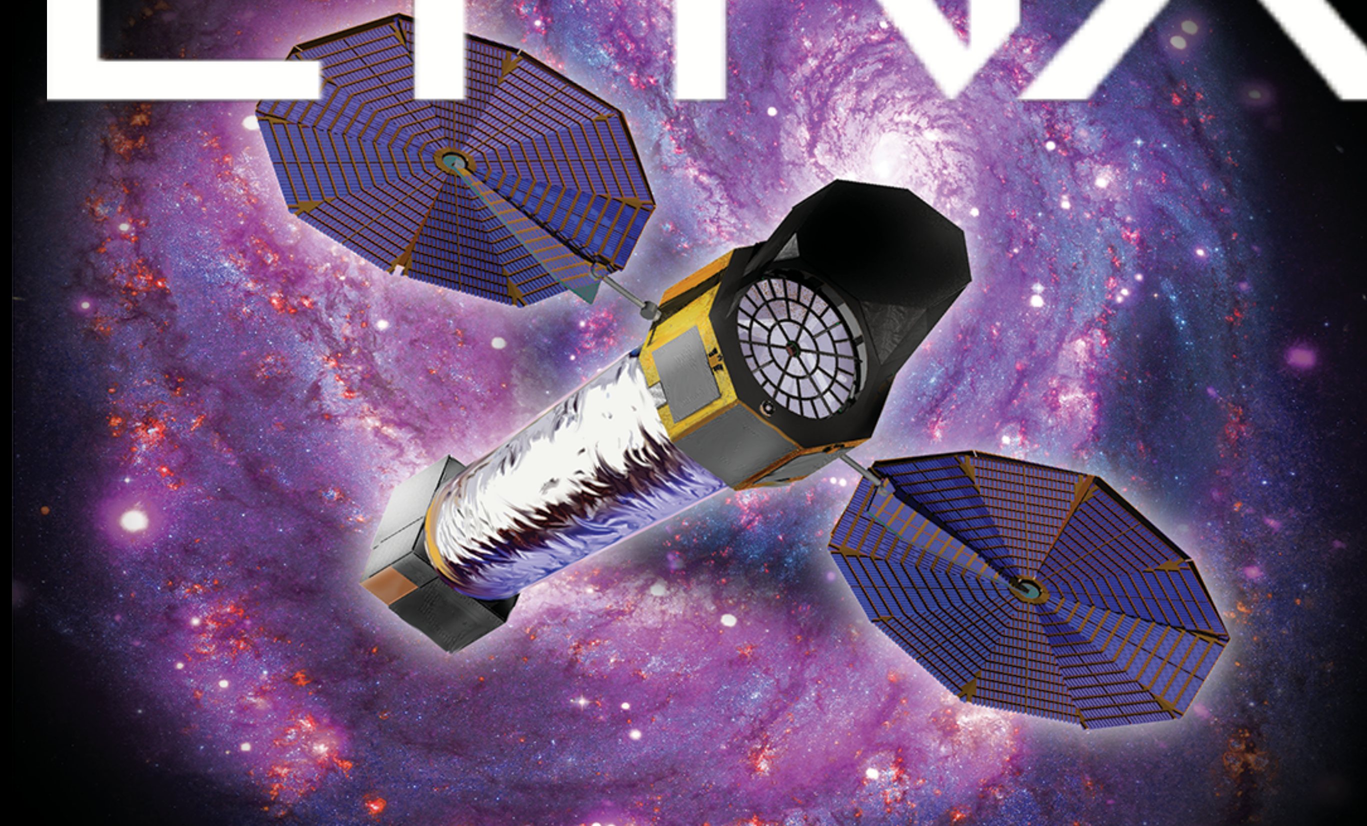
X-RAY OBSERVATORY LYNX



Reveals the otherwise invisible Universe
- to see ***the dawn of black holes***,
- reveal ***what drives galaxy formation and evolution***, and
- unveil ***the energetic side of stellar evolution and stellar ecosystems.***

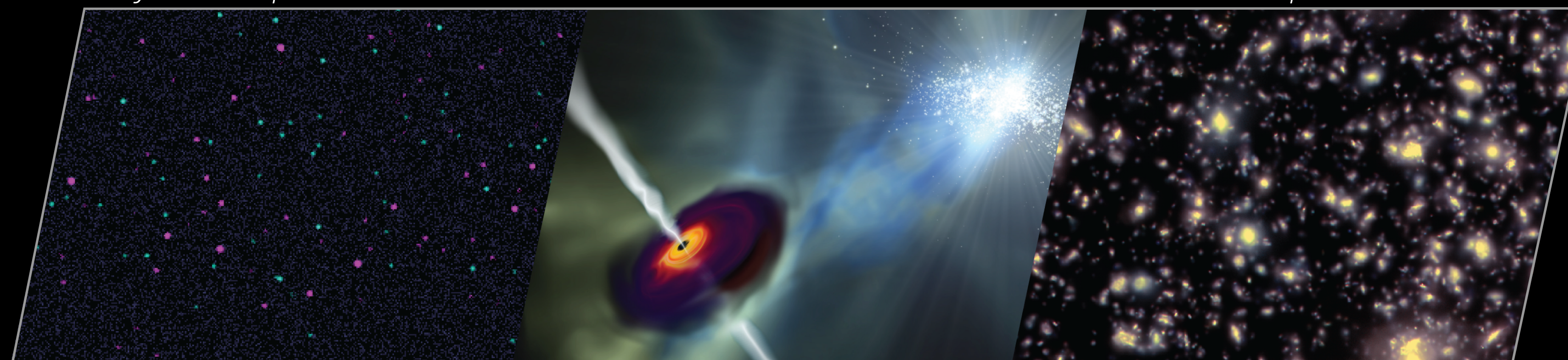
Alexey Vikhlinin, co-chair of *Lynx* STDT

