Galaxy Clusters +
Gravitational Lensing

Gamma-ray Bursts, Black Holes, and Exoplanets:
How CCD Detectors have Revolutionized Astronomy

George R. Ricker
MIT Kavli Institute for Astrophysics and Space Research

APS March Meeting
Boston MA
27 February 2012

The Story of Four Graduate Students...

Why these Four Graduate Students?

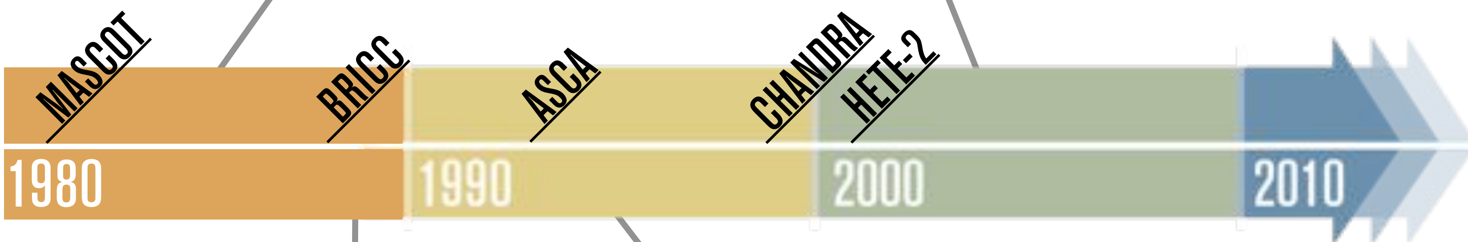
- **Each student:**
  - Developed a major new astronomical instrument in the MIT CCD Laboratory
  - Completed his MIT PhD in Physics based on astronomical observations with that instrument
  - Devoted his subsequent career to astronomical or detector research

- **My story will relate:**
  - What each student accomplished in his research
  - What each student is working on now

Dramatis Personae and Timeline

1985
Roland Vanderspek

2003
Nat Butler



1989
Gerry Luppino

1995
Keith Gendreau

A Story in Four Acts…

Act 1: Roland Vanderspek
"Multicamera CCD Sky Surveys"
Featuring Optical Flashes, GRB counterparts, and Transiting Exoplanets
…ETC ➔ HETE-2 ➔ TESS

Act 2: Gerry Luppino
"Large FOV CCD Arrays"
Featuring Galaxy Clusters and Gravitational Lensing
…Ever larger (!) FOV CCD arrays

Act 3: Keith Gendreau
"X-ray CCDs in Space: Modest FOVs"
Featuring Cosmic X-ray Background, Pulsars, Laboratory Astrophysics
…ASCA ➔ Astro-D ➔ NICER

Act 4: Nat Butler
"X-ray CCDs in Space: Large FOVs"
Featuring X-ray Flashes, Dark GRBs, Collapsars, and Shredded Stars
… HETE-2 ➔ Swift ➔ RATIR

GRB = Gamma-ray Burst
Other acronyms defined later

Act 1: Roland Vanderspek

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"Multicamera CCD Sky Surveys"
Featuring optical flashes, GRB counterparts, and transiting exoplanets
…ETC ➔ HETE-2 ➔ TESS

(MIT PhD 1985; currently MKI Research Scientist)

Roland and MASCOT at KPNO 4 meter Telescope

MASCOT= **MIT Astronomical Spectroscopy Camera for Optical Telescopes**

- Enabled simultaneous imaging and long slit spectroscopy
- One of earliest dual CCD system
- Lightweight, compact system
- Traveling instrument, deployed on many telescopes in early 1980's:
  Kitt Peak 4m; CTIO 4m; Mauna Kea 2.2 m; MDM 2.4 m

Roland's Thesis Abstract

The Explosive Transient Camera:

An All-Sky Monitor for Optical Flashes

by

ROLAND KRAFT VANDERSPEK

Submitted to the Department of Physics on November 14, 1985,
in partial fulfillment of the requirements for
the Degree of Doctor of Philosophy in Physics

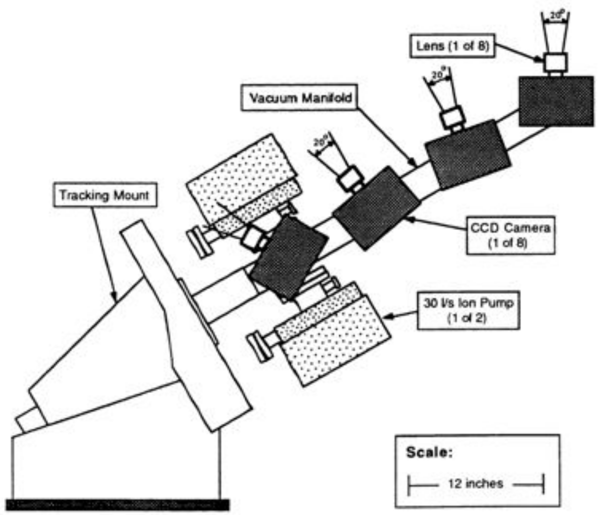
ABSTRACT

The discovery in 1973 (Klebesadel, et al., 1973) of the phenomenon of gamma-ray bursts (GRBs), seen as short (durations of 1-60 seconds), sudden (risetimes of less than a second) outbursts of γ-rays from deep space, has led to intense efforts to discover the source of these mysterious emissions. Observations in the last ten years with a series of interplanetary and terrestrial satellites have led have led to hundreds of detections of GRB events. Analyses of observational data support the hypothesis of a highly-magnetized (10^{12-13} Gauss) neutron star as the source of GRBs, yet the low precision of localization of most GRBs (tens of arc-minutes to degrees) has hindered the a posteriori identification of a quiescent counterpart to a GRB source in any energy band. To date, no convincing quiescent optical counterparts to GRB sources have been established. The discovery by Schaefer (1981) of transient optical radiation from a small GRB error region, recorded on an archived photographic plate in 1928, led to the hope the precision of localization of GRB sources might be greatly improved through the detection of optical radiation emitted during the GRB.

In 1982, the **Explosive Transient Camera** (ETC), a wide-field sky monitor sensitive to celestial optical flashes with risetimes of the order of one second, was proposed as a ground-based counterpart to gamma-ray satellites with the expressed intent of detecting optical radiation from outbursting GRBs (Ricker, et al., 1983). In 1983, construction was begun of a sub-unit of the plenary ETC, designed to test the feasibility of a full wide-field ETC. This thesis discusses the motivation, design, construction and implementation of the ETC test unit. Calculations of estimated event rates from several known sources of celestial optical transients in the plenary ETC are presented. In addition, this thesis includes the presentation and discussion of results from observations made the test unit, which comprise **the most complete wide-field search for celestial optical flashes to date**. The observations with the ETC test unit covered a solid-angle-time product of 3.0 steradian-hours and included the error regions of GRB1200+21 (24 November 1978), GRB1152+20 (1 January 1979) and GRB1140+20 (2 May 1979) (Baity, et al., 1984) as well as the flare stars V475 Her, Ross 867 and Ross 868 (Gurzadyan, 1980). The observations were expected, based on assumptions presented within, to have detected optical transient events from 1.5 flare stars and 0.008 GRBs. These observations resulted in the determination of a new upper limit on the celestial optical flash rate of 2.2 optical flashes per hour per steradian at 10^{th} magnitude, lower by a factor of 10 than the previous best upper limit determined by Schaefer, Vanderspek, Bradt and Ricker (1984).

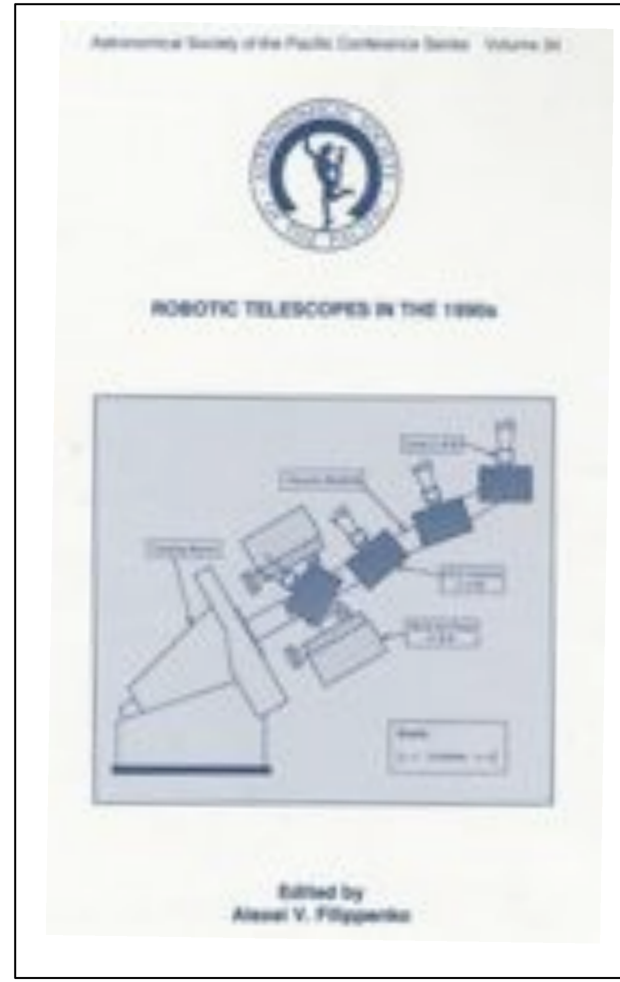
Thesis Supervisor: George R. Ricker
Title: Senior Research Scientist

Explosive Transient Camera (ETC) Basic Idea



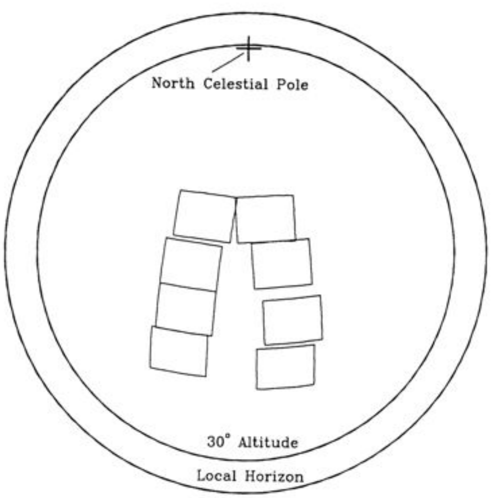
ETC Side View

ETC Camera Assembly Line



ROBOTIC TELESCOPES IN THE 1990s

Edited by
Alexei V. Filippenko



ETC Fields-of-View on Sky

Vanderspek et al 1992

ETC with Roland

ETC Results

- Technical Challenges
  - Pioneering Effort
  - Telescope in Arizona operated from Cambridge in fully-robotic manner
  - Limited RAM (~ 0.5 MB) and slow (~10 MHz) CPUs
  - Pre-Internet with dial-up modems
- Survey Limits
  - Tumbling Satellites & Orbital Debris
  - Limits on Optical Flashes from GRBs (w. BATSE)
- Look ahead
  - Optical methods needed to support satellite missions that would crack the GRB counterpart problem 15 years later
  - Template for Beppo-SAX, HETE-2, and Swift Followup Networks

Act 2: Gerry Luppino

Act 2: Gerry Luppino
"Large FOV CCD Arrays"
Featuring Galaxy Clusters and Gravitational Lensing
…Ever larger (!) FOV CCD arrays

(MIT PhD 1989; recently Professor of Astronomy, University of Hawaii; currently President & CEO, GL Scientific)

Gerry and MASCOT at Kitt Peak

Gerry's Thesis Abstract

DESIGN AND USE OF A LARGE-FORMAT CCD INSTRUMENT
FOR THE
IDENTIFICATION AND STUDY OF DISTANT GALAXY CLUSTERS

by

GERARD A. LUPPINO

SUBMITTED TO THE DEPARTMENT OF PHYSICS OF THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY ON AUGUST 1989, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN PHYSICS

ABSTRACT

This dissertation describes a search for distant clusters of galaxies (z>0.3). Cluster candidates were selected from a sample of radio sources with steep, low-frequency spectra since such radio sources are often found in rich nearby galaxy clusters. The steep-spectrum radio source (SSRS) is thought to be produced by the confinement of the radio plasma by the thermal pressure of a hot intracluster gas; therefore, we expect clusters discovered by this selection criterion to be bright x-ray sources and excellent targets for future x-ray satellites such as *ROSAT*, *ASTRO-D* and *AXAF*. These objects are also more likely to be true physical associations rather than the chance superpositions of galaxies that may plague some optically selected samples, particularly those at faint magnitudes. In order to identify the optical counterpart of the SSRS and see if the radio source was part of a distant cluster of galaxies, optical images to faint limiting magnitudes were required. Therefore, an imaging instrument incorporating mosaics of CCDs was designed and built . With this instrument, it is possible to observe faint, distant clusters of galaxies with spatial resolution limited by atmospheric seeing, while at the same time covering a relatively large field of view.

