HTRA Instrumentation I

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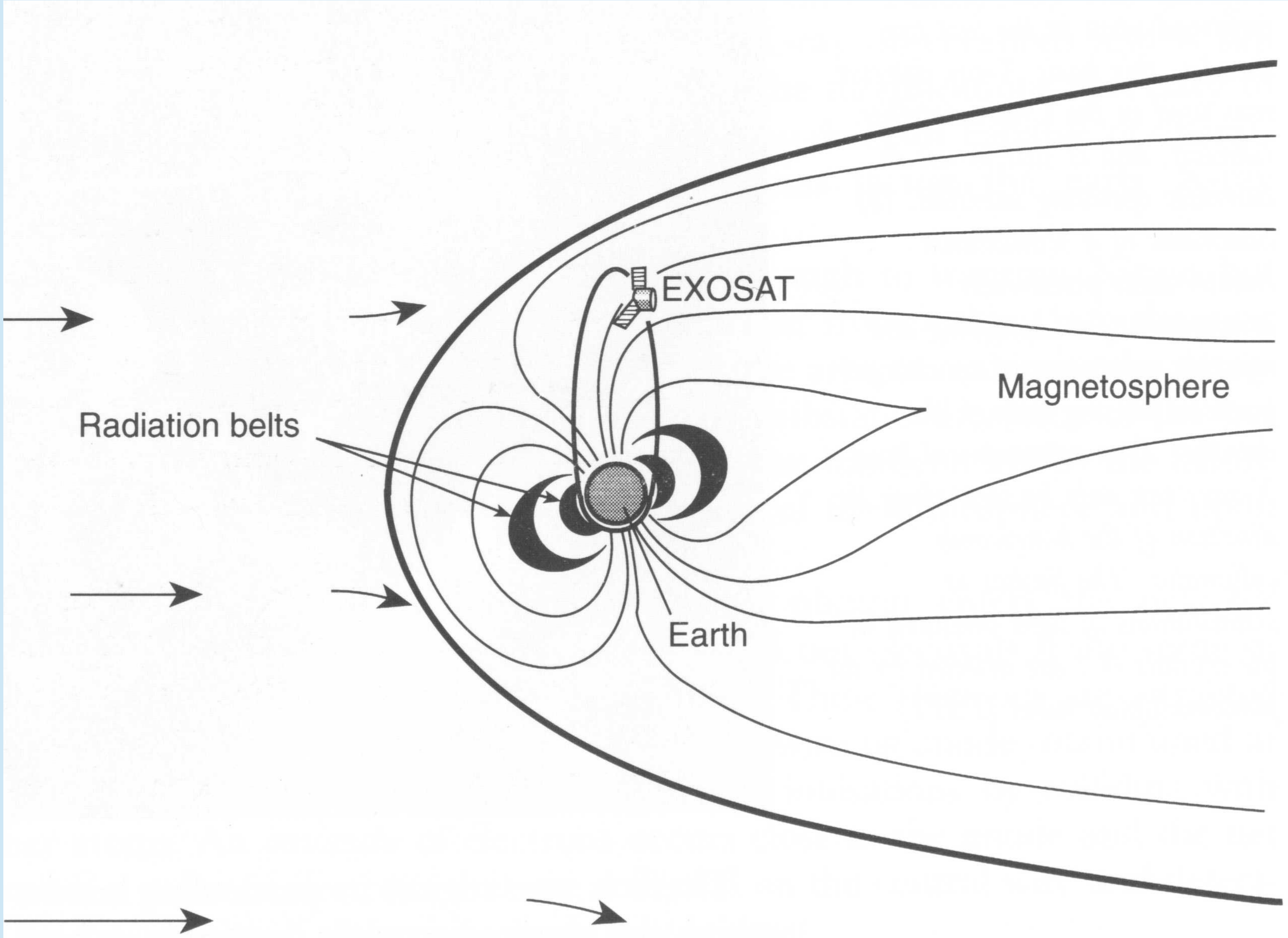
Lecture 2:

1. Current technologies used for HTRA
2. X-rays:
   - RXTE (1996) to ASTROSAT (2015)
   - Chandra, XMM
   - NuSTAR
3. Visible/IR:
   - MCPs, EMCCDs, APDs
4. UV:
   - HST, GALEX

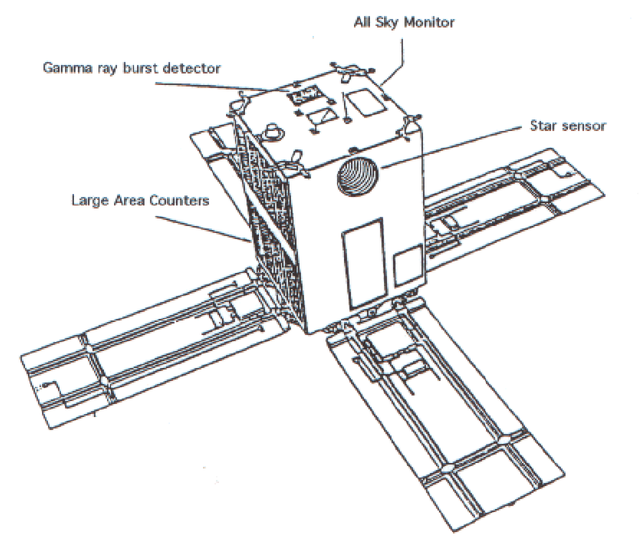
EXOSAT 1983-86

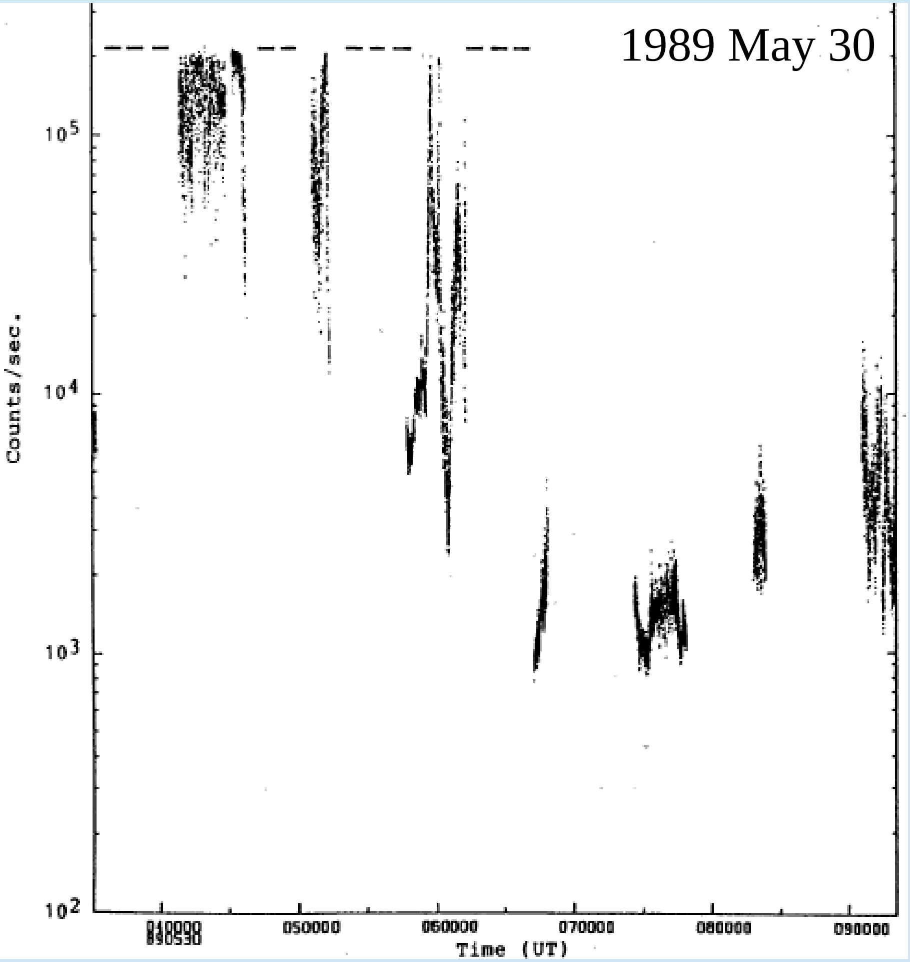


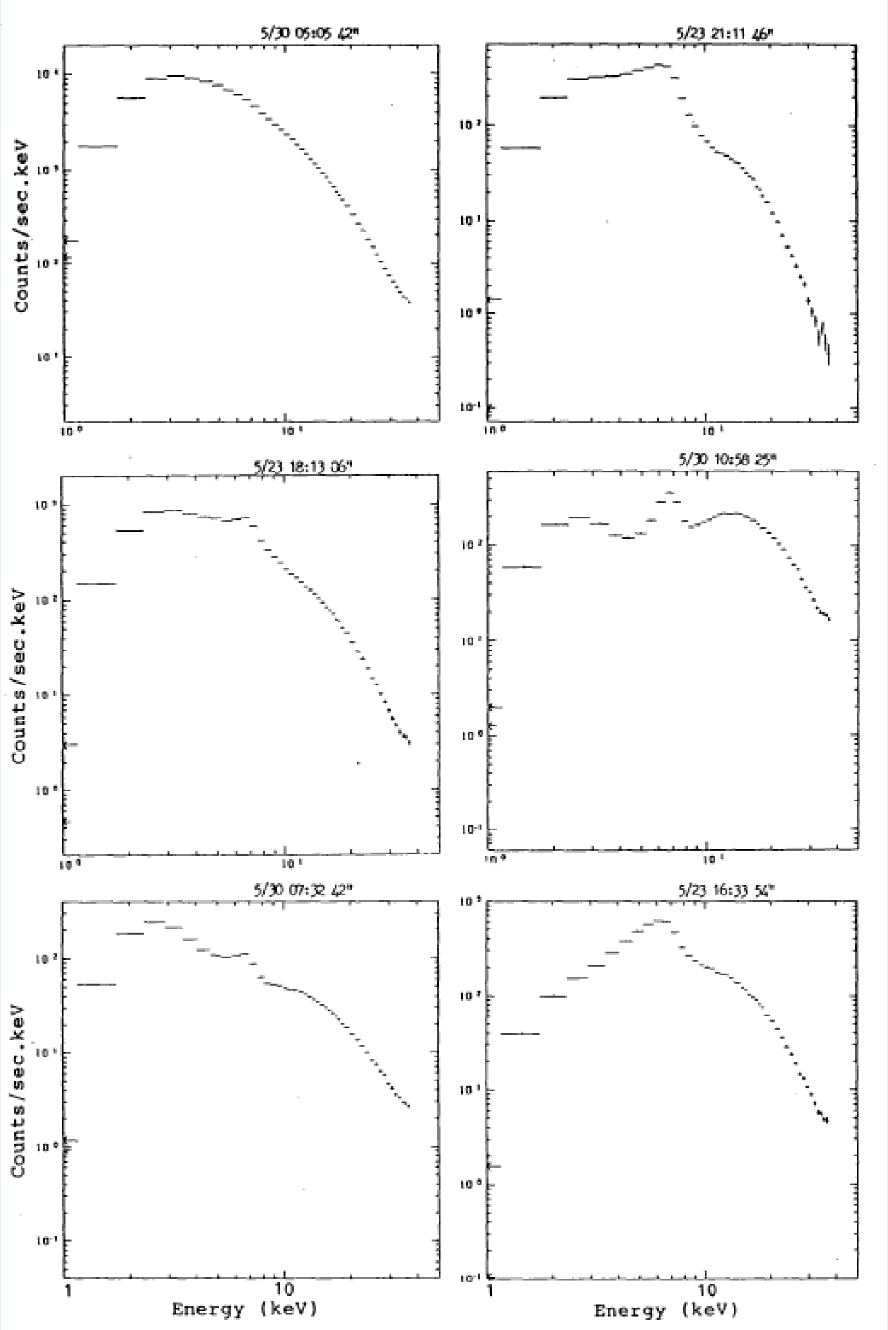
What is the main problem for operations in this orbit?

Ginga 1987-1991

- LAC large area prop counter
  - Energy Range 1.5-30 keV
  - QE >10% over E range
  - Eff Area 4000cm^2
  - FoV 0.8x1.7 sq deg
  - Ar:Xe:CO_2 @ 2Atm
  - Energy Res: <20% @ 6 keV
  - Sensitivity (2-10 keV) 0.1 mC
- ASM (1-20 keV)
  - 2 prop counters 1''x45'' FoV
- GBD (1.5-500 keV, 31.1 msec)




1989 May 30



May 30 → “saturation” at ~21Crab?

And dramatic spectral variations

- including large N_X changes

→ local, variable absorption
(up to ~5×10^{23} cm^{-2})

- hard PL ($\Gamma \sim 1$), but no “ultrasoft” component (but see Zycki+99)

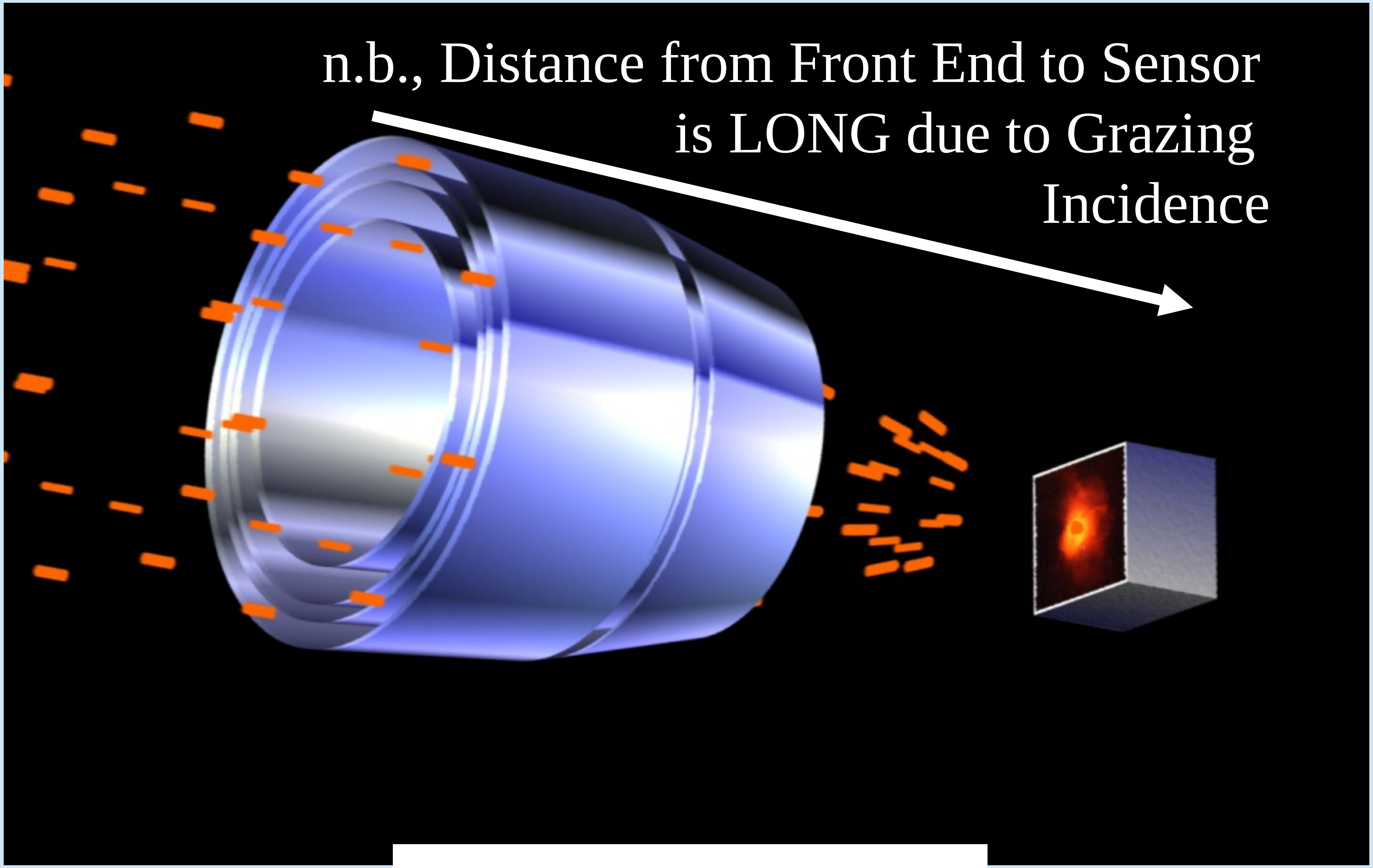
RXTE (1995-2012)

- Detectors: 5 proportional counters
- Collecting area: 6500 cm^2
- Energy range: 2 - 60 keV
- Energy resolution: < 18% at 6 keV
- Time resolution: 1 μs
- Spatial resolution: collimator with 1 degree FWHM
- Layers: 1 Propane veto; 3 Xenon, each split into two; 1 Xenon veto layer
- Sensitivity: 0.1 mCrab Background: 90 mCrab

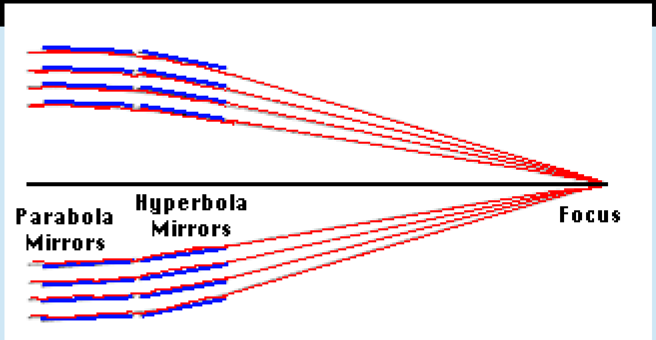
Scientific Gains from Imaging

- Increase S/N and thus sensitivity
  - Reduce detector volume and thus the associated background
- Allow more accurate background estimation
  - using background events from immediate vicinity of source
- Enable study of extended objects
  - e.g. SNRs, clusters of galaxies, galaxies, diffuse emission, jets, …
- Minimize source confusion
  - e.g. study source distributions in nearby galaxies
- Provide more precise source locations
  - identify counterparts at other wavelengths
- But how do you “image” X-rays?

