The High Definition X-ray Imager (HDXI) of the *Lynx* X-Ray Surveyor Mission

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John Mulqueen (MSFC) Doug Swartz (MSFC)

on behalf of the Lynx Science & Technology Definition Team

Community STDT
F. Özel, Arizona (Co-Chair)
A. Vikhlinin, SAO (Co-Chair)

S. Allen, Stanford
M. Bautz, MIT
W. N. Brandt, Penn State
J. Bregman, Michigan
M. Donahue, MSU
J. Gaskin, MSFC (Study Sci.)
Z. Haiman, Columbia
R. Hickox, Dartmouth
T. Jeltema, UCSC
J. Kollmeier, OCIW
A. Kravtsov, U. Chicago
L. Lopez, Ohio State
R. Osten, STScI
F. Paerels, Columbia
D. Pooley, Trinity
A. Ptak, GSFC
E. Quataert, Berkeley
C. Reynolds, UMD
D. Stern, JPL

Using X-ray eyes, Lynx will peer deeply into the ***origin and evolution of structure*** in the Universe

Lynx Concept Team

<u>Community Science & Technology Definition Team</u>
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	D. Stern, JPL

+ Instruments Working Groups: Mark Bautz (Chair)
  HDXI Co-Chairs: Abe Falcone, Ralph Kraft
  uCal Co-Chairs: Simon Bandler, Enactali Figueroa-Feliciano
  Grating Co-Chairs: Randy McEntaffer, Ralf Heilmann

+ Optics Working Group:
  Co-Chairs: Mark Schattenberg, Lester Cohen

+ 8 Science Working Groups

There are >250 people across academia, industry, government, and non-US space agencies involved in the Lynx Concept Study

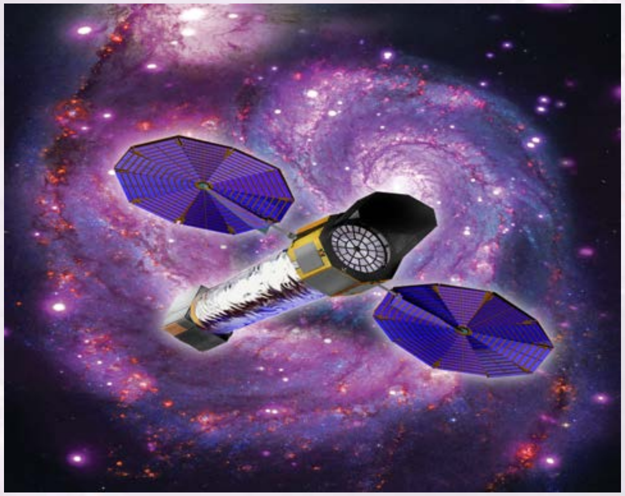
Meet *Lynx*!

X-RAY OBSERVATORY LYNX

One of 4 large missions under study for the 2020 Astrophysics Decadal, Lynx is an X-ray observatory that will directly observe the dawn of supermassive black holes, reveal the invisible drivers of galaxy and structure formation, and trace the energetic side of stellar evolution and stellar ecosystems.

Lynx will provide unprecedented X-ray vision into the “Invisible” Universe with leaps in capability over *Chandra* and *ATHENA*:

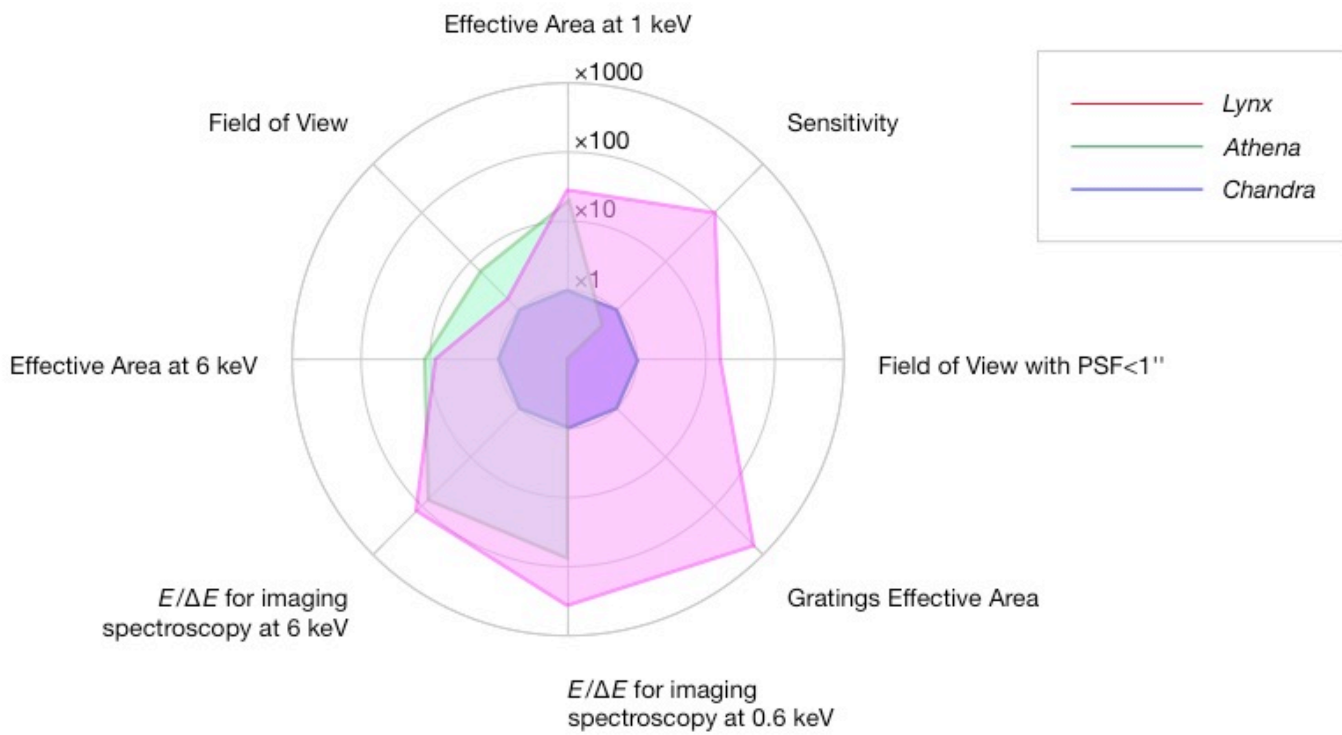
- 50–100× gain in sensitivity via high throughput with high angular resolution
- 16× field of view for arcsecond or better imaging
- 10–20× higher spectral resolution for point-like and extended sources
- ×800 higher survey speed at the Chandra Deep Field limit



