The ESA/NASA/JAXA International X-ray Observatory (IXO)

The High Time Resolution Spectrometer

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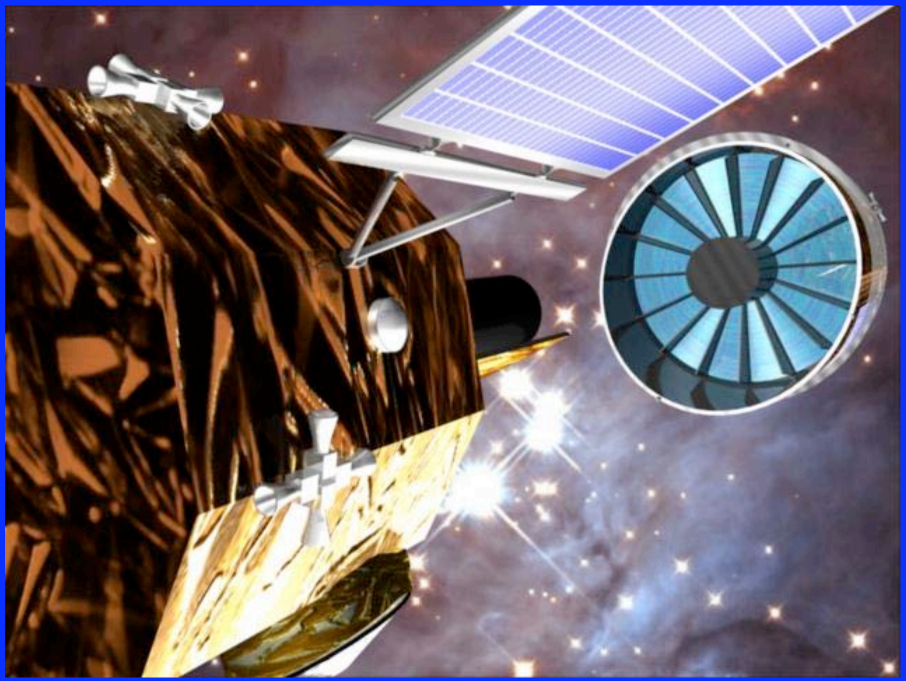
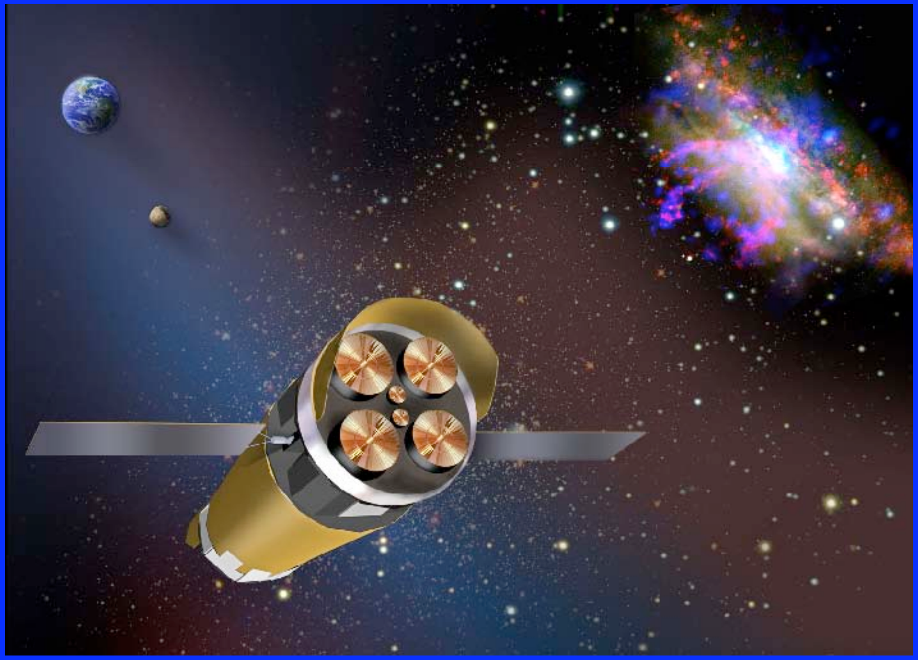
Institut d'Astrophysique de Paris, Le 6 juin 2009

History

- What after XMM-Newton and Chandra?
  - ✓ XEUS: ESA with JAXA candidate as large Cosmic Vision mission
  - ✓ Con-X: NASA concept, number two in 2000 Decadal survey
- Very similar science goals, but very different derived requirements and implementation approach
- Unlikely there will be two large X-ray missions at the same time, and it would be more cost effective to join forces





The merging

- In spring 2008, ESA and NASA HQs began an effort to see if the two missions could be merged
  - ✓ Which agency would lead a joint mission was NOT (and is still) discussed
- An ESA/JAXA/NASA coordination group was formed and agreement was reached at an ESA-NASA bilateral 2008 July 14th, with JAXA concurrence
- The Con-X and XEUS studies will be replaced by a single tri-agency study called the International X-ray Observatory
  - ✓ The result of this study will be submitted to the 2010 "Decadal Survey", Cosmic Visions and the JAXA approval process
    - ➡ IXO is then competing for the L mission slot

How to organize the study?

- Interesting exercise: science, hardware, politics - three cultures

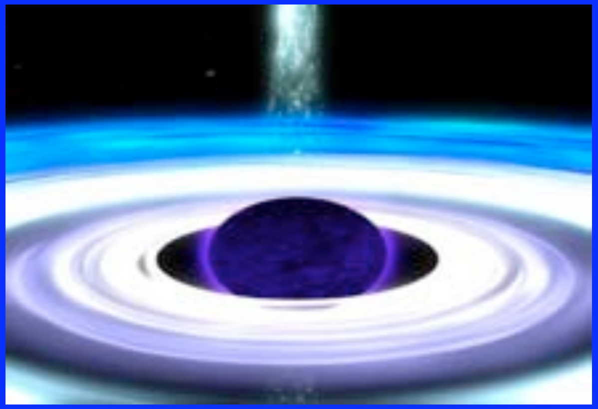
IXO Study coordination Group (ESA, NASA, JAXA)
For Europe: D. Barret, P. Nandra, L. Piro, L. Strüder

- IXO Science Definition Team
  From France: M. Arnaud
- IXO Instrument Working Group
  From France: D. Barret, L. Duband, O. Limousin, C. Pigot
- IXO Telescope Working Group

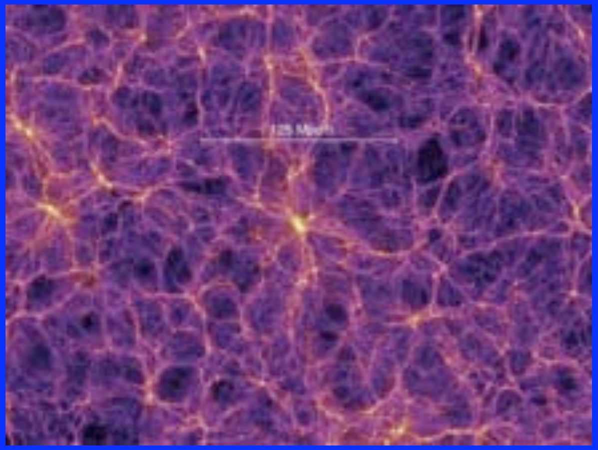
- ESA ITT for industrial studies released (May 2009)
- ESA DOI for payload consortia to be submitted on June 9th
- A lot on-going *Decadal Survey* activities (cost assessment, ...)
- End of the study by ~June 2010 for selection at the end of 2010

Key science goals for IXO

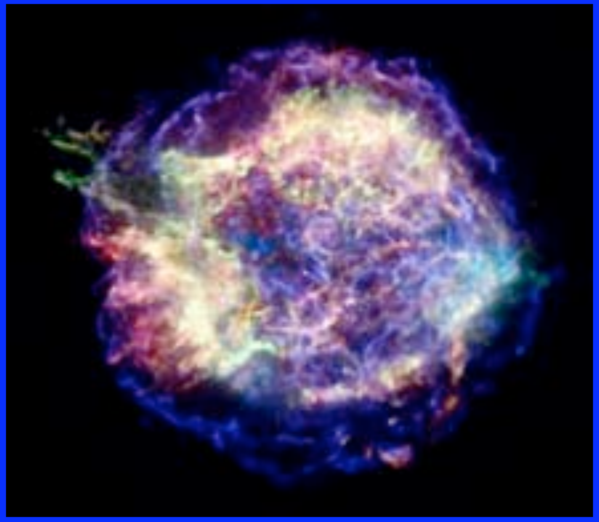
- Black holes and matter under extreme conditions



