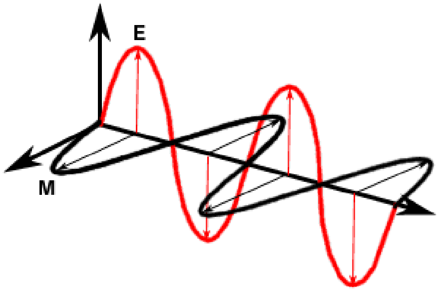
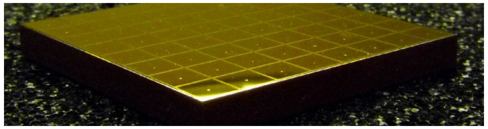
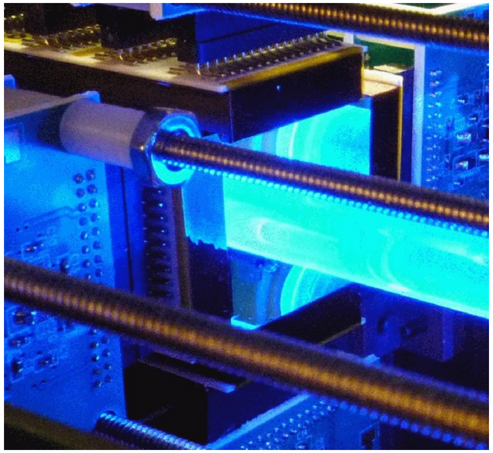
X-ray detector development
at Washington University in St.Louis







Matthias Beilicke

Washington University in St.Louis,
Physics Department &
McDonnell Center for the Space Sciences

Collaborators: GSFC, BNL

X-ray Science Analysis Group meeting
(12 April 2013, Monterey, CA)

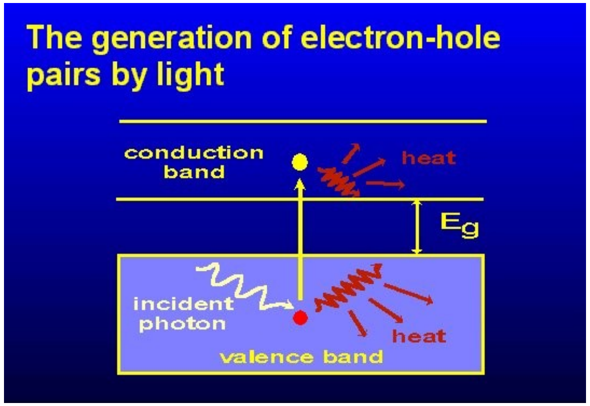
McDonnell Center for the Space Sciences

Washington University in St.Louis
Arts & Sciences

X-ray (semiconductor) detectors: Overview

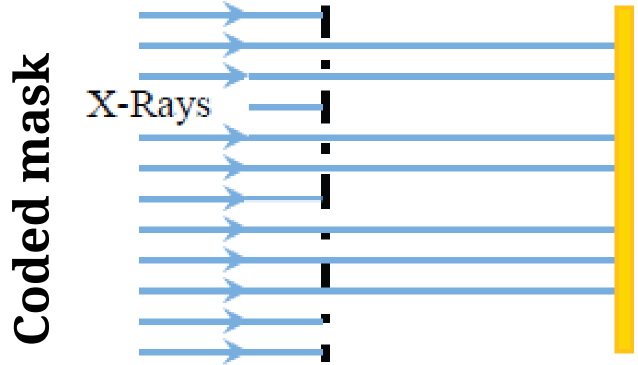
Cadmium Zinc Telluride (CZT):

- Z ~50, ρ = 5.78 g/cm^3,
- X-ray photons: photo effect & Compton scattering
- Operation at room temperature (band gap: ~1.6eV)
- Limits in energy resolution: charge fraction => phonons
- Alternatives: Measure ΔT of absorber



Application of CZT:

- Medical & homeland security
- Astrophysics (Swift: 32,768, INTEGRAL: 16,384)
  + present and future missions



Burrows et al., Mem.S.A.It., 75, 1

X-ray mirror technology:

- Major improvements in fabrication/cost/accuracy
  Zhang, et al.,Proc. of SPIE 8147 (2011) 81470K-7
- Focusing (compared to coded mask):
  larger effective area, better imaging, higher S/N

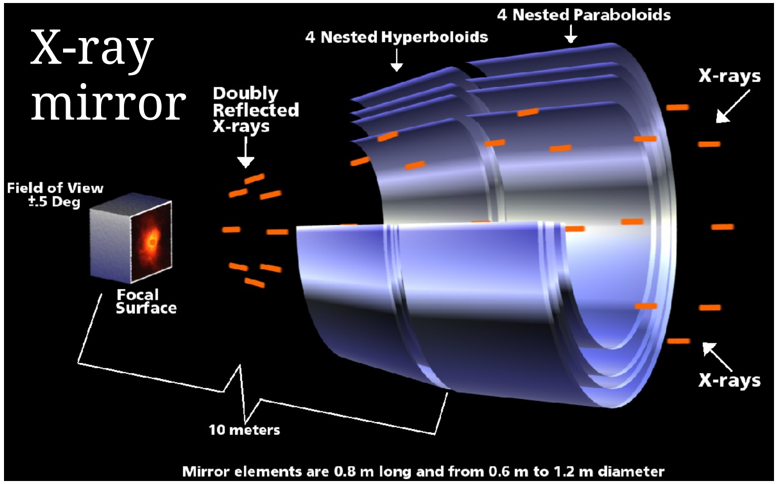
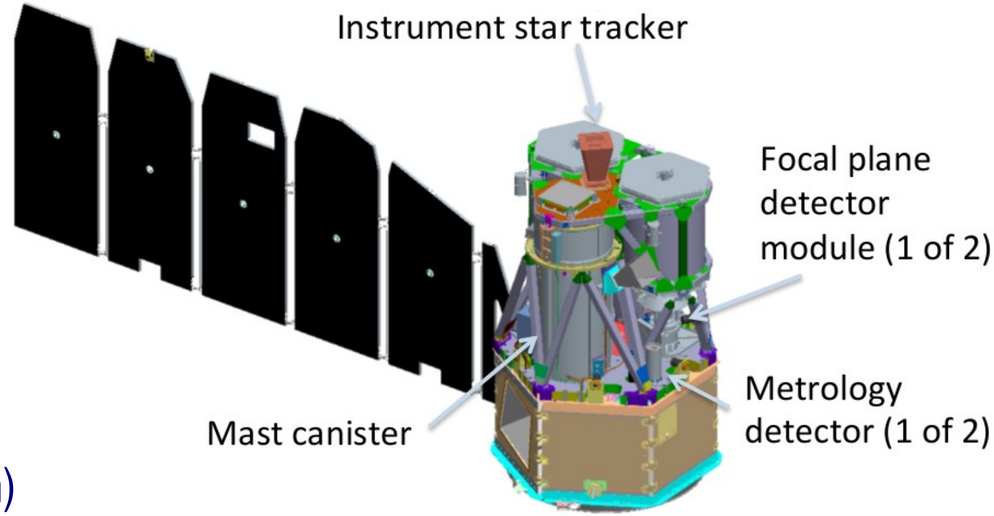


