

Finding and Characterizing High-Redshift Black Holes with Next-Generation X-ray Missions

Laura Brenneman

Center for Astrophysics | Harvard & Smithsonian

Important Open SMBH Questions from Astro2020

The Decadal survey identifies three major open questions, described in its sections on core science priorities in "**New Windows on the Dynamic Universe**" and "**Unveiling the Drivers of Galaxy Growth**"



Question 1: AGN at Cosmic Dawn

What are the origins of the first SMBHs?

The Seed Debate: Did they grow from light stellar remnants or heavy seeds?

"Little Red Dots": JWST's discovery of LRDs suggests heavy seeds ($\sim 10^4$ - $10^6 M_\odot$) at cosmic dawn, though X-ray data is critical for discerning whether their emission is driven by star formation or AGN activity.



Question 2: AGN at Cosmic Noon

How do SMBHs and their host galaxies co-evolve?

Cosmic Pacing: Co-evolutionary timing and growth rates across cosmic epochs remain unknown.

Feedback Mapping: XRISM is showing us that upstream $\rightarrow$ downstream AGN outflows are complex: more info is needed.

Obscured AGN & CXB:

Characterizing the CXB and heavily obscured AGN is crucial for probing peak SMBH growth.



Question 3: AGN as Cosmic Fireworks

What are the drivers and characteristics of binary mergers & TDAMM events?

Final Parsec Problem: How colliding central SMBHs shed orbital energy before GWs take over is unknown.

Eruptive transients: QPEs and TDEs probe accretion physics and dormant black holes. X-ray data is needed to complement and follow-up observations from Rubin, Roman, LISA, etc.

The Crucial Role of X-rays in Resolving SMBH Mysteries

Sensitive X-ray observations provide unique physical diagnostics unavailable in any other waveband



COSMIC DAWN

Unmasking First Seeds

While JWST detects "Little Red Dots", only X-rays can distinguish early AGN from dense starbursts. Sensitive soft X-ray fluxes ($\sim 10^{-18}$ – 10^{-19} cgs) isolate accretion signatures of heavy seeds ($\sim 10^4$ – $10^6 M_\odot$) at $z > 6$.

Continuum power-law: Spectral hardness over the rest-frame 0.5-10 keV band indicates coronal emission.

Reflection Spectra: Fluorescent Fe K line profiles redshifted into soft X-rays reveal early accretion environments.



COSMIC NOON

Tracing Co-Evolution

We must model the Compton-scattered continuum to study obscured growth. The combination of high-resolution and imaging X-ray spectroscopy uniquely quantifies the mass and energy of ionized outflows at their source.

Obscurer Geometry: Hard X-rays pierce heavy shrouds ($N_H > 10^{22} \text{ cm}^{-2}$), revealing the central engine.

Feedback Energetics: Only high-resolution spectra can probe launching mechanics and shock dynamics in upstream outflows.



COSMIC FIREWORKS

Mapping Mergers

Soft X-ray observations map accretion disk dynamics prior to SMBH mergers and probe accretion state changes during transient events, while hard X-rays ($> 10 \text{ keV}$) track coronal evolution during these phenomena.

Coronal cutoffs: Essential to isolate Compton humps and constrain continuum vs. reflection.

Time-Domain Sync: High-cadence monitoring maps rapid variability during transient events, probing the most energetic phenomena.

The Legacy of 21st Century AGN X-ray Observations

Chandra, XMM-Newton, Swift, NuSTAR and XRISM have made important discoveries and raised new questions



