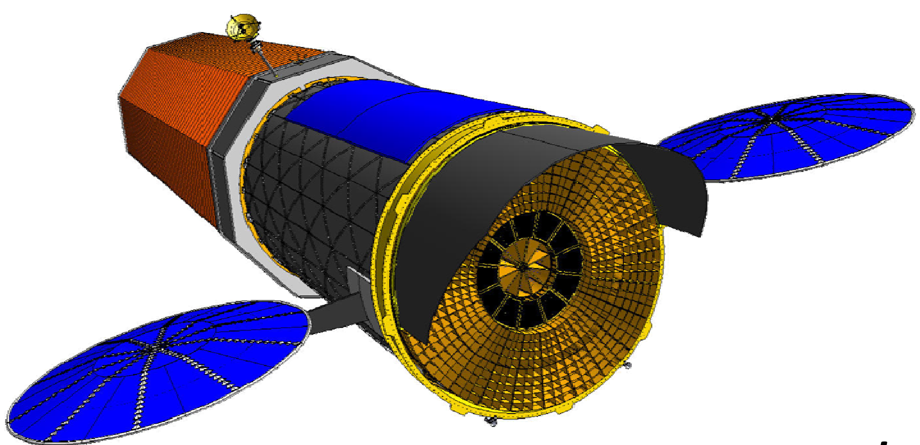
Single and Binary BH Science with IXO



Michael Garcia

Smithsonian

For the ESA-JAXA-NASA IXO Team (250+)

IXO as the successor to Chandra and XMM-Newton

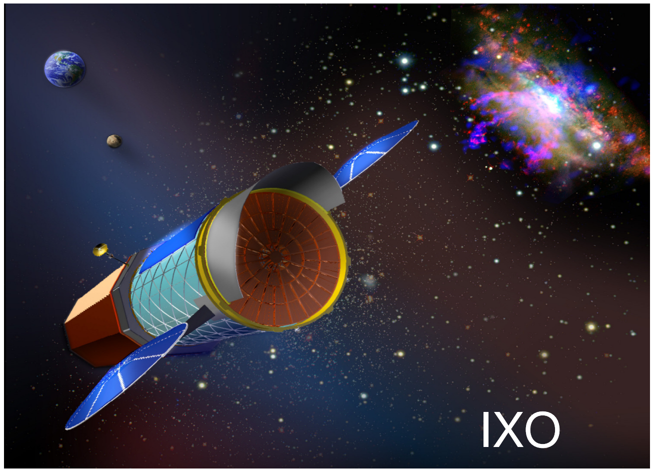
Chandra and XMM have brought X-ray Astronomy to the forefront

Sub arcsec imaging - typical of ground-based O/IR telescopes

BUT - Most X-ray SPECTRA still U/B/V (R~10) colors!

Grating exposures show richness of data - but only for brightest sources or heroic long exposures

The IXO opens the WINDOW of X-RAY SPECTROSCOPY



The IXO will change this – Routine spectra with R = 1000-3000 for 10,000s of sources –

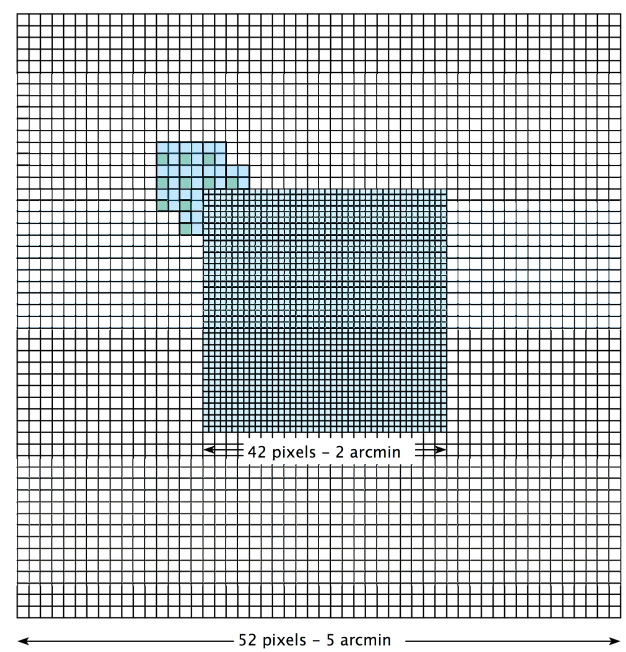
>100x Throughput for high resolution spectroscopy, AREA alone 20x XMM

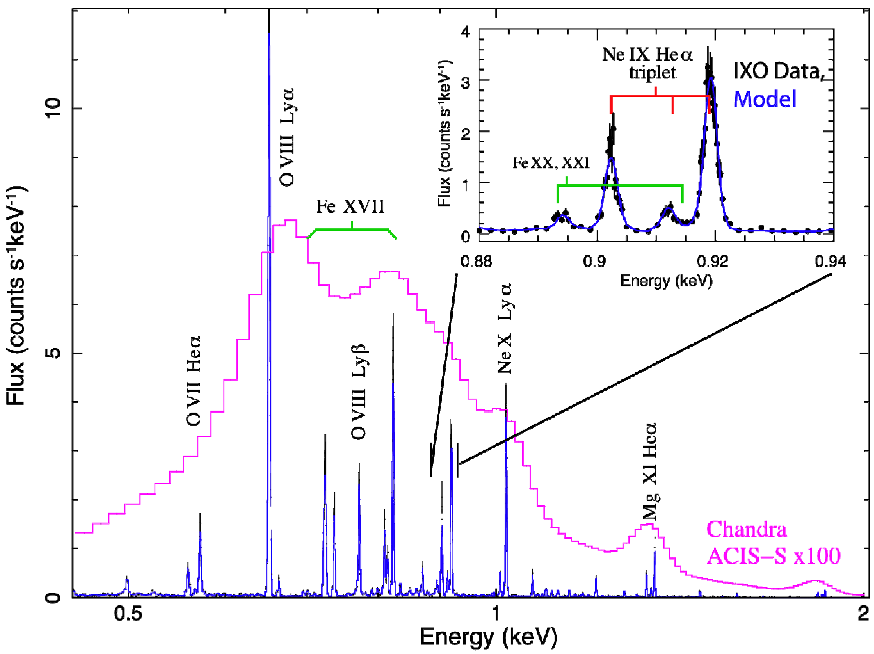
THE PHYSICS IS IN THE SPECTRA

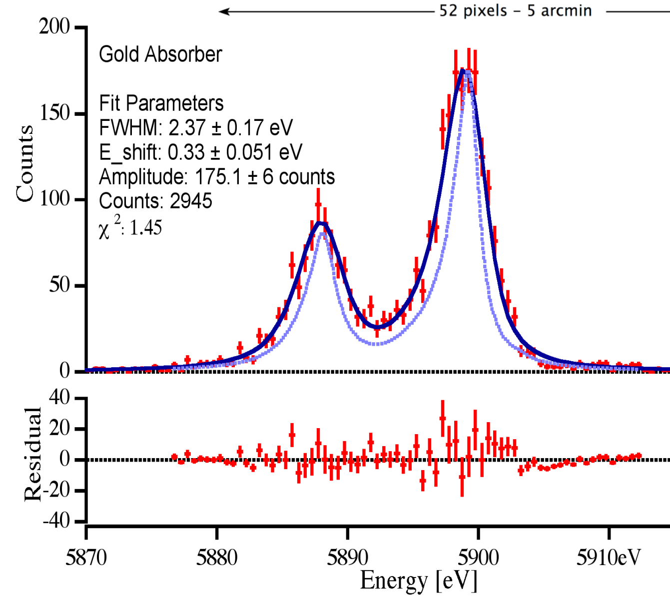
Example of Next Generation Instrument Capability X-ray Micro-calorimeter Spectrometer (XMS)

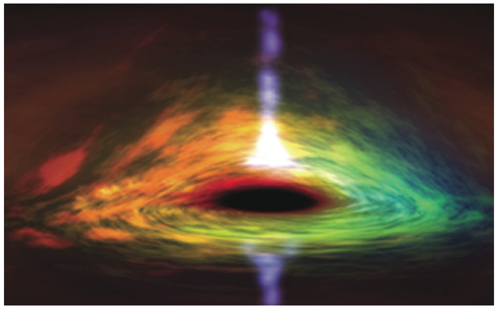
- Thermal detection of individual X-ray photons
  - High spectral resolution
  - ΔE very nearly constant with E
  - High intrinsic quantum efficiency
  - Imaging detectors

Suggested XMS array for 20m f/l confguration









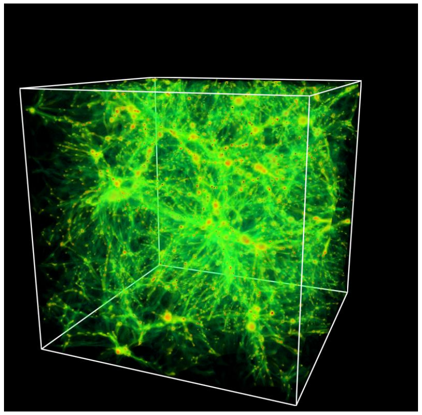
Black Hole growth and matter under extreme conditions

How do super-massive Black Holes grow and evolve?

What is the behavior of matter orbiting close to a Black Hole event horizons and does it follow the predictions of GR?

What is the equation of state of matter in Neutron Stars?

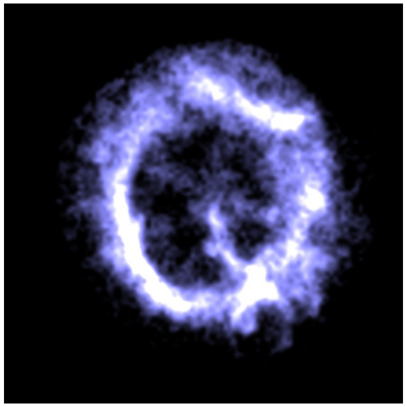
Galaxy Clusters, Galaxy Formation and Cosmic Feedback



What are the processes by which galaxy clusters evolve and how do clusters constrain the nature of Dark Matter and Dark Energy?

How does Cosmic Feedback work and influence galaxy formation?

Are the missing baryons in the local Universe in the Cosmic Web and if so, how were they heated and infused with metals?



The life cycles of matter and energy

How do supernovae explode and create the iron group elements?

