Peeking into the Early Universe with Coded-Aperture Imaging:
Energetic X-ray Imaging Survey Telescope (EXIST)

JaeSub Hong

Winter, 2008

Astrostat

1. **EXIST as cosmic probe**
    - **Background**
    - **Science Motivation**
    - **Instrument Overview**
    - **Comparison with Swift**

2. **Coded Aperture Imaging**
    - **Focusing or Non-Focusing?**
    - **Inversion or Correlation?**
    - **URA or Random Mask?**
    - **Beyond Convention: Scan, Hybrid, Auto-collimation**

EXIST Concept Study Team

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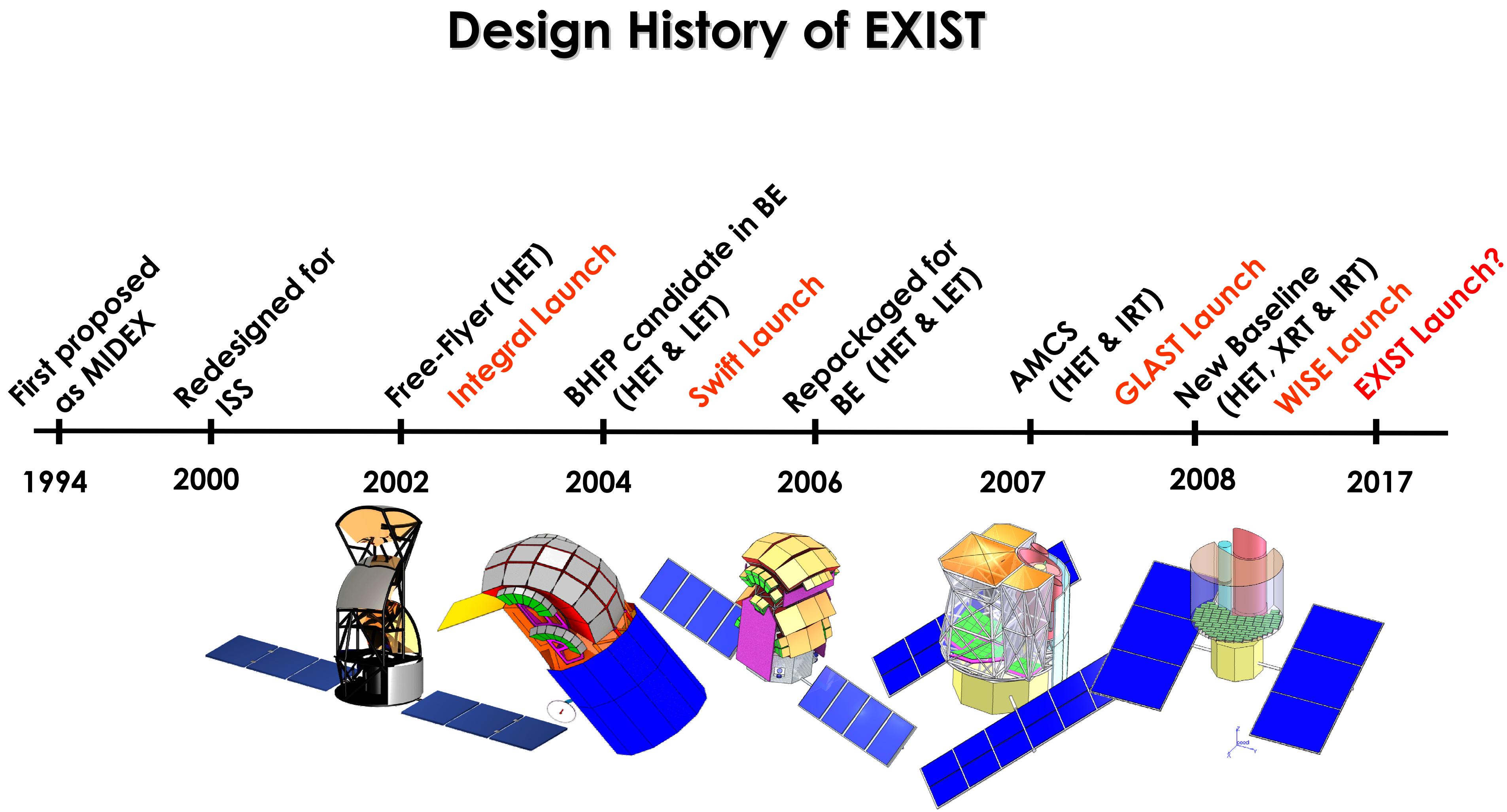
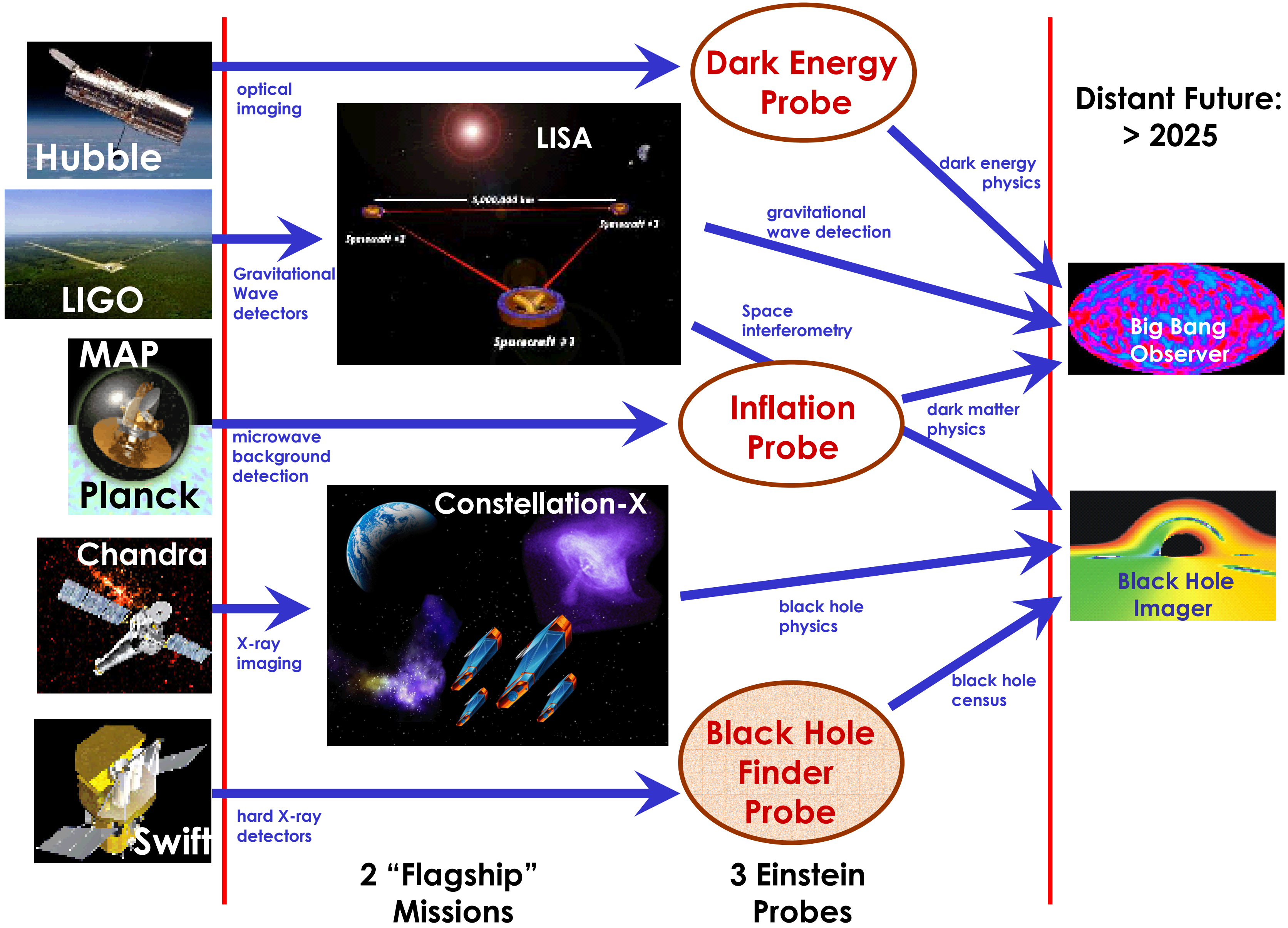
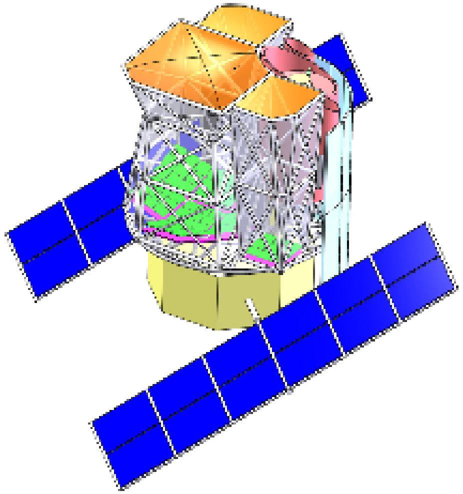


Design History of EXIST
First proposed as MIDEX
Redesigned for ISS
Free-Flyer (HET)
Integral Launch
BHFP candidate in BE (HET & LET)
Swift Launch
Repackaged for BE (HET & LET)
AMCS (HET & IRT)
GLAST Launch
New Baseline (HET, XRT & IRT)
WISE Launch
EXIST Launch?
1994
2000
2002
2004
2006
2007
2008
2017

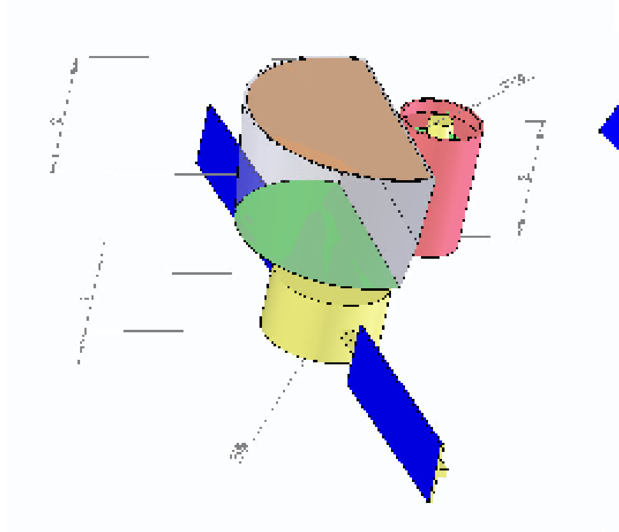
EXIST in Beyond Einstein Missions



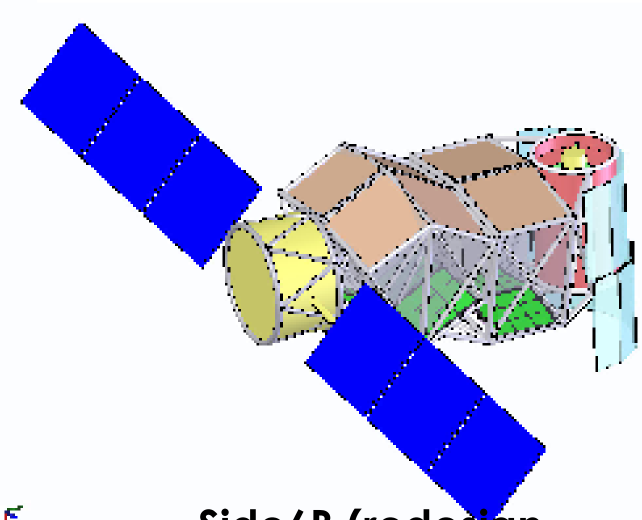
Recent HET Design History



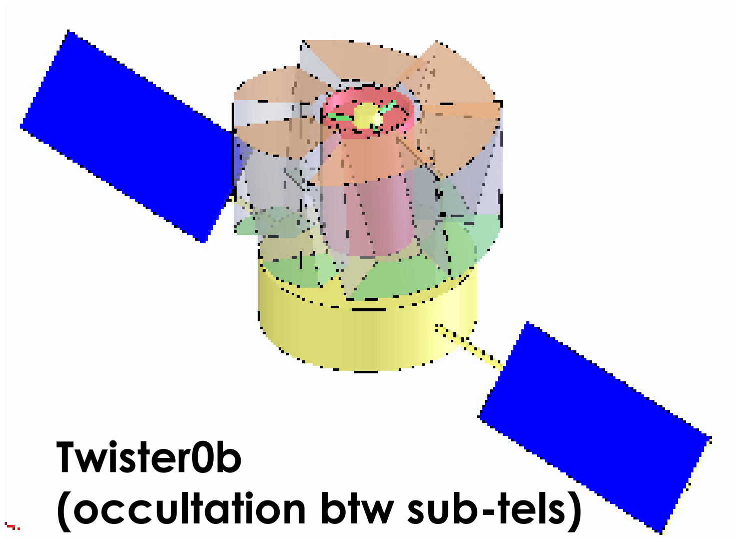
AMCS Proposal
(non-parallel mask/detector)



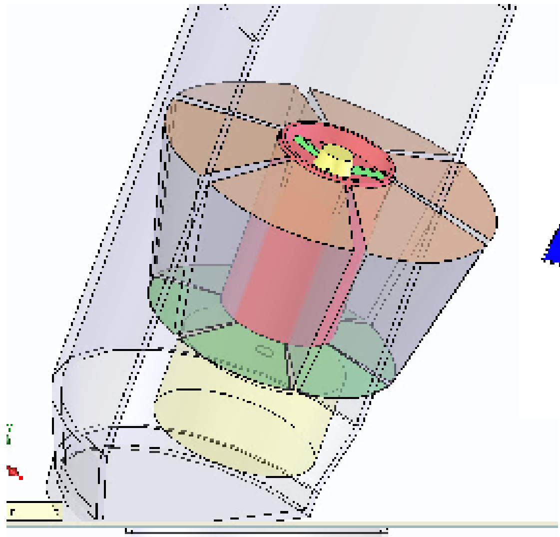
SimDD or Drum (severe
constraint on mask supports)



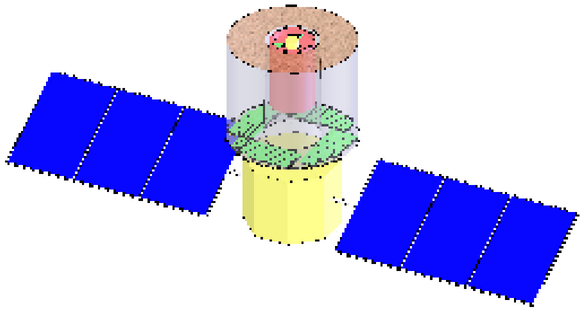
Side6B (redesign
of OTA for 90 deg launch)



Twister0b
(occultation btw sub-tels)

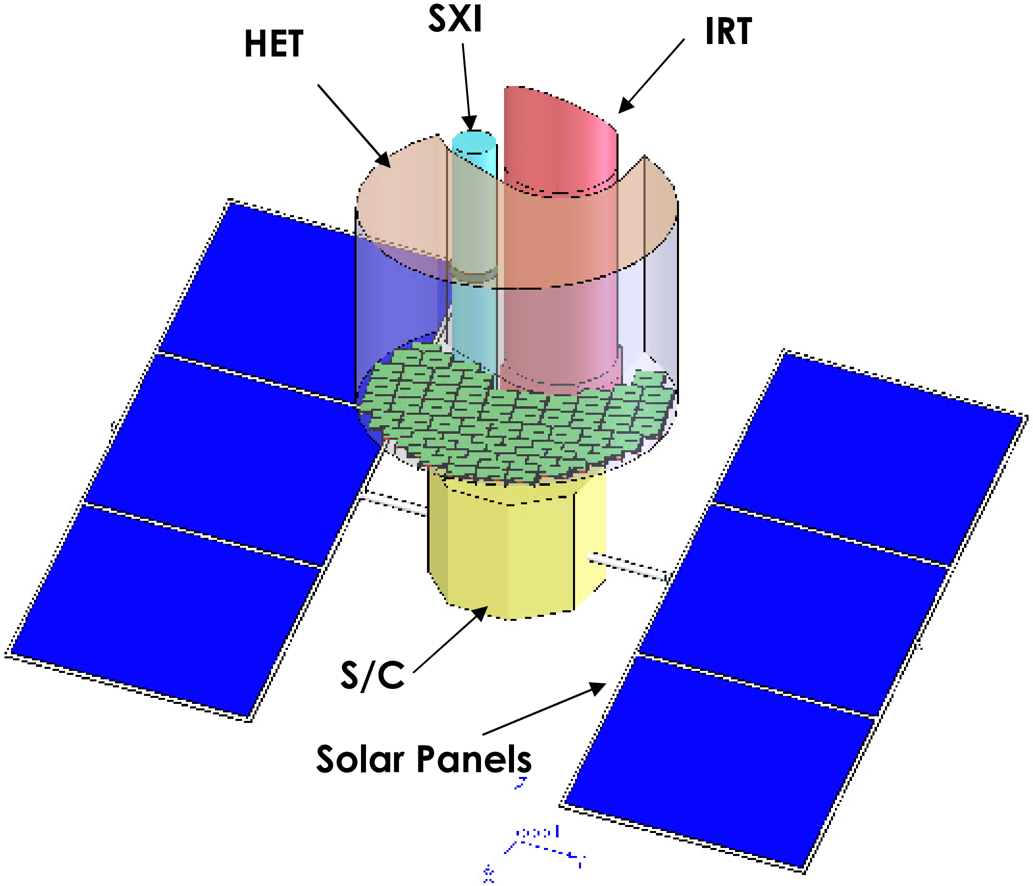


Symmetric (small FoV)



Symone (small FoV
Even with hybrid Mask)

EXIST Mission Overview



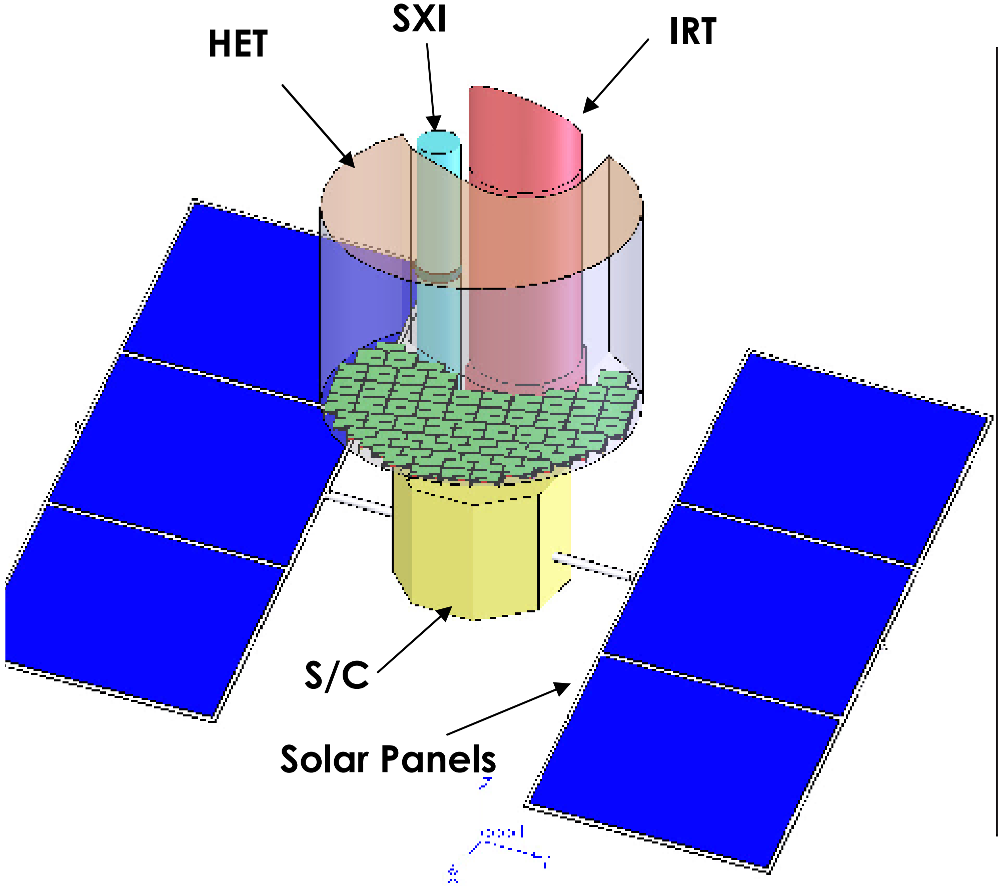
• **HET:** 5.5m^2 Cd-Zn-Te (CZT), 0.6mm pixels (<16", 90% conf. radii positions), 5 – 600 keV