Lynx will contribute to nearly every area of astrophysics and provide synergistic observations with future-generation ground-based and space-based observatories.

Unique parameter space of Lynx

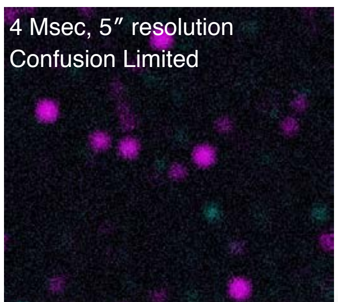
combining *superb angular resolution* with large area and excellent spectroscopy

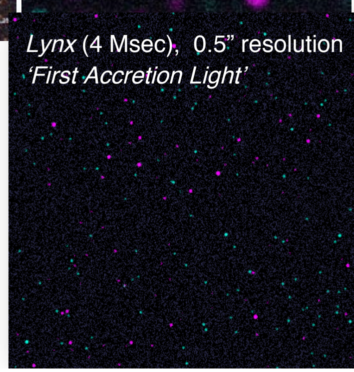


The Dawn of Black Holes

Lynx will observe the birth of the first seed black holes at redshift up to 10 and provide a census of the massive black hole population in the local and distant universe, follow their growth and assembly across cosmic time, and measure the impact of their energy input on all scales.

Simulated 2x2 arcmin deep fields

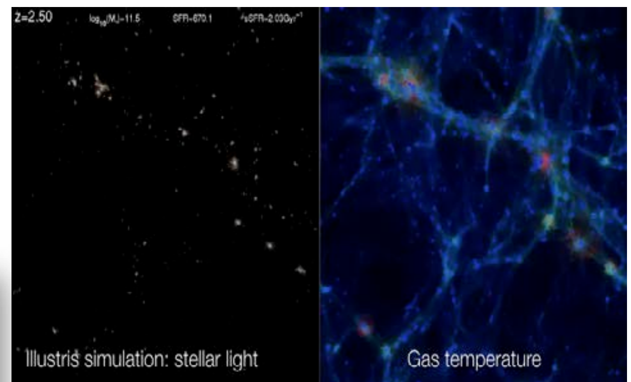




JWST will detect ~2×10^6 gal/deg^2 at its sensitivity limit (Windhorst et al.). The <0.5” angular resolution of Lynx will minimize source confusion for X-ray detected SMBHs.

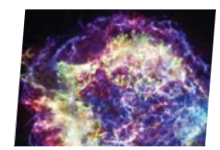
Invisible Drivers Behind Galaxy Formation and Evolution

The assembly, growth, and state of visible matter in the cosmic structures is largely driven by violent processes that heat the gas in the CGM and IGM. The exquisite spectral and angular resolution of *Lynx* will make it a unique instrument for mapping the hot gas around galaxies and in the Cosmic Web.



Energetic Side of Stellar Evolution and Stellar Ecosystems

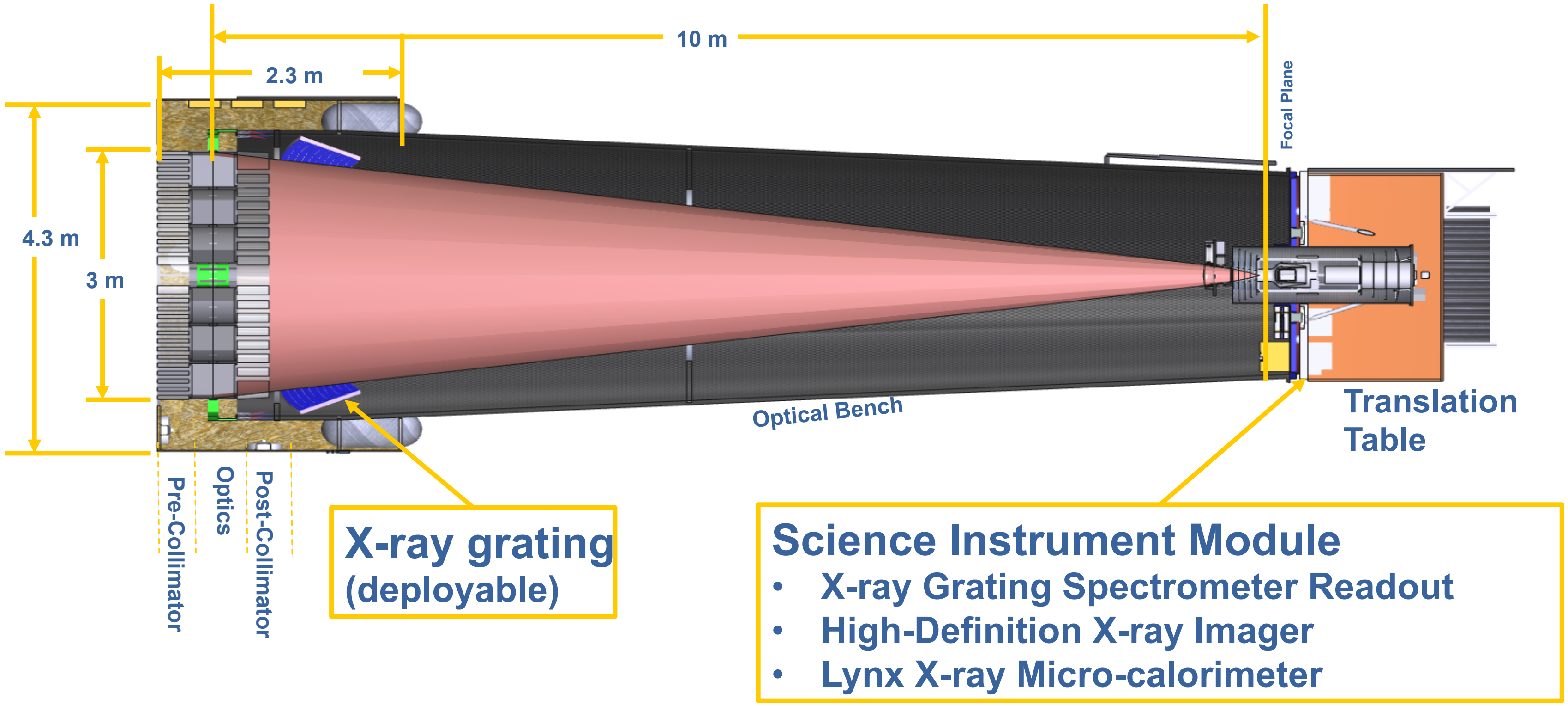
Lynx will study the endpoints of stellar evolution, stellar birth, coronal structure, and the impacts of feedback. Stellar X-ray variability measurements will enable determination of the impact of stellar activity on the habitability of planets.



