How X-ray Experiments See Black Holes: Past, Present and Future

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Introduction

- Galactic Black Holes:
  - Mass Determination
  - Spin Determination
  - Flare from our Galactic center
- Extra-galactic Black Holes:
  - Spectral Line analysis
  - Imaging jets
  - Medium-sized black holes
- Future studies
  - Constellation X
  - MAXIM

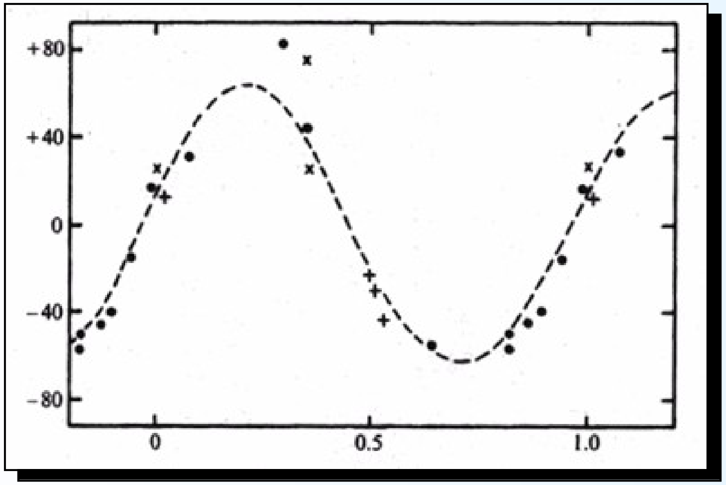
Accretion Review

- X-rays originate from 10^7 K plasma near BH event horizon from inner accretion disk
- Characteristic velocity: $(GM/R)^{1/2} > 0.5c$
- P_{orb} of circulating matter = $2 \pi \tau_{dyn} \sim 1$ ms
- Inner accretion flow occurs in region of strong field gravity - can measure GR effects
- $L_{accr} = \eta G M \dot{M}/R \sim 2.5 \times 10^{38}$ erg s^{-1} where $M = 3 M_\odot$, $R = 10$ km, $\dot{M} = 10^{-8} M_\odot$ y^{-1} and η is efficiency factor (assumed 1)

Mass Determination

- Black hole mass depends on radial velocity curve and spectral type of companion, plus limits on inclination from ellipsoidal light variations.

For Cyg X-1: Mx = 16 +/- 5 M☉



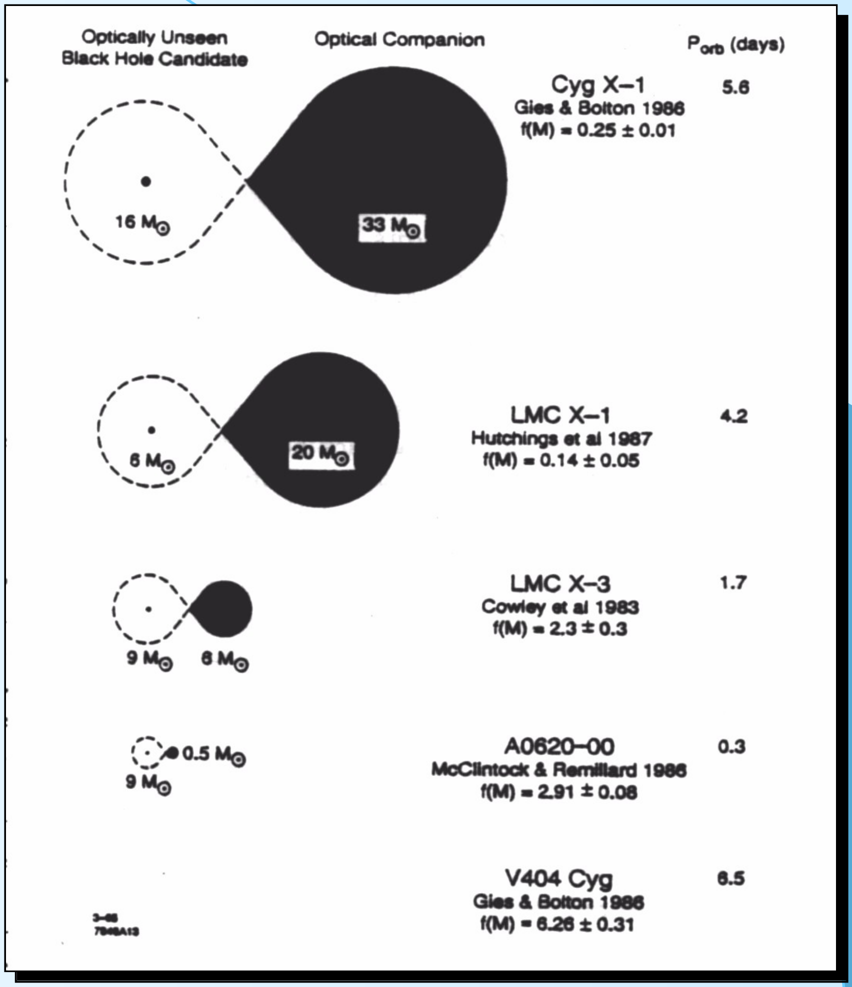
Radial velocity curve for companion of Cyg X-1

Any unseen, non-pulsing, non-bursting object with mass function greater than 3 M☉ is a candidate black hole. Other common characteristics are two-component spectra and very strong transient outbursts.

