X-Ray Surveyor Technology Priorities

[Presented On Behalf of the X-Ray Surveyor Community]

Marshall Space Flight Center

Smithsonian Astrophysical Observatory

Community STDT

F. Özel, Arizona (Co-Chair)
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S. Allen, Stanford
M. Bautz, MIT
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L. Lopez, Ohio State
R. Osten, STScI
F. Paerels, Columbia
M. Pivovaroff, LLNL
D. Pooley, Trinity
A. Ptak, GSFC
E. Quataert, Berkeley
C. Reynolds, UMD
D. Stern, JPL

Scientifically Compelling

How Did We Get Here?

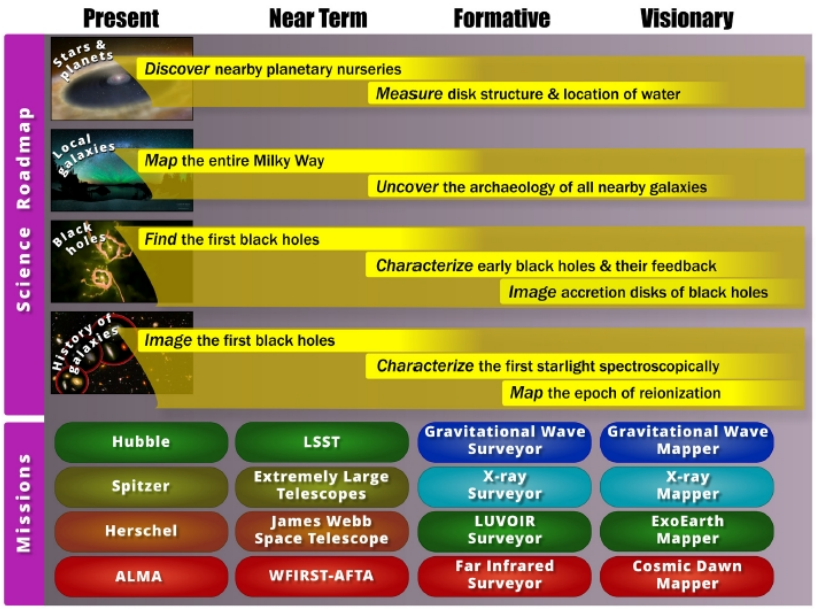


Figure 3.16 Schematic of the Cosmic Origins Roadmap, with science themes along the top and a possible mission sequence across the bottom. Credit: F. Reddy (NASA/GSFC)

How Does The Universe Work?

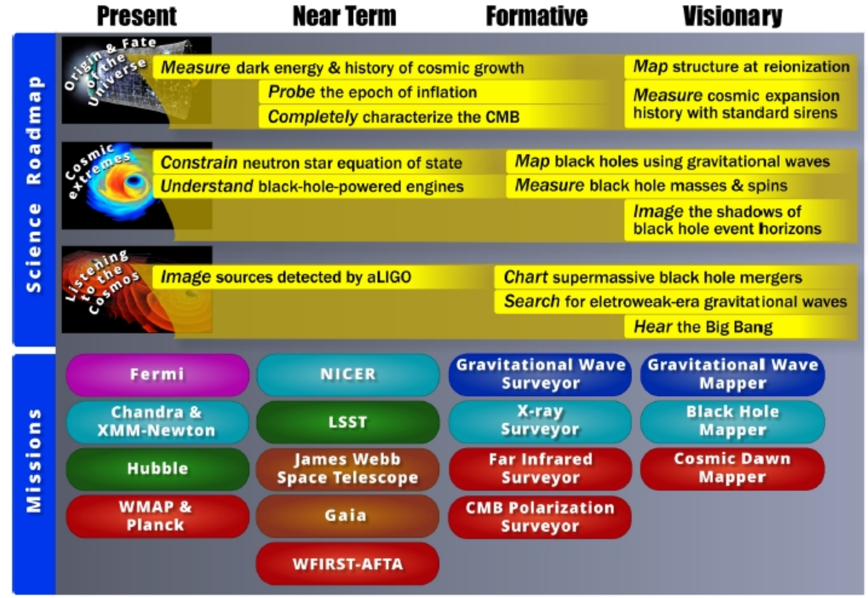


Figure 4.8 Schematic of the Physics of the Cosmos Roadmap, with science themes along the top and a possible mission sequence across the bottom. Credit: F. Reddy (NASA/GSFC)

Fundamental Science Goals:

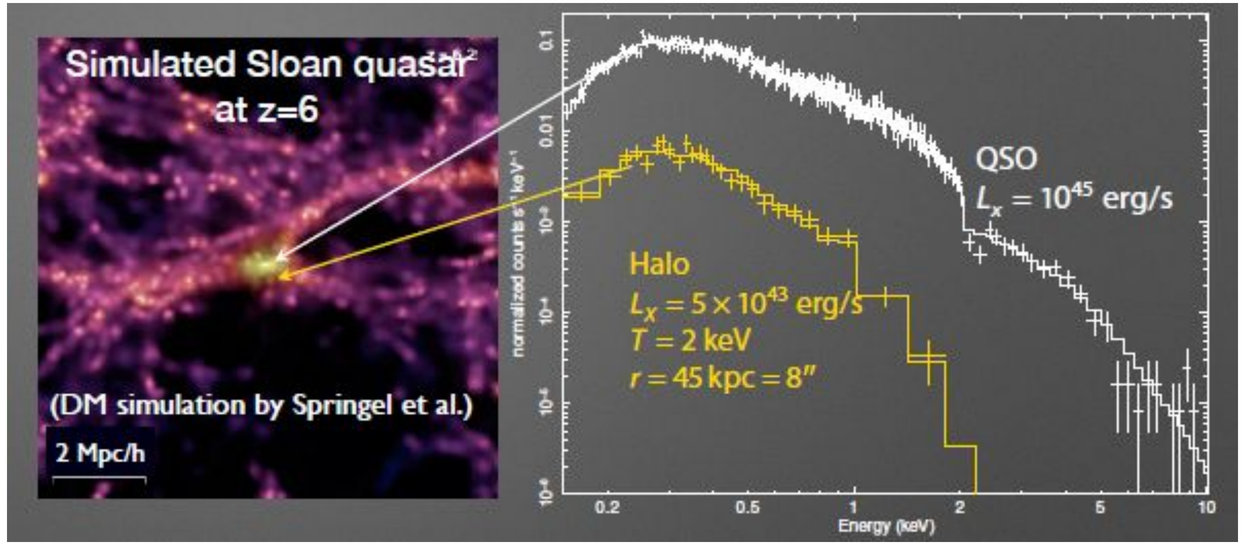
- ***The Origin and Growth of the First Supermassive Black Holes***
- ***Galaxy Evolution and the Growth of Cosmic Structure***
- ***The Physics of Matter in Extreme Environments***
- ***The Physics of Feedback and Accretion in Galaxies and Clusters***
- ***The Origin and Evolution of the Stars that make up our Universe***

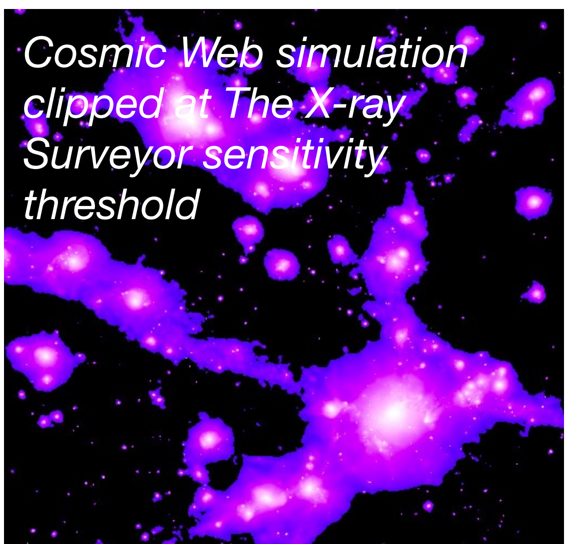
Scientifically Compelling

The Origin and Growth of the First Supermassive Black Holes

What is their origin?

How do they co-evolve with galaxies and affect their environment?





