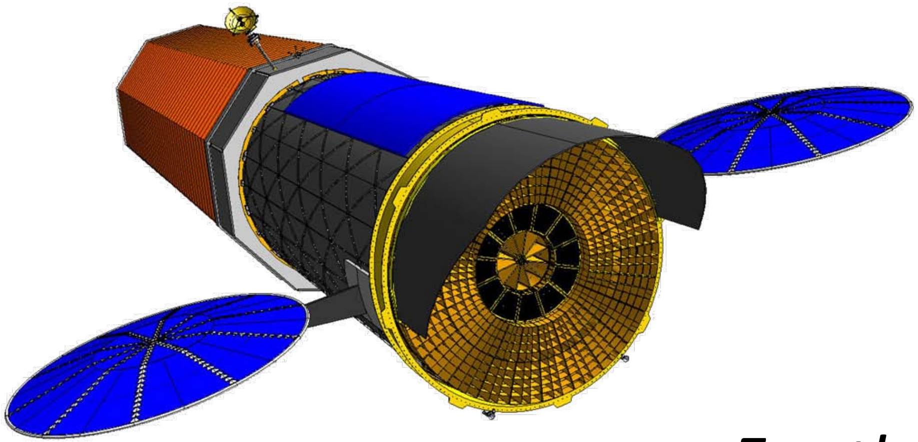
The International X-ray Observatory



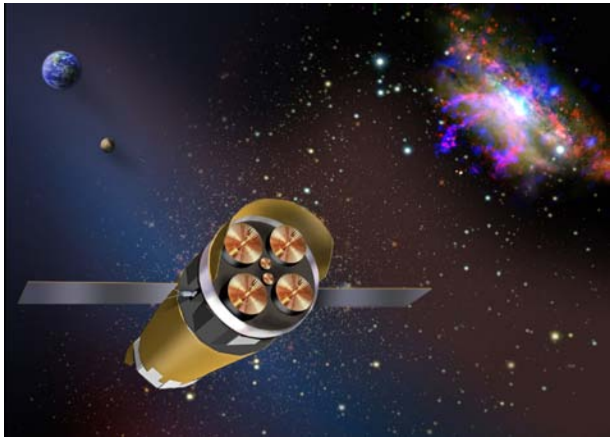
Michael Garcia

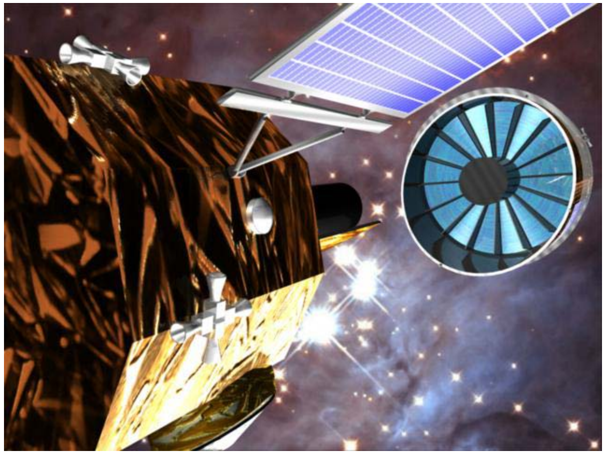
Smithsonian

For the ESA-JAXA-NASA IXO Team

(XEUS+Con-X)

History





- The science case for a large, high spectral resolution, X-ray Observatory is compelling:
  - Con-X: NASA concept, number two ‘large space-based project’ in 2000 Decadal survey
  - XEUS: ESA with JAXA candidate as large Cosmic Vision mission
- Very similar science goals, very different implementations
- Merger Summer 2008, cost savings substantial, implementation combines best of both – going to 2010 Decadal!

IXO as the successor to Chandra and XMM-Newton

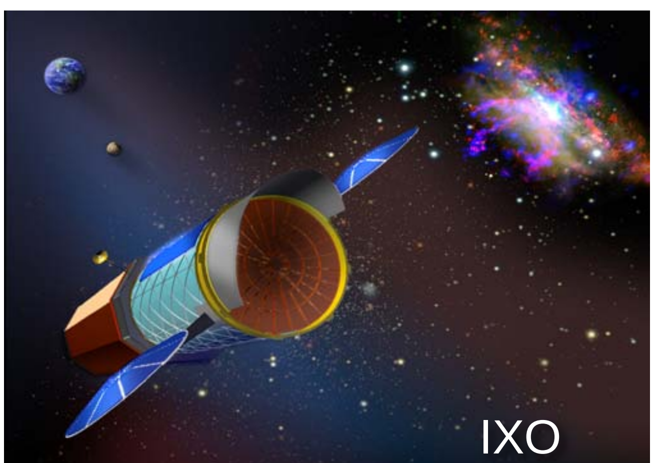
Chandra and XMM have brought X-ray Astronomy to the forefront

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



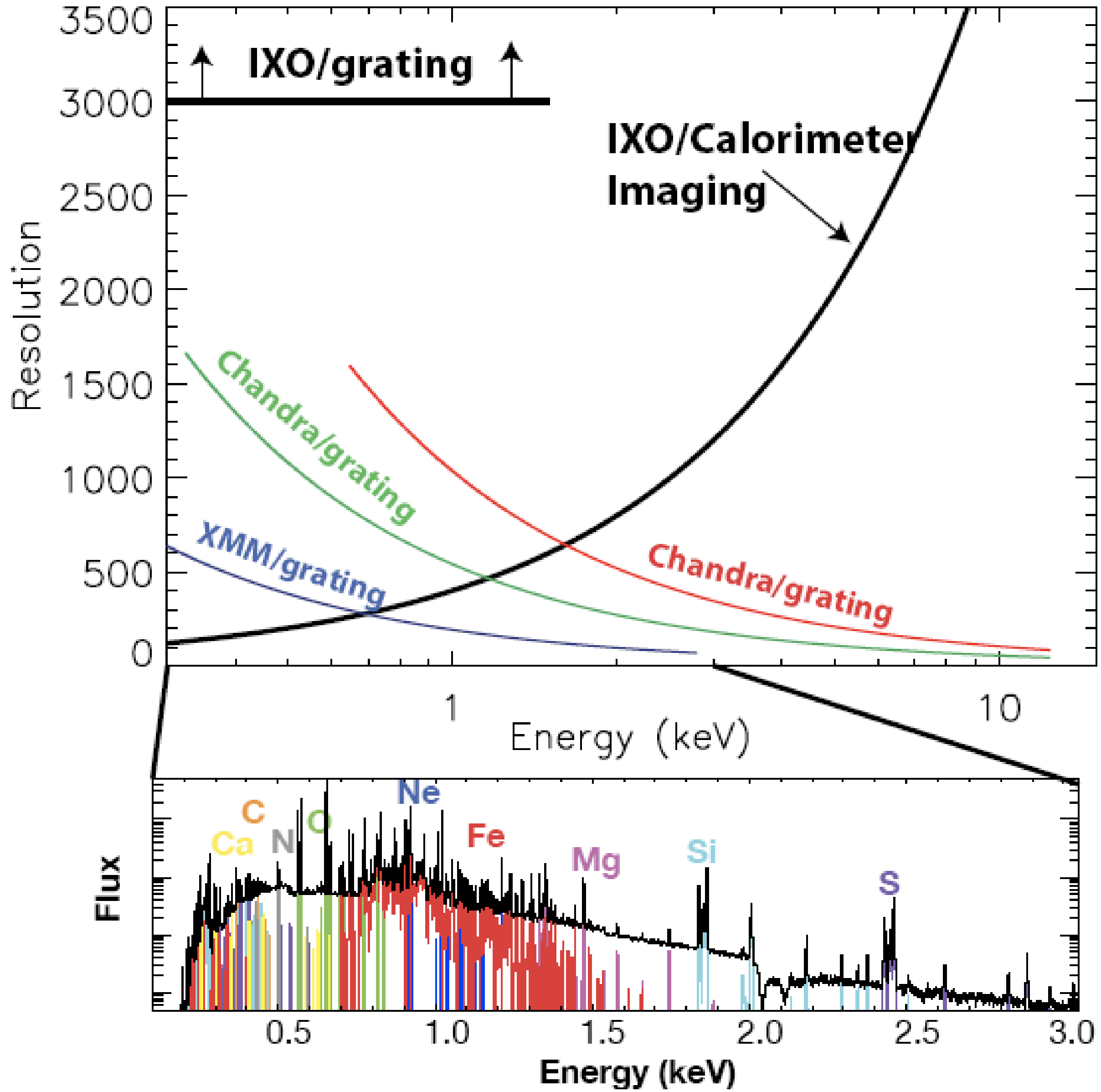
The IXO will change this – Routine spectra with R = 1000-3000 for 10,000s of sources –

>100x Throughput for high resolution spectroscopy, AREA alone 30x XMM

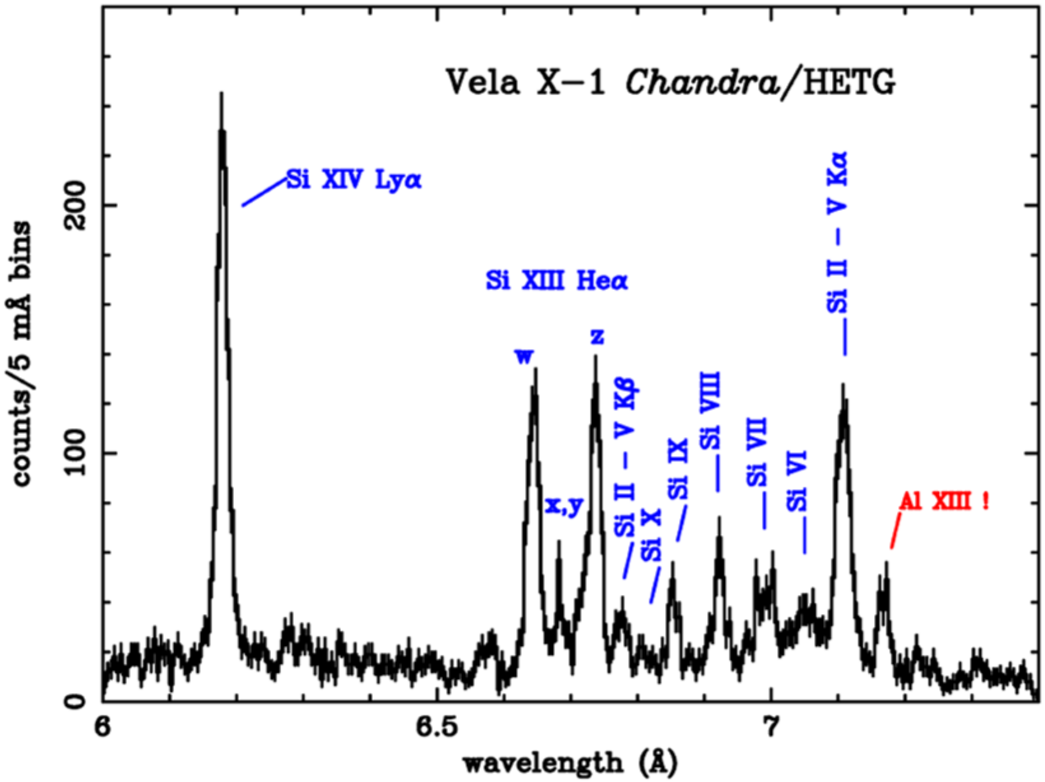
THE PHYSICS IS IN THE SPECTRA

Spectral Capability

The IXO energy band contains the K-line transitions of 25 elements Carbon through Zinc allowing simultaneous direct abundance determinations using line-to-continuum ratios, plasma diagnostics and at iron K bulk velocities of 100 km/s



Most surprising ('bizarre') spectra: X-ray binaries (Paerels, IXO Boston)

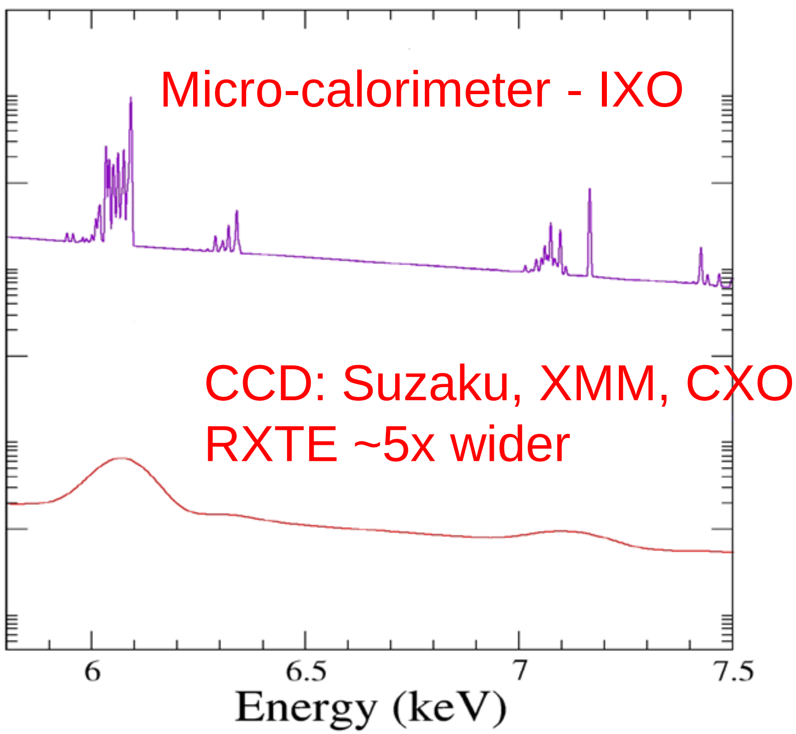


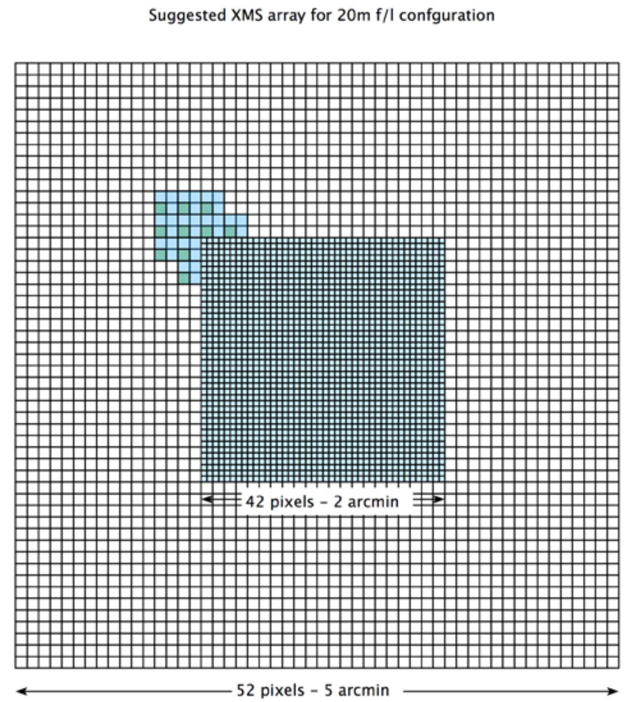
(Courtesy Masao Sako, Stanford)
(see also Watanabe et al. 2006)

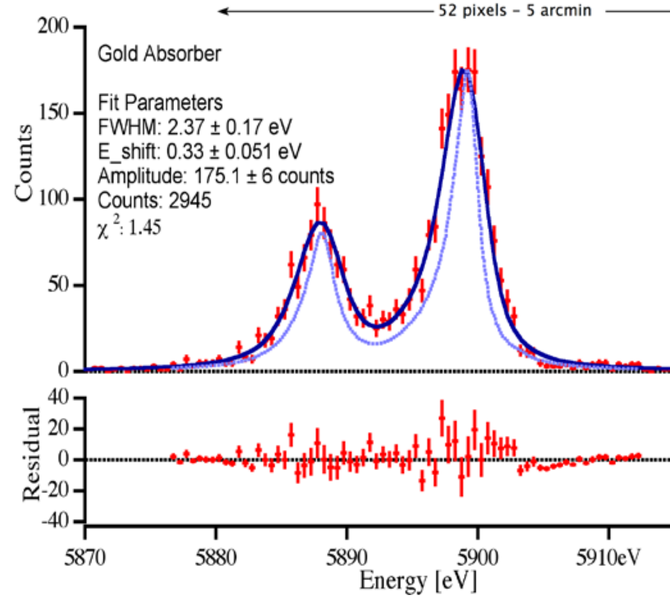
Complete K-shell spectrum of Si! [there are 24 more!]
(presence of both highly ionized, tenuous material, as well as large amounts of near-neutral Si (unknown!) in stellar wind from companion)

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

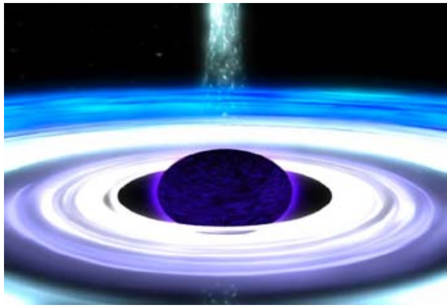




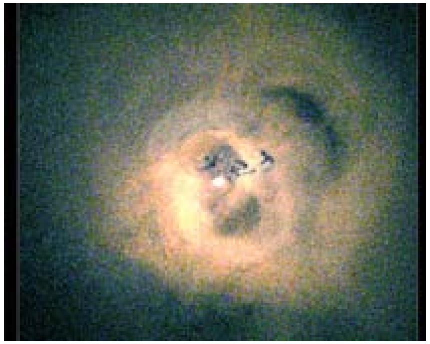


Main Science Topics

- **Black Holes and Matter under Extreme Conditions**

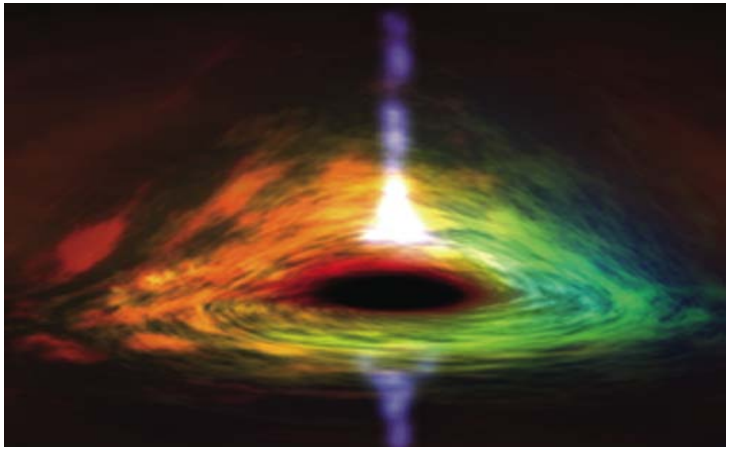


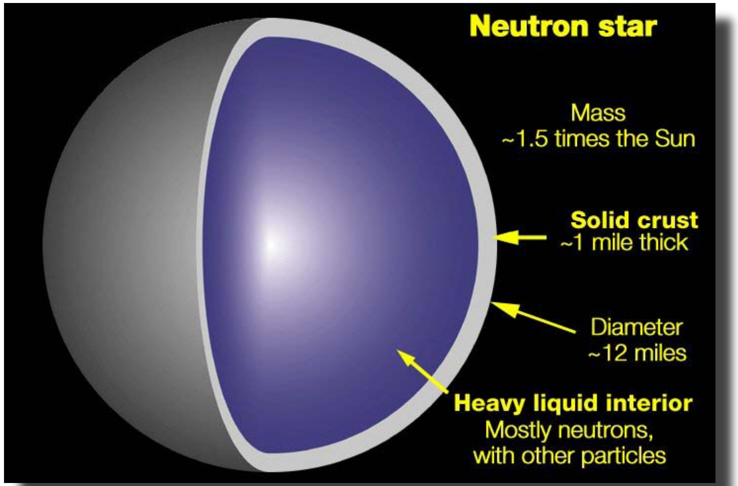
- **Formation and Evolution of Galaxies, Clusters, and Large Scale Structure**



- **Life Cycles of Matter and Energy**

Black Holes and Matter under Extreme Conditions



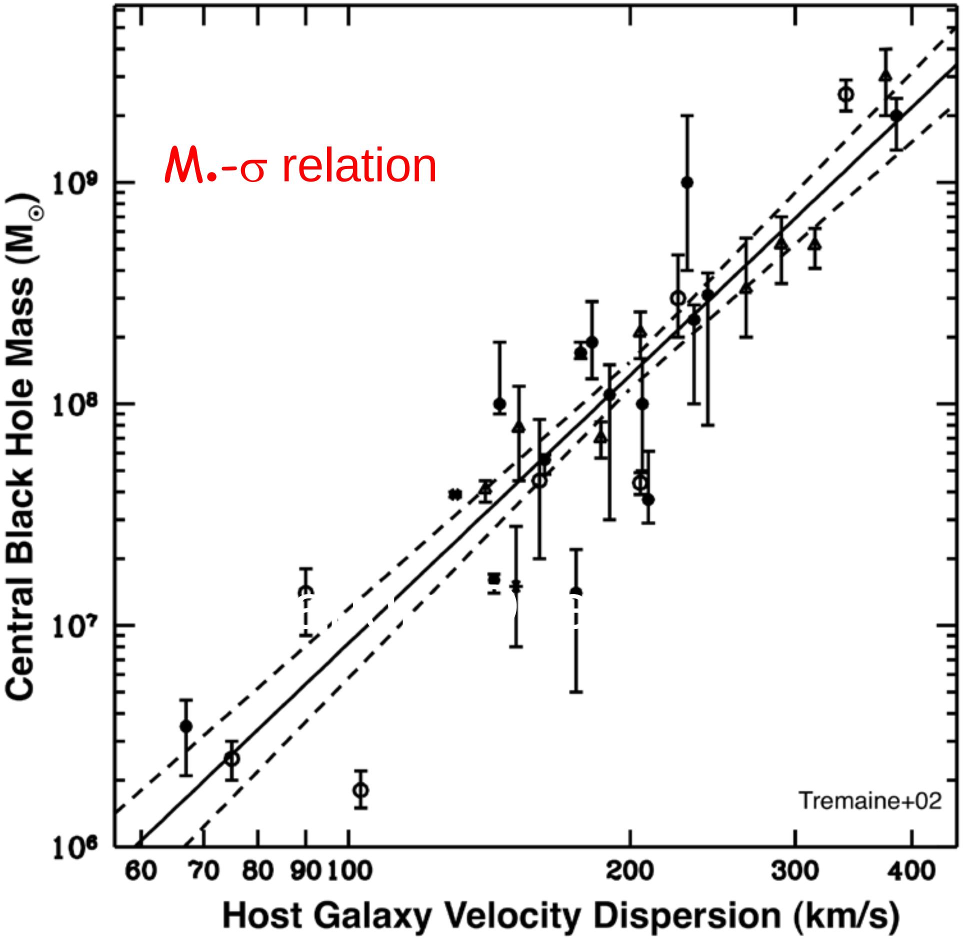


How do super-massive Black Holes grow? Does this change over cosmic time?

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?

The First Supermassive Black Holes

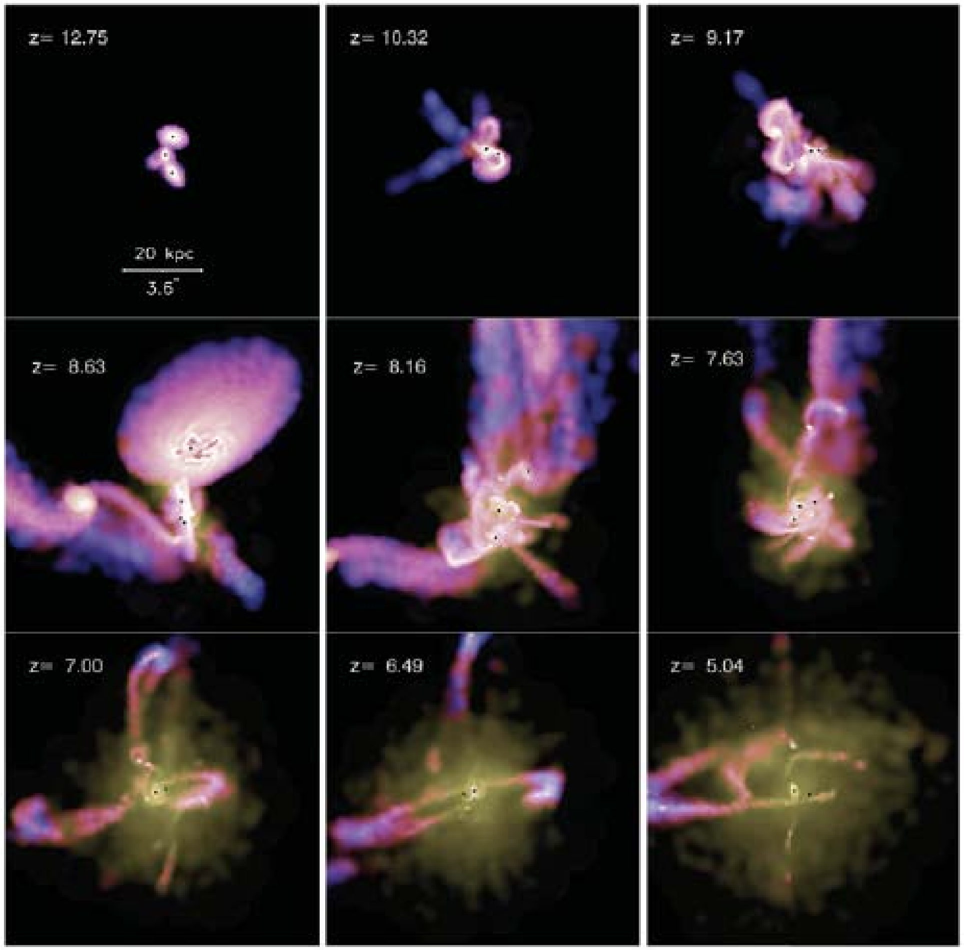


- How did the first massive black holes in the Universe feed and grow?

