THE LYNX MISSION

REVEALING THE INVISIBLE UNIVERSE

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- On behalf of the Science and Technology Definition Team (STDT)
1. Lynx – X-Ray Mission
2. LUVOIR – Large UV Optical IR
3. OST - Origins Space Telescope Far IR
4. HabEx – Habitable Exoplanets
Lynx STDT Community Members

- Steve Allen, Stanford
- Mark Bautz, MIT
- Niel Brandt, Penn State
- Joel Bregman, Michigan
- Megan Donahue, MSU
- Laura Lopez, Ohio State
- Jessica Gaskin, MSFC (Study Scientist)
- Alexey Vikhlinin, SAO (Co-Chair)
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- Ryan Hickox, Dartmouth
- Piero Madau, UCSC
- Daniel Stern, JPL
- Eliot Quataert, Berkeley
- Zoltan Haiman, Columbia
- Tesla Jeltema, UCSC
- Rachel Osten, STScI
- Dave Pooley, Trinity
- Chris Reynolds, UMD
- Andrey Kravtsov, Chicago

- 8 Science Working Groups
- Optics Working Group
- Instrument Working Group
- 7 ex-officio International members

About 300 total members!
Much of the baryonic matter and the settings of the most active energy release in the Universe are visible primarily or exclusively in the X-rays, so…

❖ A symbol of great insight
❖ Ability to see through rocks and trees to reveal the true nature of things.

The historic Accademia dei Lincei (Academy of the Lynx) based their name on this ability to perform incisive and penetrating investigations of the natural world.

Galileo himself was a proud member, and the Academy of the Lynx coined the term telescope for his marvelous device for peering into the cosmos.
The Big Questions:

How does the Universe work?

and

How did we get here?

Science goals mapped into the structure of the Science Working Groups:

- First Accretion Light in the Universe
- Cycles of Baryons in and out of Galaxies
- Physics of Energy Feedback
- Physics of Cosmic Plasmas
- Stellar Lifecycles
- Evolution of Structure and AGN populations
- Physics of High Density Matter, Compact Objects, and Accretion
**LEAPS IN CAPABILITY**

- High sensitivity in the soft X-ray band. First Accretion Light science requires mirror effective area \( \gtrsim 2 \) square meters at \( E < 2 \) keV.

- High angular resolution (sub-arcsec) is key for nearly all *Lynx* science. Desire 0.5 arcsec or better resolution.

- Detectors should provide fine imaging, low internal background, and high resolution, spatially resolved spectroscopy.

- Very high spectral resolution \( (R \gtrsim 5000) \) in the soft band.
Lynx Optics & Science Instruments

- Large-Area High-Angular-Resolution Optical Assembly
- High Definition X-Ray Imager
- X-Ray Microcalorimeter Imaging Spectrometer
- X-Ray Grating Spectrometer
Lynx X-Ray Optics and Concept

\( \Phi 3\text{m, } f=10\text{m} \) mirror system, with *Chandra*-like total mass

JWST Primary Mirror: 6.5 m
Lynx Mirror: 25 m
Taxonomy of X-ray Telescope Fabrication

- Full Shell (MSFC, SAO)
- Thermal Forming (GSFC, SAO)
- Air Bearing Slumping (MIT)
- Deposition (MSFC, XRO)
- Piezo stress (SAO/PSU)
- Magnetic & deposition stress (NU)
- Full shells (inner shells only)
- Segmented Assembly
- Ion implant stress (MIT)
- Ion beam
- Implanted layers
- INTEGRATION
- Segments
- NuSTAR

Thanks to Dan Schwartz

Schattenburg – NASA PCOS SIG, 04/2016
Mirror Fabrication

**Full Shell**

- Metal, fused silica (MSFC, SAO)
- Replication
  - Diamond turn mandrel
  - Electroform replication
- Direct Fabrication
  - Zeeko polishing machine

**Segmented**

- Glass thermal forming (GSFC, MIT, SAO)
- Slumping (GSFC, SAO)
- Air bearing slumping (MIT)
- Silicone optics
  - Slice & polish (GSFC)
  - Pore optics (ESA)
Mirror Correction

Material Add or Subtract

- Sputter deposition (MSFC, XRO, Inc.)
- Multipass metrology/polish (GSFC, MSFC)
- Others (ion polish, magnetorehologic polish, fluid jet polish, etc.)

