• 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
• AXIS is a Probe mission with these capabilities – only US has the technology

New Mirror technology is required to obtain the necessary resolution and collecting area in a lightweight optic (see Zhang et al talk)+ New generation of Si based detectors
Advanced X-ray Imaging Satellite-AXIS
An X-ray Observatory

Galaxies over Cosmic Time
Feedback in galaxies
Dual black holes
Transients
Black hole strong gravity

James Guillochon
Broad Top Level Science Areas - Observatory Class Science

- Intergalactic (IGM) and circumgalactic (CGM) medium in emission
  Detection, characterization and properties

- Black holes
  Origin, evolution and physics close to event horizon

- Transient and variable universe
  A successor to Swift with ~100x the sensitivity

- Galaxy Formation and Evolution
  Physics of feedback

- Solar system and planets
AXIS... at a glance

24 arcmin AXIS FOV

Chandra ACIS-I FOV

AXIS collecting area, PSF and field of view compared to Chandra
>10x better in many areas—allows breakthroughs
Total number of resolution elements in focal plane

Observatory Class science - large phase space for guest observers

<table>
<thead>
<tr>
<th>Feature</th>
<th>AXIS</th>
<th>Comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular Resolution</td>
<td>~0.4 arcsec</td>
<td>High angular resolution</td>
</tr>
<tr>
<td>Bandpass</td>
<td>~0.1-12 keV</td>
<td>Broad bandpass</td>
</tr>
</tbody>
</table>
| Effective Area                | 7000 cm\(^2\) @ 1 keV  
                           1000 cm\(^2\) @ 6 keV | ~10 x Chandra at launch                          |
| Energy resolution             | ~150 eV @ 6 keV | CCD-like Si detector                             |
| Detector frame readout        | ~20ms         | Timing resolution                                |
| FOV                           | ~24' diameter | Wide FOV with nearly constant PSF                |
| Detector Background           | <1/4 th of Chandra | Low background                                   |
| Rapid slew                    | 120 deg/5 minutes | High observing efficiency/TOOs                   |

Time domain figure of merit compared to other existing or planned x-ray missions
AXIS has Unparalleled Sensitivity to Low Surface Brightness- opening up a vast new area of science

Circumgalactic medium, warm/hot IGM, cluster infall, ISM of elliptical and spiral galaxies, starburst galaxies

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

figure of merit is Collecting Area/[(focal length)$^2$ x background]
Major Advance in X-ray Optics

**New technology:** precision polishing and light weighting of single-crystal silicon mirrors.

- achieved 1.3 arcsec angular resolution for a mirror pair (Zhang et al 2019)

**New Optical design**

Wolter-Schwarzschild design optimized for wide FoV with nearly constant PSF and large collecting area

(GSFC team led by W. Zhang)
Silicon Meta-shell Optics (GSFC)

- Meets requirements for
  - Mass, effective area, FOV, and stray-light
  - Launch survivability

- *X-ray-testing of mirror modules, achieved 1.3” HPD as of March 2019. Correcting for gravity distortion remaining effect is 0.58"*

![Graph showing progress over time]
Detector Technology

• Digital CCDs (MIT Lincoln Laboratory)
  – Heritage from many missions
  – Low power at high rates (2.5 MHz) demonstrated

• CMOS devices (Teledyne, PSU)
  – Radiation tolerant, fast, low power
  – Noise and gain issues are improving
  – successfully flight-proven in 2018 rocket flt.

Fast, low-noise, small pixel, imaging X-ray detectors

Eric Miller, Catherine Grant (MIT), Abraham D. Falcone (Penn State)
Spacecraft and Mission

- Rapid slewing - ~70% observing efficiency
  - 'Large' fraction of sky available
- Launch vehicle of choice (today) Falcon 9
  - Margin for 80° inclination LEO
- Low Inclination – very low cosmic ray dose-long detector life, low background
- Easy communication – flexible mission ops and TOO capability 4 hours response, several times per week
- Dry mass ~1635kg, moderate power ~650W

Cost estimate ~$1B (GSFC MDL)
Simulation of X-ray emission from large scale structure in the Universe

Formation of galaxies, groups and clusters

AXIS has the sensitivity, bandpass, low background, angular resolution and field of view to measure all of these regions.

