X-ray optics requirements for IAXO

"IAXO: The Search for Axions in the Universe"
INFN – Laboratori Nazionali Frascati
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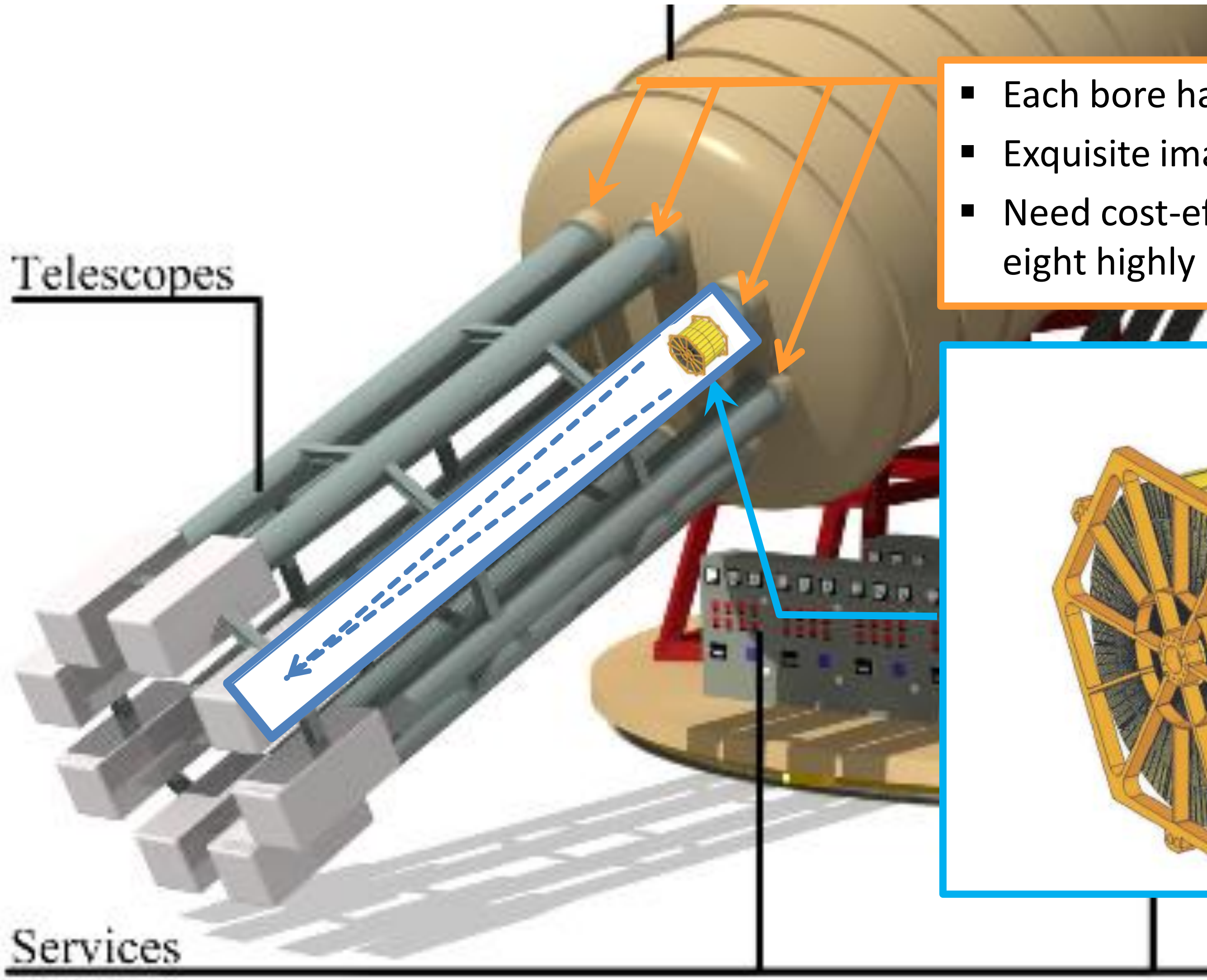
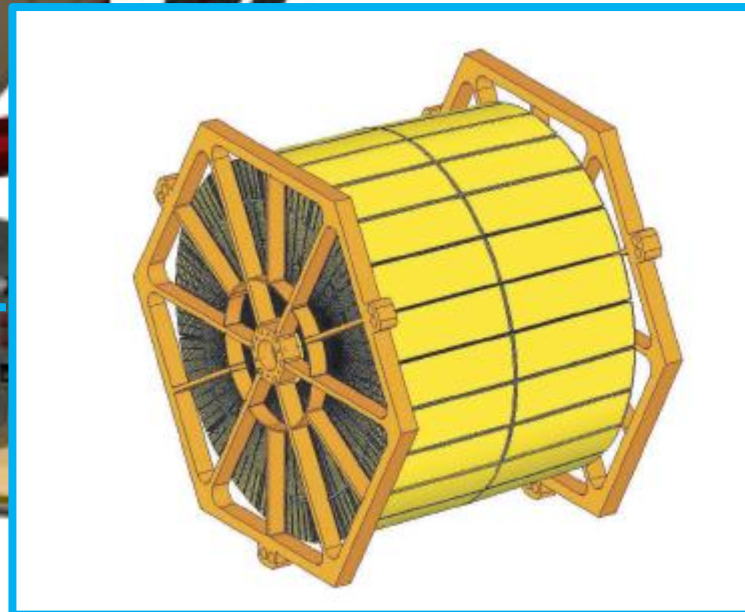
IAXO x-ray optics



