You are invited to attend 
http://axis.astro.umd.edu/
X-ray Astronomy provides a unique view of the universe

High angular resolution and high sensitivity is required to obtain a large fraction of the necessary information

New Mirror technology is required to obtain the necessary resolution and collecting area in a lightweight optic (Zhang et al 2018) Paper 10699–22
AXIS builds on the mirror technology program started by the Constellation-X/IXO program

High angular resolution lightweight X-ray optics with low weight and reasonable cost,

- utilizing precision polishing and light weighting of single-crystal silicon mirrors.
- achieved 1.5 arcsec angular resolution for a mirror pair (Zhang et al 2018)

The baseline detector is similar to the Chandra CCD but benefits from 25 years of technology development,

- allows the sampling of the PSF, in turn producing higher effective angular resolution,
- faster readout time and broader bandpass (see Falcone10699–37 or Bautz 10699–42 for lots of details).

CCD detectors with the needed properties are being developed today: digital CCDs and/or CMOS.
### Advanced X-ray Imaging Satellite

**R. Mushotzky**  UMD for the AXIS Team

#### Galaxies over Cosmic Time

- **Merging black holes**
- **Feedback in galaxies**
- **Black hole strong gravity**

| Feature                        | Value                        | Description                                      |
|--------------------------------|------------------------------|--------------------------------------------------|
| Angular Resolution            | ~0.3 arcsec                 | High angular resolution                          |
| Bandpass                      | ~0.1–12 keV                 | Broad bandpass                                   |
| Effective Area                | 7000 cm$^2$ @ 1 keV, 1000 cm$^2$ @ 6 keV | ~10 x Chandra at launch                         |
| Energy resolution             | ~150 eV @ 6 keV             | Standard Si detector                             |
| Detector frame readout        | ~20 ms                      | Timing resolution                                |
| FOV                           | ~24’ diameter               | Wide FOV with constant PSF                       |
| Detector Background           | <1/4 th of Chandra          | Low background                                   |
| Rapid slew                    | 120 deg/5 minutes           | High observing efficiency/TOOs                   |
• High Angular Resolution: <0.5”
• Large collecting area: >10x Chandra's collecting area at 1 keV, 4x XMM PN
• Large field of view: ~ 24’
• Broad band pass: 0.2–12 keV
Combination of Parameters Gives Unparalleled Sensitivity to Low Surface Brightness at E> 1 keV !!

Due to low earth orbit AXIS has ~4x lower background per detector cm$^2$ than Chandra/XMM

For background limited observations a figure of merit 65x better for AXIS than Chandra

This allows observing the outer regions of clusters, ISM of galaxies and the intergalactic medium

The figure of merit is

$$\frac{\text{Collecting Area}}{([\text{focal length}]^2 \times \text{background})}$$
Programmatic Constraints

AXIS is a Probe class mission selected for study for submission to the 2020 NAS Decadal Survey In Astronomy and Astrophysics

Probe class <$1B (strong limit)- mass is $$ keep it light and as simple as possible One telescope, one detector

Desire to be selected by Decadal for a launch in ~2030

Schedule
"Engineering run' at GSFC IDL and MDL in March/Feb 2018– no 'show stoppers' ; basic engineering, cost ~$880M

Report to be delivered to NASA Hdqtrs Dec 2018 (costs to be reviewed by NASA SOMA in spring 2019)

Decadal review mid–2019–late 2020
IF Decadal 'selects' AXIS could have start of phase–A in FY 2022

To support that date need
telescope and detector TRL 5 by 2020
need high TRL by 2022
AXIS covers a very wide range of science with high angular resolution and sensitivity......

High redshift galaxies
Clusters of Galaxies
SNR in MW and Nearby Galaxies
Star formation in MW and Nearby Galaxies
AGN and Stellar Jets
Deep Surveys
Starburst galaxies
X-ray Binaries in Nearby Galaxies
ULXs at High Redshift
Planets and comets in solar system
Imaging Feedback in AGN and Starbursts

We welcome your input
Focus on a 3 science areas:

- **Low Surface brightness**
  The intergalactic and circumgalactic medium

- **Black holes**
  Imaging of the central regions
  How accretion works
  How black holes may merge

- **Time domain science**
  A successor to Swift with 100x the sensitivity
The Outer Regions of Clusters, Groups and Galaxies

- Most of the baryonic and dark matter mass is in their outer regions
- Theory says the gas is 'clumpy' and retain signatures of accretion from the IGM

→ AXIS will make a spectacular advance in this area being able to measure temperatures and surface brightness to twice the virial radius and measure infall physics

![Comparison of Chandra 1Ms to AXIS 100ks depth](image)
Measure Clusters Beyond Virial Radius and Feedback of AGN

Figure 3. Background subtracted surface brightness profiles, comparing 1Ms Chandra to 100ks AXIS. Dashed vertical lines show $r_{500}$, $r_{200}$, $2r_{200}$.

