Hard X-ray Optics for Astronomy and the Laboratory

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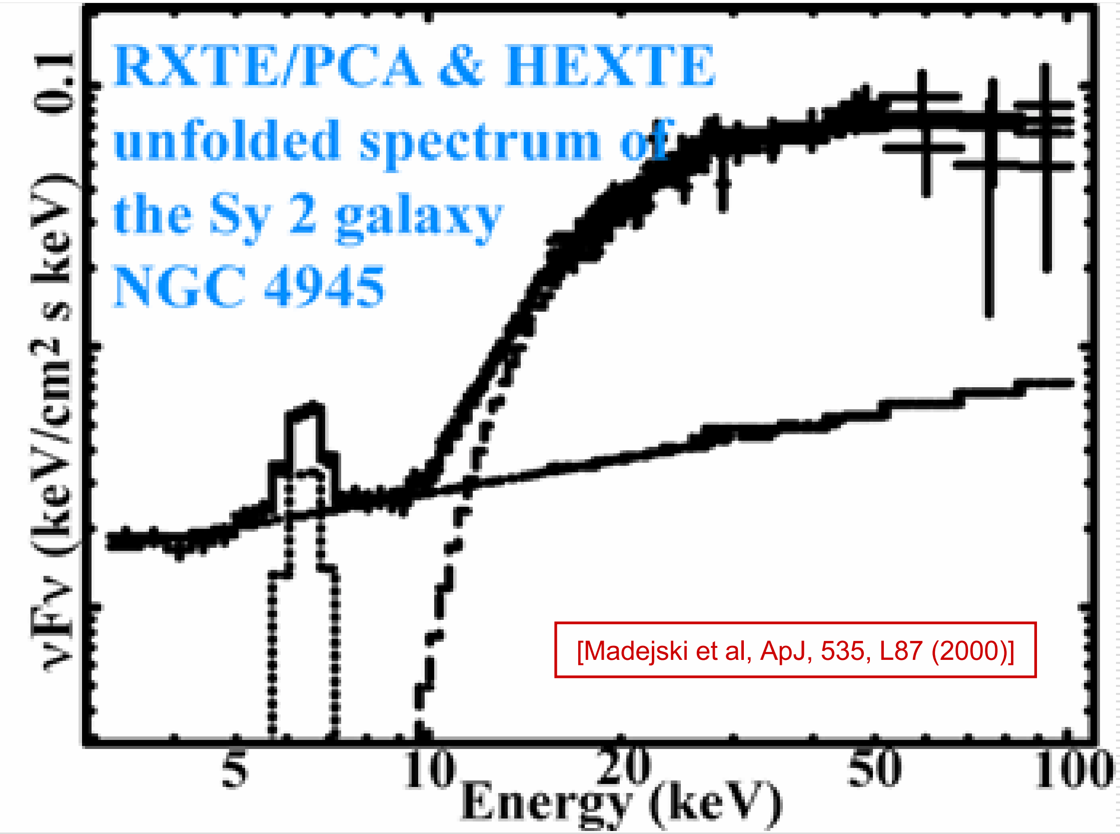
Outline

- Hard X-ray astronomy: the last frontier
  - New exotic physics
  - Planned missions and hardware
- The role of the synchrotron
  - General needs
  - Recent data from ESRF
- Other applications of reflective hard X-ray optics
  - Biomedical imaging—wide field, coarse resolution
  - Next-generation X-ray sources—condenser optics
  - NIF—sub-micron resolution and beyond

Hard X-ray Astronomy

- The 10–100 keV regime is one of the last unexplored areas of astronomy.
- Marks the region where emission transitions from thermal to non-thermal processes.
- Observations will penetrate through dusty regions.
- Crucial lever for constraining physics models.
- Three main observational thrusts:
  - Nucleosynthesis
  - Black holes & AGN
  - Galactic sources

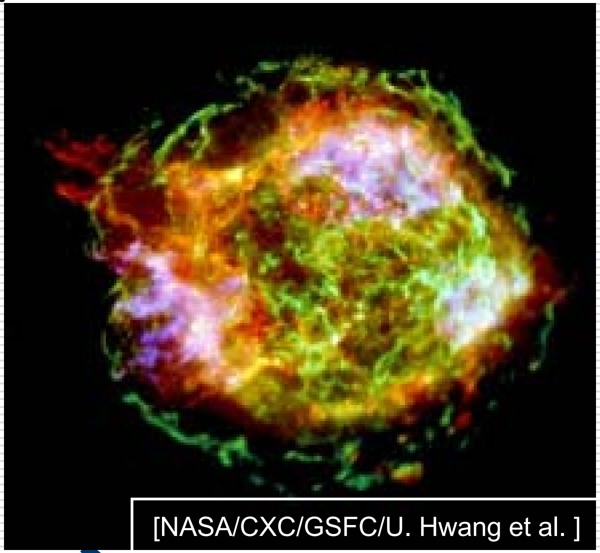


[Madejski et al, ApJ, 535, L87 (2000)]