- Formation and evolution of galaxies, clusters, and large scale structure

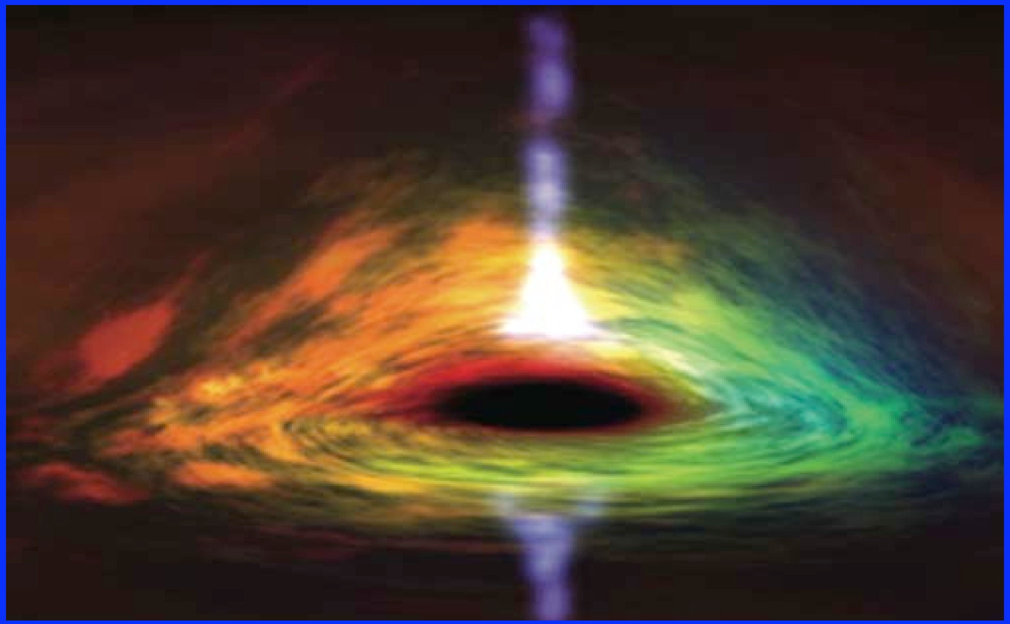


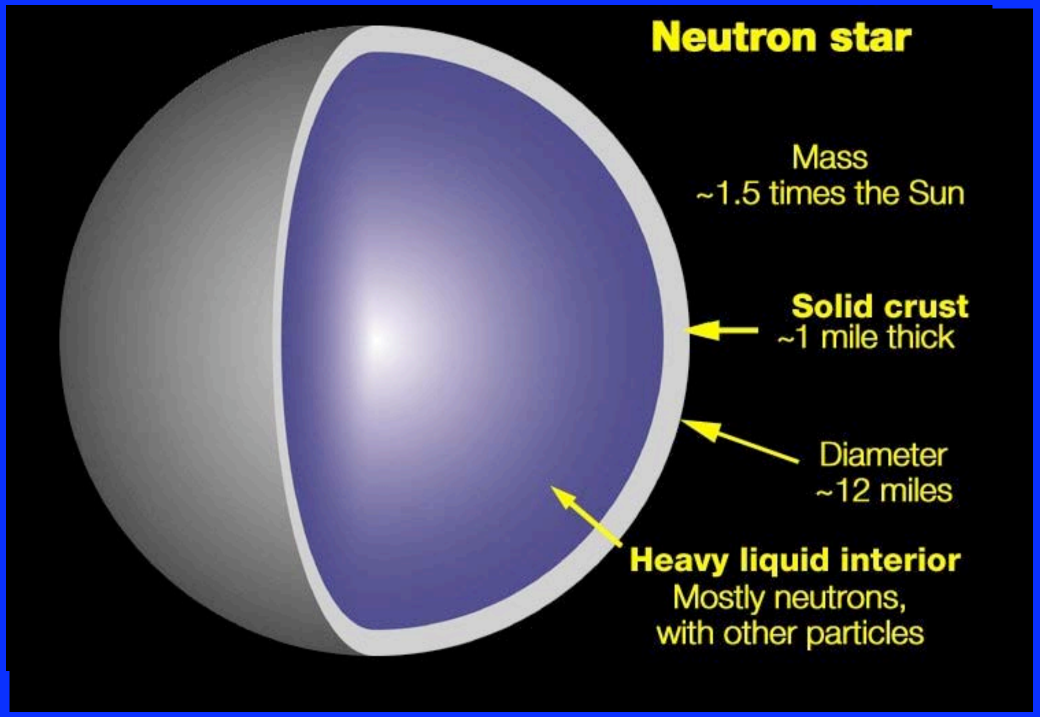
- Life cycles of matter and energy



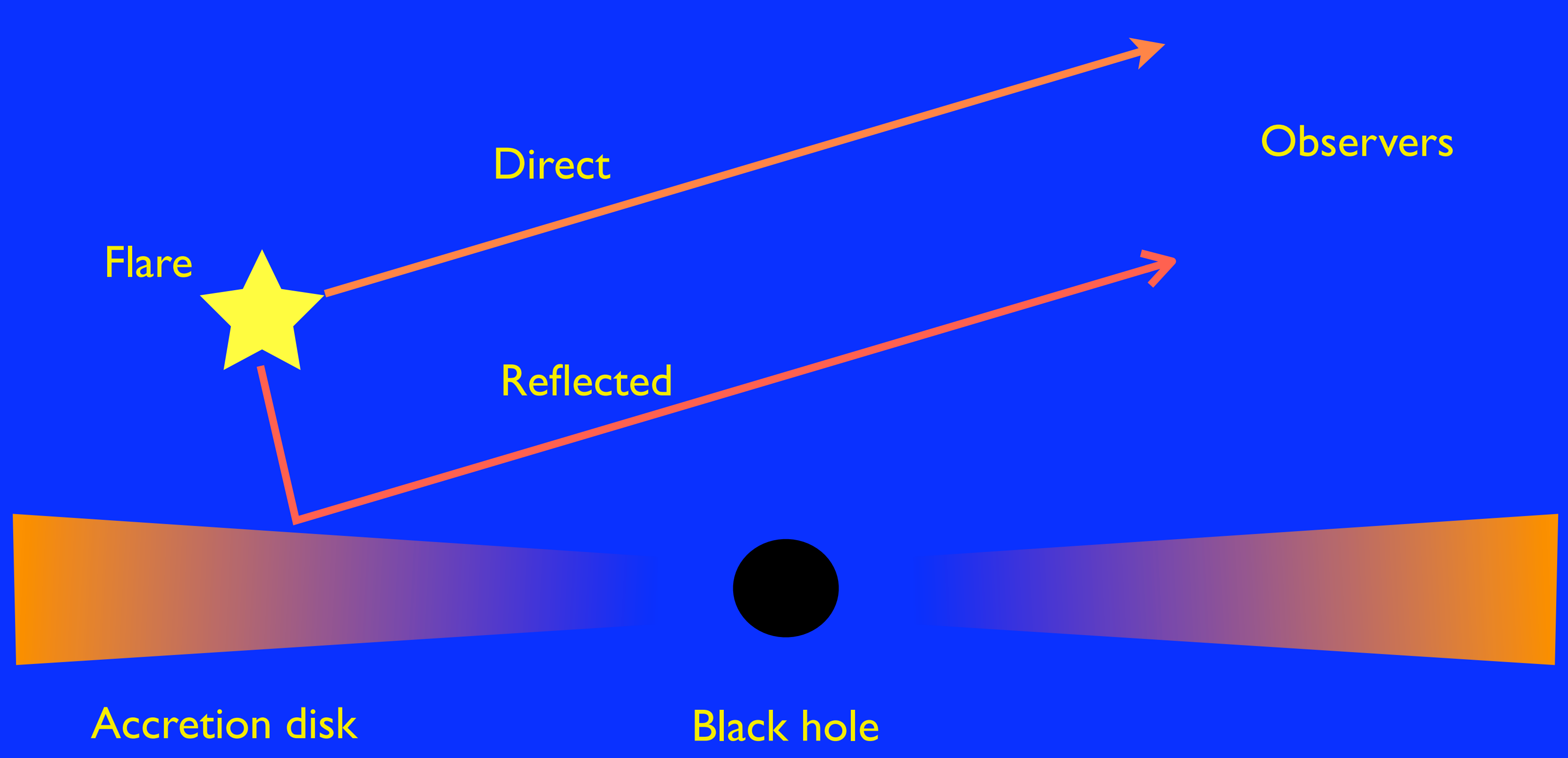
Black holes & matter under extreme conditions

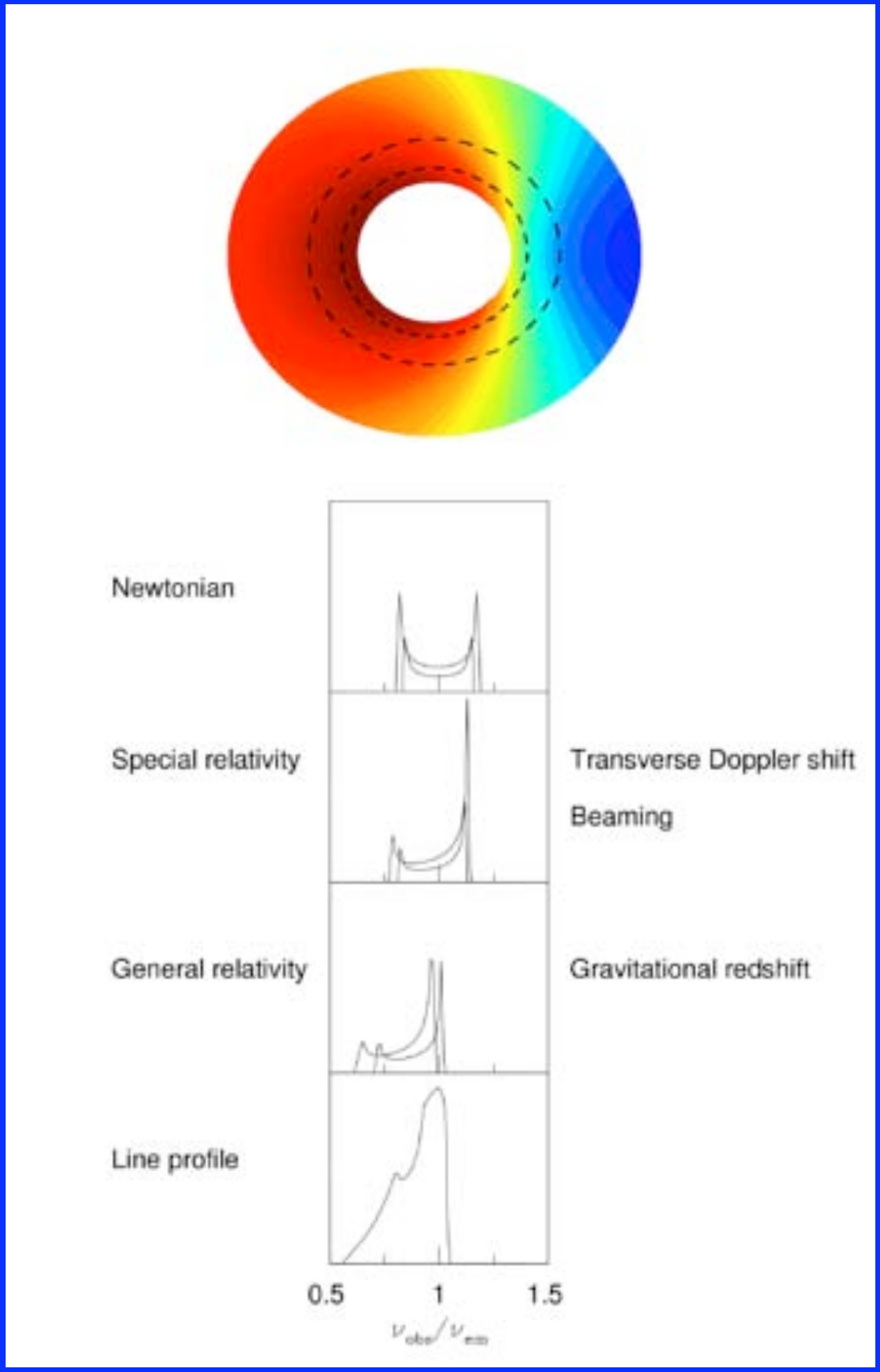
- How do supermassive black holes grow and evolve?
  - ➡ Complete census of AGNs of all kinds out to high redshifts
- *Does matter orbiting close to a black hole event horizon follow the predictions of general relativity?*
  - ➡ *Time resolved spectroscopy of orbiting hot spots around black holes*
- *What is the equation of state of matter in neutron stars?*
  - ➡ *High resolution X-ray timing and spectroscopy of neutron stars*