- Chandra 1Ms
- AXIS 100ks

virialized 'edge' of cluster
What does it look like near black holes?

Use Gravitational Micro Lensing on a Sample of QSOs to image the X-ray emitting region ($10^{-9}$ arc sec effective angular resolution).
Present day constraints on source size from Chandra *Microlensing* AXIS will drastically increase sample size and reduce uncertainties.

X-ray emission is from innermost stable orbit.

X-ray coronae are small.

Chartas +16, 17
Simulation of AXIS
Observations of
H 1413+117 (aka the Cloverleaf) a
Gravitationally lensed quasar

Notice variability of each component due to microlensing
Imaging the gravitational sphere of influence in SMBHs

How does accretion work, where does the gas come from?

\[ R_{\text{Bondi}} = \frac{2GM}{c_s^2}; \text{the radius within which gas MUST fall into black hole} \]

Chandra can measure Bondi radius in only 3 galaxies...
AXIS can measure Bondi radius in \( \sim 60 \) Galaxies!
How and when did SMBHs grow?

Constrain hierarchical structure formation and LISA progenitors with Dual AGN
Dual Nuclei In Highly Absorbed AGN

Keck adaptive optics discovery of *nuclear* mergers

SDSS and AO K or J band images

Koss + submitted to Nature
AXIS Time-Domain Astronomy

AXIS's fast slew capabilities + flexible scheduling (<4 hours response) → rapid follow-up

LSST will see 1,000–100,000 transients per night

Supernovae
Tidal Disruption Events
AGN variability
GRB afterglows
Stellar flares
X-ray binaries
GW+Neutrino events
Grav lensing caustic crossing

6 days of dust halo after a burst with Swift

AXIS, with fast slew, 100x the sensitivity of Swift and comparable angular resolution to LSST, will be vital in characterizing transients
AXIS Time–Domain Astronomy

A few examples......

Fast Radio Bursts

SKA will detect 1000x more FRBs than Parkes
AXIS will probe deeper, sharper and faster in crowded fields

Tidal Disruption Events

Thousands of TDE/year with LSST–AXIS localizes X–rays at galactic nucleus
Higher sensitivity to understand how TDEs produce X–ray emission

GW Follow–up

Chandra observation, 9 days after GW170817
sensitivity, spatial resolution, rapid response keys to discovery!
Driving Requirements

- Launch Date – 2030
- Class B
- 5 year operations, 10 year goal
- ~600 km ~8° inclination circular orbit
- Slew 120° in 7 minutes
  - Includes settling time
  - 75% observing efficiency
- 45° sun avoidance
- Respond to targets of opportunity in ≤4 hours
  - Approximately once per week
- 4 Gbits (MEV) per day on average
- Single Instrument
Technical Challenges for X–ray Optics

How to achieve high angular resolution+large area at low mass and low cost

Chandra mirrors (1995 technology) are far too heavy and expensive

A 20 year program dating back to Con–X/IXO to develop lightweight optics with the right parameters– (GSFC team led by W. Zhang )

Optical design
  Fundamental geometry and physics
  AXIS mirror design  optimized for wide FoV with ~constant PSF (>15’ diameter)

Technology
  Substrate fabrication
  Coating
  Alignment and bonding

Engineering
  Structural, thermal, and optical performance
AXIS Observatory Overview

- Telescope Tube
- Detector Assembly
- ASICs & FEE Interface Electronics
- Instrument Bench
- Tip/Tilt/Focus Mechanism
- Sensor Housing
- Vacuum Enclosure Door
- Aperture Stop
- Spacecraft not shown

Dimensions:
- Ø 720mm [28.35in]
- 9538mm [375in]
- Ø 1800mm [70.87in]
Axis Mirror Assembly (AMA) Visualized

William W. Zhang

- Secondaries (Silicon)
- Primaries (Silicon)
- Stray-light baffles
- Titanium flexures
- Thermal Baffles integrated w/ Spider (composite)
- S/C & TT Mounting flange

Dimensions:
- 0.3 m
- 0.4 m
- 1.8 m

X-rays
The Meta–Shell Paradigm

- Each mirror segment is fabricated, qualified, and then aligned by and bonded to four spacers which constrain it.

- Hundreds of mirror segments form a meta–shell.