X-RAY OBSERVATORY

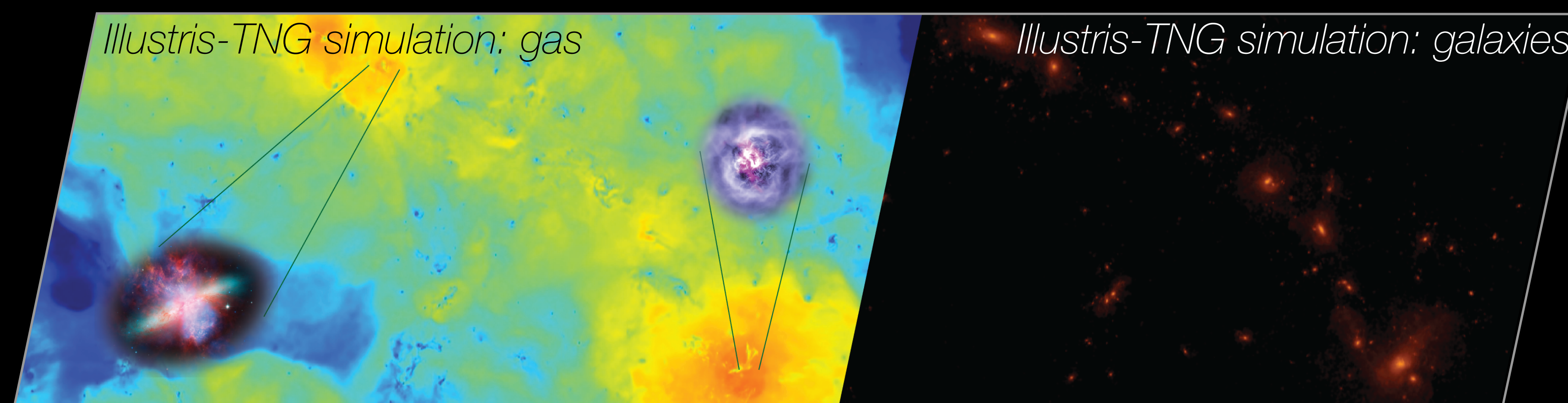
LYNX

The Dawn of Black Holes

Lynx deep field *JWST deep field*



The Invisible Drivers of Galaxy and Structure Formation

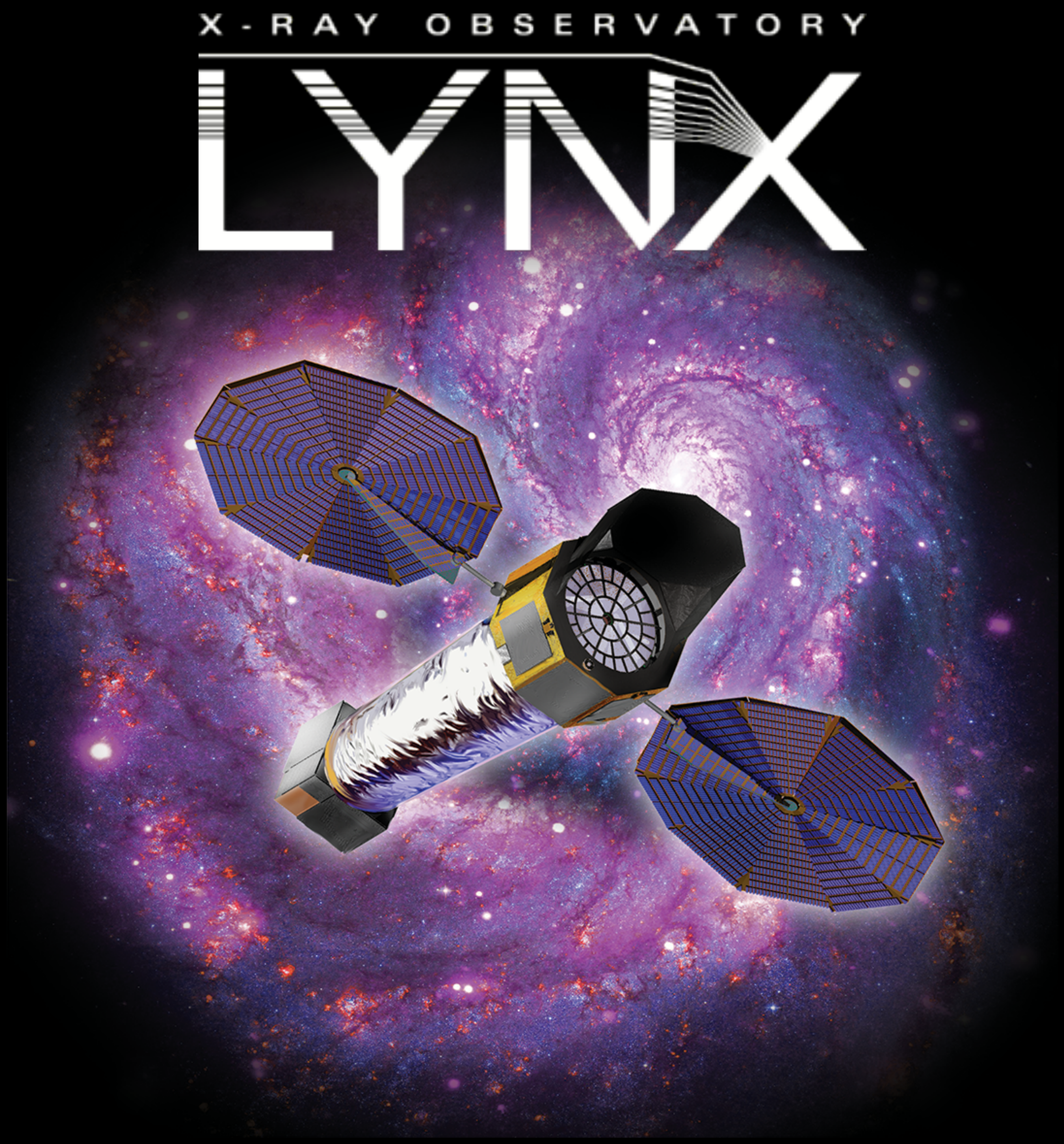


The Energetic Side of Stellar Evolution and Stellar Ecosystems

Endpoints of stellar evolution

Stellar birth, coronal physics, feedback

Impact of stellar activity on habitability of planets



Leaps in capability over *Chandra* and *ATHENA*:

- 50× increase in sensitivity via coupling superb angular resolution with high throughput;
- 16× larger field of view for sub-arcsecond imaging, leading to a 800× faster survey speed;
- 10–20× higher spectral resolution for both point-like and extended sources.

Science Traceability Matrix

Science theme / goal	Performance Driver	Key observations, physical parameters, and measurement requirements		Mirror and instrument requirements			Also required by Key Science Objectives
				Inst.	Property	Value	
Observe the Dawn of Black Holes	Observe progenitors of supermassive black holes at their seed stage or soon after.	Detection of black holes in z=6–10 galaxies down to a mass limit of M_{lim}=10,000 M_{sun} over a volume with 10^{5}–10^{7} potential host galaxies	Surveys with flux limits [0.5–2 keV]: • 1.6×10^{-19} erg/s/cm^2 over 1deg^2 • 7×10^{-20} erg/s/cm^2 over 400 arcmin^2	Mirror + HDXI	Angular resolution	<1" (HPD) across the field, 0.5" on-axis	• Tracing how growth of SMBHs proceeds from cosmic dawn to z ~ 3, and how these SMBHs are connected to their host galaxies • Search for SMBH seed relics in nearby galaxies • Cross-correlation of X-ray background with 21cm signals • Mapping diffuse baryons in Cosmic Web in emission. • QUICK SURVEY NEAR LISA SOURCES • Post-merger evolution of GW sources
					Grasp	600 m2 arcmin2	
					Imager pixel size	0.33"	
Reveal the Invisible Drivers of Galaxy and Structure	Observe the state of diffuse baryons in galactic halos	Direct imaging of hot gas in galactic halos in continuum and line emission	Image 15 low-z galaxies with M~3×10^{12} M_{sun} to reach 10% accuracy for derived thermodynamic parameters of gas in halos at 0.5 r_{200}.	Mirror + HDXI	Effective area @ 1 keV	2 m2	• Identifications of young stars in active star forming regions to d=5 kpc • Protoplanetary disk dissipation time scales. • Statistics of X-ray binary populations in nearby galaxies to constrain binary evolution models and evolutionary paths to LIGO sources • **Quasar microlensing** • Characterization of first galaxy groups at z=3–4
					Angular resolution	1" (HPD) across the FOV, 0.5" on-axis	
					Field of view	10' radius	
					Spectral resolution @ 1 keV	60 eV	
					Spectral resolution for LXM imaging in individual lines(*)	2 eV	
		Absorption line spectroscopy of galactic halos near virial radius	Observe 80 sight lines to reach the sensitivity of 1 mA for OVII and OVIII absorption lines, to characterize galactic halos near virial radius 60 galaxies with mass 10^12-10^13 Msun	XGS	Spectral resolving power	5000	• Spectroscopy of G-stars • Impact of stellar XUV flux on planetary atmospheres • Physics of accretion on young stars • Dynamos in pre-main sequence and young main sequence stars • Stellar coronal mass ejections • Energetics of AGN feedback • State of gas in the Milky Way halo
					Mirror + gratings effective area **AT ENERGIES**	4000 cm2	

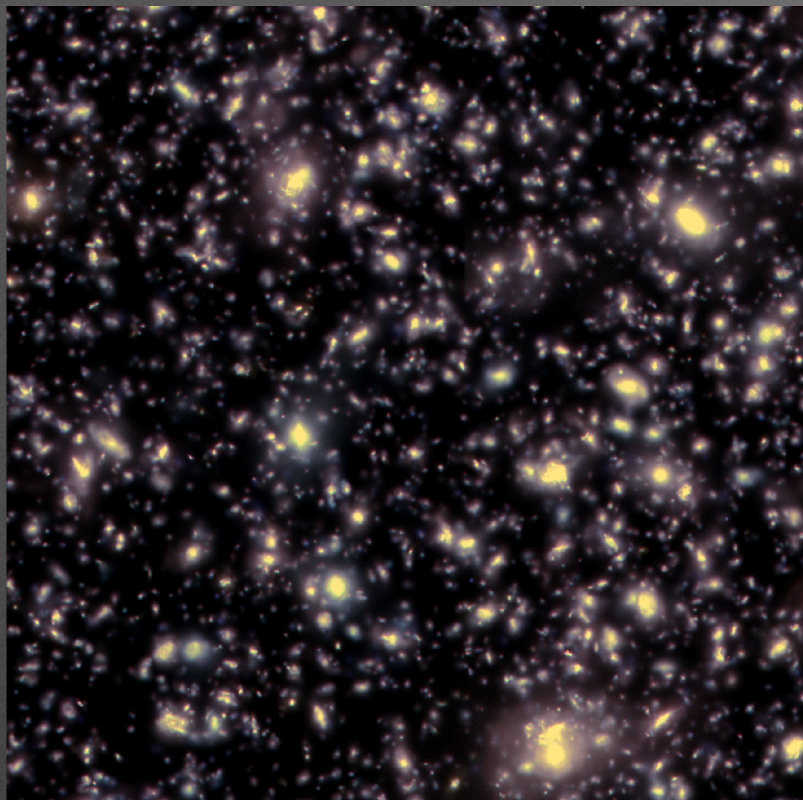
The Dawn of Black Holes

The Invisible Drivers of Galaxy and Structure Formation

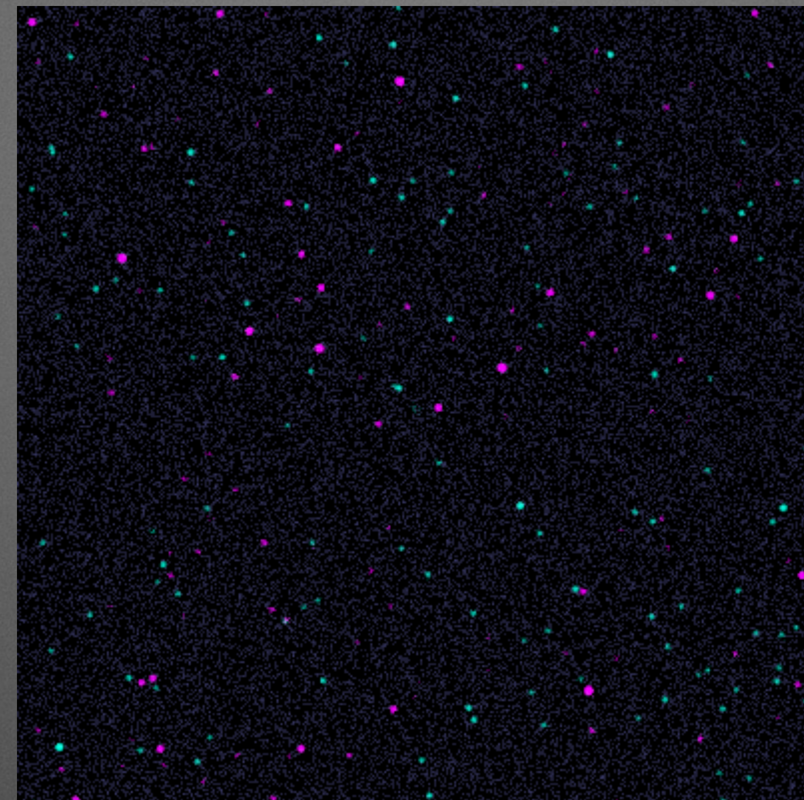
The Energetic Side of Stellar Evolution and Stellar Ecosystems

