Future Capabilities for Space-Based Stellar Observations

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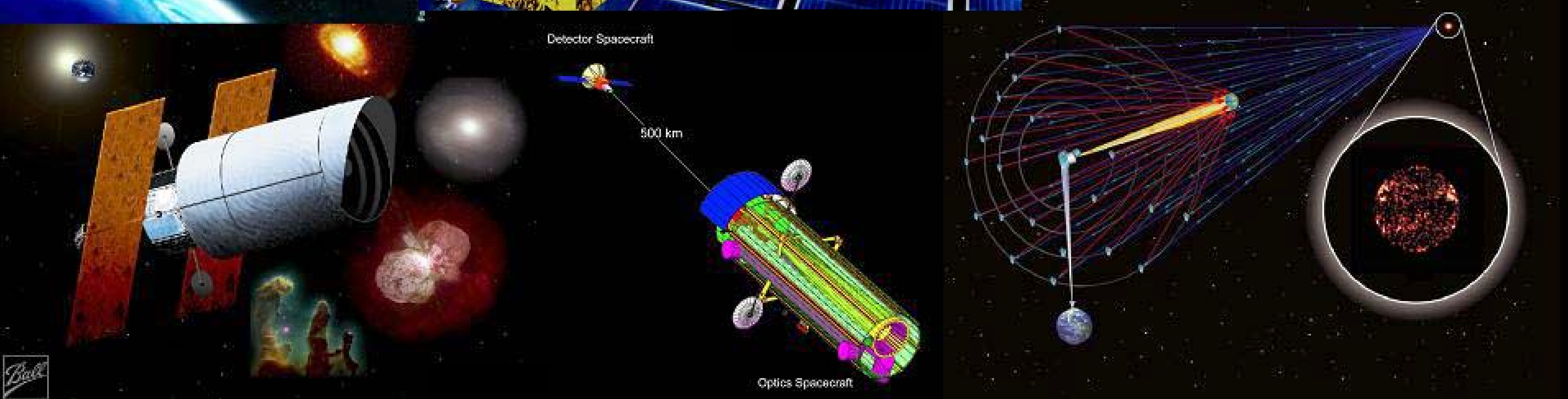
Outline of Talk

Facilities Planned for the Near-Future
Planned Intermediate-Horizon Missions
Far-Horizon Missions



Facilities Planned for the Near-Future

HST: ACS, COS and WFC3
SIRTF
ISAS: ASTRO-F

Note: Although they are not discussed in the following slides, it should be noted that ASTRO-E & NICMOS are scheduled for 'second chances', with a new launch attempt for an ASTRO-E clone now approved and the installation of a new cooling system for NICMOS expected to bring it back to life during HST Servicing Mission 3b.

Advanced Camera for Surveys (ACS) will bring large gains to HST imaging capability after SM3b (Jan. 2002)

Wide-Field Channel (WFC)

- ACS/WFC: 10x increase in “discovery potential” vs. WFPC2
- high throughput, wide field, optical & NIR (I band), spectral response = **350 - 1050 nanometers**
- optimized for surveys in the near-infrared to search for galaxies and clusters of galaxies in the early universe.
- **202" × 202" field of view with 0.049" pixel size**
- 2 butted 2048 × 4096, 15 µm/pixel CCD detectors
- **45% throughput at 700 nanometers (incl. HST OTA)**
- half critically sampled at 500 nanometers

High Resolution Channel (HRC)

- field of view comparable to WFPC2 Planetary Camera (PC), but with 2x resolution & far better UV/blue sensitivity, **200-1050 nm spectral response, 25% throughput at 600nm**
- has High Contrast Coronagraph (HCC) subchannel for imaging of faint targets near bright objects--subdwarfs, large planets, galaxy cores, QSO host galaxies
- **29.1" × 26.1" field of view with 0.028" × 0.025" pixel size**
- 1024 × 1024, 21 µm/pixel, near UV-enhanced CCD detector
- critically sampled at 500 nanometers

Solar Blind Channel (SBC)

- nearly identical device to STIS FUV, many more filters
- study hot stars, quasars,aurora
- **115-180 nm spectral response**
- **34.59" × 30.8" field of view**
- **0.033" × 0.030" pixel size**
- 1024 × 1024, Csl 25 µm/pixel MAMA detector (STIS spare)
- 6% throughput at 121.6 nm

HST: Cosmic Origins Spectrograph (COS)

"Spectroscopy lies at the heart of astrophysical inference."

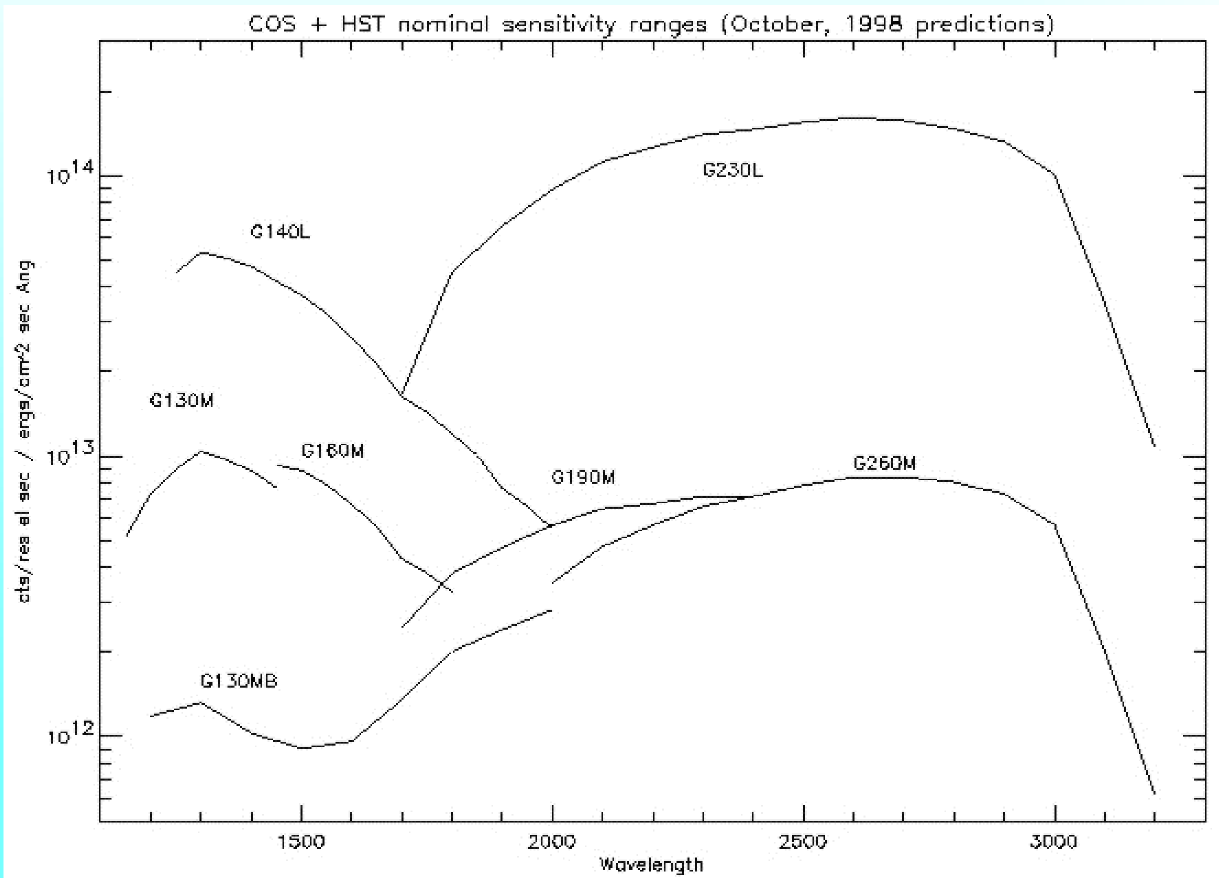
to be launched on HST Servicing Mission 4 ~ Jan. 2004

Science Goals

- Large-scale structure, the IGM, and origin of the elements.
- Formation, evolution, and ages of galaxies.
- Stellar and planetary origins and the cold interstellar medium.
- Other
  - AGN monitoring campaigns
  - UV upturn in elliptical galaxies
  - **UV monitoring of distant supernovae**
  - **observations of SN1987A as it impacts circumstellar rings**
  - **stellar winds and UV properties of LMC/SMC massive stars**
  - **monitoring of CVs and other high-energy accretion systems**
  - **SEDs of YSOs; diagnostics of heated accretion columns**
  - **chromospheres of cool stars**
  - planetary aurorae and cometary comae
  - detection of faint UV emission in ISM shocks

COS Sensitivity

COS is designed to break the "1 x 10^{-14} flux barrier" for moderate resolution UV spectroscopy, enabling order of magnitude increases in accessible UV targets for a broad range of science programs



COS Spectroscopic Modes

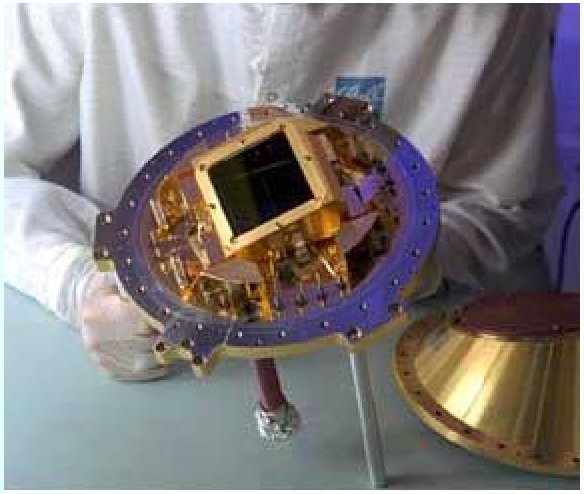
Grating	Nominal Wavelength Coverage [a]	Wavelength Range per Exposure	Resolving Power (R = l/Dl) [b]	
G130M	1150 - 1450 Å	300 Å	20,000 - 24,000	
G160M	1405 - 1775 Å	375 Å	20,000 - 24,000	
G140L	1230 - 2050 Å	> 820 Å	2500 - 3500	← "survey" mode
G190M	1700 - 2400 Å	3 x 45 Å	20,000 - 27,000	
G260M	2400 - 3200 Å	3 x 55 Å	20,000 - 27,000	
G230L	1700 - 3200 Å	1000 Å	850 - 1600	← "survey" mode
G130MB	1150 - 1800 Å	3 x 30 Å	20,000 - 30,000	