- ~12 meta–shells of different diameters form the final mirror assembly ~16,000 shells.
Silicon Meta–shell Optics (GSFC)

- **The meta–shell optics meet**
  - Mass, effective area, FOV, and stray–light requirements,
  - Structural requirements to survive launch,
  - Thermal and gravity release requirements to preserve PSF on–orbit.
- **X–ray–testing of mirror modules, achieved 2.2” HPD as of Dec 2017.**
Detector Technology

• Requirements
  - Fast readout (>2 MHz)
  - Small pixels (<16 μm)
  - Low noise (<3 e–)

• Digital CCDs (MIT Lincoln Laboratory)
  - Heritage from many previous and current missions
  - Low power at high rates (2.5 MHz) has been demonstrated

• CMOS devices (Teledyne, PSU)
  - Radiation tolerant, fast, low power
  - Noise and gain issues are improving

• Fast, low-noise imaging X-ray detectors are a priority technology development that AXIS can exploit

Eric Miller, Catherine Grant (MIT)
One Possible Focal Plane—24x24' FOV

AXIS Detector Layout

CCD1
CCD2
CCD3
CCD4
CMOS

4000 pixels
24 arcmin
6.4 cm

CBF: 30 nm Al +
45 nm polyimide @ +20°C

5 cm

6.4 cm

AXIS Focal Plane Array
The Spacecraft and Mission

- Need for rapid slewing to obtain high observing efficiency
  - Issues: long space craft (>9m), dry mass ~1635kg, moderate power ~650W, keep costs low
- Desire for 'large' fraction of the sky to be available at any one time
- Launch vehicle of choice (today) Falcon 9
  - simple calculation
    http://silverbirdastronautics.com/cgi-bin/LVPcalc.pl
  - gives large margin (2.5x) for insertion into 5 degree inclination orbit
- Mission ops: Science driver ability to do many TOOs
  (goal is ~4 hours response several times per week, similar to Swift)
Summary

• AXIS will provide breakthrough capabilities in many areas of astrophysics
• Will be compatible in sensitivity to the next generation of astronomical observatories
• Can be developed and flown in ~12 years at a cost commensurate with a Probe Mission
• Enormous synergy with Athena

Please see Other Talks
  W. Zhang Paper 10699–22
  M. Bautz et al Paper 10699–42
The END of the Beginning

If you are interested the AXIS team ... we welcome your interest and inputs.
Target of Opportunity

- Response time 4 hours
- Initiated on the ground
- Approximately once per week
- Uses same approach as Swift
  - Science team member notifies on-call member of Flight Ops Team
  - FOT works with Space Network to schedule a forward link
  - TOO information is used to generate command sequence
  - Uplinked when contact is established
  - Typically takes ~1 hour
Schedule

• Engineering runs performed at GSFC IDL and MDL in March/Feb 2018
  – no 'show stoppers’

• Report to be delivered to NASA HQ Dec 2018
  (costs to be reviewed by NASA SOMA in spring 2019)

• Decadal review mid–2019–late 2020

• IF Decadal 'selects' AXIS could have start of phase–A in FY 2022

• To support that date need
  – *telescope and detector TRL 5 by 2020* (TRL = technology readiness level)
  – need high TRL by 2022
Low Inclination LEO Gives Very Low Cosmic ray Dose– Long Detector Life
**AXIS Mission Level Schedule Graphic**

**PHASE A**
- Starts: 10/1/2023
- Preliminary Analysis: 10/1/2023
- Mission Definition: 1/1/2024

**PHASE B**
- Confirmation/ATP: 4/1/2024
- Definition/Design: 10/1/2024
- System Definition: 12/1/2024

**PHASE C-1**
- Preliminary Design: 12/1/2026
- Final Design: 11/1/2026

**PHASE C-2**
- Fabrication: 11/1/2026
- Hardware Build: 11/1/2026

**PHASE A/B/C Funded Schedule Margin**
- Starts: 3/1/2028

**PHASE D-1**
- System Assembly: 4/1/2028
- Observatory I&T/Environmentals: 3/1/2029
- Instrument I&T/Environmentals: 12/1/2029
- S/C Bus I&T/Environmentals: 9/1/2029

**PHASE D-2**
- Funding: 6/15/2030
- Launch Site Support: 9/1/2030
- Launch & EO: 9/1/2030

**PHASE E**
- Operations: 10/1/2030
- Primary Ops: 10/1/2030
- Baseline Ops: 10/1/2035
- Extended Ops: 10/1/2040

**Timeline**
- Delivery: 12/1/2028
- Shipment: 3/1/2030
- Launch: 9/1/2030
- Baseline Ops: 10/1/2035
- Extended Ops: 10/1/2040