image: Chandra/NASA

CZT on board the NuSTAR satellite

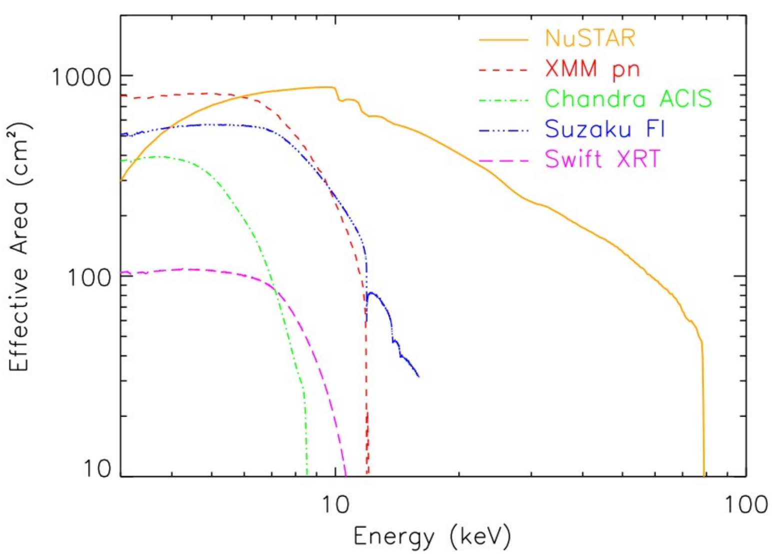


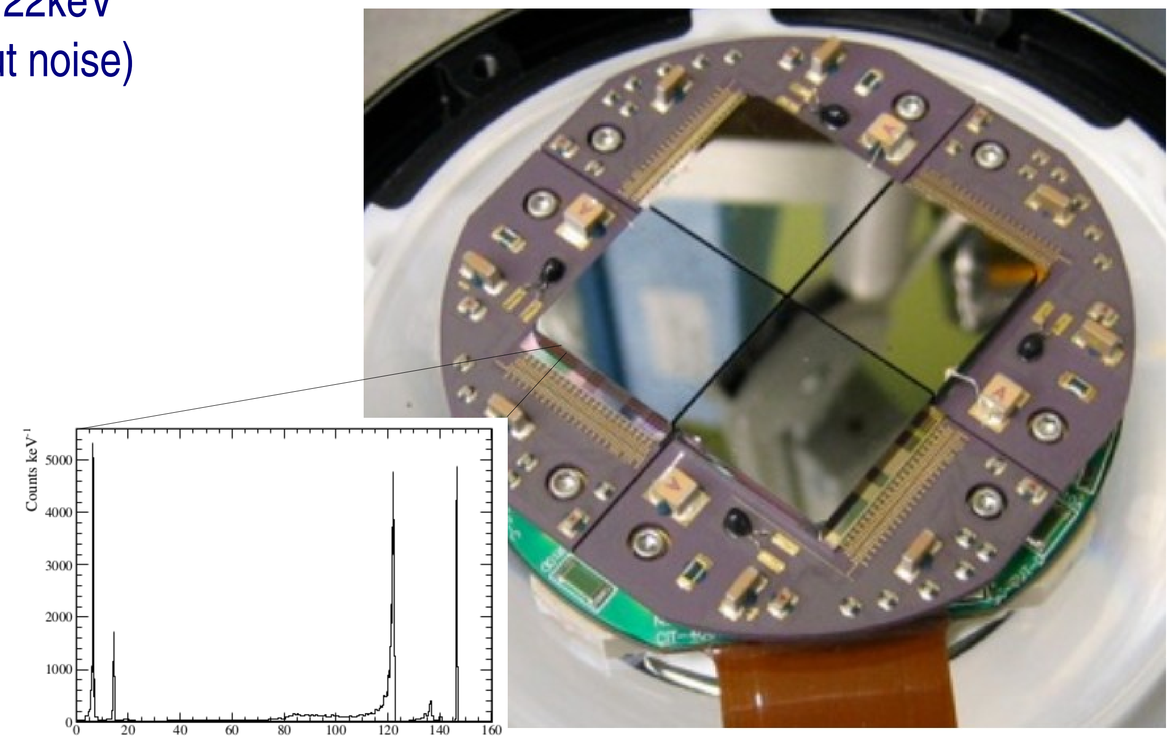
NuSTAR mission (SMEX):

- Harrison et al., arXiv 1301.7307 (2013)
  Kitaguchi et al., SPIE, 8145, 814507 (2011)
- Wolter X-ray mirror (large effective area)
- launched in 2012

Focal plane instrument:

- 2x2x0.2 cm^3 CZT detectors (32x32 pixels, 605 μm pitch)
- Energy resolution: 0.5keV@14keV, 0.9keV@122keV
- Readout: Caltech NuCIT ASIC (0.4keV readout noise)
  e-/h readout -> determine depth-of-interaction



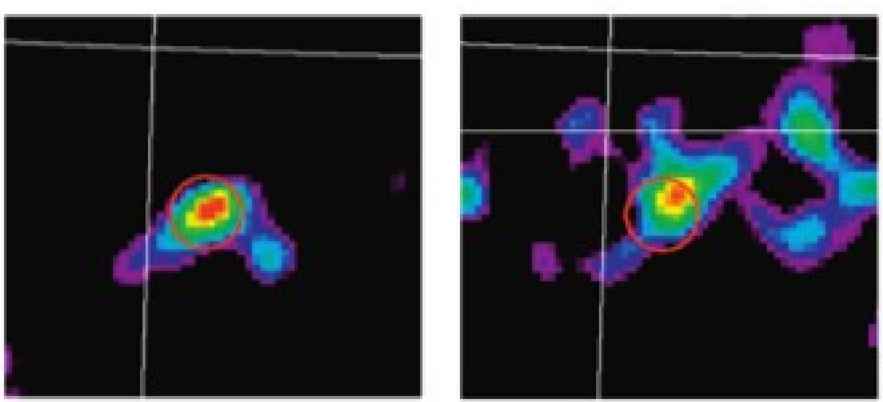


Harrison et al., arXiv1301.7307 (2013)

Coded mask and 3D imaging applications

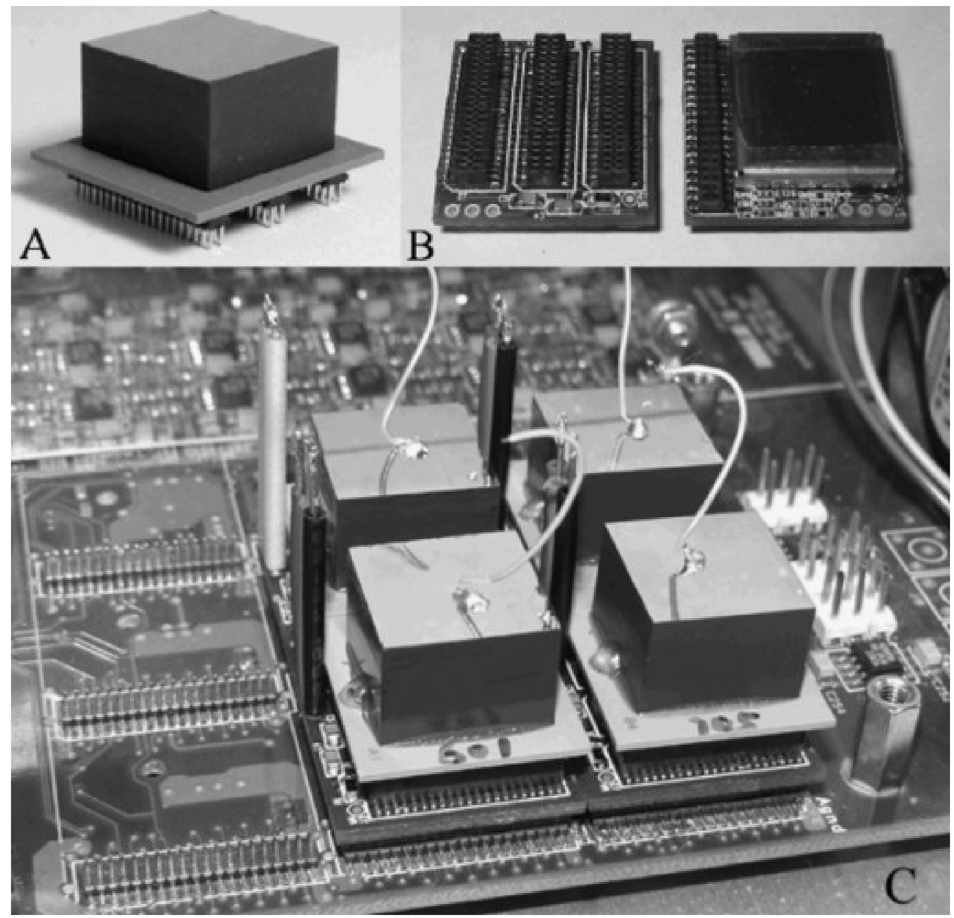
ProtoEXIST flight:
- Hong et al., NIMA, 654, 361 (2011)
- Coded mask instrument (balloon)

Instrument:
- 8x8 detectors (64 pixels each, p=2.5mm)
- RadNET ASIC (power: ~150 μW/pixel)



30-50 keV   50-80 keV

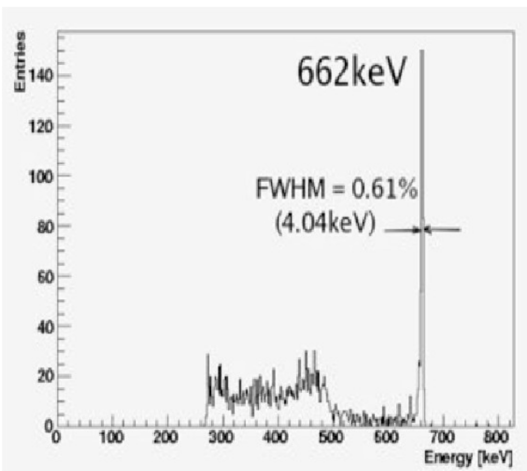
3D position sensitive detectors:
- Z.He, et al, IEEE, 54, 843 (20107)
- expertise in thick CZT detectors/readout
- 3D position sensitive: depth-of-interaction (<1% energy resolution @ 662keV)
- High-energy Compton imaging

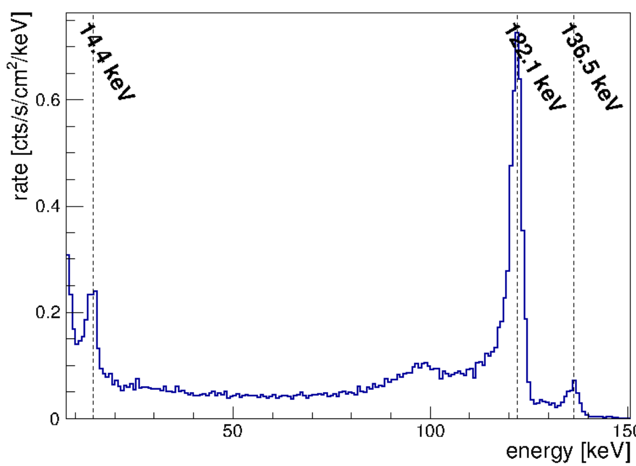


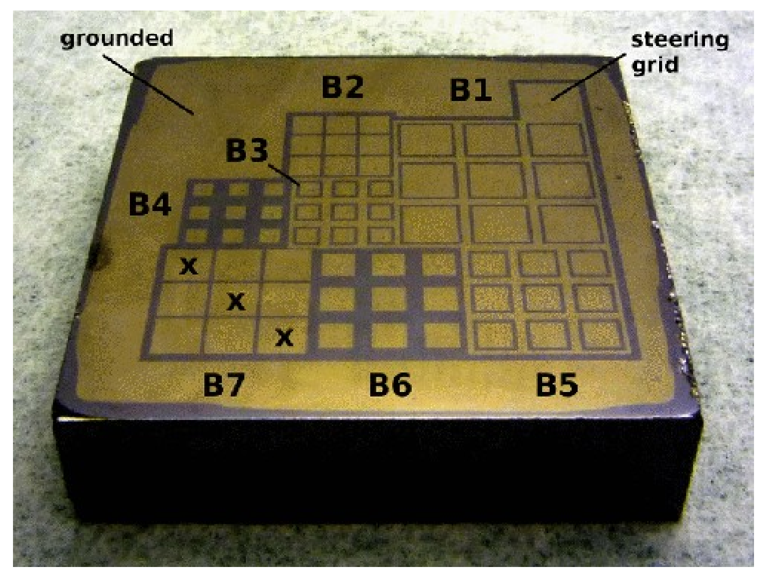
CZT X-ray detectors:
fabrication & optimization @ Washington Univ.