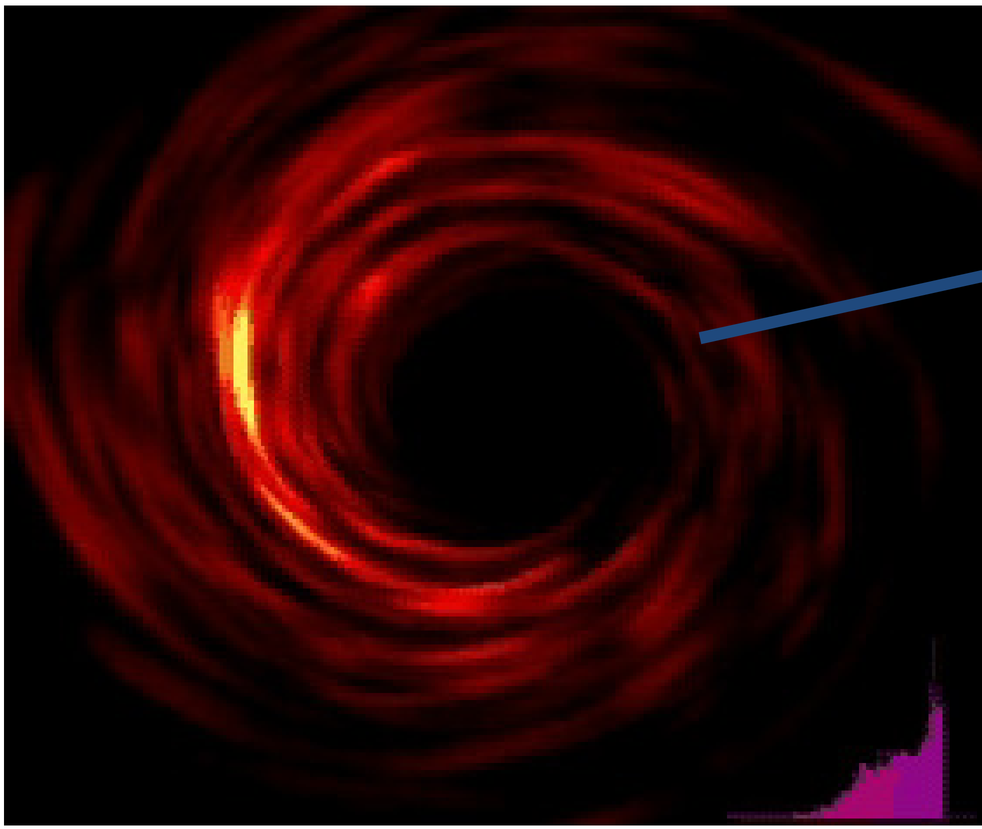
How do high energy processes affect planetary formation and habitability?

How are particles accelerated to extreme energies producing shocks, jets and cosmic rays?

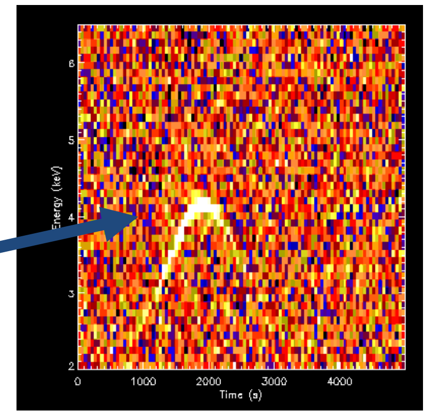
Strong GR effects: Matter Orbits

IXO will be first observatory with sufficient area to track hot spot orbits at event horizon:

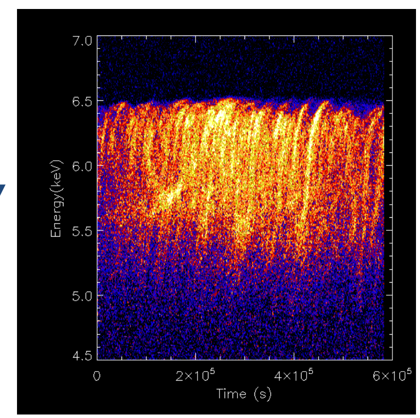
- ✓ **Dynamics of individual "X-ray bright spots" in disk to determine mass and spin, Fe Florescence**
- ✓ **Quantitative measure of orbital dynamics: Test the Kerr metric**



Single bright spot

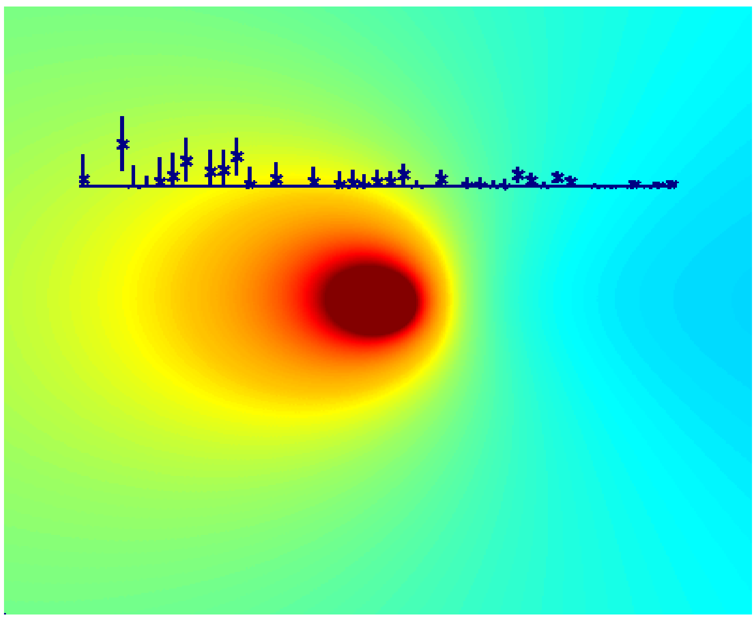


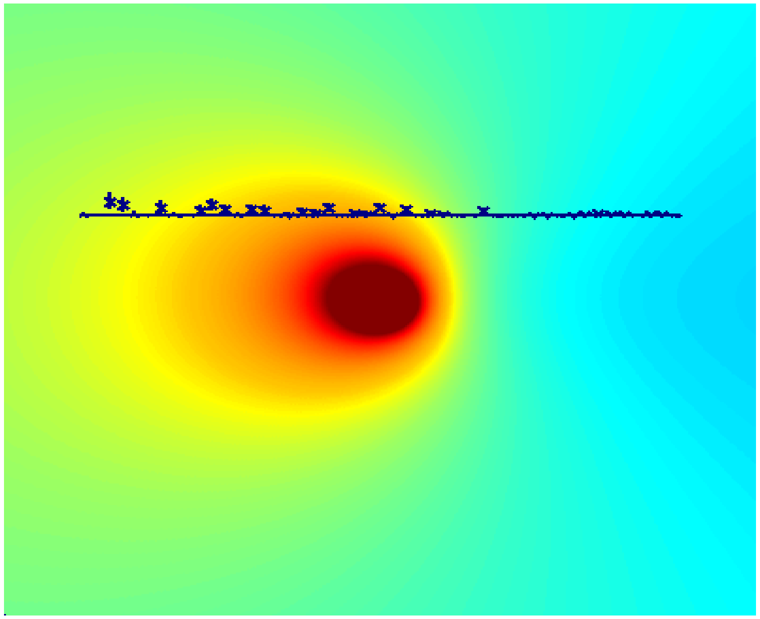
Many bright spots



Magneto-hydro-dynamic simulations of accretion disk surrounding a Black Hole (Armitage & Reynolds 2003)