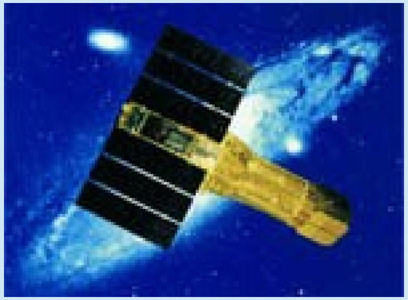
X-ray Collecting Mirrors



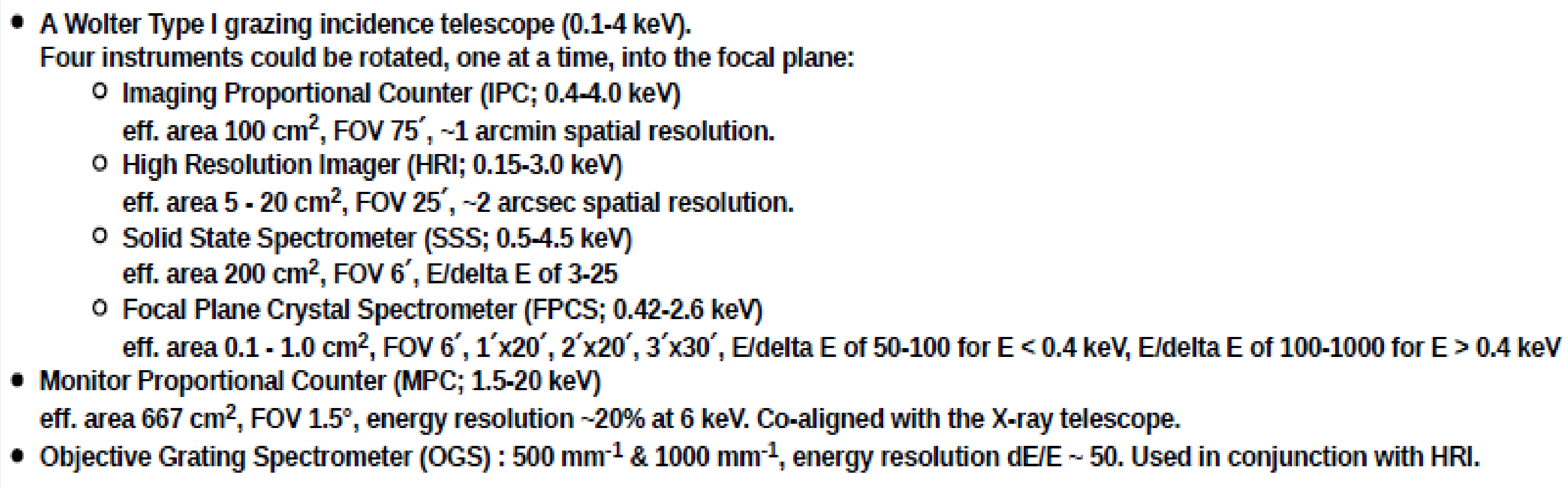
n.b., Distance from Front End to Sensor is LONG due to Grazing Incidence



Einstein Observatory (HEAO-B): 1979-1981

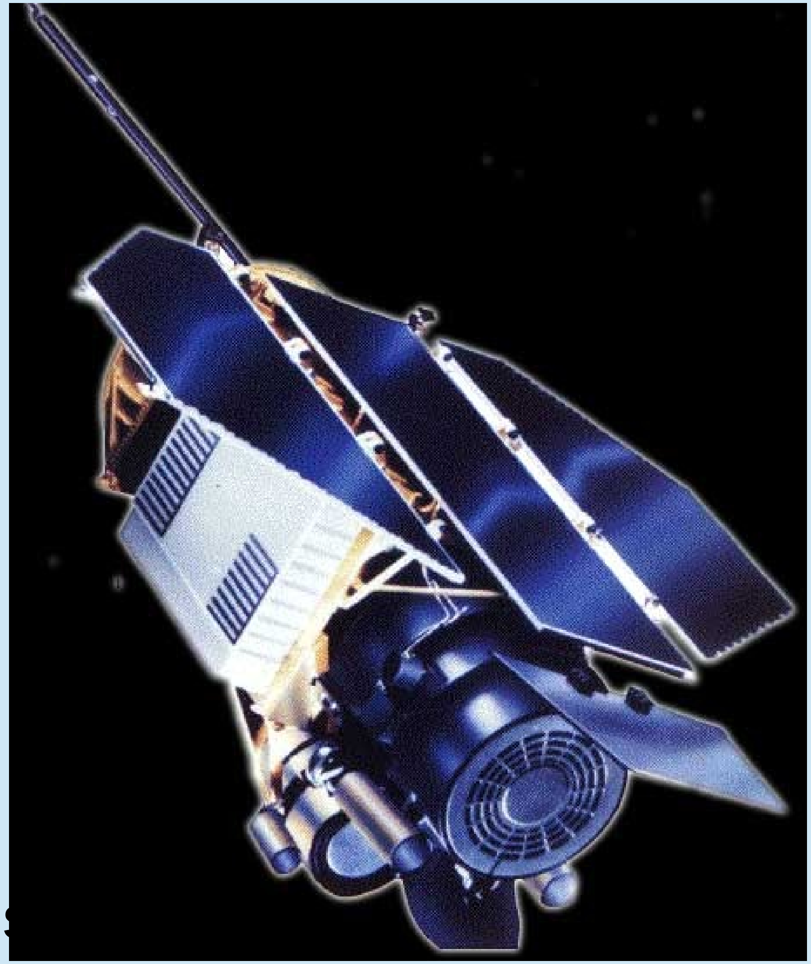


- First X-ray imaging telescope in space



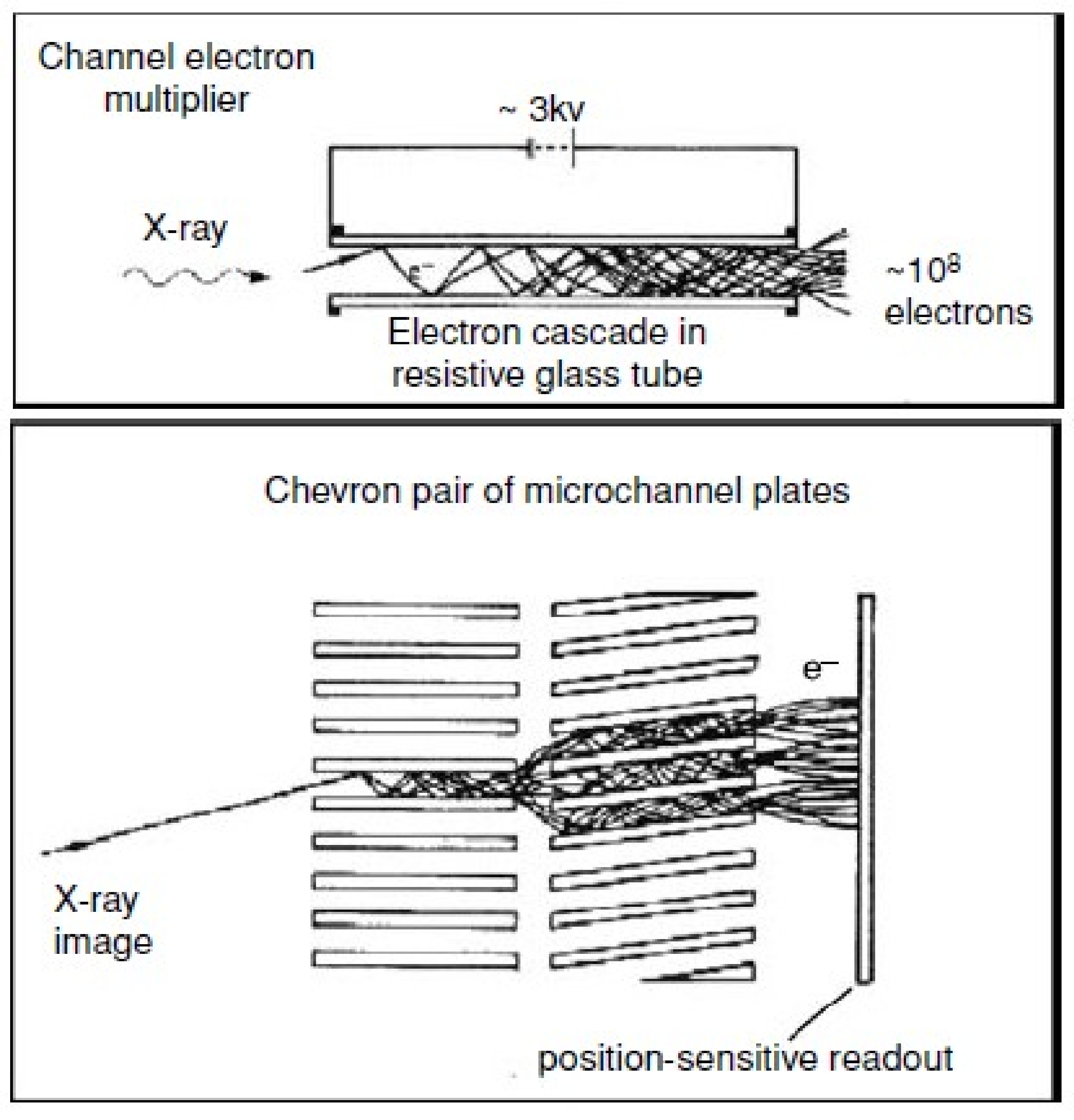
- A Wolter Type I grazing incidence telescope (0.1-4 keV).
  Four instruments could be rotated, one at a time, into the focal plane:
  - Imaging Proportional Counter (IPC; 0.4-4.0 keV)
    eff. area 100 cm^2, FOV 75′, ~1 arcmin spatial resolution.
  - High Resolution Imager (HRI; 0.15-3.0 keV)
    eff. area 5 - 20 cm^2, FOV 25′, ~2 arcsec spatial resolution.
  - Solid State Spectrometer (SSS; 0.5-4.5 keV)
    eff. area 200 cm^2, FOV 6′, E/delta E of 3-25
  - Focal Plane Crystal Spectrometer (FPCS; 0.42-2.6 keV)
    eff. area 0.1 - 1.0 cm^2, FOV 6′, 1′x20′, 2′x20′, 3′x30′, E/delta E of 50-100 for E < 0.4 keV, E/delta E of 100-1000 for E > 0.4 keV
- Monitor Proportional Counter (MPC; 1.5-20 keV)
  eff. area 667 cm^2, FOV 1.5°, energy resolution ~20% at 6 keV. Co-aligned with the X-ray telescope.
- Objective Grating Spectrometer (OGS) : 500 mm^{-1} & 1000 mm^{-1}, energy resolution dE/E ~ 50. Used in conjunction with HRI.