Angular resolution

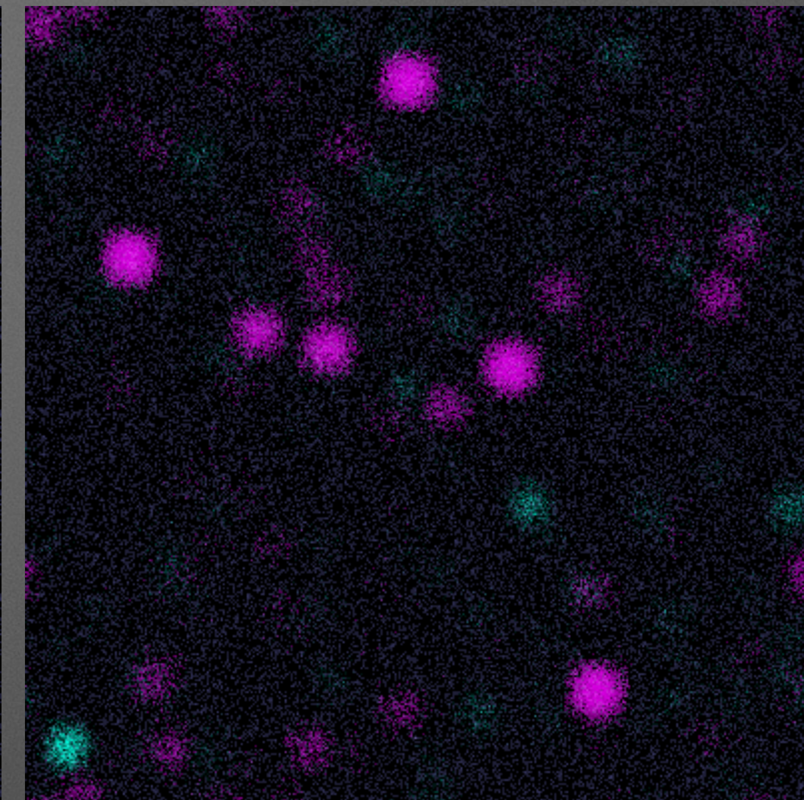
Simulated 2’×2’ deep fields:
JWST (Illustris-TNG light cone)



Lynx (purple = AGNs, green=galaxies)



Athena (5” PSF, same area as Lynx)



- Finding the first supermassive black holes in the first galaxies detected by JWST and trace their growth from the seed phase (M_{BH}=10,000 M_{Sun} at z=10) **requires sensitivities ~ 10^{-19} erg/s/cm^2**
- To avoid source confusion at these fluxes, and to uniquely associate X-ray sources with JWST and WFIRST galaxies **requires angular resolution < 1″ (HPD) across the field, 0.5″ on-axis.**
- Also required by:
  - Mapping diffuse baryons in emission in the galactic halos and Cosmic Web
  - Studies of young star forming regions
  - Energy feedback studies
  - and nearly all other Lynx science

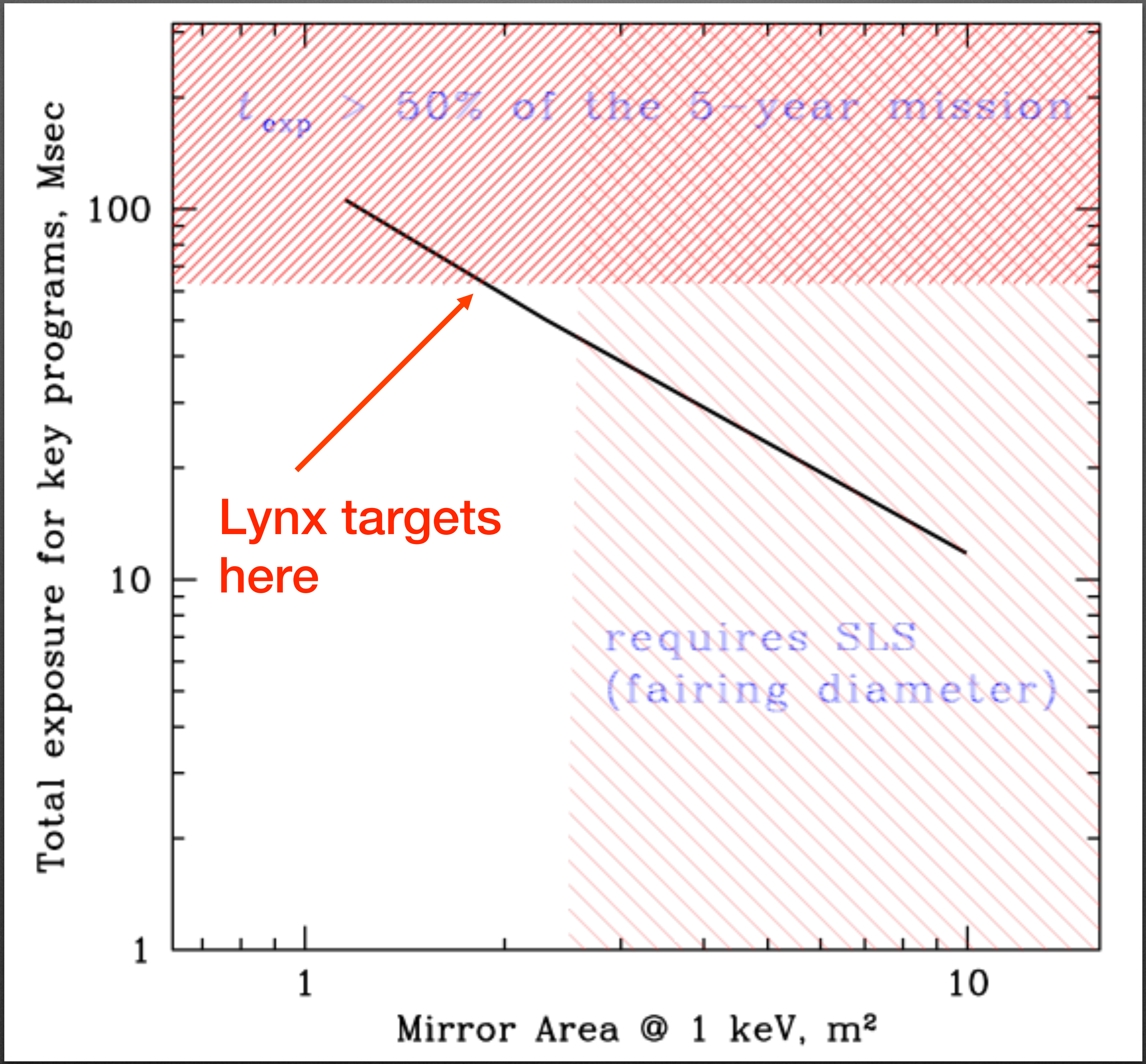
Mirror Size & Focal Length

Notional science program:

First Accretion Light					
1.1 Origin of SMBH seeds					
Surveys over 1 deg^2 to depth fx=1.6e-19 [0.5-2 keV] plus a deeper survey over 400 arcmin^2 to fx=7e-20. The depths are chosen to match the OIR survey from WFIRST and JWST which are likely to exist by the time Lynx is launched.	HPD<1" for 1deg^2 to avoid confusion; HPD<0.8" for 400 arcmin^2 survey to avoid confusion	**23 Msec, texp ~ 1/(Area*FOV)**	1) HPD = 0.75" is available 2) (Telescope Area at 1 keV) * (FOV with HPD<1") is > 2m^2 * 300 arcmin^2 3) Telescope Area at 1 keV) * (FOV with HPD<0.75") is > 2m^2 * 300 arcmin^2	Such surveys will allow us to probe BH masses down to 16,000 Msun (7000 Msun in deep) at z=10 and 6,000 Msun (2,500 Msun in deep) at z=60, if BH's are hosted in the JWST/WFIRST-detected galaxies. In the direct collapse scenario, where black holes are in 10^8 Msun halos ---undetectable by JWST, --- we can probe Mbh=1e5 down to f=focc*fduty=1e-7 or Mbh=50,000 down to f=1e-4 at z=10 or Mbh=30,000 down to f=1e-7 and Mbh=15000 down to f=1e-4 at z=6. HPD requirements likely imply an on-axis resolution of ~ 0.5", but this is a derived requirement here	
1.2 Cross-correlation of residual X-ray background and 21cm signals					survey
A survey with point source sensitivity to fx=1e-18 over 1-5 deg^2. Can be combined with 2.7 below.	Less stringent than those in 1.1	2Msec for 1deg^2 ...	Less stringent than those in ...		
1.3 Search for IMBH - Pop III BH remnants in nearby dwarf galaxies					Lynx-BHC Local BH
Baryon cycles + Feedback					
2.1 State of diffuse baryons in galactic halos -- direct imaging					
Survey of ~ 15 low-redshift isolated (spiral) galaxies, pushing 10% thermodynamic (gas density) measurements to 0.5r500 for M~3e12 and to r200 for M~1e13 Each observation requires an HDXI pointing plus a wide-formal microcalorimeter pointing for narrow-band imaging in O and Fe lines. For 3x10 configuration, these are approximately 500 ksec + 250 ksec observations. With these exposures, statistical uncertainties at the radius of interest approximately match the systematic (surface brightness contrast uncertainties)	2eV energy resolution ... 1eV for ...; large (5") pixels for mucal are OK <1" HPD for HDXI to ... ability to remove faint background sources and reduce XRB fluctuations	**12 Msec, texp ~ 1/(Area*FOV)**	... Telescope Area at 1 keV) * (FOV with HPD<1") is > 2m^2 * 300 arcmin^2 2) (Telescope Area at 1 keV) * (FOV of ... 00 arcmin^2 ... energy ... for mucal		
2.2 State of diffuse baryons in galactic halos -- absorption line spectroscopy					
Observe ~35 AGN sightlines (fagn ~ 1e-11) to detect ~ 100 absorption line systems in the foreground galaxy halos. Detection limits for absorption lines are EW ~ 3mA and down to 1mA for r>r200	R=5000 -- matching thermal widths	**5Msec, texp ~ 1/(Area * grating efficiency * fraction of aperture covered)**	1) R=5000 for gratings spectrometer, R=10000 is a goal 2) (Telescope Area) * (fraction of aperture covered) * (grating efficiency) ~ 4000 cm^2		
2.3 State of gas in MW halo					
Detect and characterize absorption lines in the MW halo, using the same set of AGNs as in 2.2	R=5000 required, R=10000 is a goal, in order to resolve the thermal width of O lines in the MW halow				
2.4 State of gas in high-redshift galaxy clusters and group					
200 ksec observations of ~ 30 objects (=~ the size of high-quality local samples today) with mucal	1 arcsec pixels in mucal 5 arcmin FOV for mucal ~5 eV energy resolution	**6Msec, texp ~ 1/Area**	1) Mucal with 5arcmin FOV and 1" pixels, ~5 eV energy resolution 2) (Telescope Area at 1 keV) > 2m^2		