Reflexion on the accretion disk





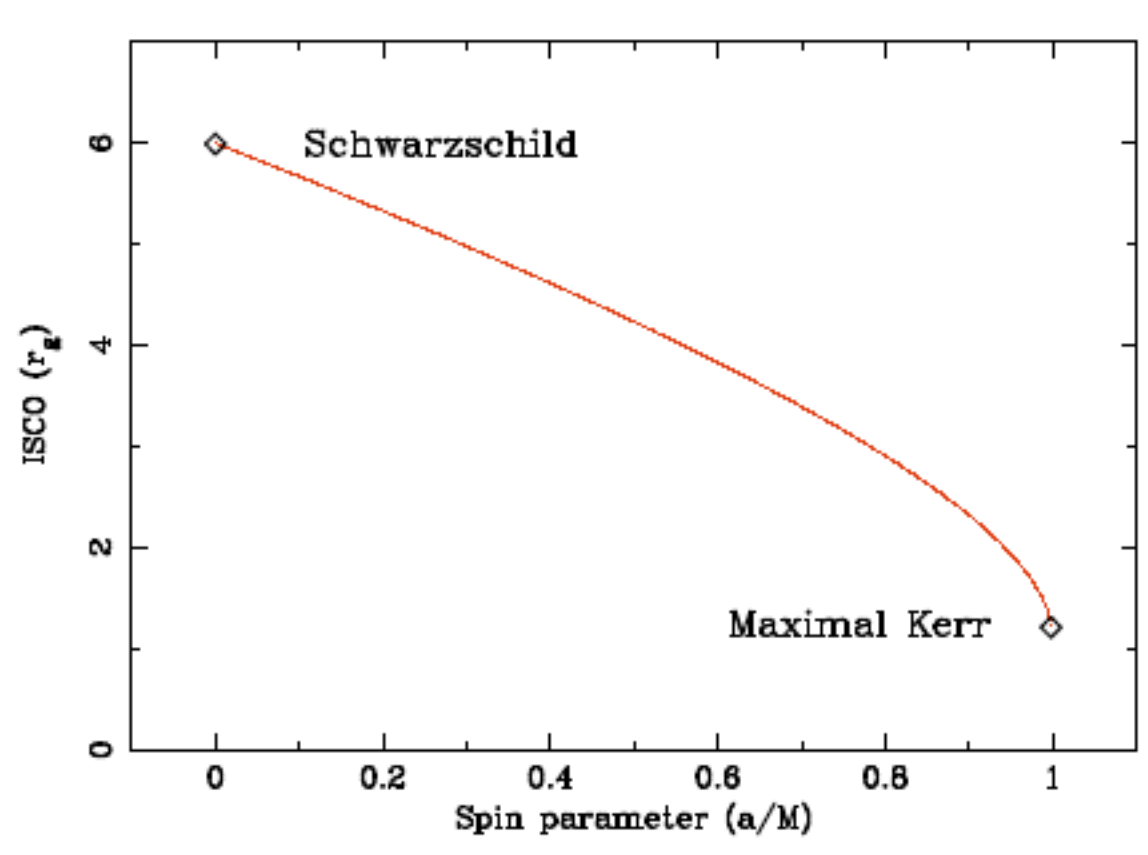
Fabian et al. (2000)

- Fluorescence lines are produced through reflexion of X-rays on a cool accretion disk - Iron K line @ 6.4 keV
  - ✓ The profile of the line is subject to gravitational redshifts, doppler shifts, light bending effects, beaming

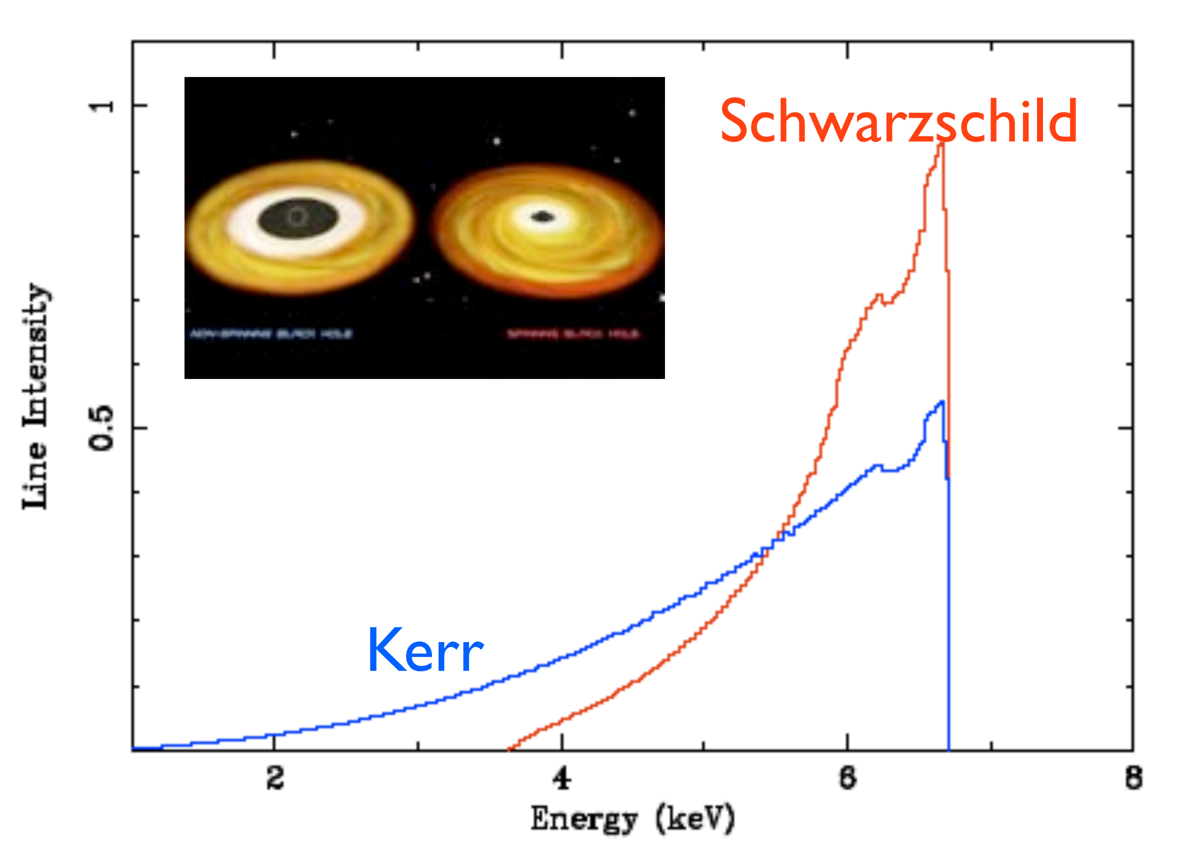
Spin constraints from the Iron line

- The profile of the line constrains the spin of the black hole

Radius of the innermost stable circular orbit versus spin



Iron line profile versus spin



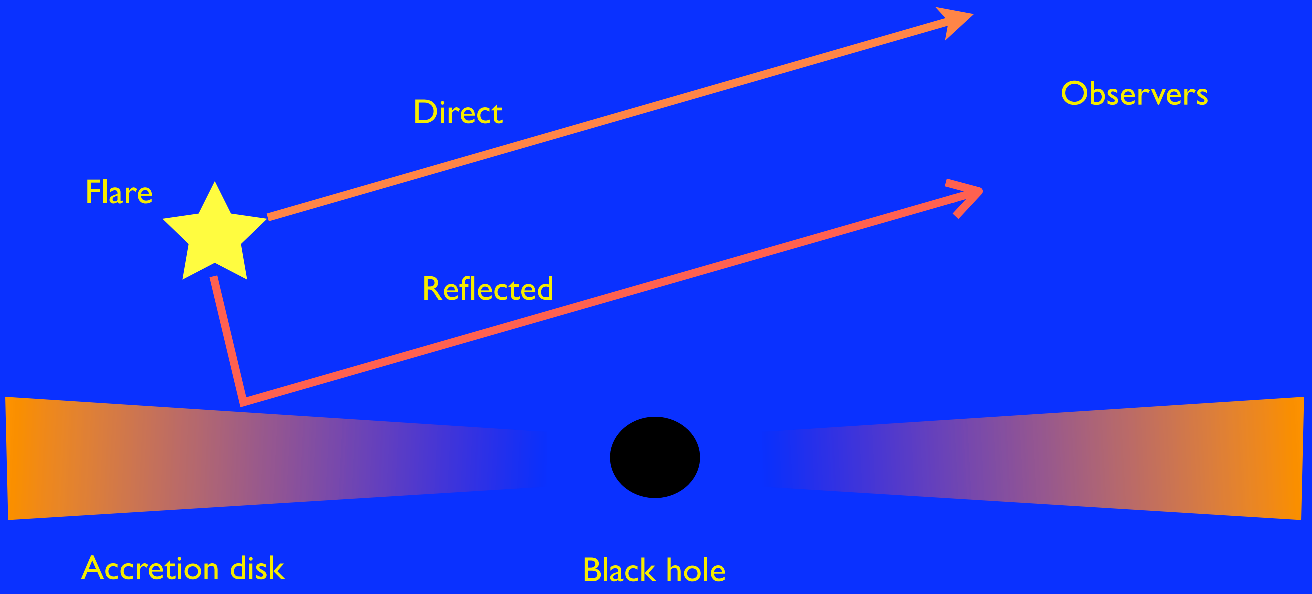
Broad line in the AGN 1H0707-495

nature   Vol 459 | 28 May 2009 | doi:10.1038/nature08007

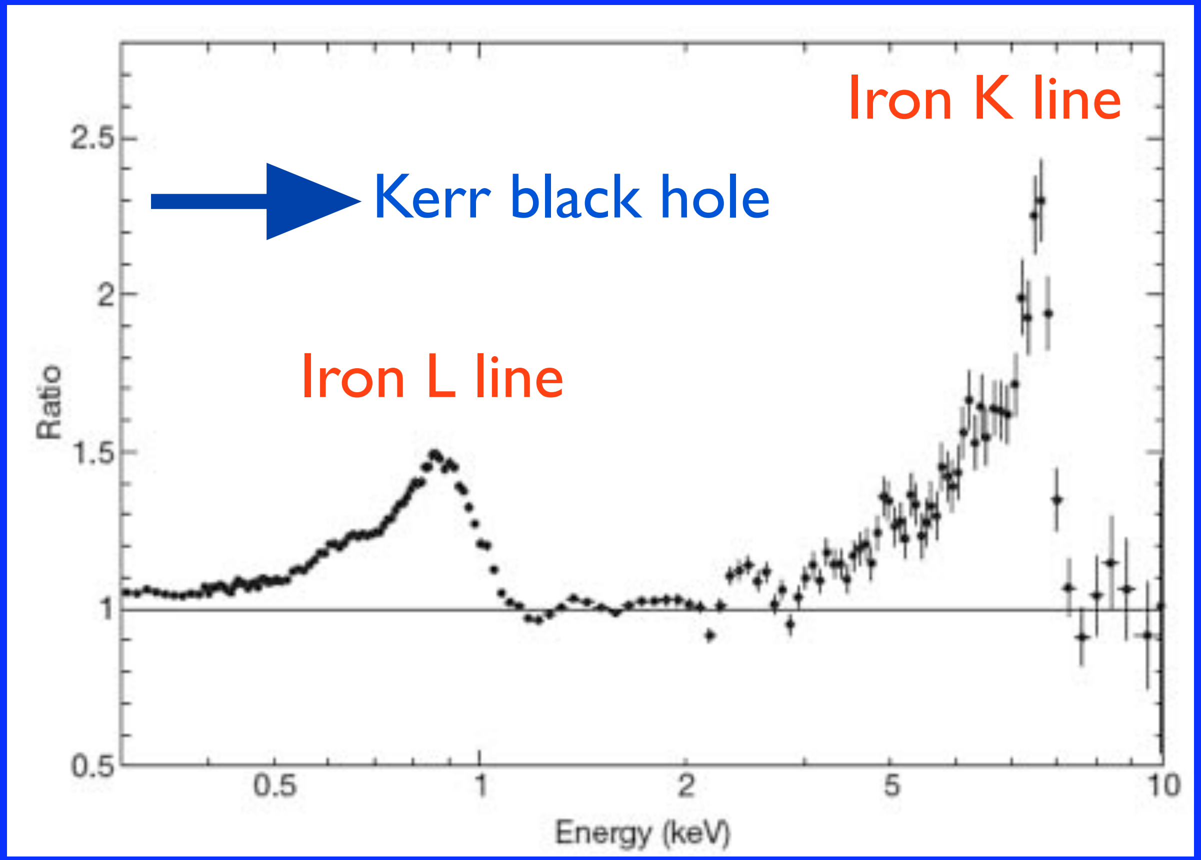
LETTERS

Broad line emission from iron K- and L-shell transitions in the active galaxy 1H 0707-495