- Each bore has an x-ray telescope
- Exquisite imaging not required
- Need cost-effective way to build eight highly nested optics



The sensitivity of a helioscope

MAGNET & TRACKING

X-RAY OPTICS

X-RAY DETECTORS

$$g_{a\gamma}^4 \propto \underbrace{(BL)^{-2}A^{-1}}_{\textit{magnet}} \times \underbrace{t^{-1/2}}_{\textit{exposure}} \times \underbrace{s^{1/2}\varepsilon_0^{-1}}_{\textit{optics}} \times \underbrace{b^{1/2}\varepsilon^{-1}}_{\textit{detectors}}$$

magnet

B = magnetic field
L = magnet length
A = cross-sectional area

exposure

t = time

optics

s = spot size
ε_0= efficiency

detectors

b = background
ε = efficiency

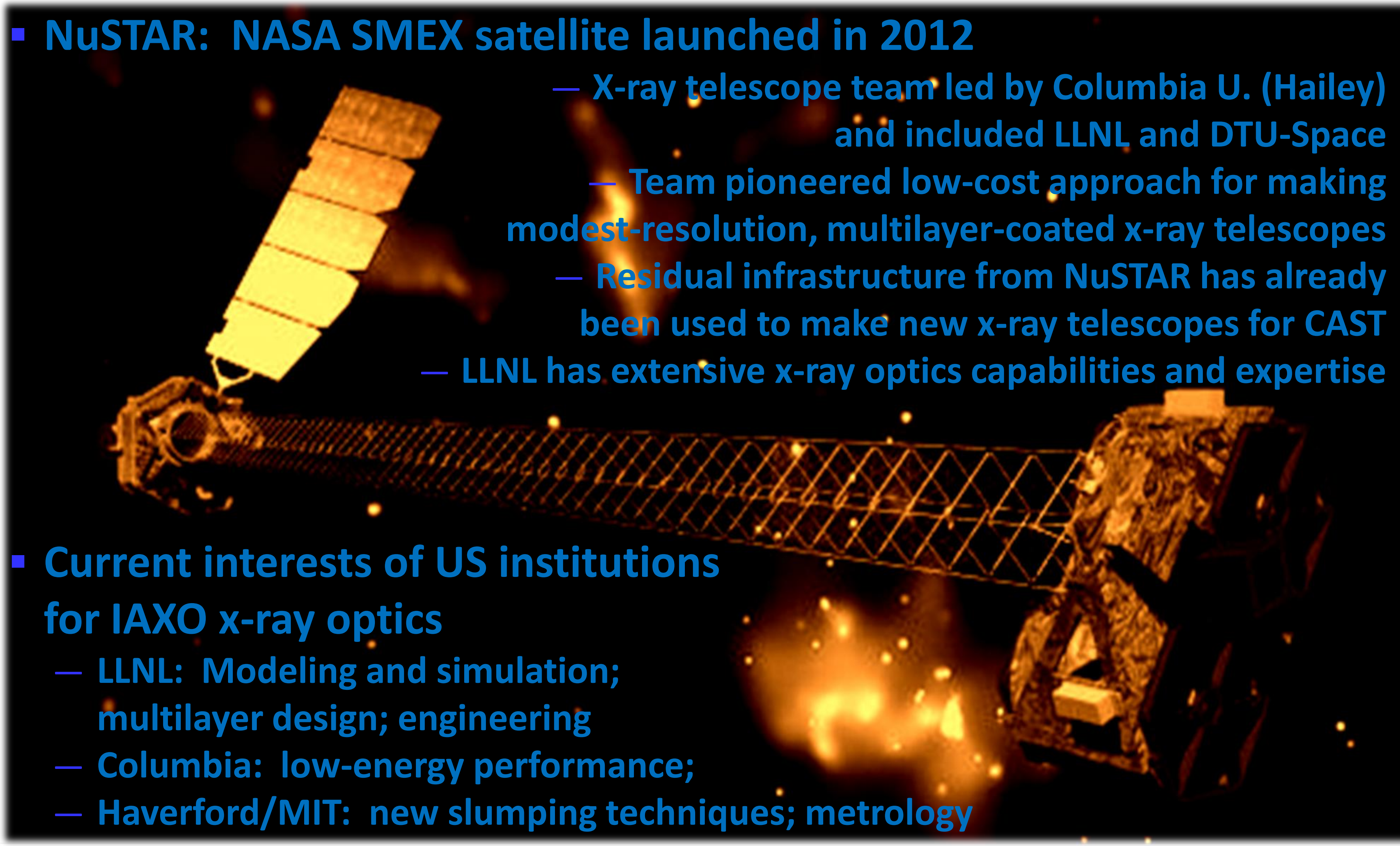
IAXO, relative to CAST:

- **≥1050× better** (magnet & exposure), **1.4× better** (optics), **14× better** (detectors)
- $S/N = g_{a\gamma}^4 \geq 20000$ → $g_{a\gamma} \geq 12\times$ better

Leveraging x-ray astronomy for IAXO

- Last decades has seen significant advances in the fabrication of reflective x-ray optics
  - New substrates, new coatings, new assembly techniques
- Several candidate approaches for IAXO
  - Segmented glass (e.g., *NuSTAR* & CAST)
  - Replicated (e.g., *Beppo-SAX, XMM*, *FOXSI, ART* & *eROSITA*)
  - Silicon pore (*ATHENA*)
- IAXO does not require fundamentally new developments, but it does have different specifications than a typical x-ray astrophysics mission
  - Near-term development activities are needed to reduce technical risks
- We have selected segmented glass as the baseline technique for IAXO because of cost, collaboration's expertise and physical constraints of experiment

The U.S. leads the x-ray optics development for IAXO because of several past projects, including *NuSTAR*



- **NuSTAR: NASA SMEX satellite launched in 2012**
  - X-ray telescope team led by Columbia U. (Hailey) and included LLNL and DTU-Space
  - Team pioneered low-cost approach for making modest-resolution, multilayer-coated x-ray telescopes
  - Residual infrastructure from NuSTAR has already been used to make new x-ray telescopes for CAST
  - LLNL has extensive x-ray optics capabilities and expertise
- **Current interests of US institutions for IAXO x-ray optics**
  - LLNL: Modeling and simulation; multilayer design; engineering
  - Columbia: low-energy performance;
  - Haverford/MIT: new slumping techniques; metrology