Mostly, or entirely, a GO program

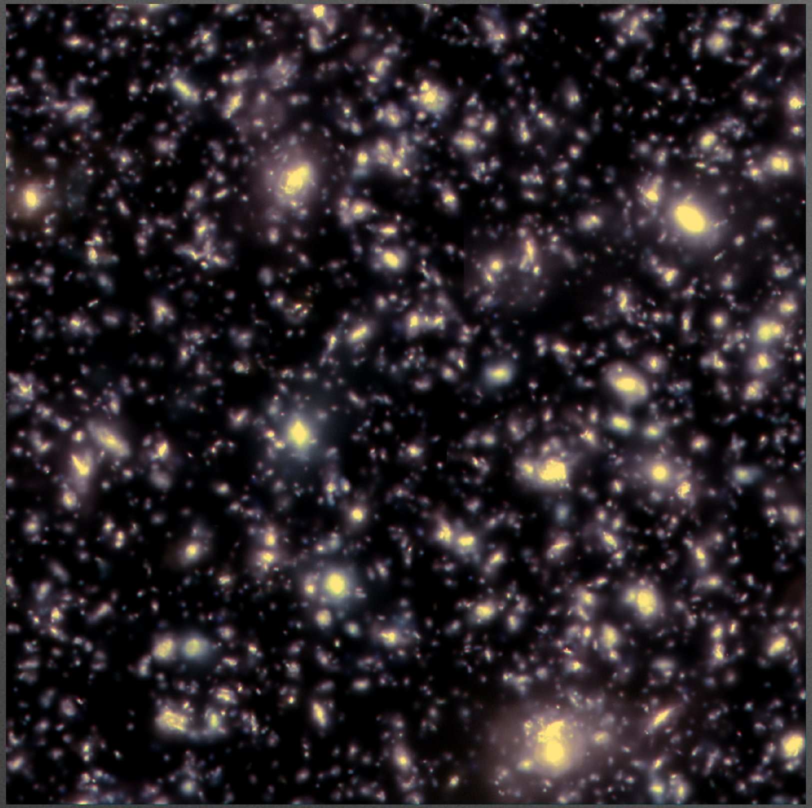
Mirro Size & Focal Length



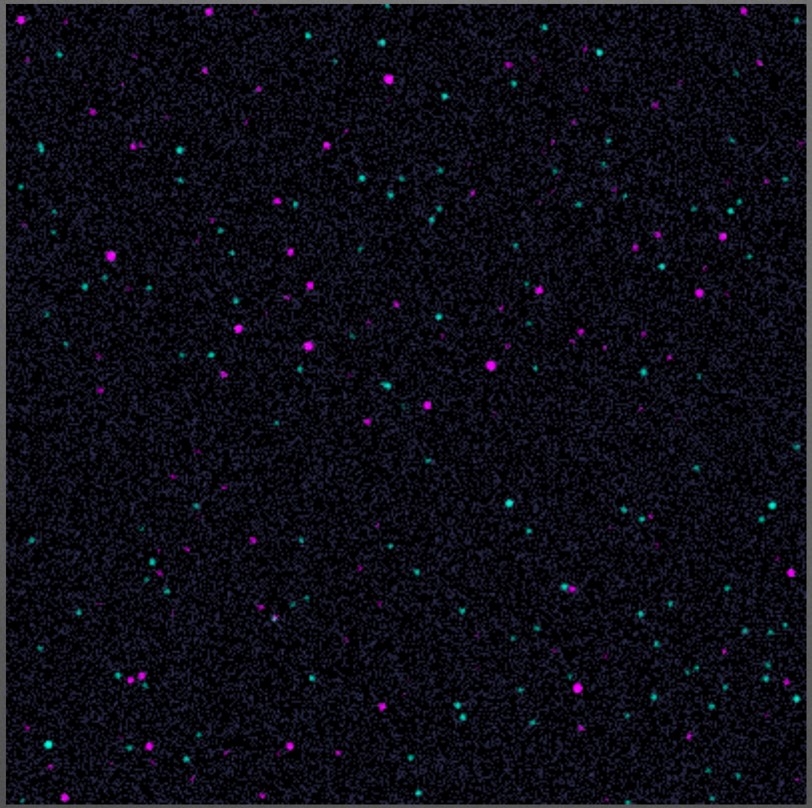
- **2 m² of effective area at *E* = 1 keV is required** to execute the science required by the three pillars in under 50% of the 5-year mission time. **Implies outer diameter ∅ = 3m and *f* = 10m**

Field of View & High-Definition X-ray Imager

Simulated 2'×2' deep fields:
JWST (Illustris-TNG light cone)



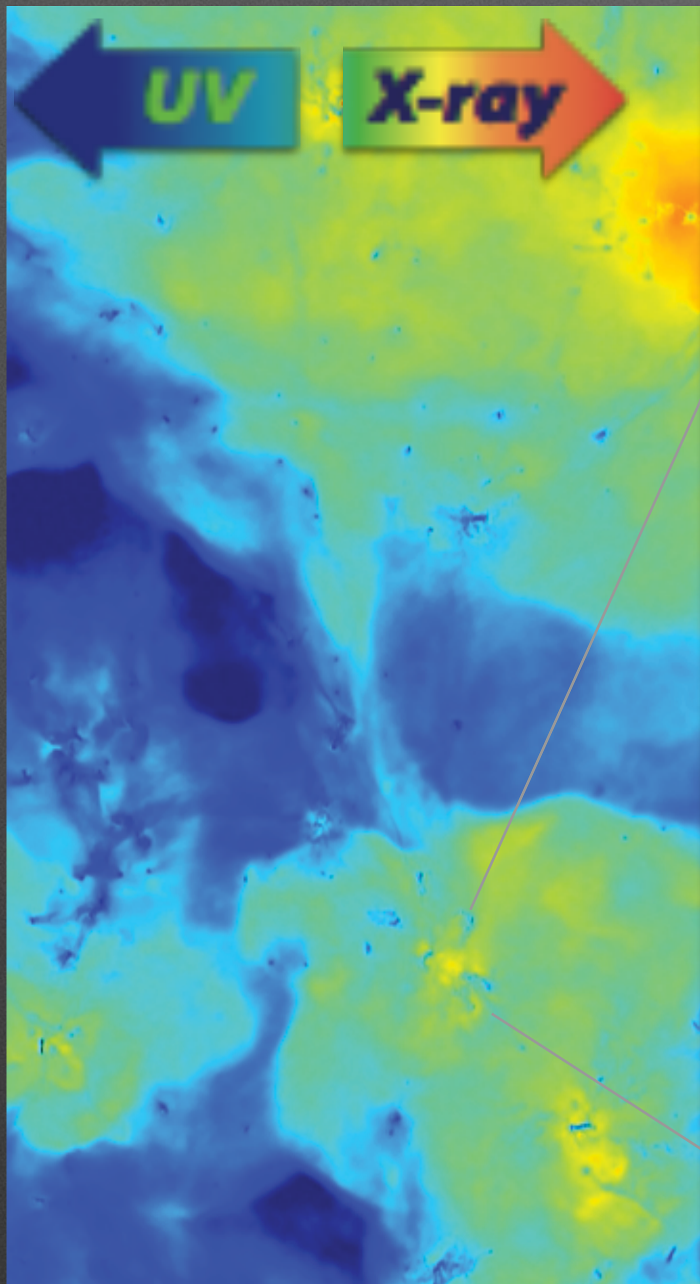
Lynx (purple = AGNs, green=galaxies)