Clean room (class-100):
- Photo-lithography masks & E-beam evaporation
- Readout electronics: BNL & Washington University

Detector characterization:
- Energy resolution & threshold, effect of steering grid
- Comparison to simulations (charge sharing/transport)

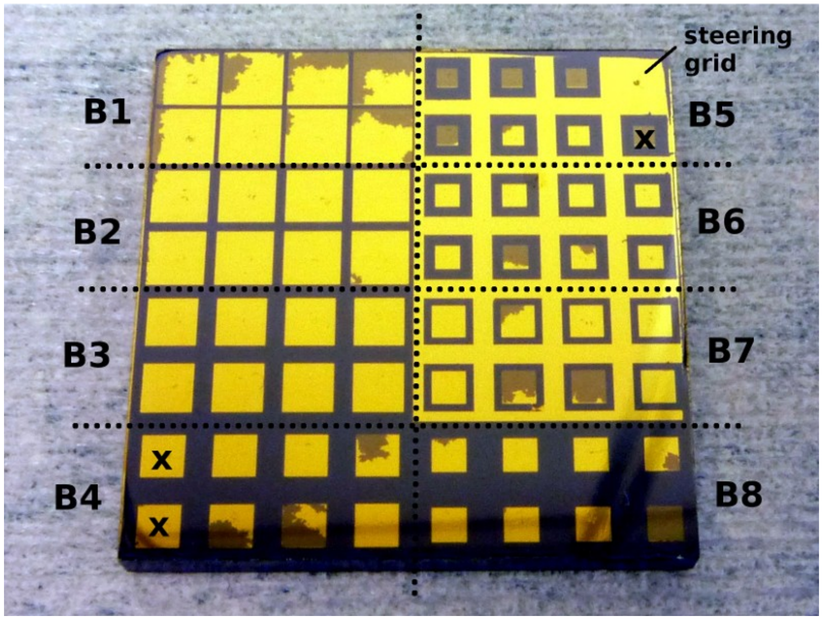






- Energy resolution: <1% @ 662keV
- threshold: down to ~15 keV

Variable size pixels (2mm detector)

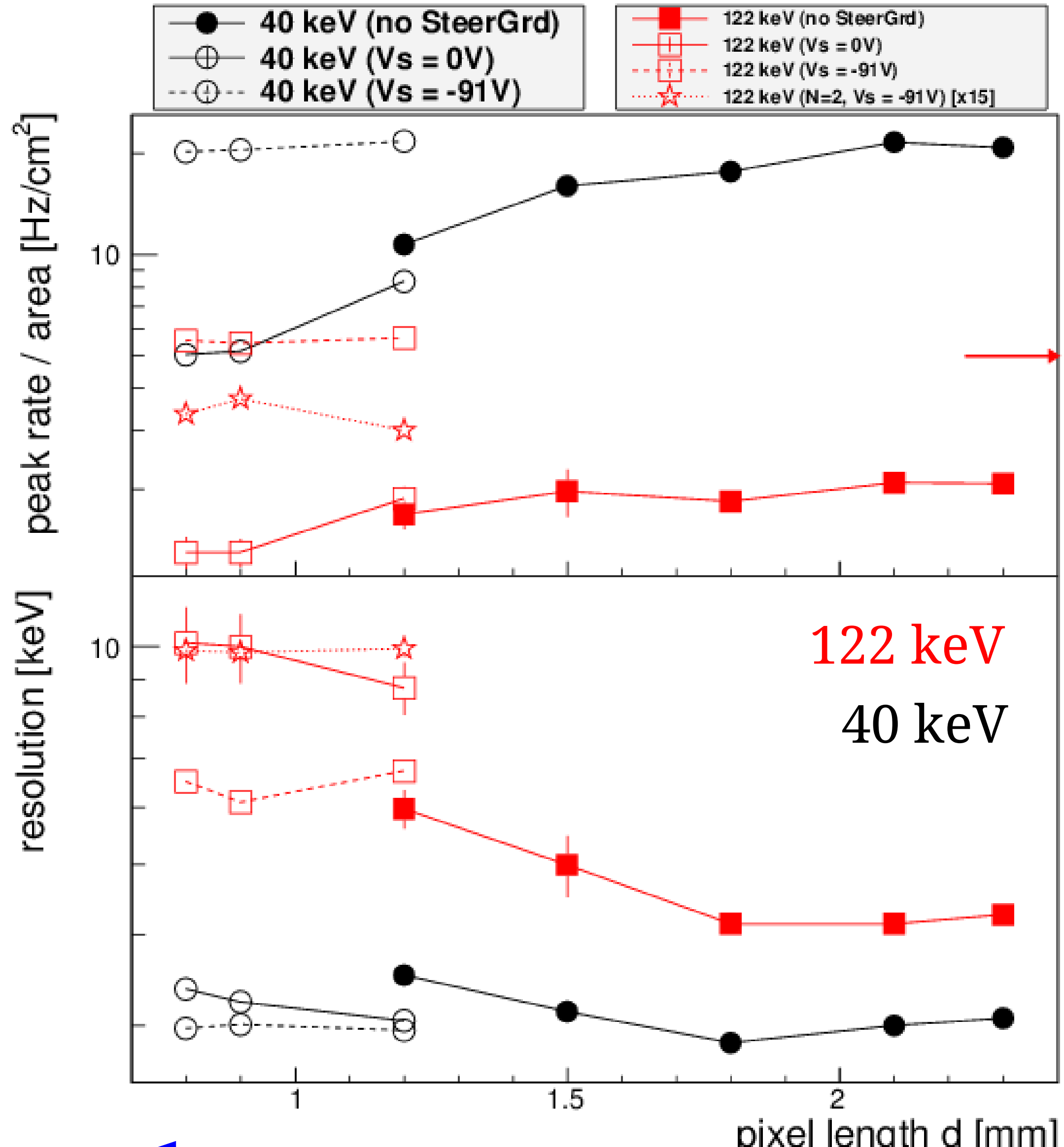


Rapid prototyping:

(1) quick configuration scan on one detector
(2) reduces uncertainties of re-fabrication

Findings:

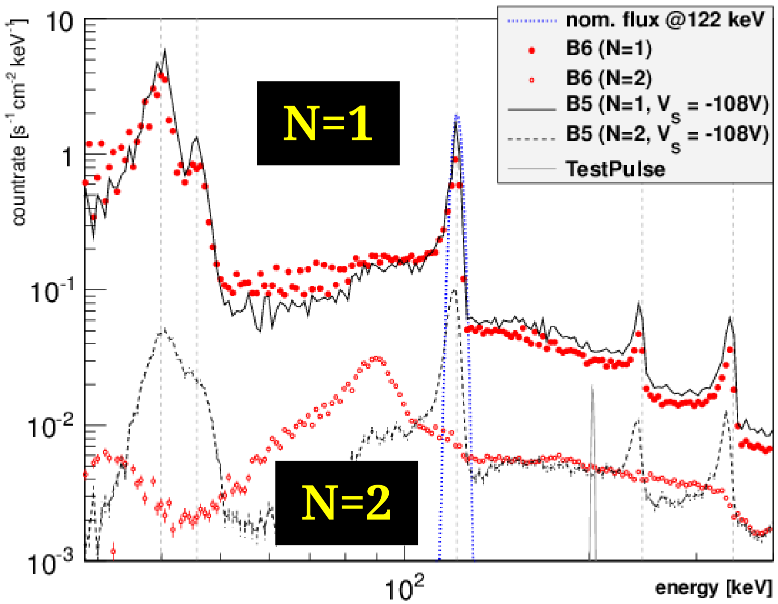
- Big pixels: better energy resolution & rate
- Steering grid improves energy resolution
- Steering grid improves rates (esp. HE)