Nucleosynthesis

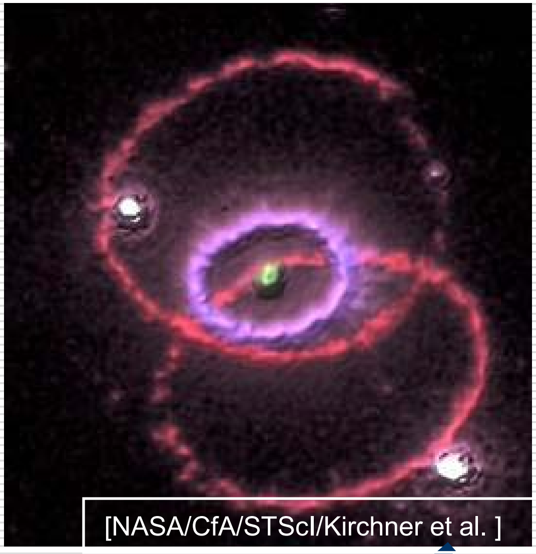
- Study recent supernova remnants (SNRs)
- Look for ^{44}Ti
  - Test theories of how stars explode.
  - Find where elements are born.

Cassiopeia A

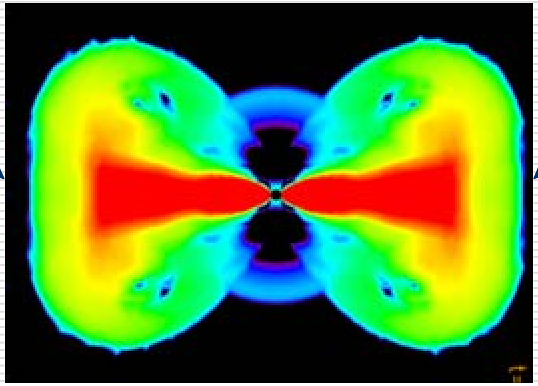


[NASA/CXC/GSFC/U. Hwang et al.]

SN 1987A



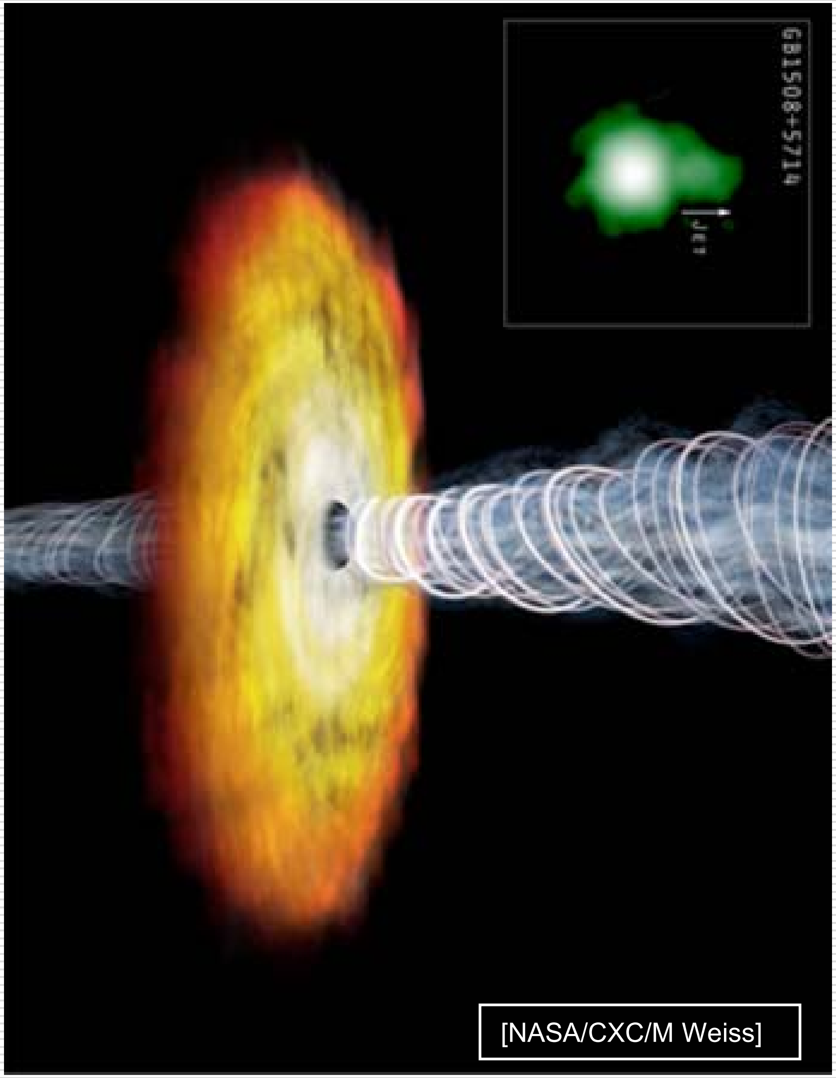
[NASA/CfA/STScI/Kirchner et al.]