LAUNCHED 1999

Chandra & XMM-Newton

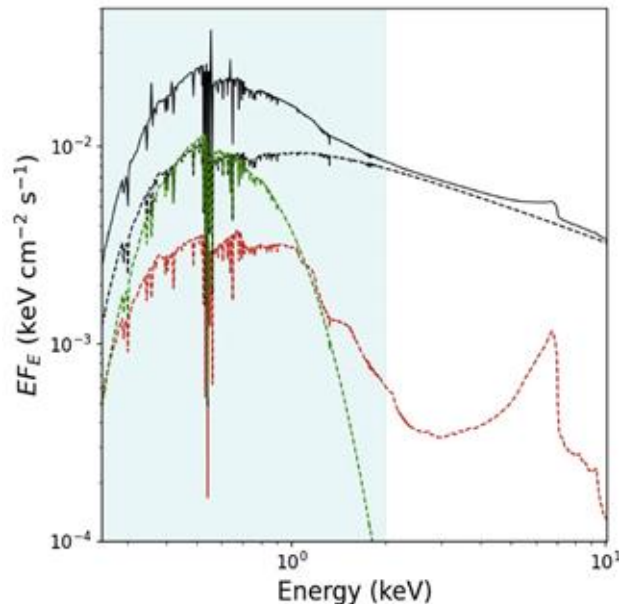
The Chandra and XMM-Newton era revolutionized X-ray observations of AGN, as these observatories combined to offer sub-arcsecond PSF and a massive increase in collecting area from **~0.3-10 keV**, as well high-resolution gratings. Together, they have resolved **~80–85%** of the Cosmic X-ray Background (CXB) below 10 keV through pioneering deep-field integrations.

Chandra

Sub-arcsecond spatial resolution enables unique spatially-resolved spectroscopy. Isolates crowded point sources, traces feeding/feedback in local AGN, and pinpoints obscured systems at $z < 6$.

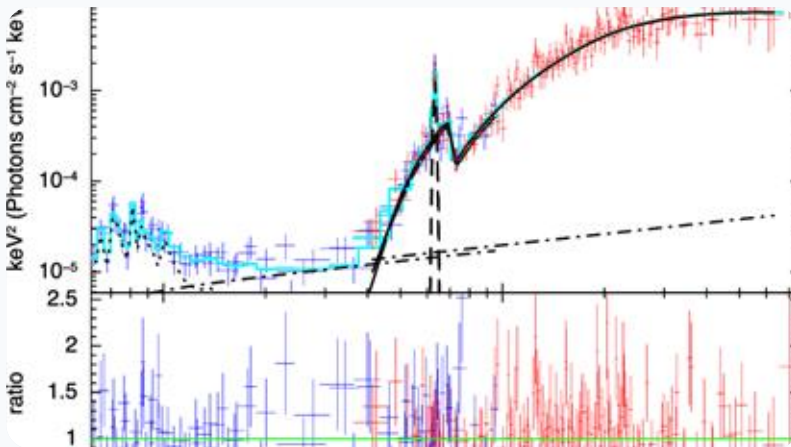
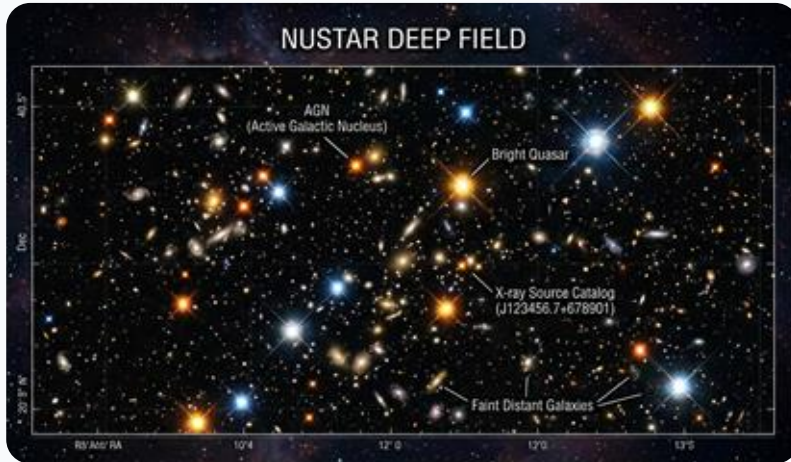
XMM-Newton

A massive effective collecting area powers high-S/N, time-resolved spectroscopy. Critical for measuring reflection, reverberation mapping, and establishing the first SMBH spin constraints.



The Legacy of 21st Century AGN X-ray Observations

Chandra, XMM-Newton, Swift, NuSTAR and XRISM have made important discoveries and raised new questions



LAUNCHED 2004 & 2012

Swift & NuSTAR

Swift transformed AGN science by identifying numerous obscured SMBHs in hard X-rays while monitoring their multiwavelength variability. NuSTAR introduced focusing X-ray optics in the bandpass (**>10 keV**), successfully resolving **~35%** of the CXB within the 8–24 keV band.