Dolag+06
Outer Regions of Clusters, Groups and Galaxies

- Most baryonic mass is in hot gas in outer regions – only visible in x-rays!
- Gas retains signatures of accretion from IGM and effects of feedback → AXIS will measure temperatures, abundances and density to twice the virial radius and determine infall and feedback physics
What does it look like near a black hole?

Gravitational Micro Lensing of a Sample of QSOs to image X-ray emitting region very near event horizon \((10^{-9} \text{ arc sec effective angular resolution})\)
X-ray Constraints on source size from Chandra

**Microlensing**

AXIS drastically increase sample size, reduce uncertainties

X-ray emission is from ~3 Schwarzschild radii-
innermost stable orbit of black hole

![Graph showing relationship between size of X-ray source and mass of black hole. The graph includes data points and a trend line indicating the relationship.](chart)

Chartas+16,17
Simulation of 2 AXIS 10ks
Observations of a* Gravitationally lensed quasar
Variability of lensed image due to microlensing

AXIS's TOO capability allows response to LSST 'warning' of caustic crossing

*H 1413+117 (aka the Cloverleaf)
How and when did SMBHs grow?

Constrain hierarchical structure formation and LISA GW progenitors with Dual AGN
Dual Nuclei In Highly Absorbed AGN (Koss et al Nature 11/2018) Keck IR adaptive optics discovery of nuclear mergers

AXIS can resolve these 'dual' AGN out to z~3 and constrain black hole mergers
LISA Follow-ups

X-rays expected to be brightest emission source in weeks before merger

AXIS detects \( \sim 10^5 \text{M}_\odot, 10^6 \text{M}_\odot \) BH counterparts at z=1,3 resp
Use the LSST catalog of galaxies down to $M_V=24$

Tile LISA error circles with AXIS. 1% of galaxies are AGN, X-rays are best indicator.\(^1\)

Binary SMBH result from galaxy mergers. Prioritize disturbed galaxies from LSST images. 10% of galaxies are disturbed\(^2\)

Select correct redshift range from LSST photometric redshifts, accurate to 10%\(^3\)

Most dual AGN are obscured; prioritize obscured AGN (1/3 of total)\(^4\)

60,000 sources

600 sources

60 sources

6 sources

2 sources
**AXIS Time-Domain Astronomy**

A few examples......

**Fast Radio Bursts**  **Tidal Disruption Events**  **GW Follow-up**

SKA will detect 1000x more FRBs
AXIS will probe deeper, sharper and faster in crowded fields- astrometry at 0.1" level- 20ms timing

Thousands of TDE/year with LSST-AXIS localizes X-rays at galactic nucleus +spectra +timing
How do TDEs produce X-ray emission?

Chandra observation, 9 days after GW170817 sensitivity, spatial resolution, rapid response keys to discovery
Need AXIS for expected ALIGO sources >3x more distant
Birth of SMBHs - The Highest Redshift Quasars - SMBHs at $z \sim 7.5$ (690 Myr after Big Bang) 
$M_{\text{SMBH}} = 8 \times 10^8 M_\odot$ (Banados et al 2018)

AXIS can detect their **progenitors** at $z \sim 13$, 300 Myrs after Big Bang.

How BH grows over time at Eddington limit

10^5 sec exposure

AXIS 10^6 sec exposure
Star Formation at \( z=3 \)

X-ray Emission from star formation-from NS+ BHs +Hot Gas-

In rapidly star forming galaxies most of energy from star formation is in hot gas

ALMA data for SDP81(molecular gas)- white contours

Colors- AXIS Simulation

ALMA continuum on AXIS (400 ks)

Lensed Star Forming Galaxy

Lensing galaxy
Planetary Science- Time variability of Jupiter's X-ray emission

~1000km spatial resolution - the polar and flux tube components couple to “weather” of Jovian magnetosphere and exosphere.