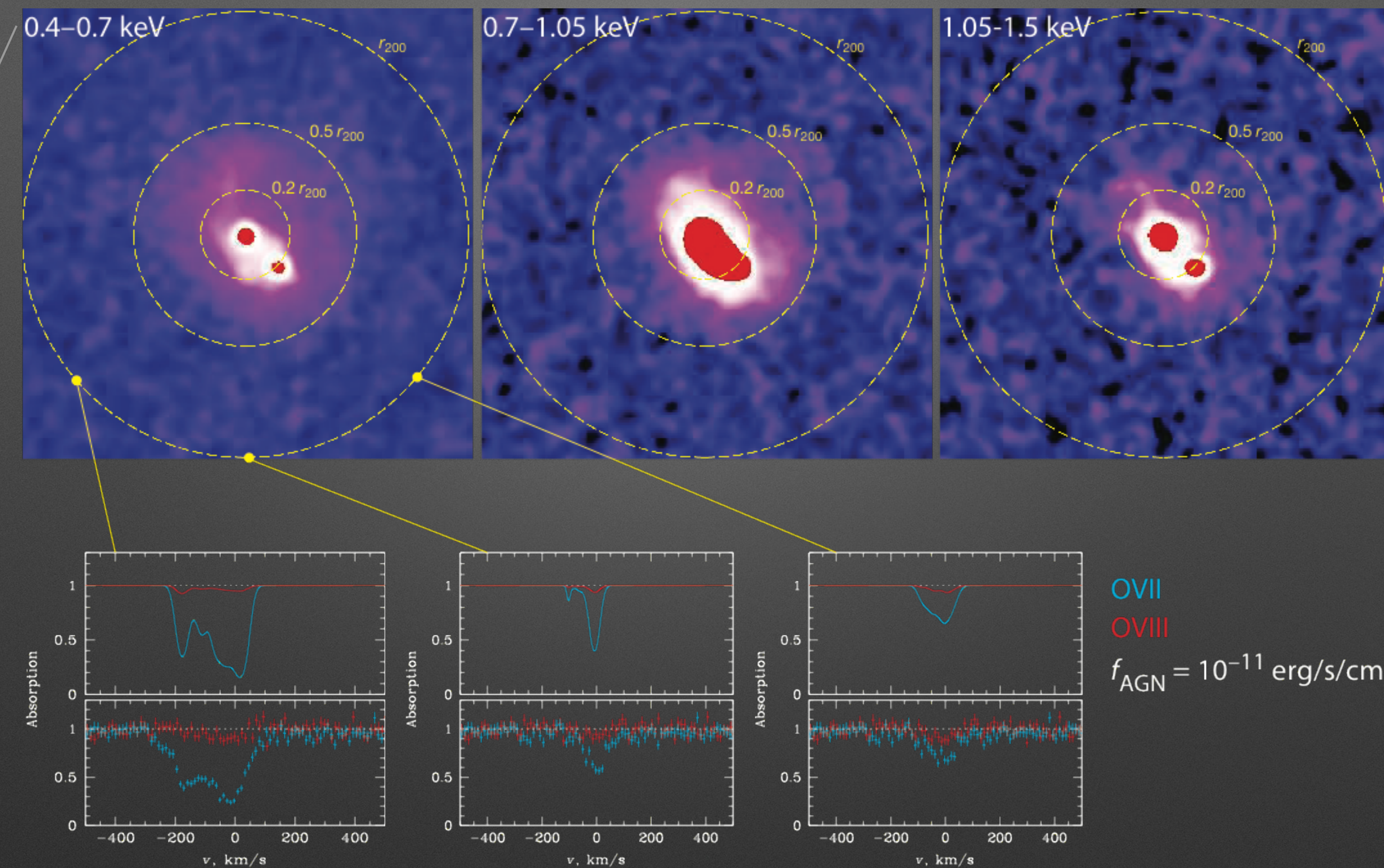


- To constrain black hole seed modes needs surveys with volumes containing 10^3–10^7 potential host galaxies ⟹ ~ 1 deg^2 deep surveys. **This requires FOV with sub-arcsec resolution extending to 10′ radius, *and a matching detector.***

- **HDXI (active pixel sensor)** is a detector with 0.33″ pixels, at least 20′× 20′ FOV, and improved soft-band throughput
- Also required by:
  - Tracing how the growth of SMBHs proceeds from cosmic dawn to z ~ 3, and how these SMBHs are connected to their host galaxies
  - Mapping diffuse baryons in emission in the galactic halos and Cosmic Web
  - Studies of young star forming regions
  - Observe LISA triggers

Grating Spectrometer

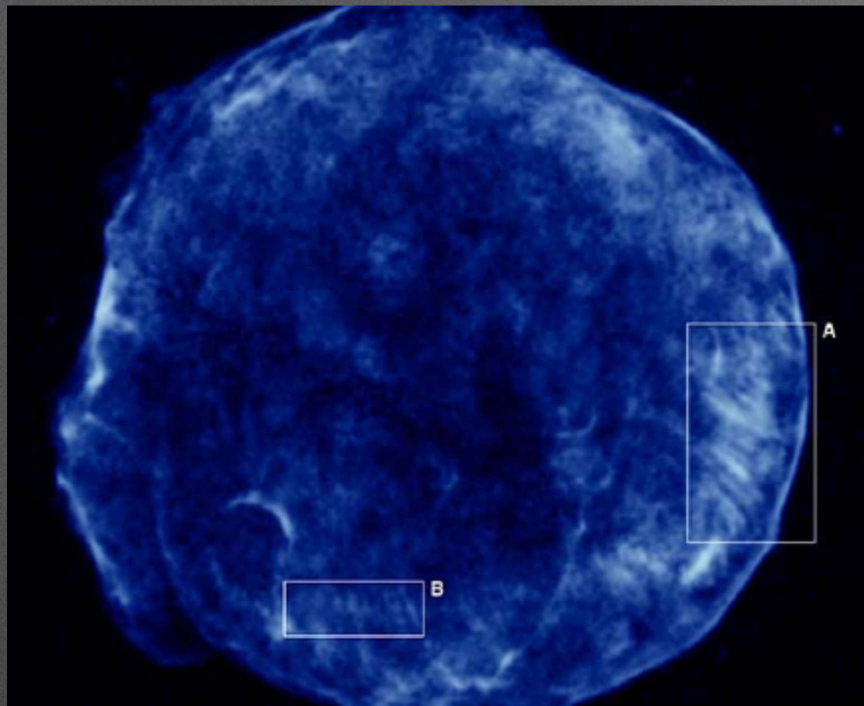


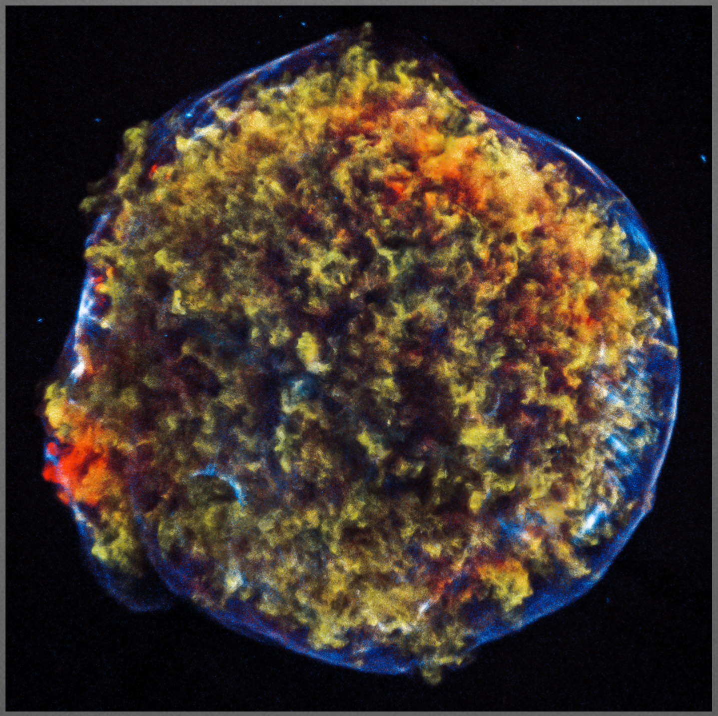
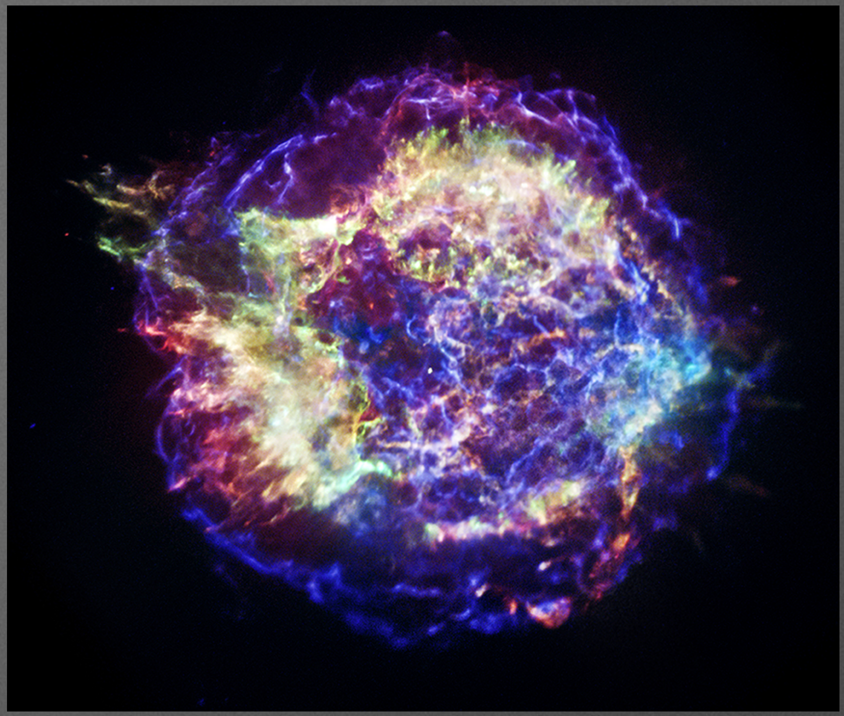


Simulated Lynx 500 ks images and 300 ks spectra revealing detailed halo density, temperature, metallicity, and velocity structures for a $3{\times}10^{12}\ M_{sun}$ galaxy at $z = 0.03$.