Swift

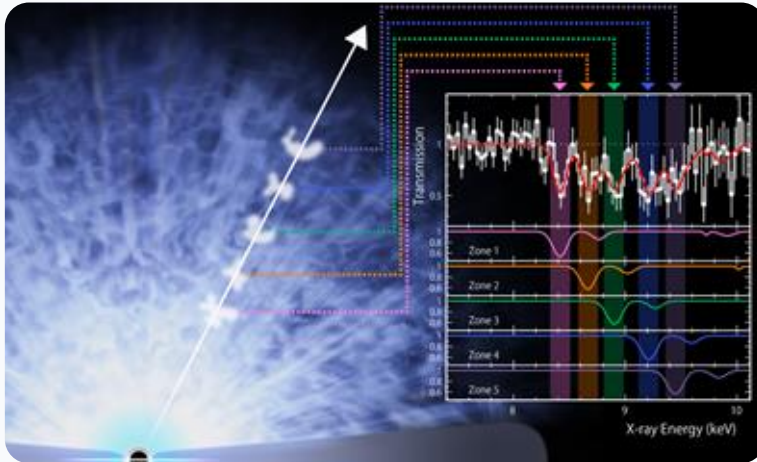
Pierces extremely dense gas obscuration to identify and characterize hidden SMBHs. Continuously tracks changing-state AGN to monitor rapid accretion flow transitions and shut-downs on human timescales.

NuSTAR

Simultaneously measures the crucial 20–30 keV Compton reflection hump and Fe K line profiles to settle long-standing debates. Proves that X-ray emitting coronae are highly compact structures, while mapping the dynamic, clumpy cloud swarm of the surrounding torus.

The Legacy of 21st Century AGN X-ray Observations

Chandra, XMM-Newton, Swift, NuSTAR and XRISM have made important discoveries and raised new questions