Highest Sensitivity Medium Resolution Spectrograph on HST

Signal/noise capabilities to > 100

Wavelength accuracy: 15 km/s requirement, 10 km/s goal

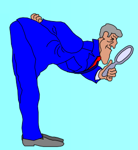
HST: Wide Field Camera 3 (WFC3)



- Instrument is a 2-channel camera with panchromatic coverage from UV to near IR
- blue optimized 4k x 4k CCD is the visible channel detector (similar to ACS/WFC, but with different wavelength optimization)
- 1kx1k IR detector channel offers very substantial gains in capabilities vs. NICMOS
  - up to 10x gain in field of view
  - potential gains of 2-3x in sensitivity due to superior detector performance
- IR channel enables high angular resolution, wide areal coverage, low-background imaging from 1.0-1.9 microns

WFC3 Specifications

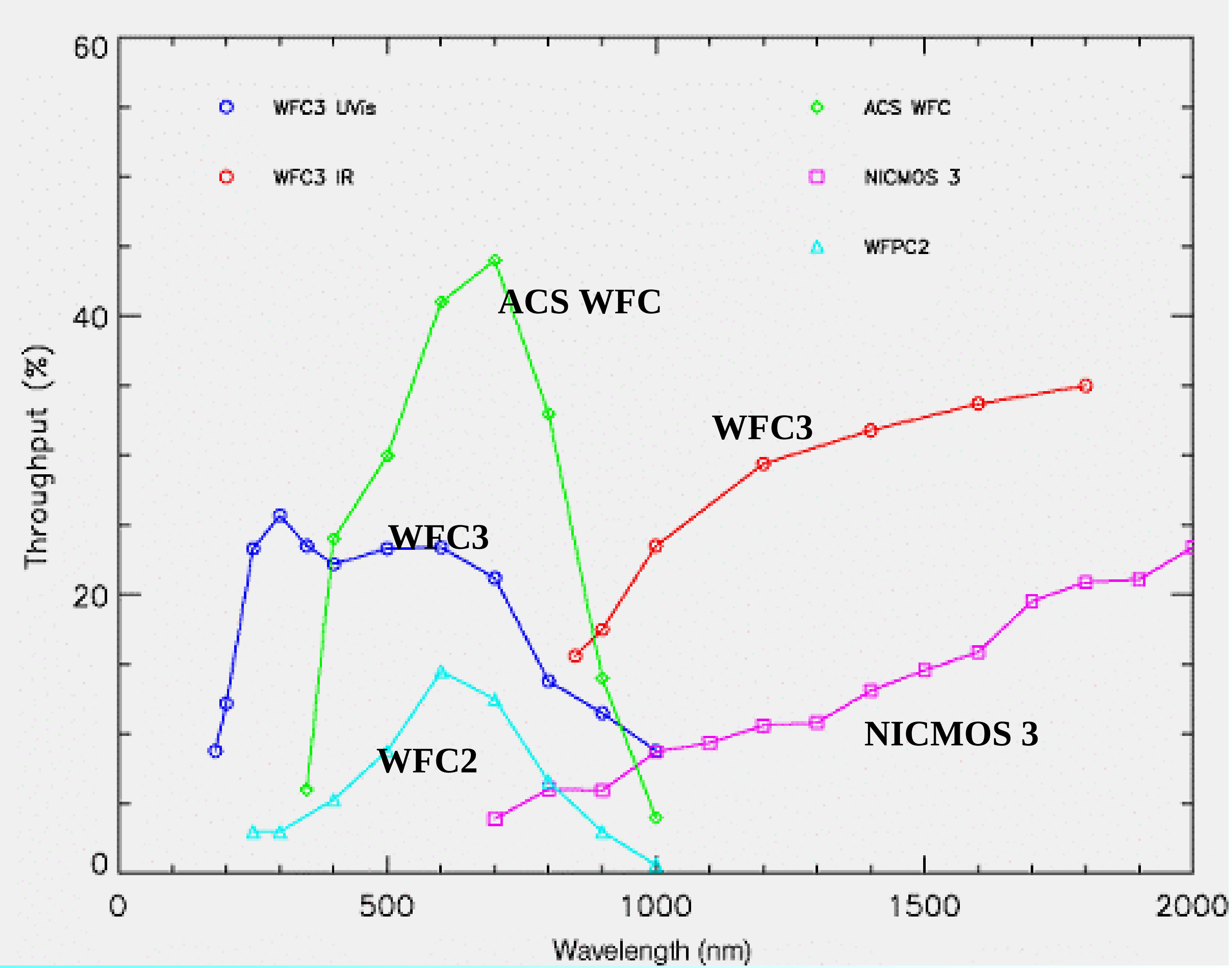
“Imaging lies at the heart of astrophysical inference.”



to be launched on HST Servicing Mission 4 ~ Jan. 2004

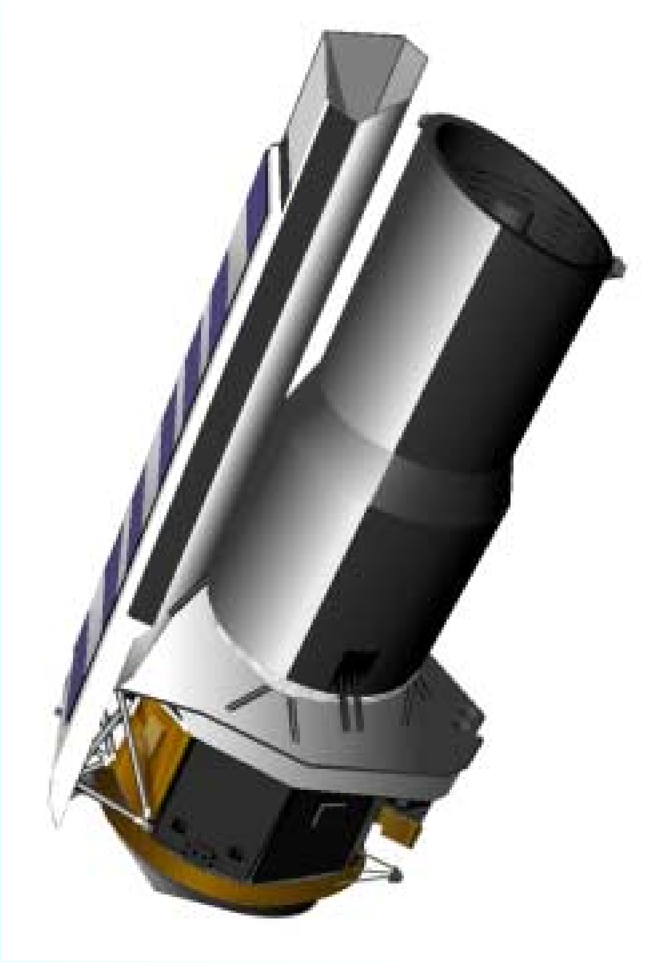
	UVIS	IR	
Format	4Kx 4K U. of A. UV or SITe Coating	1K x1K	pixels
Field Size	160 x 160	120 x 120	arcsec
Pixel Size	39	80	mas
Spectral Range	200 to 1000	600 to 1800	nm
Throughput	See Chart	See Chart	
Dark Current	< 0.003	< 0.4	e-/pix/sec
Readout Noise	< 4	< 15	e-/pix/ readout
Operating Temp	-100	-120	C
Filters	48	10	