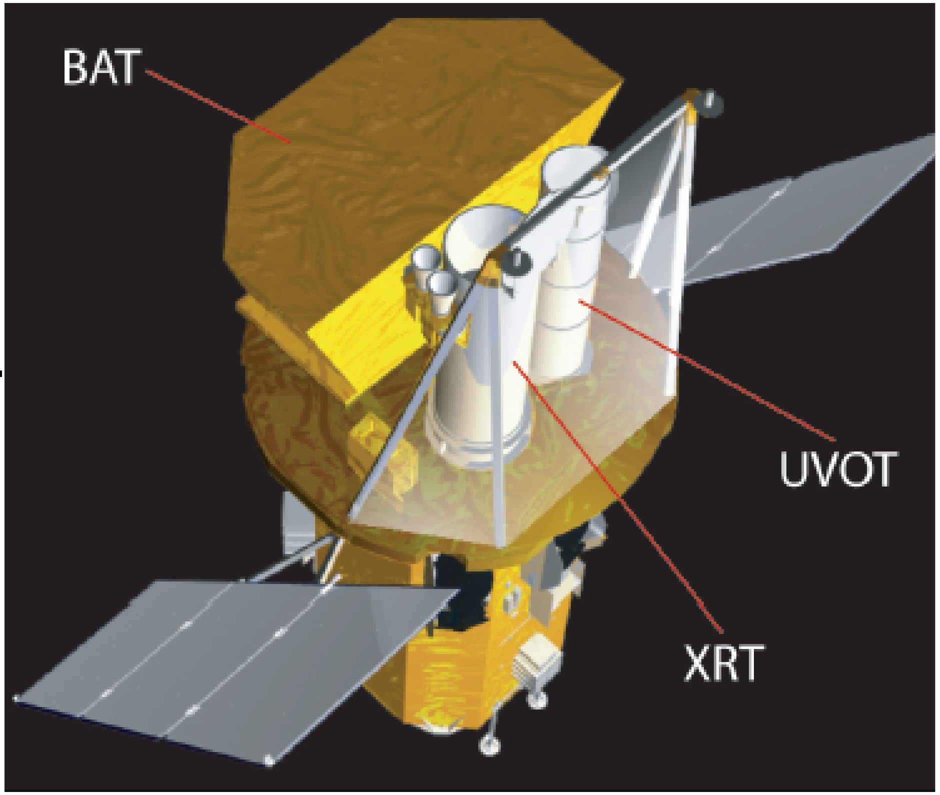
• **SXI:** 0.6m Wolter-I X-ray mirrors, CCD 0.3 – 10 keV

• **IRT:** 1.1m optical/IR telescope & obj. prism: 0.3-2.5μm spectra & z's

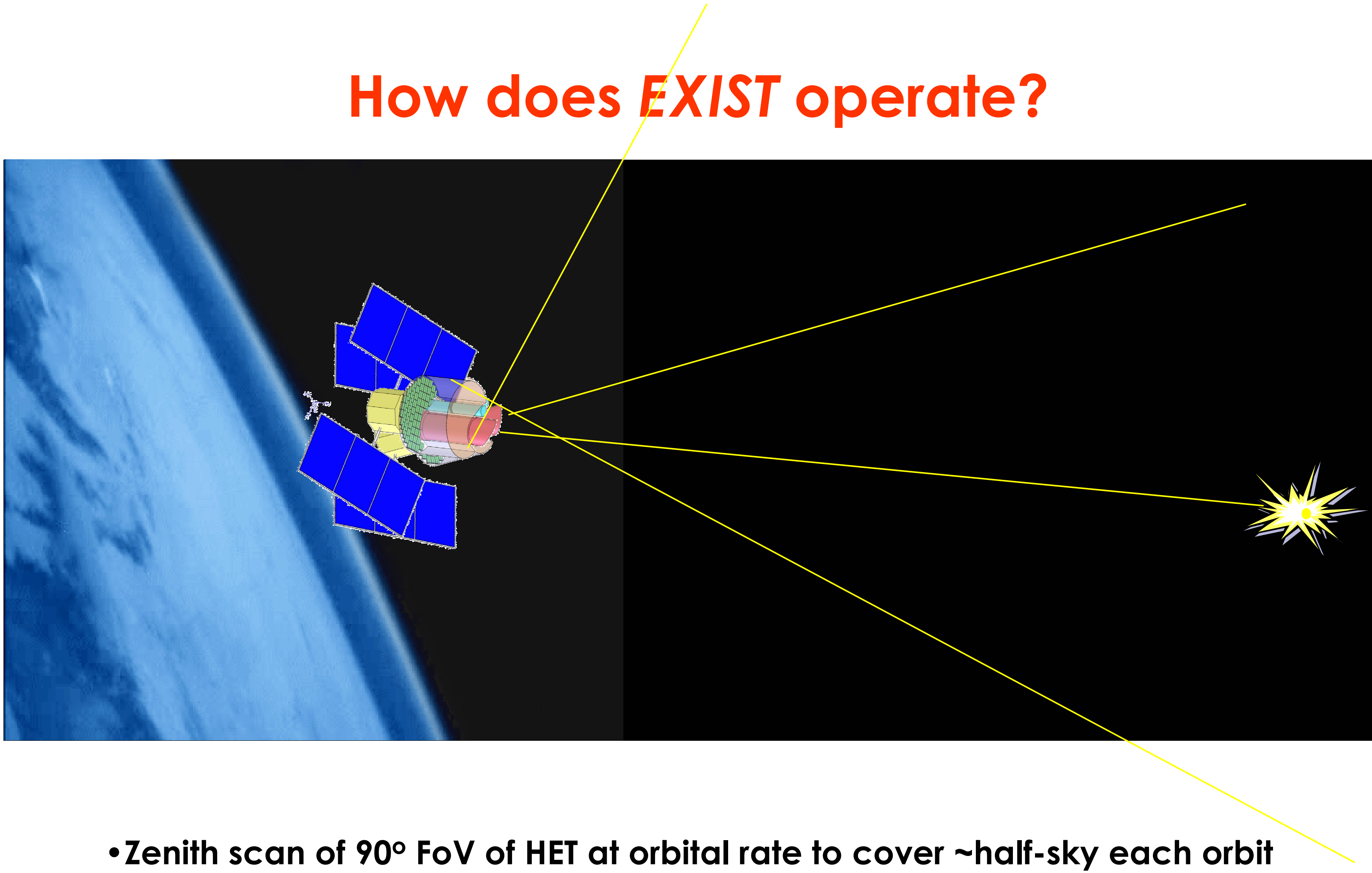
• Zenith-pointed scanning with 2sr FoV and full sky every 3hr pointings for spectra

EXIST vs Swift





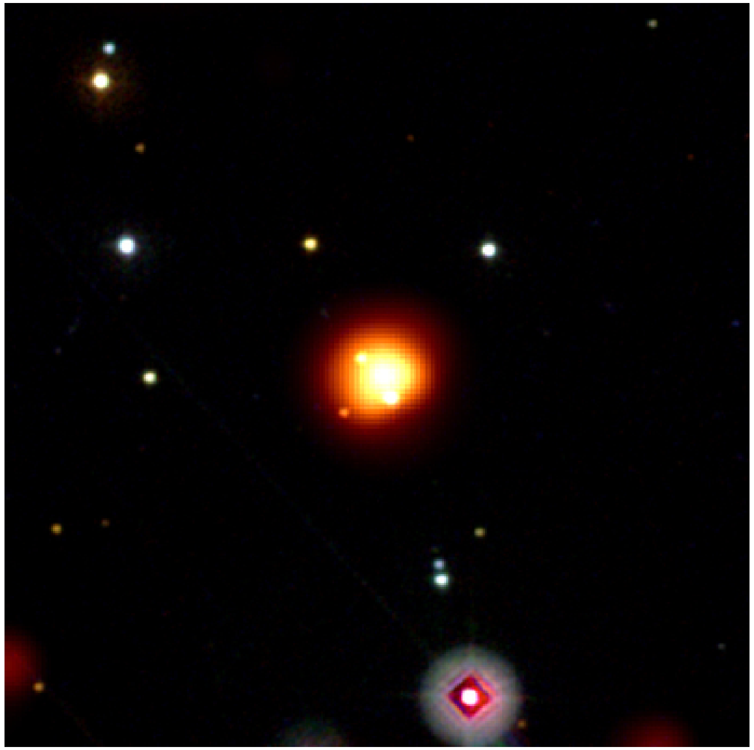
How does *EXIST* operate?



- Zenith scan of 90° FoV of HET at orbital rate to cover ~half-sky each orbit
- Imaging detects GRB or variable AGN or transient
- EXIST slews S/C onto GRB for IRT imaging and spectrum for redshift
- Stay on for 1-2 orbits

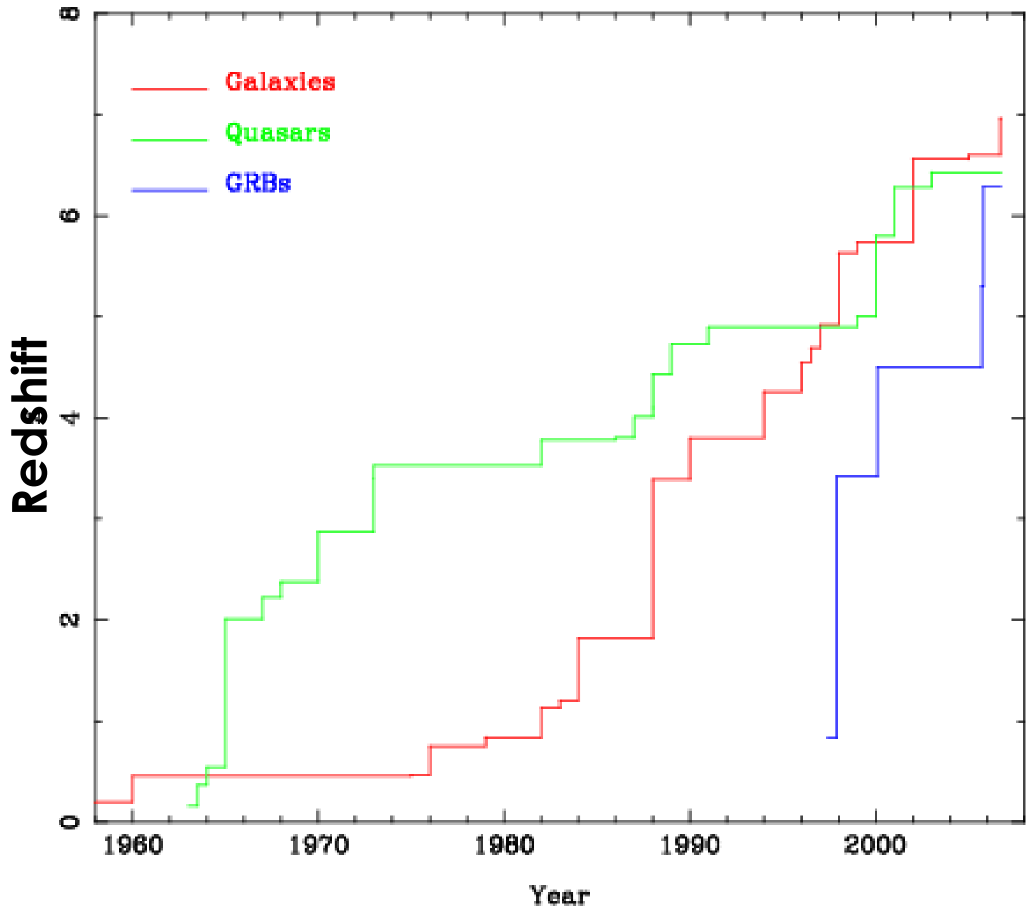
Gamma-Ray Burst

- Most Powerful explosion since Big Bang
- Birth of a Black Hole in an explosion of a massive star
- Collisions of two neutron stars.



GRB080913 (Swift/UVOT)
12.8 Billion Light Years
800Myr since Big Bang
Z=6.7
NASA/Swift/Stefan Immler

Advantages of using GRBs as Cosmic Probe



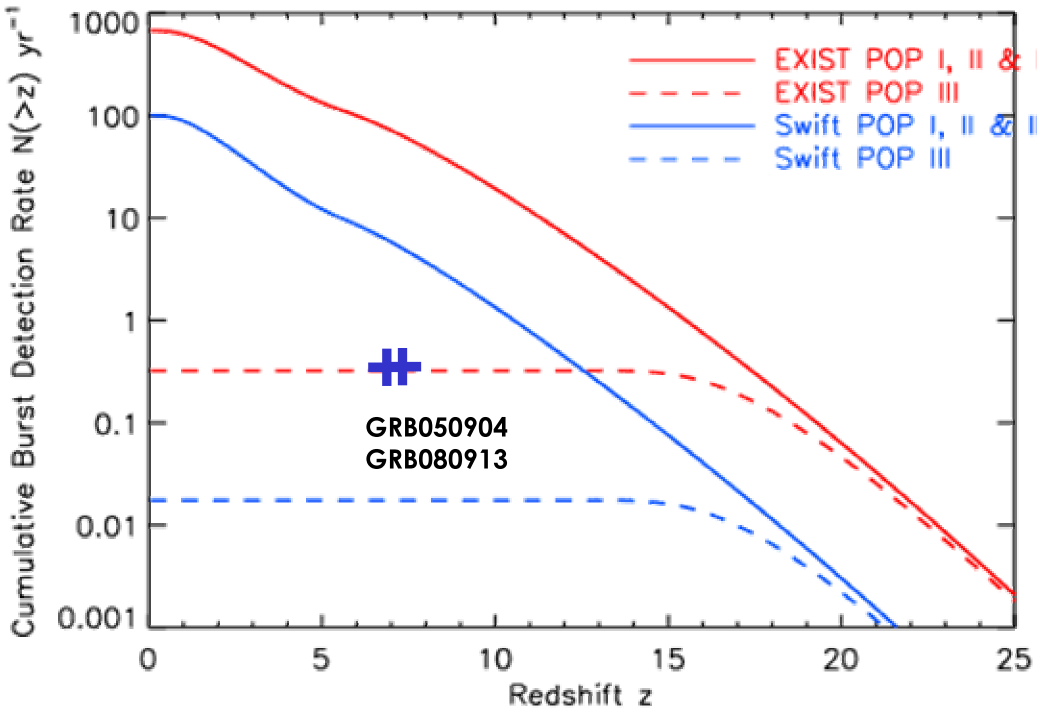
Spectroscopical High Redshift Record
Tanvir & Jakobsson (astroph/071777v1)

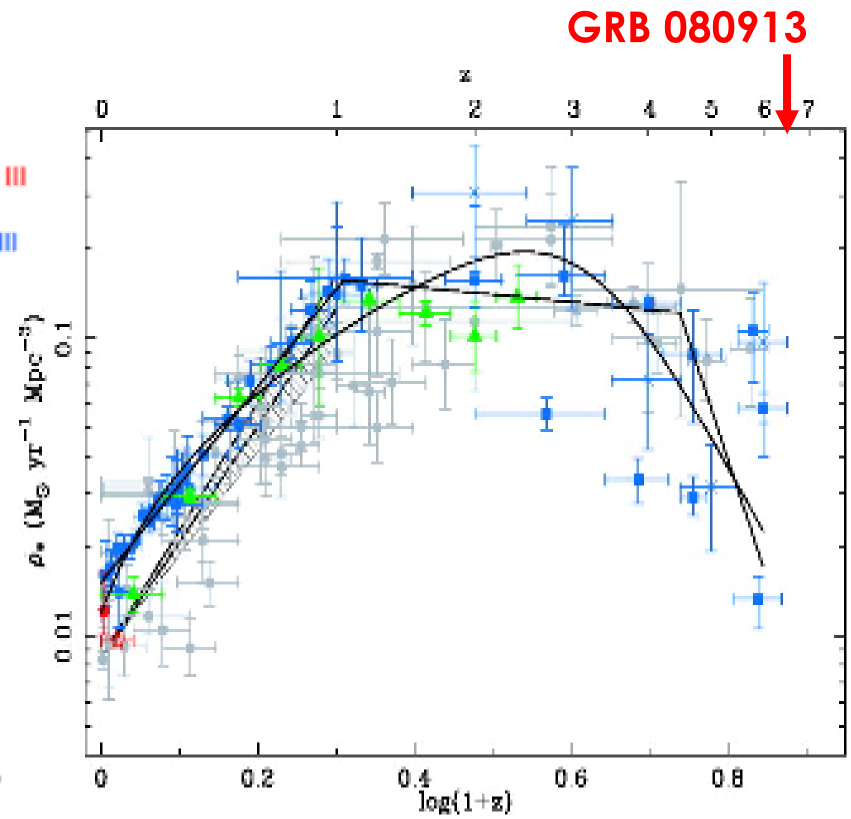
- **Observed flux is independent of redshift: Time Lag nearly cancels out luminosity distance.**

- **Featureless powerlaw afterglow spectra is ideal for hunting Ly break and absoprtion by local IGM**

- **Host Galaxy doesn't need to be massive.**

EXIST GRBs *open* universe to z ≥ 10

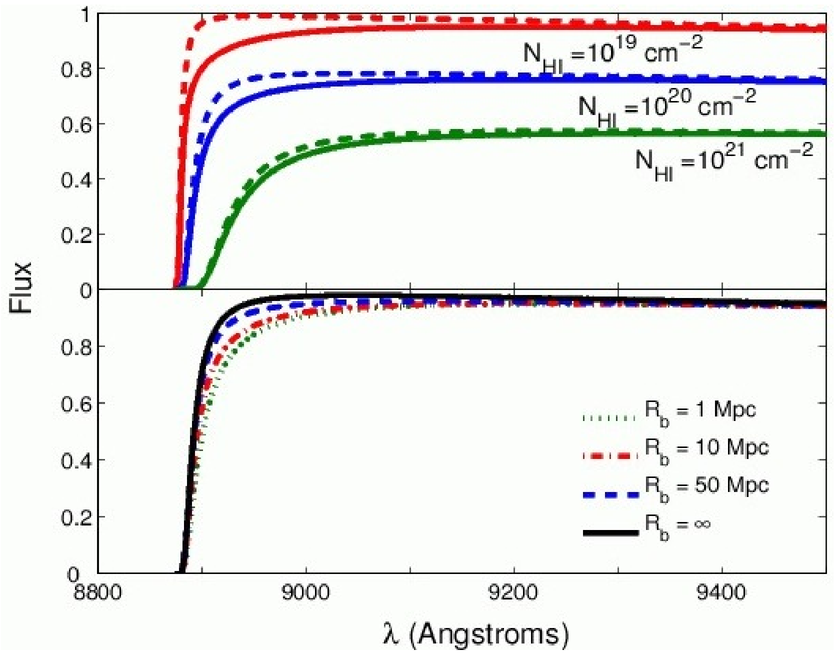




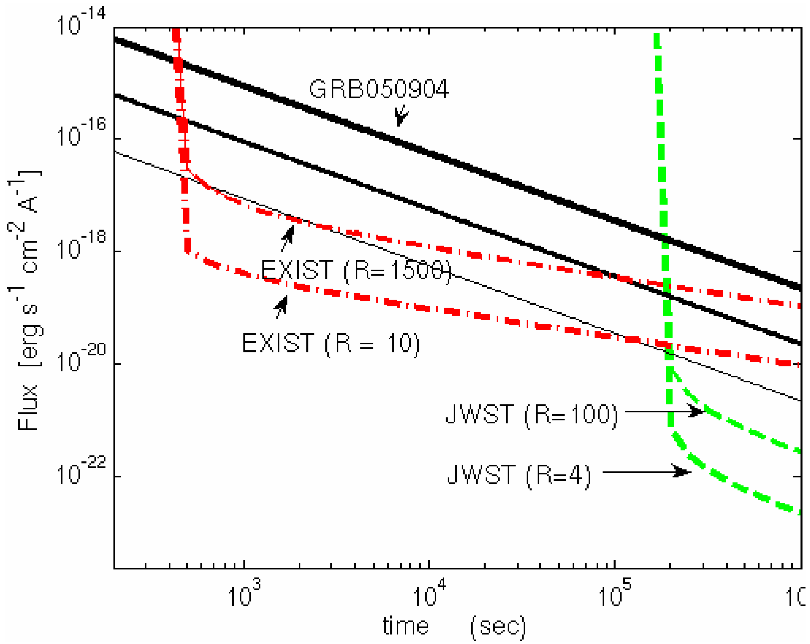
Predicted GRB rates vs. z based on Bromm and Loeb (2005). *EXIST* will detect and measure redshifts for >10-60 GRBs/yr at z >7 and may detect Pop III GRBs. Lyα spectra will explore EOR at z ~6-10.

EXIST GRBs vs. z will probe the star formation rate (SFR) vs. z at highest redshifts, and constrain/measure Pop III (Hopkins & Beacom 2006 ApJ 651, 142).

IRT spectra on board at H(AB) ~24 for GRB redshifts out to z ~20(!)