ROSAT:
1990-1999

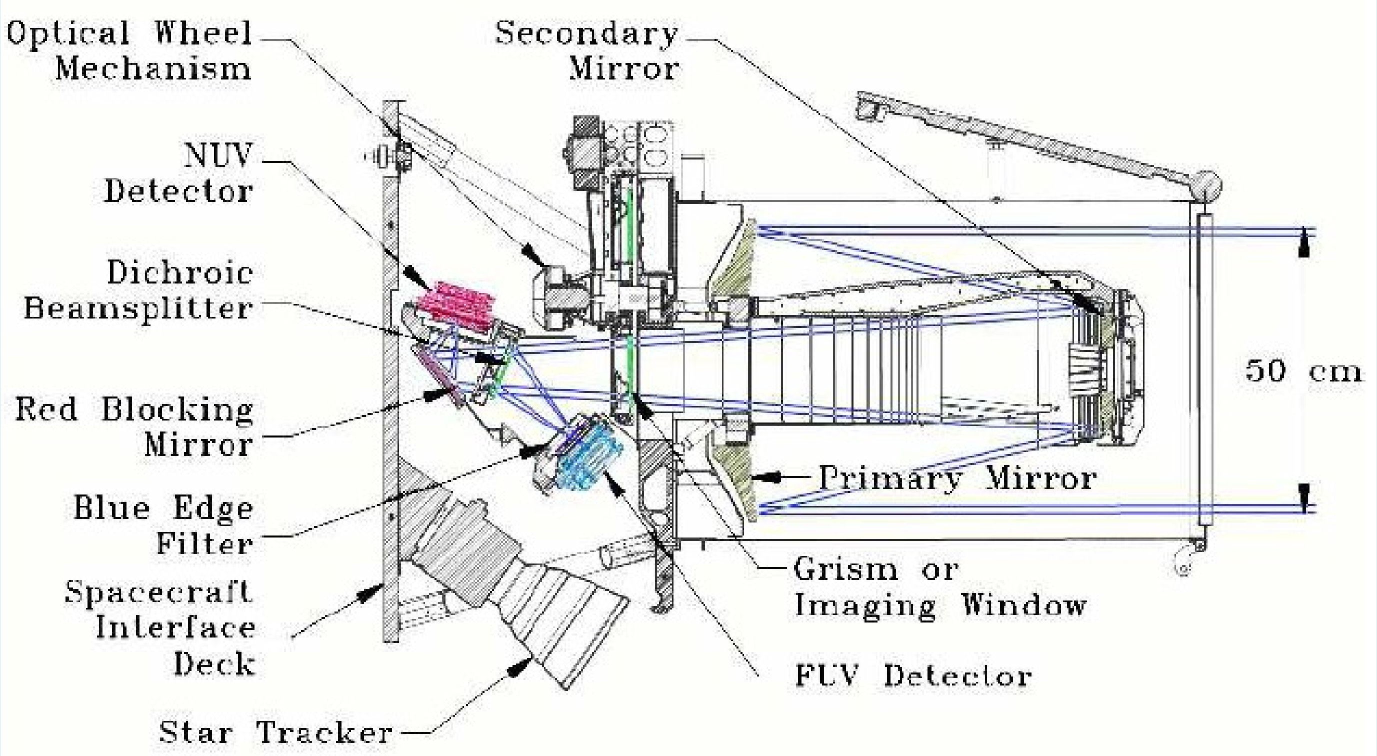


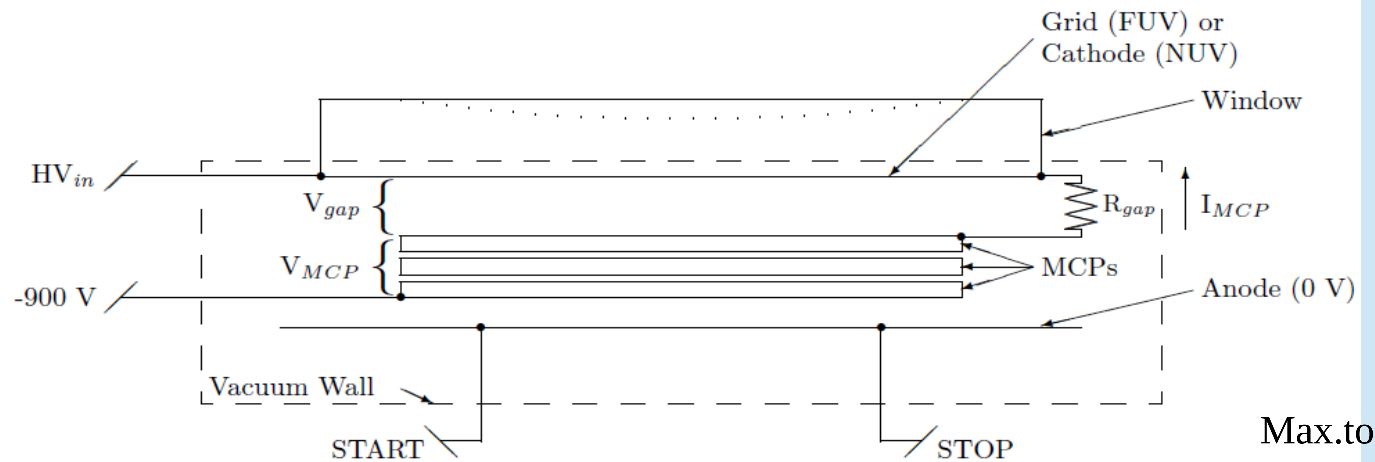
- 2 Position Sensitive Proportional Counters
  - 5 arcsec pos res
  - 0.1-2 keV
  - FoV 2 degrees
  - Eff area 240 cm^2 @ 1keV
  - Energy resn: 17% @ 6 keV
- Soft X-ray Imaging: >150 000 sources
- Low Resolution Spectroscopy

Microchannel Plates (MCPs)



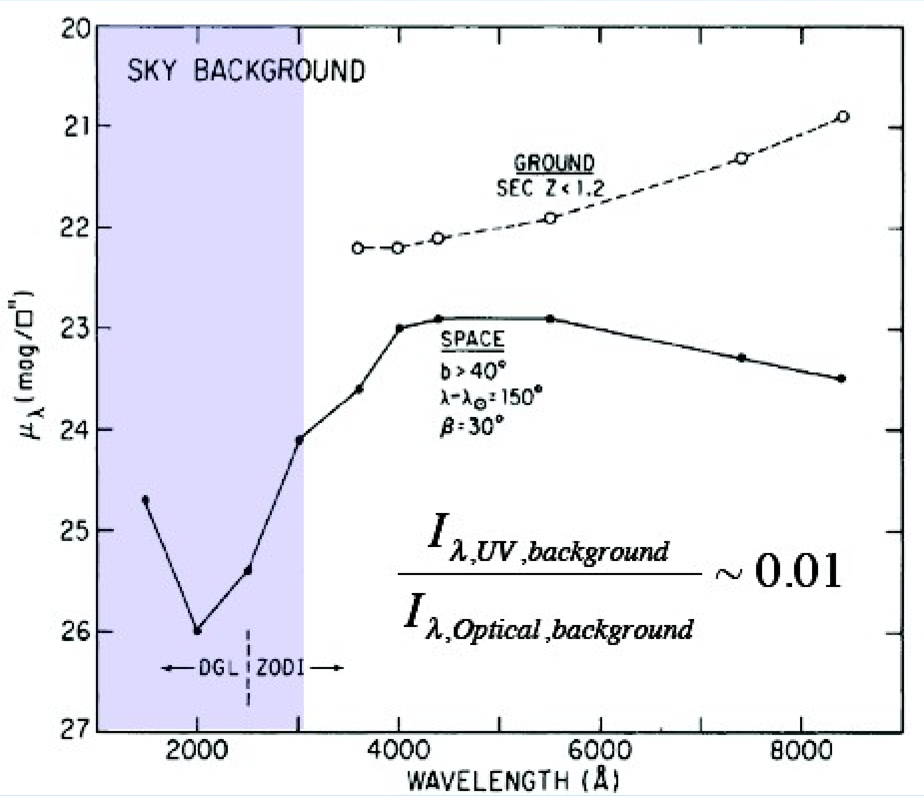
UV instrumentation: GALEX



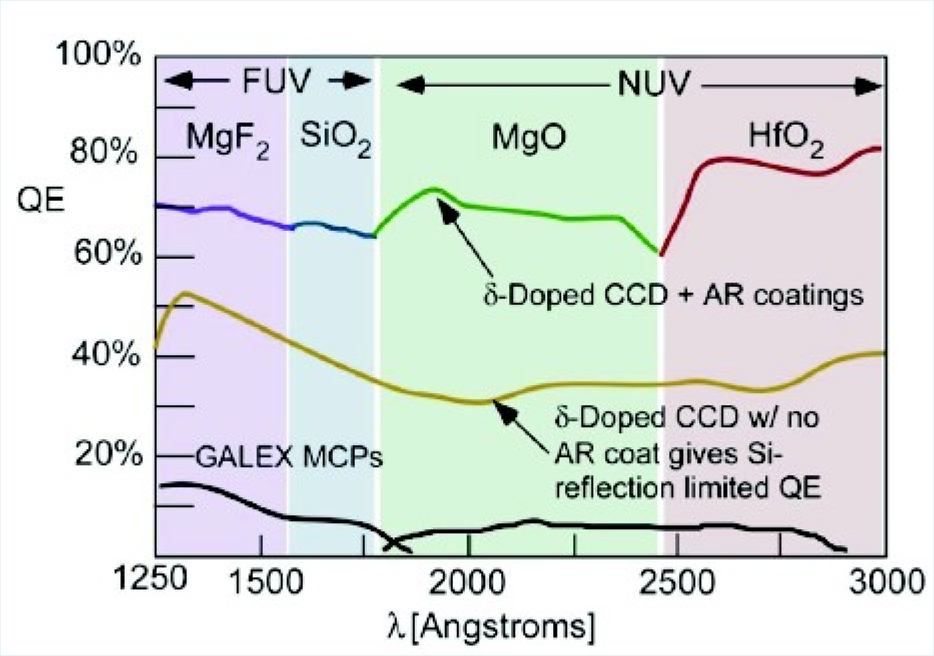


Max.total c.r.~30,000cps

UV sky b/g extremely dark → photon-counting essential to overcome detector noise



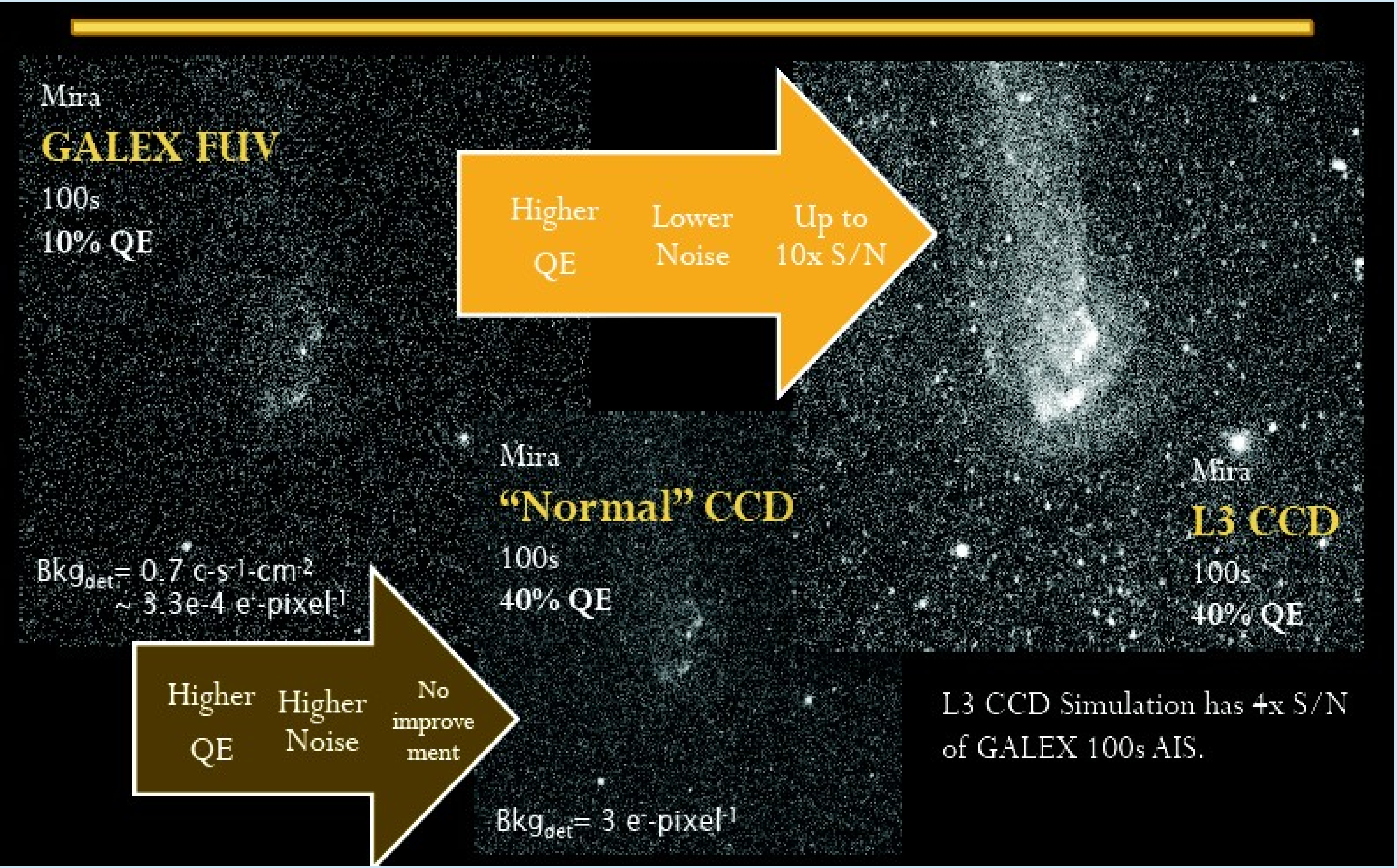
$$\frac{I_{\lambda,UV,background}}{I_{\lambda,Optical,background}} \sim 0.01$$



Next gen. enhanced UV CCDs + low noise L3

Peak photocathode efficiency ~20%

MCP vs CCD vs L3CCD



Mira
GALEX FUV
100s
10% QE

$Bkg_{det} = 0.7\ c\text{-}s^{-1}\text{-}cm^{-2}$
$\sim 3.3e\text{-}4\ e^{-}\text{-}pixel^{-1}$

Higher QE
Higher Noise
No improvement

Mira
"Normal" CCD
100s
40% QE

$Bkg_{det} = 3\ e^{-}\text{-}pixel^{-1}$

Higher QE
Lower Noise
Up to 10x S/N

Mira
L3 CCD
100s
40% QE

L3 CCD Simulation has 4x S/N of GALEX 100s AIS.

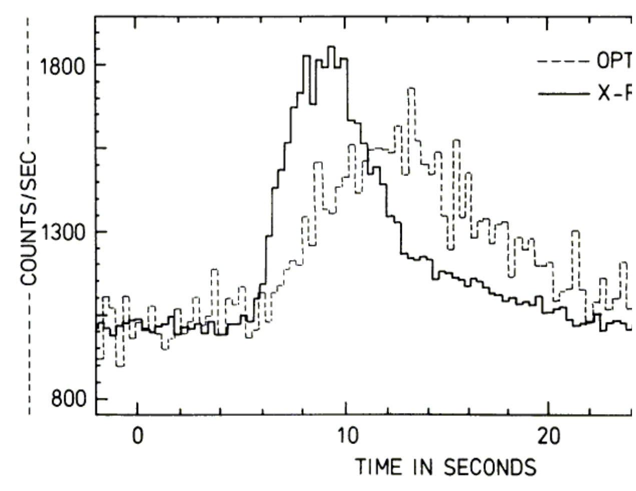
Morrissey11

Simultaneous RXTE/HST/Gemini observations of X-ray bursts →

Optical counterparts with time lags consistent with light travel times within the binary

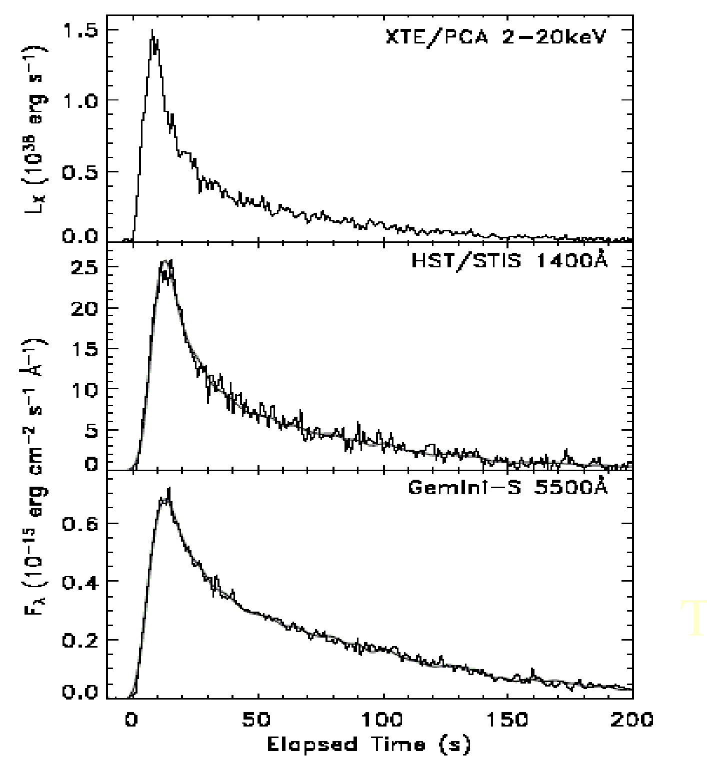
Truemper et al. 1985 SSRv

4U1636-53



Lag ~ 3 s

Hynes et al. 2006 ApJ



X0748-676

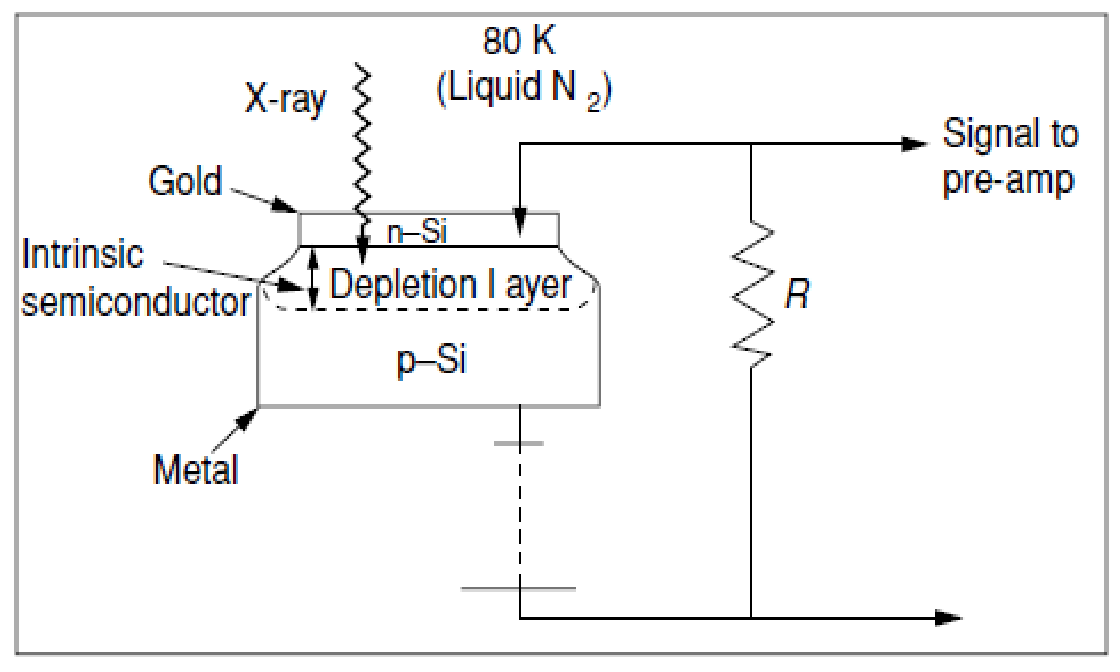
Lag = 4 s

T_{disc}=11500 K (steady)

T_{disc}=26000 K (burst-peak

N.B. STIS abs. t accuracy

Einstein Observatory Solid State Spectrometer (SSS)



SSS employed a reverse-biased junction → depletion layer to act as X-ray detecting volume.