WFC3: Throughput



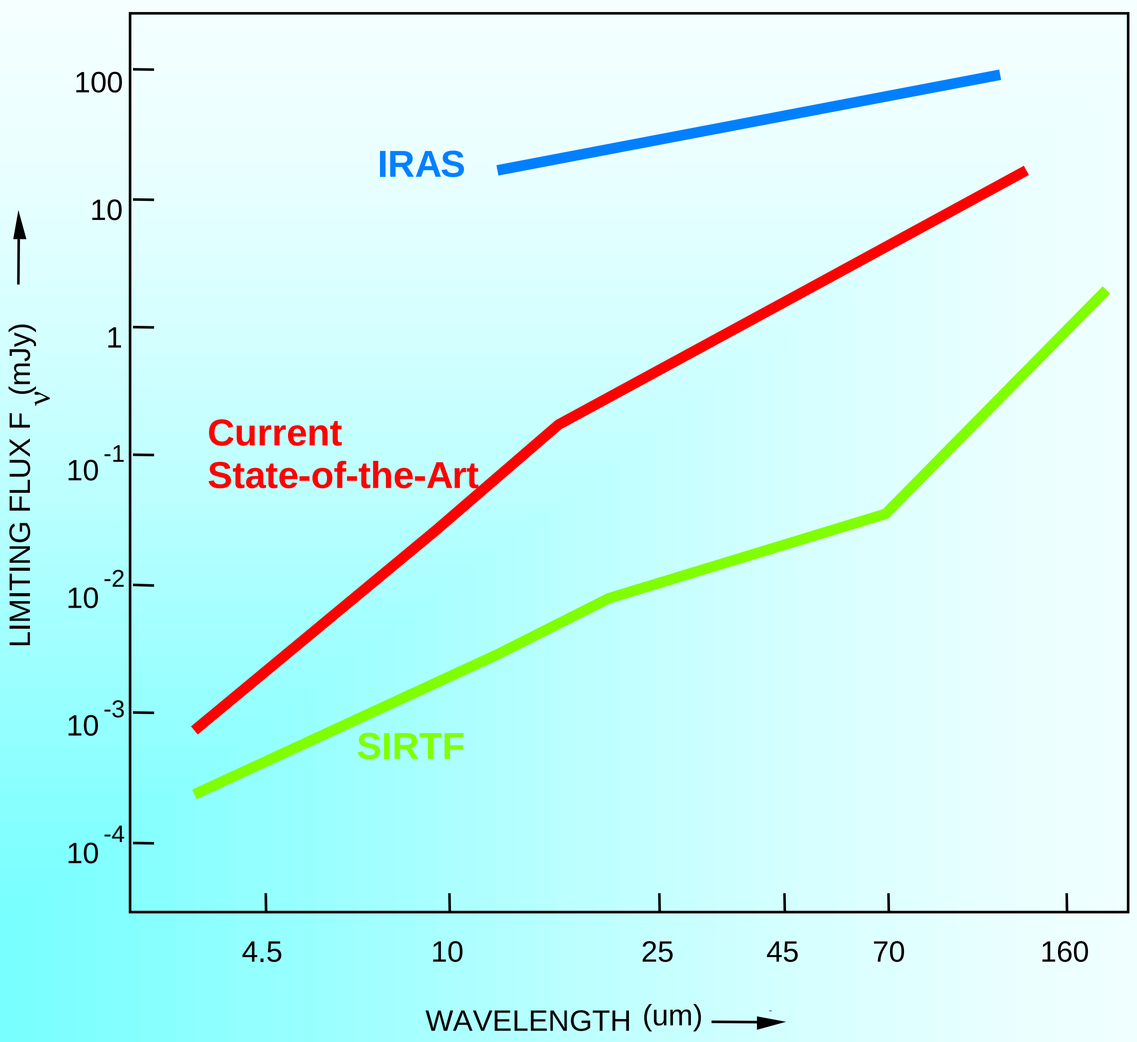
Space Infrared Telescope Facility

- **Infrared Great Observatory**
  - Background Limited Performance 3 -- 180um
  - 85 cm f/12 Beryllium Telescope, T < 5.5K
  - 6.5um Diffraction Limit
  - New Generation Detector Arrays
  - Instrumental Capabilities
    - Imaging/Photometry, 3-180um
    - Spectroscopy, 5-40um
    - Spectrophotometry, 50-100um
  - Planetary Tracking, 1 arcsec/sec
  - >75% of observing time for the General Scientific Community
  - 2.5 yr Lifetime/5 yr Goal
  - Launch in July 2002 (Delta 7920H)
  - Earth-Trailing Solar Orbit
- **Builds upon heritage of IRAS, COBE, ISO**
- **Cornerstone of NASA's Origins Program**



SIRTF

SIRTF Sensitivity Comparisons



SIRTF Primary Scientific Programs

- Protoplanetary Disks and Planetary Debris Disks
- Brown Dwarfs and Super Planets
- Ultraluminous Galaxies and Active Galactic Nuclei
- The Early Universe

The SIRTF mission is driven only by the requirements of these programs, which are called out for SIRTF in the Bahcall (Decade) Report.

The resulting system will have very powerful capabilities in many other scientific areas, allowing SIRTF to be an ***observatory for the entire scientific community.***

In addition, SIRTF will have great potential for the ***discovery*** *of new phenomena in the Universe, and the mission must exploit this potential.*

Astro-F

- planned by ISAS
  (Japan's Institute for Space and Astronautical Science)
- originally named IRIS (Infrared Imaging Surveyor)
- is a 70 cm cooled telescope
- observes from K-band to 200 µm.
- will perform an all-sky survey at wavelengths > 50 µm
- In the near- and mid-infrared ranges, large-format arrays are employed for a deep sky survey in selected sky regions
- sensitivity is much higher than that of the IRAS
  - 50-100x higher sensitivity at 100 µm, > 1000x at mid-IR wavelengths
  - The detection limits are 1 - 100 µJy in the near-mid IR and 10-100 mJy in the far-IR
- diffraction-limited angular resolution at wavelengths longer than 10 µm with pixel sizes less than 1 arcmin
- capable of low-resolution spectroscopy
  - prism spectroscopy in the near- and mid-IR
  - FTS for the wavelength range from 50 to 200 µm
- The launch now scheduled for 2003

Astro-F Science Instruments

- Two Focal-Plane Instruments
  - Far-Infrared Surveyor (FIS)
    - photometer optimized for all-sky survey with far-infrared arrays
    - will produce catalogs of infrared sources
    - can be operated as an imager or a Fourier-transform spectrometer in the pointing mode. The resolution of the spectrometer is about $0.2 cm^{-1}$
  - Infrared Camera (IRC)
    - three-channel camera that covers the wavelength bands from 2-25 μm
    - has the capability to perform low-resolution spectroscopy with prisms/grisms on filter wheels
    - The field of view of the IRC is 10 arcmin and the spatial resolution is approximately 2 arcsec.
    - Large format arrays are used to attain the deep survey with wide field and high angular resolution.
    - IRC observations are carried out only in pointing mode.

Astro-F: Key Science

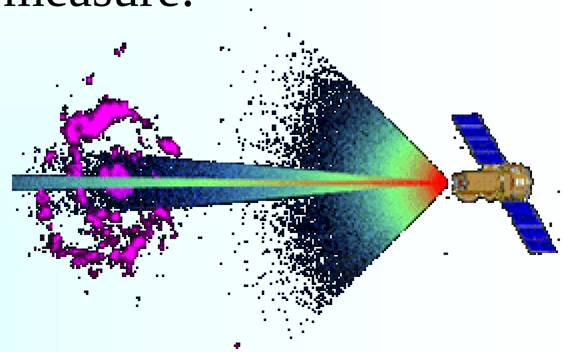
- Search for primeval galaxies, tracing the evolution of the luminous infrared galaxies and normal galaxies to high redshifts ($z>3$)
- Systematic investigation of the star formation process
  - **ASTRO-F will detect, at 100 - 200 μm, protostars in the very early stages when gas is still accreting onto newly born stars**
  - **ASTRO-F will be able to detect brown dwarfs and super planets in nearby star-formation regions and also field brown dwarfs**.
- Evolution of planetary systems
  - **ASTRO-F can trace the evolution of the protoplanetary disks beyond the weak-line T Tau stage**, which the previous surveys missed. The debris of the planetary formation around normal stars will also be extensively surveyed.

Planned
Intermediate Horizon Missions

GALEX, (KEPLER),
FAME, SIM, GAIA,
CON-X,NGST, TPF

The Galaxy Evolution Explorer (GALEX)

- GALEX uses the space ultraviolet to simultaneously measure:
  - redshift (using metal lines and the Lyman break)
  - extinction (using the UV spectral slope)
  - star formation rate (using theUV luminosity which is proportional to the instantaneous star formation rate).



- Slitless grism spectroscopy is highly efficient, providing 100,000 galaxy spectra in one year.
- The 50 cm telescope, operating from 1300-3000 Å, is
  - simple, cost-effective, efficient
  - exploits MCP detectors and optical coatings which are flight-proven and cutting-edge to attain deep, broad-band imaging and spectroscopy
- A rich survey catalog will be produced and distributed to the community with the assistance of an Associate Investigator Program
- launch planned for April, 2002

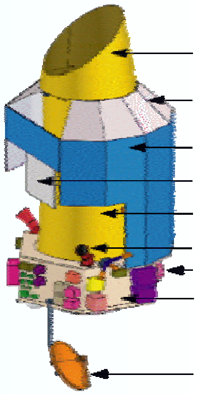
GALEX Science Highlights

- Galaxies:
  - 100,000 spectra; 10,000 resolved images inside 100 Mpc; 10,000,000 unresolved
  - History/distribution of star formation, Microhistory of star formation (bursts)
  - role of companions in driving star formation
  - Evolution in IMF; Volume limited census of local UV galaxy properties
  - Low surface brightness galaxies; Elliptical galaxies: UV rising flux turn-on
  - The extragalactic FUV & MUV background: census of total star formation to z~2
- QSOs:
  - 10,000 spectra; 1,000,000 in All-Sky Imaging Survey
  - 1000 QSOs visible in the rest EUV for the HeII Gunn-Peterson test; QSO death and galaxy evolution
  - Evolution & physics of black hole accretion disks; Large-scale structure evolution
  - QSO time variability survey
- Stellar Evolution:
  - 1000 accreting white dwarf spectra; 100,000 post main-sequence stars
  - White dwarf cooling physics ; The nature of ultra-soft X-ray sources
  - Paths to accretion-induced collapse; The evolution of disks around white dwarfs