Telescope design issues

- Astrophysics community has spent 50 years developing deep experience and design principles for X-ray optics

- These do not map directly to the needs for axion helioscopes like IAXO

Astronomy

- **Unknown source spectrum**
- **Unknown source size**

- **Desire wide FOV (up to 60′)**
- **Higher angular resolution always better**
- **Mass-constrained**

Solar axions

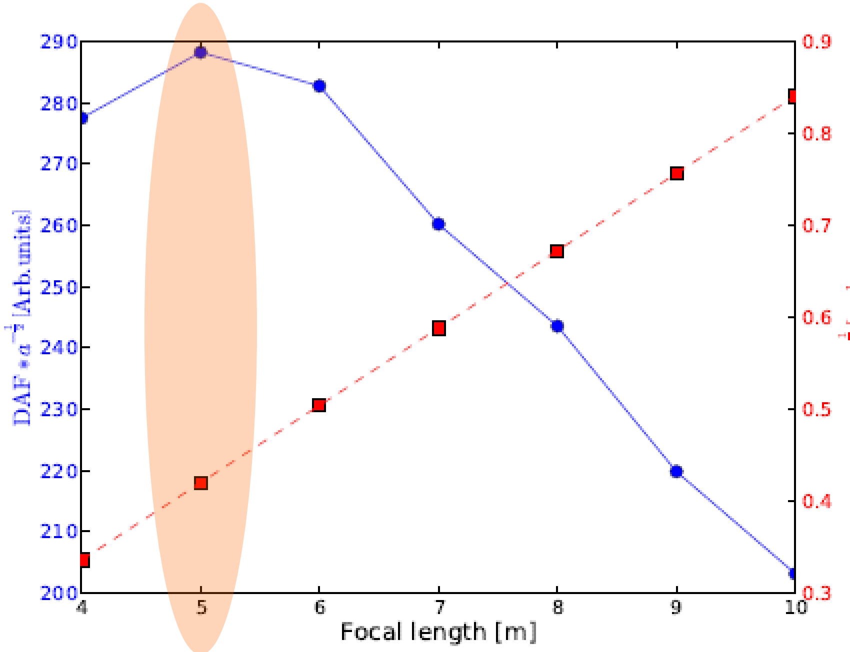
- **Known source spectrum**
- **Known source size**

- **FOV (3+1)′**
- **Modest angular resolution of a few arcmin is acceptable**
- **Not mass-constrained**

- Mirror length, spacing between nested layers and focal lengths need to be revisited; challenge standard “rules”

Telescope design issues [2]

- Figure of merit for optics: maximize number of photons, minimize background
  - Maximize photons = product of axion spectrum, telescope effective area, **detector quantum efficiency**
    - Cannot optimize without assuming a detector technology
  - Minimize spot size =
    - Conventional wisdom is use nominal *f* and keep mirrors short, but is this optimal?



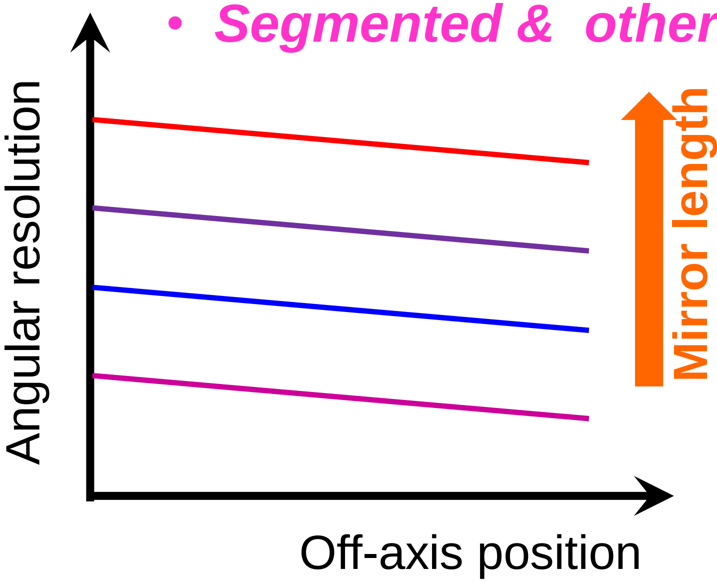
- We have performed and published preliminary studies
  - We need to systematically explore all possibilities

