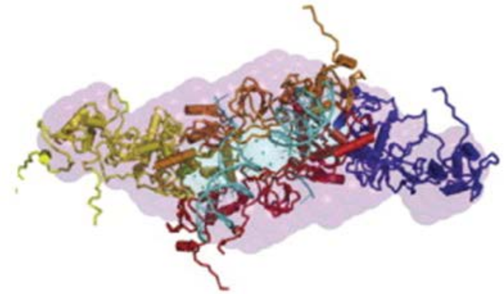
Ballistic Guides and Imaging Forming Mirrors: How to simultaneously improve resolution and intensity



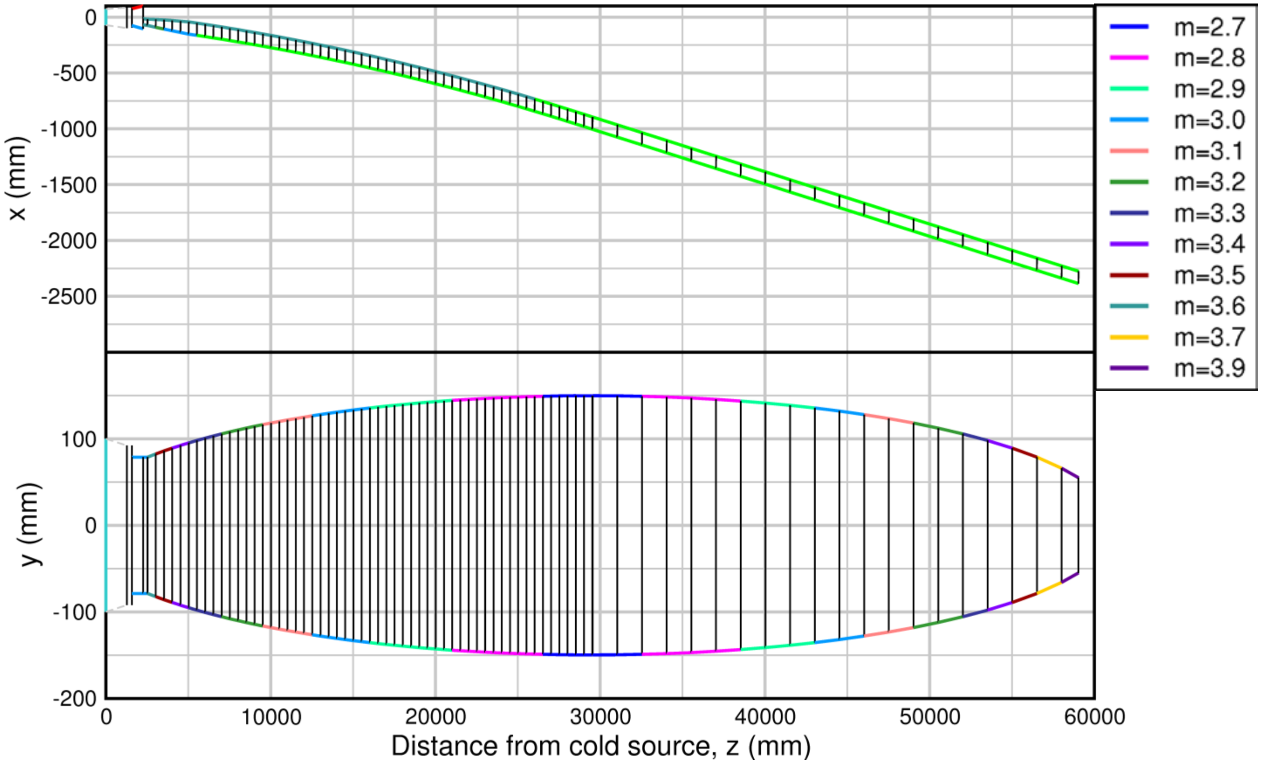
NIST Center for Neutron Research

Daniel S. Hussey
Physical Measurement Laboratory,
NIST

Outline

- The NG-C Guide
- Pinhole Optics
- Wolter Optics (axisymmetric mirrors)
- Wolter Optics Imaging and SANS Demonstration Experiments