X-ray photons create ion-pairs, but no avalanche.

Needs to be cooled to 80K + low-noise pre-amp.

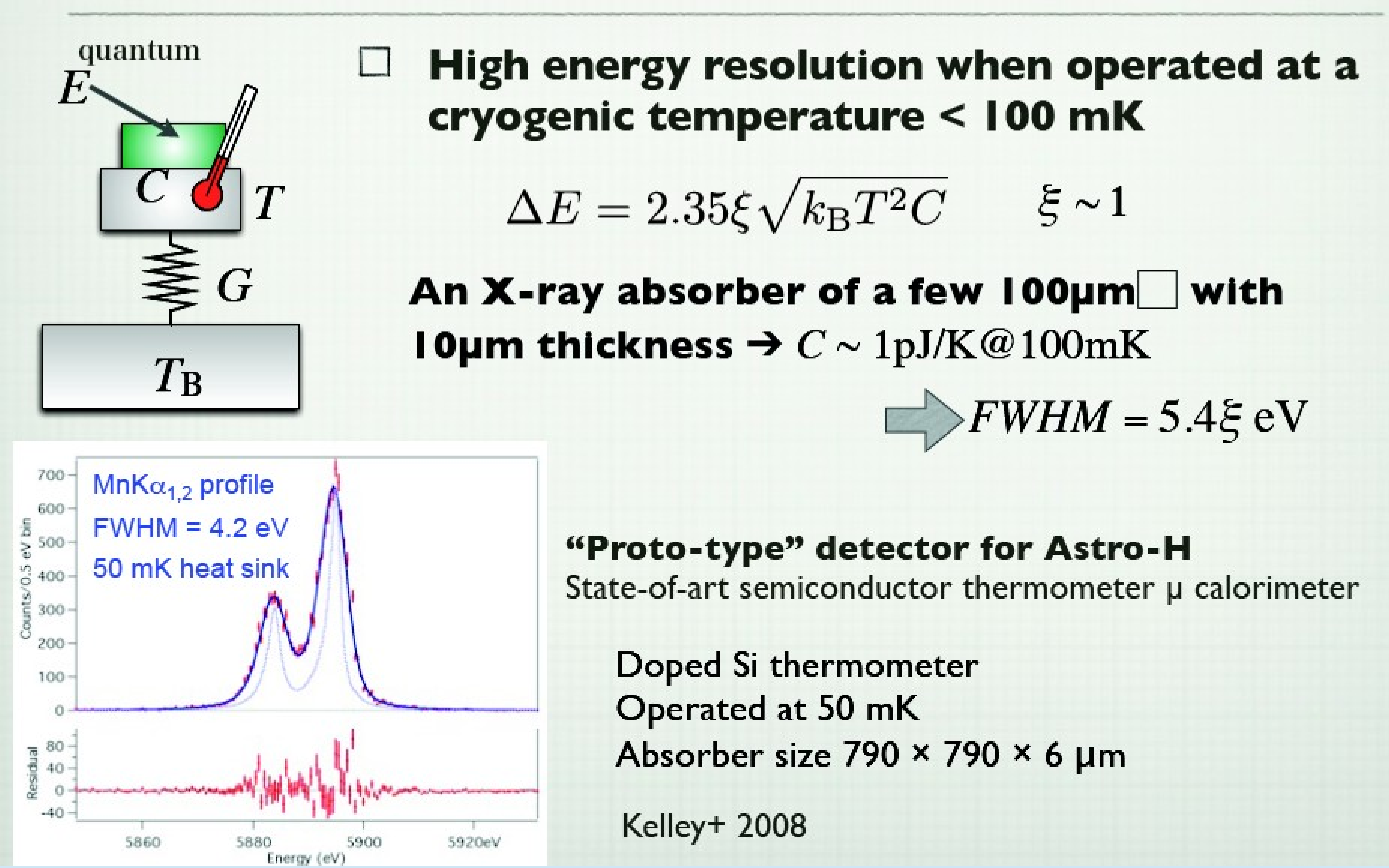
Small → use at focus of X-ray telescope

Energy Resolution

Energy resolution obeys same equation as for proportional counters, but average ionization energy is much smaller than for gases

Material	w (eV)	Fano factor	ΔE @ 6 keV
Ar	26.2	0.17	0.6-1.2
Xe	21.5	0.17	0.6-1.2
Si	3.6	0.12	0.12-0.25
Ge	3.0	0.13	0.11
CdTe	4.4	0.11	0.13-2.0

Micro-calorimeters (Astro-H: launch 2016)



☐ **High energy resolution when operated at a cryogenic temperature < 100 mK**

$$\Delta E = 2.35\xi\sqrt{k_{\mathrm{B}}T^2C} \qquad \xi \sim 1$$

An X-ray absorber of a few 100μm□ with 10μm thickness ➔ $C \sim 1\mathrm{pJ/K@100mK}$

➔ $FWHM = 5.4\xi\ \mathrm{eV}$

“Proto-type” detector for Astro-H

State-of-art semiconductor thermometer μ calorimeter

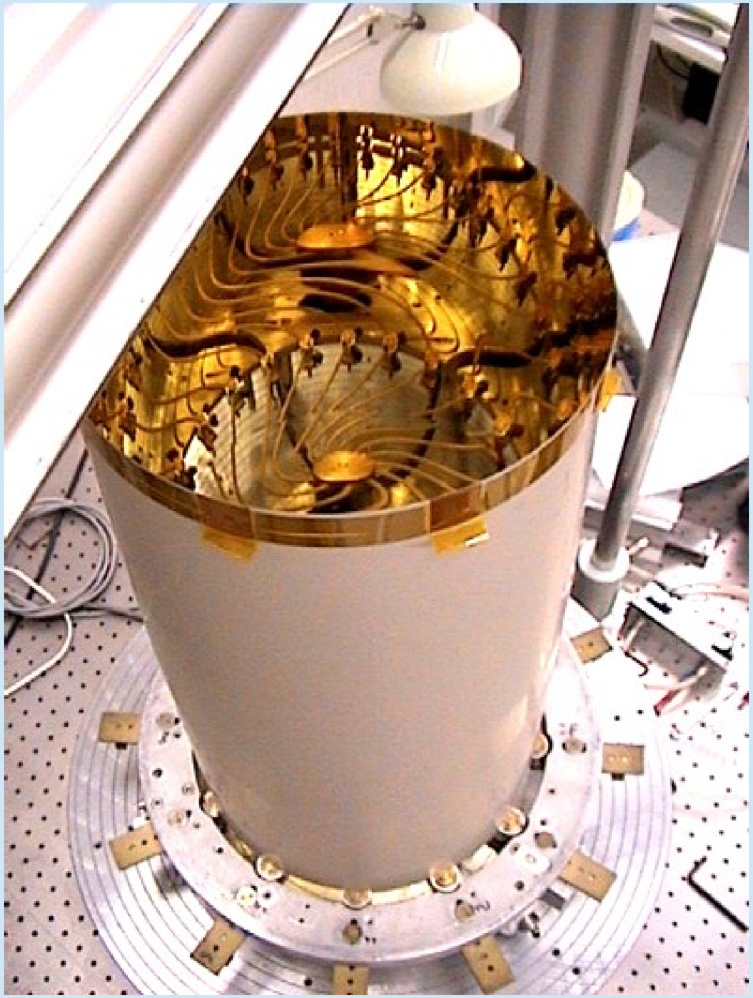
Doped Si thermometer
Operated at 50 mK
Absorber size 790 × 790 × 6 μm

Kelley+ 2008

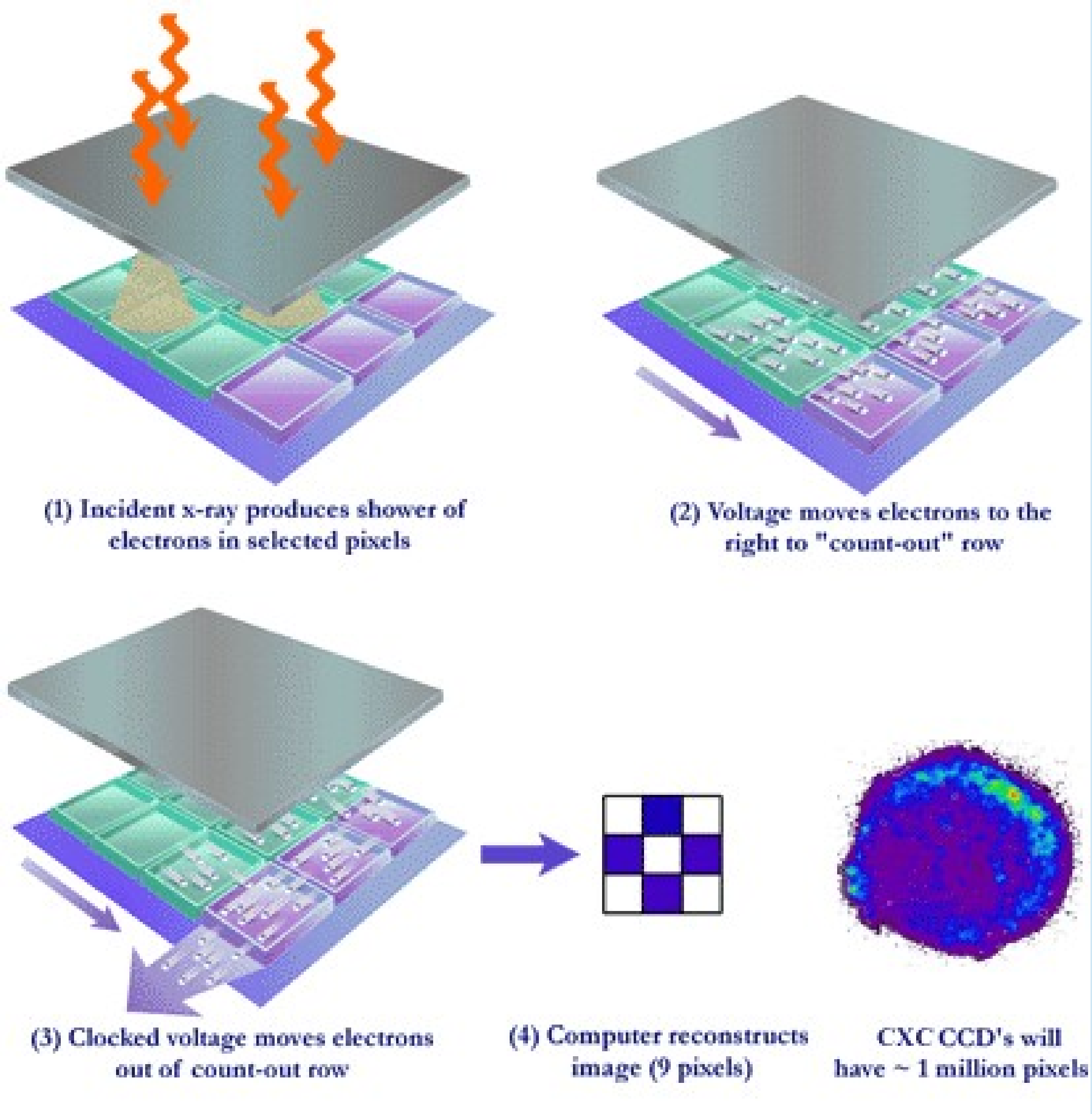
Time resolution ~ 80μs

Mitsuda 09

The XMM-*NEWTON* X-ray Mirrors



CCDs as X-Ray Detectors



(1) Incident x-ray produces shower of electrons in selected pixels

(2) Voltage moves electrons to the right to "count-out" row

(3) Clocked voltage moves electrons out of count-out row

(4) Computer reconstructs image (9 pixels)

CXC CCD's will have ~ 1 million pixels

CCDs “Count” X-Ray photons

- X-ray photon flux is smaller
  - smaller telescope collecting area
- Each absorbed X-ray has much more energy
  - deposits more energy in CCD
  - produces many photoelectrons
- Each X-ray can be counted
- Attributes of individual photons are measured independently:
  - position in detector [*x*,*y*]
  - time of event [*t*]
  - energy absorbed [*E*]
  - → data to transmit to ground per X-ray event is:

$$\left[x, y, t, E\right]$$

Why Transmit [x,y,t,E] Instead of Images?

- Images contain too much data!
  - e.g. up to 2 CCD images per second
  - 16 bits of data per pixel (2^{16}=65,536 gray levels)
  - image size is 1024 × 1024 pixels
    $\Rightarrow 16 \times 1024^2 \times 2 = 33.6$ Mbps
  - too much to transmit

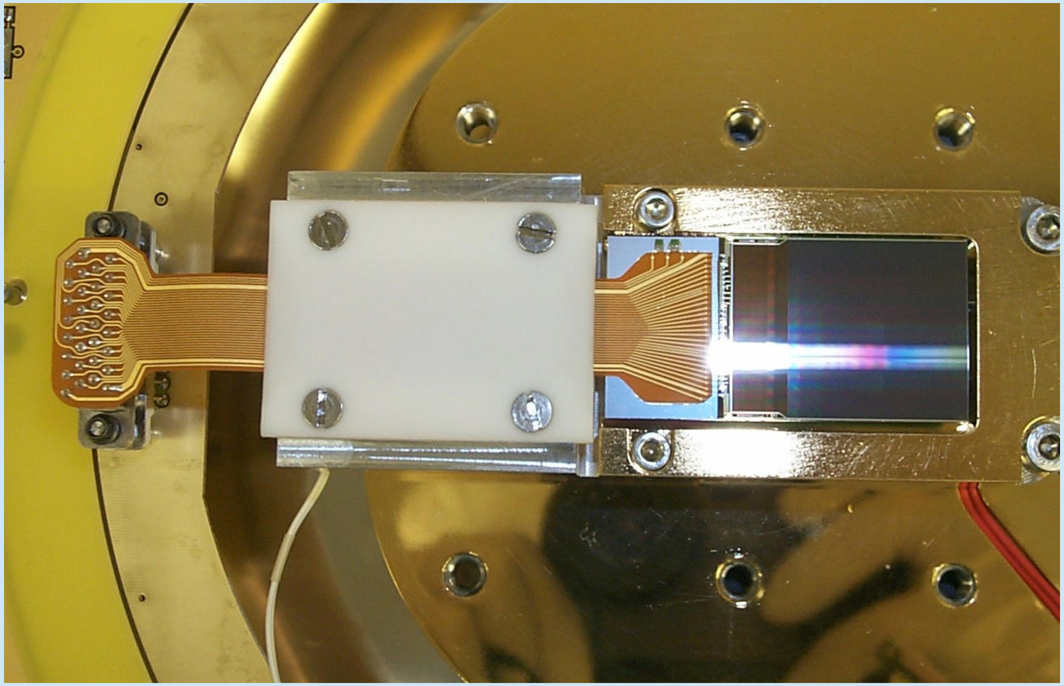
- Instead “Event Lists” of [x,y,t,E] are compiled by on-board software and transmitted
  - significantly reduces required data transmission rate