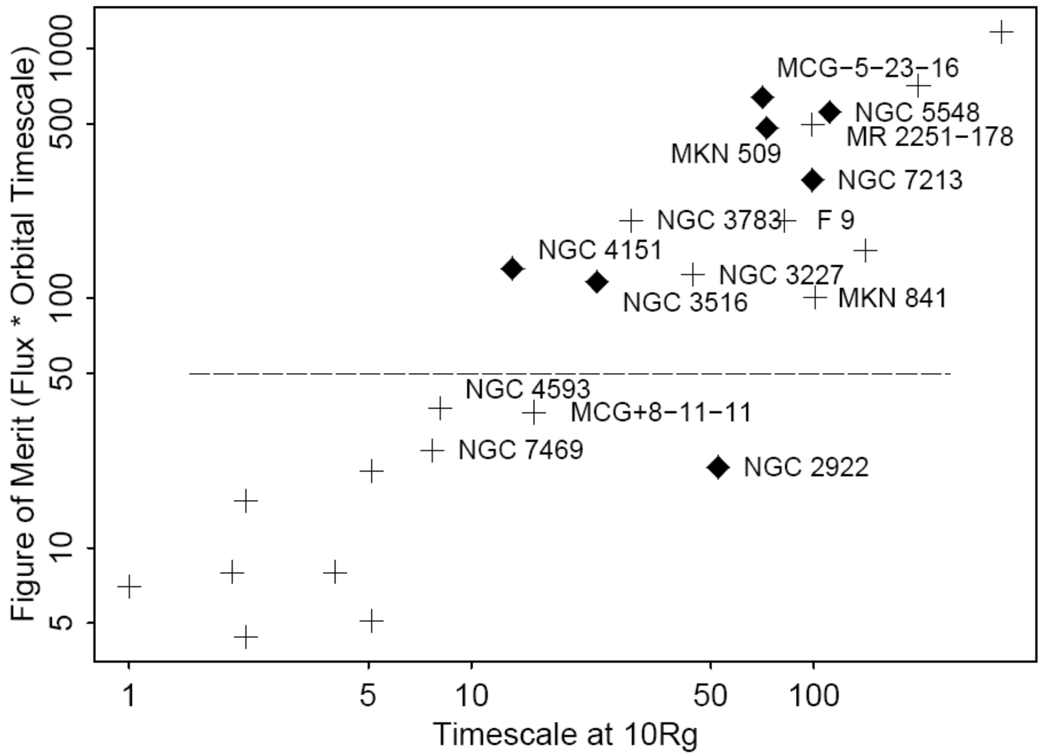
Strong GR effects: Photon Orbits





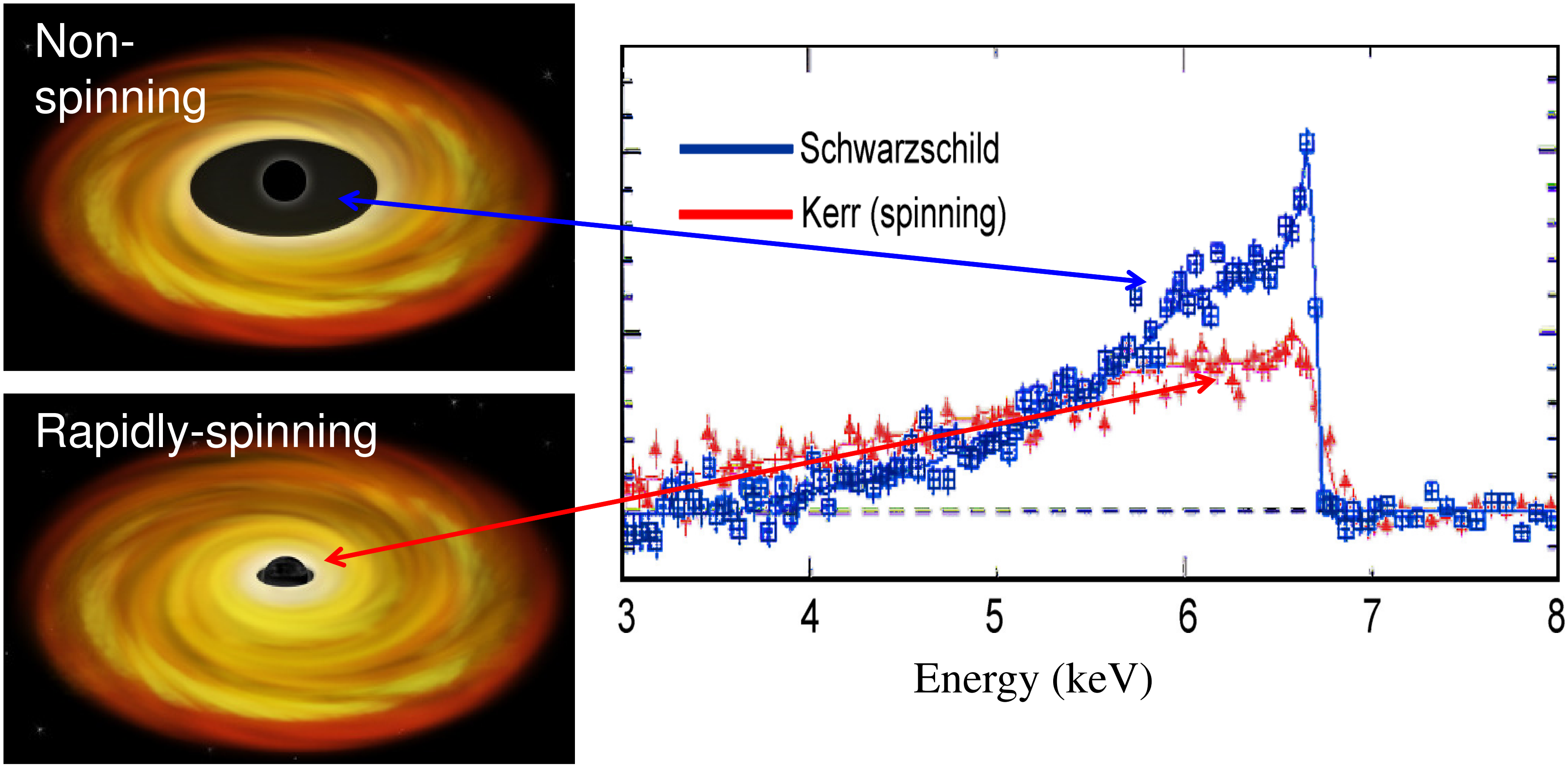
Reverberation mapping measures photon orbits - not matter orbits – in the strong field limit.
Two measurements are complimentary and can be done at same time.

Target AGN Identified



- List growing as BATSE finds more obscured AGN

Black Hole Spin & Growth



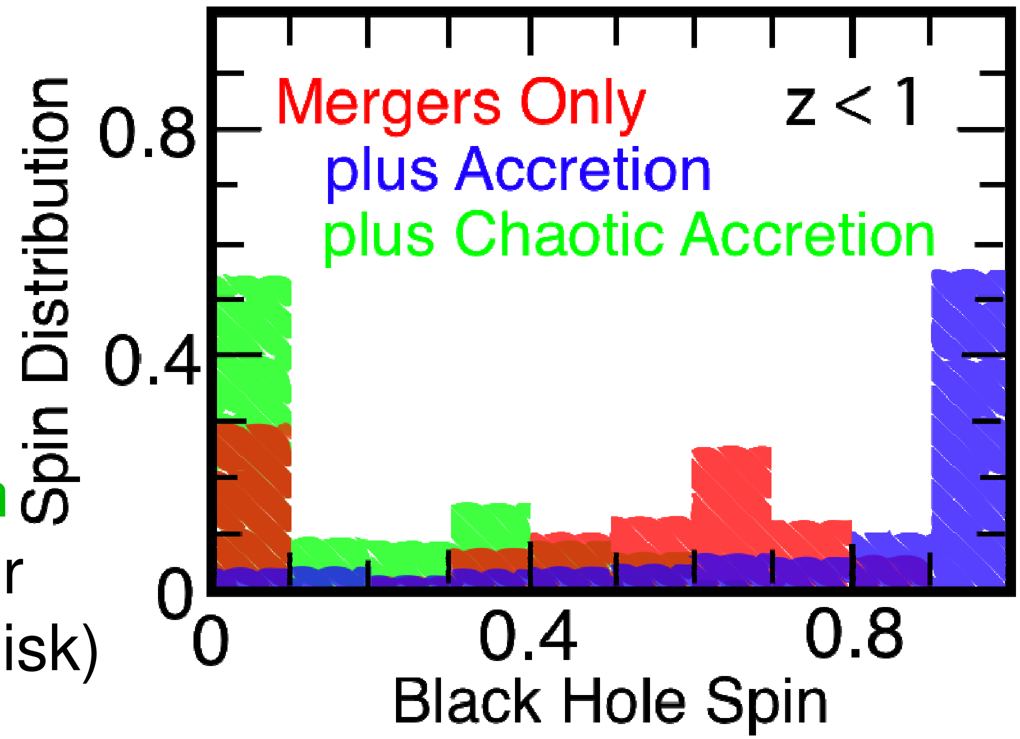
IXO will measure relativistic-broadened iron line emission, measuring the black hole's spin.

Supermassive Black Hole Spin & Growth

Mergers with standard accretion: mostly maximally spinning black holes

Mergers plus chaotic accretion (growth from absorbing smaller (0.1%) SMBHs, no accretion disk) leads to slow rotation.

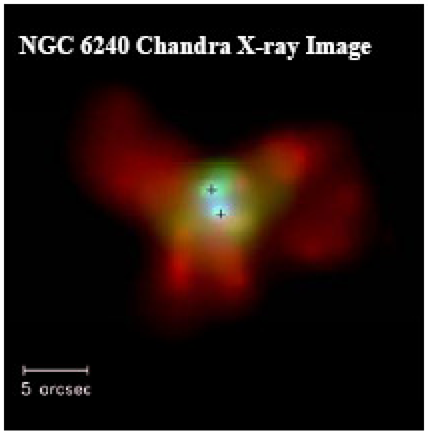
Merger-only growth: broad distribution of spins

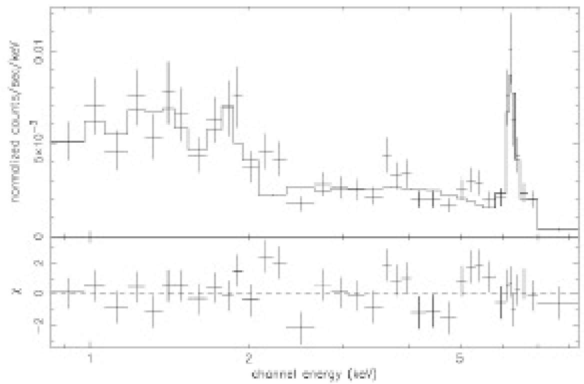


IXO will measure spin in Hundreds of AGN – record of SMBH growth method

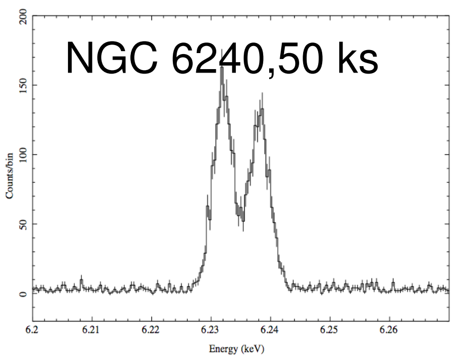
based on Berti & Volonteri (2008)

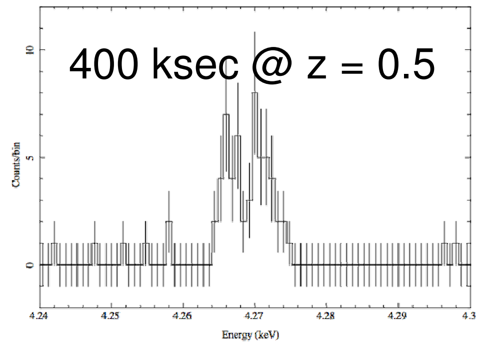
Imaging Binary AGN with Chandra

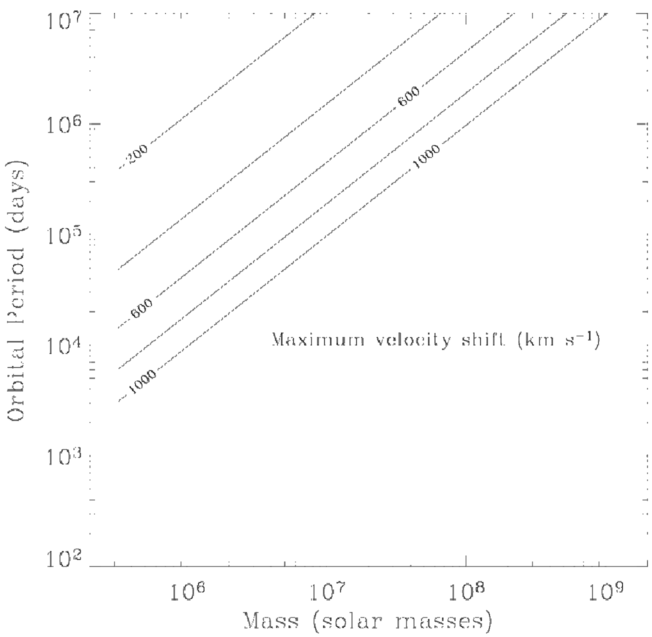




Spectroscopic Binary AGN with IXO







IXO resolution ~100 km/sec

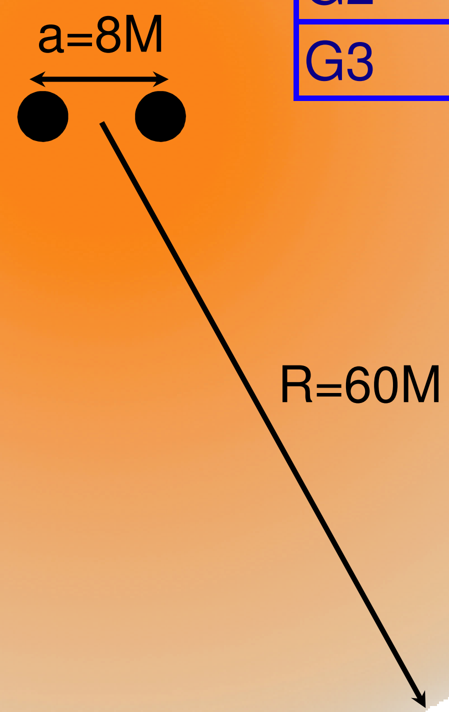
Could be ~1 binary per deep field
At z<0.5 (uncertain)