Sensitivity of Ly Breaks to local IGM



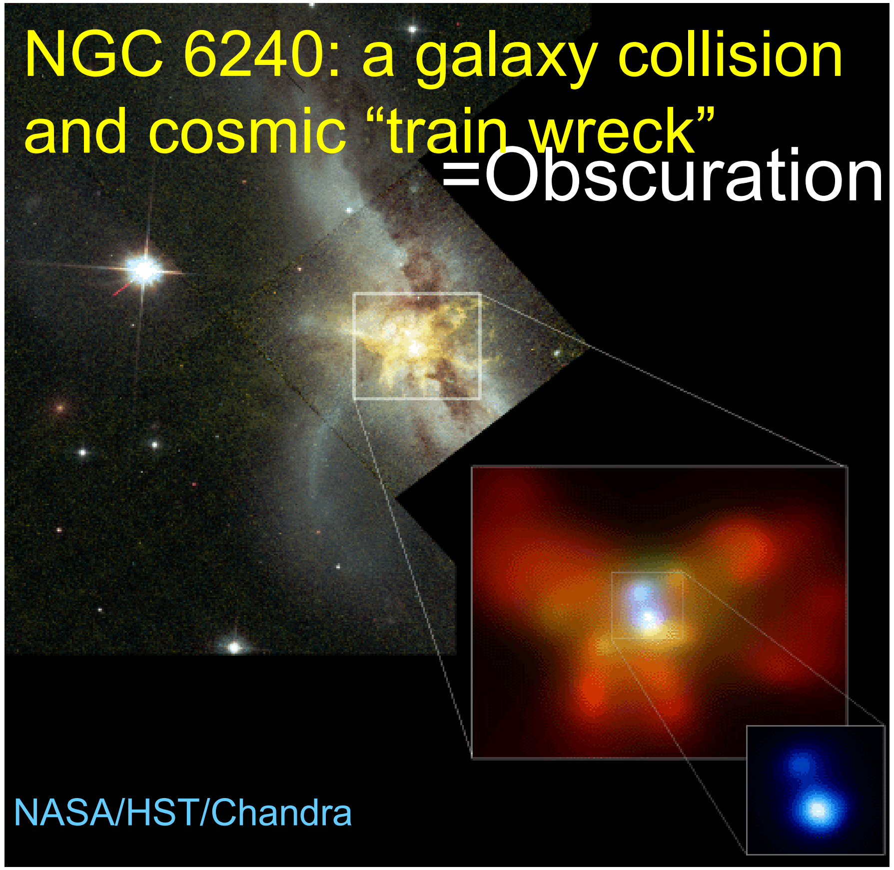
IRT vs JWST for GRB 1x, 0.1x, 0.01x flux of GRB050904

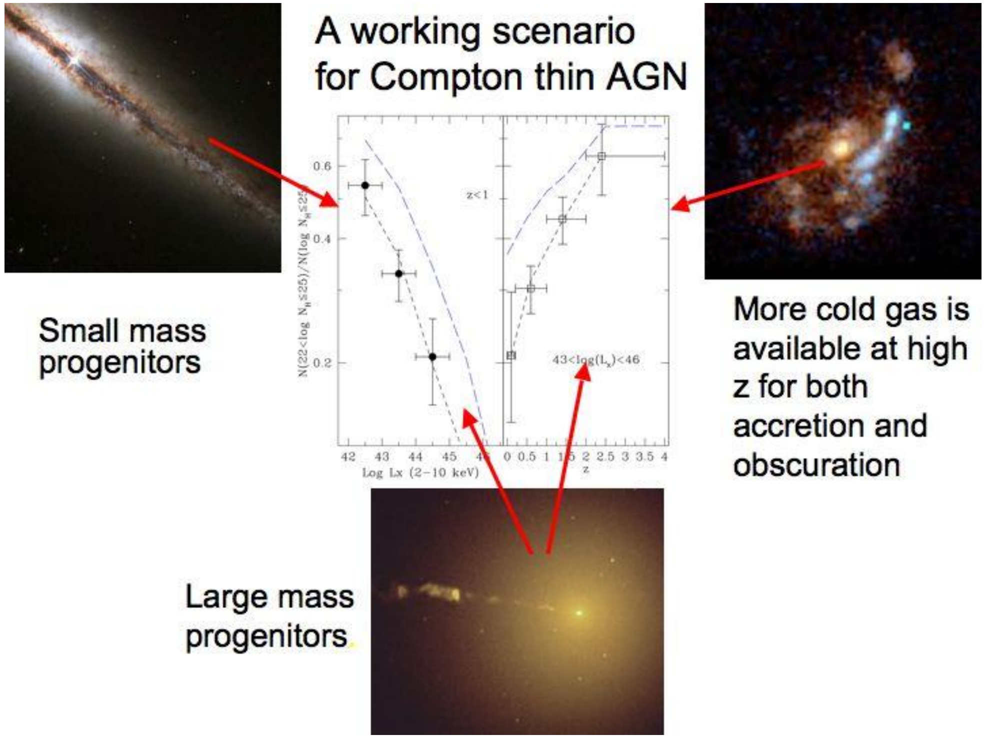
IRT spectra (objective prism, R ~15 or slit, R ~1500) for H(AB) ~24 in 600sec exp. Simultaneously for optical (0.3-1μm) and IR (0.9-2.5 μm. Measure z to 10% out to z ~20; Ly profiles for EOR studies of local IGM.

Obscured AGN (all types) & QSOs vs. z?

EXIST **can detect and discover obscured AGN over a broad range of *Lx* and absorption column NH to further constrain NH vs. z and growth of SMBHs**

EXIST **best suited to discover rare Type 2 QSOs at z ≤3**





EXIST **survey will explore the recent evidence (La Franca et al 2005 and Treister & Urry (2006) that obscured AGN are increasing as $(1+z)^{0.4}$**

Dormant SMBHs revealed by Tidal disruption of stars

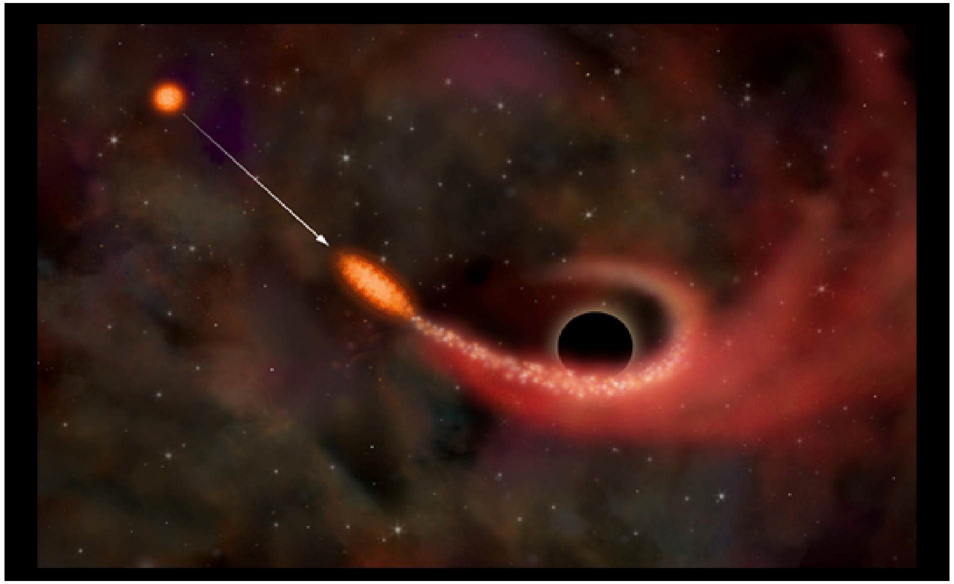
(and predicting gravitational waves from “invisible” supermassive BHs)

Tidal disruption of stars spiraling into Dormant SMBHs with mass ~10^7 M_o:

if 1% of L_{acc} in HX band, ~10^{-5} TD events/year/Mpc^3 allow EXIST to see ~30 flares/yr out to ~200Mpc (Grindlay 2004).

HX spectral comp. “confirmed” with PL spectral decay of RXJ1242 measured with Chandra/XMM!

Sub-giants with WD cores are gravitational wave LISA triggers.



Artists conception of tidal disruption of star in RXJ1242-1119 detected with ROSAT (1991) and confirmed with Chandra (Komossa et al 2004) and now also Galex results of Gezari et al (2008).

Measure $10^{6\text{-}8}M_{\odot}$ SMBH content/evolution of nearby galaxies

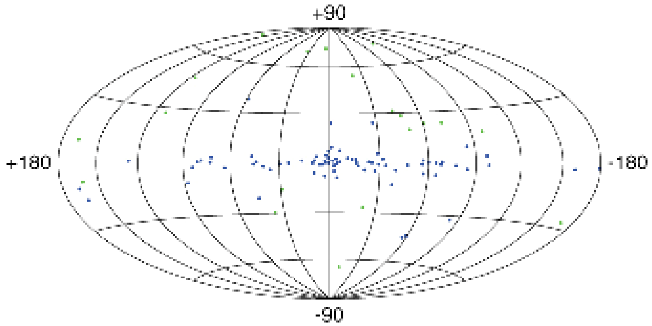
(to understand BH-Galaxy Bulge mass relation & BH-galaxy evolution)

Hard X-ray Sky

- **Hard X-ray (10-600 keV) sky not yet surveyed to ROSAT sensitivity. *EXIST* would be ~20X more sensitive than *Swift* or *INTEGRAL* and cover full sky**
- ***EXIST* will detect ≥3 x 10^4 sources, ≤10″ positions, 5-600 keV spectra**
- ***EXIST* would provide unique temporal survey: *full sky imaging every 2 orbits***

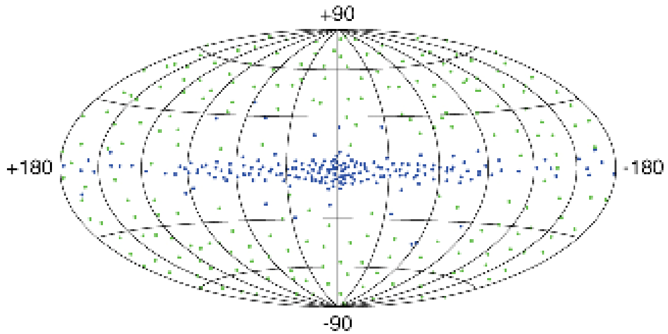
Previous Hard X-ray Sky

HEAO-1, BeppoSAX



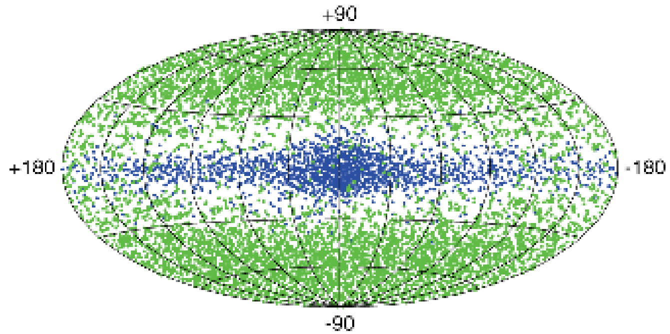
2010 Hard X-ray Sky

Swift & INTEGRAL



2017(?) Hard X-ray Sky

EXIST



Science Motivation of EXIST

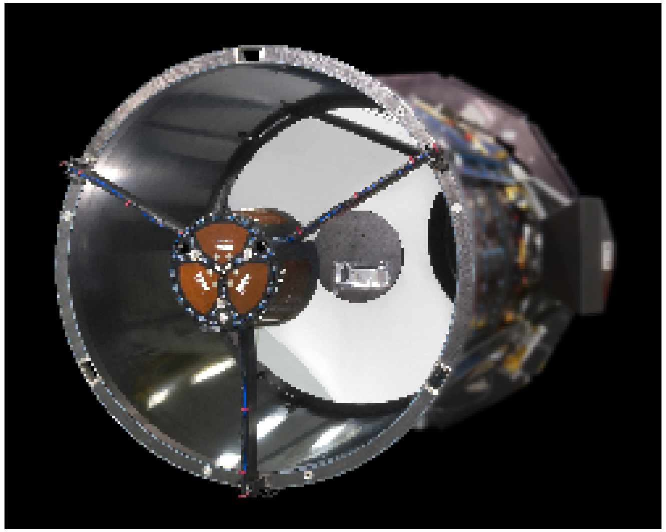
- Glimpse from Early Universe:
  - Trace reionization and cosmic structure by capturing high-Z GRBs – birth of first stellar BHs.

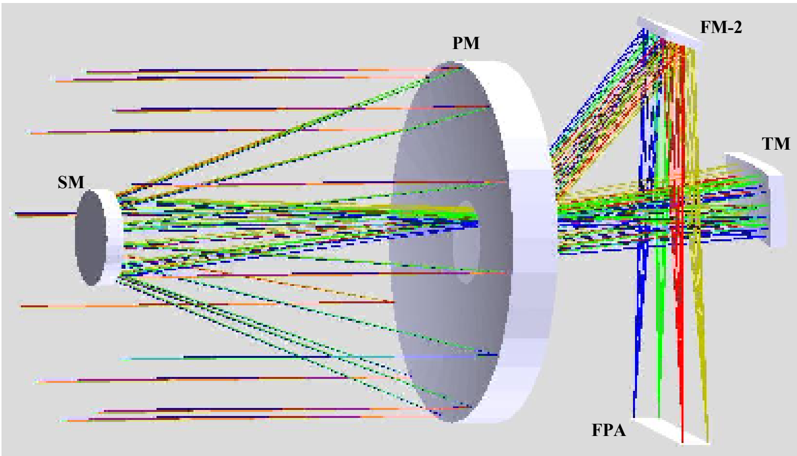
- Understanding Cosmic Landscape:
  - Search for obscured AGN & dormant BHs.
    Do all galaxies contain central BHs?
  - How did they get there and how
    do BHs affect their host galaxies?
  - Extreme Physics around the BHs.

- Transients or Exotic Variable X-ray Sources
  - Stellar BHs, SGRs, Supernovae Breakouts, …

Coded-Aperture Imaging

EXIST IRT Optical Telescope Assembly





- NextView Telescope from ITT industries.

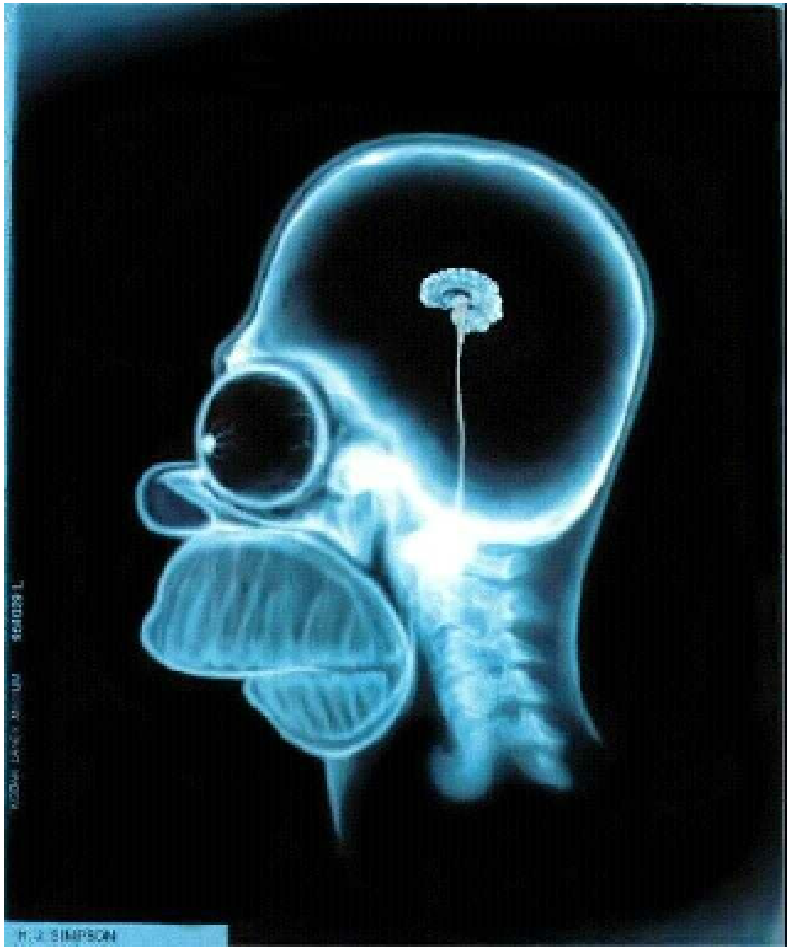
- High TRL: first tel to be launched Aug 2008.