Facility Class Observatory: Exploration Science with a Rich Community-Driven General Observer Program!

see Lynx overview for more detail (Gaskin et al., these proceedings)

Lynx Configuration



Credit: MSFC ACO

Lynx Science Instruments

Instrument Working Group Lead: M. Bautz (MIT)

•High Definition X-ray Imager (HDXI)

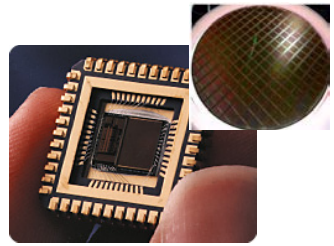
- HDXI Leads: R. Kraft (SAO), A. Falcone (PSU)
- Instrument Design Study (On-going @ MSFC ACO)

•X-Ray Grating Spectrometer (XGS)

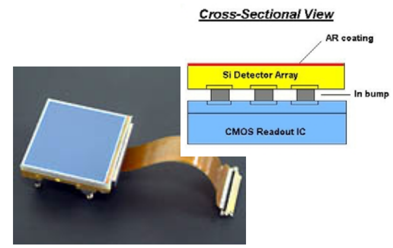
- XGS Leads: R. McEntaffer (PSU), Ralf Heilmann (MIT)
- Instrument Design Study (On-going @ MSFC ACO)

•Lynx X-ray Microcalorimeter (LXM)

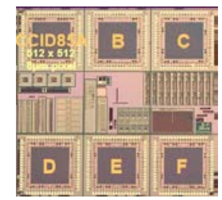
- LXM Leads: S. Bandler (GSFC), E. Figueroa-Feliciano (Northwestern)
- Instrument Design Lab (Completed 1st IDL @ GSFC)