- How did feedback from the first massive black holes influence the growth of the first galaxies?

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

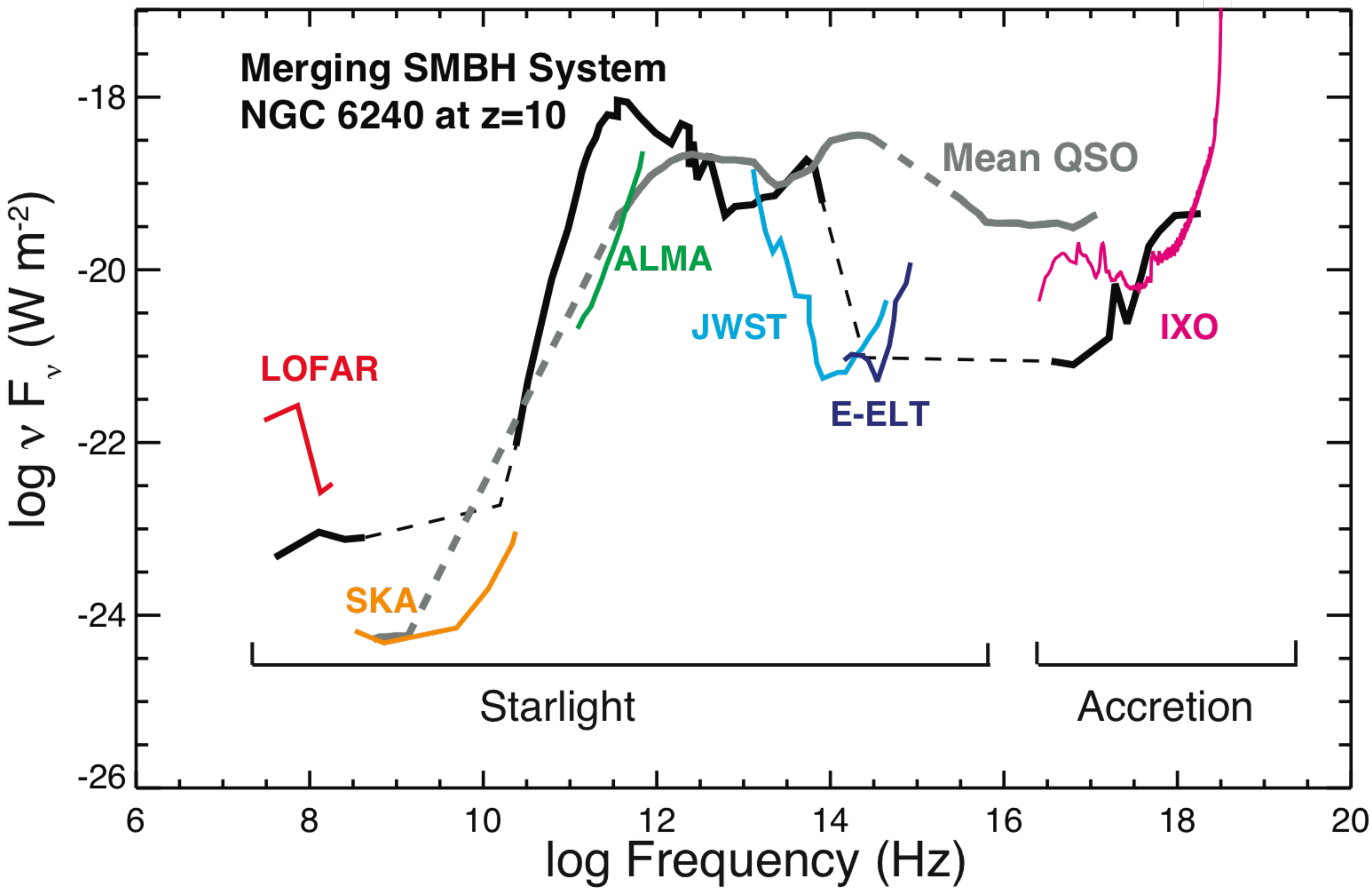
The First Supermassive Black Holes



1. Gas rich major merger
2. Inflows trigger BH accretion & starbursts
3. Dust/gas clouds obscure AGN
4. AGN wind sweeps away gas, quenching SF and BH accretion.

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

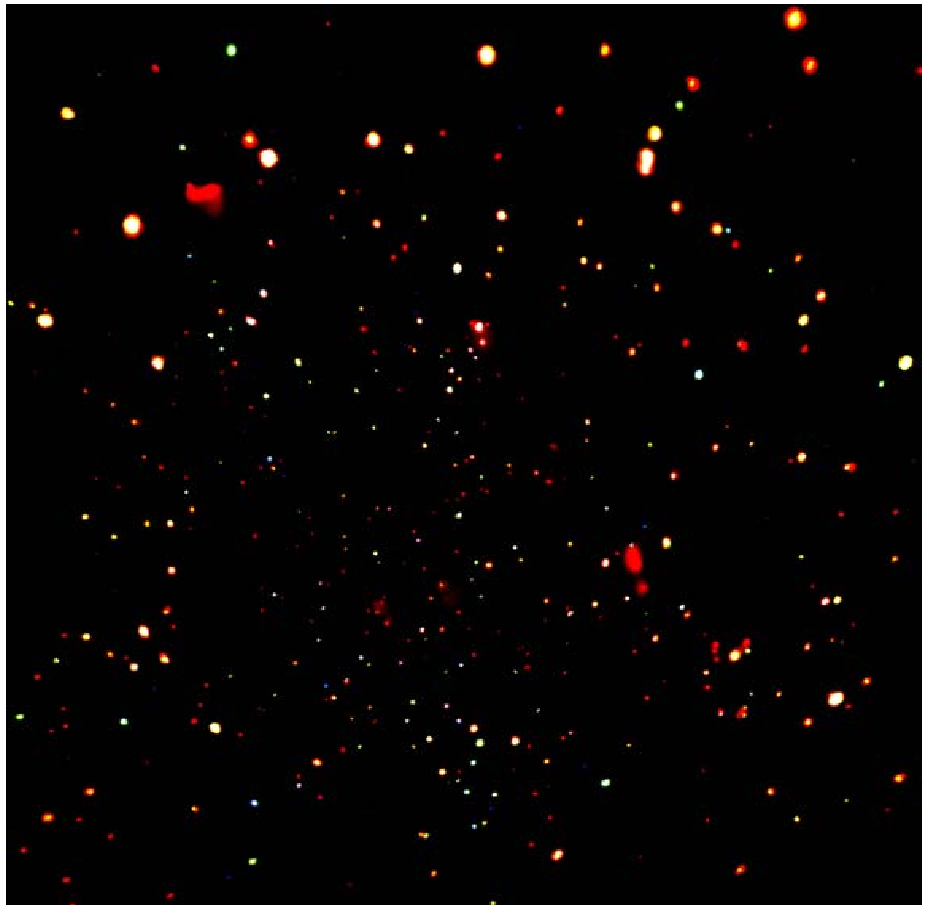
SMBH's at high redshift with IXO

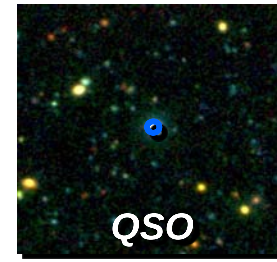


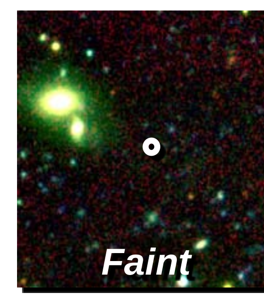
Why Study M-σ with IXO?

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

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





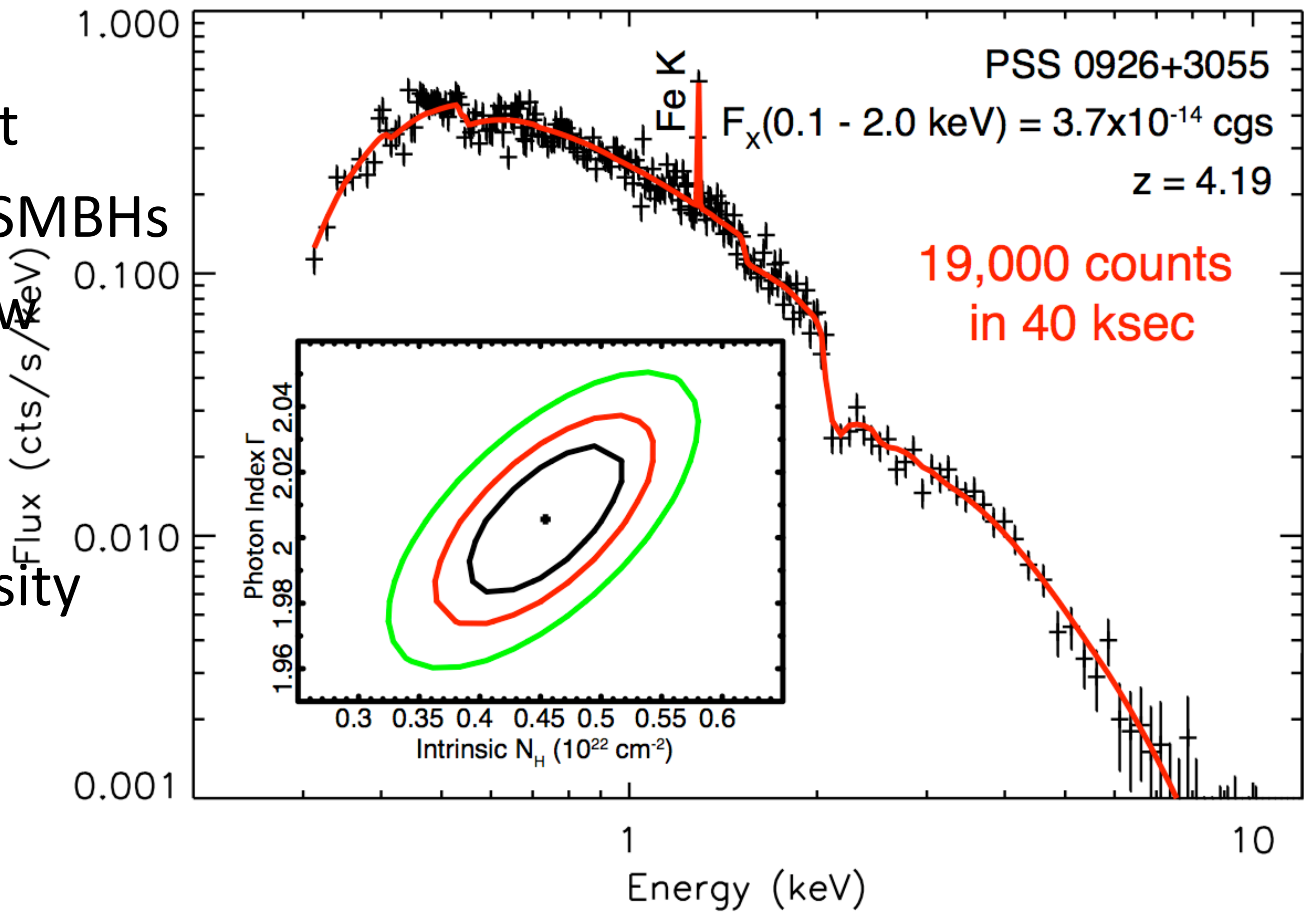


2 Megasecond Observation of the CDF-N (Alexander et al. 2003)

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

Evolution of Supermassive Black Holes

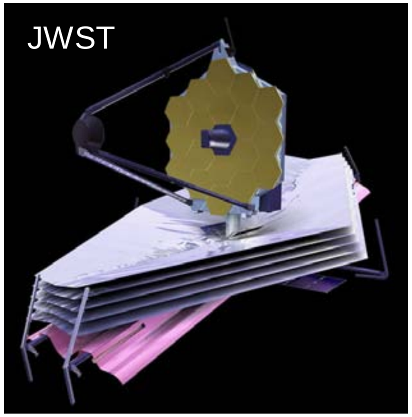
- At z=4-7, IXO will observe all types of AGN, including highly-obscured sources not visible today.
- X-ray spectra will
  - measure redshift
  - detect merging SMBHs via multiple narrow Fe Kα lines
  - Estimate % of Eddington luminosity

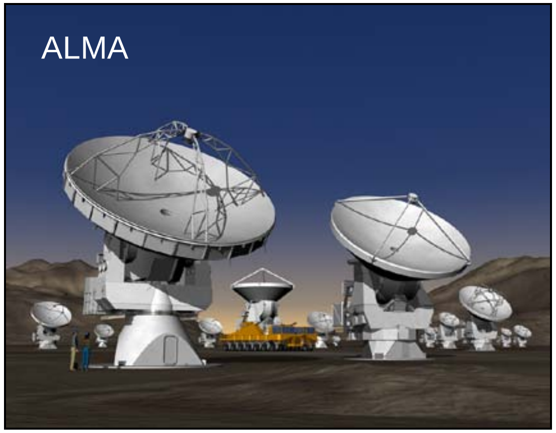


Accretion in the Universe

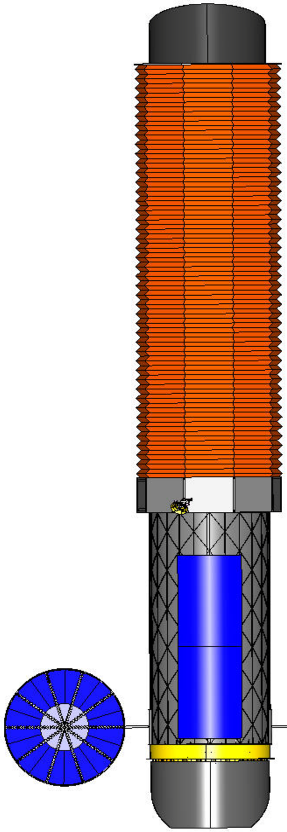
Starlight from First Galaxies

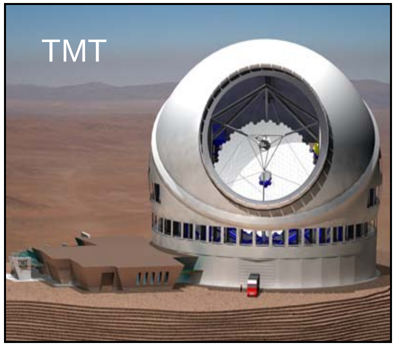
Accretion Light from First Galaxies



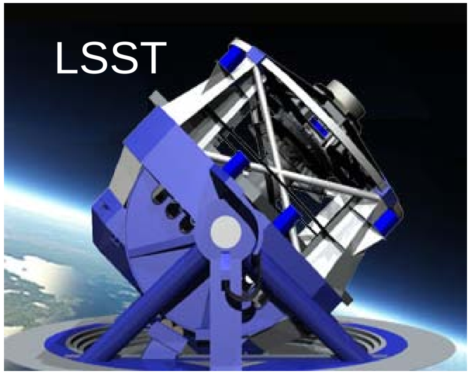


IXO

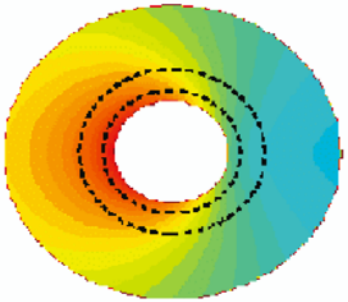


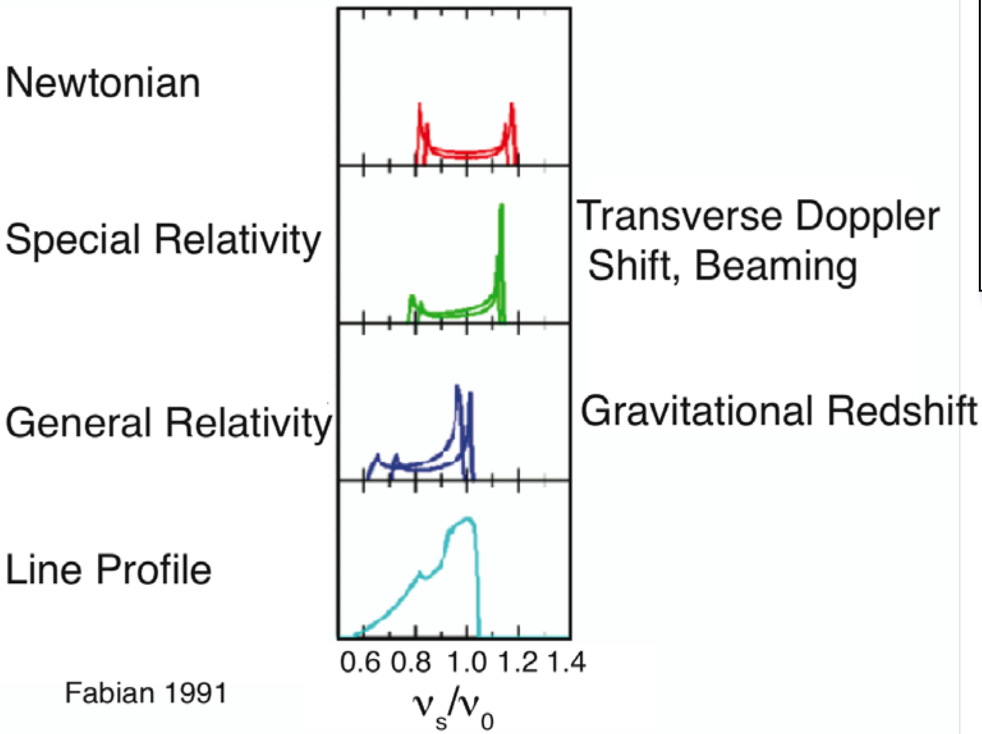


GMT

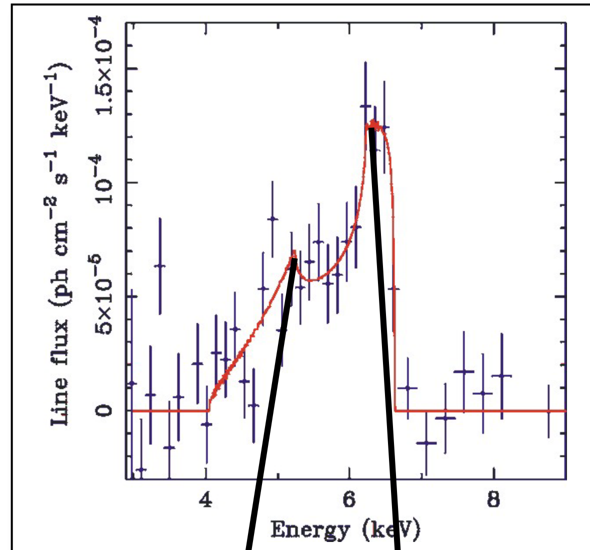


SMBH have mass and **Spin**: Fe Kα

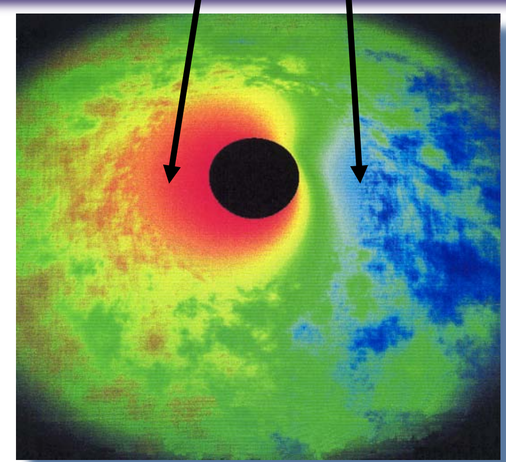




Fabian 1991

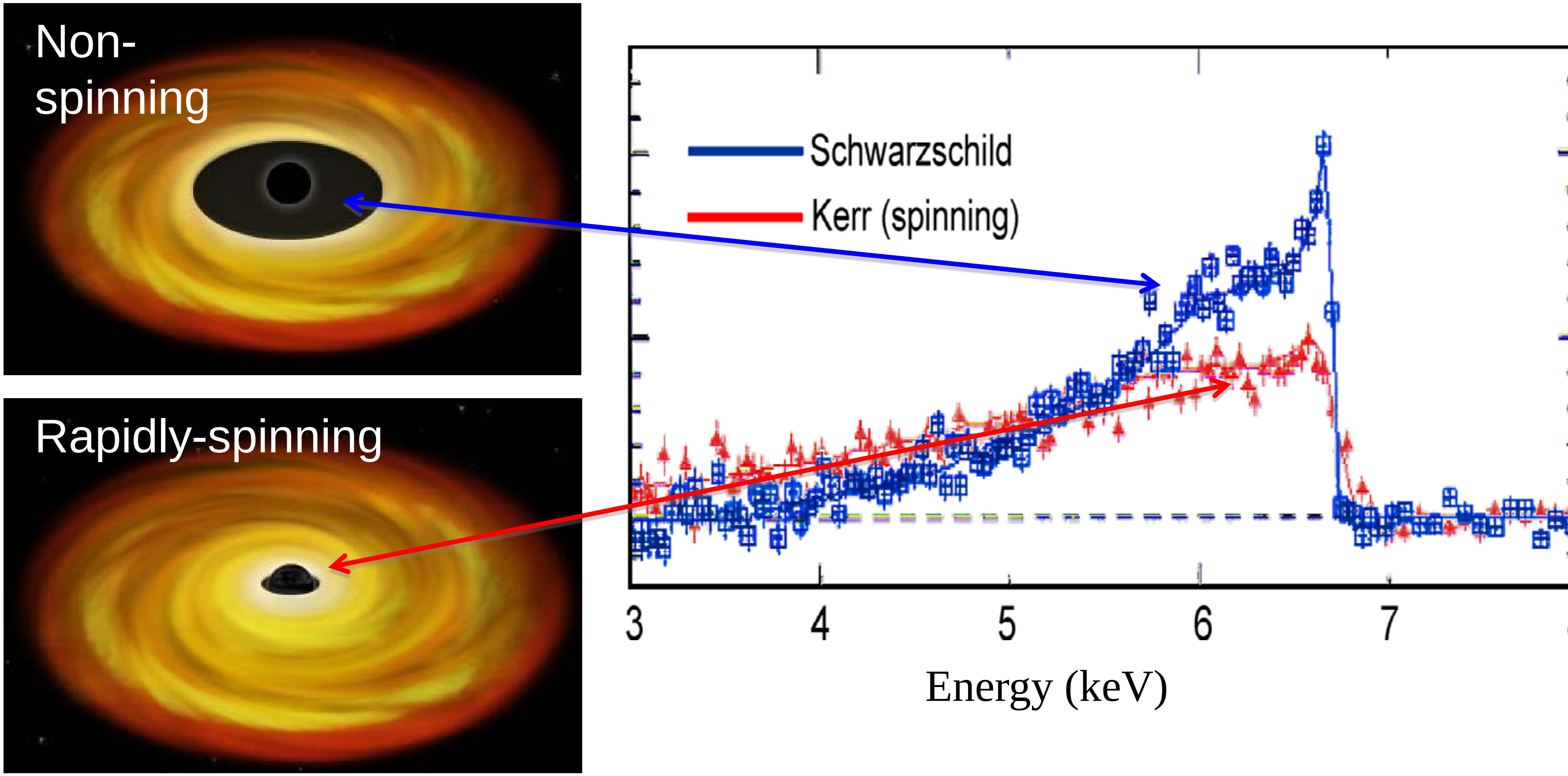


First observation Relativistic Fe line in SMBH - 1995



Theoretical ‘image’ of an accretion disk.

Black Hole Spin & Growth



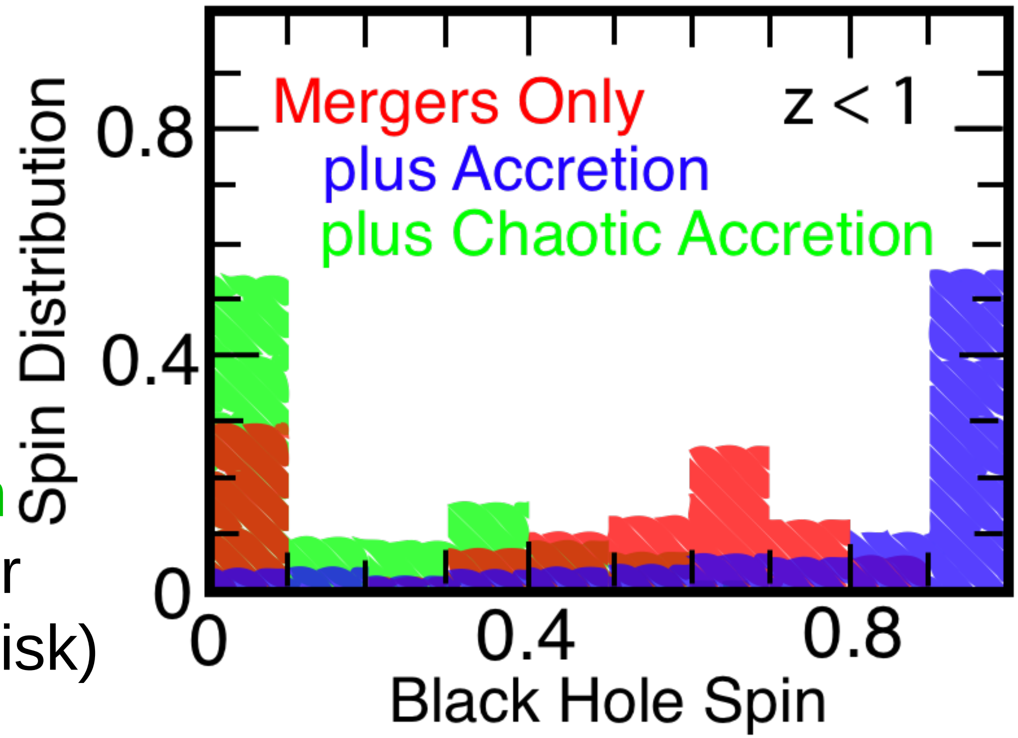
IXO will measure relativistic-broadened iron line emission, measuring the black hole’s spin.