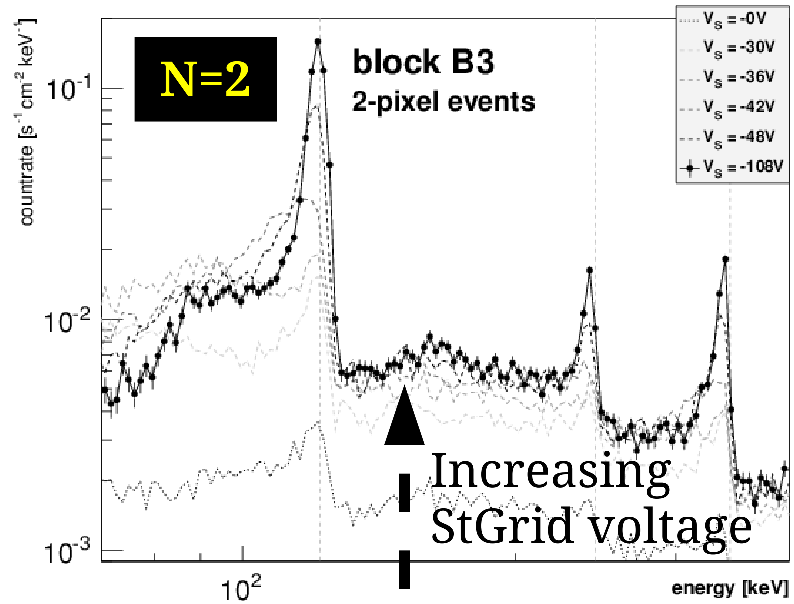


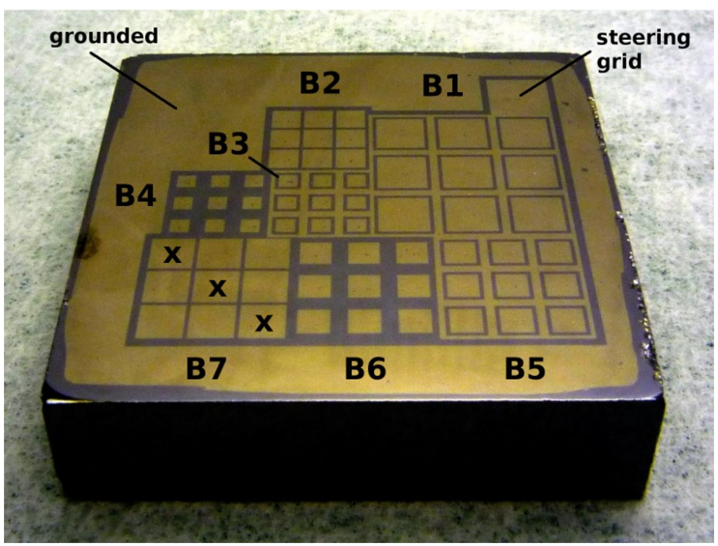
steering grid

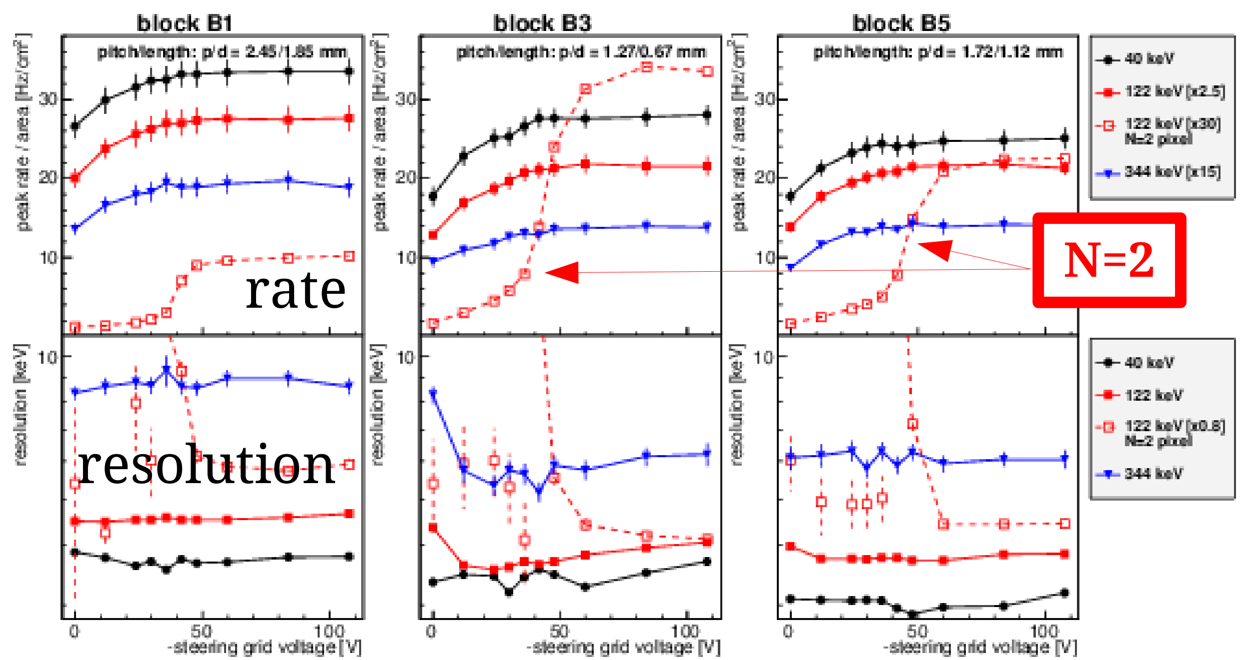
No steering grid

Variable pitch pixels (5 mm detector)



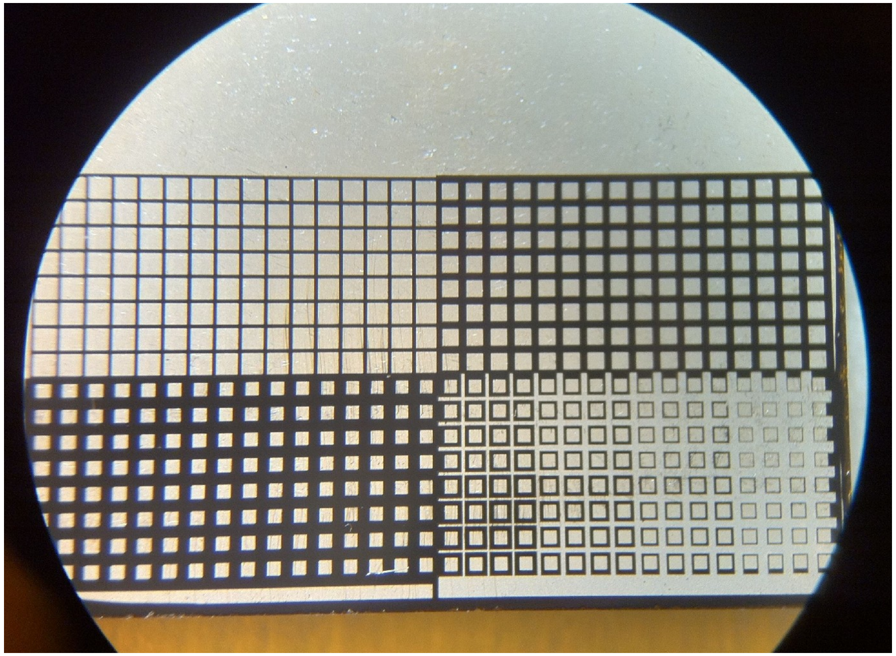


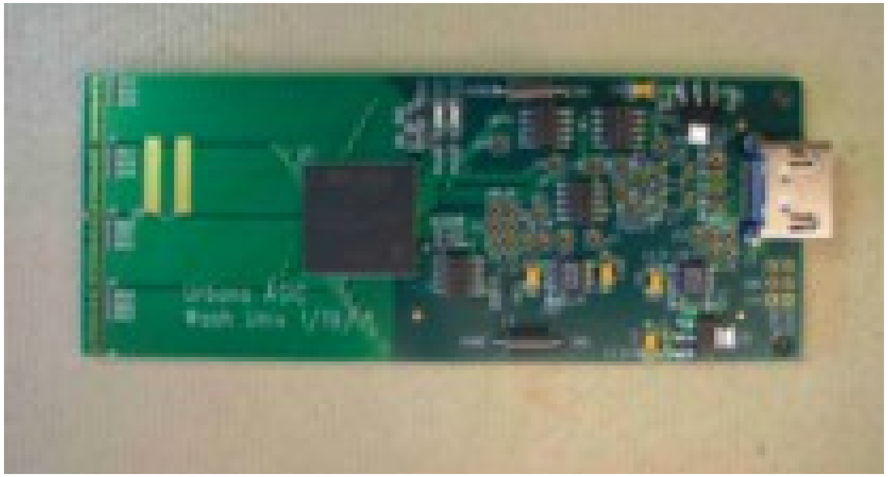




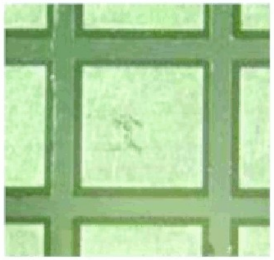
Small (sub-mm) pixels

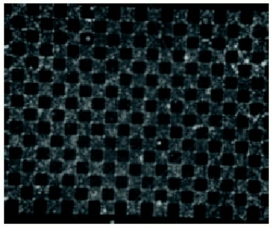
- Fabricate/test: pixel pitches 350, 600, & 700 um
- Direct bonding to ASIC broad
- Collaboration with L.J. Meng (UIUC): AJAT ASIC readout
- Collaboration with G. Jernigan (Berkeley) & Black Forest: testing 600 um pixel detectors

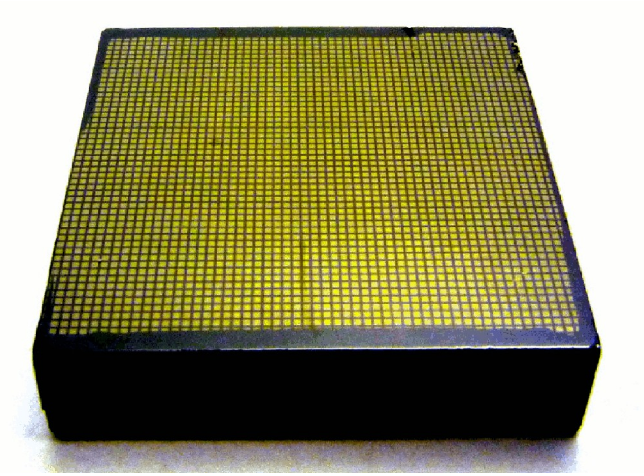




Readout board for
2048-channel AJAT ASIC.