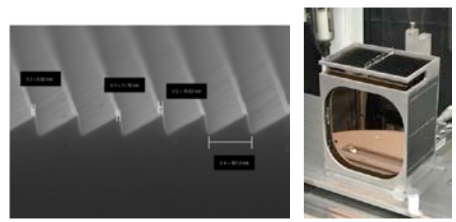
Monolithic CMOS



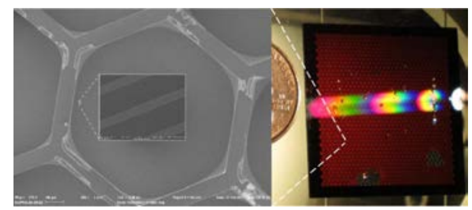
Hybrid CMOS



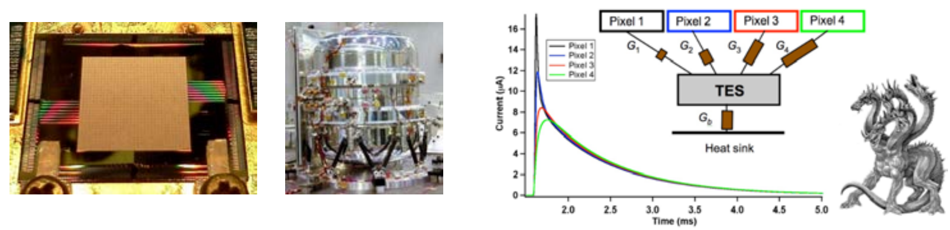
Digital CCD with CMOS readout



Off-Plane Grating Array

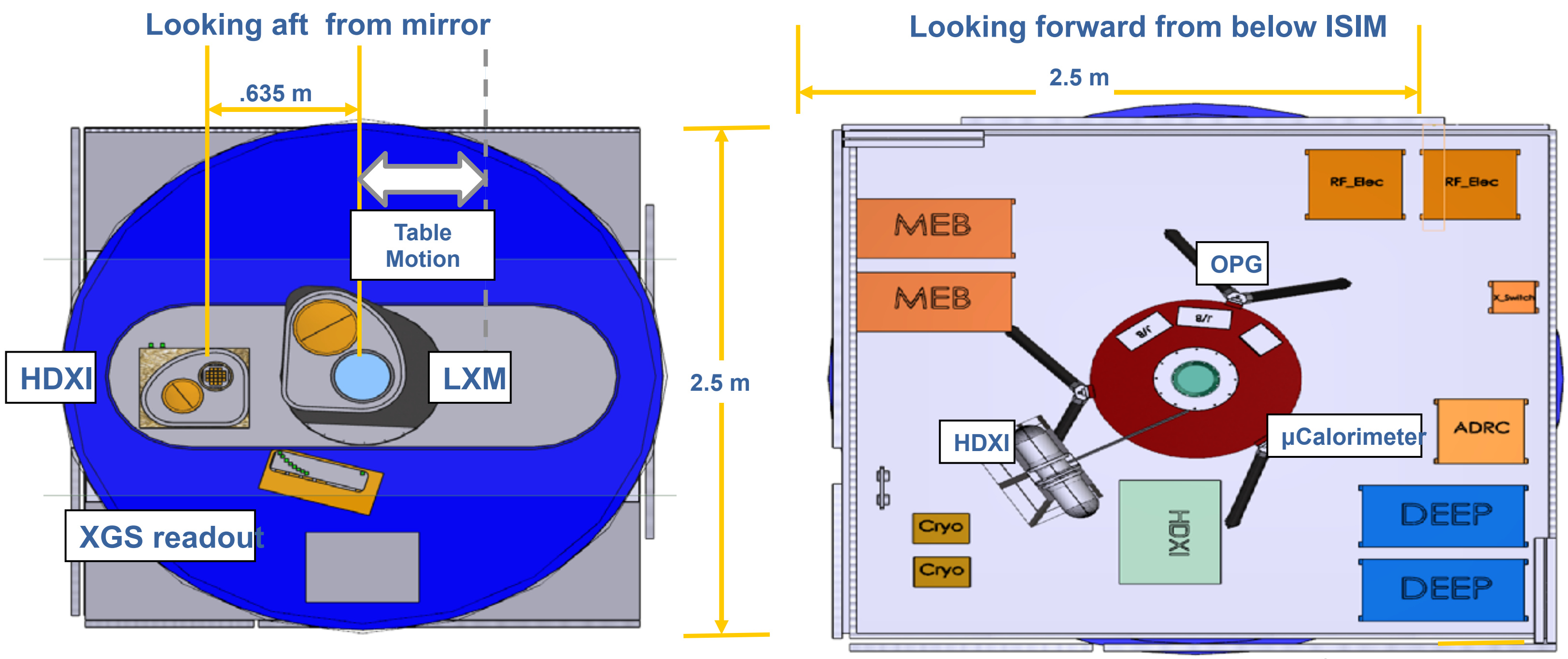


Critical Angle Transmission Grating Array



Lynx X-ray Microcalorimeter

Science Instrument Accommodation



Credit: MSFC ACO

- Translation table (gray) positions either LXM or HDXI at focus
- XGS readout mounted on stationary bench (blue)
- 4 observing configurations: (HDXI or LXM) x (w/ or w/o grating in beam)

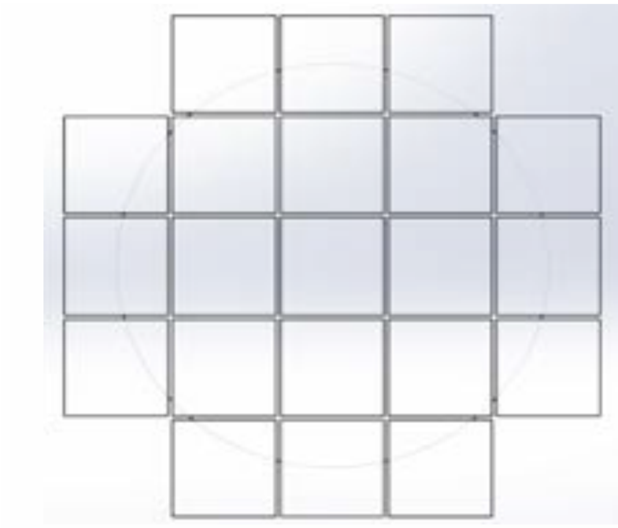
HDXI Performance requirements and goals

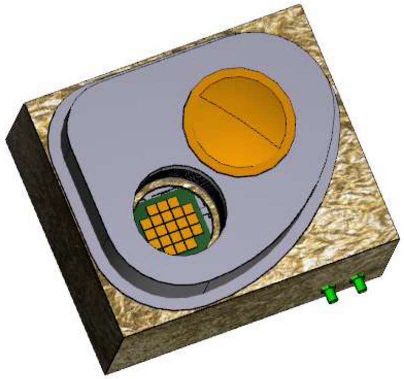
HDXI Parameter	Requirement	Science Drivers
Energy Range	0.2 – 10 keV	Sensitivity to high-z sources
Field of view	22 x 22 arcmin	Deep Survey efficiency R_{200} for nearby galaxies
Pixel size	16 x 16 µm	Pt. source sensitivity Resolve AGN from group emission
Read noise	$\leq 4\ e^-$	Low-energy detection efficiency
Energy Resolution (FWHM)	70 eV @ 0.3 keV 150 eV @ 5.9 keV	Low-energy detection efficiency
Full-field count-rate capability	8000 ct s^{-1}	No dead time for bright diffuse sources (e.g. Perseus or Cas A)
Frame Rate Full-field Window mode (20”x20”)	 > 100 frames s^{-1} > 10000 windows s^{-1}	Maximize low-energy throughput Minimize background

High Definition X-ray Imager (HDXI)

High Definition X-ray Imager (*Notional Requirements*)	
Energy Range	0.2 – 10 keV
QE (including filter)	>0.85 at 0.5-7 keV, >TBD from 0.15-0.5 keV
FOV	22' x 22' (4k x 4k pixels)
Pixel Size	16 x 16 μm (≤ 0.33")
Read Noise	≤ 4 e^-
Energy Resolution	≤ 70 eV@0.277 keV, ≤ 150 eV@5.9 keV (FWHM)
Frame Rate	> 100 frames/s (full frame) > 10000 frames/s (windowed region)
Radiation Tolerance	10 yrs at L2