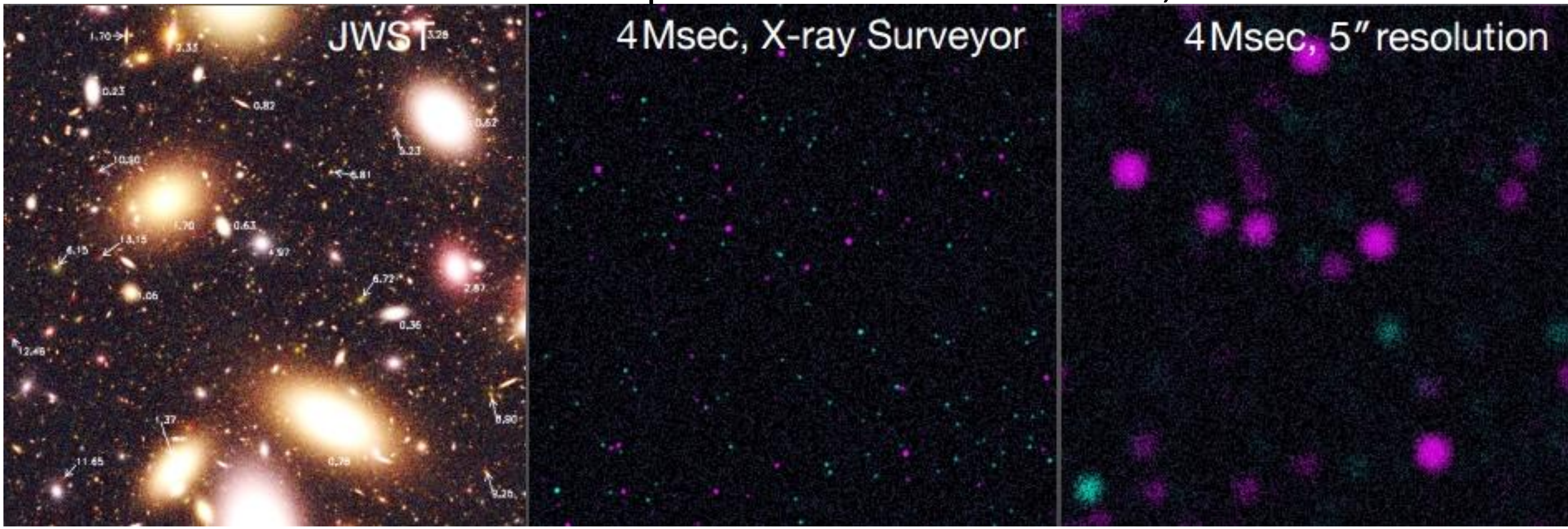
Galaxy Evolution and the Growth of the Cosmic Structure

Structure of the Cosmic Web through observations of hot IGM *in emission*

How did the "universe of galaxies" emerge from initial conditions?

Determining The Nature of Black Hole Seeds

Simulation of 2×2 arcmin^2 deep fields observed with *JWST*, *XRS* and *ATHENA*



Goal:
Find the x-ray counterparts galaxies detected by JWST at its sensitivity limit

How:
- With sensitivity of 10^{-19} erg/s/cm^2, detect BHs with mass of 10^4 $M_\odot$ @ Z=10
- Make sure they are not confusion limited

Requirements:
- effective area: few m^2
- angular resolution: ≤ 0.5″

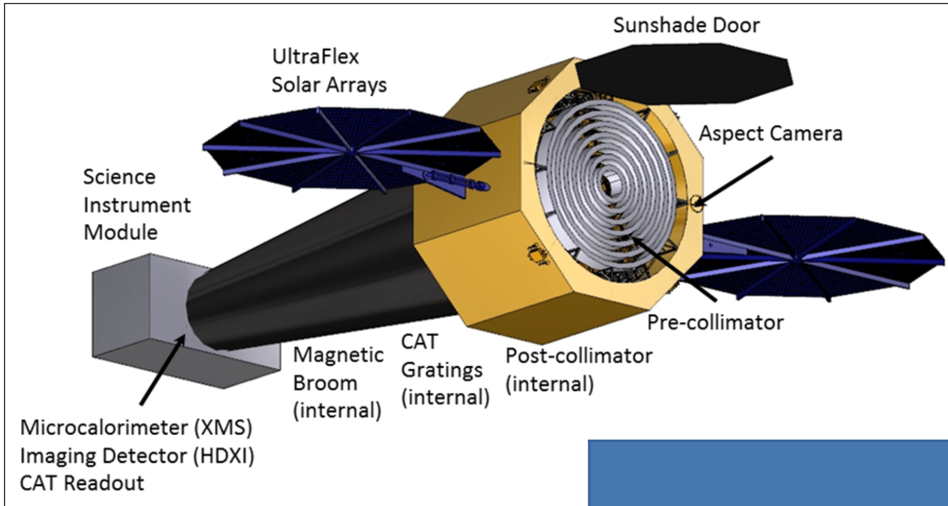
The *XRS* STDT is just beginning its work

- Define a compelling science case for addressing critical science questions in the following decades
- Technical parameters necessary to achieve the goals, will include:
  - Design Reference Mission, including payload
  - Technology assessment
  - Notional time to mature technology and develop mission
- And at the very end: Cost assessment, major technical issues, and risk reduction plans as a function of science capability

[Hertz16]

- **The STDT is in the process of defining top-level science drivers, which are required before *final* instrument requirements can be specified**
- **Preliminary STDT science discussions show the need for Chandra-like high-angular resolution coupled with much higher photon throughput.**

Notional Optics & Instruments



- High-resolution X-ray telescope
- Critical Angle Transmission XGS
- X-ray Microcalorimeter Imaging Spectrometer (XMIS)
- High Definition X-ray Imager (HDXI)

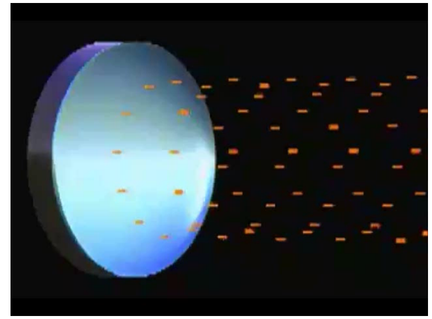
Concept Payload for:
- Feasibility (TRL 6)
- Mass
- Power
- Mechanical
- Costing (~**$3B**)

NOT THE FINAL CONFIGURATION!!!

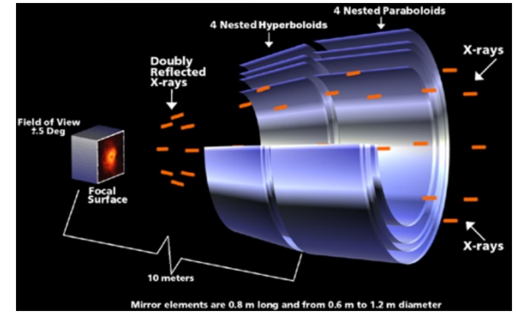
	Chandra	X-Ray Surveyor
Relative effective area (0.5 – 2 keV)	1 (HRMA + ACIS)	50
Angular resolution (50% power diam.)	0.5”	0.5”
4 Ms point source sensitivity (erg/s/cm²)	$5x10^{-18}$	$3x10^{-19}$
Field of View with < 1” HPD (arcmin²)	20	315
Spectral resolving power, R, for point sources	1000 (1 keV) 160 (6 keV)	5000 (0.2-1.2 keV) 1200 (6 keV)
Spatial scale for R>1000 of extended sources	N/A	1”
Wide FOV Imaging	16’ x 16’ (ACIS) 30’ x 30’ (HRC)	22’ x 22’

Key Technology Gaps

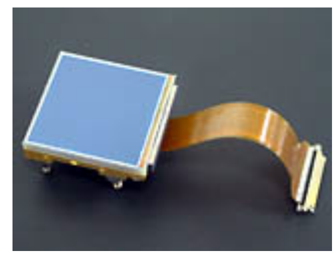
- High-resolution lightweight X-ray **optics**



CXC/D. Berry

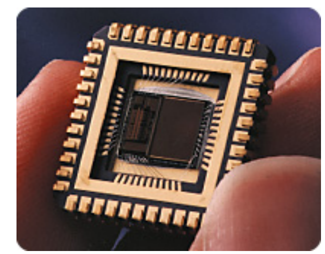


- Fast low-noise megapixel X-ray **imaging arrays** with moderate **spectral** resolution



Hybrid CMOS

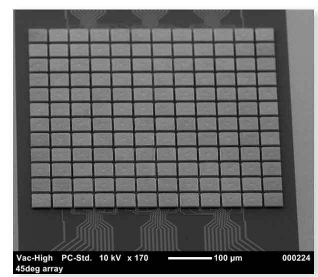
MIT/LL and PSU/Teledyne



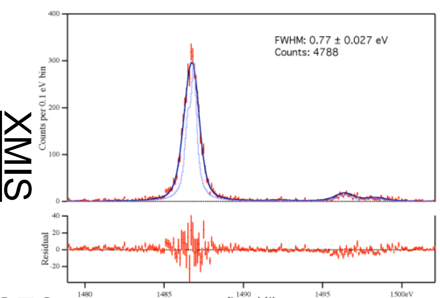
Monolithic CMOS

SAO/Sarnoff and MPE

- Large-format high spectral resolution small-pixel X-ray **microcalorimeter** arrays

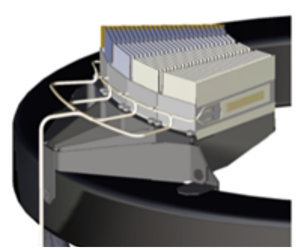


XMS



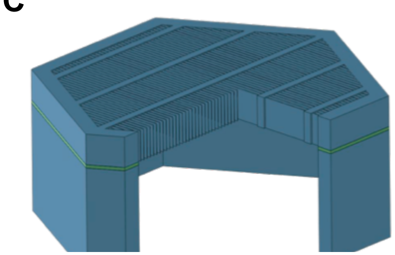
GSFC

- High-efficiency X-ray **grating** arrays



OPRG

U Iowa/Penn State



CATG

MIT

Capability Gap: X-ray Optics

Key Technology Goal = High-Resolution, Lightweight X-ray Optics

Optics development is highest priority Technology Gap!