- To detect and characterize CGM near virial radius of Milky Way type galaxies **requires grating spectrometer with $R \geq 5000$ and effective area ~ 4000 cm^2 over 0.25–0.7 keV band**
- Also required by:
  - Energetics of AGN feedback
  - Spectroscopy of G stars; impact of stellar actvity on planet habitability; physics of accretion on pre-main sequence stars

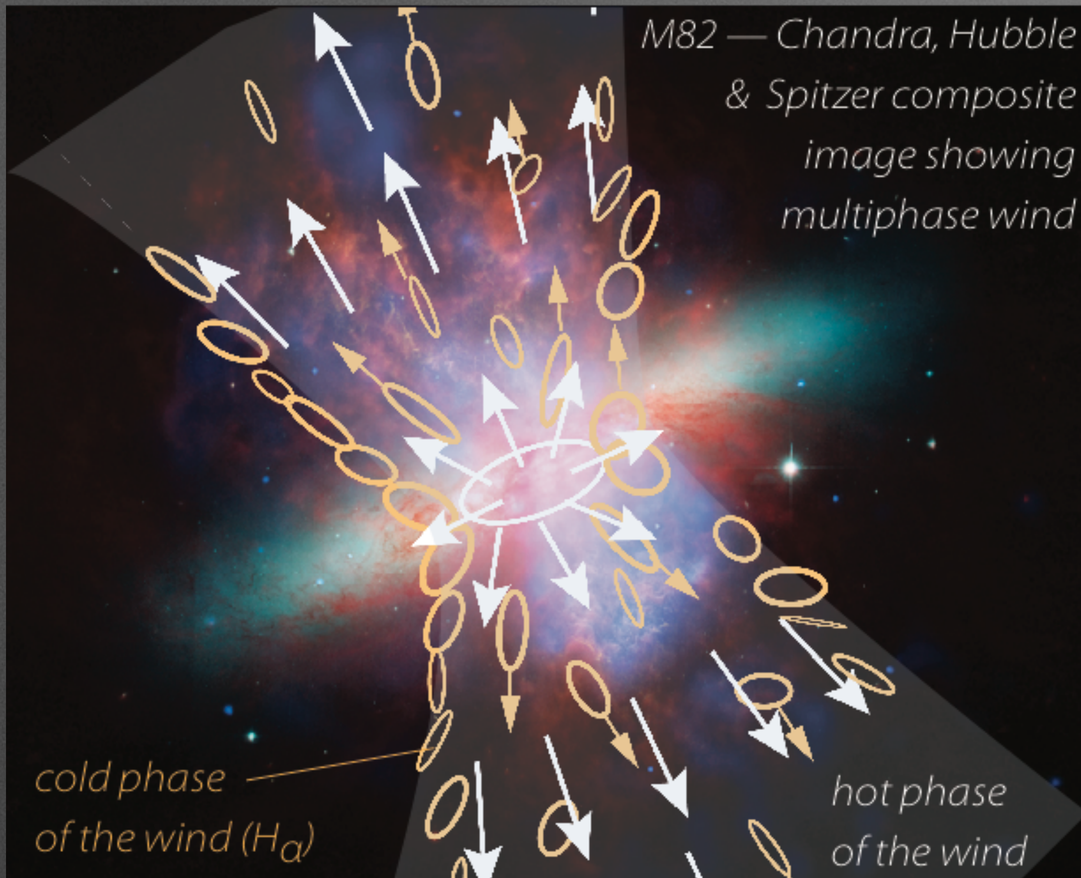
X-ray Microcalorimeter

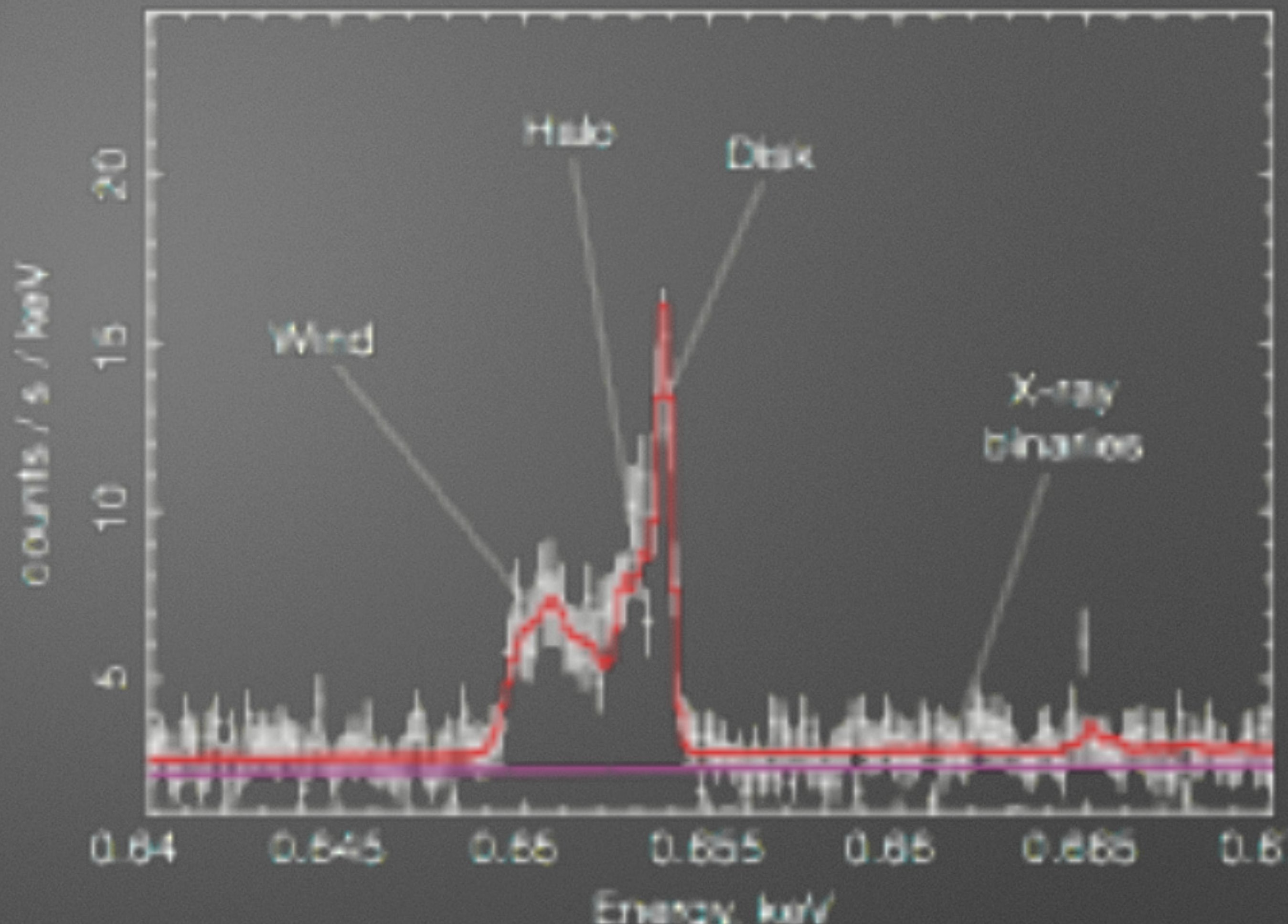


- Observations of SNRs in Local Group galaxies to constrain explosion physics, origin of elements, and a relation between SN activity and local environment **need a microcalorimeter with 1″ pixels, < 5 eV energy resolution over 0.5–7 keV, and 5′×5′ field of view**
- Also required by:
  - Using metallicity in galaxy clusters to z=3 as a probe of galaxy formation processes near the peak of cosmic star formation
  - Study plasma physics effects related to dissipation of energy from AGN outflows.
  - Studies of hot ISM and stellar feedback in active star forming regions in the Milky Way and nearly all other Lynx science
  - Identifications of young NS in Galactic SNRs
  - Much of Lynx general observatory science

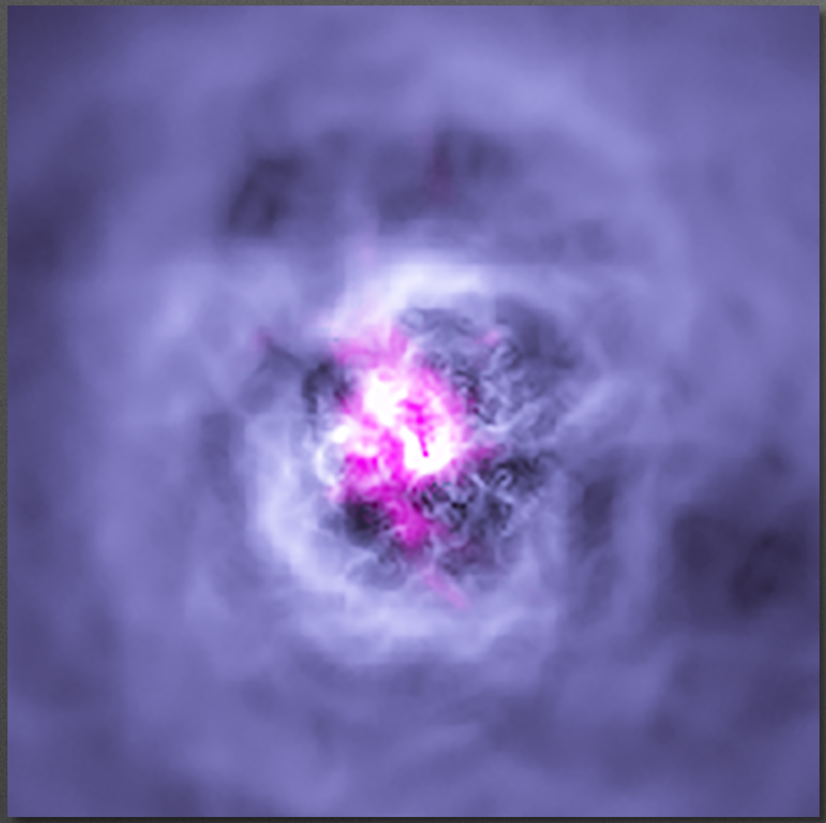
X-ray Microcalorimeter Subarrays: High Spectral Resolution





- To spatially and spectrally resolve the structure of starburst-driven winds **requires a microcalorimeter ~ 0.3 eV energy resolution ⟹ subarray with with 1″ pixels, < 0.3 eV energy resolution at E<1 keV, and 1′× 1′ field of view**
- Also required by:
  - Energetics and statistics of AGN feedback
  - Impact of X-ray flares on protoplanetary disks
  - Stellar wind measurements
  - Transit spectroscopy down of superearths around M-dwarfs
  - Pre-explosion evolution of SN progenitors of recent core-collapse SNs within 10Mpc

