Advanced X-ray Imaging Satellite

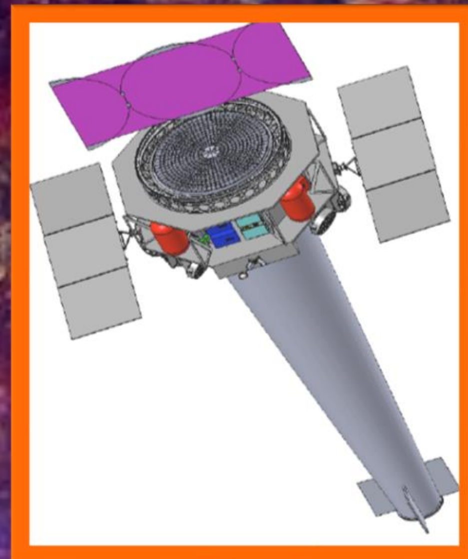
R. Mushotzky (UMD) for the AXIS Team

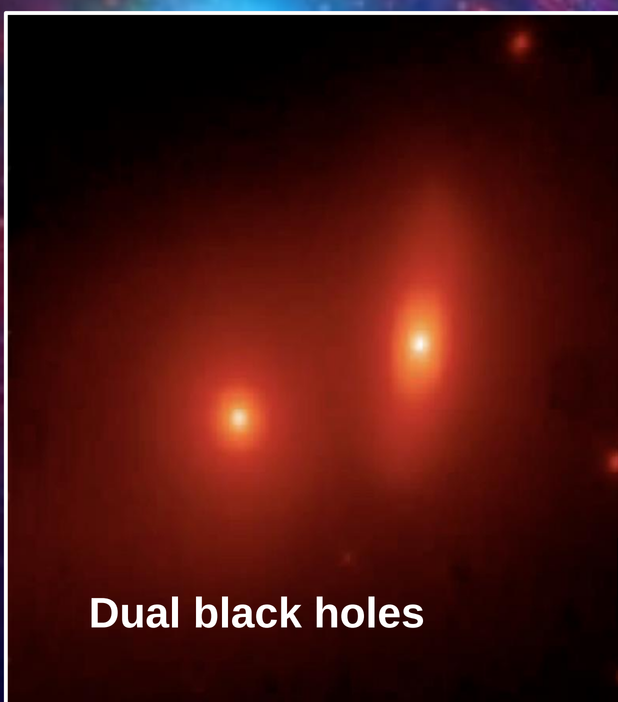
http://axis.astro.umd.edu/
arxiv/1903.04083.pdf

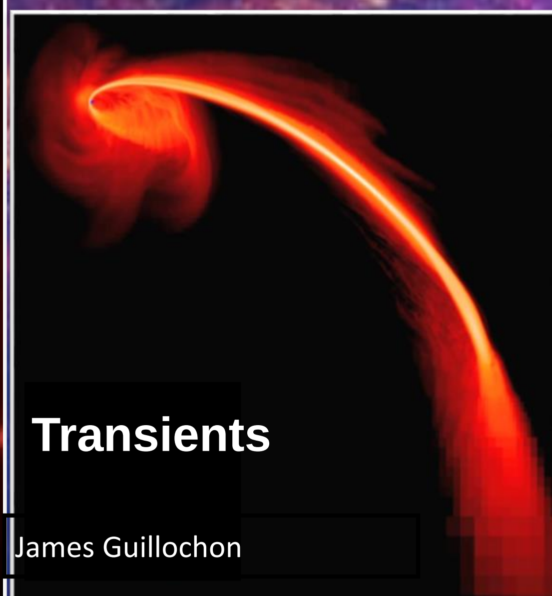
- X-ray Astronomy provides a unique view of the universe
- High angular resolution and high sensitivity is required to obtain a large fraction of the necessary information
- AXIS is a Probe mission with these capabilities – *only US has the technology*

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





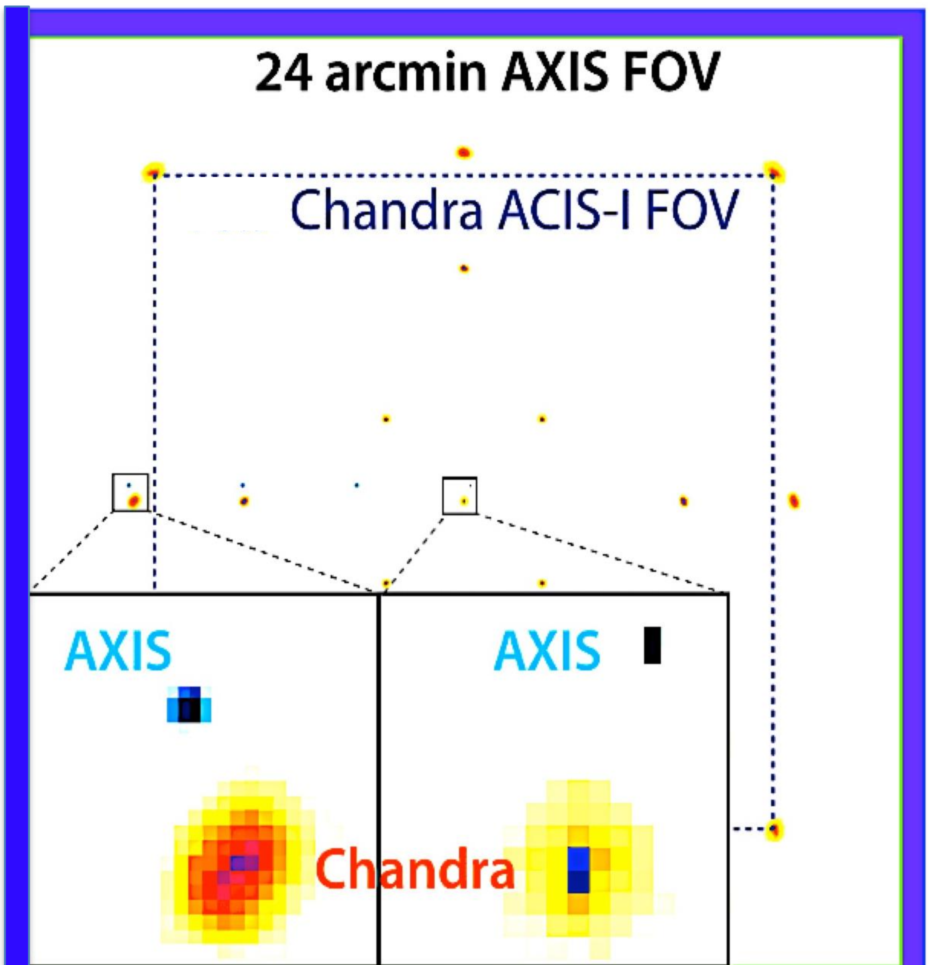


Broad Top Level Science Areas- Observatory Class Science

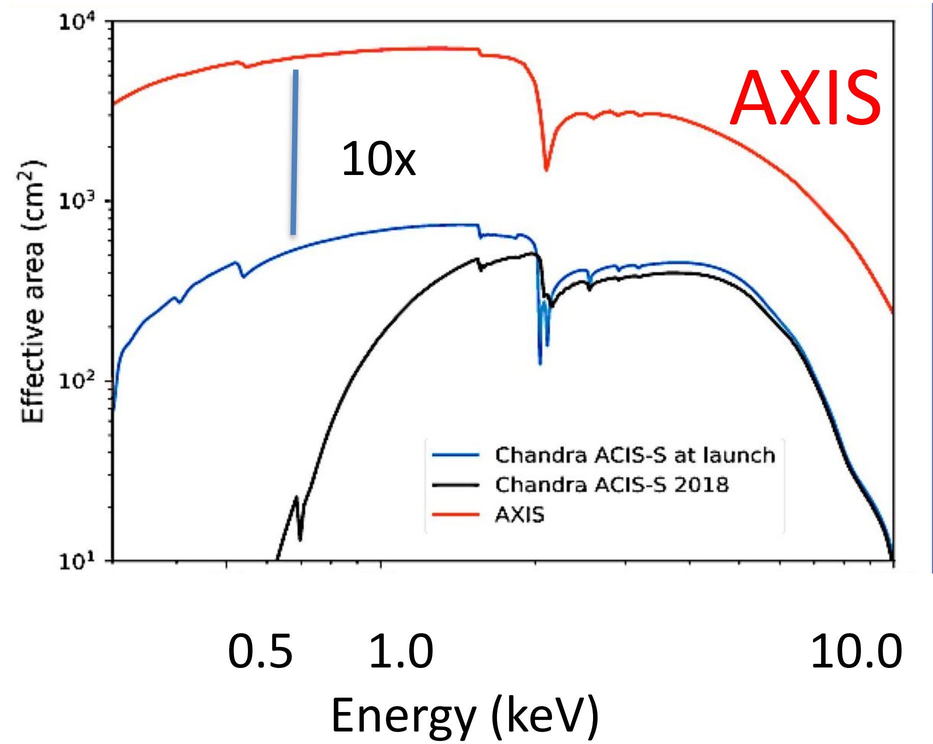
- **Intergalactic (IGM) and circumgalactic (CGM) medium in emission**
  Detection, characterization and properties

- **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**

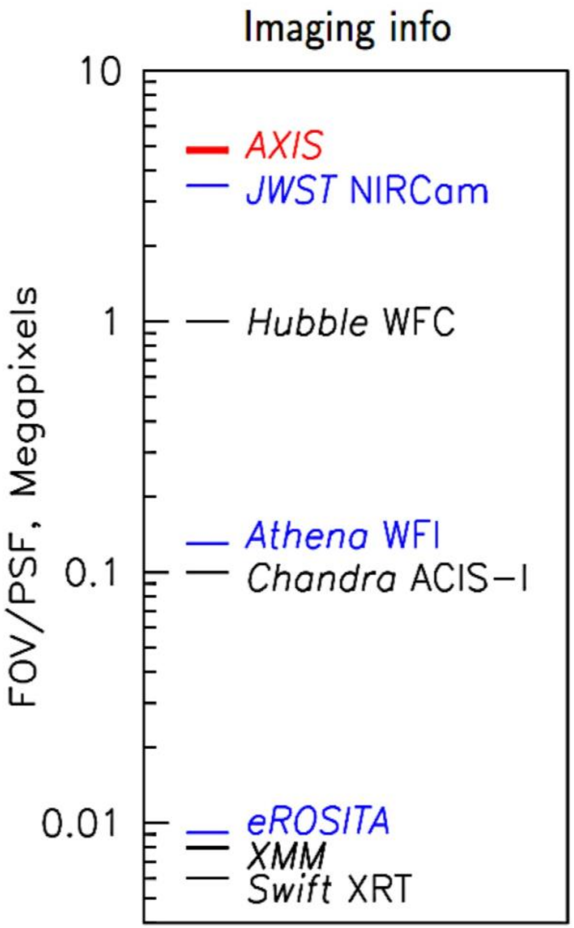
AXIS…
at a glance



A.1 The AXIS field of view and PSF, shown in comparison to Chandra

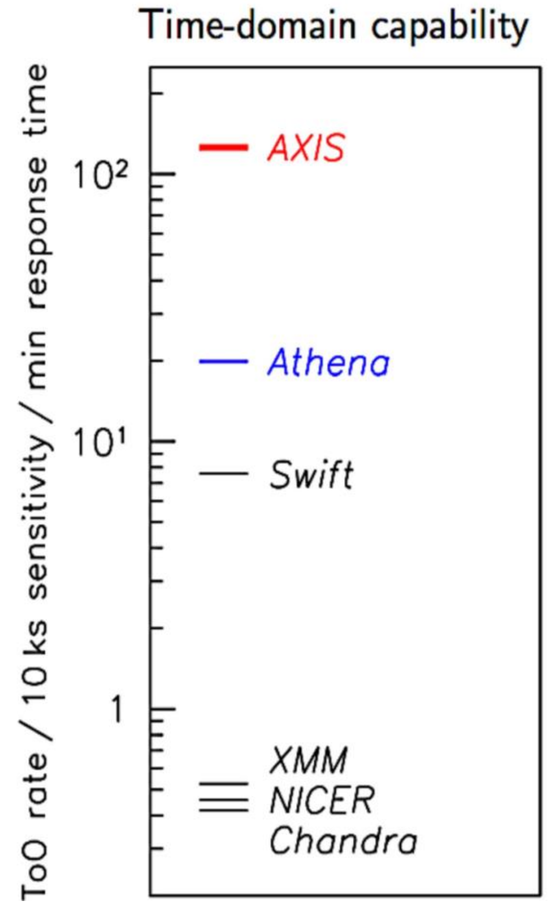


AXIS collecting area, PSF and field of view compared to Chandra
>10x better in many areas- allows breakthroughs



Total number of resolution elements in focal plane

Angular Resolution	~0.4 arcsec	High angular resolution
Bandpass	~0.1-12 keV	Broad bandpass
Effective Area	$7000 cm^2$ @1 keV $1000 cm^2$ @ 6keV	~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

Observatory Class science- large phase space for guest observers

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**

ADVANCED X-RAY IMAGING SATELLITE
AXIS
X-RAY VISION FOR THE 2020s

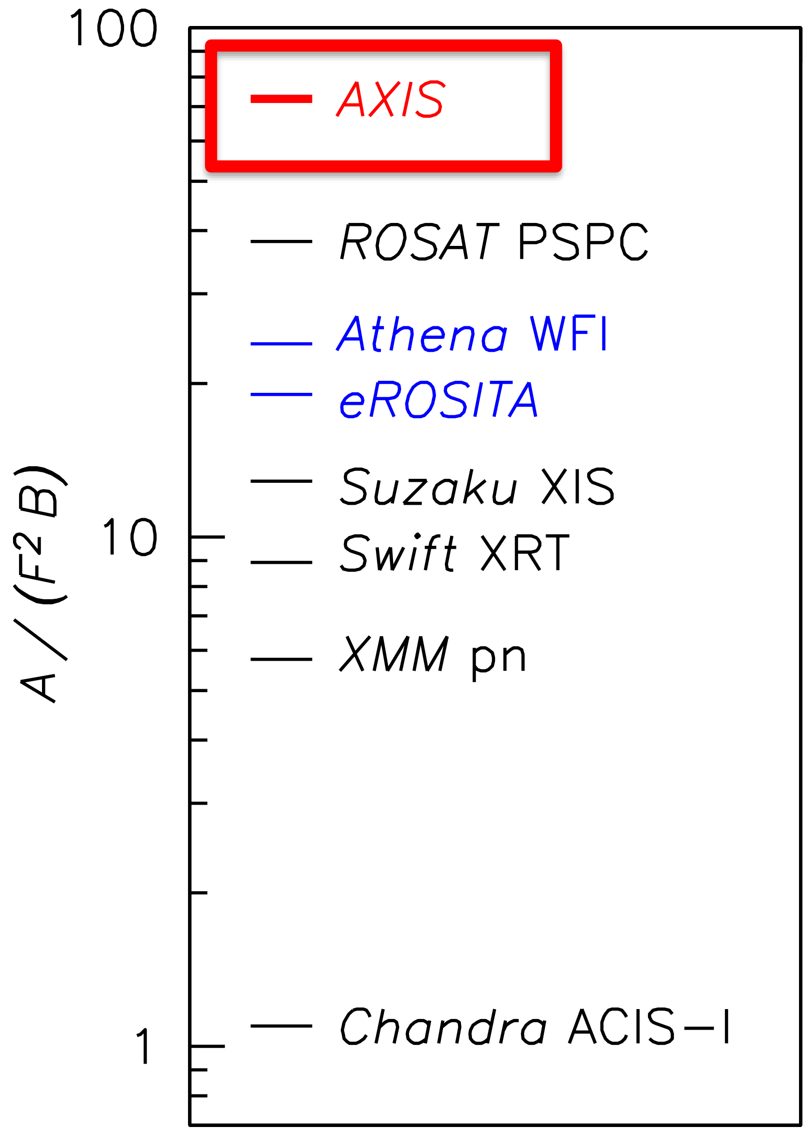


figure of merit is Collecting Area/[(focal length)^{2}xbackground]

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)

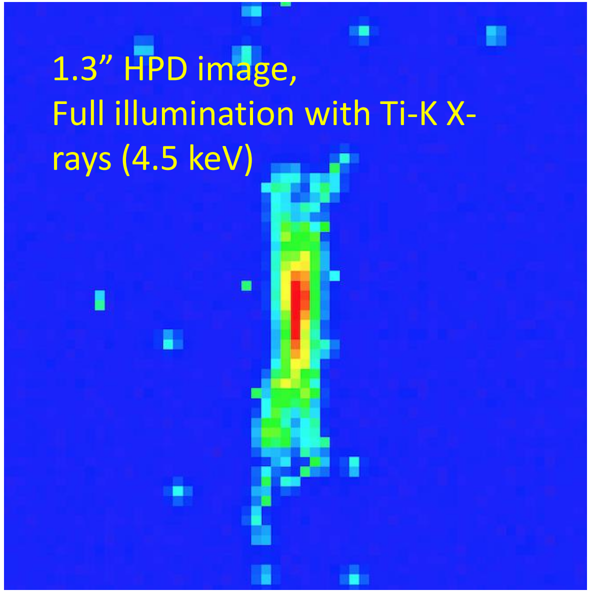
New Optical design

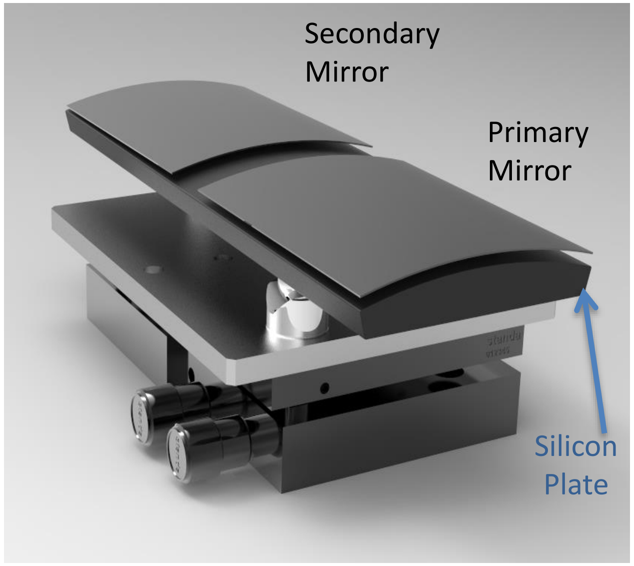
Wolter-Schwarzschild design optimized for wide FoV with nearly constant PSF and large collecting area

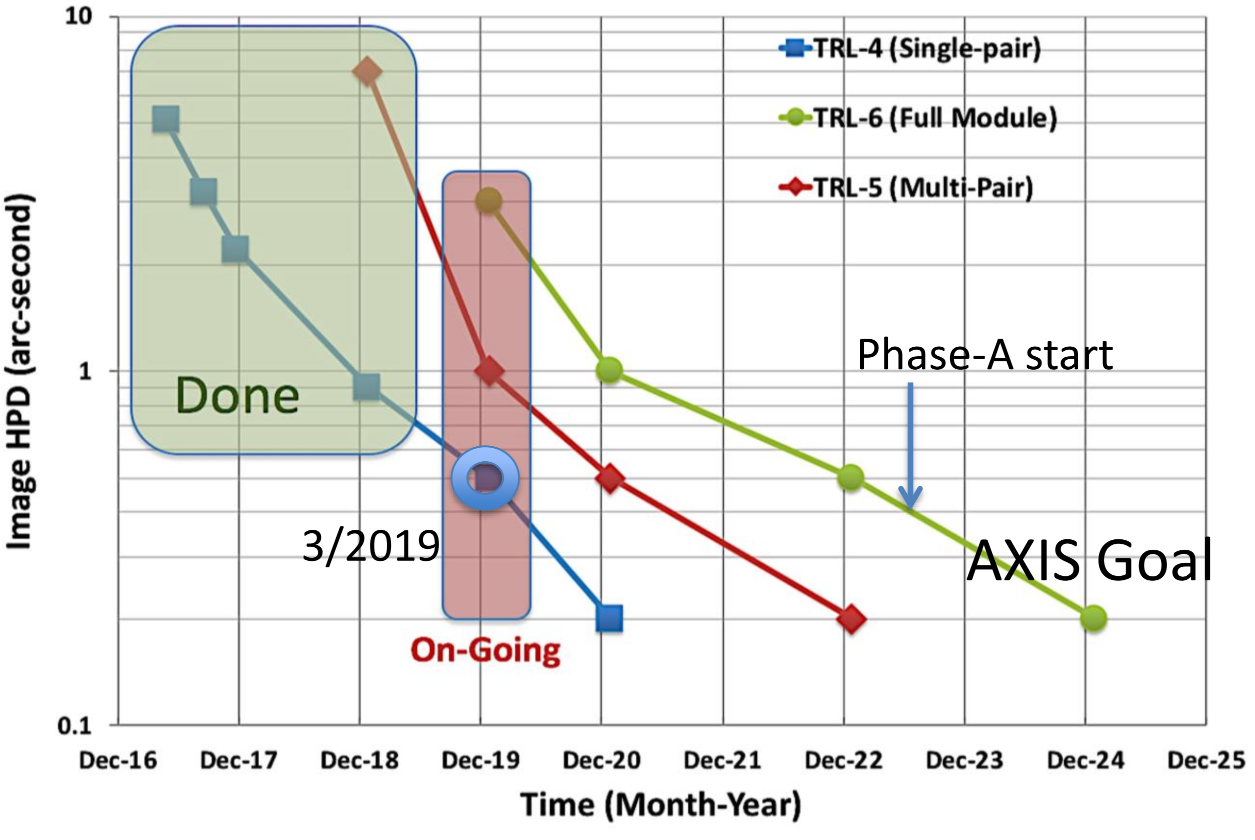
(GSFC team led by W. Zhang)

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"***

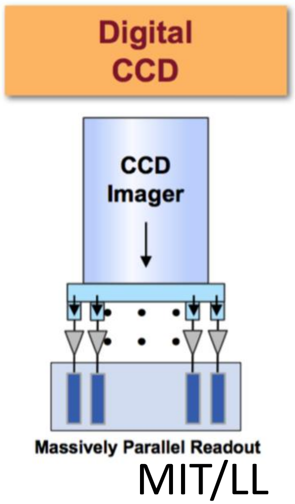


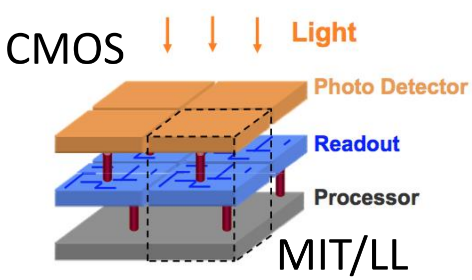




Detector Technology

- 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.