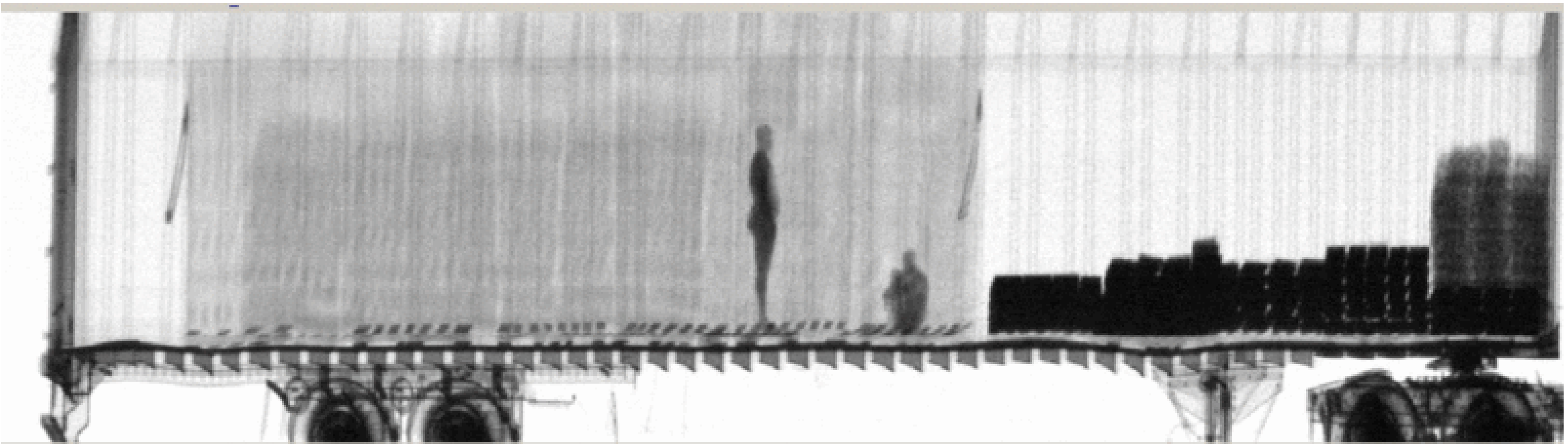
- long heritage: Chandra, IKONOS

- 1.1 m clear aperture, 13m EFL

- Meets and exceeds aggressive optical requirements

- Passive design with the exception of focus control

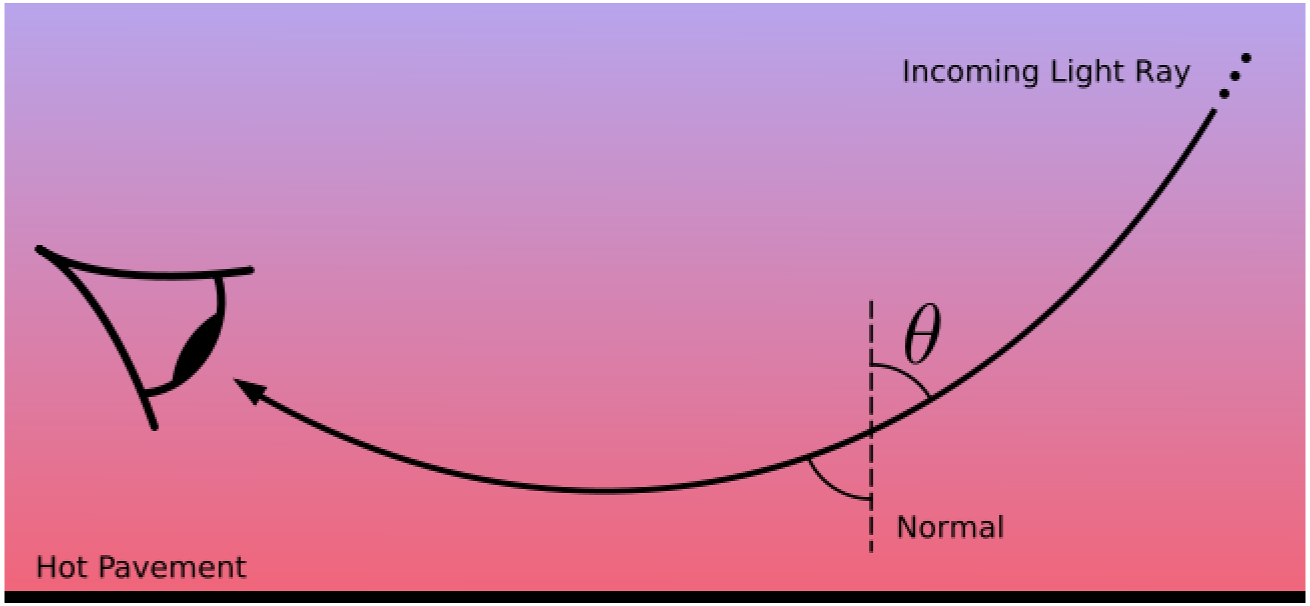

H. J. SIMPSON



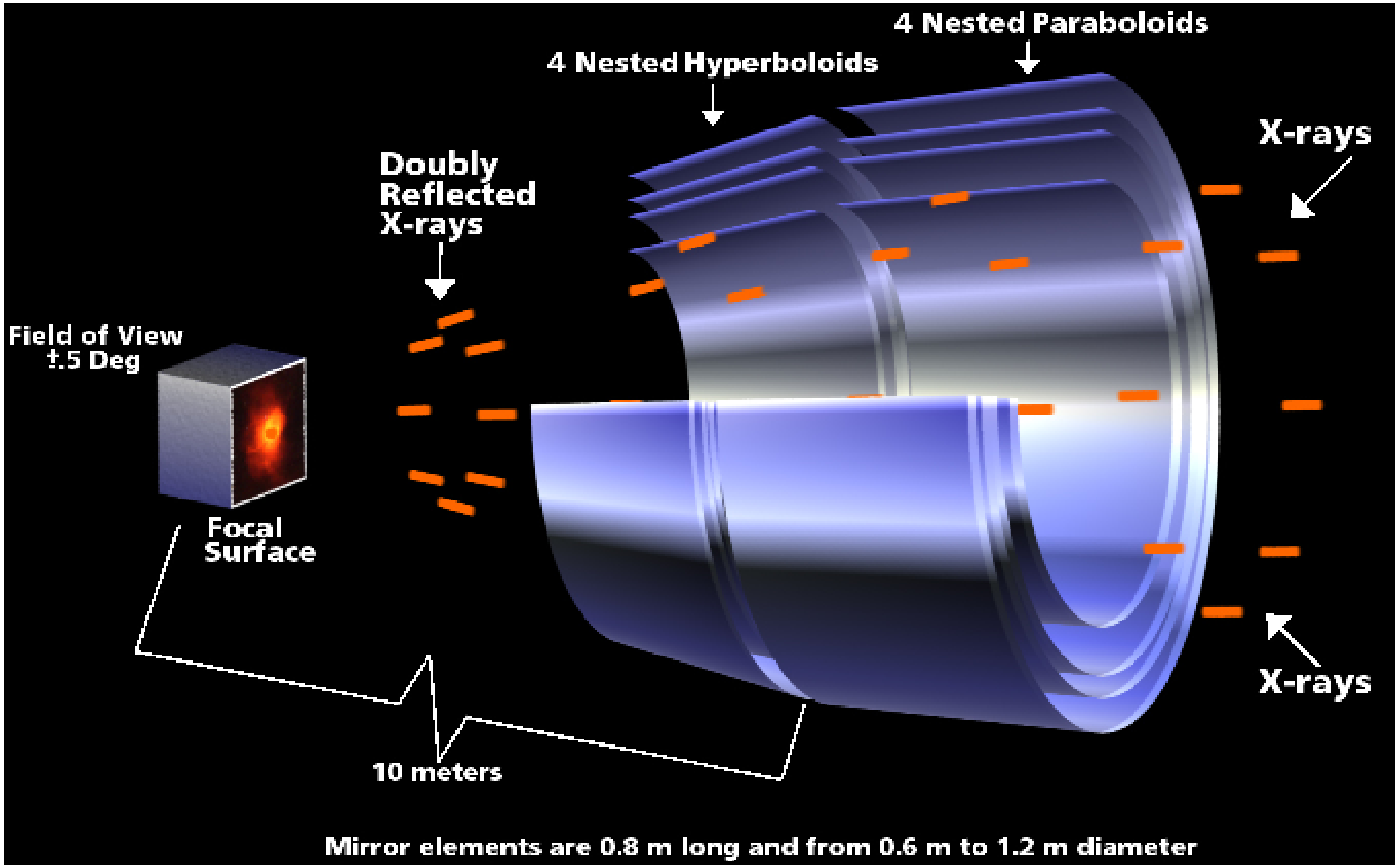

40



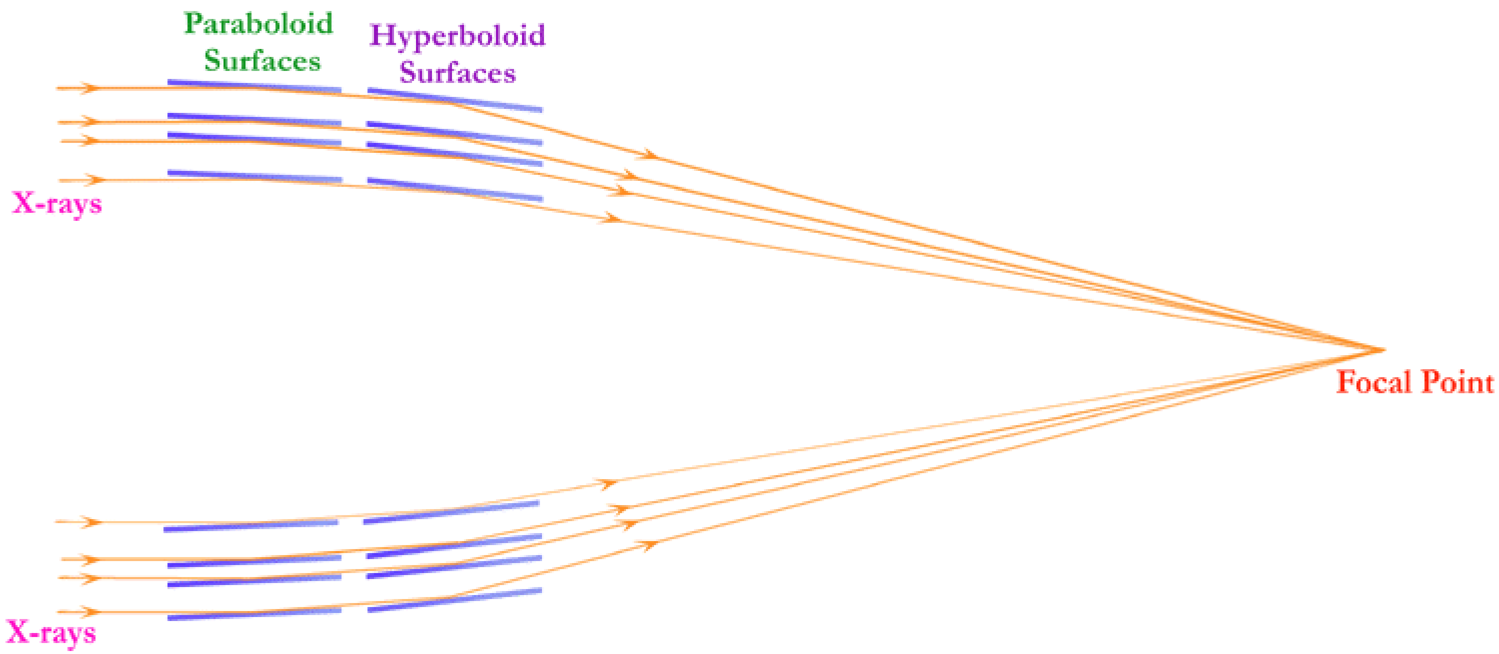
Inferior Mirage


Incoming Light Ray
θ
Normal
Hot Pavement

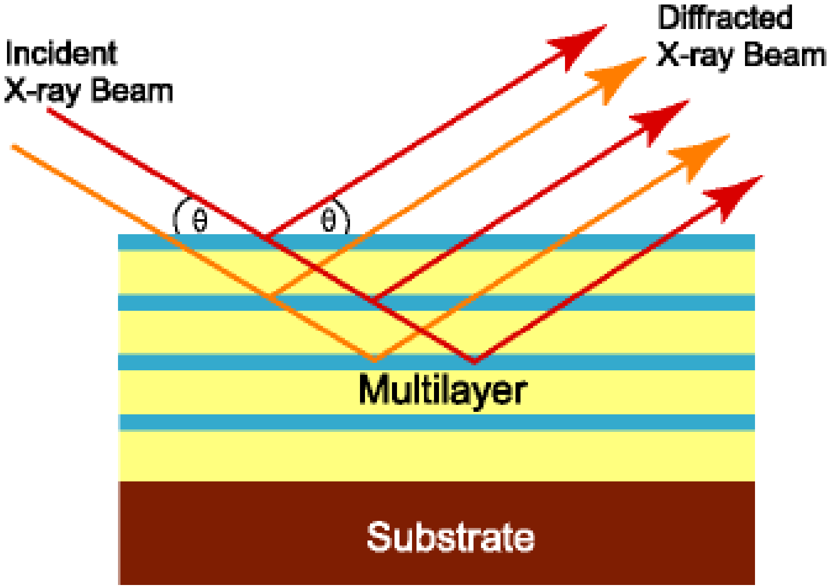
Chandra X-ray Observatory
Grazing Incidence Optics: up to ~10 keV

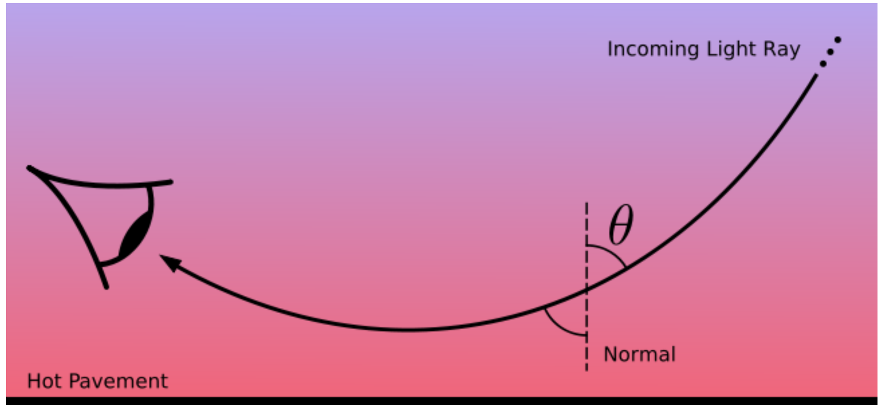


Chandra X-ray Observatory, SXI on EXIST, etc
Grazing Incidence Optics: up to ~10 keV



Grazing Incidence+Multi-Layer Optics
Up to ~70 – 80 keV





The Nuclear Spectroscopic Telescope Array (NuStar) 2011

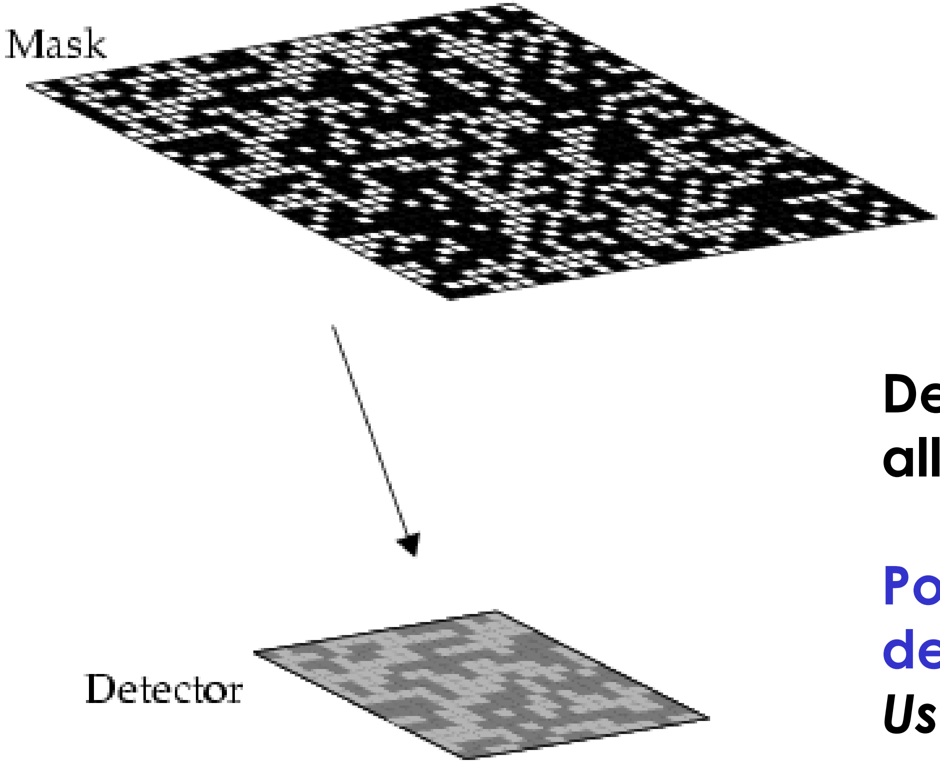
What about X-rays above 100 keV?
Focusing & Non-focusing?

- IR, Visible, UV: Normal Incidence Optics

- Soft X-ray, Hard X-ray, Soft Gamma-ray
  - < 10 keV: Grazing incidence
  - < 100 keV: Grazing+MultiLayer Optics
  - > 100 keV: ?

- Narrow Field vs Wide Field?

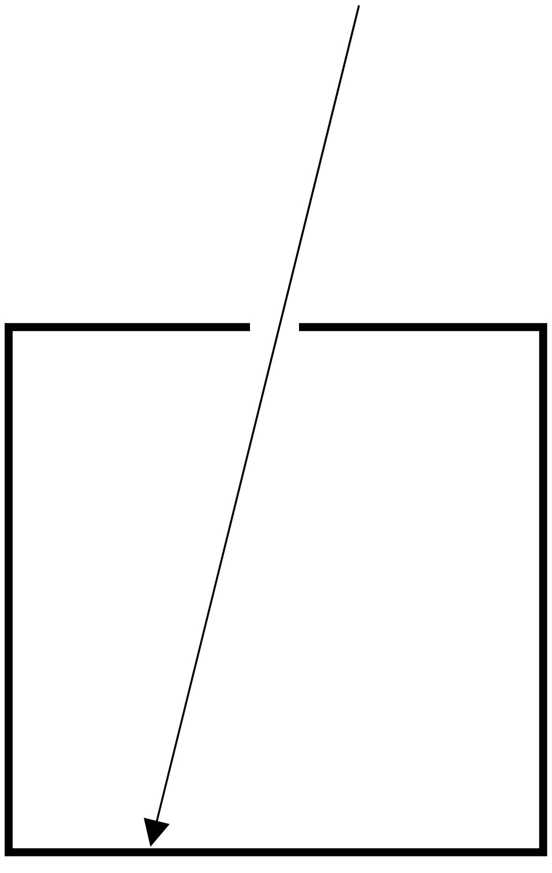
Coded-Aperture Hard X-ray Imaging Telescope



Decoding Shadowgram allows wide-field imaging.

Position-sensitive hard X-ray detectors needed:
Use Cd-Zn-Te (CZT) arrays.

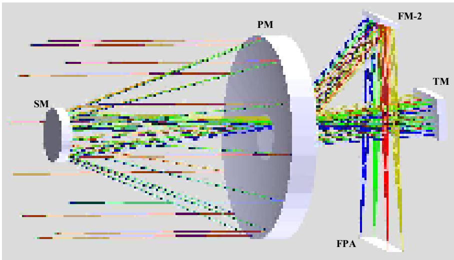
Pin Hole Camera



Extremely Inefficient

►Low sensitivity

Basics in Coded-Aperture Imaging
Sensitivity

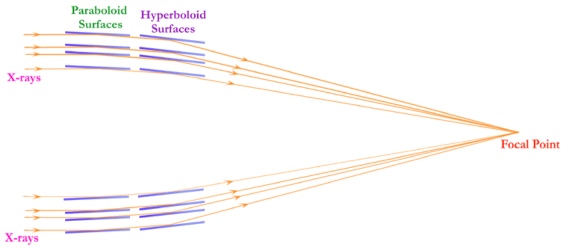


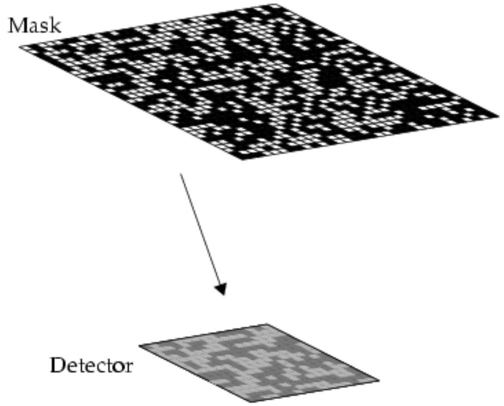
- Size does matter? Yes

- But the size of what?

more lights ► more sensitive

focusing telescopes: mirror size
non-focusing telescopes: detector size





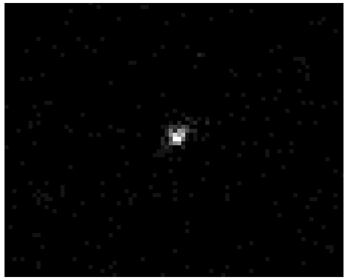
Basics in Coded-Aperture Imaging
Sensitivity

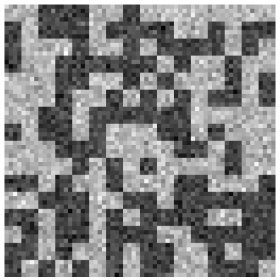
- For faint source at the sensitivity limit
  Focusing Tel: Photon Limited
  Non-focusing Tel: Background Dominated

$$S/N = S/\mathrm{sqrt}(B) = s\,A\,T/\mathrm{sqrt}(b\,A\,T) = s/\mathrm{sqrt}(b)\ \ \mathrm{sqrt}(A\,T)$$

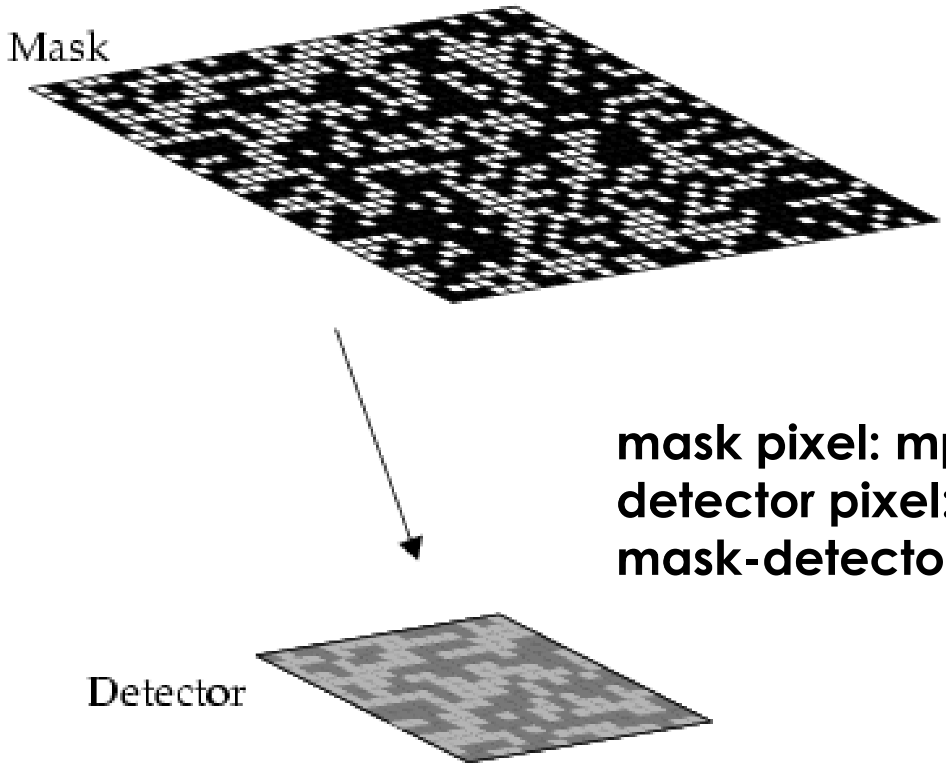
S: Total Source Cts, B: Total Bkgnd Cts
s: cts/s/cm^2 , b = cts/s/cm^2
A: Area, T: Time (exposure)

- Lose a half of the detector: lose only 30% of sensitivity





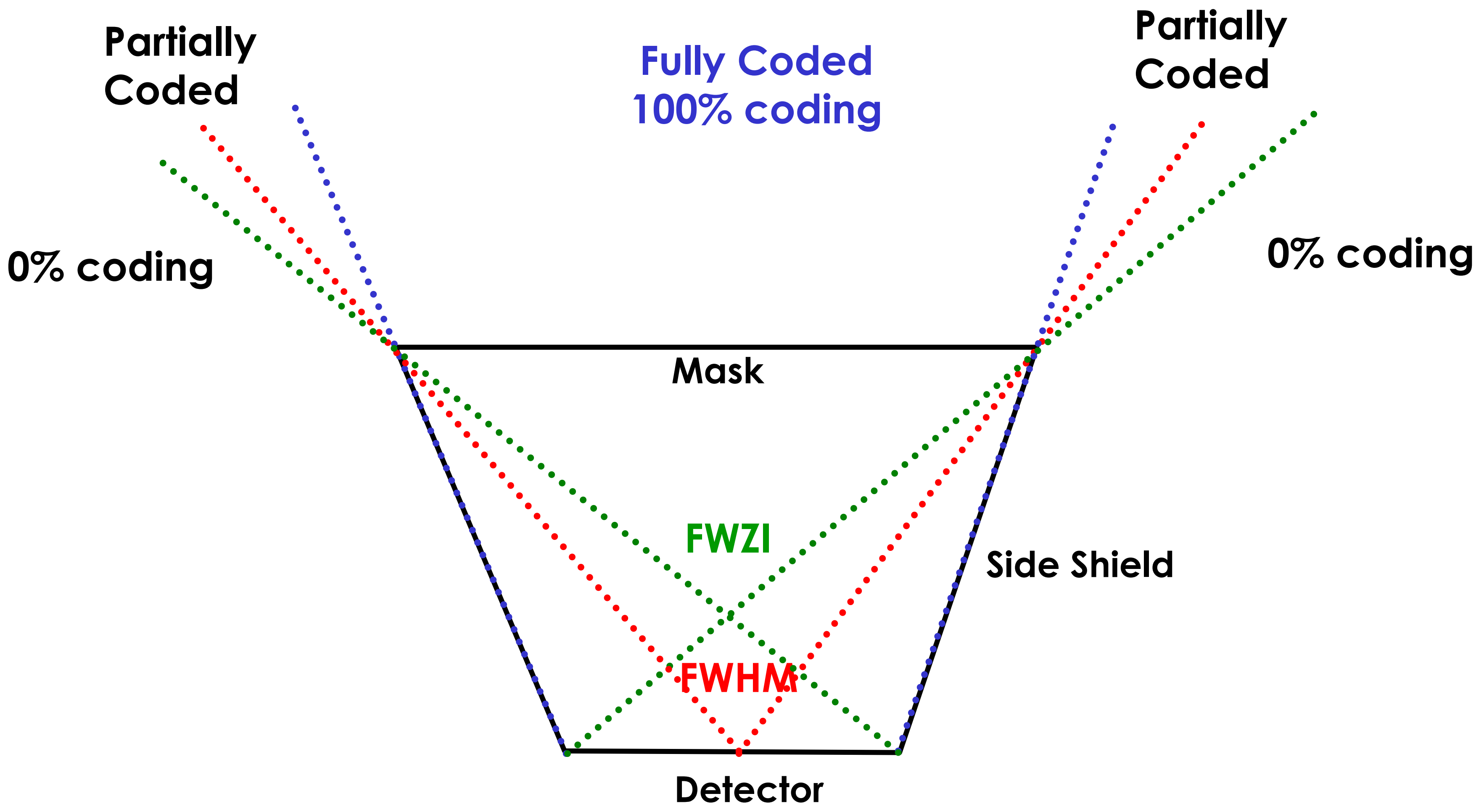
Basics in Coded-Aperture Imaging
Angular Resolution & Localization



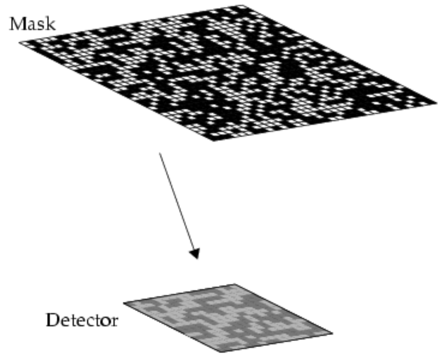
mask pixel: mp = 1.25 mm
detector pixel: dp= 0.6 mm
mask-detector separation: f = 2.5 m