- Recreate image in subsequent data analysis
  - can select on E to create data cube of x,y,E

X-ray CCDs
1977 --

- ASCA
- XMM
- Chandra
- *Swift*
- Suzaku

Swift XRT CCD



CCD Modes

Photodiode Mode

- Provides highest resolution timing - ~μsec
- Spectroscopy - Fluxes < pile-up

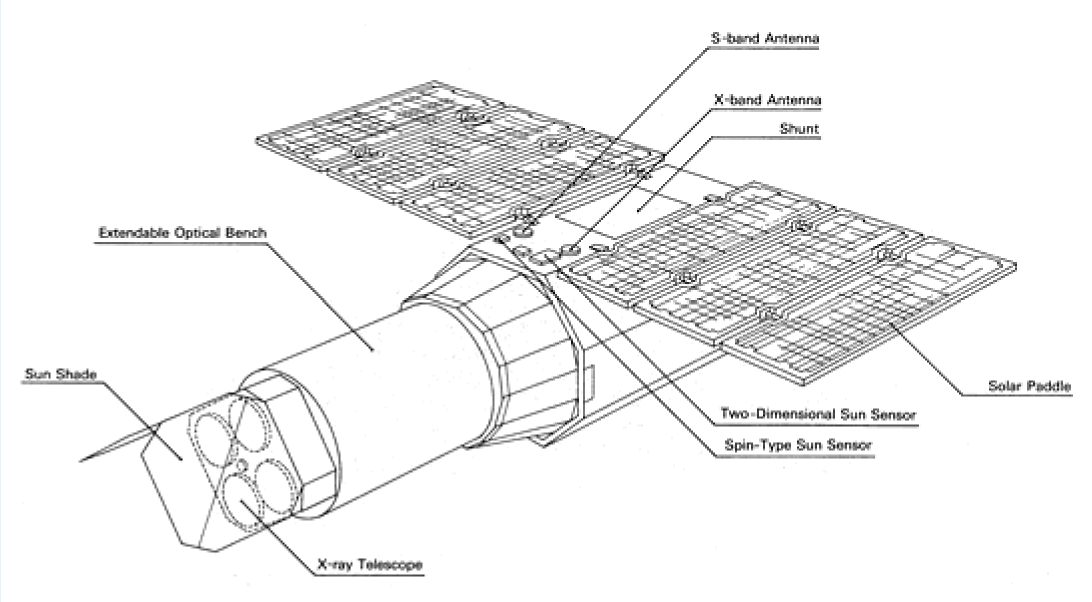
Windowed Timing Mode

- Timing Resolution - ~ msec
- Spectroscopy
- 1-D position

Photon-counting Mode (Nominal)

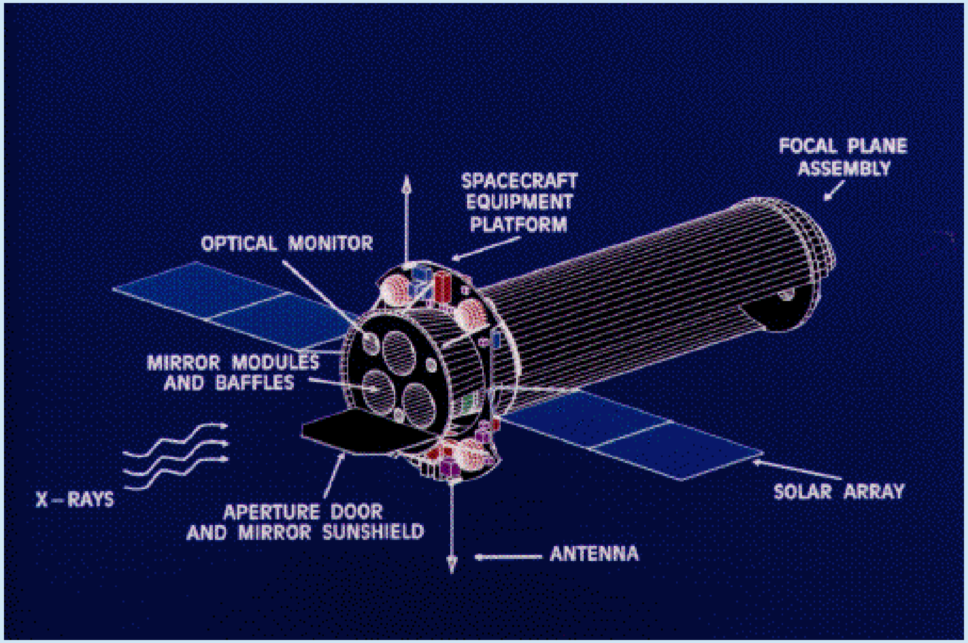
- Low resolution timing – ~ sec
- Spectroscopy
- 2-D position

ASCA 1993-2001



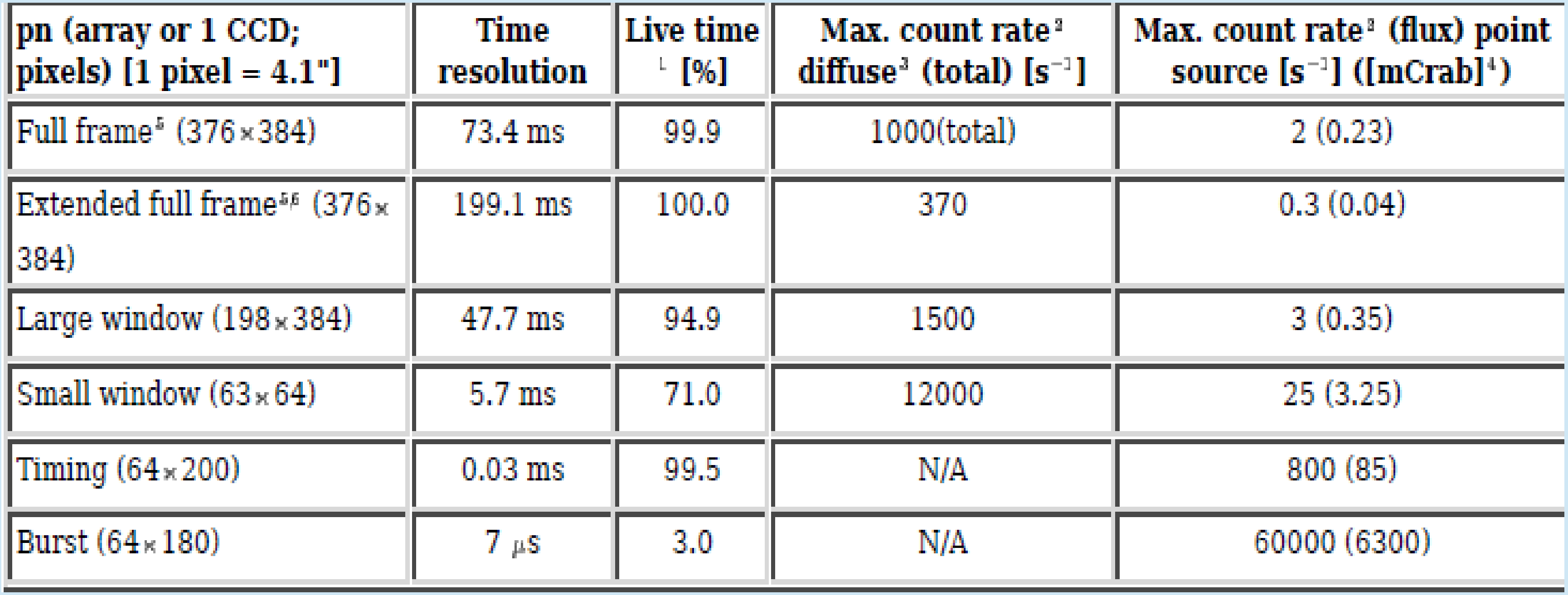
- First mission to use X-ray CCDs
  - i.e. Imaging+broad bandpass+good spectral resolution+large A_{eff}
- 0.4-10 keV
- 4 telescopes w/ 120 nested mirrors, 3’ HPD
  - 2 proportional counters
  - 2 CCDs
- A_{eff}: 1300 cm^2 @ 1 keV
- Energy res. 2% at 6 keV

XMM - EPIC MOS
1999 --



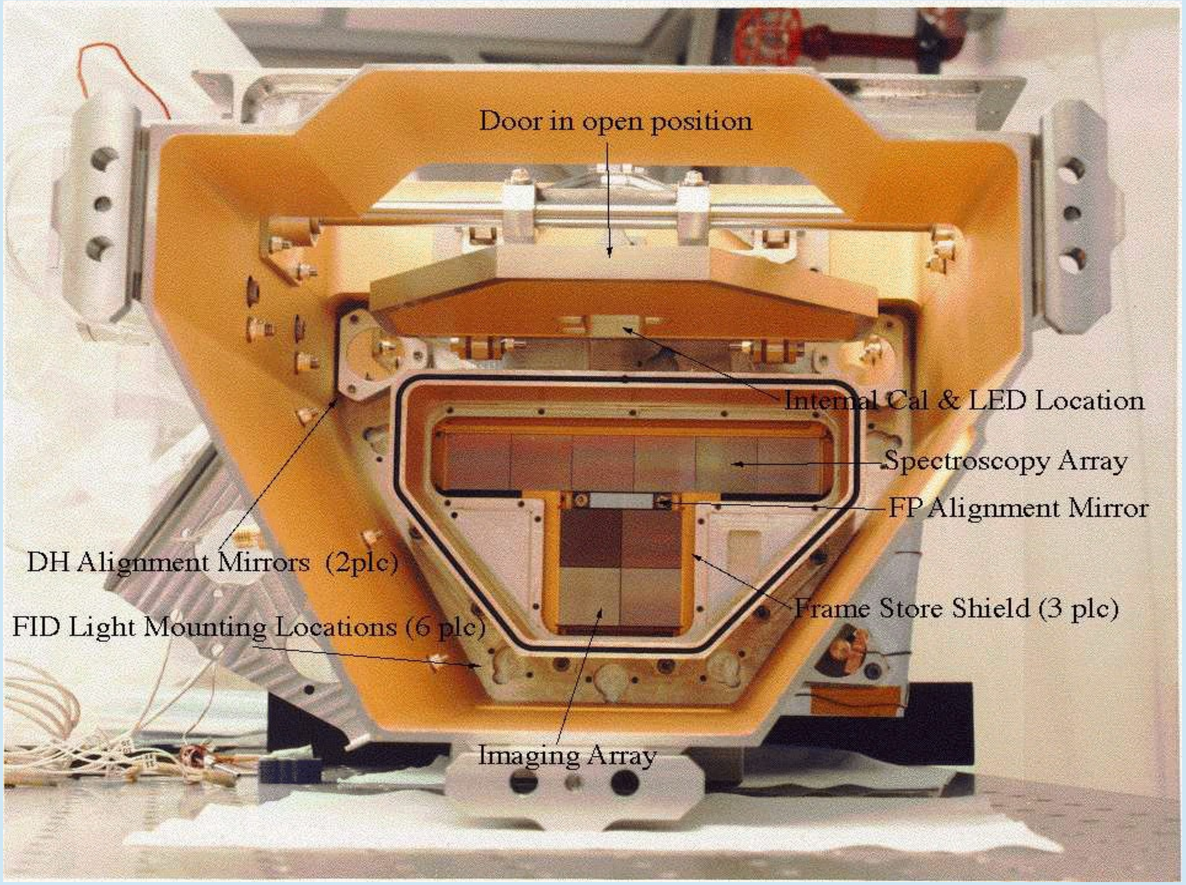
- 3 Telescopes
- Pos Res 15”
- 2 EPIC 1 PN cameras
    - 0.1-15 keV
    - ~1000 cm^2 @ 1 keV
    - E res: 2-5 %
    - FoV 33’
- Large collecting area
- High resolution spectroscopy with RGS
    - R~400 (0.35-2.5 keV)

Fast timing available with EPIC pn cameras



pn (array or 1 CCD; pixels) [1 pixel = 4.1"]	Time resolution	Live time [1] [%]	Max. count rate[2] diffuse[3] (total) [s^{-1}]	Max. count rate[3] (flux) point source [s^{-1}] ([mCrab][4])
Full frame[5] (376×384)	73.4 ms	99.9	1000(total)	2 (0.23)
Extended full frame[5,6] (376× 384)	199.1 ms	100.0	370	0.3 (0.04)
Large window (198×384)	47.7 ms	94.9	1500	3 (0.35)
Small window (63×64)	5.7 ms	71.0	12000	25 (3.25)
Timing (64×200)	0.03 ms	99.5	N/A	800 (85)
Burst (64×180)	7 μs	3.0	N/A	60000 (6300)