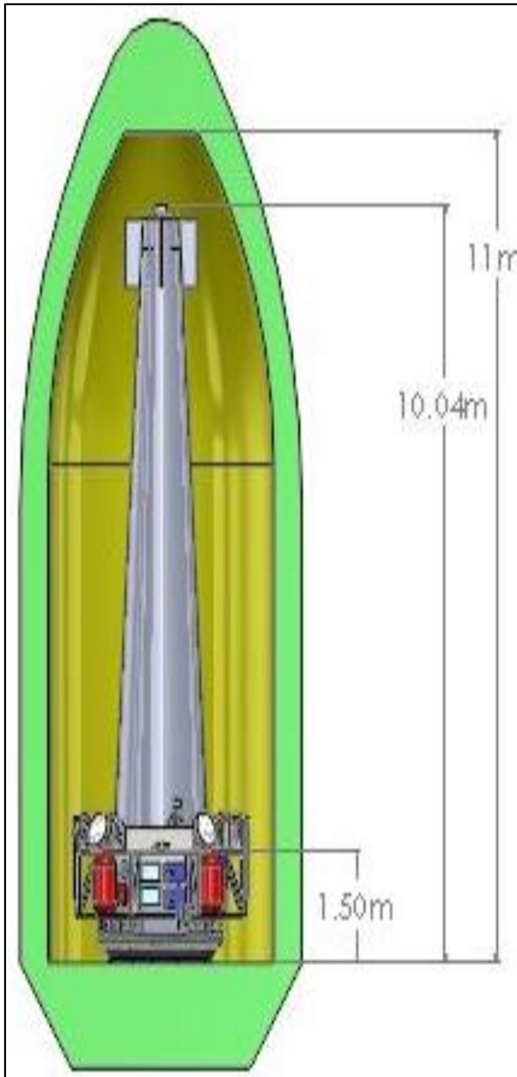
Fast, low-noise, small pixel, imaging X-ray detectors

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

Spacecraft and Mission

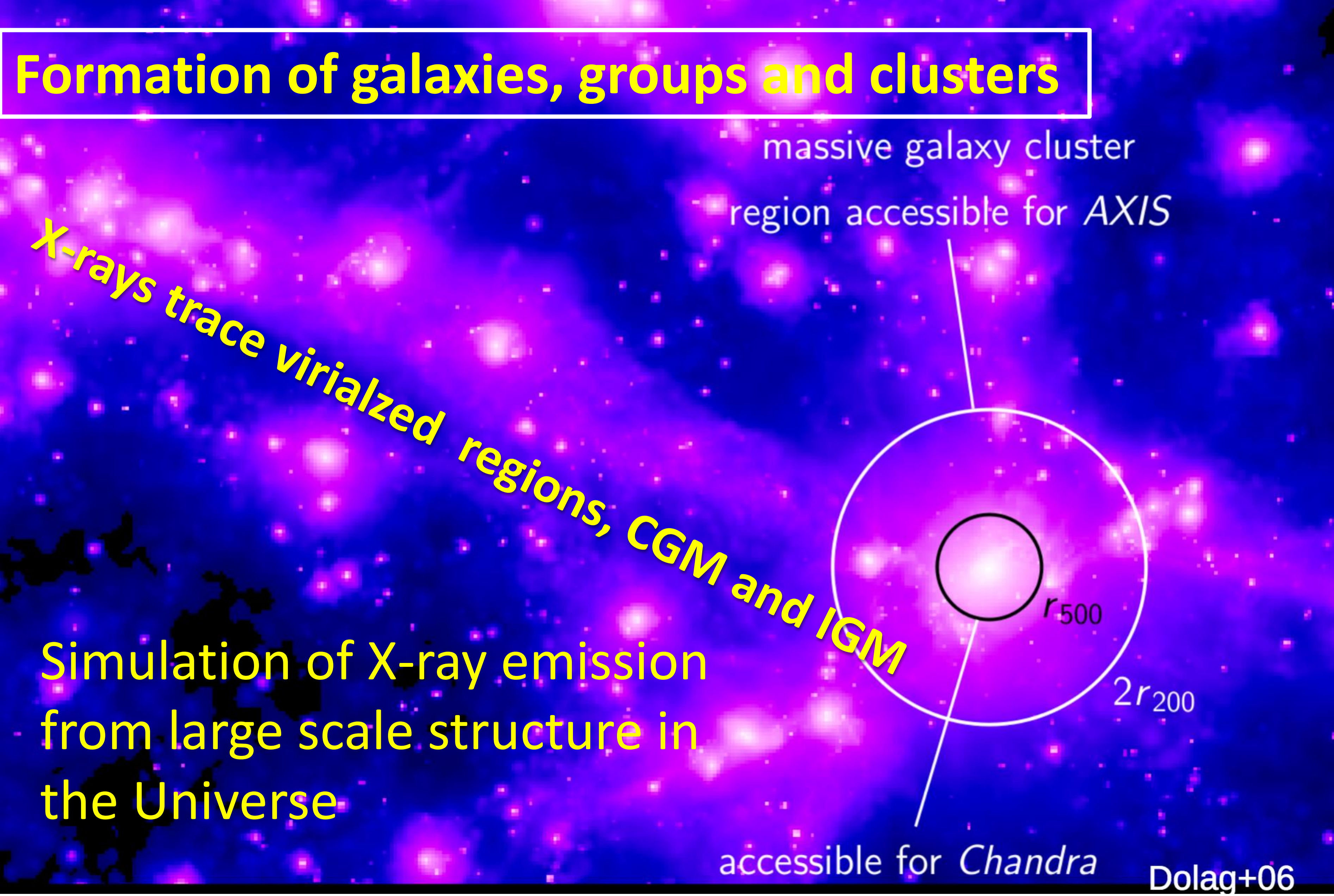
- Rapid slewing - ~70% observing efficiency
  - 'Large' fraction of sky available
- Launch vehicle of choice (today) Falcon 9
  - Margin for 8^0 inclination LEO
- Low Inclination –very low cosmic ray dose- long detector life, low background
- Easy communication – flexible mission ops and TOO capability 4 hours response, several times per week
- Dry mass ~1635kg, moderate power ~650W

Cost estimate ~$1B (GSFC MDL)



Falcon 9 shroud

Formation of galaxies, groups and clusters

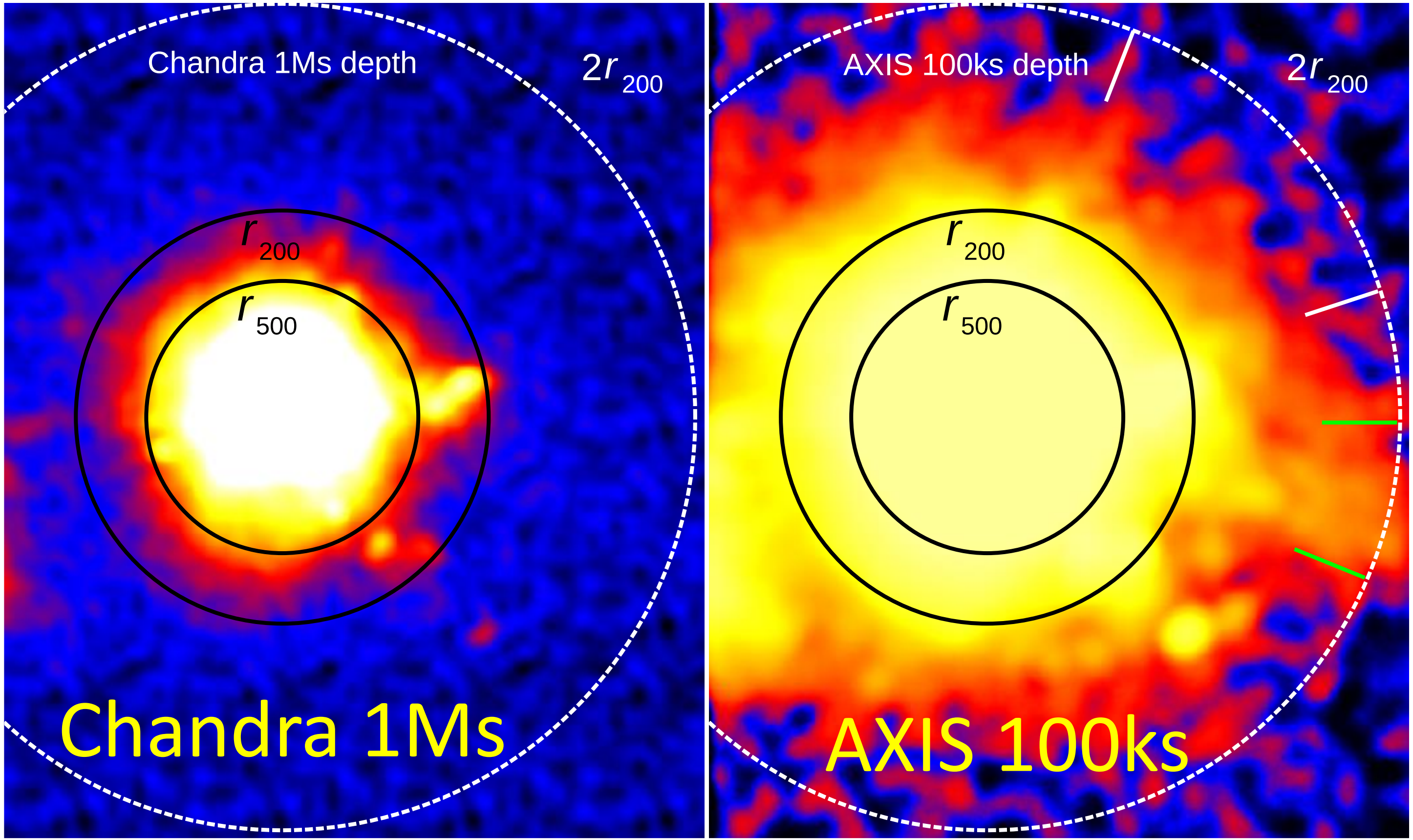


AXIS has the sensitivity, bandpass, low background, angular resolution and field of view to measure all of these regions.

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



Cluster at z=0.1

AXIS 100ks

Chandra 1Ms

S. Walker et al 2019

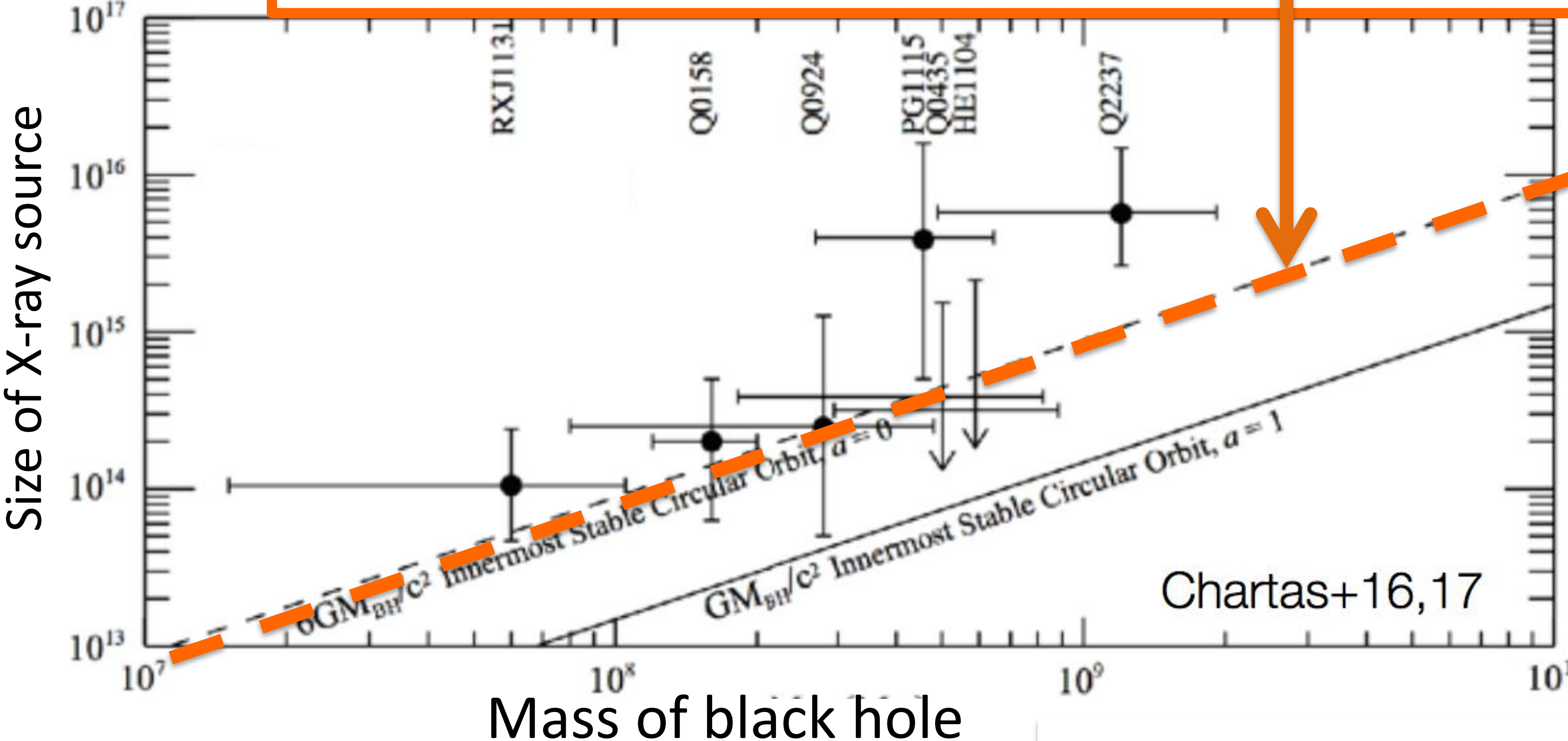
What does it look like near a black hole ?

Gravitational Micro Lensing of a Sample of QSOs to **<u>image</u>** X-ray emitting region *very near event horizon* (***10^{-9}*** arc sec effective angular resolution)

X-ray Constraints on source size from Chandra ***Microlensing***

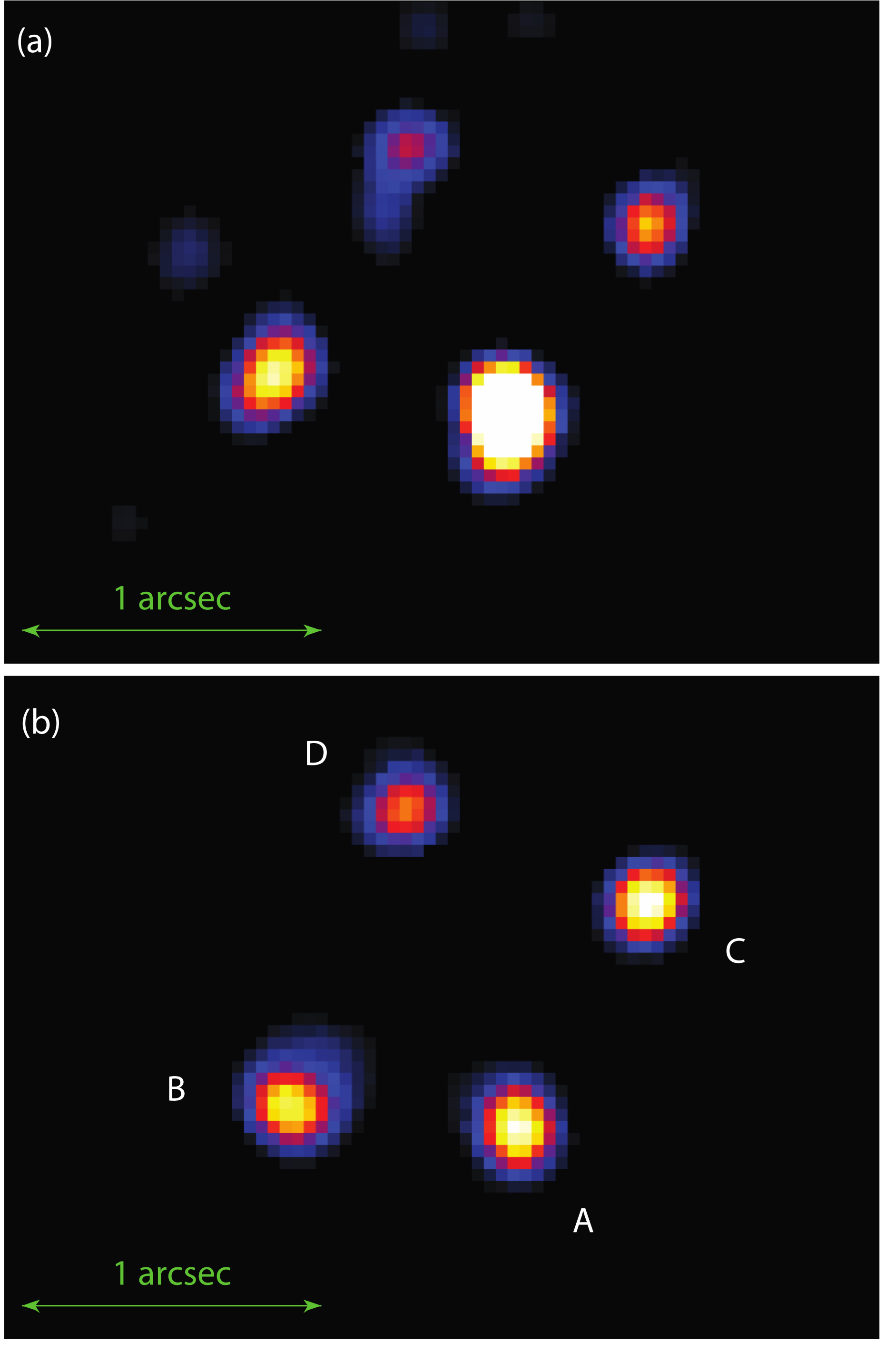
AXIS drastically increase sample size, reduce uncertainties

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



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)

ADVANCED X-RAY IMAGING SATELLITE

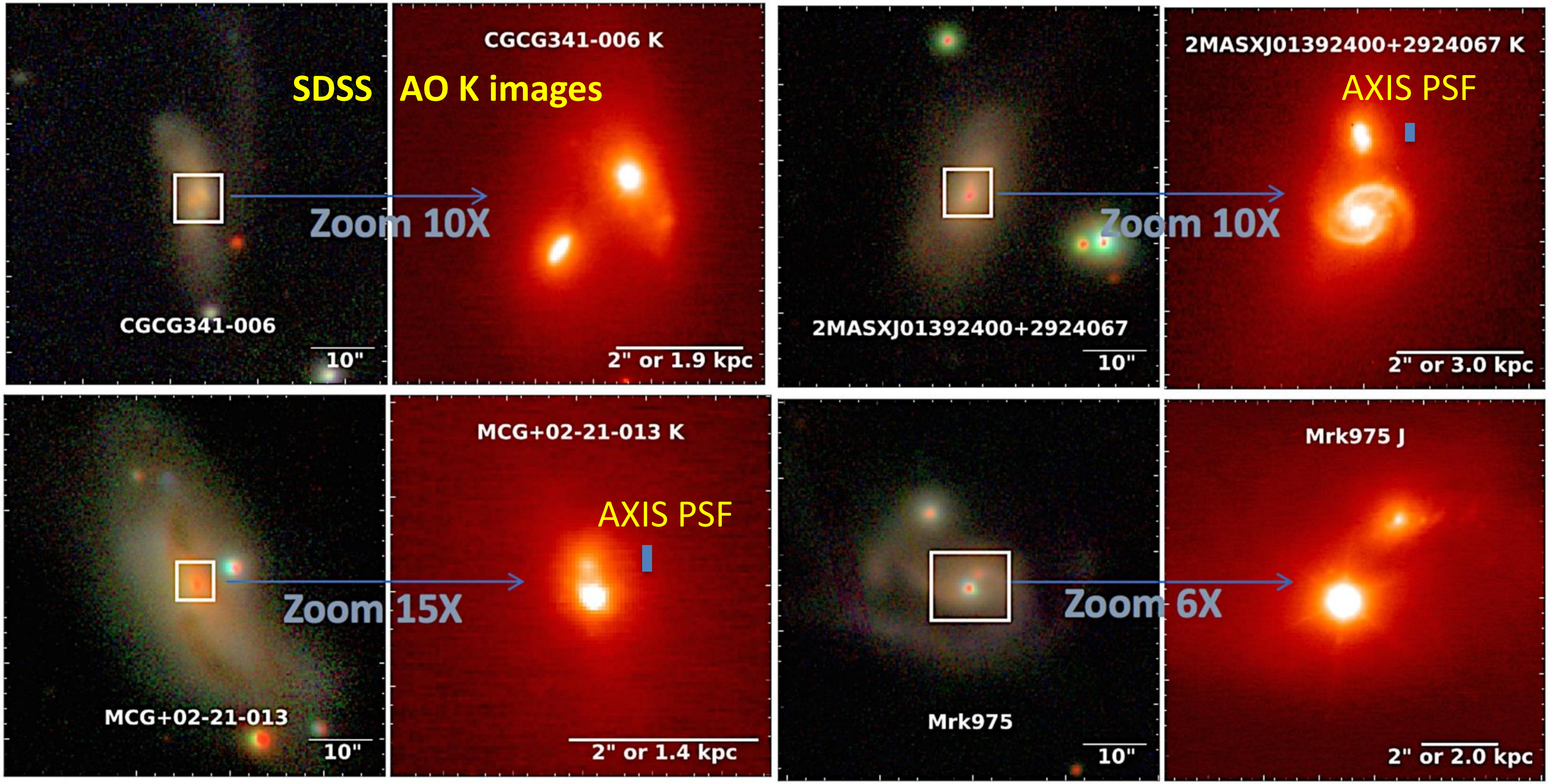
AXIS

X-RAY VISION FOR THE 2020s

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

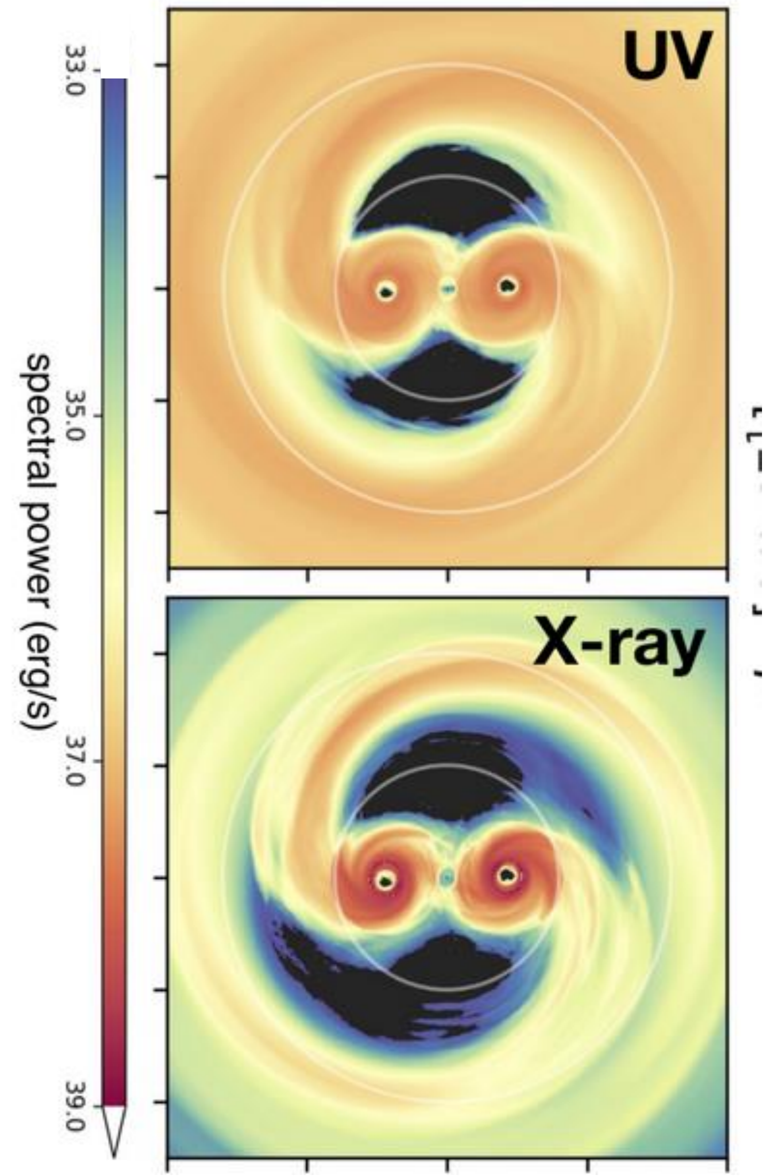
X-rays expected to be brightest emission source in weeks before merger

