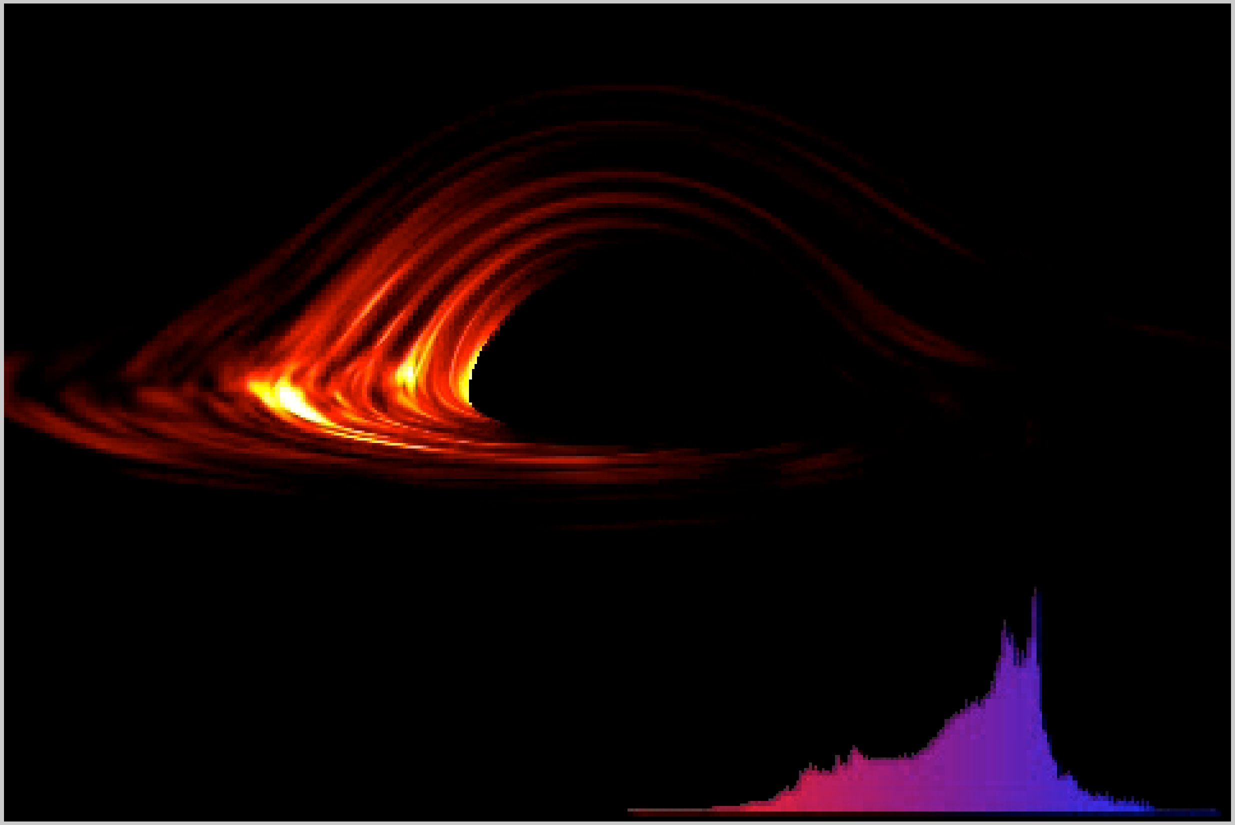
Map the motions of gas in the vicinity of a black hole event horizon and compare to GR predictions

Science Objectives for the Black Hole Imager (2)



Determine how relativistic jets are formed as well as the role of black hole spin in the process

Science Objectives for the Black Hole Imager (3)