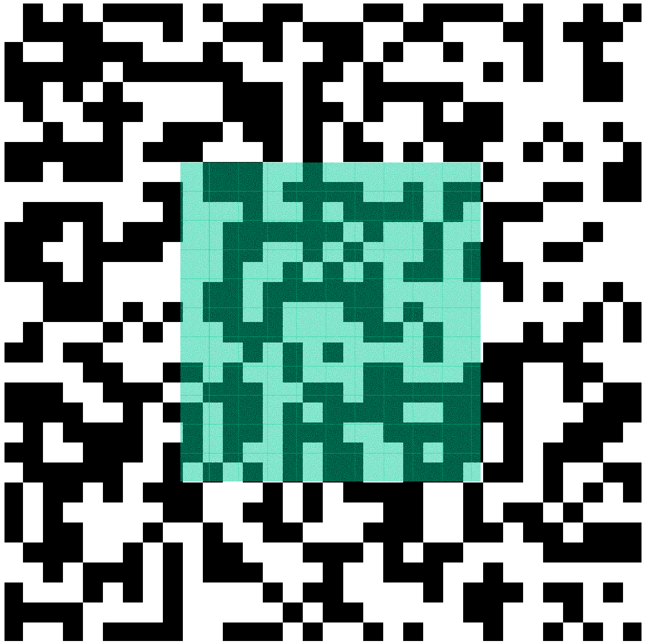
Angular Res: $r = \mathrm{atan}\ (\mathrm{sqrt}\ (mp^2+dp^2)/f) = 1.9'$
Source Localization: $l = 0.7\ r/(\sigma+b) = 16''$
for 90% radius, 5σ source, $b \sim 0$

Coding Fraction & Exposure

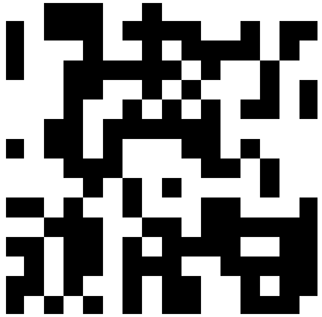


Random Mask Pattern





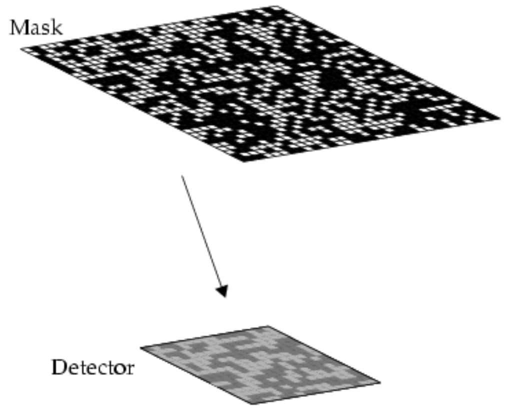
Random Mask

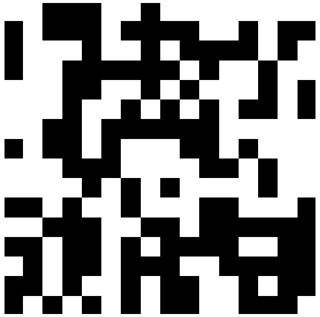


On-Axis response

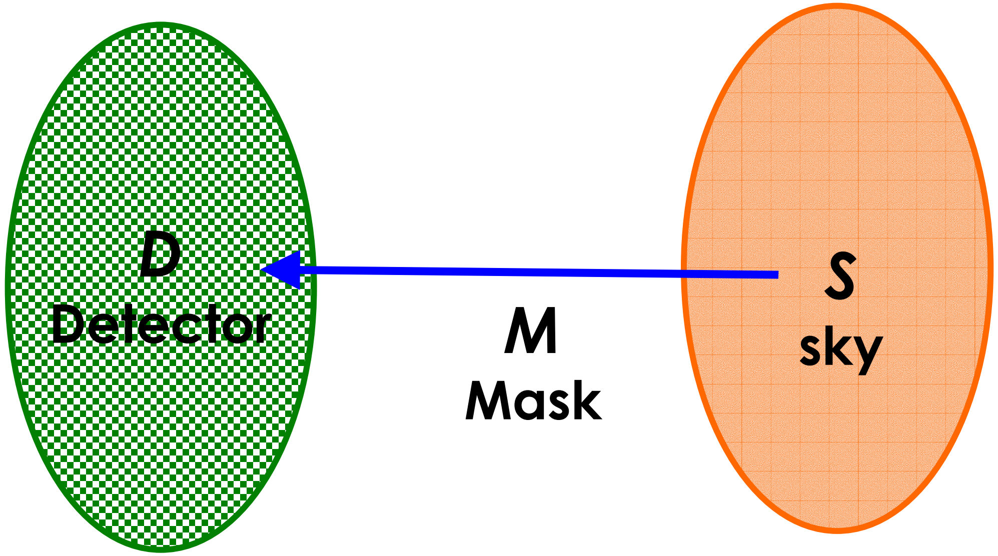
Image Recording

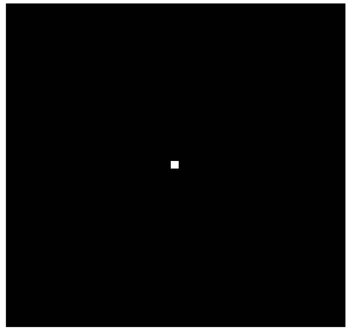
$$D = M \cdot S$$





An Ideal response from an on-axis point source



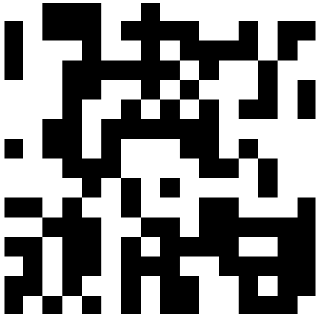


D=(d,0,…,d,0,…,0)

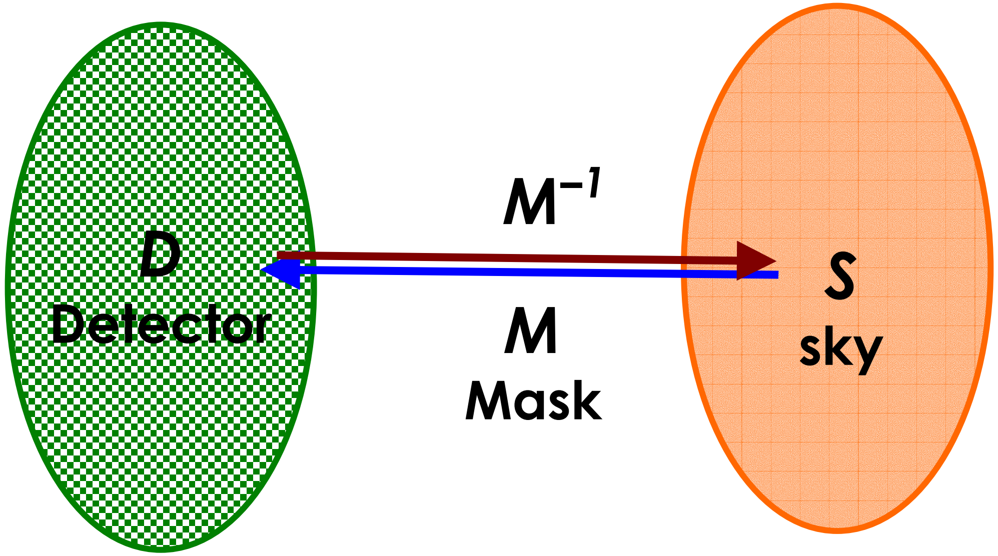
S=(0,0,…,s,0,…,0)

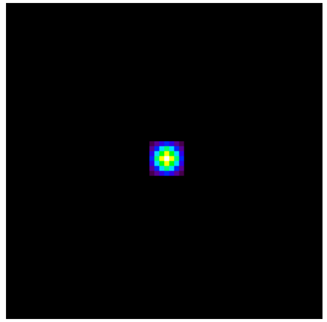
Image Reconstruction: Inversion?

$$D = M \cdot S$$



An Ideal on-axis response



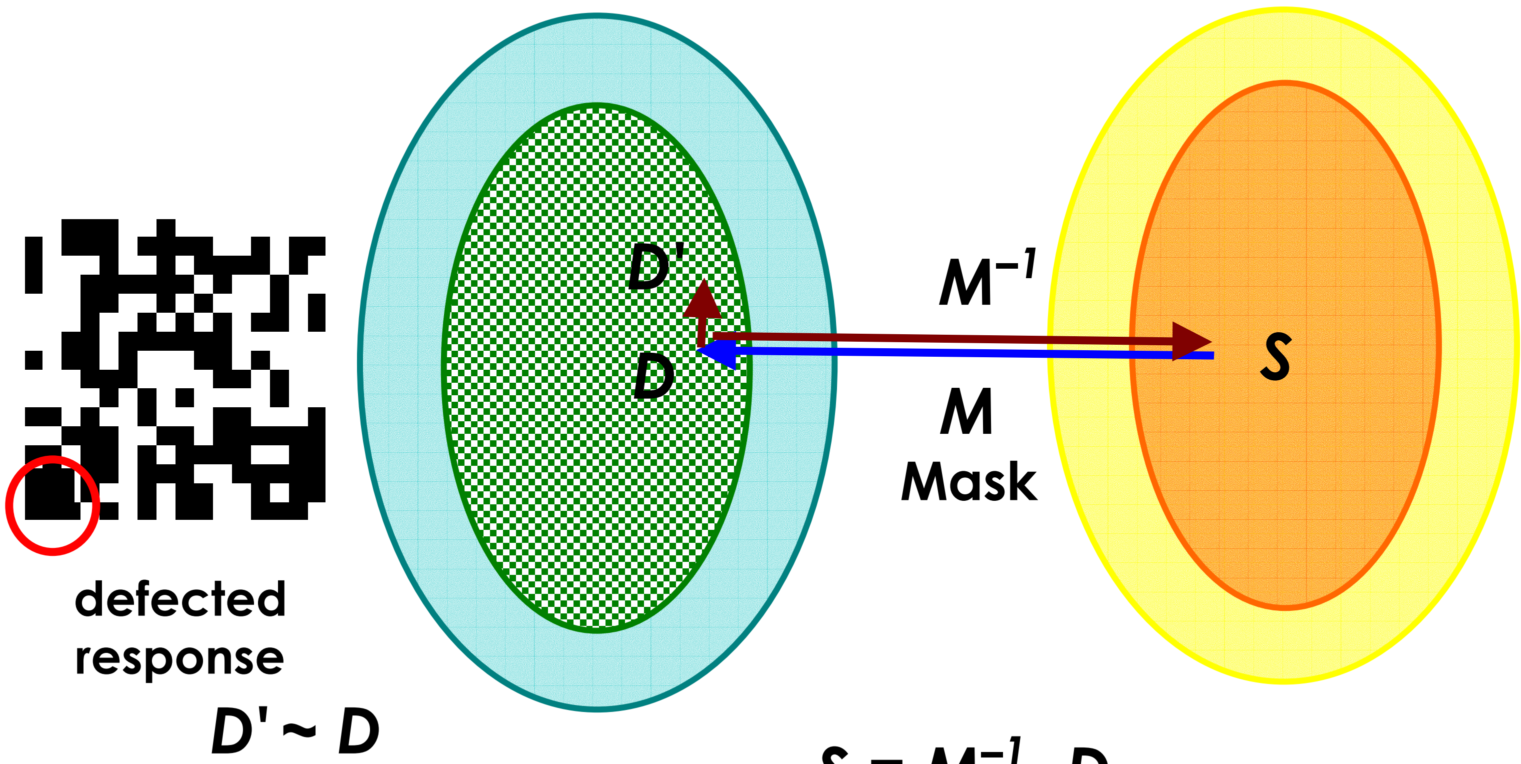


An Ideally reconstructed Sky Image

$$M^{-1} \cdot D = M^{-1} \cdot M \cdot S$$
$$= I \cdot S = S$$

Image Reconstruction: Inversion?

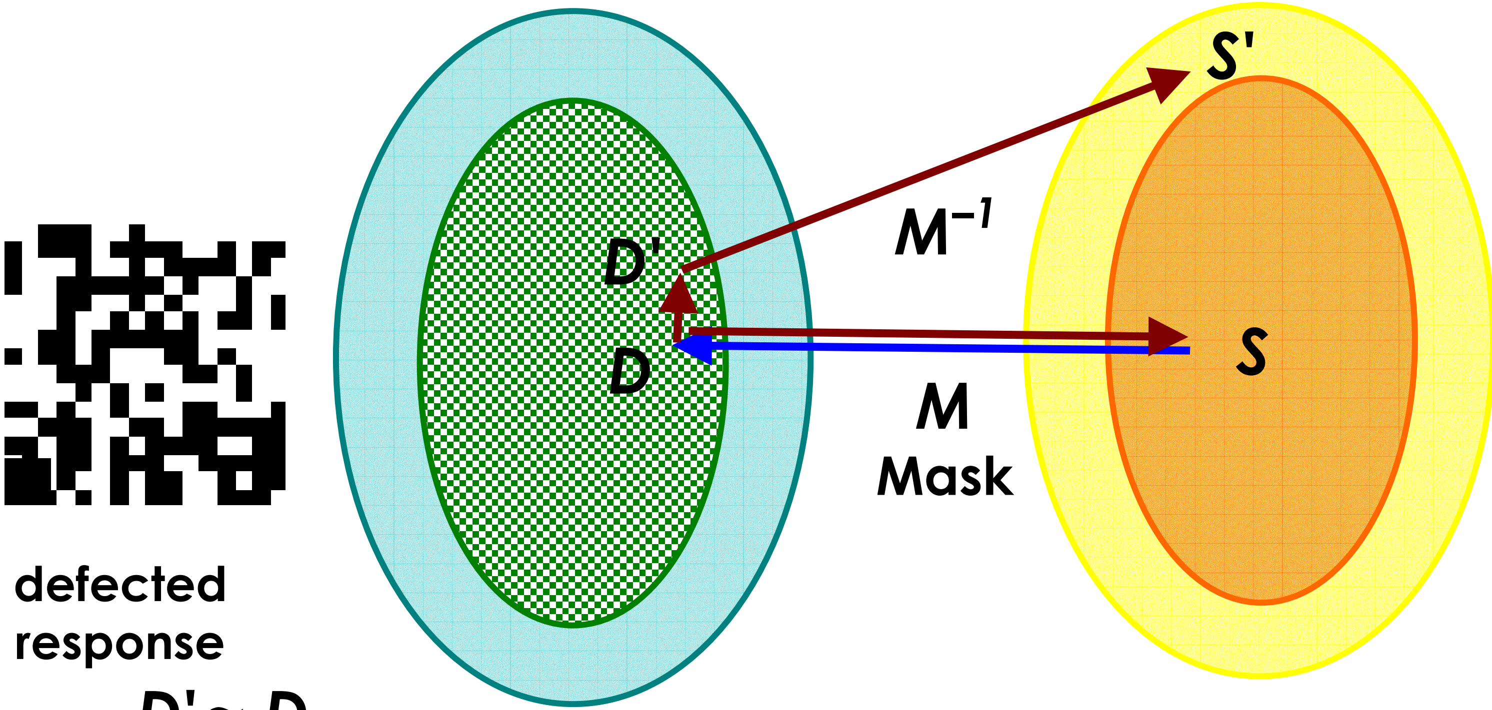
$$D = M \cdot S$$



$$S = M^{-1} \cdot D$$

Image Reconstruction: Inversion?

$$D = M \cdot S$$



defected response

$D' \sim D$

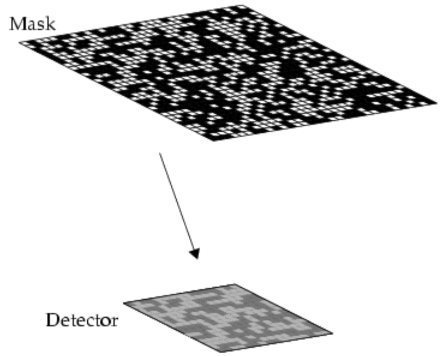
$S' \neq S$

► quantum noise

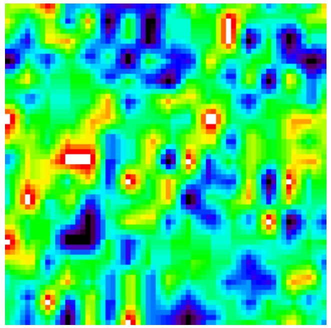
$$S = M^{-1} \cdot D$$

$$S' = M^{-1} \cdot D'$$

Random Mask Pattern



ΔD



Sky Vector to create ΔD

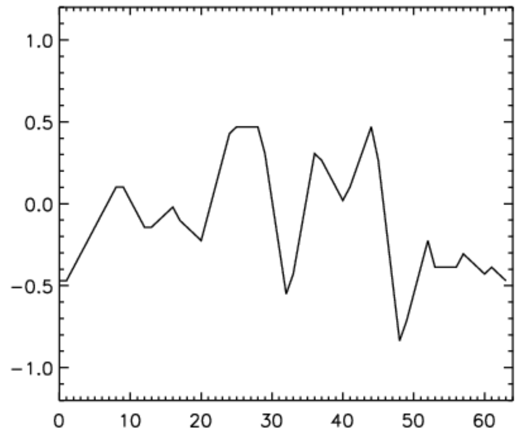
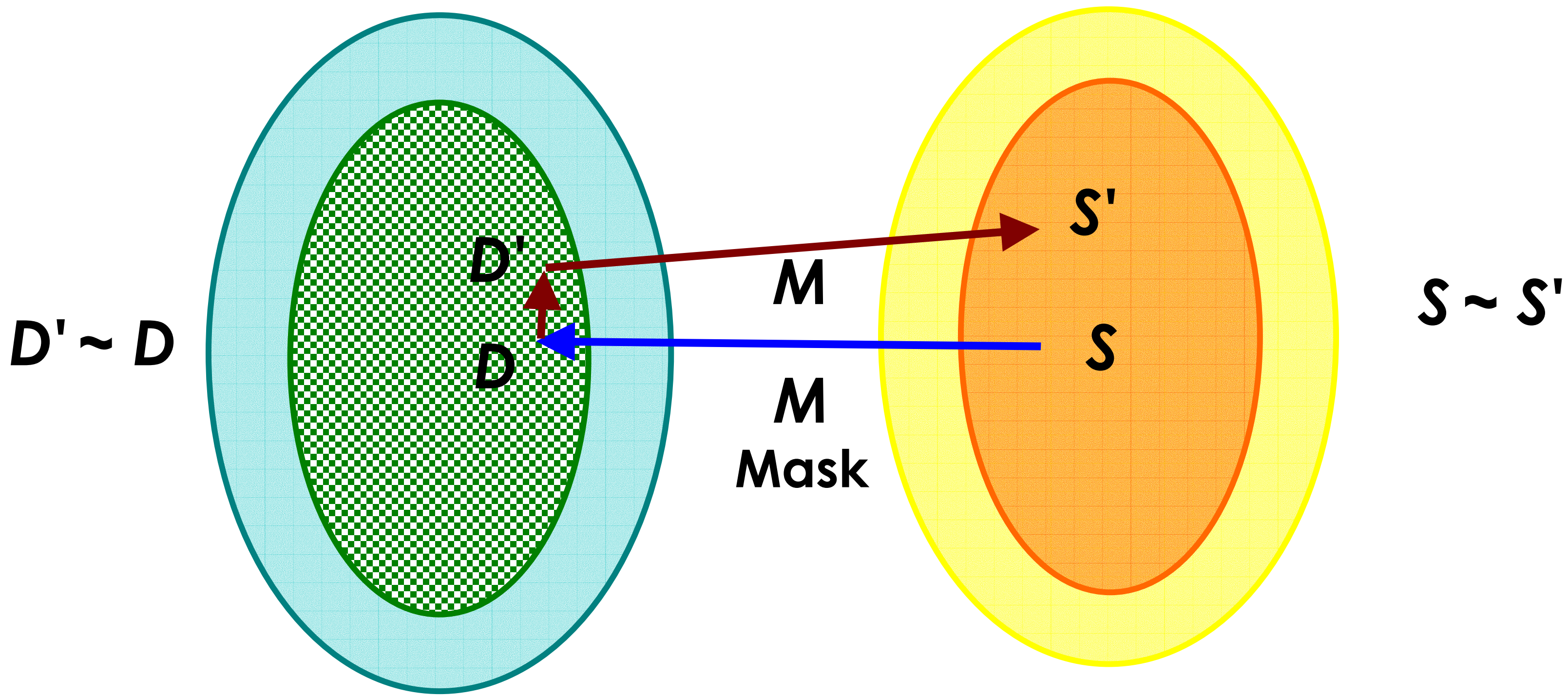