Fe Kα lines identify binary SMBH,
While lines from double optical AGN
may be due to geometry from Ionized
regions far away from SMBH

Relativistic mergers of SMBHs

(Bode, Haas, TB, Laguna, Shoemaker 09)

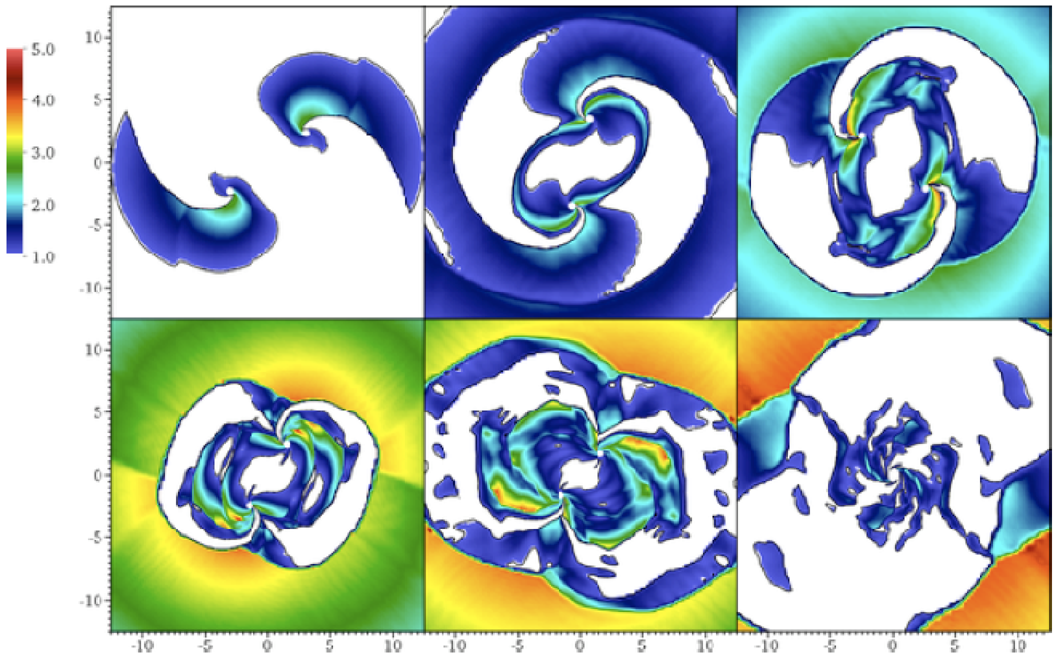
- Fully relativistic hydro study
- Late inspiral and merger
- Equal mass, spinning SMBHs: $M=10^7 M_\odot$
- Initial BH separation of 8M
- Surrounded by hot ($T \sim 10^{12}$K) and tenuous ($\rho \sim 10^{-11}$g/cm^3) gas
- Radiatively inefficient accretion flow (opposite of the circumbinary disk)
- No AGN feedback, no magnetic fields, no radiative cooling.



runs	s_1	s_2
G0	0	0
G1	+0.4	+0.4
G2	+0.6	+0.6
G3	+0.4	-0.4

Emission from the hot gas q=1, s1= s2= +0.6

(Bode+ 09)

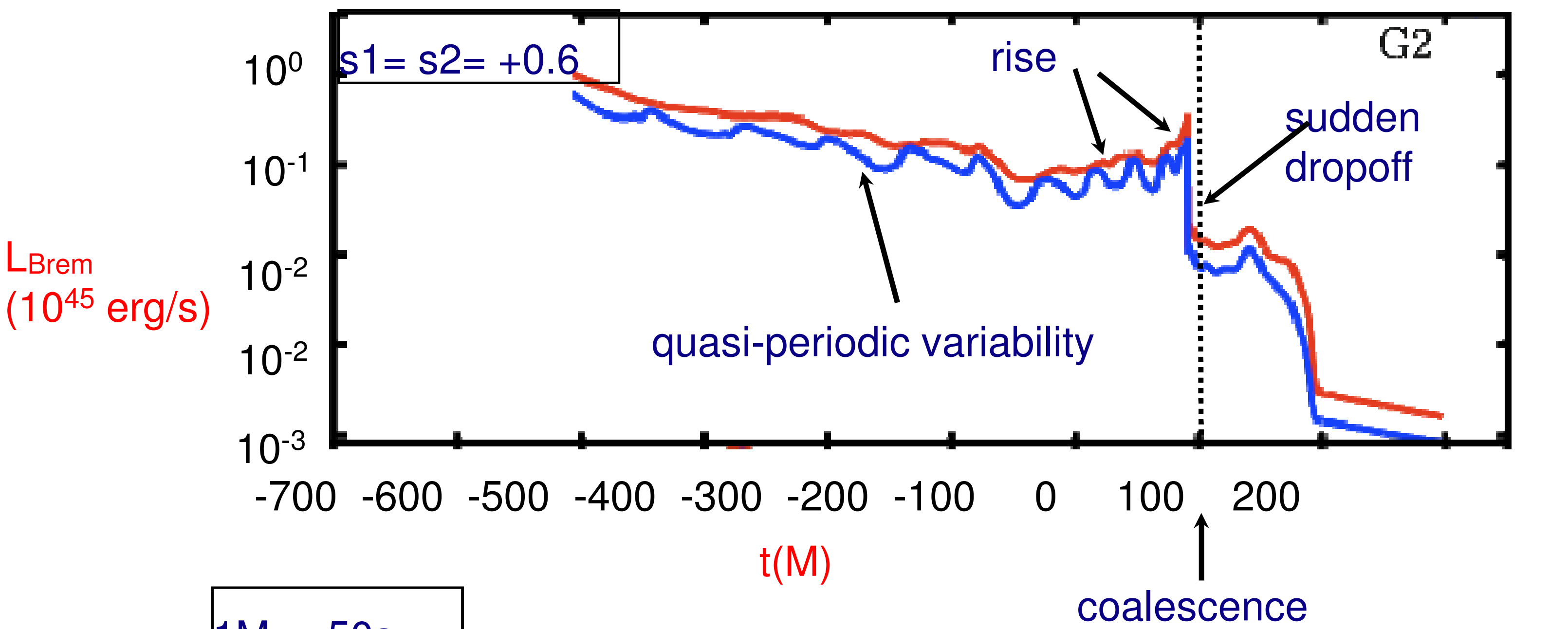


Insert movie here Instead of figure

Bremsstrahlung luminosity

(Bode+ 09)

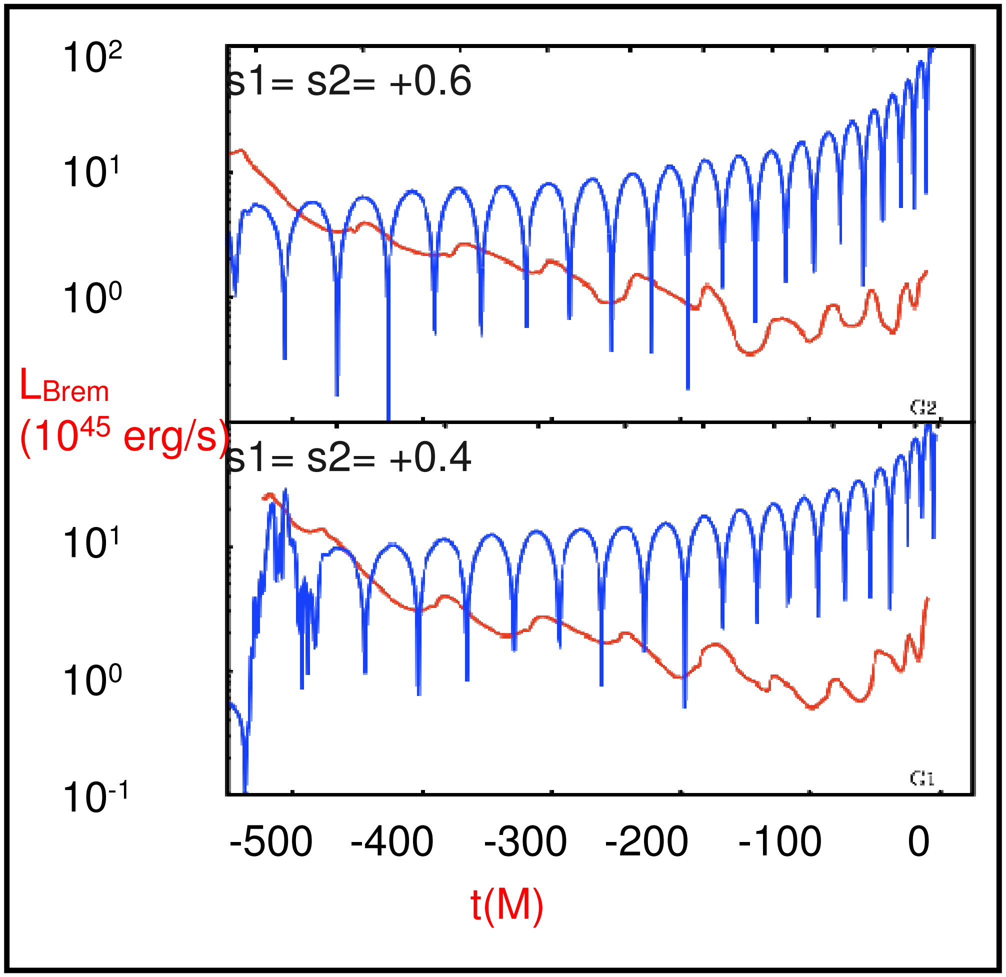
$$L_{\rm brem} \approx 4\times 10^{44}\,{\rm erg\,s^{-1}} \left(\frac{\rho}{10^{-11}\,{\rm g\,cm^{-3}}}\right)^2 \left(\frac{R}{10M}\right)^3 M_7^3 \left(\frac{T_e}{10^{10}\,{\rm K}}\right)^{1/2} \left[1+4.4\times\left(\frac{T_e}{10^{10}\,{\rm K}}\right)\right]. \quad 5.4$$