<u>Needed Capabilities</u>

- Large-throughput mirror assembly with sub-arcecond resolution
- Low mass per unit collecting area

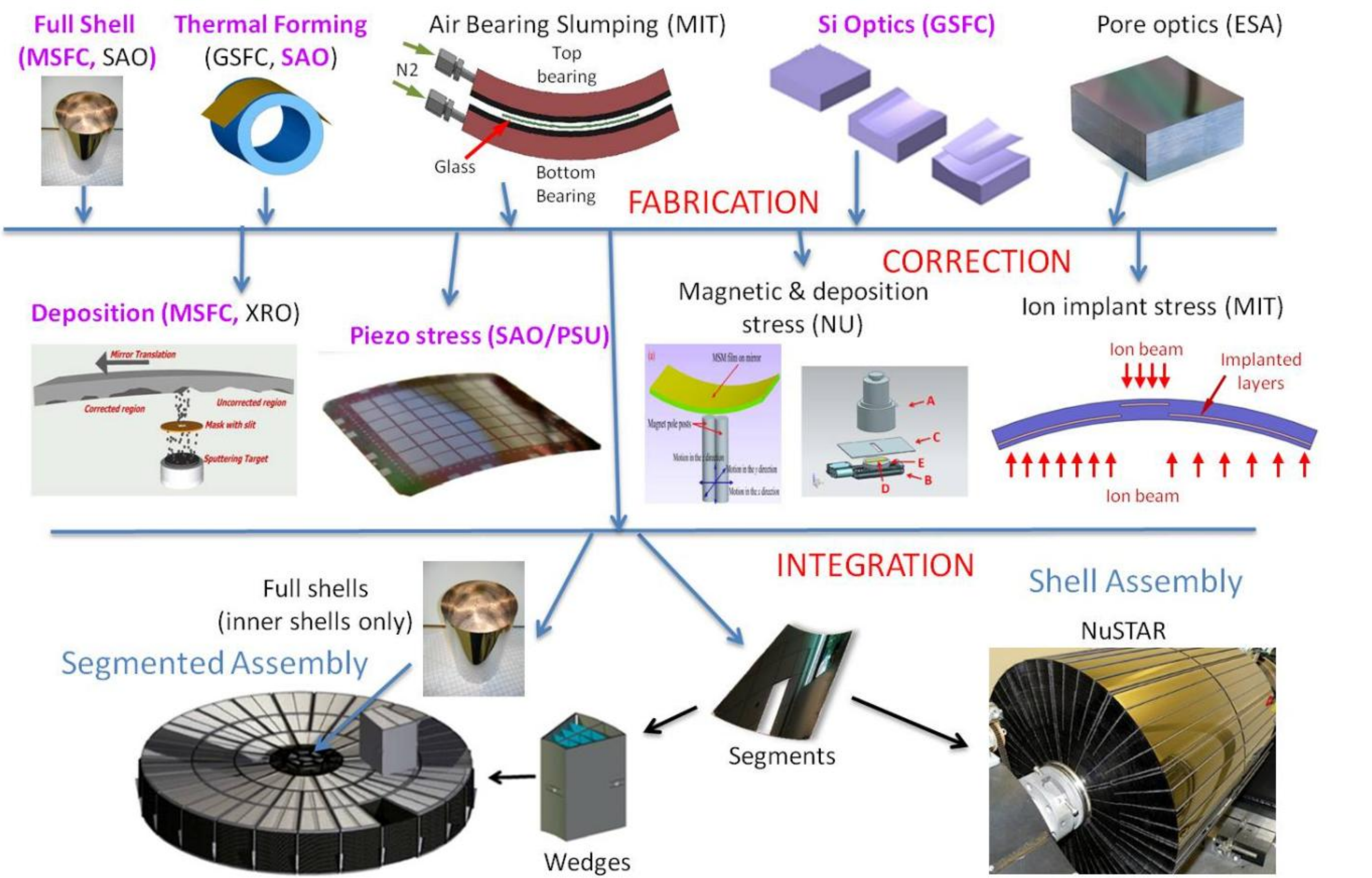
<u>Capability Goals</u>

- Angular resolution of order 0.5 arcseconds
- Scalable to a few square meter class mirror assemblies

<u>Current State-of-the-Art</u>

- TRL 2-3 for fabrication, coatings, and figure correction techniques

X-Ray Telescope Fabrication



Credit: Dan Schwartz (CfA)

X-Ray Optics Development Needs

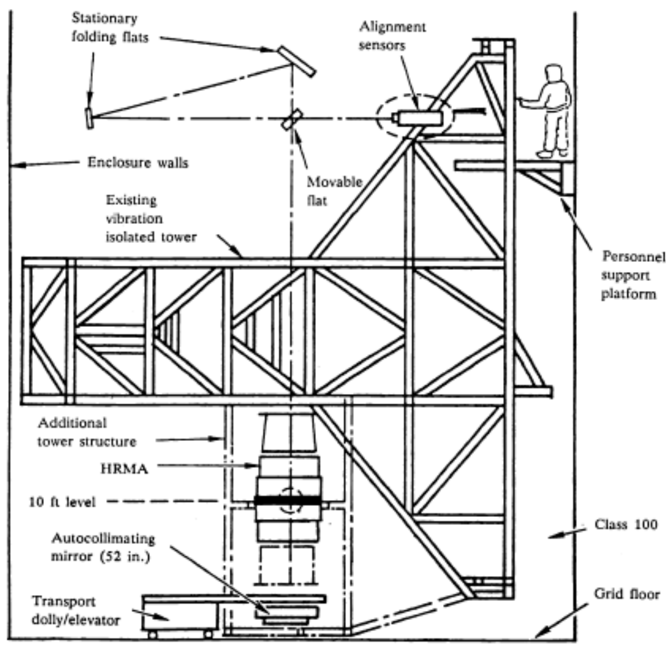
Achieving low cost per unit mirror area requires industry collaboration

Development needs include:

- high-resolution light-weight mirror fabrication processes
- mirror coating processes and stress mitigation methods
- static and active post-fabrication figure correction techniques
- Large-scale production techniques

Old School

The core of this facility still exists. Some of the AXAF engineers are still active in industry; Figure 9 from Spina, *SPIE*, 1113:2 (1989)



Disruptive

Robotic manufacturing at Raytheon/Tucson (Apr 2016)
http://www.popularmechanics.com/military/research/a20456/raytheon-factory-robots-make-missiles/

Capability Gap: High Definition X-Ray Imager

Key Technology Goal = Fast, low-noise, megapixel X-ray imaging arrays with moderate spectral resolution

Needed Capabilities

- Wide field of view with high spatial resolution (megapixel or higher)
- Moderate spectral resolution

Capability Goals

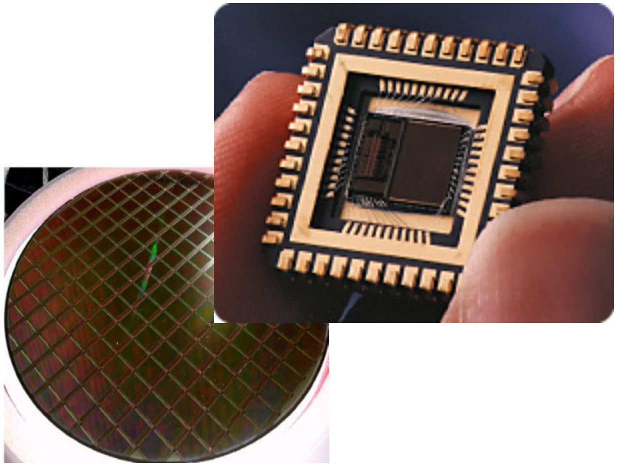
- Small pitch so as not to compromise optics performance
- large-format abuttable arrays (to best approximate the focal surface)
- Energy range of 0.2-10 keV
- Fano-limited spectral resolution
- Frame rates exceeding 100 frames/s
- Optical blocking filters with minimal X-ray absorption above 0.2 keV
- Radiation hardness to support >5 year mission at L2 or Chandra-like orbit