NG-C Curved, Ballistic Guide



Total Length: 57.49 m
Radius : 933 m

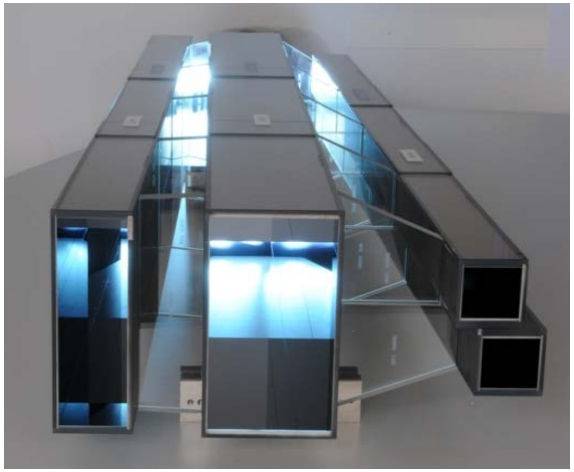
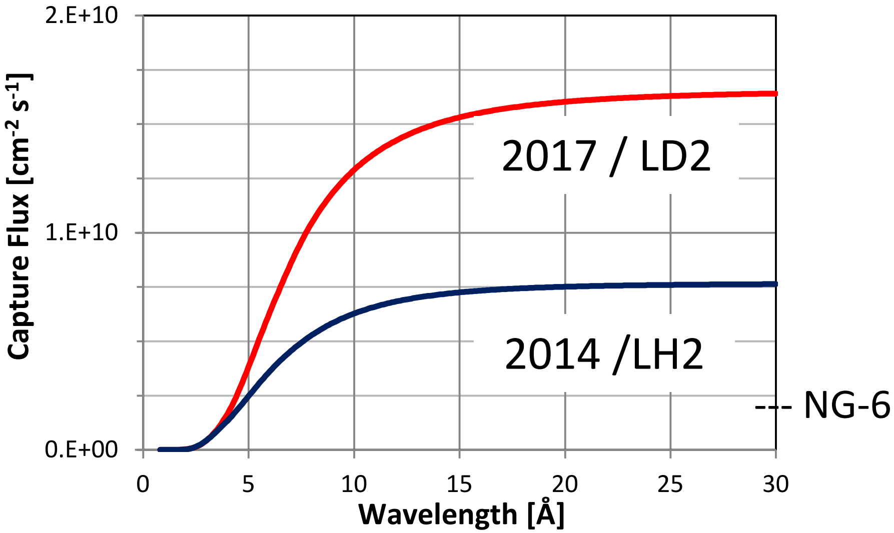
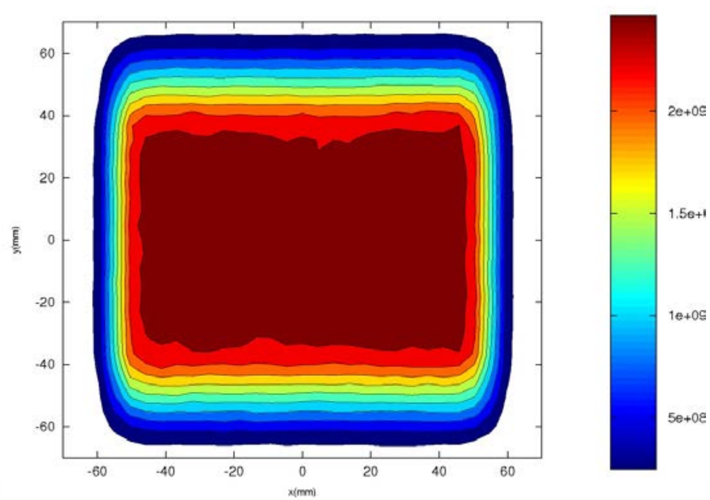


Photo of NG-D, NG-C and NG-B sections that are closest to the cold source

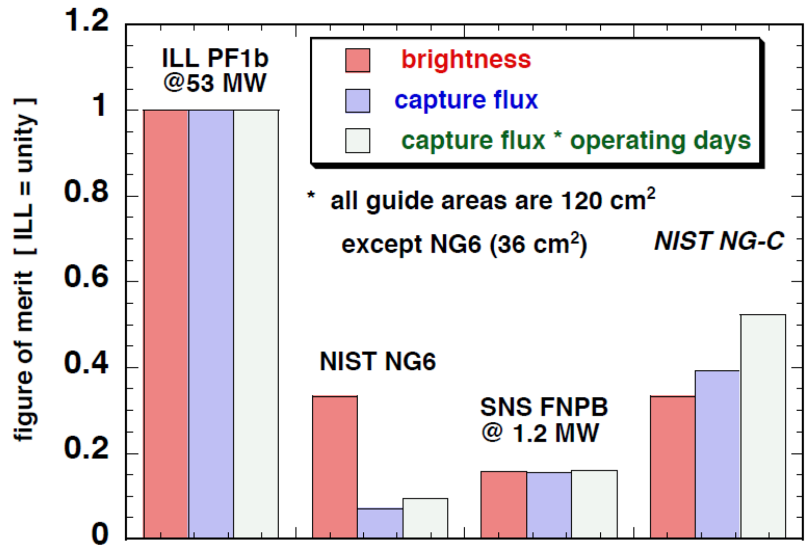
NG-C Guide Performance



Neutron Distribution
0.5 m from Guide



NG-C w/ LH2 vs. ILL and SNS



With the LD cold source upgrade, NG-C will rival the most intense neutron beam, despite the ~3x lower power of the source.