Active Galactic Nuclei & Black Holes

- Study the most extreme physical environments in the Universe.
- Teaming with γ-ray telescopes, hard X-ray observations will play a crucial role in understanding how giant particle accelerators in massive black holes work.

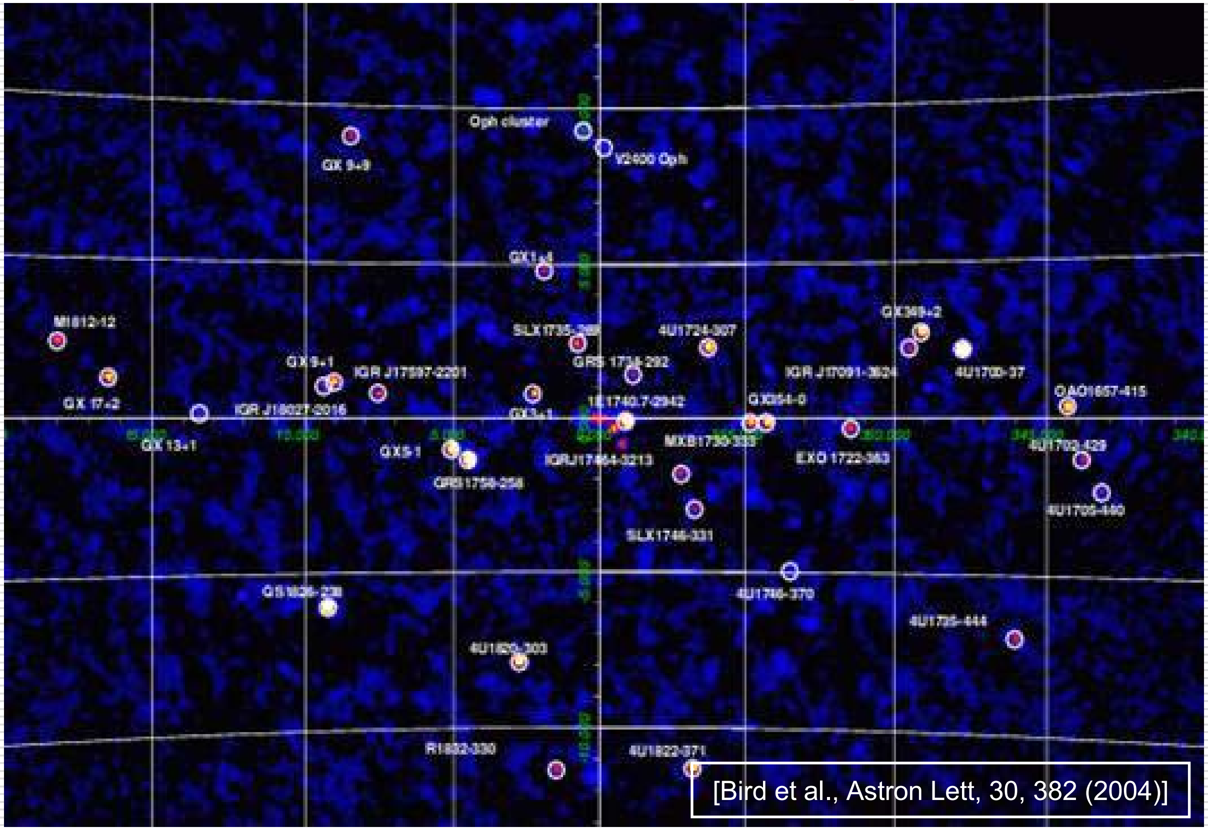
Quasar GB1508+4714



Galactic Observations

- Recent missions have detected a class of hard and highly-obscured sources.
- Hard X-ray missions will perform Galactic surveys to obtain localizations, spectra and help discover the nature of this new population of objects.