Current State-of-the-Art

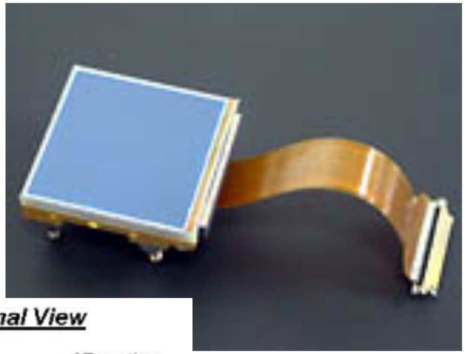
- Si Active Pixel Sensors (TRL 6) but noise & soft X-ray sensitivity needs improvement
- Sparsified readout allows fast frame rates (TRL 3)

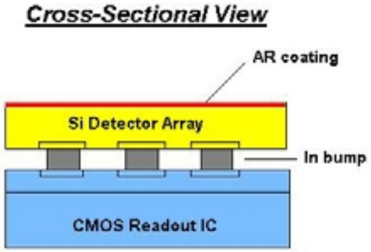
Examples of Active Pixel Sensors

- Monolithic CMOS
  - – Single Si wafer used for both photon detection and read out electronics
  - – Sarnoff/SAO and MPE



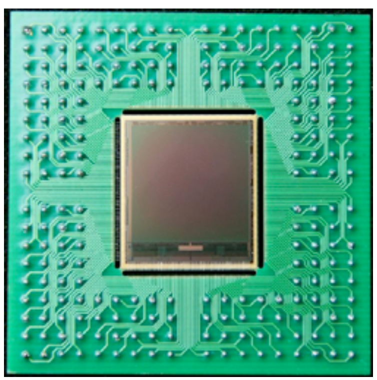
- Hybrid CMOS
  - – Multiple bonded layers, with detection layer optimized for photon detection and readout circuitry layer optimized independently
  - – LL/MIT and Teledyne/PSU



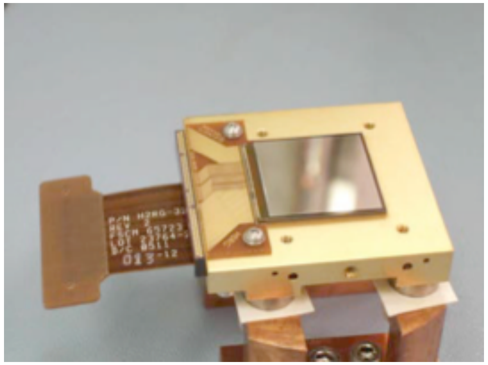


High Definition X-ray Imager

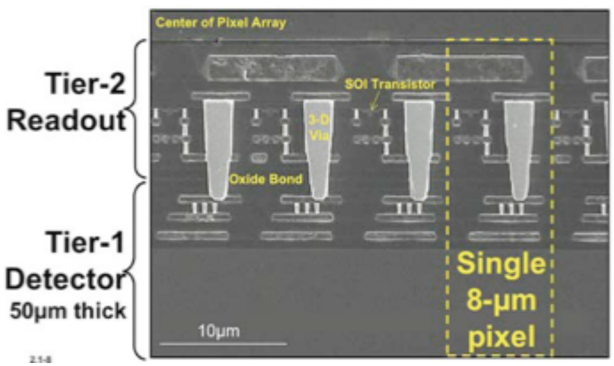
Parameter	**Notional Goal**
Energy Range	0.2 – 10 keV
Field of View	22 arcmin x 22 arcmin
Energy Resolution	37 eV @ 0.3 keV, 120 eV @ 6 keV (FWHM)
Quantum Efficiency	> 90% (0.3-6 keV), > 10% (0.2-9 keV)
Pixel Size / Array Size	<16 x 16 μm (< 0.33 arcsec/pixel) / 4096 x 4096 (or equivalent)
Frame Rate	> 100 frames/s (full frame) > 10000 frames/s (windowed region)
Read Noise	< $4e^-$ rms



SAO/Sarnoff



PSU/Teledyne

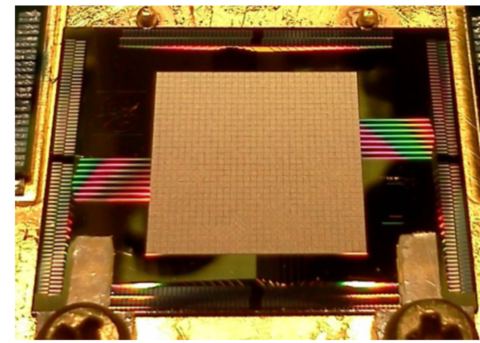


MIT/Lincoln Labs

Challenges: Develop sensor package that meets all requirements, and approximates the optimal focal surface

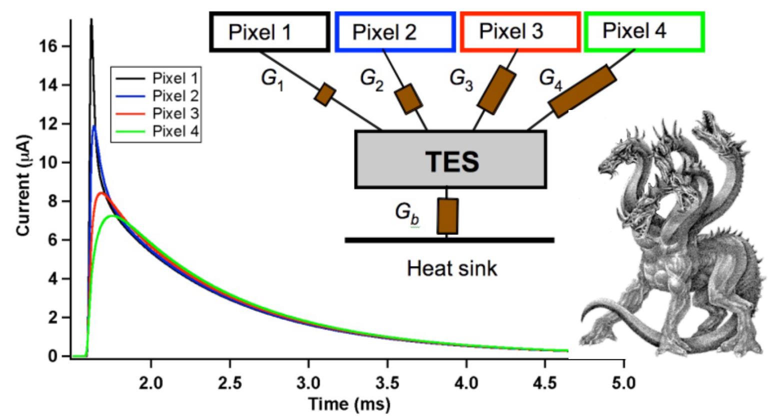
Capability Gap: X-ray Microcalorimeter

Key Technology Goal = Large-format high spectral resolution small-pixel X-ray microcalorimeter arrays



Needed Capabilities
- High spectral resolution
- High spatial resolution (sub-arcsecond; matching optics imaging)
- Wide field of view (>5 arcminutes)
- Improved Multiplexing (thermal and electrical)

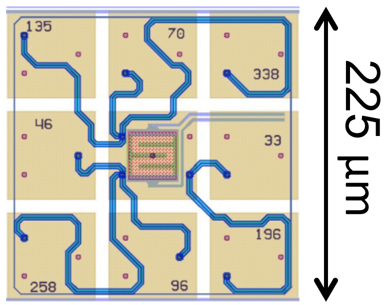
Capability Goals
- >100,000 pixel arrays
- ~4 eV FWHM spectral resolution over 0.2-10 keV range
- 50 micron pitch
- Optical/IR filters with high throughput above 0.2 keV



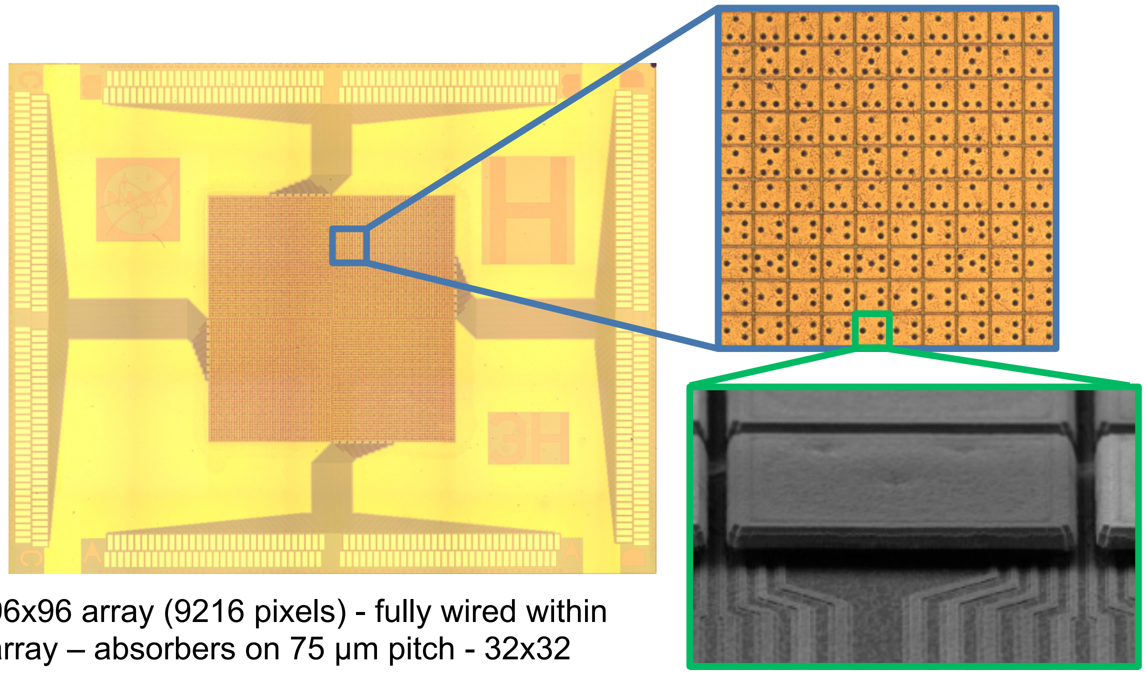
Current State-of-the-Art
- moderate-sized arrays
  (TRL 3; 9216 pixels, 9 per sensor, 75 micron pitch)
- small arrays with large pitch (TRL 9; Hitomi)
- multiplexing of transition-edge sensors (TRL 4 to 5)
- multiplexing with microwave SQUIDs (TRL 3)

