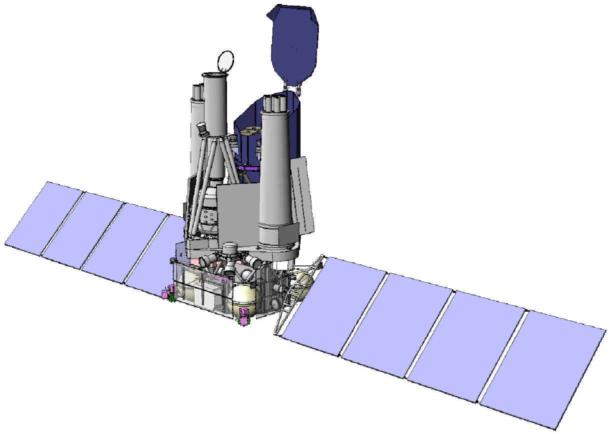
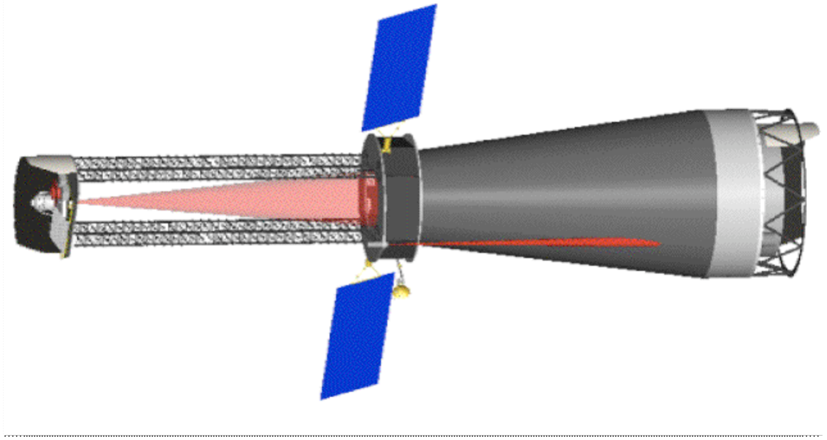
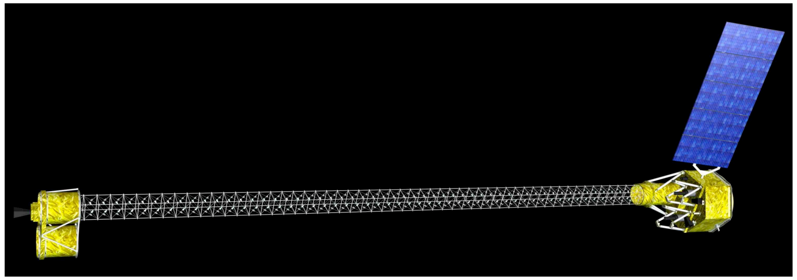


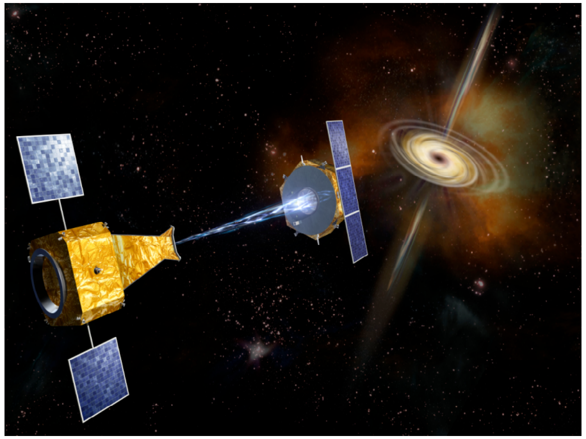


Future of High Energy Astrophysics

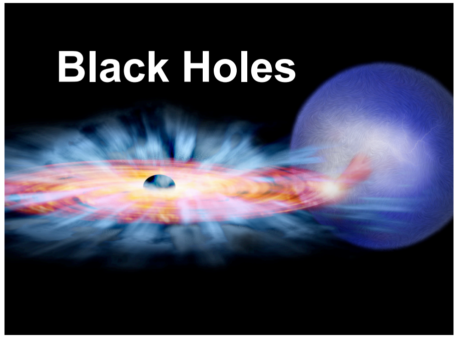
Nicholas White

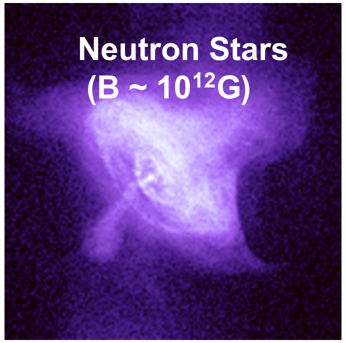
NASA GSFC

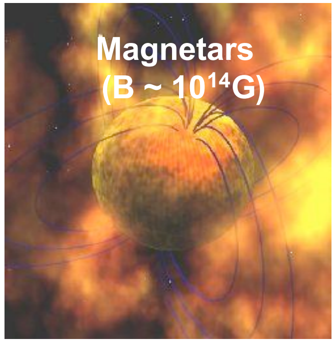


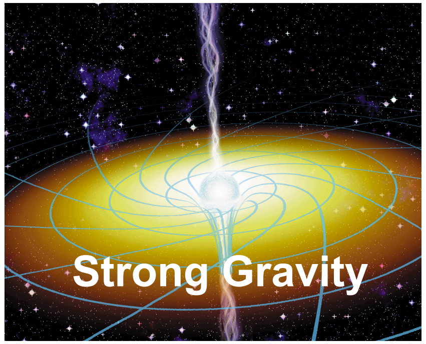


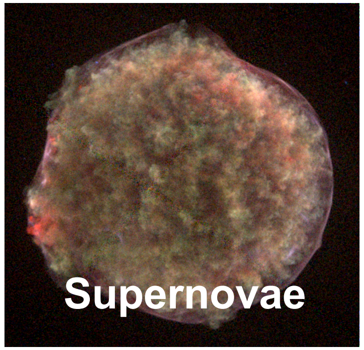
X-ray emission probes the physics of extreme processes, places and events





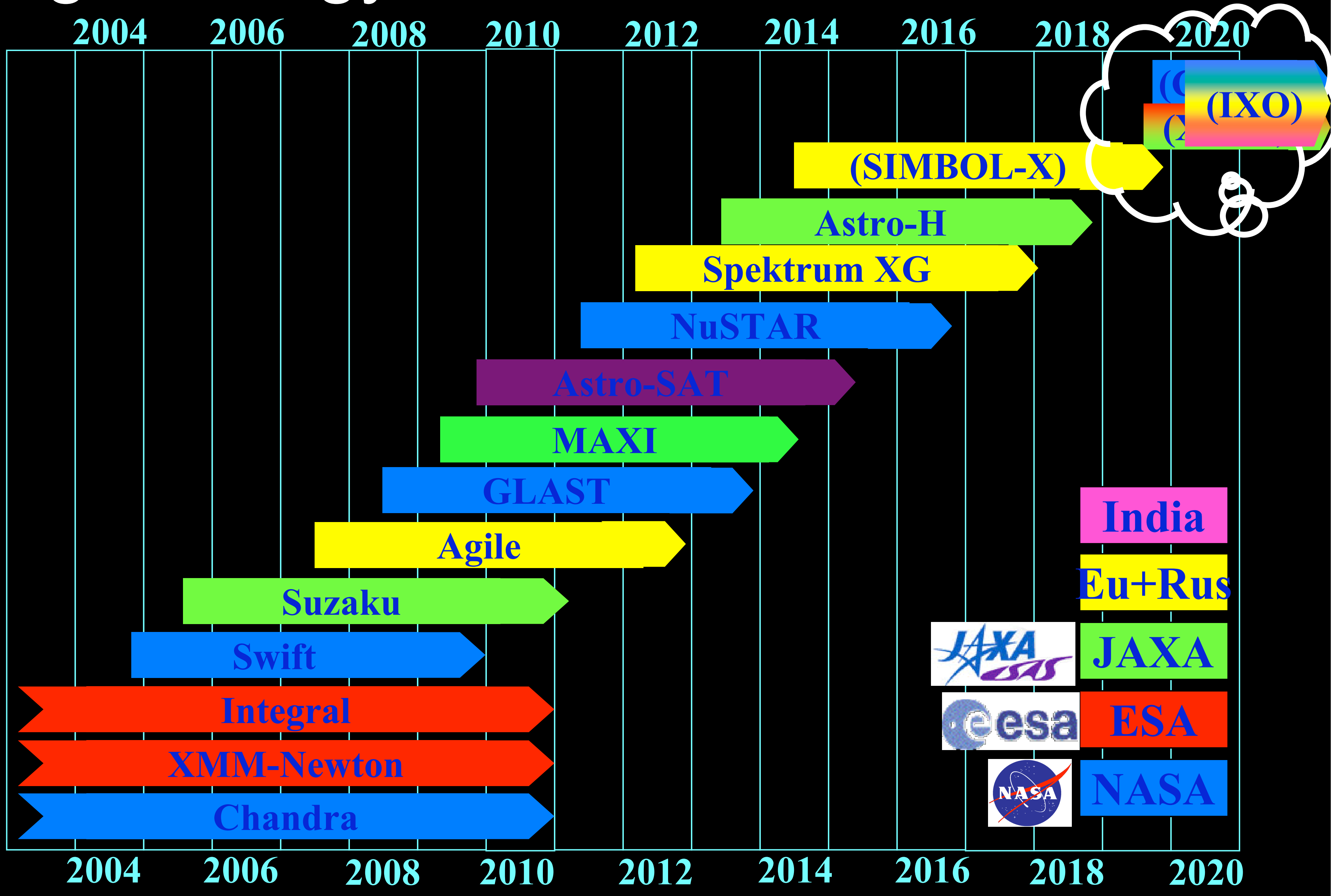


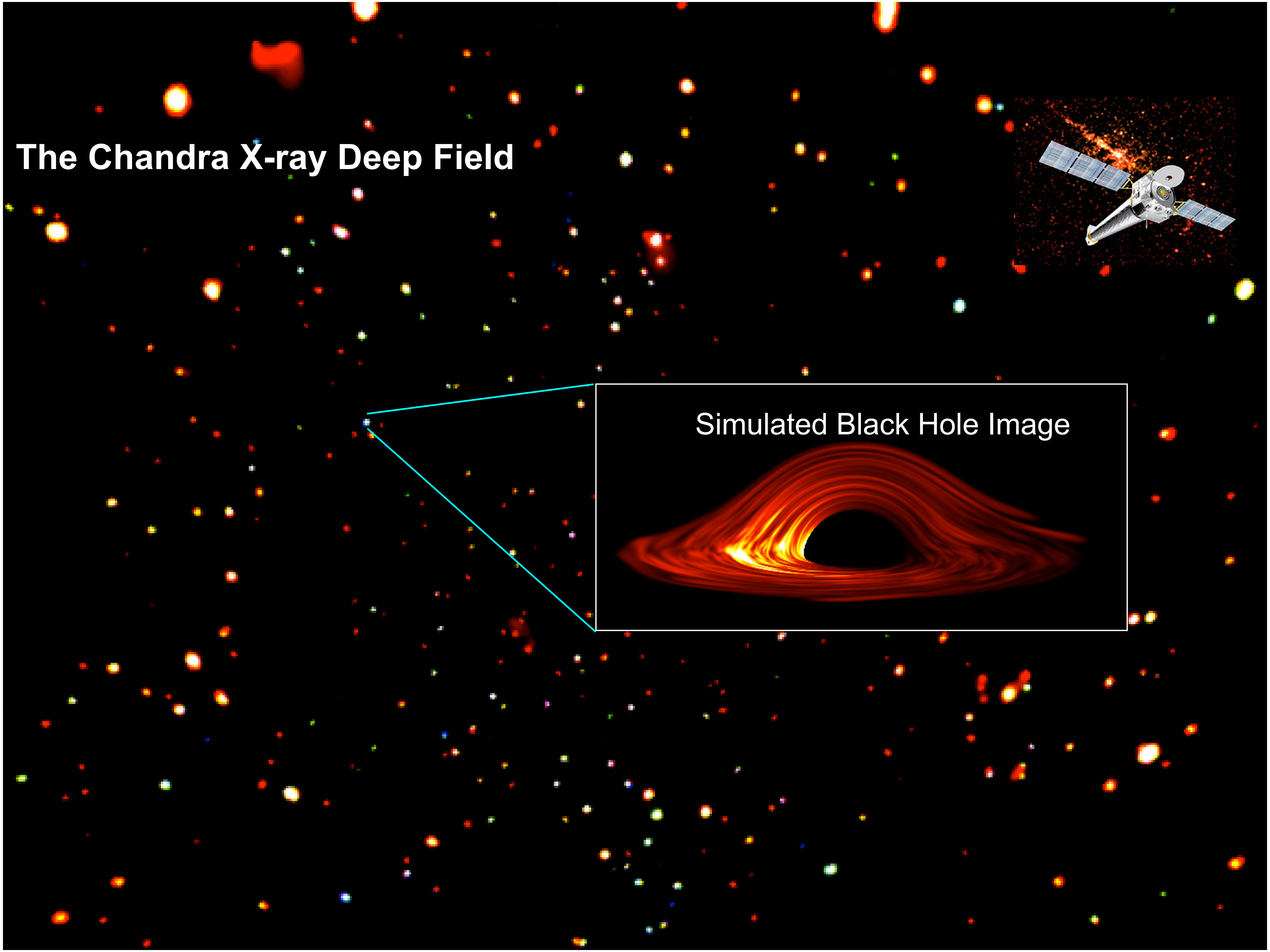




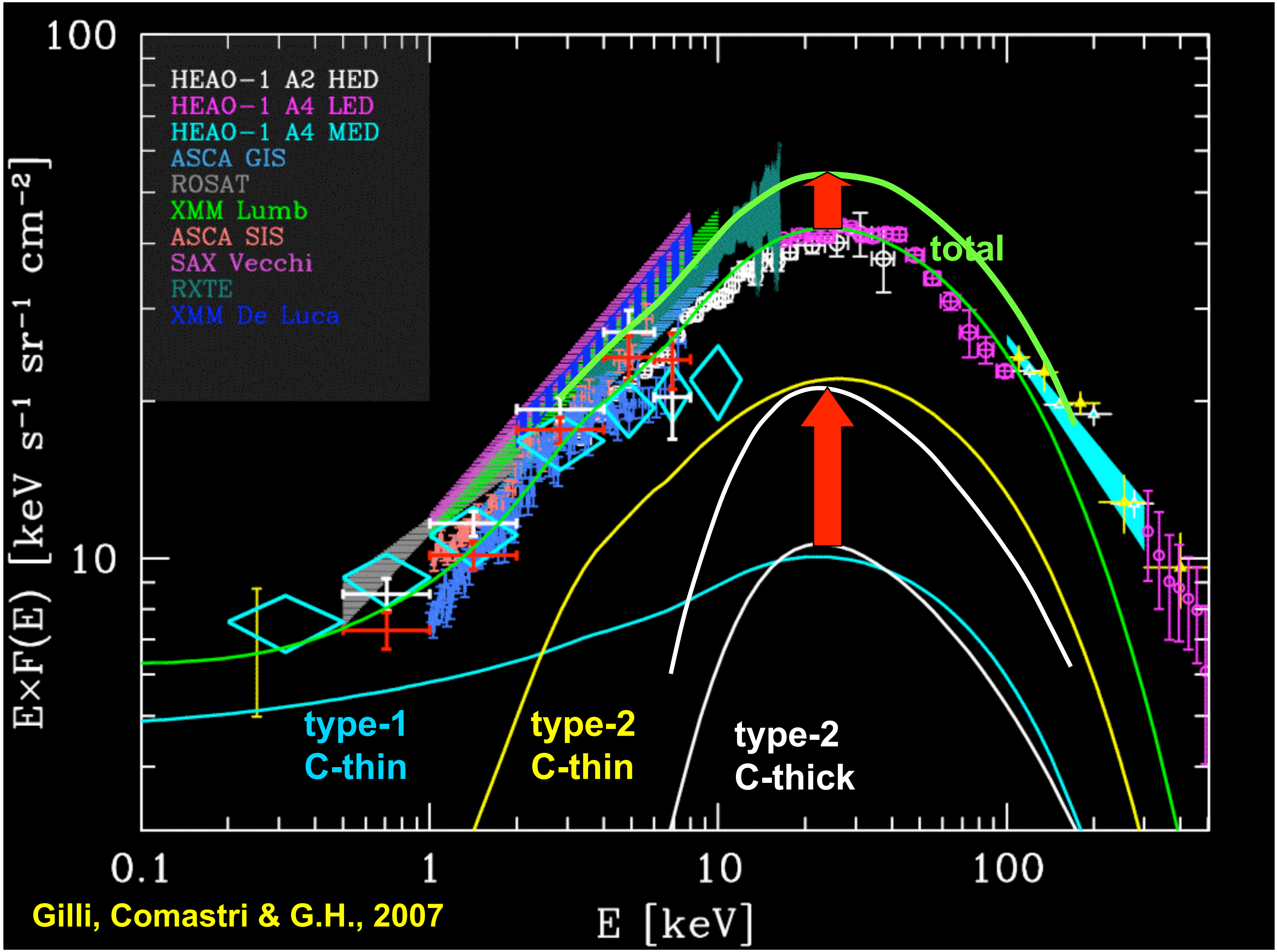
- **High temperatures, intense gravity, strong magnetic fields — explosions, collisions, shocks, and collapsed objects**
- **Conditions not achievable in earth-bound labs or accelerators**
- **X-ray observations can only be made from space**

High-Energy Observatories 2004-2022



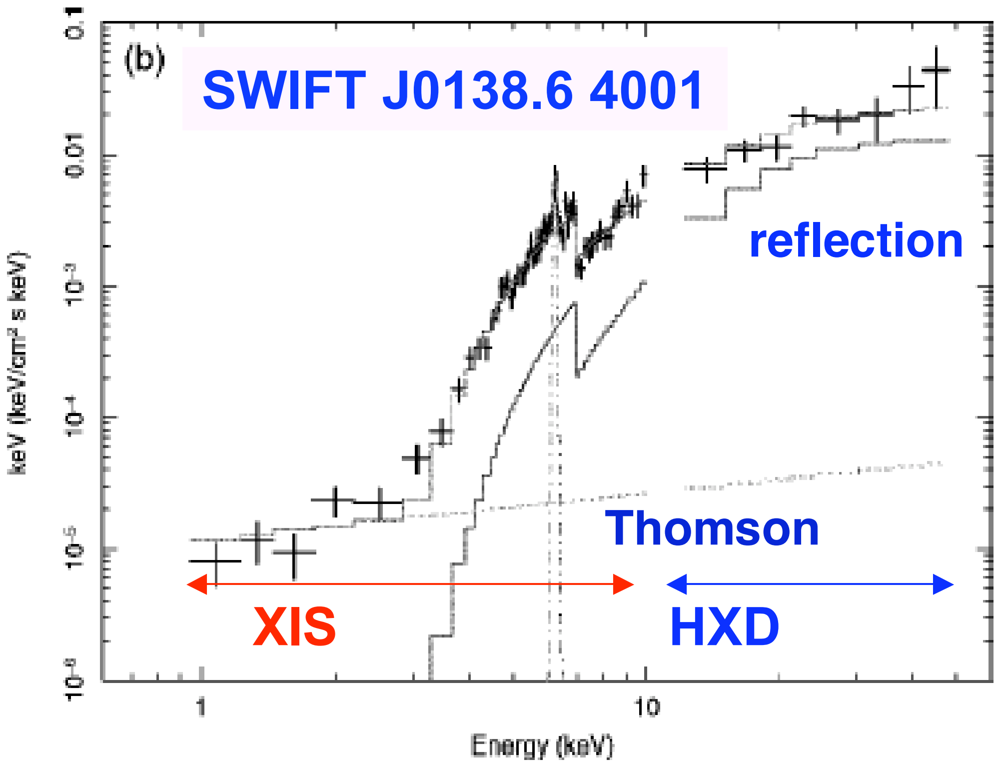

The Chandra X-ray Deep Field
Simulated Black Hole Image

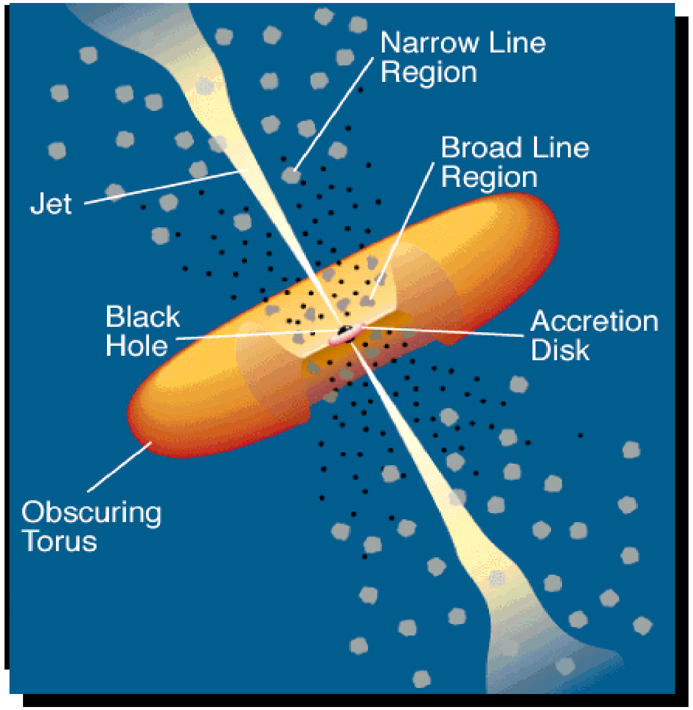
X-ray Background Spectrum



Energetics and Evolution of Black Holes in AGN

Most Black Holes at the center of galaxies are thought to be hidden behind an inner thick torus of material