Supermassive Black Hole Spin & Growth

Mergers with standard accretion: mostly maximally spinning black holes

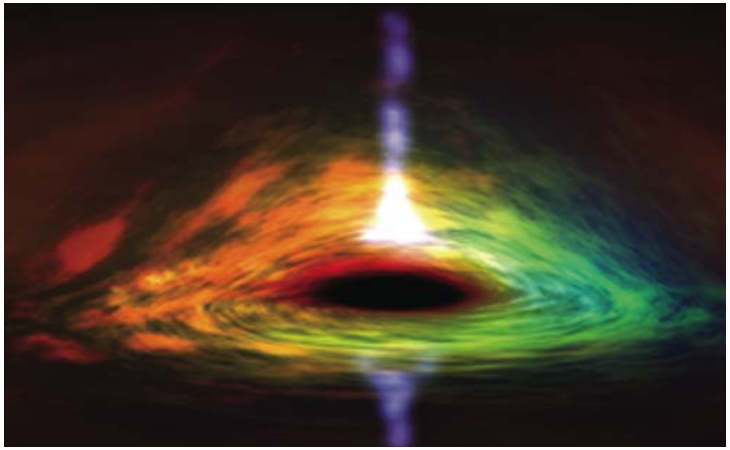
Mergers plus chaotic accretion (growth from absorbing smaller (0.1%) SMBHs, no accretion disk) leads to slow rotation.

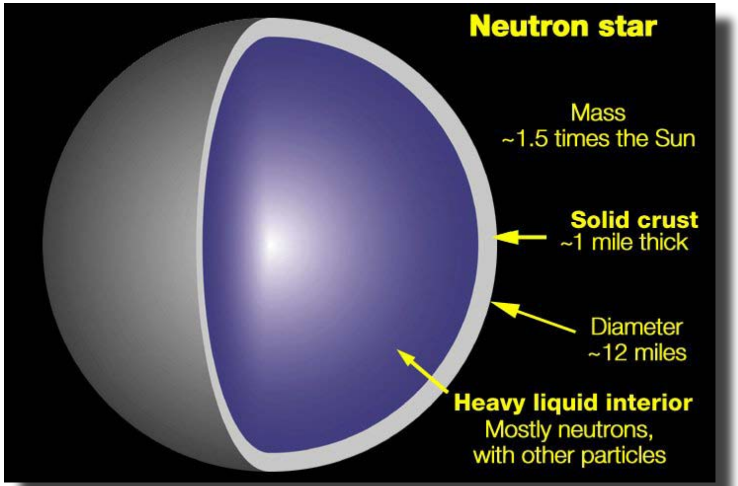
Merger-only growth: broad distribution of spins



based on Berti & Volonteri (2008)

Black Holes and Matter under Extreme Conditions





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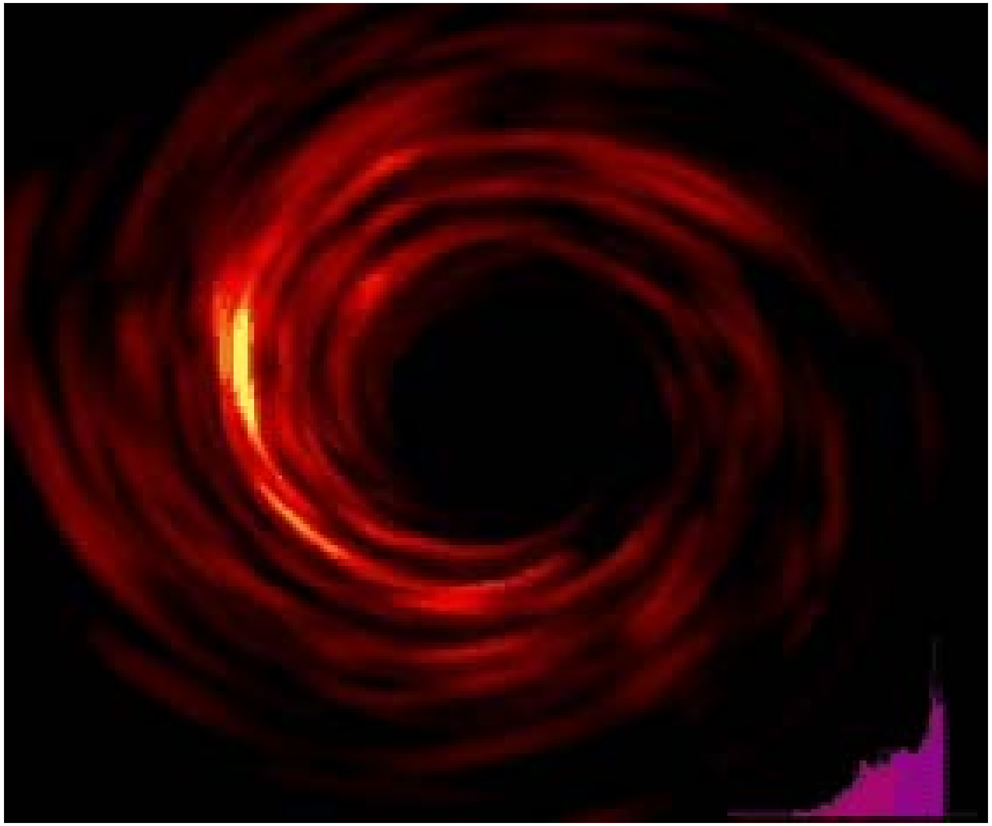
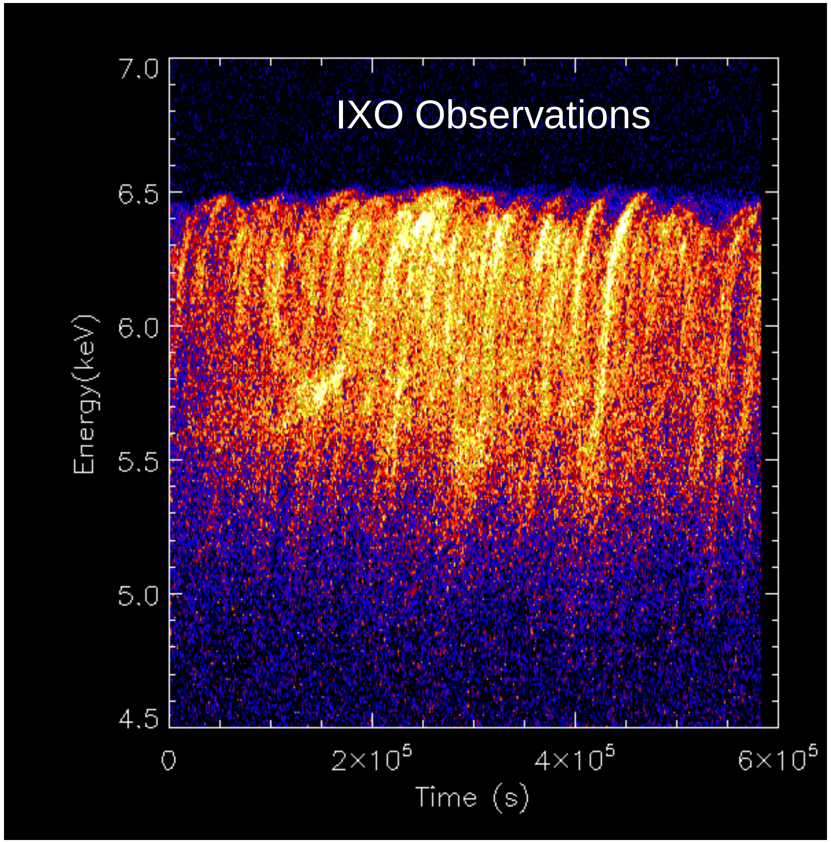
Testing GR: Black Hole Spin

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

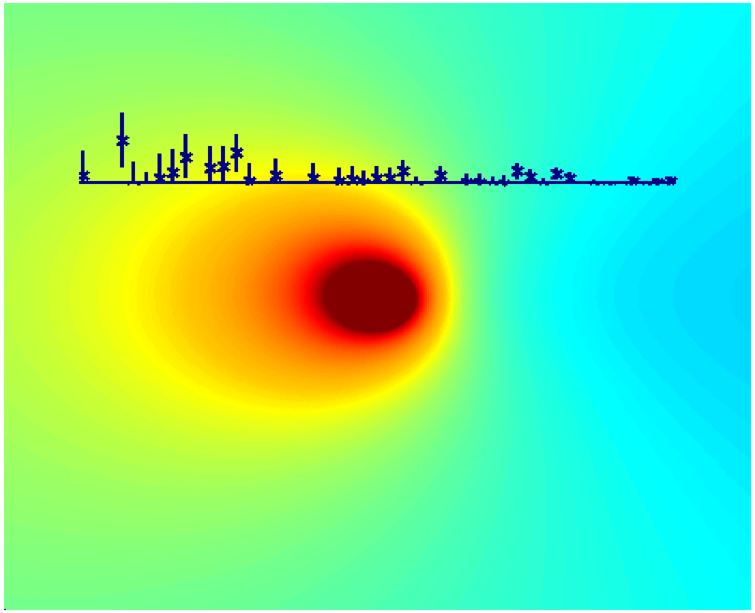
- ✓ **Dynamics of individual “X-ray bright spots” in disk to determine mass and spin**
- ✓ **Quantitative measure of orbital dynamics: Test the Kerr metric**

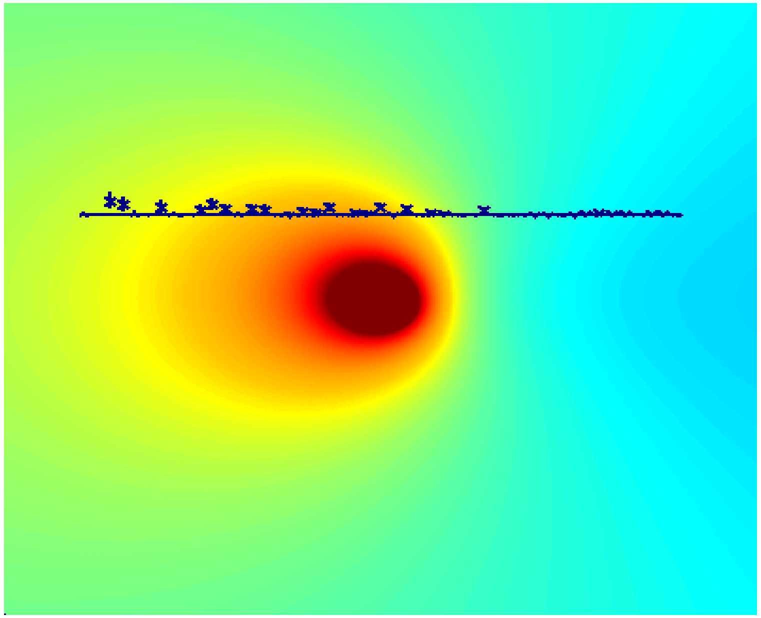




Magneto-hydro-dynamic simulations of accretion disk surrounding a Black Hole (Armitage & Reynolds 2003)

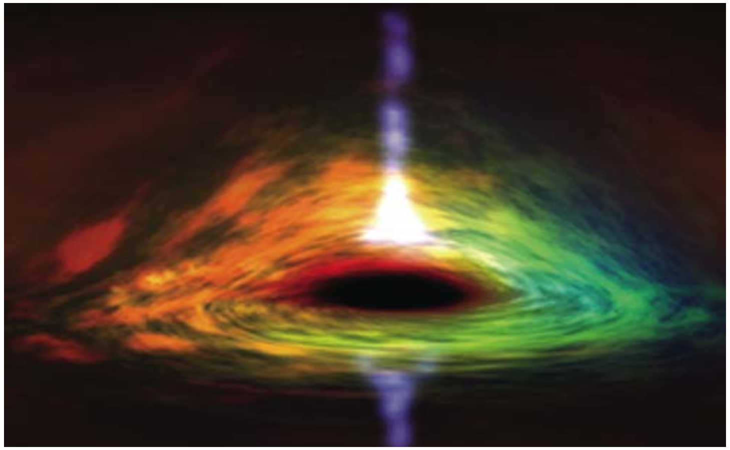
Iron Line Reverberation Mapping (Photon Orbits as well as Matter Orbits)

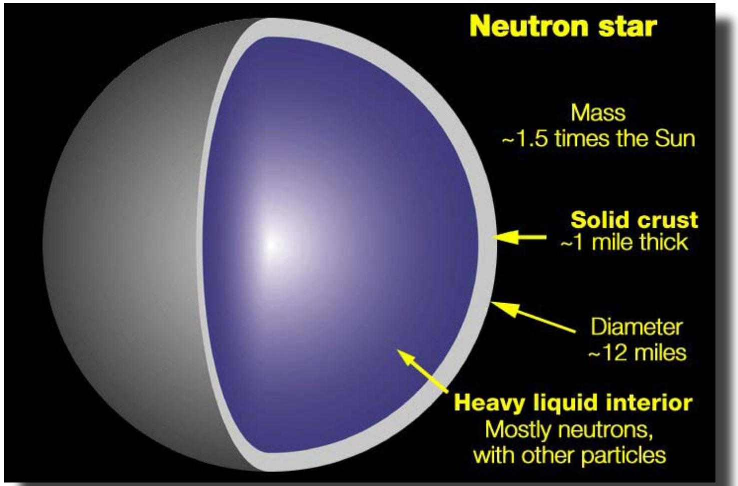




Reverberation mapping measures photon orbits - not matter orbits – in the strong field limit.
Two measurements are complimentary and can be done at same time.

Black Holes and Matter under Extreme Conditions





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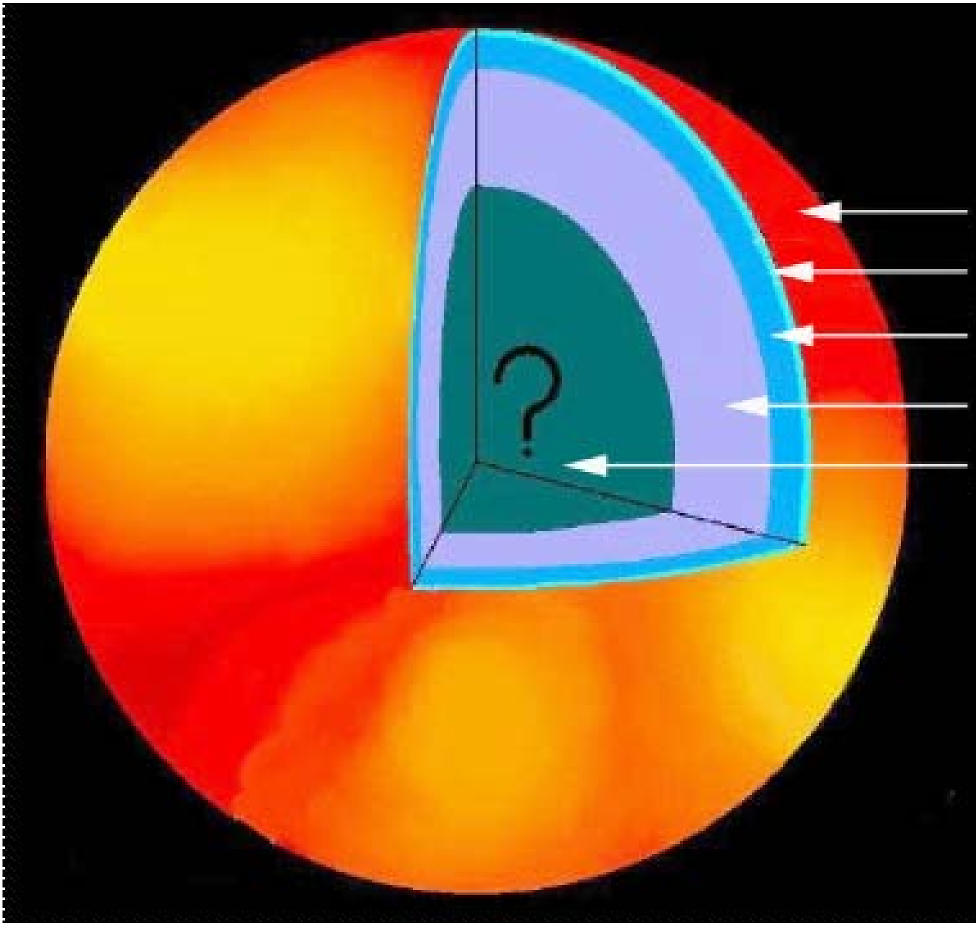
Neutron Star Equation of State



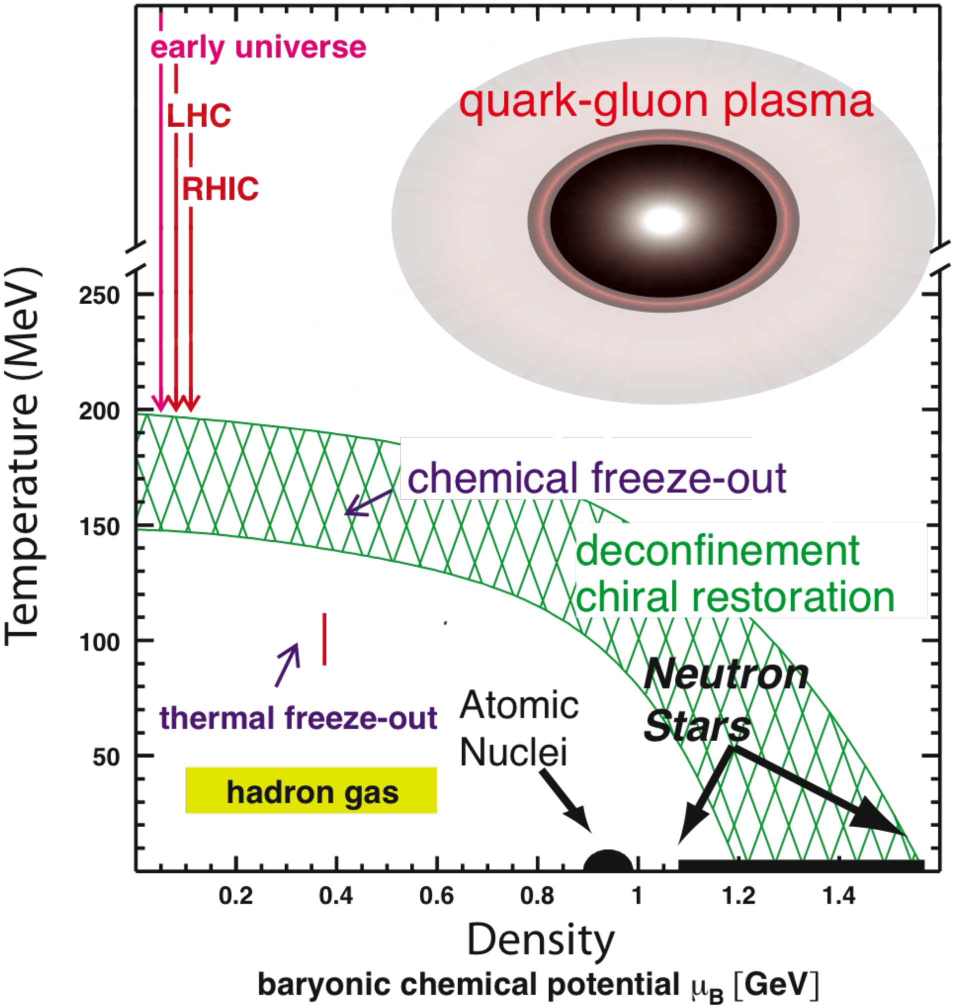
- Outer crust 'normal', but core uncertain.
- Hard to extrapolate from normal nuclei (~50% protons) to the high-density regime of nearly 0% proton fraction.
- EOS models depend upon assumptions made about the phase of matter in the core: (e.g., hadrons, Bose-Einstein condensates, quark matter).
- Each new phase increases the compressibility of the star, allowing for a smaller NS.

Neutron Star Equation of State

Interiors of neutron stars present extremes of density **not found anywhere else in the Universe**

Nature of matter in these conditions a deep mystery – entirely new states may be present

Neutron star **mass** & **radius** measurements will provide limiting high-density data needed to advance QCD theory

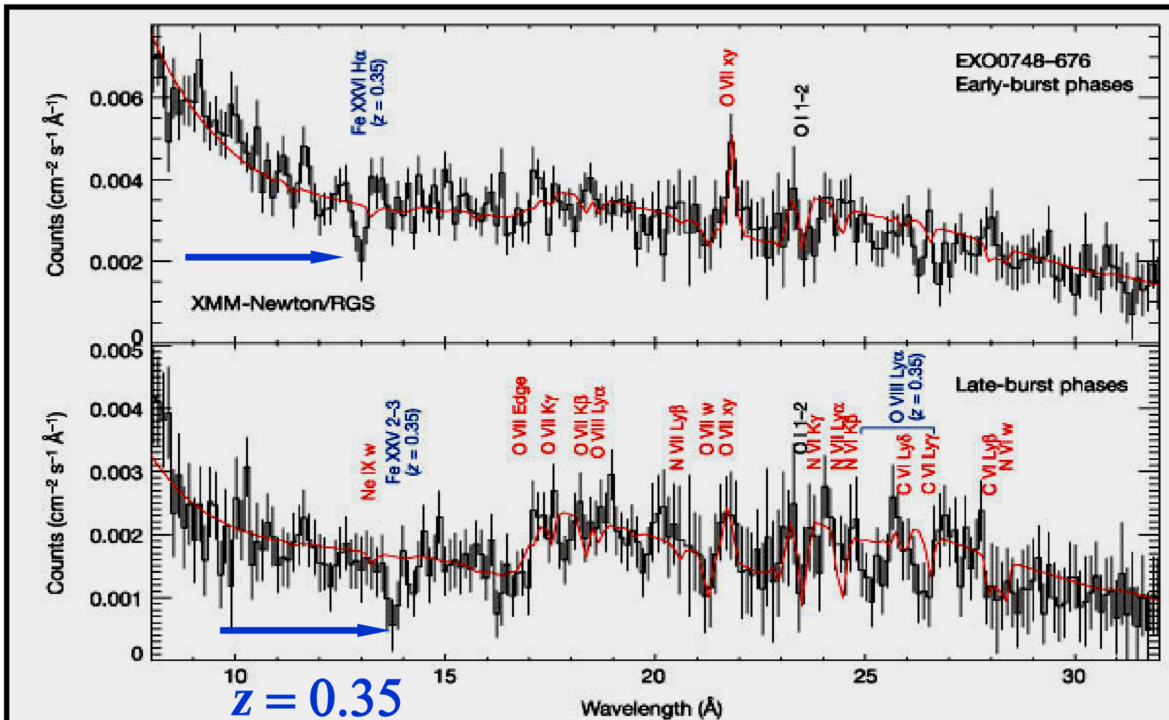


Photospheric absorption during X-ray bursts

EXO 0748-676, a known X-ray burster

XMM-Newton observed it as a calibration target:

~ 335 ks with RGS cameras; spectra of 28 X-ray bursts co-added.



Absorption lines at λ 13.0Å and λ13.7Å in the combined early- and late-burst spectra, respectively.

Fe XXVI (n = 2–3) and Fe XXV (n = 2–3), respectively, at the same redshift $z = 0.35 \pm 0.01$.