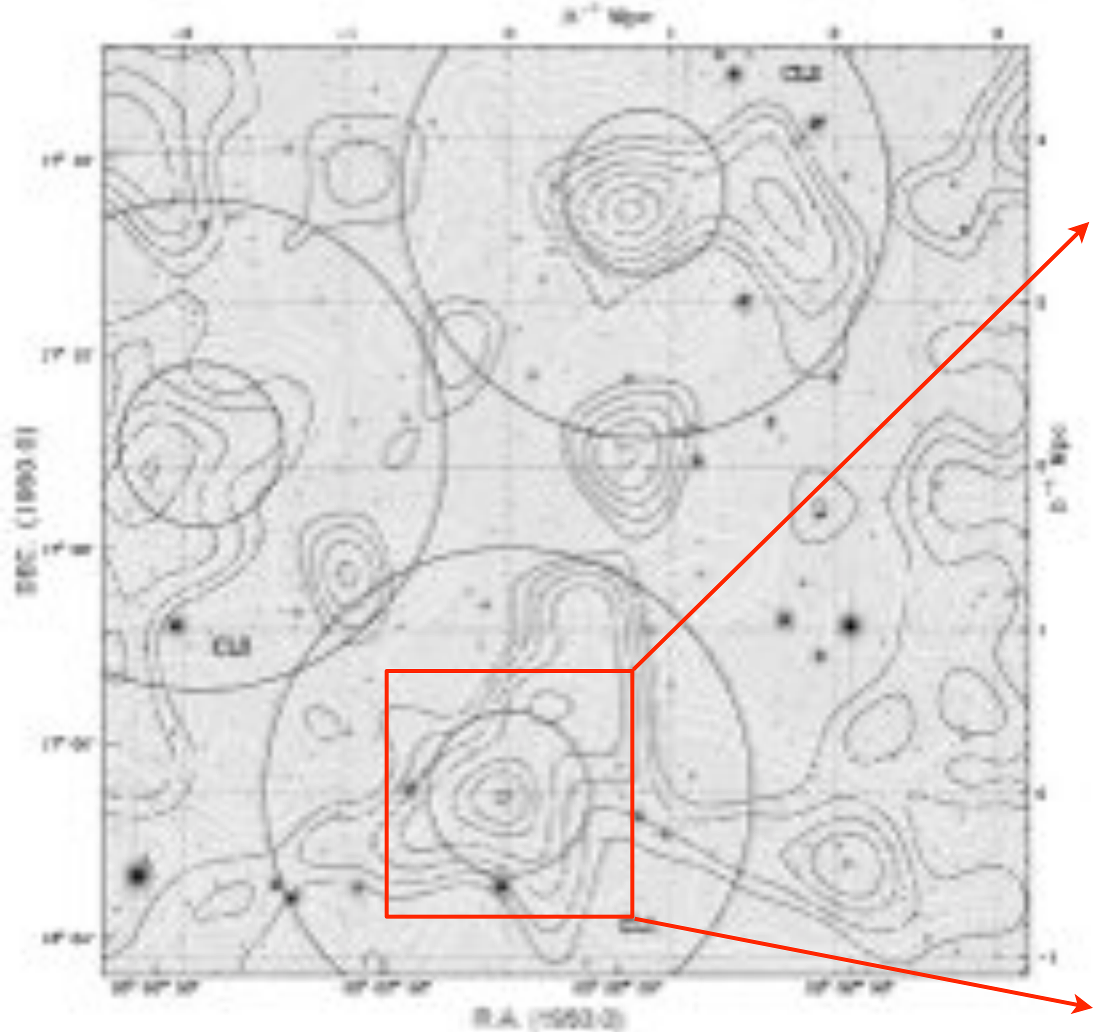
The major task in the creation of this instrument was the design and construction of two separate CCD camera systems; each based on different CCD mosaics. The first camera system incorporates four prototype, TI 850 × 750 virtual-phase CCDs (22.3 μm square pixels) arranged in a square pattern with the device packages abutted. The second camera system is designed to operate a four-chip CCD imager made by MIT Lincoln Laboratory. The imaging area of this CCD mosaic is 840 × 840 pixels (27 μm square pixels) formed by abutting four 840 × 420 framestore devices with seam losses less than 6 pixels. Details of the CCD camera electronics design as well as details of the mechanical design of the CCD cameras and LN_2 dewars are described.

A total of 30 SSRS fields were observed with this CCD instrument mounted on the 1.3m and 2.4m telescopes of the Michigan-Dartmouth-MIT (MDM) Observatory on Kitt Peak. Additional CCD images of 5 of these radio sources were obtained with the Kitt Peak 4m telescope equipped with the KPNO prime focus CCD. Of these 30 SSRSs, 26 have been optically identified. In all, 15 of the observed fields contain visible clusters of galaxies, some of which are quite rich. Of the remaining 15 SSRSs, 6 are identified with faint galaxies , 2 are identified with poor groups, 3 are probably quasars, and 4 of the fields have uncertain or no optical counterpart. The median value for the estimated redshift of the 15 clusters is z=0.43 and the median richness is Abell Class 2. Nearly all of the radio sources have classical double-lobed morphology, and in half of the sources associated with clusters, the radio source is identified with a fainter cluster member rather than with the brightest cluster galaxy. In all cases where the cluster is BM Type I, however, the radio source is identified with the optically dominant galaxy.

Observations are also presented of three distant clusters that were not part of the radio selected sample: 0414+009, an x-ray bright BL Lac object coincident with the optically dominant galaxy in a Richness Class 1 cluster; 1217+1006, a compact group containing an extremely blue $(B-R) = 0.0$ object that may be either a QSO or a BL Lac; and 1358+6245, a new, x-ray luminous (L_x (0.5–4.5 keV) = 8.4×10^{44} erg s^{-1}), extremely rich (Richness Class 3 or 4), distant cluster of galaxies (z=0.323) which exhibits the Butcher-Oemler effect with a blue galaxy fraction $f_b = 0.18$ or $f_b = 0.10$ depending on the background galaxy correction.

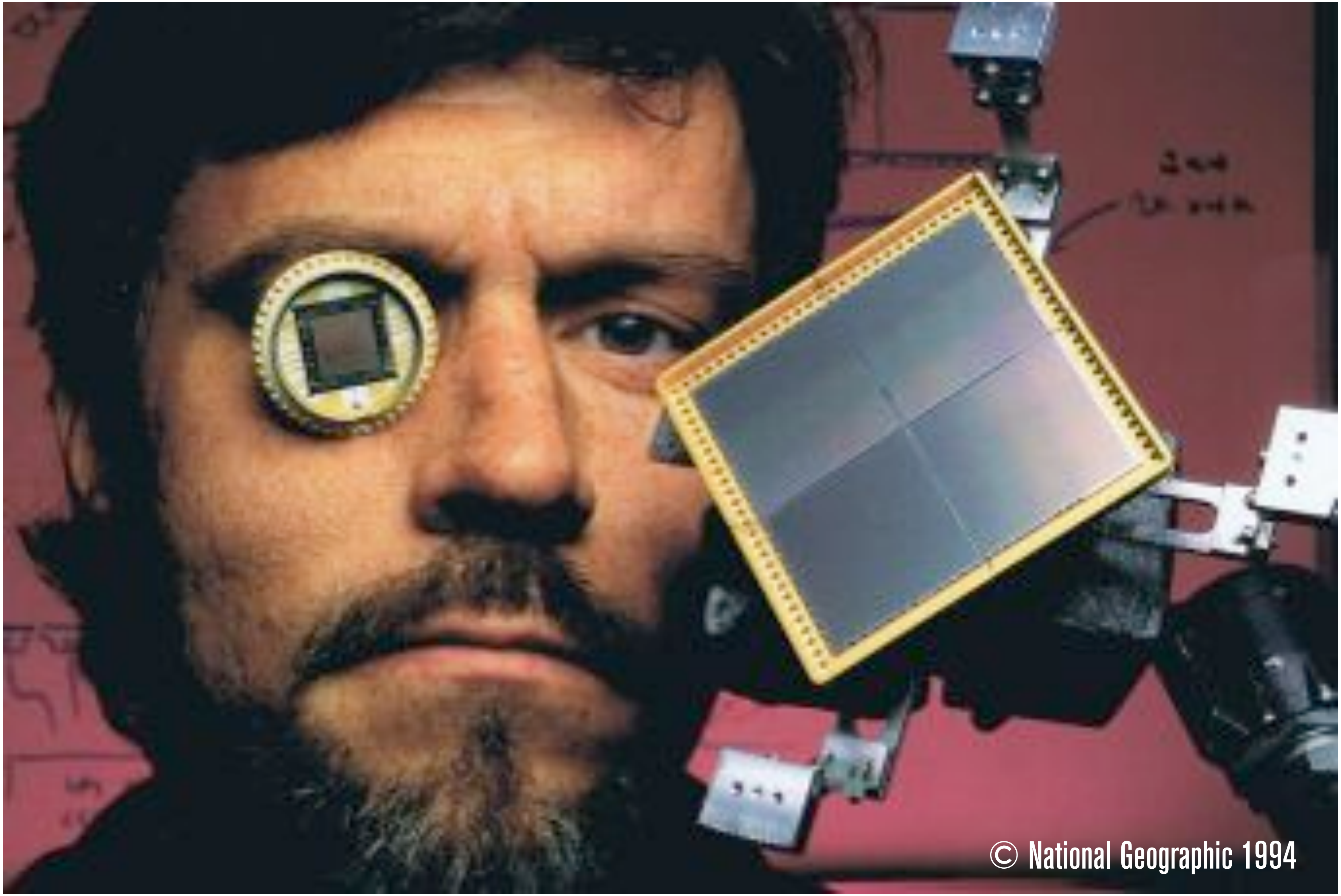
Thesis Supervisor: George R. Ricker
Title: Senior Research Scientist