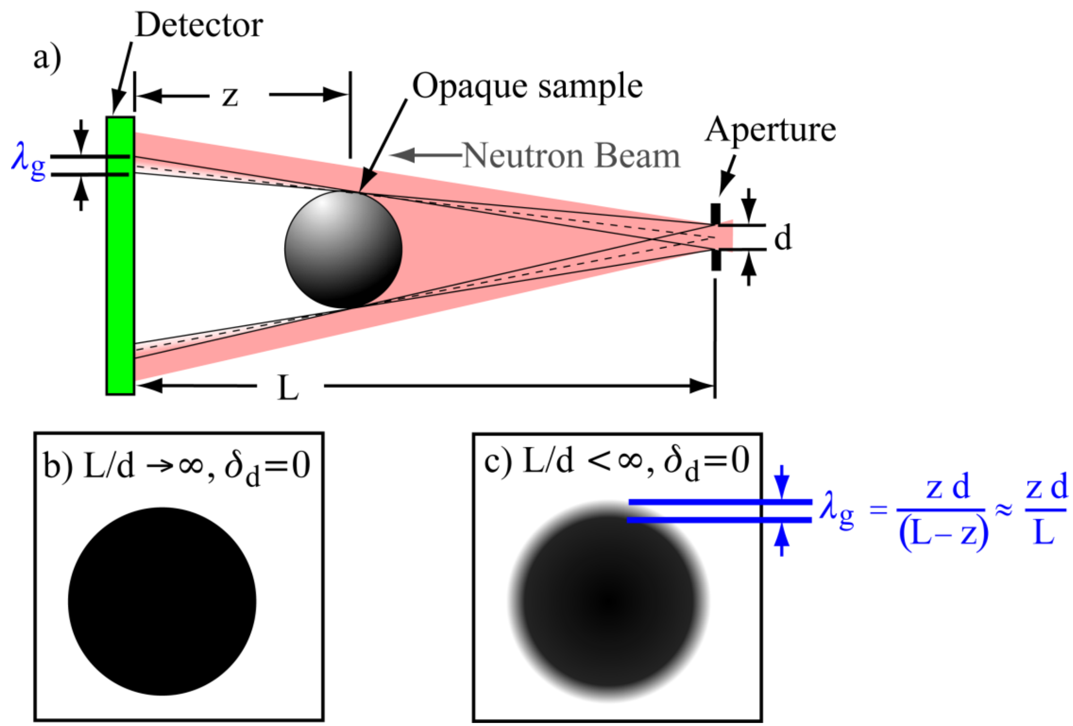
Graphic curtesy T. Gentile

Pinhole Optics: Neutron Image Formation

- Pinhole optics is basis of conventional neutron image formation
- Poke hole in reactor wall, form image of core at detector
- Best resolution obtained when object contacts detector due to using large apertures (1-10 mm)
- Resolution derived from collimation, where geometric blur is given by:

  $\lambda_g \approx z\, d\, /\, L$

  - High resolution requires small aperture (*d*) and/or large *L*
- Since Flux goes as $(d/L)^2$, Small *d* and/or large *L* → small Flux → ☹
- Also, no magnification, so intrinsic detector resolution only path to higher resolution
- Even with better detectors, in a 1 µm pixel with a 10^6 flux $cm^{-2}\ s^{-1}$, there's only 1 neutron every 100 s. ☹ ☹



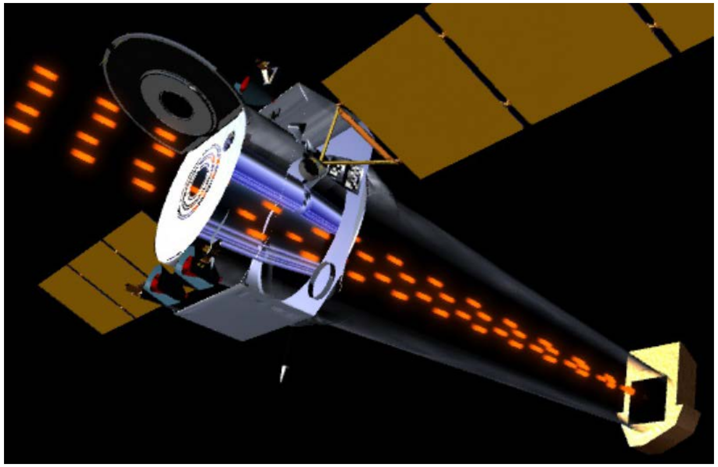
Pinhole Optics: Take Home Message

- Simple setup and has produced lots of nice images and scattering patterns but …
- Low Flux + No Magnification = ☹ ☹ ☹ ☹

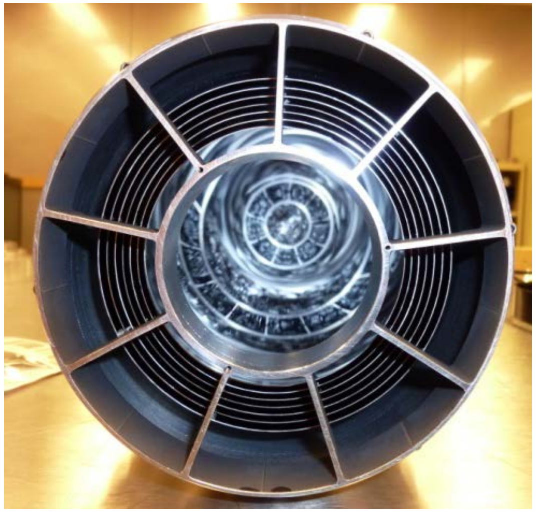
- ***If only we had an achromatic neutron imaging-forming lens …***

Drawing Inspiration from NASA

- Faint x-ray sources (nebula, etc.) need to be focused for good imaging
- In CHANDRA, the mirrors are coated on 2 cm thick glass substrates, which are heavy for space flight, and impractical for neutrons
- NASA is developing a new fabrication technique to create Wolter Optics from nested Ni-foil mirrors – light for space telescopes and *perfect for neutrons*
- Reflection is achromatic, Wolter Optics have reasonable off-axis imaging properties
- Resolution from the lens not collimation
- No collimation for resolution can yield *100-1000 flux increase* for imaging and SANS
- Magnification of 10x can improve *spatial resolution to 1 µm*