Jakobsen et al. *Proc SPIE* **8861**:886113 (2013)
Armengaud et al. *JINST* ***9*** T05002 (2014)

Telescope design issues [3]

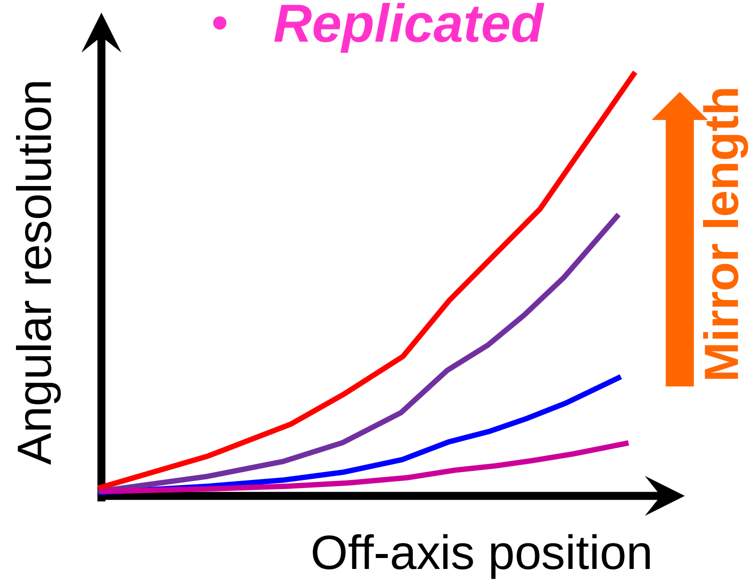
Cone-approximation Wolter

- ***Segmented & others***



Wolter I

- ***Replicated***

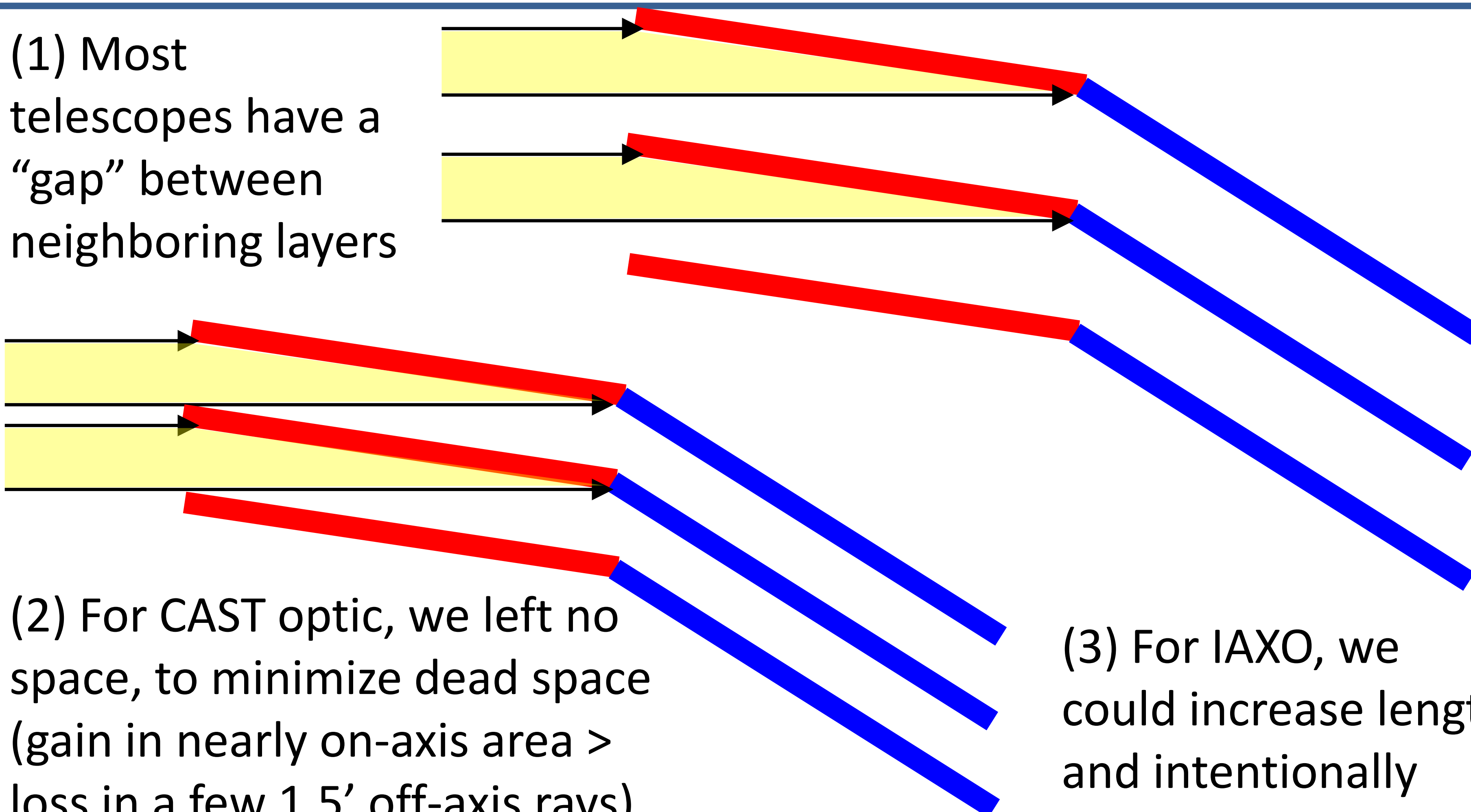


- In most cases, telescopes have been designed to minimize spot size for point-like sources located in the central region of the FOV

- For IAXO, we are imaging an known 3 arcmin source centered directly in the FOV
  - Much different optimization strategy for solar axion detection
  - Also depends on fabrication technique

Telescope design issues [4]

(1) Most telescopes have a "gap" between neighboring layers



(2) For CAST optic, we left no space, to minimize dead space (gain in nearly on-axis area > loss in a few 1.5' off-axis rays)

(3) For IAXO, we could increase length and intentionally overlap shells to minimize spot size

Summary of high-level requirements

Telescopes required:	8 + 1 (“flight” optics + spare)
Expected focal length:	5.0±0.5 m
Energy range, desired:	0.1−10 keV (will depend on detectors)
Energy range, minimum:	0.5−8 keV (will depend on detectors)
Coatings:	multilayers (e.g., W/B_4C)
Radius:	50−300 mm
Graze angles:	2.6−15 mrad or 0.15−0.86 deg
Shells:	~120 (will depend on mirror length)
Angular resolution, desired:	1.0 arcmin (no gain in FOV, if smaller)
Angular resolution, minimum:	2.5 arcmin (sensitivity loss, if larger)
Cost, baseline:	≤ 10M€ for entire program (fabrication, calibration & installation)