Gravitational Lensing in a Triple Cluster of Galaxies



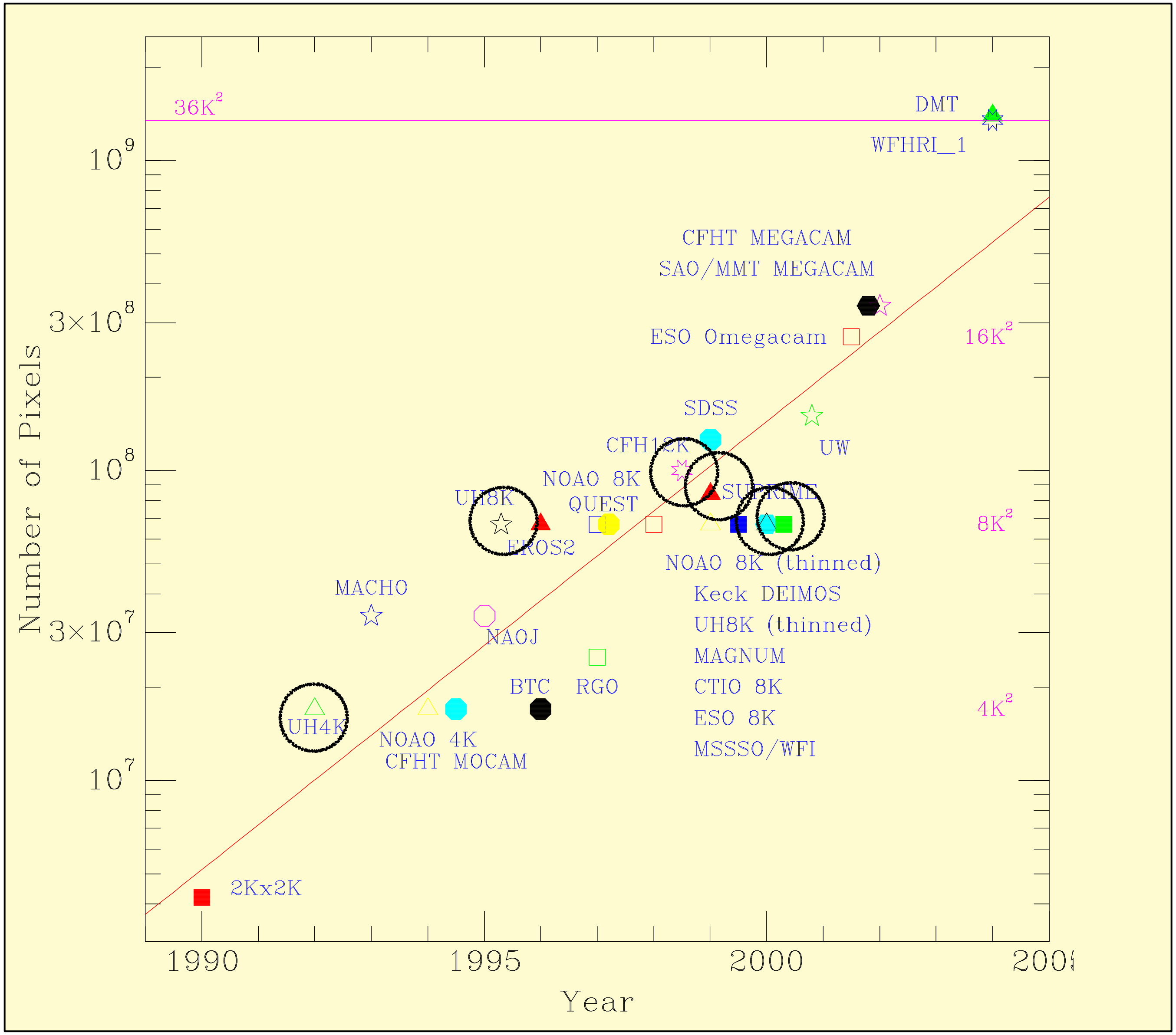
Luppino et al.(2008)

Gerry Builds CCD Arrays!



Canada-France-Hawaii Telescope 12K x 8K Array (ca 1998)

"Gerry's Law" for CCD Camera Arrays



Array systems built or consortia CCDs produced by Gerry

Pixel Count in astronomical arrays doubles every 2 years!

Act 3: Keith Gendreau

Act 3: Keith Gendreau
"X-ray CCDs in Space: Modest FOVs"
Featuring Cosmic X-ray Background, Pulsars, Laboratory Astrophysics
...ASCA ➔ Astro-D ➔ NICER

(MIT PhD 1995; currently NASA Goddard Astrophysicist)

X-ray CCDs for Space Applications: Calibration, Radiation Hardness, and Use for Measuring the Spectrum of the Cosmic X-ray Background

by

Keith Charles Gendreau

Submitted to the Department of Physics
on May 14, 1995, in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Abstract

This thesis has two distinct components. One concerns the physics of the high energy resolution X-ray Charge Coupled Devices (CCD) detectors used to measure the cosmic X-ray background (XRB) spectrum. The other involves the measurements and analysis of the XRB spectrum and instrumental background with these detectors on board the Advanced Satellite for Cosmology and Astrophysics (ASCA).

The XRB has a soft component and a hard component divided at ~2 keV. The hard component is extremely isotropic, suggesting a cosmological origin. The soft component is extremely anisotropic. A galactic component most likely dominates the soft band with X-ray line emission due to a hot plasma surrounding the solar system. ASCA is one of the first of a class of missions designed to overlap the hard and soft X-ray bands.

The X-ray CCD's energy resolution allows us to spectrally separate the galactic and cosmological components. Also, the resolution offers the ability to test several specific cosmological models which would make up the XRB. I have concentrated on models for the XRB origin which include active galactic nuclei (AGN) as principal components. I use ASCA data to put spectral constraints on the AGN synthesis model for the XRB.

The instrumental portion of this thesis concerns the development and calibration of the X-ray CCDs. I designed, built and operated an X-ray calibration facility for these detectors. It makes use of a reflection grating spectrometer to measure absolute detection efficiency, characteristic absorption edge strengths, and spectral redistribution in the CCD response function.

Part of my thesis research includes a study of radiation damage mechanisms in CCDs. This work revealed radiation damage-induced degradation in the spectral response to X-rays. It also uncovered systematic effects which affect both data analysis and CCD design. I have developed a model involving trap energy levels in the CCD band gap structure. These traps reduce the efficiency in which charge transfers through the CCD. I have used the model to extract information about characteristic trapping and detrapping times for electrons in these energy levels out of the X-ray data.

Thesis Supervisor: George R. Ricker
Title: Senior Research Scientist

X-ray Sky: Source Environment

- X-ray sky is <u>very dark</u>
  - 10^6 times lower surface brightness than optical sky
  - Photon flux equivalent to V=+40 mag arcsec^2
  - Blocked by earth's atmosphere—must go to space

- Thus, a few X-rays from a point source can be very significant
  - Photon-counting detectors are essential
  - Detectors should provide spatial, temporal, and energy information for each detected photon!
  - Examples:
    - ASCA's CCD detector provides energy measurements in ~50 "X-ray colors" simultaneously
    - HETE-2's CCD camera can establish ~10" source locations with only a dozen X-ray photons

Photon Absorption Depth in Silicon

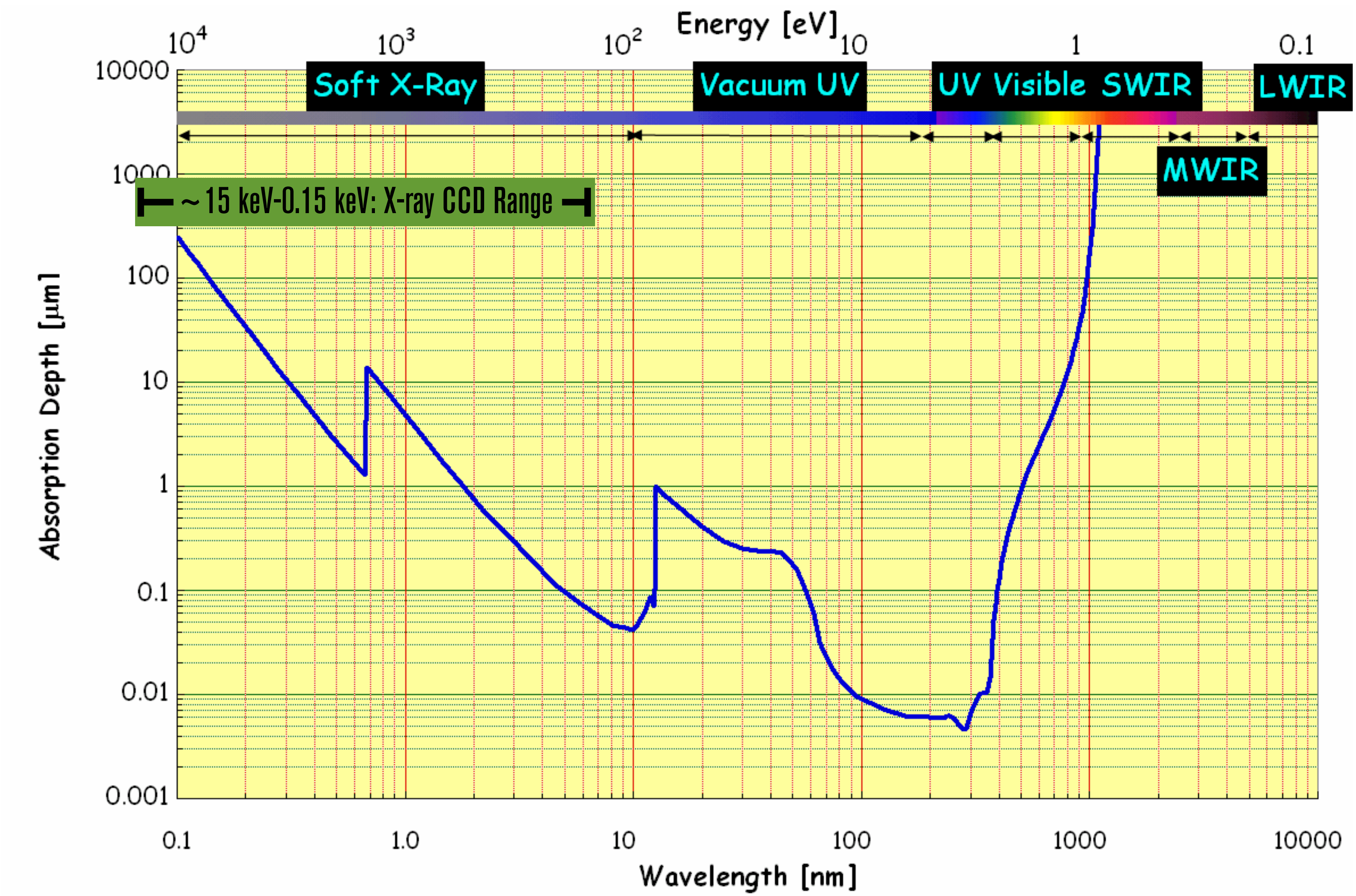
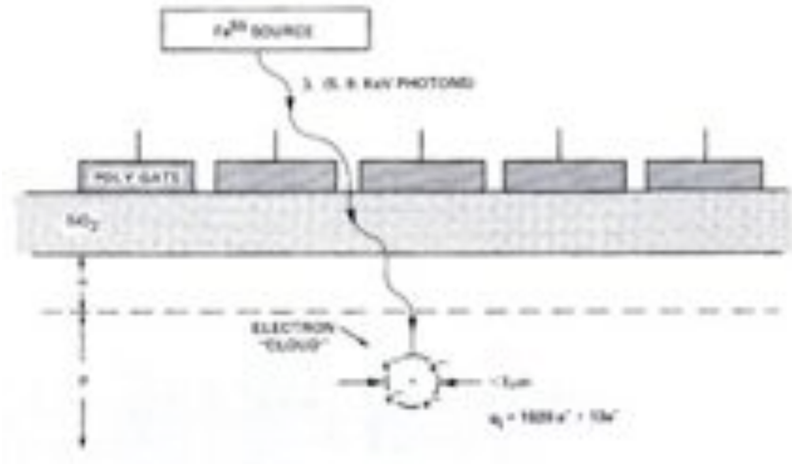


Figure from J. Beletic 2012

X-ray CCD: Principles of Operation



$$\Delta E_{FWHM} = 2.354 \times 3.65 \sqrt{N^2 + \frac{F E_x}{3.65}}$$

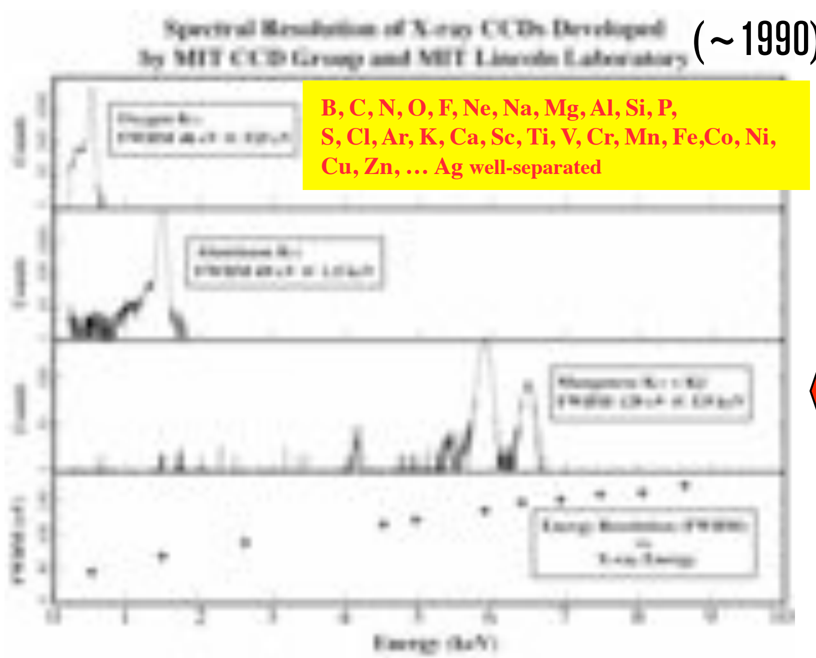
where:

ΔE_{FWHM} = Energy resolution (eV)

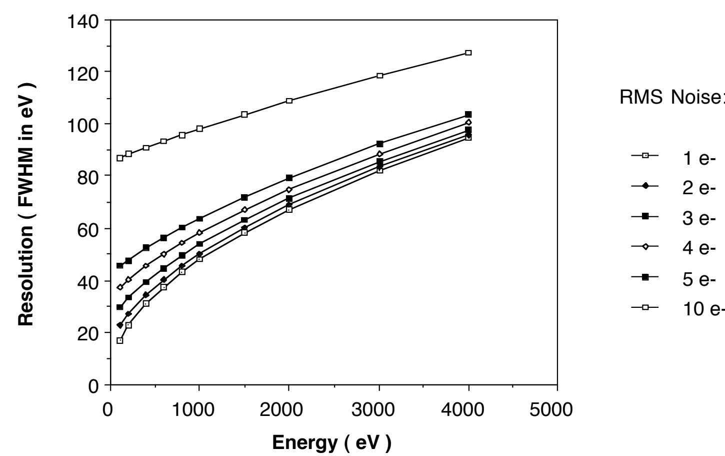
N = readout noise (electrons RMS)

F = Fano factor (~0.1 for Si)

E_x = X-ray energy (eV).