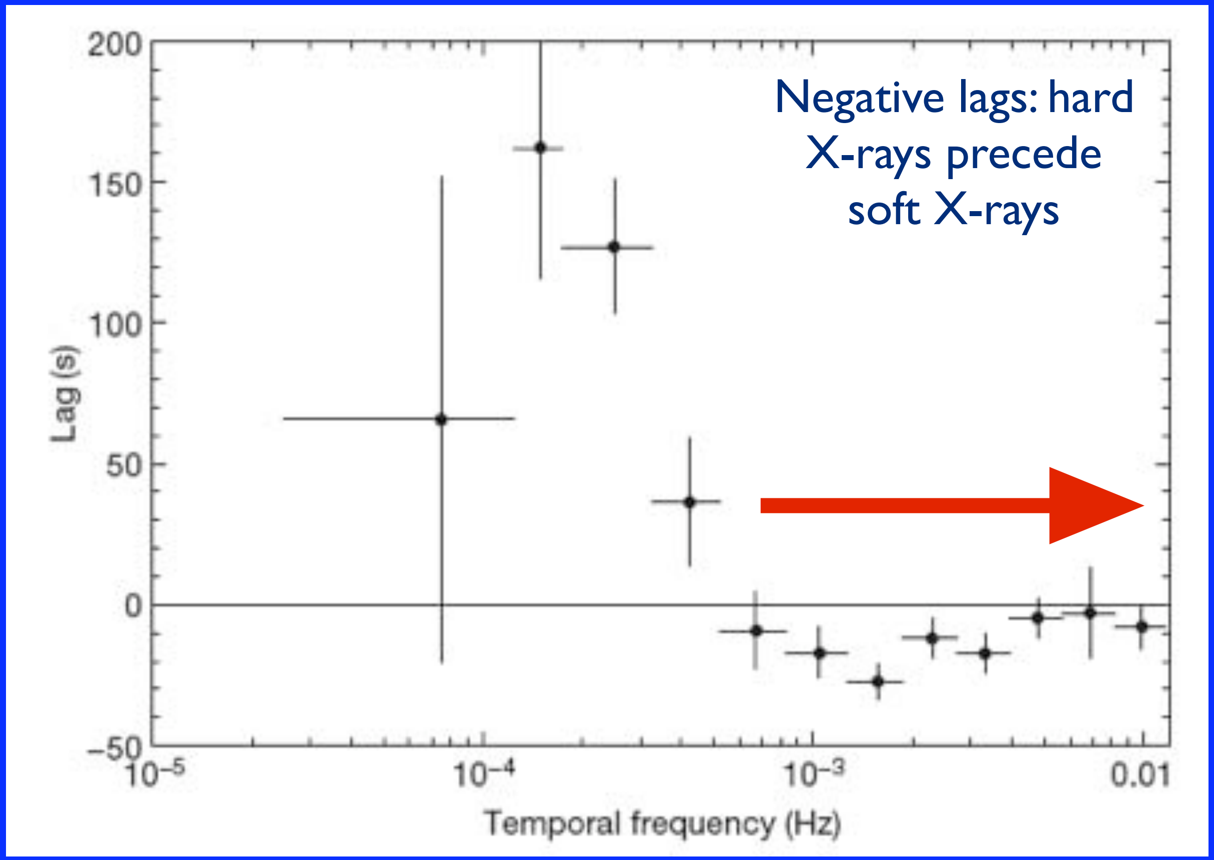
A. C. Fabian[1], A. Zoghbi[1], R. R. Ross[2], P. Uttley[3], L. C. Gallo[4], W. N. Brandt[5], A. J. Blustin[1], T. Boller[6], M. D. Caballero-Garcia[1], J. Larsson[1], J. M. Miller[7], G. Miniutti[8], G. Ponti[9], R. C. Reis[1], C. S. Reynolds[10], Y. Tanaka[6] & A. J. Young[11]



Residual X-ray spectrum



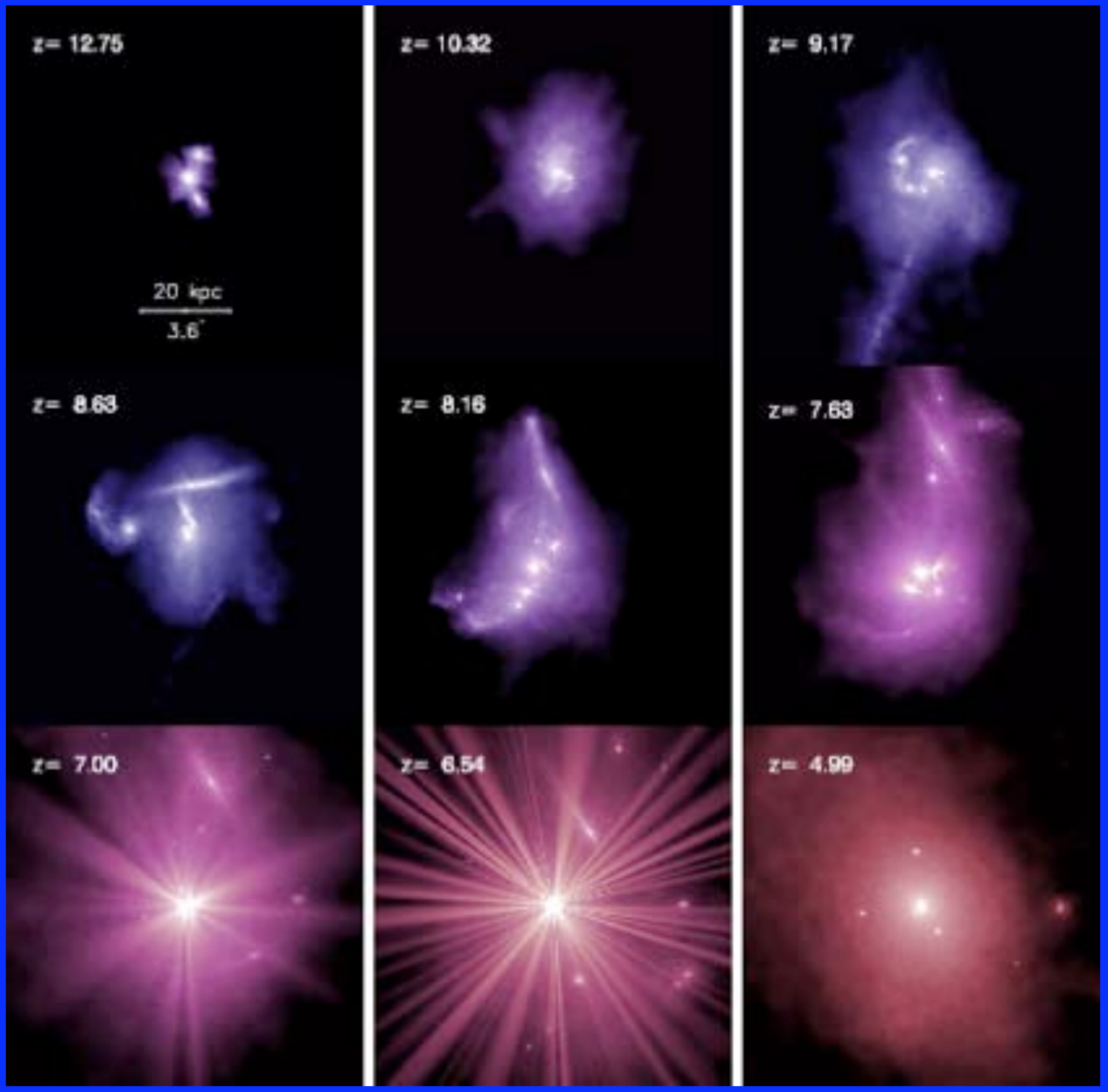
Lag spectrum between the 0.3–1-keV and 1–4-keV bands



How do supermassive grow and evolve?

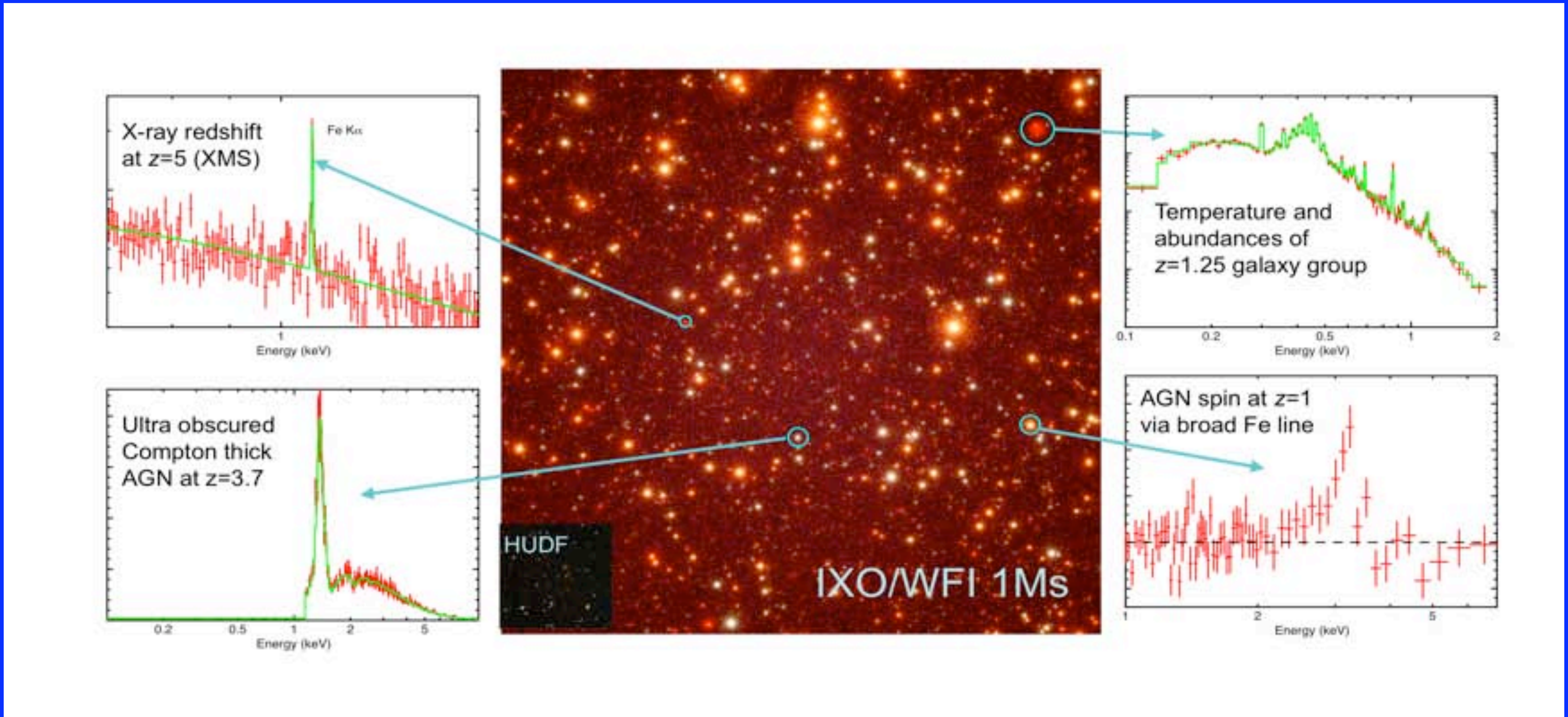
- **Intense star formation**
  - ✓ The quasars appear very faint and buried
- **Strong interactions between galaxies**
  - ✓ Boost star formation and black hole accretion, creating highly irregular morphologies and extremely blue galaxies. The quasars are heavily obscured by dense gas
- **Feedback from the black holes**
  - ✓ Quenches star formation, allowing the galaxy color to redden. The quasar becomes optically visible as strong outflows blow out the gas
    - ➡ X-rays offers a unique window to obscured accretion

Li et al. 2007



Blue indicates massive star formation in the galaxies, while red indicates little star formation. Rays illustrates quasar activity.