Galactic Plane map



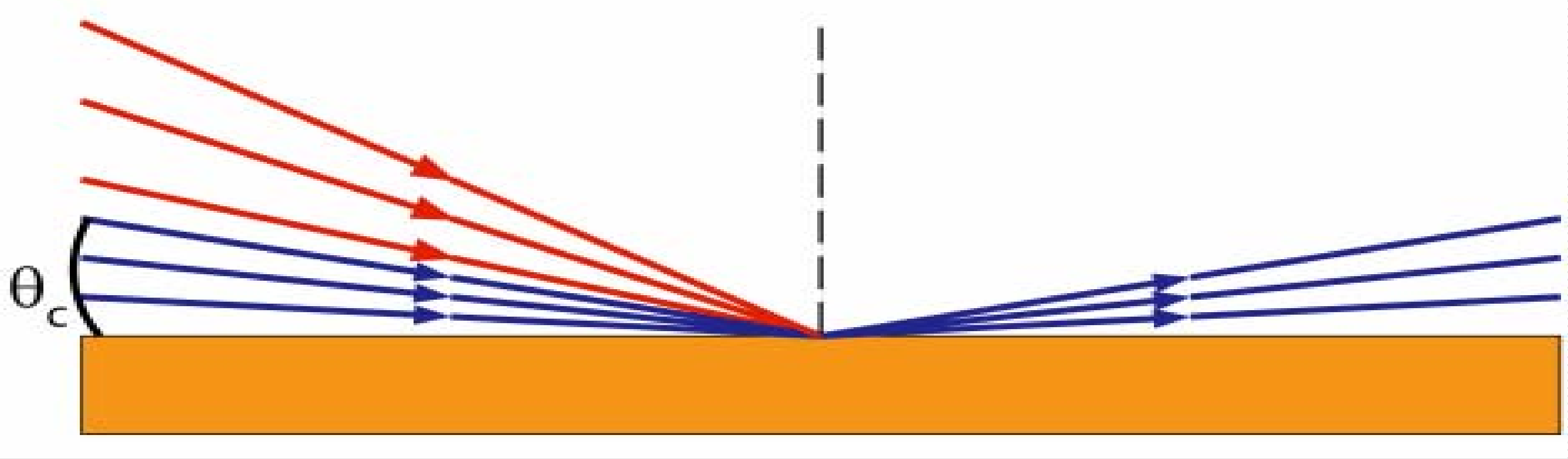
[Bird et al., Astron Lett, 30, 382 (2004)]

Hard X-ray Missions

- Several balloon projects underway; test-bed for technology and proof-of-concept
  - HEFT: Caltech, Columbia, DSRI, LLNL
  - HERO: NASA MSFC
  - *InFocμs*: NASA GSFC, Nagoya
- Proposed Satellite Missions:
  - *Constellation-X*: NASA (2012)
  - *XEUS*: ESA (2015)
  - *NeXT*: JAXA (2011)
  - *NuSTAR*: NASA-funded (2007−2008);
    - Caltech, Columbia, DSRI, LLNL, Stanford
    - Decision in November 2004

Hard X-ray Optics

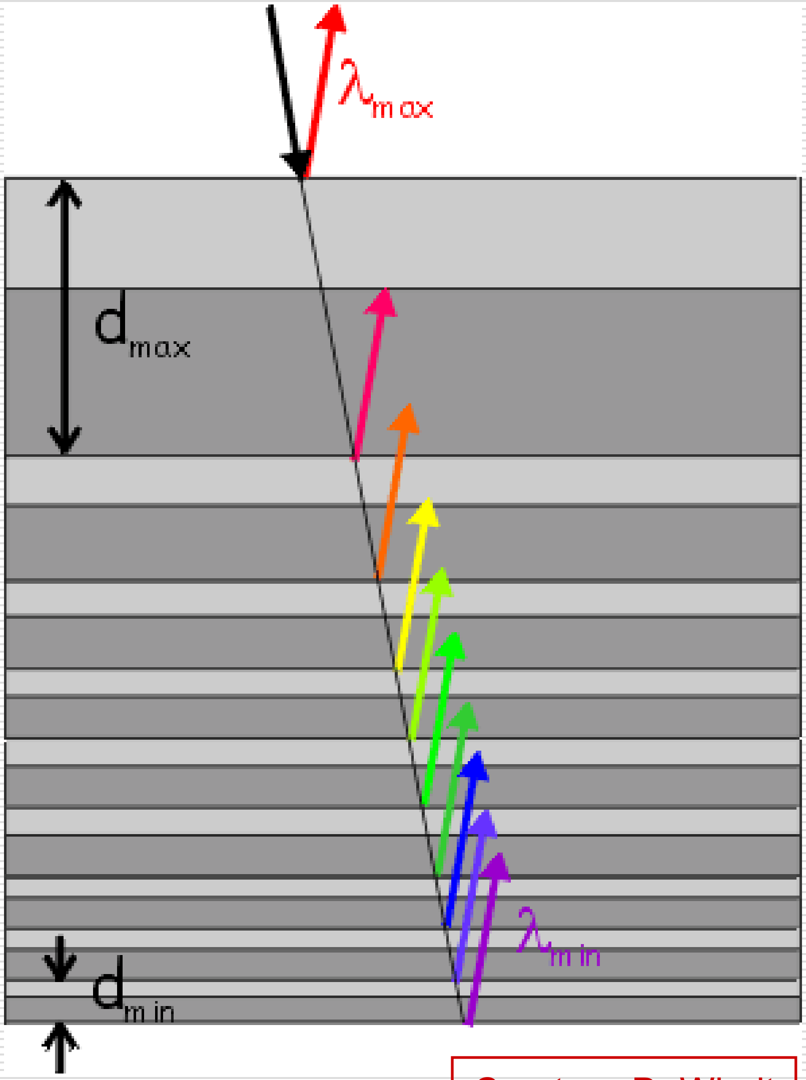
- Traditionally, X-ray optics utilize Wolter designs that rely on total external reflection of light from metals at shallow incident angles ($n = 1 - \delta - i\beta$).