 XRB p. 126

Mass Determination

Best BHC masses are for "X-ray novae" - optical studies done in quiescence are not contaminated by light from the accretion disk. There are 8 well-studied X-ray novae: best case is V404 Cyg, where the mass function (lower limit on BH mass) $f(M/M_\odot) = PK^3/2\pi G = 6.08 \pm 0.06$, where K is the radial velocity in km s^{-1}

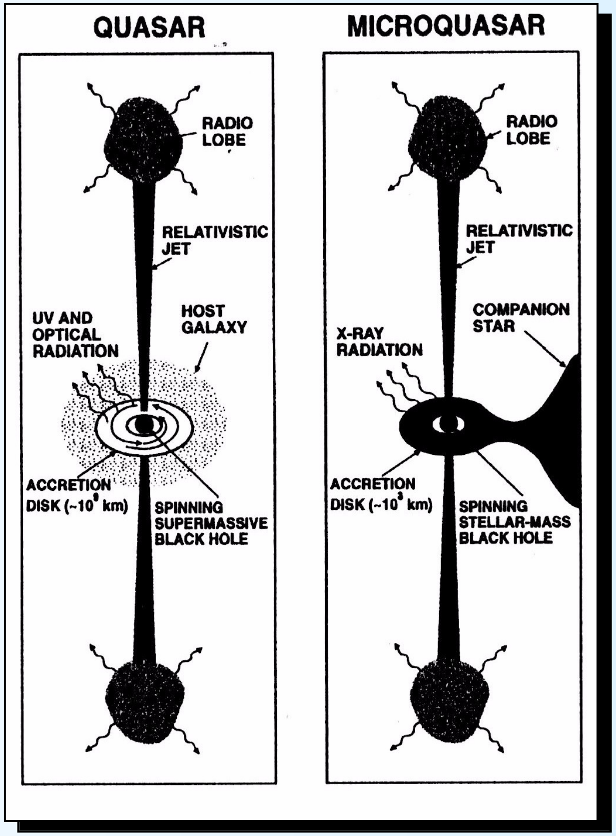


Bender et al. 1995

Microquasars

- Superluminal galactic sources with radio jets and transient, highly variable X-ray emission: *e.g.*, GRS1915+105 and GRO J1655-40.

M ~ 10^6 M⊙	M ~ 10 M⊙
R_{disk} ~ 10^9 km	R_{disk} ~ 10^3 km
T_{disk} ~ 10^3 K	T_{disk} ~ 10^7 K
UV/optical	X-rays
R_{lobe} ~ 10^6 lt-y	R_{lobe} ~10 lt-y



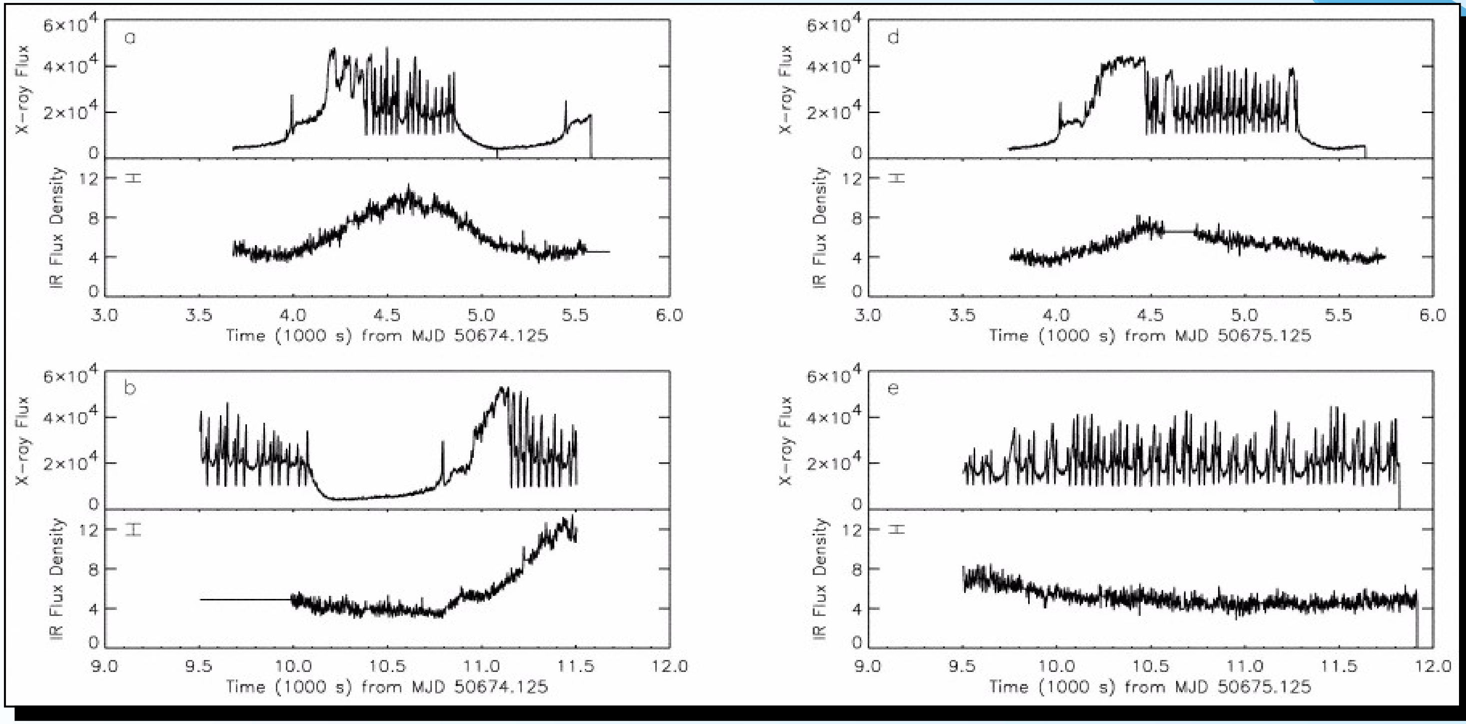
Mirabel and Rodriguez 1998

Disk Jet Interaction

- Coordinated IR/RXTE observations of GRS 1915+105
  - X-ray and IR are correlated at the beginning of flares
  - X-ray and IR flares have constant offset
  - IR then decouples from X-ray, which oscillates wildly
  - IR, Radio emission is non-thermal