Future goal: 150 um pixel detectors

Motivation:

- New X-ray mirrors: improved point spread function

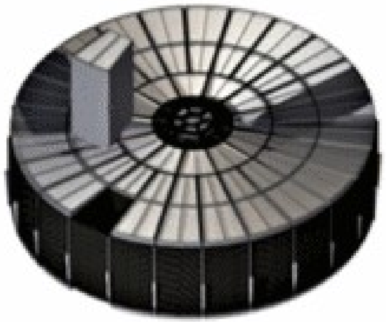
Project goals:

- Detectors with 150 um pixel pitch (5-10 arc sec)
- Low energy threshold (<5keV)
- Optimized readout electronics: BNL

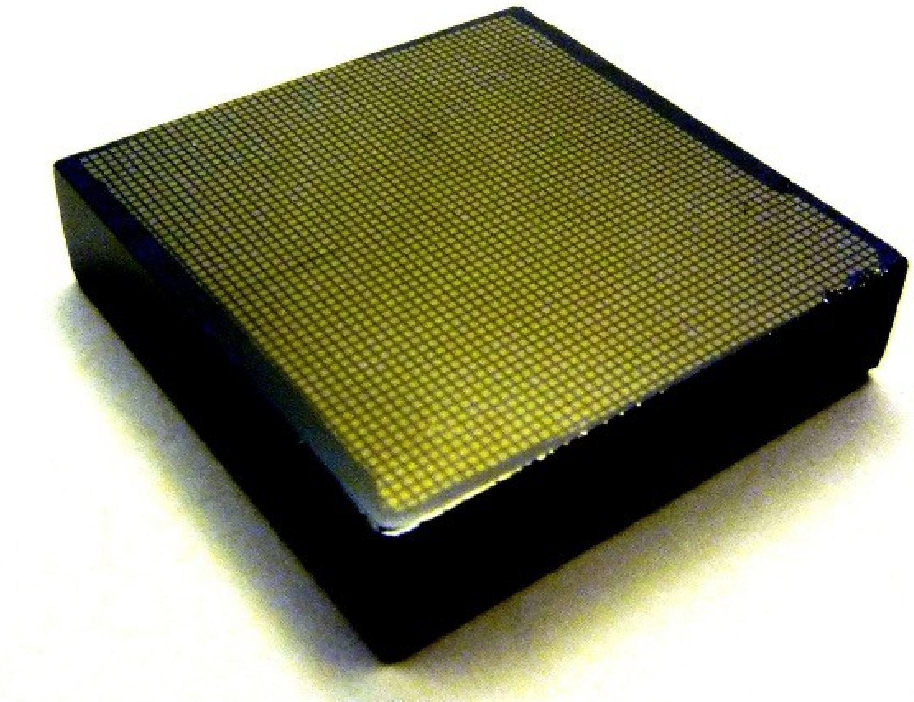
Astrophysical applications:

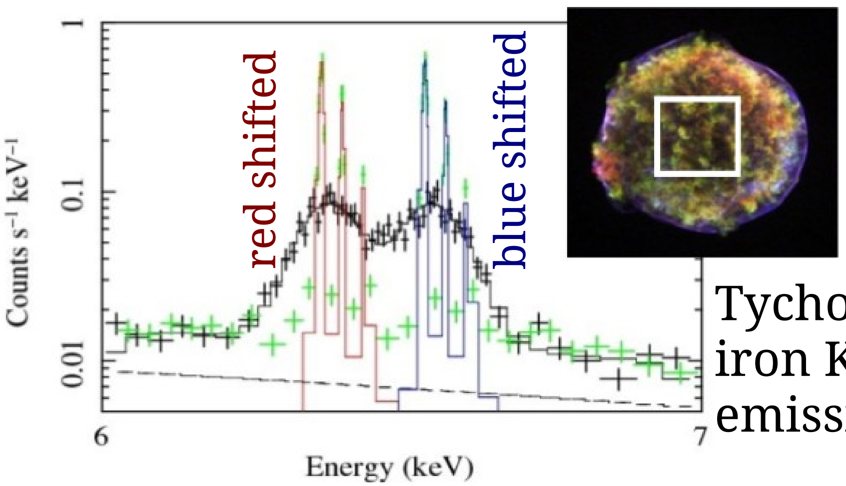
- Black hole vicinity (Fe K band absorption lines)
- Supernova remnants: element emission (C to Ni), relative line power: mechanisms of explosion
- Velocity distribution of rotating gas

Zhang, et al.,Proc. of SPIE 8147 (2011) 81470K-7



See also differential deposition: Weisskopf et al.