$1M_7 \approx 50$s

Correlated EM & GW emission

(Bode+ 09)



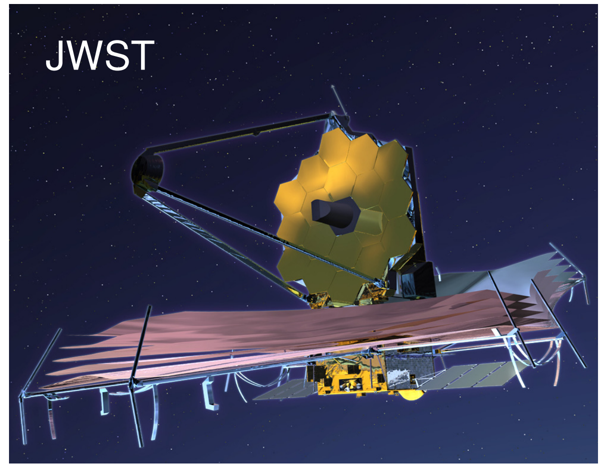
Summary

- IXO will allow breakthrough spectroscopy over a wide of astrophysics – Area for high-resolution spectroscopy >100x previous, area alone >20x previous missions
- First observatory with sufficient area to time-resolve orbits at event horizon of SMBH
- Spin survey of several hundred AGN will constrain merger history of SMBH
- Possible correlated EM and GW emission from mergers
- Part of Astro2010 Decadal Survey and ESA Cosmic Visions program

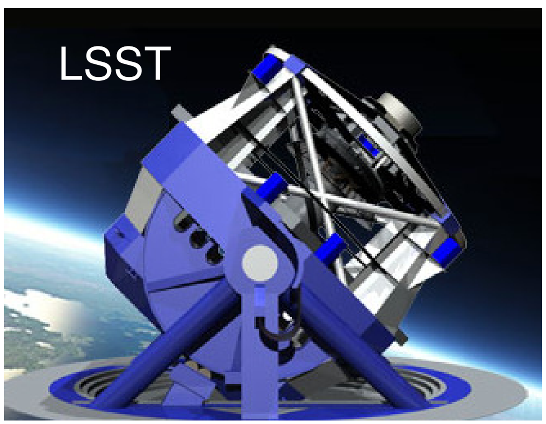
Backup slides

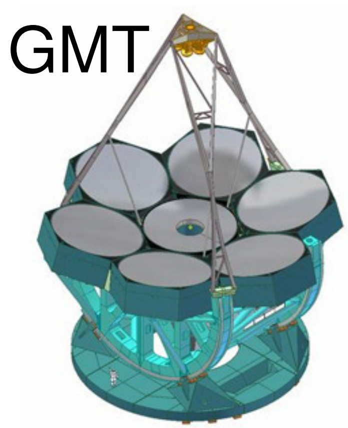
IXO: A Future Great Observatory

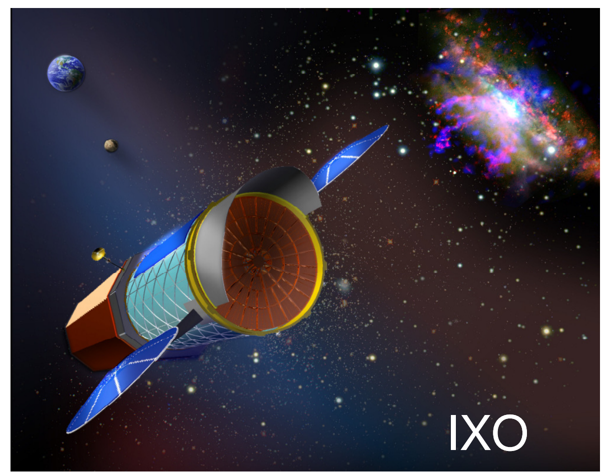
Sub-mm



IR







X-ray

Optical

The two order of magnitude increase in capability of IXO is well matched to that of other large facilities planned for the 2010-2020 decade

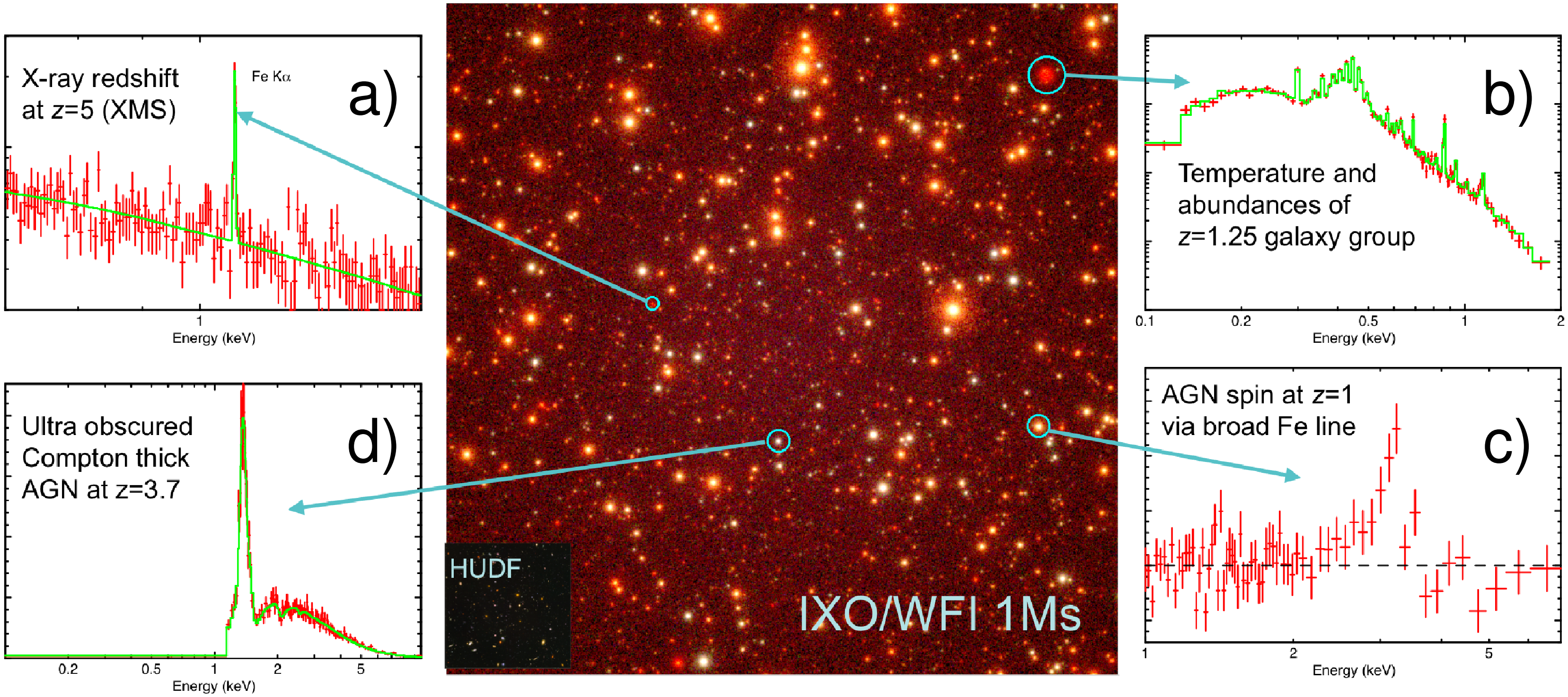
Galaxies with multiple nuclei

- Merging galaxies are a prediction of standard hierarchical structure formation models
- Mergers play an important role in
  - Fueling AGN and quasar activity
  - The growth and spin evolution of SMBHs
  - Galaxy spheriod formation
- IXO can spectroscopically resolve the Fe Kα lines associated with each of the two SMBHs in a merger

Statistics

- There could be ~0.3 SMBH / yr coalescing at z < 0.5 (very uncertain)
- When two galaxies merge, their SMBHs form a binary system in ~10^6 years, and a tight binary in ~10^7 years, although these timescales are uncertain
- ~ few x 10^6 double AGN with z < 0.5
  – Roughly one per deep IXO FOV

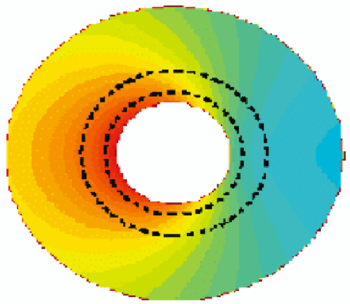
IXO Surveys – Deep and Wide Simultaneously



Hundreds of AGN at z~7, pushing to z=8 to 10:

a) determine redshift autonomously in the X-ray band (binary SMBH via Fe line)
b) determine temperatures and abundances even for low luminosity galaxy groups
c) make spin measurements of AGN to a similar redshift
d) uncover the most heavily obscured, Compton-thick AGN