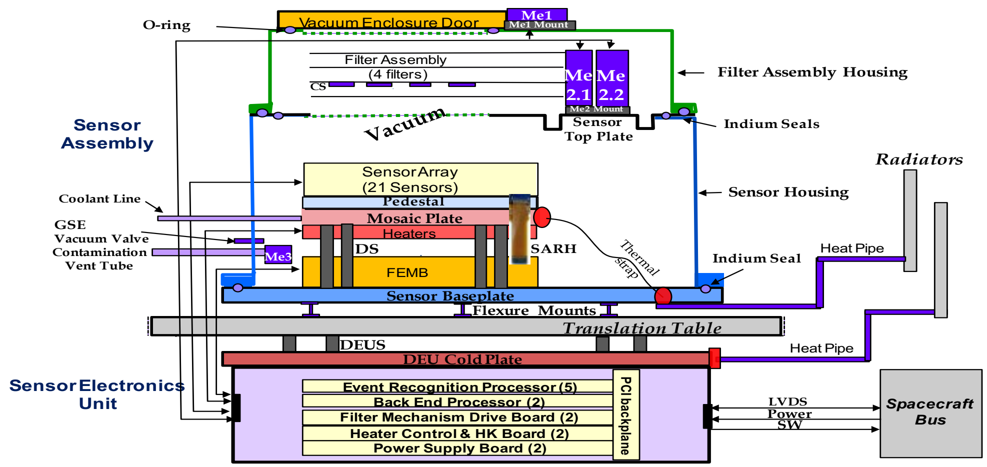
detector focal plane layout : 21 tilted detectors with 1024x1024 pixels (≤16 μm pixel pitch) per detector.



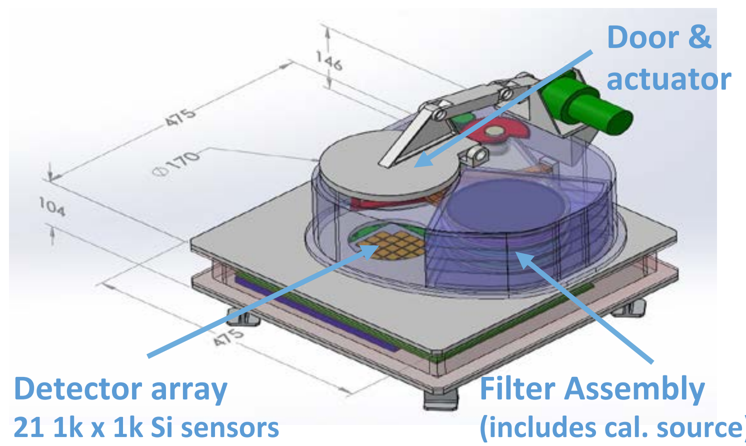


Notional HDXI Instrument Configuration

Block Diagram



Detector Housing Concept

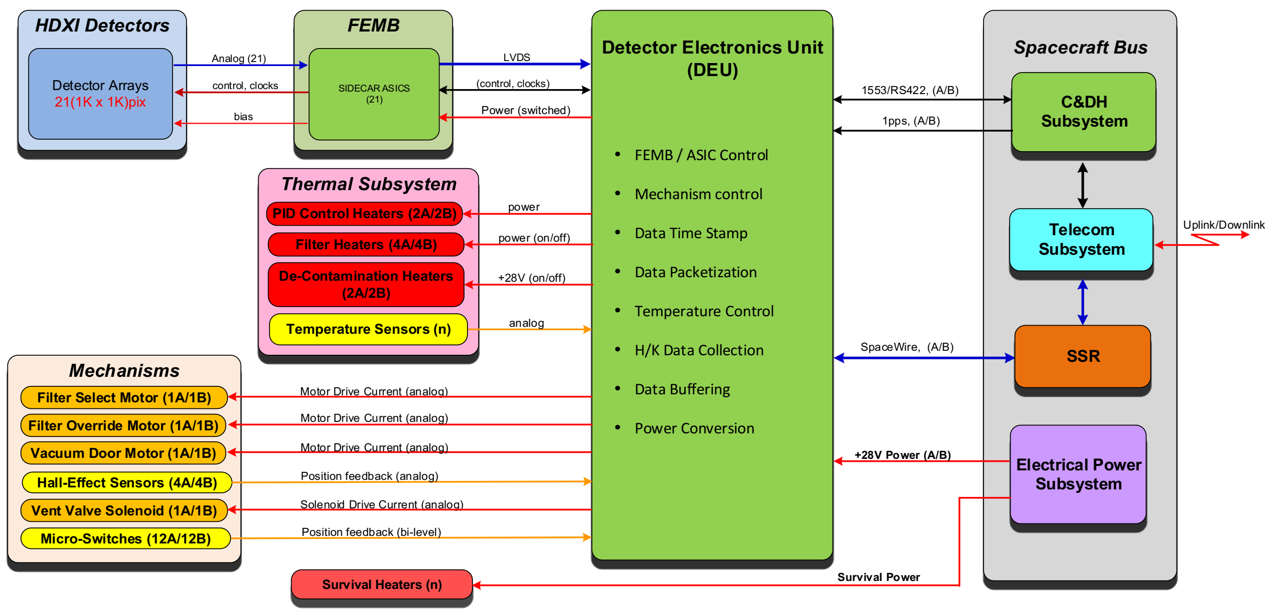


Credit: GSFC IDL

Resources	
Power (W)	**175**
Mass (kg)	**48**
Detector Assy	36
Electronics	12
Data Rate	<600 kBytes/s

High Definition X-ray Imager (HDXI)

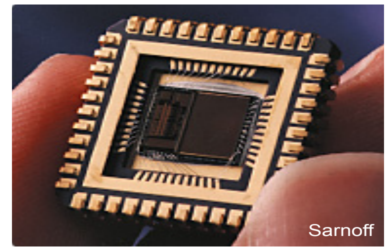
Electronics & Interfaces



3 Different HDXI Sensors Approaches

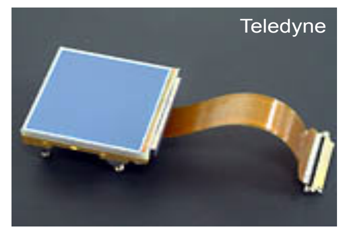
- Monolithic CMOS Active Pixel Sensor
  - Single Si wafer used for both photon detection and read out electronics
  - Sarnoff/SAO and MPE

  (see Kraft et al.)