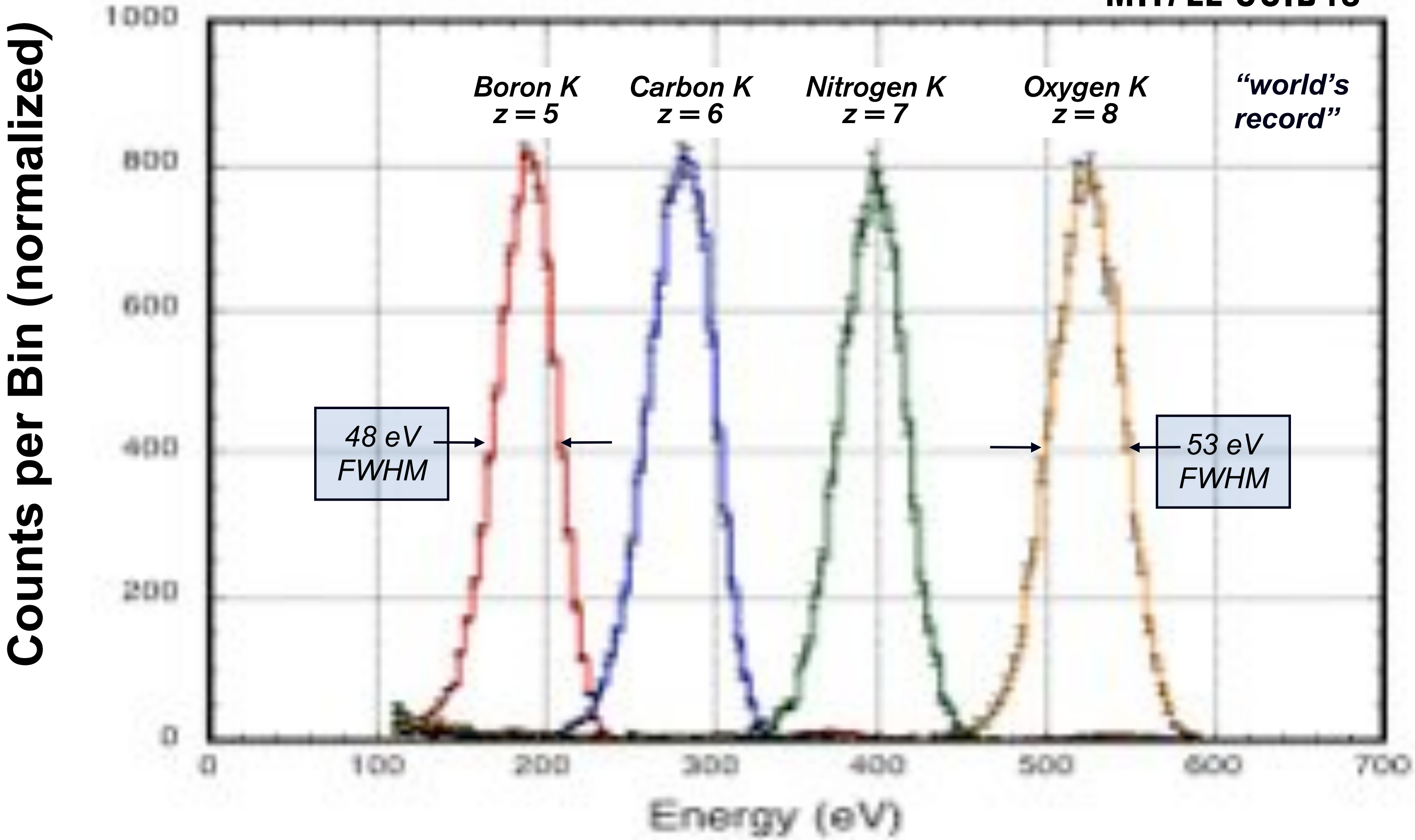


CCD Readout Noise: Effect on Spectral Resolution



X-ray Photopeak Resolution in MBE BI X-ray CCD

MIT/LL CCID48



Flight Heritage: MIT X-ray CCD Detectors

Photo	Satellite Program	X-ray CCD Detector	Launched	Camera Remarks
	Advanced Satellite for Cosmology & Astrophysics (ASCA) –Solid Sate Imaging Spectrometer (SIS)	LL CCID-7: Two Hybrid Focal Planes; 420 x 420 arrays; 8 devices Total	Feb 1993	Japan-US; 8 year operations (satellite re-entry); developed, constructed at MIT
	Chandra X-ray Observatory – Advanced CCD Imaging Spectrometer (ACIS)	LL CCID-17: Mosaiced Focal Plane; 1K x 1K arrays; 10 Devices Total	Jul 1999	NASA "Great Observatory" principal imager; 12+ years operations (ongoing); developed, constructed at MIT
	High Energy Transient Experiment (HETE) – Soft X-ray Camera (SXC)	LL CCID-20: Two Mosaiced Focal Planes; 2K x 4K arrays; 4 Devices Total	Oct 2000	US-Japan-France gamma-ray burst observatory; 6 years operations; satellite bus and SXC developed, constructed at MIT
	AstroE2–X-ray Imaging Spectrometer (XIS)	LL CCID-41: Single Device Focal Planes; 1K x 1K arrays; 4 Devices Total	Jul 2005	Japan-US; successfully commissioned; 6+ years operations (ongoing); focal plane, electronics developed, constructed at MIT

All MIT Lincoln Lab CCDs

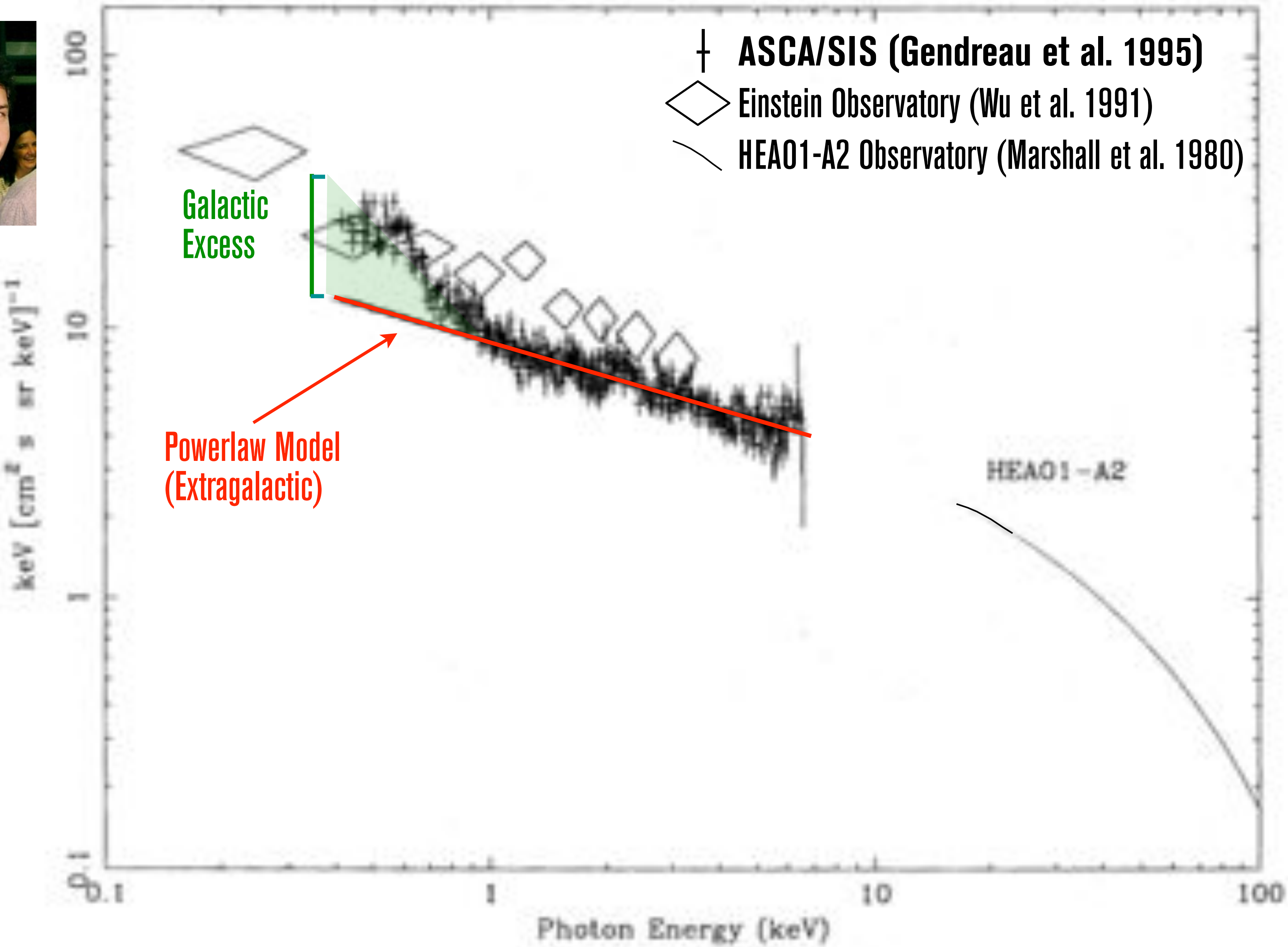
ASCA SIS X-ray Camera

Solid State Imaging Spectrometer (SIS) for the ASCA Satellite
(...First photon-counting CCD array flown in space)

ASCA (= Astro-D) Launch

ASCA launched from ISAS's Kagoshima Space Center on 20 February 1993
(Reentry on 2 March 2001)

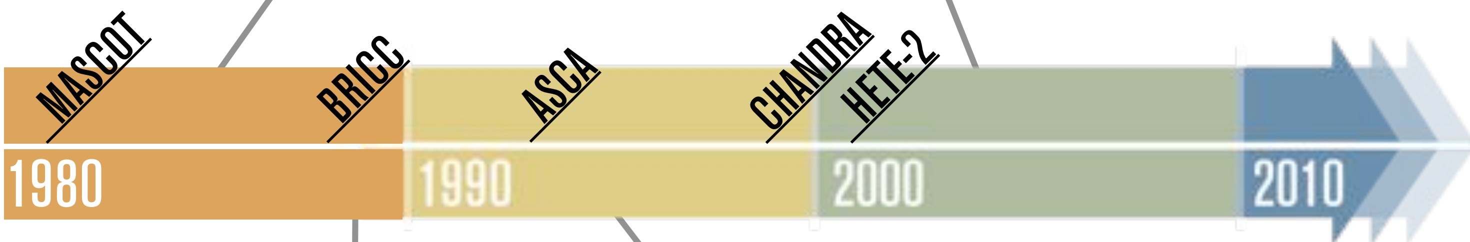
Keith Celebrating with ISAS Colleagues


ASCA/SIS (Gendreau et al. 1995)
Einstein Observatory (Wu et al. 1991)
HEAO1-A2 Observatory (Marshall et al. 1980)
Galactic Excess
Powerlaw Model (Extragalactic)
HEAO1-A2
keV [cm^2 s sr keV]$^{-1}$
100
10
1
0.1
0.1
1
10
100
Photon Energy (keV)