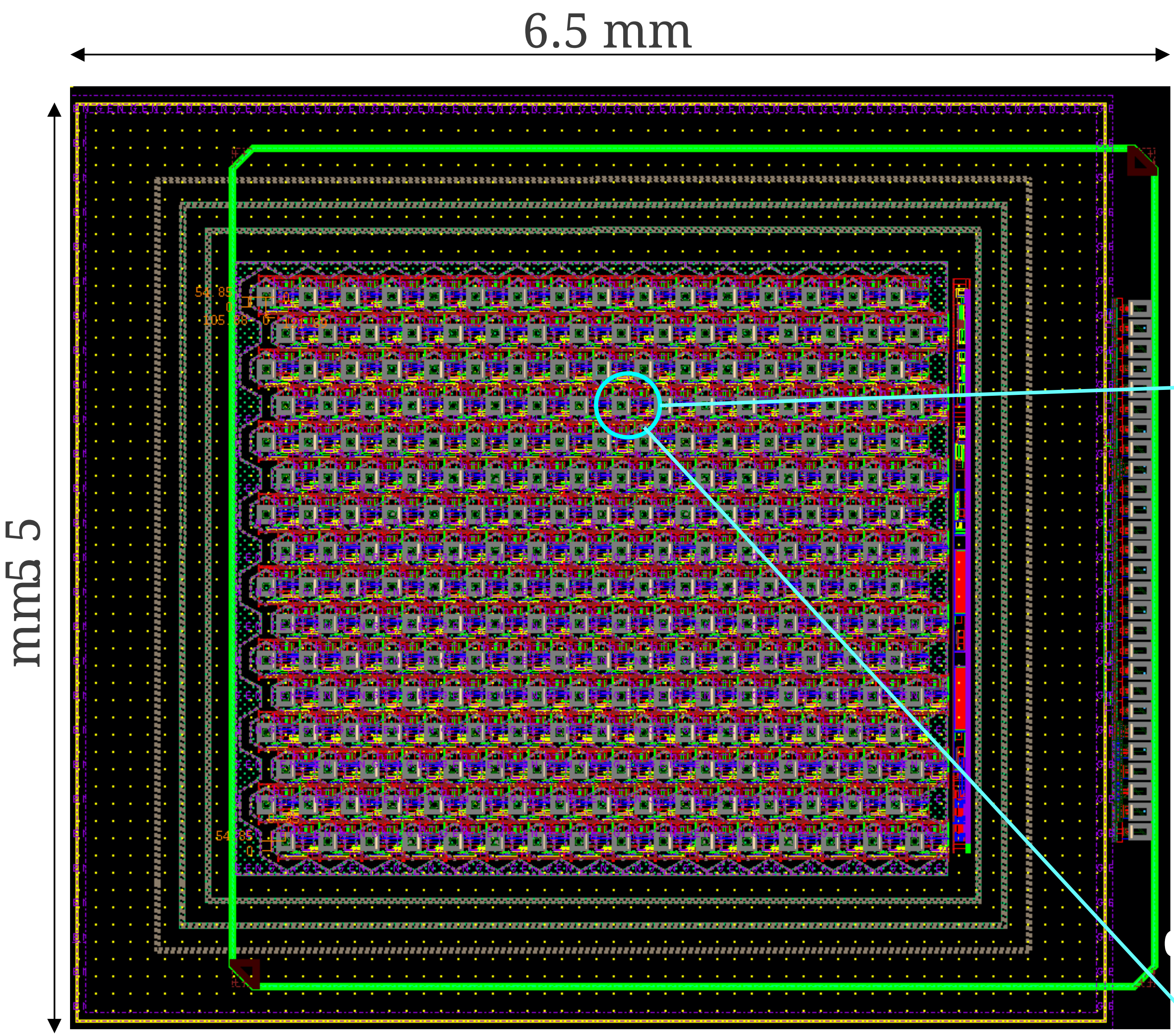
Tycho SNR: iron K-shell emission

2-D ASIC Development for Hi-Resolution X-ray Imager at BNL

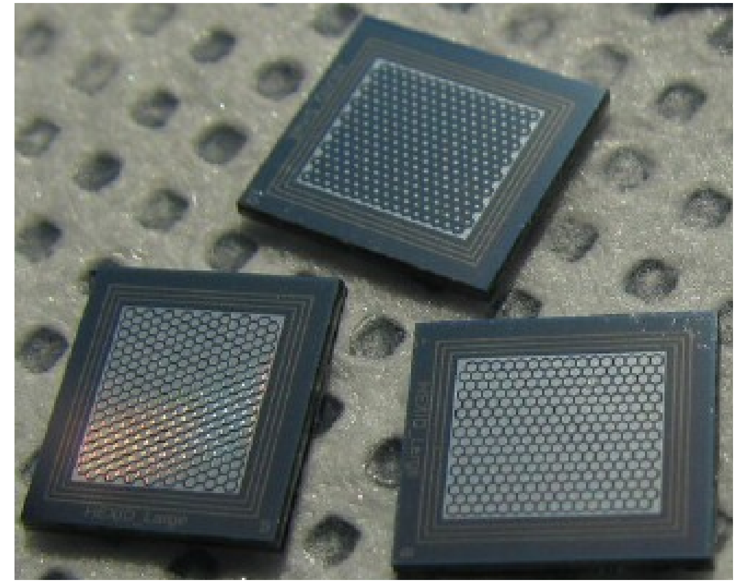
Li & DeGeronimo

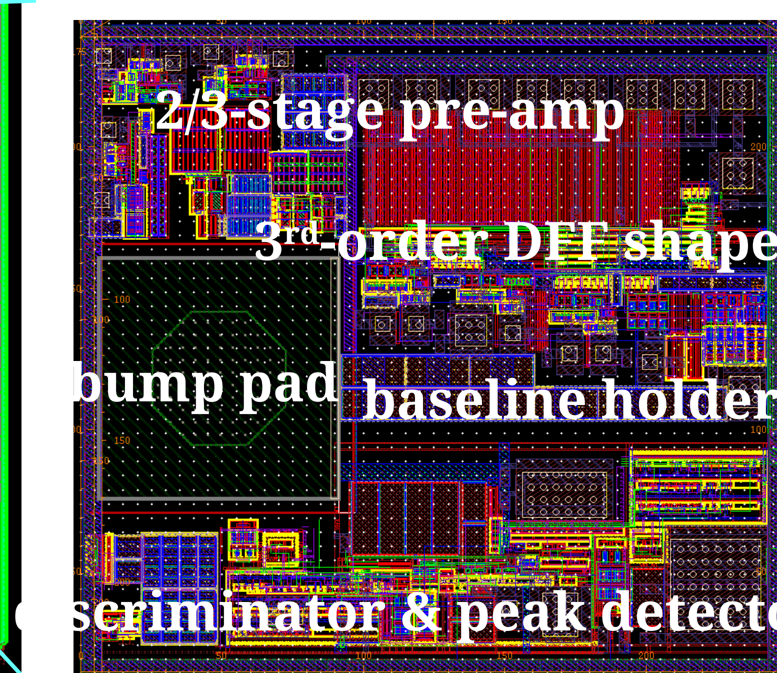
BROOKHAVEN NATIONAL LABORATORY

Bump-bonding Si detector to small-pixel ASIC
Preliminary ASIC layout overlapping the silicon sensor:
16 by 16 array, 250-µm pitch, 0.6mW/pixel, ENC<10 electrons



Si sensors (16 by 16 arrays)





X-ray polarization: motivation & status

X-ray astronomy:

- Spectral/morphology studies well established (non-thermal astrophysical sources)
- Spectro-polarimetric observations: access fraction & angle of polarization

Processes resulting in polarized radiation:

Synchrotron radiation (linear, ^ to **B**), curvature radiation (circular), Thomson scattering (perpendicular to scattering plane)

X-ray polarimetry: Mission Status

- OSO-8: Crab: 2.6/5.2 keV polarization (20%, 30^{o} relative to jet) [ApJ, 220, L117, 1978]
- INTEGRAL: Crab polarization (0.1-1MeV): ~46% [Science, 321, 1183, 2008]

Astrophysics (extract):

- Accreting black holes (BHs): testing accretion disk & BH mass/spin
- Pulsars/PWN: constrain magnetic field & particle populations
- Active galactic nuclei: testing magnetic jet structure

X-ray polarimetry: Possible/future missions:

- ~~Gravity and Extreme Magnetism SMEX (GEMS)~~: 2-10 keV (100 x OSO-8) [Swank]
- Astro-H: E>10 keV, Compton Polarimetry (systematics) [SPIE, 7732, 34, 2010]

X-Calibur design (PI: H.Krawczynski)

measure polarization of 20-80keV X-rays

1: Compton scattering in low-Z scintillator:

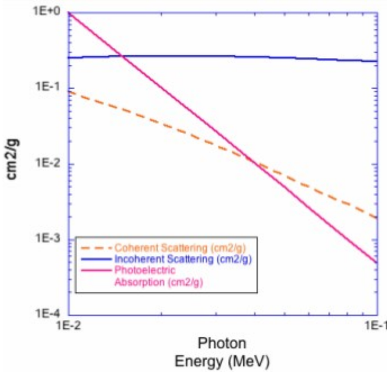
more likely ⊥ to **E** field vector of photon

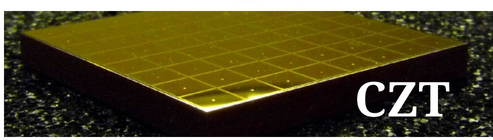
EJ-200, ρ~1g/cm^3, read by Hamamatsu R7600U PMT

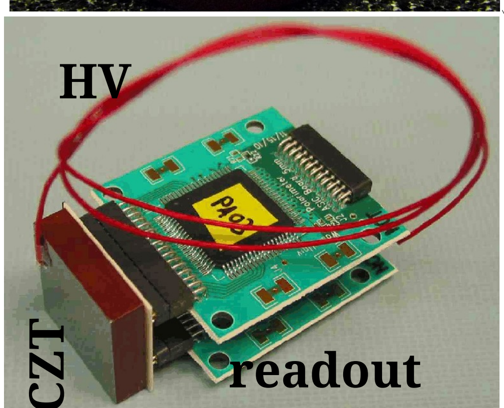
2: photo-absorption in high-Z CZT

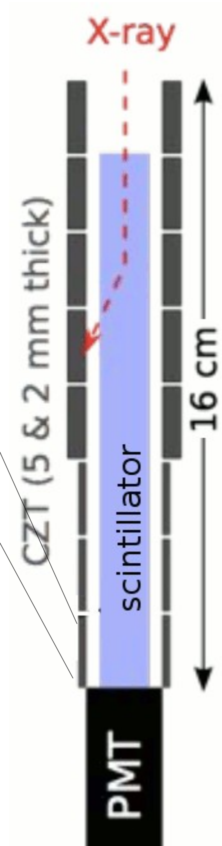
8x8 pixels each, read by BNL ASIC (DeGeronimo & Wulf)

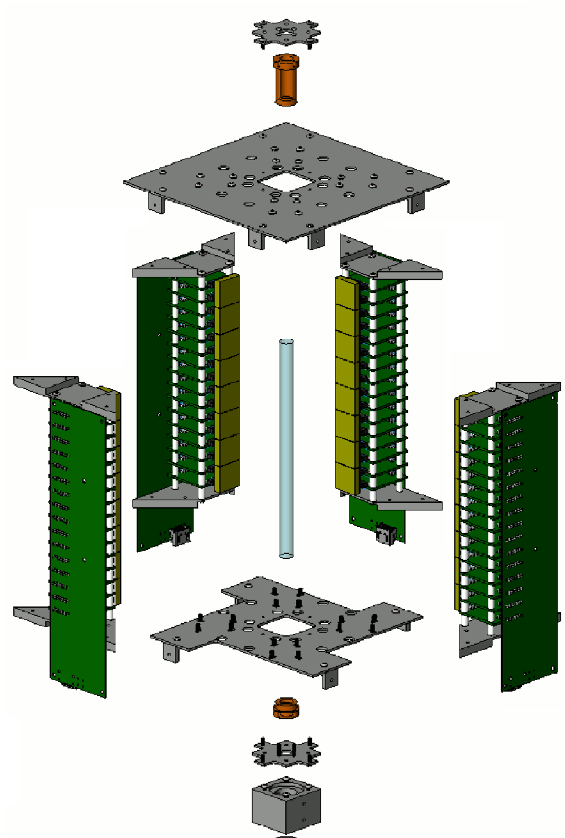
3: signature in azimuthal scattering distribution