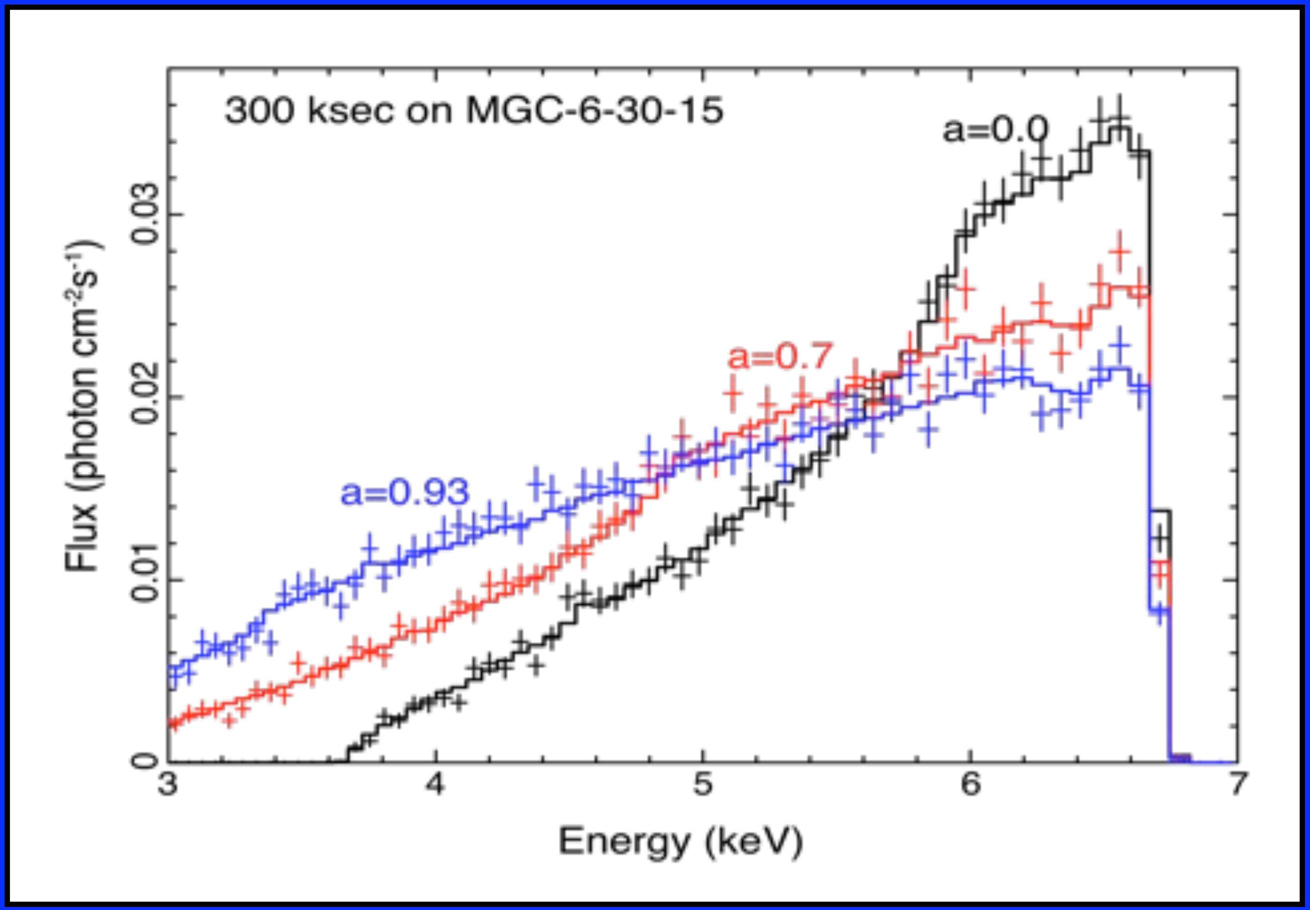
AGN census

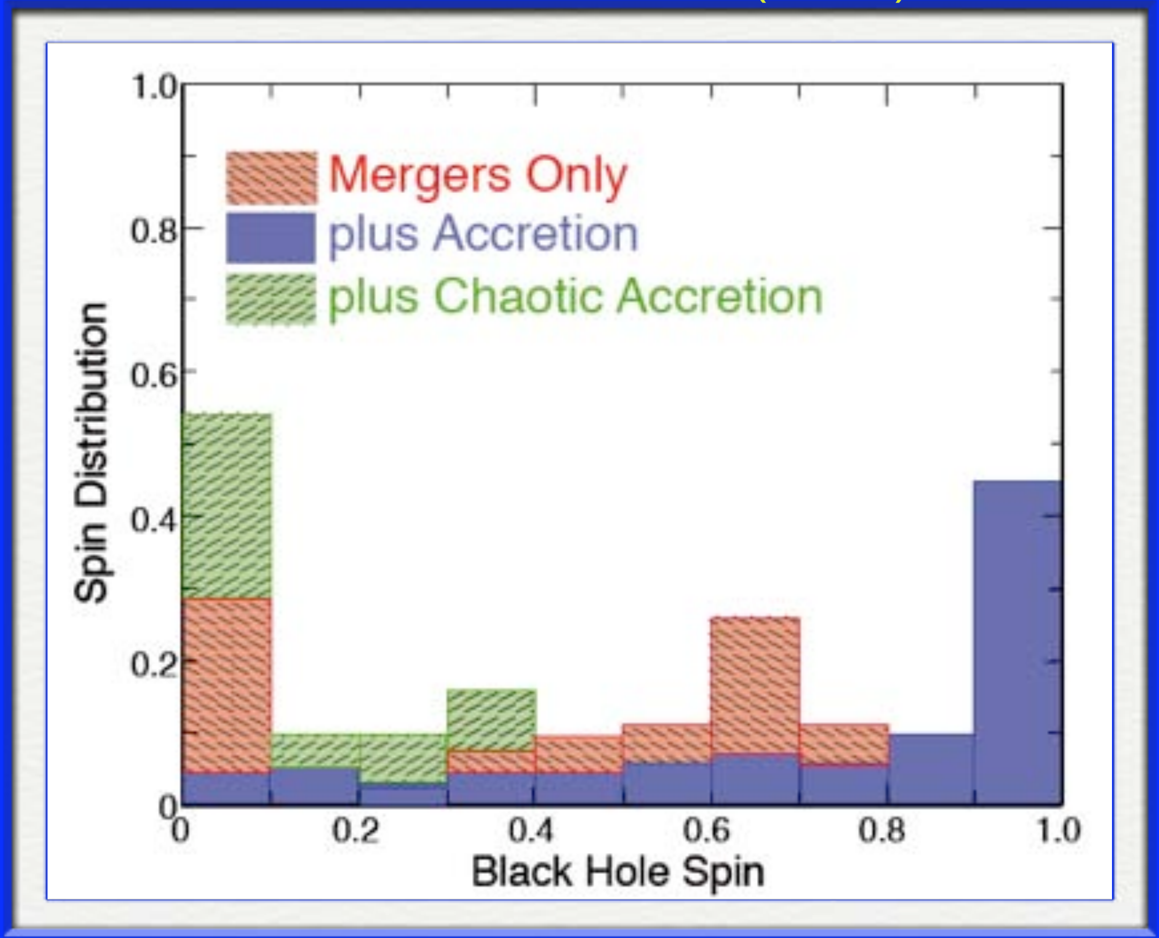


- ➡ determine redshift autonomously in the X-ray band
- ➡ determine temperatures and abundances even for low luminosity galaxy groups
- ➡ make spin measurements of the brightest AGNs
- ➡ uncover the most heavily obscured, Compton-thick AGNs

Black hole spins and growth

Berti & Volonteri (2008)

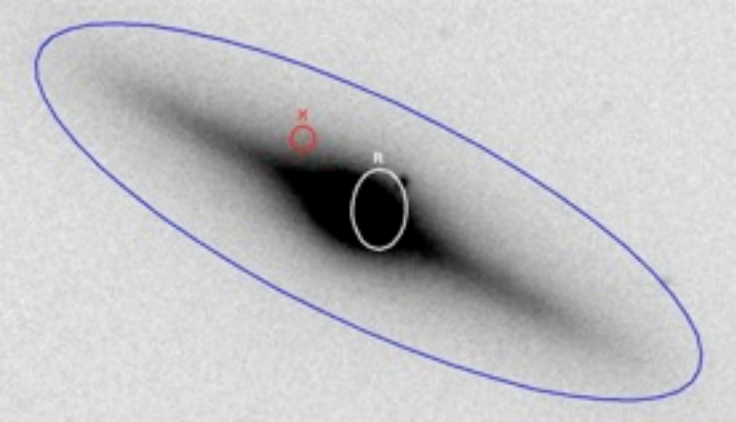




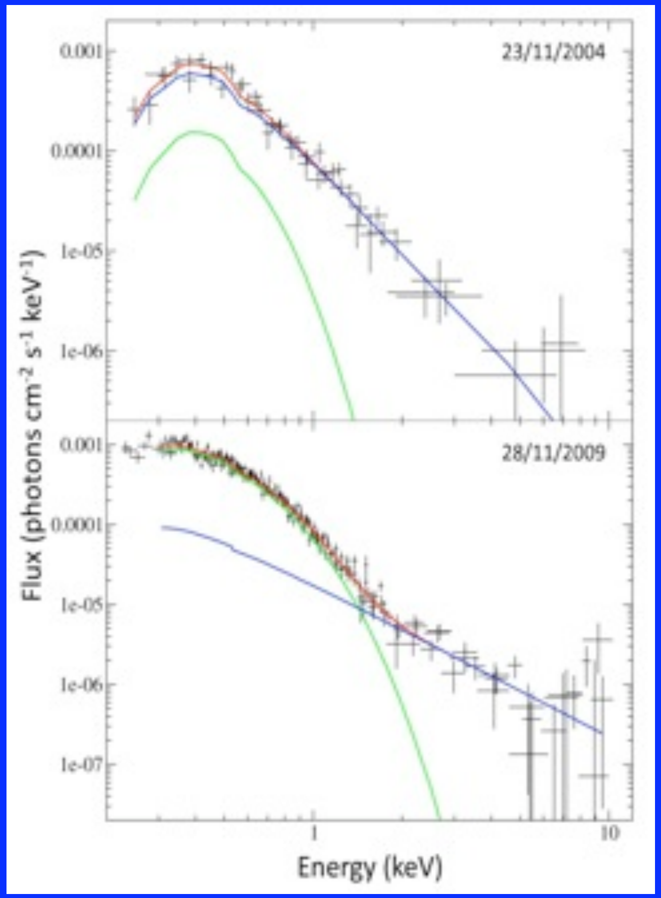
- IXO will use the relativistic Fe K line to determine the black hole spin for 300 AGN within z < 0.2 to constrain the super massive black hole merger history