triggered by same event

emission regions separate



X-ray

IR

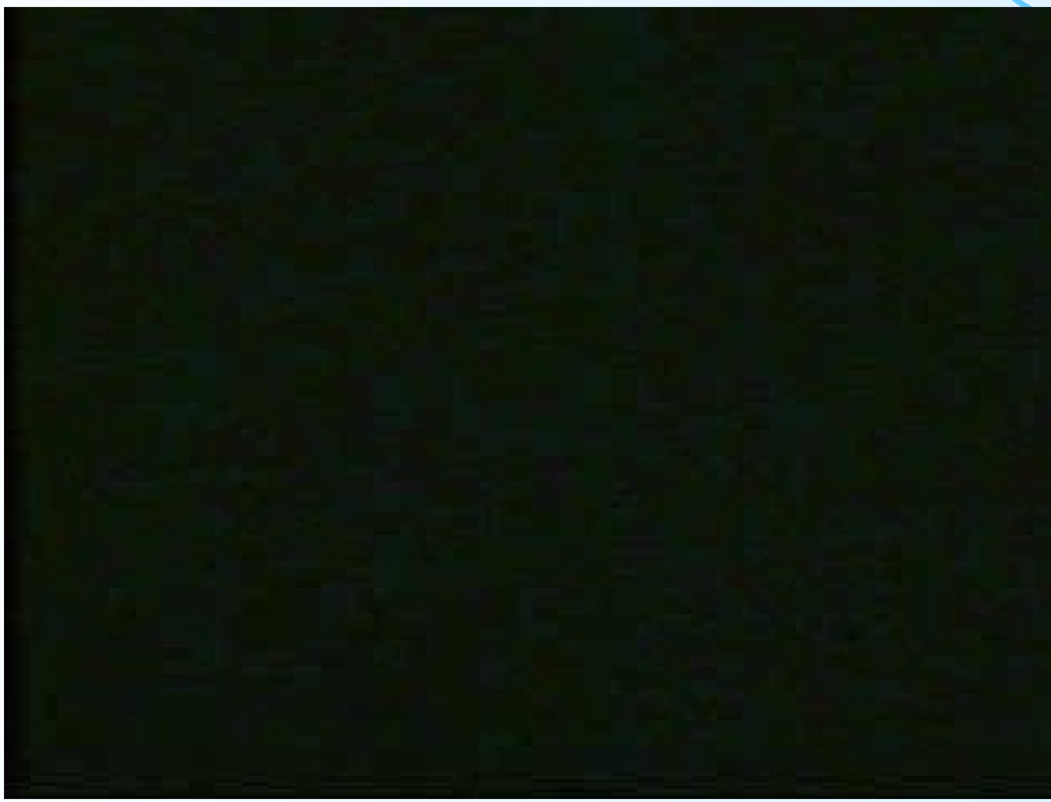
X-ray

IR

Eikenberry et al. 1998

Old Faithful Black Hole/GRS 1915+105

movie

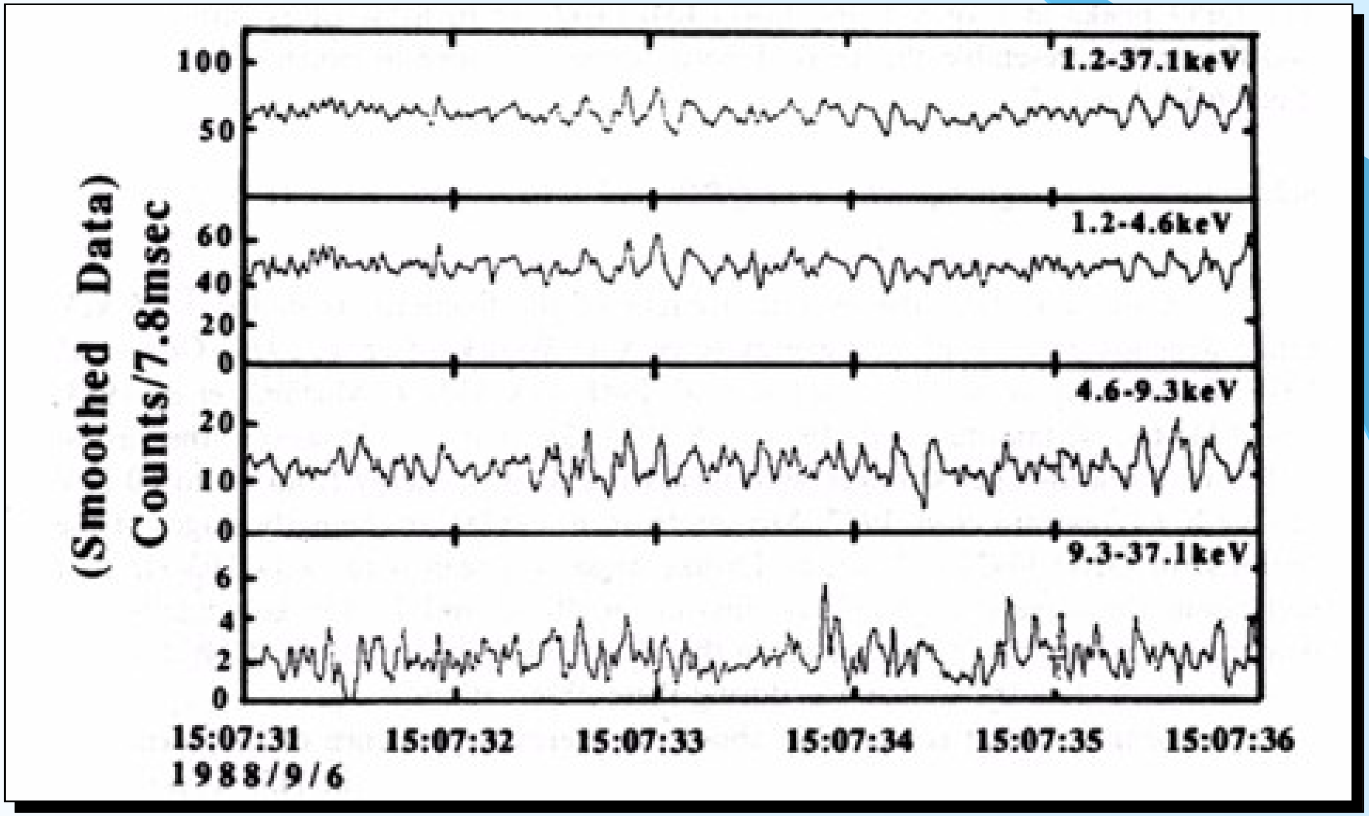


- ~10 second oscillations within
- ~30 minute outbursts
- repeat every 90 minutes