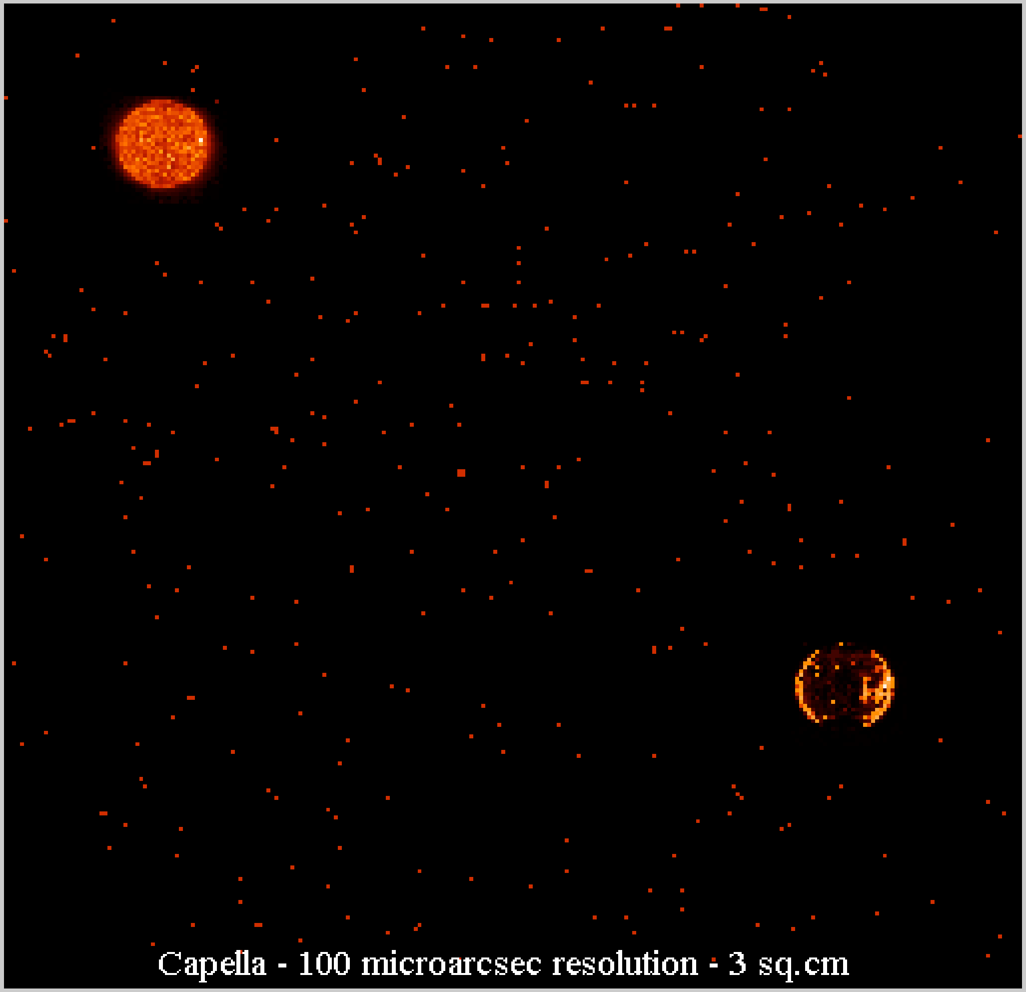


Map the release of energy in black hole accretion disks –

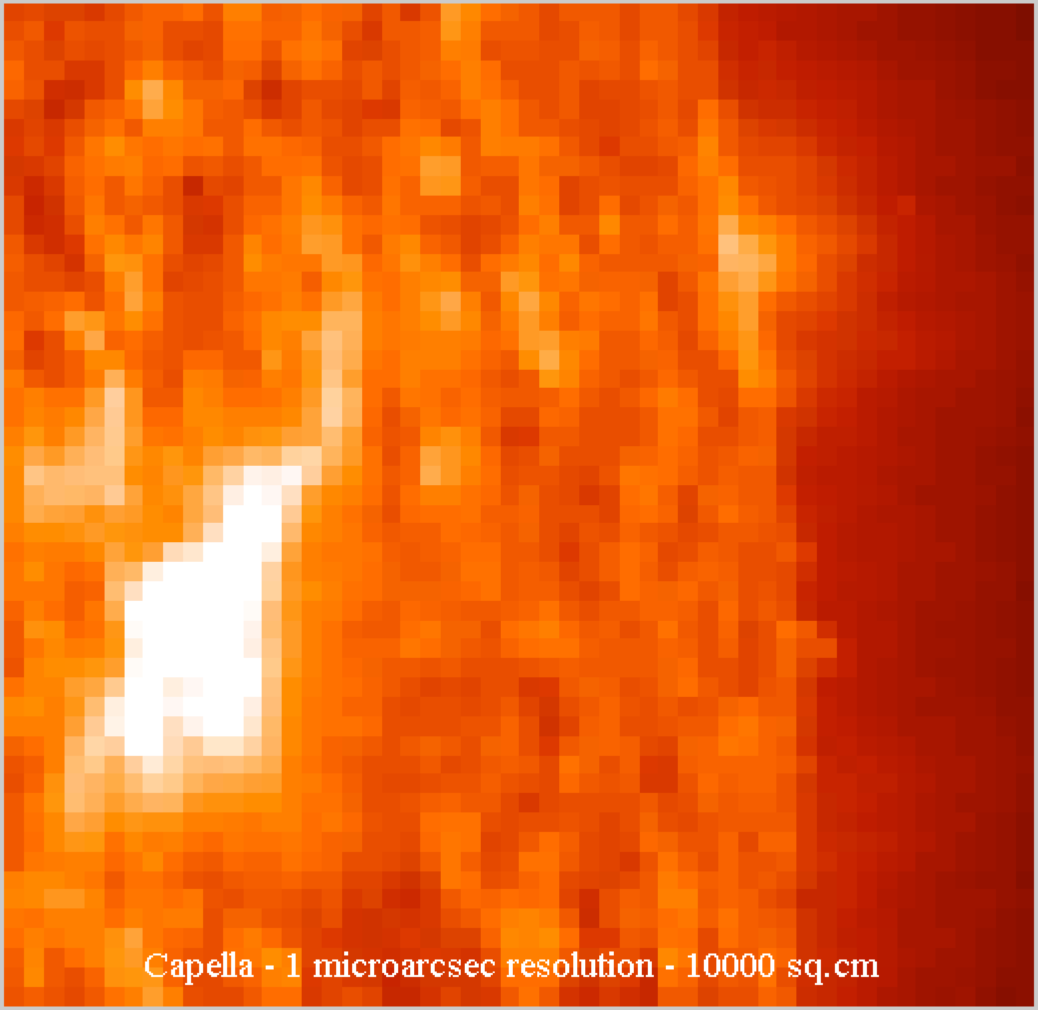
Image x-rays at 0.1μas

Courtesy of Phil Armitage, U. Colorado and C. Reynolds, U. Maryland

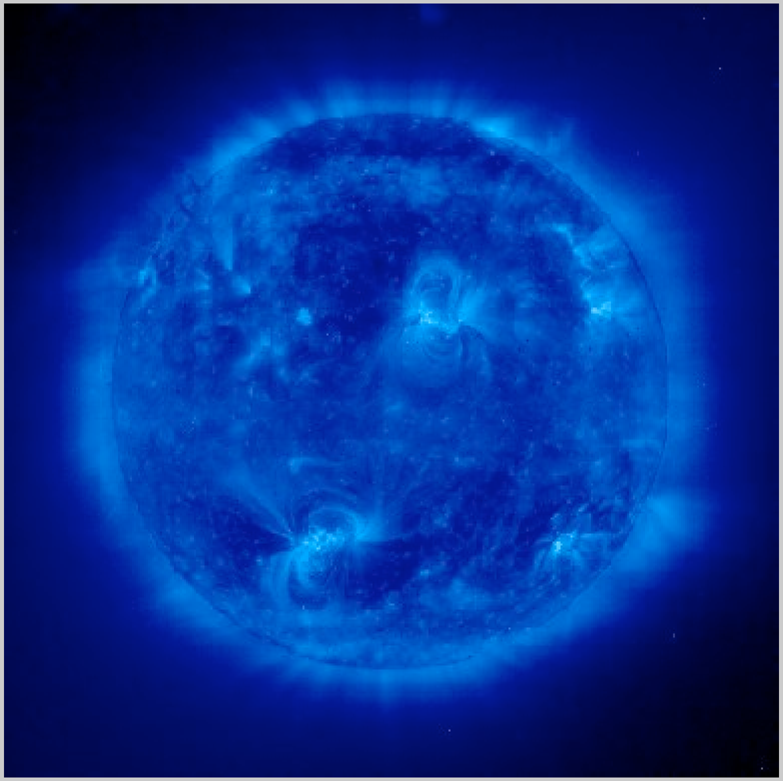
Capella 100μas



Capella 0.000001”