AXIS’ sensitivity provides monitoring and mapping with a cadence allowing correlation with JUNO optical and UV maps.
Summary

- AXIS will provide breakthrough capabilities in many areas of astrophysics – fundamental new results provide many targets over wide range of science areas for strong guest observer program

- Compatible in sensitivity to the next generation of astronomical observatories at other wavelengths

- Can be developed and flown in ~12 years at Probe Mission cost

- Enormous scientific synergy with Athena and other new observatories of the 2020's and beyond
Extra Slides
Hierarchical Process to Build AXIS Mirror

16,568 mirror segments individually fabricated and qualified.

6 meta-shells built out of 188 modules from the 16,568 segments.

1 mirror assembly out of the 6 meta-shells.
New Results !!!

Produced X-ray images with 1.27” HPD at 4.5 keV.

The number 1.27” included two contributions
- fabrication/alignment/bonding error and gravity distortion
- The gravity distortion has been determined by finite element analysis to be 1.13” HPD.

The contribution of the other errors is estimated to be
\[ \sqrt{(1.27^2 - 1.13^2)} = 0.58” \]

Zhang et al have produced an image, for all intents and purposes, as good as Chandra’s but with mirrors that are 30 times lighter.
AXIS Time-Domain Astronomy

AXIS's fast slew capabilities + flexible scheduling (<4 hours response) → rapid follow-up + 20ms timing

LSST 1,000-100,000 transients per night for AXIS to follow up

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 has 100x sensitivity of Swift and angular resolution similar to LSST
Broad Top Level Science Areas - Observatory Class Science

- The intergalactic (IGM) and circumgalactic (CGM) medium
  Detection, characterization and properties
- Black holes
  Origin, evolution and physics close to the event horizon
- The transient and variable universe
  A successor to Swift with ~100x the sensitivity
- Galaxy Formation and Evolution
  The physics of feedback
- Solar system and planets
  Magnetospheres, solar wind interaction

Cosmological simulations by E. Rasia & K. Dolag
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

And many others!
Driving Requirements

- **Observatory Class science** - large phase space for guest observers
- Launch Date ~2030
- Class B
- 5 year operations, 10 year goal
- ~600 km ~8° inclination circular orbit - long life orbit
- Slew 120° in 7 minutes
  - Includes settling time
  - ~70% 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
- **Telescope and detector TRL 5 by 2021**
- **Need high system TRL by 2022**
AGN and Stellar Feedback over the Entire Mass Scale
X-ray evidence for large amounts of hot gas excited by a quasar and star formation
**Fundamental Plasma Astrophysics**

Clusters of galaxies and supernova remnants are perfect places to study plasma physics with x-ray imaging.

Effects of anisotropic thermal conductivity on x-ray images of clusters

J. Zuhone

**Key Concepts**

- Kelvin-Helmholtz Instabilities
- Thermal Conduction
- Shock Acceleration
- Thermal Conduction
- Viscosity
- Shocks
- Electron-proton equilibration timescale
- What is the ratio of electrons to protons in radio sources/jets?
- Physics of CR streaming
- CR pressure support
- NEI+Recombining Plasmas
- Very strong magnetic fields
- Particle acceleration
- Jet physics in AGN

**Images**

- $\beta = 1000, \mu = 0$
- $\beta = 1000, \mu = 0.1\mu_{Sp}$
- $\beta = 100, \mu = 0$

Bellomi et al., in prep
AXIS builds on the mirror technology program started by the Constellation-X/IXO program - 20 years of development of high angular resolution, lightweight X-ray optics at reasonable cost -(Chandra mirrors (1995 technology) are far too heavy and expensive)

**Goal** to achieve high angular resolution + large area at low mass (30x lighter than Chandra per unit area) and low cost (30x cheaper per collecting area)

Mirror technology development initiated in 2001 and funded through 2011 by Con-X/IXO. Continually funded since 2012 by ROSES/APRA and PCOS/SAT

• The baseline detector is similar to the Chandra CCD but benefits from 25 years of technology development,
  • allows the sampling of the PSF, producing higher effective angular resolution, faster readout time and broader bandpass (see Falcone SPIE 10699-37 or Bautz SPIE 10699-42 for lots of details).