Stress Layer

- Piezo stress (SAO/PSU)
- Magnetic stress (NU)
- Sputter deposition stress (NU)
- Ion implant stress (MIT)
Next-Generation X-ray Mirror

New mirror is built from densely packed thin mirror elements. 3.0m outer diameter. ~1200 kg for 2.3m² of collecting area

Chandra mirror shells are 2.5cm thick. 1,500 kg for 0.08m² of collecting area

Innovative technologies for mirror elements are pursued at MSFC, SAO, GSFC, MIT, etc. Optics Working Group is in place, with a charge to facilitate technology development, industry participation, and assist the STDT with the trades and development of the technology development roadmap.
High throughput with sub-arcsec resolution

- × 50 more effective area than Chandra.
- × 16 larger solid angle for sub-arcsec imaging — out to 10 arcmin radius
- × 800 higher survey speed at the Chandra Deep Field limit
**X-ray Microcalorimeter Imaging Spectrometer ("Whiskers")**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>0.2 – 10 keV</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>1 arcsec</td>
</tr>
<tr>
<td>Field-of-View</td>
<td>5 arcmin x 5 arcmin (min)</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>&lt; 5 eV</td>
</tr>
<tr>
<td>Count Rate Capability</td>
<td>&lt; 1 c/s per pixel</td>
</tr>
<tr>
<td>Pixel Size / array size (10-m focal length)</td>
<td>50 µm pixels / 300 x 300 pixel array</td>
</tr>
</tbody>
</table>

**Challenge:** Develop multiplexing approaches for achieving ~$10^5$ pixel arrays
Progress with respect to multiplexing:

- Transition Edge Sensors (TES) with SQUID readout.
- Multiple absorbers per one TES ("Hydra" design)

- Lab results with $3 \times 3$ Hydra, 65μm pixels on 75μm pitch shows 2.4 eV (FWHM) resolution at 6 keV
- 20-absorber TES Hydras have been successfully implemented. Absorbers are 50x50x4.2μm electroplated Au
- $<\Delta E_{\text{FWHM}}>$ = 3.39 ± 0.18 eV at Cr(5.4 keV) for all 20 pixels.

High Definition X-ray Imager ("Spots")

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<tbody>
<tr>
<td>Energy Range</td>
<td>0.2 – 10 keV</td>
</tr>
<tr>
<td>Field of View</td>
<td>22 arcmin x 22 arcmin</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>37 eV @ 0.3 keV, 120 eV @ 6 keV (FWHM)</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>&gt; 90% (0.3-6 keV), &gt; 10% (0.2-9 keV)</td>
</tr>
<tr>
<td>Pixel Size / Array Size</td>
<td>&lt;16 µm (&lt; 0.33 arcsec/pixel) / 4096 x 4096 (or equivalent)</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>&gt; 100 frames/s (full frame)</td>
</tr>
<tr>
<td></td>
<td>&gt; 10000 frames/s (windowed region)</td>
</tr>
<tr>
<td>Read Noise</td>
<td>&lt; 4e⁻ rms</td>
</tr>
</tbody>
</table>

All have been demonstrated individually

Challenges: Develop sensor package that meets all requirements, and approximates the optimal focal surface
Advantages of Active Pixel Sensors

Current State of the Art

- All of the key requirements are met by one or more of the sensor technologies
- No single sensor meets them all – lots of work to do!

Key Advantages:

- 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
- Near room temperature operation
- Large format (up to 4Kx4K abutable devices)

X-Ray Grating Spectrometer ("Claws")

Resolving power = 5000 & effective area = 4000 cm²

- Energy range 0.2 – 2.0 keV

Challenges: improving yield, developing efficient assembly processes, and improving efficiency
CAT grating combines advantages of transmission gratings (relaxed alignment, low weight) with high efficiency of blazed reflection gratings.

Blazing achieved via reflection from grating bar sidewalls at graze angles below the critical angle for total external reflection.

High energy x rays undergo minimal absorption and contribute to effective area at focus.

200 nm pitch CAT grating bars

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 \mu m  
aspect ratio d/b = 150
Critical Angle Transmission Gratings (MIT)

Advantages:
- low mass
- relaxed alignment & figure tolerances
- high diffraction efficiency
- up to 10X dispersion of Chandra HETGS
- no positive orders (i.e., smaller detector)

- Gratings, camera, and focus share same Rowland torus.
- Blazed gratings; only orders on one side are utilized.
- Only fraction (50%) of mirrors is covered: “sub-aperturing” boosts spectral resolution.

Schattenburg –XR-SIG meeting, Jan. 5, 2014
LYNX
X-ray vision into the “Invisible Universe” for true understanding of the origins and underlying physics of the cosmos

- **Leaps in Capability:** large area with high angular resolution for 2–3 orders of magnitude gains in sensitivity, field of view with subarcsec imaging, high resolution spectroscopy for point-like and extended sources. May be possible with a *Chandra*-like overall mission envelope.

- **Scientifically compelling:** frontier science from Solar system to first accretion light in Universe; revolution in understanding physics of astronomical systems.