What about intermediate mass BH?

edge-on spiral galaxy ESO 243-49



- New ultra luminous X-ray source (ULX) discovered in 2XMM catalog with unabsorbed max $L_X \sim 10^{42}$ erg s^{-1}
  - ➡ Beats previous record holder by factor 5 in Lx
  - ➡ No radio counterpart - No optical counterpart down to 24th
- ✓ Spectrum best fit by steep (Γ = 3.2) power law with relatively low absorption (NH = 8 x 10^{20} cm^{-2})
  - ➡ Micro-blazar hypothesis excluded
- Follow-up observation with XMM found variability – now requires low temperature (kT = 0.18 keV disc blackbody component)
  - ➡ LX and blackbody temp consistent with ULX spectrum
  - ➡ Intermediate mass black hole with mass ~500 – 100,000 Msol



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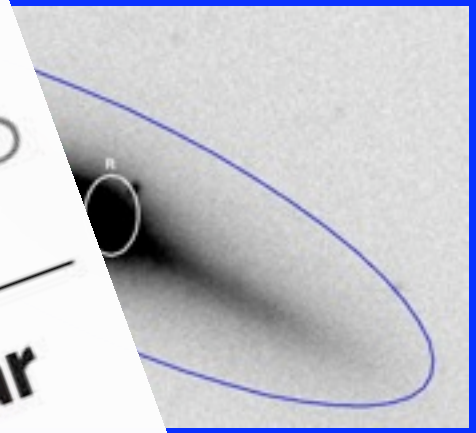

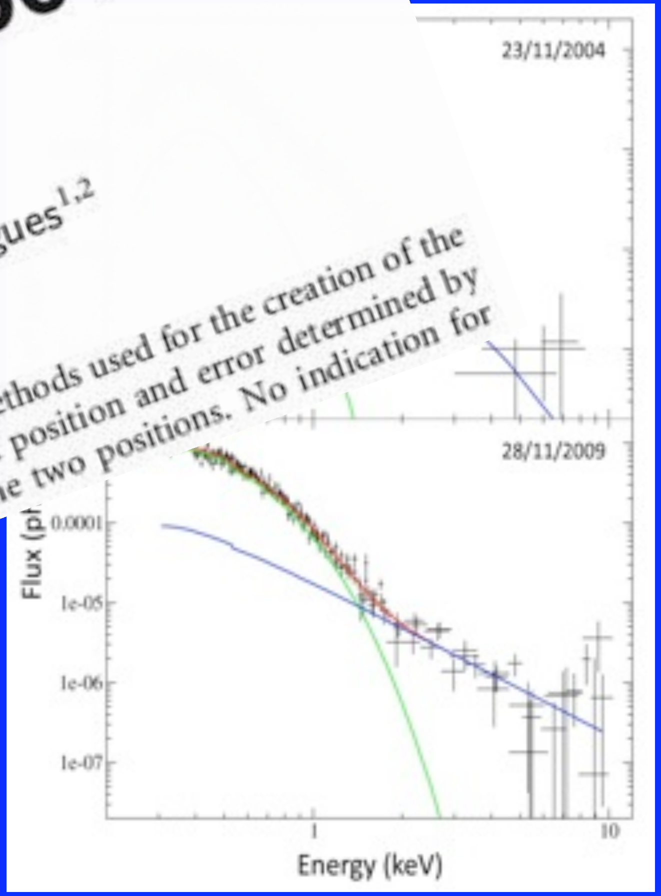


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LETTERS
Vol 000|00 Month 2009|doi:10.1038/nature08083

To appear July 2nd, 2009

An intermediate-mass black hole of over 500 solar masses in the galaxy ESO 243-49

Sean A. Farrell[1,2]†, Natalie A. Webb[1,2], Didier Barret[1,2], Olivier Godet[3] & Joana M. Rodrigues[1,2]

Ultraluminous X-ray sources are extragalactic objects located outside the nucleus of the host galaxy with bolometric luminosities[1] exceeding 10^{39} erg s^{-1}. These extreme luminosities—if the

derived in accordance with the methods used for the creation of the 2XMM catalogue[2], with the final position and error determined by taking the weighted mean of the two positions. No indication for

Black holes & matter under extreme conditions

- *How do supermassive black holes grow and evolve?*
  - ➡ *Complete census of AGNs of all kinds out to high redshifts*
- Does matter orbiting close to a black hole event horizon follow the predictions of general relativity?
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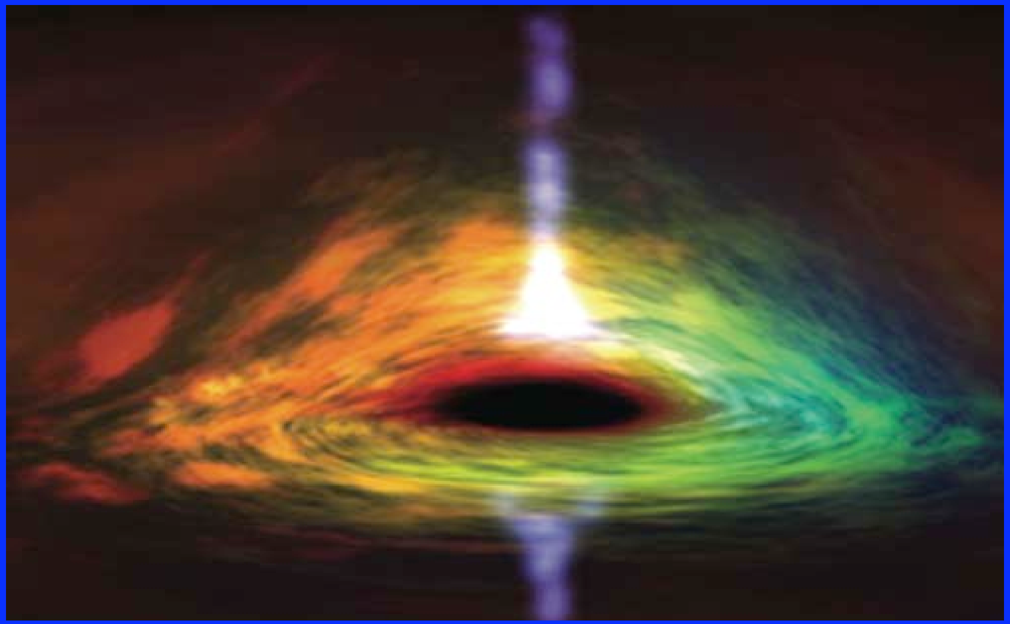
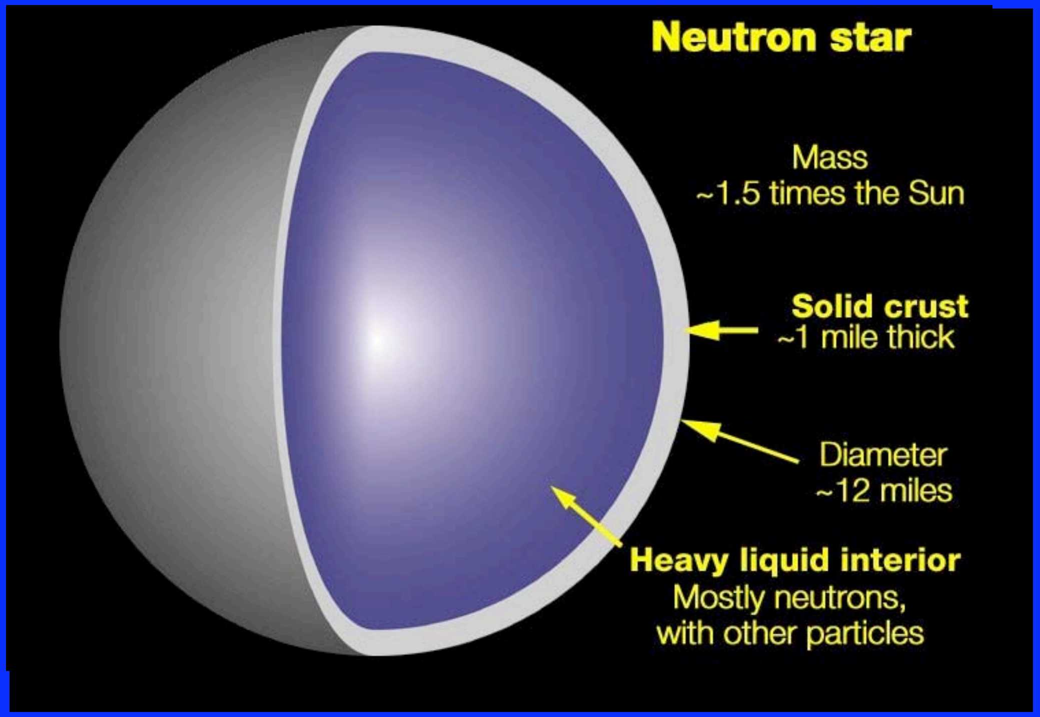
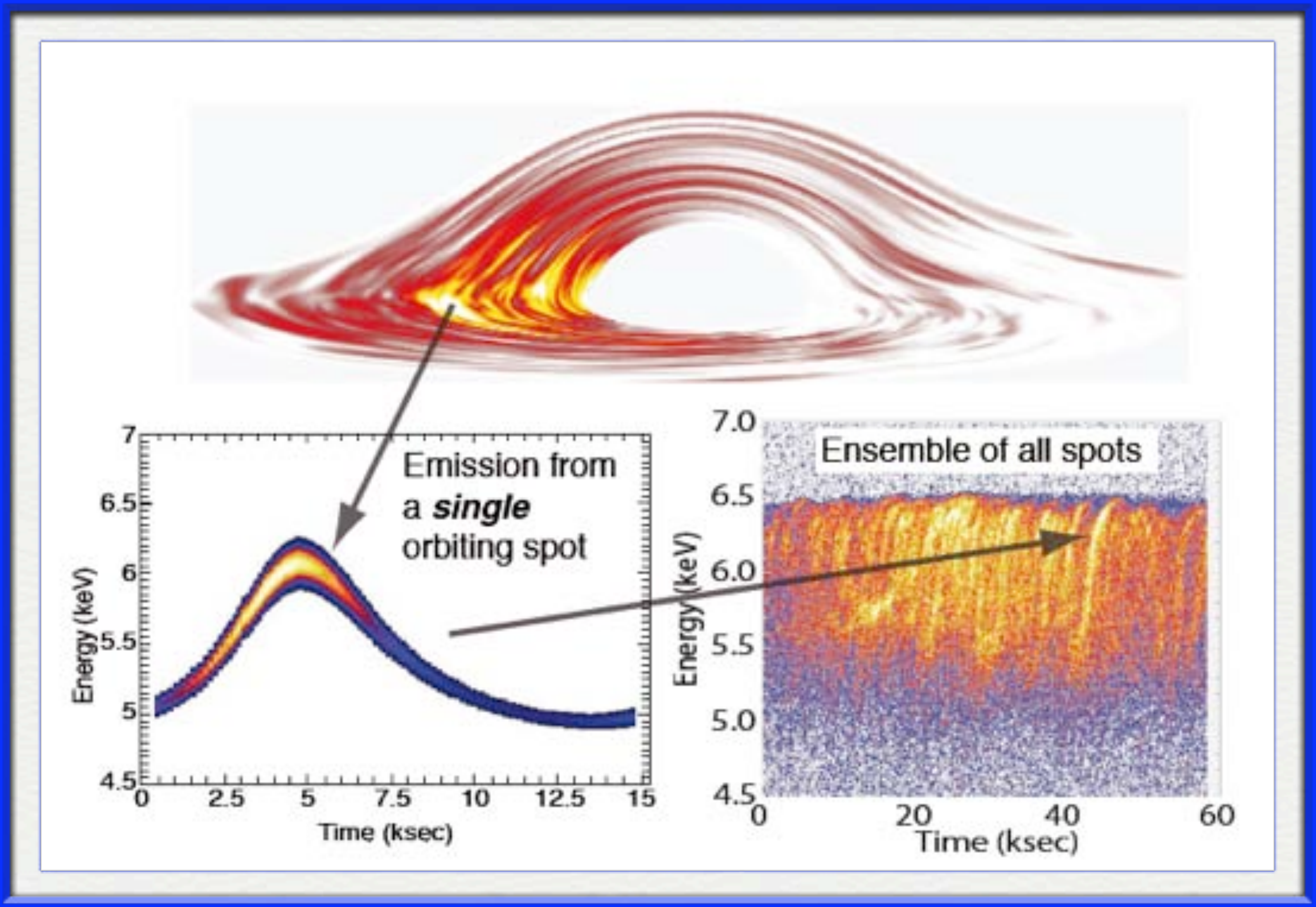