Eikenberry et al. 1998

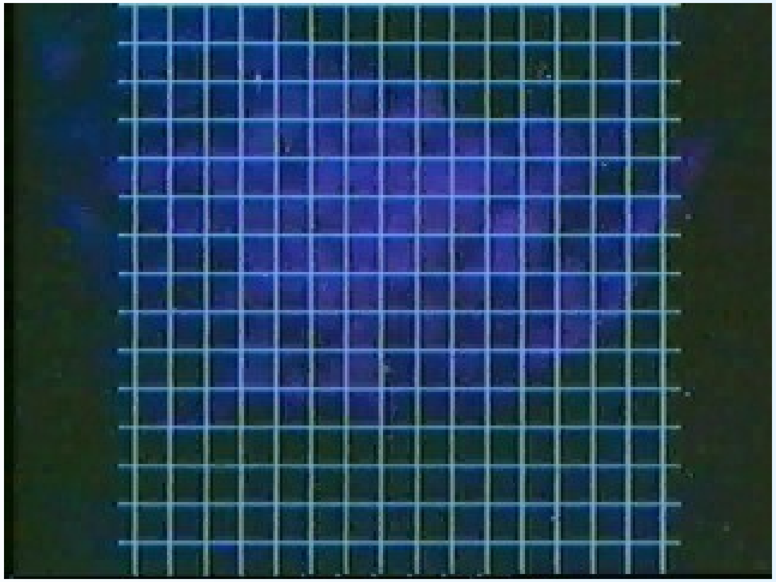
Quasi-Periodic Oscillation

- Original 6 Hz QPOs from GX 339-4 (BHC)



XRB p. 267

Relativistic Effects : frame-dragging



movie

- Stella and Vietri (1998) first proposed the Lense-Thirring effect to explain ~20 Hz QPOs in LMXBs with kHz QPO “twin peaks”. Assumes beat frequency model, NS spin is kHz difference frequency. Orbital plane of test particle is tilted with respect to spin axis of NS.

- Cui, Zhang and Chen (1998) extended this explanation to the strong field limit to include the microquasar BHCs, for different values of angular momentum and tilt angle. The BHC QPOs are then interpreted as X-ray modulation at the disk precession frequency due to frame-dragging.

Spin Determination

- Observations of the “ultra-soft” component in many BH spectra is interpreted as blackbody emission from inner disk at r_{ms}. BB spectral fits to L, T can be used to classify BHCs on the basis of spin:

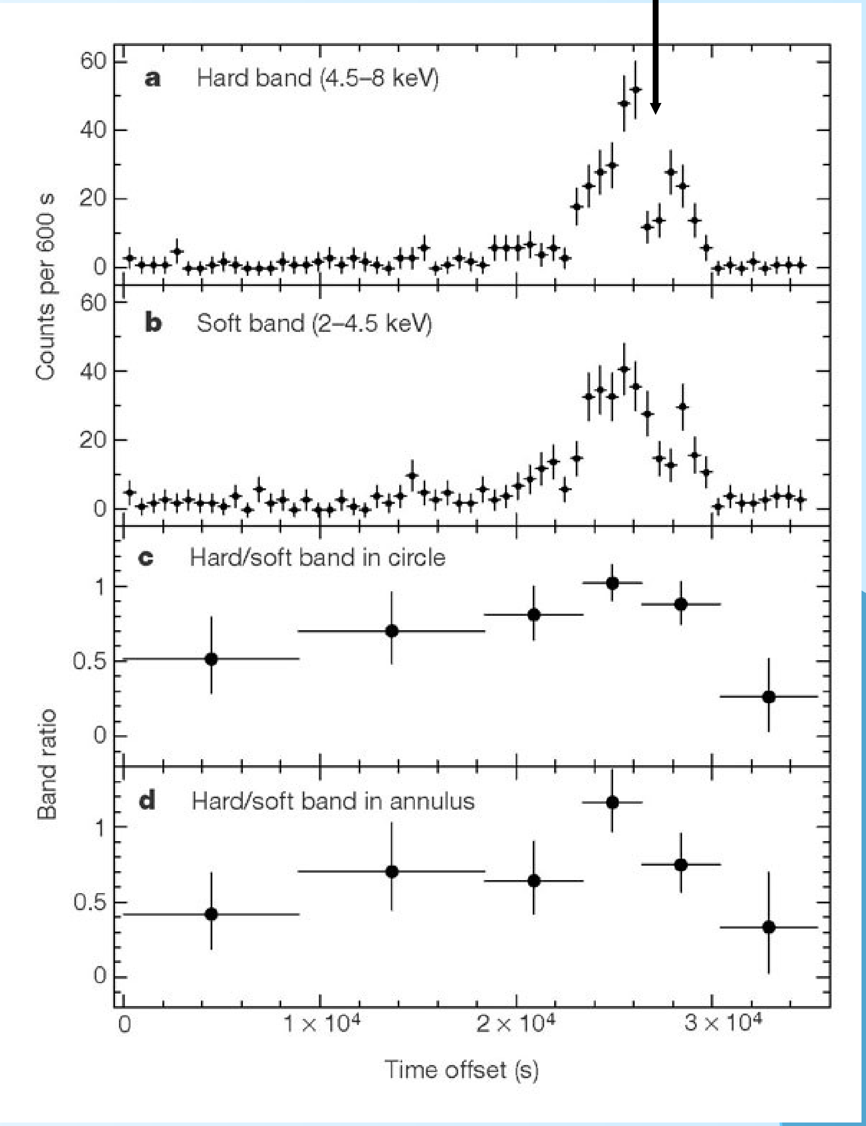
	η	$r_{ms}/(GM/c^2)$
– extreme prograde (maximal Kerr)	30%	1
– slowly or non-rotating (Schwarzschild)	6%	6
– extreme retrograde	3%	9

- Microquasars, which have harder spectra, are found to be extreme prograde, with spins between 70-100% of maximal rate.
- Strong “ultra-soft” emitters are non-rotating BHs.
- BHCs that have no detectable “ultra-soft” emission are extreme retrograde BHs, as the emission has gotten too soft for the X-ray bandpass.