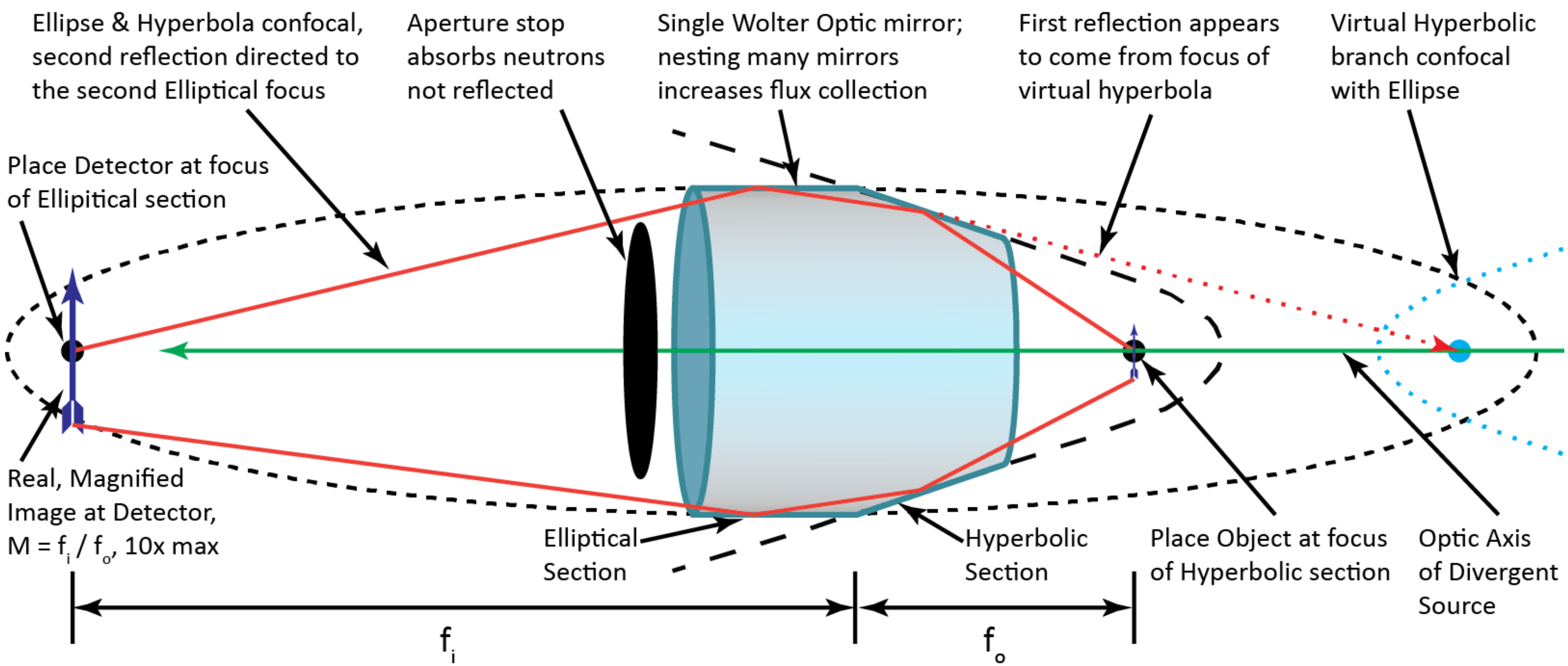


Wolter Optics power CHANDRA



Ni-foil Focused X-ray Solar Imager

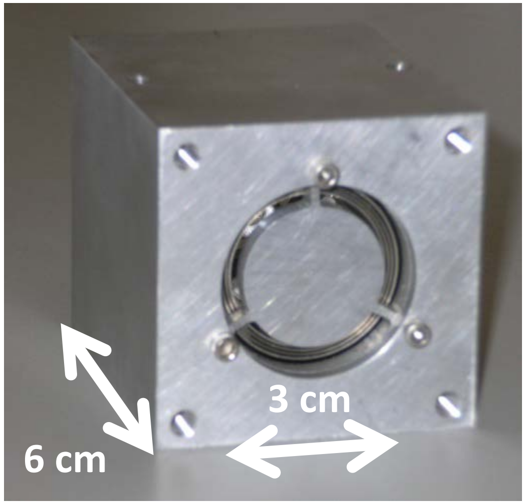
A Neutron Microscope using Wolter Optics



Challenges:

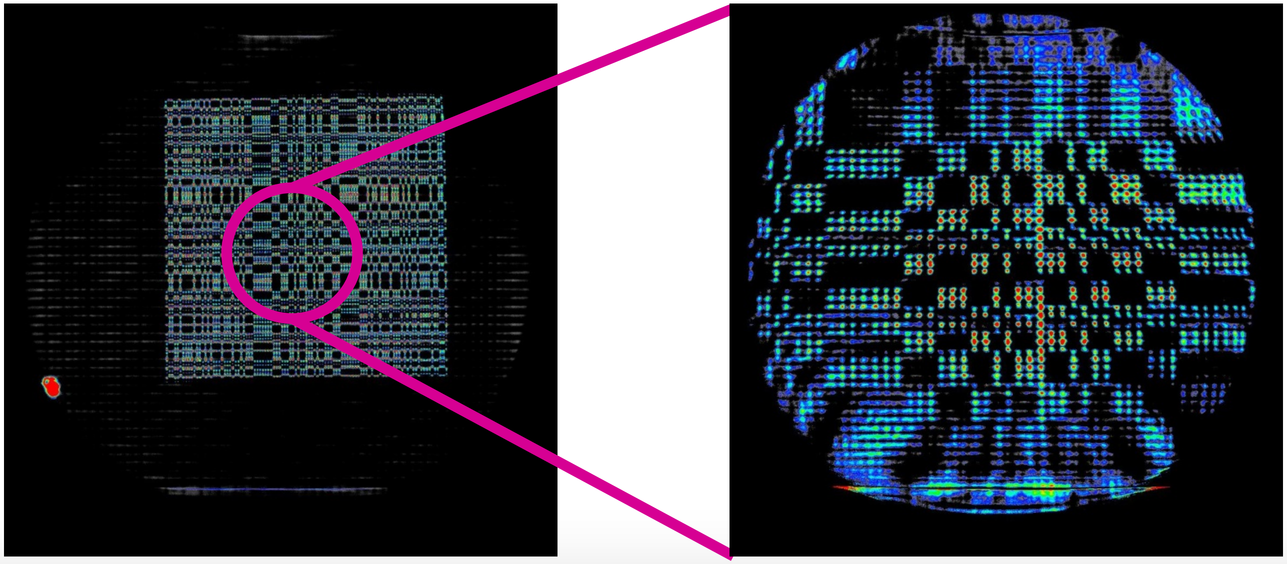
- Gravity bends neutrons and deforms mirrors: *correct with prisms*
- Surface roughness can produce background for SANS: *RMS finish of <5Å possible*
- Depth of focus and field curvature*: improved with large diameter, short length optics*