CCD and CMOS detectors with the needed properties are being developed today: digital CCDs and/or CMOS (cf M. Bautz (MIT), A. Falcone (Penn State)
AXIS ALIGO Followups

Need <1" spatial resolution to identify source
Sensitivity <2x10^{-16} to reach ALIGO Horizon

If have ~10GW/year 20ks each exposure (10)=
2MS ~10% of observing time
- **Focal Plane**: 4 x CCD plus CMOS in the center
- **CCD format**: 1500 x 2500 pixels, frame transfer
- **Pixel size**: 16 x 16 um
- **Detection range**: 0.1 to 10keV
- **Frame Rate**: 20 fps
- **Read Noise**: < 4e
- **CMOS Format**: 1k x 1k
- **CMOS Frame Rate**: > 20fps
- **Operating temperature**: 183K

- **Outputs per CCD**: 32
- **Readout speed**: 2.5Mpixels/s
- **Data format**: 12 bits
AXIS-X-ray Skies Meeting
Thank you for attending

Invited Speakers
Eduardo Bañados
Laura Blecha
Samar Sari-Harb
Brian McNamara
Jörn Wilms
Stephanie LaMassa
Kevin France
Ori Fox
Dave Pooley

Science Topics
Stellar Populations, Milky Way
Supernovae and Remnants
The Transient Universe
Large-scale structure in Clusters
AGN Feedback
Hot ISM across Cosmic Time
The high-redshift Universe
Quasar Microlensing
The Solar System
Dual AGN

Local Organizing Committee
Richard Mushotzky
Mike Loewenstein
Brian Williams
Hiroya Yamaguchi
Erin Kara
Lynne Valencic
John Mulchaey

Join us in Washington, DC
6-7 August 2018
Carnegie Institute of Science
Register by: 21 July 2018
Visit axis.astro.umd.edu
AXIS Observatory Overview

Detector Assembly  ASICs & FEE Interface Electronics

Instrument Bench
Tip/Tilt/Focus Mechanism

Vacuum Enclosure Door

Telescope Tube

Sensor Housing

Aperture Stop

AMA + FPA + Tube ~ 751 kg

297W  Orbital Average in Science Mode
197W Instrument + 100W Operational Heaters
IDL: AXIS Detector Assembly Block Diagram

- Telescope Tube
- GSE Cooling Line
- Fiducial LED (4x)
- Vacuum Gauge
- Readout Harness and connector (1 of x)
- Contamination Blocking Filter
- O-ring
- Vacuum Enclosure Door
- Aperture Stop
- Me1 Tip / Tilt / Focus
- Me2
- Me3 Tip / Tilt / Focus
- FPA Mounting Plate
- Heaters
- Sensor Housing Baseplate
- Sensor Housing
- Instrument Bench
- ASICS & FEE Interface Electronics
- Heat Pipe
- Radiator
- Decontamination Heater
- 55Fe Calibration Source (4x) and collimators

NOTE: See Thermal presentation for configuration of sunshields and radiator.
At lower redshifts, most submm AGN have higher absorption than the general X-ray population (dots). They are not Compton thick, but they have high hydrogen column densities.

High-z sources are near to or Compton thick.
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
Most AGN are not associated with merger: but the most luminous quasars generally are -> important mode of BH growth
• Strong selection effects in finding them in other wavebands
• Dual AGN: unambiguous evidence of merger-triggered BH growth
• EM signatures of binary BHs are elusive, but kpc-scale dual AGN constrain the merger rate, BH binary formation & early inspiral
• High-res x-ray follow-up of X-ray or IR-selected AGN in mergers is revealing new obscured dual nuclei
• AXIS will reveal a large new population of close dual AGN, across a wide range in luminosity and redshift

Detecting "Feedback"

- Theoretical studies of how galaxies form indicate that energy from Supermassive black holes have had a critical influence on the formation and evolution of galaxies (called feedback).

- AXIS can image the signature of that process and determine how it 'works'.