- **Synergy:** Great synergy and complementarity with the next-generation facilities ― JWST, WFIRST, GSMT, LISA, ALMA, SKA

www.astro.msfc.nasa.gov/lynx
BACKUP SLIDES
**Athena**

Key Goals:
- Microcalorimeter spectroscopy ($R \approx 1000$)
- Wide, medium-sensitivity surveys

Area is built up at the expense of angular resolution (10× worse) & sensitivity (5× worse than Chandra)

**X-ray Surveyor**

Key Goals:
- Sensitivity (50× better than Chandra)
- $R \approx 1000$ spectroscopy on 1″ scales, adding 3rd dimension to data
- $R \approx 5000$ spectroscopy for point sources

✓ Area is built up while preserving Chandra angular resolution (0.5″)
✓ 16× field of view with sub-arcsec imaging

**Chandra**
A Successor to Chandra

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

- Incorporated relevant prior (Con-X, IXO, AXSIO) development and Chandra heritage
- Limits most spacecraft requirements to Chandra-like
- Achieves Chandra-like cost ($2.95B for Phase B through launch)
The Lynx Science Case

Doug Swartz
Universities Space Research Association
Great Observatories of the 1980’s and 1990’s:
- *Hubble, Compton, Chandra, Spitzer*
- Open Discovery Space

Targeted Missions addressing Specific Questions:
- *Planck, Kepler*
- Meeting Gov’t-funded “Metrics”

What will be the mission for the 2030’s?

- Steve Kahn @ Lynx Synergy Workshop
Though astronomers have been studying stars for thousands of years, it is only in the past 35 or so years that they have been able to employ instruments that detect light across the entire electromagnetic spectrum—from radio waves to gamma rays—to peer into the dusty clouds where stars are born in our own Galaxy. **If we are to comprehend how the universe makes stars—and planets that orbit them today—we must continue to study stars and galaxies with ever more powerful telescopes.**

It is still unknown whether the universe created black holes with the first generation of stars or whether these exotic objects were created by the first generation of stars. **Because black holes represent the most extreme physical conditions of spacetime and generate some of the most energetic phenomena following the Big Bang, black holes are the ultimate physical laboratories for testing theories of the universe.**
Seven Science Working Groups
Cassiopeia A SNR

Si
Fe
O/Ne/Mg
Imagine what can be done with a micro-calorimeter!
NGC 6357 Star-Forming Region

Supernova-blown Cavities

- Giant HII region w/ 3 MYSCs
- 1.7 kpc distant; ~30’ diameter
- 3100 X-ray sources
  - magnetic reconnection flares, protostars, massive star wind shocks
  - add IR: best stellar census
- unresolved emission is hot plasma due to massive star wind shocks
- transport of metals
  - ISM heating = star formation quenching, gas dispersion, turbulence
  - \( \Rightarrow \) stellar feedback

- Leisa Townsley et al.
• Giant HII region w/ 3 MYSCs
• 1.7 kpc distant; ~30’ diameter
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=>stellar feedback

- Leisa Townsley et al.
Imagine Chandra resolution with 30x throughput!
• **stellar feedback** extends to galactic scales
• drives baryons into the CGM and regulates galaxy growth
• SNe in dwarf galaxies
• **AGN feedback** in massive galaxies

**M82 Starburst Galaxy**

- cool warm and hot X-ray-emitting galactic super wind in M82
Optical light sees ‘only’ the stars

- actual distribution of galaxies in the nearby Universe to $z \sim 0.1$
- traces the Cosmic Web filaments, galaxy groups, and clusters of galaxies
Imagine tracing the Cosmic Web with X-ray spectroscopy!

Optical light sees ‘only’ the stars

- **AGN feedback** regulates growth of LSS (groups/clusters) at cosmic web ‘nodes’
- Hot, diffuse IGM contains most of the baryons (UV absorption spectra sample only a small fraction)

- Color denotes gas Temperature
- Same simulations but different feedback treatments give very different observational results


*Imagine tracing the Cosmic Web with X-ray spectroscopy!*
First accretion light in the Universe

Masses of initial BH seeds
Early accretion history of seed BHs
Contribution to Re-ionization
Observational signatures of Super-Eddington flows
Importance of mergers
When do the correlations between BHs and their hosts get set-up

- Priya Natarajan @ X-ray Vision Workshop
First accretion light in the Universe

Low-mass Seeds from Pop III stars at $z \sim 20$
- $10-100 \, M/M_\odot$ but mass and number of first stars uncertain
- A challenge to grow to $10^9 \, M/M_\odot$ by $z \sim 3$; requires super-Eddington growth

Massive Seeds by Direct Collapse
- $1000 \, M/M_\odot$ collapse of a nuclear star cluster
- Higher mass seeds only postulated
- Must mitigate H$_2$ cooling
- Must avoid fragmentation of porto-galaxy & centrally concentrate mass

Masses of Initial Black Hole Seeds
First accretion light in the Universe

Early accretion history of seed black holes

massive seeds vs. Pop III remnants
Only Lynx has the sensitivity and angular resolution needed:

- Can detect $5 \times 10^4 \, M_\odot$ seeds at $z \sim 10$
- Confusion limit: expect only 0.03 galaxies per 0.5” Lynx beam
It is still unknown whether the universe created black holes with the first generation of stars or whether these exotic objects were created by the first generation of stars.

When do the correlations between BHs and their hosts get set up
It's tough to make predictions, especially about the future

- Yogi Berra