First prototype microscope



- 3 nested Ni mirrors w/ellipsoid and hyperboloid sections
- Overall focal length of 3.2 m
- The lens truly formed neutron images with:
  - 1 cm FOV & 4x magnification
  - 75 µm spatial resolution, 5 mm depth of focus

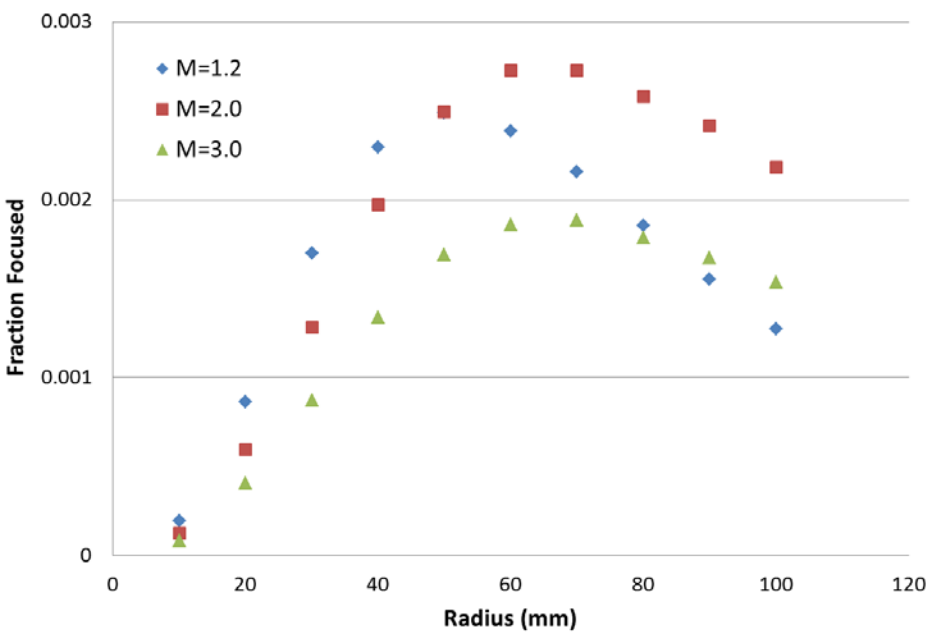
More work: x100 resolution, x100 flux, x5 depth of focus



2cm x 2cm Pinhole mask, with 0.1 mm diameters on 0.2 mm centers
Left: Contact Image;
Right: Lens Image

D. Liu et al, Applied Physics Letters 102 (18), 183508

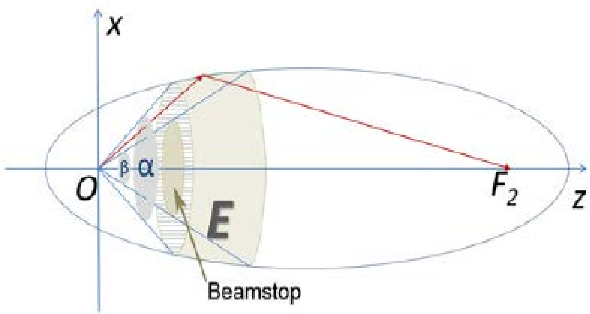
Fraction of incident flux focused for one shell

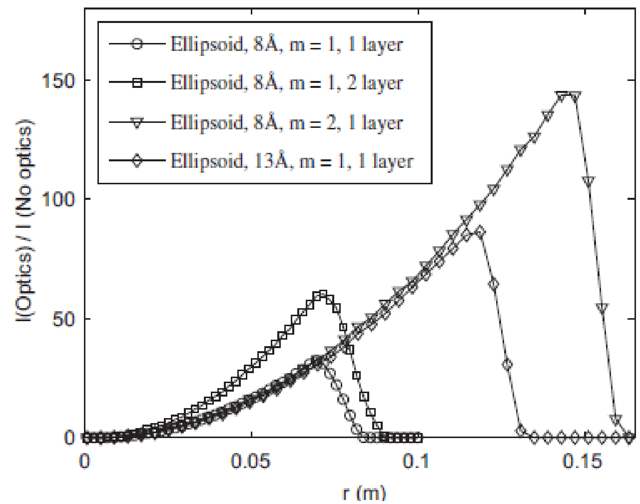


- Ray tracing of an optic:
  - paraboloid-paraboloid
  - total optic length of 20 cm
  - focal length of 7.5 m
  - sample 1 cm from the guide
- Larger radius reduces field curvature and improves field of view
- Nesting 14 mirrors with M=1.2 guide yields x100 over BT2 for 10 µm image resolution

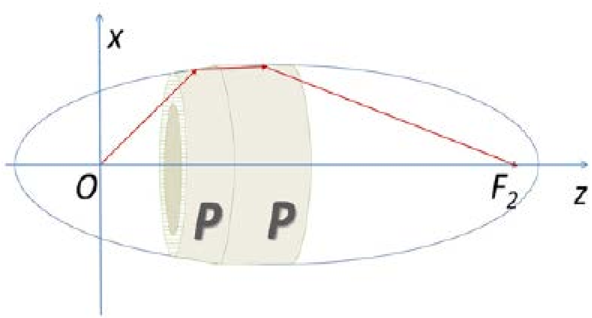
Mirror Configuration and Flux Collection