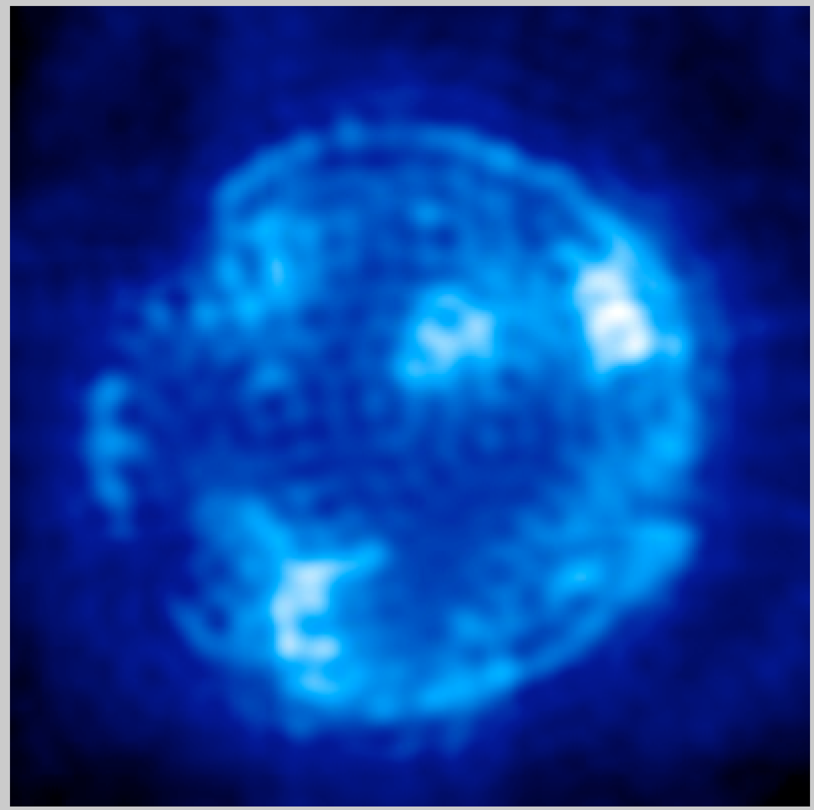


Stars

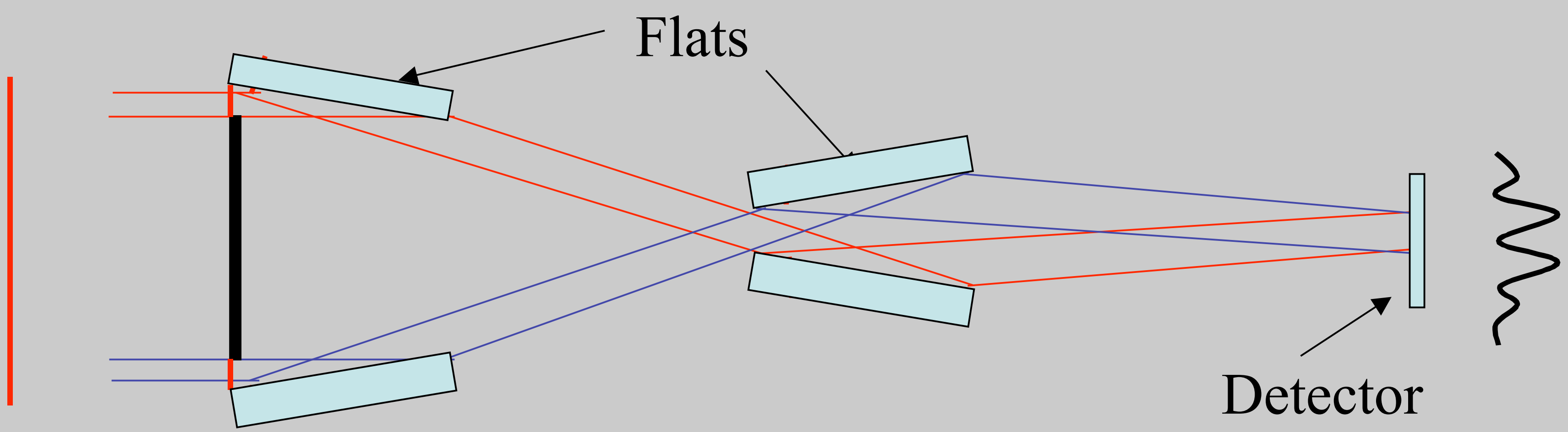


Sun with SOHO

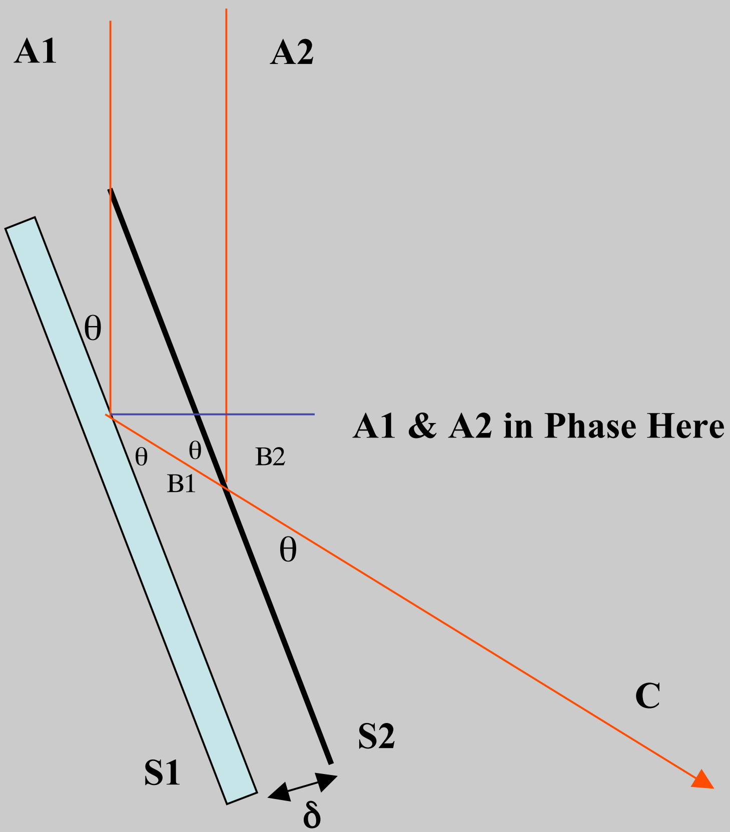
Simulation with Interferometer



A Simple X-ray Interferometer



Pathlength Tolerance Analysis at Grazing Incidence



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

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

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

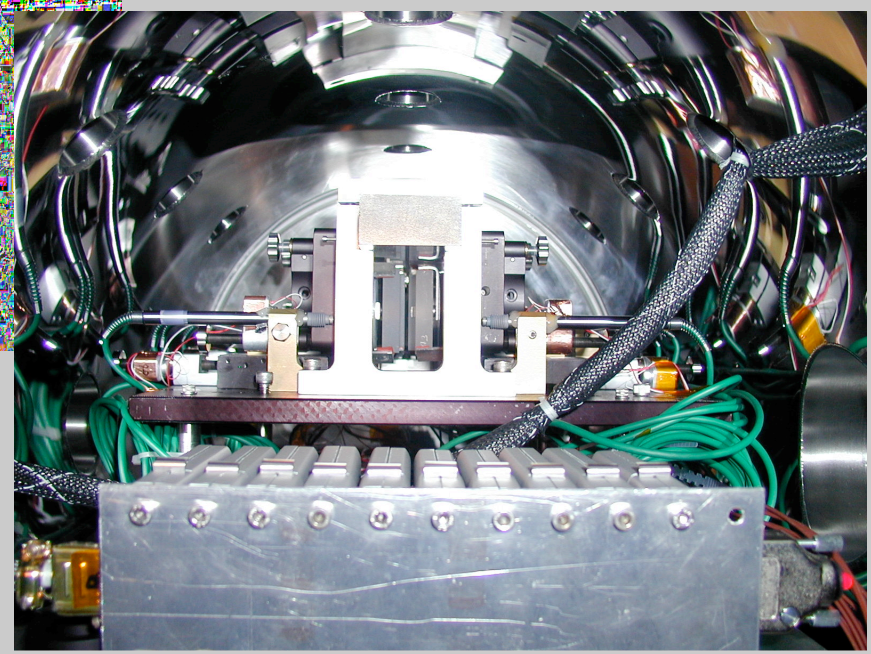
If OPD to be < λ/10 then $\delta < \dfrac{\lambda}{20\sin\theta}$

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

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

GSFC X-ray Interferometer

- 80 m long X-ray beam line
- 25 m source to optics
- 50 m focal length
- ~ 1mm baseline
  - (0.25 arcsec at 1 keV)



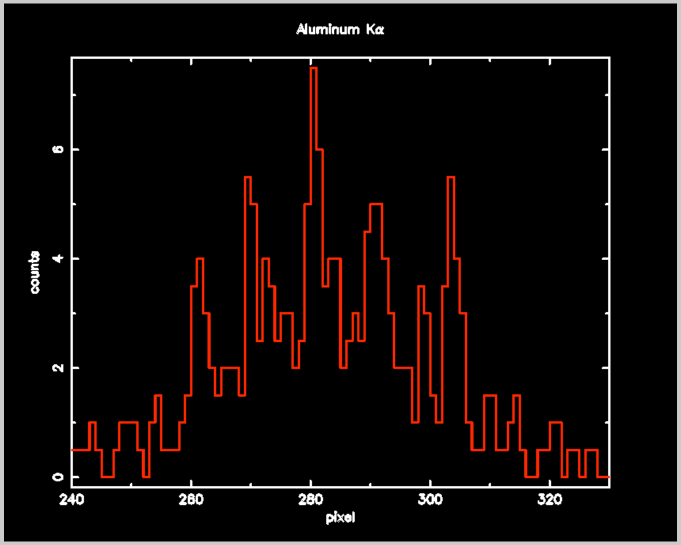
- Fringe Spacings of 75 to 250 microns-> simple vibration suppression at 3 stations

GSFC X-ray Interferometer Results

- Detected fringes @ 0.525 keV (23 Å) and 1.49 keV (8.35 Å) with a 650 micron baseline (~0.1” at 1.49 keV)
- There are several significant implications of this years work:
  - We have demonstrated interferometry over a factor of 3 of wavelength within the X-ray band.
  - Our measurement at 8.35 Å is the shortest wavelength light to have produced fringes in a broadbandpass interferometer.
  - We have successfully proven a core MAXIM concept