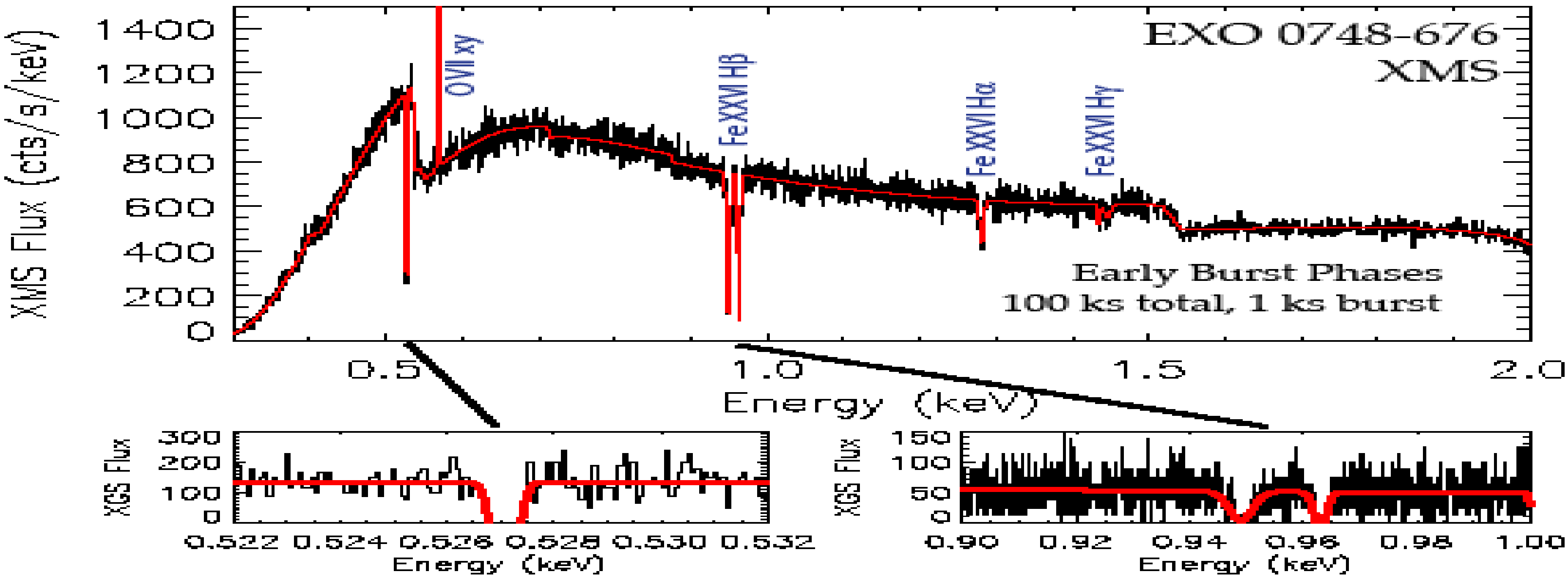
Cottam, Paerels & Méndez

What is the Neutron Star Equation of State?

IXO will provide many high S/N measurements of X-ray burst absorption spectra:

- Measure of gravitational red-shift at the surface of the star for **multiple** sources, constrains M/R over range of M.

1ks at 40mCrab,
~100ks stare time

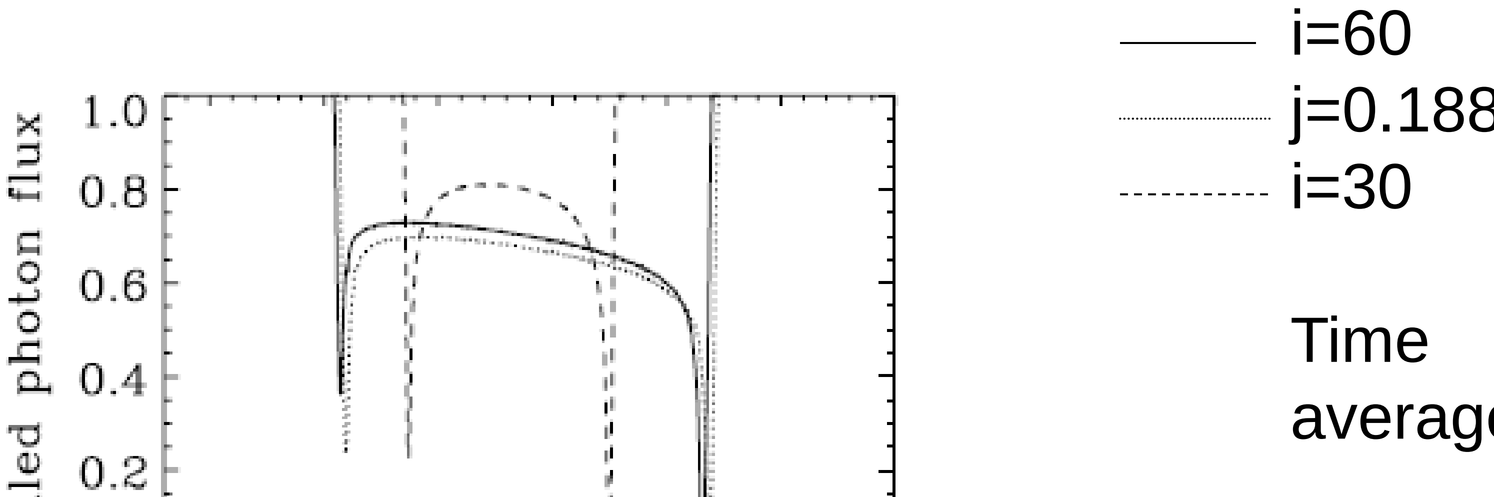


Determining M, R separately

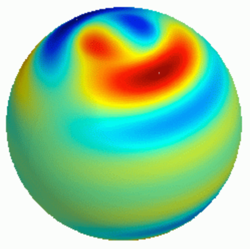
Beaming makes blue wing stronger

Frame dragging seen if S/N high enough

Dependence on higher powers of M&R while z~M/R



Time averaged



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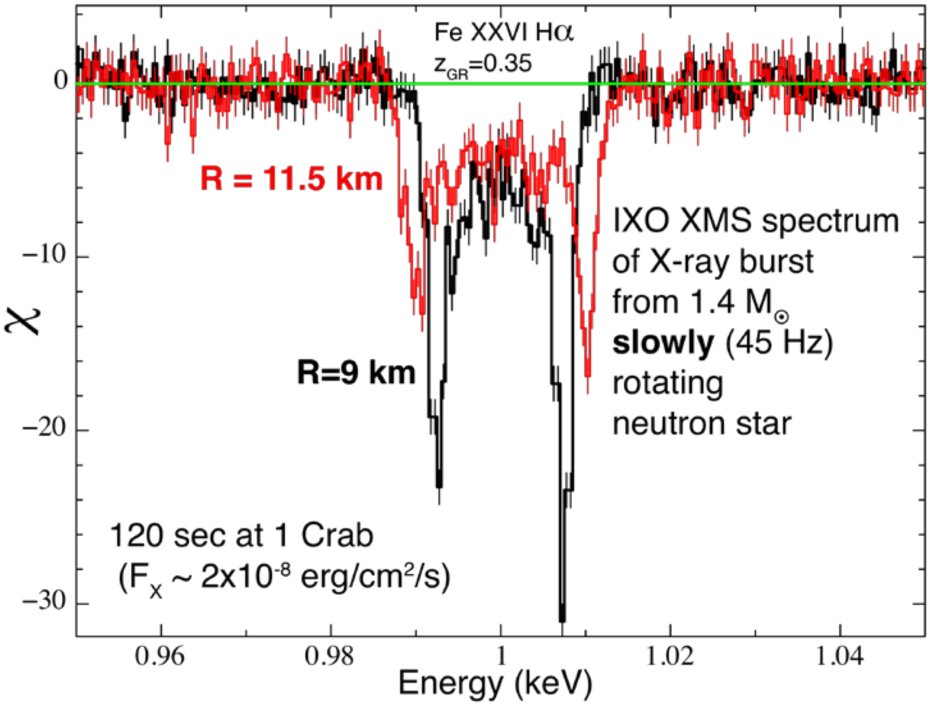
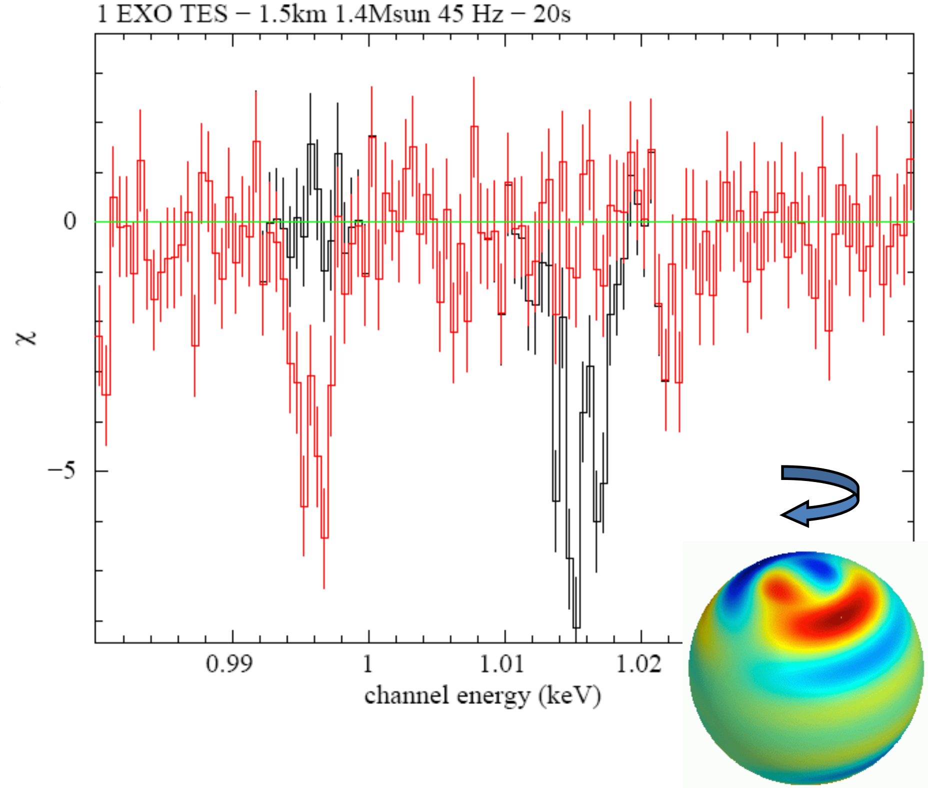
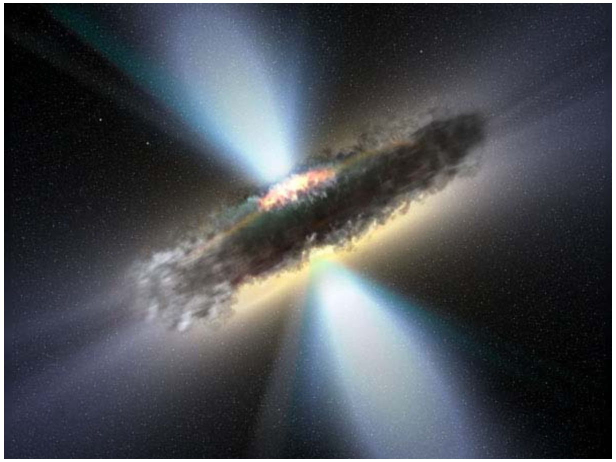
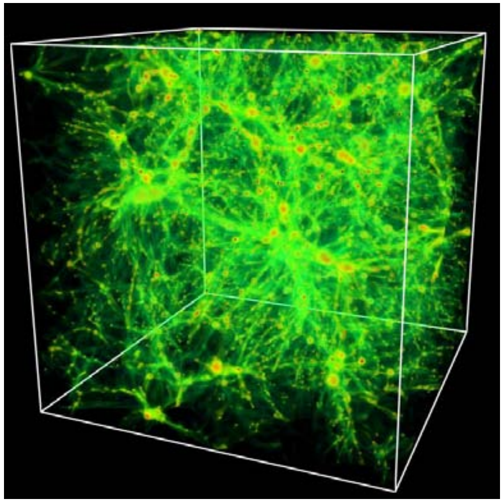




Multiple techniques will be used: pulse phase spectroscopy will give M and R independently and provide additional consistency check

Formation and Evolution of Galaxies, Clusters, and Large Scale Structure





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?

Cosmic Feedback

$$E_{BlackHole} > 30 \times E_{Galaxy}$$

Energy released by growth of Black Hole

Gravitational Binding Energy of Host Galaxy

The central SMBH has the energy; but how does an object the size of the Solar System connect with a galaxy?

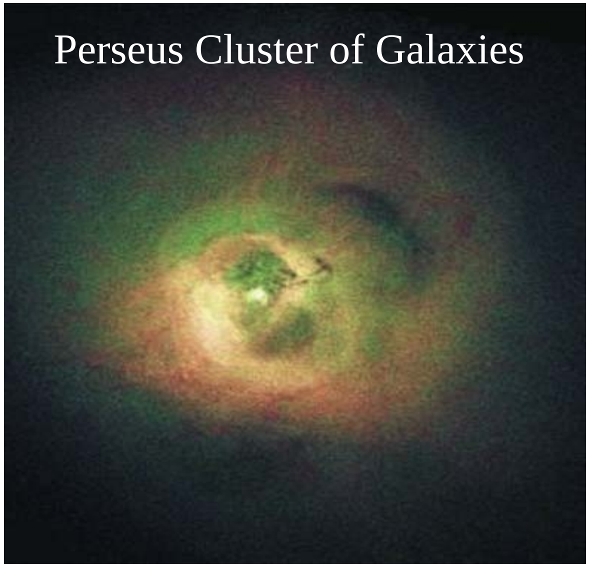
Possible major modes for the interaction: Kinetic (radio/jet) and Radiative (quasar)

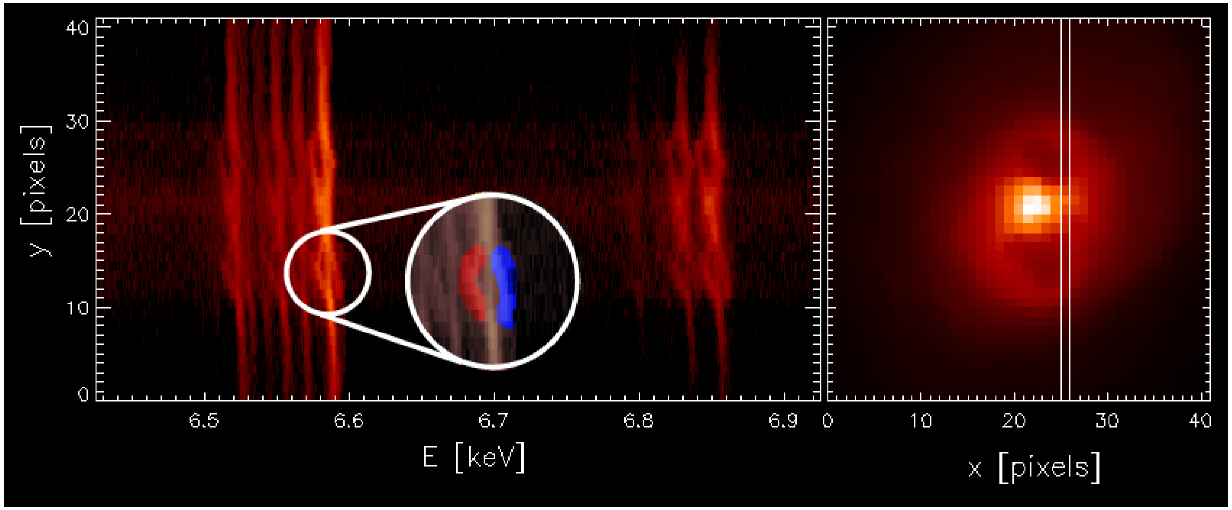
Cosmic Feedback

AGN feedback must regulate the growth of galaxies and clusters of galaxies

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

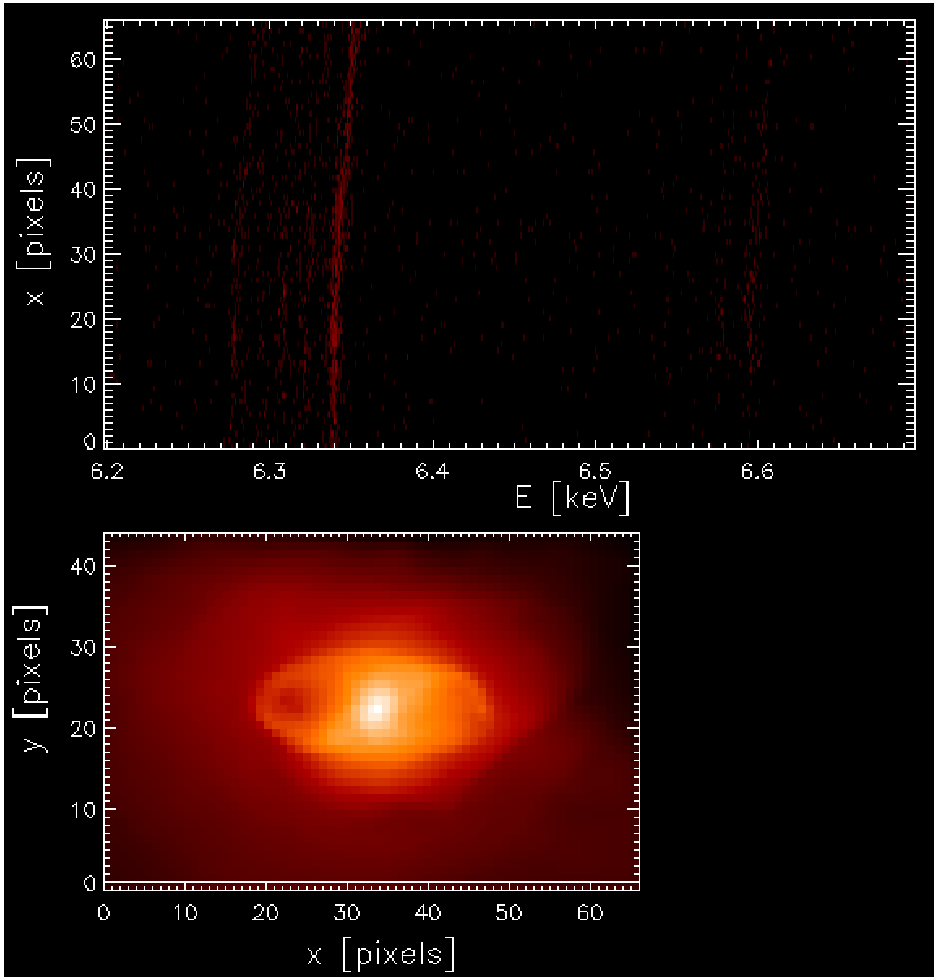
IXO will probe the hot ICM/IGM through velocity measurements accurate to the required ~100 km/s





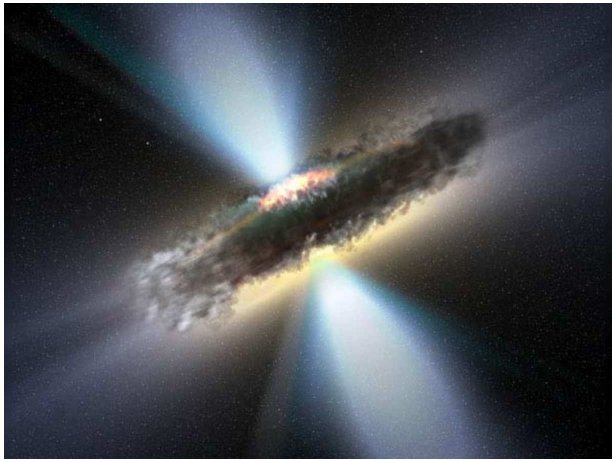
Cosmic Feedback

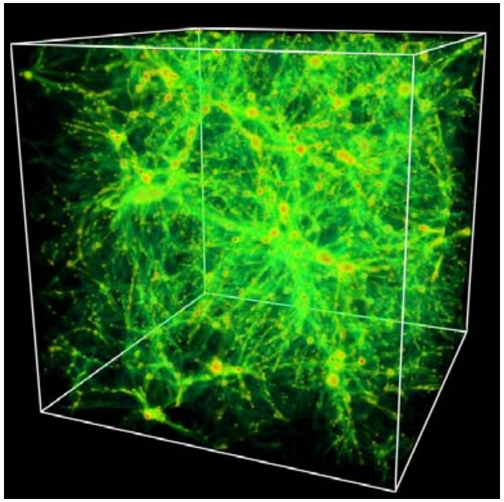
Cyg A



Non-dispersive spectral/spatial measurements will determine the temperature, ionization state, and velocities in the intra-cluster medium – observing feedback in action.

Formation and Evolution of Galaxies, Clusters, and Large Scale Structure





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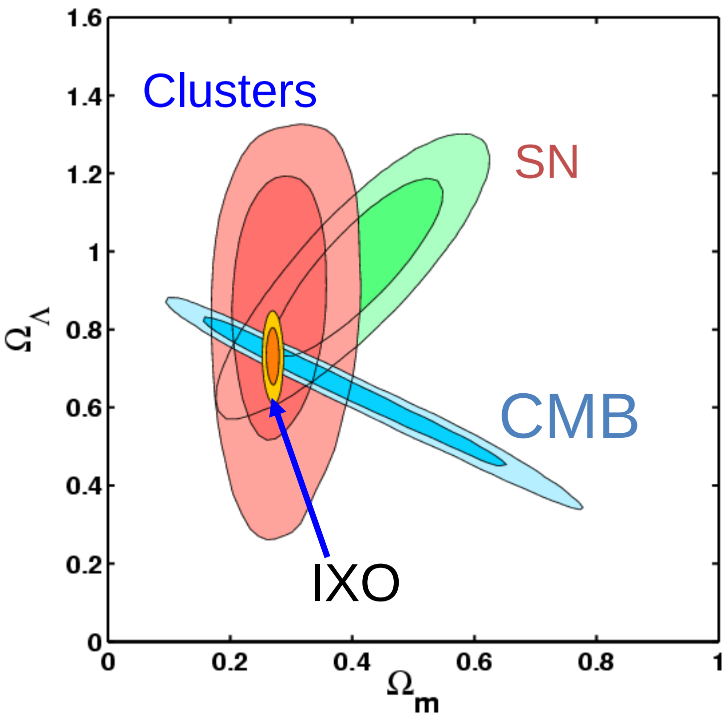
Cosmology with IXO

<u>The F(gas) experiment: the largest, relaxed clusters have proven to be good 'standard candles'</u>



Chandra, Allen et al 2008

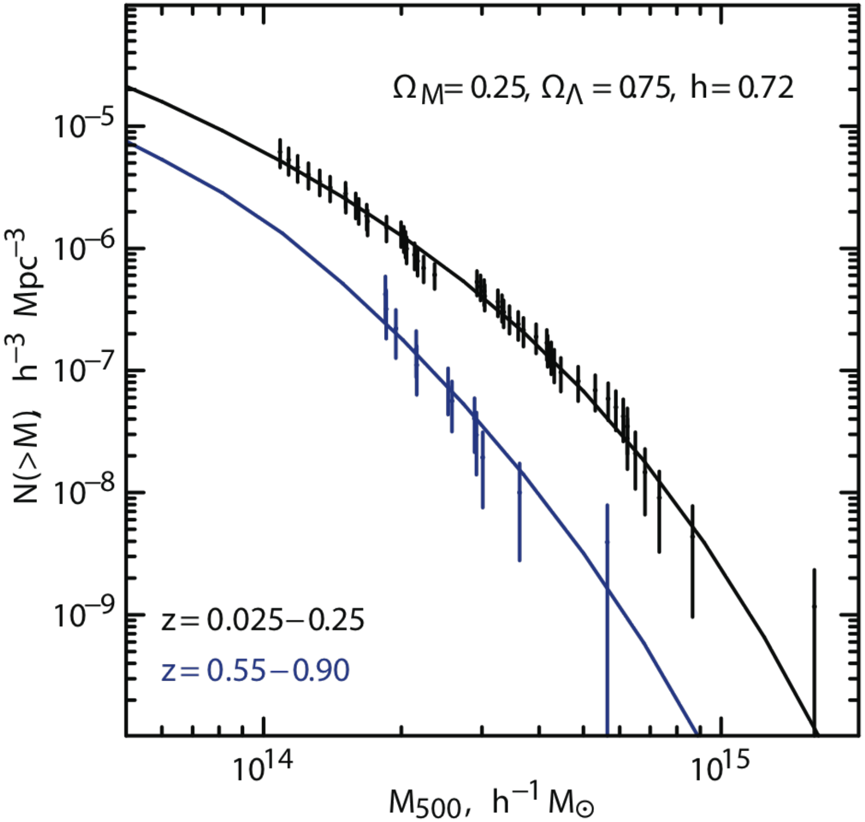
Weighted mean scatter only 5% in fgas (3.3% distance). For SNIa, systematic scatter is detected at ~7% level (distance). No sign as yet of systematic scatter in fgas(z) data.