Capability Gap: X-ray Microcalorimeter

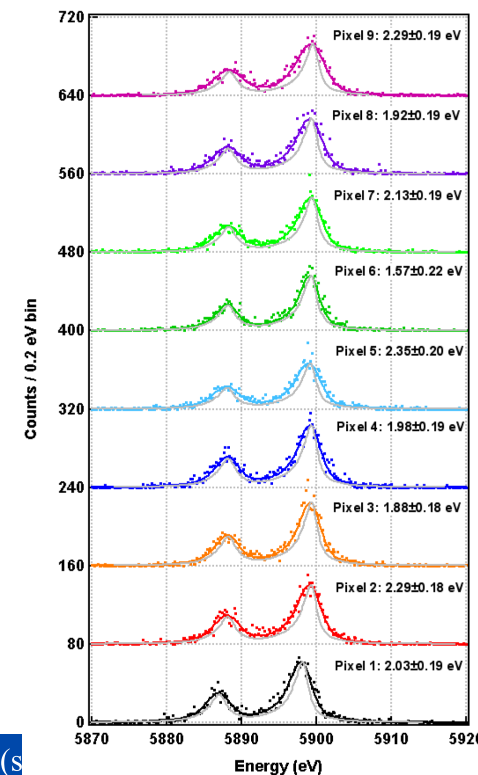
Parameter	Notional Goal
Energy Range	0.2 – 10 keV
Spatial Resolution	1 arcsec
Field-of-View	5 arcmin x 5 arcmin (min)
Energy Resolution	< 5 eV
Count Rate Capability	< 1 c/s per pixel
Pixel Size / array size (10-m focal length)	50 µm pixels / 300 x 300 pixel array



ΔErms = 2.4 eV (FWHM) at 6 keV, Mn-Kα



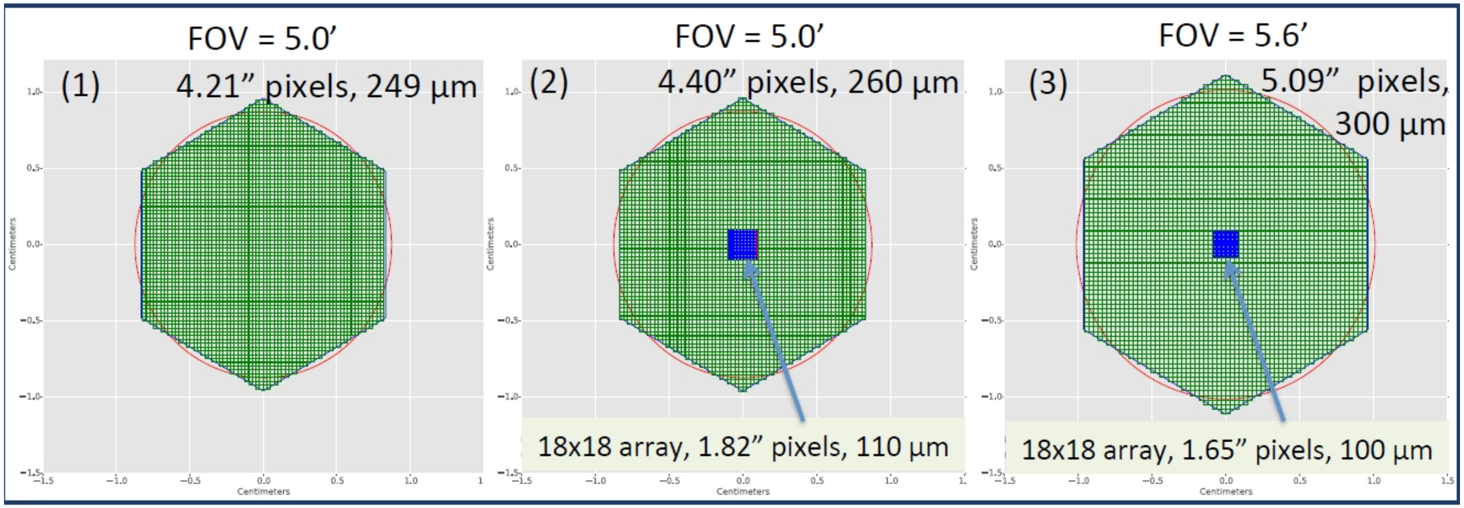
96x96 array (9216 pixels) - fully wired within array – absorbers on 75 µm pitch - 32x32 array of 3x3 Hydras



XRS Needs are Different from Athena

X-Ray Surveyor: 300 x 300 array => 90,000 pixels (5' Field-of-View with 1" pixels)

Athena: ~3840 pixels (5' Field-of-View with ~5" pixels)



Simon Bandler (GSFC), X-Ray Surveyor STDT Talk 06/08/2016

- If we assume "Hydra" approach for X-Ray Surveyor,

  With ~25 absorbers per TES=> the number of sensors needed to be read out (~3600) is close to that currently proposed for the X-ray Integral Field Unit instrument on Athena.

More development is needed!

Capability Gap: X-ray grating arrays

Key Technology Goal = High-efficiency grating arrays for high-resolution spectroscopy

Needed Capabilities

- High-efficiency, light-weight, large-format X-ray grating arrays
- High spectral resolving power, R
- Insertable/retractable gratings intercepting majority of input beam

Capability Goals

- 40% or higher efficiency (0.2-2.0 keV energy band)
- R>5000
- X-ray beam coverage of >50%

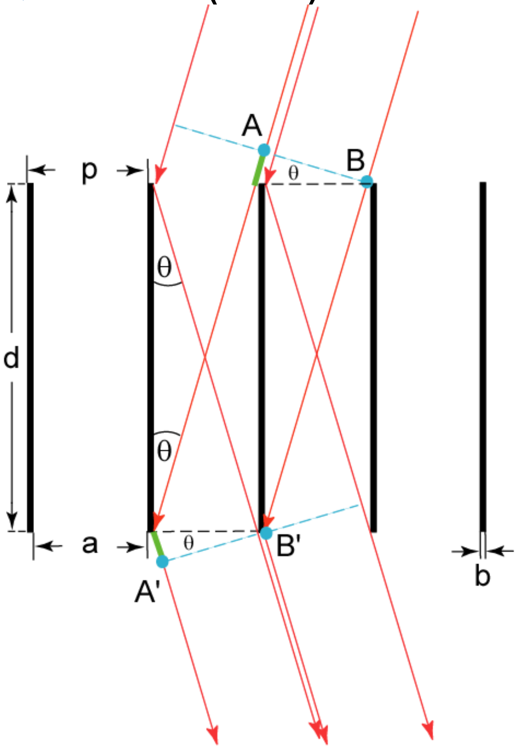
Current State-of-the-Art

- Chandra & XMM-Newton gratings have insufficient collecting area, R, and efficiency
- >40% efficiency demonstrated (TRL 4)
- R>10000 in soft X-ray (TRL 4)

X-ray Grating Arrays

Challenges: improving yield, developing efficient assembly processes, and improving efficiency

◆ CATG (MIT)

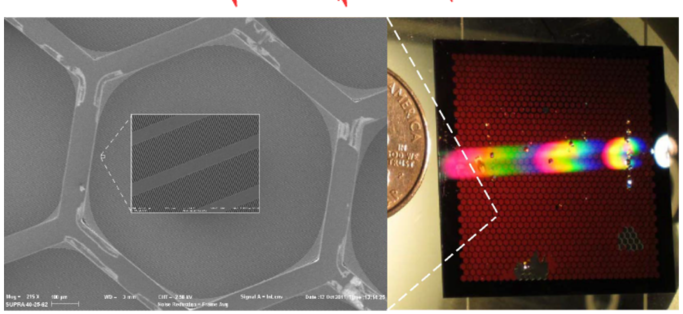


Grating equation:
$m\,\lambda = p\,(\sin(\theta) + \sin(\beta_m))$,
m = diffraction order