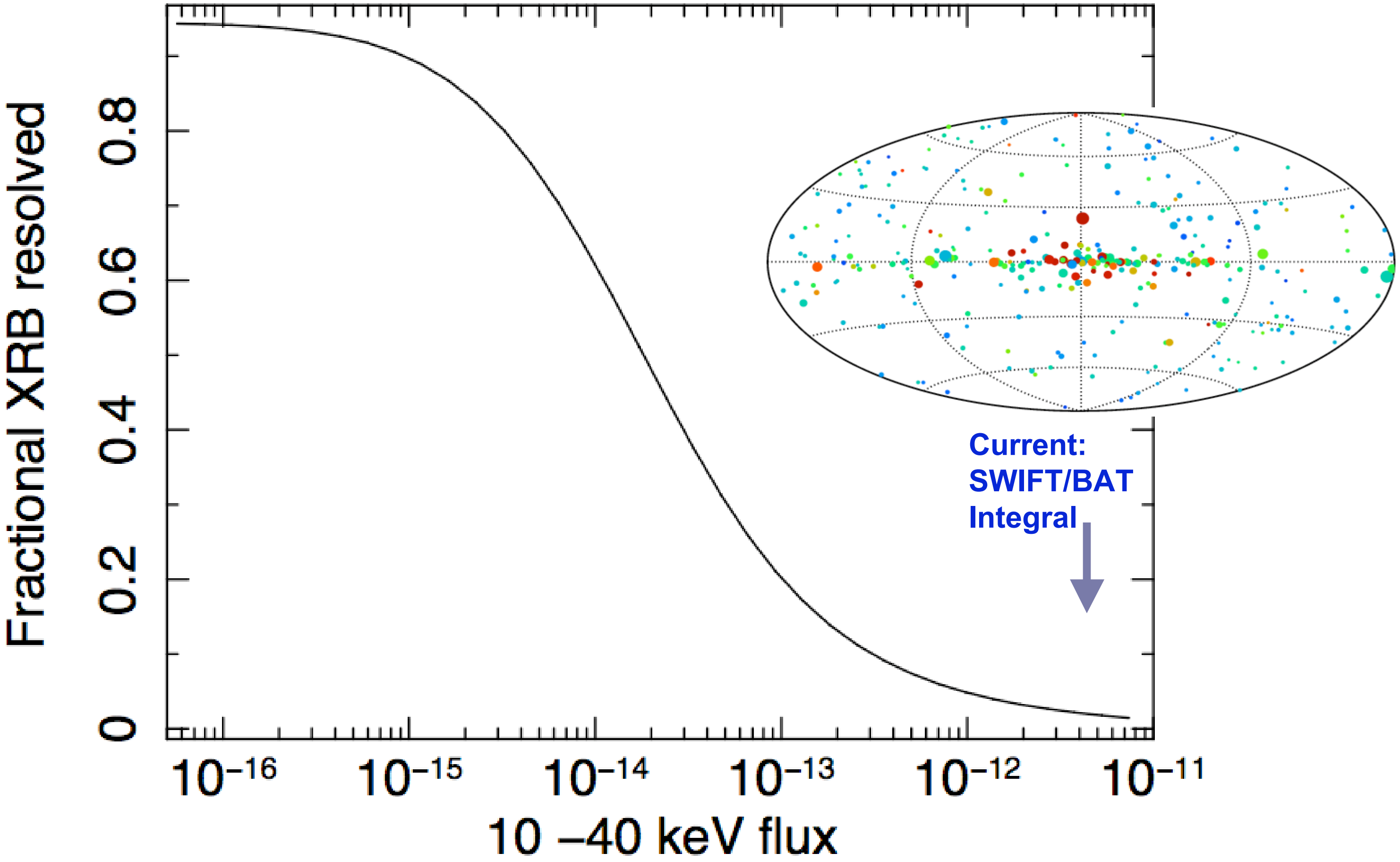




Hard X-rays can penetrate this torus above 10 keV and be seen as a very absorbed source, Swift is detecting the very brightest of these

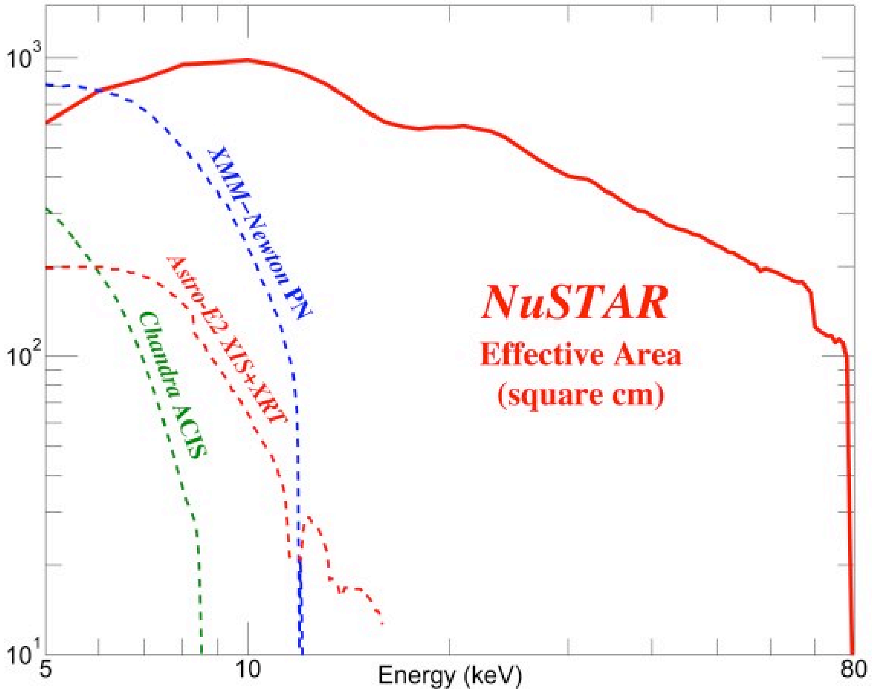
Overall geometry is not known, and is critical to understand the hard X-ray background and constrain the evolution of black holes

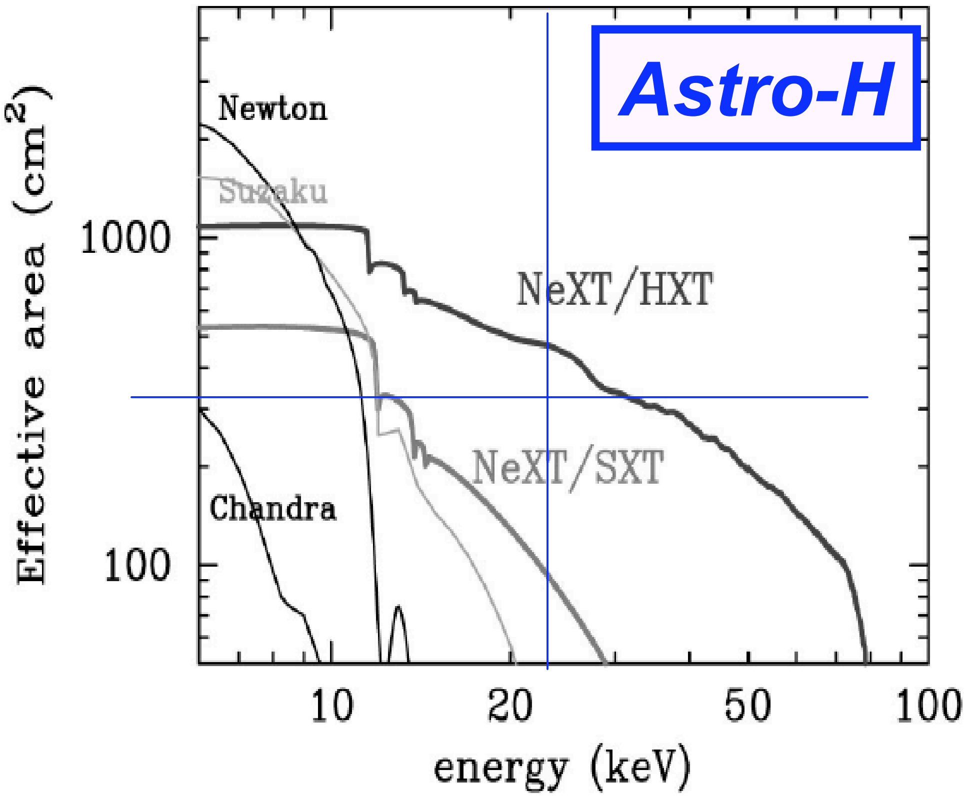
Resolving the 10-40 keV X-ray Background



Requires two order of magnitude improved sensitivity

Multilayer Hard X-ray Telescopes



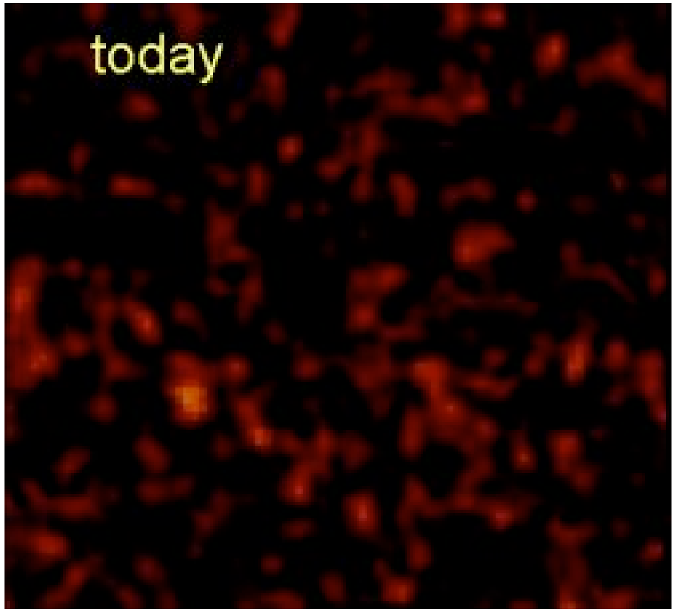


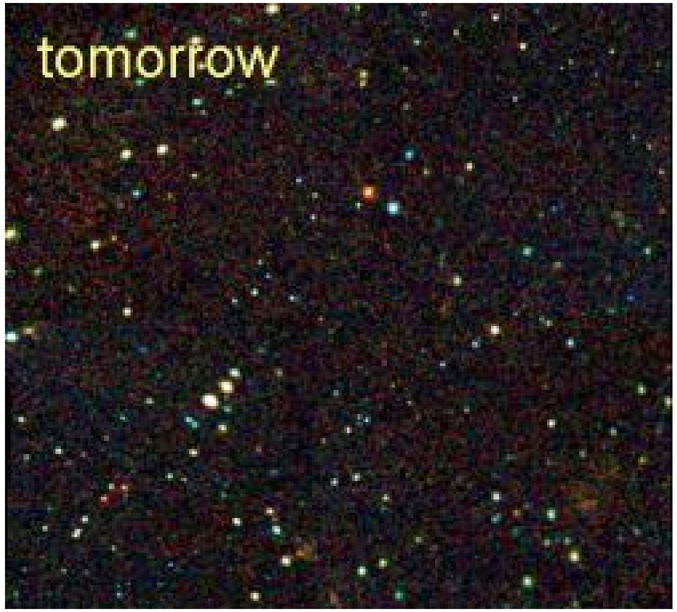
New technology that will open up the hard X-ray band by bringing focused imaging to increase sensitivity by several orders of magnitude

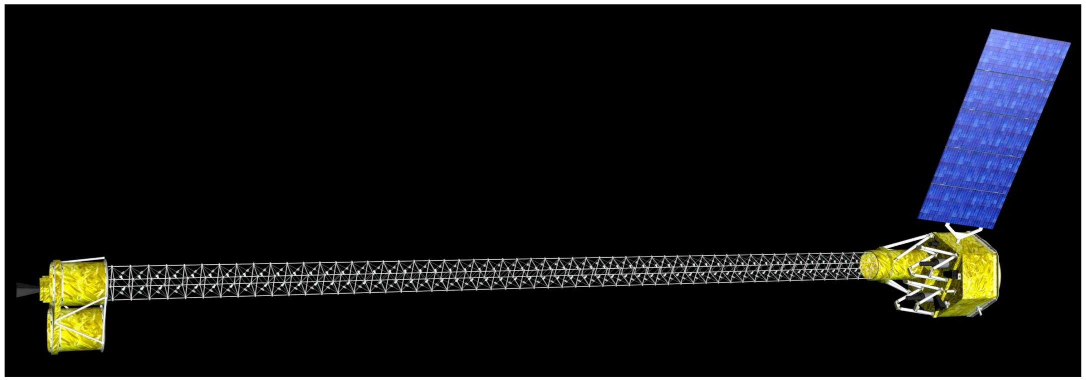
NuStar – Hard X-ray Imaging/Survey

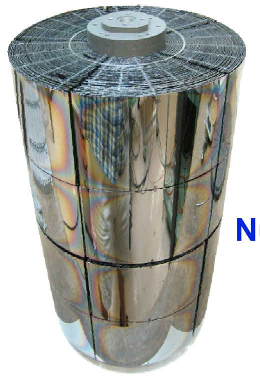
2011

Hard X-ray imaging ~ 40 arc sec to resolve the 40 keV background

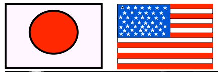


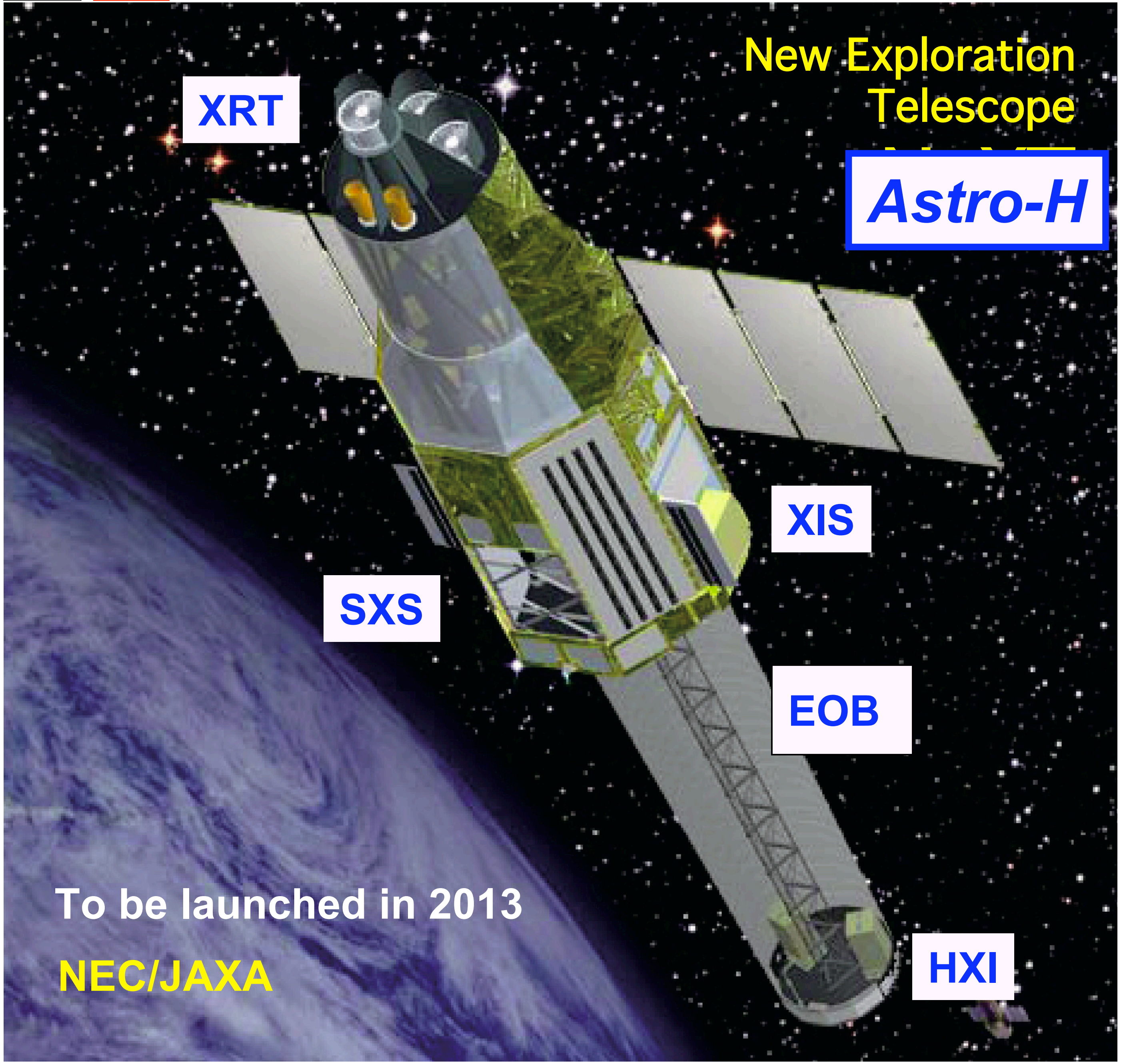






NuSTAR optic

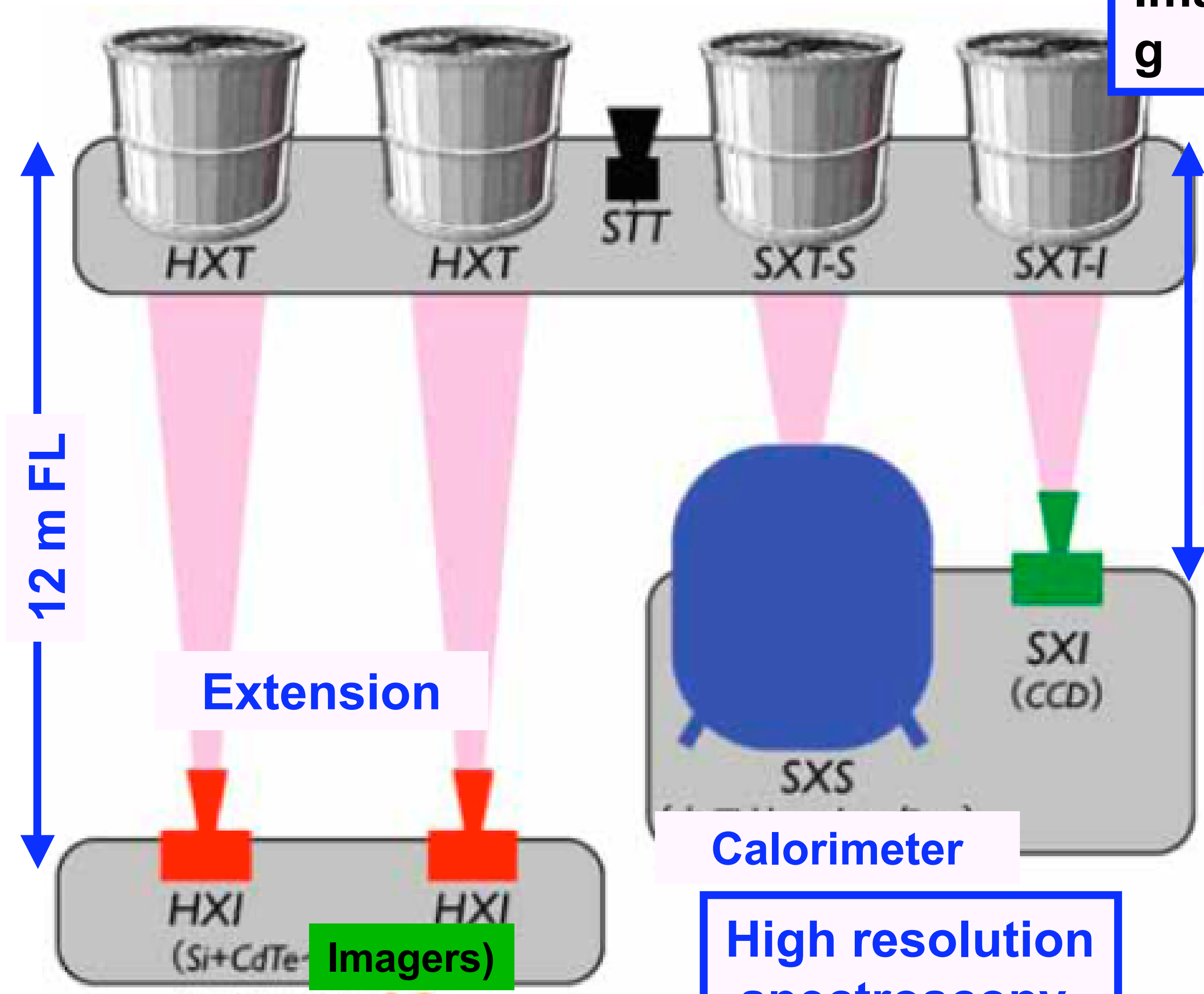



New Exploration
Telescope
Astro-H
XRT
XIS
SXS
EOB
HXI
To be launched in 2013
NEC/JAXA

Astro-H Concept

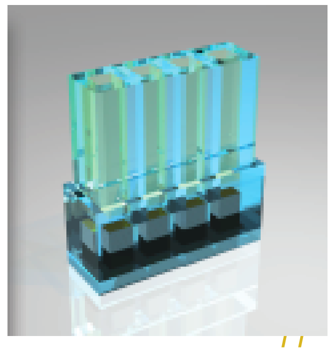
Hard X-ray Imaging ~ 1 arc min

Soft X-ray Imaging



Soft _-ray Detectors

High resolution spectroscopy



Simbol-X

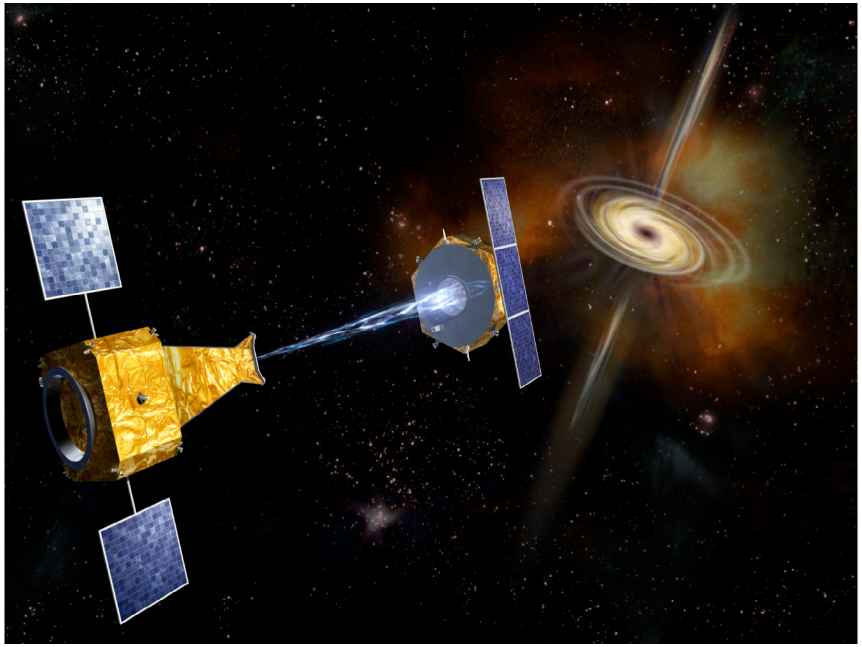
Formation Flying with focal length 20m

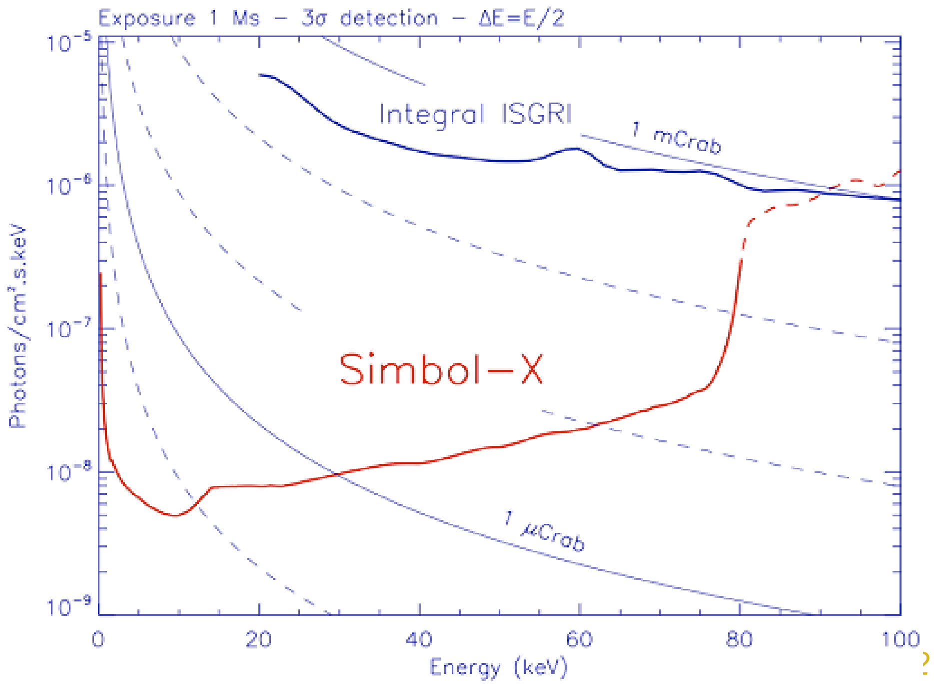
Mirror: XMM-type (20 arc sec)