- For graze angle less than the critical angle [$\theta_C = \sqrt{2\delta(E)}$], photons are reflected with efficiency.
- θ_c drops rapidly with increasing energy, so hard to make efficient optics for E > 10 keV.
- Use multilayers to extend energy range into hard band.

Hard X-ray Multilayers

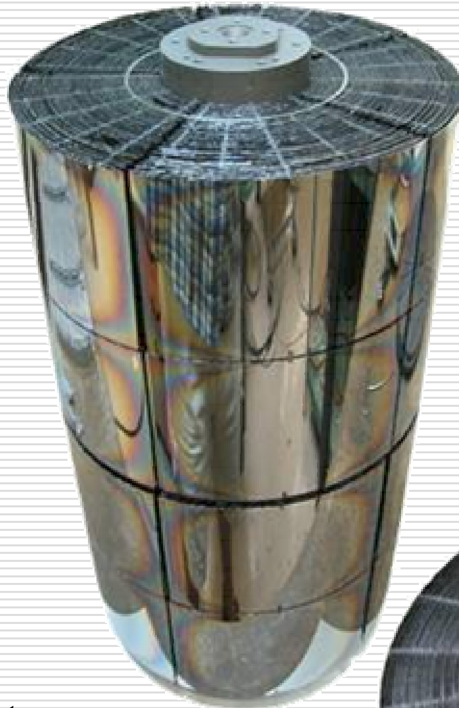
- Multilayers rely on coherent reflections that satisfy Bragg's law: $m\lambda = 2d\sin\theta$.
- Key realization by Christensen *et al*. (1991): vary *d*-spacing to achieve high reflectivity over a range of *E* and *θ*.
  - Wide energy band-pass
  - Wide-field imaging



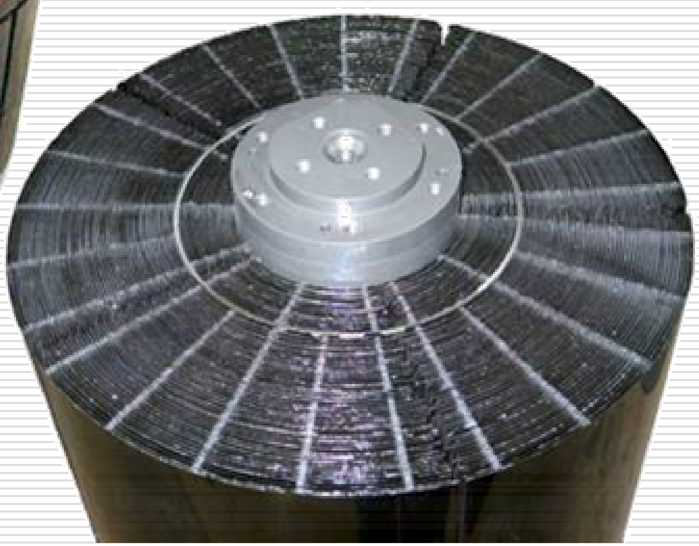
Courtesy D. Windt

Hard X-ray Telescopes

- Mirrors substrates formed from a variety of materials and techniques:
  - Integral Ni shells replicated from mandrels
  - Thermally-formed segmented glass
  - Segmented, epoxy-replicated Al or glass
  - Plastic
- Each telescope will consist of several tens to hundreds of highly-nested multilayer-coated mirrors.
- One to five telescope modules per satellite.



First two telescope modules from the HEFT program.