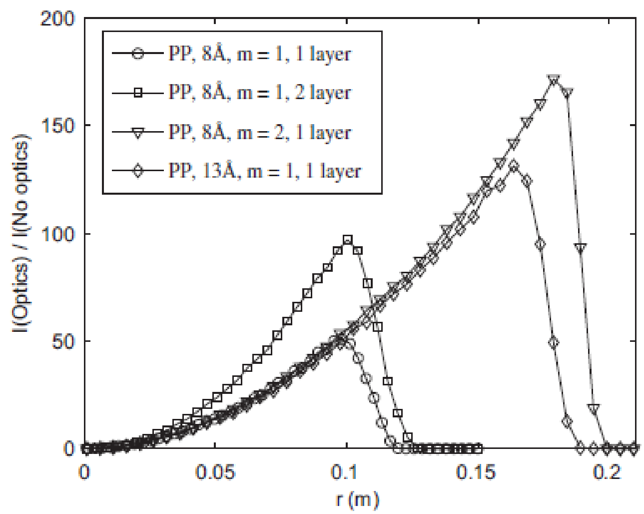
Single Ellipsoidal Mirror





Wolter Optic Type I with 2 paraboloid mirrors



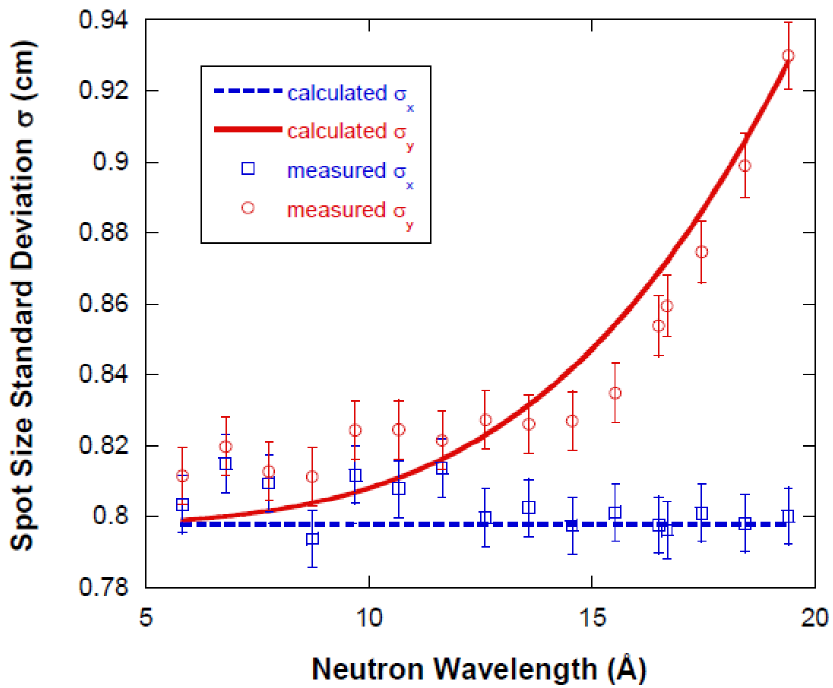


- Radius is taken at the middle of the mirror
- Plots are intensity ratio between the total neutron intensity with and without mirrors
- Pinhole setup, the source and sample apertures are both 5 mm radius
- Ellipsoid mirror is 0.4 m long
- One paraboloid is 0.4 m (0.8 m total)

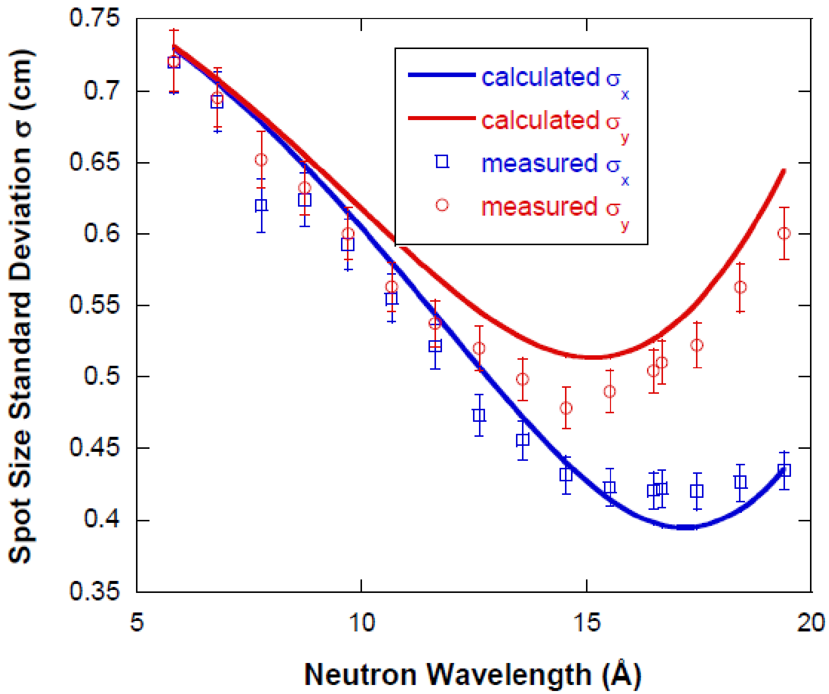
D. Liu et al, *NIM A,* **686**,145-150 (2012)