AXIS detects $\sim 10^5 M_\odot, 10^6 M_\odot$ BH counterparts at z=1,3 resp

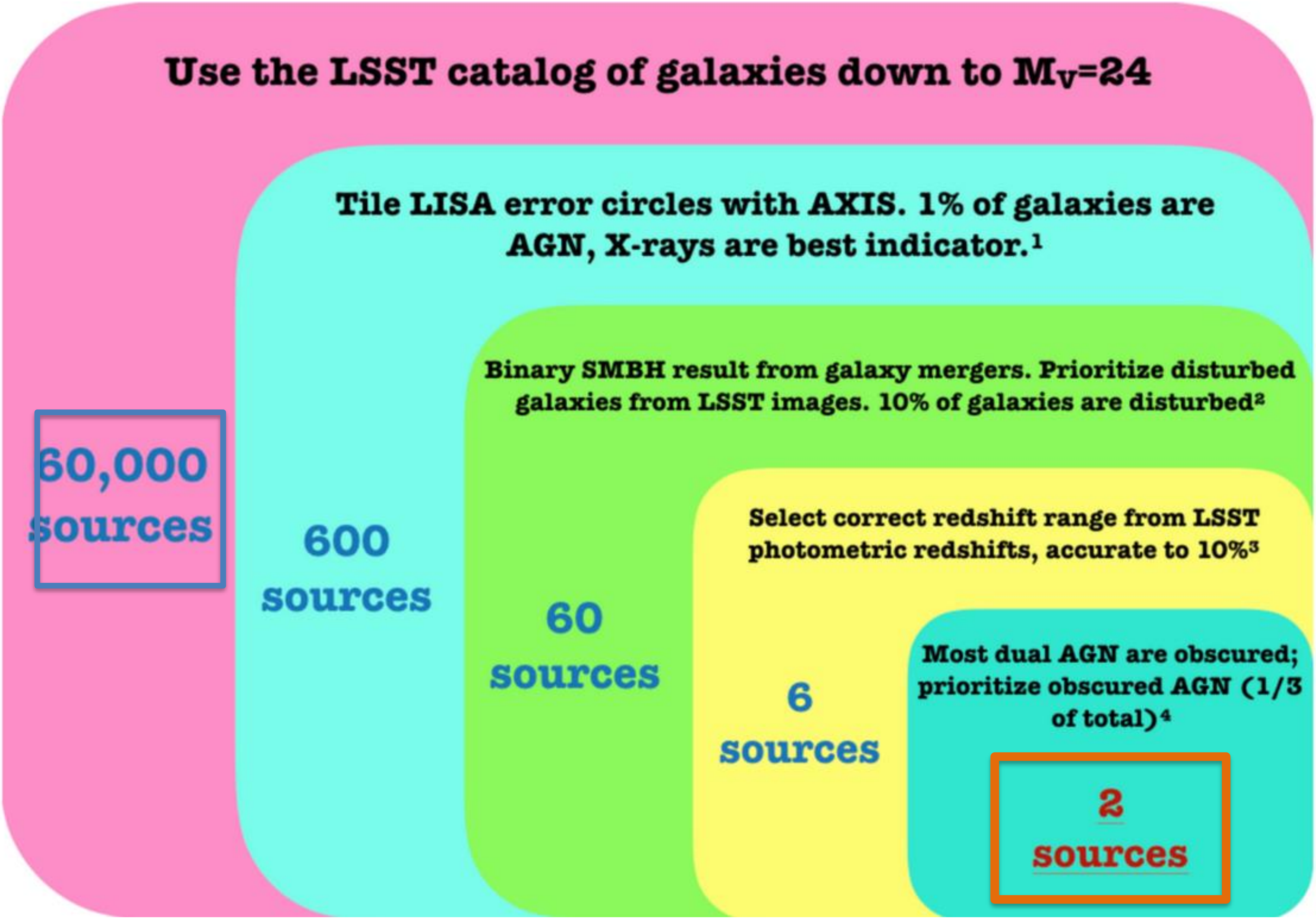
ADVANCED X-RAY IMAGING SATELLITE

AXIS

X-RAY VISION FOR THE 2020s



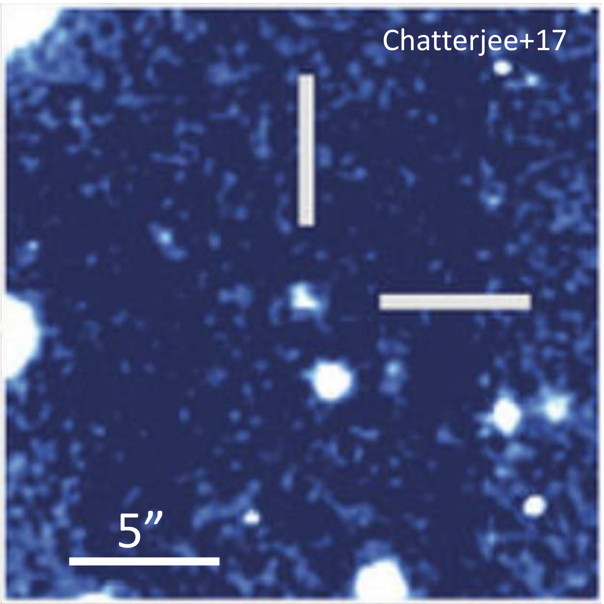
How to Find LISA Sources with AXIS- Needle in Haystack



AXIS Time-Domain Astronomy

A few examples……

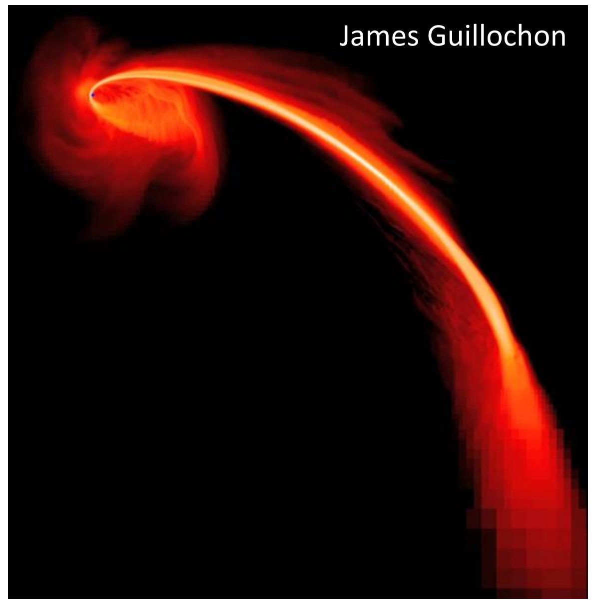
Fast Radio Bursts



SKA will detect 1000x more FRBs

AXIS will probe deeper, sharper and faster in crowded fields- astrometry at 0.1" level- 20ms timing

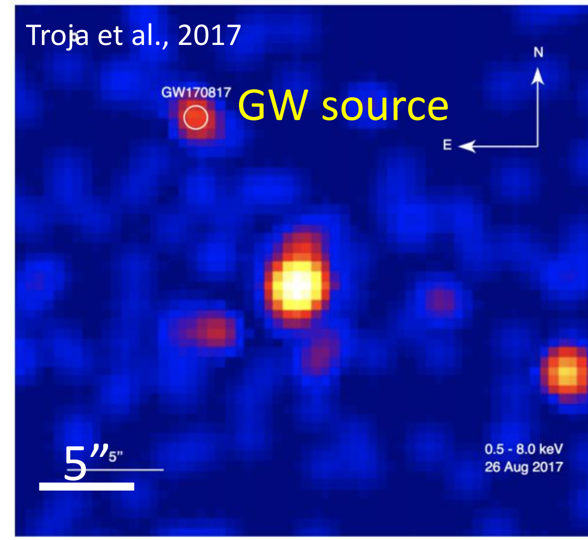
Tidal Disruption Events



Thousands of TDE/year with LSST-**AXIS localizes X-rays at galactic nucleus +spectra +timing**

How do TDEs produce X-ray emission?

GW Follow-up



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

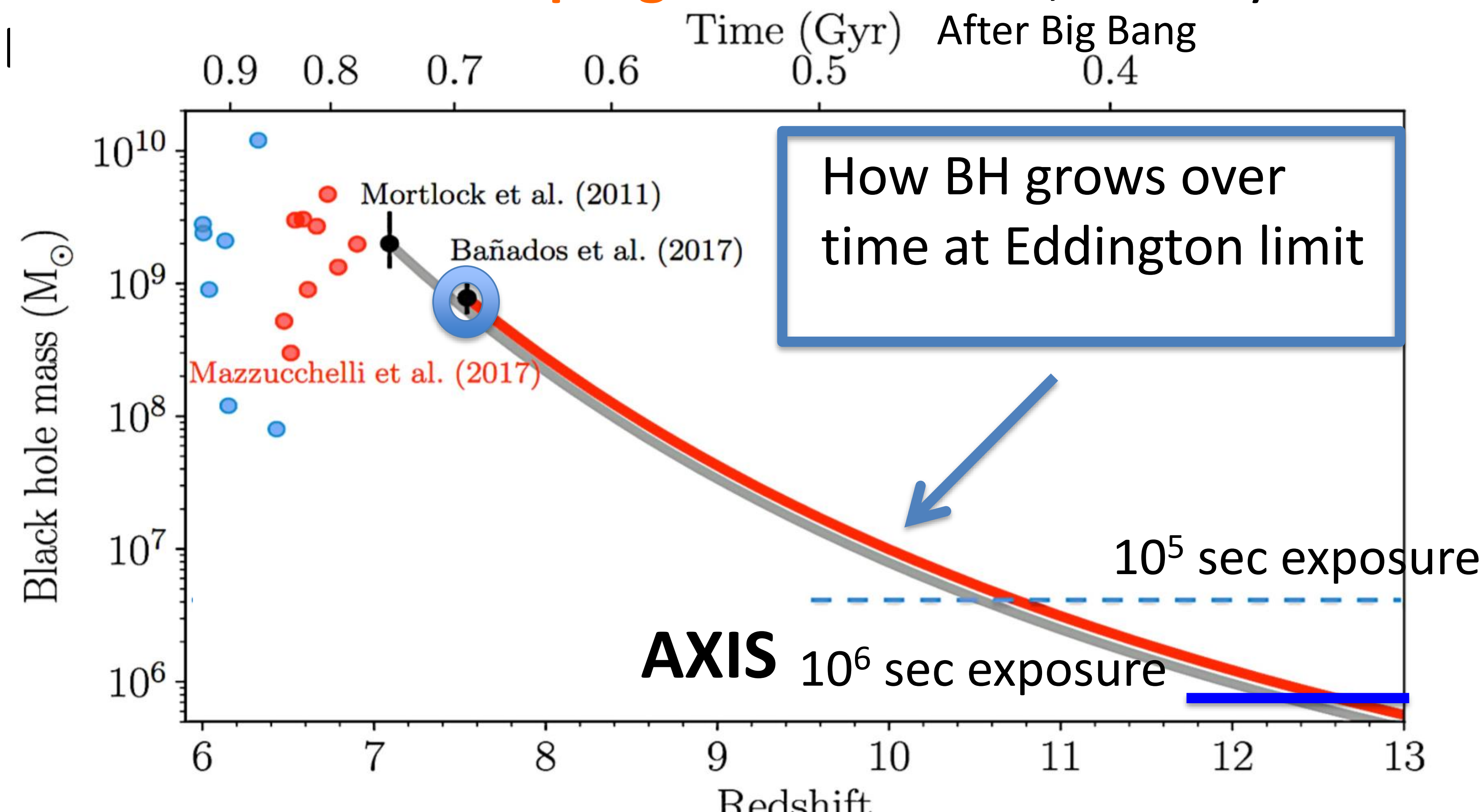
Need AXIS for expected ALIGO sources >3x more distant

Birth of SMBHs-The Highest Redshift Quasars-

SMBHs at z~7.5 (690 Myr after Big Bang)

$M_{SMBH}=8x10^8\ M_{sun}$ (Banados et al 2018)

AXIS can detect their **progenitors** at z~13, 300 Myrs after Big



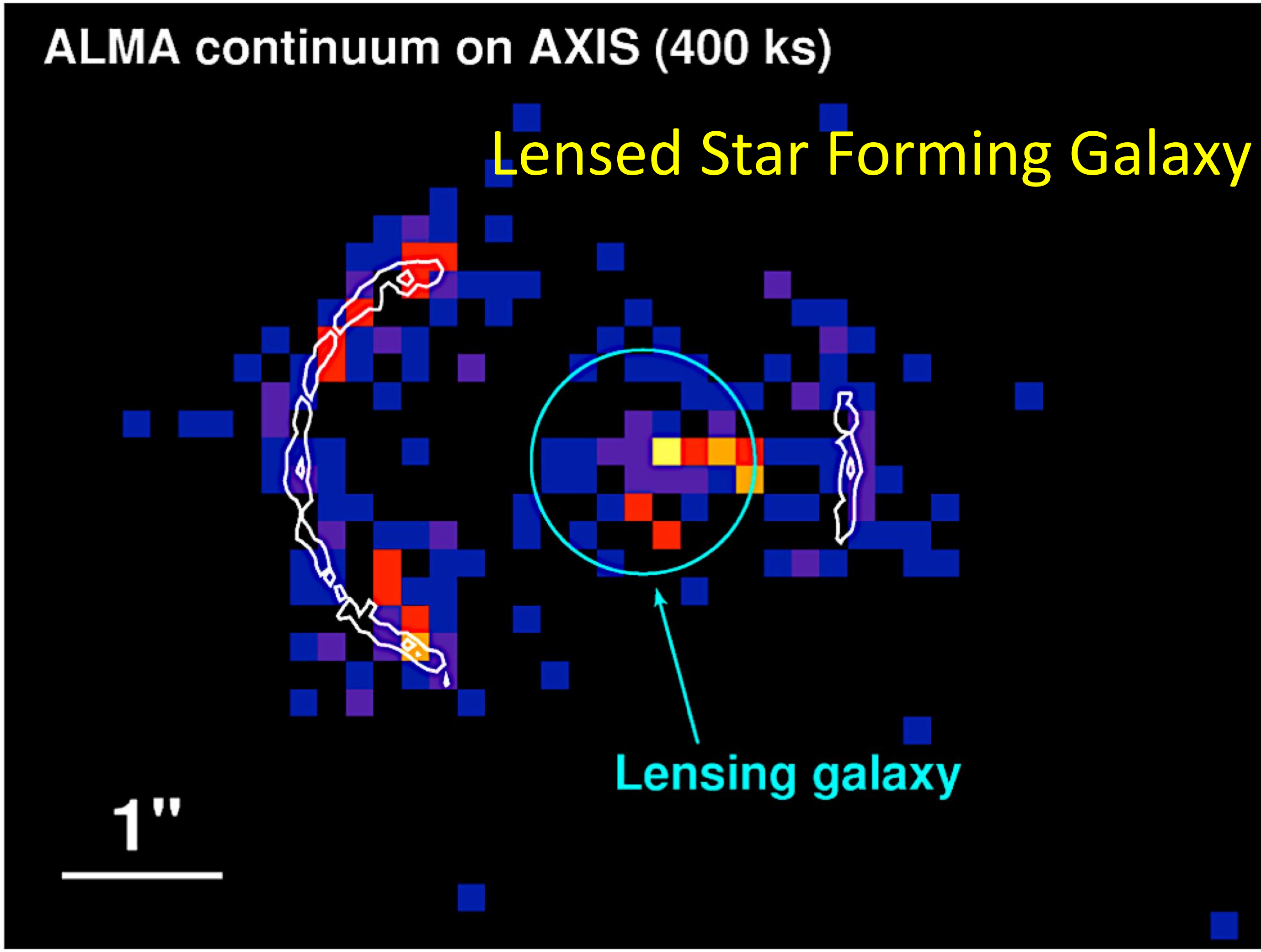
Star Formation at z=3

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

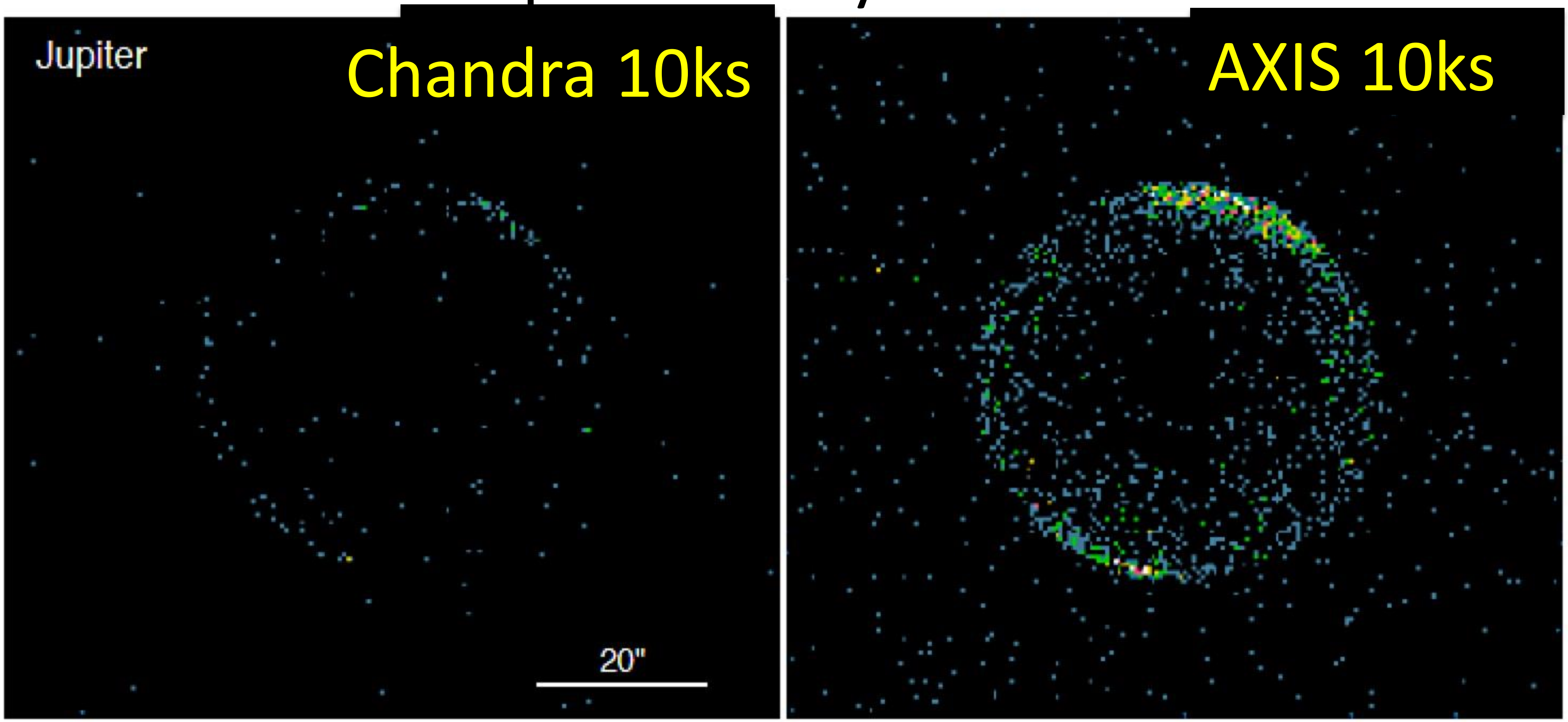
In rapidly star forming galaxies most of energy from star formation is in hot gas

ALMA data for SDP81(molecular gas)- *white contours*

Colors- AXIS Simulation



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

Mirror Segment

16,568 mirror segments individually fabricated and qualified.

Meta-shell

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

Mirror Assembly

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"**

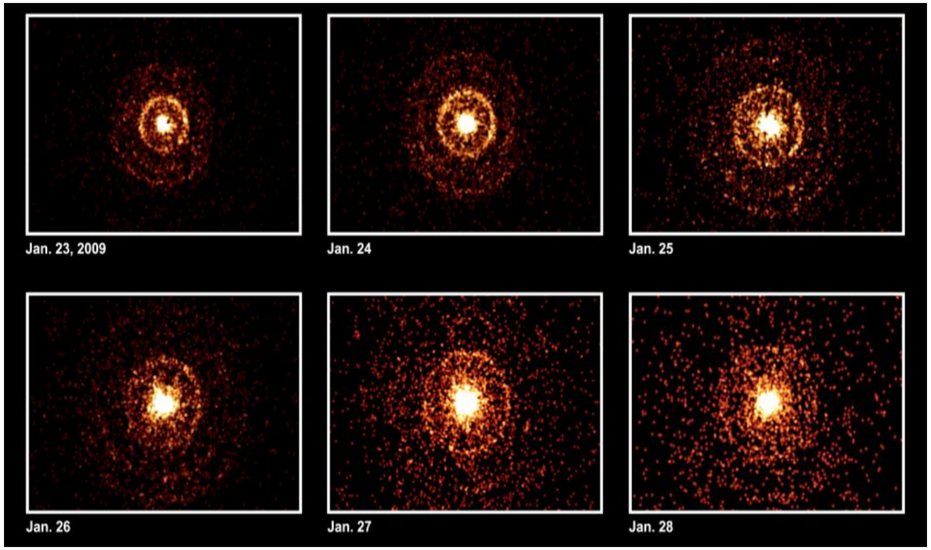
Zhang et al have produced an image, for all intents and purposes, as good as Chandra's but with mirrors that are 30 times lighter

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

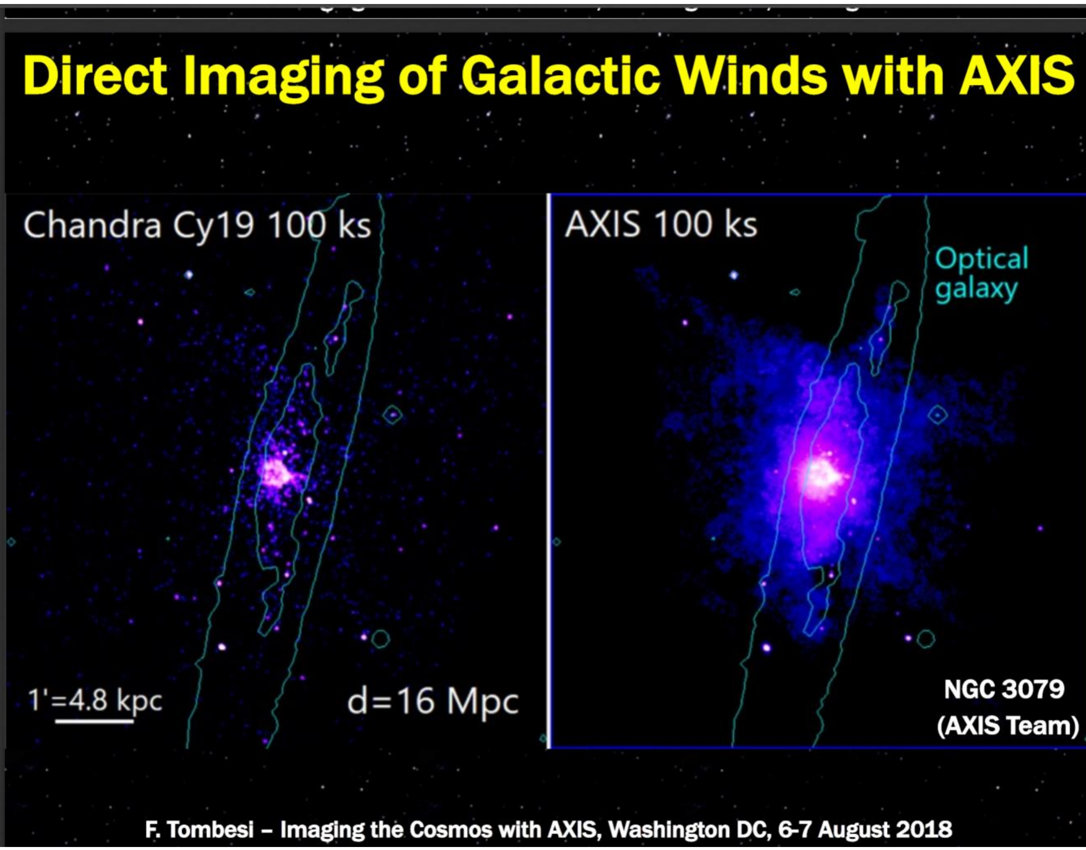
And many others!