Kepler

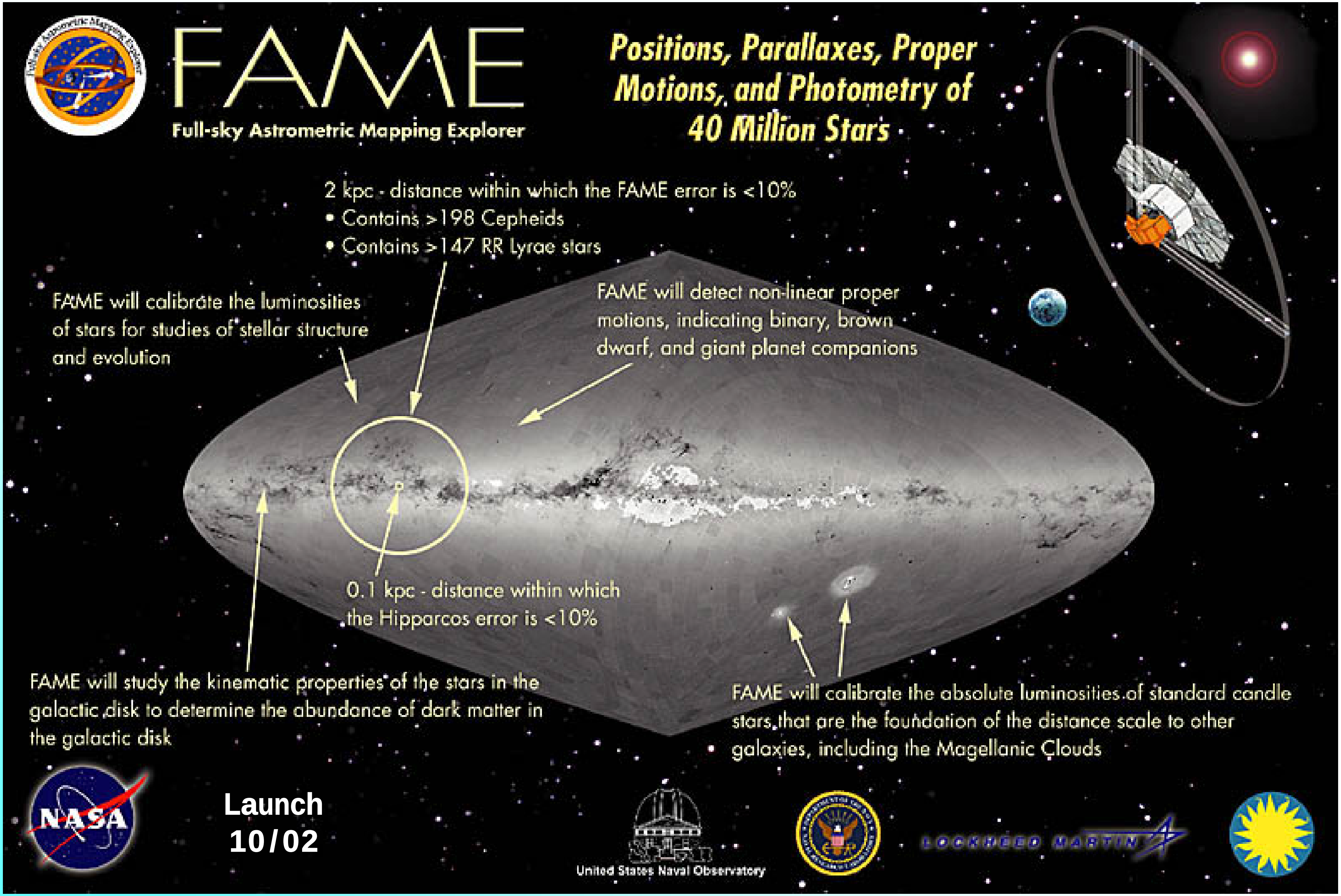
- Candidate Discovery Mission (see Basri poster)
  - Currently in Phase A Study (down-selection in 9/01, launch 8/05)
- Purpose: explore the structure and diversity of planetary systems by observing a large sample of stars to
  - Determine the frequency of terrestrial and larger planets in or near the habitable zone of a wide variety of spectral types of stars.
  - Determine the distributions of their sizes and orbital semi-major axes
  - Estimate the frequency of planets and orbital distribution of planets in multiple-stellar systems.
  - Determine the distributions of semi-major axis, albedo, size, mass and density of short-period giant planets
  - **Determine the properties of those stars that harbor planetary systems**
    - **The spectral type, luminosity class, and metallicity for each star showing transits are obtained from ground-based observations**
    - **Rotation rates, surface brightness, inhomogeneities and stellar activity are obtained directly from the Kepler photometric data**
    - **Stellar age and mass is determined from Kepler p-mode measurements.**

Kepler Design

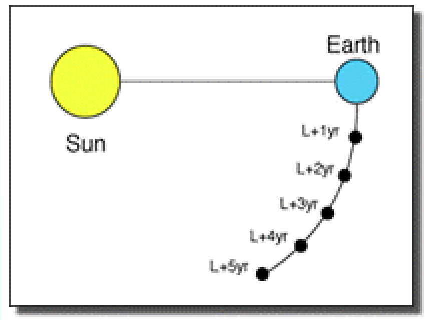


- Schmidt telescope with 0.95-meter aperture and 105 deg^2 FOV
- It is pointed at and records data from just a single group of stars for the four year duration of the mission.
- The single photometer is composed of an array of 42 CCDs
  - Each 50x25 mm CCD has 2048x1024 pixels.
  - The CCDs are read out every three seconds to prevent saturation.
  - Only the information from the CCD pixels where there are stars brighter than mv=14 is recorded.
  - The CCDs are not used to take pictures. The images are intentionally defocused to 25 arc seconds to improve the photometric precision.)
- The instrument has the sensitivity to detect an Earth-size transit of an m_v=12 G2V (solar-like) star at 4 sigma in 6.5 hours of integration.
- The instrument has a spectral bandpass from 400 nm to 850 nm.
- Data from the individual pixels that make up each star of the 100,000 main sequence stars brighter than mv=14 are recorded continuously and simultaneously.

Full-sky Astrometric Mapping Explorer

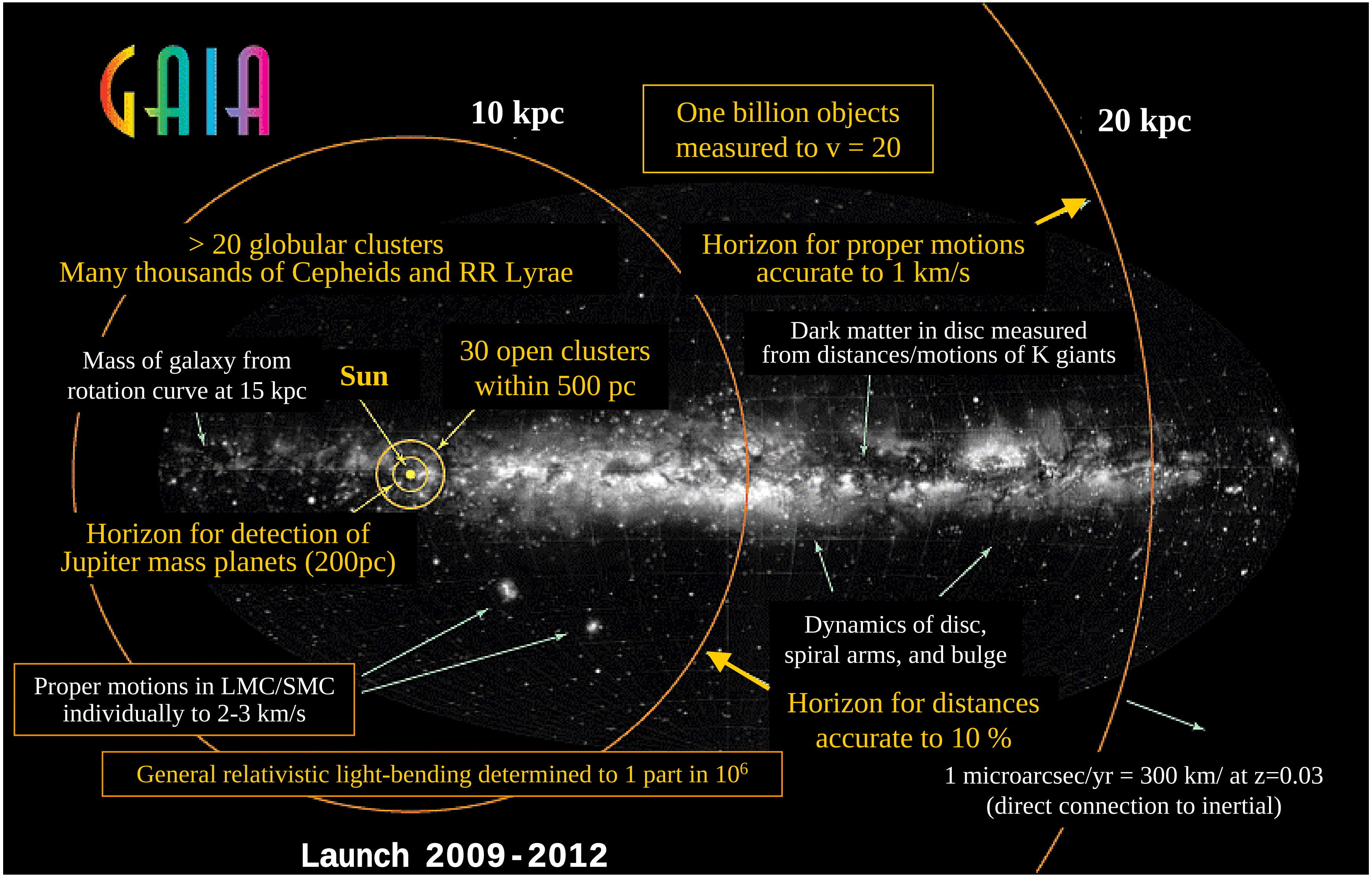


Space Interferometry Mission (SIM)



Baseline	10 m
Wavelength range	0.4 - 0.9µm
Telescope Aperture	0.3 m diameter
Astrometric Field of Regard	15° diameter
Astrometric Narrow Angle Field of View	1° diameter
Imaging Field of View	1 arcsec
Detector	Si CCD