SMBH have mass and **Spin**: Fe Kα



Newtonian

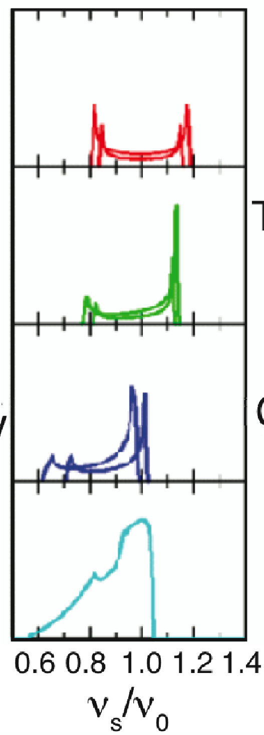
Special Relativity

Transverse Doppler Shift, Beaming

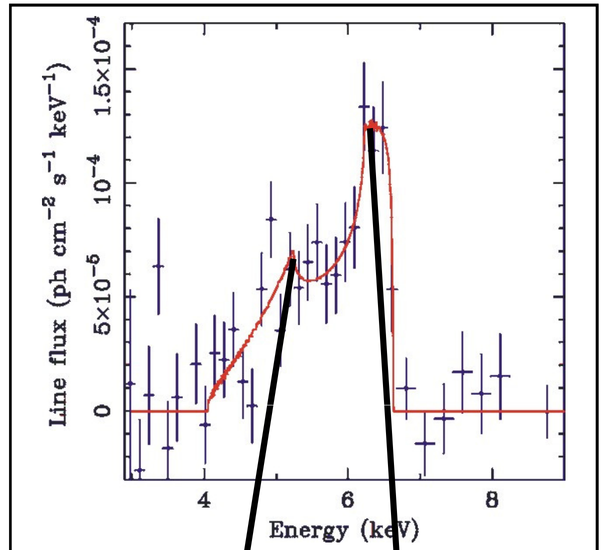
General Relativity

Gravitational Redshift

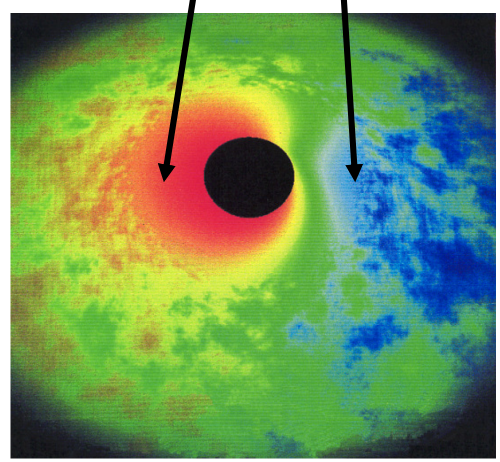
Line Profile



Fabian 1991

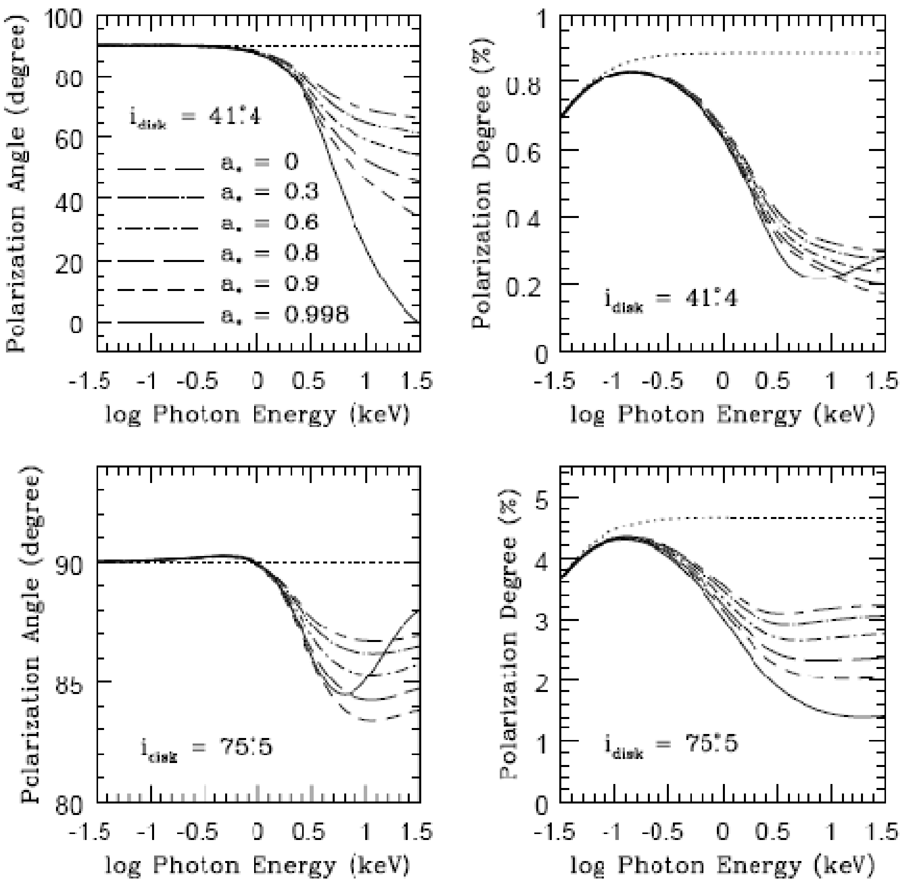


First observation Relativistic Fe line in SMBH - 1995



Theoretical 'image' of an accretion disk.

Another way to measure Spin: Polarization – Change in angle and % increases with Energy



GR effects strongest closest to BH, therefore at highest T regions – so effects stronger with increasing energy.

Another way (of six with IXO) to measure spin.

Li, Narayan, McClintock 2009
See also Schnittman and Krolik 2009

Key Performance Requirements

Mirror Effective Area	3 m^2 @1.25 keV 0.65 m^2 @ 6 keV, goal of 1m^2 150 cm^2 @ 30 keV, goal of 350cm^2	Black hole evolution, large scale structure, cosmic feedback, EOS Strong gravity, EOS Cosmic acceleration, strong gravity
Spectral Resolution/FOV	ΔE = 2.5 eV within 2x2 arc min (0.3-7.0 keV) 10 eV within 5x5 arc min < 150 eV @ 6 keV within 18 arc min diameter (0.1-15keV) $E/\Delta E$=3000 with 1,000 – 3,000 cm^2 (0.3-1.0 keV) ΔE = 1 keV within 8x8 arc min (10-40 keV)	Black Hole evolution, Large scale structure Missing baryons using tens of AGN
Mirror Angular Resolution	≤5 arc sec HPD (0.1-7 keV) ≤30 arc sec HPD (7-40 keV), goal of <5 arcsec	Large scale structure, cosmic feedback, black hole evolution, missing baryons
Count Rate	1 Crab with >90% throughput ΔE < 150 eV @ 6 keV (0.1-15keV)	Strong gravity, EOS
Polarimetry	1% MDP on 1 mCrab in 100 ksec (2 -6 keV) at 3σ	AGN geometry, strong gravity
Astrometry	1 arcsec at 3σ confidence	Black hole evolution
Timing	50 μsec absolute	Neutron star studies

Energy Resolution of various Grades

Still a lot of work being done on the best way to analyze fast, critically-damped pulse data. How many time constants are optimal???

Simulations will be done on this in the coming months. For now we expect something like the following:

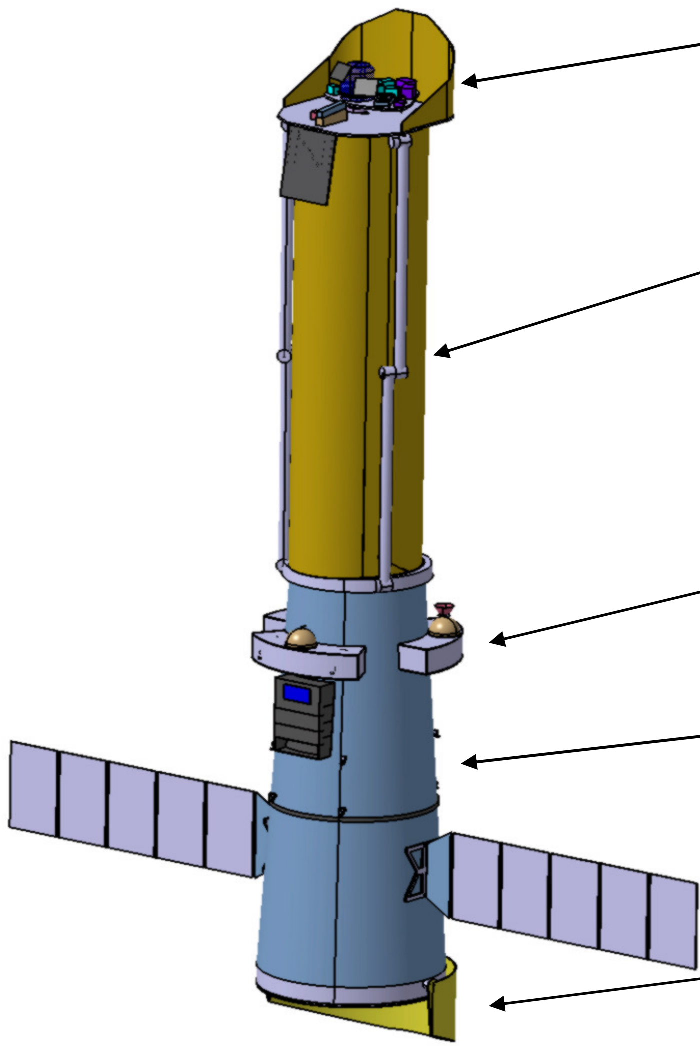
- Hi-res events will have the highest spectral resolution (e.g, 2.5 eV)

- Mid-res may be ~ twice the hi-res

  Mid-res secondaries would be worse, but it should be possible to correct the pulse heights of secondary pulses. This requires a lot of calibration data (large range of Δt's and E's!)

- Low-res events will likely have > 10 eV resolution

ESA IXO configuration



Instrument module

Optical bench deployment mechanism

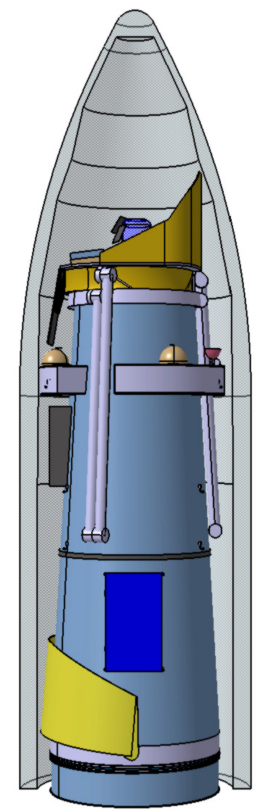
(+ deployable shroud)