Dramatis Personae and Timeline

1985
Roland Vanderspek

2003
Nat Butler

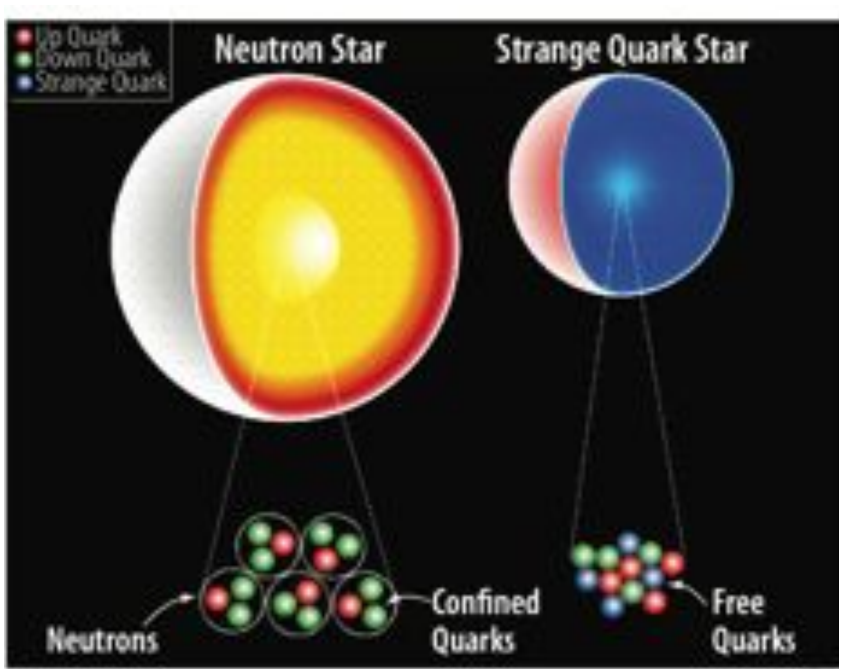


1989
Gerry Luppino

1995
Keith Gendreau

NICER on ISS 2016

Keith's Recent Initiative: NICER Mission



NICER will measure stellar radii, a key distinguisher between true neutron stars and currently indistinguishable alternatives such as quark stars.

Flight Heritage: MIT X-ray CCD Detectors

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	Advanced Satellite for Cosmology & Astrophysics (ASCA) –Solid Sate Imaging Spectrometer (SIS)	LL CCID-7: Two Hybrid Focal Planes; 420 x 420 arrays; 8 devices Total	Feb 1993	Japan-US; 8 year operations (satellite re-entry); developed, constructed at MIT
	Chandra X-ray Observatory – Advanced CCD Imaging Spectrometer (ACIS)	LL CCID-17: Mosaiced Focal Plane; 1K x 1K arrays; 10 Devices Total	Jul 1999	NASA "Great Observatory" principal imager; 12+ years operations (ongoing); developed, constructed at MIT
	High Energy Transient Experiment (HETE) – Soft X-ray Camera (SXC)	LL CCID-20: Two Mosaiced Focal Planes; 2K x 4K arrays; 4 Devices Total	Oct 2000	US-Japan-France gamma-ray burst observatory; 6 years operations; satellite bus and SXC developed, constructed at MIT
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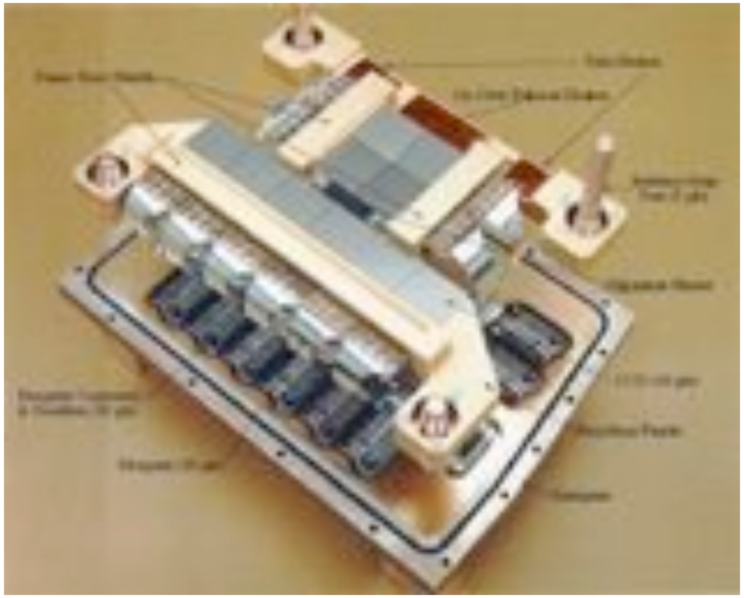
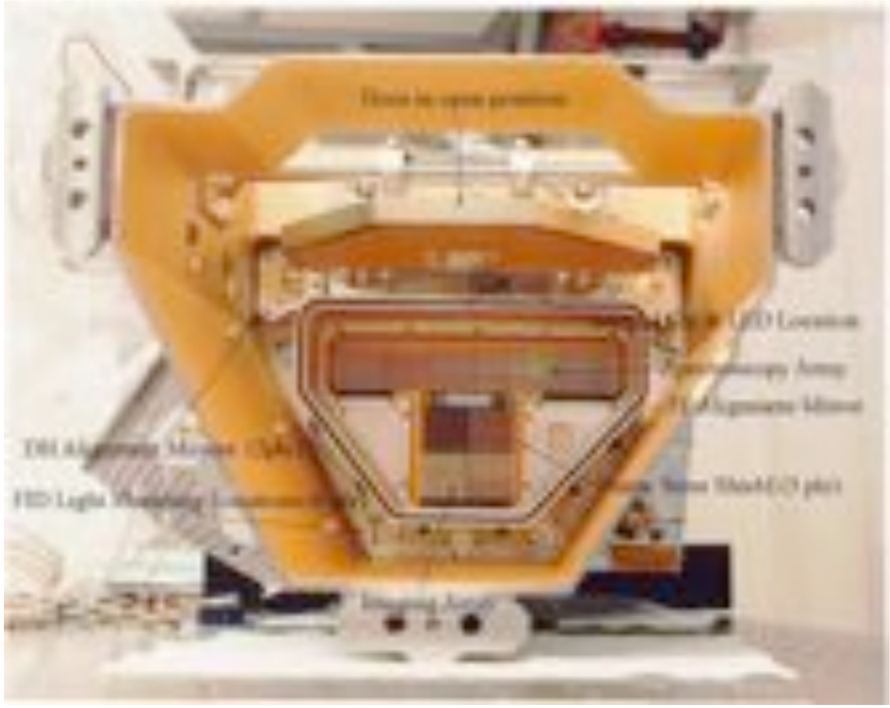
All MIT Lincoln Lab CCDs

Chandra ACIS – Two Views



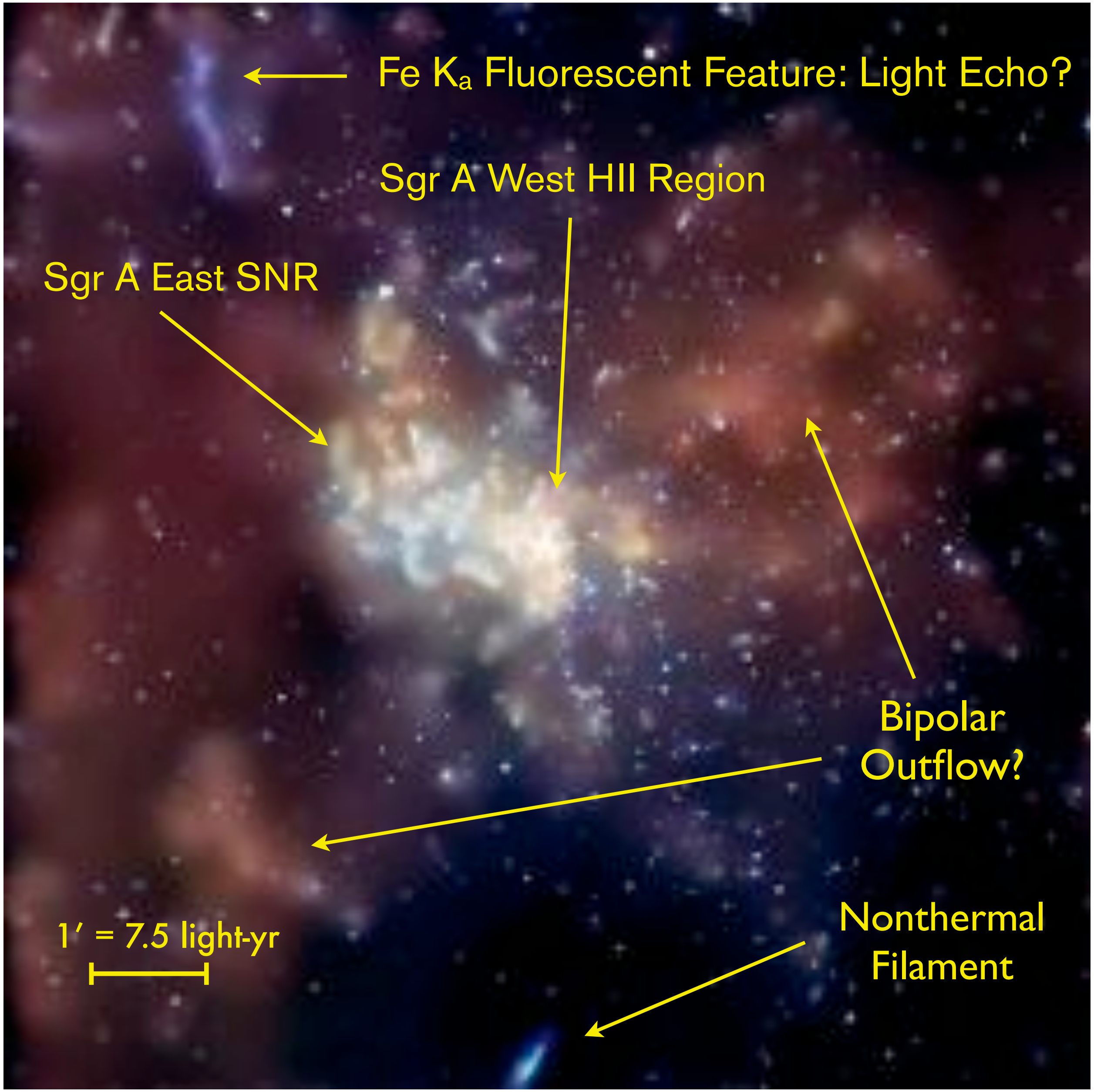
CCD Flight Focal Plane Assembly

CCDs viewed from the X-ray Telescope



Chandra launched successfully by Space Shuttle *Columbia* on 23 July 1999; ACIS still operating well