Reduced spot size – lower Qmin

Spot Size without a Lens



Spot Size with Refractive Lens



Taken from the "SANS Toolbox" by B. Hammouda

Reflective Optics are achromatic

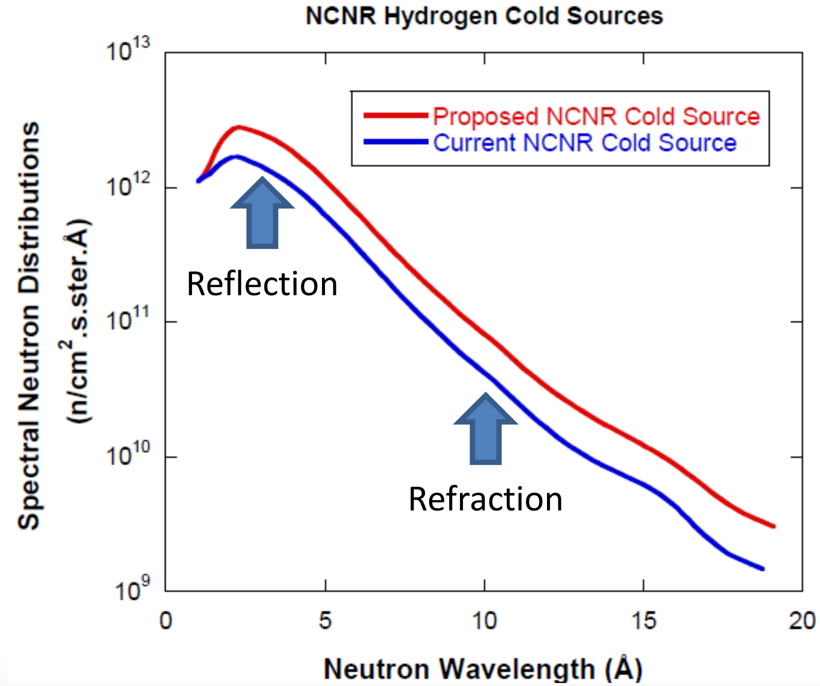
- Chromatic aberration limits X_{min}:

$$X_{min} = \frac{L_2}{L_1} R_{source} + \frac{\Delta x_{det}}{2} + \frac{L_1 + L_2}{L_1} 2 \left(\frac{\Delta\lambda}{\lambda}\right) R_{sample}$$

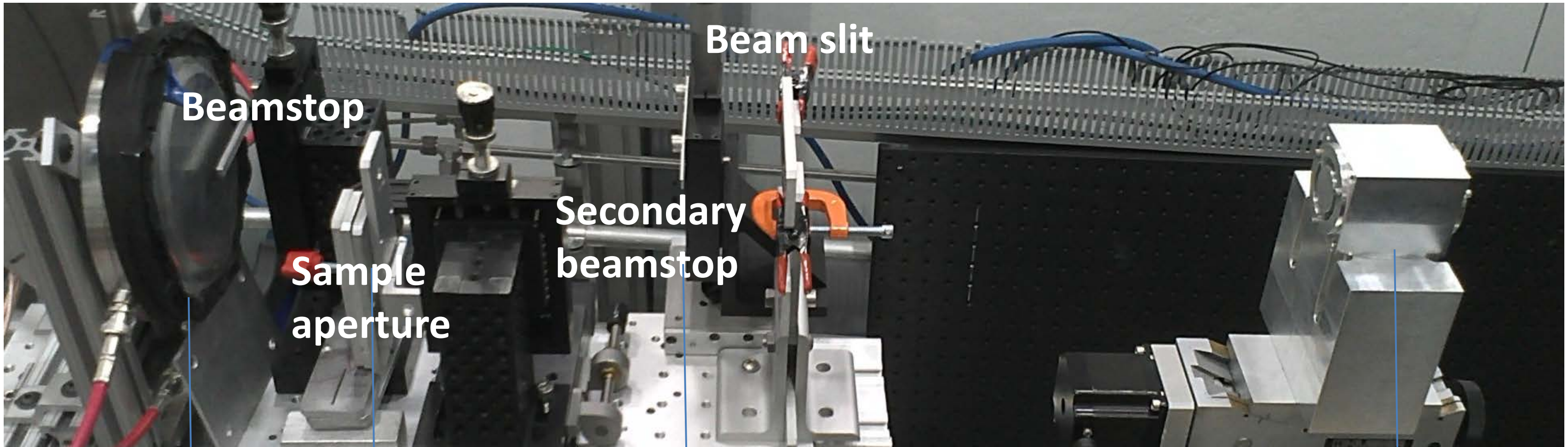
- Reflective optics x_{min} depends on source aperture and detector:

$$X_{min} = \frac{L_2}{L_1} R_{source} + \frac{\Delta x_{det}}{2}$$

- Achromatic also means higher flux:
  - Refractive lens focal length = $\pi R (\rho b_c \lambda^2)^{-1}$
    - Strongly chromatic and on the order of 100 m!
    - Must use λ >~ 10 Å means LOW flux
  - Reflection achromatic
    - Focal length of order few m
    - Can use λ = 4-5 Å
    - ***×10 increase in flux from this alone***



Mirror based SANS at HFIR, CG1 with Chopper



MCP detector (1024x1024, 48 micron/pixel)