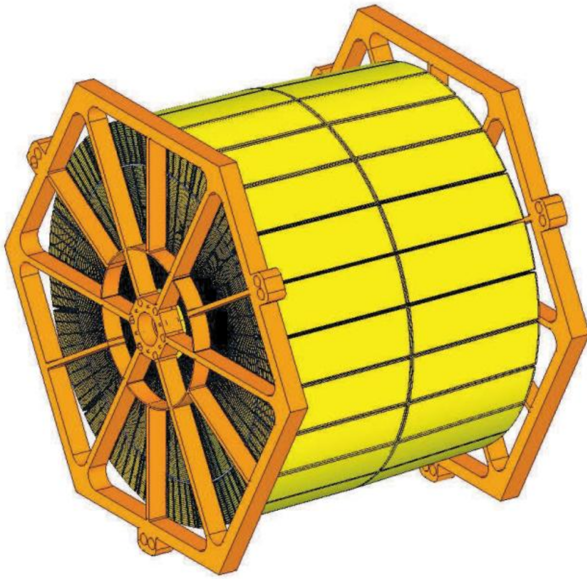
Armengaud et al. *JINST* ***9*** T05002 (2014)

Specific issues

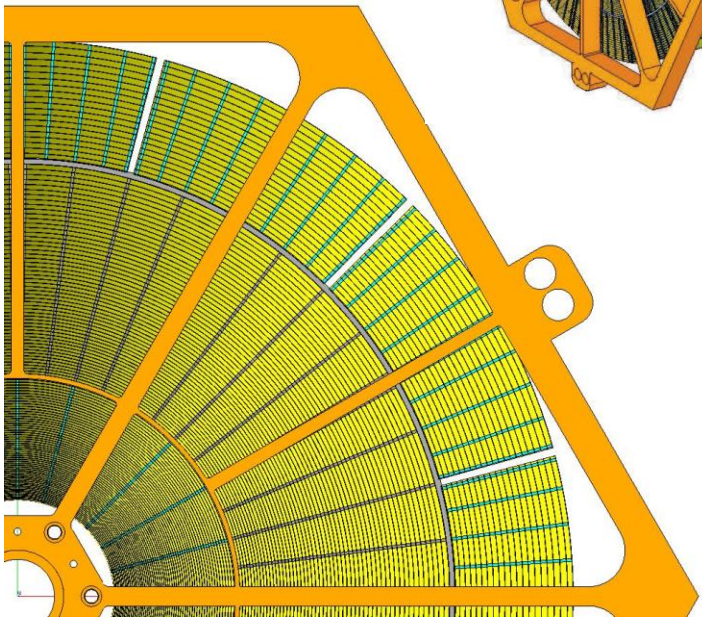
- Highest priorities **(independent of fabrication technique)**
  - Telescope design (Modeling and Simulation [M&S])
  - Multilayer development (M&S; R&D)
  - Substrate development (R&D; prototyping; M&S)

- Other important areas **(depends on fabrication technique)**
  - Metrology
  - Definition of response files for end-to-end simulations
  - Calibration plan and facilities
  - Techniques to alignment and bore-sight x-ray telescopes to IAXO pointing structure and star-trackers

NuSTAR-like optics for IAXO



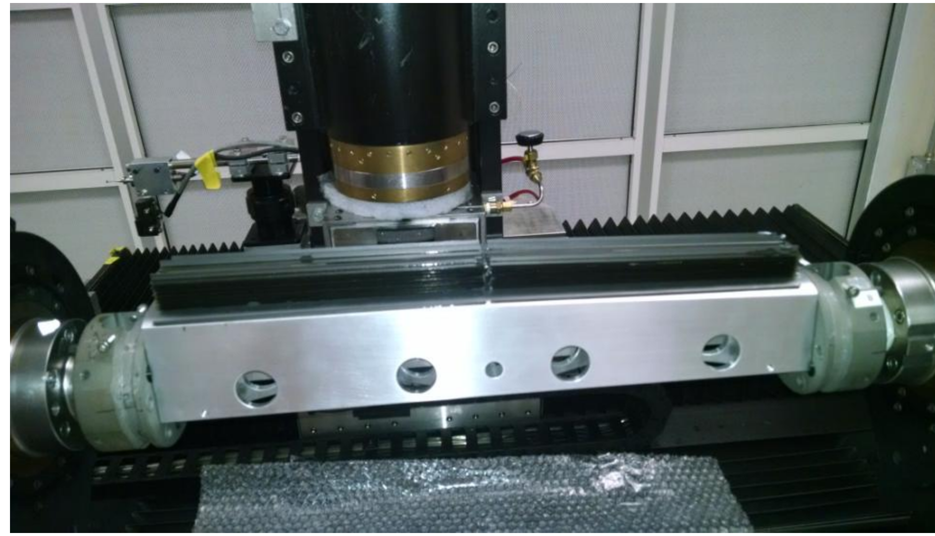
- Approximately same number of shells, but much larger radii (18 cm →30 cm)
- Would require using 20 deg azimuthal segments ("18ths")
- Easy to deposit multilayer coatings—but need to verify performance E < 1 keV is compatible with fabrication methods and operations
- Would need to either create new assembly machines or extend range of two tools fabricated for NuSTAR