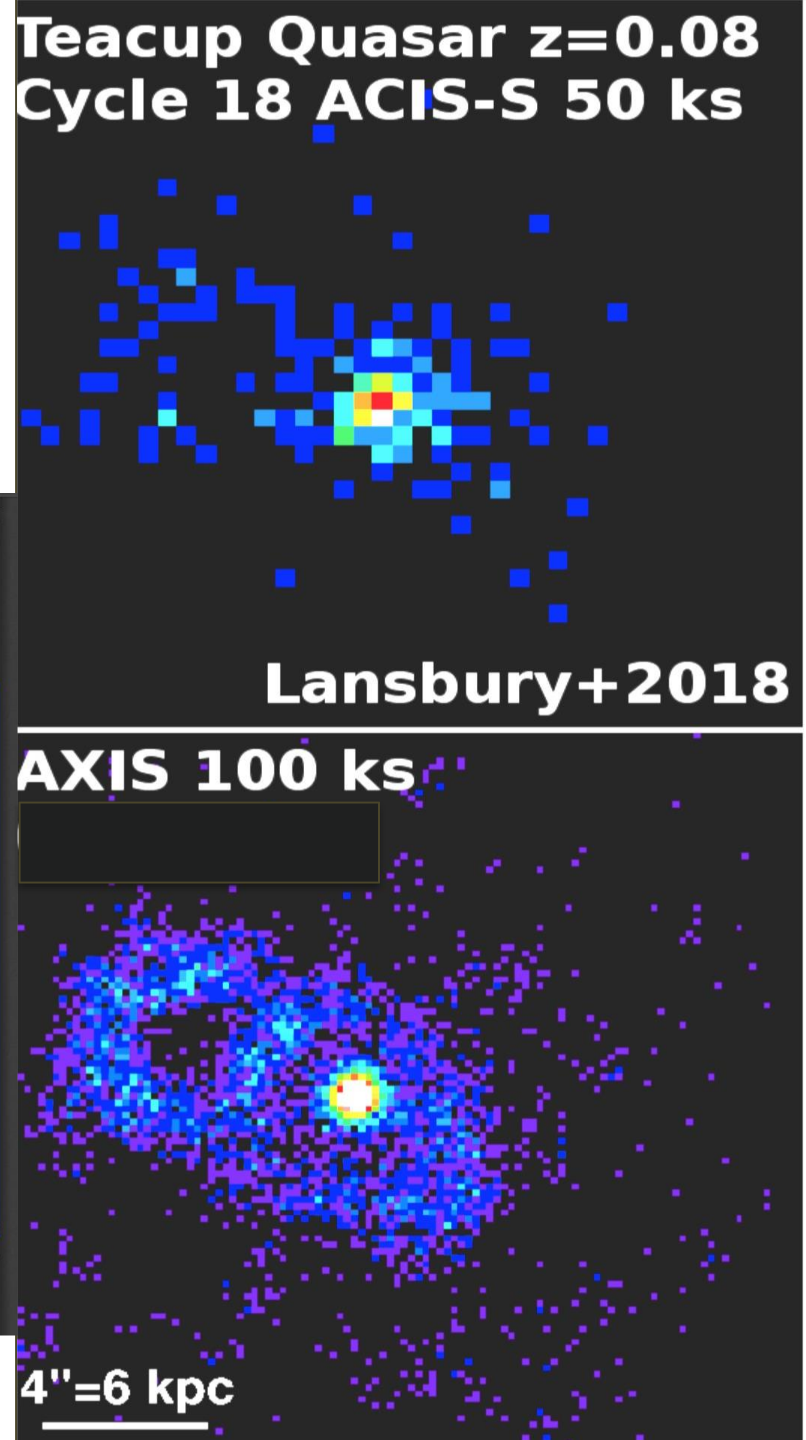
Driving Requirements

- **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 7minutes
  - 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



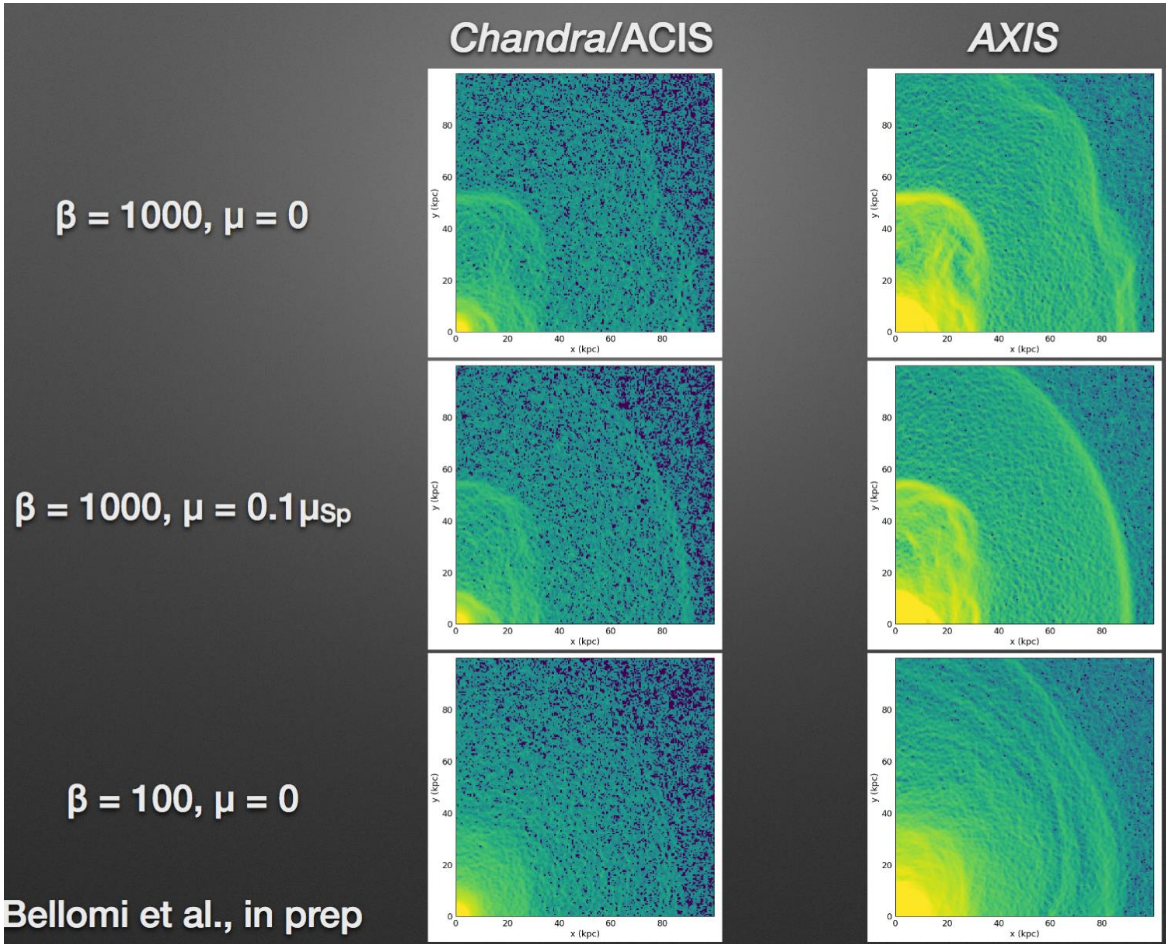


Fundamental Plasma Astrophysics

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

Kelvin-Helmholtz Instabilities
Thermal Conduction
Shock Acceleration
Thermal Conduction
Viscosity
Shocks
Electron-proton equilibration
timescale
What is 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

Effects of anisotropic thermal conductivity on x-ray images of clusters
J.Zuhone



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)

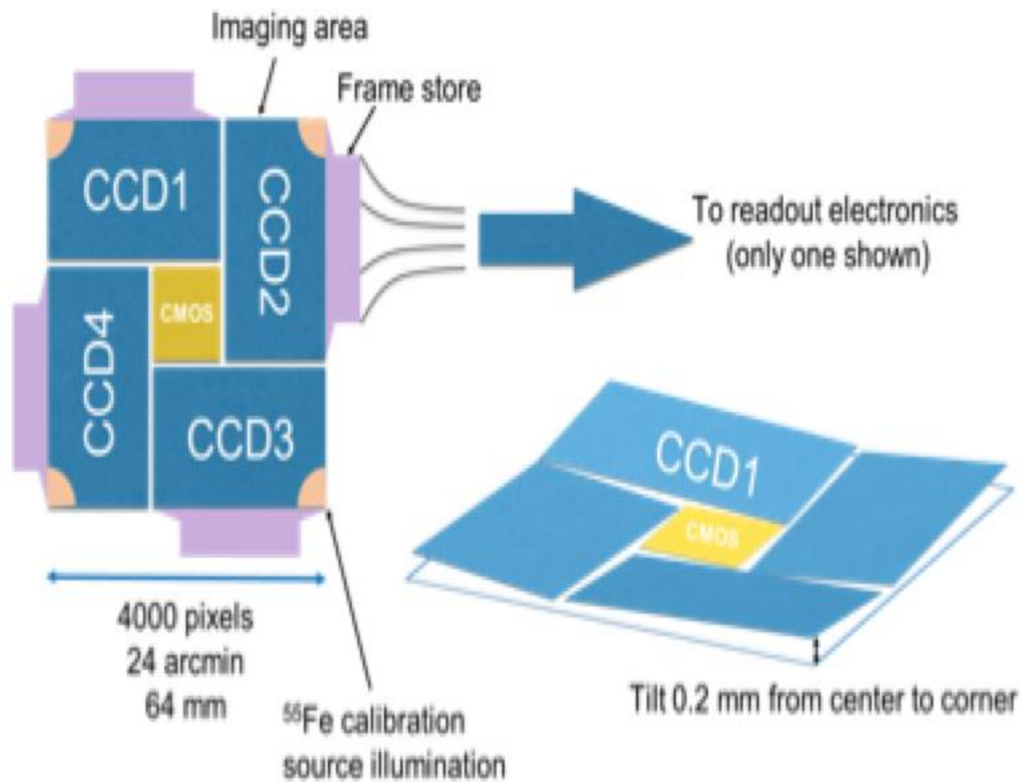
AXIS ALIGO Followups

Need <1" spatial resolution to identify source
Sensitivity $<2\times10^{-16}$ 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

AXIS Observatory Overview

Telescope Tube

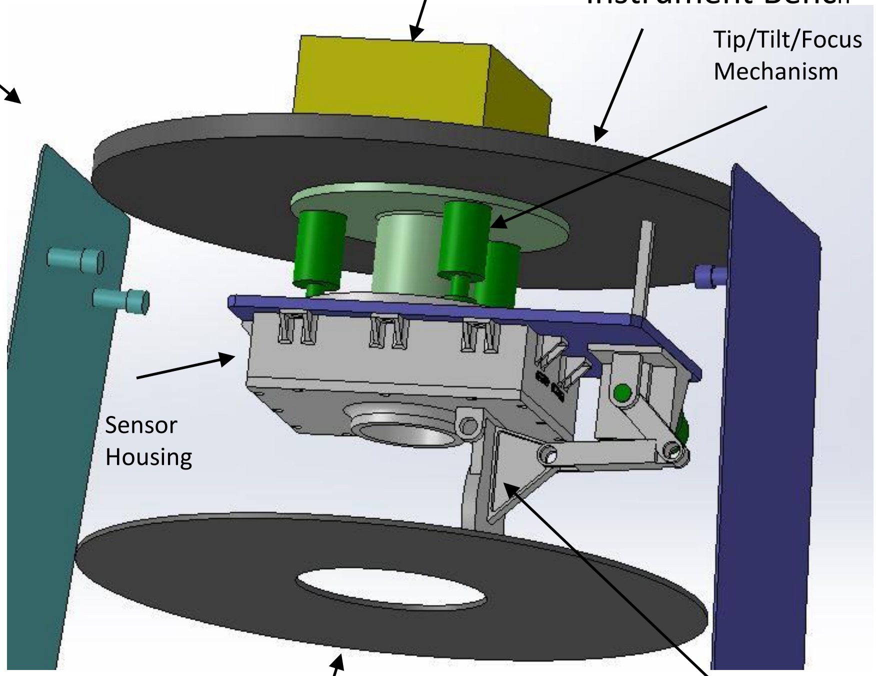
Spacecraft not shown

AMA + FPA + Tube ~ 751 kg

Detector Assembly

ASICs & FEE Interface Electronics

Instrument Bench



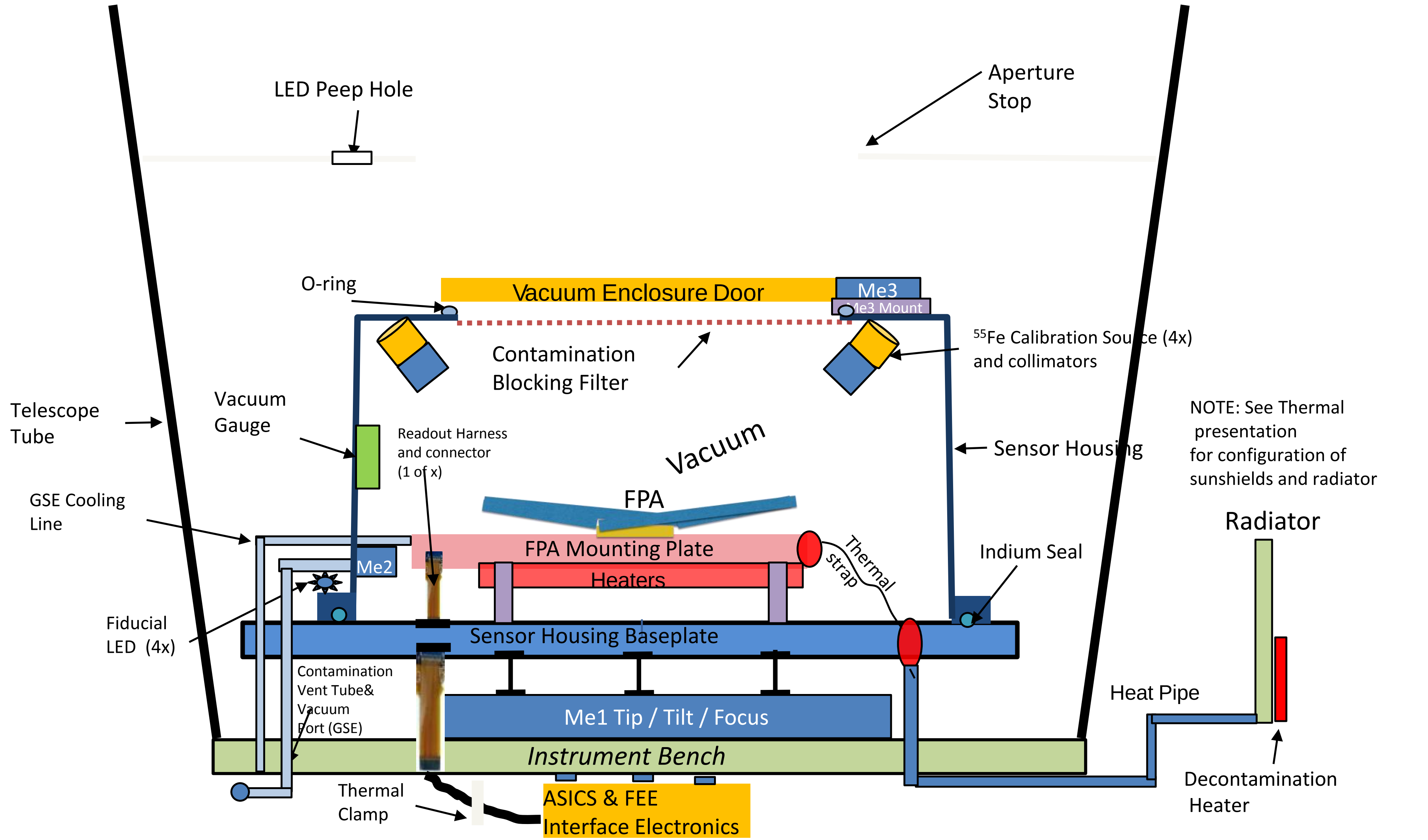
Aperture Stop

Vacuum Enclosure Door

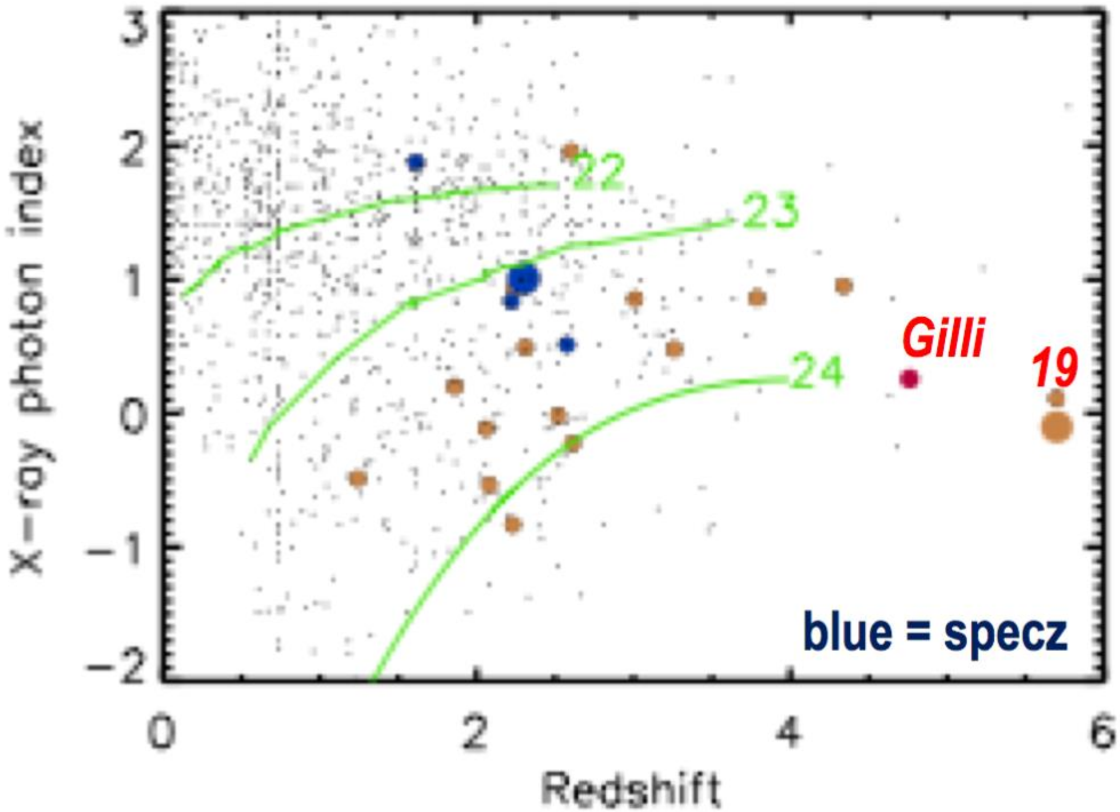
297W Orbital Average in Science Mode

197W Instrument + 100W Operational Heaters

IDL: AXIS Detector Assembly Block Diagram



What is the obscuration in the submm AGN?



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

from L. Blecha http://axis.astro.umd.edu/images/blecha.pdf

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'

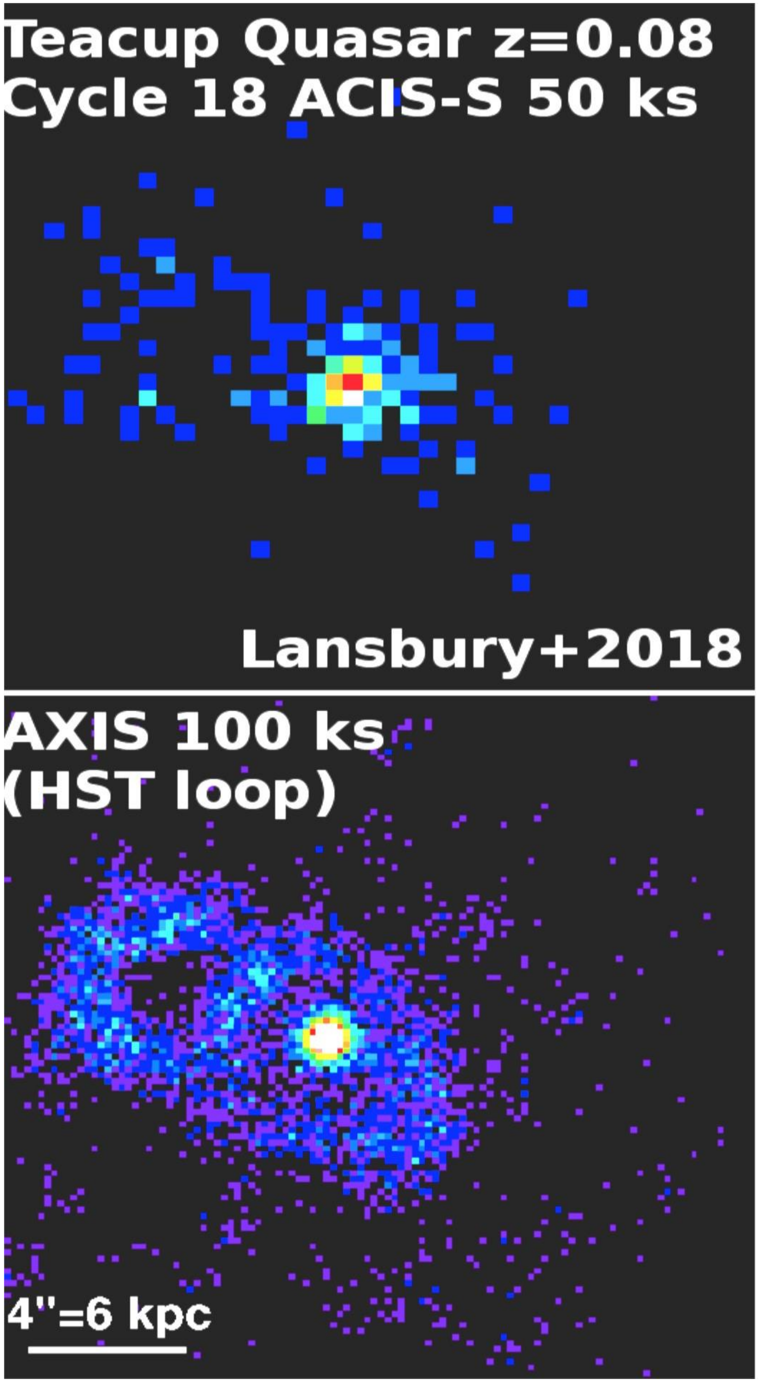
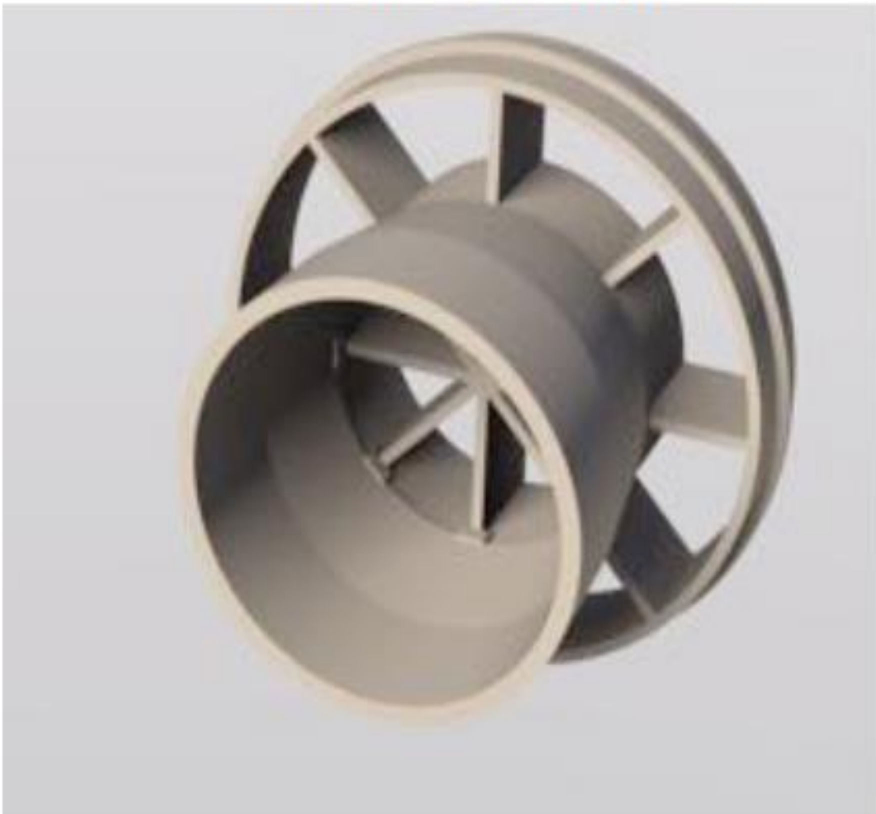