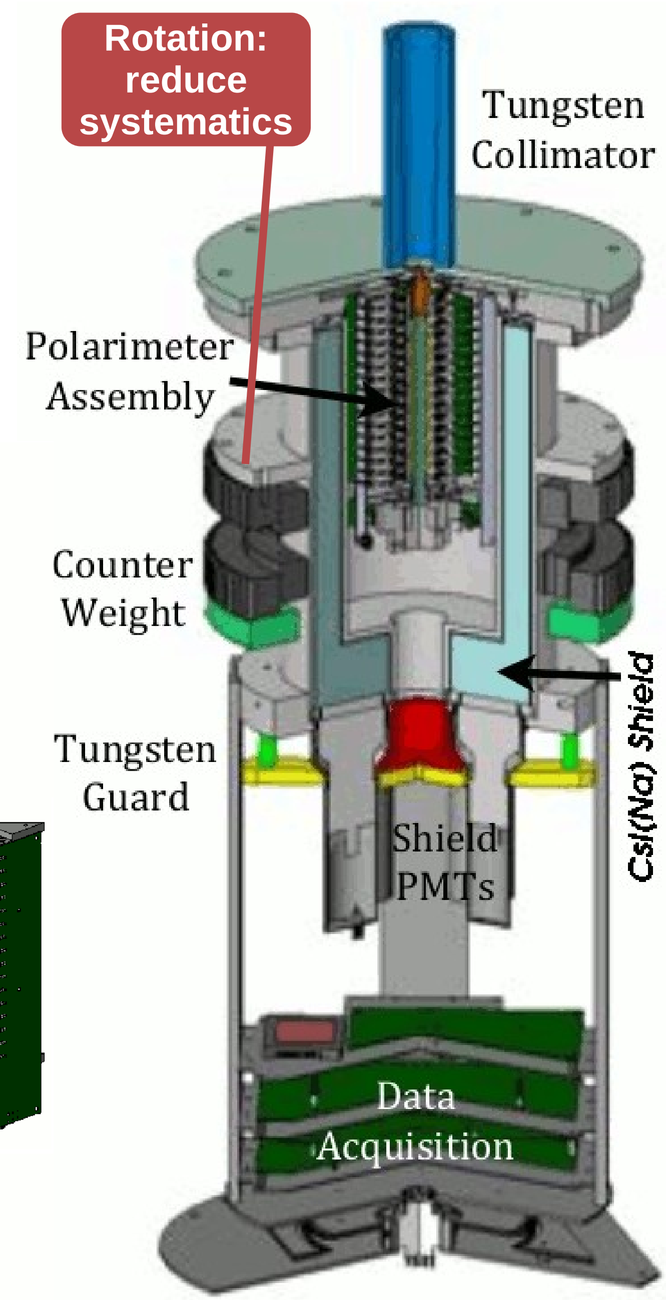








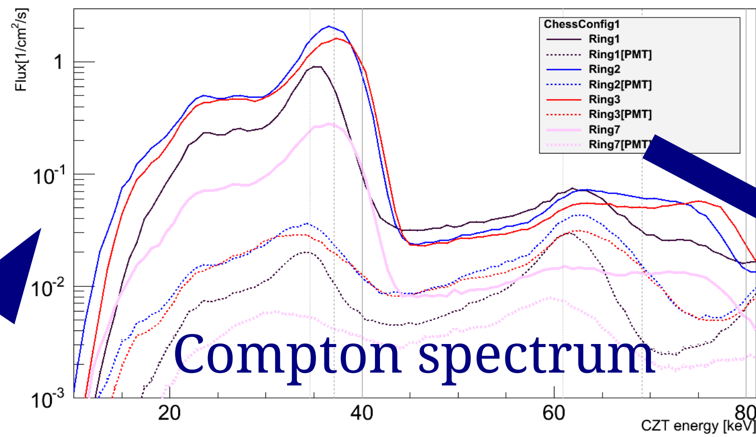




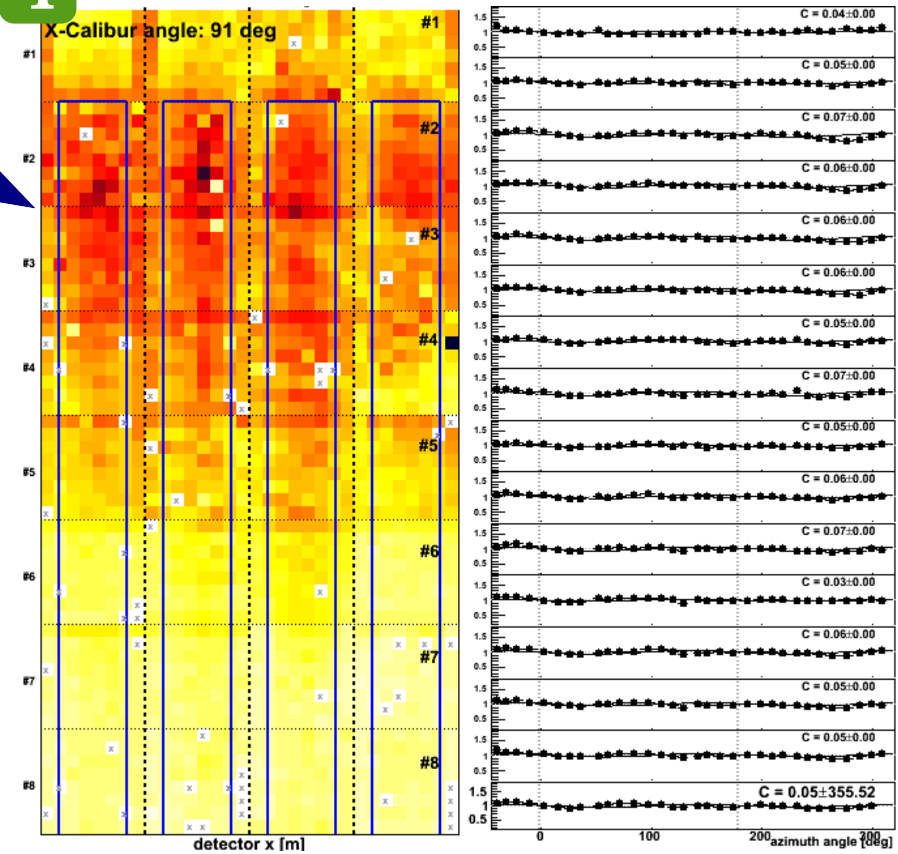
X-Calibur: Polarized X-rays @ CHESS

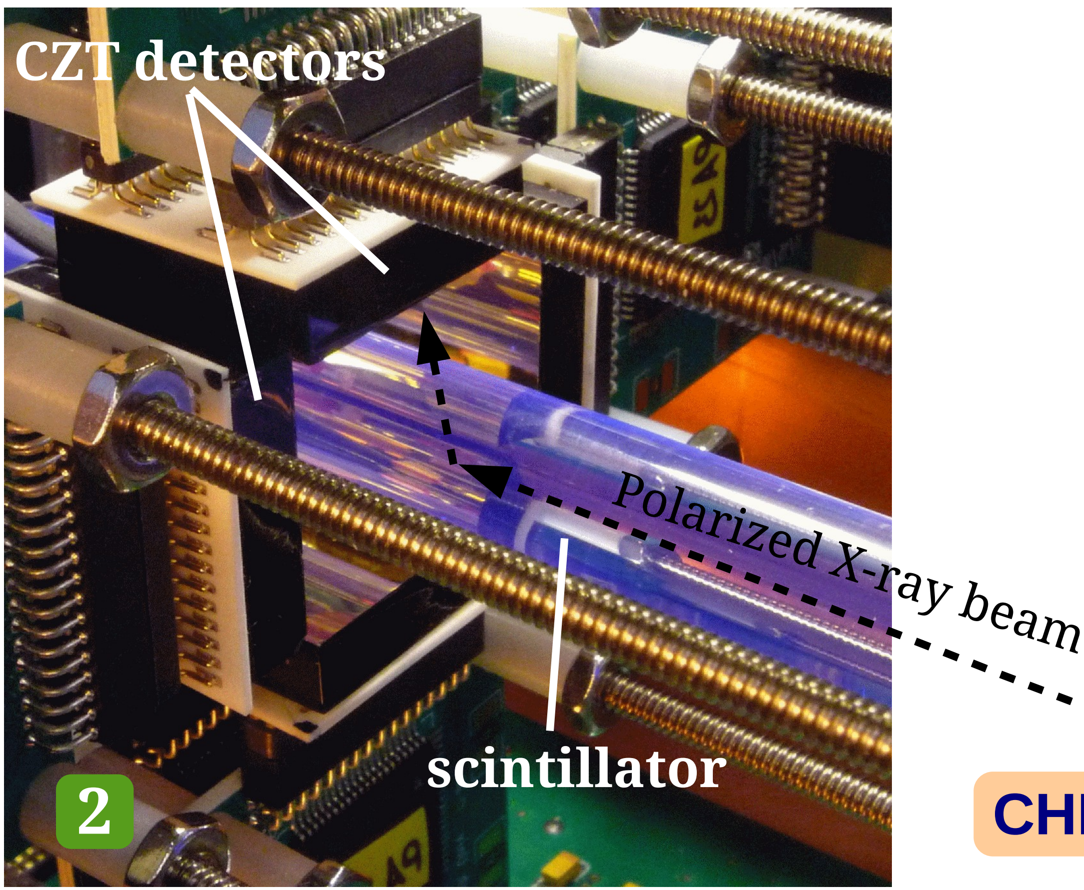
Cornell high-energy synchrotron sources (CHESS)