Solar Orbit	Earth-trailing
Science Mission Duration	5 years (launch in 2009)
Wide Angle Astrometry	**4 µas mission accuracy**
Narrow Angle Astrometry	**1 µas mission accuracy**
Limiting Magnitude	20 mag
Imaging Resolution	10 milliarcsec
Interferometric Nulling	Null depth 10-4


GAIA
10 kpc
One billion objects measured to v = 20
20 kpc
> 20 globular clusters
Many thousands of Cepheids and RR Lyrae
Horizon for proper motions accurate to 1 km/s
Dark matter in disc measured from distances/motions of K giants
Mass of galaxy from rotation curve at 15 kpc
Sun
30 open clusters within 500 pc
Horizon for detection of Jupiter mass planets (200pc)
Dynamics of disc, spiral arms, and bulge
Horizon for distances accurate to 10 %
Proper motions in LMC/SMC individually to 2-3 km/s
General relativistic light-bending determined to 1 part in 10^6
1 microarcsec/yr = 300 km/ at z=0.03
(direct connection to inertial)
Launch 2009 - 2012

GAIA Compared with Hipparcos

Parameter	**Hipparcos**	**GAIA**
Magnitude limit:	12	20 - 21 mag
Completeness:	7.3 – 9. 0	~20 mag
Bright limit:	~0	~3 - 7 mag
Number of objects:	120 000	26 million to V = 15
		250 million to V = 18
		1000 million to V = 20
Effective distance limit:	1 kpc	1 Mpc
Quasars:	None	$\sim 5 \times 10^5$
Galaxies:	None	10^6 - 10^7
Accuracy:	~1 milliarcsec	4 μ arcsec at V = 10
		10 μ arcsec at V = 15
		200 μ arcsec at V = 20
Broad band:	2-color(B and V)	4-color to V = 20
Medium band:	None	11-color to V = 20
Radial velocity:	None	1- 10 km/ s to V = 16- 17
Observing program:	Pre- selected	On- board and unbiased

The Constellation X-ray Mission

An X-ray VLT

- **Use X-ray spectroscopy to observe**
  - **Black holes: gravity in their vicinity & their evolution**
  - **Large scale structure in the Universe & trace the underlying dark matter**
  - **Production and recycling of the elements**
- **Mission parameters**
  - **Telescope area:** 1.5 m^2 at 1.5 keV
    100 times XMM/Chandra for high resolution spectroscopy
  - **Spectral resolving power:** 300-3,000
    5 times improvement at 6 keV
  - **Band pass:** 0.25 to 40 keV
    100 times more sensitive at 40 keV

Constellation-X Capabilities

Spectroscopy X-ray Telescope

- 0.25 to 10 keV coverage
- resolution of 300-3000 with 2 eV calorimeter array and reflection grating CCD
- angular resolution matched to confusion limit
  - 5-15 arcsec
  - 5 arcsec pixels
  - 2.5 arcmin FOV

Hard X-ray Telescope

- 10 to 40 keV
- 1,500 sq cm at 40 keV
- energy resolution < 1 keV
- 60 arcsec HPD angular resolution
- Overall factor of 20-100 increased sensitivity

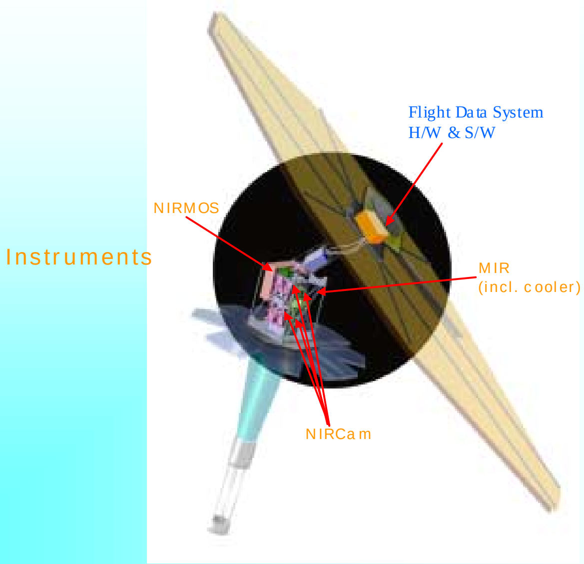
Launch 2009

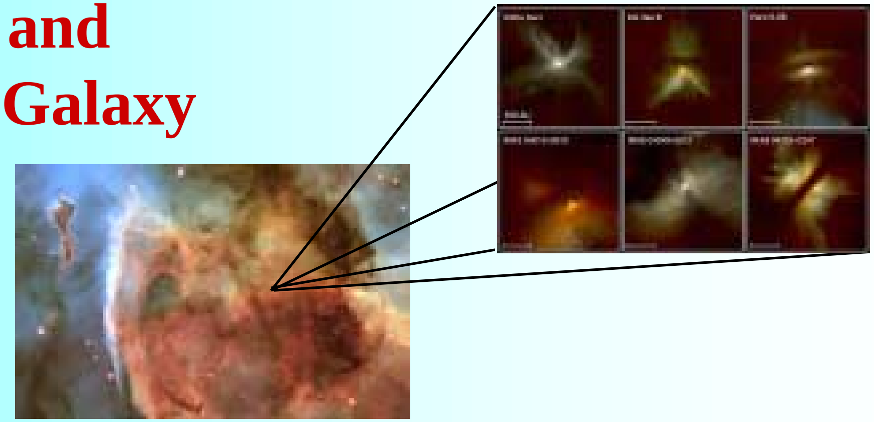
NGST: Key Science Objectives

- Detect and Characterize the First Stars and Galaxies to Form after the Big Bang
  - *"First Light" Machine*
- Measure the Complete Formation Processes of Galaxies and the Creation of Heavy Elements
  - *Visiting a Time When Galaxies Were Young*
- **Study the Details of Star and Planet Formation in our Galaxy**
  - *Prolog to Astrobiology*

http://www.ngst.nasa.gov

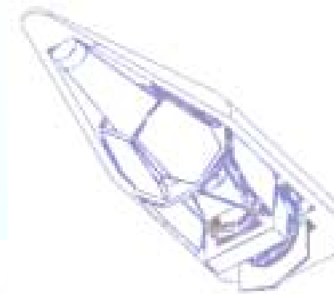
ISIM is the Payload of NGST

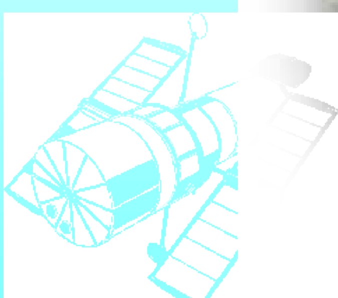




NGST at a Glance

- Primary Mirror: 8 m .. 7 m ... 6 m ← *Standby for Live Update!*
- 0.6-10+ µm Wavelength Range
- 5 year Mission Life (10 year goal)
- Passively Cooled to <50K
- L2 Orbit





Recommended Instruments for NGST Goals

- 4´ x 4´NIR Camera (8k x 8k pixels)
  - Nyquist sampled at 2 µm, 0.6-5 µm, *R*~100 grism mode
    - First light, galaxy formation, dark matter, supernovae, young stars, Kuiper Belt Objects (KBO), stellar populations
- 3´ x 3´ NIR *R*~1000 Multi-Object Spectrograph
  - Simultaneous source spectra, 1-5 µm
    - Gal formation/diagnostics (clustering, abun., star form., kinematics), Active Galactic Nuclei, young stellar clusters (Initial Mass Function (IMF)/stellar populations)
- 2´ x 2´ Mid IR Camera/*R*~1500 Spectrograph
  - Nyquist sampled at ~10 µm, 5-28 µm, grisms & slit
    - Physics of old stars at high redshift, z~5 obscured star form. & Active Galactic Nuclei to *z* ~ 5, PAHs to *z*~5, Ha to z~15 , cool stellar IMF, protostars and disks, KBO sizes, comets

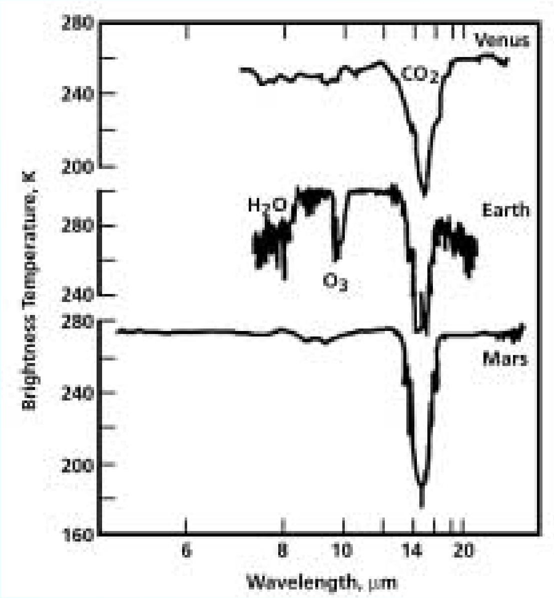
Terrestrial Planet Finder(TPF) and IRSI/Darwin