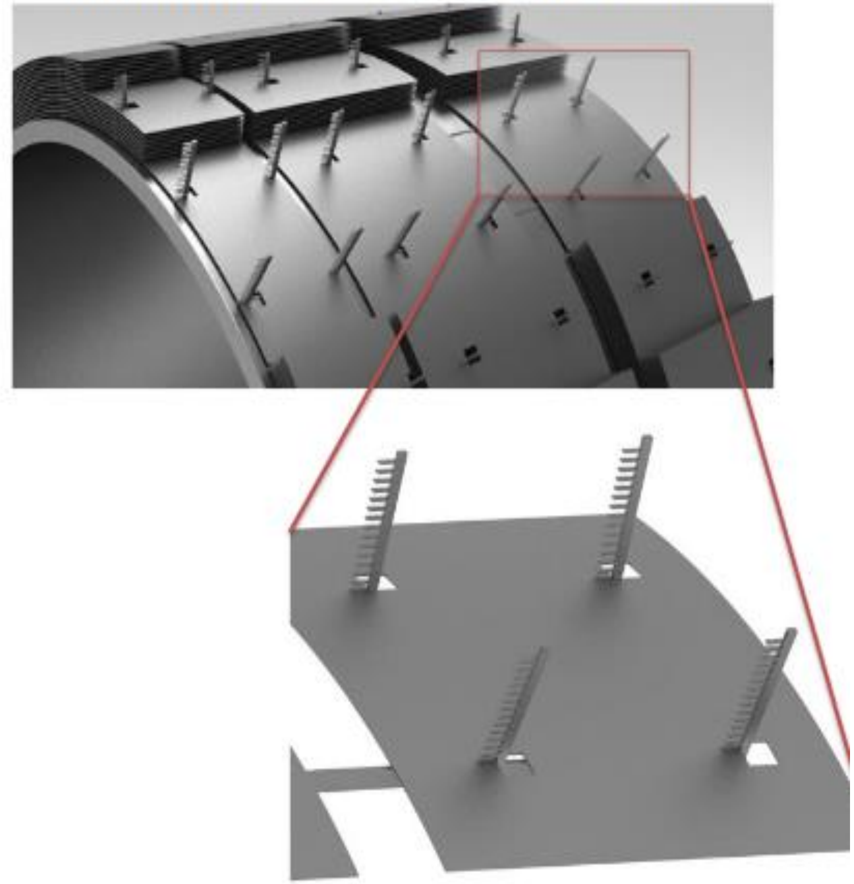
Image of enormous (10kpc) x-ray
and optical 'superbubble' inflated by the AGN

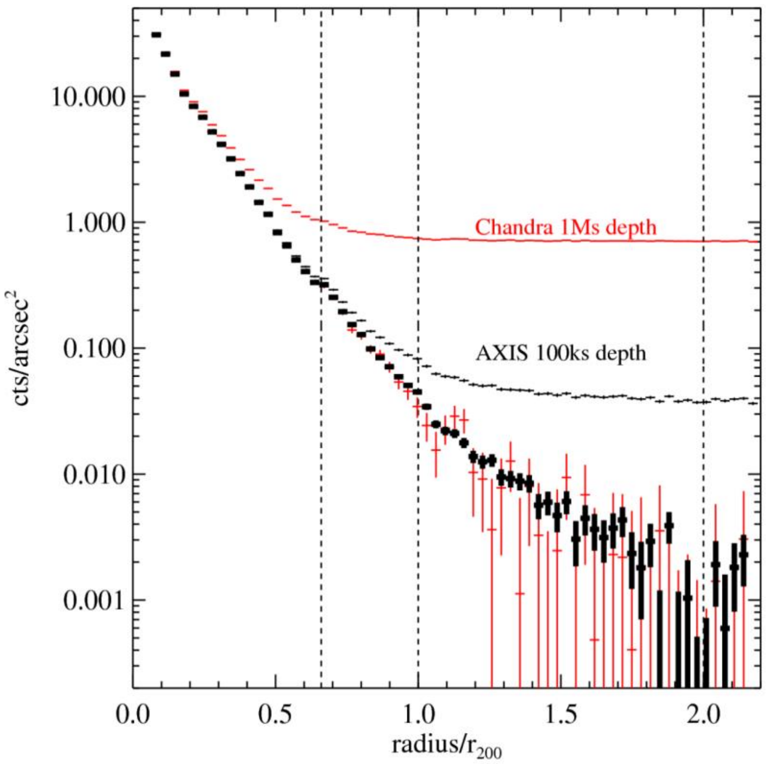
The Meta-Shell Approach

Principle of the Approach

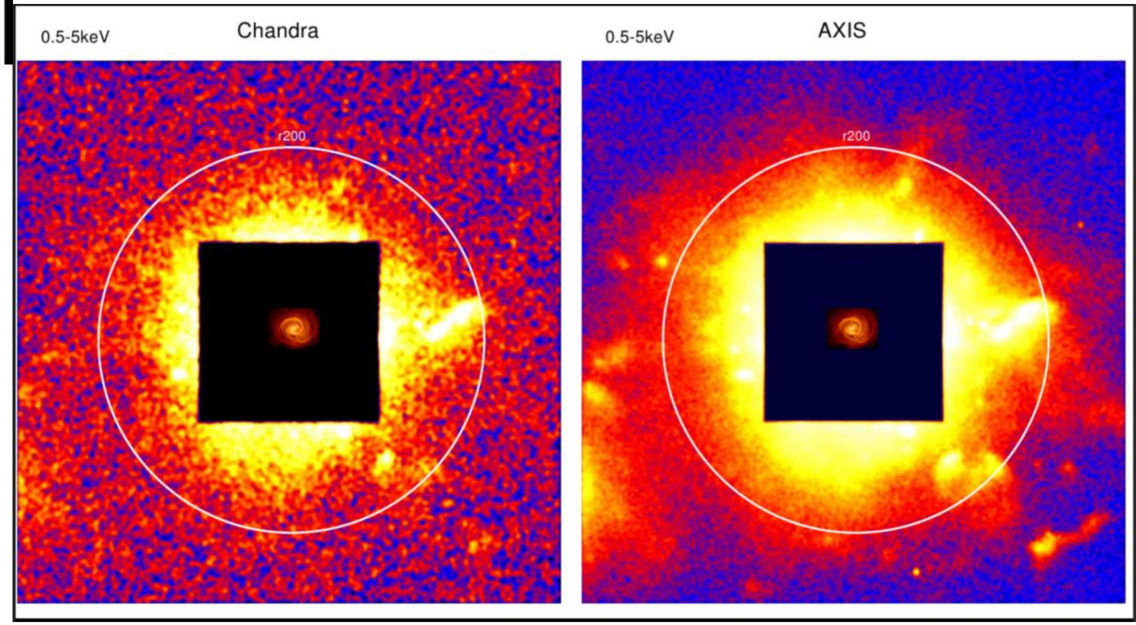


Implementation of the Approach

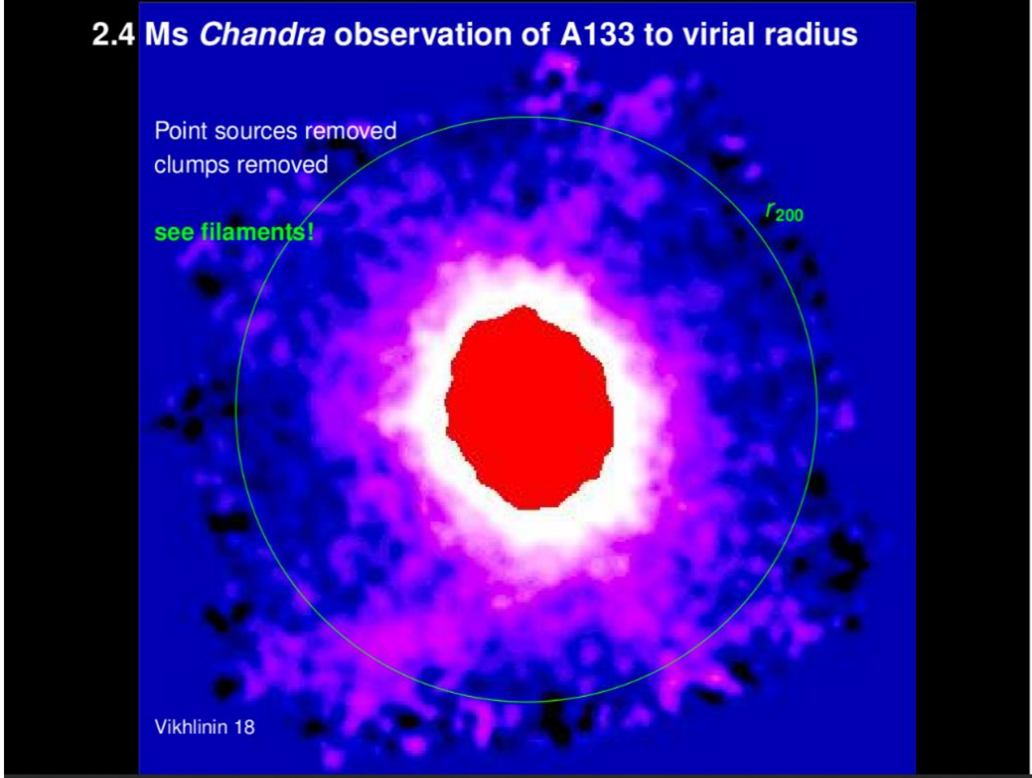


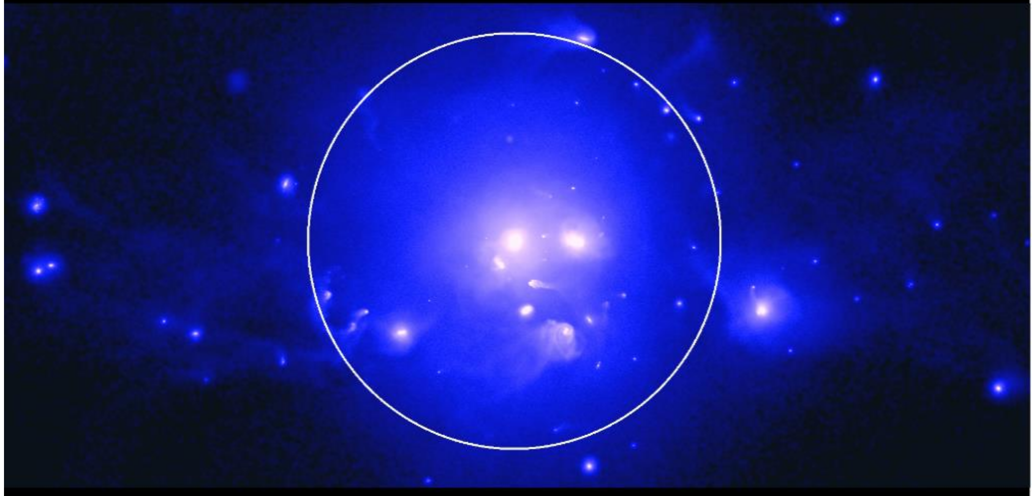


Most of the baryons are in the outer regions of clusters and this is where infall from the cosmic web occurs



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





Why LIGO and LISA Need AXIS-Brian Morsony

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

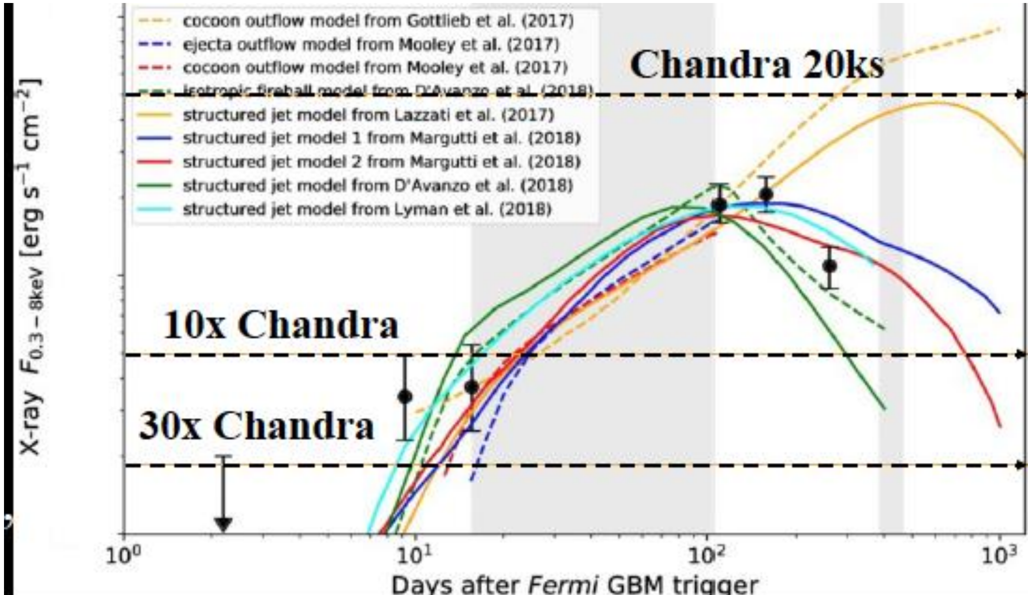
However
GW170817 was at 40 Mpc
- As aLIGO and VIRGO reach design sensitivity, most events will be at ~200 Mpc (early 2020's) •

25x fainter in EM emissions

– 18th → 22rd mag Kilonova
– 3.610^{-15} → $1.5x10^{-16}$ erg/s/cm^2 X-ray

Would require 5 day Chandra exposure !

Easy to get rise, fall with AXIS



Transient Science

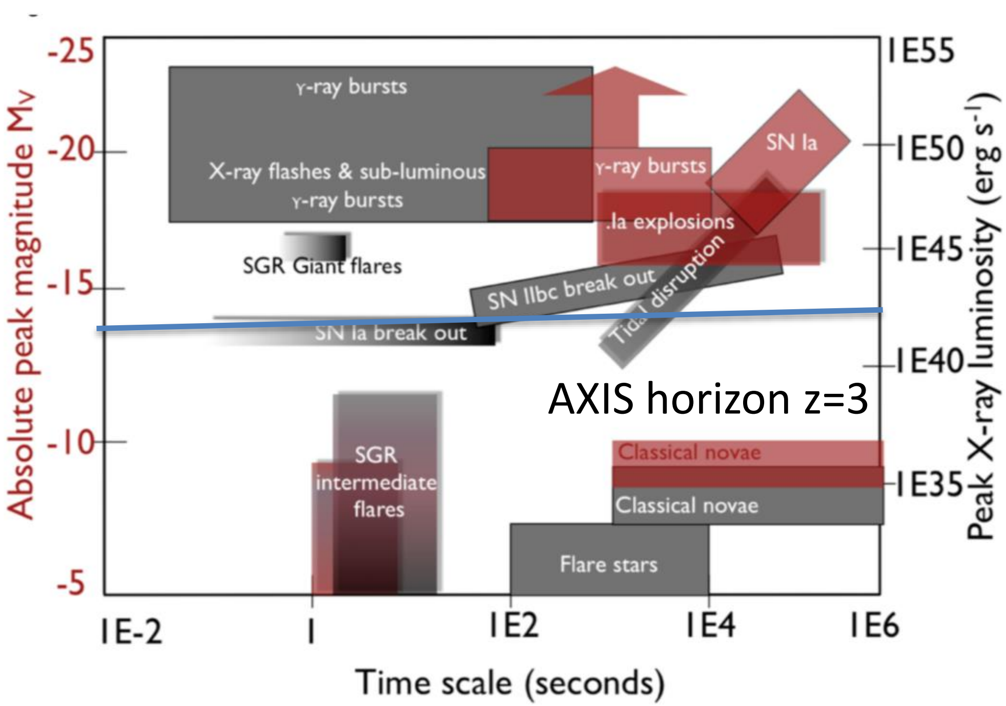
AXIS will have the Swift quick response capabilities but

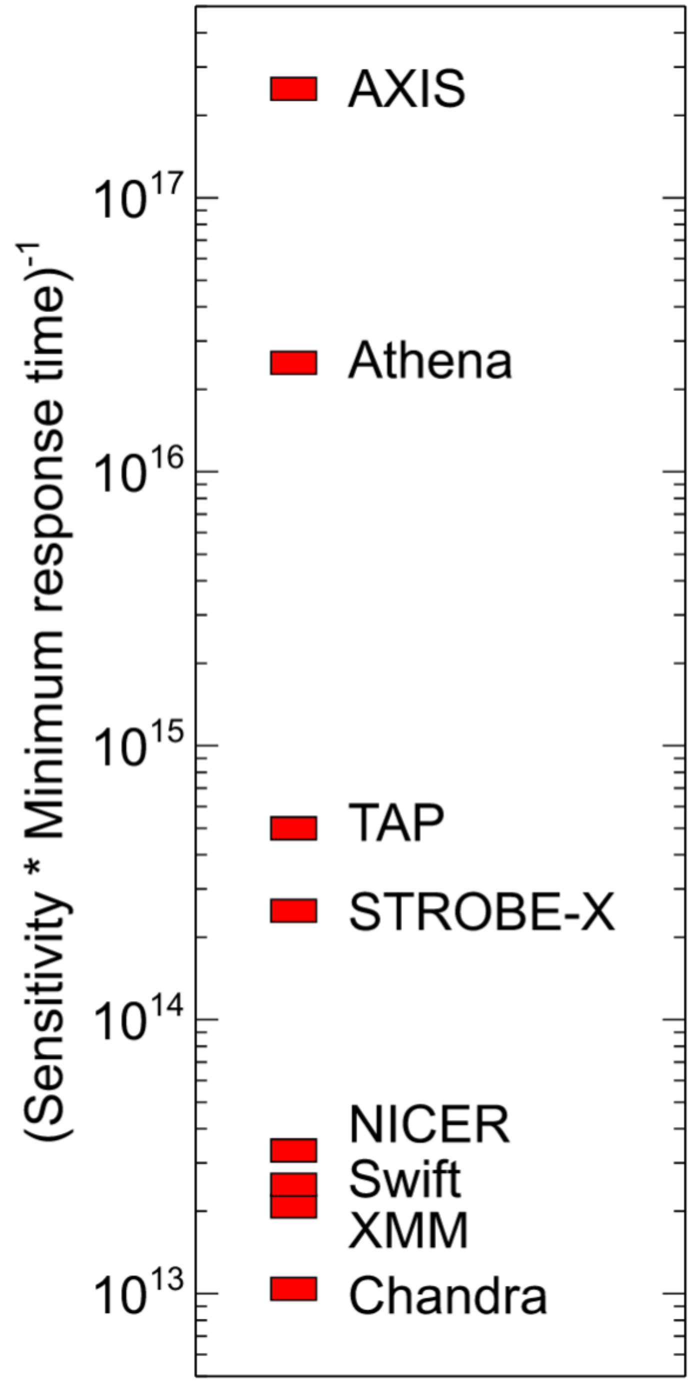
be ~70x more sensitive

30x better angular resolution

50x better time resolution than Chandra

Do all the Swift science but with vastly better sensitivity and angular resolution.

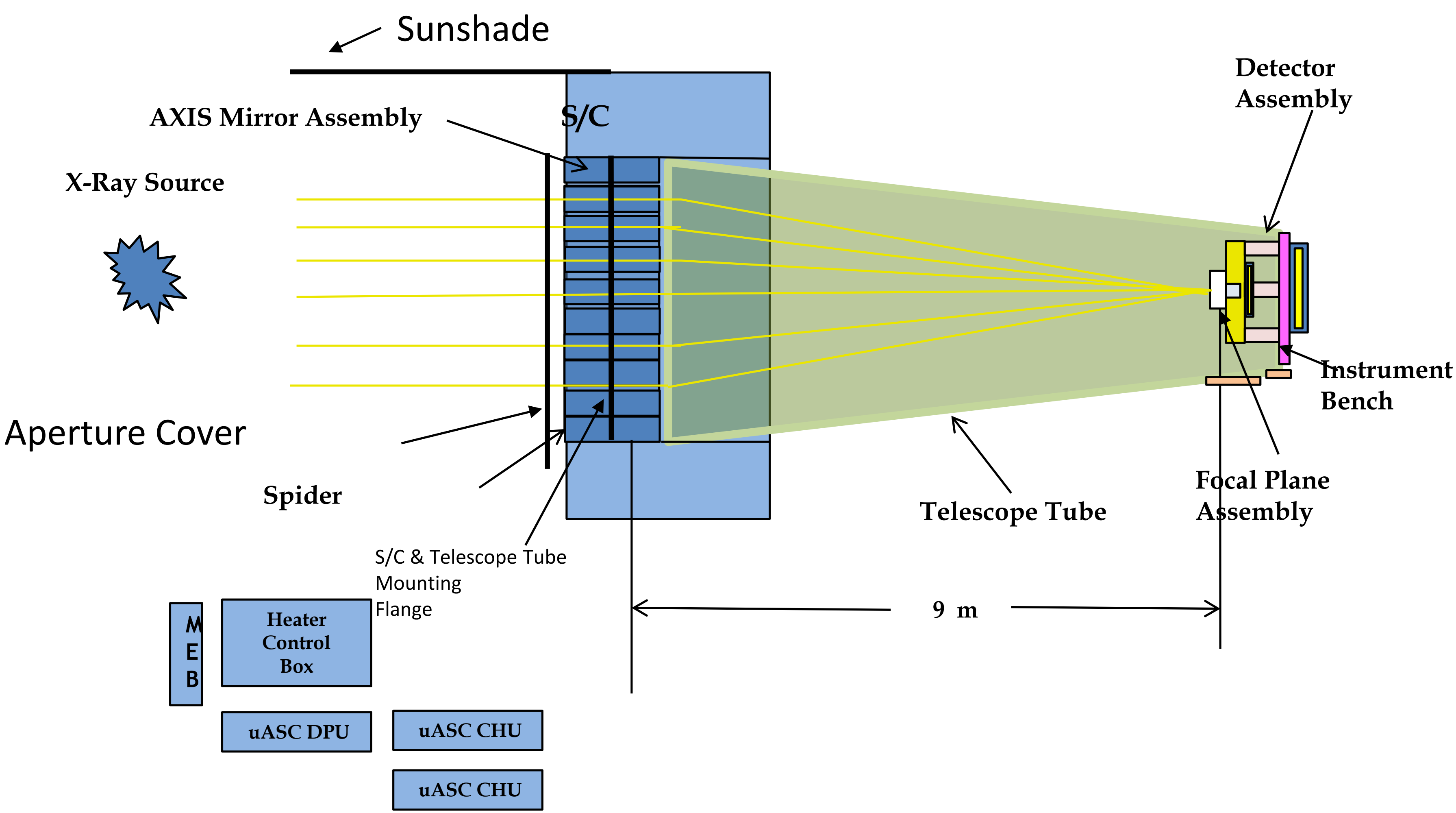




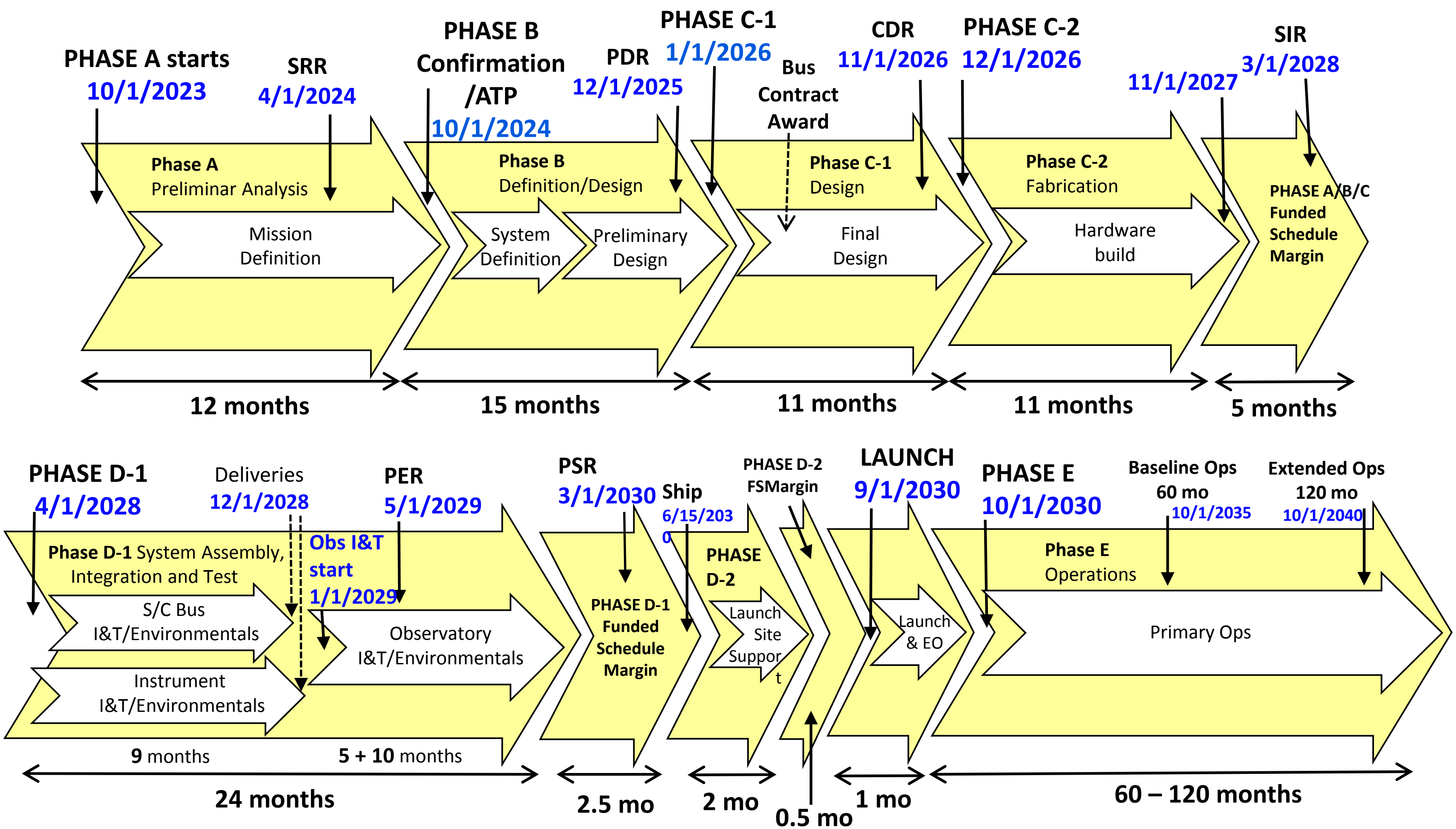
Key Ingredients of Approach

- 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.