3



4 Azimuth scatter distribution





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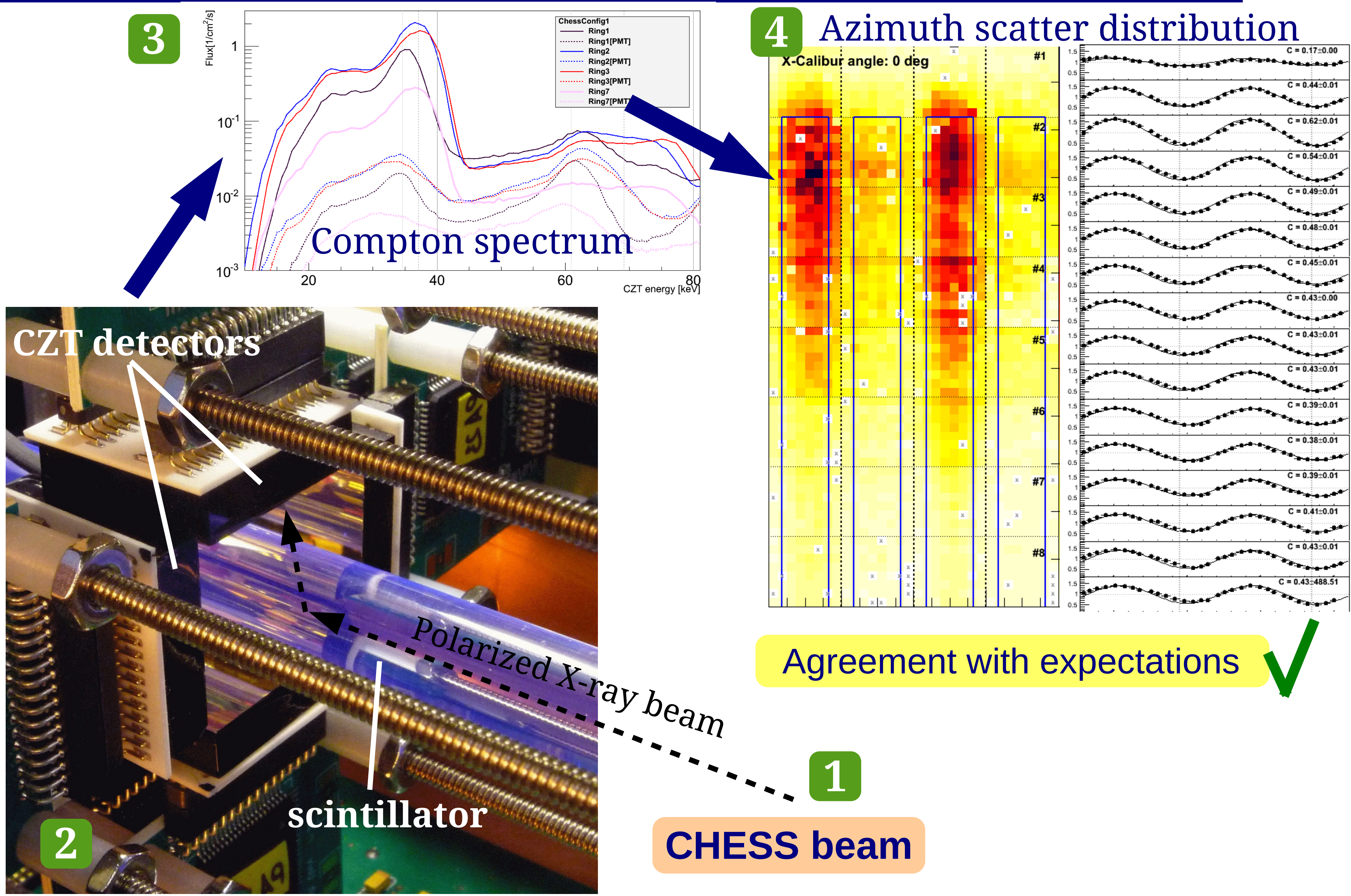
CHESS beam

X-Calibur: Polarized X-rays @ CHESS

Cornell high-energy synchrotron sources (CHESS)



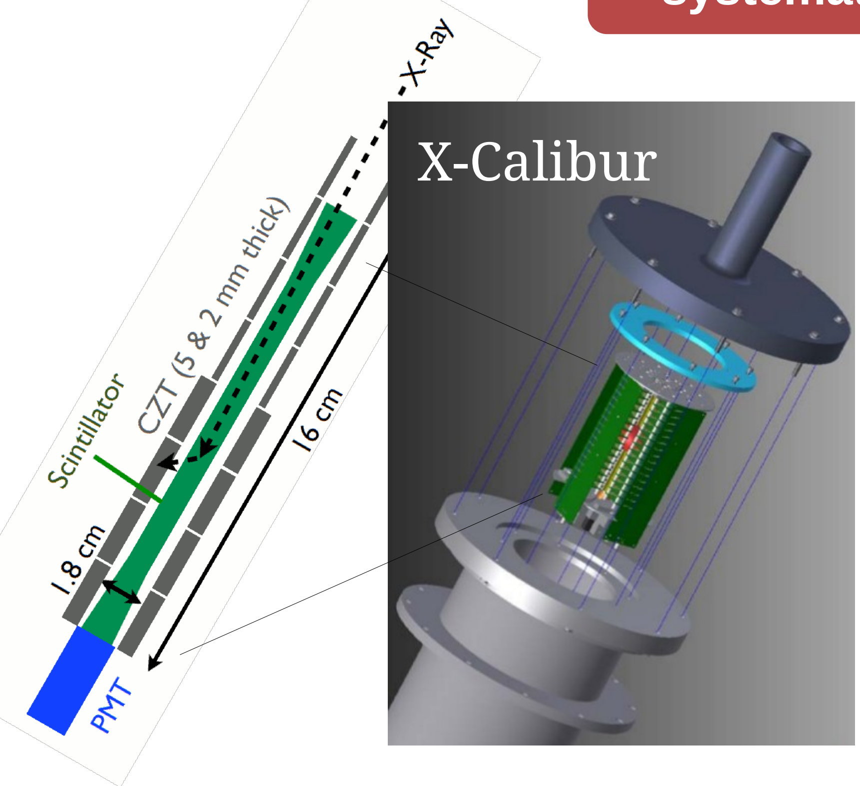
X-Calibur flight: InFOCuS X-ray telescope

8m focal length, 1.4t, grazing incidence Wolter X-ray mirror

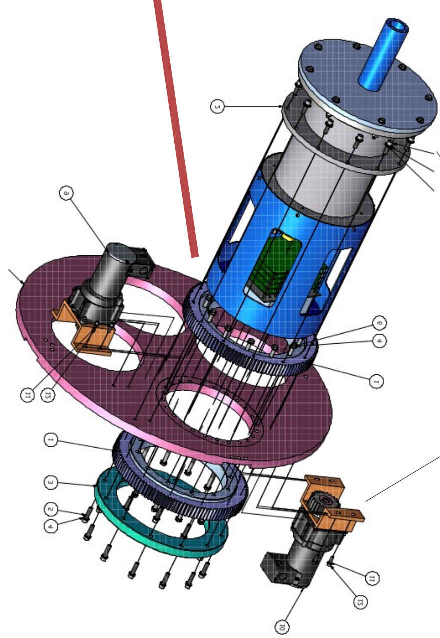
X-Calibur/InFOCuS:

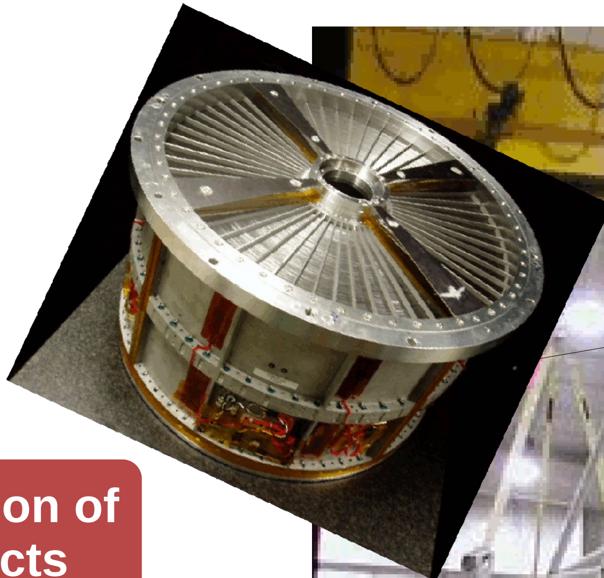
1: High detection efficiency (80%)
2: low background (low volume)
3: control/reduction of systematics
Flight: 2013 (1day, New Mexico)

Crab, Her X-1, Cyg X-1, GRS 1915, Mrk 421, EXO 0331



Rotation: Reduction of systematic effects





Summary & Conclusion

Cadmium-Zinc-Telluride:

→ Material of choice for hard X-ray detectors

Future CZT detector/ASIC development:

→ Smaller pixels (~200 um pitch)
→ Low threshold (<5 keV) ASIC

Hard X-ray polarimeter X-Calibur:

→ Detector fully assembled, calibrated & tested at CHESS
→ 2013-day X-Calibur/InFOCuS balloon flight
(Crab, Her X-1, Cyg X-1, GRS 1915, EXO 0331, Mrk 421)
→ Applied for long-duration flight (goal: 2keV threshold)

Acknowledgements: NASA grants: NNX10AJ56G & NNX12AD51G, discretionary funding from the McDonnell Center for the Space Sciences. CHESS: This work is based upon research conducted at the Cornell High Energy Synchrotron Source (CHESS) which is supported by the National Science Foundation and the National Institutes of Health/National Institute of General Medical Sciences under NSF award DMR-0936384.