Plunging into the black hole



Best done with AGNs - 10^2-10^3 lower count rates than XRBs but 10^5-10^8 more massive, hence 10^2-10^6 more counts per orbital timescale

Can still be done with XRBs by averaging over many more orbital timescales than possible with AGNs

- 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

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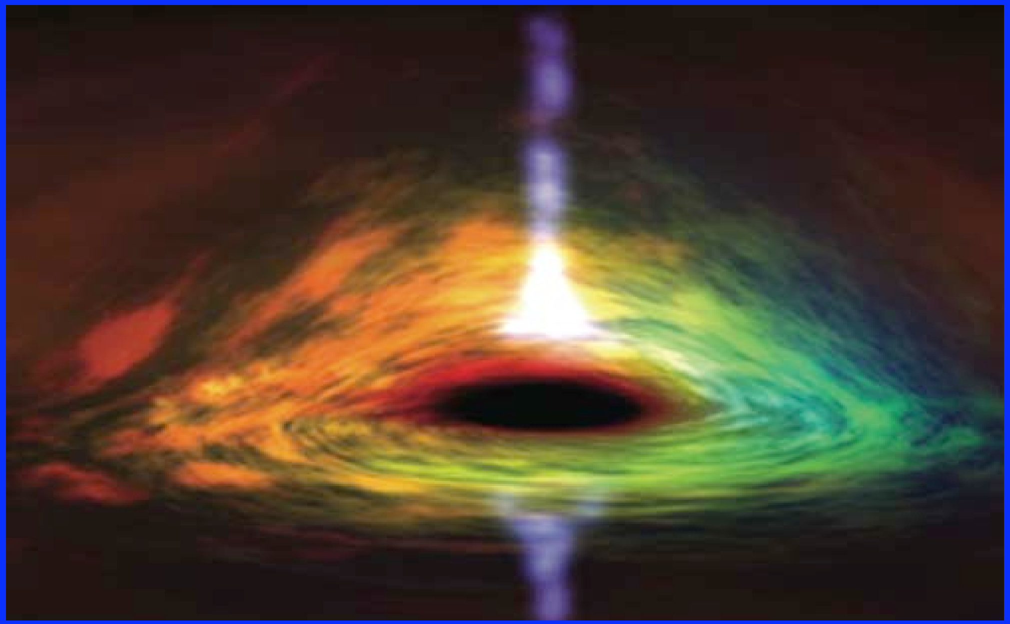
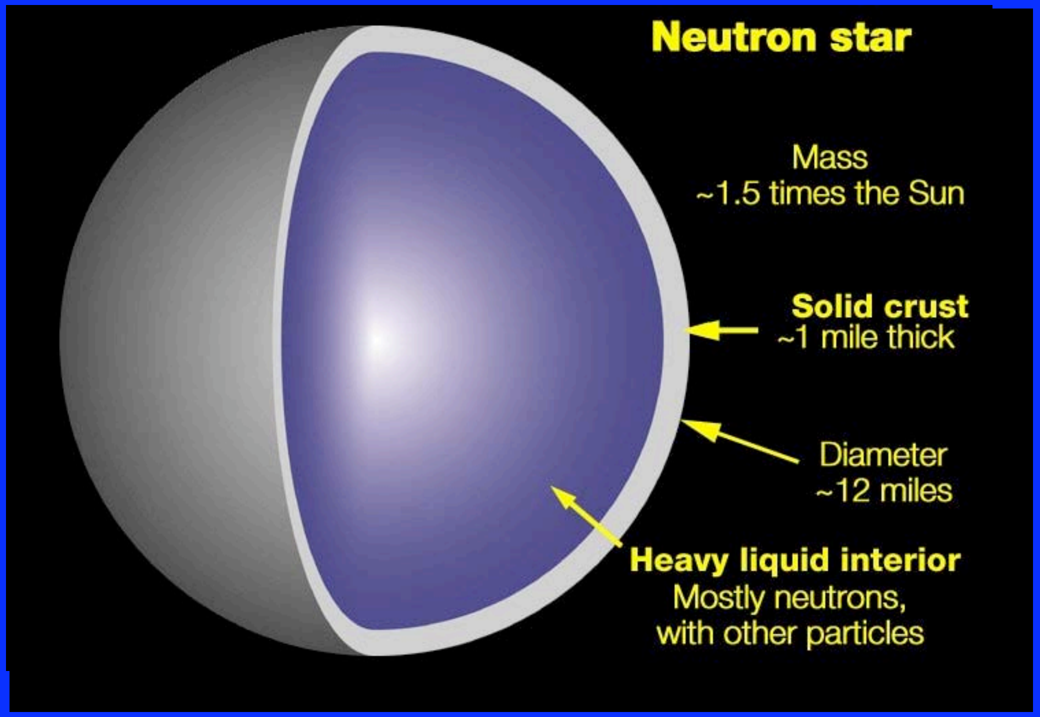
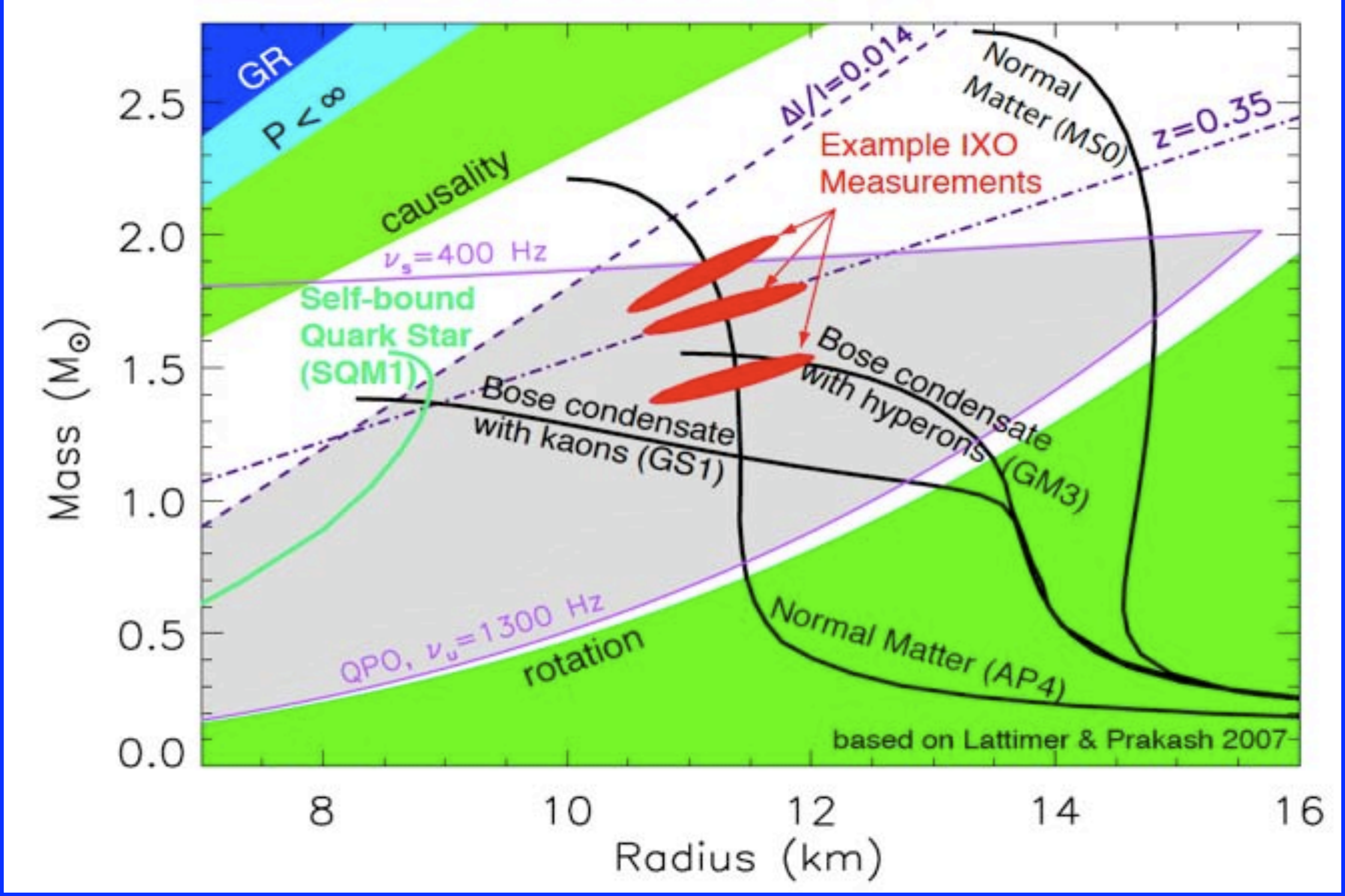