72 nested shells:
1440 total pieces of glass

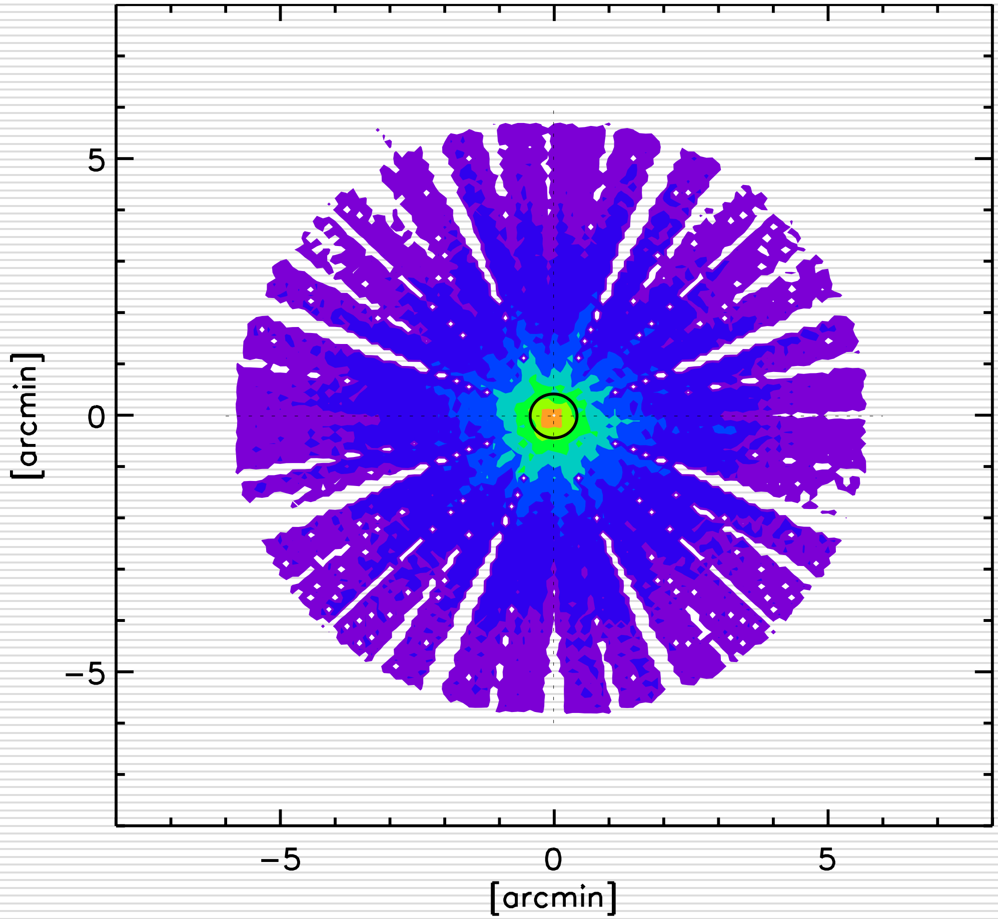
Calibration: Overview

- Reliable science results → Precise calibration
- Traditionally, soft X-ray telescopes have been calibrated at long beam facilities (PANTER, XRCF).
- Use M-, L- and K-shell characteristic emission lines (e^- impact sources & monos) to span the energy band.
- Problematic at hard energies:
  - Sources need to be run up to 200 kVp.
  - Not tunable: sporadic coverage from 30–100 keV
    - Limited anode materials
    - Only K-shell lines
- Very expensive to maintain.

Calibration at Synchrotrons

- Bright, hard beamlines (SPring8, ESRF, APS) offer excellent alternative to large facilities.
- Ideal for characterizing prototypes.
- Mirror performance & PSF synthesized from many azimuthal scans.

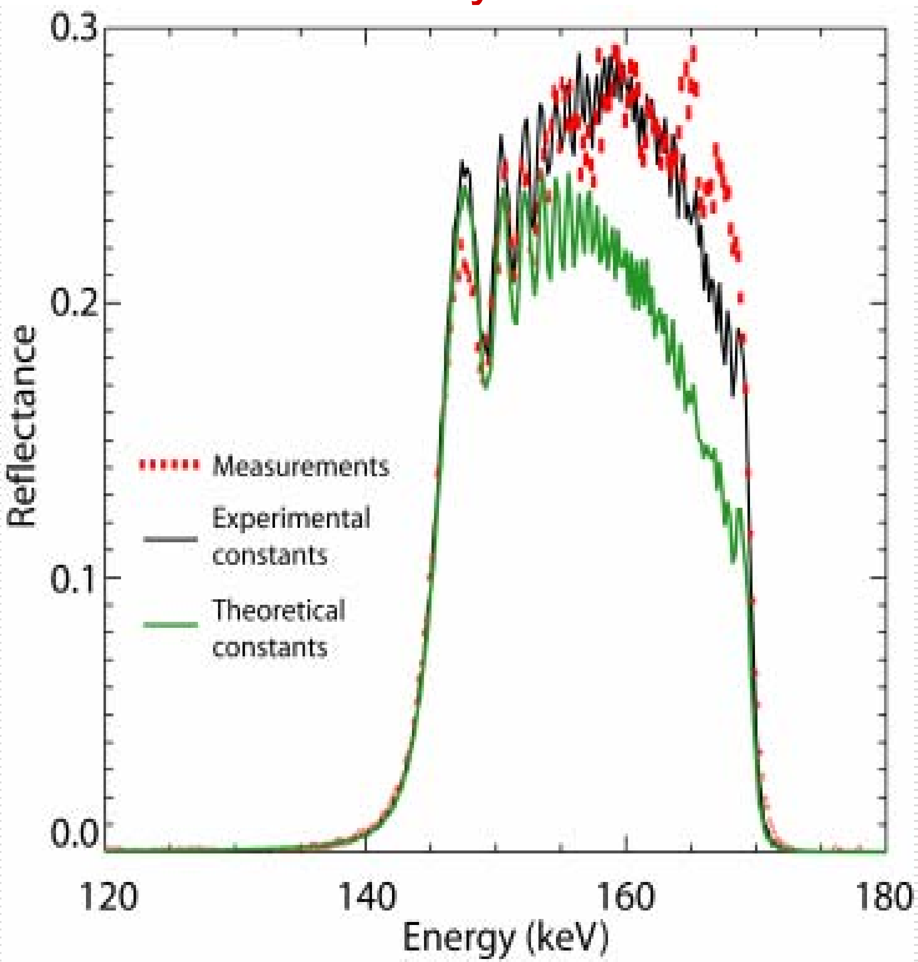
PSF of prototype telescope;
@ 40 keV, ESRF April 2004



Calibration at Synchrotrons (2)

- Crucial for measuring atomic constants needed to optimize multilayers.
  - Very little experimental data to date
  - Theoretical values do not account for Compton scattering
- Once multilayers are designed, verify reflectivity of prototypes and complete telescopes.