Zhang, Cui and Chen 1997

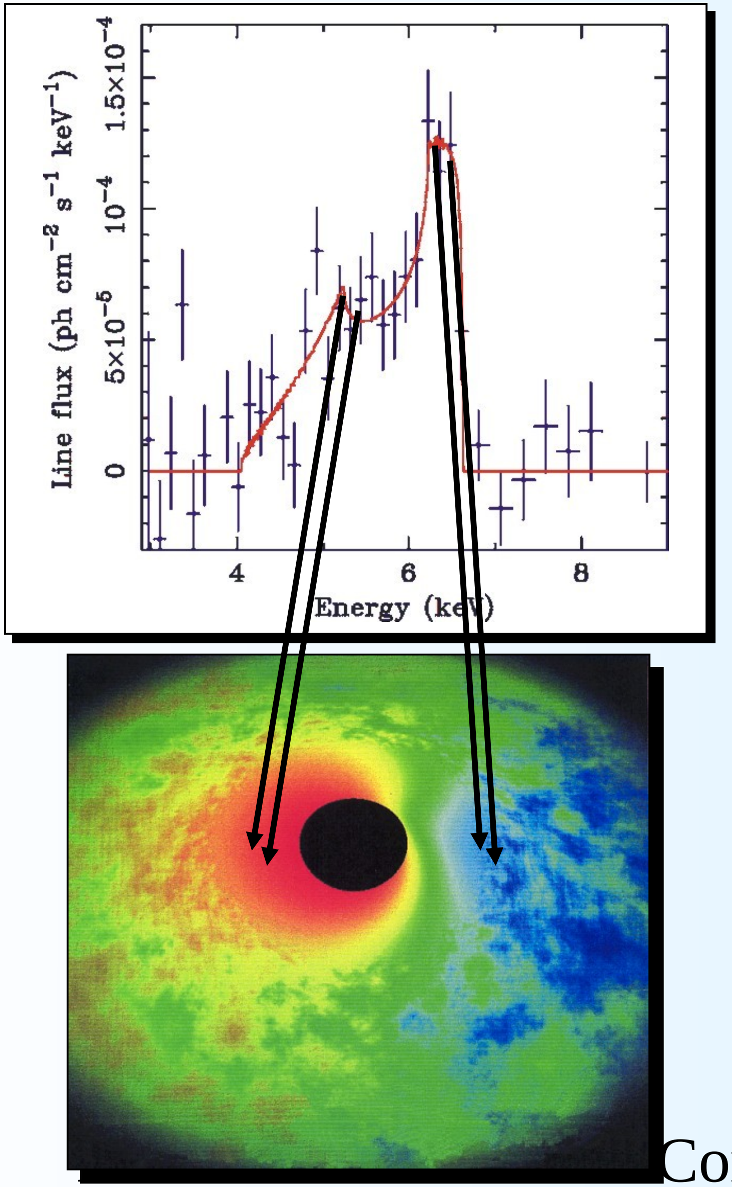
Flare from our Galactic Center

- Chandra imaging observations discover small flare from GCX;
- ~1 x10^{35} erg/s at peak
- Rapid variability (100 s) within 10,000 s flare implies region < 10 R_s
- Accretion of comet-sized mass or magnetic reconnection?



Baganoff et al. 2001

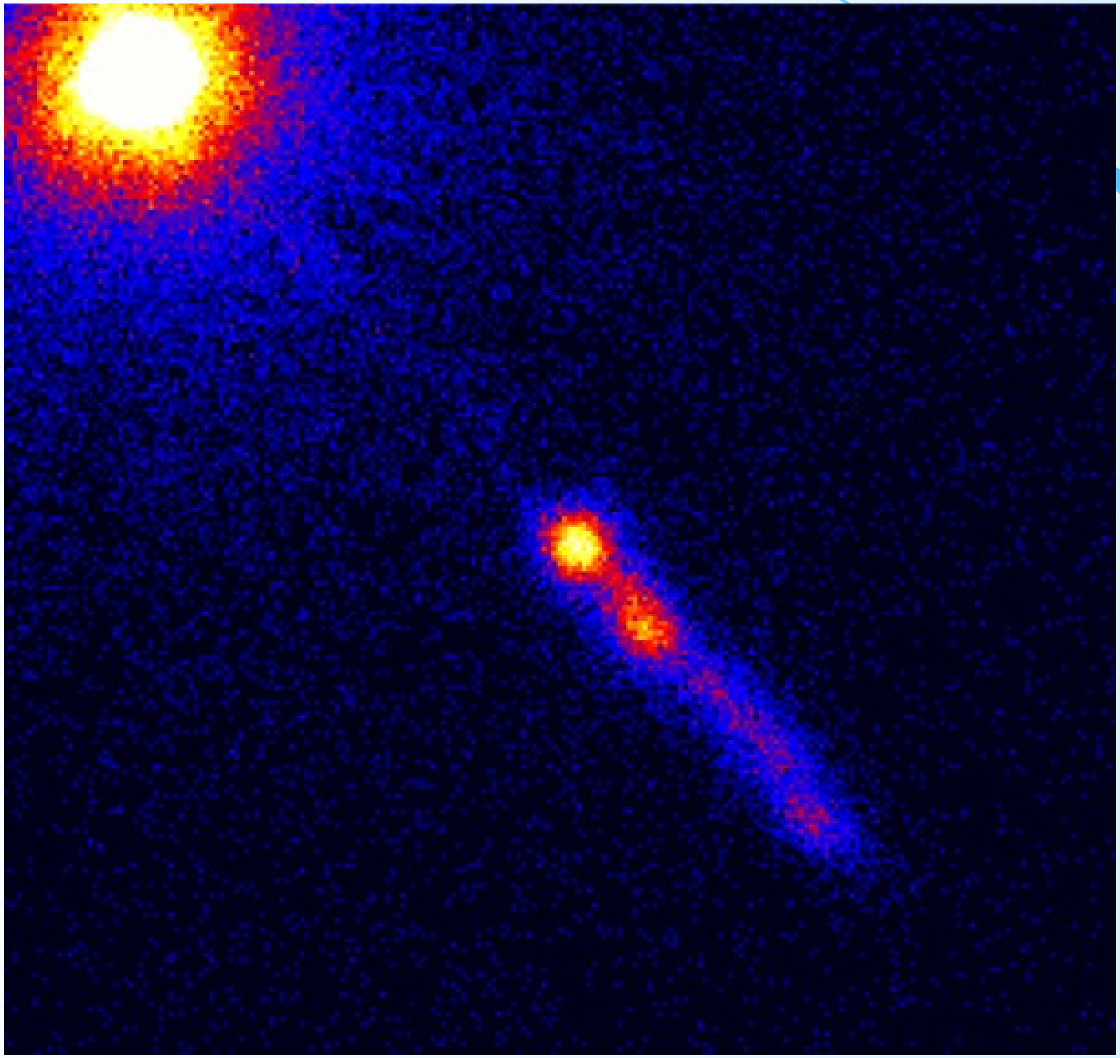
Spectral Line Analysis



- ASCA has discovered relativistically broadened iron K-α lines that come from close to the event horizon
- This line provides a unique probe of the inner region near black holes, observing the effects of GR in the strong field limit