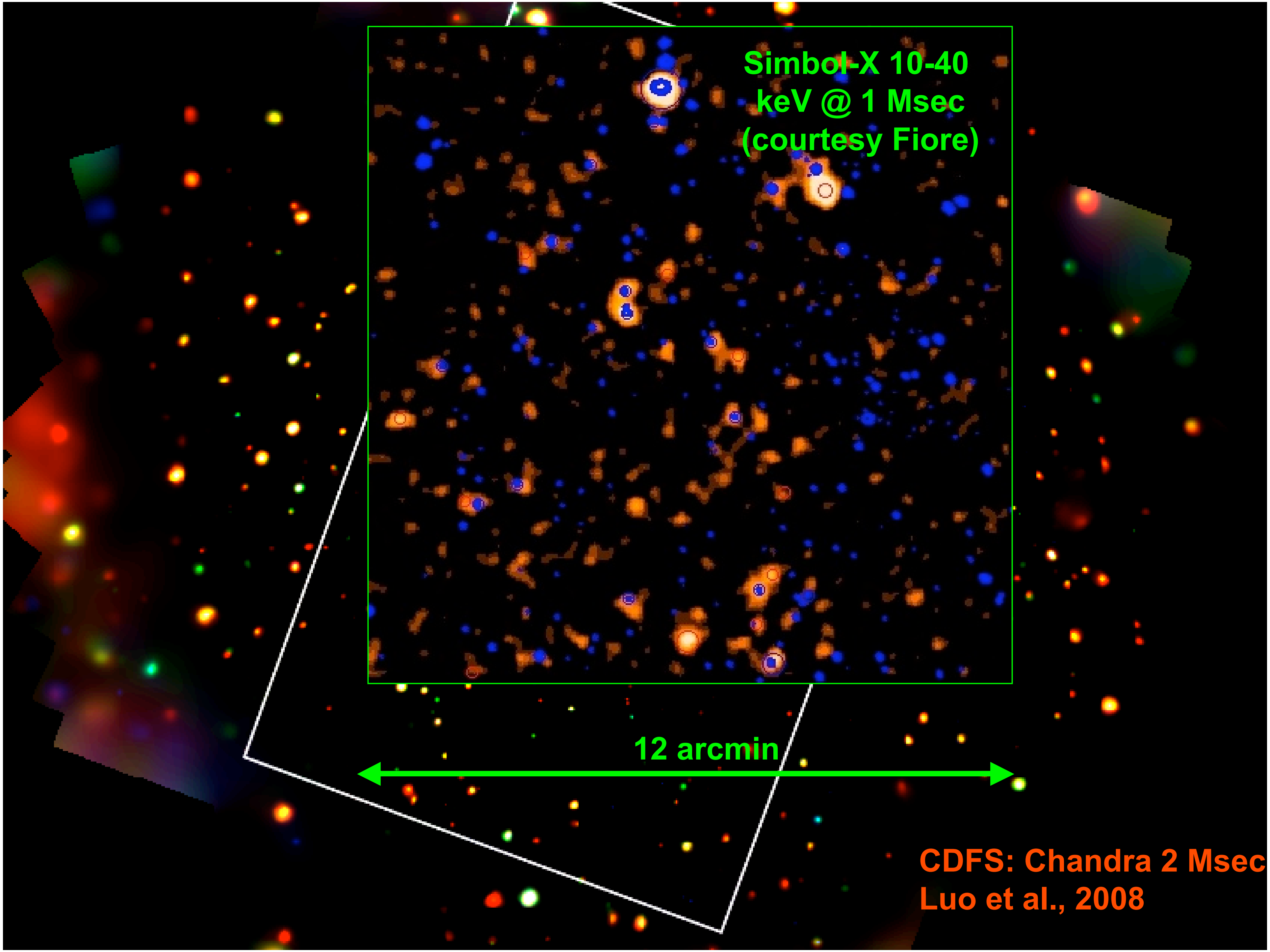
Detector: DEPFET/CdZnTe Sandwich

Collaboration between France (detector spacecraft, HE focal plane), Italy (mirror spacecraft, mirrors) & Germany (LE focal plane detector, mirror test, calibration)

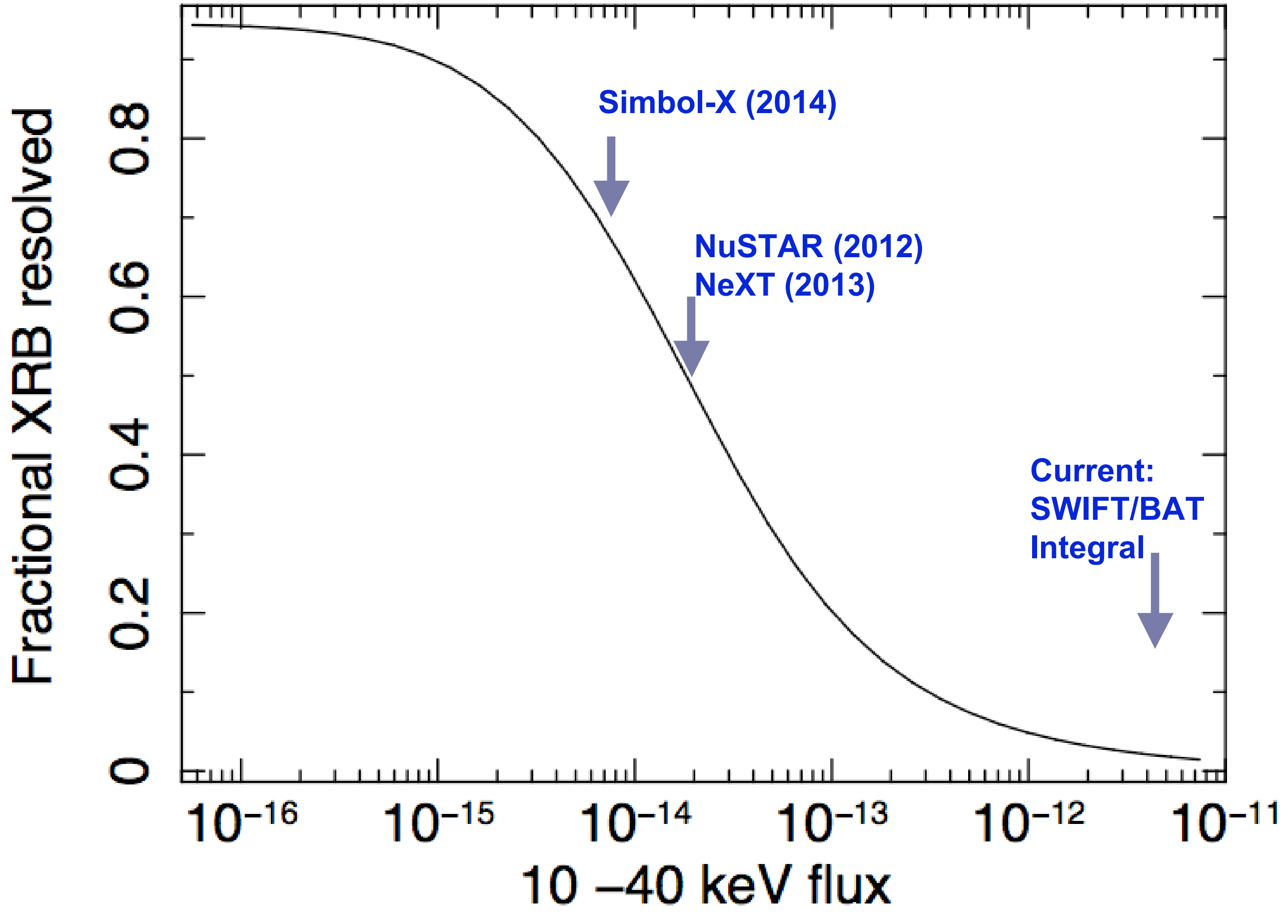
Proposed for 2014





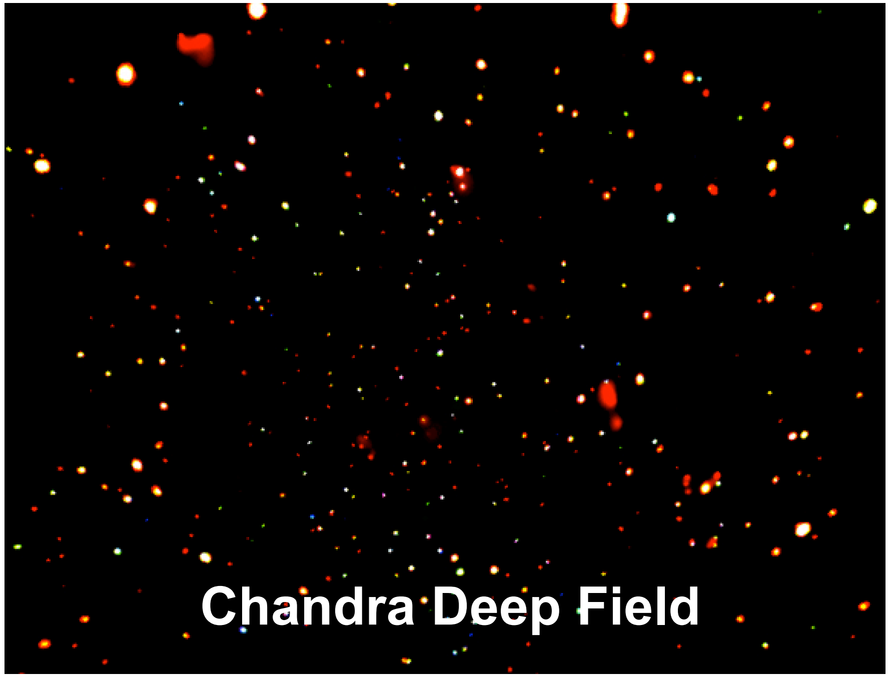

Simbol-X 10-40
keV @ 1 Msec
(courtesy Fiore)
12 arcmin
CDFS: Chandra 2 Msec
Luo et al., 2008

Resolving the 10-40 keV X-ray Background



IXO The International X-ray Observatory

The missions formerly known as Con-X and XEUS



Chandra and XMM-Newton provide our deepest view of the X-ray Universe, revealing a rich diversity of sources

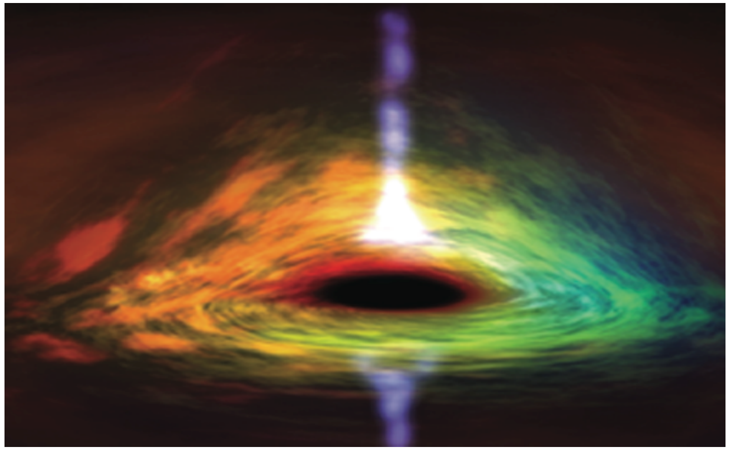
Most X-ray spectra currently available have moderate resolution CCD spectra E/ΔE < 30, insufficient for diagnostics routinely available in other wavebands

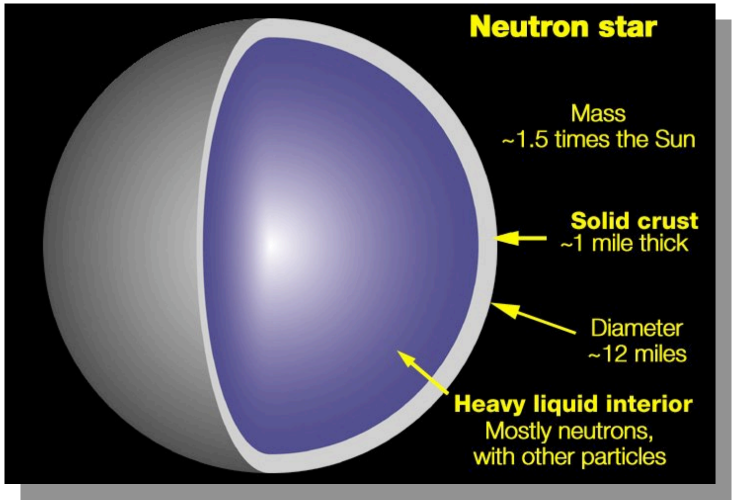
The X-ray band is rich in diagnostic features for the elements with atomic number from Carbon through to Zinc

IXO will be a facility that provides a factor of 10-100 increase in effective area with high spectral resolution and deep imaging to open a new era in X-ray astronomy:

- **Telescope area: ~ 3 m^2 @ 1 keV, ~ 1 m^2 @ 6 keV, ~ 0.07 m^2 @ 40 keV**
- **Angular resolution of ~ 5 arc sec or better**
- **Spectral resolution (E/ΔE) of ~ 1250-2400 (over 0.5 to 7 keV)**
- **FOV of ~ 5 arc min or better**

IXO I. Black Holes and Matter under Extreme Conditions



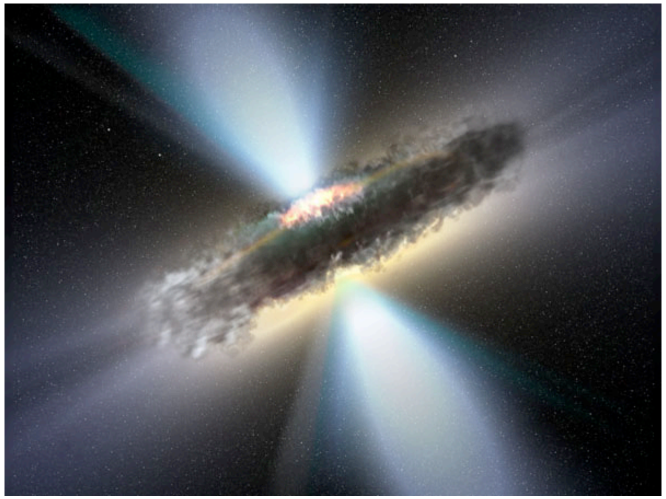


How do super-massive Black Holes grow and evolve?

Does matter orbiting close to a Black Hole event horizon follow the predictions of General Relativity?

What is the Equation of State of matter in Neutron Stars?

IXO II. Galaxy Formation, Galaxy Clusters and Cosmic Feedback

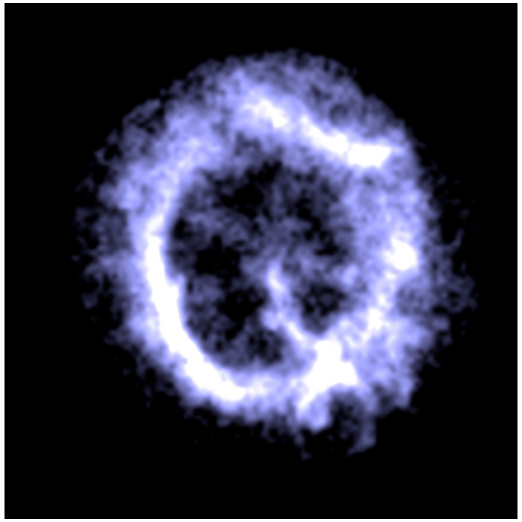


How does Cosmic Feedback work and influence galaxy formation?

How does galaxy cluster evolution constrain the nature of Dark Matter and Dark Energy?

Where are the missing baryons in the nearby Universe?

IXO III. Life Cycles of Matter and Energy



When and how were the elements created and dispersed?

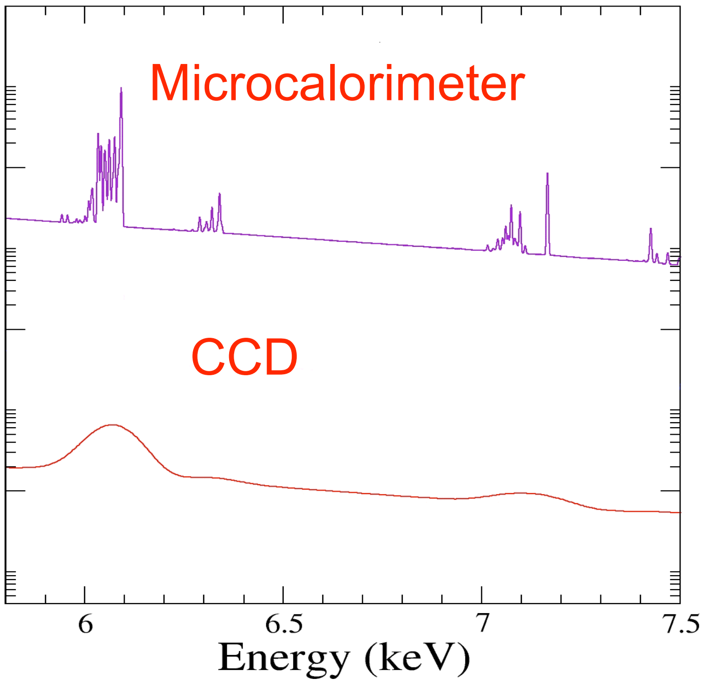
How do high energy processes affect planetary formation and habitability?

How do magnetic fields shape stellar exteriors and the surrounding environment?

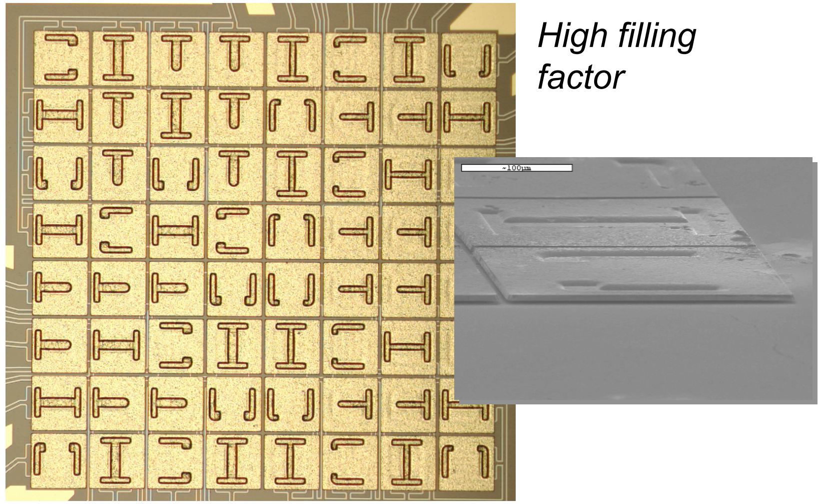
How are particles accelerated to extreme energies producing shocks, jets and cosmic rays?

X-ray Micro-calorimeter Spectrometer (XMS)

- X-ray microcalorimeter: thermal detection of individual X-ray photons
  - High spectral resolution
  - ΔE very nearly constant with E
  - High intrinsic quantum efficiency
  - Non-dispersive — spectral resolution not affected by source angular size



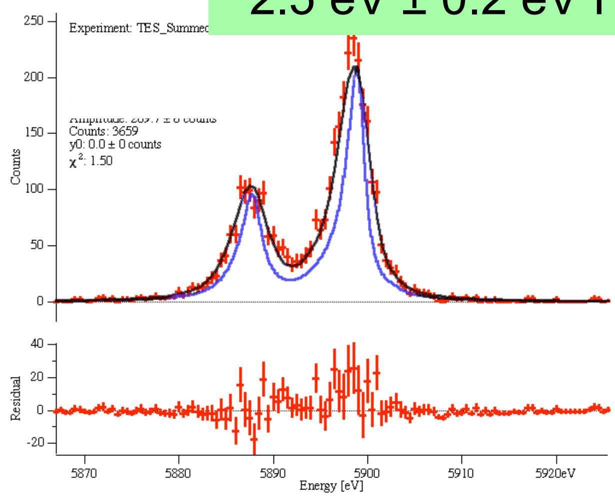
Arrays under development and approaching goal of 2 eV at 6 keV.