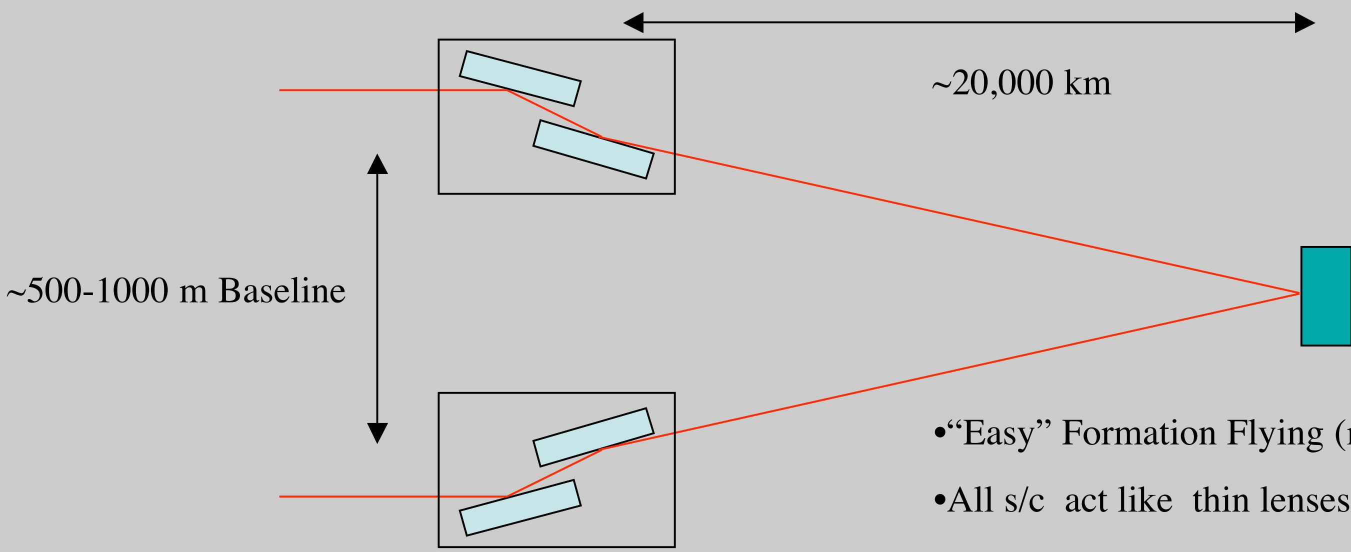
Fringes at 8.35 Å

25 November 2002



Improved MAXIM Implementation

Group and package Primary and Secondary
Mirrors as “Periscope” Pairs

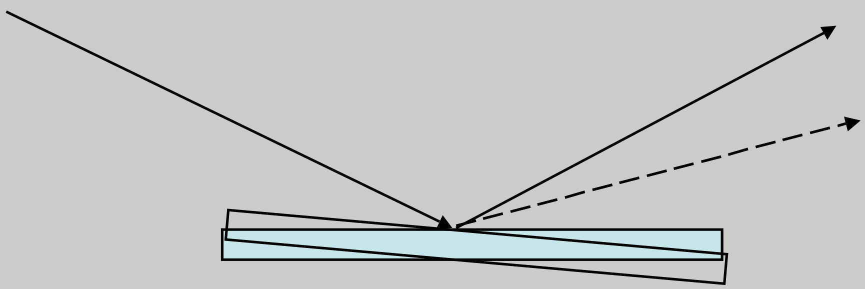


- “Easy” Formation Flying (microns)
- All s/c act like thin lenses- Higher Robustness
- Possibility to introduce phase control within one space craft- an x-ray delay line- More Flexibility
- Offers more optimal UV-Plane coverage- Less dependence on Detector Energy Resolution
- Each Module, self contained- Lower Risk.

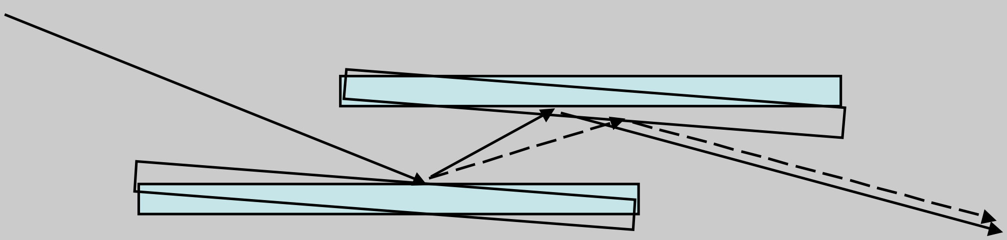
A scalable MAXIM concept.

Periscope Requirements

- Even Number of Reflections

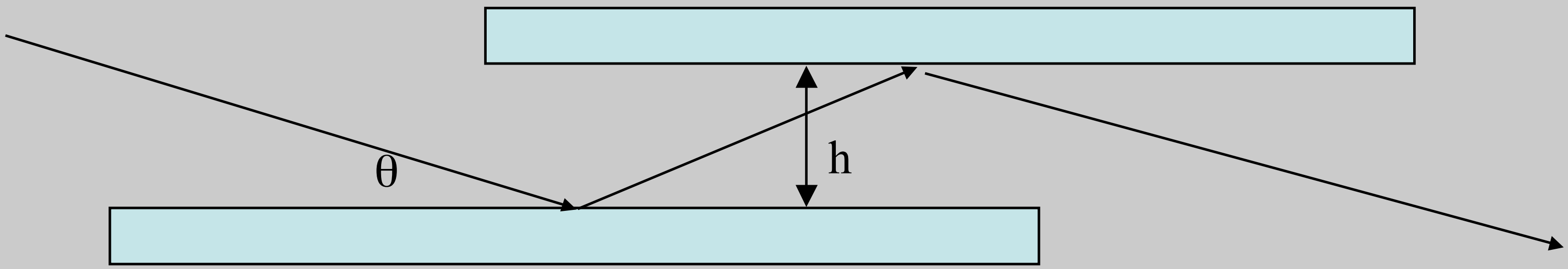


With odd number of reflections, beam direction shifts with mirror tilt



With even number, the mirrors compensate and beam travels in same direction.

Phase Shift



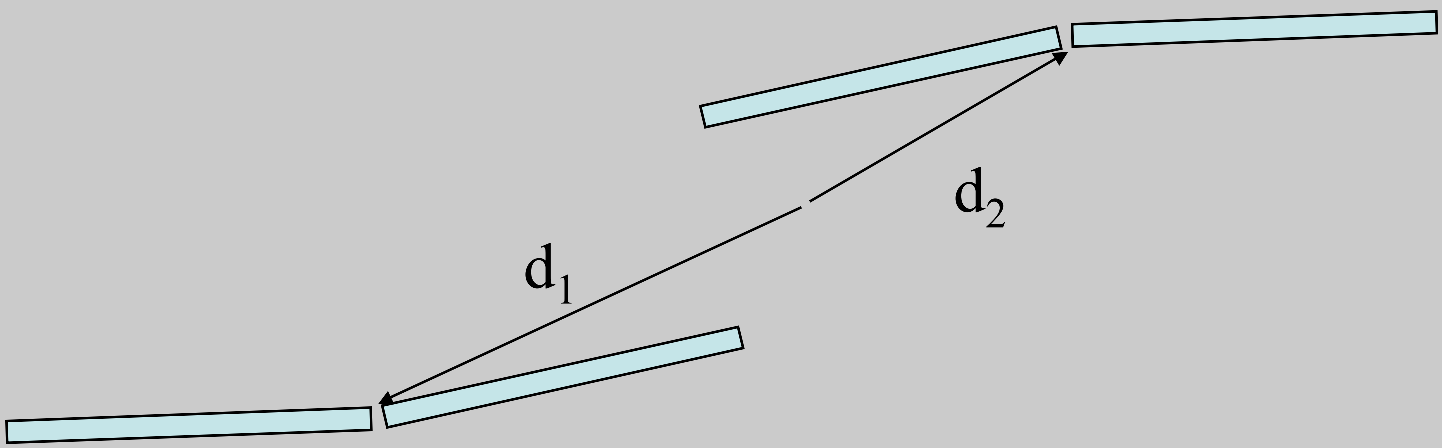
Path Delay = h sinθ

so h $\delta\theta < \lambda$ /10 for phase stability

if h~1cm then $\delta\theta < 10^{-8}$ (2 milli-arcsec)

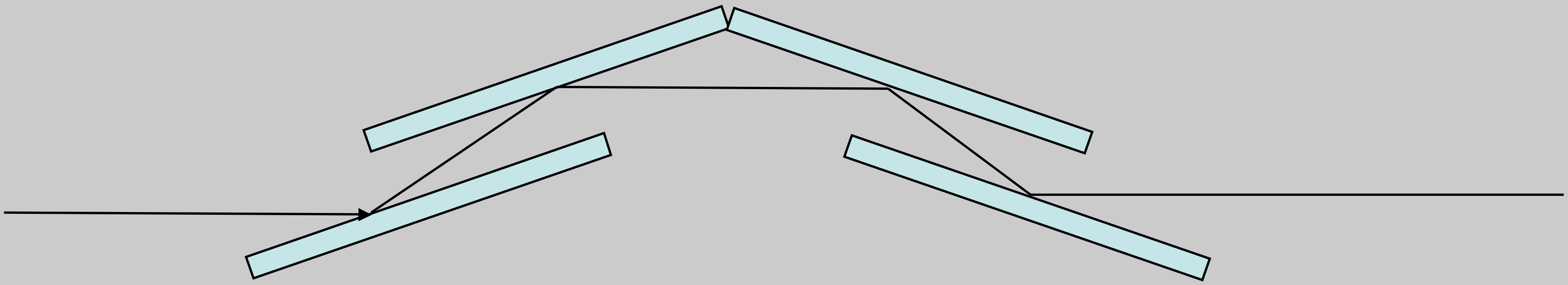
This can be done, but it's not easy.

Phase Delay



$$P = d_1(\cos\beta - \cos\beta\sec(2\theta_2 - 2\theta_1) - \sin\beta\cot\theta_2 + \sin\beta\sec(2\theta_2 - 2\theta_1)(\cot\theta_1 - \cos 2\theta_1(\cot\theta_1 - \cot\theta_2))$$
$$+ d_2(\cos\beta_2 - \cos\beta_2\sec(2\theta_4 - 2\theta_3) - \sin\beta_2\cot\theta_4 + \sin\beta_2\sec(2\theta_4 - 2\theta_3)(\cot\theta_3 - \cos 2\theta_3(\cot\theta_3 - \cot\theta_4))$$

There are Solutions



This solution can be direction and phase invariant

Dennis Gallagher has verified this by raytrace!