Wolter Mirror

0.26 m

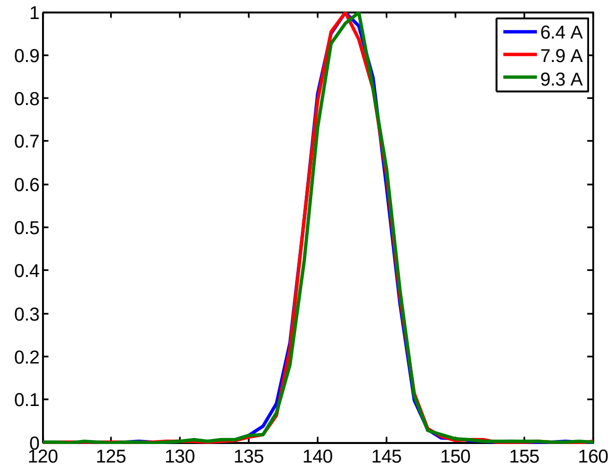
0.64 m

2.56 m to source

0.08 m

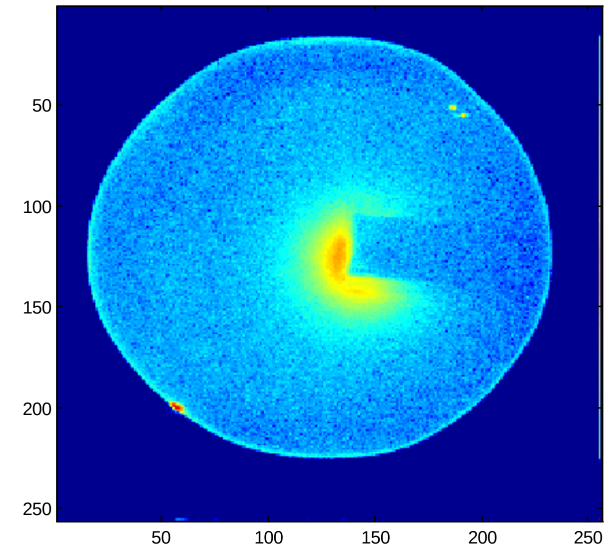
D. Liu et al, ICNS, 2013

SANS performance of prototype lens

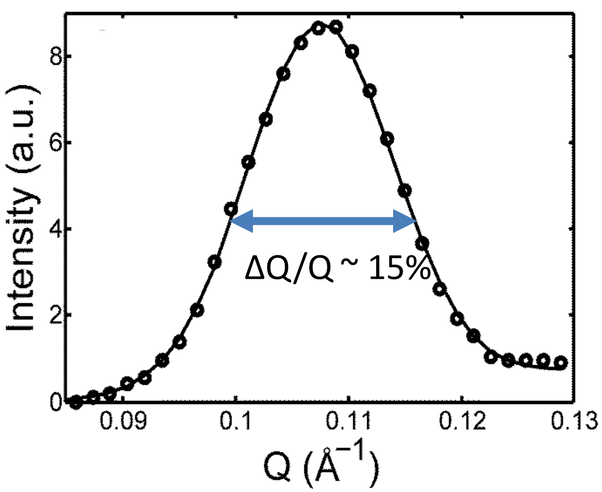


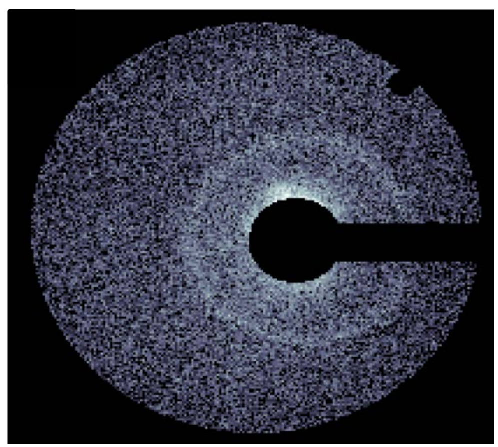
Focal Spot size independent of wavelength

Porasil B data: Q_{min} = 0.02 A^{-1}

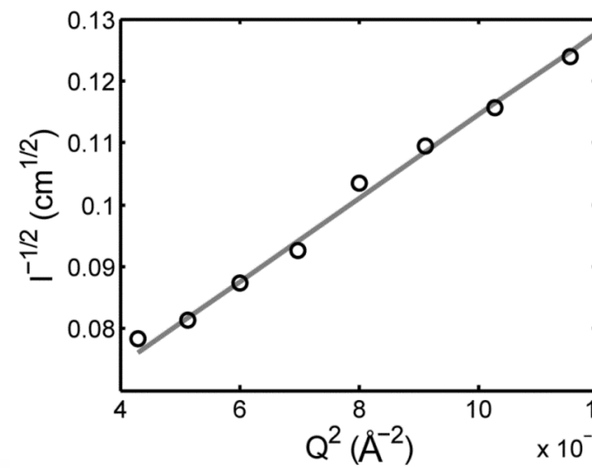


Silver Benhate Data shows good Q-resolution





λ = 6.8 Å.



D. Liu et al, Nat. Commun. 4:2556 doi: 10.1038/ncomms3556 (2013)

NIST is supporting development through an IMS project

- Year 1:
  - ☑ *Test a new prototype lens that is targeted for neutron imaging and SANS*
  - ☑ *Use characterization data to verify lens-modeling results and give confidence to new designs*
- Year 2:
  - *Install new cold neutron imaging instrument at NG-6 (12/14 – 04/15)*
  - *Characterize neutron performance of NASA's new fabrication scheme with a goal to demonstrate 10 μm image resolution (12/15)*
  - *Finalize design and begin fabrication of a 1:1 optic for high speed imaging*
- Year 3:
  - *Deploy fully optimized, nested 1:1 imaging optic for high speed imaging, investigate SANS quality (12/16)*
  - *Begin user operation for lens-based imaging at 10 μm resolution (12/16)*
  - *Design for 10x magnifying lens*
- Year 4 & 5:
  - *1 μm imaging with 10x lens*
  - *Fully developed user program for imaging and SANS*

Conclusions

- New guides can greatly increase the neutron flux
  - NG-C is 4x the capture flux of NG-6
- Reflective focusing optics provide gains in flux and resolution
  - Imaging Gains:
    - With a 1:1 optic time resolution can be improved by ~x100 for 10 µm image resolution
    - With a 10x magnifying optic, image resolution can reach ~ 1 µm
    - Increased instrument flexibility with large space after the sample for beam conditioning or bulky sample environments
  - SANS Gains:
    - Achromatic lens results in lower Qmin
    - Reflection means measurements can make use of shorter wavelengths
    - Possible large gains in flux to enable time resolved measurements, polarized SANS, etc.
  - May enable new measurement schemes
- NIST in collaboration with NASA and MIT are developing the first neutron microscope through a NIST IMS project, just in its 1st year

- ***Thanks for your attention***