Iwasawa et al 1996

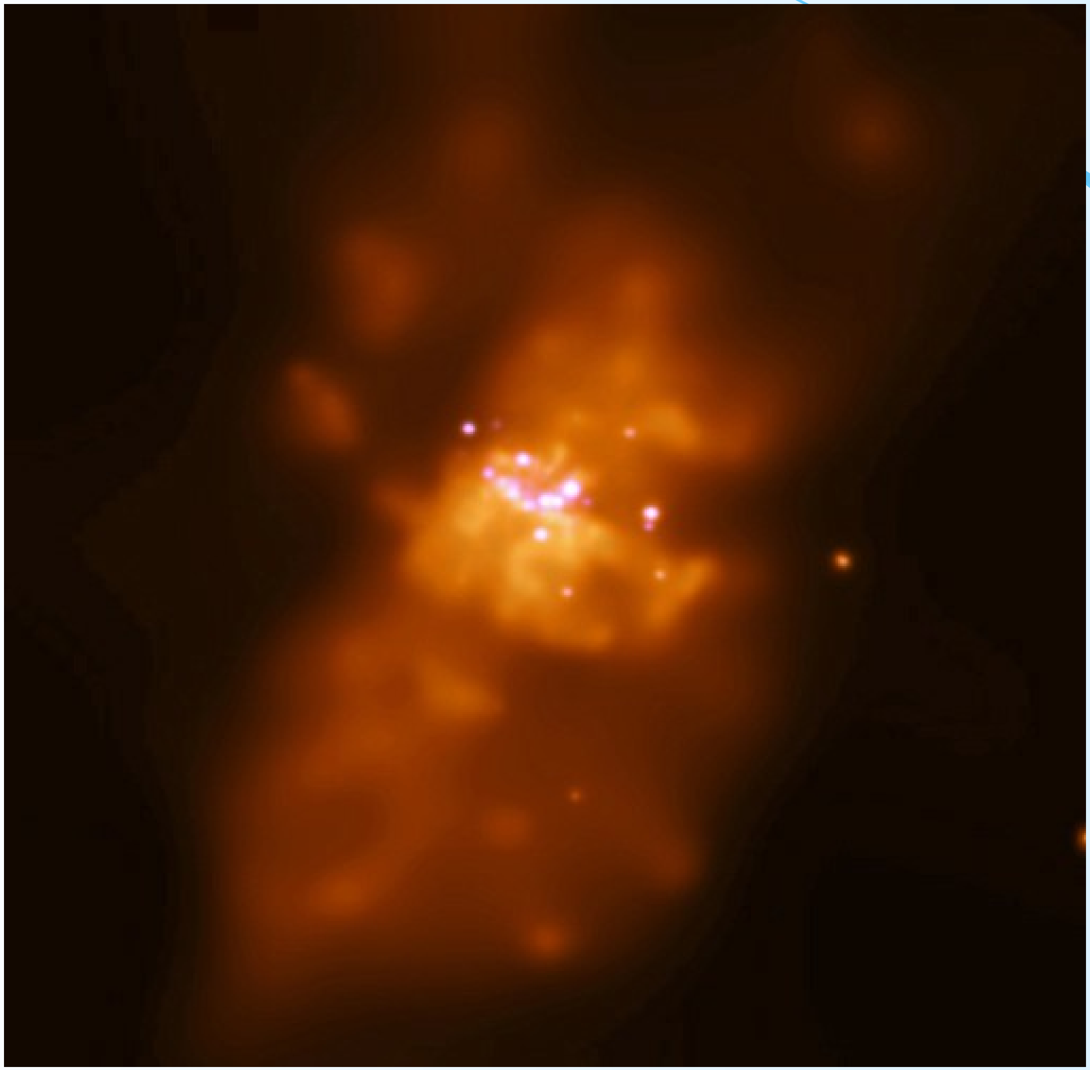
Chandra:3C273 Jet



- Many X-ray jets have been observed from AGN with Chandra
- Knots of X-ray emission dominate optical and radio light
- X-ray emission seen to within 5-10” of core

Marshall et al. 2001

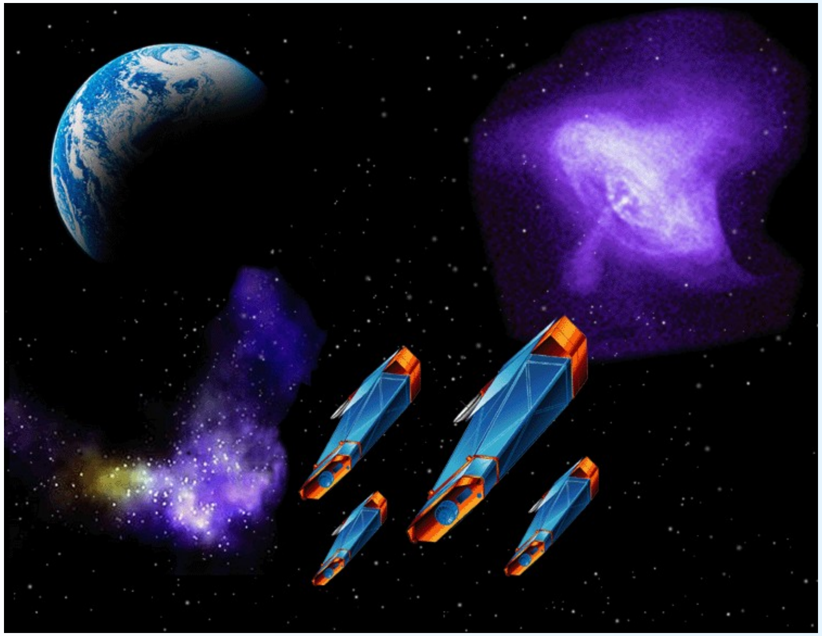
Chandra: M82 Starburst Galaxy



- Population of ultra-luminous X-ray sources (ULX)
- Consistent with mid-mass black holes (in binaries) or with systems that are beaming directly at us (aka IXO)
- Brightest object is offset from the center of the galaxy, and is the brightest ULX seen to date.