Service module

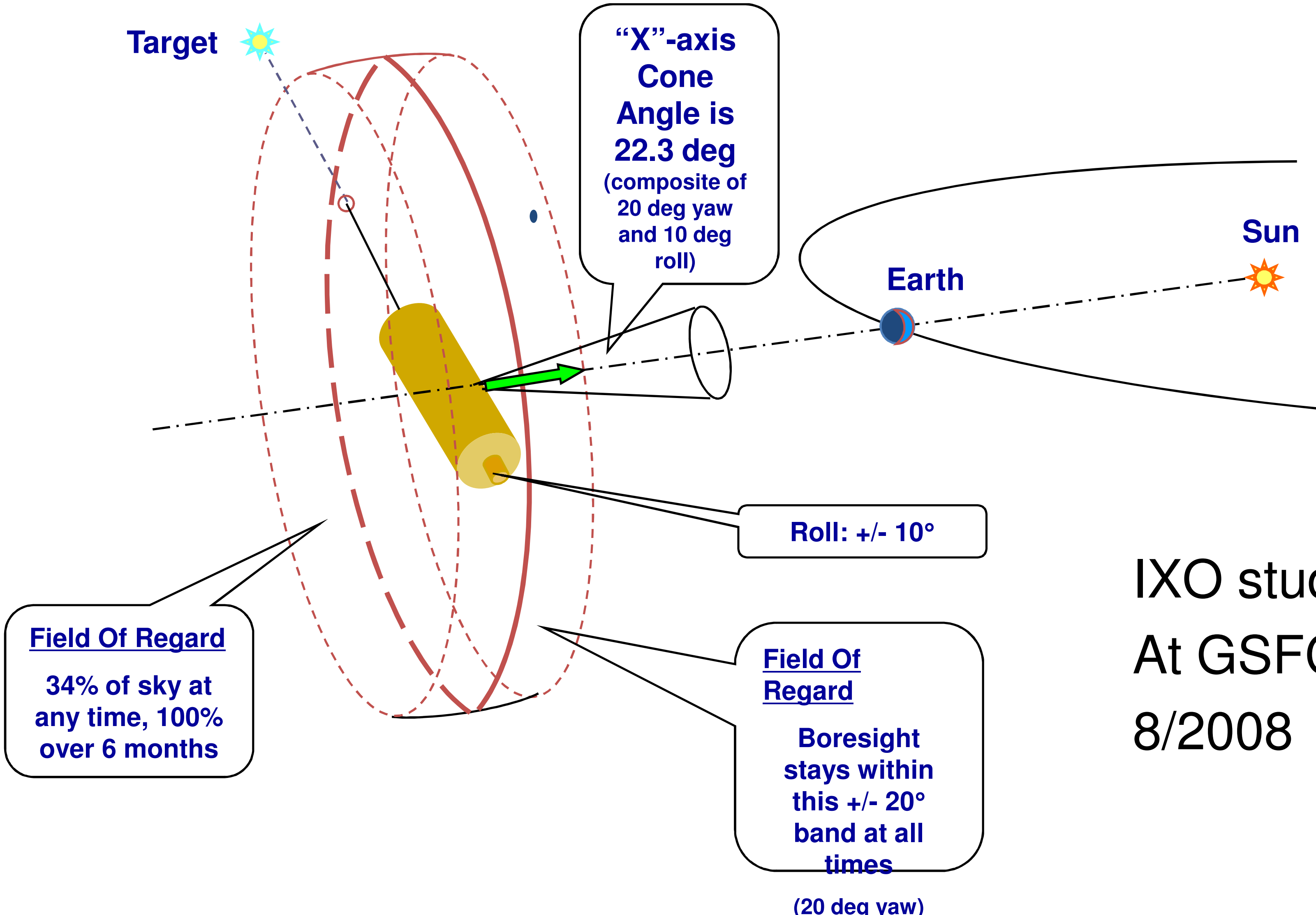
Fixed conical optical bench

Mirror assembly (Pore Optics)

(+ deployable sun shield)

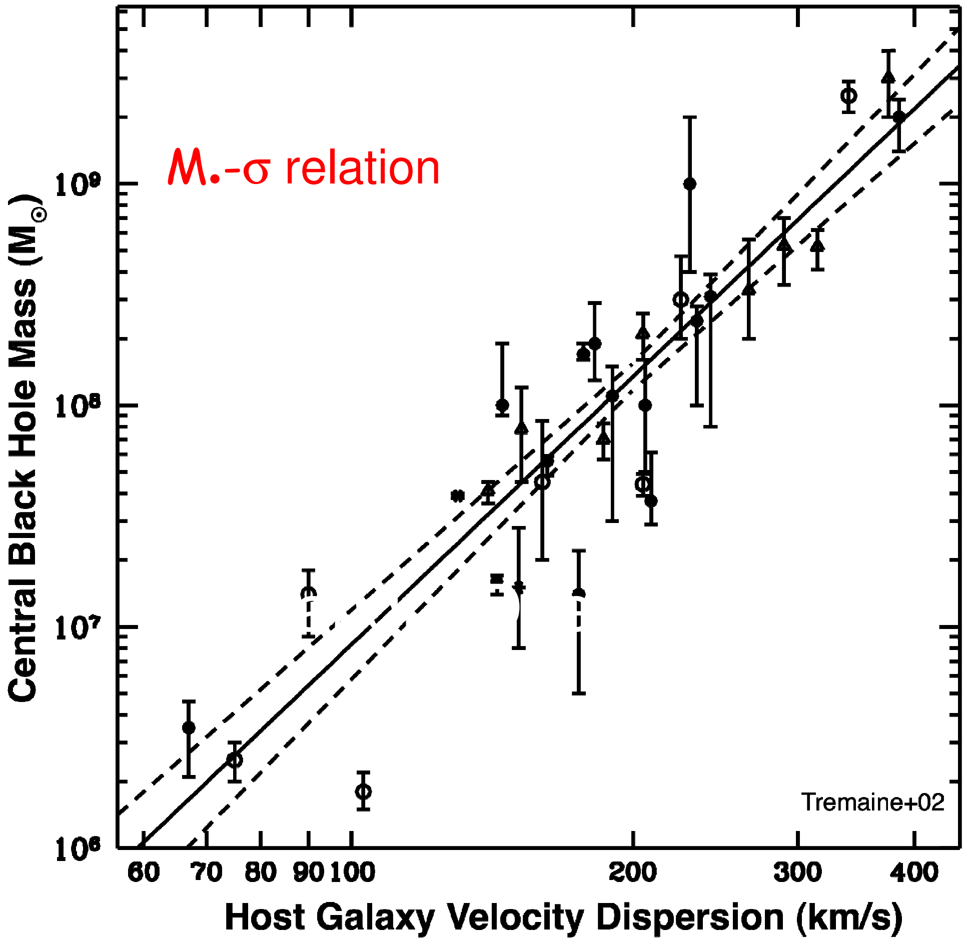


ToOs: IXO Capabilities



IXO study
At GSFC MDL
8/2008

Extending Bulge-SMBH Mass Relationship to High z



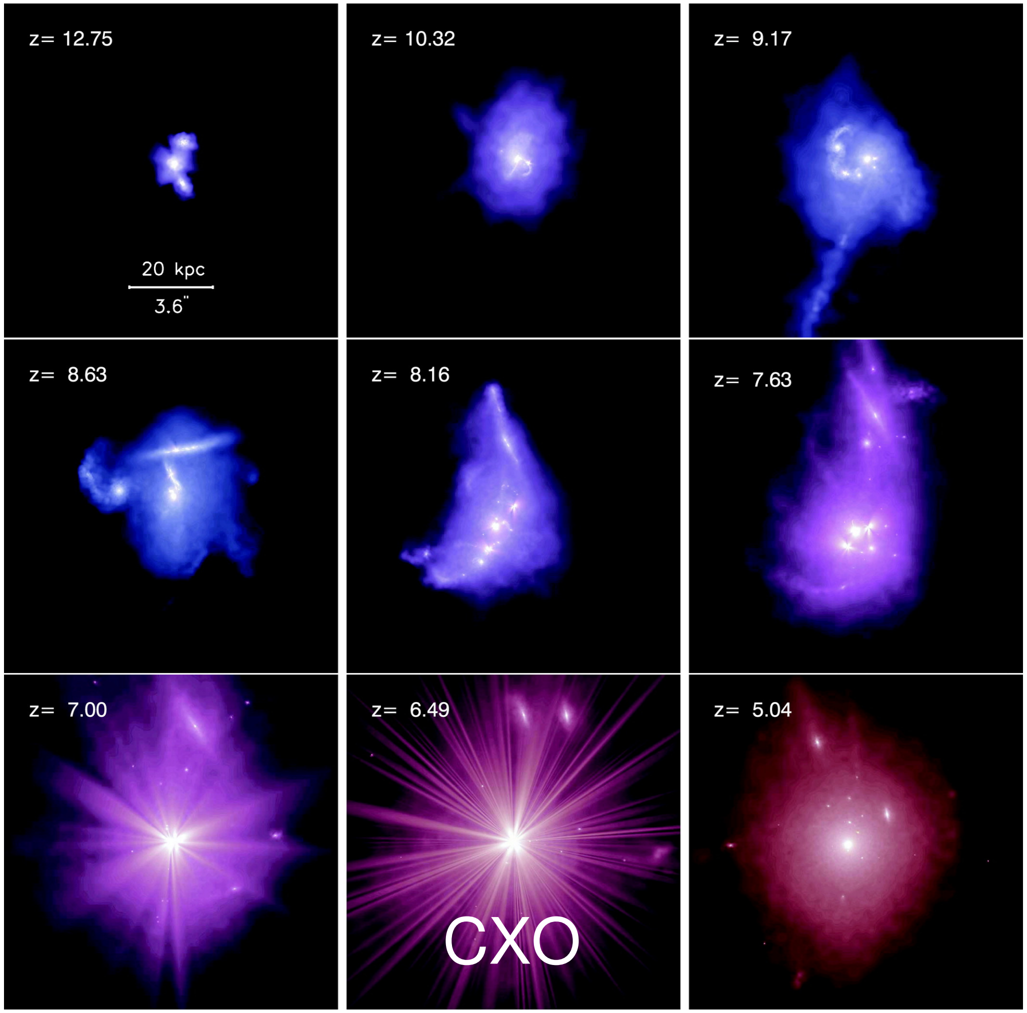
Graph shows direct evidence for co-evolution of local galaxies and AGNs

BH accretion process influences growth of entire galaxy and vice versa

IXO addresses how the first massive black holes fed and grew and tests the extension of the Magorrian relationship to higher redshift

Magorrian et al. 1988; Gebhardt et al. 2000; Ferrarese & Merrit 2000; Tremaine et al. 2002