Image Reconstruction: Correlation

$$D = M \cdot S$$

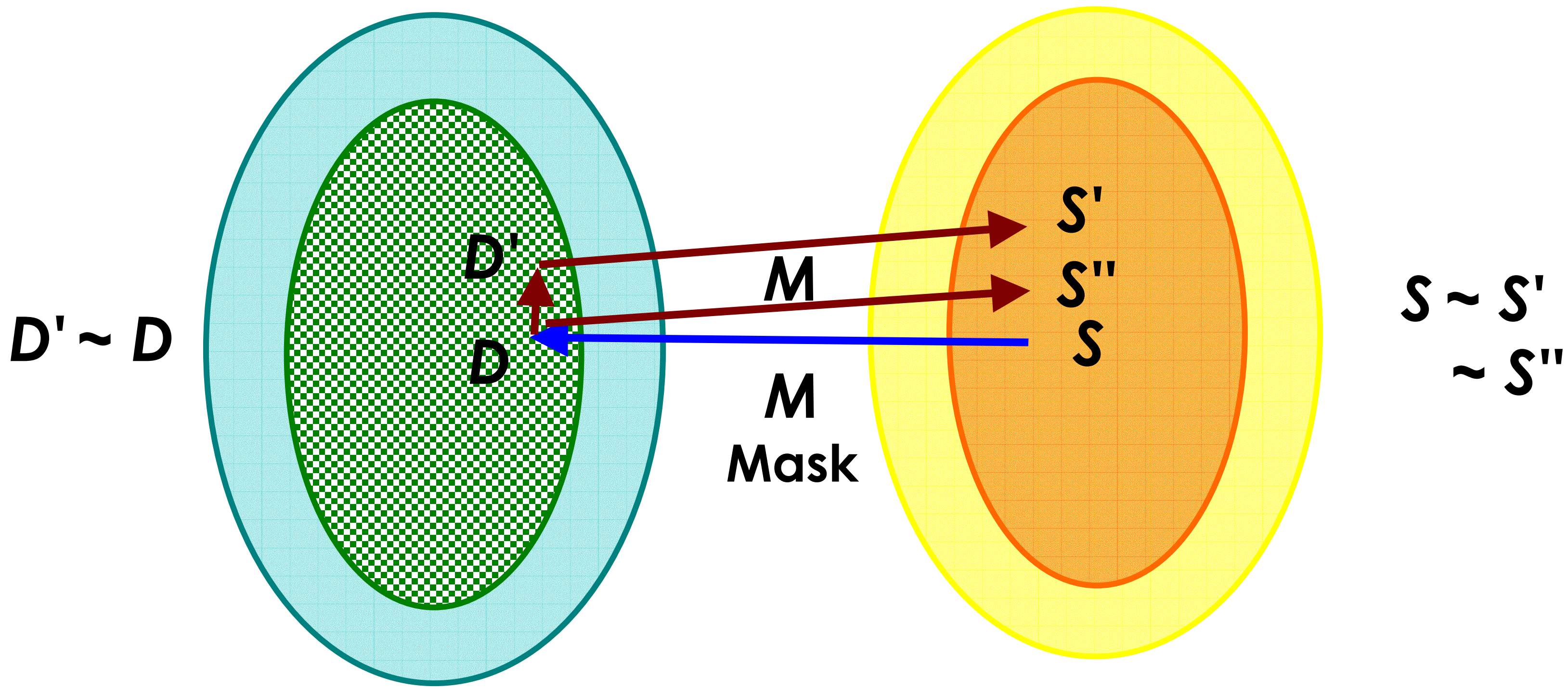


$$S' = M \cdot D'$$

$$M \cdot M \neq I$$

Image Reconstruction: Correlation

$D = M \cdot S$



$S' = M \cdot D'$

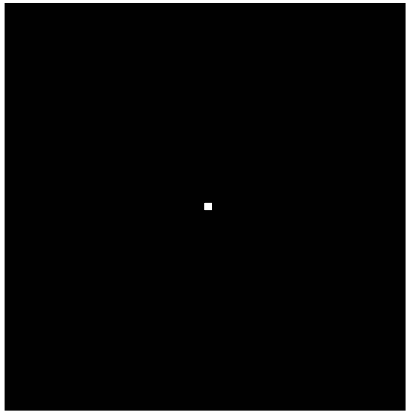
$S'' = M \cdot D$

$M \cdot M \neq I$

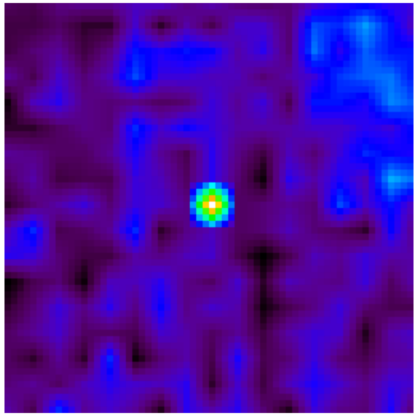
► coding noise

✓ Fast Calc: FFT

Random Mask Pattern

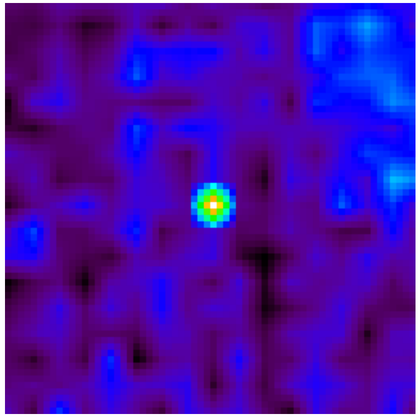


True Sky
(an on-axis point source)



S'

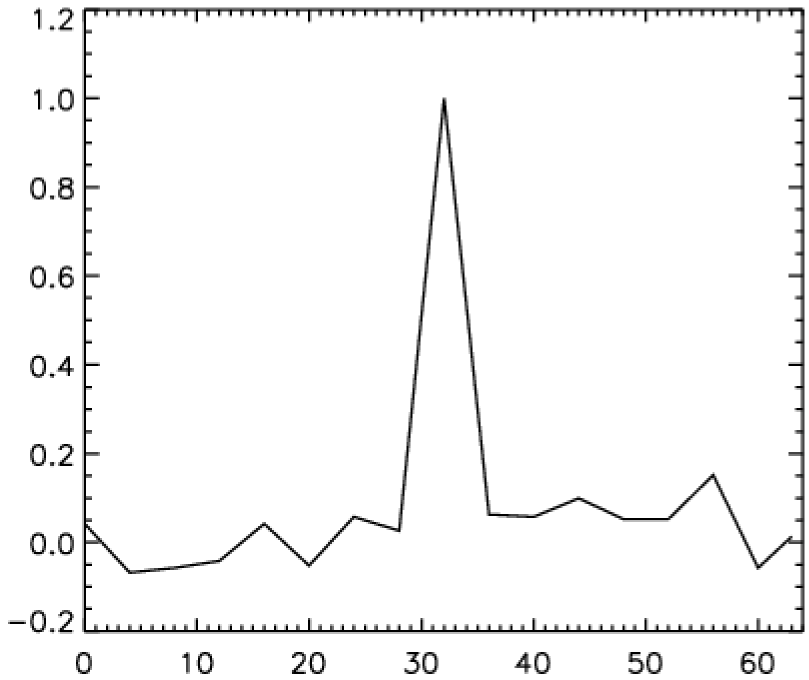
Reconstructed Sky Image without defects by cross-correlation

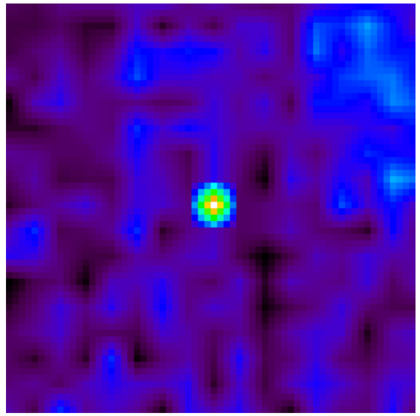


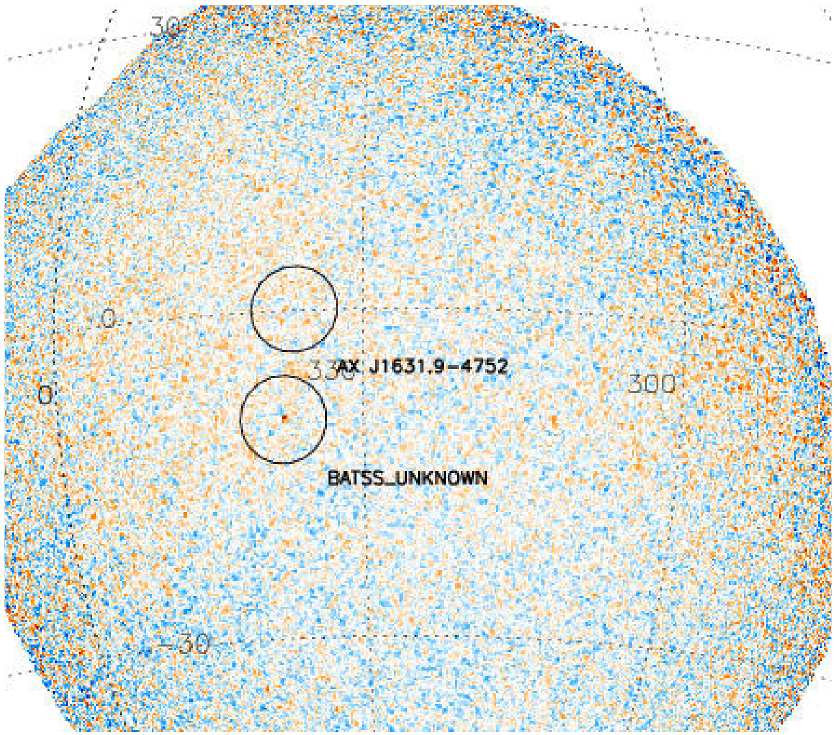
S''

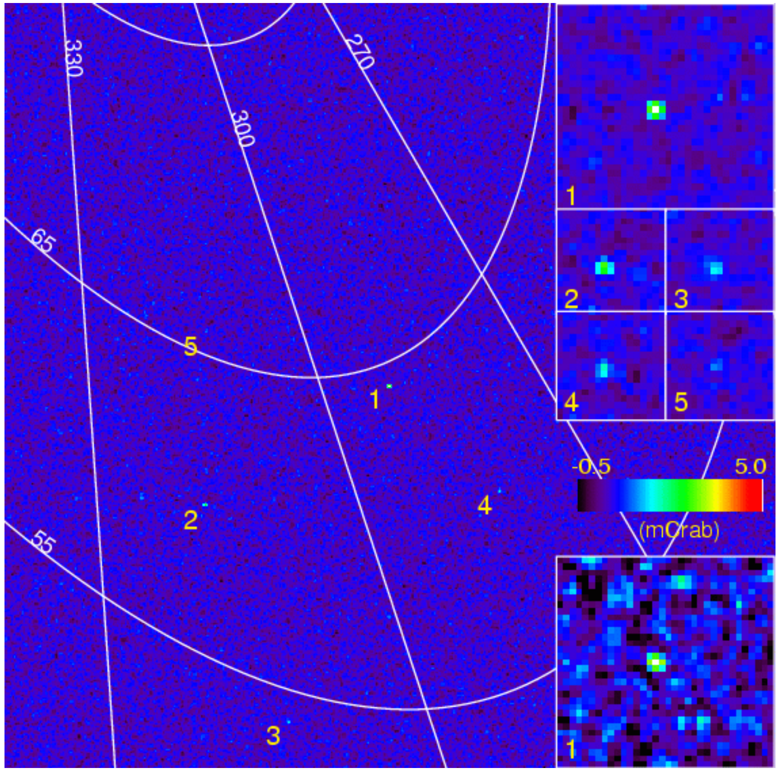
Reconstructed Sky Image with a defect by cross-correlation

Coding Noise & Point Spread Function

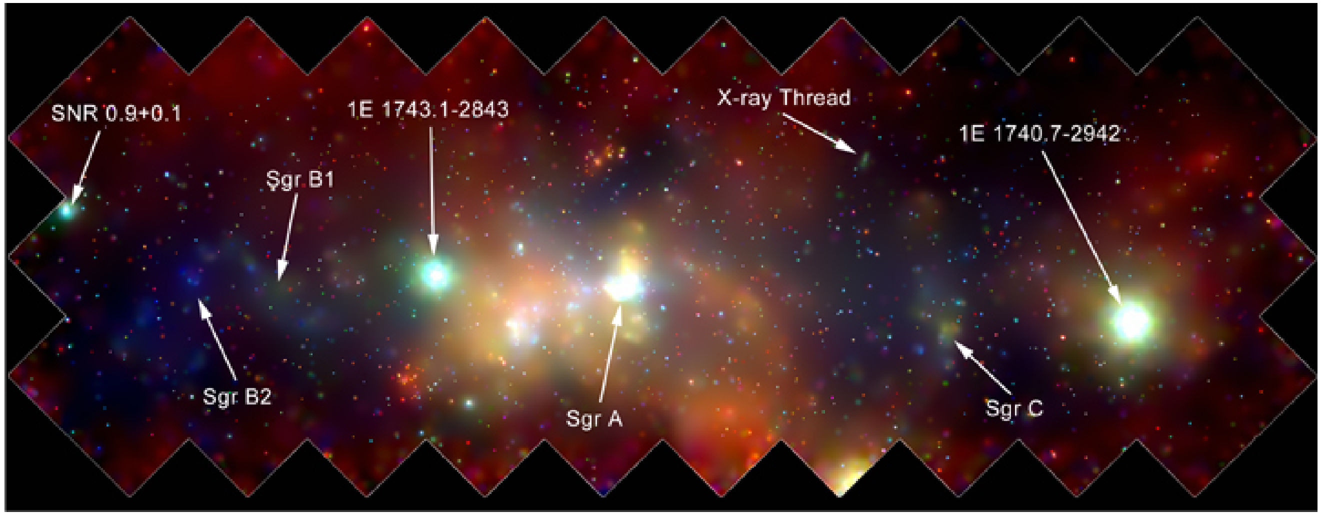






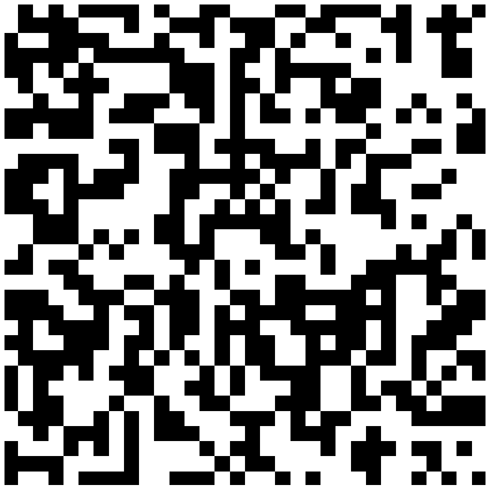


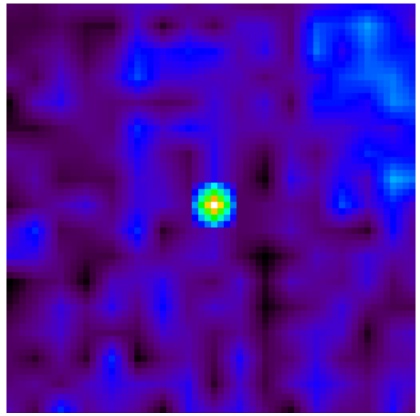
Typical Images

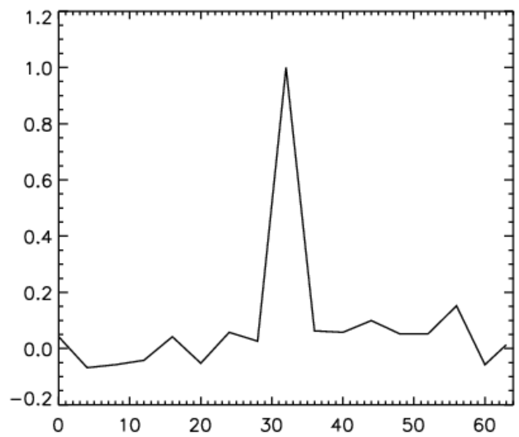


Mask Pattern

- **Random Pattern**
  no constraint on mask geometry
  coding noise approaches zero as # of elements increase





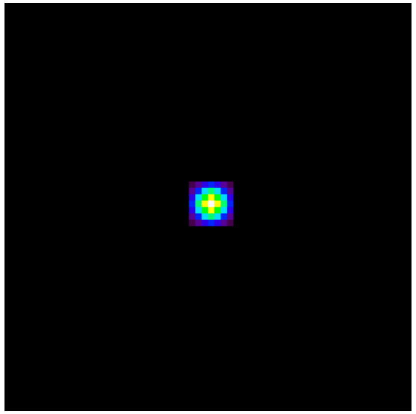


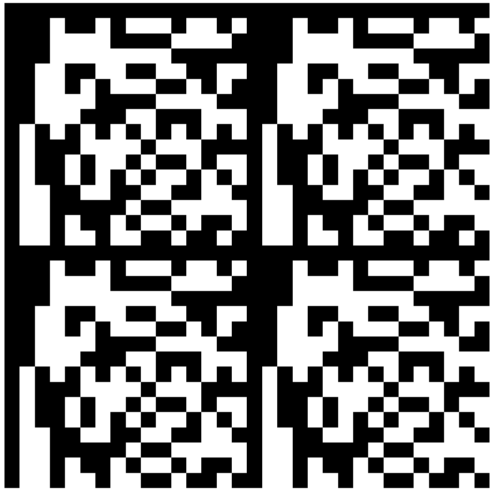
Mask Pattern

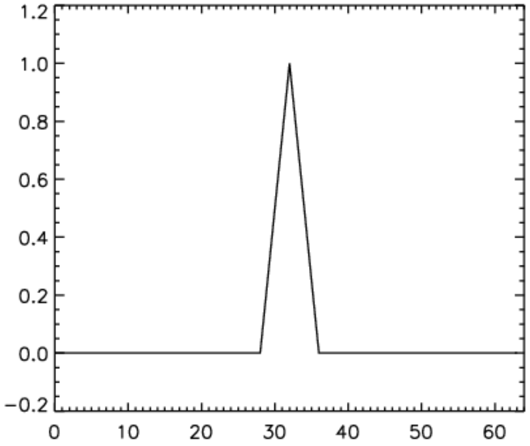
- **Uniformly Redundant Array (URA)**

  $$M \cdot M = I$$

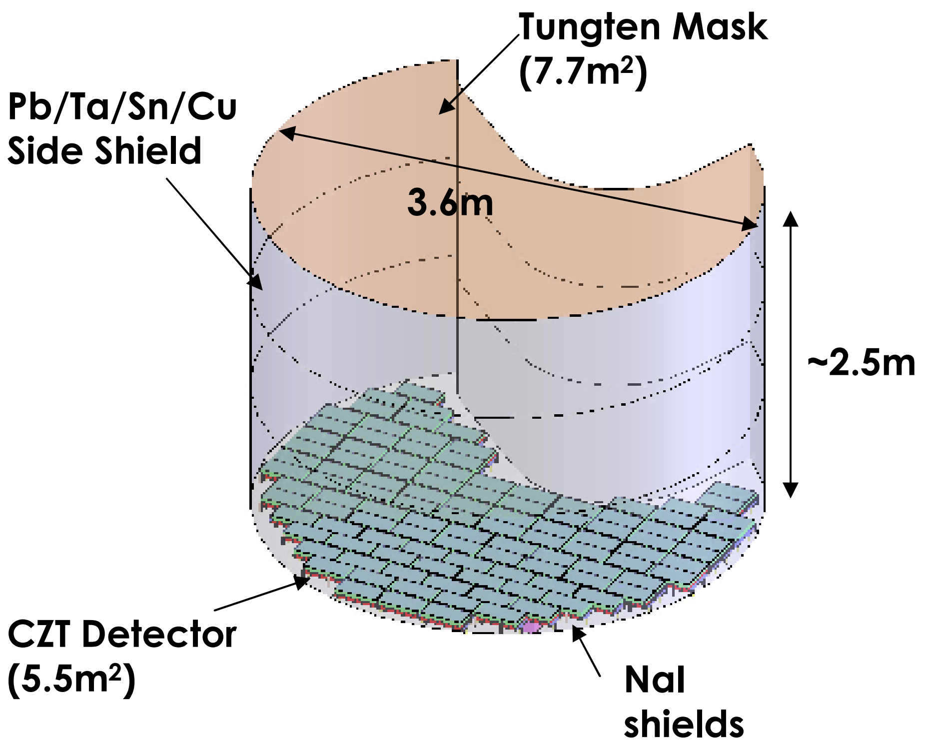
  No coding noise
  No quantum noise
  limited available geometries
  ghost images
  hard to perfect it

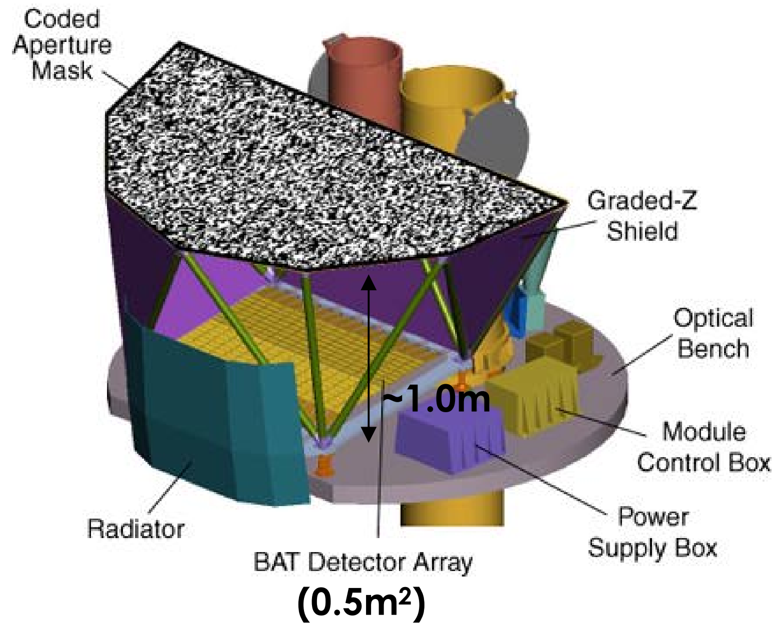






EXIST/HET vs Swift/BAT



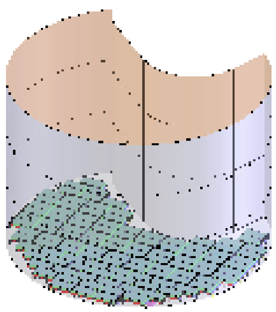


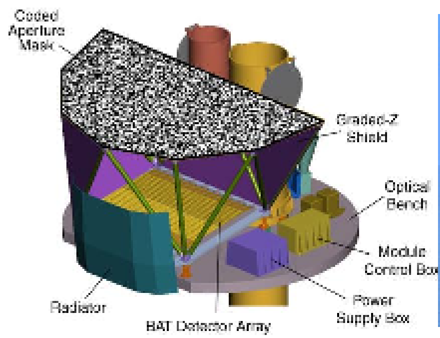
HET: Pushing the envelope

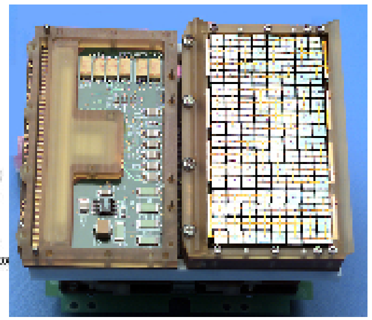
- Accurate GRB localization: ~16 arcsec
- Fast GRB localization: <10 sec
- Slew and lock on the target in ~100 sec
- Optical/IR spectroscopy in ~100 sec