Simulations of Crain et al (2006) suggest scatter should be at few % level in fgas → method offers prospect to probe cosmic acceleration to high precision with Con-X

Cosmology with IXO

Measure the growth of cosmic structure by measuring the mass of a survey of clusters as a function of z;

V. Springel



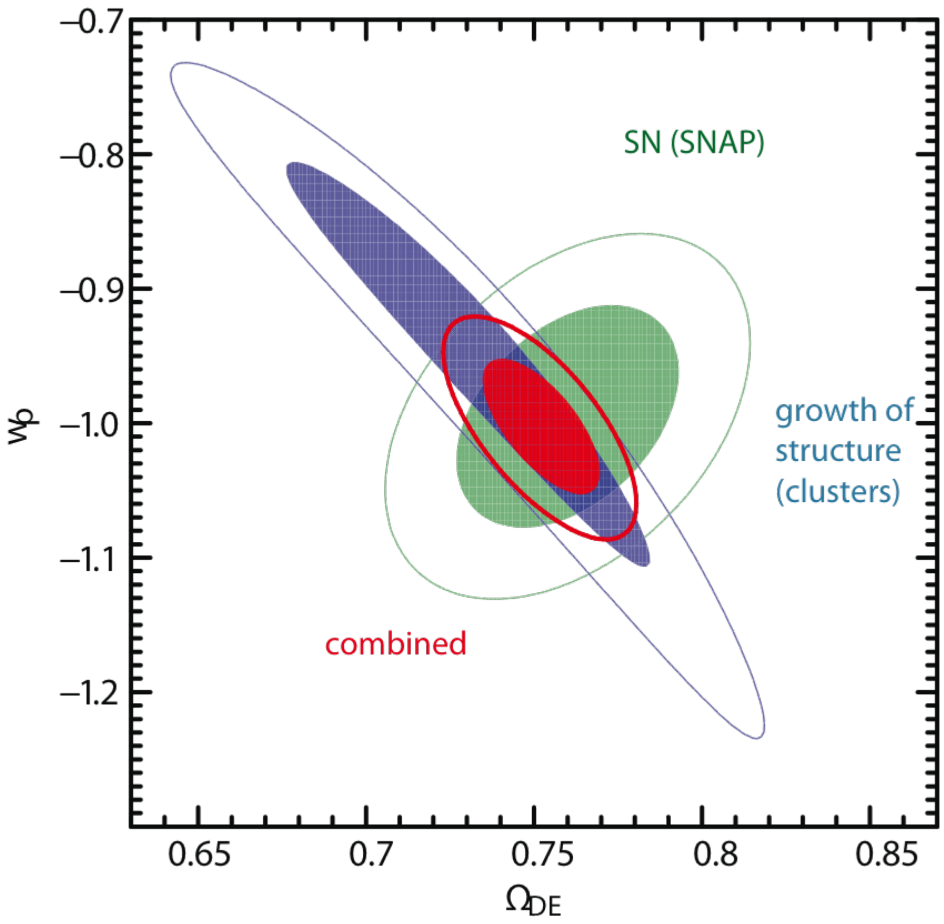
Vikhlinin+09

Cosmology with IXO

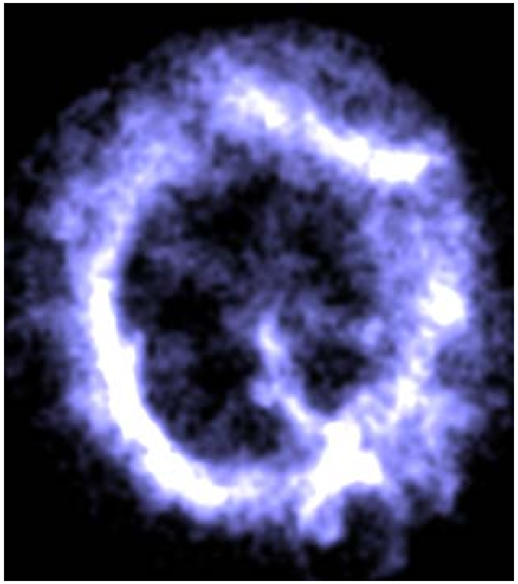
IXO will powerfully complement other dark energy measurements

The uncertainties in cosmological parameters from cluster `growth of structure’ work (itself a distinct approach from standard-candle methods) are dominated by uncertainties in the mass-observable relation.

IXO will provide a quantum leap in constraining power and, in combination with hydrodynamical simulations, SZ and gravitational lensing observations, the tightest possible control of systematics.

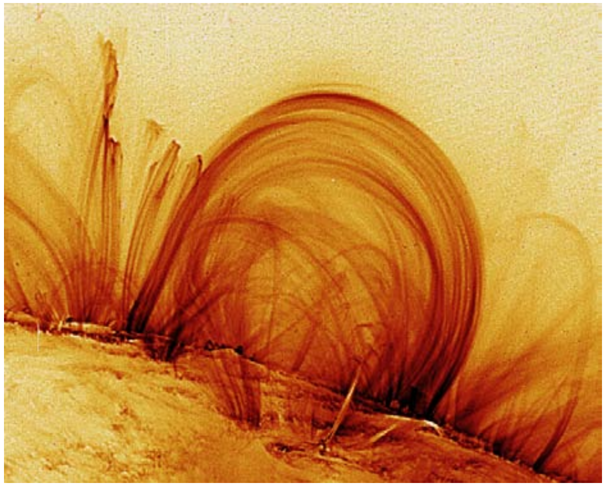


Life Cycles of Matter and Energy



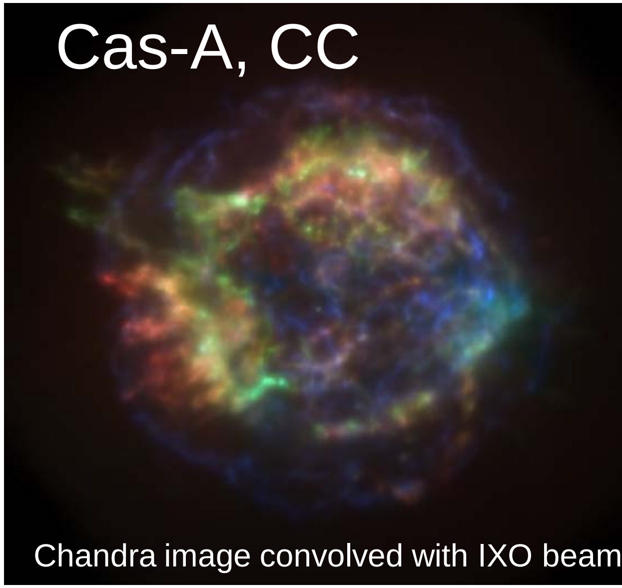
When and how were the elements created and dispersed?

How do high energy processes affect planetary formation and habitability?



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

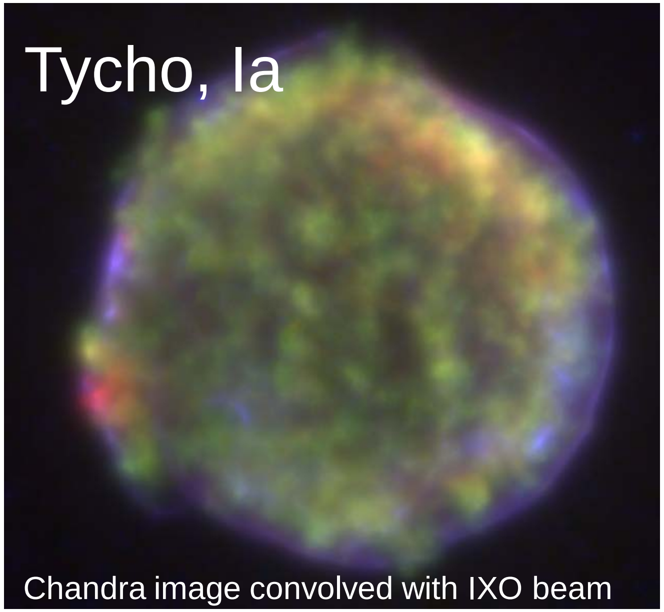
Forming the Elements



Chandra image convolved with IXO beam

X-rays:

- **Uniquely** illuminate the composition and dynamics of the shocked ejecta and ambient medium
- offer a 3-D view of SN **remnant** ejecta – in an individual point-like SN, only sample line-of-sight



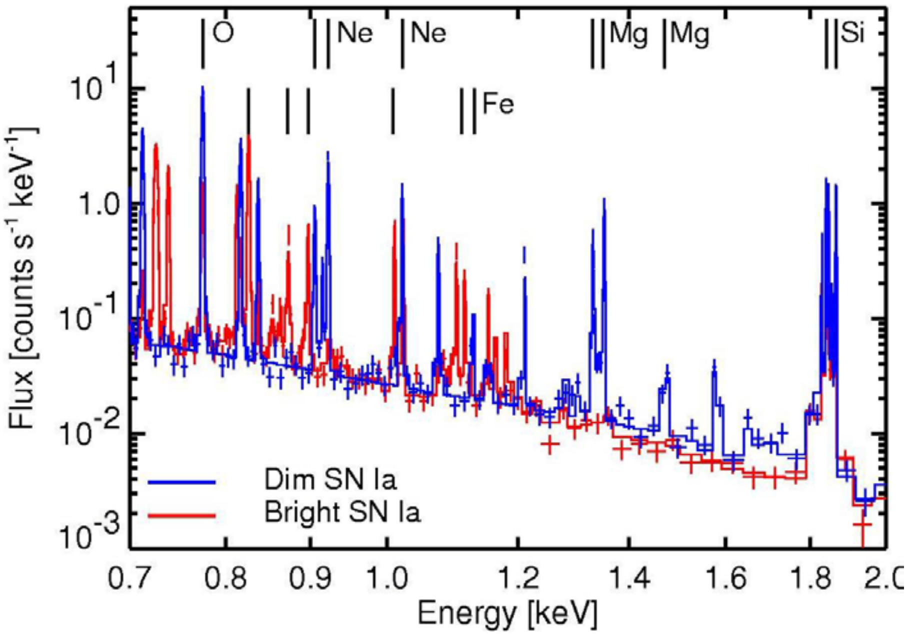
Chandra image convolved with IXO beam

Fe-group synthesis

- CC SNe – Fe comes from the innermost parts of the exploding star next to the jet/neutrino-driven convection that drives the explosion
- In SN Ia, nucleosynthesis **is** the explosion (provides the energy to unbind the star); amount of Fe is key to optical light curve
- Fe is seen in galaxy clusters to cosmological distances

Remnants of SN Ia in M33?

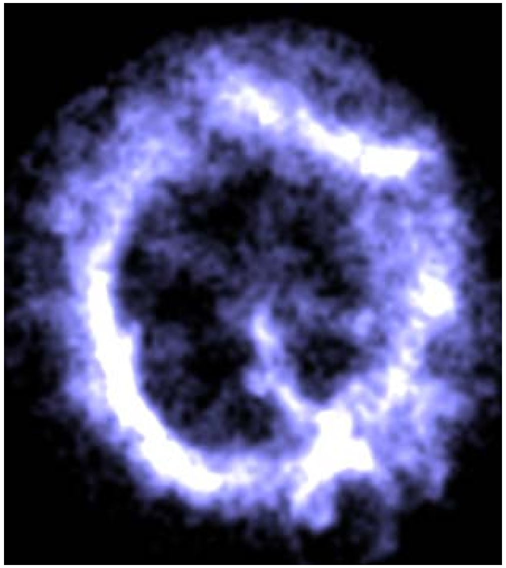
An example science project, once young SN Ia remnants are found in M33:



IXO will allow a statistical study of SN Ia progenitor properties in relation to stellar populations in M33 (and M31).

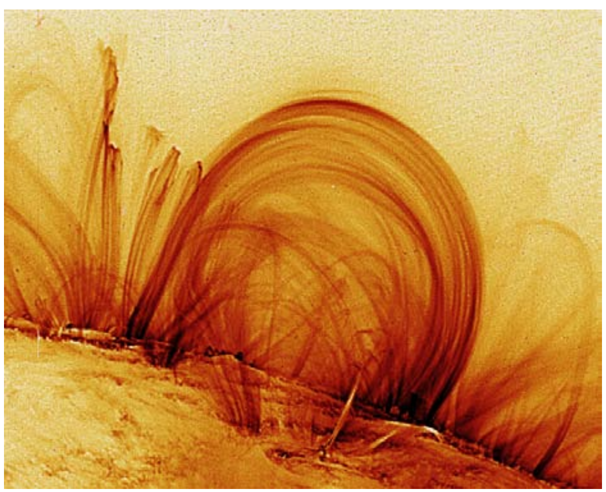
There is growing evidence that bright and dim Type Ia SNe have different progenitors (Scannapieco & Bildsten 2005). Systematics due to environmental evolution (Kim etal 04)? X-ray spectra of the remnants can distinguish between SN Ia subtypes (Badenes at al. 2006, 2008). *IXO* simulations (left) show obvious differences between bright (Fe-rich) subtypes (red curve) and dim (Fe-poor) ones (blue) in 100 ks long observations of 400-yr old SNRs.

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?

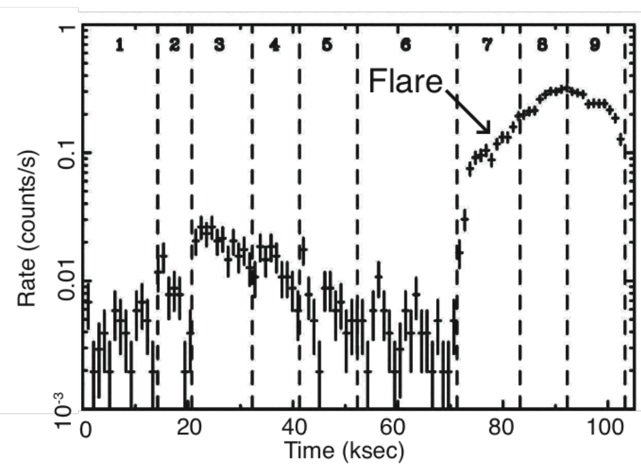


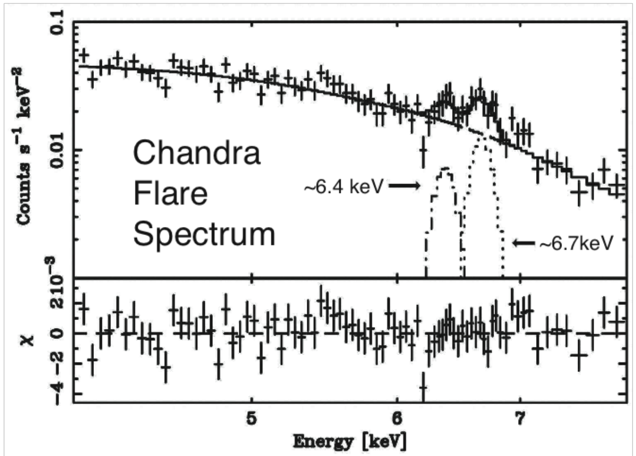
How do magnetic fields shape stellar exteriors and the surrounding environment?

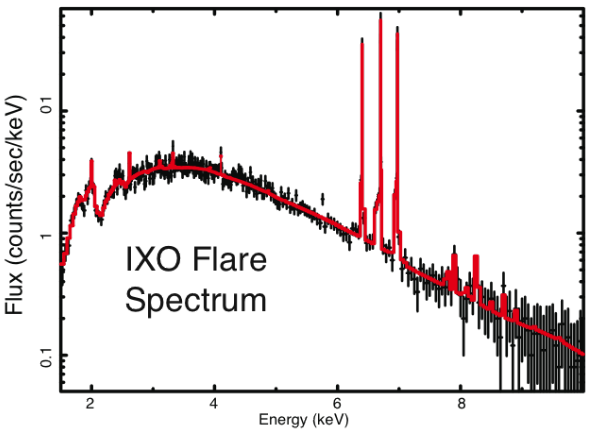
X-ray and Planetary Disks

How do X-rays influence planet formation in protoplanetary disks?

YLW 16A: protostar in Oph

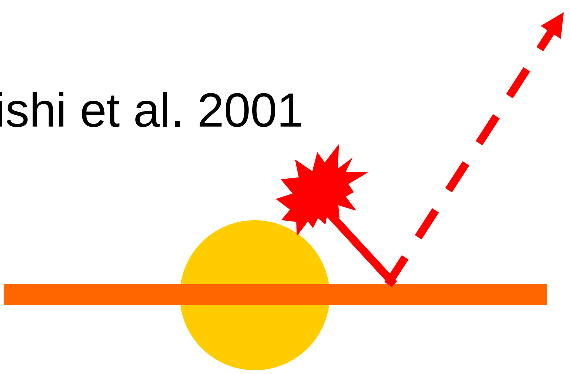






Chandra YLW 16A superflare, 1.2 days
Imanishi et al. 2001

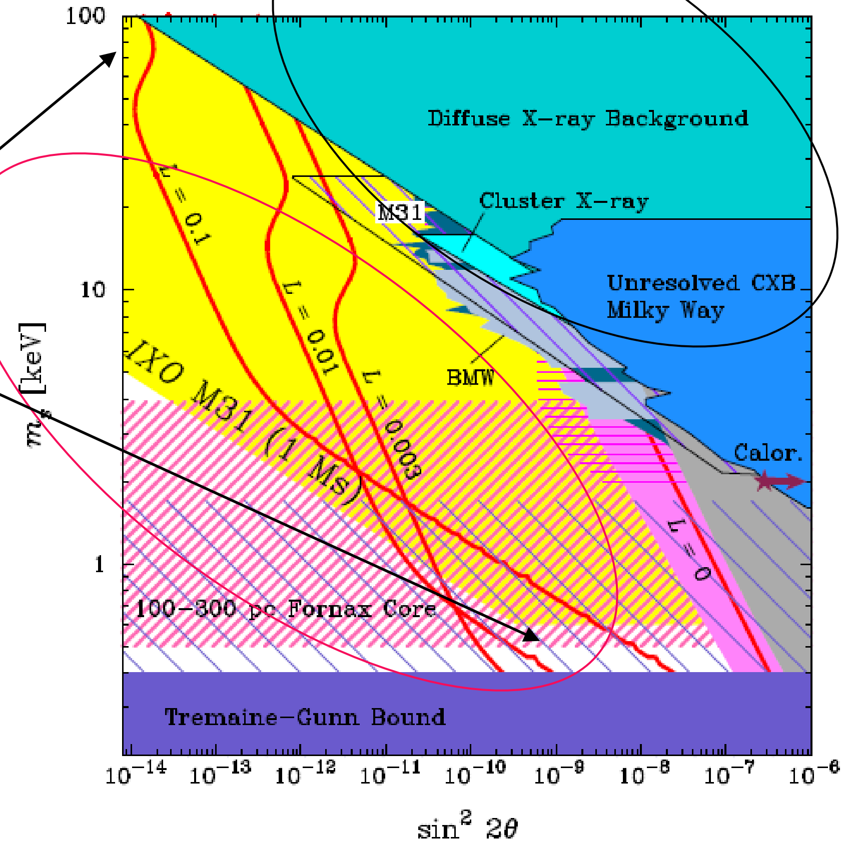
Imanishi et al. 2001



Dark Matter Decay?

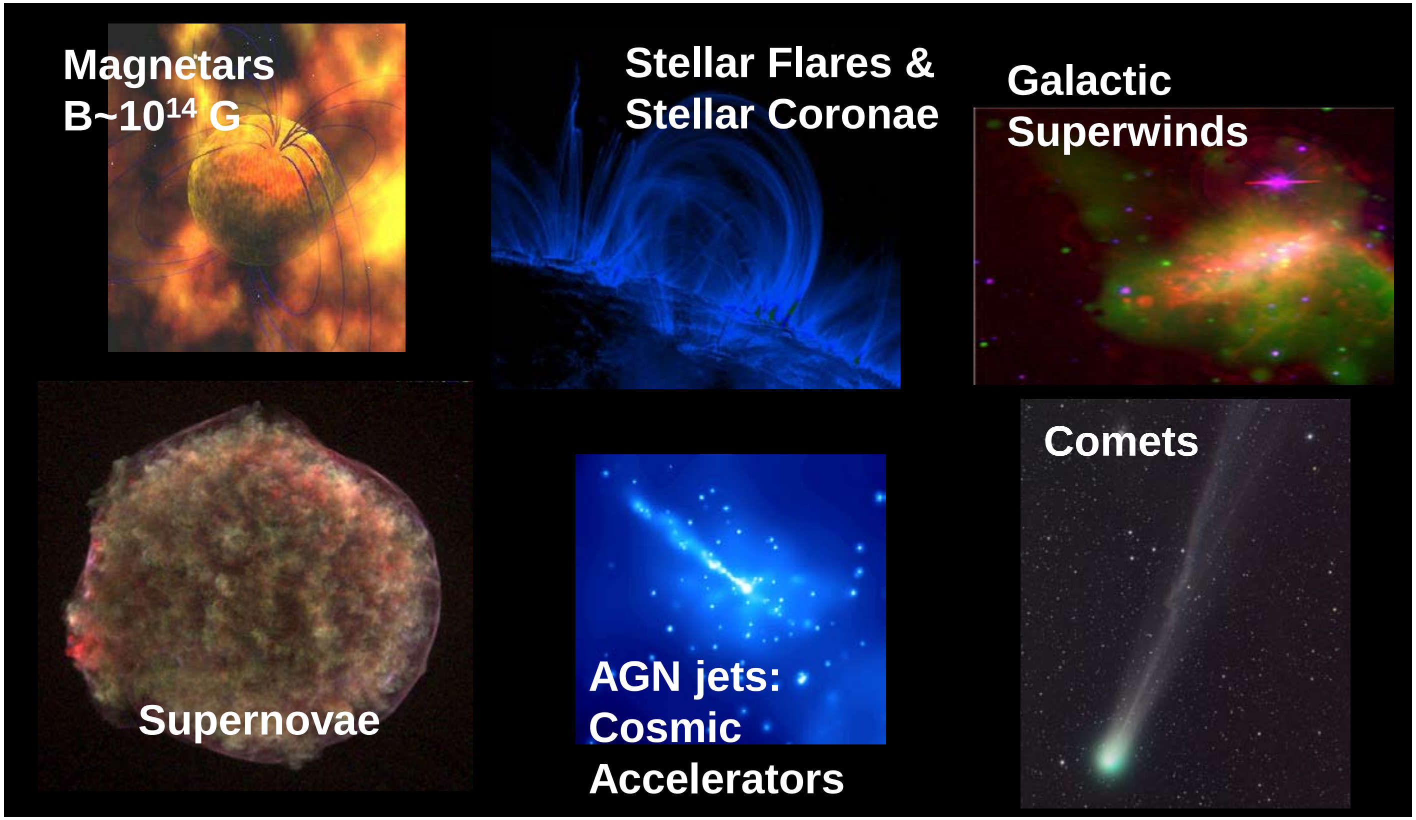
- Kev Abazajian
- Sterile Neutrino?
- IXO ~100x more sensitive for direct detection of decay particle IF sterile neutrino

Ruled out



favored

Wide Range of Science Topics:



As a General Observer, Observatory Class mission, the IXO will be open for use by all via A peer-reviewed process. NAS/NRC: '[the IXO] will make the broadest and most diverse Contributions to astronomy of any of the candidate Beyond Einstein Missions.'

Mission Payload

Flight Mirror Assembly (FMA)

- Highly nested grazing incidence optics

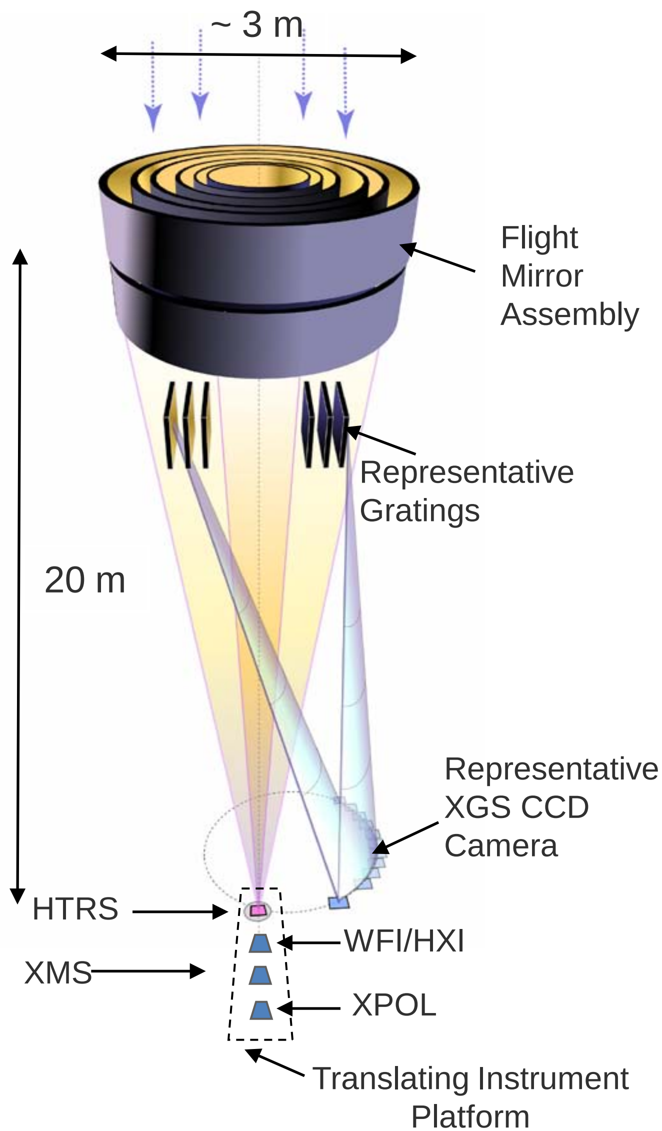
Spectroscopy Instruments

- X-ray Micro-calorimeter Spectrometer (XMS) - BSDO
- X-ray Grating Spectrometer (XGS)