Image of enormous (10kpc) x-ray and optical 'superbubble' inflated by the AGN.
The Meta-Shell Approach

Principle of the Approach

Implementation of the Approach
Most of the baryons are in the outer regions of clusters and this is where infall from the cosmic web occurs.
AXIS has the angular resolution, sensitivity, low background and field of view to observe many clusters out to the virial radius and explore the regions where clusters form.
X-ray Observations of GW170817 were crucial in determining the nature of the afterglow (a structured jet)

- Lack of cooling break constrains external density and observer angle
- Constrain external density, magnetic fields, jet structure
- Constrain angle between Earth and center of the jet
  Useful for cosmology

However
GW170817 was at 40 Mpc
- As aLIGO and VIRGO reach design sensitivity, most events will be at ~200 Mpc (early 2020’s)
  25x fainter in EM emissions
  - 18th → 22nd mag Kilonova
  - 3.6×10^{-15} → 1.5×10^{-16} erg/s/cm² X-ray

Would require 5 day Chandra exposure!

Easy to get rise, fall with AXIS
Transient Science
AXIS will have the Swift quick response capabilities but
be ~70x more sensitive
30x better angular resolution
50x better time resolution than Chandra
Do all the Swift science but with vastly better sensitivity and angular resolution.
Key Ingredients of Approach

• Precision polishing -good PSF
  – Tremendous advancement since the 1990s when Chandra was made.
• Mono-crystalline silicon -thin (or lightweight) mirrors
  – Free of internal stress
  – Abundantly and inexpensively available.
• Nanofabrication -accurate & fast integration
  – Fabrication of alignment and integration structures.
  – Lowest possible costs for making precision structures.
• Mass production -low cost
  – Industry standard equipment for making/processing wafers.
  – Eliminate/minimize use of custom-designed and built equipment.
• Keep it simple –reliability
  – Simple to engineer, build, and test.
AXIS Mission Level Schedule Graphic

PHASE A starts 10/1/2023
PHASE A Preliminary Analysis

PHASE B Confirmation / ATP 10/1/2024
PHASE B Definition/Design

PHASE C-1 1/1/2026 PDR 12/1/2025
PHASE C-1 Design

PHASE C-2 12/1/2026
PHASE C-2 Fabrication

PHASE A/B/C Funded Schedule Margin

PHASE B Confirmation / ATP 10/1/2024
PHASE B Definition/Design

PHASE D-1 4/1/2028
PHASE D-1 System Assembly, Integration and Test

PSR 3/1/2030
PHASE D-1 Funded Schedule Margin

PER 5/1/2029
Observatory I&T/Environmentals

LAUNCH 9/1/2030
PHASE D-2
PHASE D-2 Ship 6/15/2030
launch & EO

PHASE E 10/1/2030
PHASE E Operations

Baseline Ops 60 mo 10/1/2035
Extended Ops 120 mo 10/1/2040

PHASE D-1
PHASE E

Observatory I&T/Environmentals
Instrument I&T/Environmentals
S/C Bus I&T/Environmentals
Basic Ops 60 mo 10/1/2030
Extended Ops 120 mo 10/1/2040

Baseline Ops 60 mo 10/1/2035
Extended Ops 120 mo 10/1/2040

Use or disclosure of this data is subject to the restriction on the title page of this document
- 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
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 ~$940M

Report delivered to NASA Hdqtrs March 2019 (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
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

AXIS Focal Plane Array

5 cm
6.4 cm
Target of Opportunity Goals

based on Swift

• Response time 4 hours
• Initiated on the ground
• Approximately once per week
• Uses same approach as Swift

Is this the right thing in the post-2028 time frame??
How Did the Seeds for First SuperMassive Black Holes Form?

3 Ideas of How these form:

- AXIS can test these ideas by detecting these objects to $z \sim 12$

Priyamvada Natarajan

**Predicted high redshift Luminosity Functions**

**Pop III SEED + STELLAR COMPONENT STANDARD DISK, HIGH Z**

AXIS 32 Ms deep field: flux limit of $3 \times 10^{-18}$ erg/s/cm$^2$
Direct Imaging of Galactic Winds with AXIS

Chandra Cy19 100 ks

AXIS 100 ks

1' = 4.8 kpc
d = 16 Mpc

NGC 3079
(AXIS Team)

F. Tombesi – Imaging the Cosmos with AXIS, Washington DC, 6-7 August 2018
How Galactic Winds Work

AXIS Simulation

HST Hα image

5'' = 450 pc
Chandra Can Just Barely test Electron-Proton Equilibration in Long Observation of "Best" Source
AXIS will do 10x better
Mapping the cosmic ray acceleration sites: The origin of high-energy cosmic rays (PeVatrons), magnetic field amplification, shock precursors, connection to Galactic magnetism
I. Population studies: Missing SNR problem, Star formation rate, Stellar Evolution
   **SKA (precursors), eROSITA, G/TMT, IFU...LIGO/LISA (SN)**
   - SN1987A/extragalactic CCOs/PWNe
   - witnessing long overdue Galactic SN explosion+nearby SNe!