Block Diagram
Observatory Level

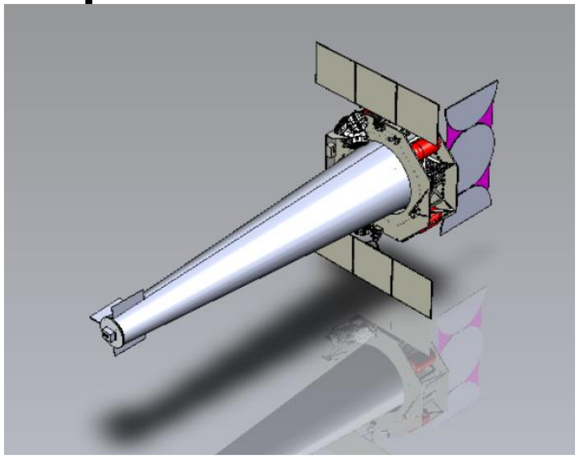


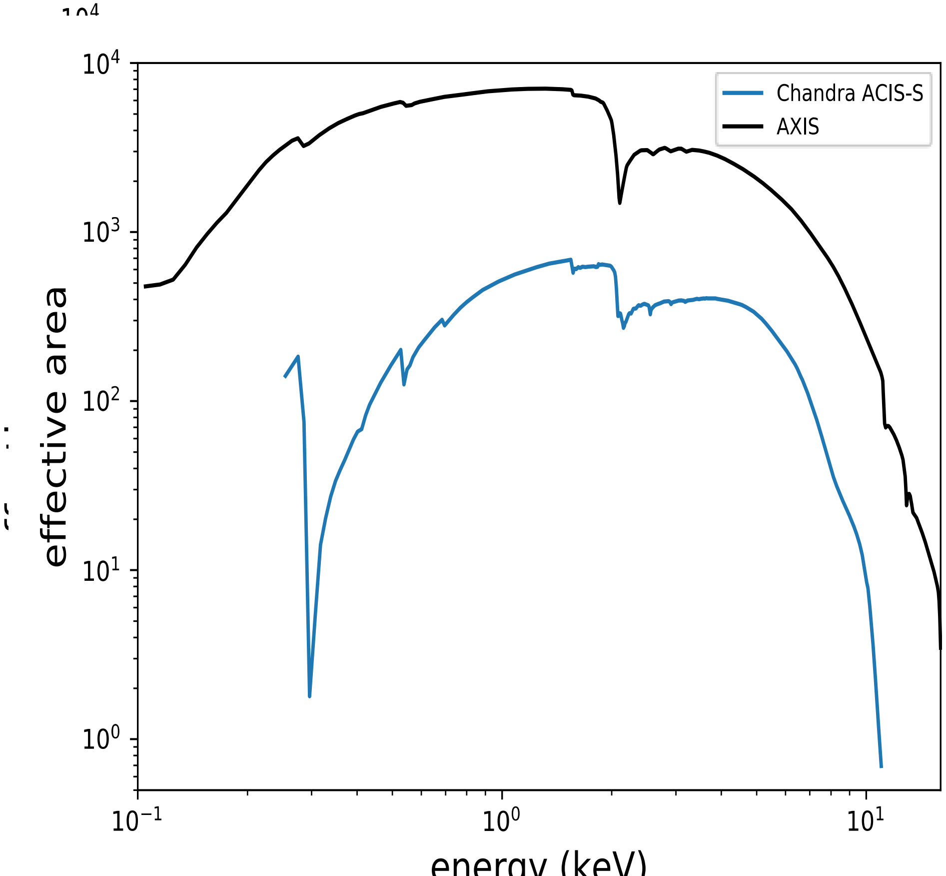
AXIS Mission Level Schedule Graphic

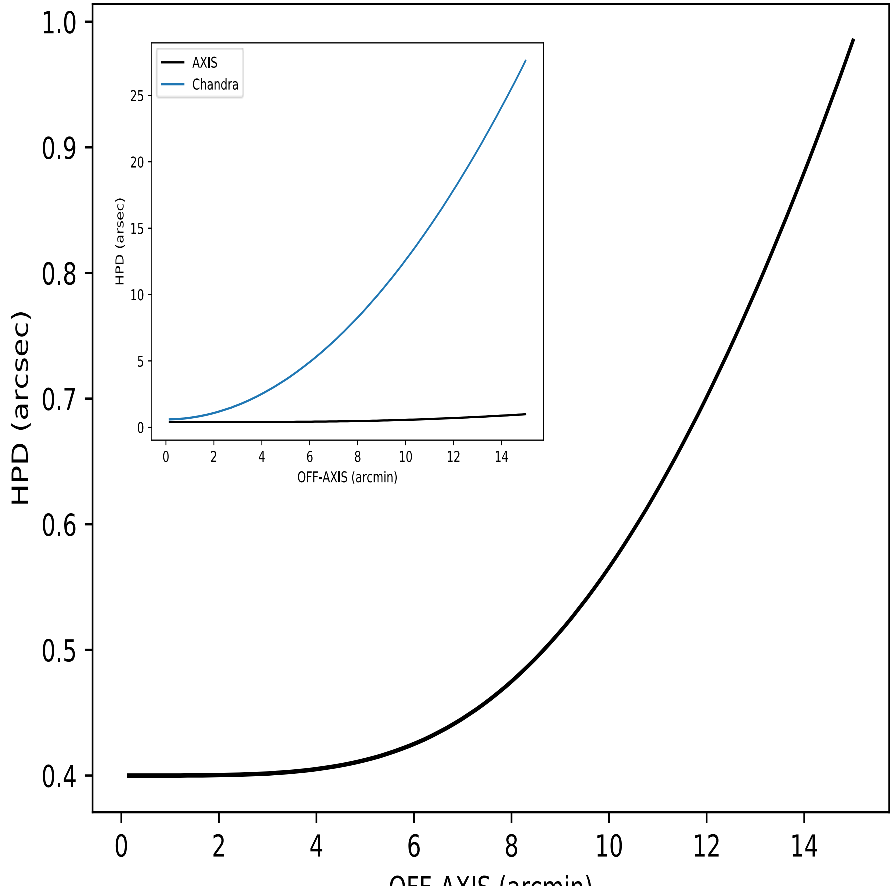


Goals and Implementation

- 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

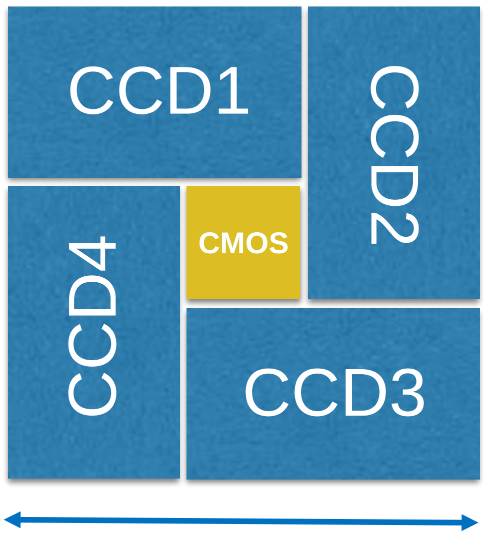
Report delivered to NASA Hdqtrs March 2019 (costs to be reviewed by NASA SOMA in spring 2019)

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

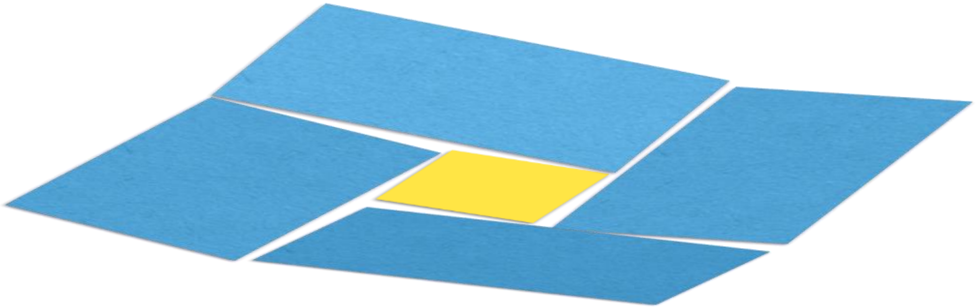
To support that date need

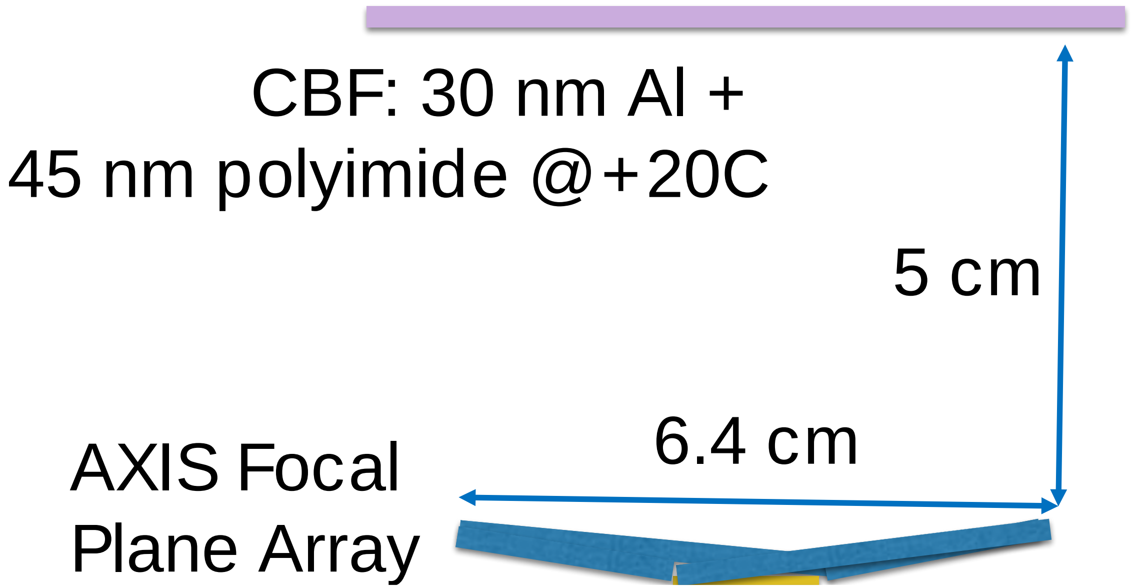
telescope and detector TRL 5 by 2020
need high TRL by 2022

One Possible Focal Plane- 24x24' FOV



4000 pixels
24 arcmin
6.4 cm





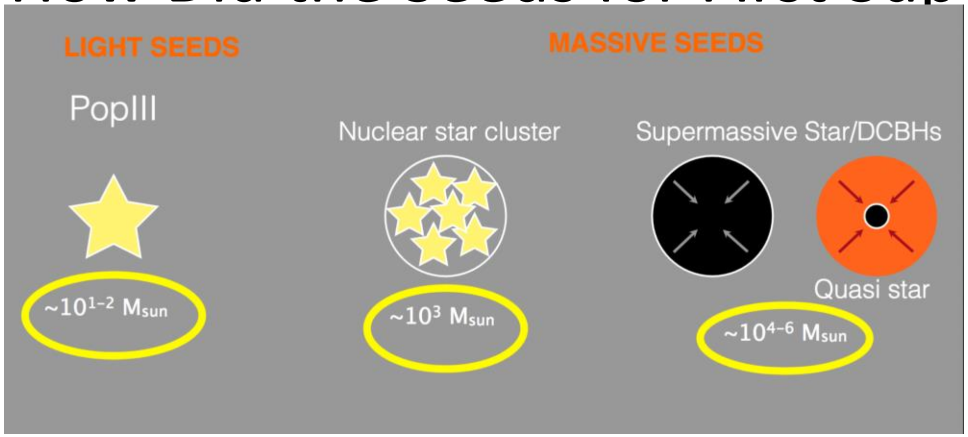
Target of Opportunity Goals

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?

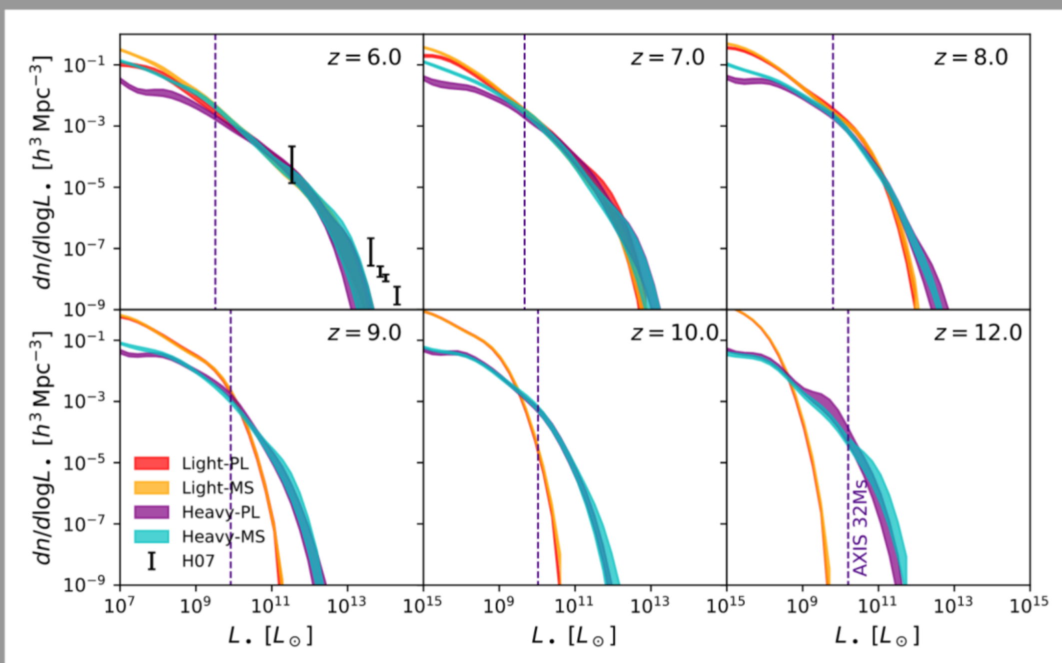


3 Ideas of How these form-

AXIS can test these ideas by detecting these objects to z~12

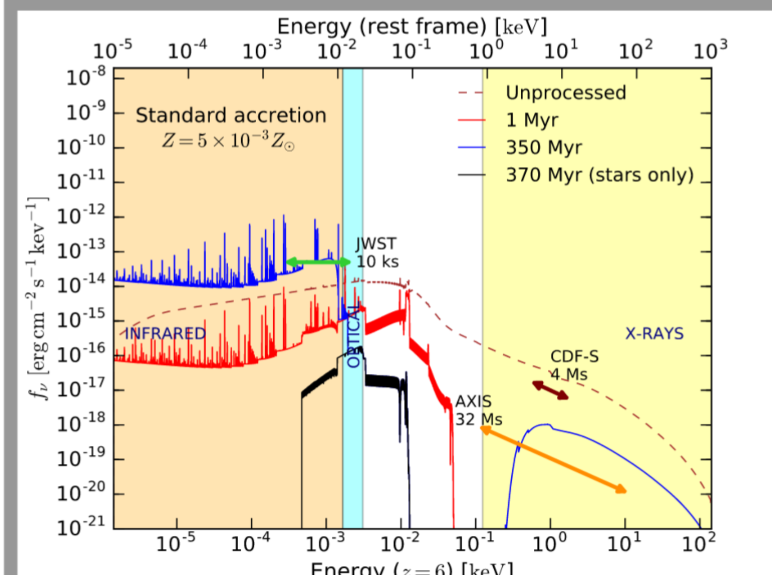
Priyamvada Natarajan

Predicted high redshift Luminosity Functions

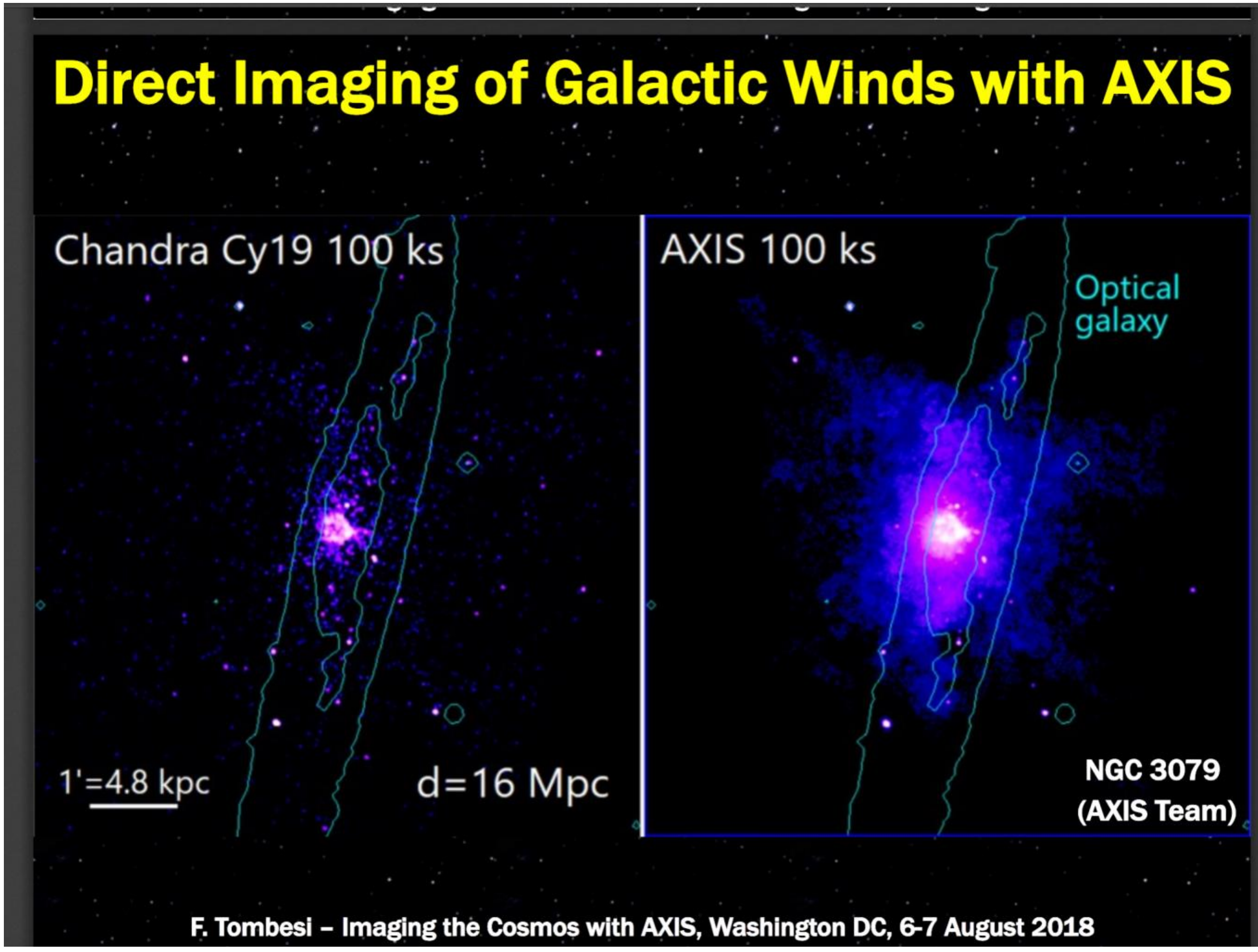


AXIS 32 Ms deep field: flux limit of 3e-18 erg/s/cm^2

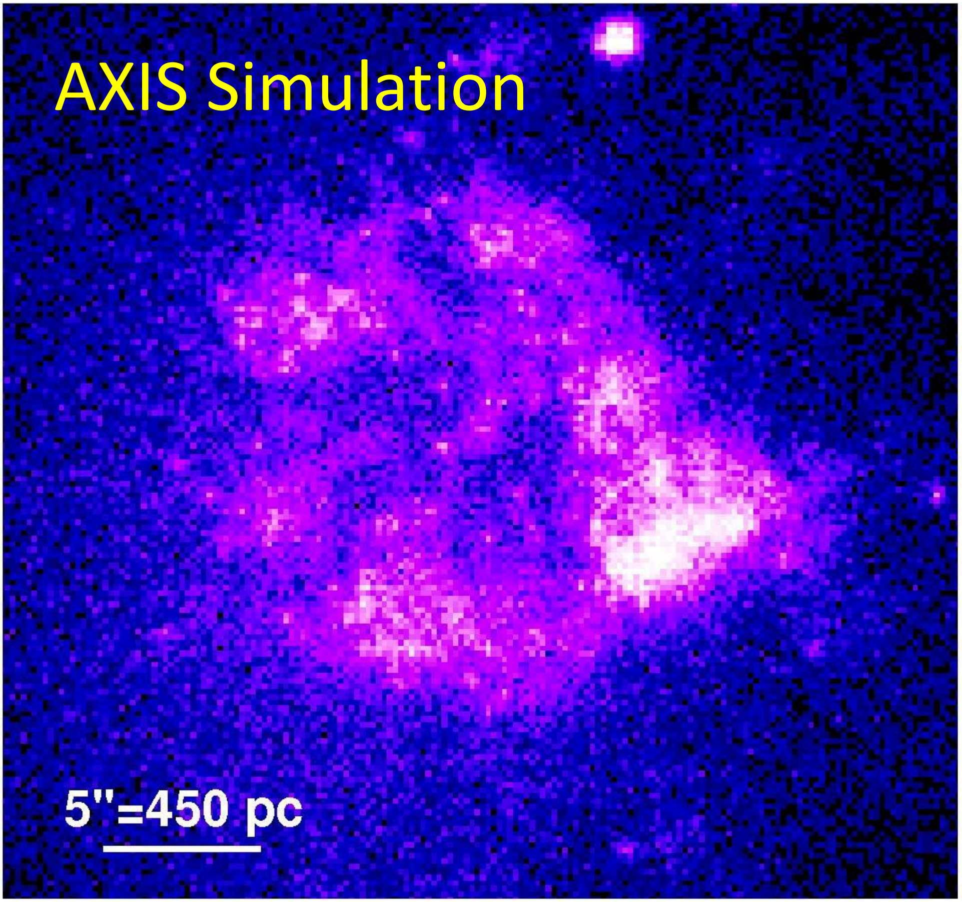
Pop III SEED + STELLAR COMPONENT STANDARD DISK, HIGH Z