EXIST/HET vs SWIFT/BAT

Parameters	EXIST/HET	SWIFT/BAT
Telescope	5.5m^2 CZT Det. + 7.8m^2 W Mask	0.5m^2 CZT Det. + 2.7m^2 Pb Mask
Energy Range	5 – 600 keV (5mm thick CZT) 600 – 3000 keV (CsI for GRBs)	15 – 200 keV (2mm thick CZT)
Sensitivity (5σ)	0.06 mCrab (<150 keV, ~1yr survey) 0.6 – 1mCrab (>200 keV, ~1yr survey) 24 mCrab (<150 keV, ~10s on-axis)	1mCrab (<150 keV, ~2 yr survey)
Field of View	45° dia (FWHM)	50°×100° (50% coding)
Angular & Positional Resol.	1.9′ resolution 16″ pos for 5σ source (90% conf. rad)	17' resolution 3' pos for 5σ source
Sky Coverage	Nearly full sky every two orbits (3hr)	10s orbits – a few days
Spectral Resolution	2 – 3 keV (3% at 60 keV, 0.5% at 511 keV)	3 – 4 keV (5% at 60 keV)
Timing Resol.	10 μsec	100 μsec
CZT Detector	2x2x0.5cm^3, 0.6mm pix, 15M pix	4x4x2mm^3, 4mm pixel, 32k pix



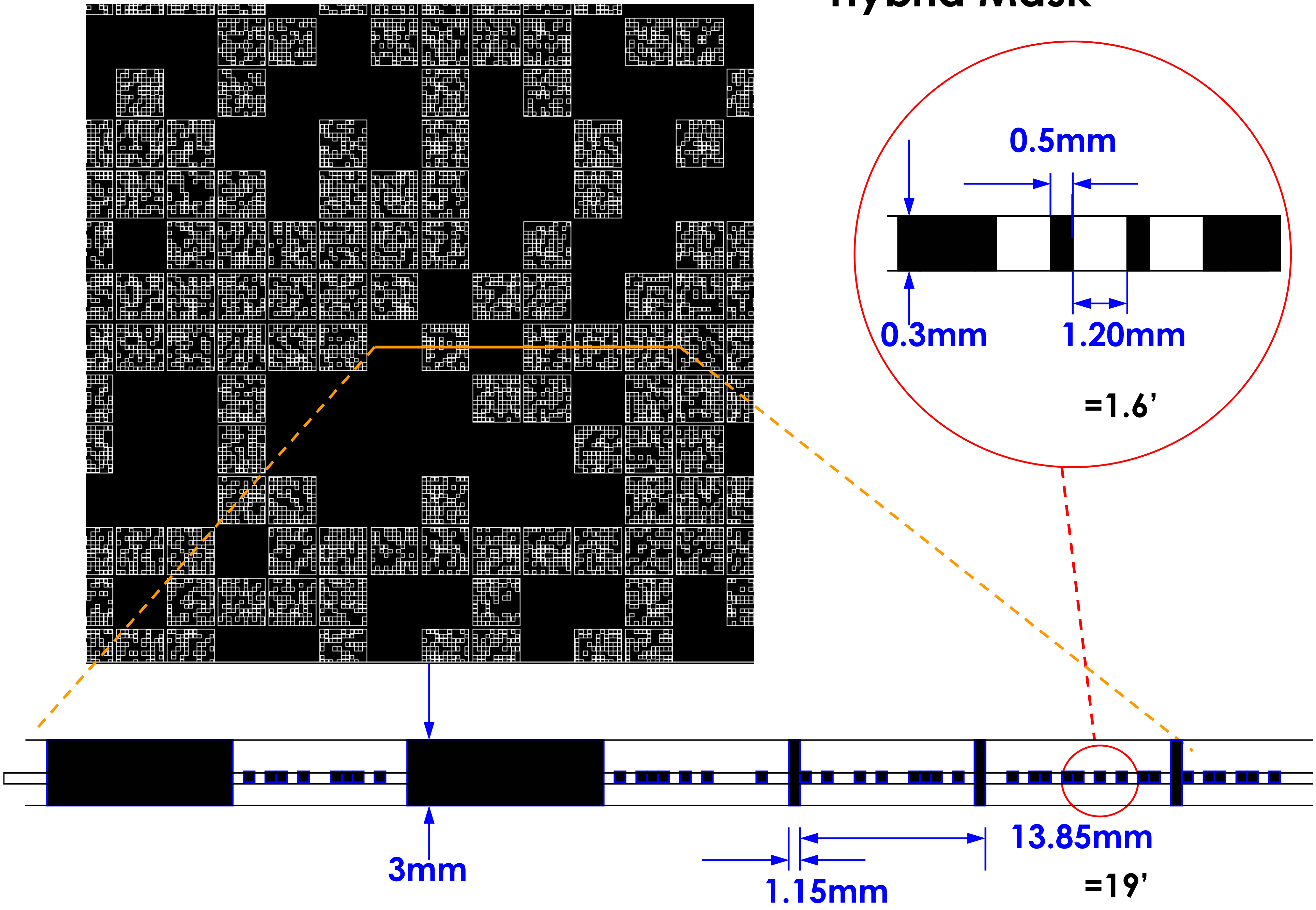




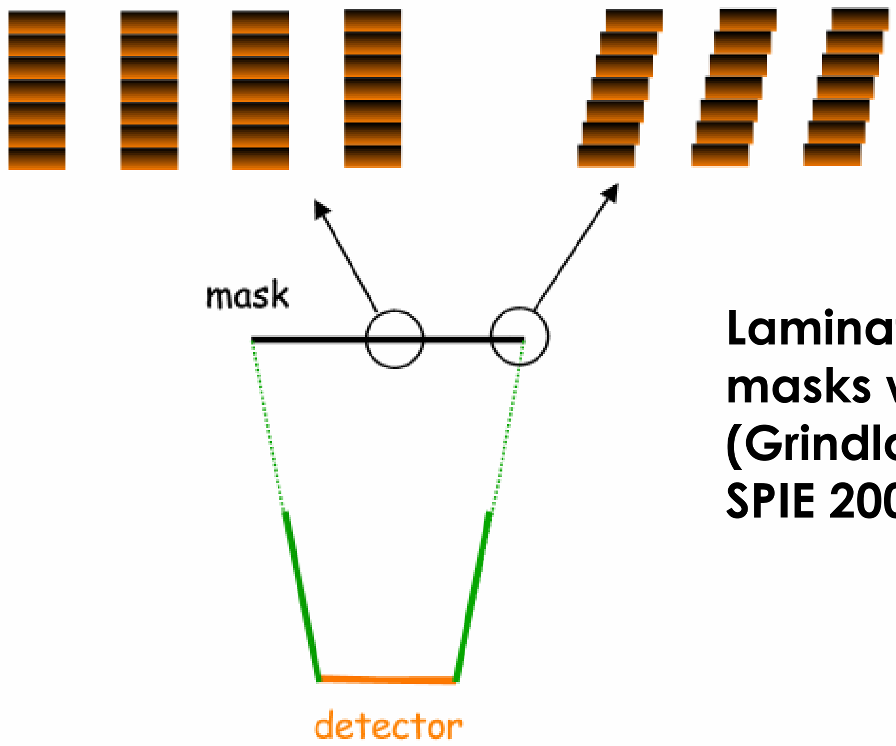
Pushing the envelope

- **Wide Energy Range (5 – 600 keV): Hybrid Mask**
- **Wide FoV (90 deg) : Radial Holes to reduce auto-collimation**
- **Beat down systematics: continuous scan**

Hybrid Mask

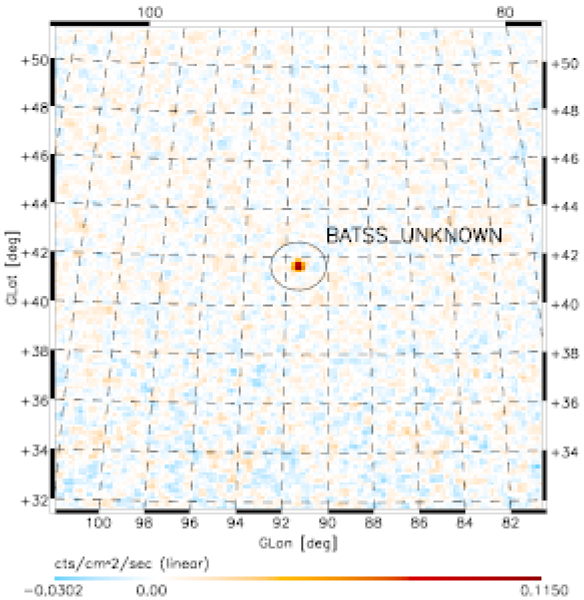


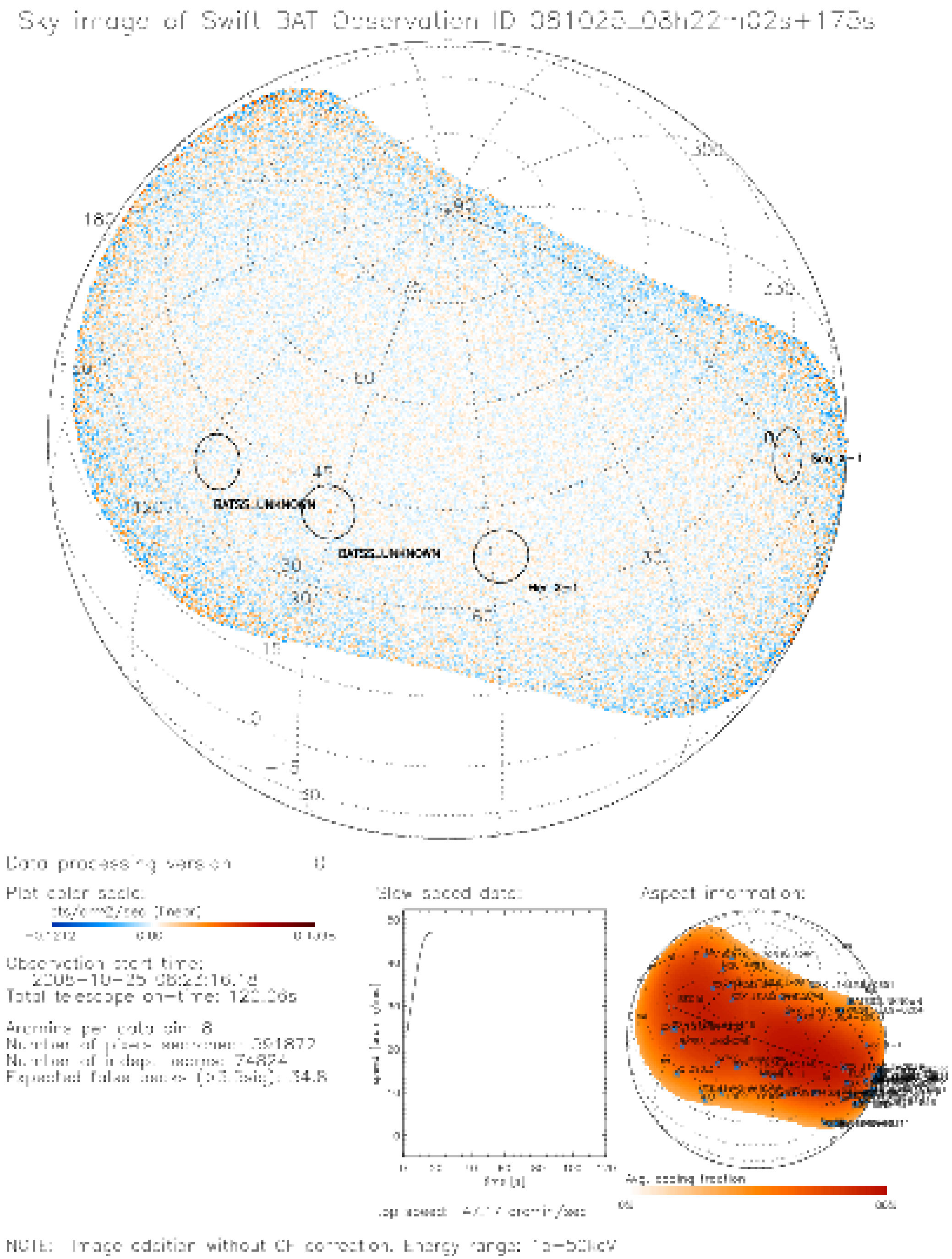
Radial Mask Holes



Laminate several layers of thin flat masks with a slowly varying pitch (Grindlay et. al. SPIE 2003, Hong et al. SPIE 2004)

BATSS
BAT Slew Survey





Summary

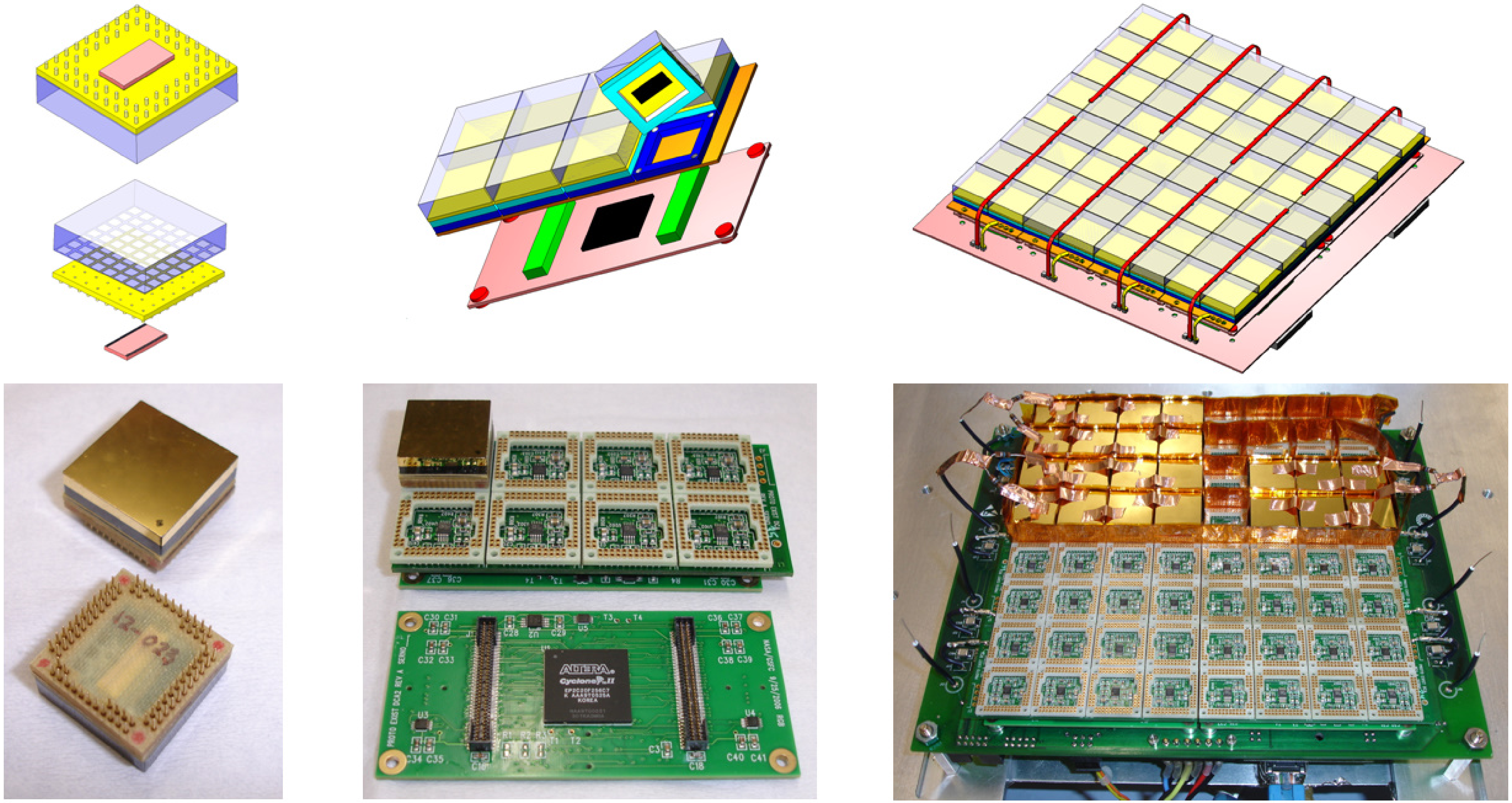
- EXIST will probe the early Universe through GRBs as comic probe and find black holes on all scales.

- EXIST will boost the coded-aperture imaging technique to another level.

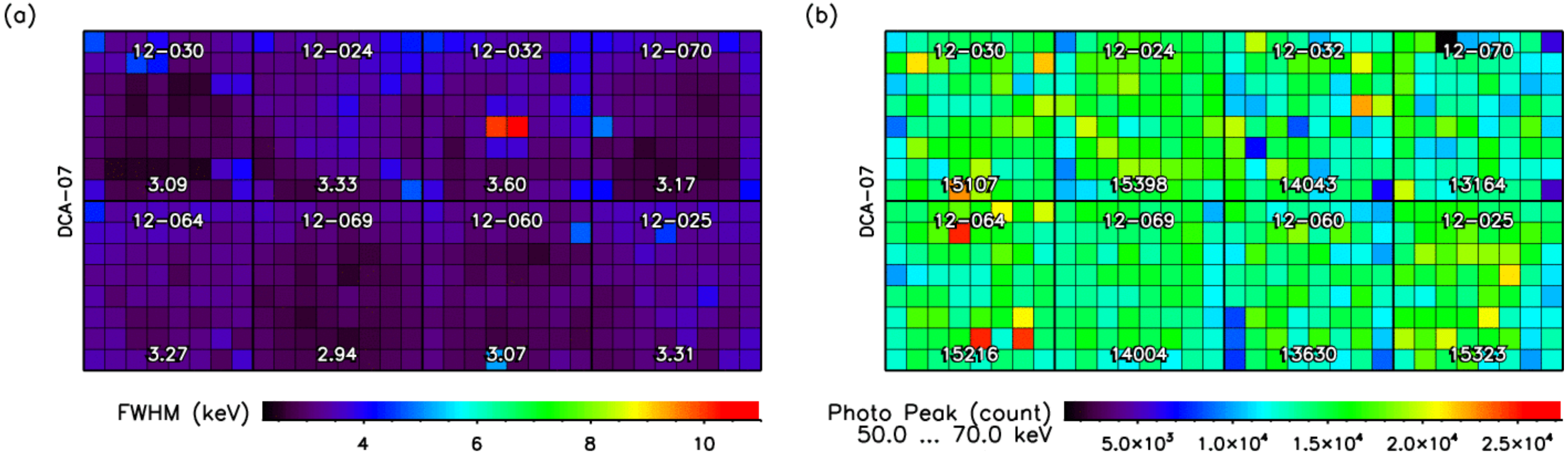
(a) Detector Crystal Unit: DCU, 4 cm^2

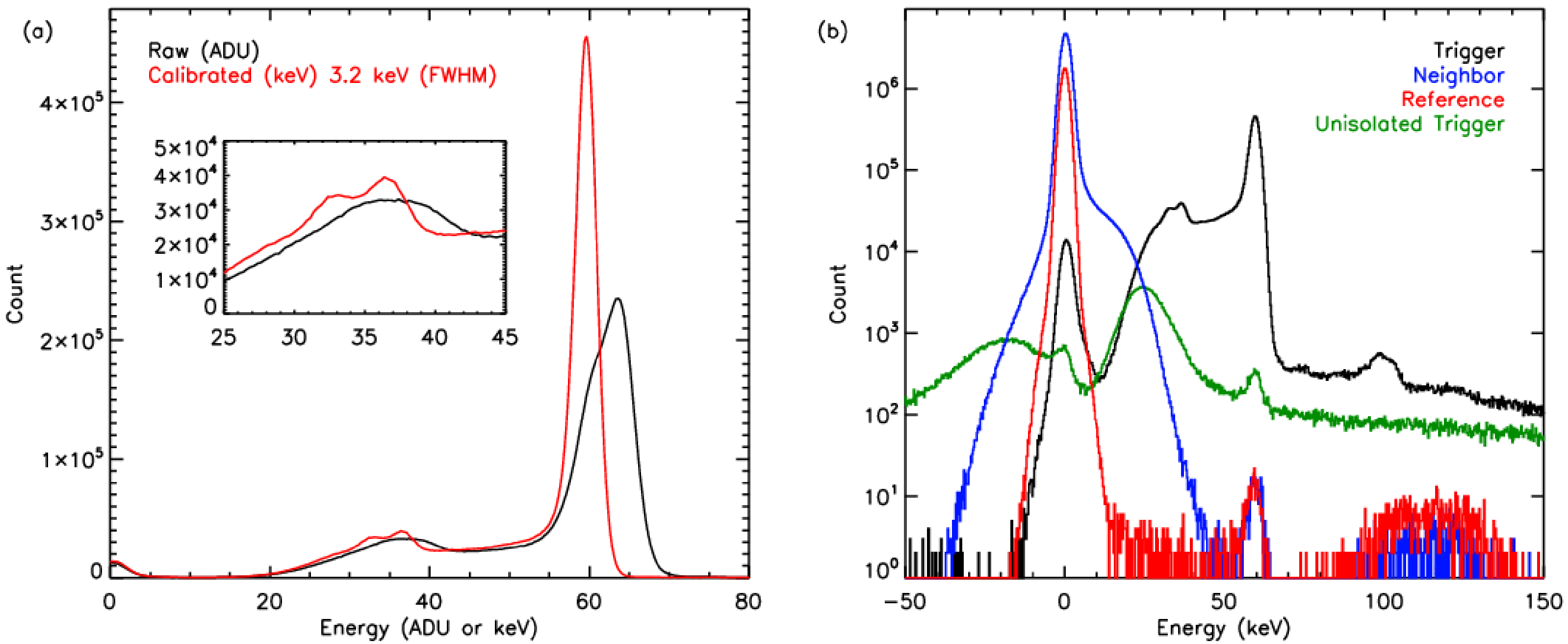
(b) Detector Crystal Array: DCA, 32 cm^2