High filling factor

8x8 development Transition Edge Sensor array with 250 μm pixels

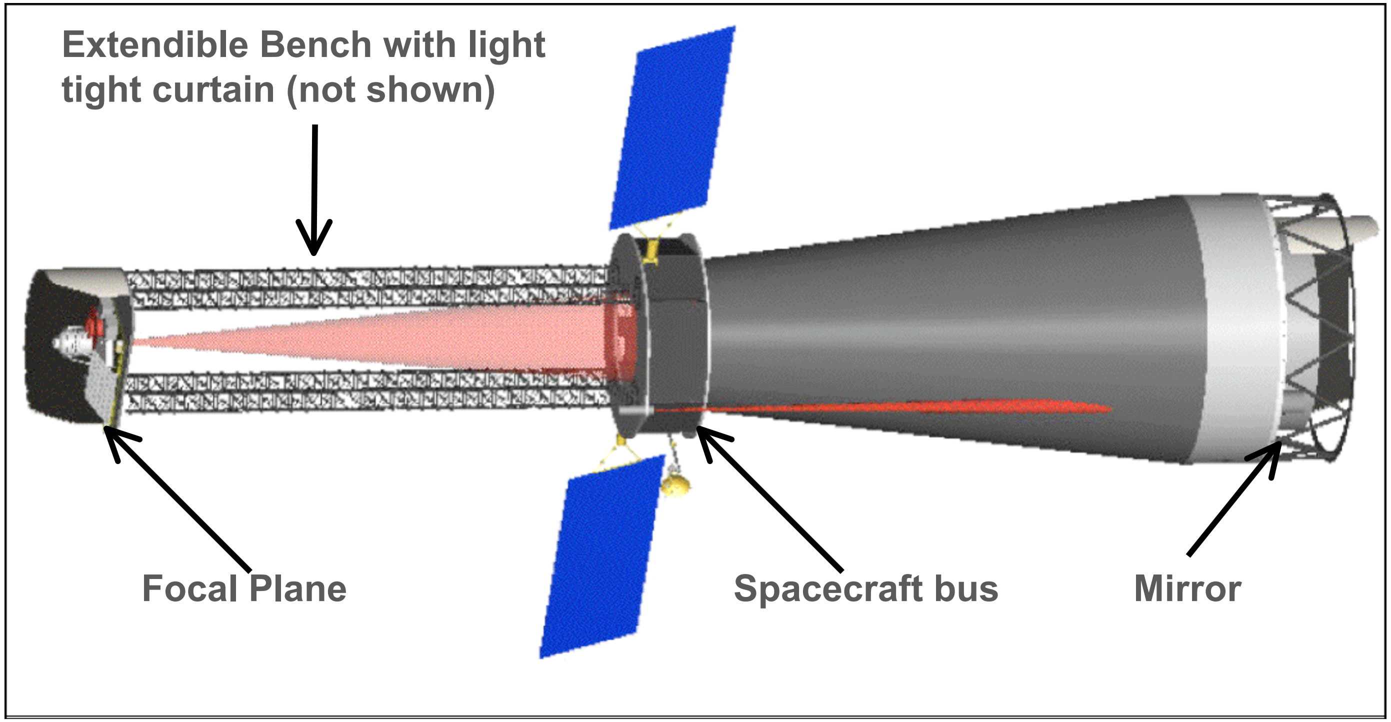
2.5 eV ± 0.2 eV FWHM



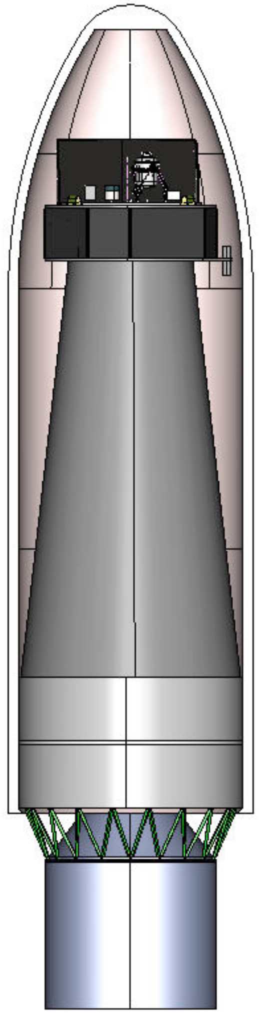
IXO: Baseline ESA-JAXA-NASA Concept

- Focal length of 20-25m with extendible optical bench
- Concept must accommodate both glass (NASA) and silicon (ESA) optics technology (with final select at appropriate time)
- Core instruments to include:
  - X-ray Micro-calorimeter/Narrow Field Imager
  - Wide Field Imager
  - X-ray Grating Spectrometer
  - Allocation for further modest payload elements
- Concept compatible with Ariane V and Atlas V 551

IXO Mission Concept

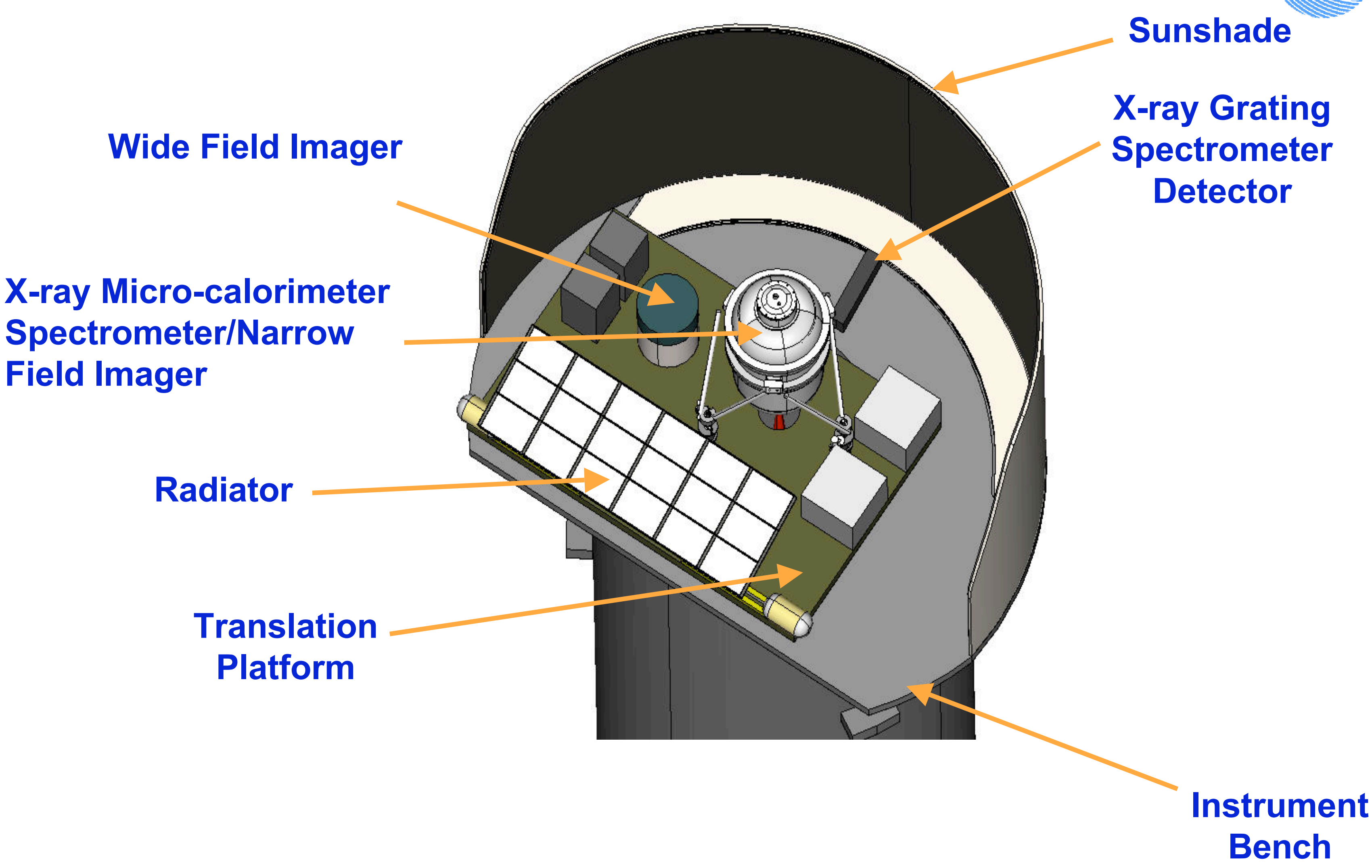


- L2 Orbit; 700,000 km radius halo orbit
  - High operational efficiency
  - Uninterrupted viewing
  - Stable temperature
- 5 year life; 10 years or more consumables



IXO in Atlas V 551fairing

IXO Focal Plane Preliminary Layout

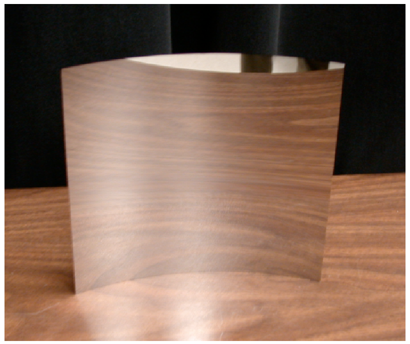


IXO

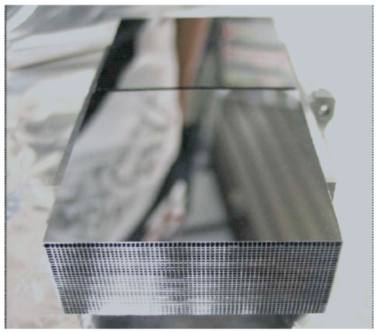
X-ray Mirror Baseline

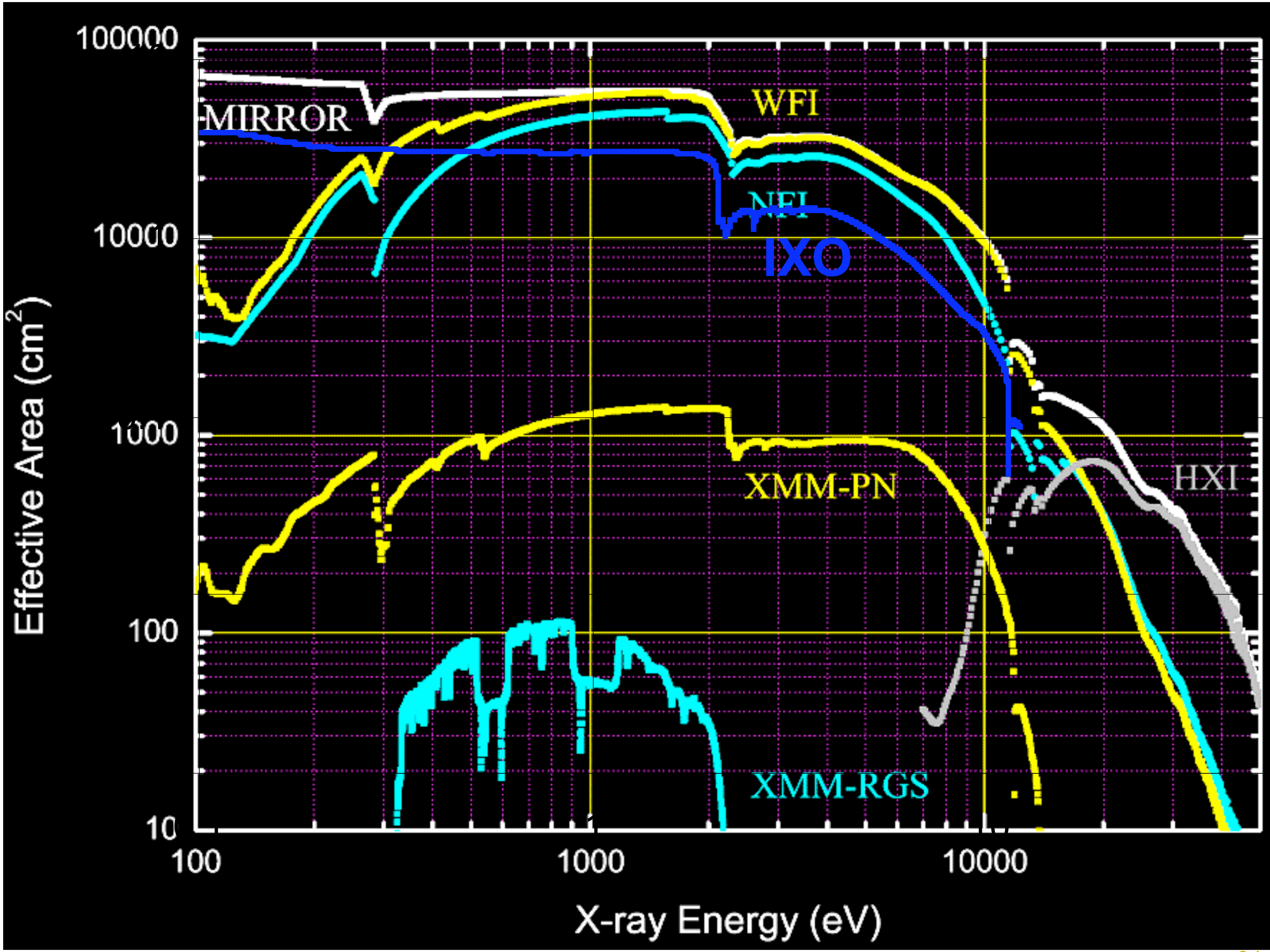
- Key requirements:
  - Effective area ~3 m^2 @ 1.25 keV ; ~1 m^2 @ 6 keV
  - Angular Resolution <= 5 arc se
- Single optic with design optimized to minimize mass and maximize the collecting area ~3.4m diameter
- Two parallel technology approaches being pursued
  - Silicon micro-pore optics – ESA
  - Slumped glass – NASA
- Both making good progress

Glass



Silicon

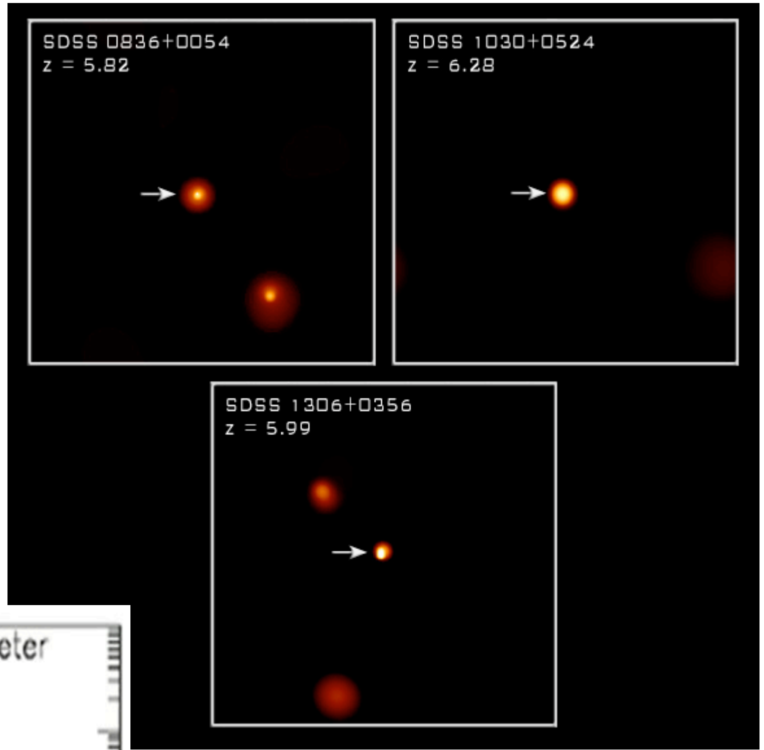


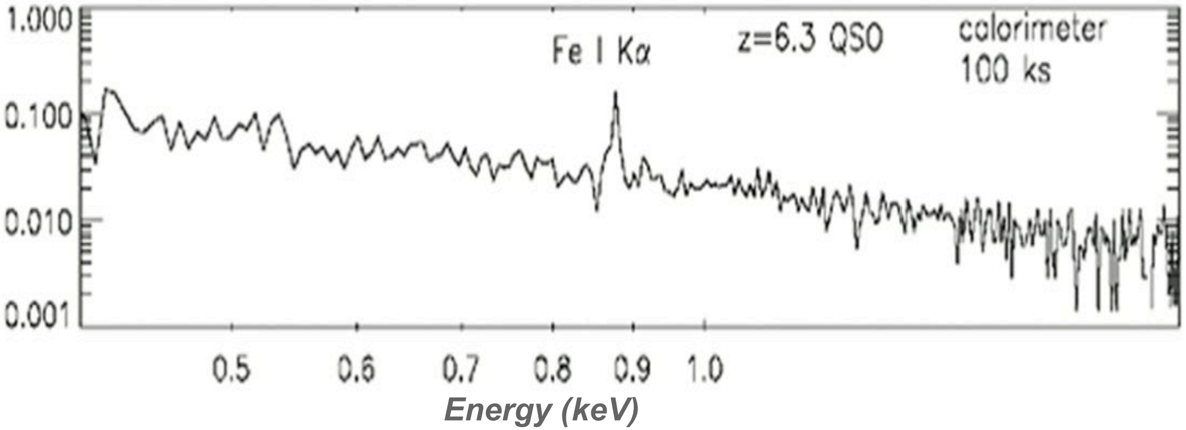

100000
10000
1000
100
10
100
1000
10000
Effective Area (cm^2)
X-ray Energy (eV)
MIRROR
WFI
NFI
IXO
XMM-PN
HXI
XMM-RGS

High Redshift Quasars

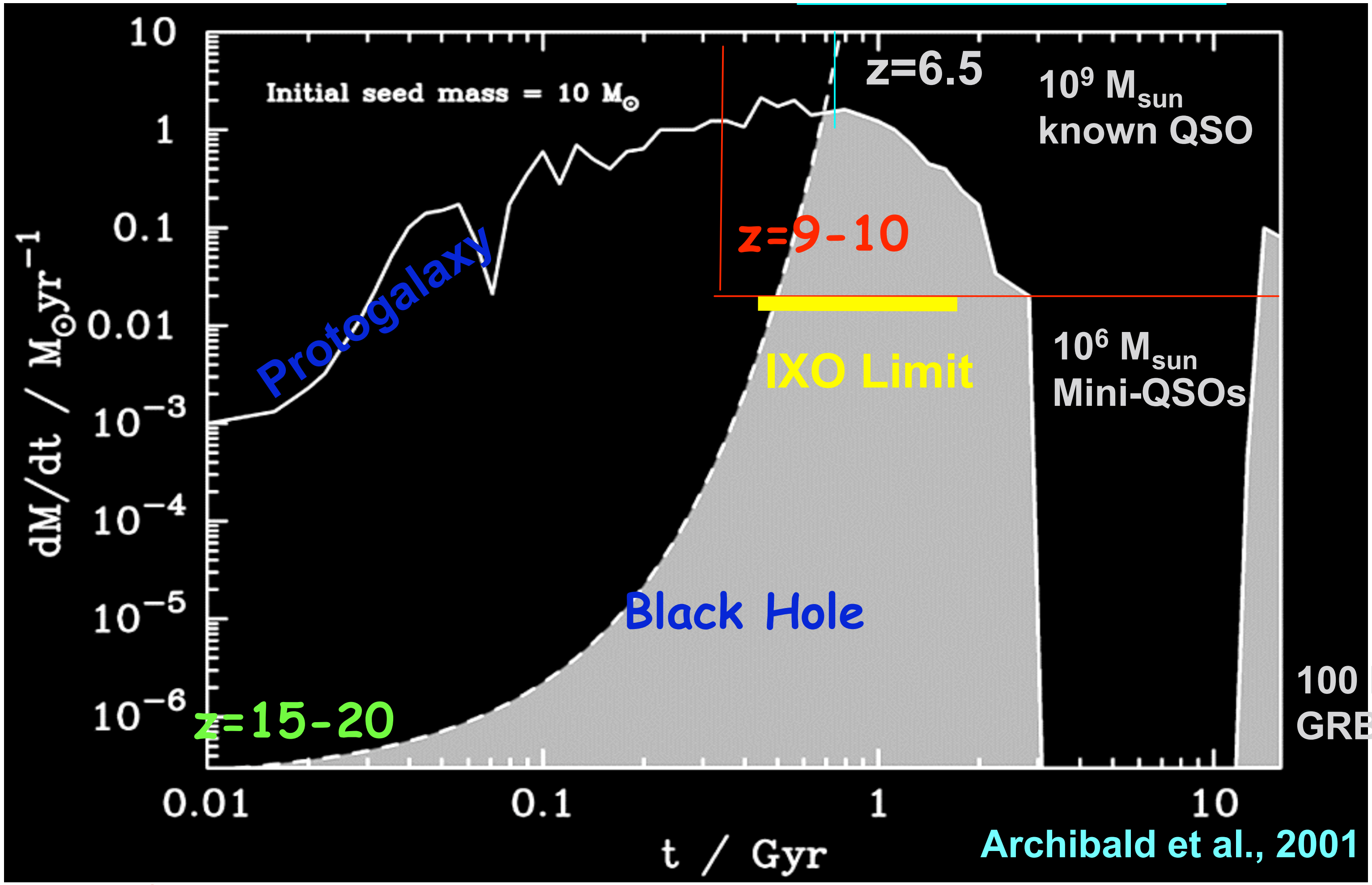
Chandra has detected X-ray emission from ~100 high redshift quasars at z > 4 (3 examples shown)

Flux is typically 2-10 x 10^{-15} erg cm^{-2} s^{-1} beyond grasp of XMM-Newton and Chandra high resolution spectrometers, but within the capabilities of IXO



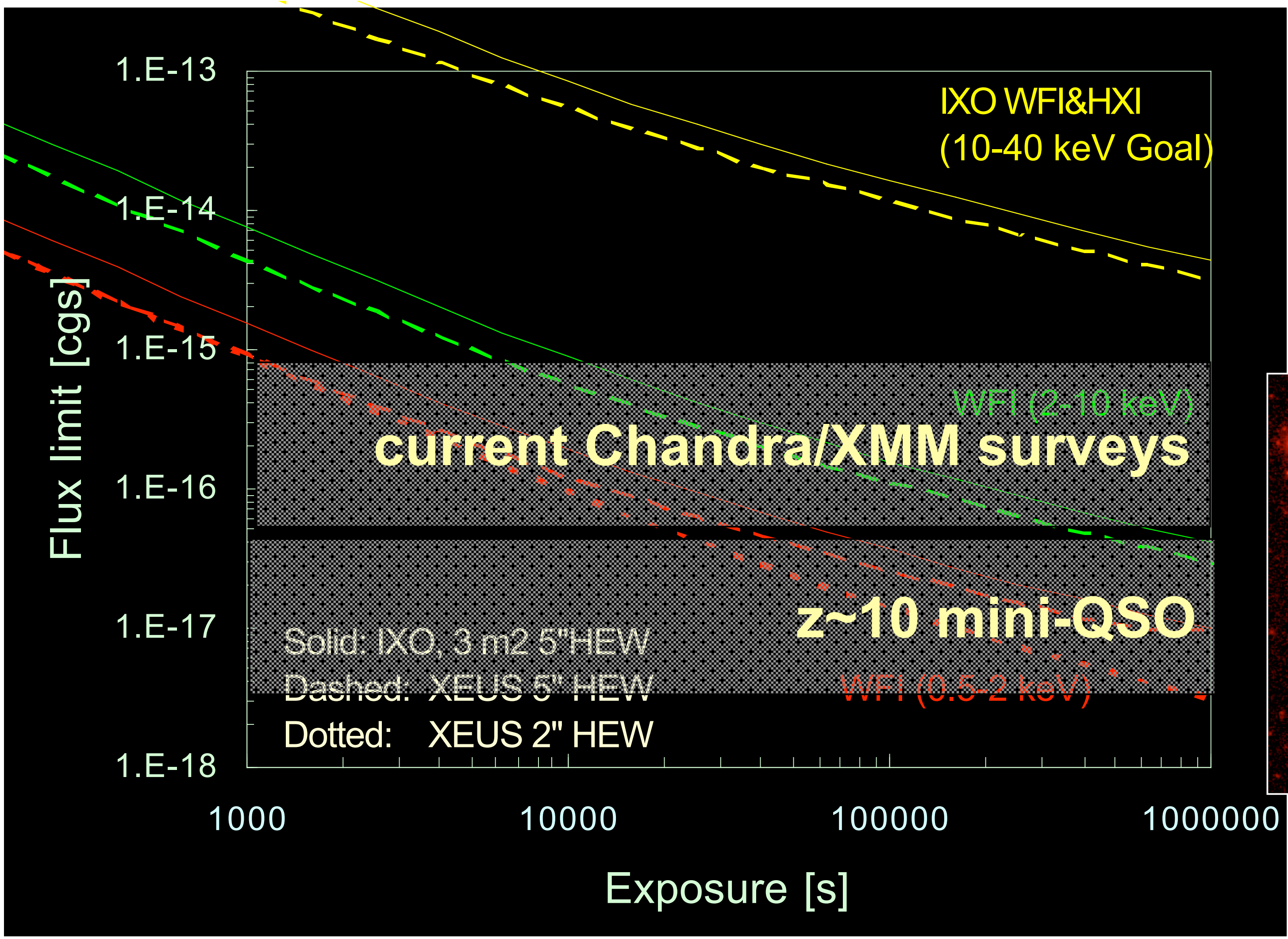


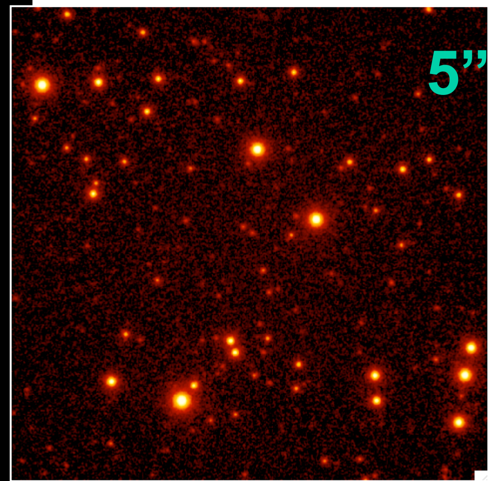
IXO First Black Holes



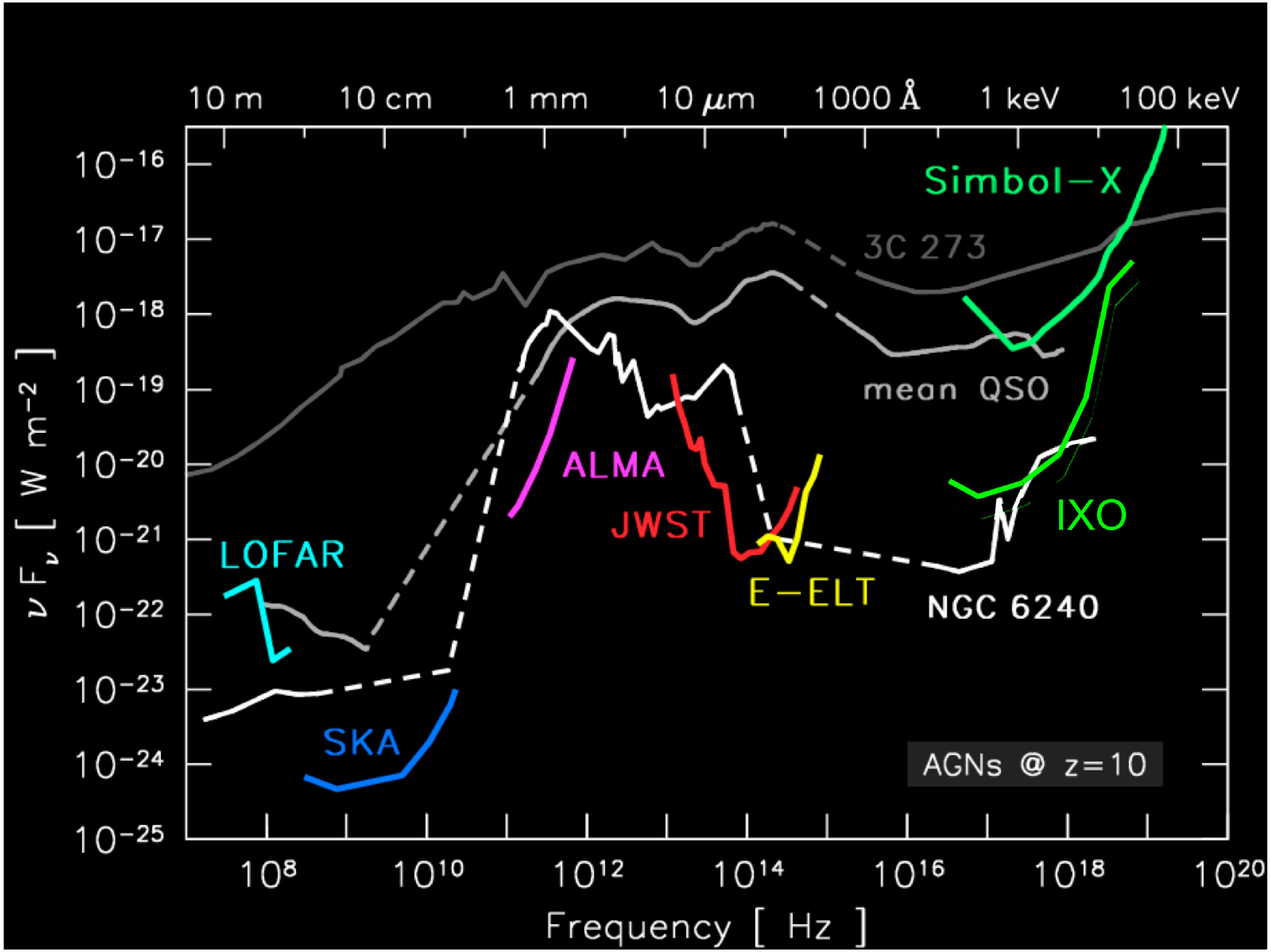
10^6 M_o @ redshift of 10 is detectable by IXO