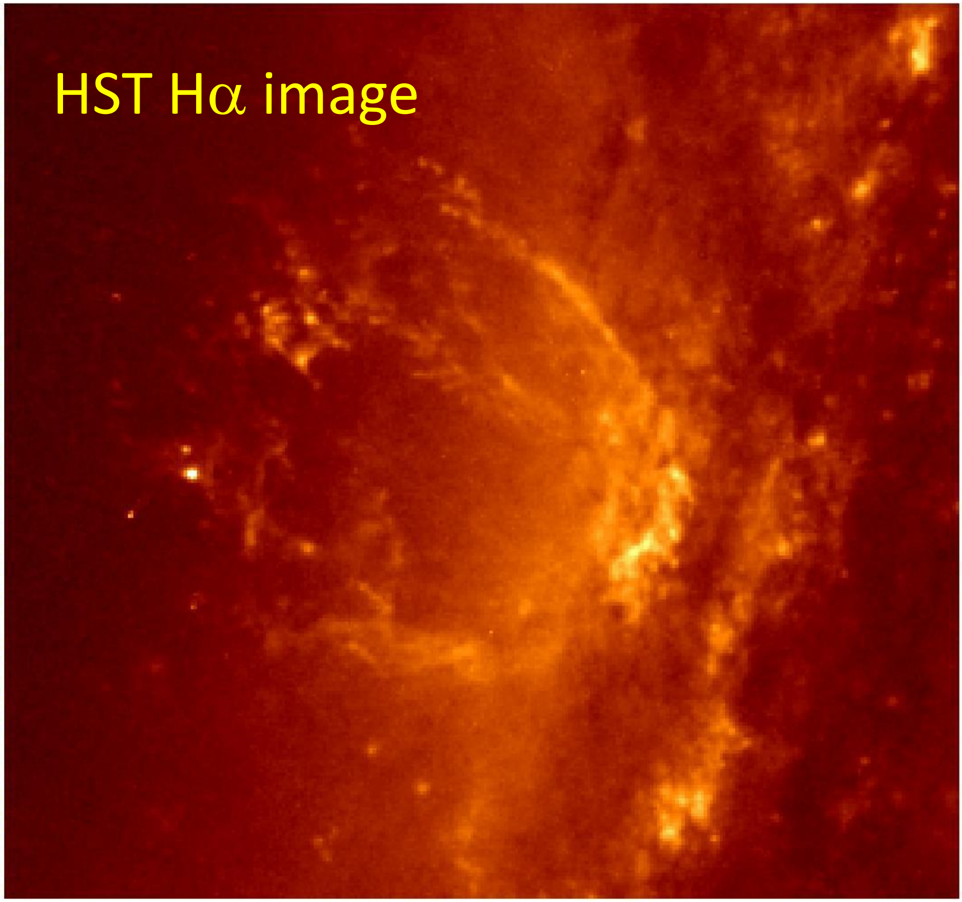


AXIS Survey would uncover these sources


Direct Imaging of Galactic Winds with AXIS
Chandra Cy19 100 ks
1'=4.8 kpc
d=16 Mpc
AXIS 100 ks
Optical
galaxy
NGC 3079
(AXIS Team)
F. Tombesi – Imaging the Cosmos with AXIS, Washington DC, 6-7 August 2018

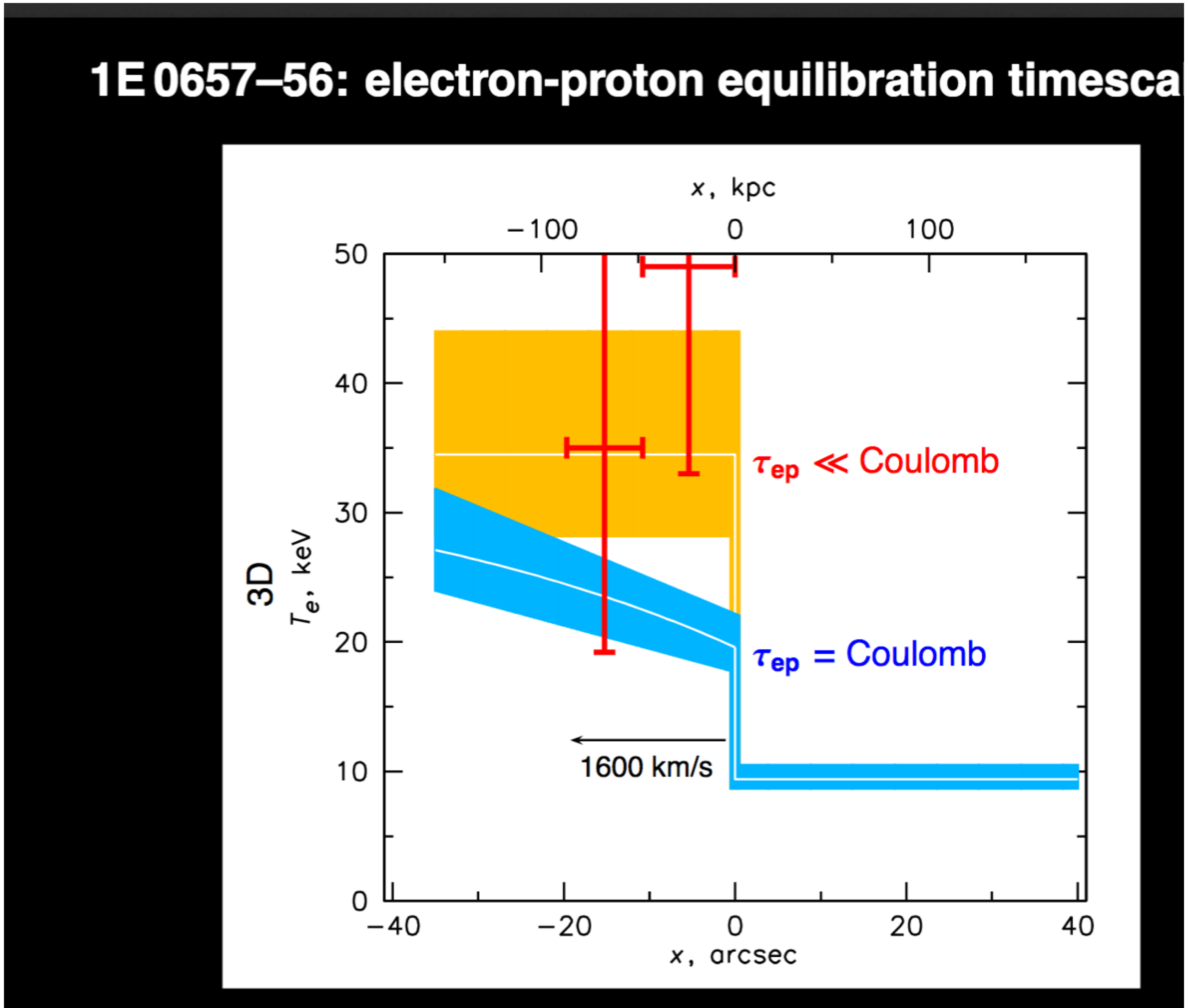
How Galactic Winds Work





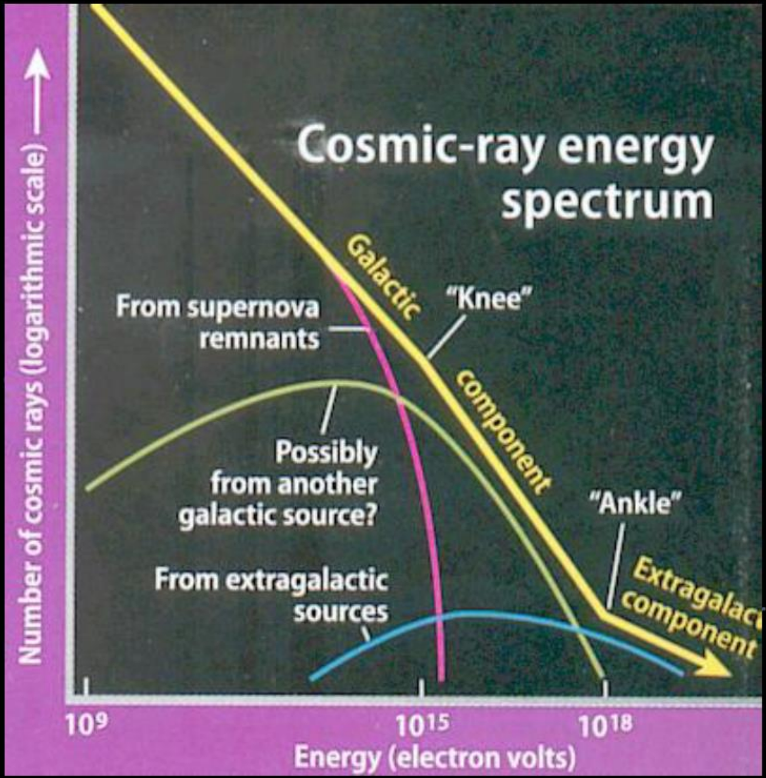
Chandra Can Just Barely test Electron-Proton Equilibration in Long Observation of "Best" Source

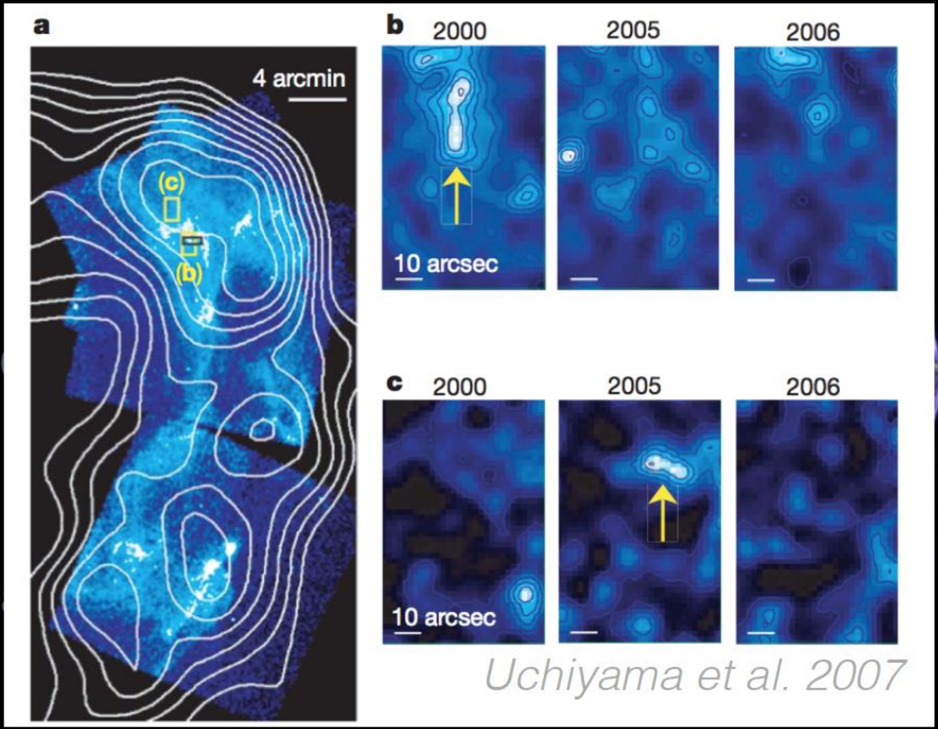
AXIS will do 10x better



Big Science Topics

The non-thermal Universe





Uchiyama et al. 2007

- 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 relativisitic winds and jets.

SKA (+precursors), LSST, IXPE, CTA

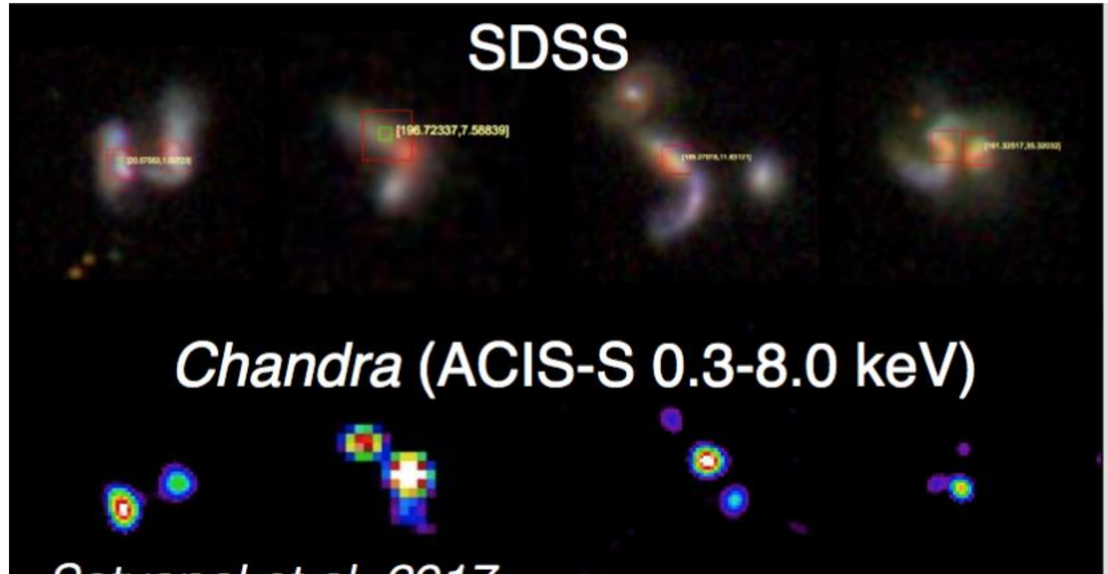
- ⋆ Growing compact PWN classes that defy classification;
  ToOs of bursting sources (HBPs, XDINSs?, CCOs??)

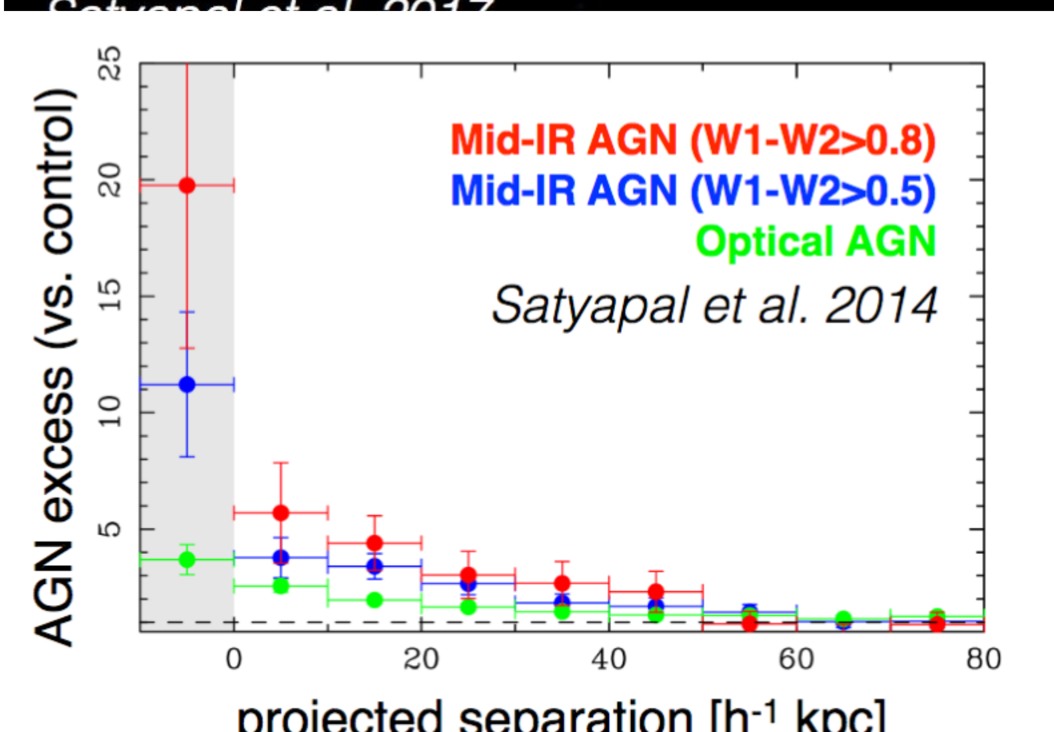
S. Safi-Harb

Dual AGN- The Progenitor Population of SMBH Mergers

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.

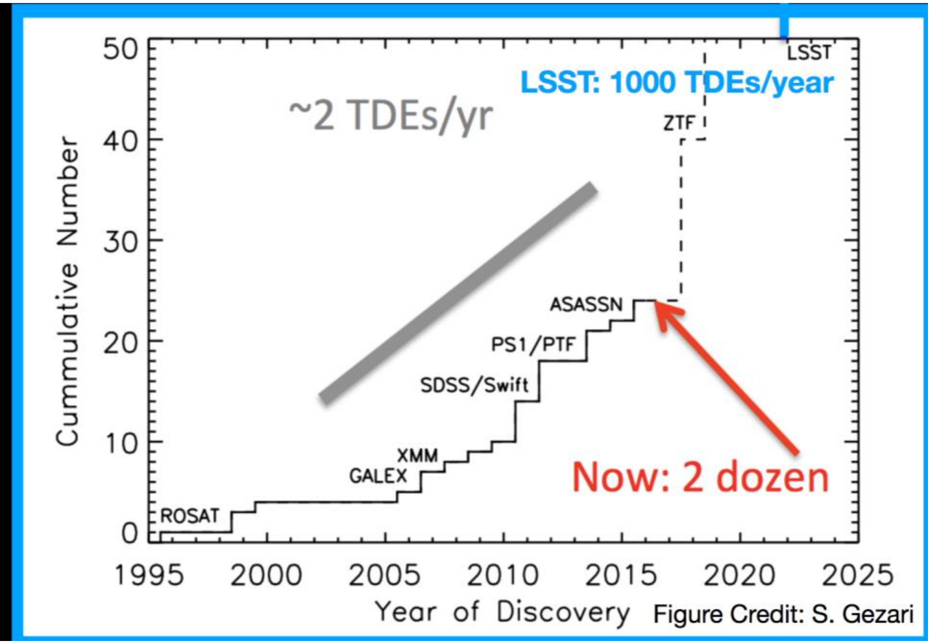




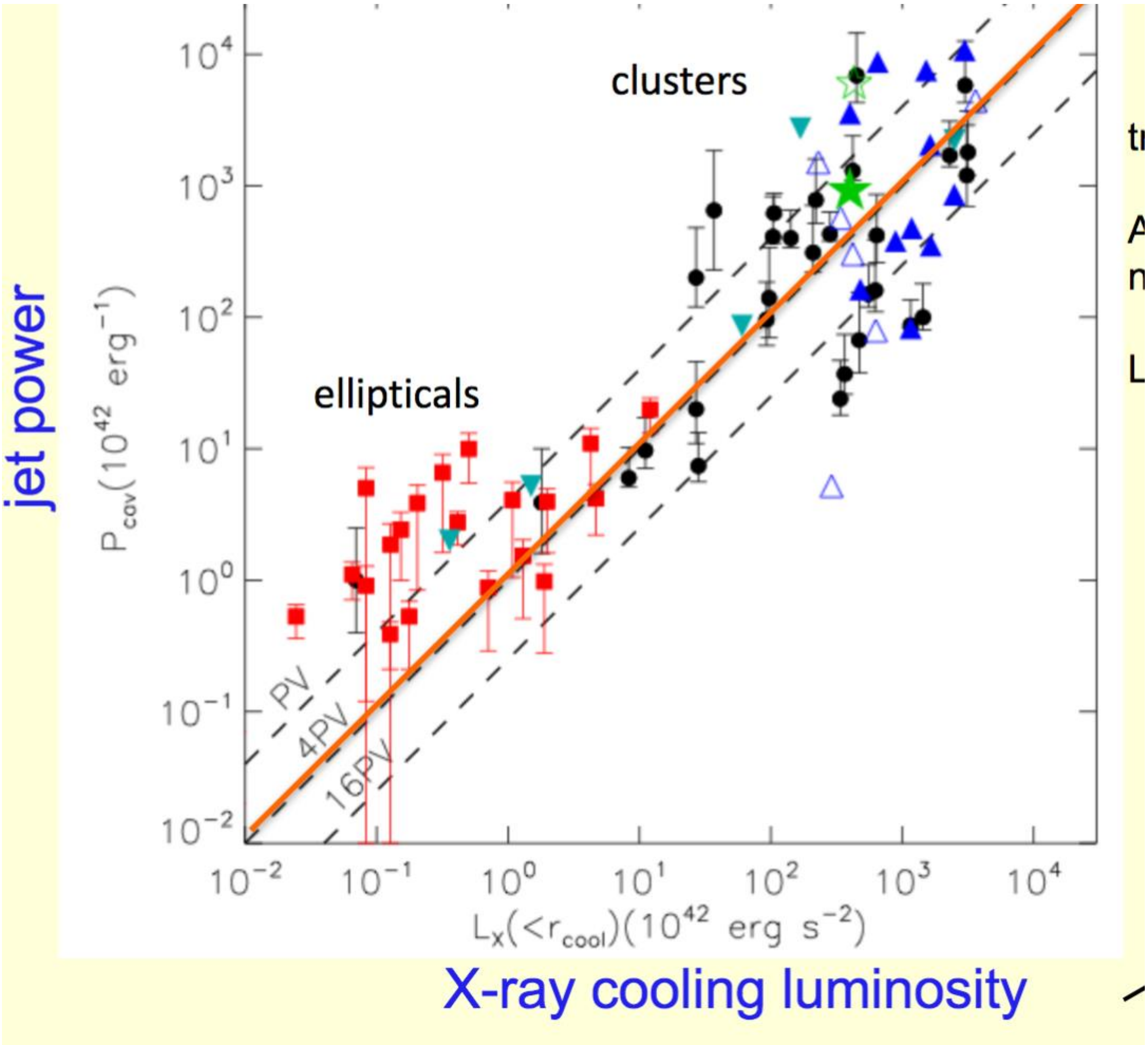
Transient Science

Tidal disruption events directly probe 'delta function' accretion

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



AGN heating balances cooling of X-ray atmospheres



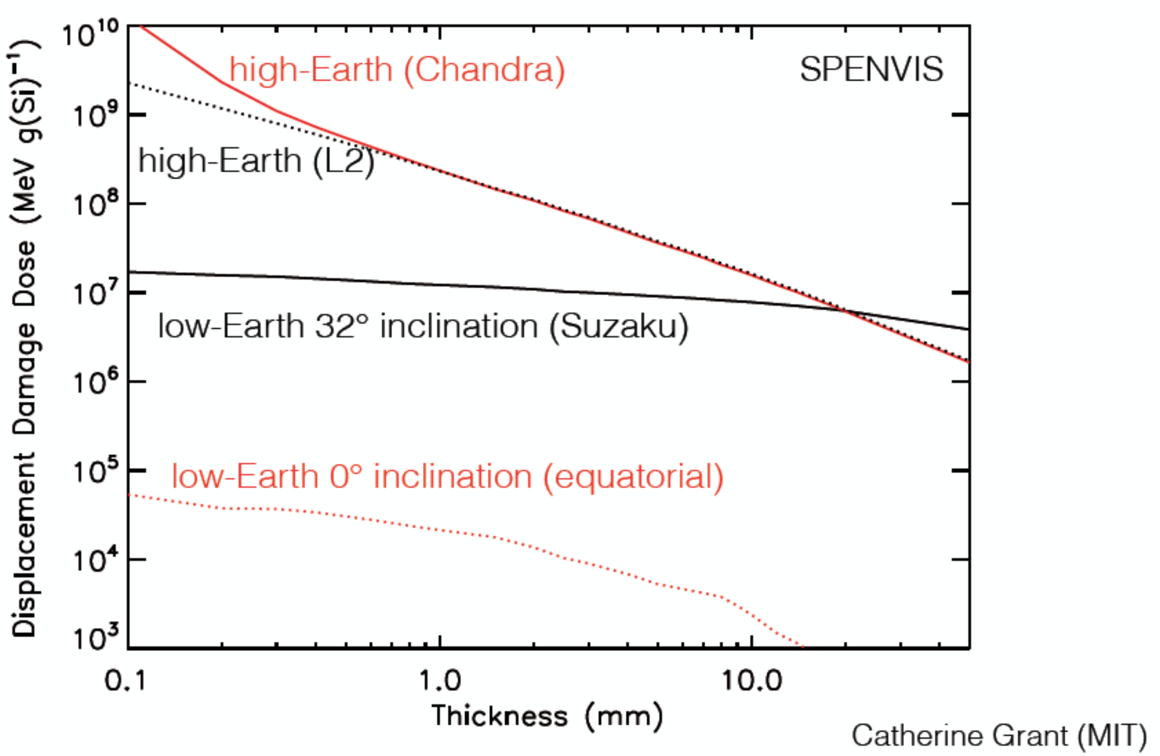
How does an object smaller than the Solar System control the thermodynamic history of an entire galaxy?