Griffiths et al. 2000

The Constellation X-ray Mission



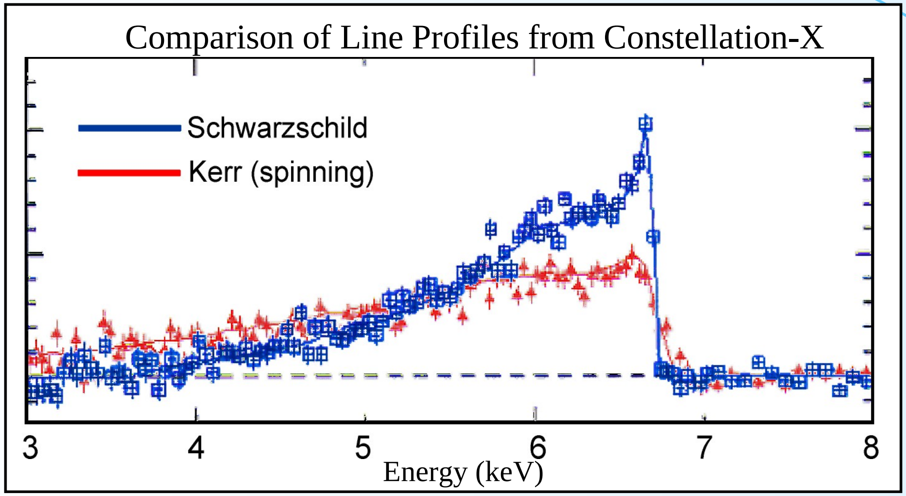
- Black holes:
  - Probing close to the event horizon
  - Evolution with redshift
- Dark side of the universe
  - Clusters of galaxies
- Production & recycling of the elements
  - Supernovae & interstellar medium

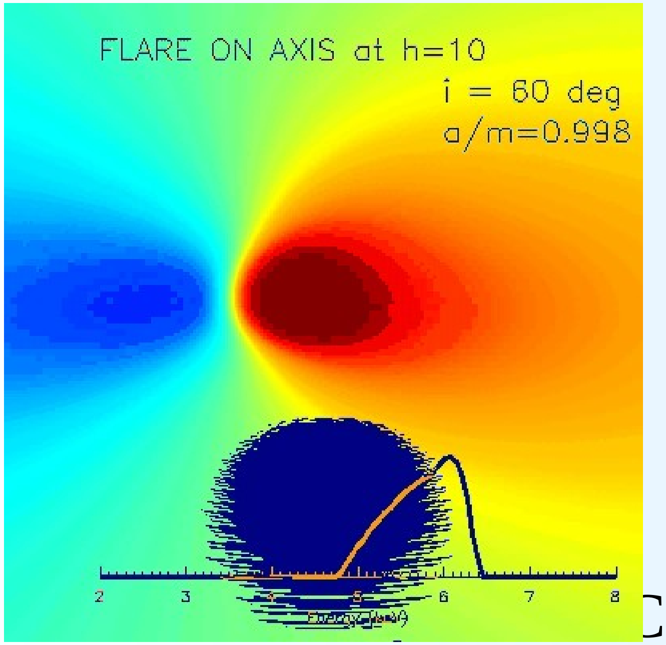
Mission parameters:

- 25-100 times sensitivity gain for high resolution spectroscopy
- 100 times more sensitive in the hard X-ray band at 40 keV