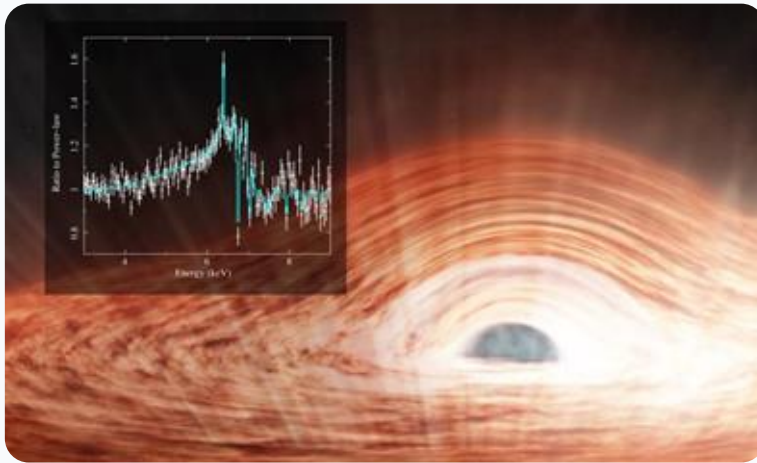


LAUNCHED 2023

XRISM

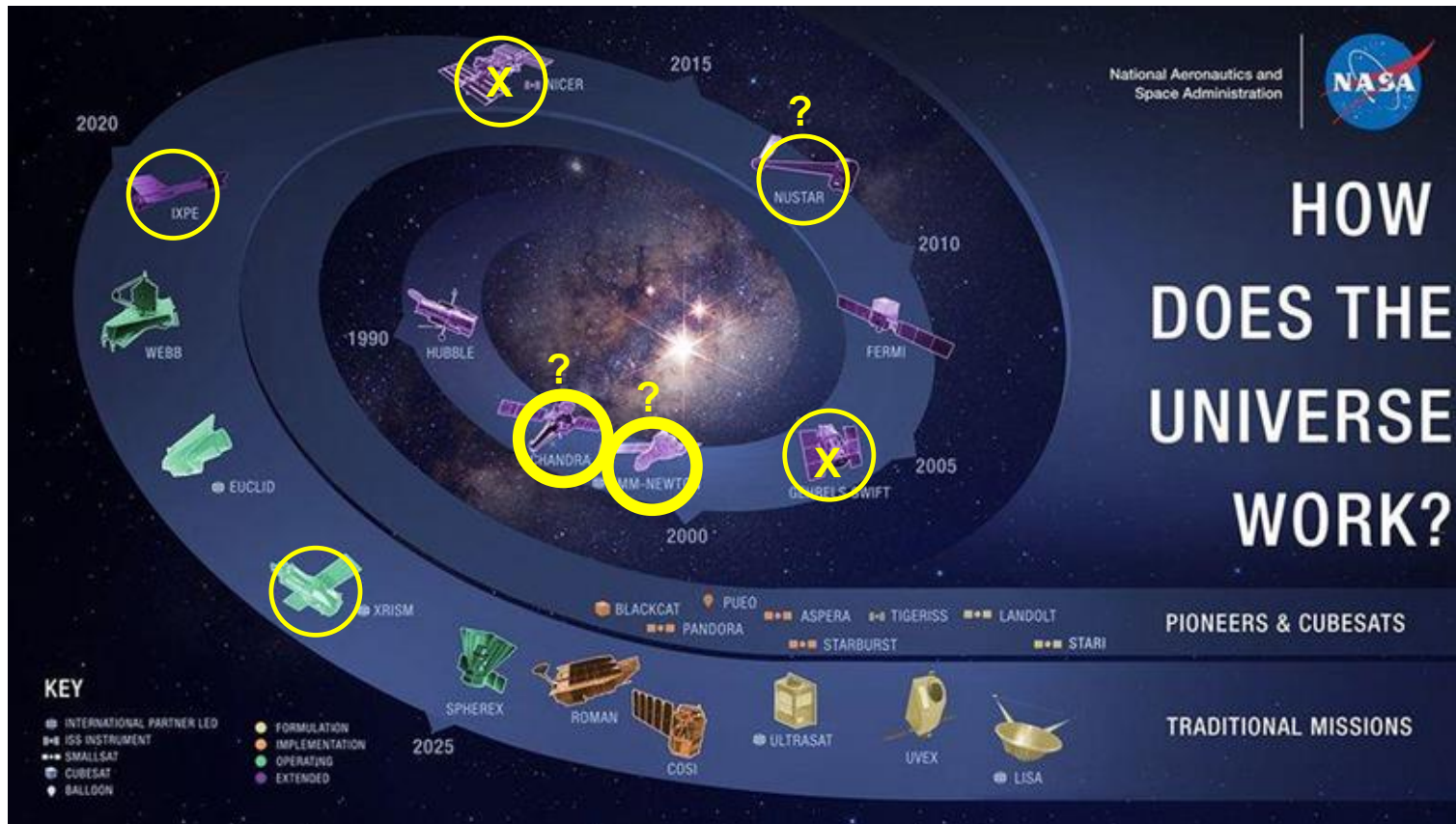
XRISM's groundbreaking Resolve microcalorimeter offers unparalleled spectral resolution over the $\sim 2\text{--}12$ keV bandpass.

- **High-Resolution Spectroscopy:** $<5\text{-eV}$ resolution delivers an order-of-magnitude leap in diagnostics to resolve narrow line components.
- **3D Gas Mapping & Dynamics:** Definitively resolves the velocity structure and morphology of lines in the Fe K band. Separation of narrow and broad components reveals plasma dynamics from the innermost accretion disk to pc-scale winds.
- **Outflows & TDAMM Science:** Isolates highly stratified, clumpy outflowing wind zones ($200\text{--}20,000$ km/s) to map episodic feedback, such as transient UFO launches.



The X-ray Desert of the 2030s and Beyond

We must prevent the critical loss of X-ray coverage in the panchromatic mission portfolio and leverage synergies with JWST, Roman, Rubin and LISA



- Existing X-ray flagships are now >25 years old with no plans for servicing.
- Swift (SMEX) and NICER (SMEX) are expected to fail imminently.
- NuSTAR (SMEX) will be ~20 years old in the 2030s.
- IXPE (SMEX) has limited effective area and bandpass.
- XRISM (MOO) has limited effective area and bandpass.

Next-Generation X-ray Mission & Instrument Requirements for AGN Science

Essential capabilities needed to address the most pressing SMBH mysteries identified by Astro2020



COSMIC DAWN

First SMBH Seeds

Arcsecond-class Resolution: A PSF of $\sim 0.1''$ HPD is required to prevent source confusion and isolate faint seeds from stellar feedback.