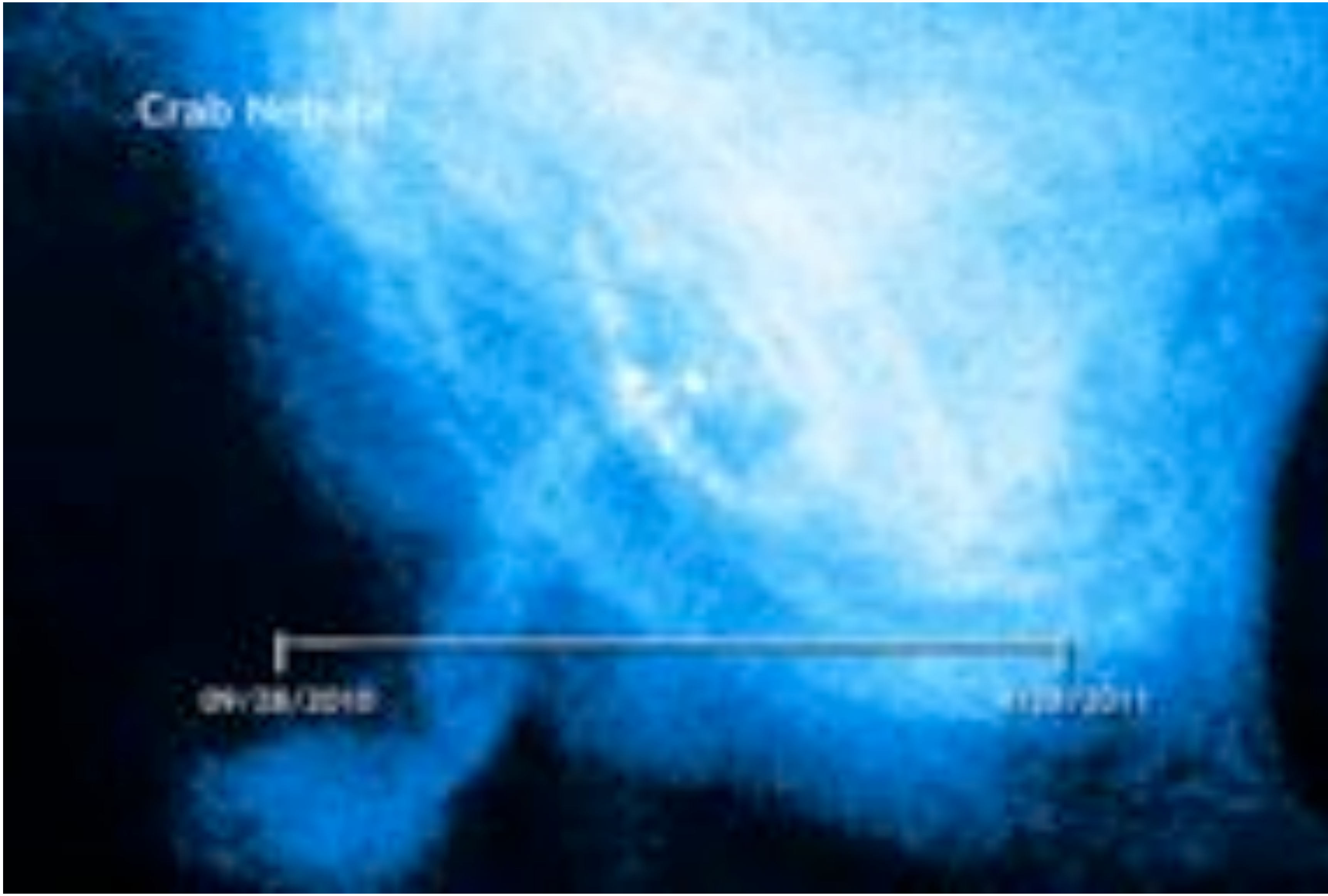
ACIS Observations of Galactic Center (Sgr A Complex)



FOV has ~2000 Cataclysmic Variables & X-Ray Bursters

Bagenoff et al. 2003

Crab Nebula over Seven Months with ACIS



Weisskopf et al 2011

Act 4: Nat Butler

Act 4: Nat Butler
"X-ray CCDs in Space: Large FOVs"
Featuring X-ray Flashes, Dark GRBs, Collapsars, and Shredded Stars
… HETE-2 ➔ Swift ➔ RATIR

(MIT PhD 2003; currently Assistant Professor, Arizona State University)

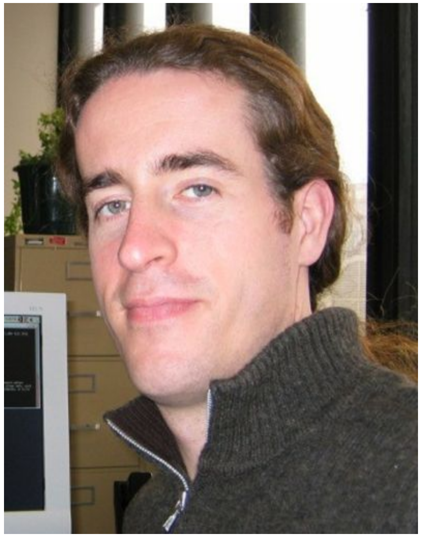
Nat's Thesis Abstract

The First 2.5 Years of HETE: Toward an Understanding of the Nature of Short and Long Duration Gamma-Ray Bursts

by

Nathaniel Richard Butler

Submitted to the Department of Physics
on August 29, 2003, in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy in Physics



Abstract

The HETE satellite became operational on the 2nd of February, 2001. In the first 2.5 years of the mission prior to July 1 of 2003, 42 Gamma-ray bursts (GRBs) were promptly localized and publicized over the GRB Coordinates Network (GCN). The first part of this thesis deals with the detection of GRBs in data down-linked from the HETE satellite using a suite of automated routines. This "ground triggering" was designed to supplement the HETE on-board triggering systems. To date, it has facilitated the broadcast of six HETE GRBs to the GCN. A novel trigger search routine using wavelets, which is included in the suite, is discussed. Near real time searches for very long duration (> 300s) GRBs using this and other methods are presented. The second part of the thesis focuses on imaging observations with Chandra of two GRB X-ray afterglows and high-resolution spectroscopic observations of five GRB X-ray afterglows. The imaging observations explore the nature of the class of short/hard GRBs and the class of "optically dark" GRBs, while the spectroscopic observations probe the relation of the long/soft class of GRBs to supernovae. Our observations suggest that no long/soft GRBs are optically dark. Rather, many appear to be "optically faint." In one case, a short/hard GRB may have been optically dark, because it lacked entirely an afterglow in the optical, radio, and X-ray bands. Finally, If the emission lines we detect in a Chandra spectrum of the X-ray afterglow to GRB 020813 are real, then a supernova likely occurred $\gtrsim 2$ months prior to the GRB. The statistical significance of the discrete spectral features reported to date in high resolution spectra taken with Chandra are discussed in detail, as the believability of the features is critical to moving forward in the field.

Thesis Supervisor: George R. Ricker
Title: Senior Research Scientist, Center for Space Research

Flight Heritage: MIT X-ray CCD Detectors

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	High Energy Transient Experiment (HETE) – Soft X-ray Camera (SXC)	LL CCID-20: Two Mosaiced Focal Planes; 2K x 4K arrays; 4 Devices Total	Oct 2000	US-Japan-France gamma-ray burst observatory; 6 years operations; satellite bus and SXC developed, constructed at MIT
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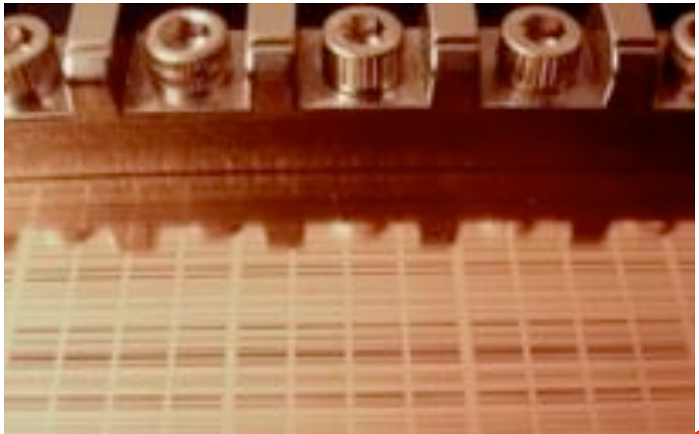
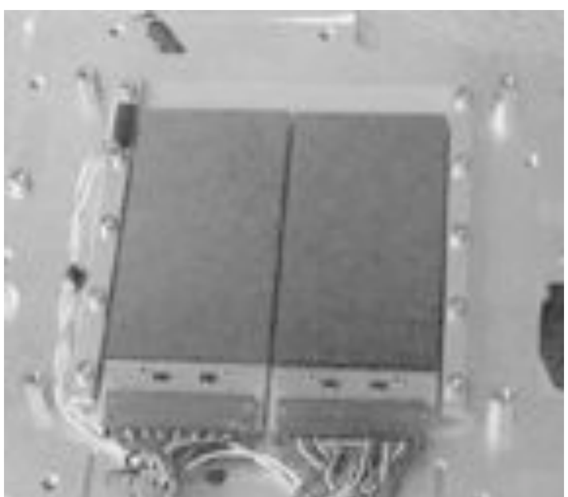
All MIT Lincoln Lab CCDs

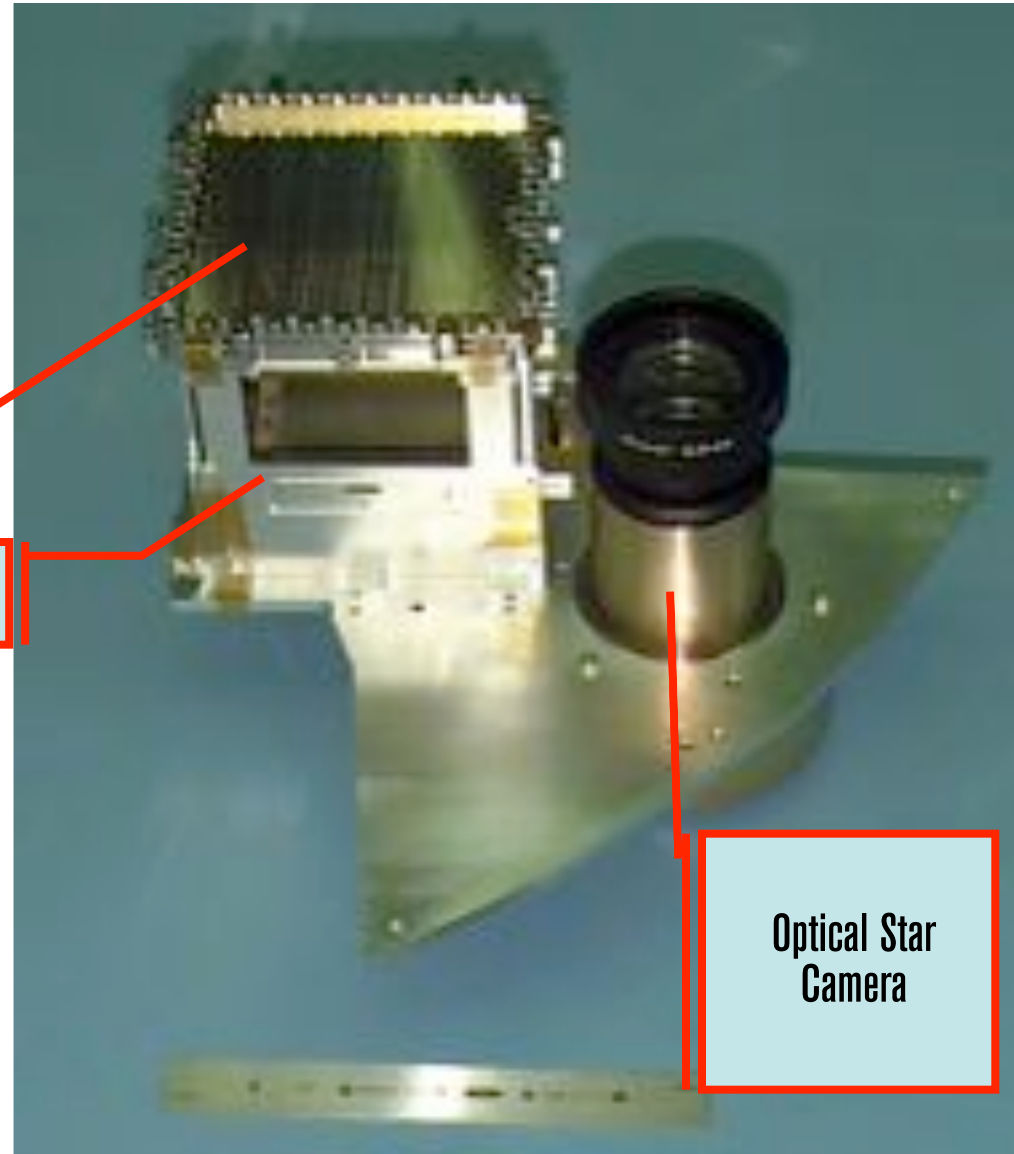
Assembly of HETE-2 Soft X-ray Camera (SXC)