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

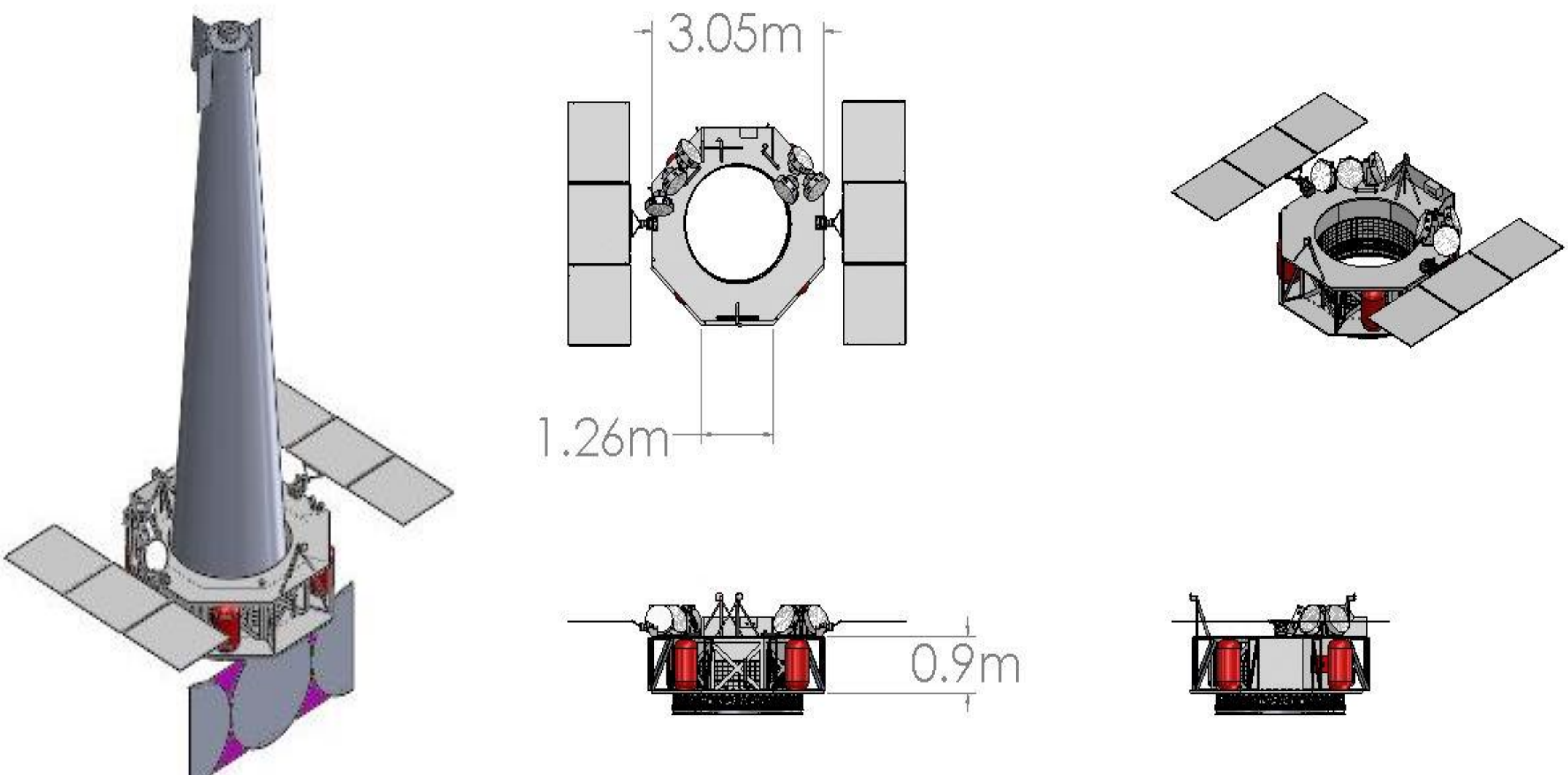
AXIS extends the study of this process from z~0.1 to z~1.0- the full range of cluster formation –synergy with SPT + eRosita + LOFAR + SKA

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 8^0 inclination

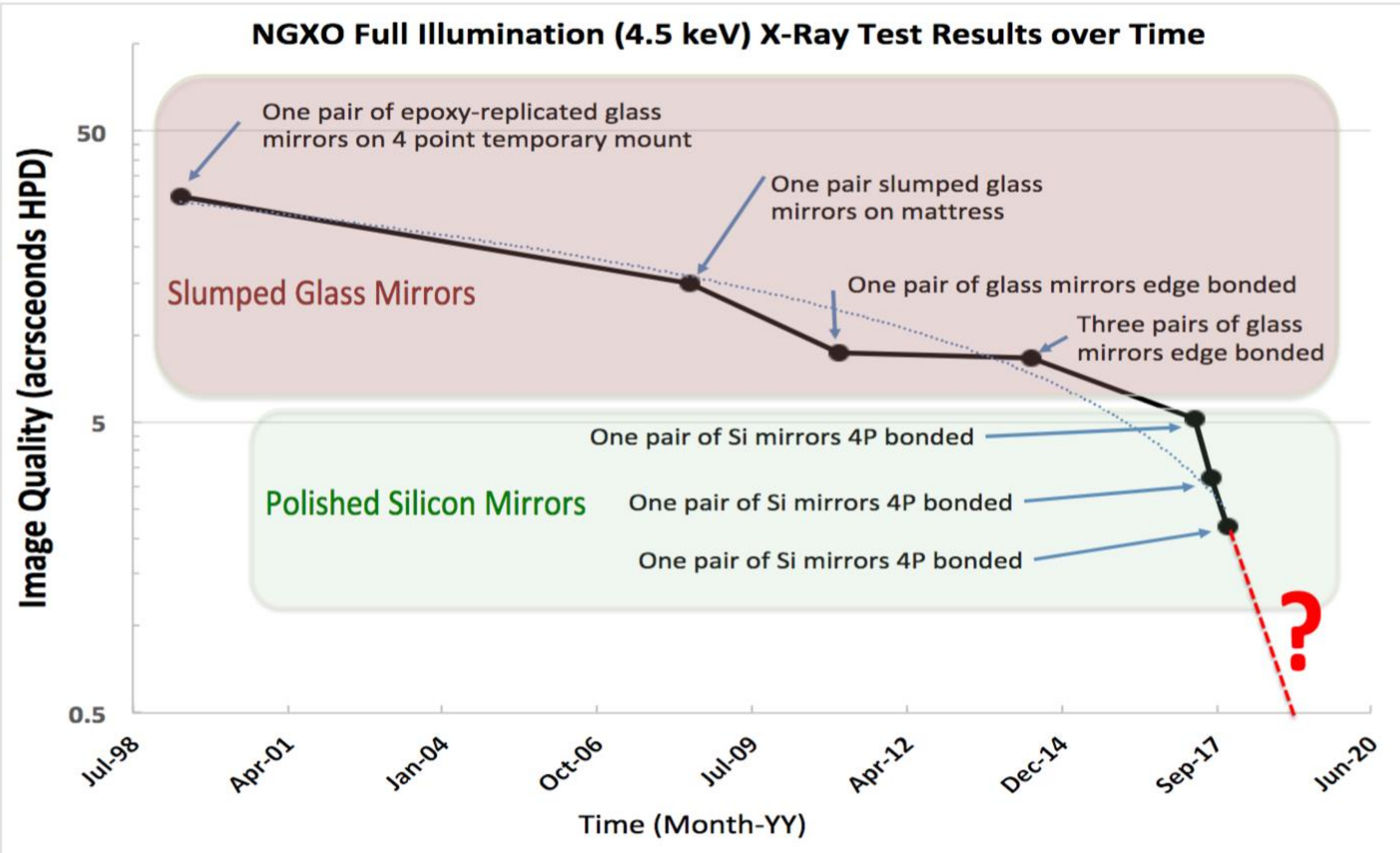


AXIS Technology

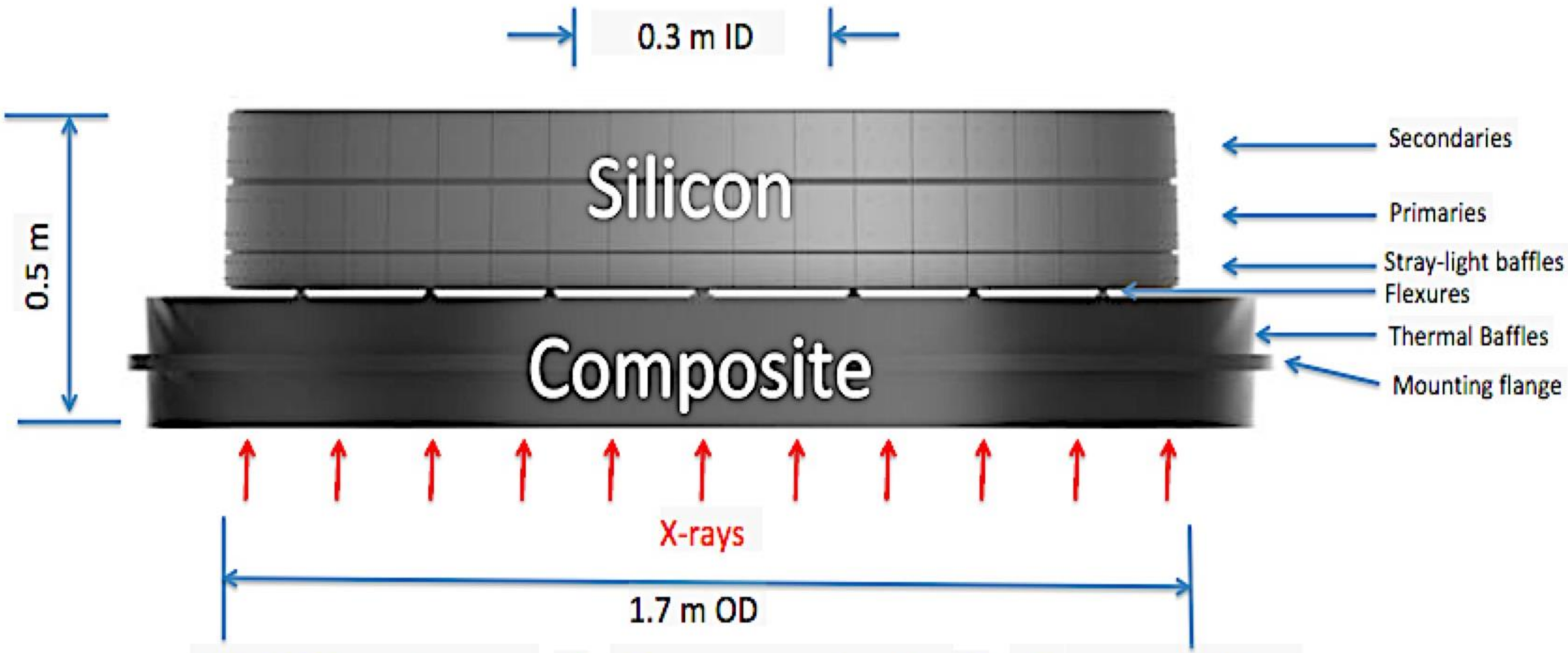


GSFC MDL Design

Continuous Progress in Next Generation X-ray Optics Angular Resolution over 20 years



AXIS Mirror Assembly

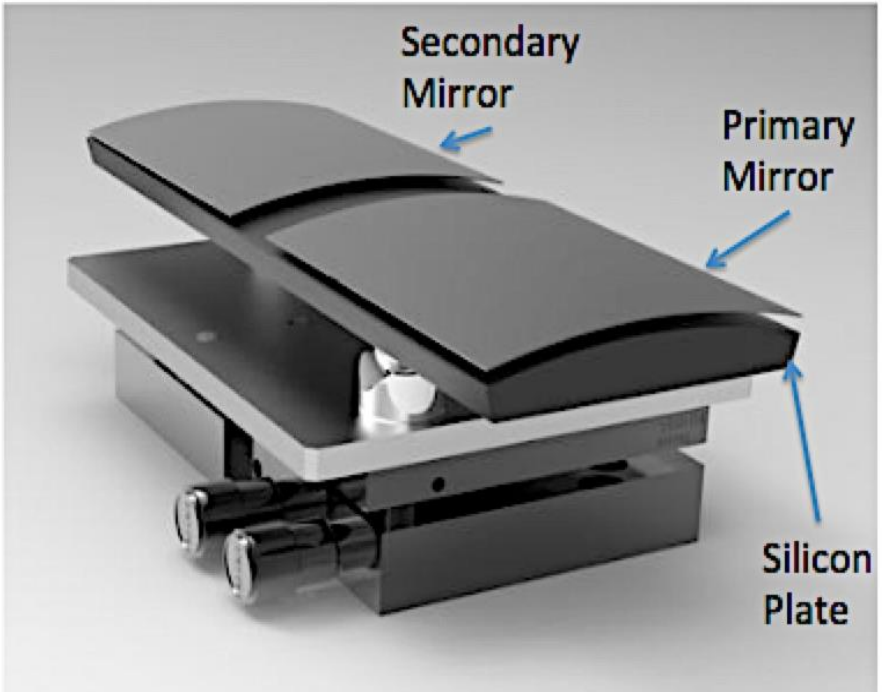


16,568 mirrors → 6 meta-shells → 1 assembly

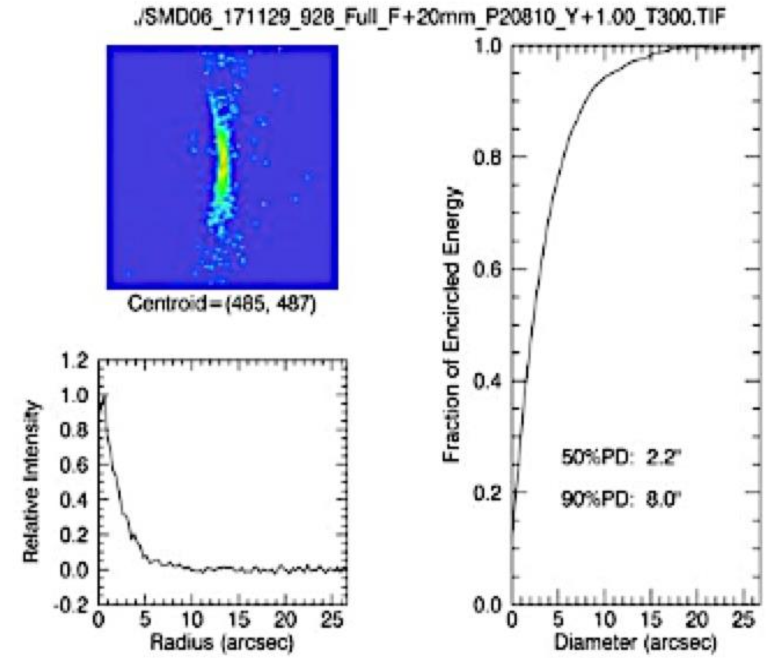
Mass: ~454 kg **Heater Power: ~300 W**

Eff. Area@1keV: 0.77 m^2 with traditional Ir coating

Entire Process Validated by X-ray Testing



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



Full illumination with Ti-K X-rays (4.5 keV)

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

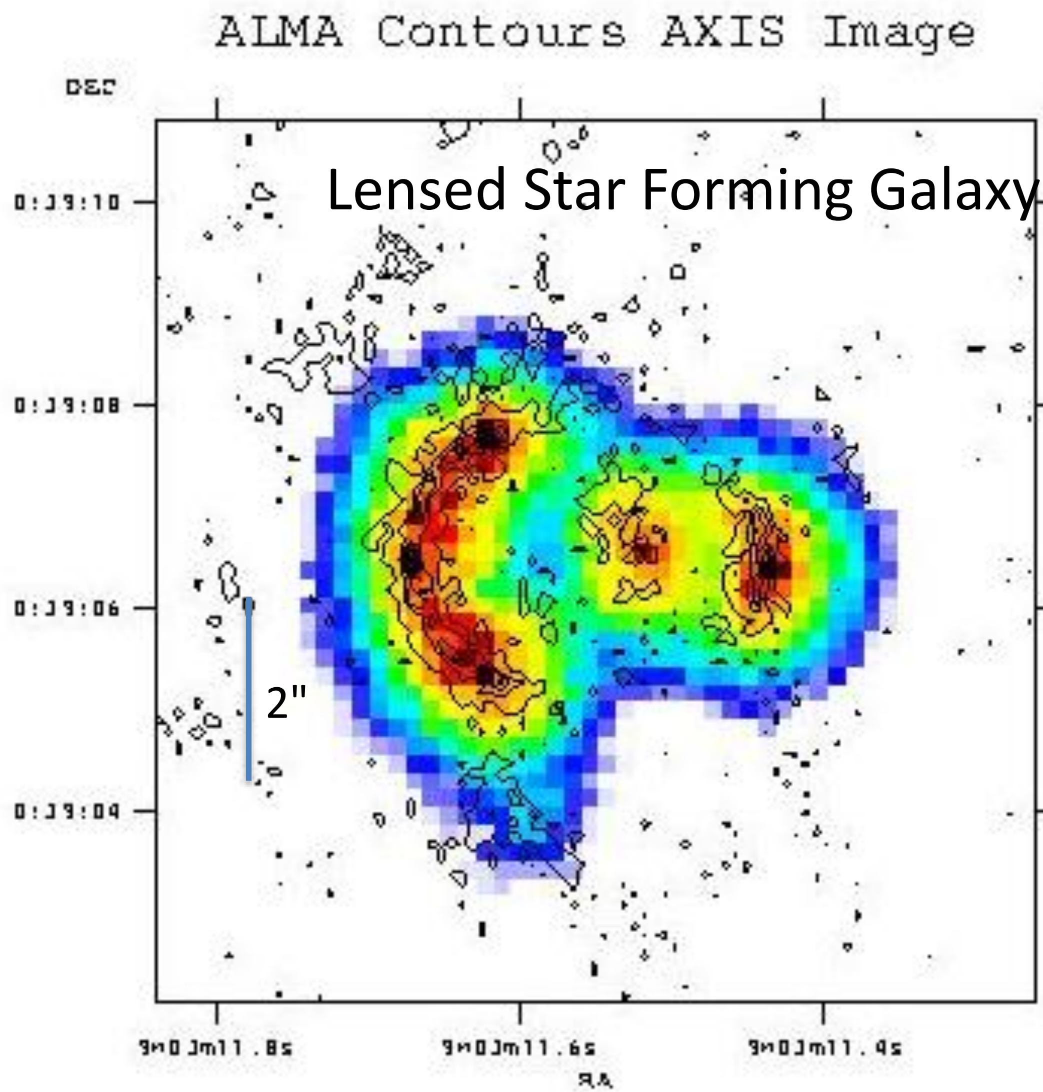
Acknowledgement: Thanks to Vadim Burwitz and his team at Panther who performed this measurement.

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

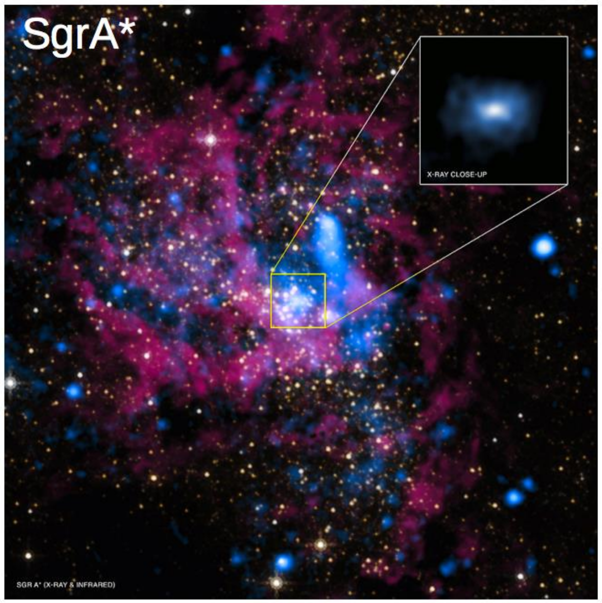
Colors- AXIS Simulation



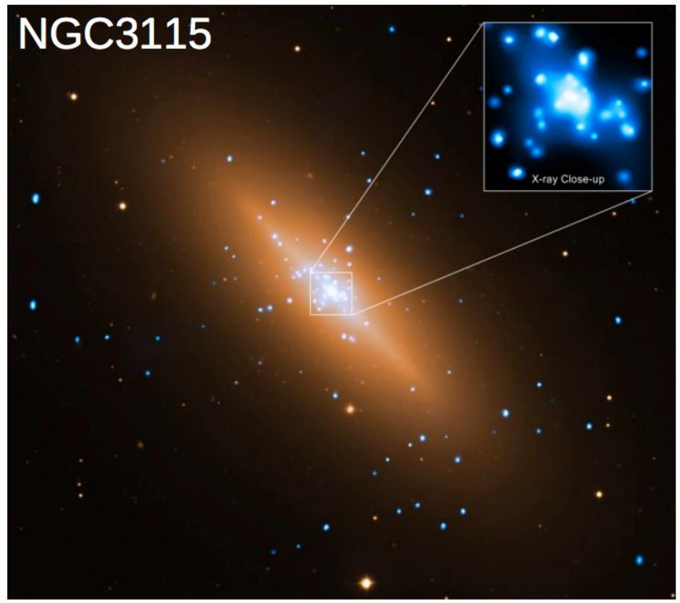
Imaging the gravitational sphere of influence in SMBHs

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

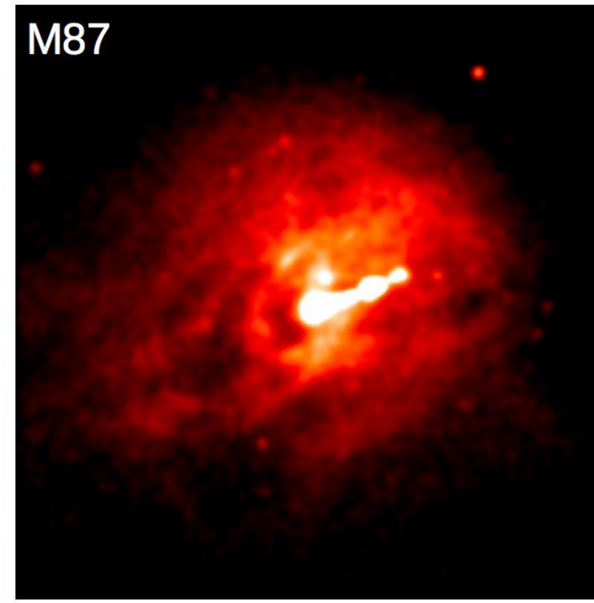
$R_{Bondi}=2GM/c_s^2$; the radius within which gas MUST fall into black hole



Wang et al. 2013



Wong et al. 2014



Forman et al. 2005, Russell et al. 2016

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 ~$10^5 M_\odot$, $10^6 M_\odot$ 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.