Blazing: $\beta_m \sim \theta$

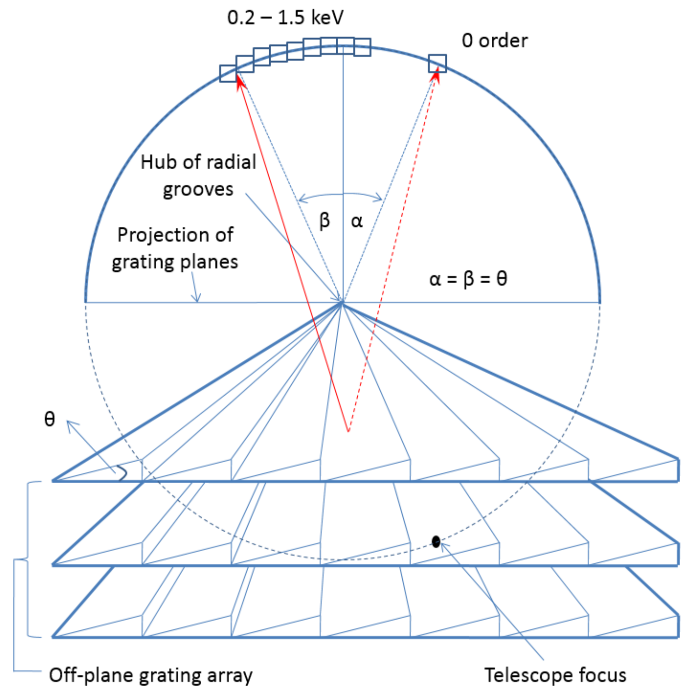
High reflectivity:
$\theta < \theta_c$ = critical angle of total external reflection

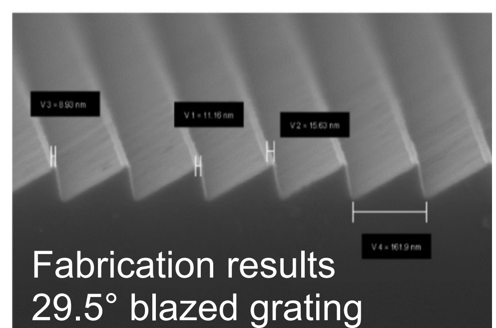
Strawman:
Silicon grating, $\theta = 1.5^{\circ}$
p = 200 nm
b = 40 nm
d = 6 μm
aspect ratio d/b = 150

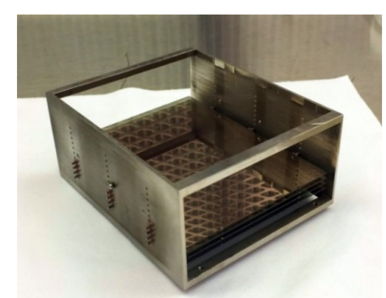


200 nm-period silicon grating membrane with integrated L1 & L2 supports, > 30x8 mm^2

◆ OPG (UIowa/Penn State)

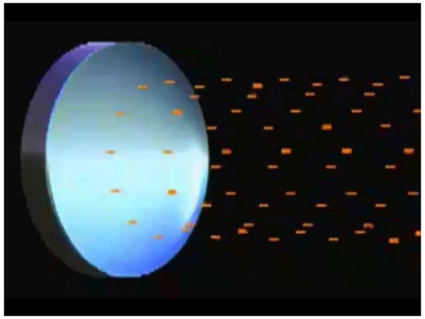




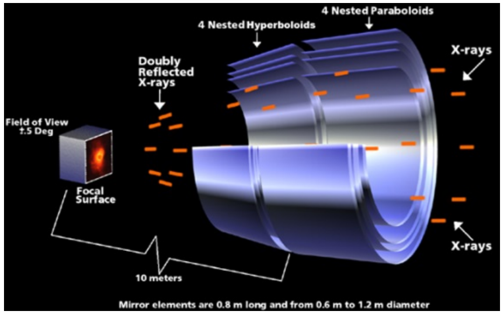


Key Technology Gaps

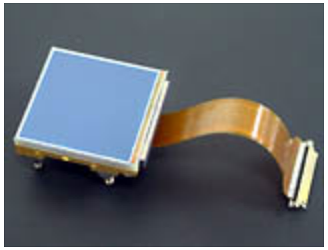
- High-resolution lightweight X-ray **optics**



CXC/D. Berry

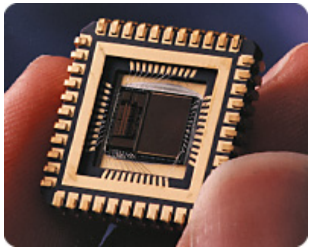


- Fast low-noise megapixel X-ray **imaging arrays** with moderate **spectral** resolution



Hybrid CMOS

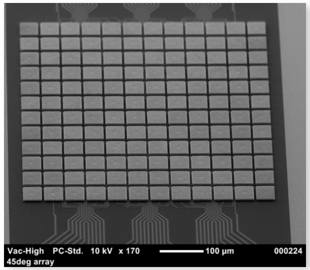
MIT/LL and PSU/Teledyne



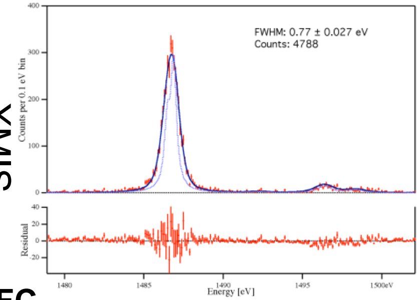
Monolithic CMOS

SAO/Sarnoff and MPE

- Large-format high spectral resolution small-pixel X-ray **microcalorimeter** arrays

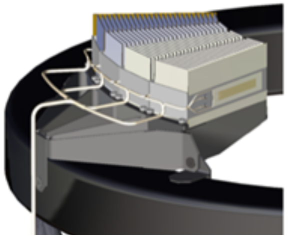


XMIS



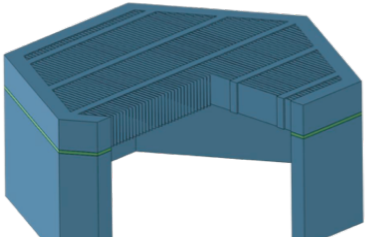
GSFC

- High-efficiency X-ray **grating** arrays



OPRG

U Iowa/Penn State



CATG

MIT

Acknowledgements

- The XRS STDT and instrument community provided input into the ***NOTIONAL*** instrument requirements and worked to define relevant technology gaps.

- Slides and images came from multiple presentations:
  - Optics (M. Pivovaroff, LLNL, SPIE 2016)
  - HDXI (A. Falcone, PSU, STDT Talk 2016)
  - Microcalorimeter (S. Bandler, GSFC, STDT Talk 2016)
  - Grating Spectrometer (R. McEntaffer, PSU, STDT Talk 2016)
  - Grating Spectrometer (R. Heilmann, MIT, STDT Talk 2016)

BACKUP SLIDES

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Steve Allen, Stanford


Mark Bautz, MIT


Niel Brandt, Penn State


Joel Bregman, Michigan

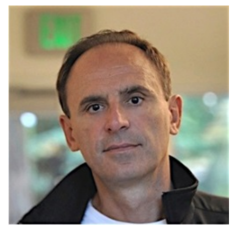

Megan Donahue, MSU

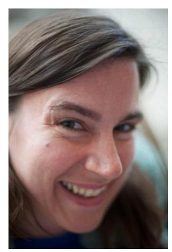

Ryan Hickox, Dartmouth


Tesla Jeltema, UCSC


Juna Kollmeier, OCIW


Laura Lopez, Ohio State


Piero Madau, UCSC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Dave Pooley, Trinity


Andy Ptak, GSFC


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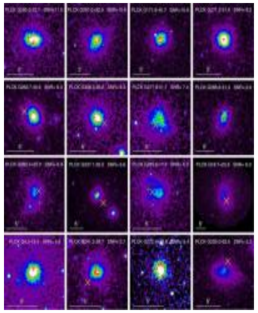
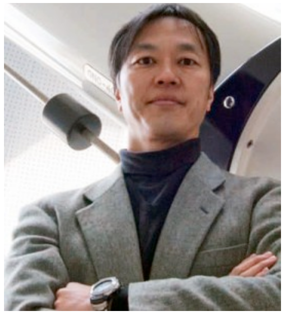
Arvind Parmar ESA-Appointed Observer

Kirpal Nandra DLR-Appointed Observer

Brian McNamara CSA-Appointed Observer



Gabriel Pratt CNES-Appointed Observer



Makoto Tashiro JAXA-Appointed Observer

MSFC AND SAO STUDY TEAM LEADERSHIP

Smithsonian Astrophysical Observatory

NASA

SRO Science Research Office

Alexey Vikhlinin,
SAO, STDT Co-Chair

Jessica Gaskin,
MSFC, Study Scientist

Mark King
MSFC Study Manager

Harvey Tananbaum
SAO Senior Scientist

Martin Weisskopf
MSFC Senior Scientist

Doug Swartz, USRA/MSFC
Deputy Study Scientist

Preliminary *XRS* mission features– large throughput telescope with excellent focusing

The *XRS* STDT is in the process of defining top-level science drivers, which are required before instruments can be specified

- Better understanding of the required properties of the X-ray telescope
  - *Chandra*-like resolution: O ~ 1″
  - Significantly larger area than any current mission: O ~ 1 m^2

Which x-ray optics technologies will support the telescope needed for *XRS*?