W/SiC multilayer at $\theta = 0.2^{\circ}$



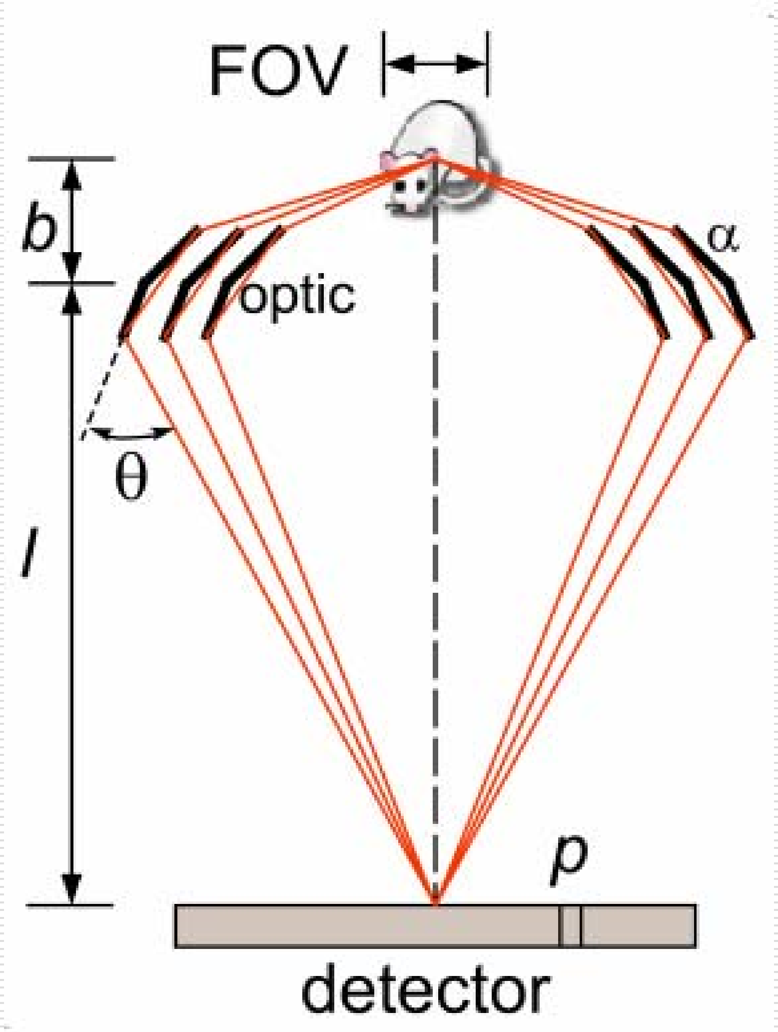
[Windt et al., AppOp, 42, 2415 (2003)]

Other Applications of Hard X-ray Optics

- Investment in multilayer development & substrate fabrication by astronomy community has led to a wide variety of other applications.
- Still employ Wolter optical prescriptions, with slight modifications.
- Designs driven by resolution (*R*), FOV and throughput (Ω) requirements.
  - Biomedical: R ≤ 100 μm, FOV = 0.5–2 cm
  - Condensers: R = 10–100 μm, high Ω
  - NIF: R ≤ 1 μm, FOV = 0.2–1 mm

Small-animal Radionuclide Imaging

- Animal models (particularly mice) are crucial for biomedical research.
- *In vivo* imaging of radionuclide tracers allows functional assessment.
- Hard X-ray optics provides a 10× improvement in resolution over current absorptive collimation techniques.