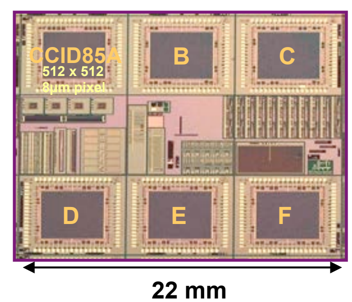
- Hybrid CMOS Active Pixel Sensor
  - Multiple bonded layers, with detection layer optimized for photon detection and readout circuitry layer optimized independently
  - Teledyne/PSU

  (see Hull, S. et al., these proceedings)



- Digital CCD with CMOS readout
  - CCD Si sensor with multiple parallel readout ports and digitization on-chip
  - LL/MIT

  (see Bautz, M. et al, these proceedings)



Current State of the Art

- Each of the sensor technologies presently meets some of the expected requirements.
- No single sensor meets them all –> work to do between now and phase A and during phase A.

Key improvements over ACIS and EPIC

- Orders of magnitude higher frame rates (>100 full-frame/sec, >10000 subframe/sec)
- Significantly improved radiation hardness
- Fully addressable (i.e. high speed windowing)
- Near Fano-limited resolution over entire bandpass
- Lower power
- Large format (up to 4Kx4K) abuttable devices

Key sensor trade-offs

1) Pixel size
   - Small pixel size desired to oversample PSF. However, this decreases energy resolution – requires better noise and faster readout
   - Small pixels increases number of sensors required to fill focal plane
   - Small pixels increase number of pixels over which charge is spread, thus limiting low-E sensitivity
   - Larger pixels could be used to perform sub-pixel centroiding (this would require deep depletion and multi-pixel events)
2) Deep Depletion
   - Thick devices improve QE above 5 keV but could degrade energy resolution below 1 keV
3) Higher Frame Rates
   - Mitigates pileup and *may* improve background rejection, but increases complexity and power of read out electronics

HDXI: Technical Challenges

Primary technology development required for HDXI is sensor technology. Three technologies currently being developed – each meets some of the requirements but none presently meet all.

- **Quantum Efficiency:** Hybrids and CCDs 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;
  pixel size, operating voltage, and depletion depth will need optimization

- **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 and to achieve the required read noise while simultaneously achieving fast frame rates (>100 frame/sec for >16 Mpix camera)

- **High QE down to 0.15 keV:** STDT science discussions suggest Emphasis on soft (<1 keV) efficiency as a key driver. This will require high quantum efficiency from the sensor and high transmission from the optical blocking filter.

Some additional HDXI Technology Development

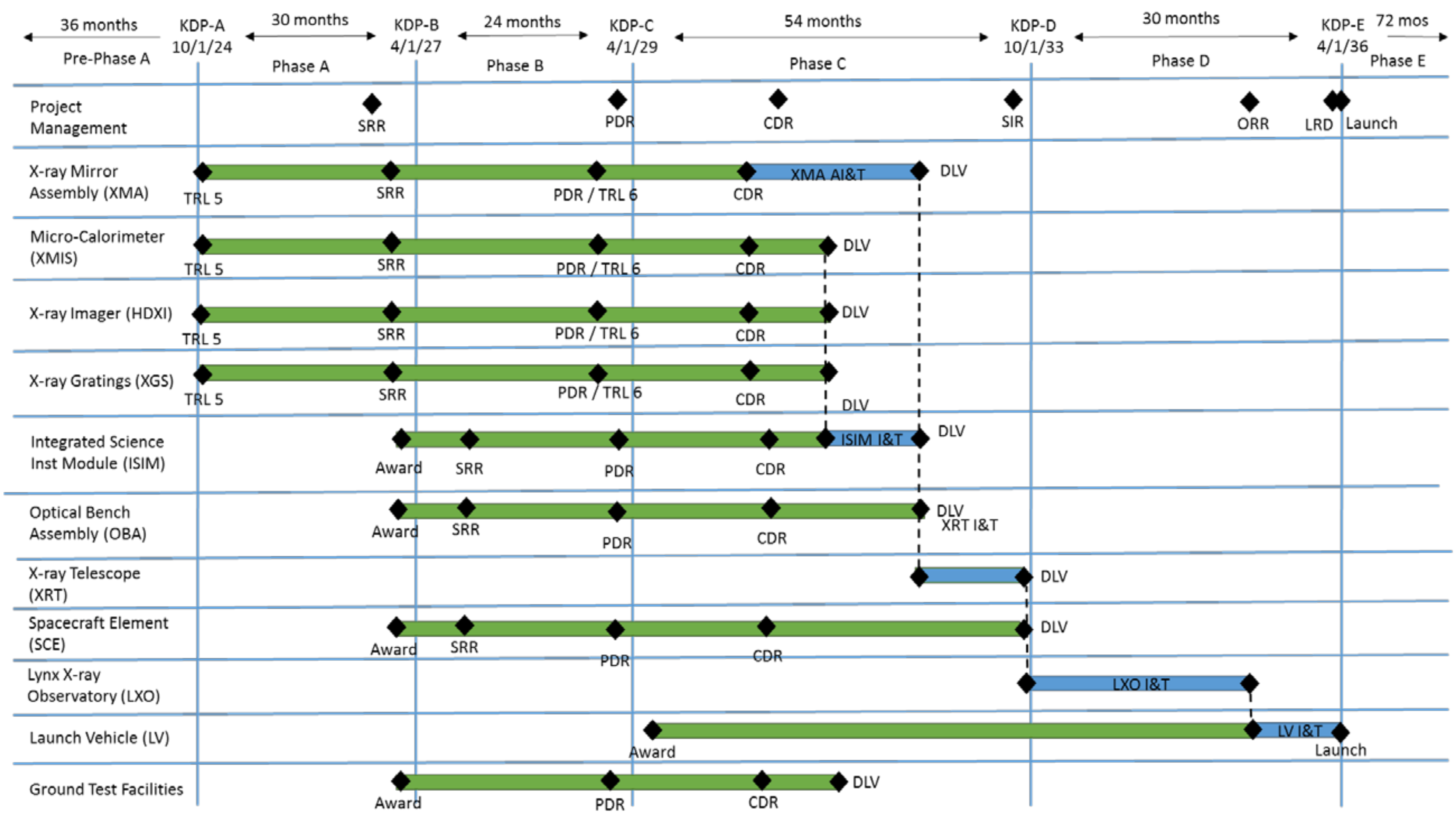
Additional technical and engineering development required in three areas:

- Driver ASICs
  - Depending on sensor technology chosen for flight, a custom ASIC may need to be developed to clock sensors. However, digitization on chip could alleviate much of this.

- FPGA/Event Recognition processors
  - Event recognition will be done in radiation tolerant FPGAs with sufficient processing power to keep up with large (>2 Gpix/s) data rate from sensors. Requires development of flight firmware and software

- Optical blocking filters
  - Large area, thin unsupported optical blocking filters (Al on polyimide) need to demonstrate sufficient mechanical and thermal stability

Lynx X-ray Observatory – Notional Mission Lifecycle Schedule



Summary

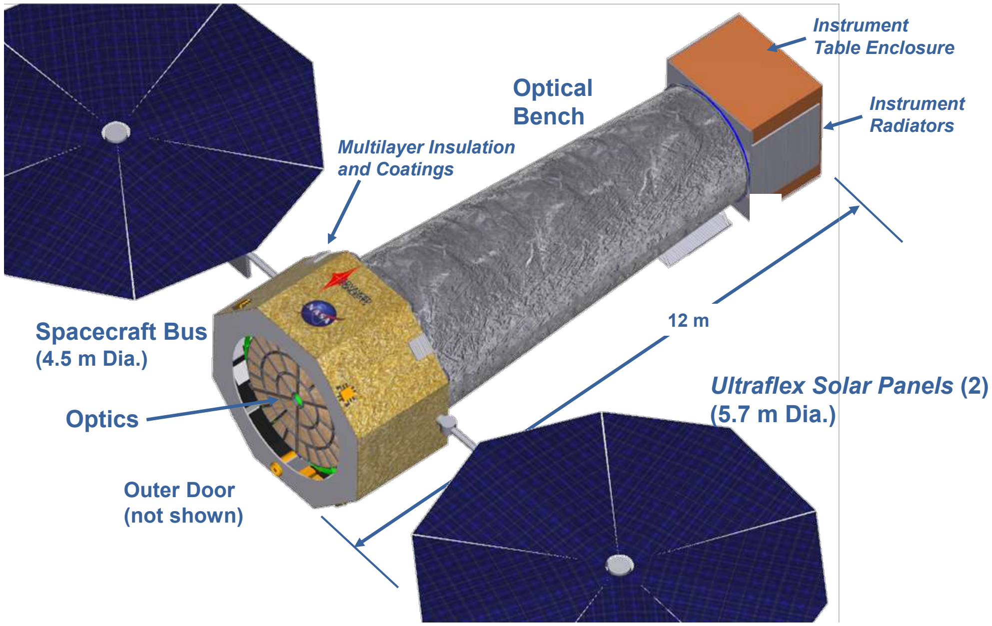
The Lynx High Definition X-ray Imager will provide:
unique and extraordinary science-driven capabilities

- HDXI will achieve <0.5 arcsec imaging resolution (<1 arcsec over a r>10’ field of view) while performing moderate spectroscopy
- HDXI will enable deep and wide surveys, with minimal source confusion
- HDXI will have soft response (<1 keV), enabling studies at high redshift
- The HDXI notional design has benefited and matured rapidly due to the strong efforts of the MSFC-ACO instrument design process and the GSFC Instrument Design Lab (IDL) process.

Thank You!

For the latest Lynx news and events, and to sign up to the News Distribution visit us at:

https://wwwastro.msfc.nasa.gov/lynx/



Backup Slides

CMOS Hybrid Sensors (PSU/Teledyne)

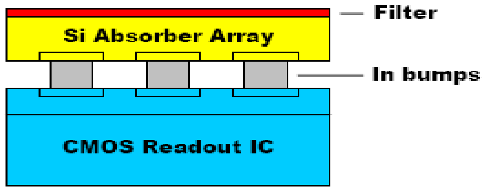
- Silicon detector array and readout array bump-bonded together
  - Allows separate optimization of detector and readout
  - Readout electronics for each pixel
  - ***Optical blocking filter deposited on detector***
- Based on IR detector technology with heritage from JWST and high TRL/flight-heritage from OCO
- Back illuminated with 100-300 micron fully depleted depth
  → ***excellent QE across 0.2-15 keV band***
- Inherently **radiation hard**, with no charge transfer across detector
- Up to 4k×4k pixels, with abuttable designs
- ***High speed*** (10 Mpix/sec × N outputs) with ***low-power***
- Read noise (~5-10 e^-) needs improvement. Fano-limited performance is expected, with work in progress.