IXO Mission Sensitivity



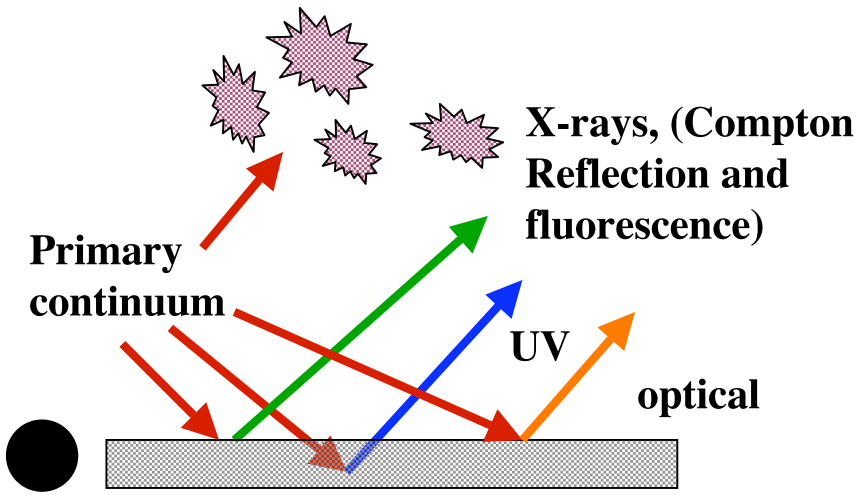


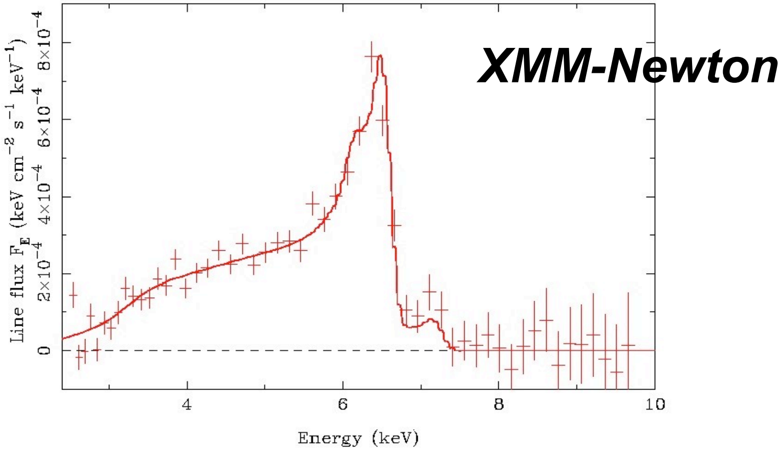
IXO Multi-λ Power of future facilities @ z=10

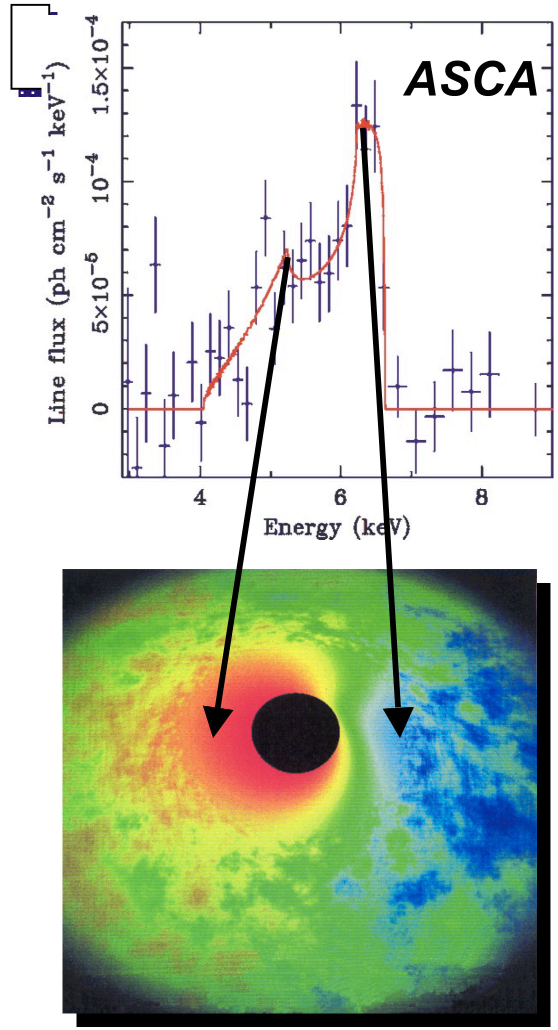


Black Holes, Accretion Disks and X-ray Reflection

The Iron fluorescence emission line is created when X-rays scatter and are absorbed in dense matter, close to the event horizon of the black hole.



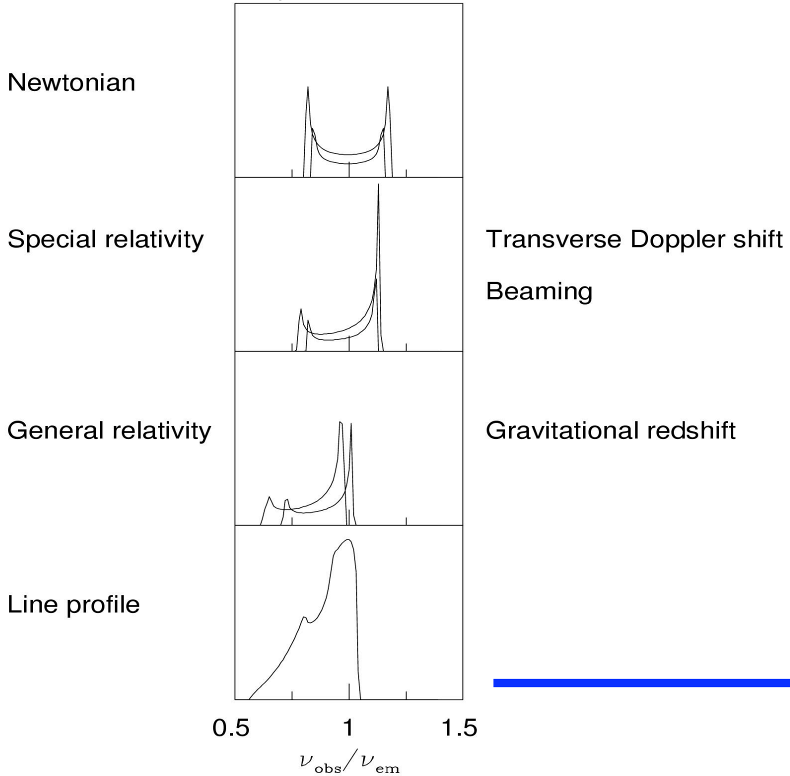


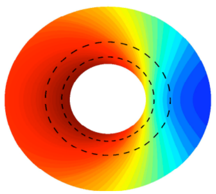


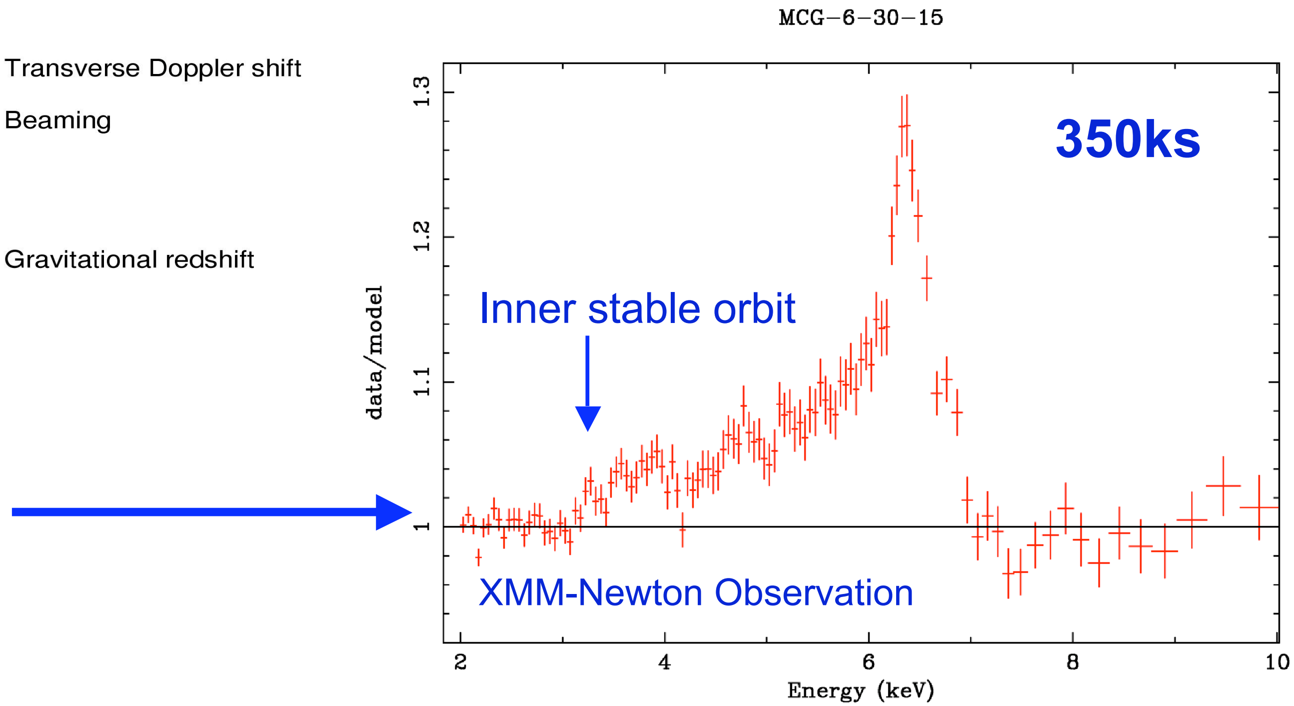
Theoretical 'image' of an accretion disk.

Black Hole Relativistic Iron K Lines

Fluorescent iron K line from an accretion disk close to the Black Hole event horizon reveals the redshift and broadening from the effects of *strong gravity* predicted by General Relativity

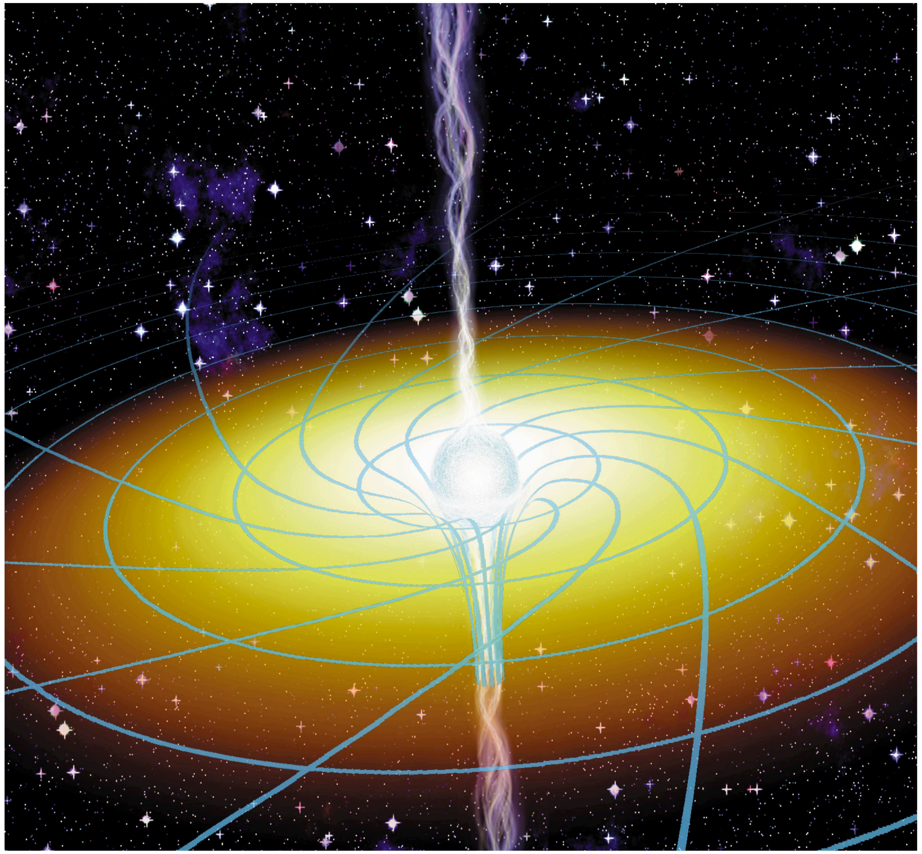


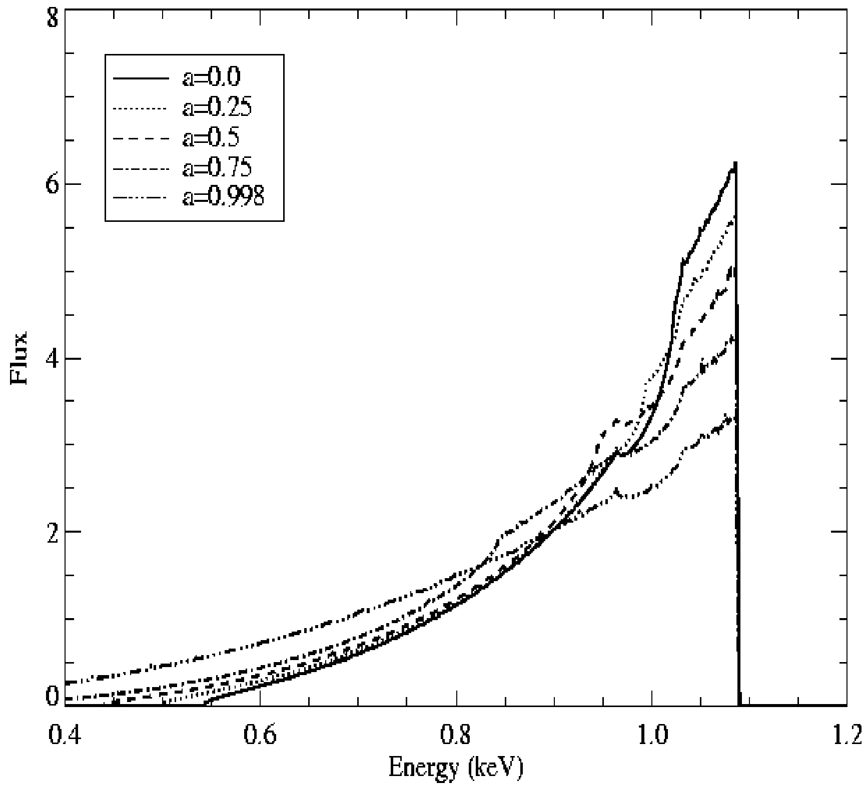




Fabian 1989, Laor 1990, Dovciak 2004, Beckwith & Done 2005

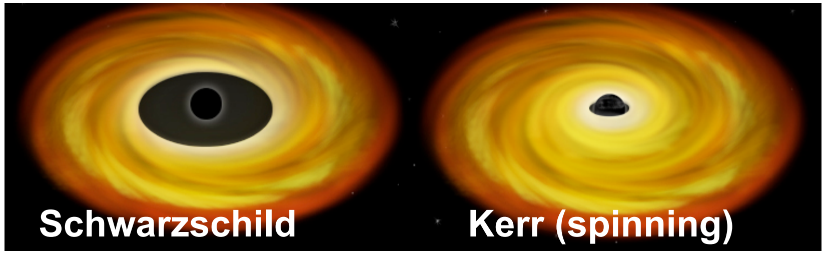
Probing Black Hole Spin

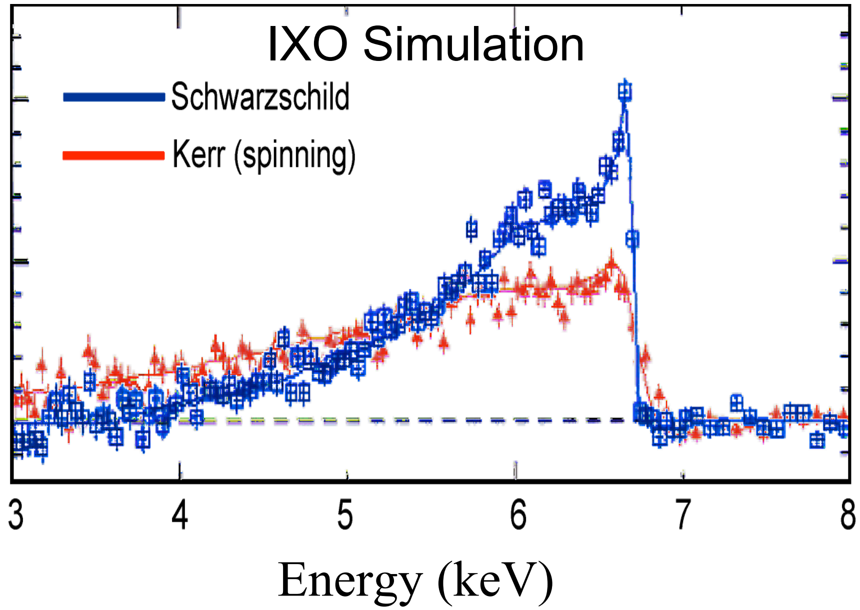




Black Hole Science with IXO

- Nature is providing us with a new and direct probe of strong field General Relativity in the vicinity of Black Holes
- Relativistically broadened iron K lines have been detected from within 6 gravitational radii of Black Hole by ASCA, XMM-Newton, Chandra and Suzaku
- IXO will test the predictions of GR in the strong gravity limit on orbital timescales near the event horizon
- Measure the spin of Black Holes for hundreds of AGN, over a large range of redshift, to test evolution models: mergers verses accretion



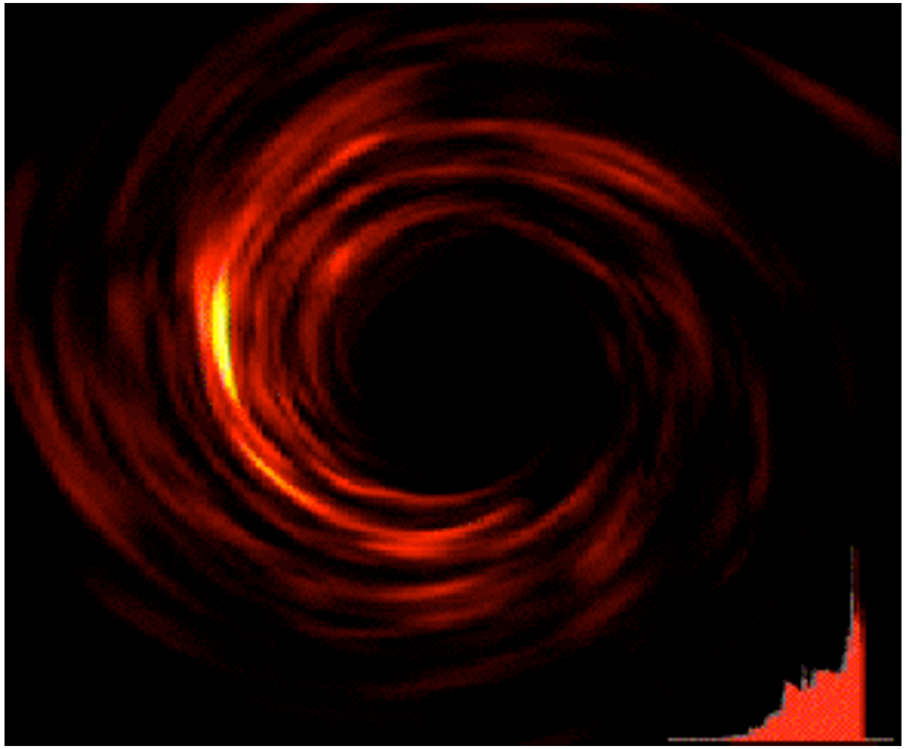


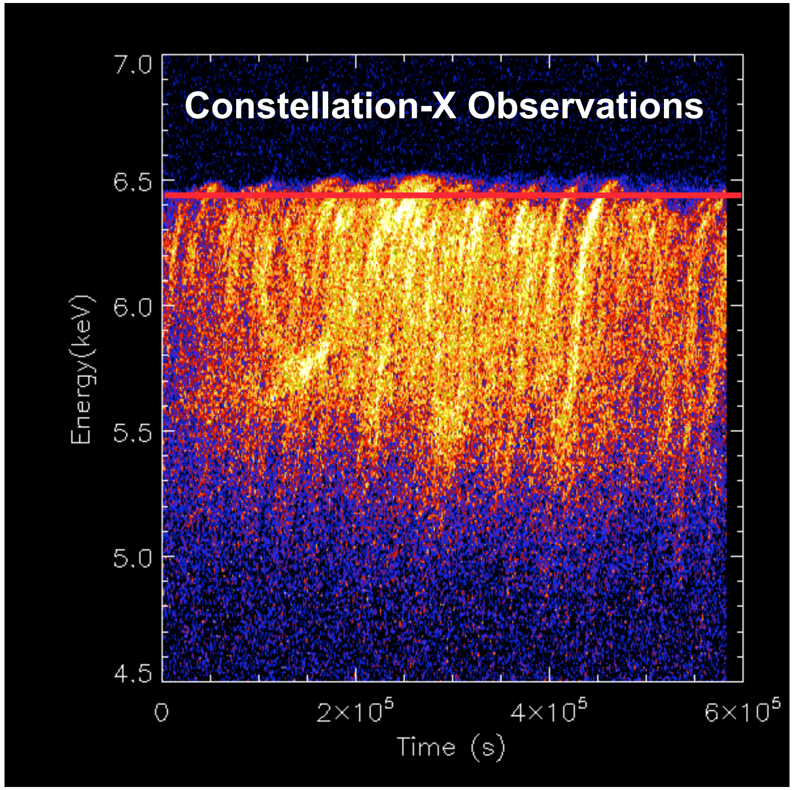
Very Broad Line = Spinning BH

Constellation-X Observing Strong Gravity

Constellation-X will study detailed line variability on orbital times scale close to event horizon in nearby supermassive Black Holes:

- ✓ Dynamics of individual “X-ray bright spots” in disk to determine mass and spin
- ✓ Quantitative measure of orbital dynamics: Test the Kerr metric

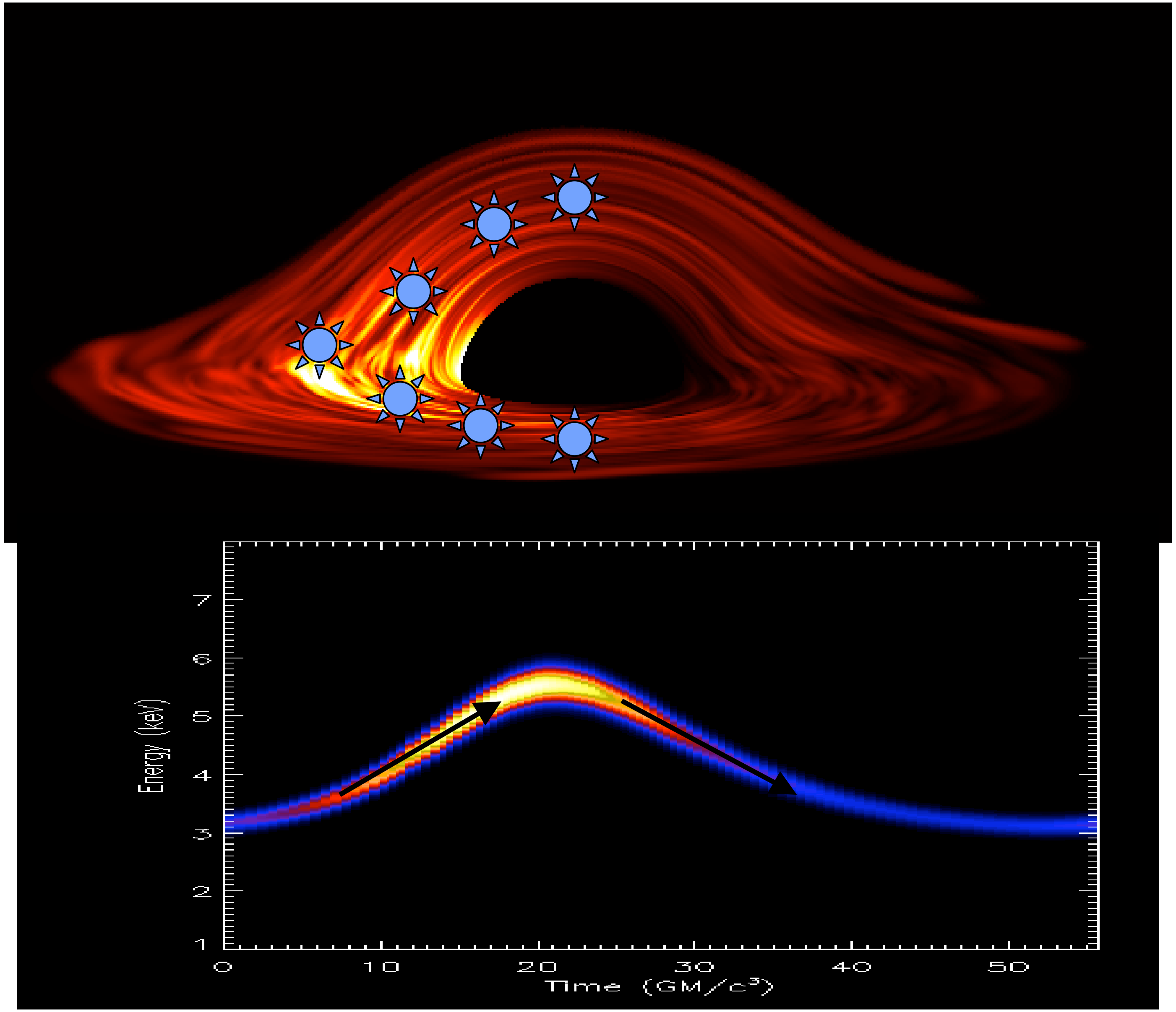




Magneto-hydro-dynamic simulations of accretion disk surrounding a Black Hole (Armitage & Reynolds 2003)

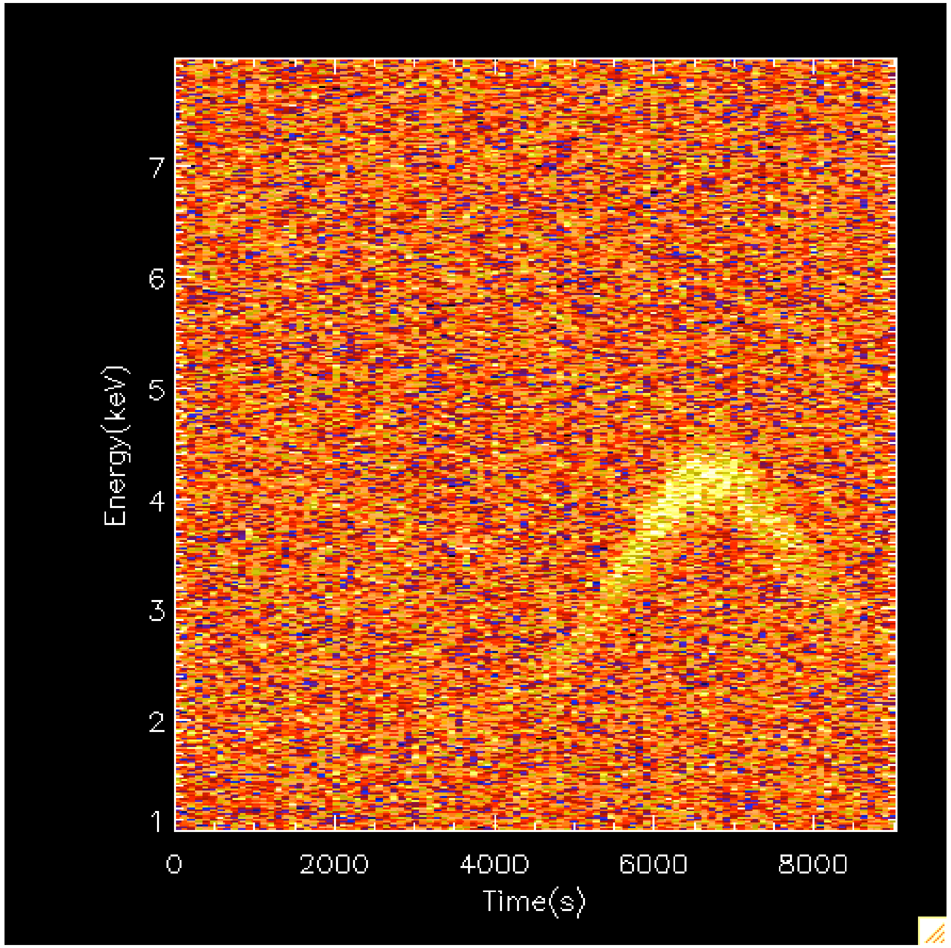
Predicted orbits of individual bright spots

a(spin)=0.98
Radius=3.0
Inclination=30



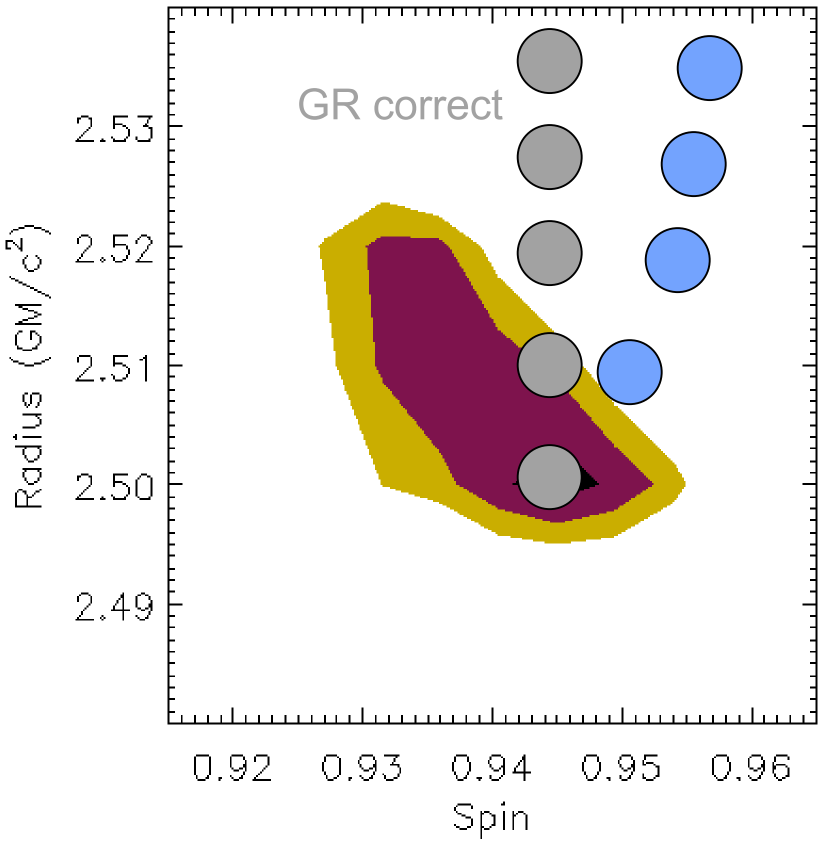
C. Reynolds University of Maryland

Testing GR via consistency of measurements



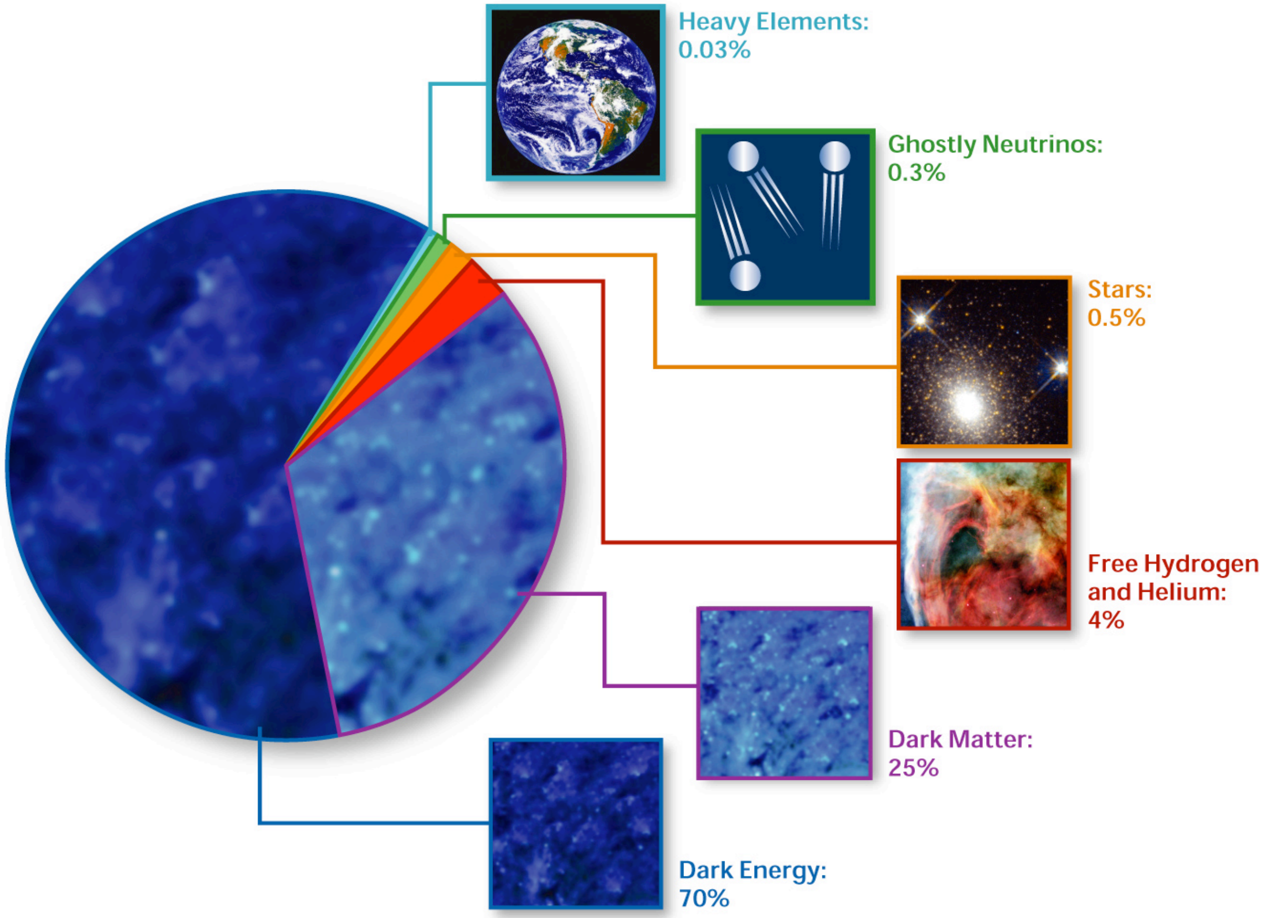
F=5×10^{-11} erg/s/cm2; EW=20eV; M=6×10^{7}
r=2.5 ; a=0.95 ; i=30 degrees

If GR is correct, Con-X measured spin and mass should be independent of radius of bright spot



C. Reynolds University of Maryland

What is Dark Energy?



We do not know what 95% of the universe is made of!

Solving this mystery may fundamentally change our view of the Universe and also may impact the standard model of particle physics!

What is Dark Energy?

In the standard cosmological framework the acceleration of the expansion of the Universe is caused by dark energy that makes up 70% of mass-energy density of the Universe *in the current epoch*

Several Possibilities:

- Dark Energy constant in space & time (Einstein's Λ)
- Dark Energy varies with time
- GR or standard cosmological model incorrect
- Or something new and completely unexpected….

There are no leading theoretical explanations for Dark Energy, to help guide us as to the right experiment to perform

Multiple approaches to measure the expansion of the universe are vital to look for inconsistencies

→ **the answer may be where we least expect it!**

Dark Energy Experimental Approaches

Many observational routes are being pursued

CMB (WMAP, Planck), SNIa (LSST, JDEM), BAO (LSST, SKA, JDEM), weak lensing (LSST, SKA, JDEM), cluster counts (X-ray, LSST)

+ distance measurements to galaxy clusters (Con-X ---- space only).

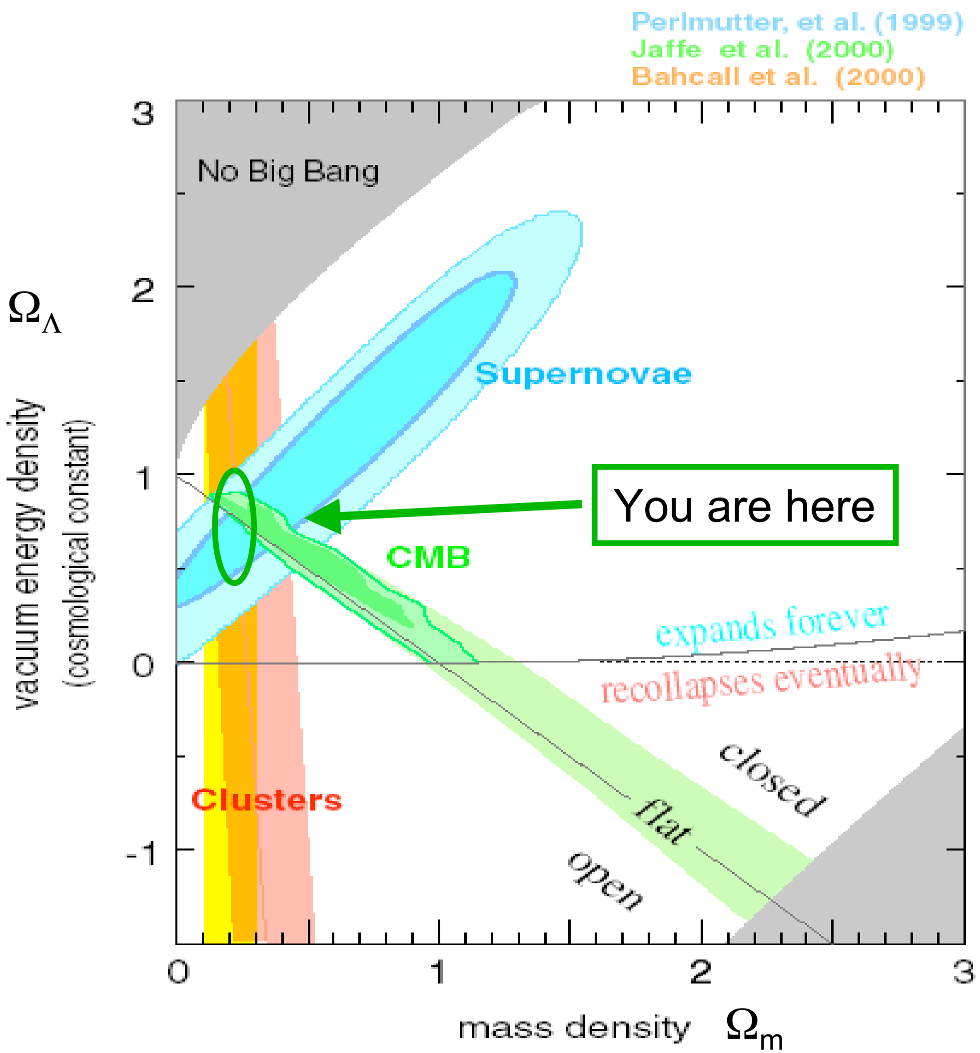
These methods have different strengths/weaknesses and are sensitive to dark energy in essentially two different ways:

1) Absolute distances/expansion history (CMB, SN1a, BAO, clusters)
2) Growth of structure (weak lensing, cluster counts)

Differences between these two approaches may point to problems with GR on large scales

From Steve Allen Kipac/SLAC

Constraining Dark Energy and Dark Matter



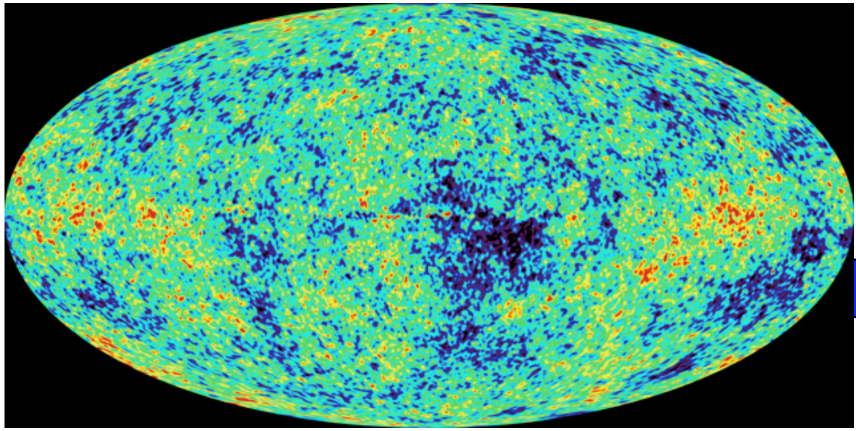
The constraints from different techniques on the mass content of the universe - notice that different techniques are "orthogonal" in this diagram

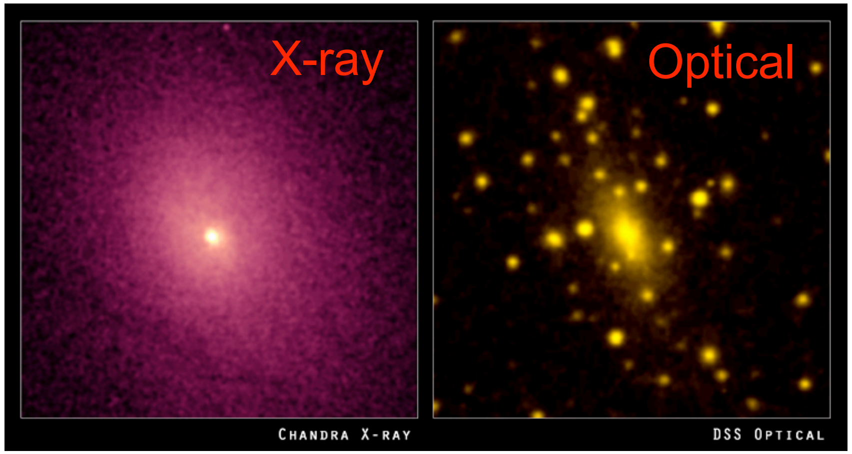
Need several precision techniques relatively free from systematic error or whose errors can be measured and quantified

The breakthrough may come from increased precision for each technique and disagreement between them!