X-ray Microcalorimeter Subarrays: High Spatial Resolution

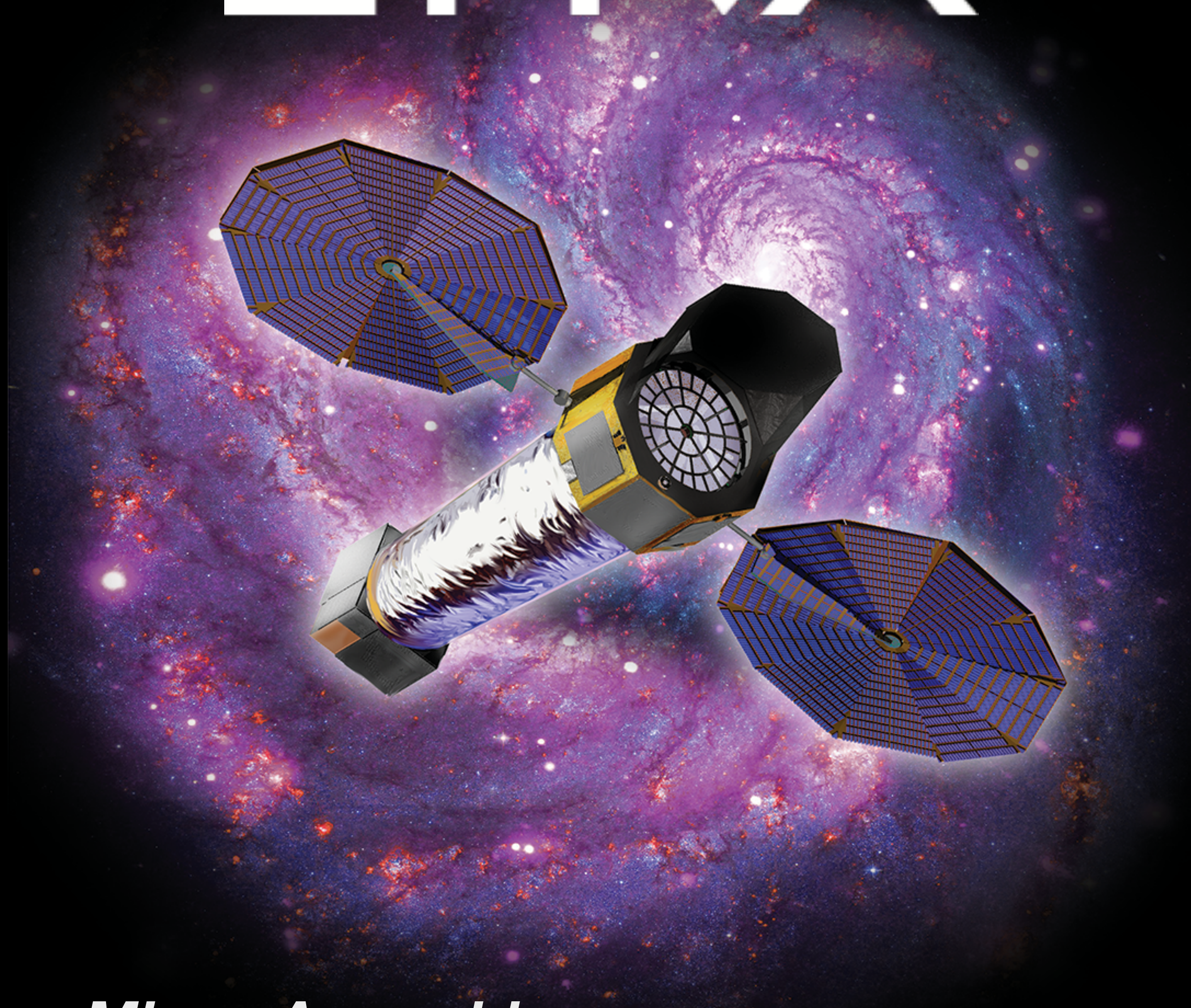


- To determine the effects of AGN energy feedback on ISM, and determine the physical state of gas near the SMBH sphere of influence in nearby galaxies **requires a microcalorimeter with < 1″ pixels ⟹ subarray with with 0.5″ pixels, < 5 eV energy resolution over *E*=0.5–7 keV, and 1′×1′ field of view**

- Also required by:
  - Stellar spectroscopy in crowded regions
  - Non-thermal physics in Galactic SNRs and PWNs

X-RAY OBSERVATORY

LYNX



High-definition X-ray imager

- Silicon sensors with ~0.3″ pixels, closely following the optimal focal surface. FOV ≥ 20′×20′.
- ΔE~100 eV over 0.1–10 keV band.
- High frame rates to minimize pile-up.

X-ray microcalorimeter

- The main array provides non-dispersive spectroscopy with ΔE<3 eV over the 0.2–7 keV band and imaging with 1″ pixels over a 5′×5′ FOV.
- Two subarrays are optimized for sub-arcsec imaging are 0.3 eV energy resolution.

Mirror Assembly

- Densely packed, thin, grazing incidence mirrors.
- Outer diameter of 3m, focal length f = 10m, and effective area > 2 m^2 at 1 keV.
- 0.5″ on-axis PSF (50% power diameter).
- Sub-arcsec PSF out to 10′ off-axis.

X-ray grating spectrometer

- Resolving power $\lambda/\Delta\lambda$ > 5000
- Effective area > 4000 cm^2 covering X-ray emission and absorption lines of C, O, Mg, Ne, and Fe-L.

Key Mission Design Goals

Lynx DRM has been designed to meet science objectives while capitalizing on the use of heritage (subsystems, processes, and operation) and redundancy, and minimal technologies requiring development.

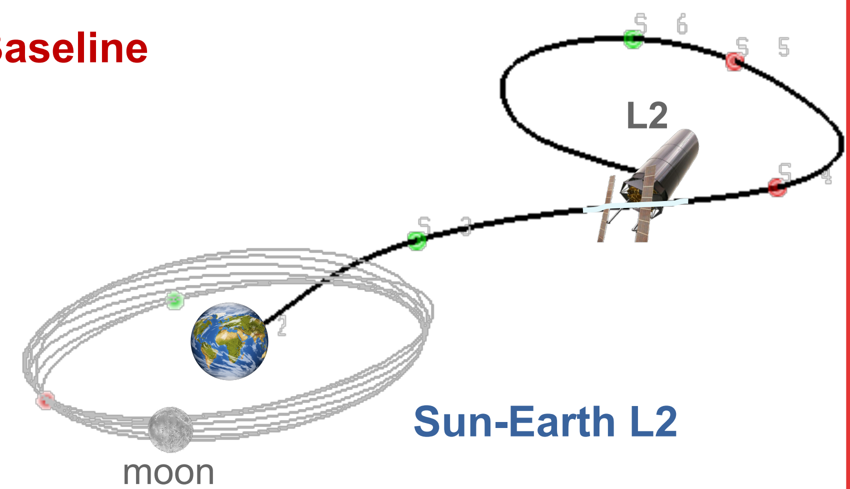
- ***Long Mission Lifetime:*** 5 yr. baseline, enough margin in consumables for 20 yr
- ***Observing Efficiency:*** ~85% (Chandra is ~70% due to radiation belt passages)
- ***Field of Regard:*** Only restriction is 45 deg Sun avoidance angle
- ***Relatively Benign Environment:*** Thermal, Radiation, Meteoroid, etc…
- ***Absolute Pointing Accuracy:*** 10 arcsec (3 sigma)
- ***Post-facto Ground Aspect knowledge:*** 0.2 arcsec stability, ~1 arcsec absolute
- ***Data Rate:*** 240 Gbits/day and 48 hrs on-board storage
- ***Flexible spacecraft accommodation:*** Fits standard 5-m launch vehicle fairing
- ***Low-Risk Design and Operation:*** Uses standard spacecraft elements, no special operation or deployments required, or in-space servicing

Orbit Trades: Conclusions

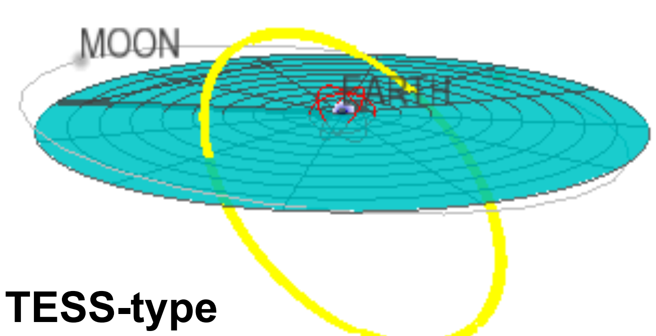
Evaluated Science, duration, environments, thermal delta-V, communications, launch vehicle trajectory and launch opportunity