II. **SNR=>SN**: Nucleosynthesis, SN explosion mechanism and progenitor, chemical evolution of galaxies and clusters, diversity of compact objects, neutron stars kicks
   - Black hole formation vs metallicity!  **JWST**,
   - Ia explosion mechanism (single vs double degenerate scenario)

III. **PWN and compact object studies**: The physics of the extreme and relativistic winds and jets.
   - Growing compact PWN classes that defy classification; ToOs of bursting sources (HBPs, XDINSs?, CCOs??)

S. Safi-Harb
In the low redshift universe (where we have sufficient spatial resolution) X-ray observations have found a population (Koss et al 2012, Satypayl 2017) of 'dual AGN' - 2 AGN very close (<10 Kpc) from each other.

AXIS can find such objects to the highest redshifts (subject to their luminosity) within 3kpc of each other.
Transient Science

Tidal disruption events directly probe 'delta function' accretion

X-rays seem to be primary (disruption radius $\sim 10-30R_G$ where effective temperature is very high)

Now: 2 dozen

Figure Credit: S. Gezari
AGN heating balances cooling of X-ray atmospheres.
How does an object smaller than the Solar System control the thermodynamic history of an entire galaxy?

Radio-mechanical feedback—“radio mode” feedback regulates fuel supply in elliptical galaxies

AXIS extends the study of this process from $z \sim 0.1$ to $z \sim 1.0$—the full range of cluster formation—synergy with SPT + eRosita + LOFAR + SKA
**Orbit Choice**

- Low Inclination LEO Gives Very Low Cosmic ray Dose - Long Detector Life
- Ease of Communication allows flexible satellite and TOO capability — rapid slewing gives ~70% observing efficiency
- High mass to orbit margin for Falcon 9 - no mass problem with spacecraft at 8° inclination

![Graph showing displacement damage dose vs. thickness for different inclinations](image)
Continuous Progress in Next Generation X-ray Optics Angular Resolution over 20 years.
AXIS Mirror Assembly

0.3 m ID

0.5 m

1.7 m OD

Silicon

Composite

16,568 mirrors → 6 meta-shells → 1 assembly

Mass: ~454 kg

Heater Power: ~300 W

Eff. Area@1keV: 0.77 m² with traditional Ir coating
Entire Process Validated by X-ray Testing

Two uncoated mono-crystalline silicon mirrors aligned and bonded on a silicon platform.

Effective Area at Ti-K (cm$^2$): 0.266 predicted, 0.260 measured, agreeing within 2.3%.

Acknowledgement: Thanks to Vadim Burwitz and his team at Panther who performed this measurement.
AXIS Observation of star formation at $z=3$

X-ray Emission from star formation due to NS and BHs + Hot Gas - In rapidly star forming galaxies most of the energy from star formation goes into the hot gas

ALMA data for SDP81 (molecular gas) - white contours

Colors - AXIS Simulation
Imaging the gravitational sphere of influence in SMBHs

How does accretion work, where does the gas come from how does it fall in?

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

Chandra can measure Bondi radius in only 3 galaxies... confusing results

AXIS can measure Bondi radius in ~25 Galaxies and explore how accretion works!
LISA Follow-ups

How to find the EM counterpart?

- AXIS can tile a LISA 1 sq deg error box to detect host AGN in ~1 day of observation (detect a $\sim 10^5 M_\odot, 10^6 M_\odot$ BH counterparts at $z=1,3$ resp).
  - optical/UV imaging cannot find the absorbed AGN which is the host of the mergers.

What is the population from which BH-BH mergers are drawn?

AXIS will find most dual AGN (progenitor population from which GW sources are drawn) over a large redshift range.