Imaging, Timing and Polarimetry Instruments

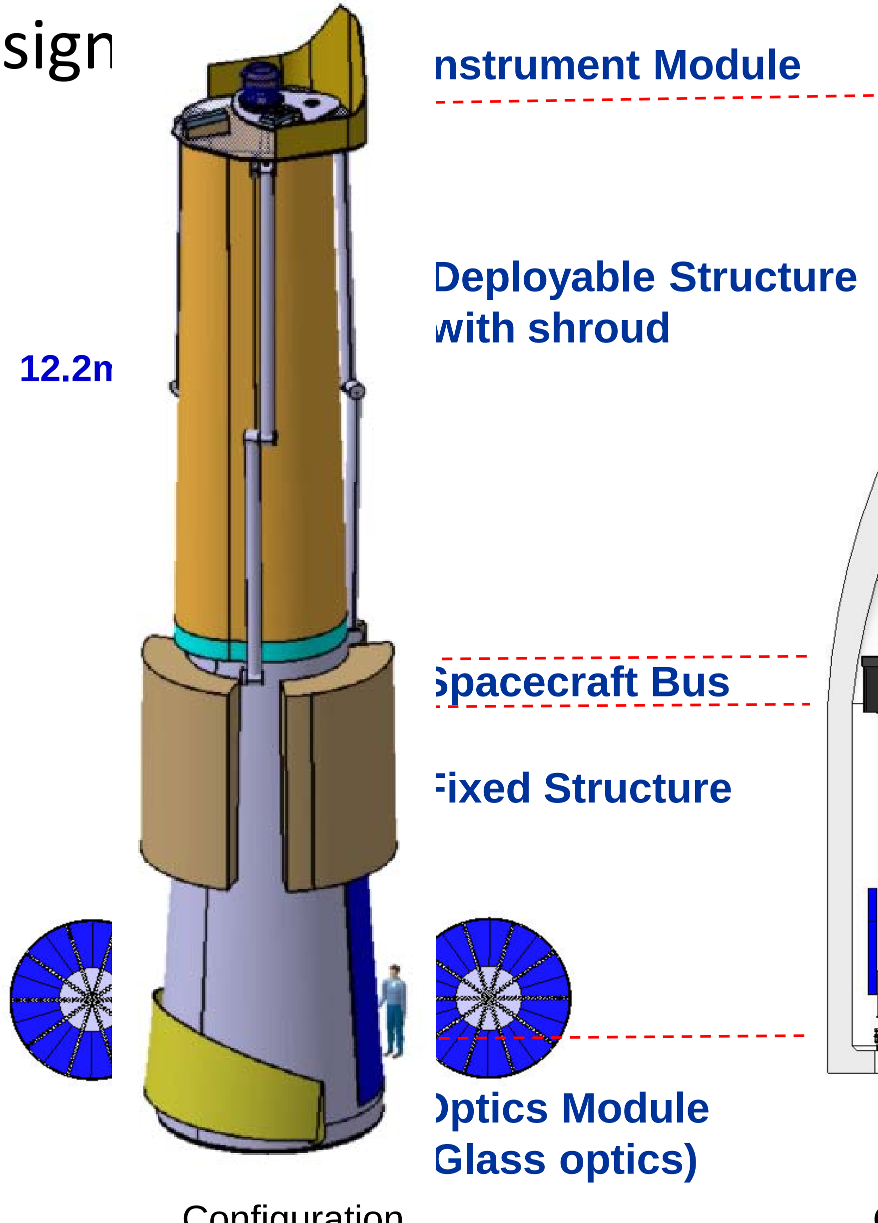
- Wide Field Imager (WFI) and Hard X-ray Imager (HXI)
- X-ray Polarimeter (XPOL)
- High Time Resolution Spectrometer (HTRS)

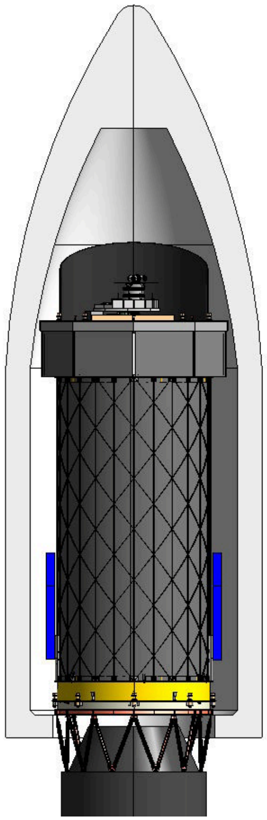
XMS, WFI/HXI, XPOL and HTRS observe one at a time by being inserted into focal plane via a Translating Instrument Platform



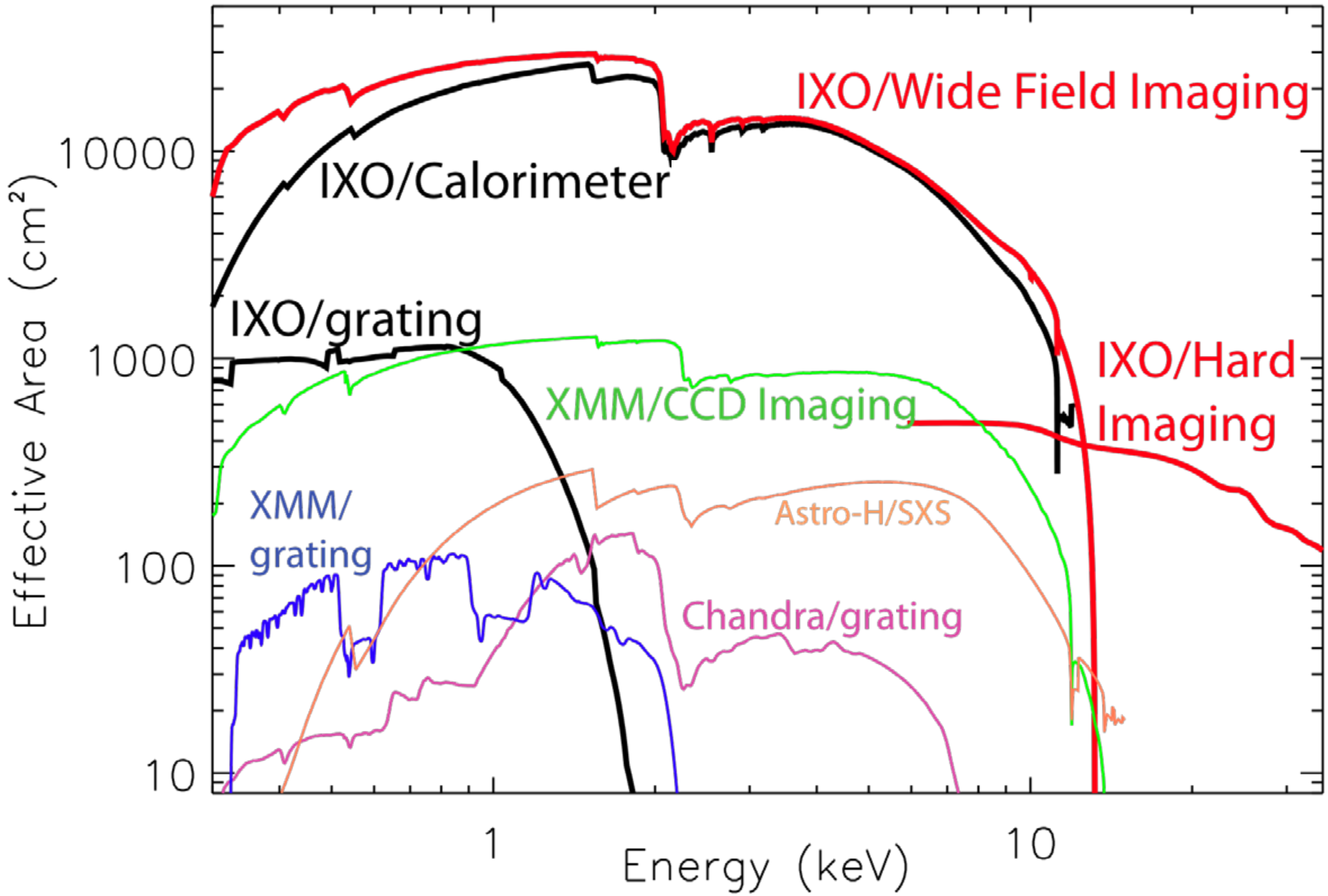
NASA/ESA Mission Design

- The observatory is deployed to achieve 20 m focal length
- Observatory Mass ~6100 kg (including 30% contingency)
- Launch on an Atlas V 551 or Ariane V
- Direct launch into an 800,000 km semi-major axis L2 orbit
- 5 year required lifetime, with expendables for 10 year goal



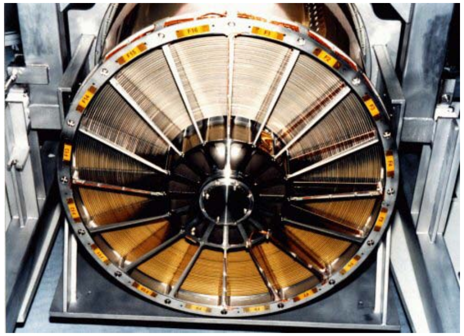

Stowed IXO Configuration

Effective area comparison



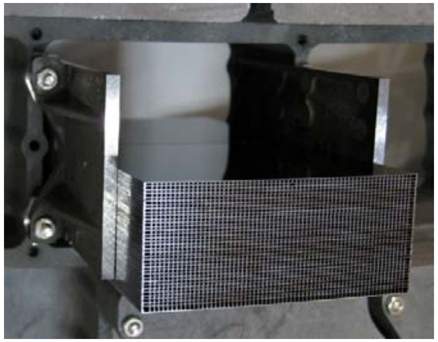
Optics Technologies: Resolution and Mass

CHANDRA
0.5″
18500 kg/m^2
A_{eff} @ 1 keV



XMM-NEWTON
14″
2300 kg/m^2
A_{eff} @ 1 keV

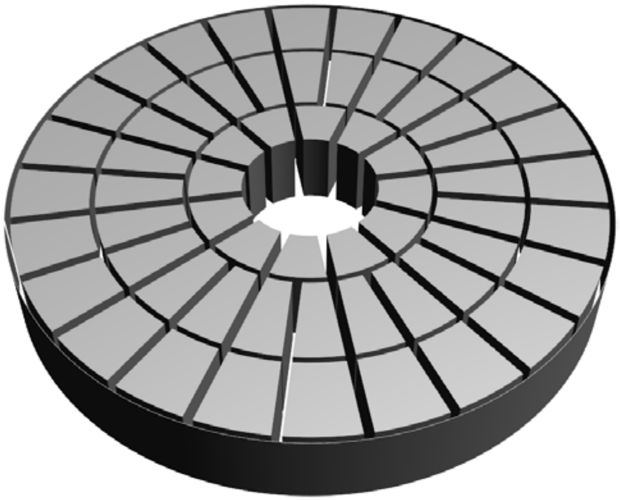
Slumped Glass
5″
~270 kg/m^2
A_{eff} @ 1 keV



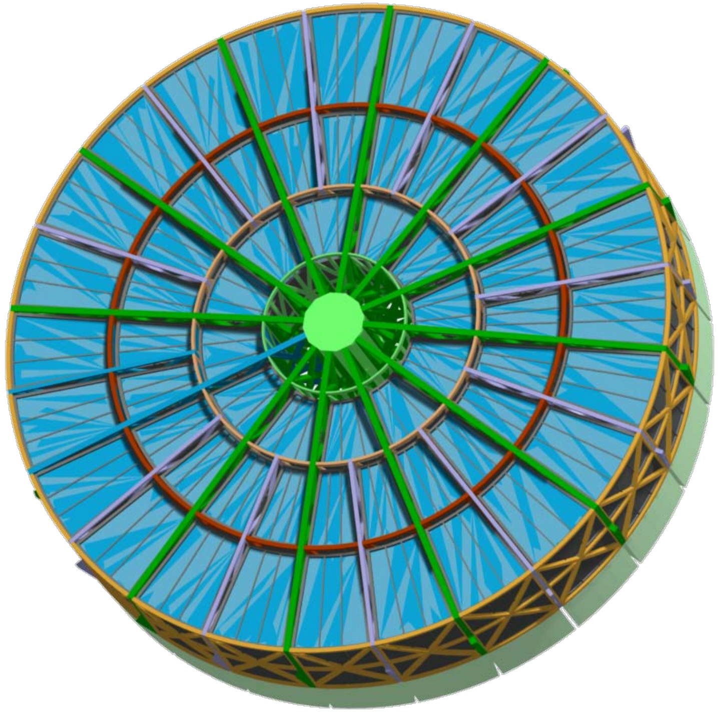
Si-HPO
5″
~200 kg/m^2
A_{eff} @ 1 keV

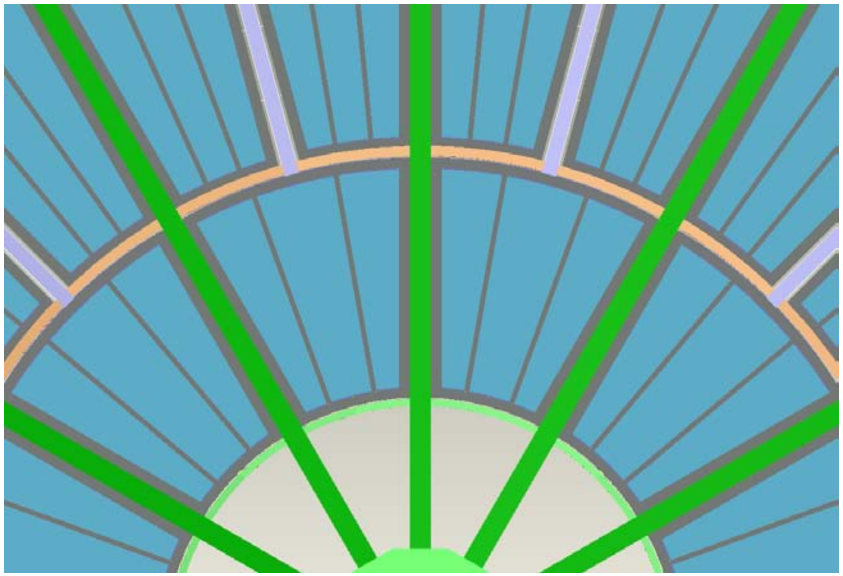
IXO Options

FMA Module Layout

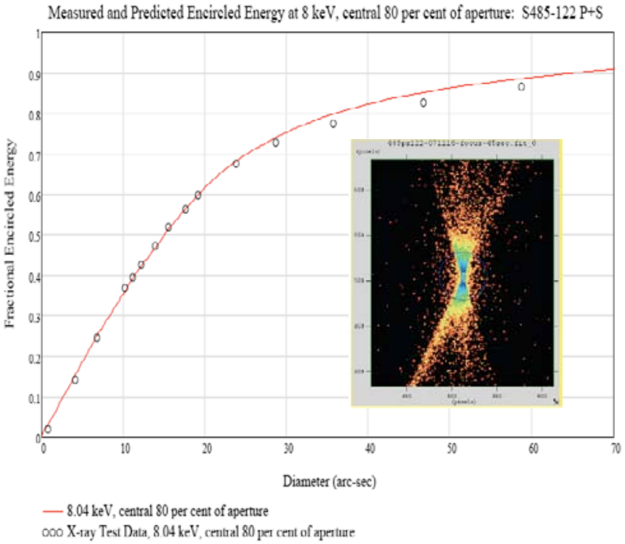


- Module size constrained by glass size (<35 cm)
- 5022 segments in 27 outer modules
  4248 segments in 18 middle modules
  2538 segments in 9 inner modules





Status of Cradle/Mattress/Cube



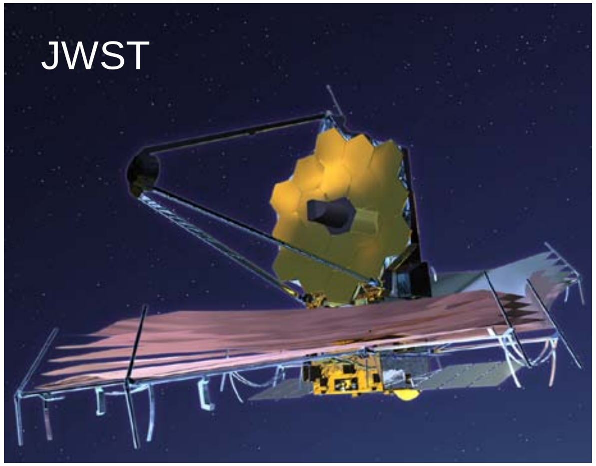
- Reasonably good figure and focus quality can be achieved quickly and repeatably
- Good x-ray test result achieved, demonstrating the validity of optical metrology; Figure distortion dominates X-ray image quality
- More X-ray tests in both temporary and permanent configurations are forthcoming

Summary

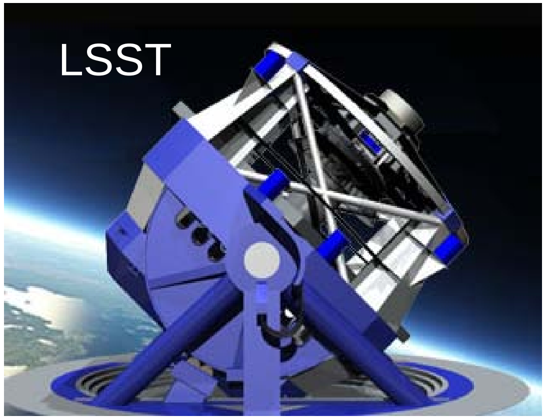
- IXO will allow breakthrough spectroscopy over a wide of astrophysics – Area for high-resolution spectroscopy >100x previous, area alone >10x previous missions
- Logical successor to Chandra (>2600 users) and XMM(>3500 users), peer reviewed Guest Observatory
- Separate studies by ESA and NASA demonstrate that the mission implementation for a 2020 launch is feasible
- Part of Astro2010 Decadal Survey and ESA Cosmic Visions program
- See ixo.gsfc.nasa.gov and register for ixo-supporters email list for periodic updates

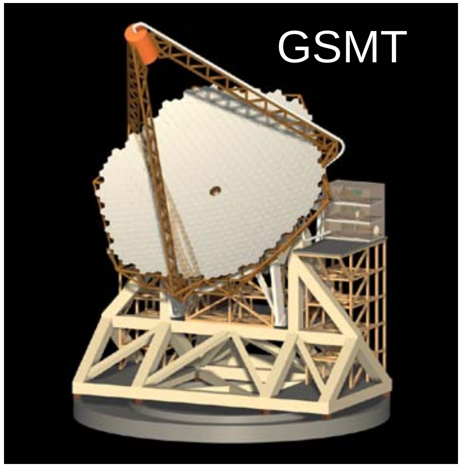
IXO: A Future Great Observatory

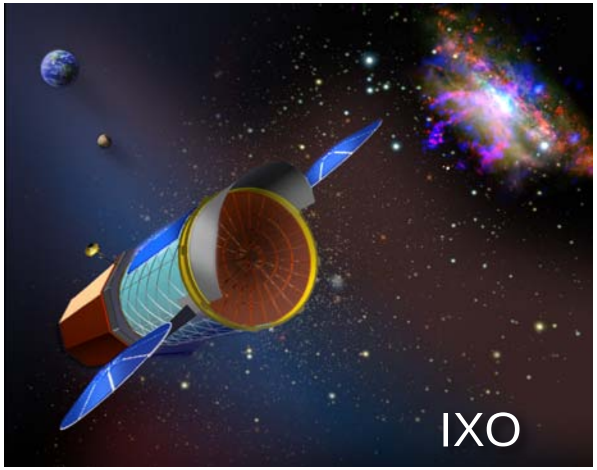
Sub-mm



IR







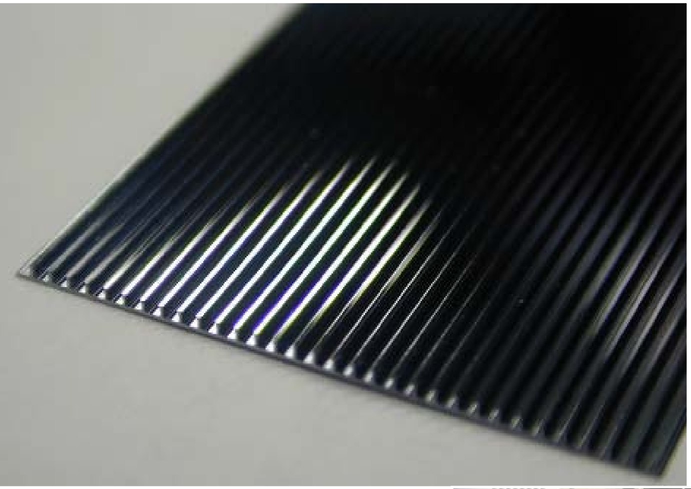
X-ray

Optical

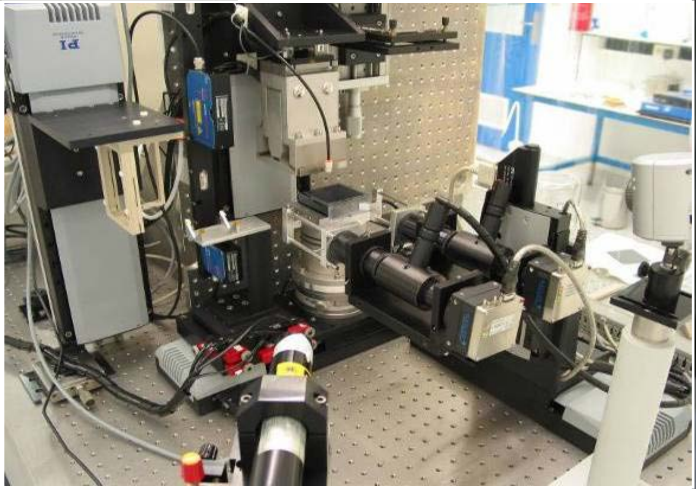
The two order of magnitude increase in capability of IXO is well matched to that of other large facilities planned for the 2010-2020 decade

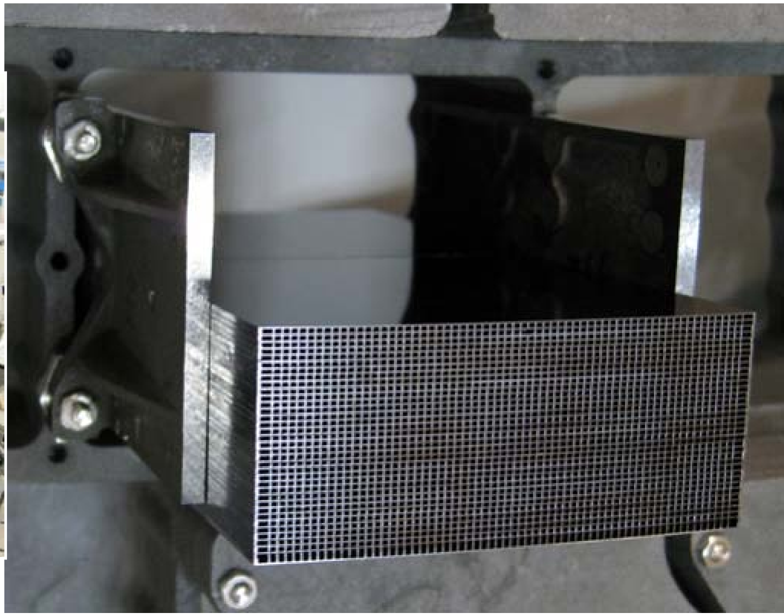
Backup slides

Silicon Pore Optics



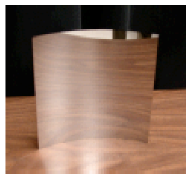
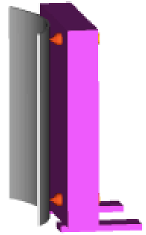
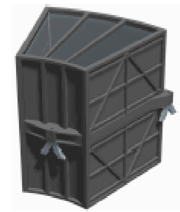
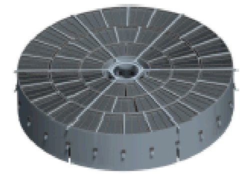
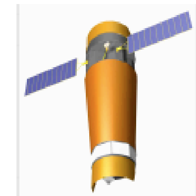
SPO: from mirror plates
to Mirror Module and Petal:
A multi-industrial/institutional undertaking

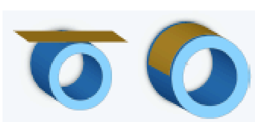


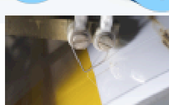


SRON Netherlands Institute for Space Research
MPE
KAYSER-THREDE
cosine
DANISH NATIONAL SPACE CENTER
micronit microfluidics bv
ZEISS We make it visible.
qimonda

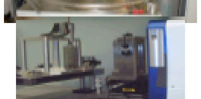
Overview of Mirror Tech Development

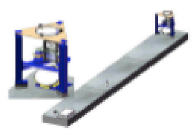
	Mandrel	Mirror	Transfer Mount	Module	Assembly	Observatory
						
HPD	6"	10"	10"	12"	13"	15"
	2.0"	3.5"	3.6"	4.0"	4.5"	5.0"
	Schedule/Cost	← Core of Technology Development →			← Design, Analysis, & Test →	

Slumping 

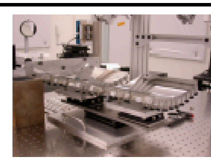
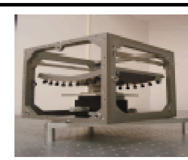
Cutting 

Coating 

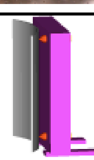
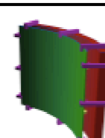
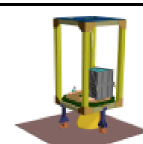
Measuring 