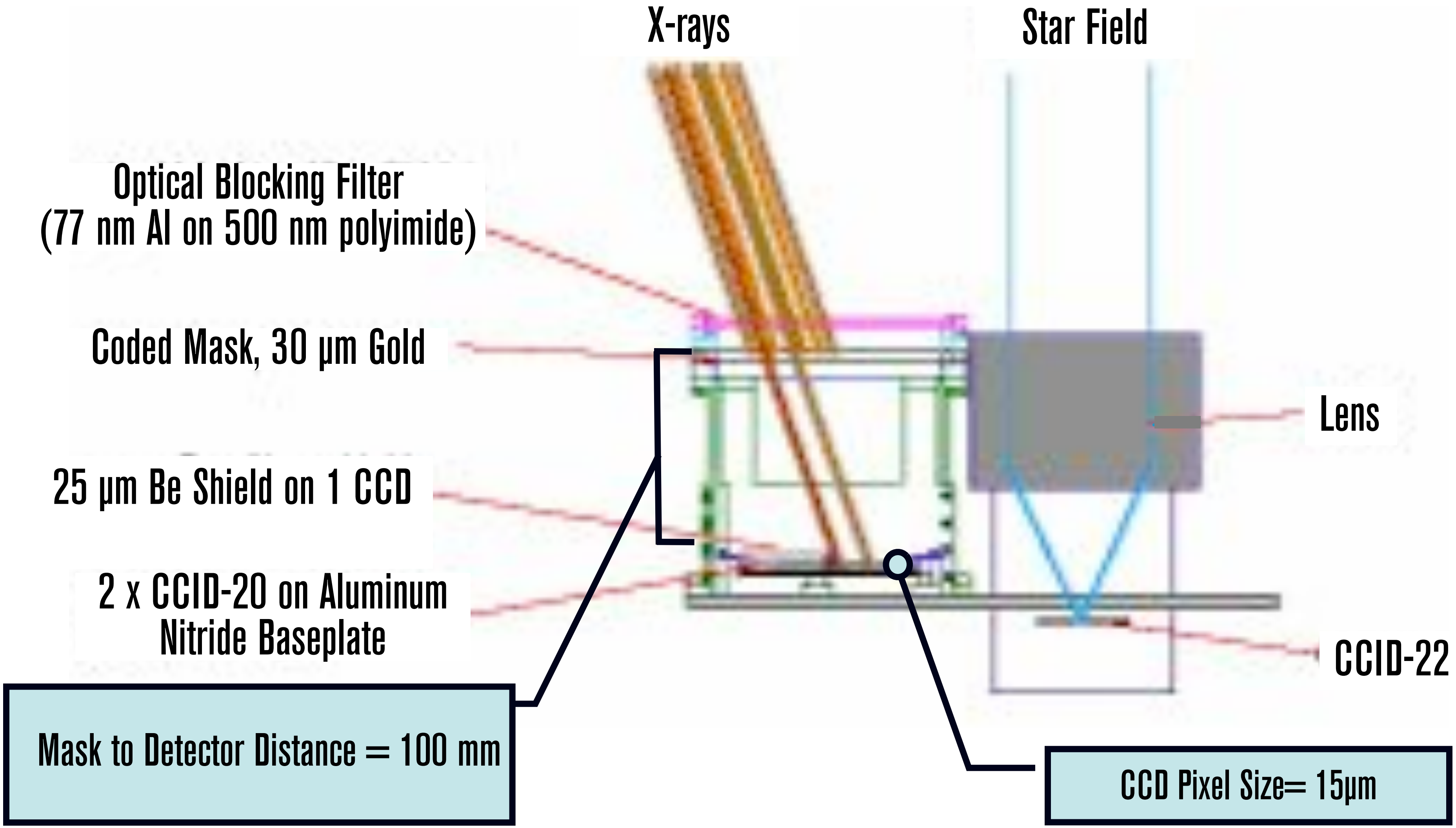
Coded Mask

X-ray CCDs

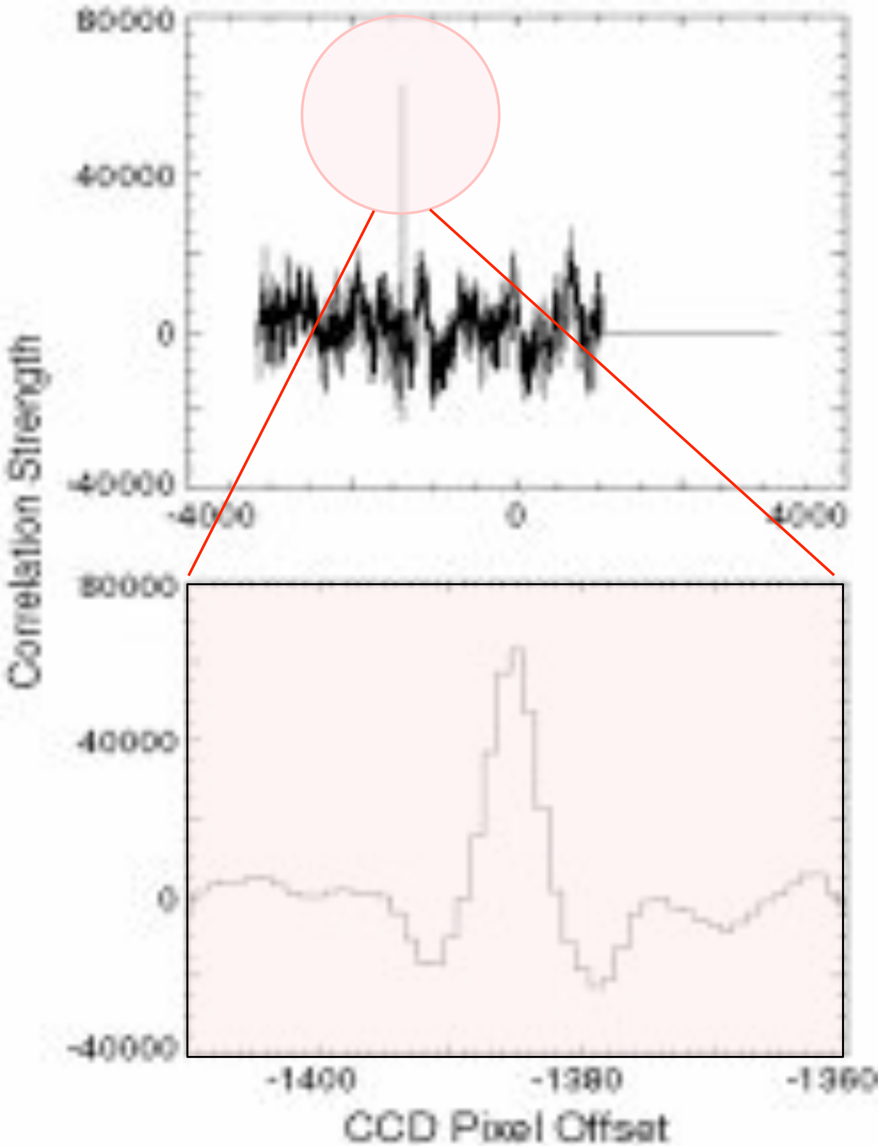




Schematic of HETE-2 Soft X-ray Camera (SXC)



Mask Pattern Correlation for HETE-2 SXC



Entire Correlation Space

Close-up of Correlation Peak

NB:
1 correlation step is ~ 30”

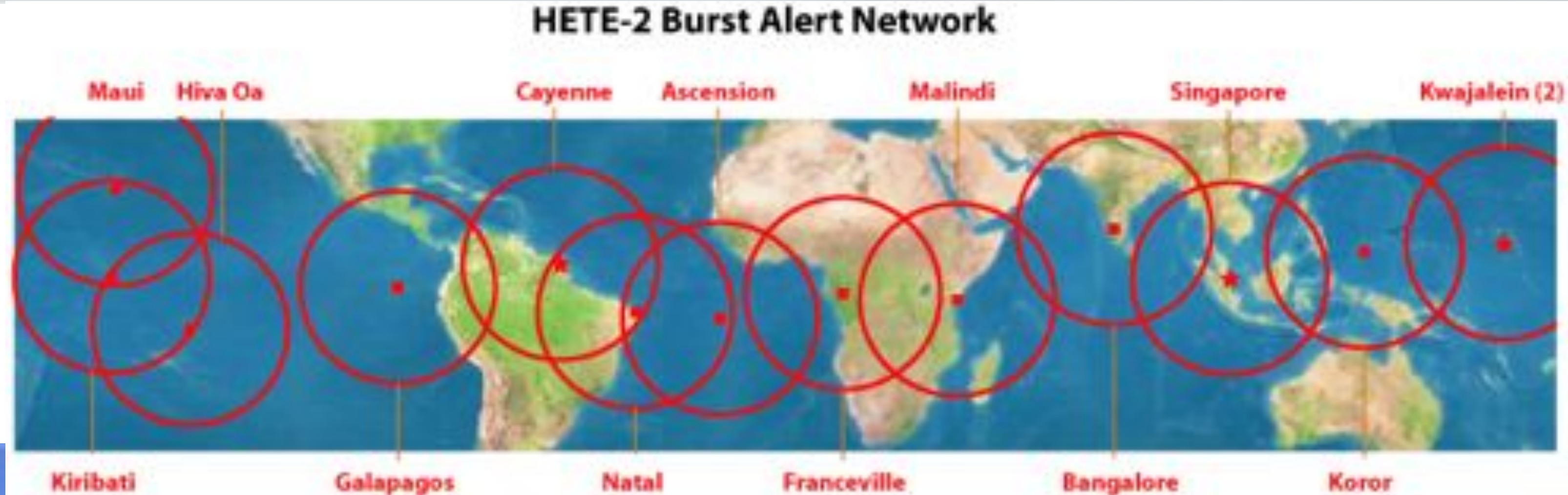
∴ ~3-5” locations achievable for high S/N detections in SXC

SXC Flight Unit on HETE-2 Satellite

SXC= Soft X-ray Camera

OBC= Optical Boresight Camera

Nat's Preparation for HETE-2 Launch



MIT CCD Group:

--Constructed the SXC and optical cameras

--Built the spacecraft bus

--Integrated & tested the instruments & bus

--Developed a dedicated HETE-2 telemetry network

--Participated in the launch

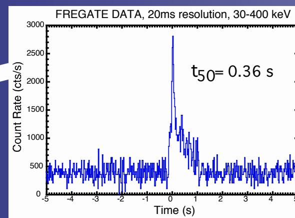
--Operated the satellite 24/7

--Analyzed & published the science data (with HETE-2 Science Team)

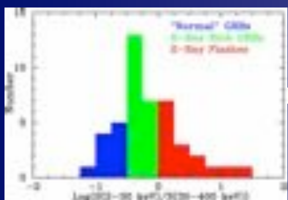
Launch of HETE-2 on a Pegasus Rocket

HETE-2 GRB MicroSat (125 kg): Operated 2000-2006

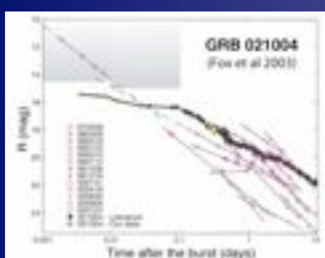
HETE-2 Gamma-ray Bursts: Six Major Scientific Insights



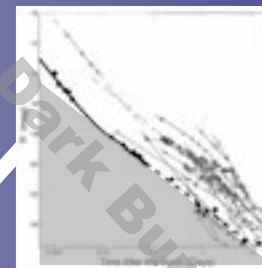
GRB020531:
First detection of short GRB with prompt optical/X-ray followup



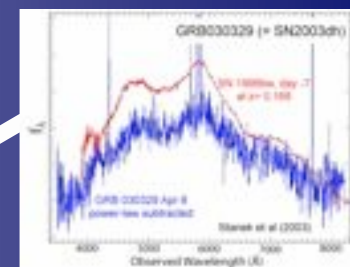
GRB020903:
Elucidation of "X-ray Flashes"