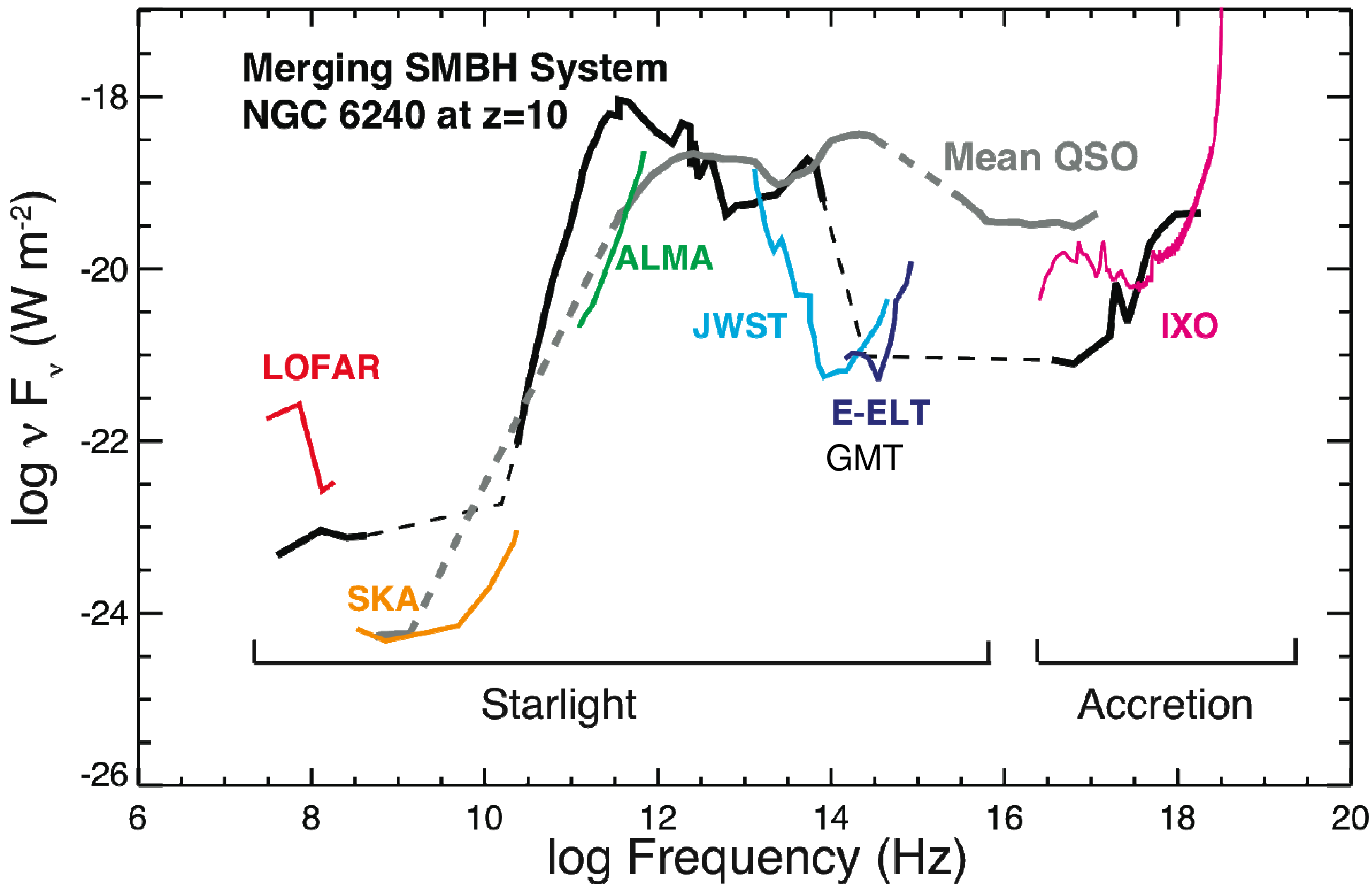
The First Supermassive Black Holes



1. Gas rich major merger From Li et al. 2007, Hopkins et al. 2005
2. Inflows trigger BH accretion & starbursts
3. Dust/gas clouds obscure AGN
4. Luminous quasar forms with strong wind/outflow
5. AGN wind sweeps away gas, quenching SF and BH accretion

From Li et al. 2007, Hopkins et al. 2005

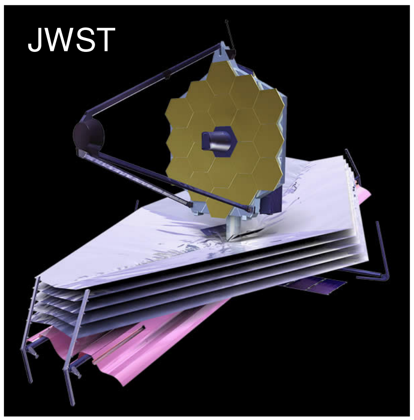
SMBH's at high redshift with IXO

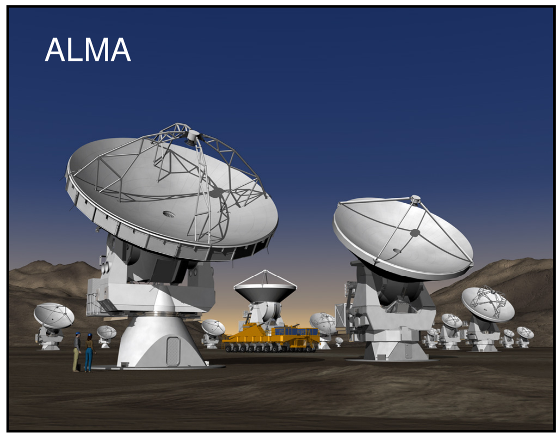


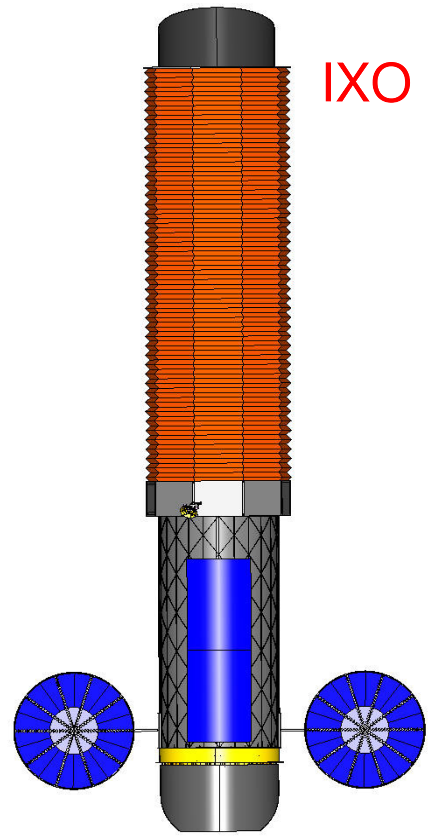
Accretion in the Universe

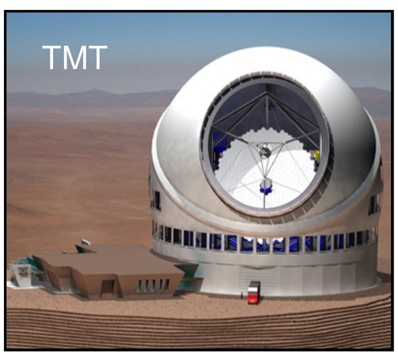
Starlight from First Galaxies

Accretion Light from First Galaxies

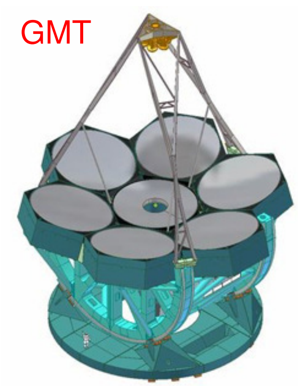


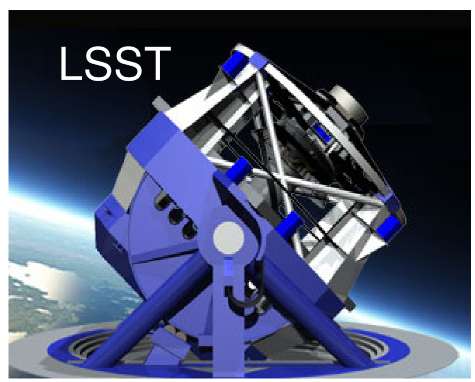






GMT



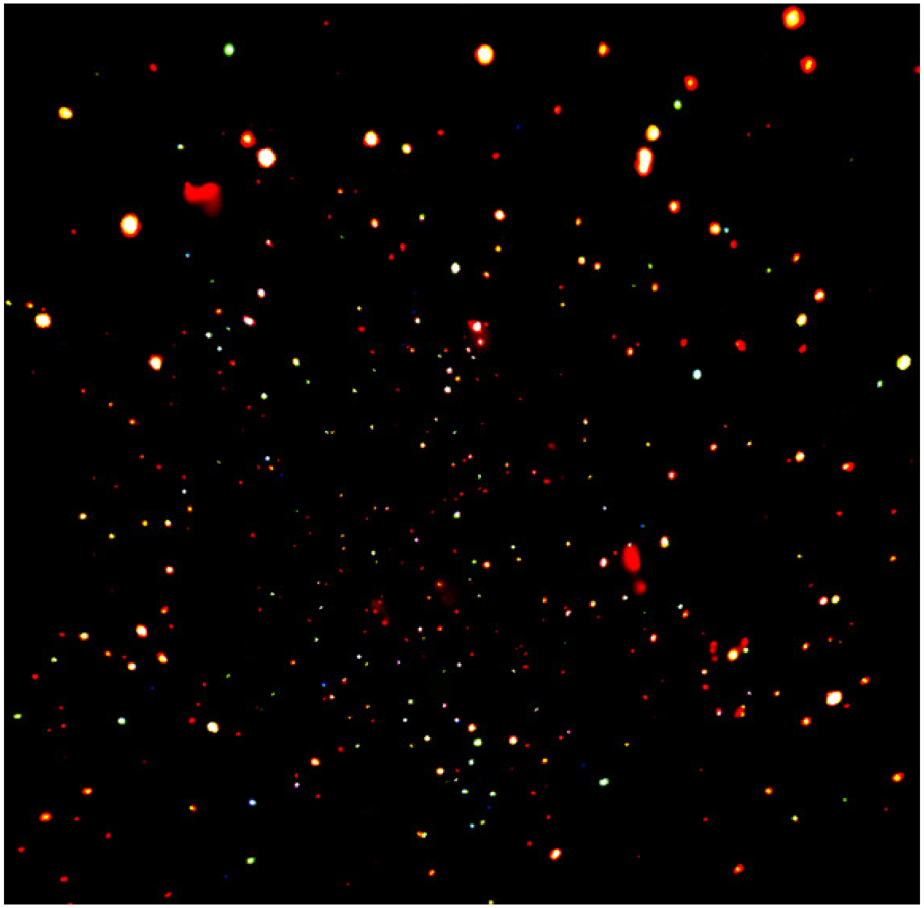


Why Study M-σ with IXO?

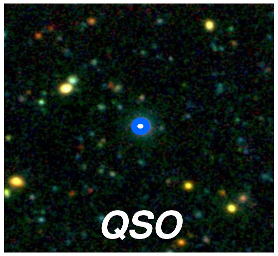
X-rays give most direct view of growing SMBH in AGN

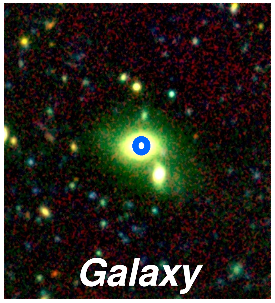
- Chandra deep surveys have the sensitivity to **detect (few)** AGN up to z~8 BUT IXO will give direct measurements of redshift and source diagnostics

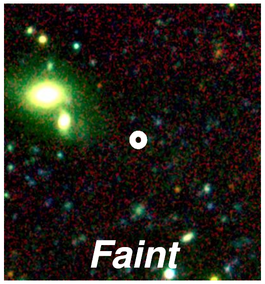
- IXO gets to CDF depths 20x faster!



2 Megasecond Observation of the CDF-N (Alexander et al. 2003)







Chandra sources identified with mix of active galaxies and normal galaxies, many are optically faint and unidentified