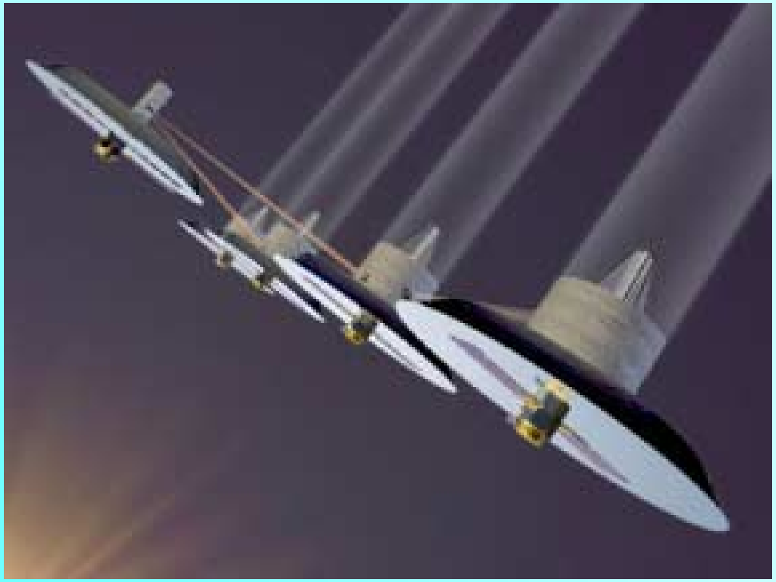
- Science: Detect Earth-like planets; perform spectroscopic analysis on planetary atmospheres; perform synthetic imaging & astrophysics

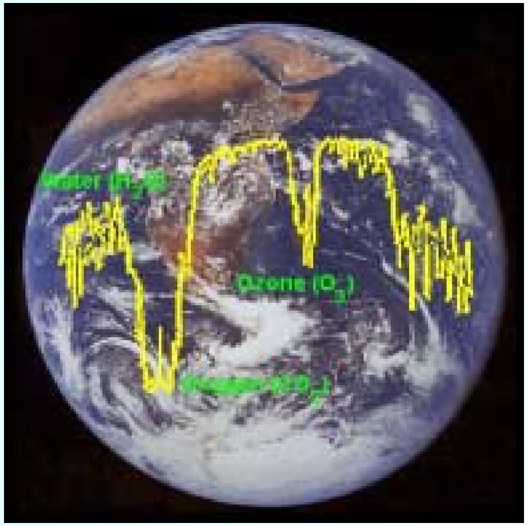
- Instruments: IR Nulling interferometer or visible coronagraph (TPF opt)

- Target: Survey stars within 5-15 parsecs

- Mission Duration: Five years







TPF and IRSI/Darwin

- Orbit: TPF: Earth-trailing, 1 AU from the Sun; gradually drifts away from Earth, reaching 0.6 AU in five years
  Darwin: L2

- Launch: 2010 on EELV; no post-injection trajectory correction maneuvers -- injection accuracy of the launch vehicle is adequate.

- Spacecraft: Four collector spacecraft; one combiner spacecraft.

- Formation: 45-135 m baseline for planet-finding;
  up to 1 km baseline for astrophysics.

- Operations: Planet finding: 8 hours to rotate spacecraft 360 degrees.
  Spectroscopy: slow, 3 degrees/hour continuous rotation.
  Astrophysics: various, slow drift at 45 m to 1 km baseline.

Far-Horizon Missions

“Next HST”,
SPIRIT/SPECS, SI, MAXIM,
XEUS, PI

UV/Optical Follow-on to HST

- SUVO, HST2, NHST ...
- 4 - 8 m filled-aperture
- original concept: spectroscopy only
- likely concept: imaging as well
- workshop scheduled winter 2002 at STScI to define science requirements and best architecture

See also poster by Wamstecker et al. on “World Space Observatory”

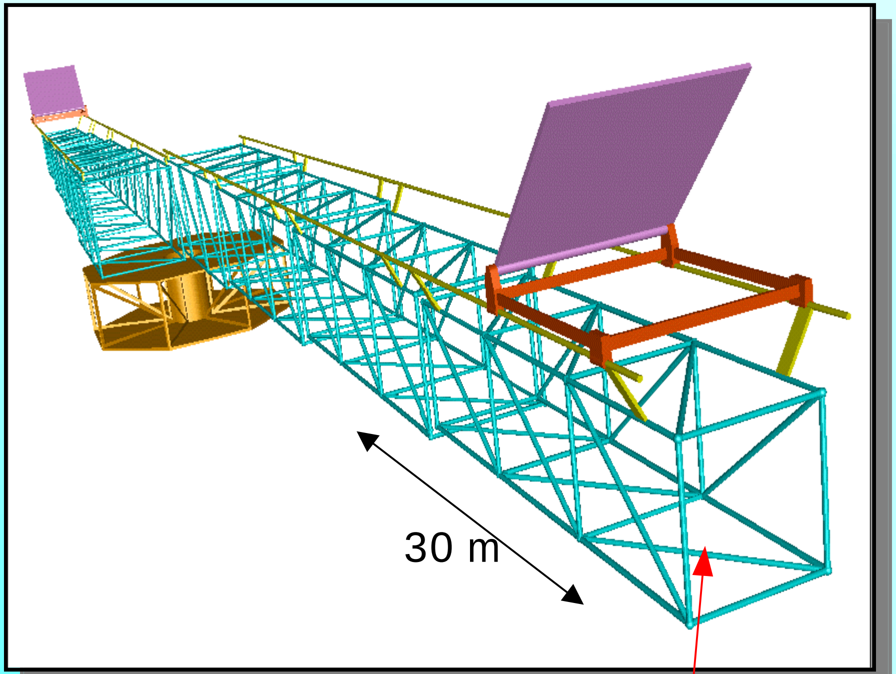
SPIRIT and SPECS: Far IR/sub-mm Space Interferometry

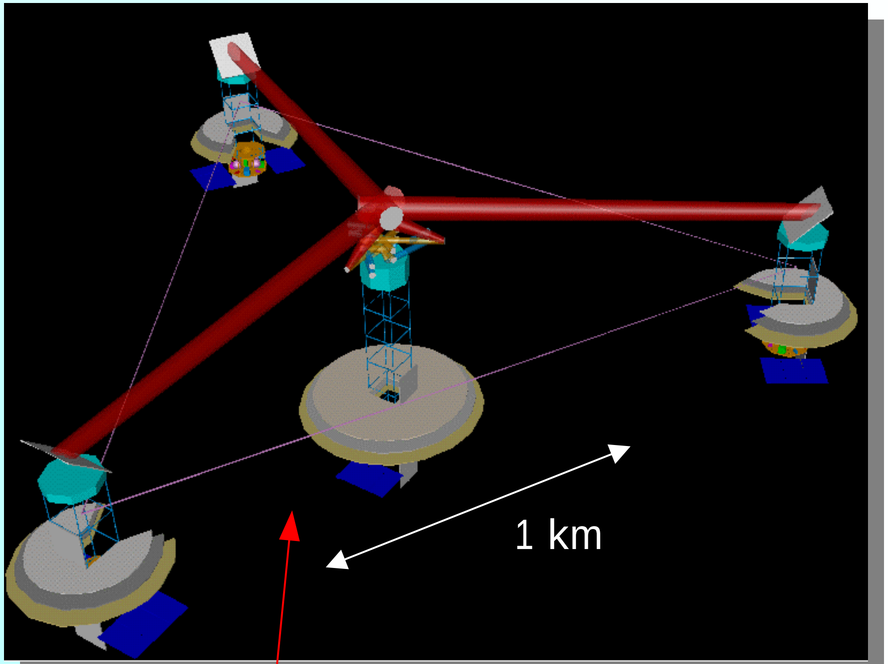
SPIRIT ~2010

Space IR Interferometry Telescope

SPECS ~2015

Submillimeter Probe of the Evolution of Cosmic Structure





Deployable truss

Tethered spacecraft formation

http://space.gsfc.nasa.gov/astro/specs

Far-IR/Sub-mm Science Overview

NAS Decadal Report recommends:

– Develop enabling technologies this decade

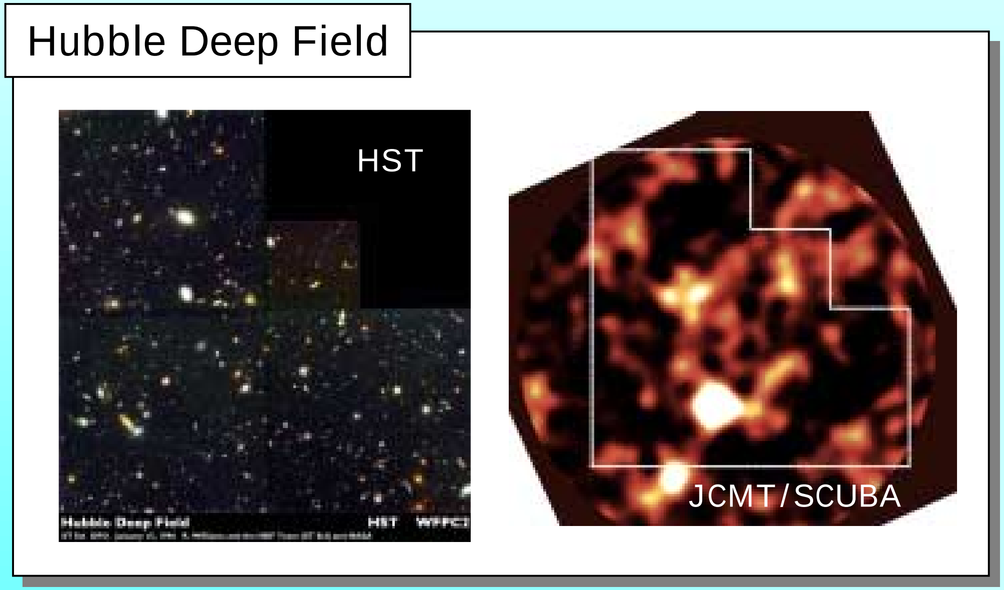
– Space-based far-IR interferometer next decade

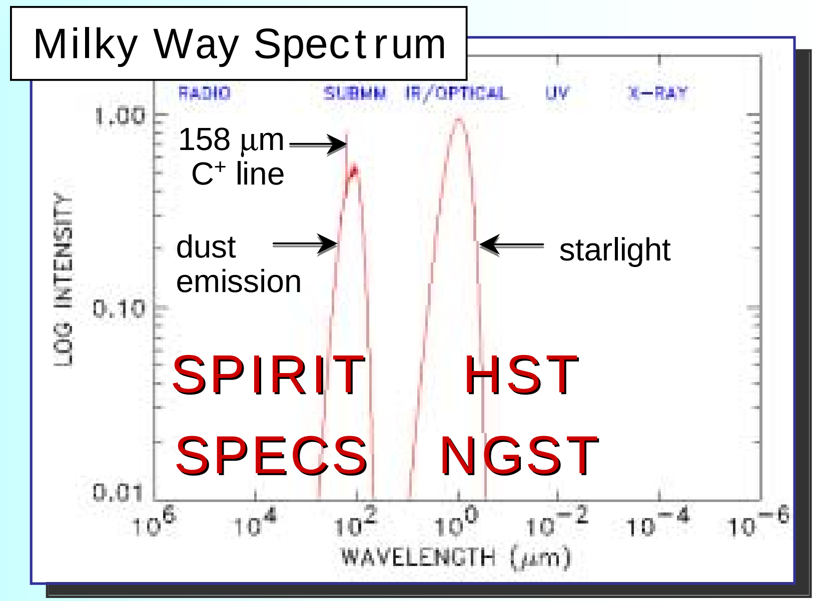
Science goals are major OSS objectives:

– How did structure in the universe (galaxies, stars, planets) form and evolve over time?