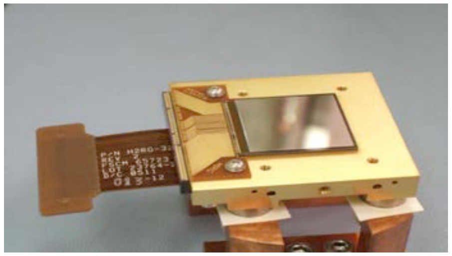
Selection of recent progress

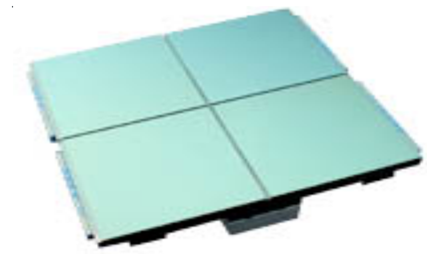
- Inter-pixel ***crosstalk eliminated*** with CTIA amplifiers
- ***Event-driven readout*** on 40 μm pixels (very fast frame rates)
- New test devices with small ***(12.5 μm) pixels*** *and* ***in-pixel CDS***, fabricated and tested to have ~5.6 e- readnoise

Future work:

- (1) scaling small-pixel test design up to larger detector, (2) reduce read noise further with improved component tolerance, while maintaining low read noise at high readout rates, (3) attempting to implement event-driven readout in smaller pixels, (4) investigating sub-pixel centroiding in large pixels



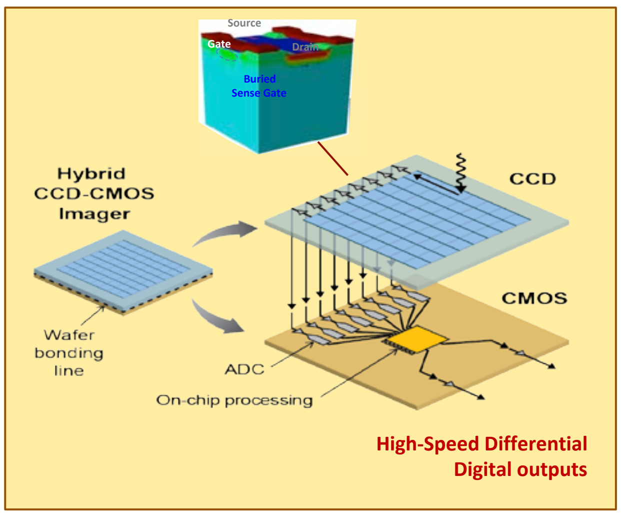


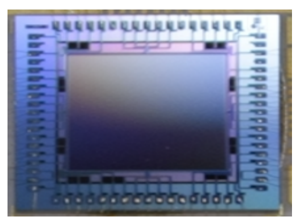


Hybrid CMOS X-ray detectors, Falcone et al.

Digital CCD (MIT Lincoln Laboratory)

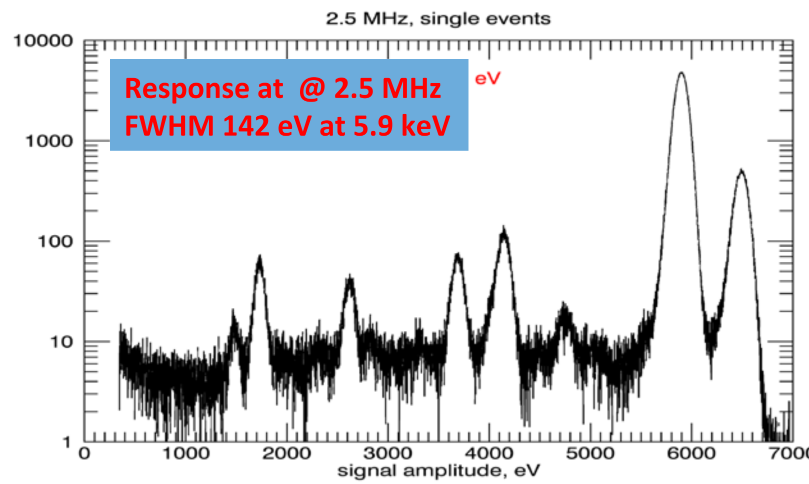
Concept: Hybrid CCD-CMOS Imager
- High Frame Rate
  - Very fast outputs (~5 MHz)
  - Integrated parallel signal chains
- Low Noise: High-responsivity, sub-electron read noise amplifier
- Low-power: CMOS-compatible CCD



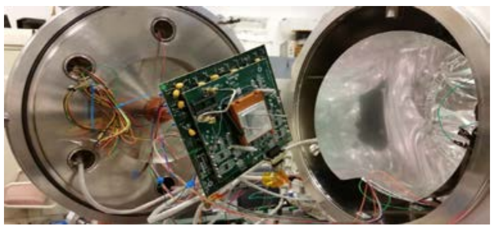


Test Device

Current status: CMOS-compatible CCD with conventional amplifier:
- Noise < 7 e^- RMS @ 2.5 MHz (25x faster than Chandra)
- Excellent charge transfer at CMOS levels (± 1V; ~same clock power/area as Chandra @ 25x higher rate)
- 8 µm pixels (oversamples Lynx PSF)



Monolithic CMOS Sensors (SAO/Sarnoff)



BI Monolithic device with Optical Blocking Filter in SAO test chamber

- 1k by 1k, 16μm pitch devices.
- High sensitivity ~135μV/e pixel (<Carbon x-ray> produces ~10mV @ pixel!)
- Row-at-a-time on chip CDS (1k by 1k device can CDS process 1k pixels in ~20μ sec)
- Modest cooling requirements. Back thinned by Mike Lesser @U. of Arizona
- High through-put mitigates dark current and out-of-band optical light

Pixel size and soft response well matched to envisioned Lynx optic PSF

2016 APRA: Demonstrate PMOS devices (photo holes vs photo electrons)

- Lower read noise (~1h rms)
- "No" Random Telegraph Signal (RTS) noise
- Lower recombination of photo charge