Clusters of Galaxies as Cosmological Probes

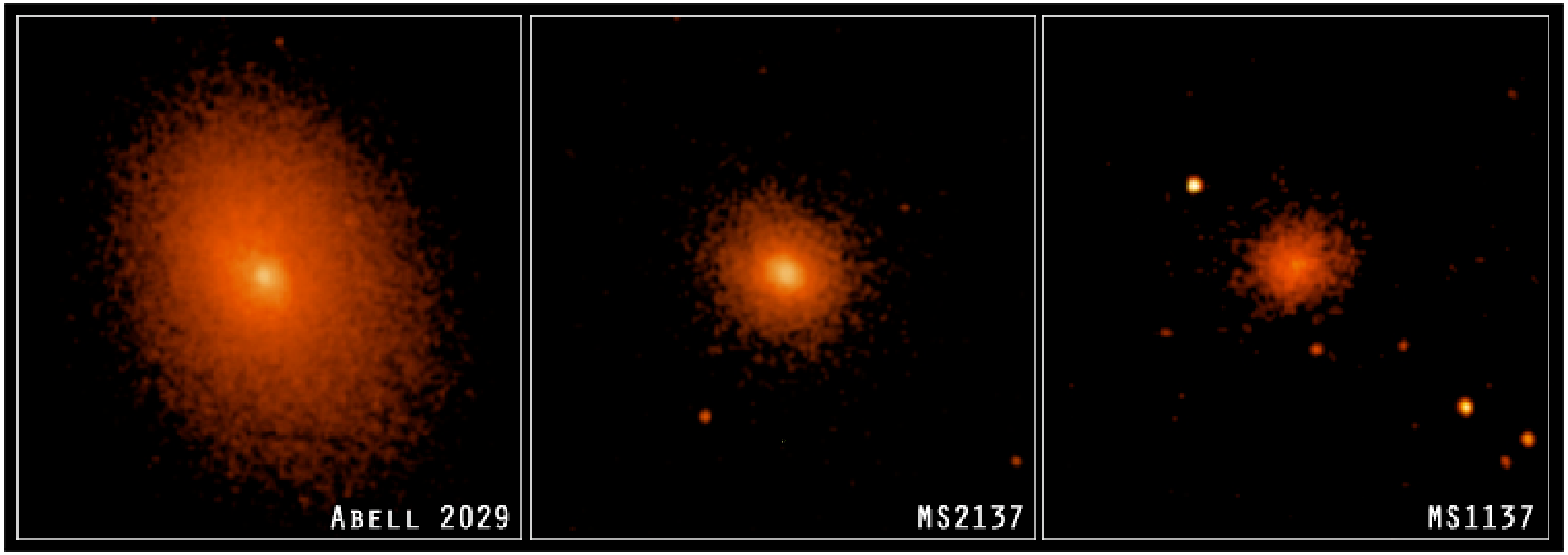
Clusters of galaxies are the largest objects in the Universe and grow from the initial fluctuations seen in the microwave background





Clusters of galaxies are the largest objects in the Universe and their properties and evolution are sensitive to the Cosmological parameters

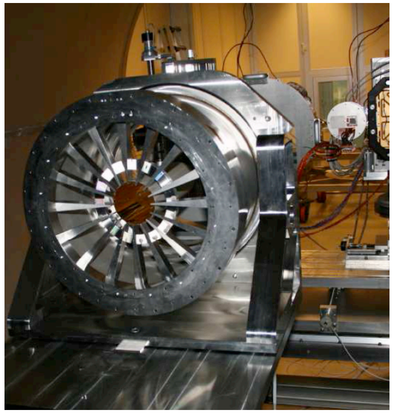
Chandra data on Clusters

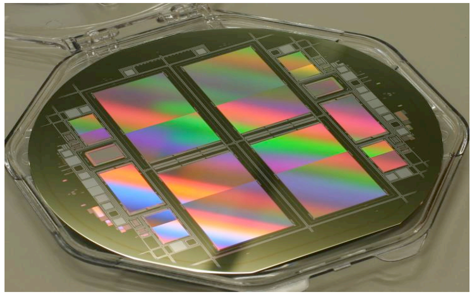


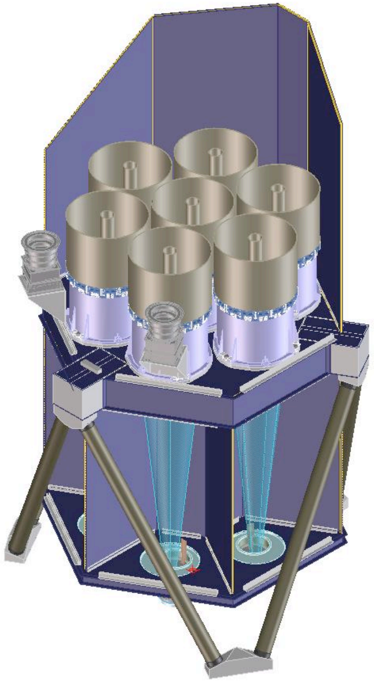
Dynamically relaxed, highly X-ray luminous clusters spanning the redshift range 0<z<1.1 (look back time of 8Gyr)

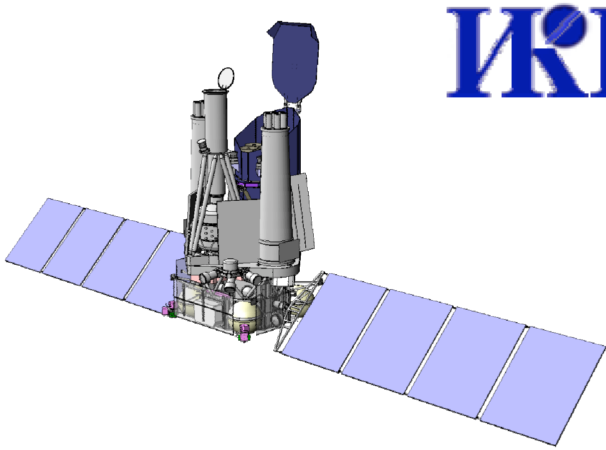
From Steve Allen Kipac/SLAC

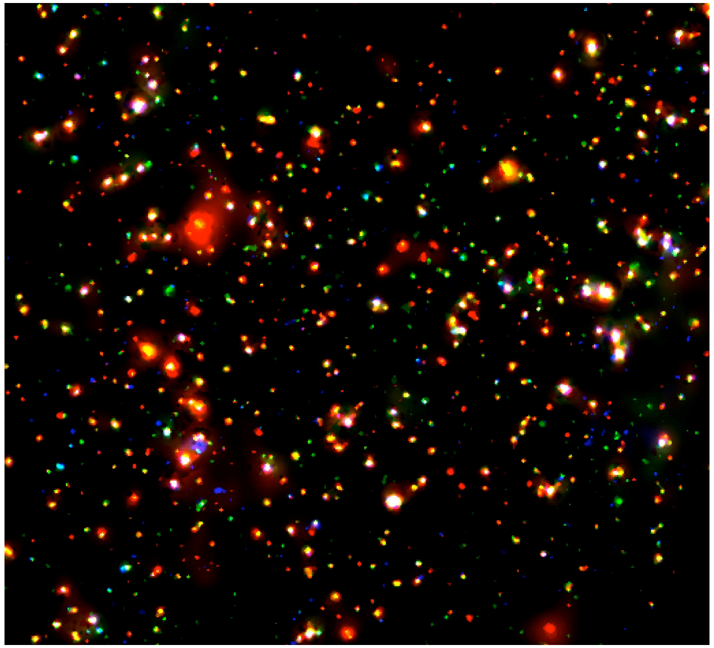
E-Rosita on the Spektrum-X-G Mission







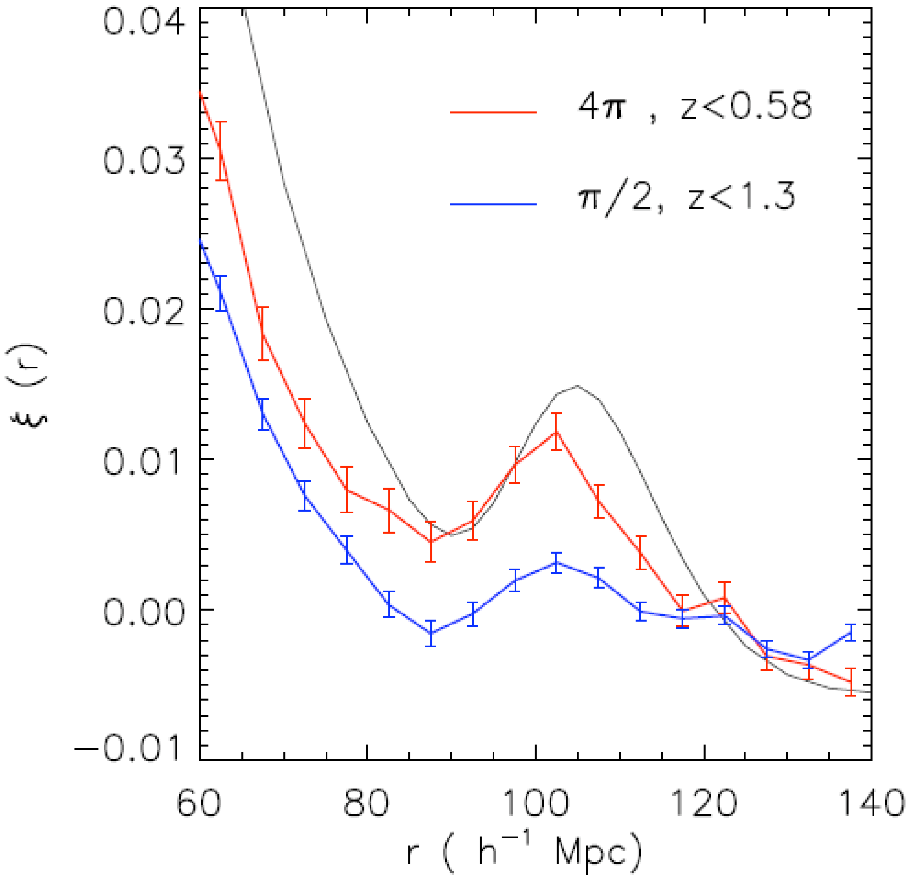




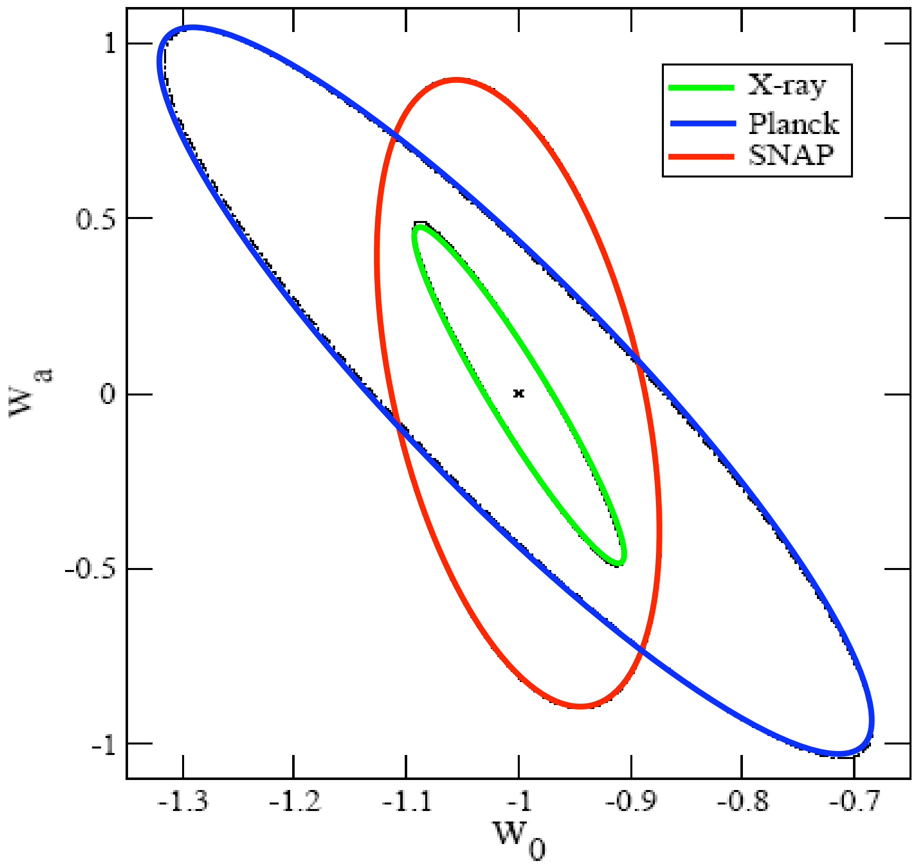
4 yrs all-sky survey yield
100,000 clusters of galaxies (DE!)
3.5 Million AGN
Lots of other interesting science!

eROSITA Dark Energy Constraints

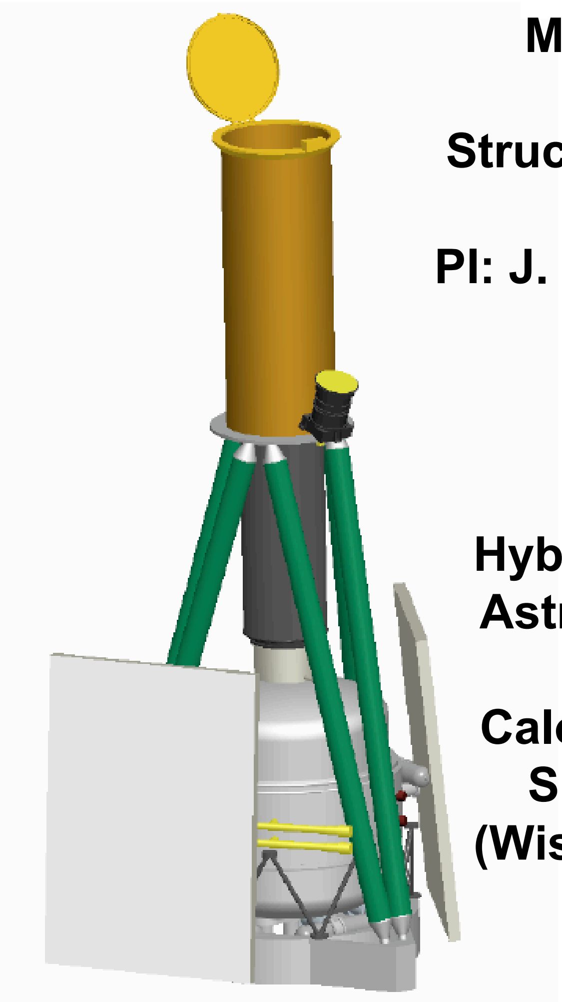
Cluster Baryonic Wiggles



100K cluster constraints



Spektrum XG X-ray Calorimeter

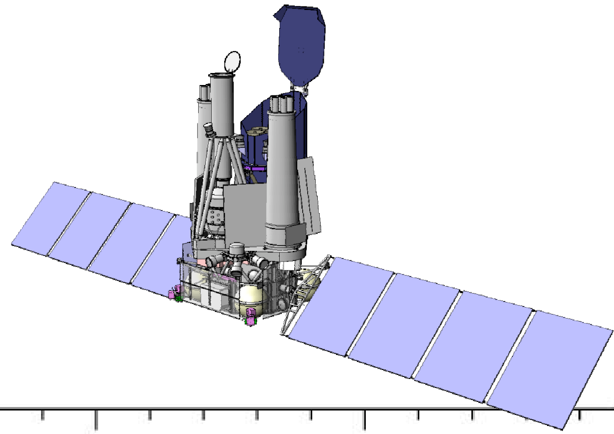


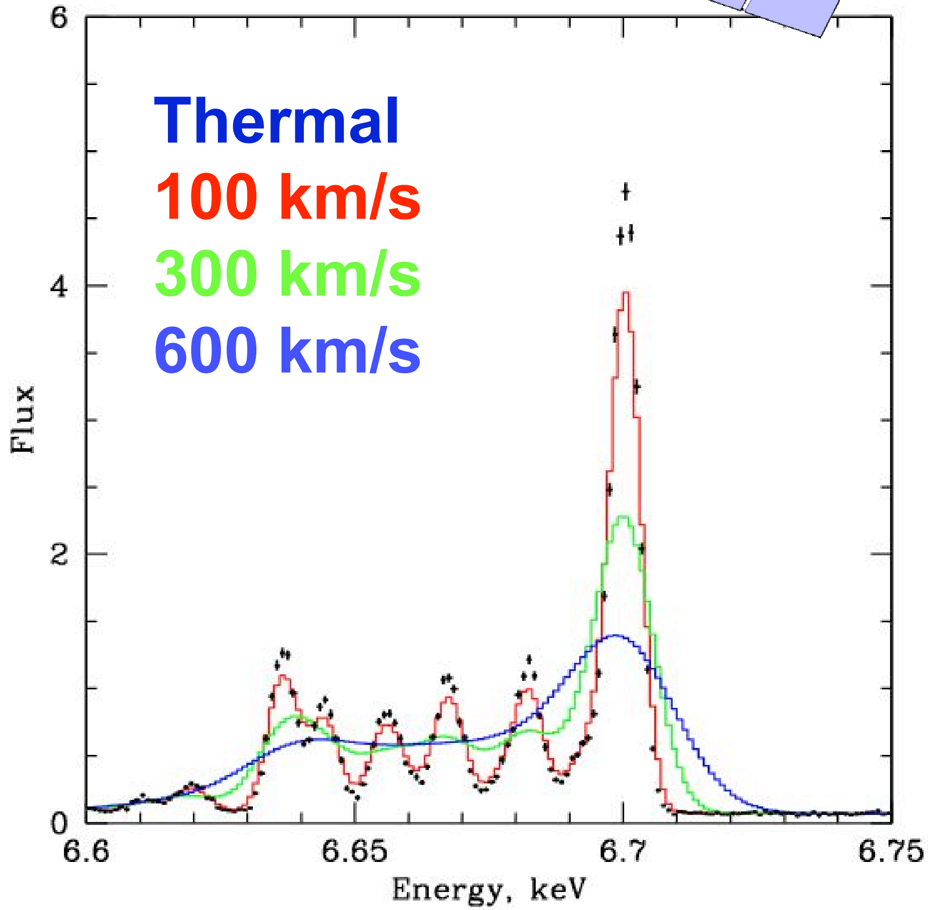
Mirror (MPE)

Structure & System (SRON, PI: J. W. den Herder)

Hybrid Cryocooler Astro-H EM (ISAS)

Calorimeter Array Suzaku spare (Wisconsin/GSFC)





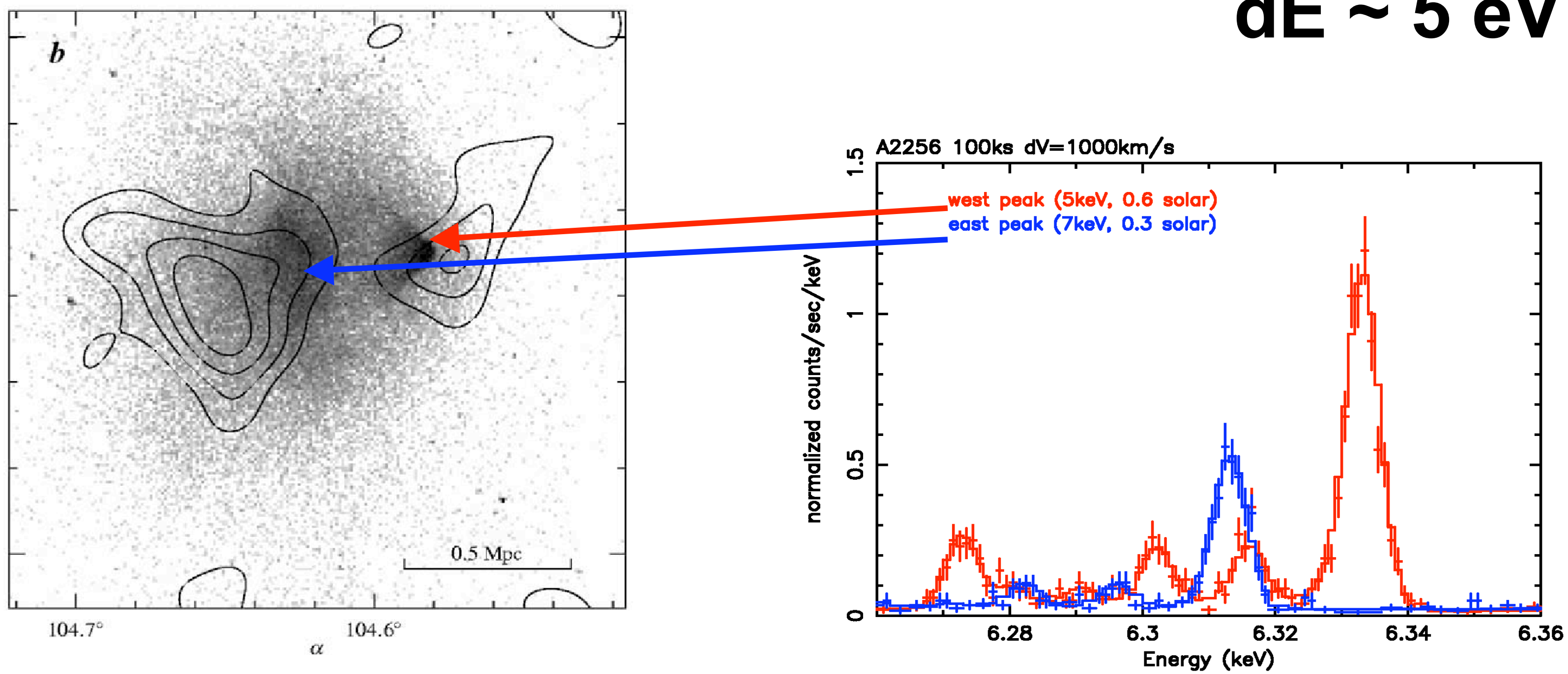
Astro-H: High resolution spectroscopy(dE≤10eV)

Expected with Astro-H SXS

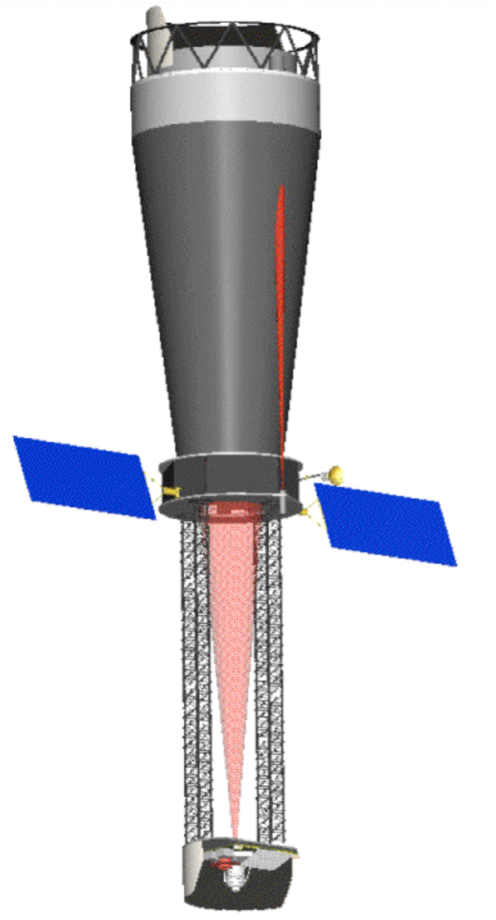
Dynamics of plasmas in clusters

A2256

dE ~ 5 eV



IXO Dark Energy



IXO will derive cosmological parameters using (at least) three different galaxy cluster techniques:

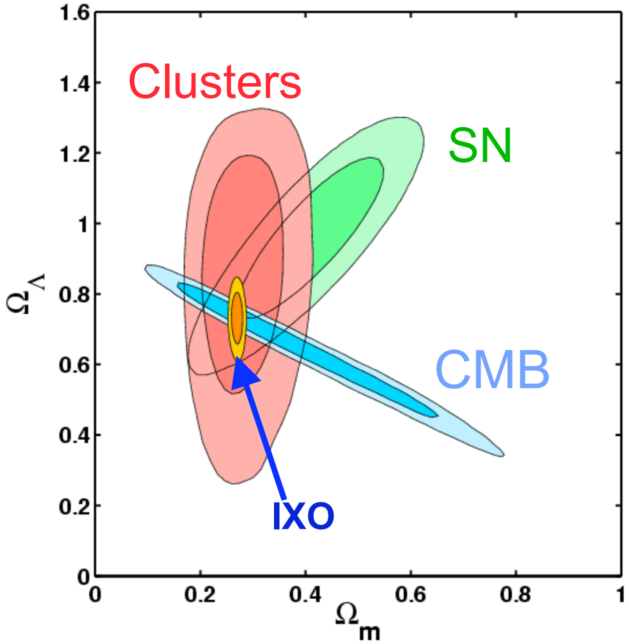
1. Using the gas mass fraction in clusters as a "standard candle"