– What is the cosmic history of energy release?

– What is the history of chemical element formation & dissemination?

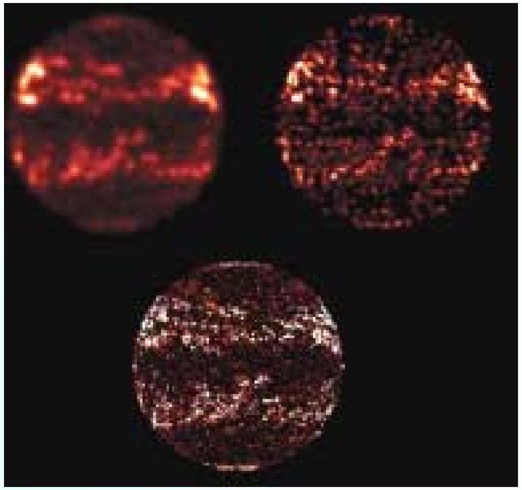




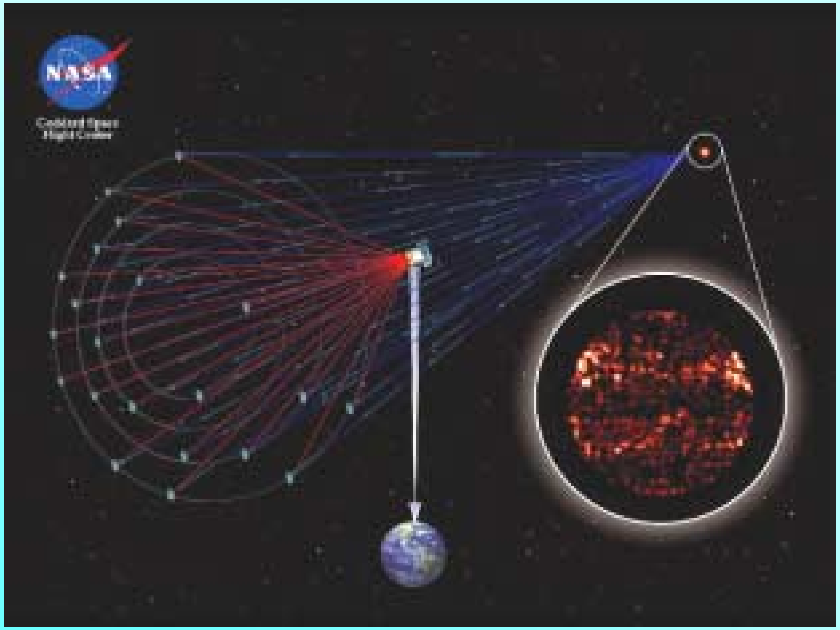
- Many objects have no UV/optical counterparts
- Star and planet formation are totally hidden

- Half of the energy is in the far-IR

Stellar Imager (SI)



- UV-Optical Fizeau Imaging Interferometer, 60 microarcsec resolution at C IV 1550 A
- 30 “mirrorsats” formation-flying with central beam-combining hub, maximum baseline ~500 m
- Launch > 2015, into Lissajous orbit around L_2
- Mission duration: 10 years
- Produces about 1000 pixels/stellar image



Prime Science Goals

image surface features of other stars and measure their spatial/temporal variations

to understand the underlying dynamo process(es) and

enable improved forecasting of solar/stellar activity and its impact on planetary climates and life

http://hires.gsfc.nasa.gov/~si

Primary SI Mission

- A Population study of cool stars
  - To understand the dynamo, we need to know how magnetic fields are generated & behave in different circumstances - the sun is only one example and provides insufficient constraints on theories of dynamos, turbulence, structure, and internal mixing
    - we must observe other stars to *establish how mass, rotation, brightness and age affect the* ***patterns of activity*** & determine:
      - What determines cycle strength and duration? Can multiple cycles exist at the surface? How do polar spots form?
      - How common is solar-like activity? What are extremely (in)active stars like? What are Maunder-minimum states like?
- Asteroseismology (acoustic imaging) to look beneath surface
  - Although its clearest manifestations are visible on the stellar surface, a full understanding of the dynamo requires a knowledge of the underlying layers
    - Where is the seat of the dynamo? What determines differential rotation and meridional circulation, and what role do they play in the dynamo?
    - What is the impact of magnetic deceleration on internal rotation and stellar evolution? How are stellar interiors modified in extremely active stars?

SI and General Astrophysics

A long-baseline interferometer in space benefits many fields of astrophysics

Active Galactic Nuclei, Quasi-stellar Objects & Black Holes

close-in structure, accretion processes, origin/orientation of jets

Supernovae

close-in spatial structure

Stellar interiors

internal structure, including, e.g., opacities, in stars outside solar parameters

Hot Stars

hot polar winds, non-radial pulsations, extended gaseous envelopes and shells

Binary stars

observe companions & orbits, stellar properties, key tests of stellar evolution. resolve mass-exchange, dynamical evolution/accretion

Cool, Evolved Giant & Supergiant Stars

spatio-temporal structure of extended atmospheres/winds, shocks

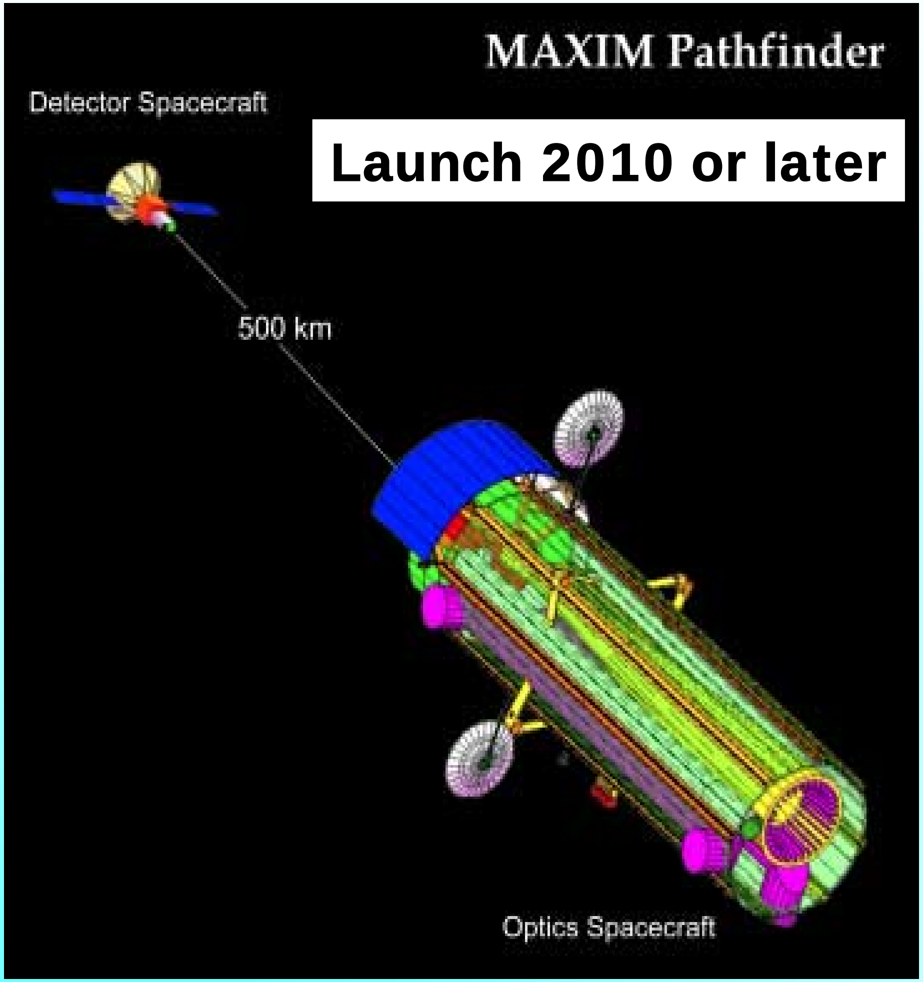
Micro-Arcsecond X-ray Interferometry Mission (MAXIM): *Image a Black Hole!*