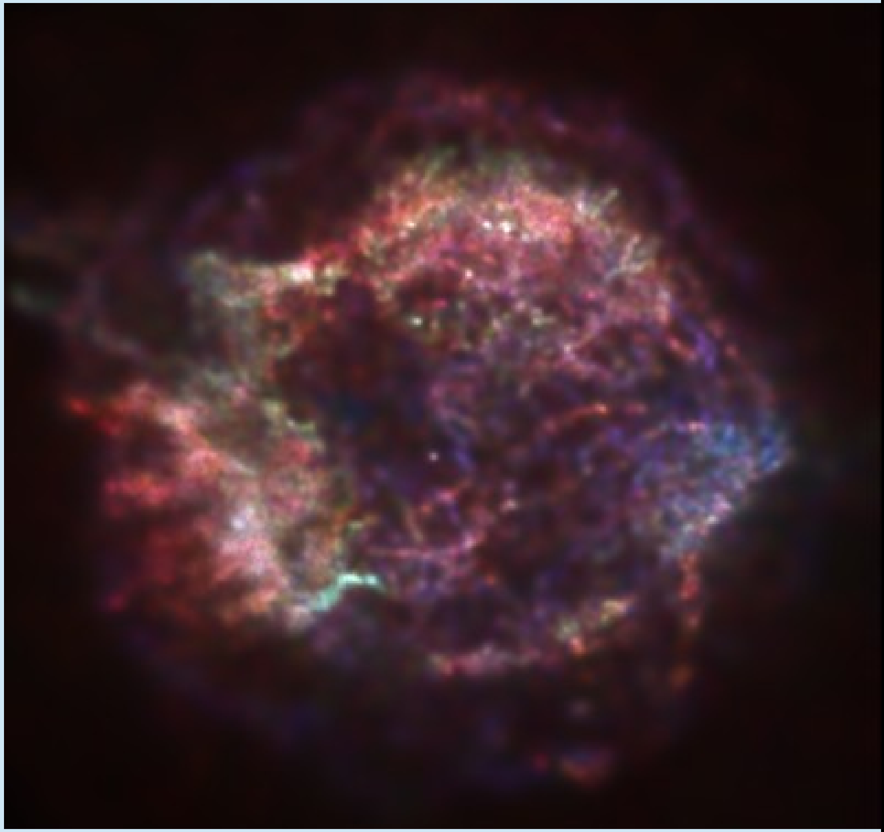
Chandra - ACIS
1999 --

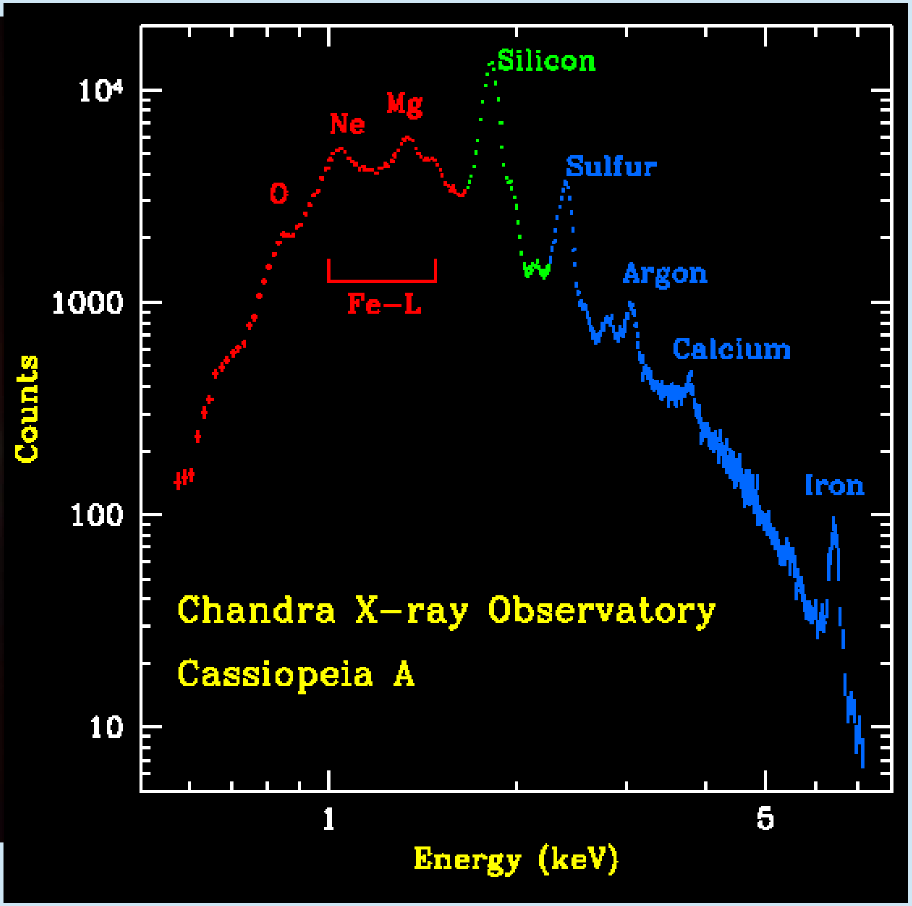


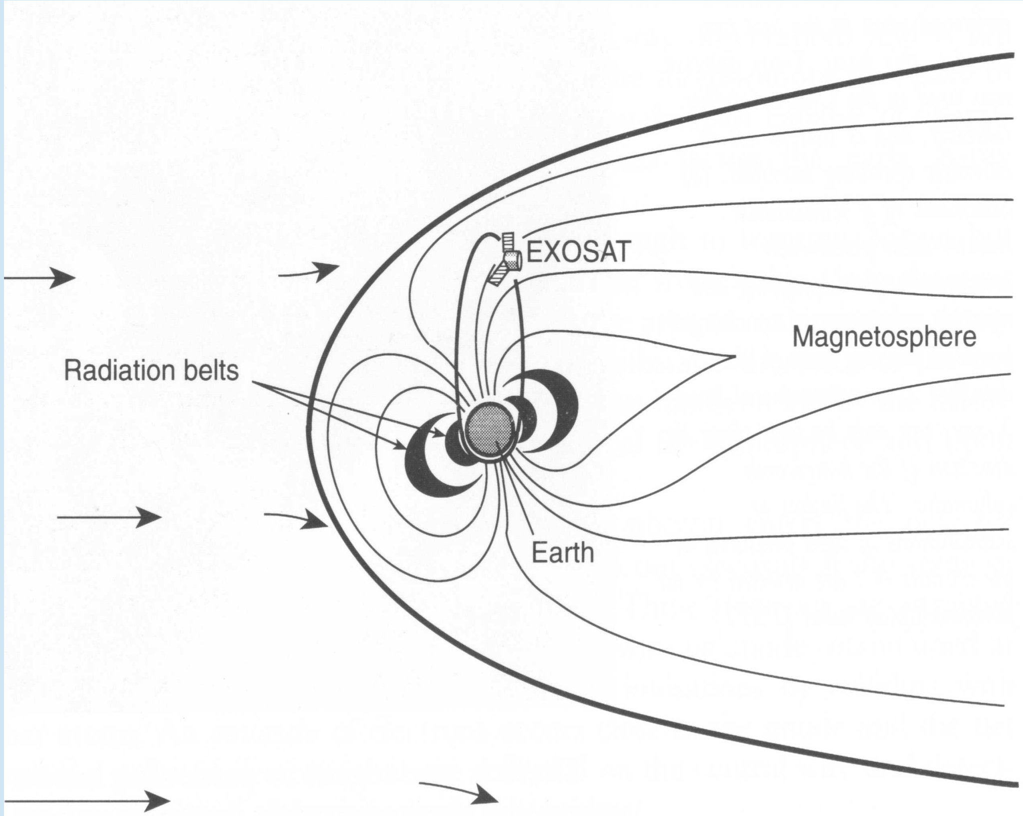
- A_{eff} 340cm^2@1 keV
- 0.2 - 10 keV
- Angular Res.: <1 arcsec HPD
- Energy resolution
  - w/ grating ~0.1-1%
  - w/o 1-5%
- High resolution imaging & high resolution spectroscopy

CCD Cas-A

- Chandra ACIS image and spectrum



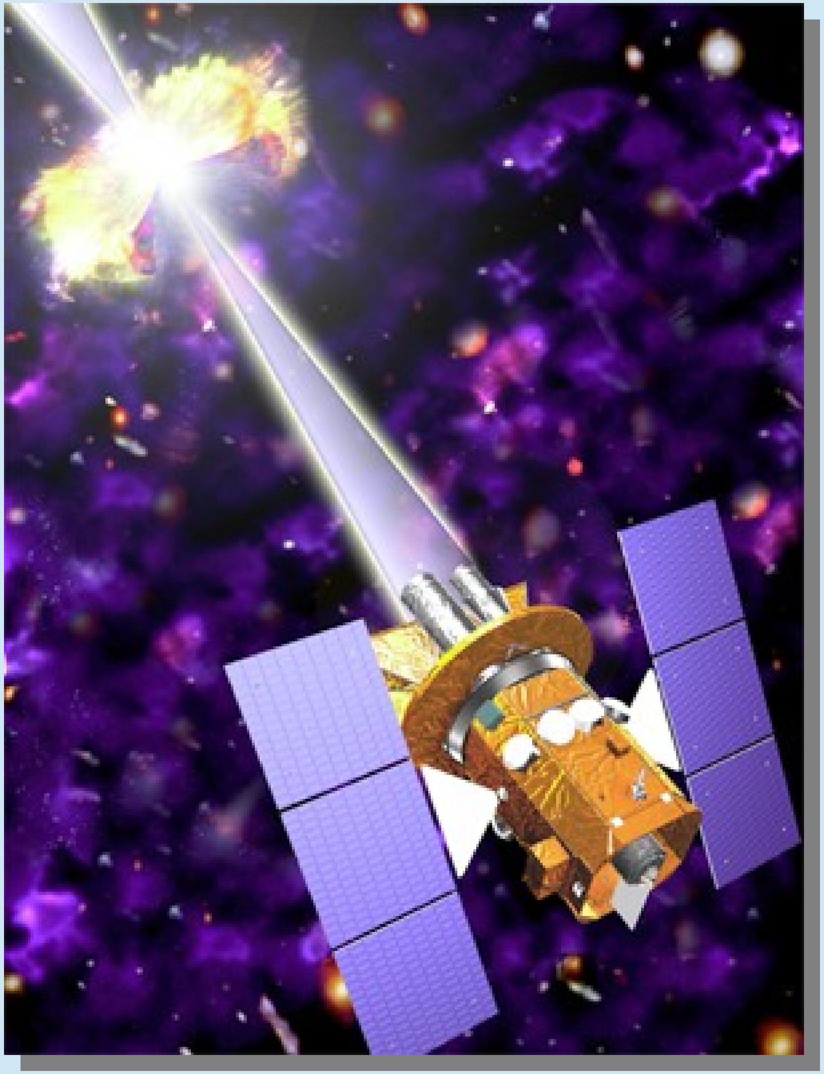




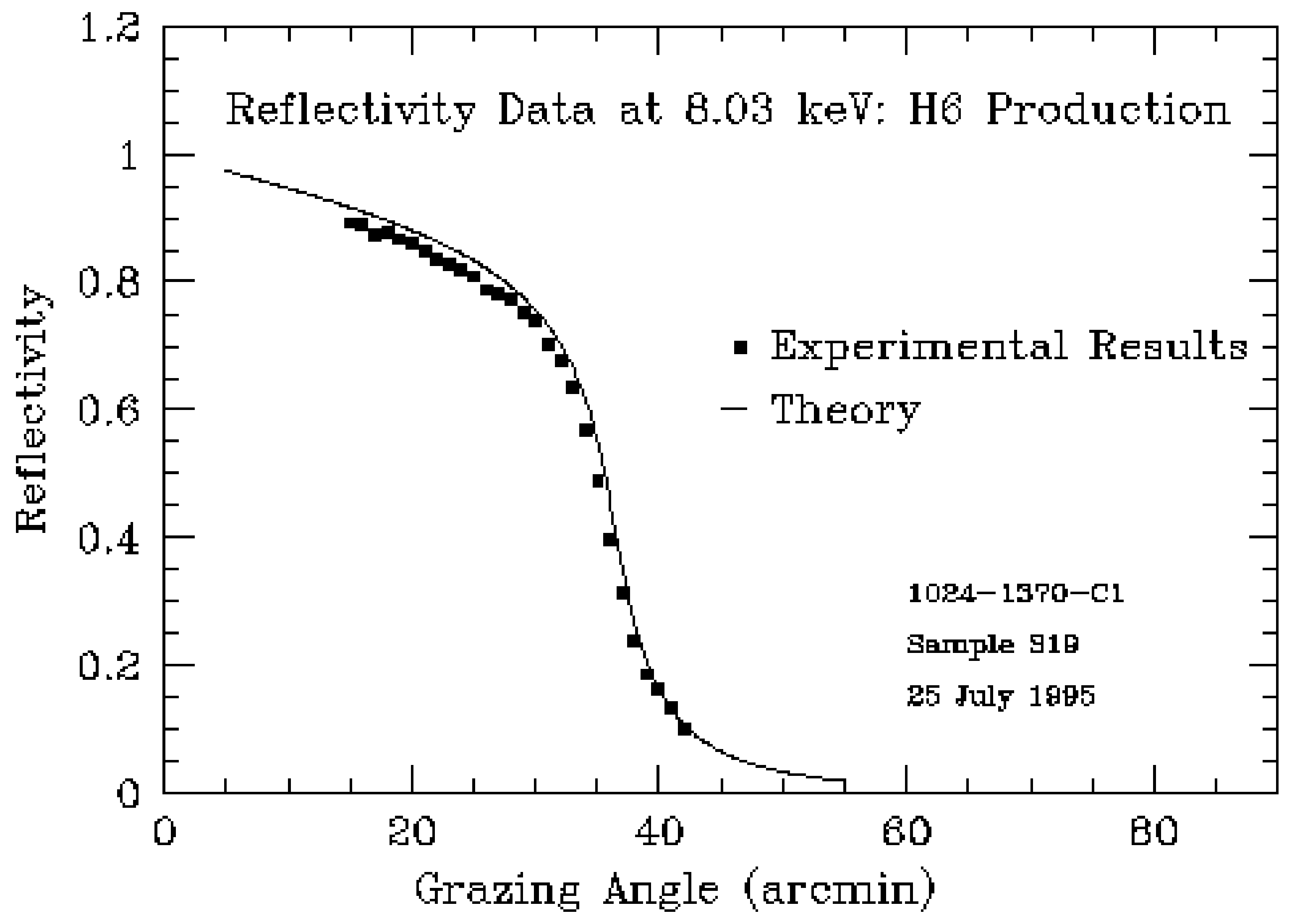
XMM, Chandra in high, ~4d orbits (as was true for EXOSAT) → substantial advantage in studying X-ray binaries

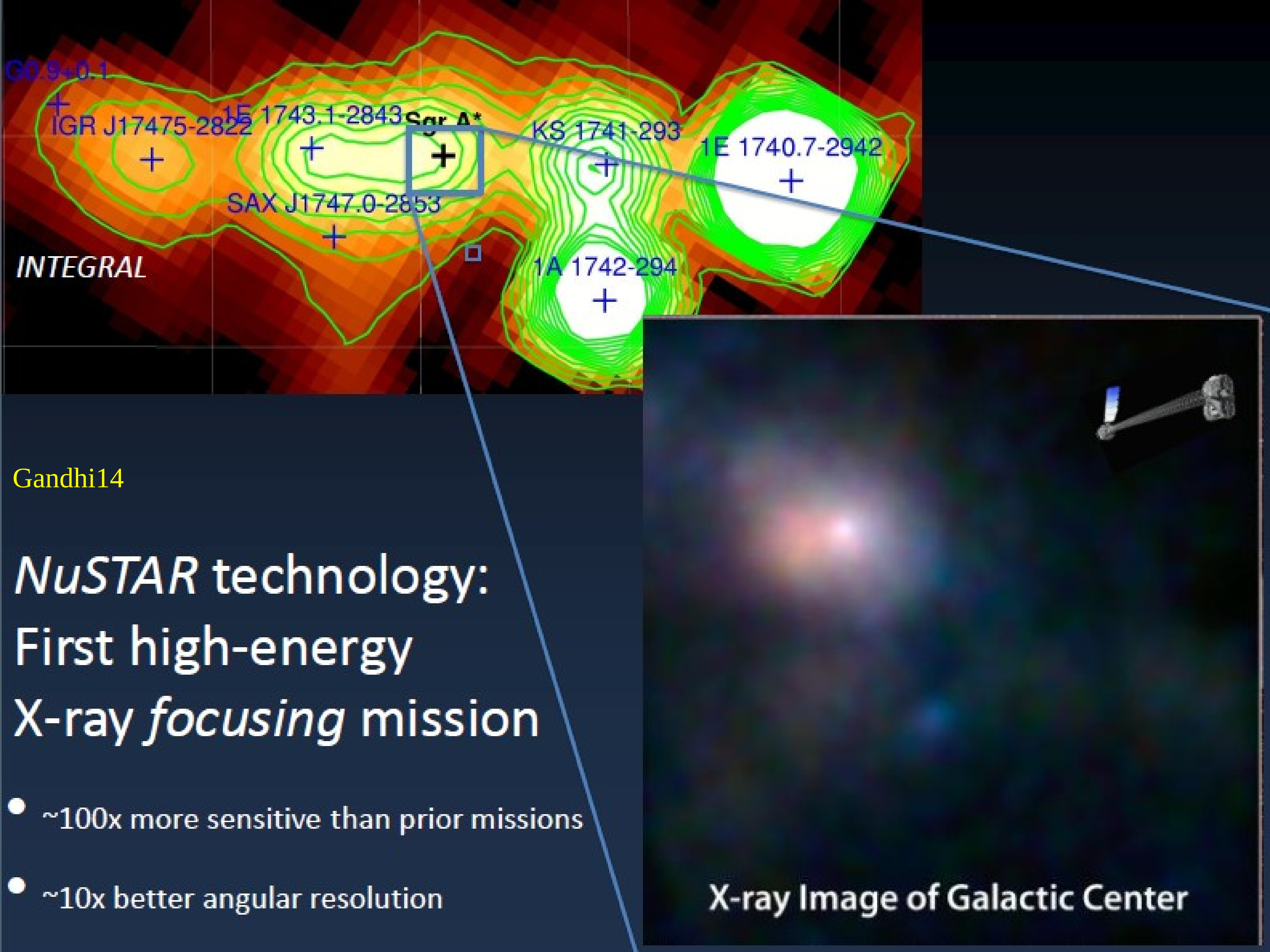
Swift XRT
2004 --

- Measure positions of GRBs to <5'' in <100 seconds
- 0.3-10 keV
- 18'' HPD
- 125 cm^2 @ 1.5 keV
- Automated operation
- Superb for XRT follow-up
- "HT" in terms of response



X-Ray Reflectivity





X-ray Image of Galactic Center

Gandhi14

NuSTAR technology: First high-energy X-ray *focusing* mission

- ~100x more sensitive than prior missions
- ~10x better angular resolution

Detector developments

- CCD downside; large readout time + readout noise
- fast readout modes for CCD

  rather than reading out the whole CCD for each exposure, a small section is shifted rapidly, then readout