Pointing can wander arcseconds, even arcminutes, and beam holds fixed!

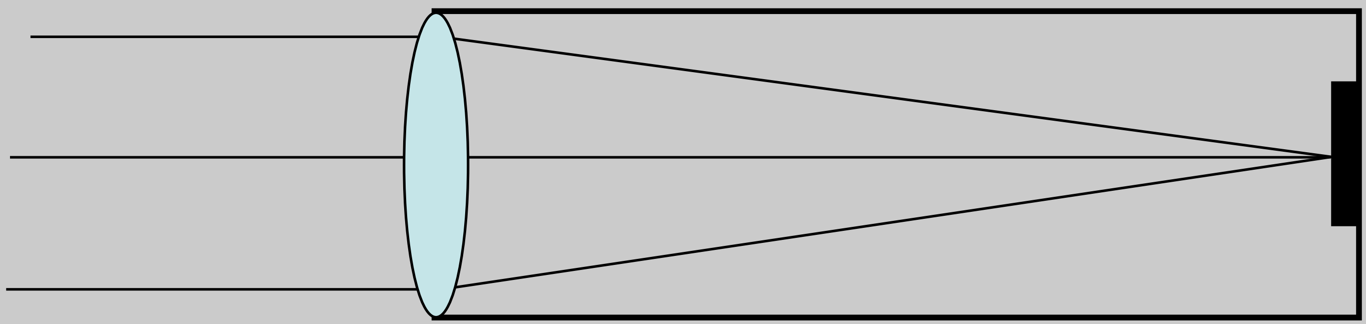
Array Pointing

- 4 mirror periscopes solve problem of mirror stability

- But what about array pointing?

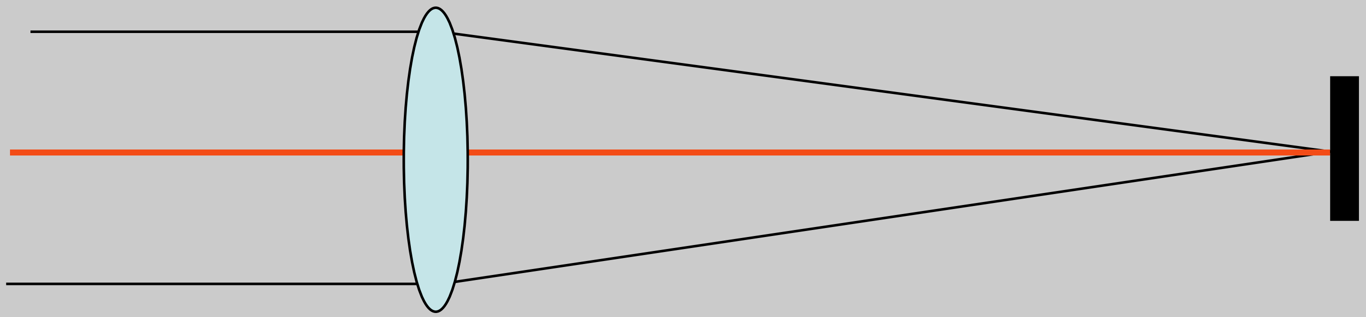
- Doesn't the array have to be stable to 1μas if we are to image to 1μas?

Thin Lens Behavior



As a thin lens wobbles, the image in space does not move
Position on the detector changes only because the detector moves

Formation Flying



If detector is on a separate craft, then a wobble in the lens has no effect on the image.

But motion of detector relative to Line of Sight (red) does!

Much easier than stabilizing array.
Still the toughest nut for full Maxim.
Variety of solutions under development.

Technical Components: Line-of-Sight

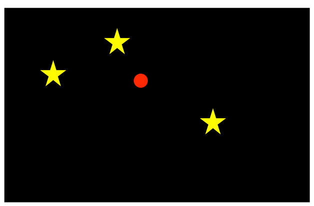
- The individual components need an ACS system good to only arcseconds (they are thin lenses)

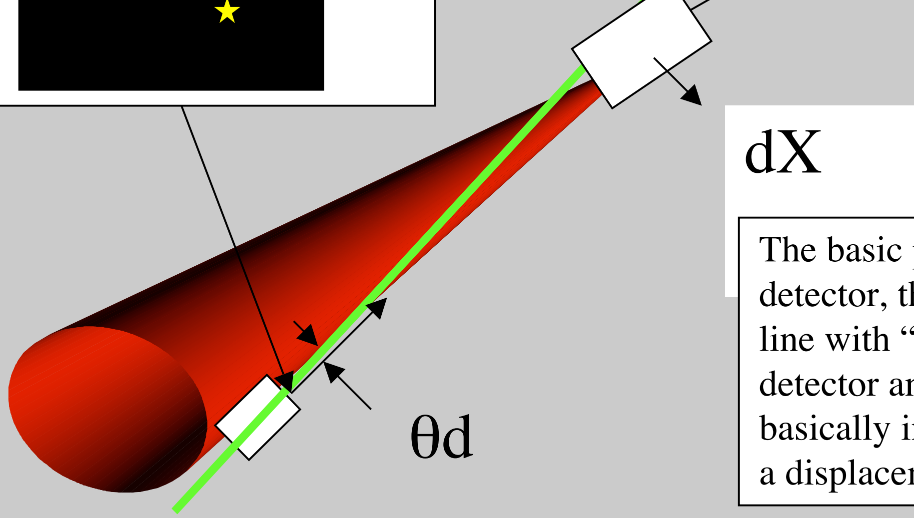
- We only ask for relative stability of the LOS- not absolute astrometry

- This is the largest technical hurdle for MAXIM- particularly as the formation flying tolerance has been increased to microns

Using a "Super Startracker" to align two spacecraft to a target.

In the simplest concept, a Super Star Tracker Sees both Reference stars and a beacon on the other space craft.
It should be able to track relative drift between the reference and the beacon to 30 microarcseconds- in the case of MAXIM Pathfinder.