- Draw upon optics developed over last decade (for other programs)
- Follow several technology efforts
  - **Segmented, actuated glass (CfA + PSU)**
  - **Segmented Si (NASA GSFC + partners)**
  - **Full shell (NASA MSFC + partners)**
  - **Others (domestic & international)**

  XRS STDT will have an optics working group that will help teams coordinate and tap-into other communities

X-Ray Surveyor Mission Concept Study

Study output will provide the Decadal Survey Committee with:

1. The ***science case*** for the mission

This is where we are at

2. A ***notional mission*** and observatory, including a report on any tradeoff analyses
3. A ***design reference mission***, including strawman payload trade studies.
4. A ***technology assessment*** including: current status, roadmap for maturation & resources
5. A ***cost assessment*** and listing of the top technical risks to delivering the science capabilities
6. A ***top level schedule*** including a notional launch date and top schedule risks.

The Future: Active Pixel Sensors

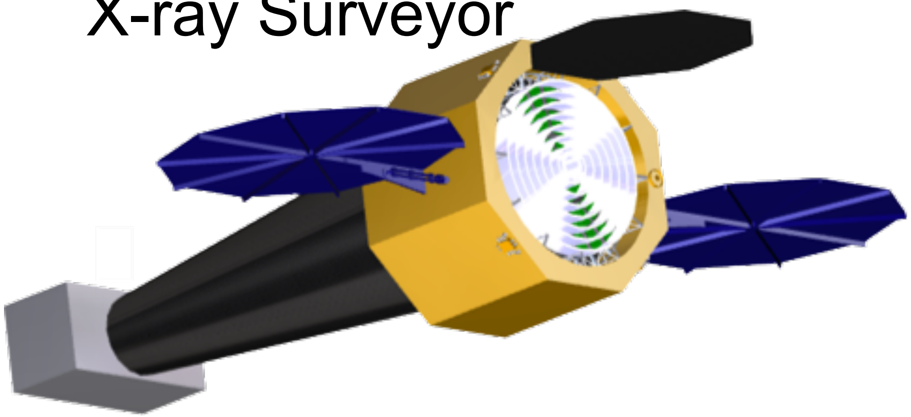
- Random-access pixel readouts
- Silicon-based devices:
  - Similarities to CCDs:
    - Photoelectric absorption in silicon
    - Energy resolution should be comparable to CCDs
    - Large arrays like CCDs
  - Radiation hard (charge is not transferred across the device)
  - High count rate capability with low pile-up (arbitrary window readout vs entire device readout for CCD, and multiple output lines boosts full frame rate)
  - Low power (<100 mW for some devices)
  - On-chip integration of signal processing electronics
  - Some devices have >200 μm depletion depths à full soft X-ray energy range
  - Large formats (up to 4k × 4k abuttable devices)
  - Pixel sizes from 8 μm to 100 μm

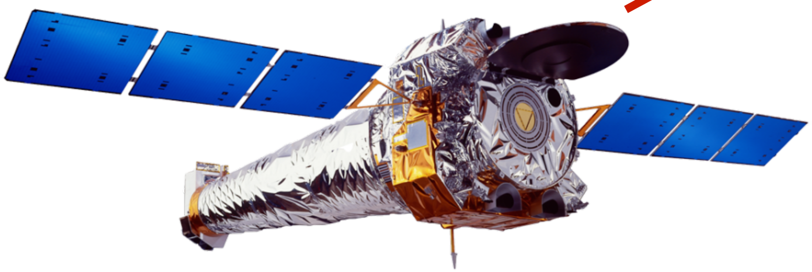
Hybrid CMOS X-ray detectors, Falcone et al.

Notional Concept

We are now in the process of defining the successor to Chandra.

X-ray Surveyor





Chandra

<u>Goals:</u>

- Sensitivity (50× better than *Chandra*)
- *R*≈1000 spectroscopy on 1″ scales, adding 3rd dimension to data
- *R*≈5000 spectroscopy for point sources

✓Area is built up while preserving *Chandra* angular resolution (0.5″)

✓16× field of view with sub-arcsec imaging

How can *XRS* involve industrial partners ?

- Segmented silicon
  - X-ray mirrors
    - Production of silicon "blanks"
    - Semiconductor production: silicon etch, metrology and potentially even coating
  - Assembly
    - Robotic manufacturing
- Segmented, actuated glass
  - X-ray mirrors
    - Semiconductor production: piezo application, implantation?
  - Assembly
    - Robotic manufacturing
- Full-shell approaches
  - X-ray mirrors
    - Additive and advanced manufacturing techniques

Ultimately, teams must answer this question, but there seems to be potential

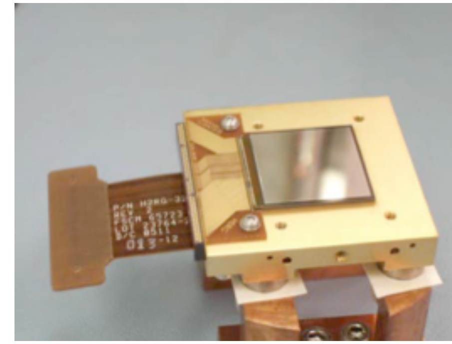
Technical Challenges

Quantum Efficiency: Hybrids have achieved the depletion depths required for high quantum efficiency across the X-ray band, but the monolithic devices still need to make further developments to achieve these depletion depths

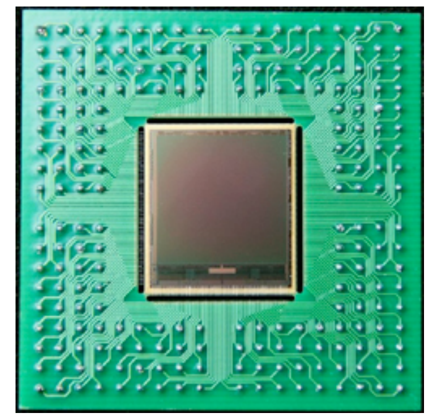
Read Noise: Monolithic architectures have achieved low read noise, but hybrids still need to progress further to achieve < 4 e-

Small Pixels/Aspect Ratio: All devices have achieved small pixel sizes, but further development is needed to do this while retaining other advantages and while limiting impacts of increased charge diffusion due to the increase in the aspect ratio of pixel depth-to-width

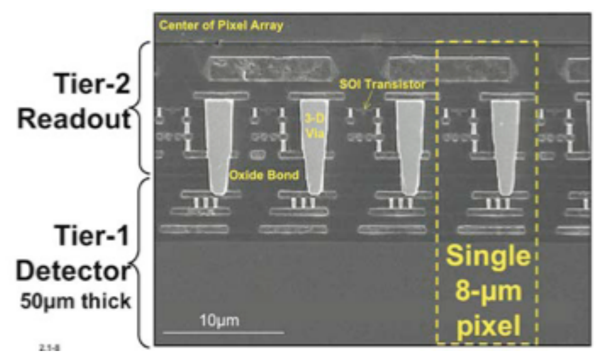
Rate: While higher frame rates are already possible with APSs, relative to CCDs, significantly more development is needed to handle the data from these increased frame rates at the focal plane level for short/medium term missions and to achieve the required read noise while simultaneously achieving fast frame rates for the long-term mission requirements (>100 frame/sec for >16 Mpix cameras)