BEST OPTIONS	SATISFACTORY	CHALLENGING

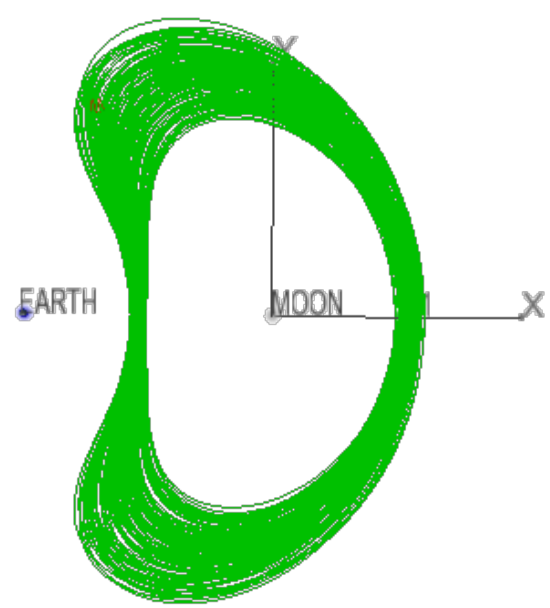
Baseline



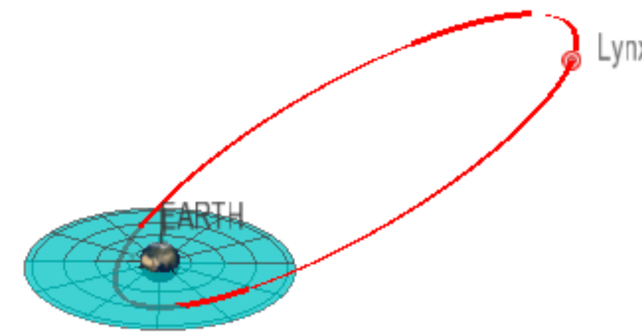
Sun-Earth L2



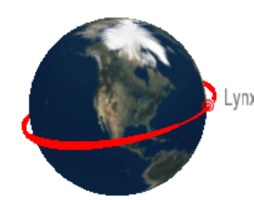
TESS-type Orbit



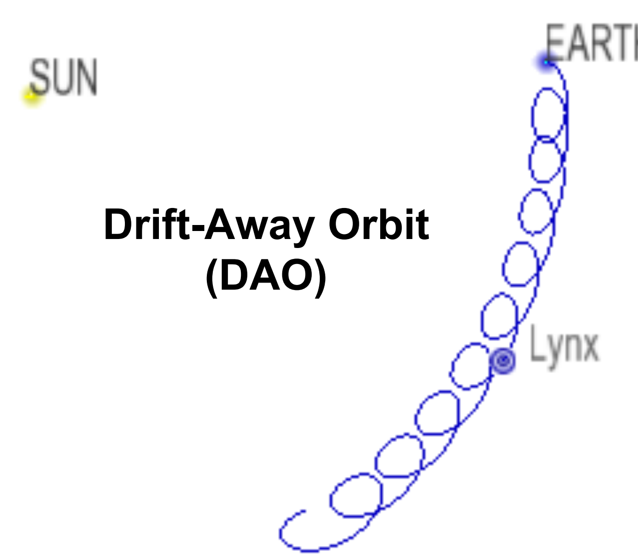
Lunar Distant Retrograde Orbit (LDRO)



Chandra-type orbit (CTO)

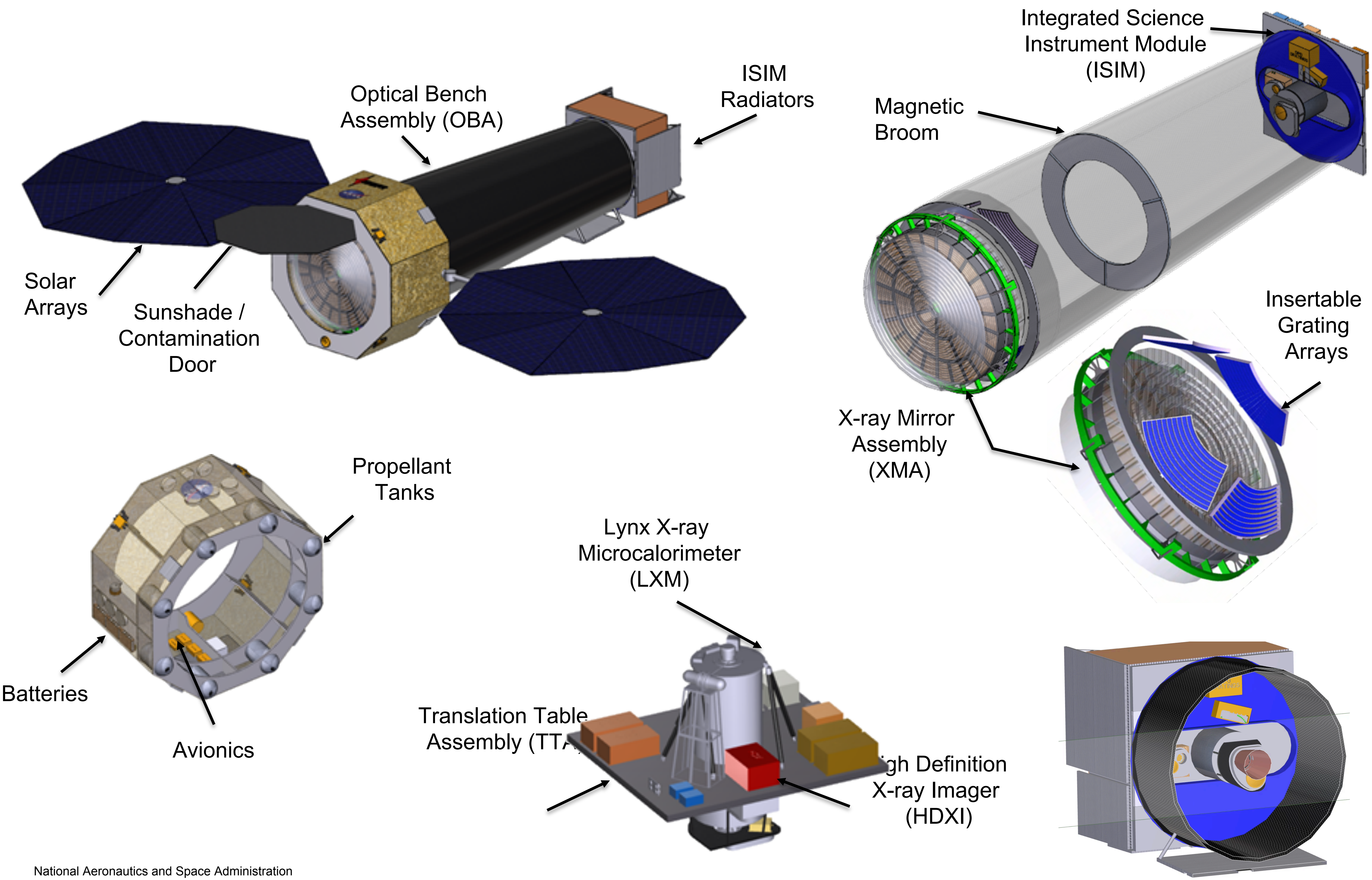


LEO

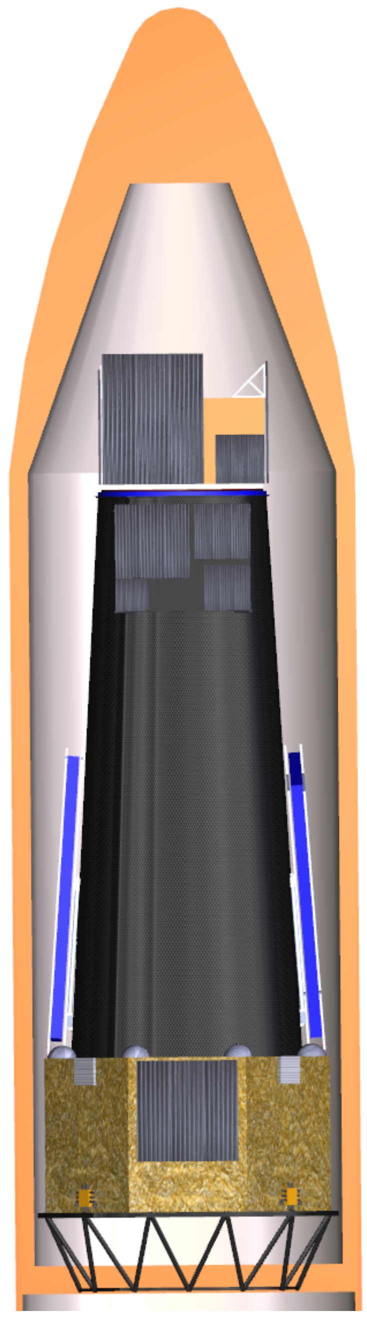


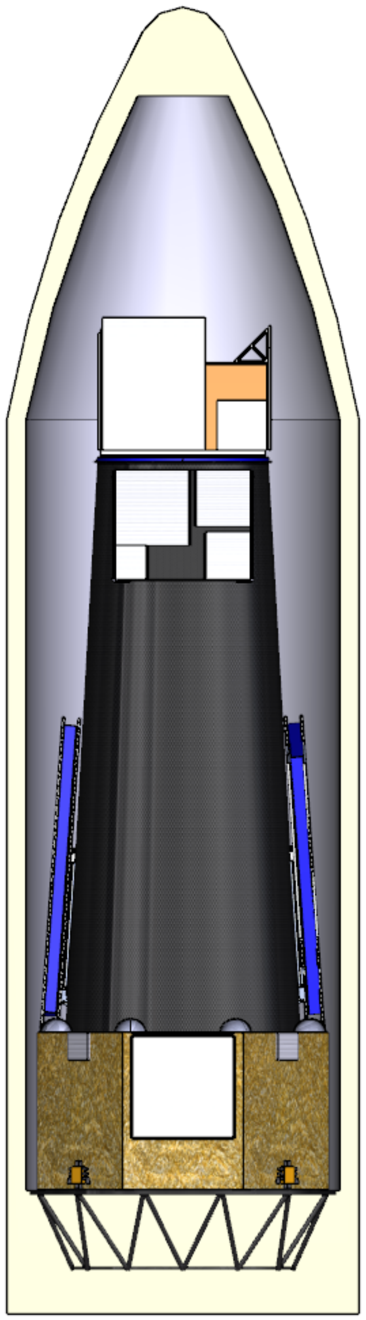
Drift-Away Orbit (DAO)

Lynx Observatory



Launch Vehicle





- Comfortably fits into a Heavy-class launch vehicle (mass, volume),
- Initiating a trade study for using SLS (as co-manifested payload)
- May still fit into Intermediate-class LV
- SLS co-manifested payload and Intermediate-class LV may need extendable bench.

Google: ***Lynx MSFC***

wwwastro.msfc.nasa.gov/lynx