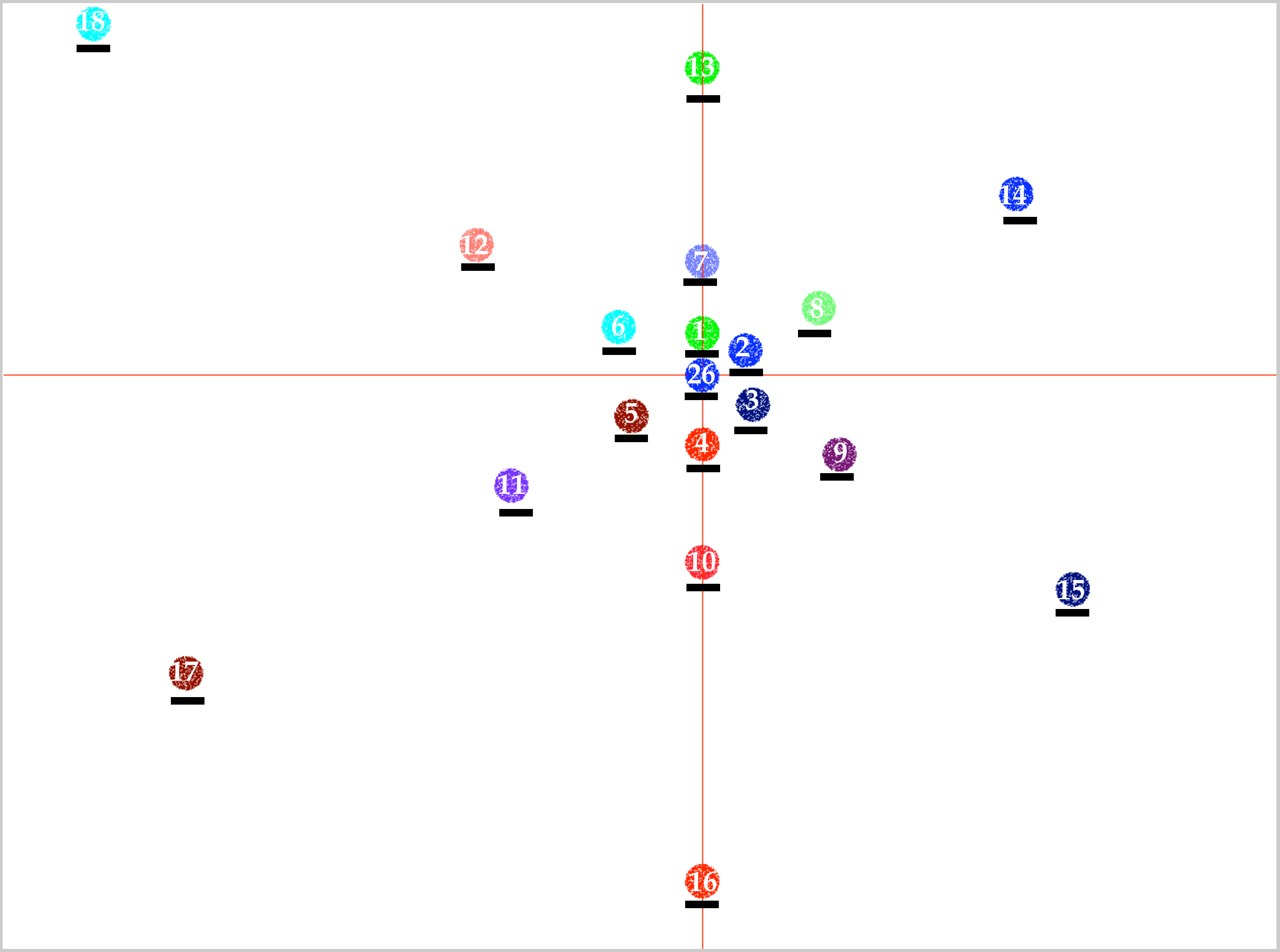




For a number of reasons (proper motion, aberration of light, faintness of stars,…) an inertial reference may be more appropriate than guiding on stars. The inertial reference has to be stable at a fraction of the angular resolution for hours to a day. This would require an extremely stable gyroscope (eg GP-B, superfluid gyroscopes, atomic interferometer gyroscopes).

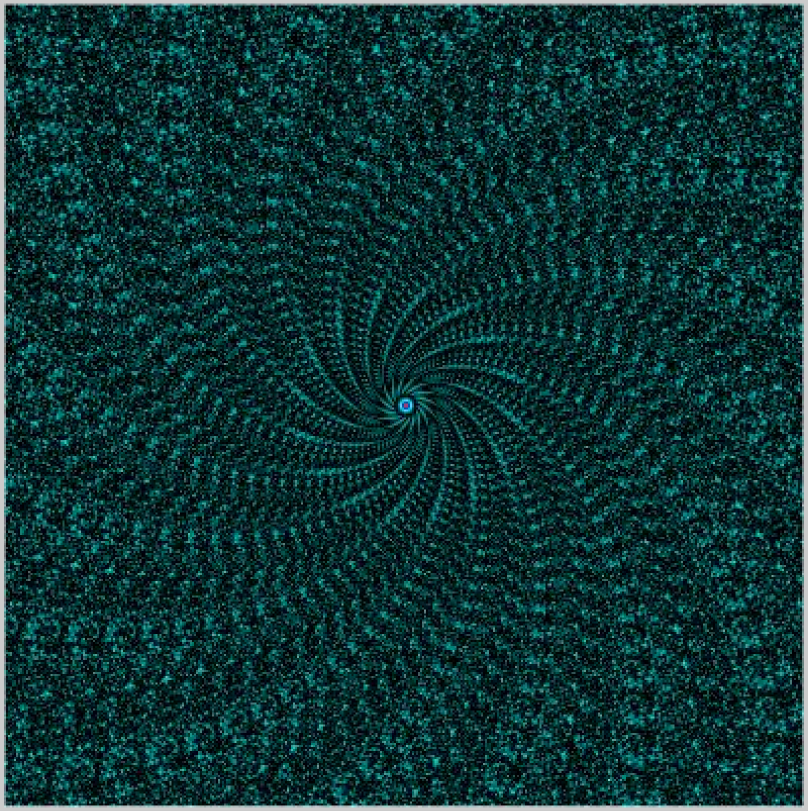
The basic procedure here, is to align three points (the detector, the optics, and the target) so they form a straight line with "kinks" less than the angular resolution. The detector and the optics behave as thin lenses- and we are basically insensitive to their rotations. We are sensitive to a displacement from the Line-of-Sight (eg dX).

Aperture Locations (central area)

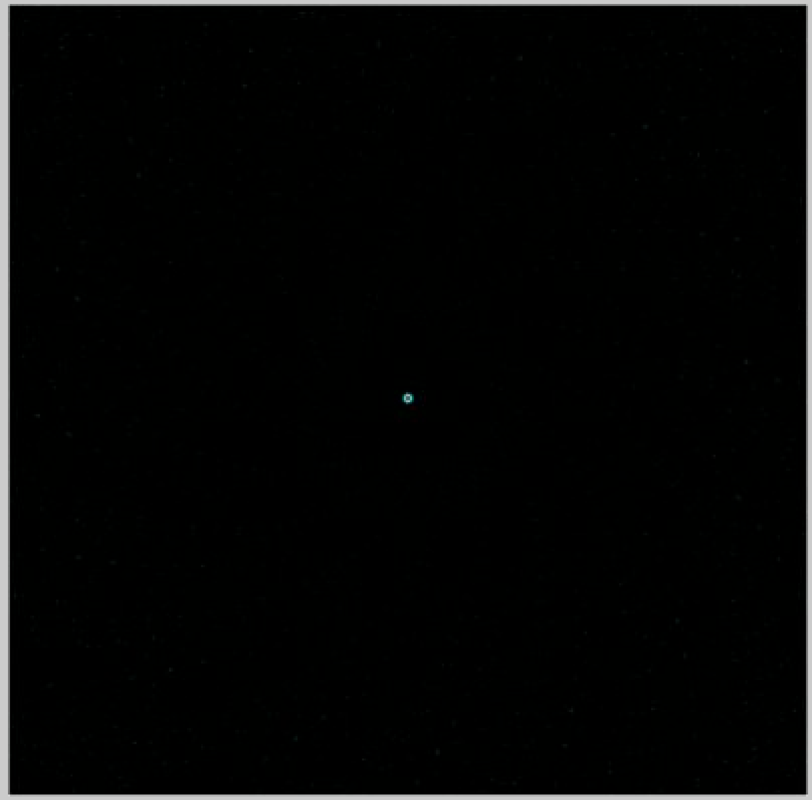


Beam from One Craft

(1000cm^2 effective, 60μas resolution)



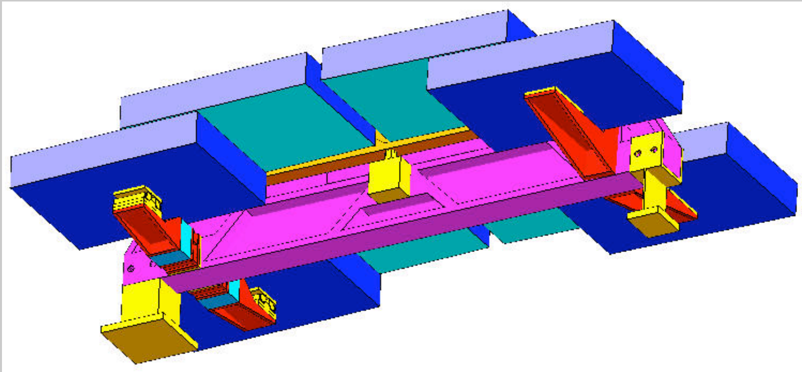
Amplitude

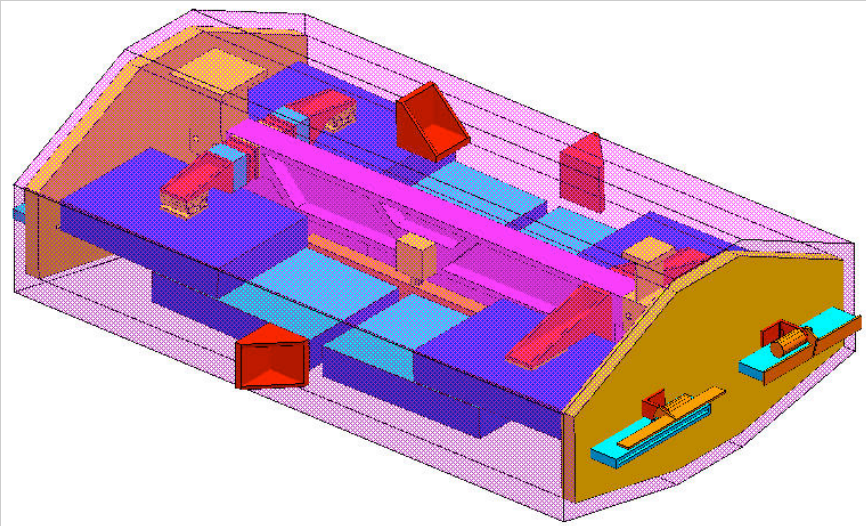


Intensity

Evolution of the Periscope Design

- A 2 mirror periscope has tight (mas) pointing requirements
- We get around this by adding 2 more mirrors- now the pointing requirement is 10 arcseconds
- Reduced effective area, but we still enjoy advantages
  - ~10 micron formation flying
  - Phasing to allow better UV plane coverage
  - Lower risk
  - Lower Cost (~<$60M to make 1000 cm^2 of area)