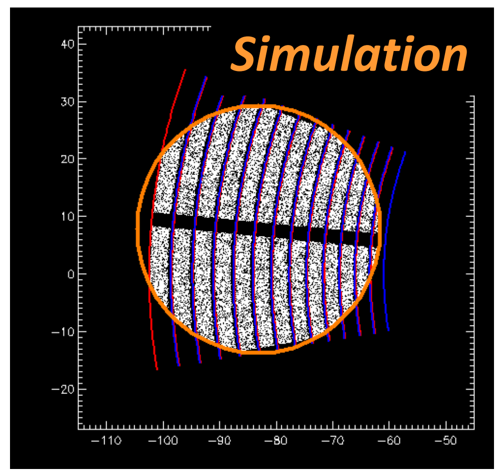


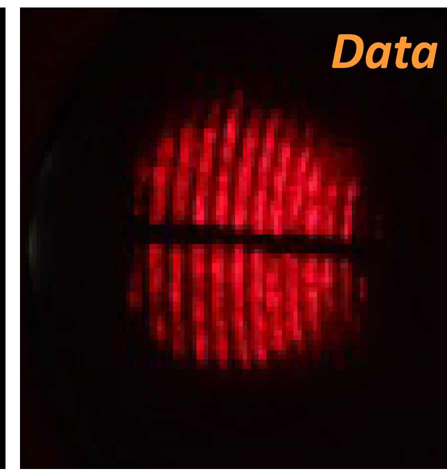
Recent efforts have concentrated on reducing risks by building IAXO-like optics for CAST

Near-term x-ray optics needs (i.e., for IAXO TDR X0) for segmented-glass approach

- Calibrate new CAST x-ray telescopes at PANTER facility (Germany)
  - Required for analysis of CAST science data from 2015; will result in record-best experimental sensitivity to $g_{\alpha\gamma\gamma}$ over the widest axion mass range
  - Provides a way to baseline performance of segmented glass telescopes for IAXO
- Explore new slumping techniques (for radii >180 mm) for segmented glass







Aznar et al. *JCAP* ***12*** 008 (2015)

Low-energy telescope response

- How well will multilayer-coated, segmented glass telescopes work below 3 keV?
  - Benefit: maximize sensitivity for axion-electron coupling
- *NuSTAR* is sensitive from 3−80 keV, with no obvious loss of performance, but lacks high-quality end-to-end ground calibration at low energies
- Magnetron sputtered multilayers made for soft x-ray (0.8 keV) diagnostics for NIF work well
  - These x-ray mirrors used epoxy and were exposed to air
  - Carefully calibrated at LBNL/ALS soft X-ray synchrotron; excellent agreement between modeled response and actual measurements
- Work for IAXO must include
  - Serial studies to look for time-dependent degradation at $E < 2$ keV
  - Evaluate composition and thickness of hydrocarbon layers
  - Any evidence of scatter induced by graphite particulate