(c) Detector Module: DM, 256 cm^2

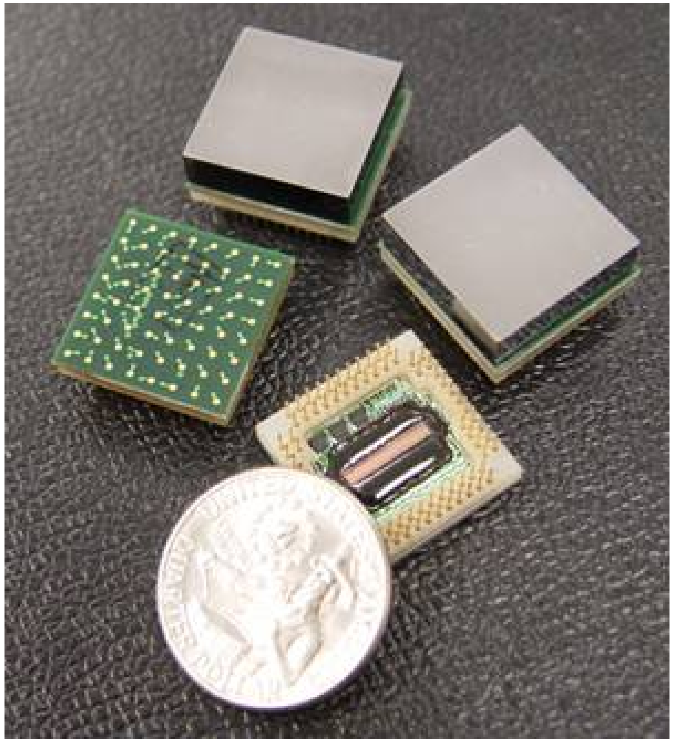


End

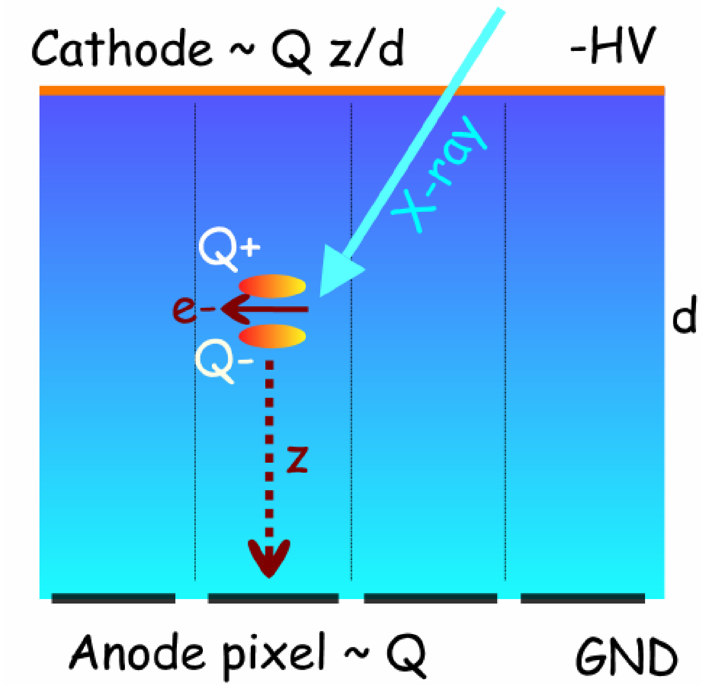

(a)
(b)
DCA-07
12-030
12-024
12-032
12-070
12-064
12-069
12-060
12-025
3.09
3.33
3.60
3.17
3.27
2.94
3.07
3.31
15107
15398
14043
13164
15216
14004
13630
15323
FWHM (keV)
4
6
8
10
Photo Peak (count)
50.0 ... 70.0 keV
5.0×10³
1.0×10⁴
1.5×10⁴
2.0×10⁴
2.5×10⁴


(a)
Raw (ADU)
Calibrated (keV) 3.2 keV (FWHM)
Count
Energy (ADU or keV)
(b)
Trigger
Neighbor
Reference
Unisolated Trigger
Count
Energy (keV)

Cd-Zn-Te (CZT) Hard X-ray imaging detector

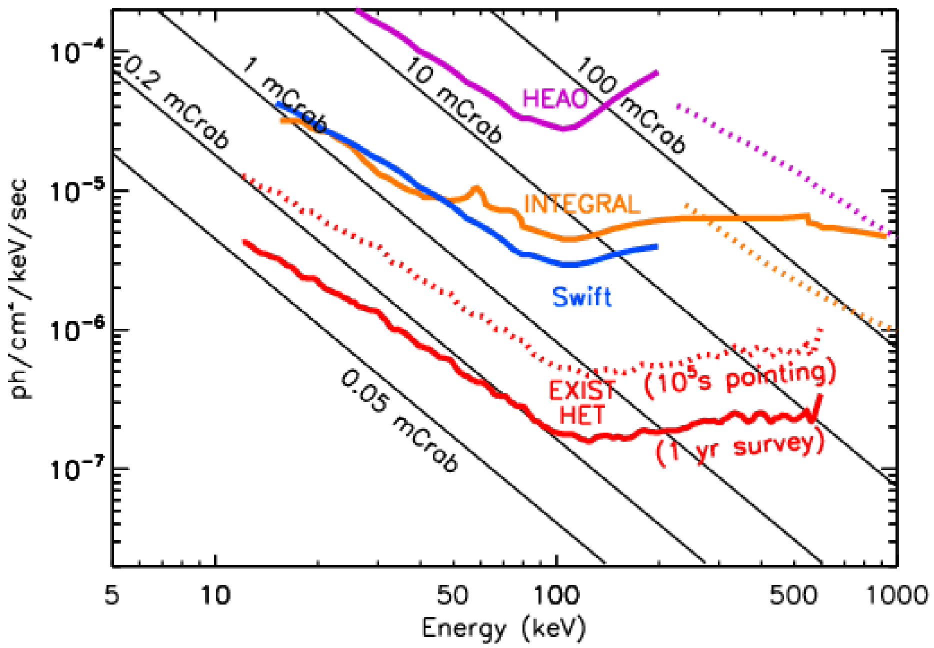


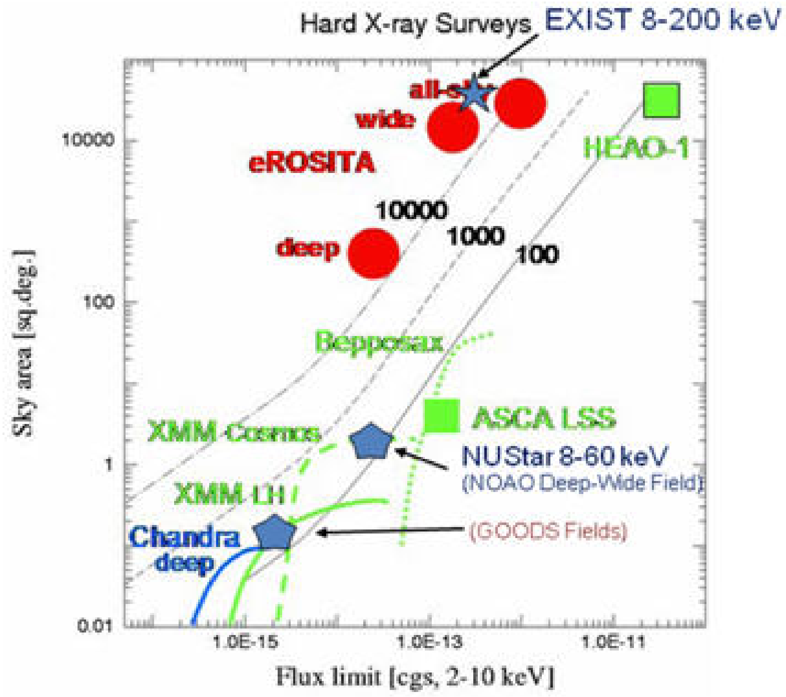
CZT Detectors
8 x 8 pixels on each 20 x 20mm
CZT crystal (pixels on bottom)



Schematic CZT detector:
Electrons drift to anode
Under –600V bias

EXIST sky survey sensitivity





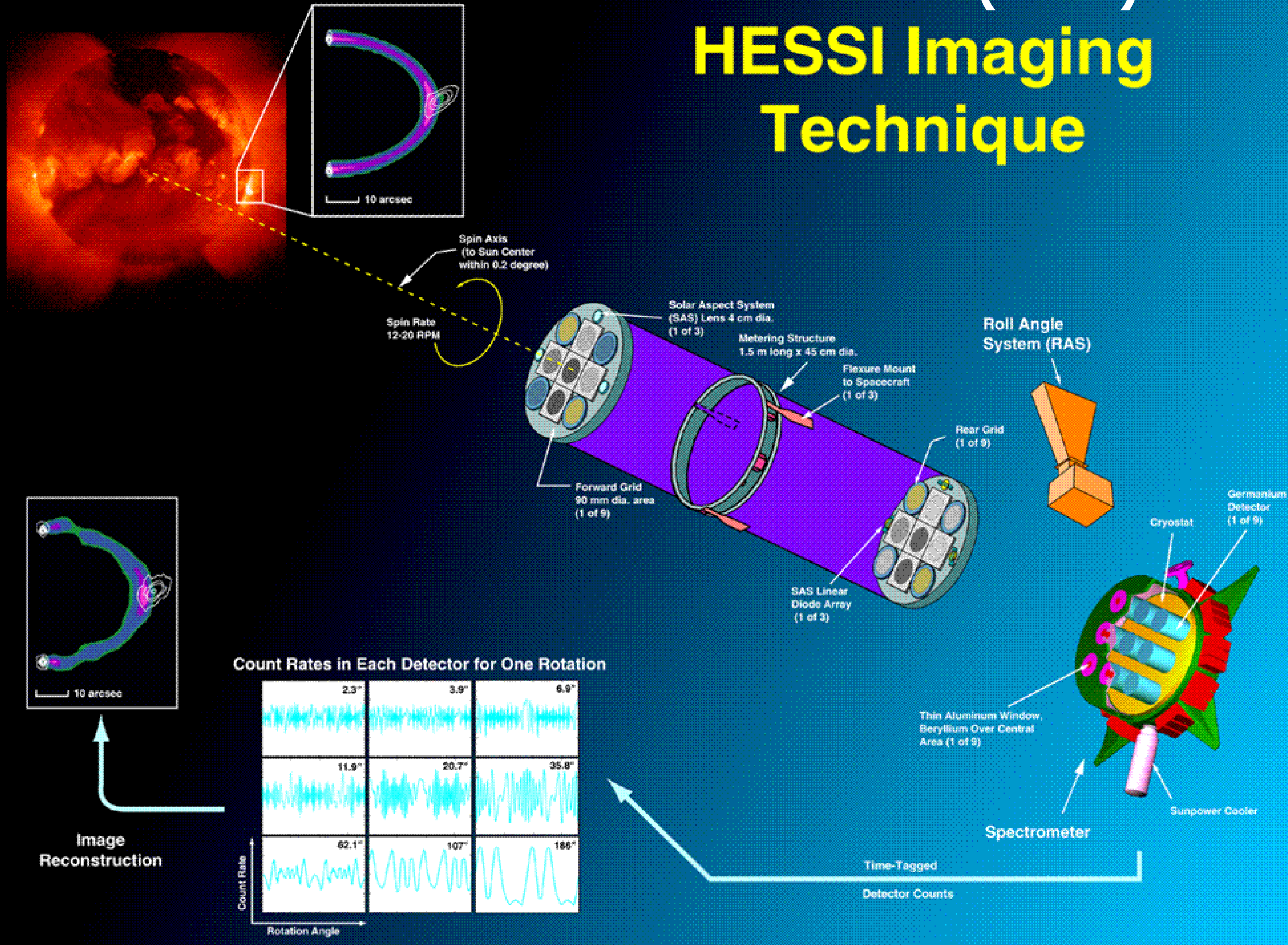
5σ in 1 yr sky survey flux sens. over band ΔE

at 600 km 20° orbit incl (30% reduct for 5° incl)

- **0.06mCrab = 7 x 10^{-13} cgs, (~12X below *Swift/BAT*) for HET Σ(10-100 keV)**
- **~0.5mCrab = 1 x 10^{-11} cgs (~50X below *INTEGRAL/IBIS)* for HET 100-600 keV**
- **511 keV line sensitivity ~10^{-5} photons/cm^2-sec or ~2X below INTEGRAL/SPI**
- **unique ~20% duty cycle coverage on any source, full-sky ea. 3h**

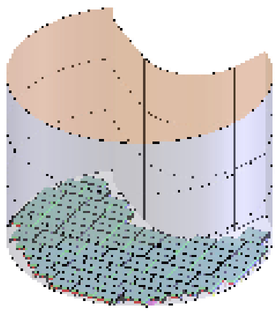
Rotational Modulation Collimator (RMC)

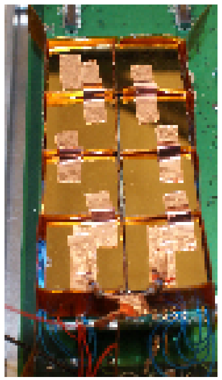
HESSI Imaging Technique

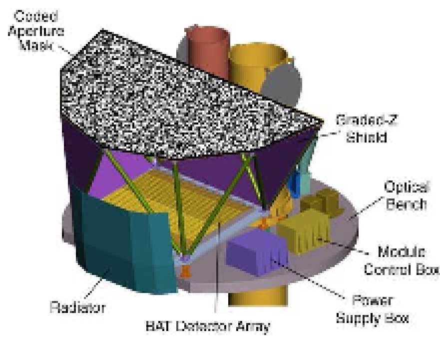


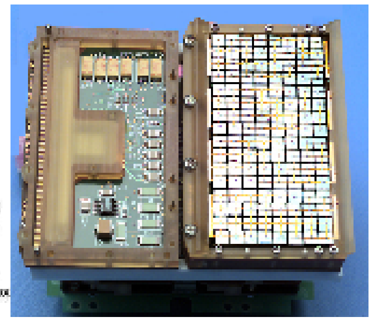
EXIST/HET vs SWIFT/BAT

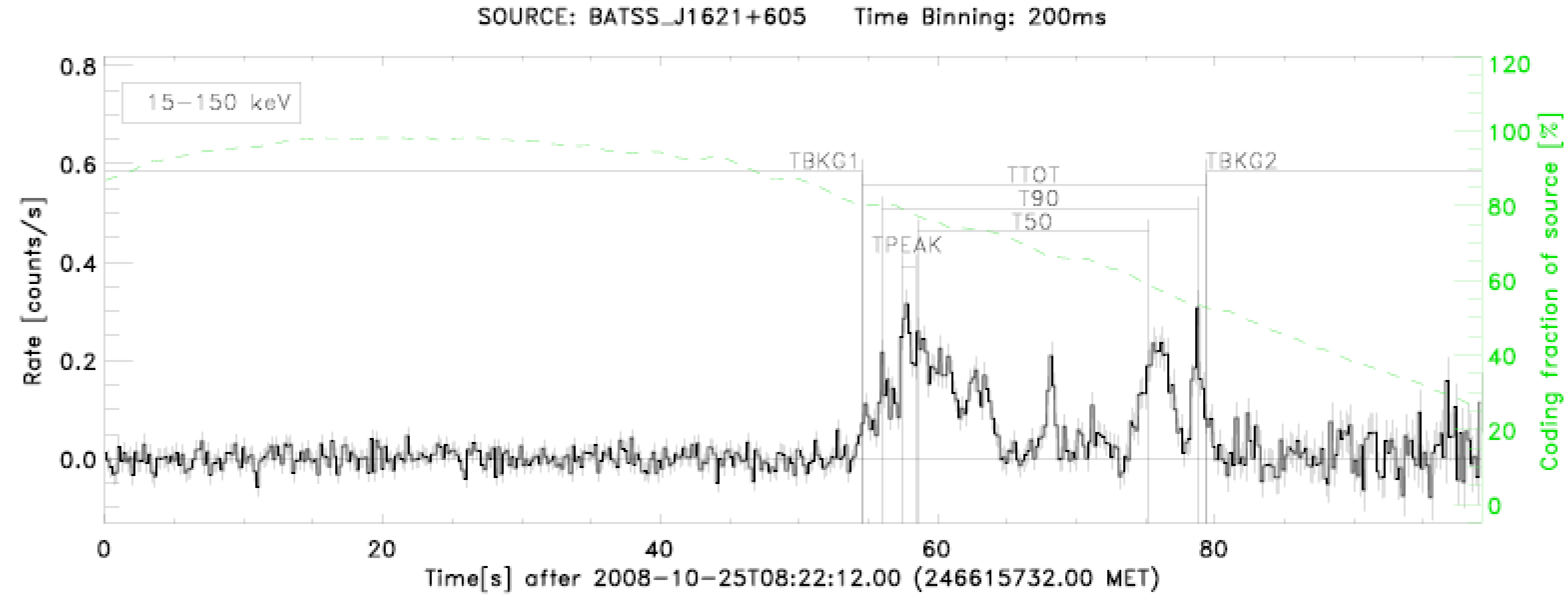
	EXIST/HET	Swift/BAT
Size	3.7m × 2.5m	2m × 1m
Detector Size	5.5m^2	0.5m^2
Detector Pixel size	0.6mm	4mm
Number of pixels	15M	33k
90% conf. localization	16"	180"
FoV	~90 deg dia	100 deg × 90 deg



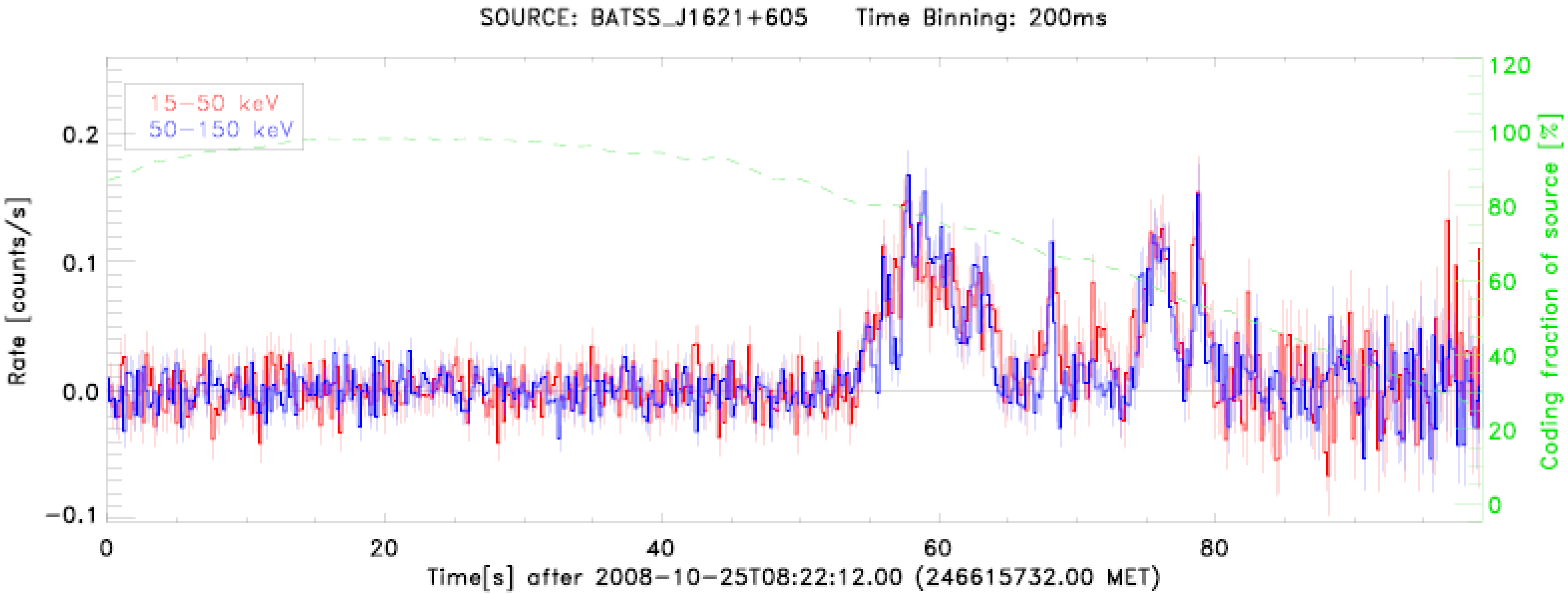








SOURCE: BATSS_J1621+605 Time Binning: 200ms
15–150 keV
TBKG1
TTOT
T90
T50
TPEAK
TBKG2
Rate [counts/s]
Coding fraction of source [%]
Time[s] after 2008-10-25T08:22:12.00 (246615732.00 MET)



SOURCE: BATSS_J1621+605 Time Binning: 200ms
15–50 keV
50–150 keV
Rate [counts/s]
Coding fraction of source [%]
Time[s] after 2008-10-25T08:22:12.00 (246615732.00 MET)