PSU/Teledyne

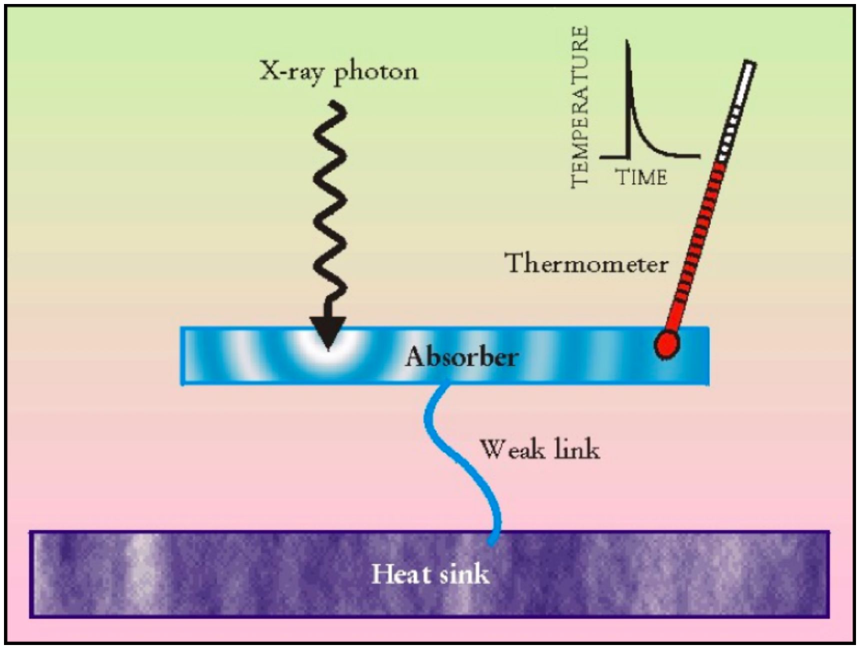


SAO/Sarnoff



MIT/Lincoln Labs

Key Technology Goal: Large-format high spectral resolution small-pixel X-ray microcalorimeter arrays

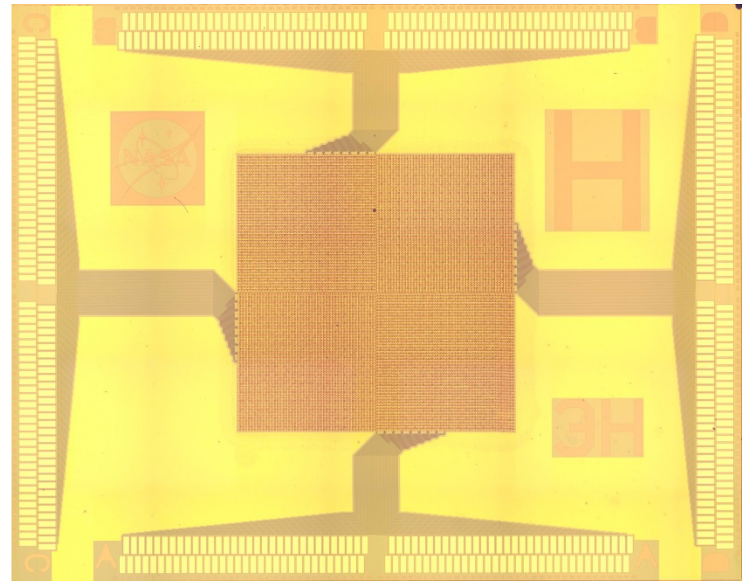


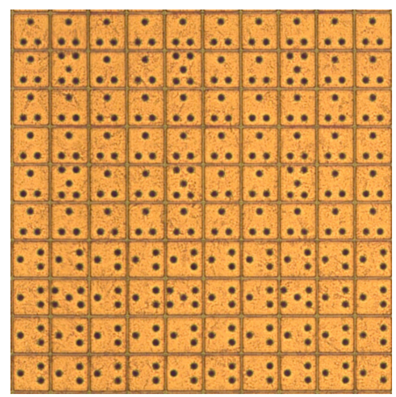
$$\delta T = \frac{E}{C_{\mathrm{tot}}}$$

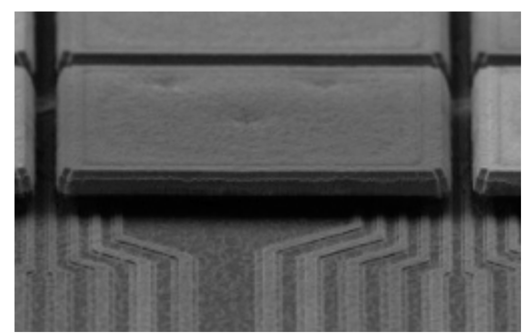
Thermal relaxation time:

$$\tau = \frac{C_{\mathrm{tot}}}{G}$$

Thermal conductance

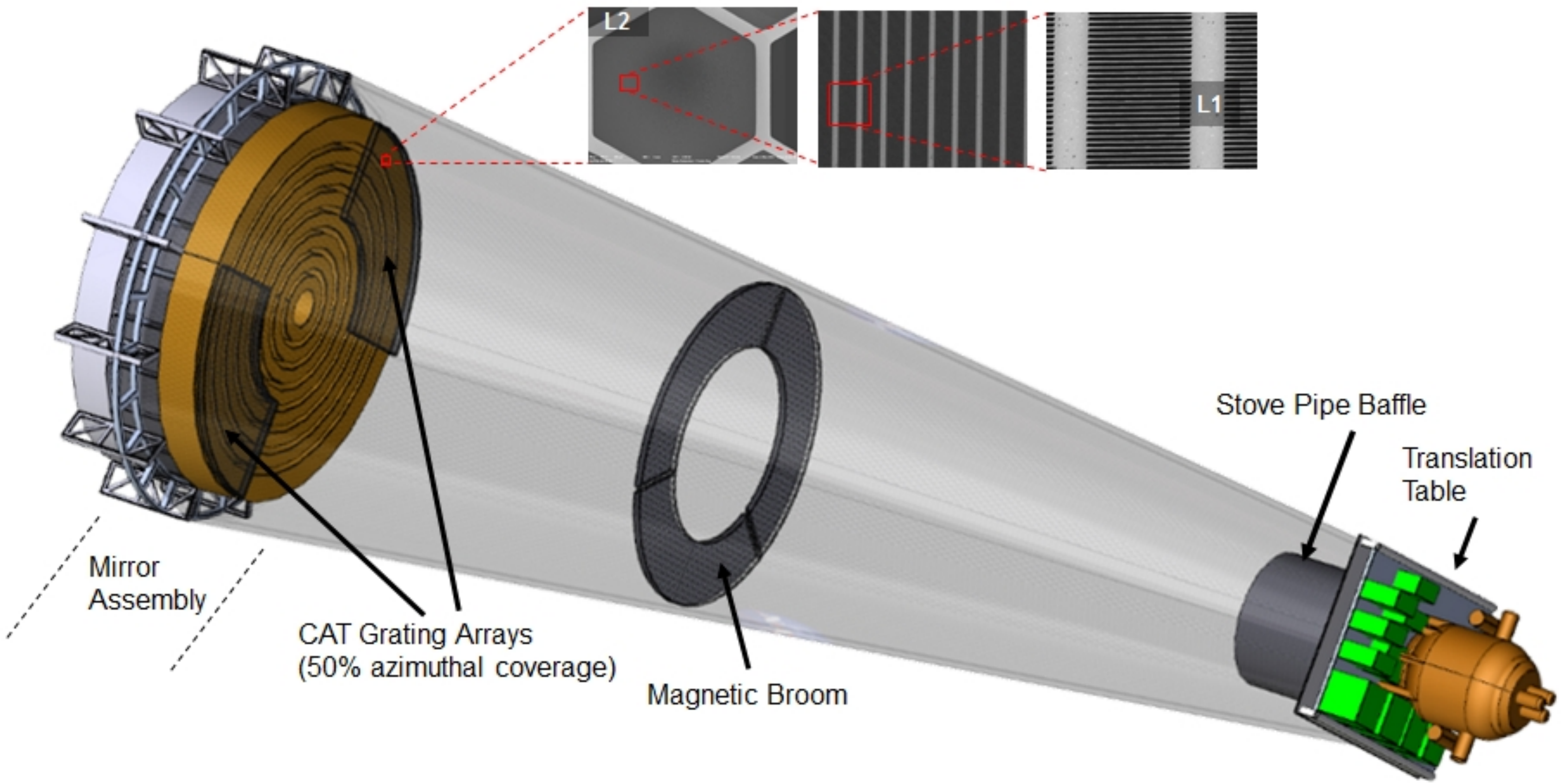






96x96 array (9216 pixels) - fully wired within array – absorbers on 75 μm pitch - 32x32 array of 3x3 Hydras

Critical Angle Transmission Gratings (MIT)



Schattenburg –XR-SIG meeting, Jan. 5, 2014

A Successor to *Chandra*

Preliminary *XRS* mission features:

- Angular resolution at least as good as *Chandra*
- Much higher photon throughput than *Chandra* (observations are photon-limited)

Incorporate relevant prior (Con-X, IXO, AXSIO) development and *Chandra* heritage

Limit most spacecraft requirements to *Chandra*-like

Achieve *Chandra*-like cost