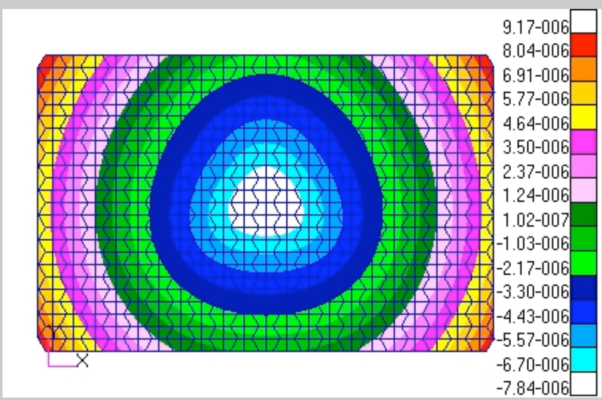




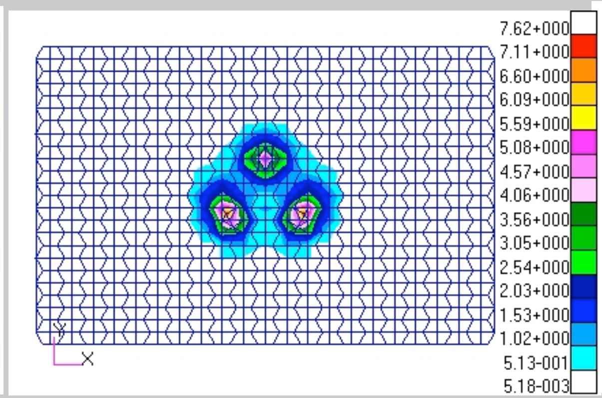
Mirror Analysis Summary

Analysis	Goal/Req.	Result	Comments
1^{o}c Bulk Temp Load	min surface deformation	PtoV=6.2nm, RMS=1.2nm	
1^{o}c X Gradient	min surface deformation	PtoV=3.2nm, RMS=0.6nm	Gradient across mirror surface
1^{o}c Y Gradient	min surface deformation	PtoV=3.1nm, RMS=0.6nm	Gradient across mirror surface
1^{o}c Z Gradient	min surface deformation	PtoV=17.0nm, RMS=3.8nm	Gradient through mirror thickness
Fixed Base Dynamics	FF > 100 Hz	FF=278 Hz	Mirror on flexures, but not entire mount
20g Quasi Static Load	Mount Stress < Yield	35 MPa maximum	20g Y Loading
20g Quasi Static Load	Low Mirror Stress	7.6MPa maximum	20g Y Loading

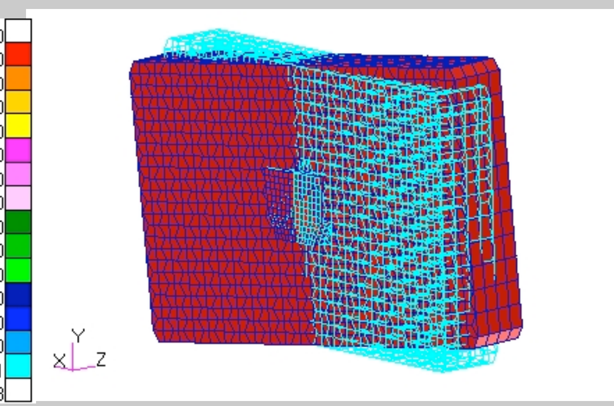
1cZ Mirror Deformations (mm)



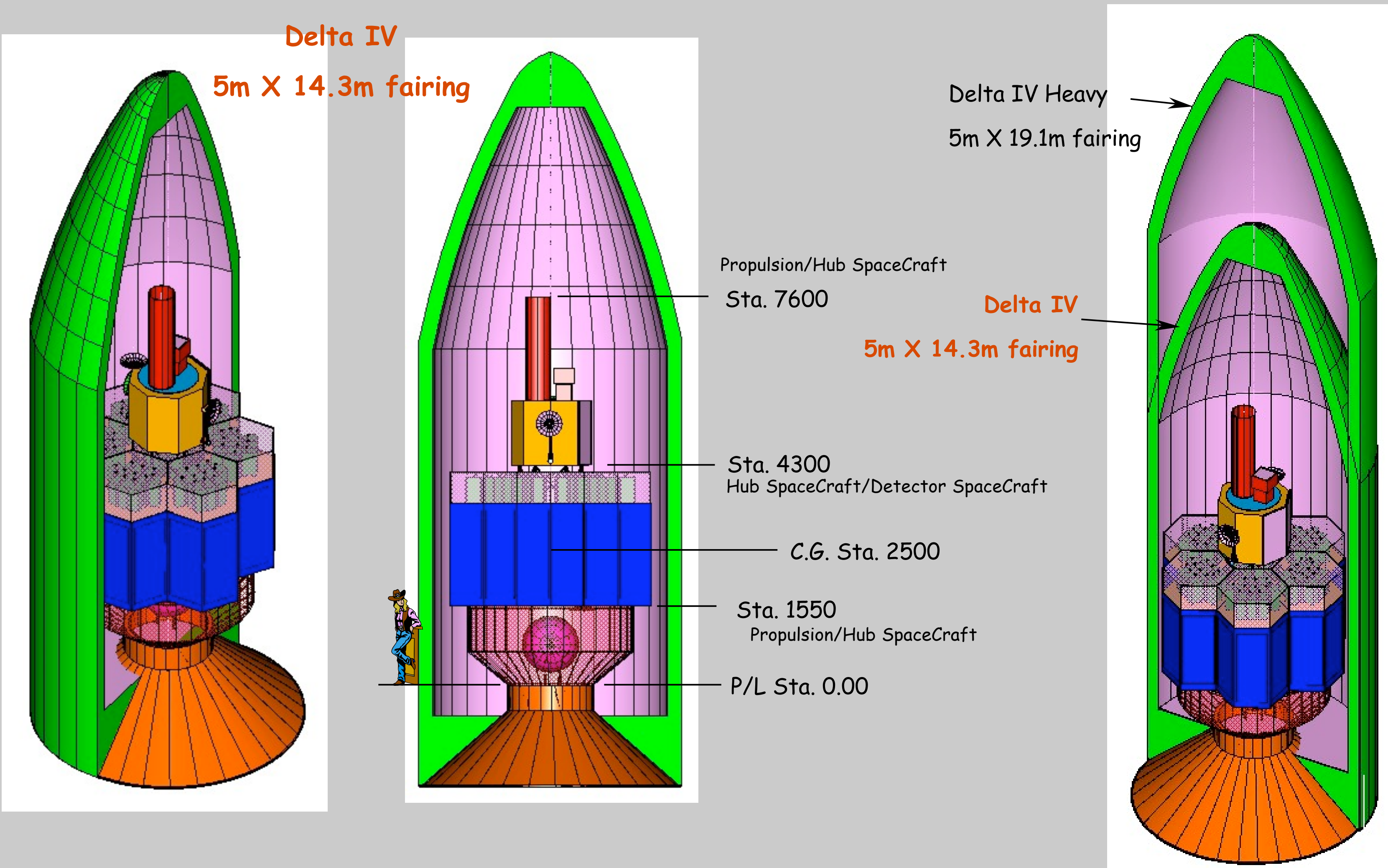
20gY Mirror Back Stresses (MPa)