10x–100x Effective Area: Massive collecting area peaking at 0.6–3 keV to detect the faintest high-redshift quasars.

Soft Band Optimization: Sensitivity down to ~ 0.1 keV is vital to capture highly redshifted X-ray signatures.



COSMIC NOON

SMBH/Host Co-Evolution

High Spectral Resolution ($R > 2000$): Both gratings (< 2 keV) and microcalorimeters (> 2 keV) are vital to resolve ionized wind diagnostics (O VII, O VIII, C V, Fe K).

Broad Bandpass (0.1–80 keV): Required to capture soft spectral signatures down to carbon/oxygen edges and hard Compton reflection humps simultaneously out to $z = 3$.

Graded-Pixel Focal Plane: Sub-arcsecond inner pixels ($\sim 0.5''$) for core physics, transitioning to wider outer survey pixels.



COSMIC FIREWORKS

SMBH TDAMM Phenomena

Wide-Field Grasp: Large FOV (~ 10 – $15'$) and WFM to capture extended regions and transient events.

Autonomous Slewing: Rapid, responsive observatory targeting to track highly volatile, time-varying sources.

Dual-Band Diagnostics: Soft band (< 10 keV) for transient accretion physics; hard band (~ 10 – 150 keV) for coronal cutoffs and Compton humps.

Bridging the Generational Gap in X-ray Astronomy

Key requirements to transition from the Chandra, XMM, Swift, NuSTAR, and XRISM era to answering next-generation science questions

1. NEXT-GEN OPTICS

The single most critical technological need to make the leap to future science is the development of next-generation X-ray optics that can be used across multiple bandpasses and mission designs.

New mirror substrates and fabrication methodologies are essential to enable the massive leap in sensitivity and angular resolution required to resolve early cosmic structures.

2. KEY REQUIREMENTS

- **Arcsecond-Class PSF**

Necessary for high spatial resolution to prevent source confusion and isolate faint celestial signatures.

- **10-100x Effective Area**

A massive improvement in collecting area is vital to observe incredibly faint, highly redshifted X-ray targets.

- **Flexible, Modular Design**

Needed to adapt the optics technology for seamless integration into multiple different mission architectures to address the array of open questions in AGN science.

SAO Next-Generation X-ray Optics Development

An optimized, highly stable X-ray mirror architecture to meet next-generation AGN science requirements in a variety of mission architectures

Key Design Approaches

1. Stiffer 3mm Mirror Substrate

Eases fabrication, assembly, and alignment for achieving arcsecond-class PSF.

2. Enhanced Thermal Control

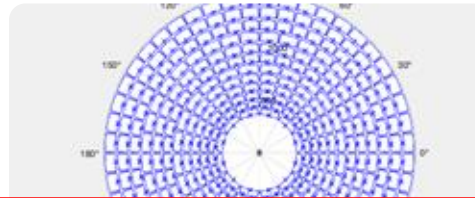
ULE substrates and active thermal control.

3. Lithographic

Leverages ion beam figuring for exceptional surface finish precision.

4. Monolithic Design

Fabricates primary/secondary segments on one substrate, eliminating critical alignment interfaces.



Optics & Alignment

Optimized Optical Design

Computer-optimized optics using arbitrary polynomials offer tunable

distance
Volter
er-
and are
ement with
lishers.

**See Poster #137 by C. DeRoo
and Talk #114 by P. Cheimets.**

2000mm OD / 560mm ID

Configuration B (Intermediate)

2800mm OD / 560mm ID

Configuration C (Maximum Sensitivity)

4000mm OD / 720mm ID

Rapid Assembly & Lock-in

Fiducials enable quick initial placement, refined by centroid detectors and 100nm precision hexapods. Instantly cured via UV epoxy.

Manufacturing Feasibility

Within the expanded mass limits of new LV capabilities, X-ray mirrors capable of addressing next-gen AGN science should be within the range of existing manufacturing techniques.

Development Timeline

First demonstration mirror segments should be made and tested in **2026**. Full modules could be demonstrated by **2029**, assuming funding.