Endorsed by NAS McKee-Taylor Survey as 2nd priority large mission

BH Mass and Spin using Iron K Line

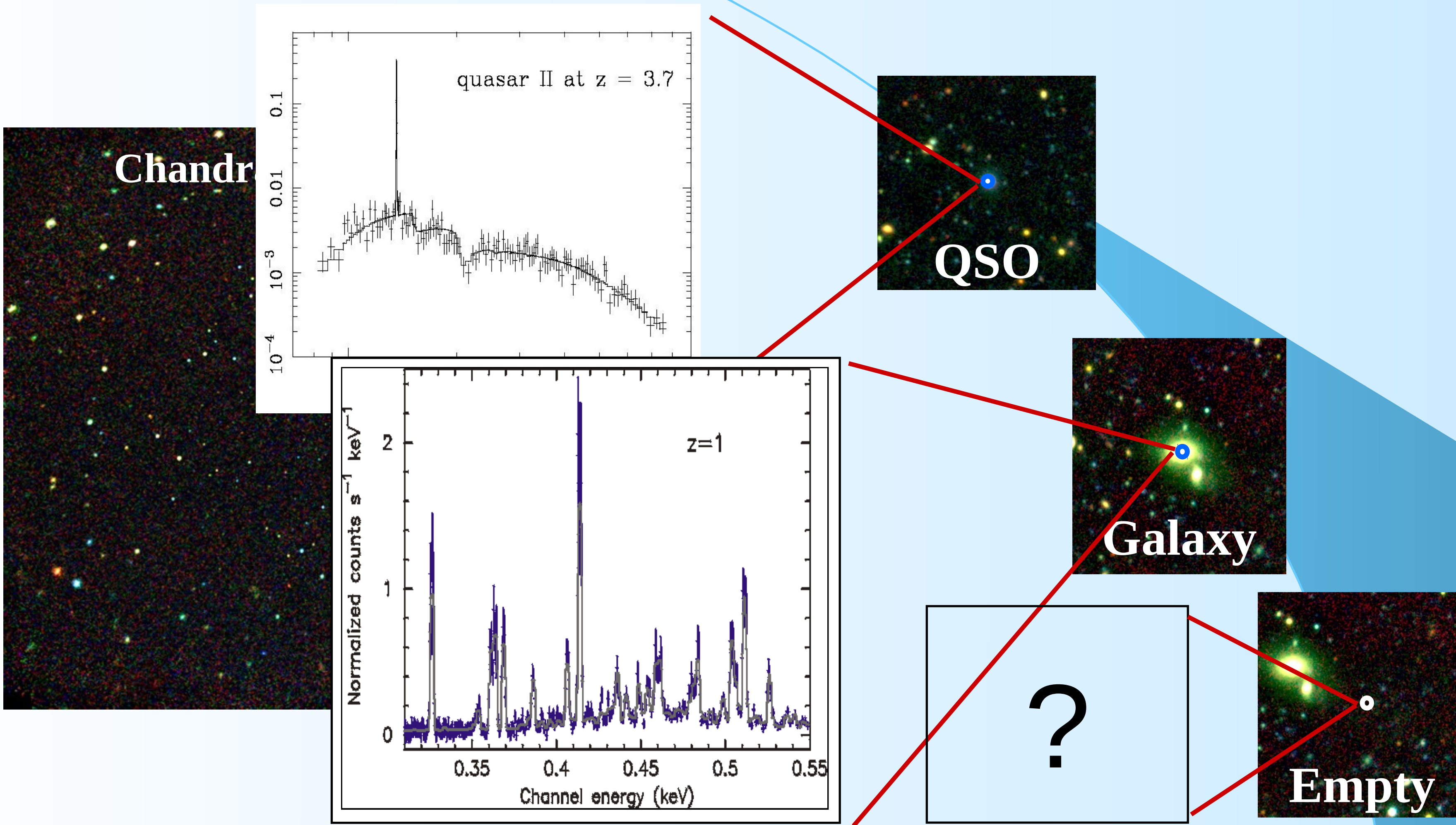




- Spin from the line profiles
- Mass from the time-linked intensity changes for line and continuum emission
- Reconstruct via deconvolution of the line profile "images" of inner disk

Constellation-X will probe close to the event horizon with 100 times better sensitivity than before

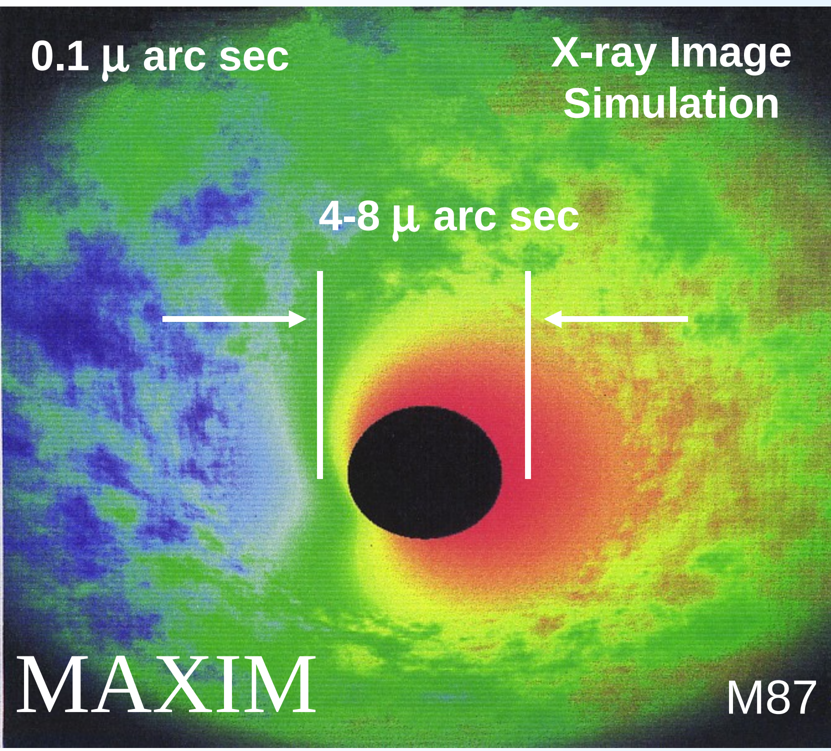
Black Hole Evolution

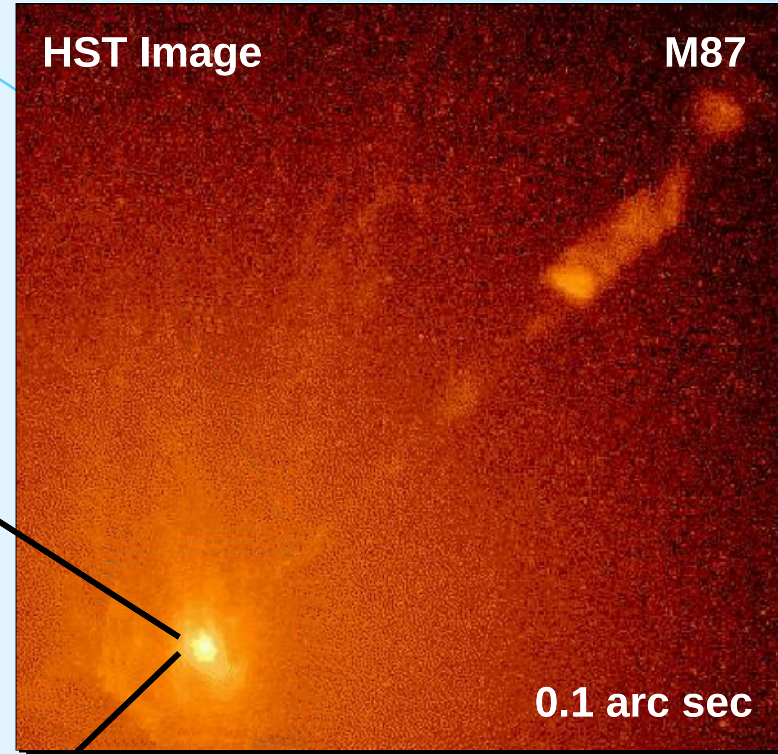


MAXIM: MicroArcsecond X-ray Imaging Mission

Goal: direct image of a black hole event horizon

Requires 0.1-1μ arc second imaging





X-ray interferometry

- Baseline of 20 m at 1 Å for 1 μ arc second
- 1-10 million times higher resolution than Chandra!

Summary

- Detailed X-ray observations of black holes have provided precise measurements of physical parameters for these compact objects.
- General relativistic effects are being observed and are yielding information about the metric.
- Future observations may be able to test predictions of GR in strongest possible gravitational fields and…..

Image a black hole!

For more information:

- http://www-glast.sonoma.edu/~lynnc/presentations.html (see SLAC Summer Institute 1998)
- http://chandra.harvard.edu
- http://journeys.gsfc.nasa.gov
- http://constellation.gsfc.nasa.gov
- http://maxim.gsfc.nasa.gov
- X-ray Binaries by W. Lewin, J. van Paradijs and E. van den Heuvel (1995, XRB)