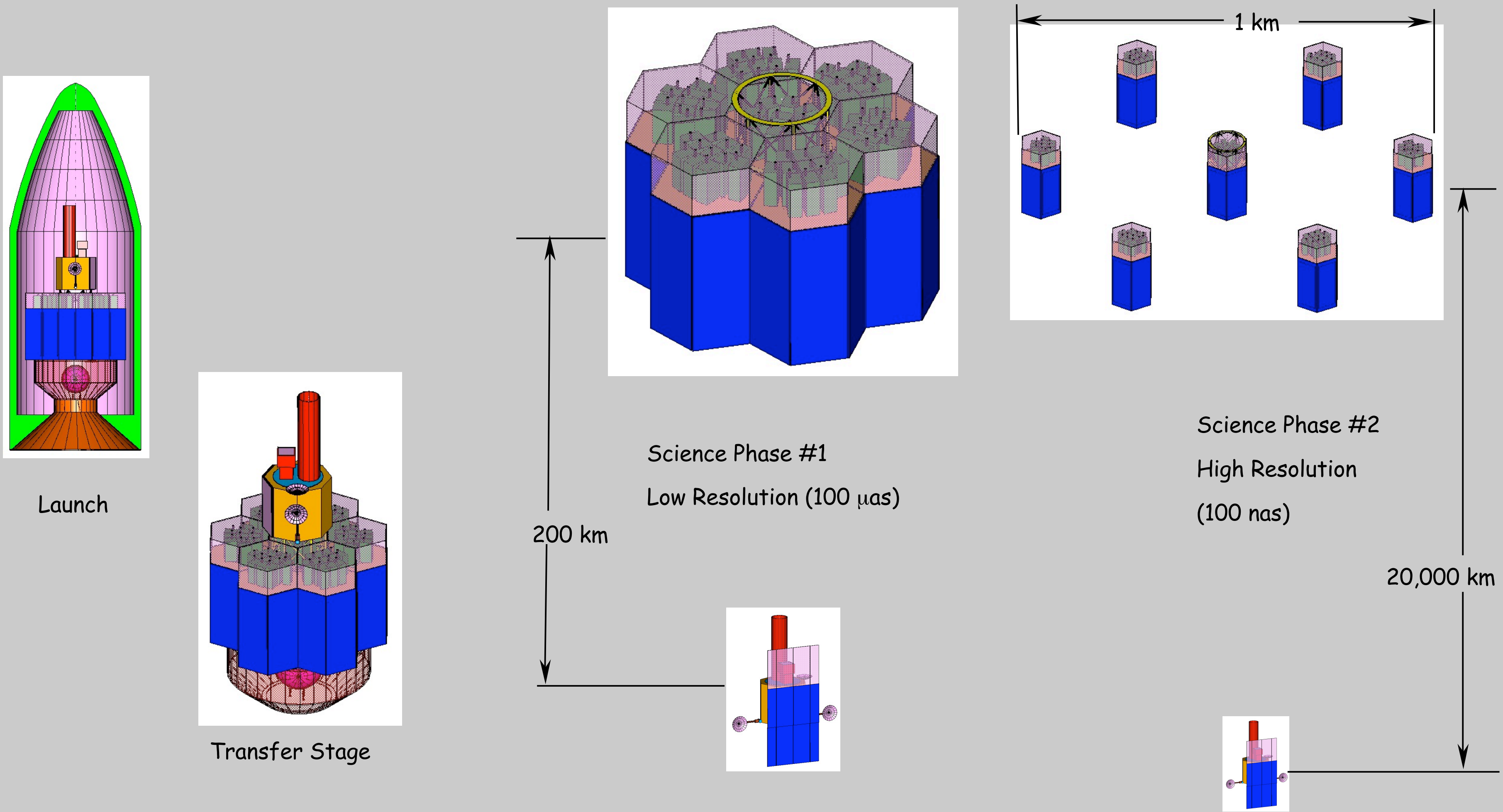
Mirror First Mode = 278 Hz



Pathfinder Configuration



Mission Sequence



Key Technical Challenges

- Optics State of the Art (but not beyond)
- “Periscope” implementation loosens formation flying tolerance from nm to μm.
- Line-of-sight alignment of multiple spacecraft with our target is the most serious challenge- and MAXIM is not alone with this.
- Optimal image formation through pupil densification is being studied

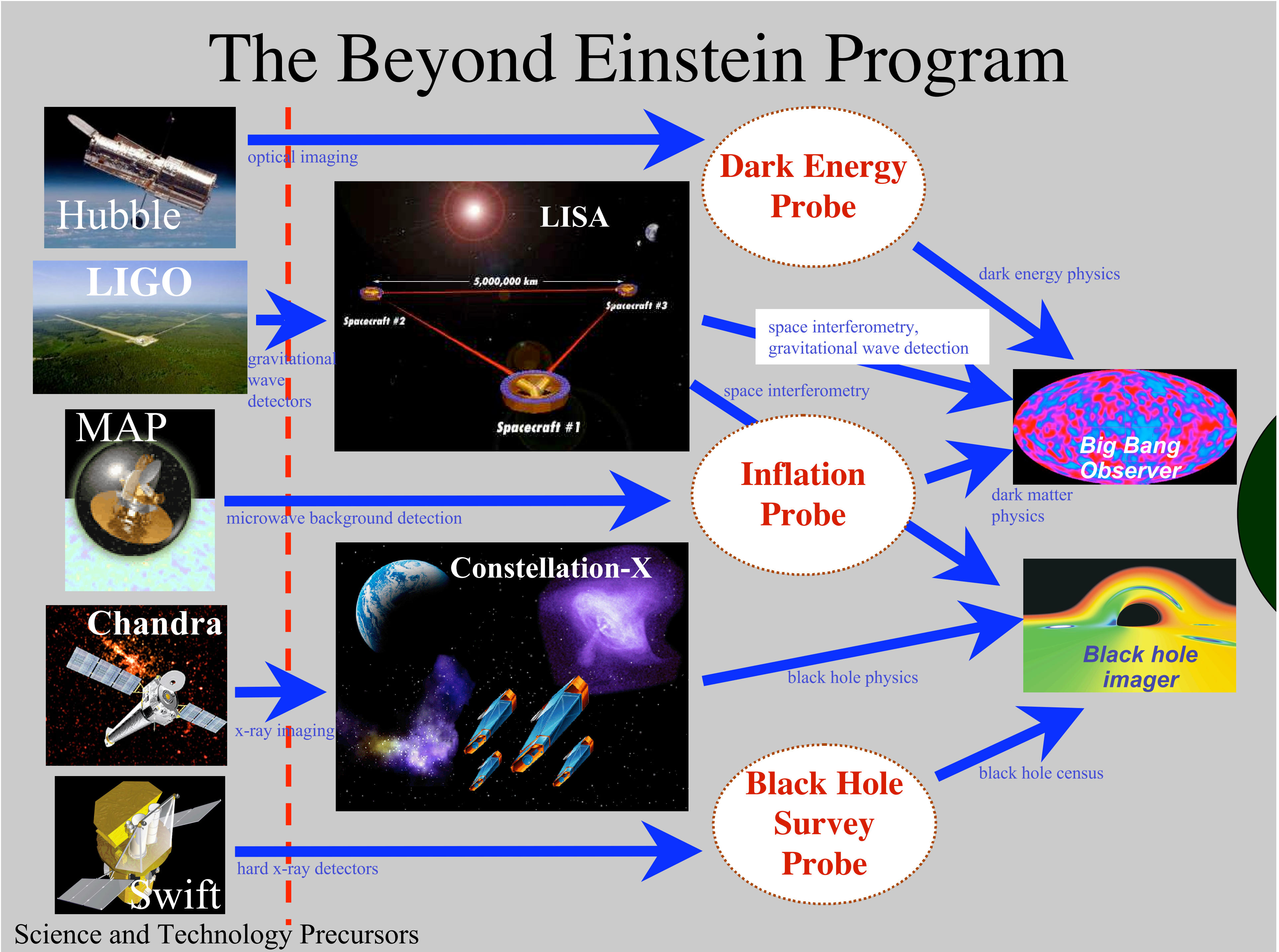
IMDC has verified that this mission is achievable with today's technology.

Decadal review recommended technology development money that so far has not been forthcoming

Launch is in the indefinite future

But

once we know its possible then we are going to have to do it


The Beyond Einstein Program
Hubble
optical imaging
Dark Energy Probe
LISA
5,000,000 km
Spacecraft #2
Spacecraft #3
Spacecraft #1
LIGO
gravitational wave detectors
dark energy physics
space interferometry, gravitational wave detection
space interferometry
MAP
Big Bang Observer
Inflation Probe
dark matter physics
microwave background detection
Constellation-X
Chandra
Black hole imager
black hole physics
x-ray imaging
black hole census
Black Hole Survey Probe
Swift
hard x-ray detectors
Science and Technology Precursors