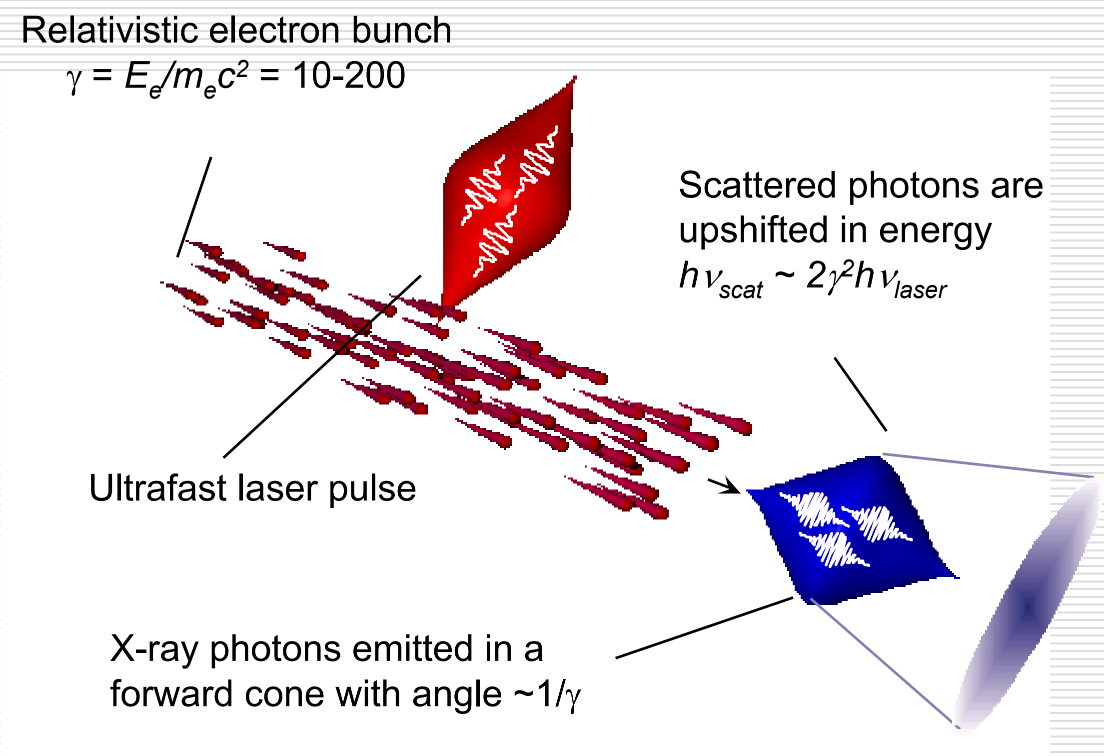


[Pivovaroff et al., SPIE 5199, 147 (2004)]

Condensers for Novel X-ray Sources

- New generation of fast, bright hard X-ray sources.
- Emerging beam often divergent, and may require significant separation between source and sample.
- Optics can focus and relay flux to samples.

PLEIADES:
LLNL Thompson Source

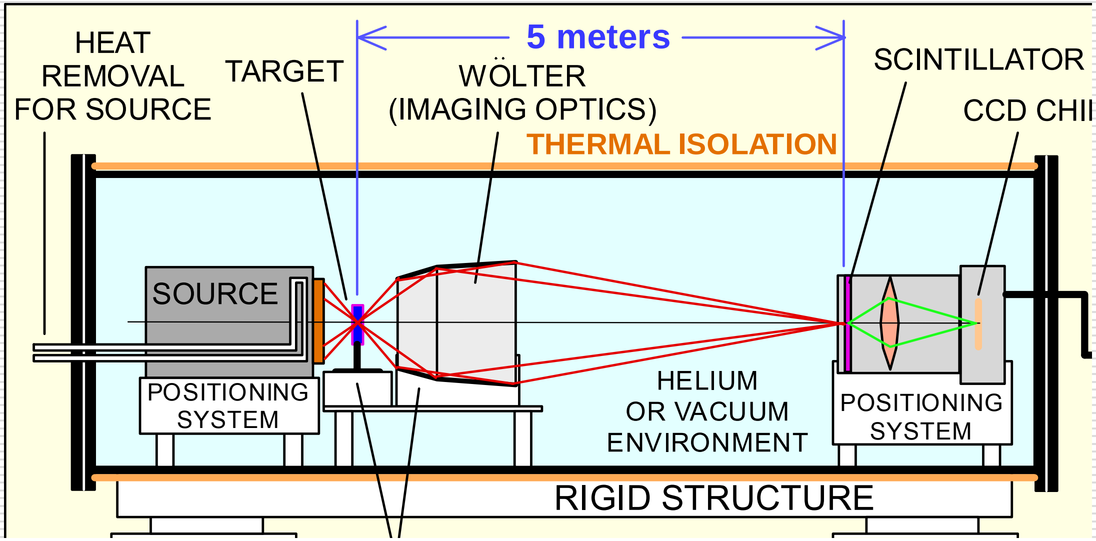


[Gibson et al., Phys Plasma, 11,2857, (2004)]

Energies up to 200 keV

X-ray Imaging for NIF

- Characterization of targets
  - ≤ 1 μm resolution
  - 1–2 mm FOV
  - Hard X-rays needed
  - for high-Z targets



- Diagnostics for actual experiments
  - Intrinsically bright, or use backlighter to illuminate target during shot.
  - Wolter systems may provide better performance (photons per resolution element) than Zone plates or high-magnification point projection schemes.

Conclusions

- Next decade will see construction of several major hard X-ray telescopes—synchrotron facilities can play a crucial role in R&D and calibration.
- Investment by astronomical community had allowed development of hard X-ray optics for a variety of disciplines.
- Some systems will have relevance for synchrotron applications (*e.g.,* microscopy).
  - Groups at SPring-8 have already built soft X-ray microscopes. [Takeuchi et al., Rev Sci Ins, 71, 2000]