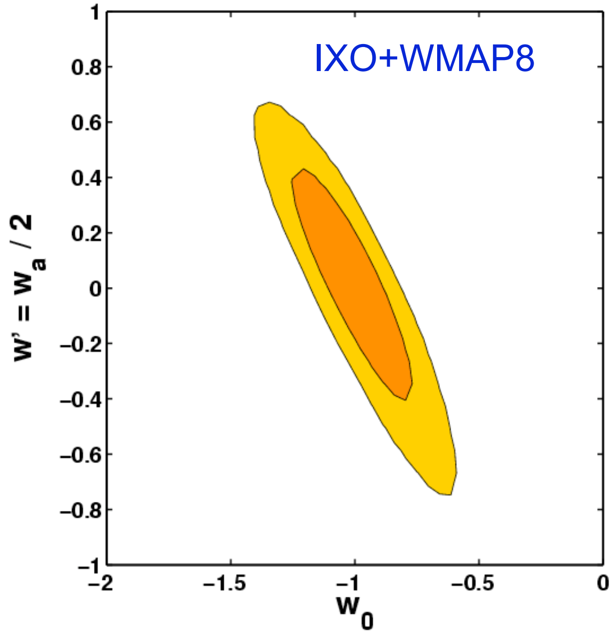
2. in combination with microwave background measurements the Sunyaev-Zeldovich technique to measure absolute distances

3. Measuring the evolution of the cluster parameters and mass function with redshift (=growth of structure)

1 and 2 are 'distance rule' techniques (ala SNIa), 3 is a "growth of structure" technique which depends on GR

IXO Dark Energy Cosmology





Factor of ten improvement

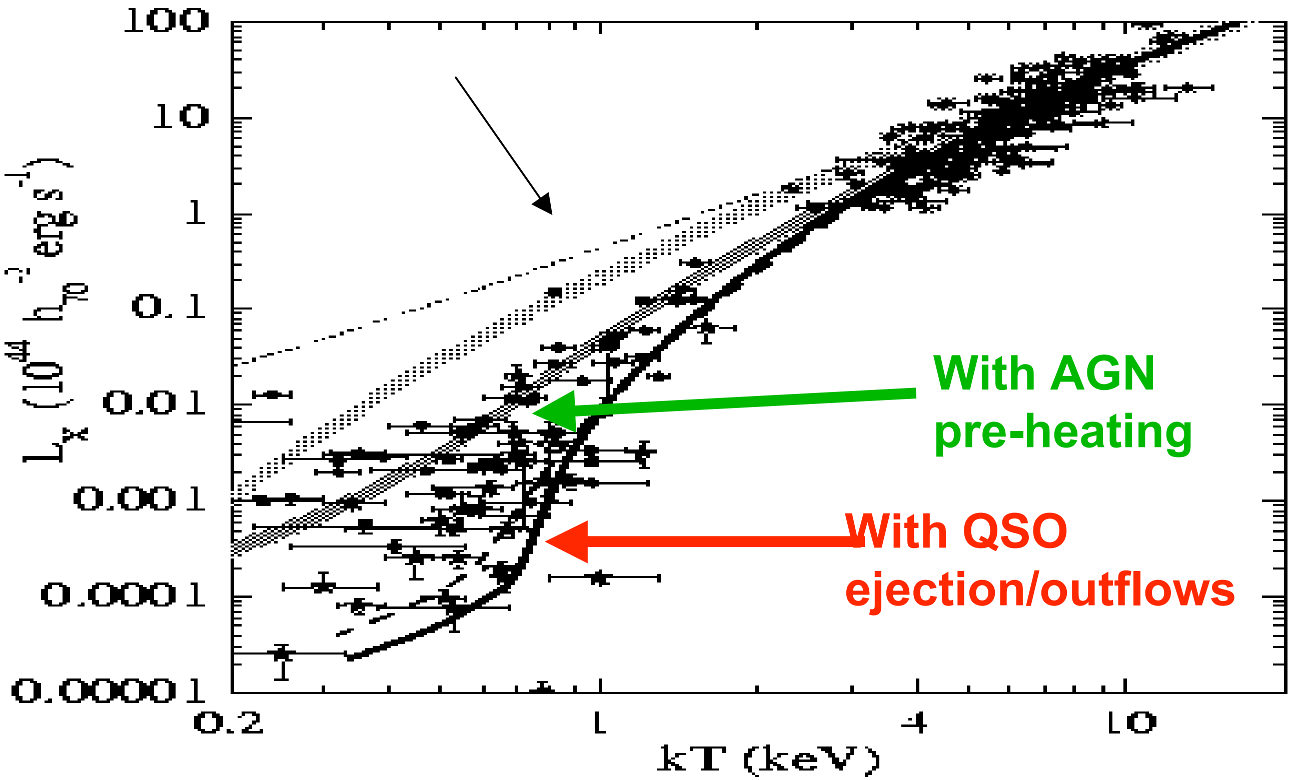
In the terms of the Dark Energy Task Force Figure of Merit this is a Stage IV result

Rapetti, Allen et al 2006 (Astro-ph/0608009)

- Using the gas mass fraction as a standard ruler measures f_{gas} to 5% (or better) for each of 500 galaxy clusters to give Ω_M=0.300±0.007, Ω_Λ=0.700±0.047
- Cluster X-ray properties in combination with sub-mm data measure absolute cluster distances via the S-Z effect and cross-check f_{gas} results with similar accuracy
- Determining the evolution of the cluster mass function with redshift reveals the growth of structure and provides a powerful independent measure of Cosmological parameters (see papers by Vikhlinin, Nagi, Kravtsov)

Growth of Black Holes and Galaxies

Groups and Clusters of Galaxies and the importance of AGN feedback



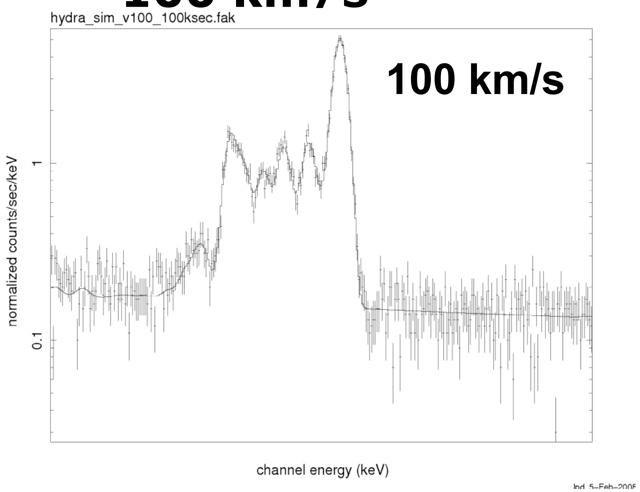
Lapi, Cavaliere & Menci (2005)

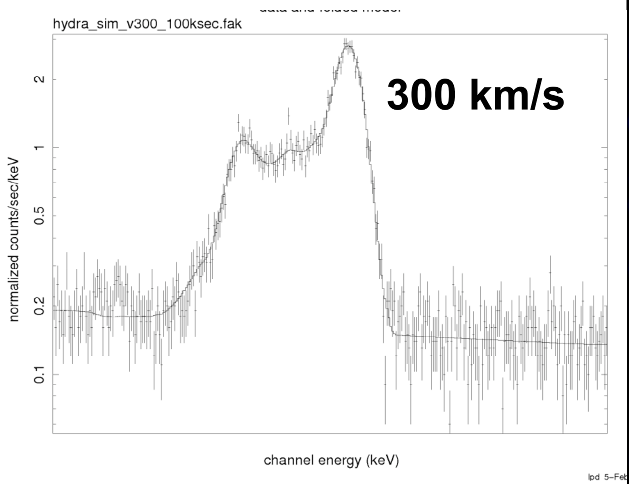
IXO Cosmic Feedback

Large scale-structure simulations require AGN feedback to regulate the growth of galaxies and clusters of galaxies

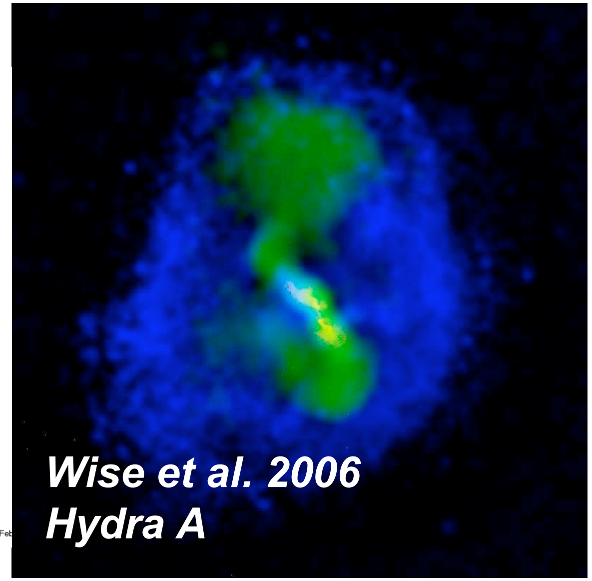
Velocity measurements crucial to determine heating and state of Intra-cluster medium

IXO will probe the hot ICM/IGM through velocity measurements to the required ~100 km/s

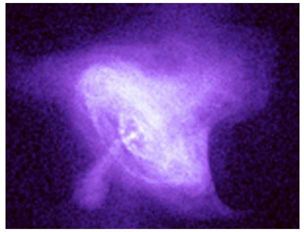


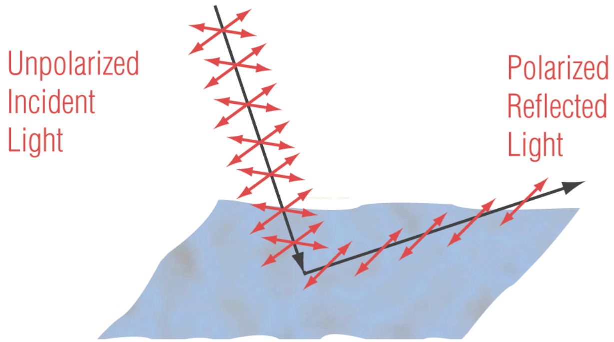


IXO Simulation



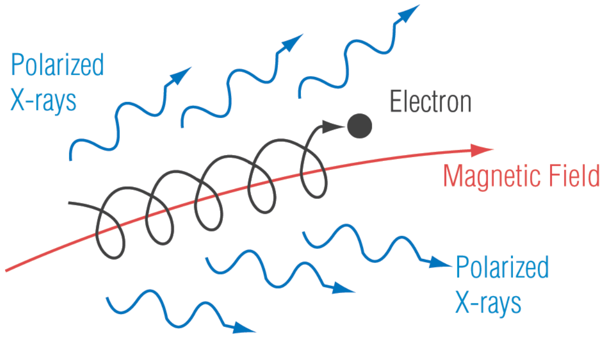
Why X-Ray Polarization is important





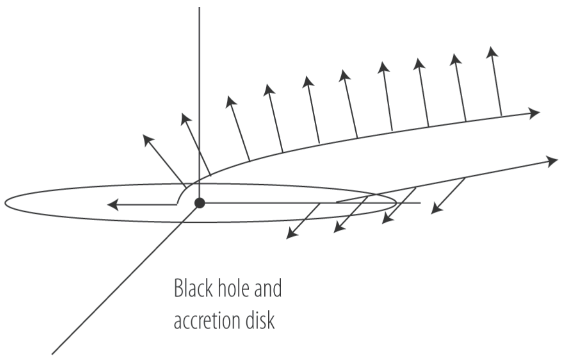
Scattering induces polarization.

The polarization is sensitive to the geometry of the source environment.



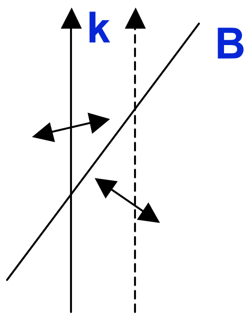
Synchrotron emission in a strong magnetic field.

In magnetic fields electrons radiate with polarization perpendicular to B.



Gravitational distortions of space bend the photon trajectories and rotate polarization.

In neutron star atmospheres, the opacity is affected by the electron's Landau energy levels and the polarization.



X O modes
⊥ || kB plane
Extraordinary Ordinary

Polarization Detection Break Through

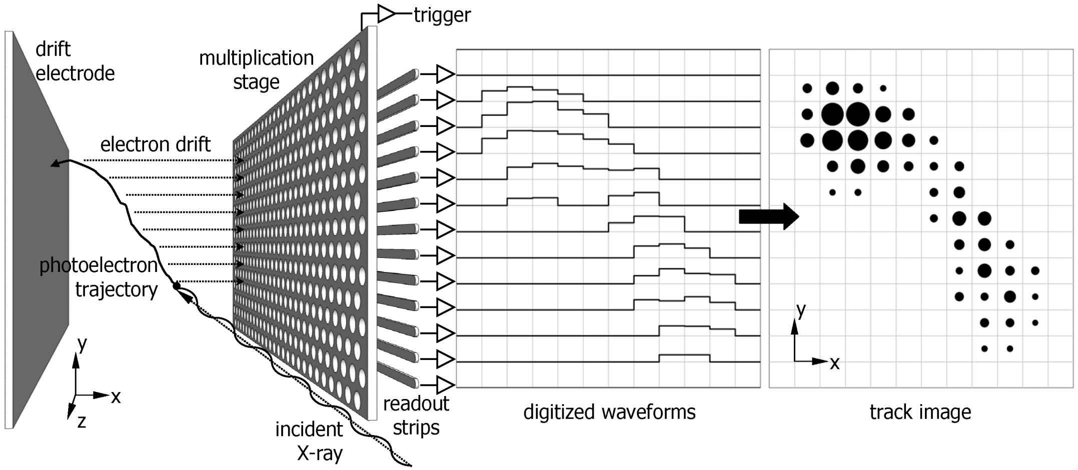
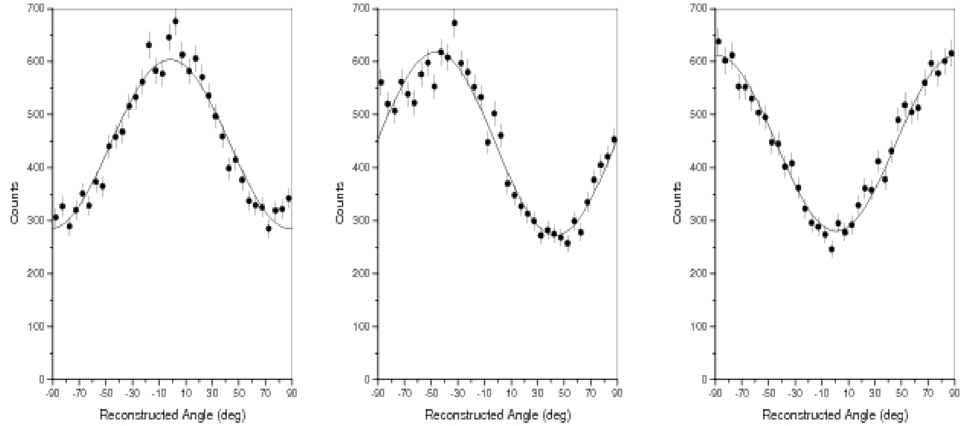


Photo-electrons from an ionizing X-ray follow the E-vector

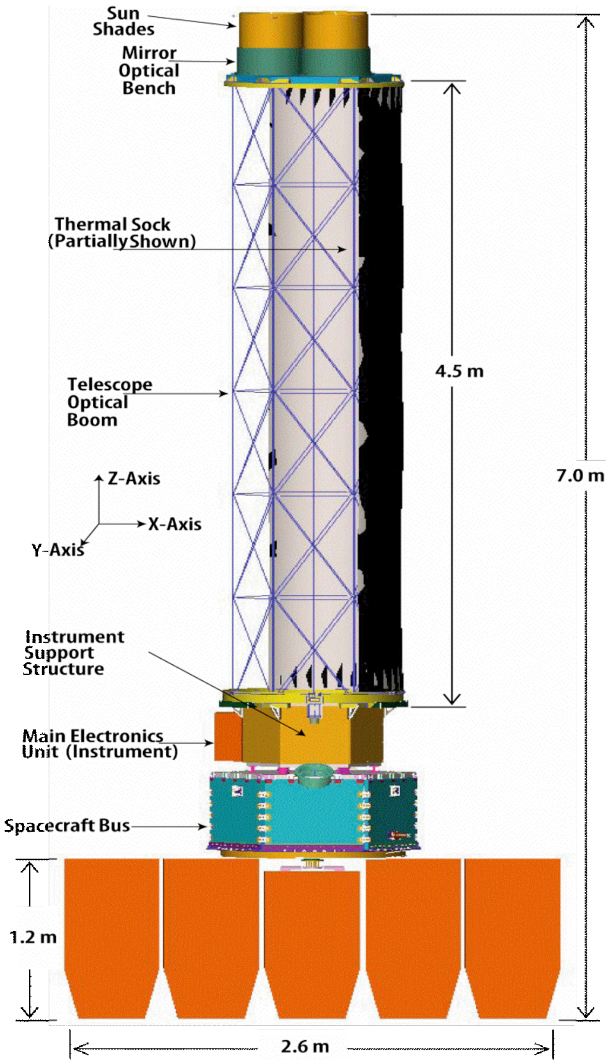
Costa et al. (2001) showed that new gas detector technology could resolve the electron track

Black, Baker, Deines-Jones, Hill, & Jahoda (2006) developed the time projection chamber which provides both sensitivity to polarization and high detector efficiency



Sample modulation for Ne/Nitromethane gas. μ ~0.4

The GEMS Instrument and Spacecraft



PI: Jean Swank

Selected for Phase A SMEX study

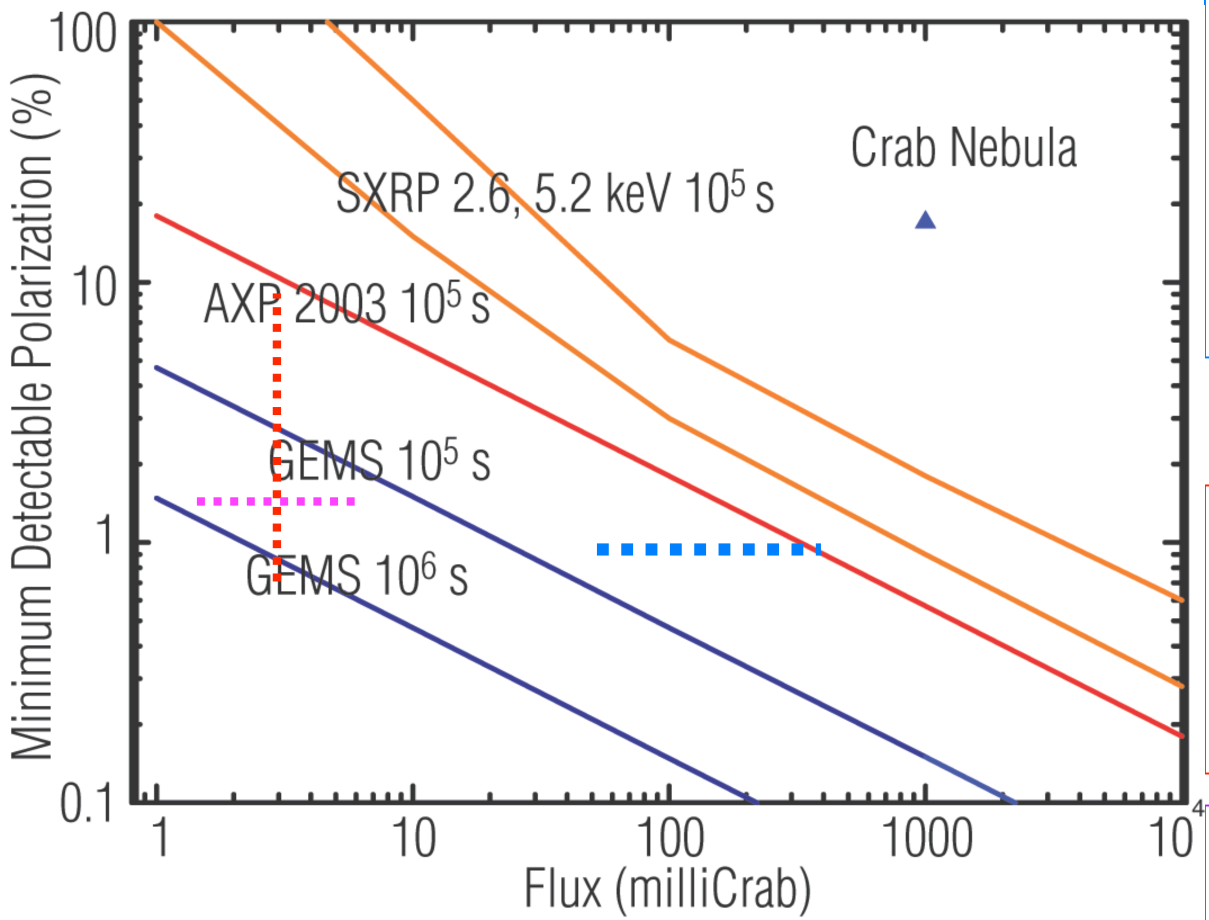
Suzaku-like telescopes are deployed on a boom.

The spacecraft rotates at 0.1 rpm. This allows measurement of and correction for polarization produced by systematic errors

Pointing 90±30 degrees from the sun will allow any direction to be seen every 6 months

The mission is sized for 2 yr, while the baseline program sampling types of sources would take 8-12 months, with the remainder for a Guest Observer program

Sensitivity for predicted 1 % Polarizations



SXRP Spectroscopic X-ray Polarimeter
AXP Imaging polarimeters proposed in 2003

Important model predictions for black holes are 1-3%. LMXB could be similar (Sazonov & Sunyaev 2001). Possible in few x 10^4 s observations. Predictions for millisecond pulsars are larger (Viironen & Poutanen 2004).

Magnetars are weak persistent sources (few mCrabs), but polarization may be strong.

Seyferts are weak and may have low polarization. But long observations are possible.

Summary

- The future of high energy Astrophysics is bright!
- GLAST is on orbit and ready to deliver tremendous new gamma ray data
- The coming decade will:
  - open up the hard X-ray band to imaging spectrometers (NuSTAR, Astro-H, SIMBOL-X) and reveal the geometry and energetics of Black Holes
  - provide a new X-ray survey (Spektrum XG) that will reveal 100,000 new clusters of galaxies to constrain Dark Energy
  - fly the first micro-calorimeter arrays to open a new era of X-ray spectroscopy (Astro-H and Spectrum-XG)
  - possibly see the first dedicated X-ray polarization mission (GEMS)
- ESA, JAXA and NASA are planning for the end of the decade an International X-ray Observatory (IXO) 10-100 times more capable than XMM-Newton and Chandra, that will search for the first Black Holes and probe close to the event horizon, place tight constraints on Dark Energy and provide a major new astrophysics facility