Direct image of a black hole event horizon

- **Fundamental importance to physics**

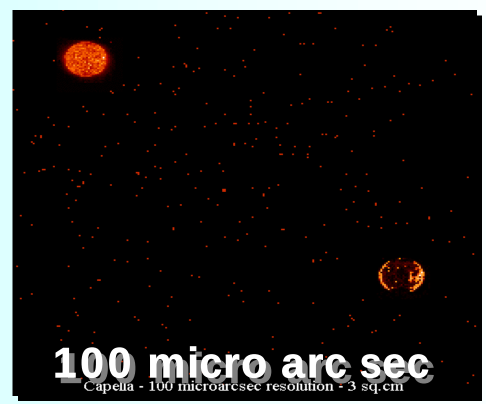
http://maxim.gsfc.nasa.gov/

MAXIM Pathfinder:
Demonstrate an X-ray interferometer in space



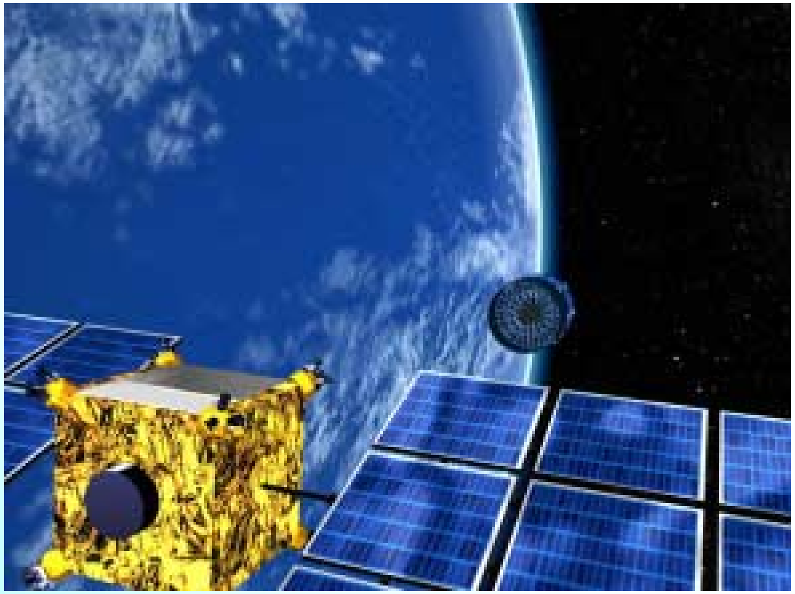
Two formation-flying spacecraft separated by 500 km

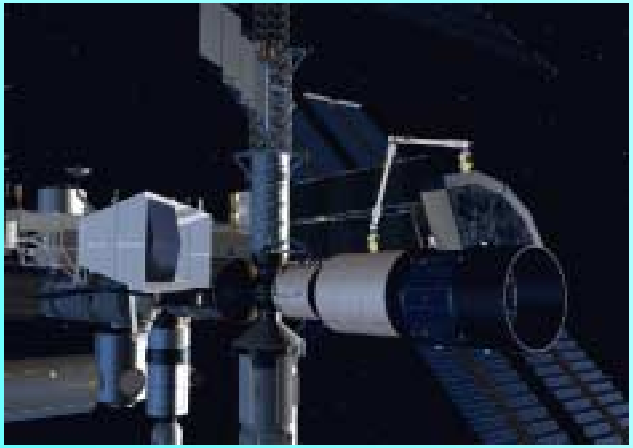
- 100 micro-arc sec resolution
  - ➤ ***1000 times better than Chandra!***
- 1 to 2 m baseline
  - ➤ **optics on single spacecraft**
- Science:
  - ➤ **Imaging nearby stars**

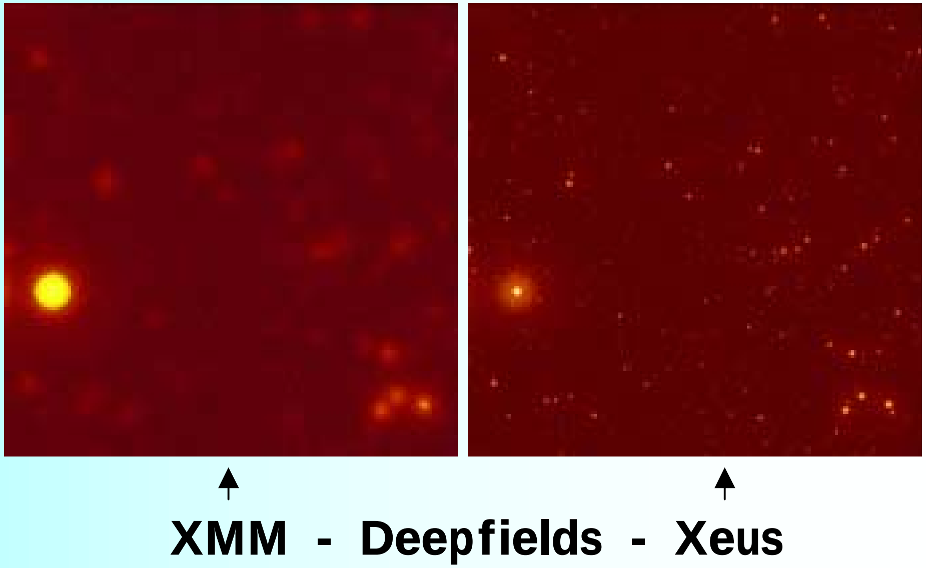


Xeus

- A potential follow-on to ESA's Cornerstone Spectroscopy Mission (XMM-NEWTON).
  - It will be around 250 times more sensitive
- It will be a permanent space-borne X-ray observatory with a sensitivity comparable to the most advanced planned future observatories such as NGST, ALMA and Herschel
- Planned for refurbishment/enlargement at ISS
- The scientific goals include the study of the:
  - First massive black holes.
  - First galaxy groups and their evolution into the massive clusters observed today
  - Evolution of heavy element abundances
  - Intergalactic medium using absorption line spectroscopy. ...

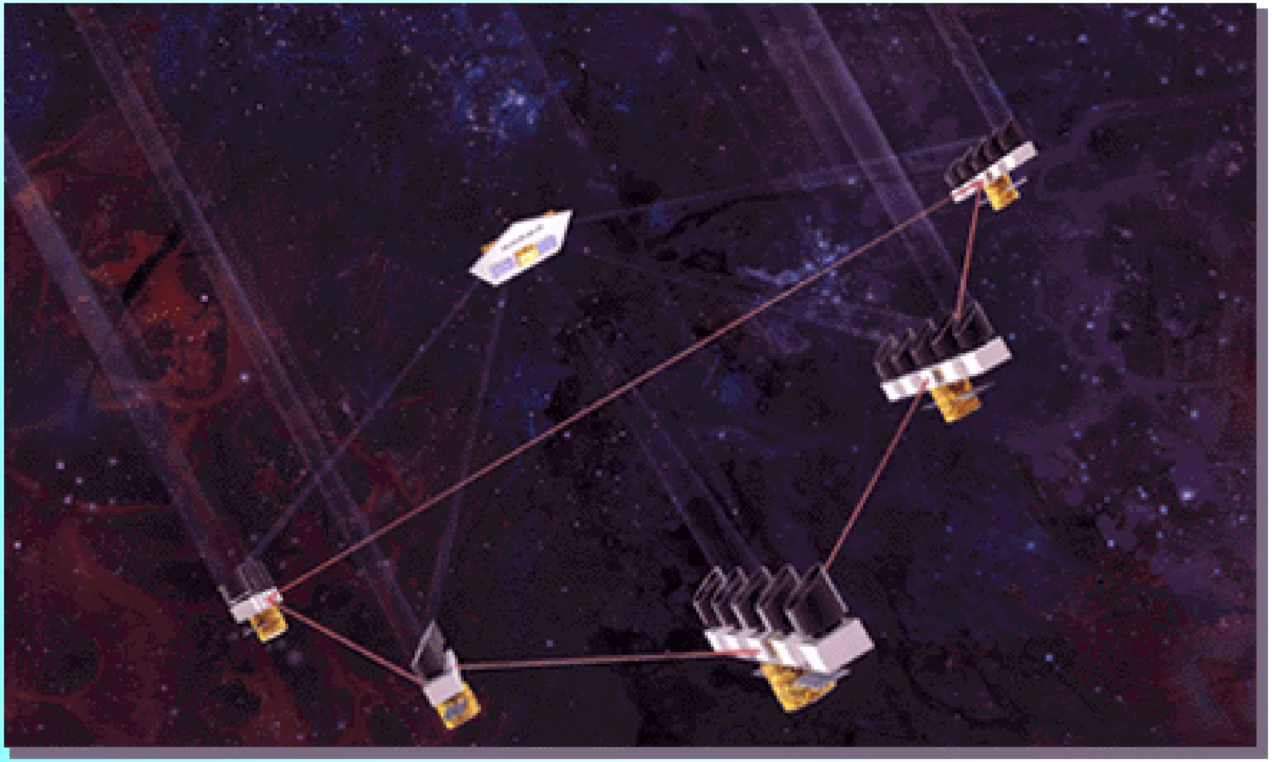






Planet Imager (PI)

- Ultimate Goal of NASA Origins Program: Obtain resolved images of terrrestrial-type planets around other stars
- Strawman Concept: An interferometer composed of interferometers: 5 formation flying interferometers, each composed of five 8-m mirrors (to yield 25x25 pixel images)



Summary

- Surveys:
  GALEX, ASTRO-F, KEPLER (prec. Phot.)
- Great Observatories: SIRTF
- High Sensitivity/High Resolution/Large FOV/Broad Wavelength Coverage Cameras: ACS, WFC3
- High Sensitivity Spectrographs:
  COS, SUVO/HST2, CON-X
- Precision Astrometry: FAME, SIM, GAIA
- Ultra-High Angular Resolution Imaging Inteferometers:
  SPECS, SI, MAXIM, PI