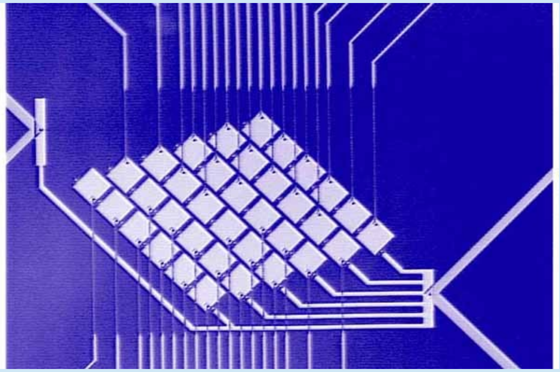
\- frame transfer CCDs as fast photometers (UCT, ULTRACAM)

\- drift mode for spectroscopy

- Back to photon counting style detectors

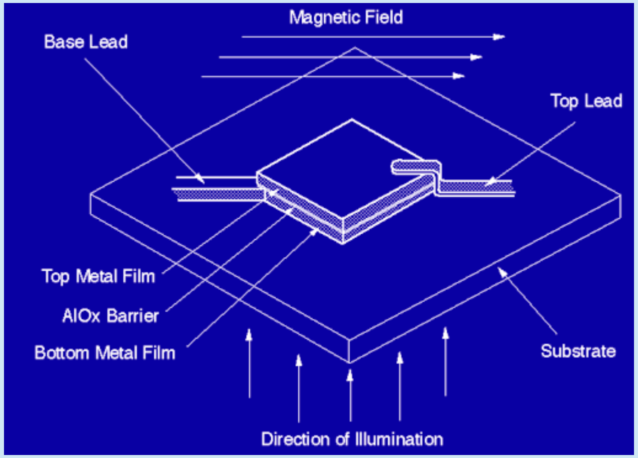
  \- STJ camera developed by ESTEC

  \- Hybrid MIC camera from UCL



Back to photon counting I - SCAM

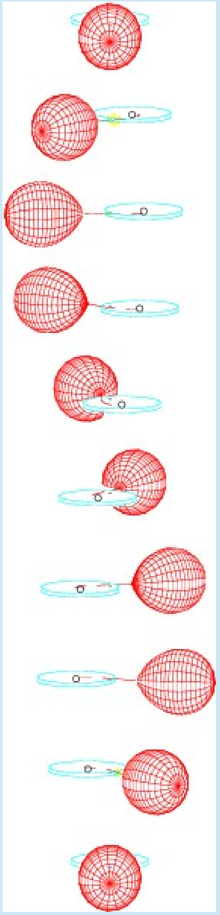
- ESTEC has developed a photon counting detector for optical astronomy ; S-CAM
- Each pixel in the camera is a tunnel junction device that acts as a photon counter if cooled to superconductivity temperatures (<1K!)

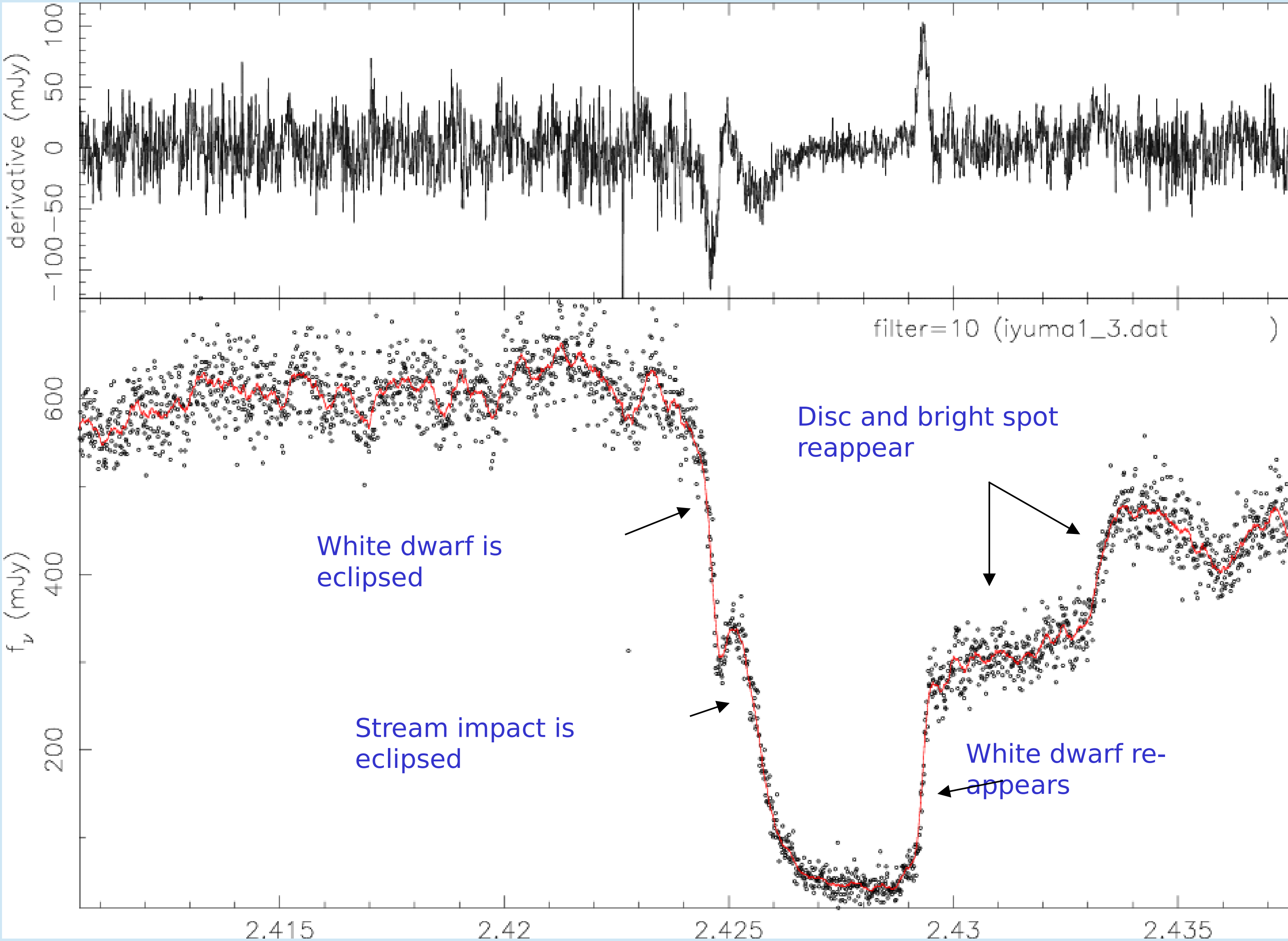


- Photon arrival time and energy is stored
- Timing accuracy: 5 μs
- Energy resolution; limited to R=10 now, but much better in future
- Up to 5000 photons/s/pixel can be recorded
- Quantum efficiency ; close to 100%, now limited by optics

- A newly discovered eclipsing CV was observed with 4.2m WHT and the ~2000 implementation of S-CAM (Steeghs et al)

S-CAM ; IY UMa eclipse (Steeghs et al)





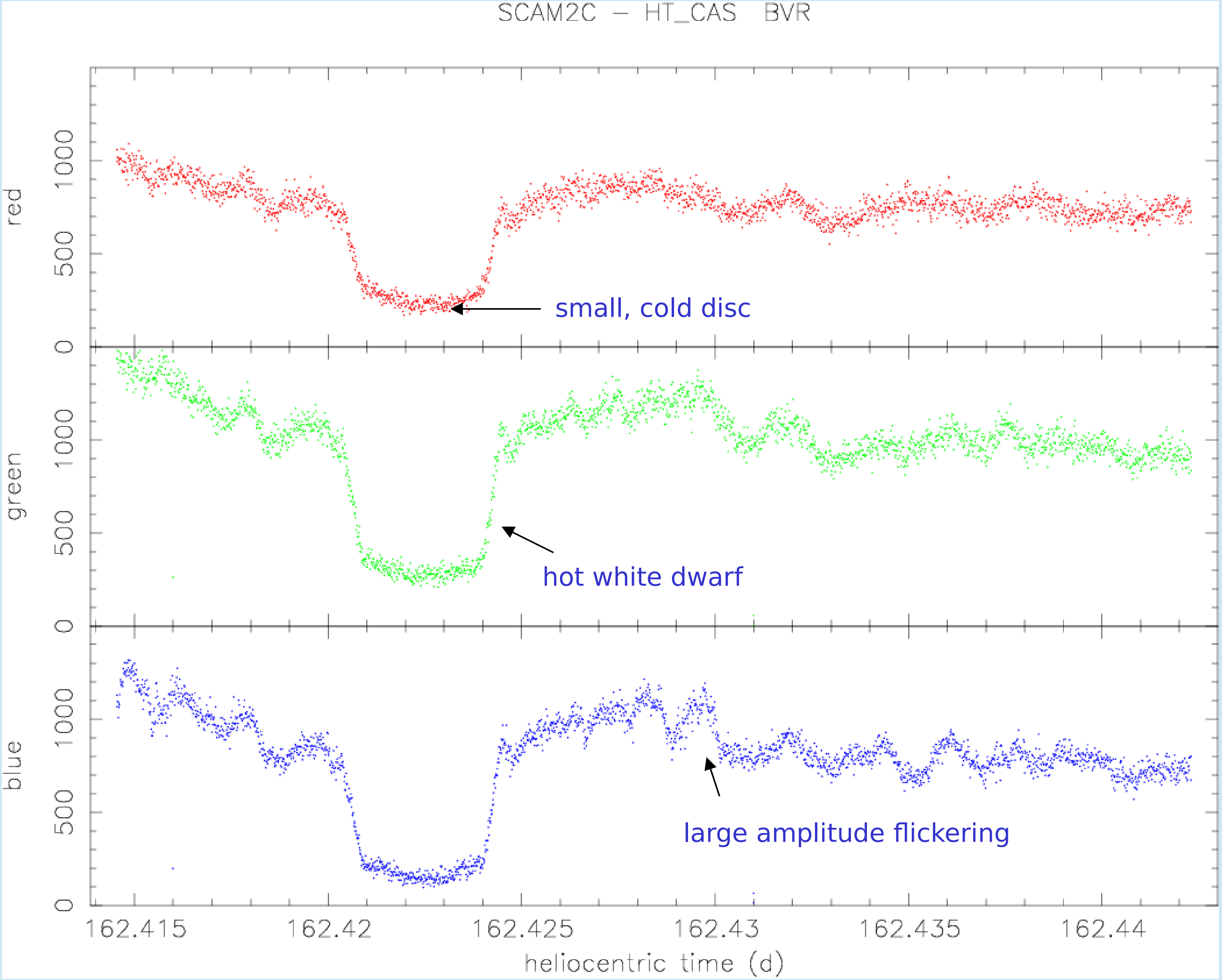
White dwarf is eclipsed

Stream impact is eclipsed

Disc and bright spot reappear

White dwarf re-appears

S-CAM ; HT Cas (Steeghs et al)



small, cold disc

hot white dwarf

large amplitude flickering

Photon counting II – MIC (Fordham)

- MIC is a Microchannel plate Intensified CCD detector capable of operating in several photon counting modes (also on XMM optical monitor)

- Microchannel plate intensifies each photon event by factor 10^7

  - event position is registered by a fast readout CCD to allow true photon counting (no readout noise)

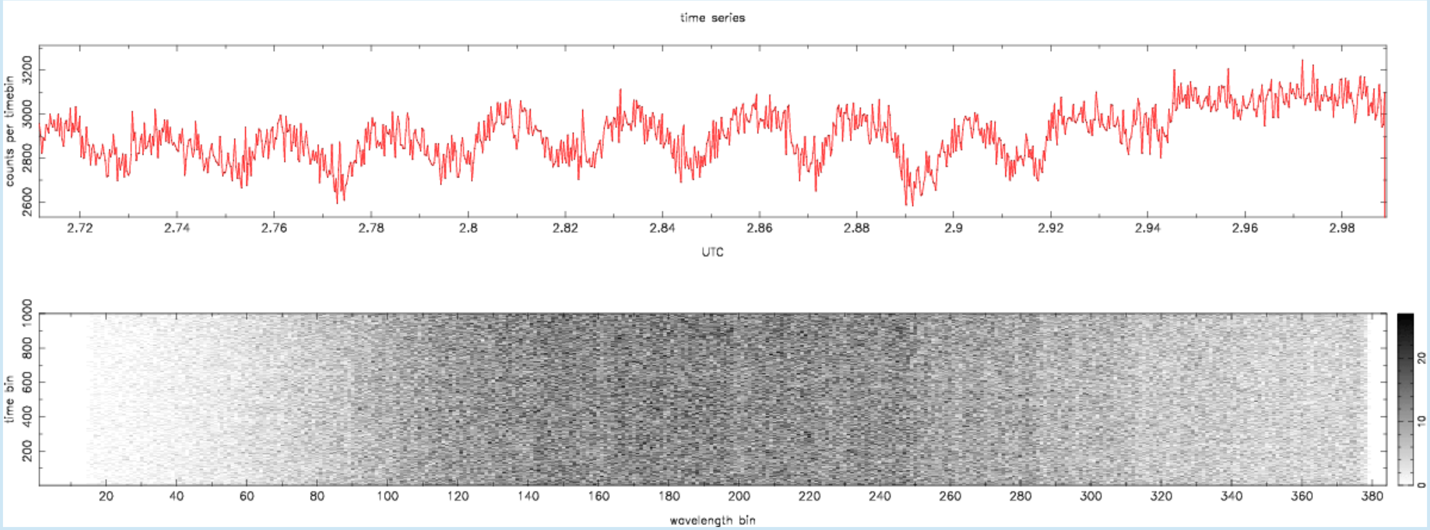
✓ camera can be attached to either imagers or spectrographs

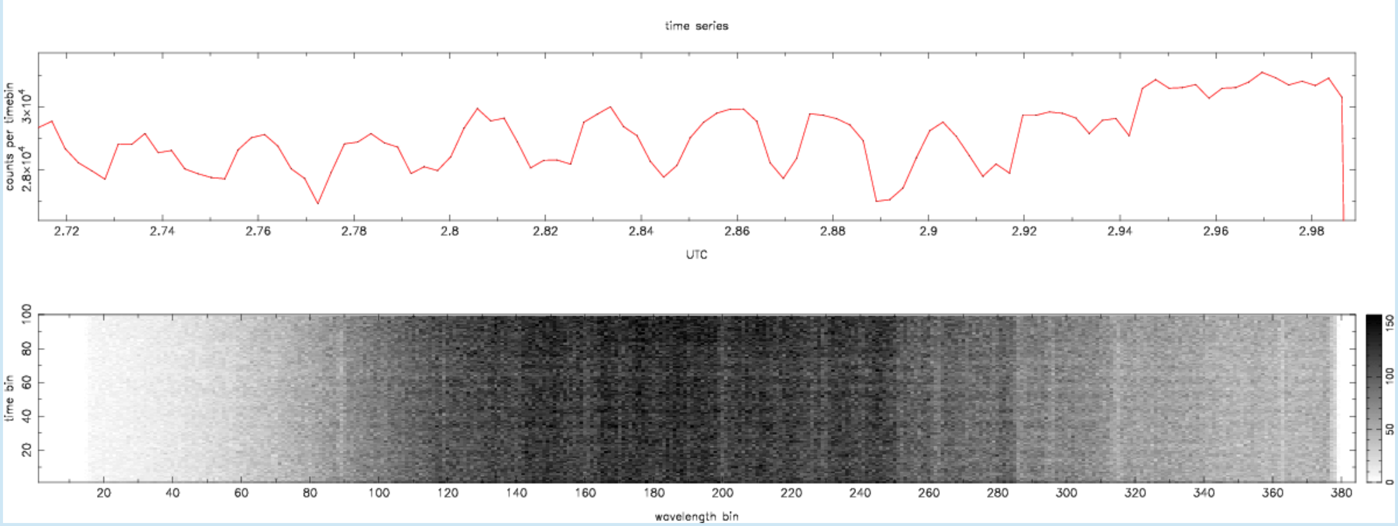
✓ allows fast spectroscopy exploiting full resolution of spectrograph