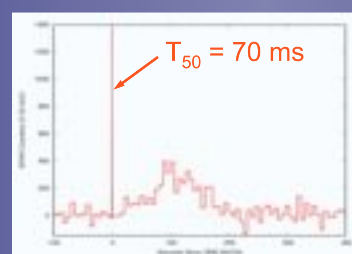
GRB021004:
Refreshed shock or inhomogeneous jet



GRB021211:
Insight into "Optically Dark" GRB Mystery



GRB030329:
GRB-SN Connection (SN2003dh; z=0.168)



GRB050709:
Short-hard GRB identified (z=0.16)

Nat's Recent work: SN2011fe in Whirlpool Galaxy

Li et al. , Nature, **480,** 348-350 (15 December 2011)

LETTER RESEARCH

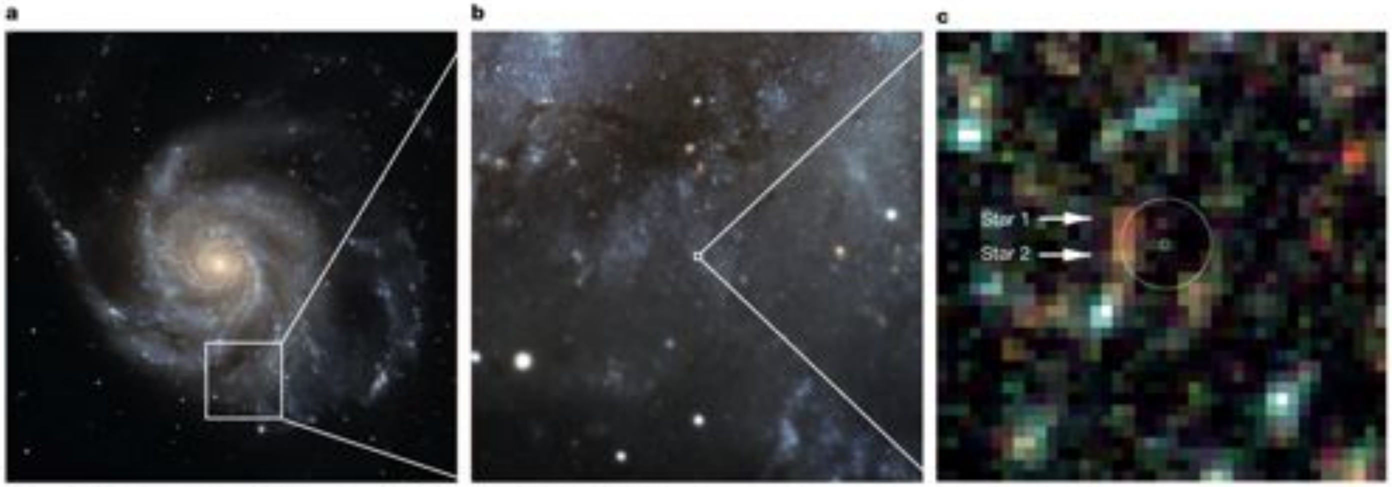


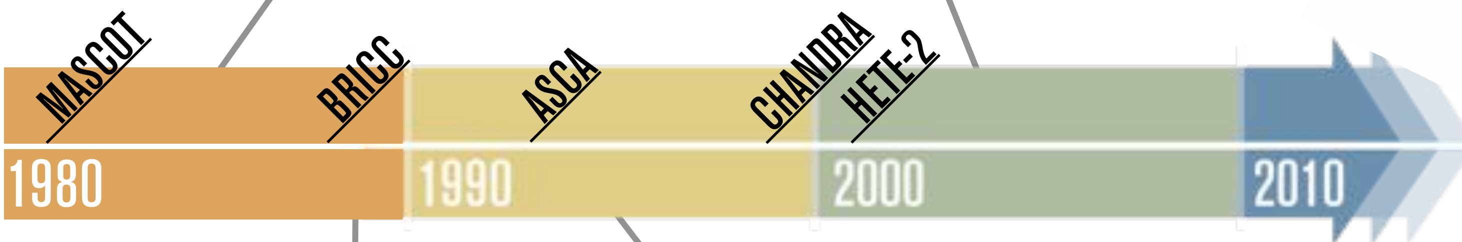
Figure 1 | The site of SN 2011fe in galaxy M101 as imaged by the Hubble Space Telescope/Advanced Camera for Surveys. **a**, A full-view colour picture of the face-on spiral galaxy M101 (18′ × 18′ field of view) constructed from the three-colour Hubble Space Telescope/Advanced Camera for Surveys images taken at multiple mosaic pointings. North is up and east to the left. M101 displays several well-defined spiral arms. With a diameter of 170,000 light years, M101 is nearly twice the size of our Milky Way Galaxy, and is estimated to contain at least one trillion stars. **b**, A cutout section (3′ × 3′) of **a**, centred on the supernova location. SN 2011fe is spatially projected on a prominent spiral arm. **c**, A cutout section (2″ × 2″) of **b** centred on the supernova location, which is marked by two circles. The smaller circle has a radius of our 1σ astrometric uncertainty (21 mas), and the bigger circle has a radius of nine times that. No object is detected at the nominal supernova location, or within the 8σ error radius. Two nearby red sources are labelled 'Star 1' and 'Star 2'; they are displaced from our nominal supernova location by about 9σ, and hence are formally excluded as viable candidate objects involved in the progenitor system of SN 2011fe. Credit for the colour picture in **a** (from http://hubblesite.org): NASA, ESA, K. Kuntz (JHU), F. Bresolin (University of Hawaii), J. Trauger (Jet Propulsion Lab), J. Mould (NOAO), Y.-H. Chu (University of Illinois, Urbana) and STScI.

Conclusion: Luminous red giant companion is excluded a progenitor to youngest Type 1a supernova ever discovered

1985
Roland Vanderspek

2003
Nat Butler

*



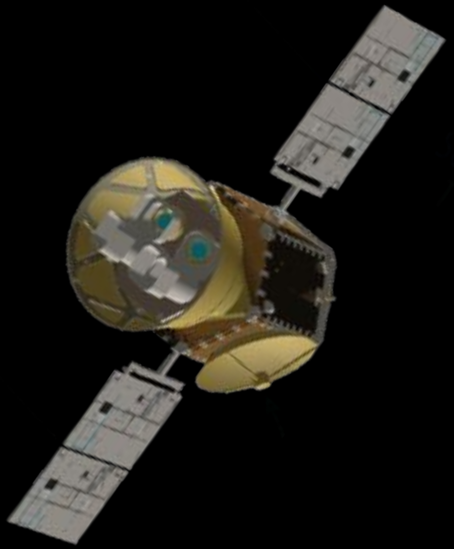
1989
Gerry Luppino

1995
Keith Gendreau

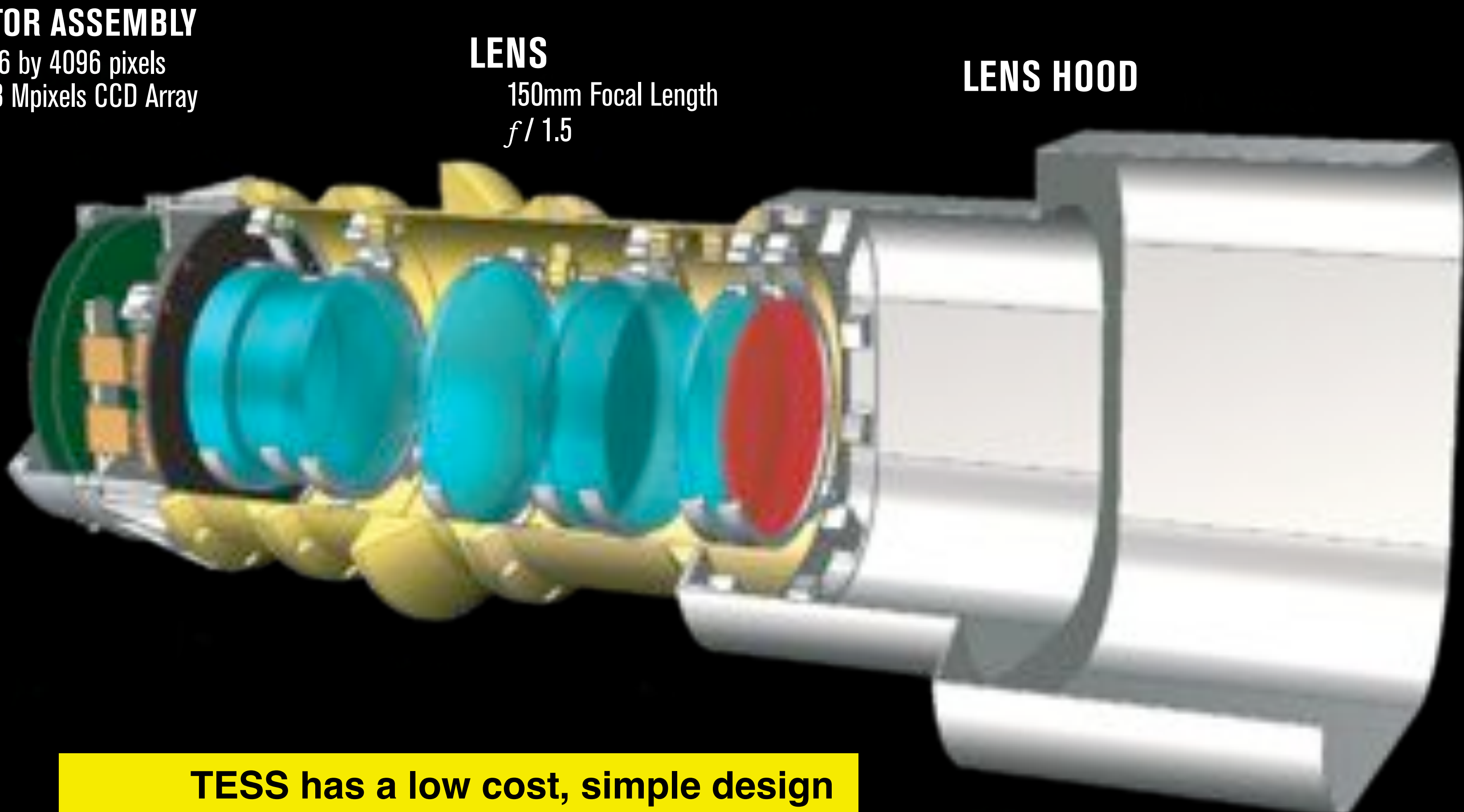
Transiting Exoplanet Survey Satellite (TESS)

What is TESS?

- TESS is an Explorer Class Mission selected by NASA in 2011 for Phase A Study
  - ➡ Previously selected for Phase A in last SMEX round
  - ➡ Launch planned in 2016
- TESS will conduct the first All Sky Exoplanet Search from space
  - ➡ Two year survey duration
  - ➡ Targets stars brighter than ~12 magnitude
- TESS is low cost and simple in design
  - ➡ Payload has four wide FOV cameras



TESS Camera Assembly

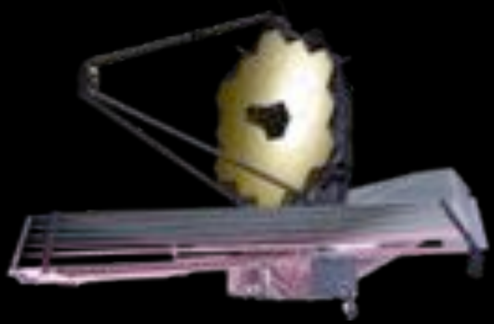


TESS has a low cost, simple design based on four wide FOV cameras

TESS Science Legacy

- **TESS will discover new exoplanets transiting the "best stars" for followup: the *<u>nearest</u>* and *<u>brightest</u>* stars**
  - ➡ TESS will monitor 500,000 stars
  - ➡ TESS science goals focus on
    - ➡ Earths and super-Earths (<2.0 R_E)
    - ➡ Host stars with stellar types F5 to M5

- **TESS provides ELTs and JWST with the very best exoplanet targets for detailed characterization**



Thank You!