Addressing Open Questions Requires Multiple Distinct Mission Designs

A core Flagship or Probe (0.1–12 keV) could be complemented by smaller, more specialized missions to better address high-energy imaging and spectroscopy as well as rapid transient response demands



1. Next-gen Chandra

Core 0.1–12 keV Observatory

- **High Resolution:** Sub-arcsecond imaging (PSF < 0.5") to resolve crowded regions. Microcalorimeters & gratings ($R > 2000$) to probe AGN feedback.
- **Architectural Gaps:** No support above 10 keV or rapid slewing for transient tracking.
- **Mission Concept:** Large Probe or Flagship likely needed for optics and detectors.



2. Next-gen NuSTAR

Hard X-ray (~10–80 keV)

- **Optics Architecture:** Requires long focal lengths and specialized coatings for high-energy X-rays.
- **Resolution Trade-off:** High spatial resolution complements Next-gen Chandra; high spectral resolution not required.
- **Mission Concept:** Could be realized as a MIDEX- or small Probe-class package.



3. Next-gen Swift

TDAMM-focused (~0.2-150 keV)

- **Autonomous Operations:** Demands rapid repointing and a dedicated WFM to minimize the time needed to acquire targets.
- **Next-gen Detectors:** Advanced silicon detectors enable faster readouts and prevent photon pileup.
- **Mission Concept:** Could be realized as an Explorer-class package.

EXTRAS

The Legacy of 21st Century AGN X-ray Observations

Chandra, XMM-Newton, NuSTAR and XRISM have made important discoveries and raised new questions



Chandra & XMM (1999): Deep fields resolved ~80–85% of the Cosmic X-ray Background below 10 keV.

Chandra: Sub-arcsecond resolution enables spatially-resolved spectroscopy of feeding/feedback in local AGN; isolates sources in crowded fields and obscured AGN at $z < 6$.

XMM-Newton: Massive collecting area enables high-S/N, time-resolved spectroscopy of coronal emission, reflection/reverberation, and first SMBH spin measurements.

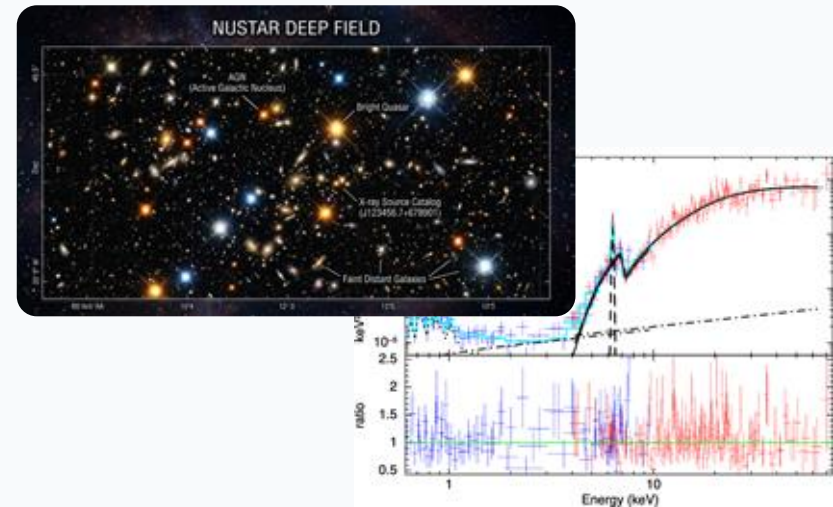
NuSTAR (2012): High-energy focused bandpass diagnostics (>10 keV), resolving 35% of Cosmic X-ray Background (8–24 keV).

Compton-Thick AGN: Pierces dense gas to discover hidden SMBHs.

Black Hole Spins: Settles debates by measuring the 20–30 keV Compton reflection hump and Fe K line simultaneously.

Corona & Torus: Proves coronas are compact and the torus is a dynamic, clumpy cloud swarm.

Extreme Transients: Tracked CSAGN shutting down on human timescales.



XRISM (2023): Crucial high-resolution spectroscopy (<5 eV).

3D Gas Mapping: Microcalorimeter definitively separates narrow and broad emission and absorption features.

Relativistic Outflows: Isolates outflowing wind zones (200 - 20,000 km/s) to quantify feedback.

TDAMM science: Just beginning, including observations of UFOs being launched.