Optical Alignment Pathfinder – III

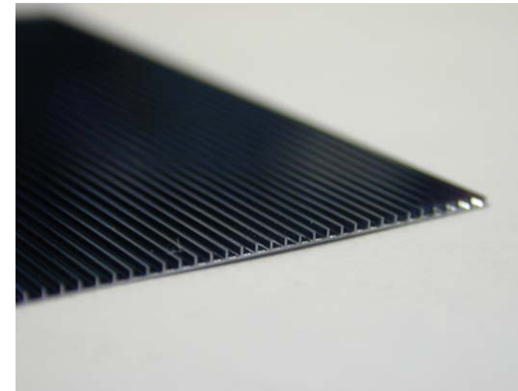
 

Cradle, Mattress, & Cube

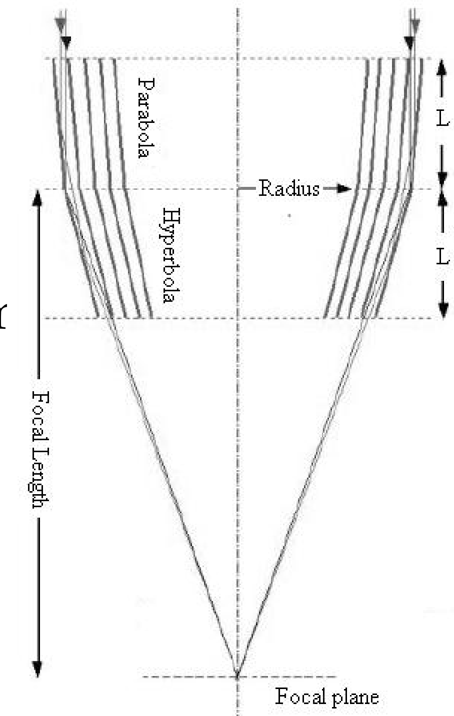
  

Suspension mount,
Curved housing simulator,
& Vertical Alignment

Silicon Pore Optics

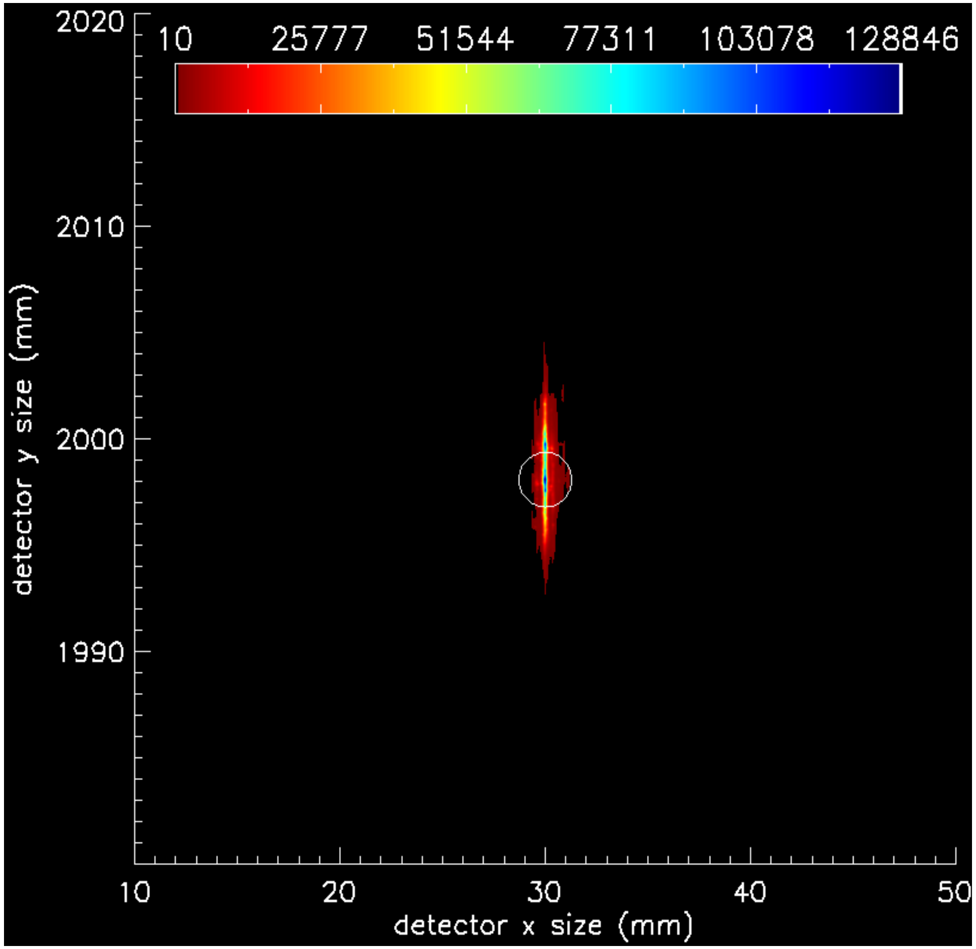


- Uses commercial high-quality 12” silicon wafers
  - plane-parallel < 0.6 μm over 300 mm
  - TTV 0.2 - 0.6 μm over 300 mm
  - large-scale production, cheap
- Surface finish
  - determined during wafer production
  - $50 \times 50\ \mu m^2$ $\sigma_{rms} < 0.1$ nm (AFM)
  - 1×1 mm^2 $\sigma_{rms} < 0.4$ nm (Chapman, cut-off 250 µm
  - not significantly influenced by dicing, ribbing and assembly process
- Optics performance (angular resolution, PSF):
  - Determined during assembly process



Current performance

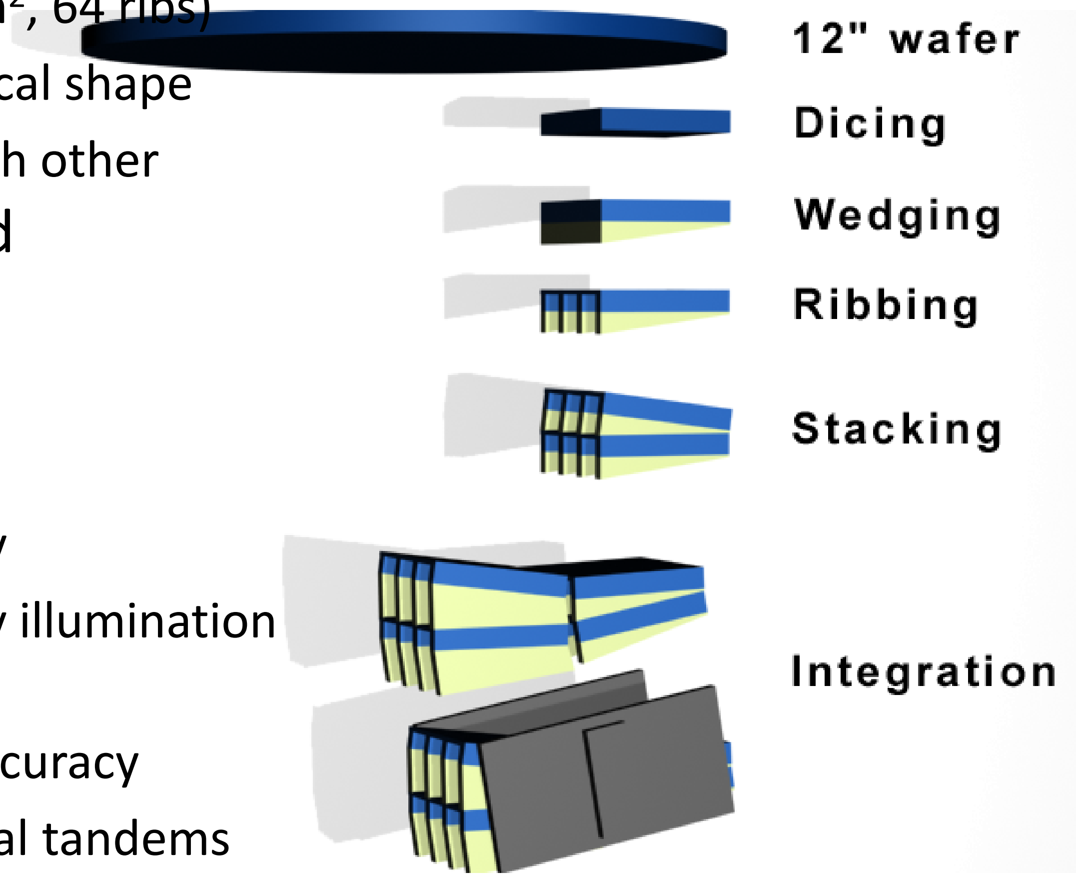
- HEW 17" @ 50 m
  - double reflection
  - mounted optics
  - absolute
  - no subtraction
- Plates 1-4
  - full width



Acol = 1.25 cm^2 (= 13% of innermost XMM mirror shell)

Silicon Pore Optics

- Ribbed Si plate stacking
  - diced and ribbed (66 x 66 mm^2, 64 ribs)
  - elastically bent into a cylindrical shape
  - directly bonded on top of each other
- Stacking process established
  - Automated
  - Currently up to 35 plates
- Tandem integration
  - Installed dedicated metrology
  - Assembly directly under X-ray illumination
  - Can set and fix kink-angle between two mirrors to 1” accuracy
  - Verified by assembly of several tandems
- X-ray performance testing
  - Testing mounted optics in double reflection

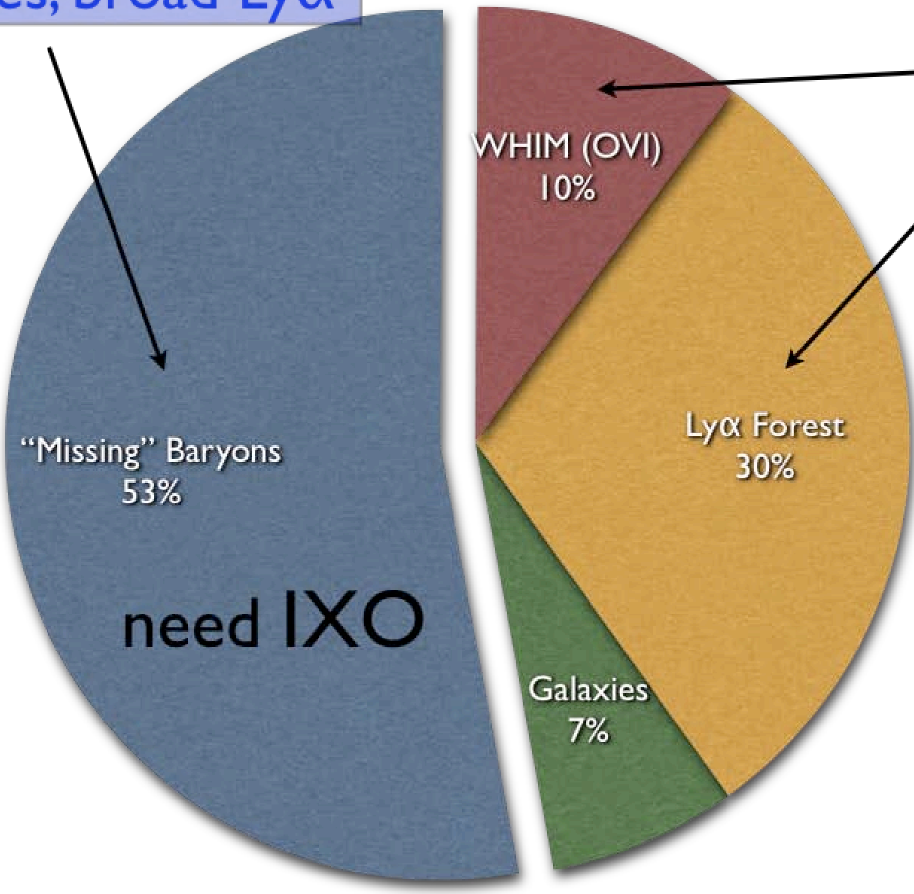


The Missing Baryons: Here and Beyond

Probed by X-ray lines, broad Lyα

Baryon Census (low-z)

Both of these are uncertain

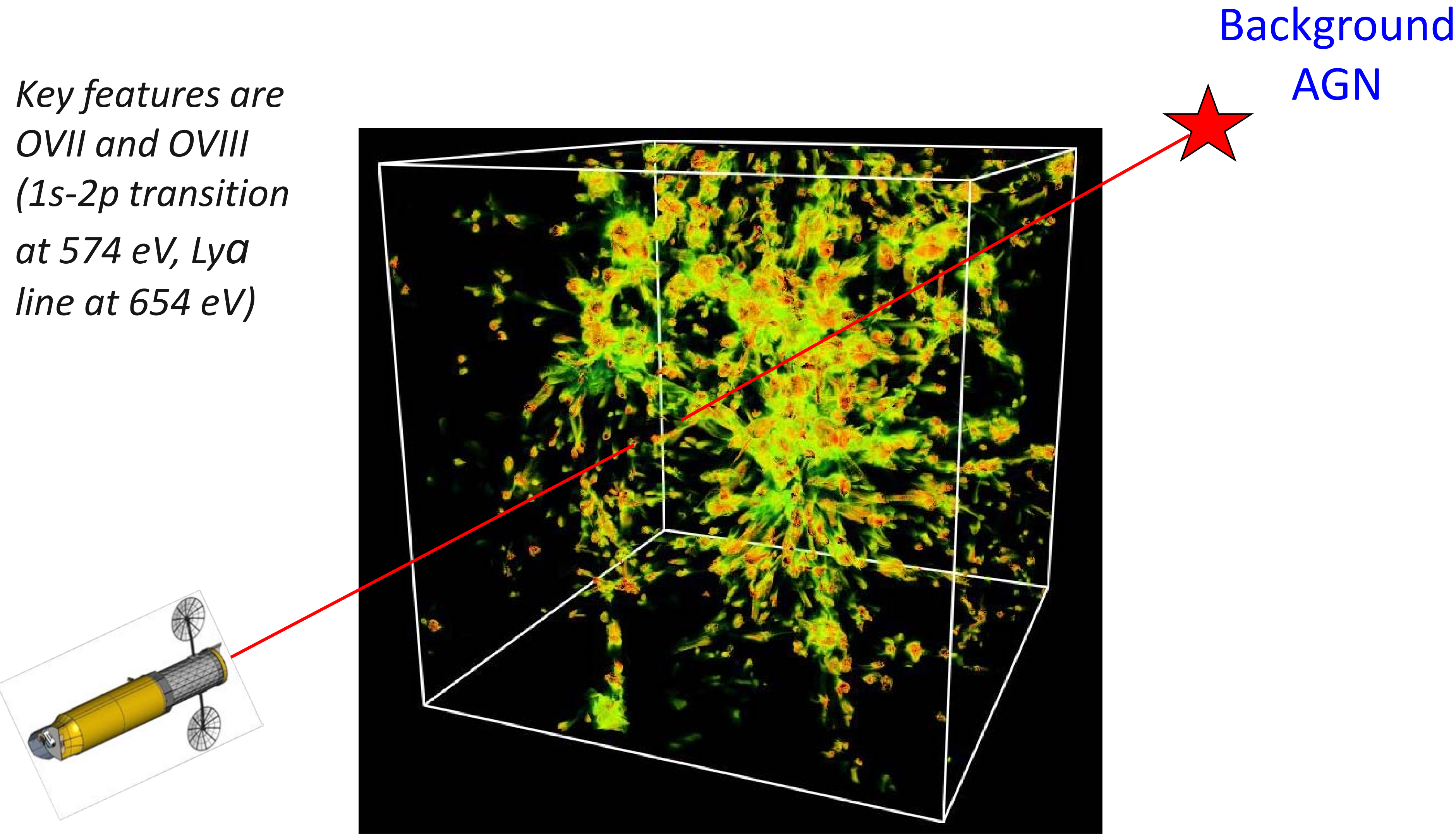


IGM Systematics:

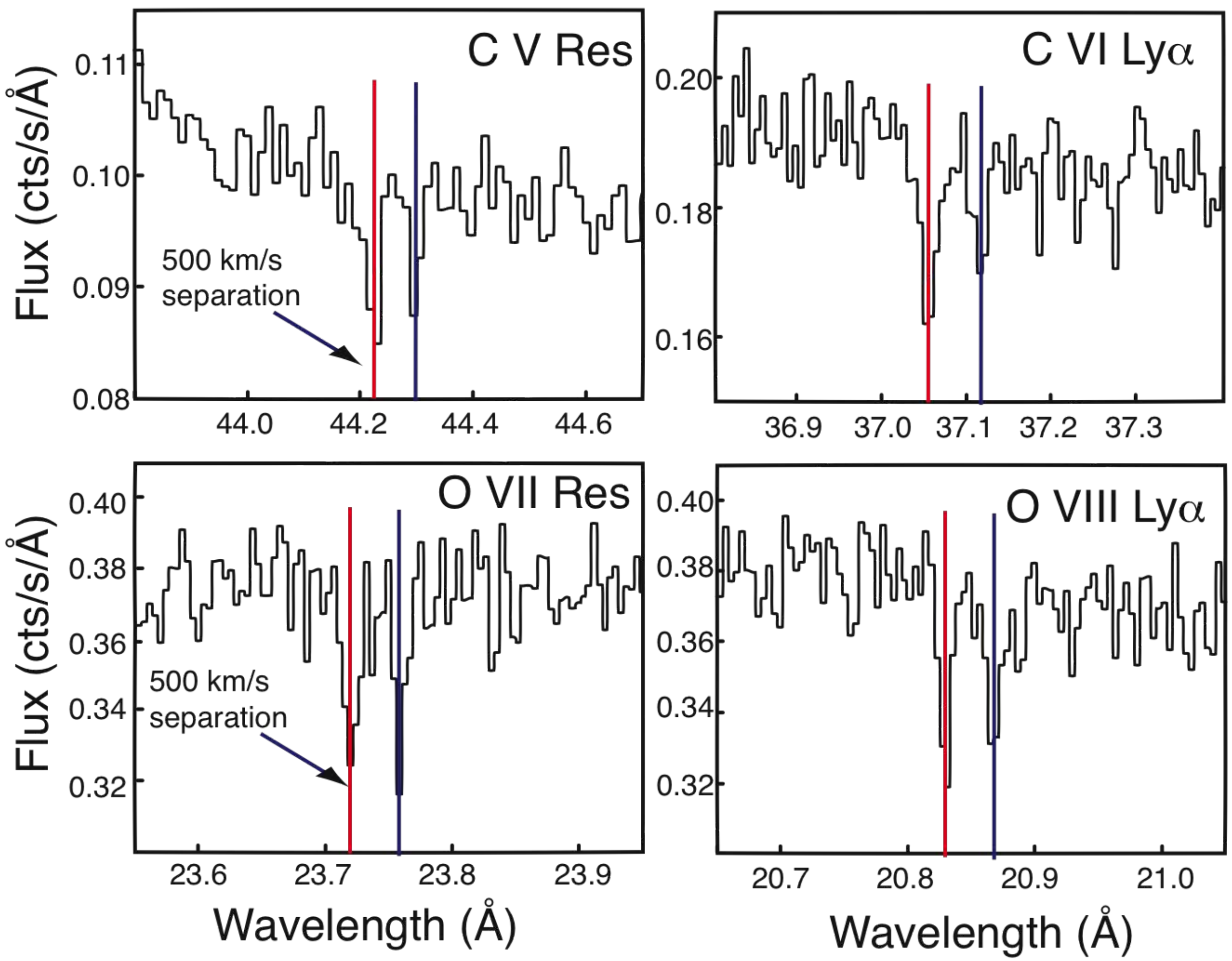
- EUV radiation field
- Oxygen metallicity
- Ioniz corrections
- Cloud geometry

The Missing Baryons – Big Picture

Key features are OVII and OVIII (1s-2p transition at 574 eV, Lyα line at 654 eV)



The Missing Baryons

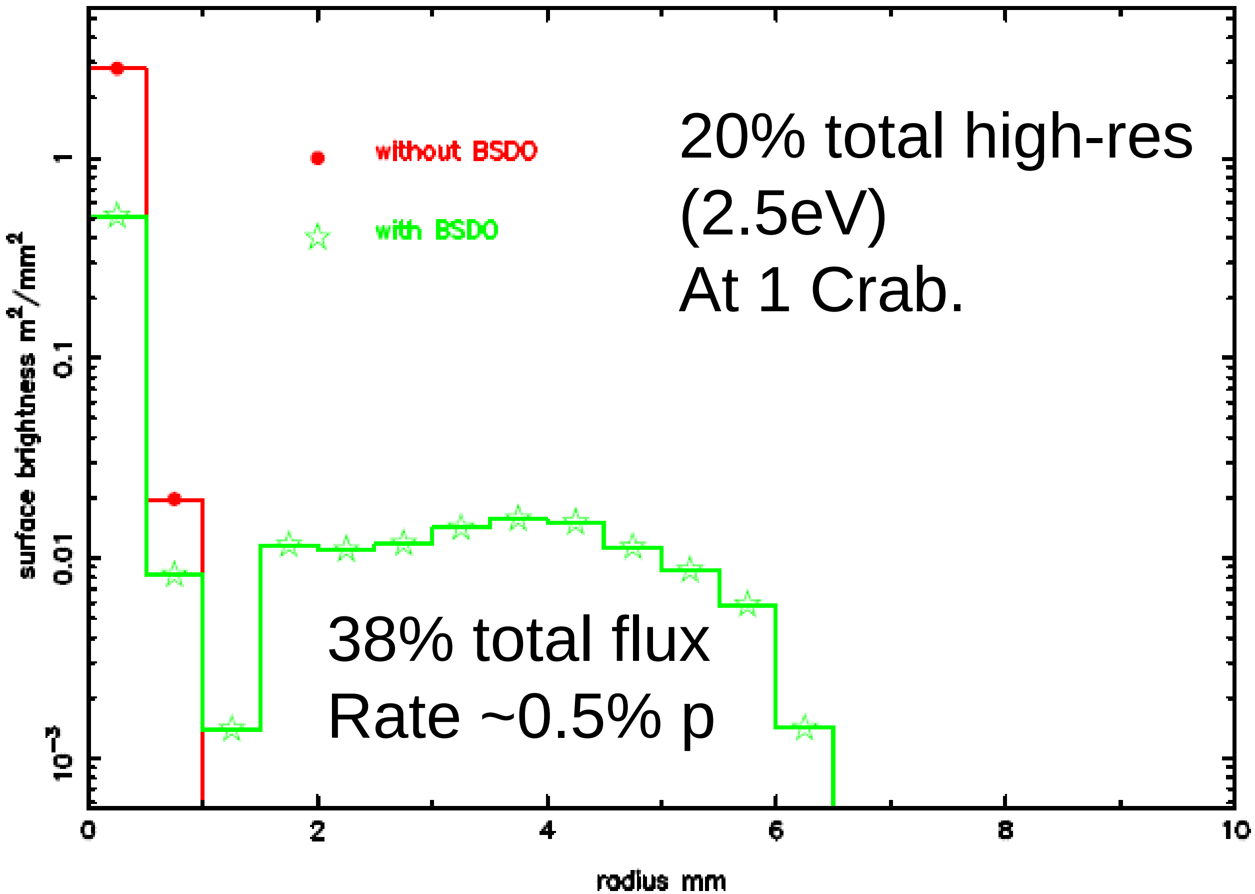


- Using existing surveys, 30+ suitable sources.
- Expect ~ 3-10 Metal Systems per line of sight in 200-300 ks with IXO Gratings: 100-300 OVII WHIM systems in < 10 Msec

Key Performance Requirements

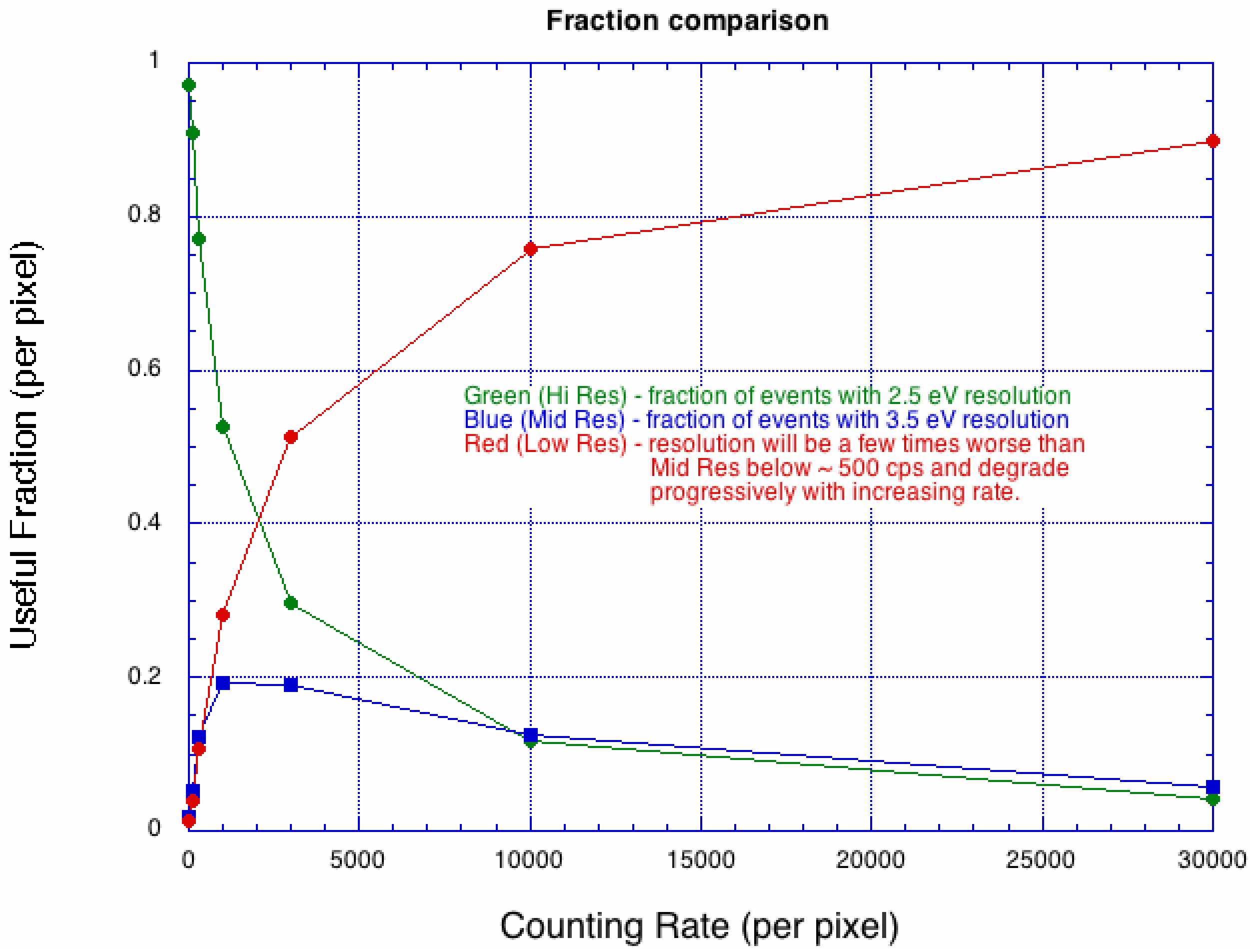
Mirror Effective Area	**3 m^2 @1.25 keV** **0.65 m^2 @ 6 keV, goal of 1m^2** **150 cm^2 @ 30 keV, goal of 350cm^2**	**Black hole evolution, large scale structure, cosmic feedback, EOS** **Strong gravity, EOS** **Cosmic acceleration, strong gravity**
Spectral Resolution/FOV	**ΔE = 2.5 eV within 2x2 arc 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/ΔE=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**