✗ MCP limits overall quantum efficiency

- CV campaigns at Kitt Peak and San Pedro Martir observatories

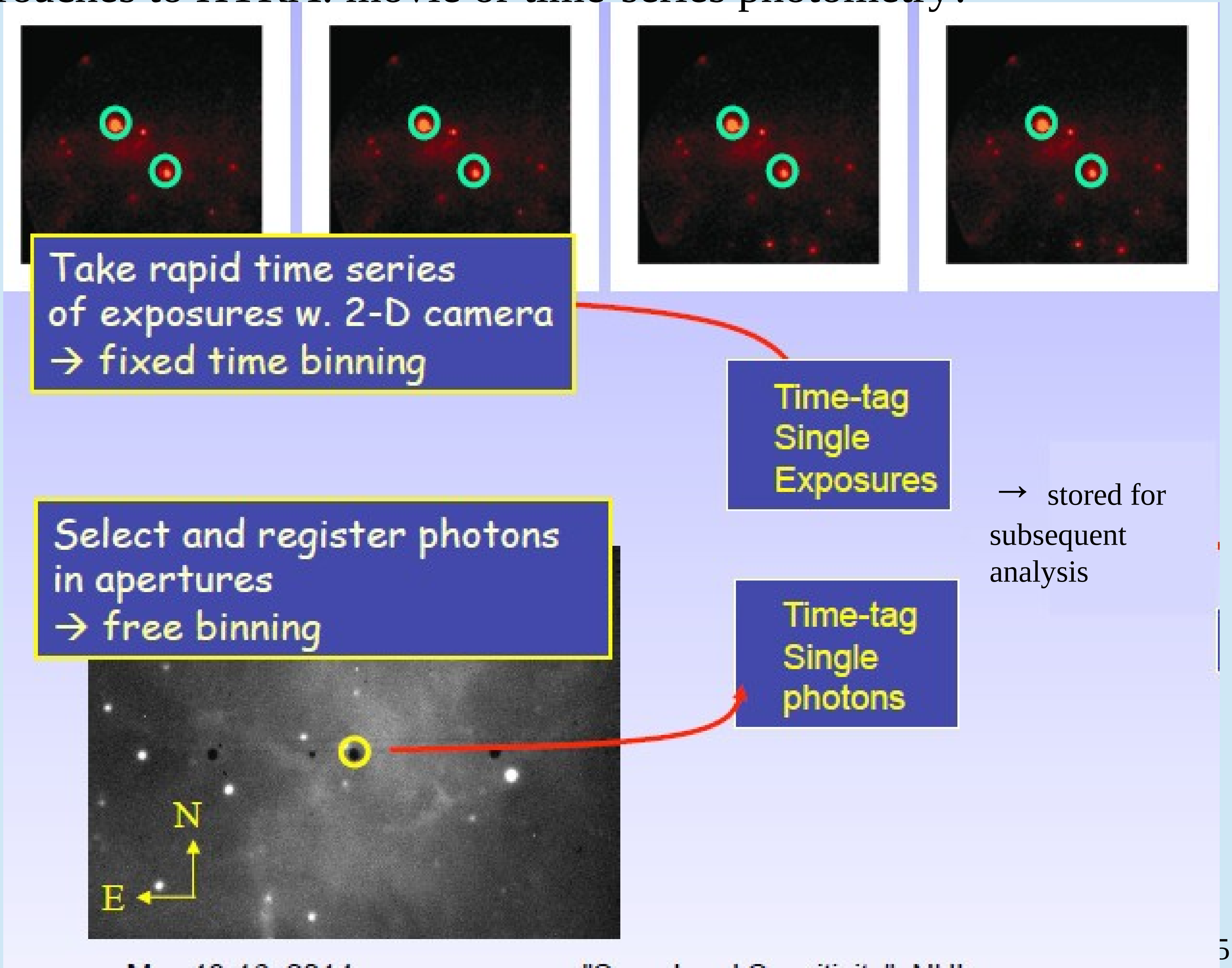
MIC : spinning magnetic WD





Data can be binned to optimal time resolution depending on science goals

2 approaches to HTRA: movie or time-series photometry?



Take rapid time series of exposures w. 2-D camera → fixed time binning

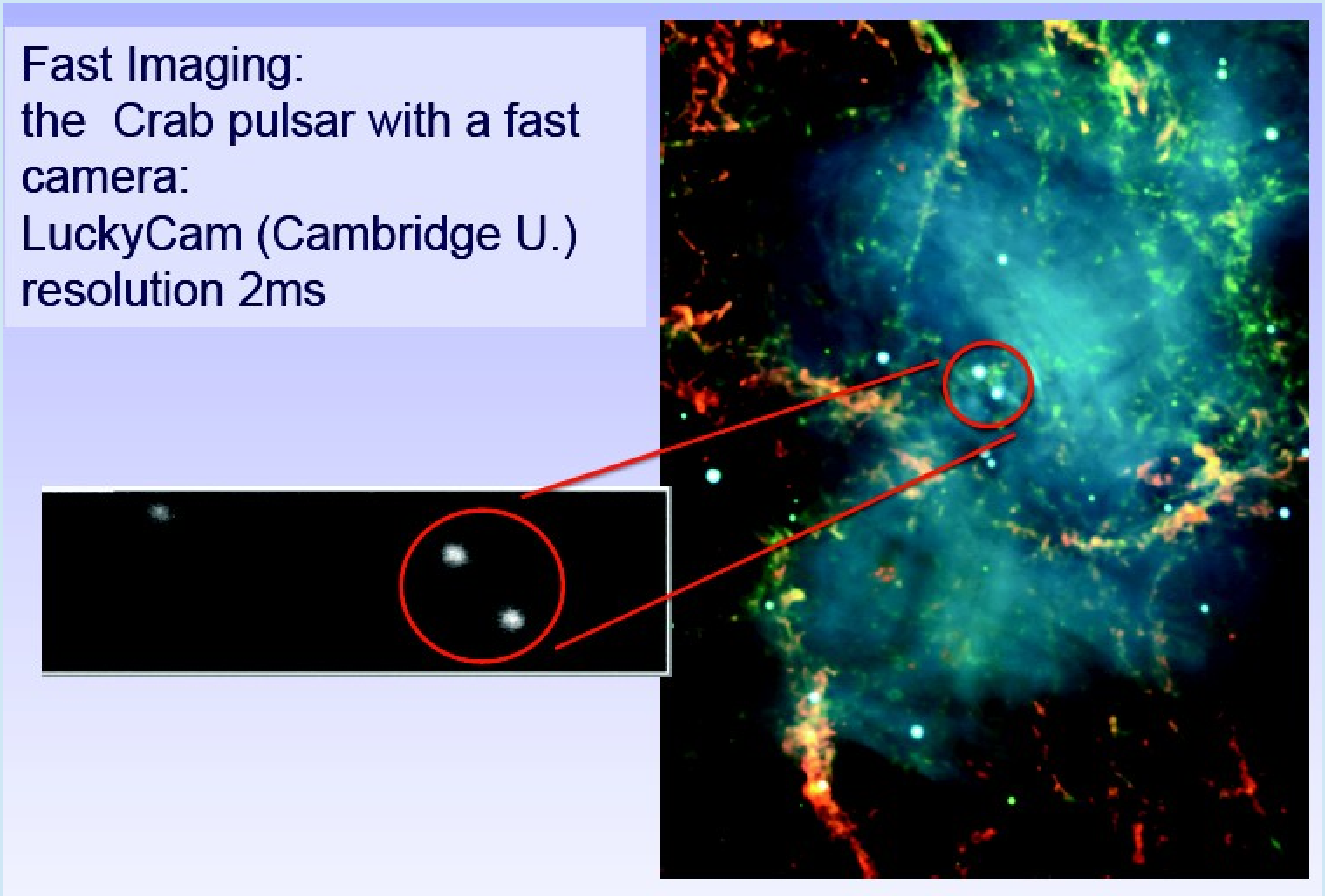
Time-tag Single Exposures

→ stored for subsequent analysis

Select and register photons in apertures → free binning

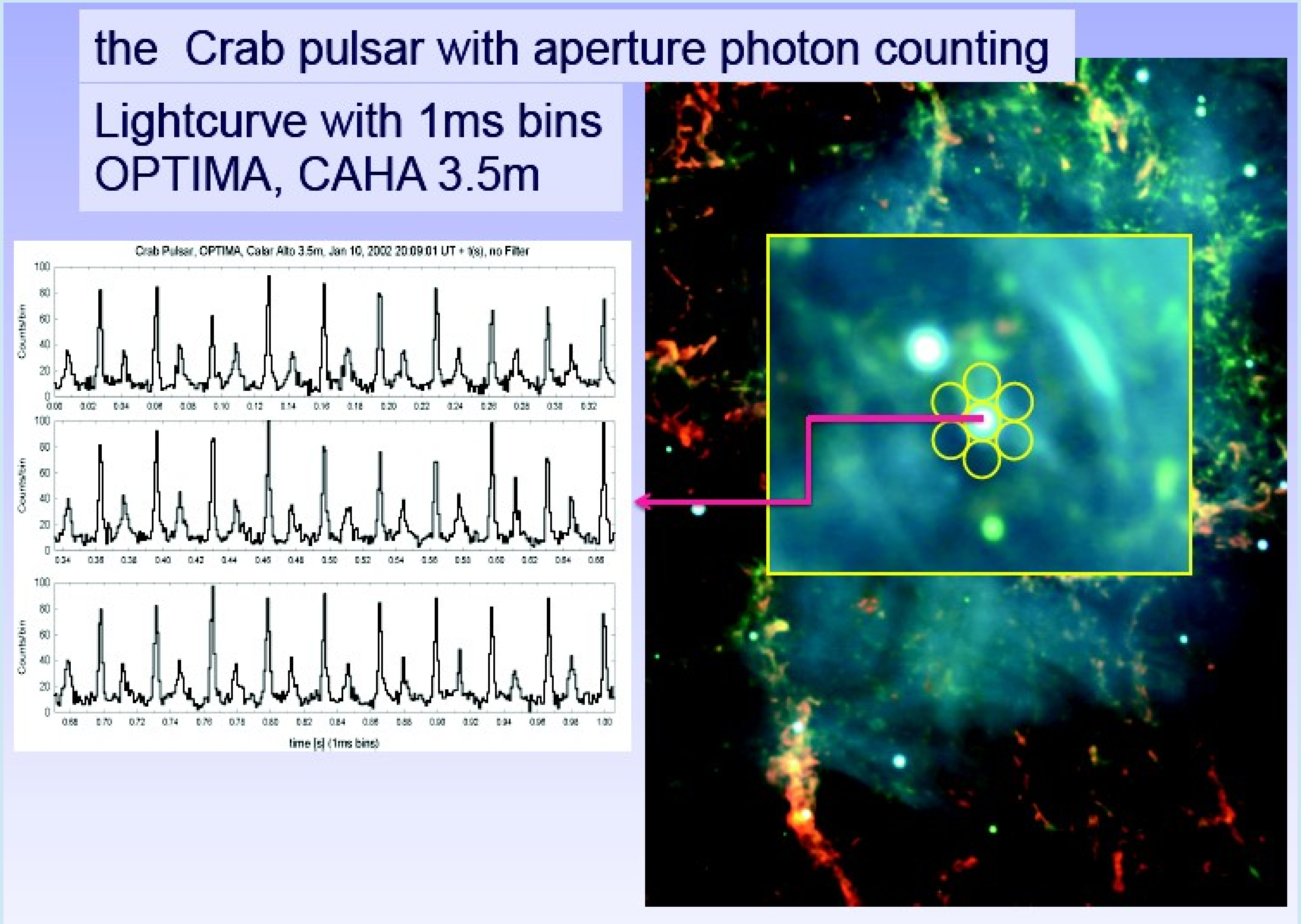
Time-tag Single photons

e.g. Craig McKay's “Lucky Cam”:



Fast Imaging:
the Crab pulsar with a fast camera:
LuckyCam (Cambridge U.)
resolution 2ms

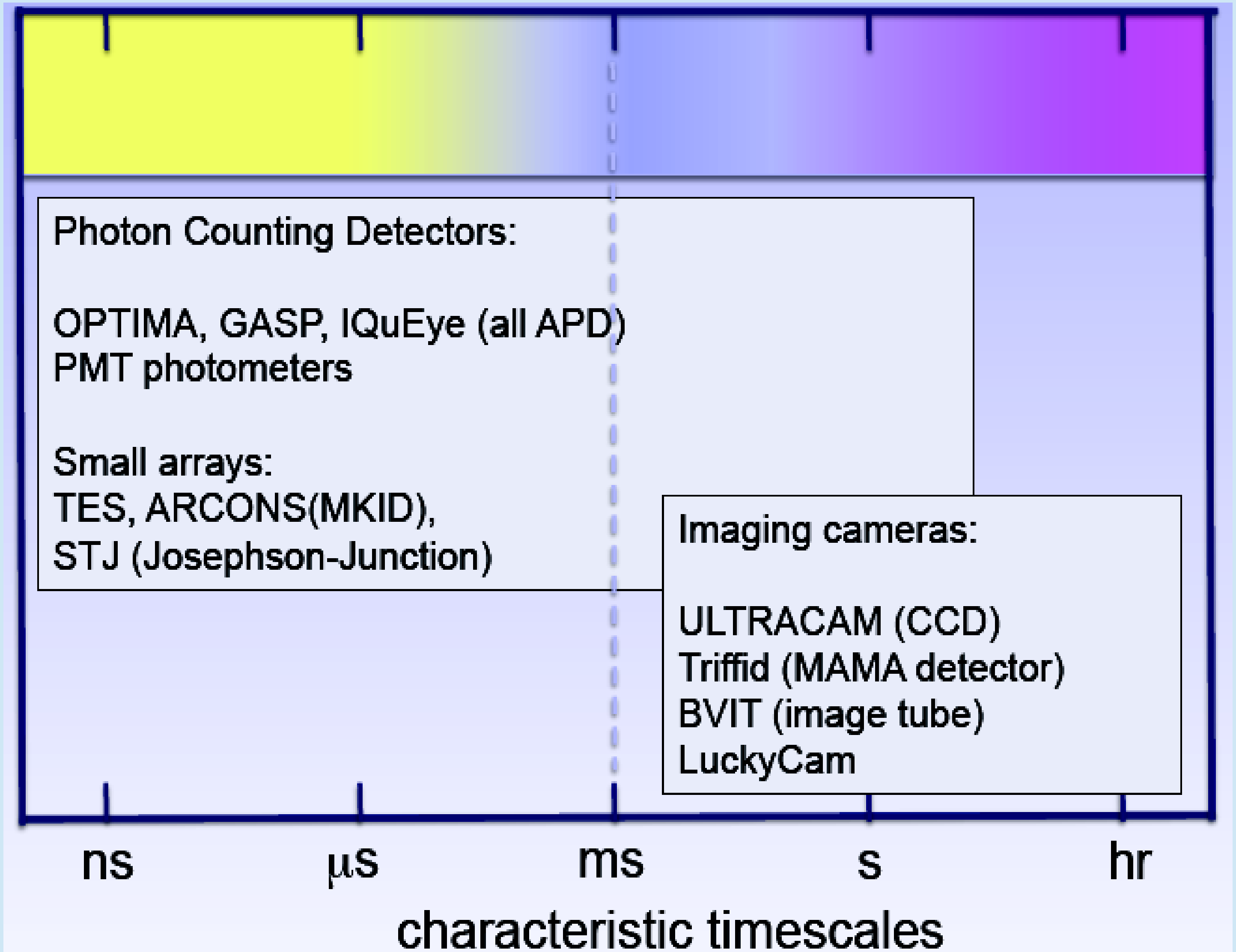
Or Gottfried Kanbach's OPTIMA:



the Crab pulsar with aperture photon counting

Lightcurve with 1ms bins
OPTIMA, CAHA 3.5m

Techniques and instruments:



Photon Counting Detectors:

OPTIMA, GASP, IQuEye (all APD)
PMT photometers

Small arrays:
TES, ARCONS(MKID),
STJ (Josephson-Junction)

Imaging cameras:

ULTRACAM (CCD)
Triffid (MAMA detector)
BVIT (image tube)
LuckyCam

Kanbach 2014