BSDO



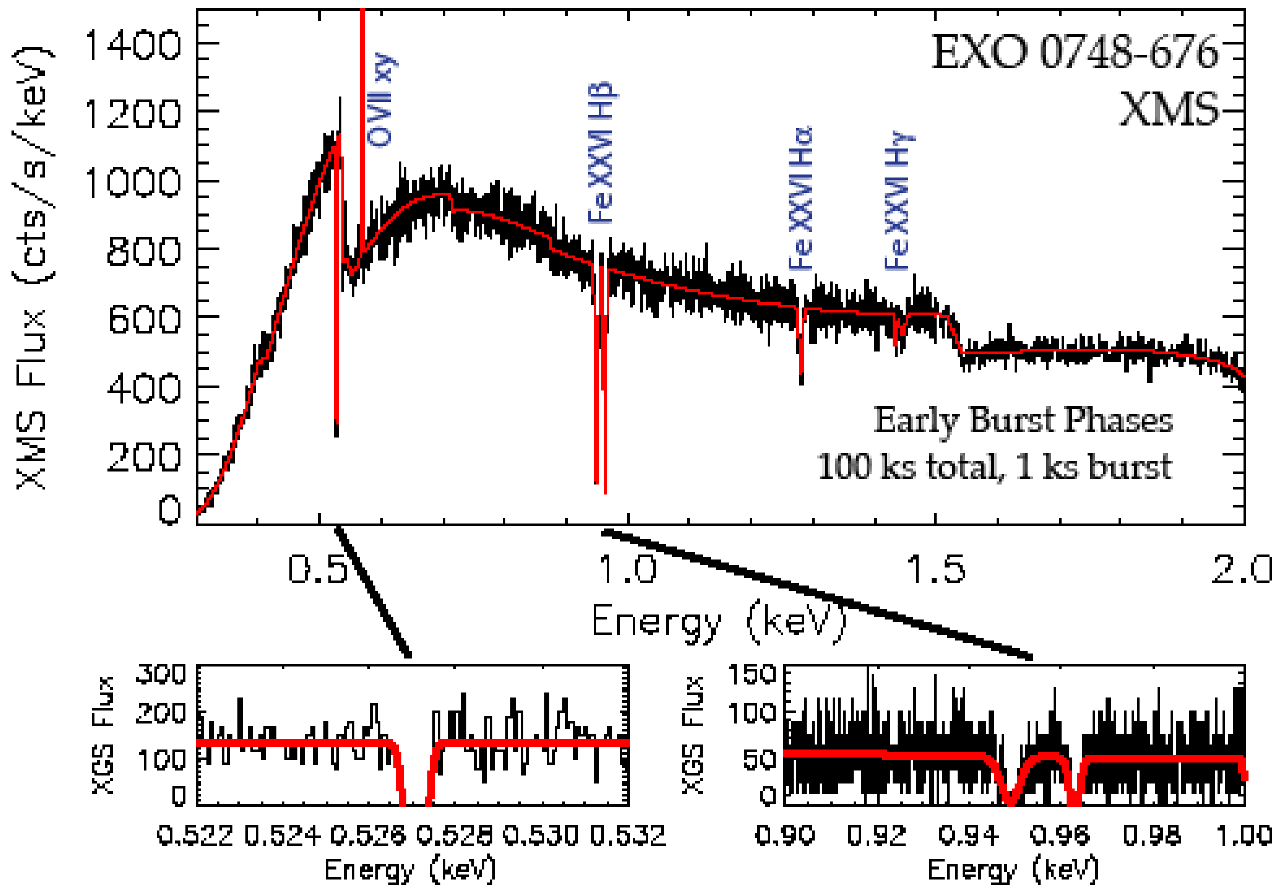
1 arc-min

Total Throughput



1 Crab in
central pixel

What is NS Equation of State?



Peak Flux EXO 0748 ~ 40mCrab !

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:

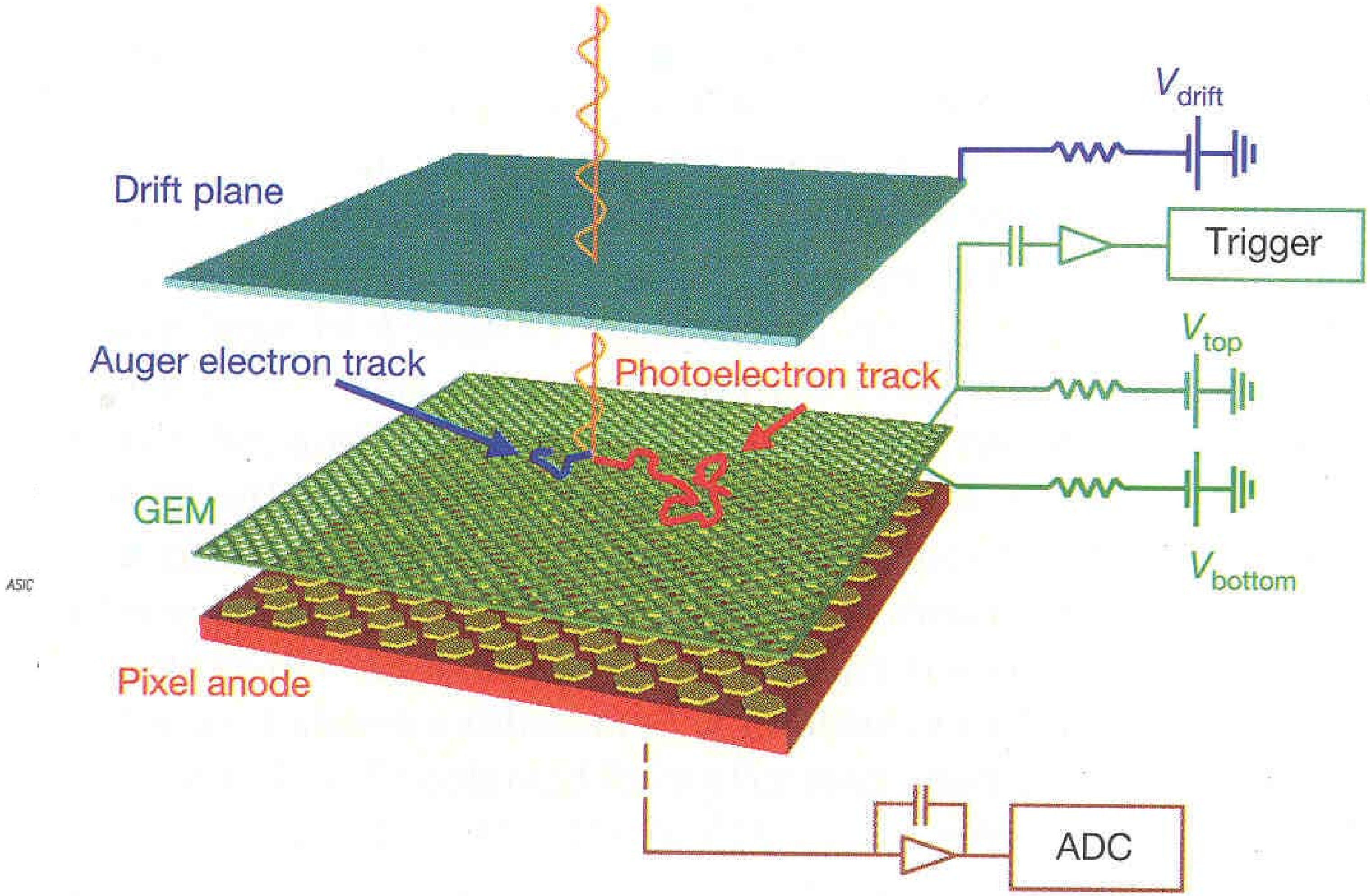
- Hi-res events will have the highest spectral resolution (e.g, 2.5 eV)

- 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

IXO X-ray Polarimeter



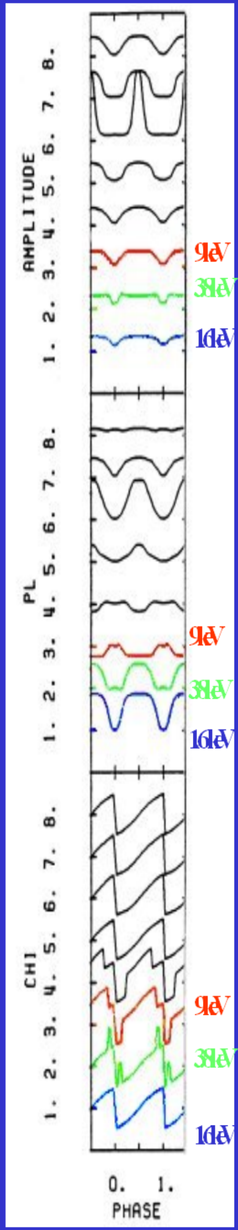
Electron track encodes photon polarization

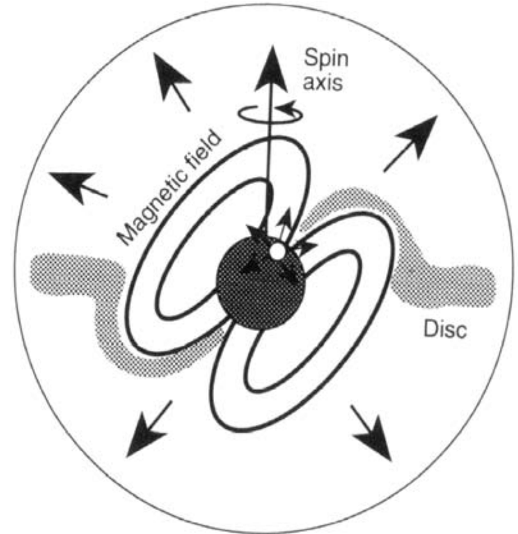
Strong Magnetic Fields

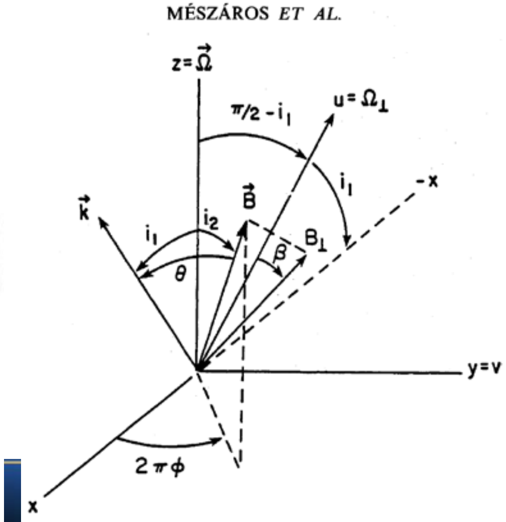
Polarized by:

- Emission process: cyclotron
- Scattering on highly magnetized plasma: $\sigma_{\parallel} \neq \sigma_{\perp}$

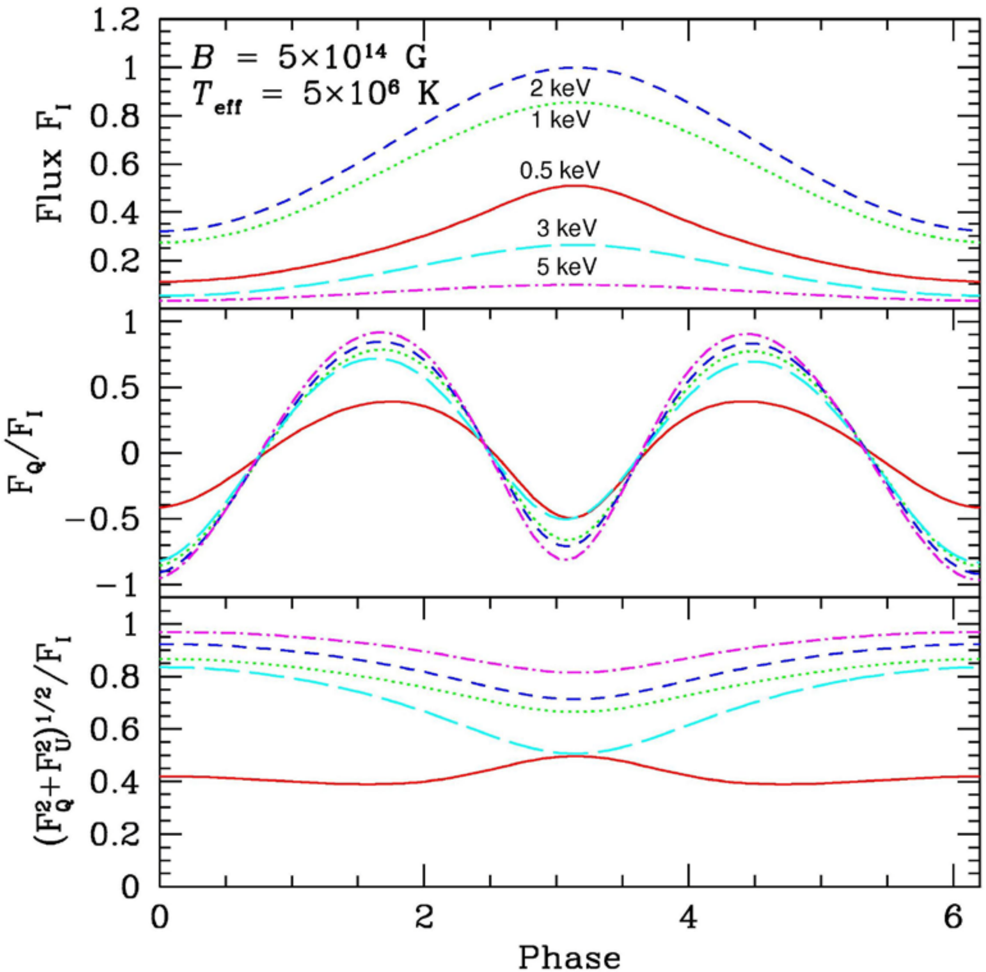
Polarization is modulated and the swing of the polarization angle with phase directly measures the orientation of the rotation axis on the sky and the inclination of the magnetic field: in the figure the 45° case is illustrated (from Meszaros et al. 1988)







XPOL: Extreme Magnetic Fields: magnetars



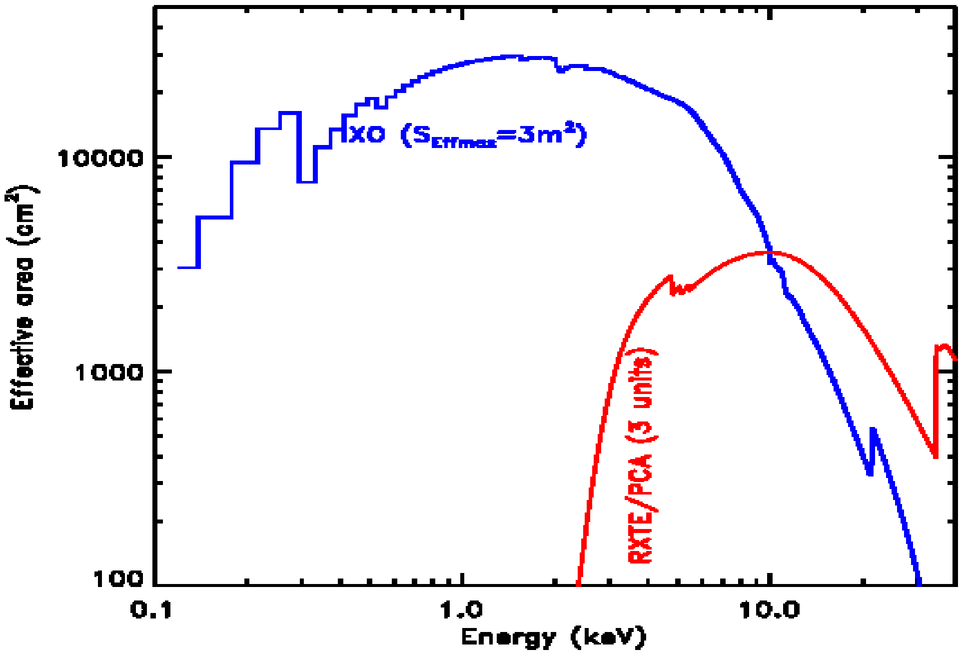
van Adelsberg & Lai 2006

Soft Gamma Repeaters and Anomalous X-ray Pulsars are interpreted in the frame of the Magnetar Theory (Thompson & Duncan 1993): neutron stars with extreme magnetic fields.

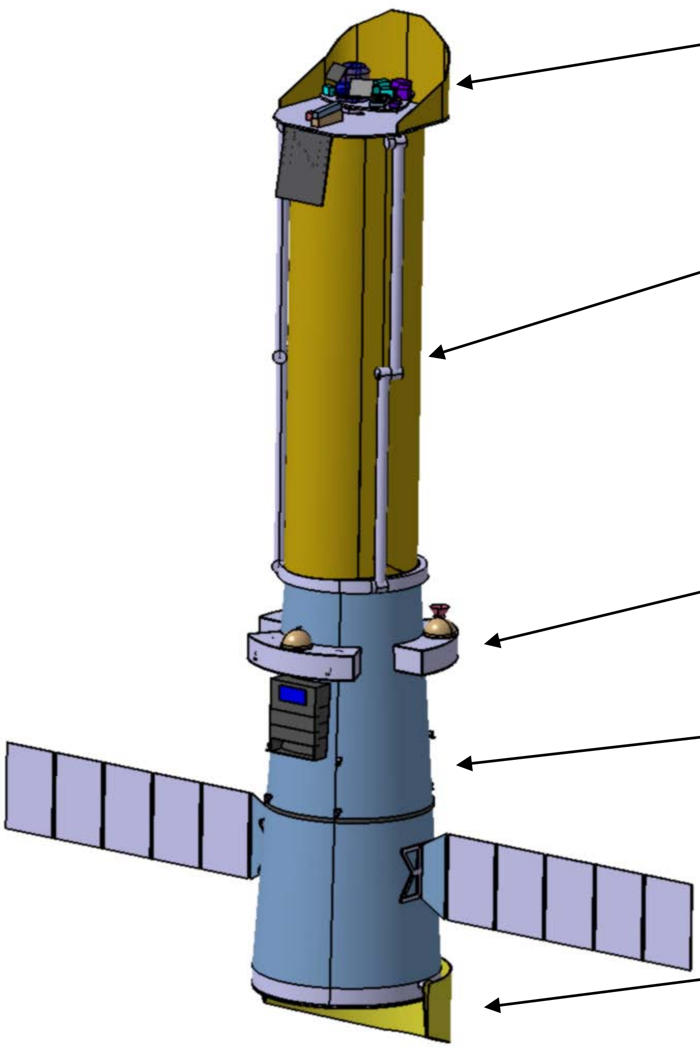
For B ≥ 7x10^{13} G strong-field QED (vacuum polarization) becomes important, significantly changing the dependence on the phase *and the energy* of the polarization, providing a measurement of B, a test of the magnetar paradigm and a probe of strong-field QED

Comparison to RXTE

(D. Barret)



Much of the flux from the surface of NS
Is at modest (~1keV) temps



Instrument module

Optical bench deployment mechanism

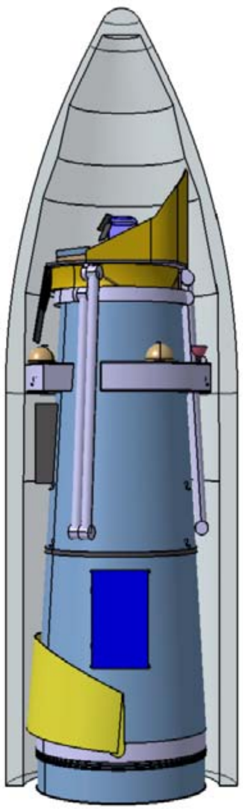
(+ deployable shroud)

Service module

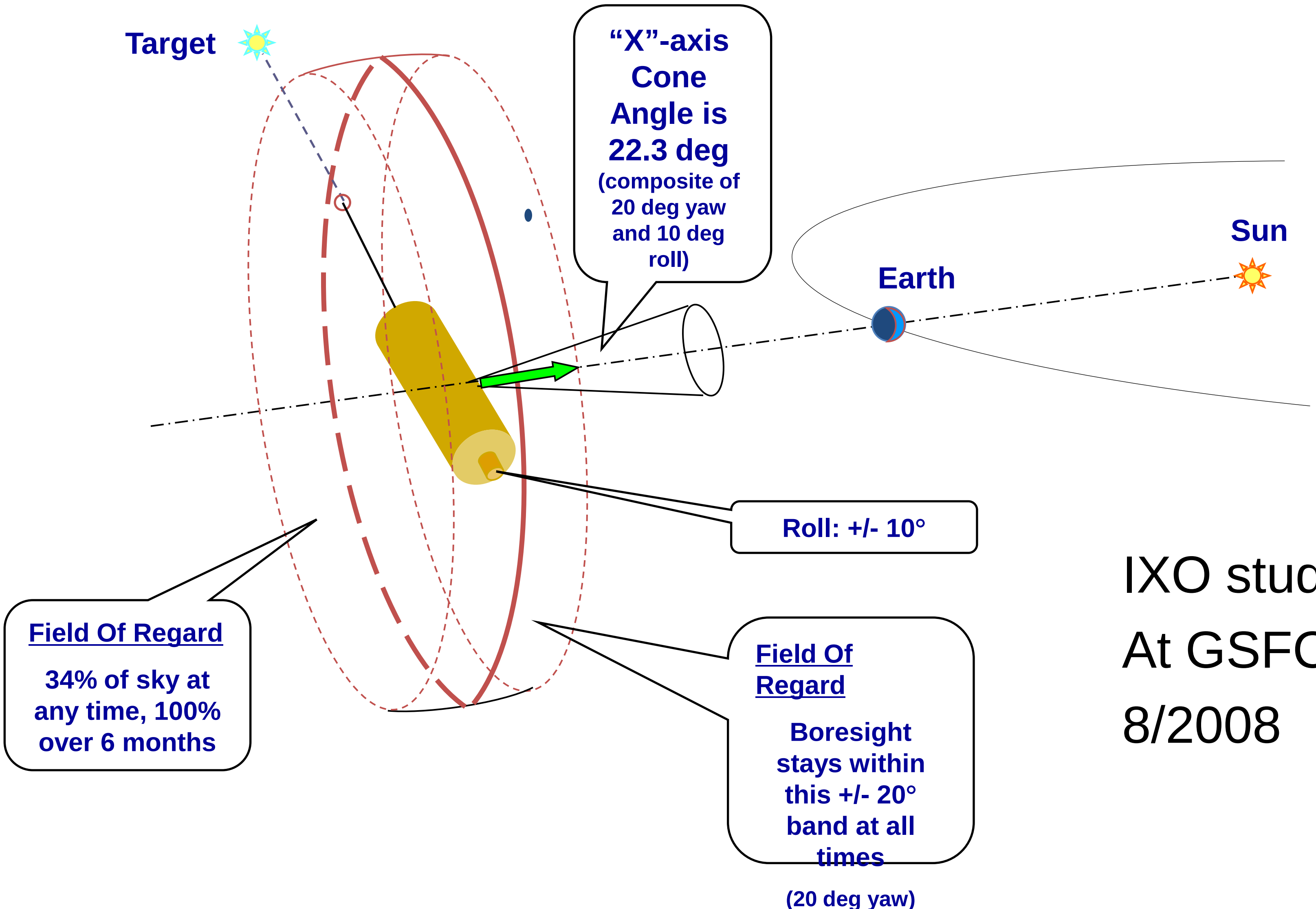
Fixed conical optical bench

Mirror assembly (Pore Optics)

(+ deployable sun shield)



ToOs: IXO Capabilities



IXO study
At GSFC MDL
8/2008

Numbers/Types of TOOs?

- Compare Chandra and XMM TOO rates
  - Chandra: 215 unique targets/9 years = 24 targets/year
  - XMM: 104 unique targets/8 years = 13 targets/year
- Ratio of rates (=1.85) same as ratio of FOR (=1.81) – implies FOR predicts TOO capability

ASSUME: TOO distribution not correlated with FOR;
therefore sky coverage = capacity to observe ToO
(Caveat: Galactic center, overprediction?)

Chandra	XMM	IXO
Pitch = 45^o-180^o	Pitch = +/- 28^o	Yaw=+/-20^o
FOR=85%	FOR=47%	FOR=34%
Rate=24/y	Rate=13/y	Rate=9.4/y ?

TOOs: IXO Capabilities

- Field of Regard (FOR):
  - 34% of sky at any moment
  - 100% of sky within 6 months
  - Solar arrays, sunshades, thermal control system all sized for +/- 20 degrees yaw
- Slew rate
  - 60 degrees in <1 hour
  - Includes settle time
- Response time

  <24hr nominal, but Swift/like OBS may enable hours