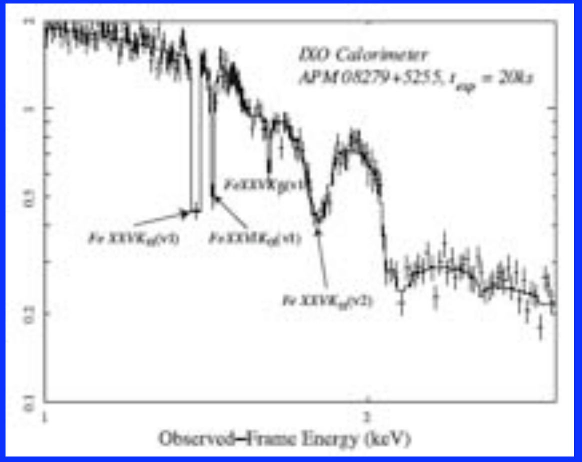
Determining the EoS

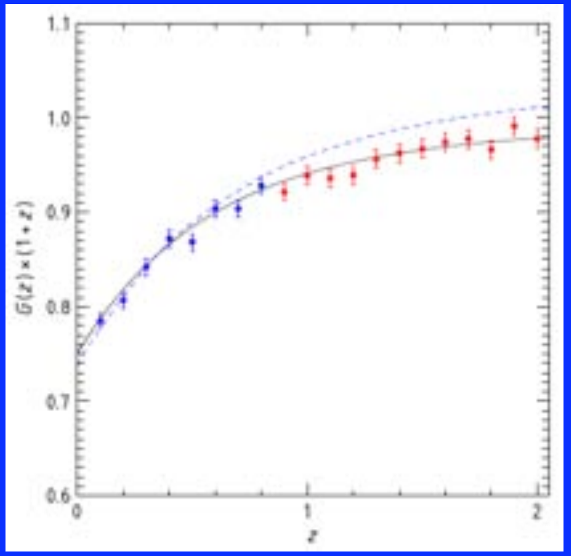
- Combining multiple diagnostics from multiple sources will enable us to determine the EoS

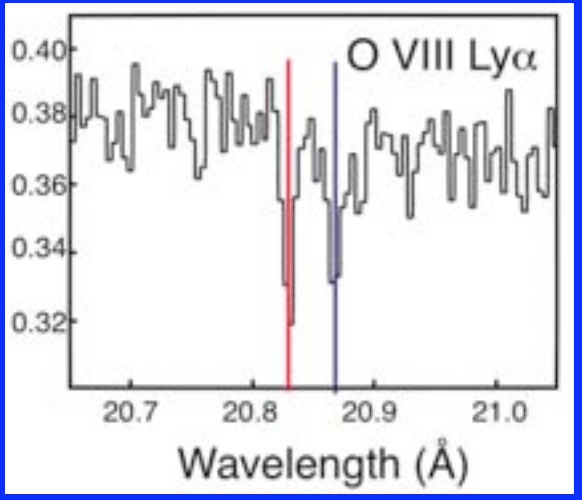


Galaxy evolution

- How does cosmic feedback work and influence galaxy formation?
  - ➡ Spatially resolved spectroscopy of the intra-cluster medium: temperatures, ionization states and velocities
- How does galaxy cluster evolution constrain the nature of dark matter and dark energy?
  - ➡ Measurement of the growth rate of clusters out to z=2
- Where are the missing baryons in the nearby Universe? Are they in the cosmic web?
  - ➡ High resolution spectroscopy of OVII and OVIII in absorption using background AGNs

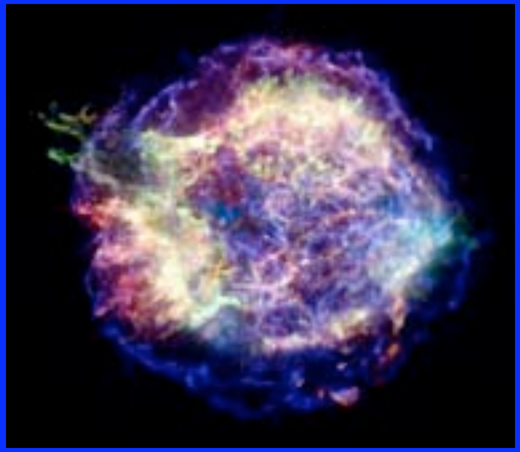


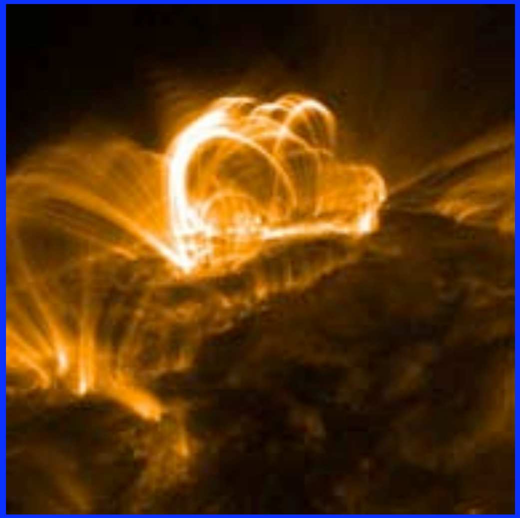




Life cycles of matter / energy

- When and how were the elements created and dispersed?
  - ➡ High resolution spectroscopy of SNe: CC versus type 1a
- How do high energy processes affect planetary formation and habitability?
  - ➡ Probing disks with reverberation mapping
- How do magnetic fields shape stellar exteriors and the surrounding environment?
  - ➡ Unbiased X-ray survey of bright stars
- How are particles accelerated to extreme energies producing shocks, jets and cosmic rays?
  - ➡ e.g. spatially resolved hard X-ray imaging of SNe remnants





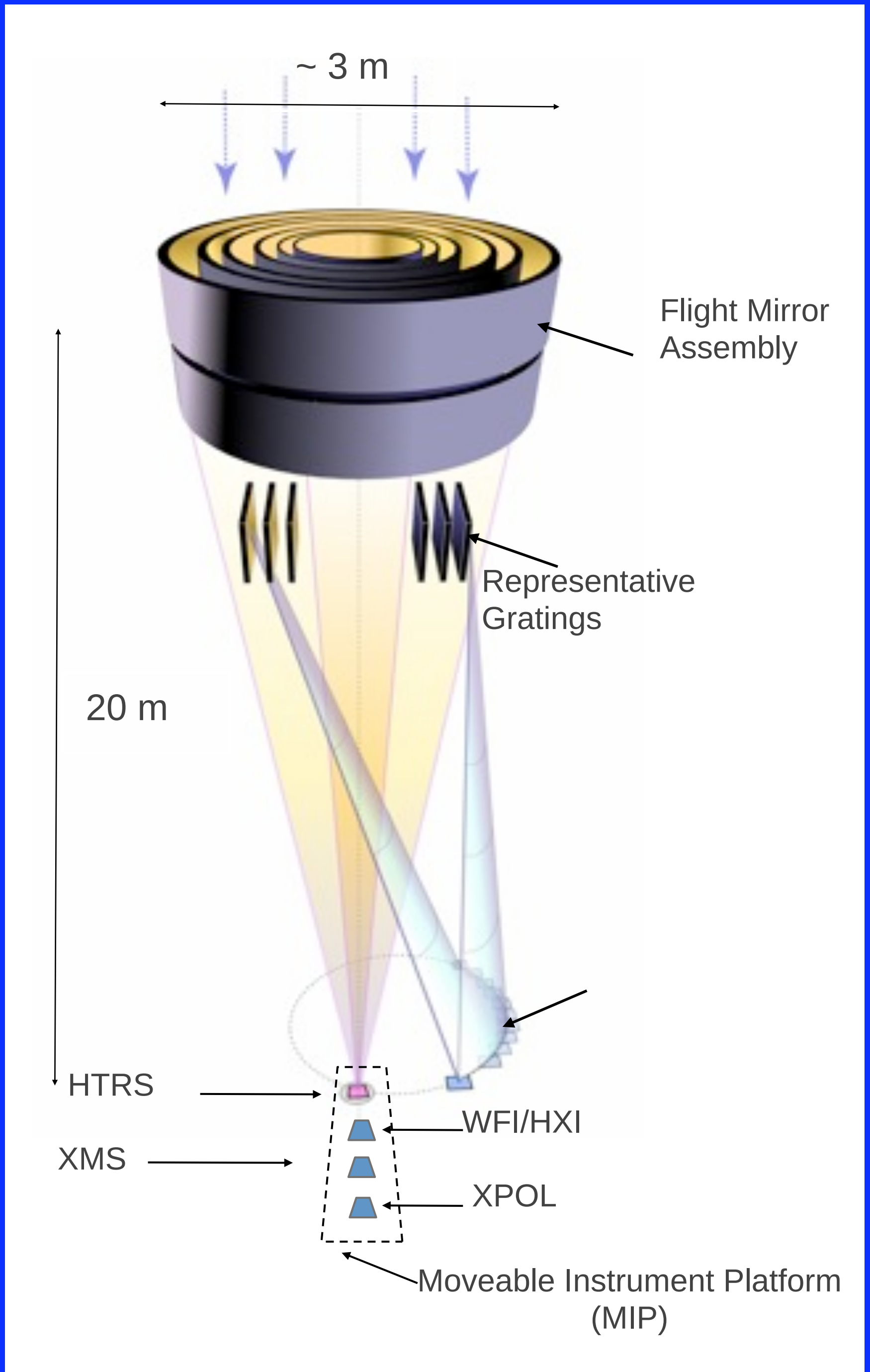
Key performance requirements

- The science goals are converted into performance requirements

Mirror Effective Area	3 m^2 @1.25 keV 0.65 m^2 @ 6 keV with a goal of 1 m^2 150 cm^2 @ 30 keV with a goal of 350 cm^2	Black hole evolution, large scale structure, cosmic feedback, equation of state Strong gravity, equation of state Cosmic acceleration, strong gravity
Spectral Resolution	ΔE = 2.5 eV within 2 x 2 arc min (0.3 – 7 keV) . ΔE = 10 eV within 5 x 5 arc min (0.3 - 7 keV) ΔE < 150 eV @ 6 keV within 18 arc min diameter (0.1 - 15 keV) $E/\Delta E$ = 3000 from 0.3–1 keV with 1,000 cm^2 for point sources ΔE = 1 keV within 8 x 8 arc min (10 – 40 keV)	Black Hole evolution, Large scale structure Missing baryons using tens of background AGN
Mirror Angular Resolution	≤5 arc sec HPD (0.1 – 10 keV) 30 arc sec HPD (10 - 40 keV) with a goal of 5 arc sec	Large scale structure, cosmic feedback, black hole evolution, missing baryons Black hole evolution
Count Rate	1 Crab with >90% throughput. ΔE < 200 eV (0.1 – 15 keV)	Strong gravity, equation of state
Polarimetry	1% MDP on 1 mCrab in 100 ksec (2 - 6 keV)	AGN geometry, strong gravity
Astrometry	1 arcsec at 3σ confidence	Black hole evolution
Absolute Timing	100 µsec	Neutron star studies

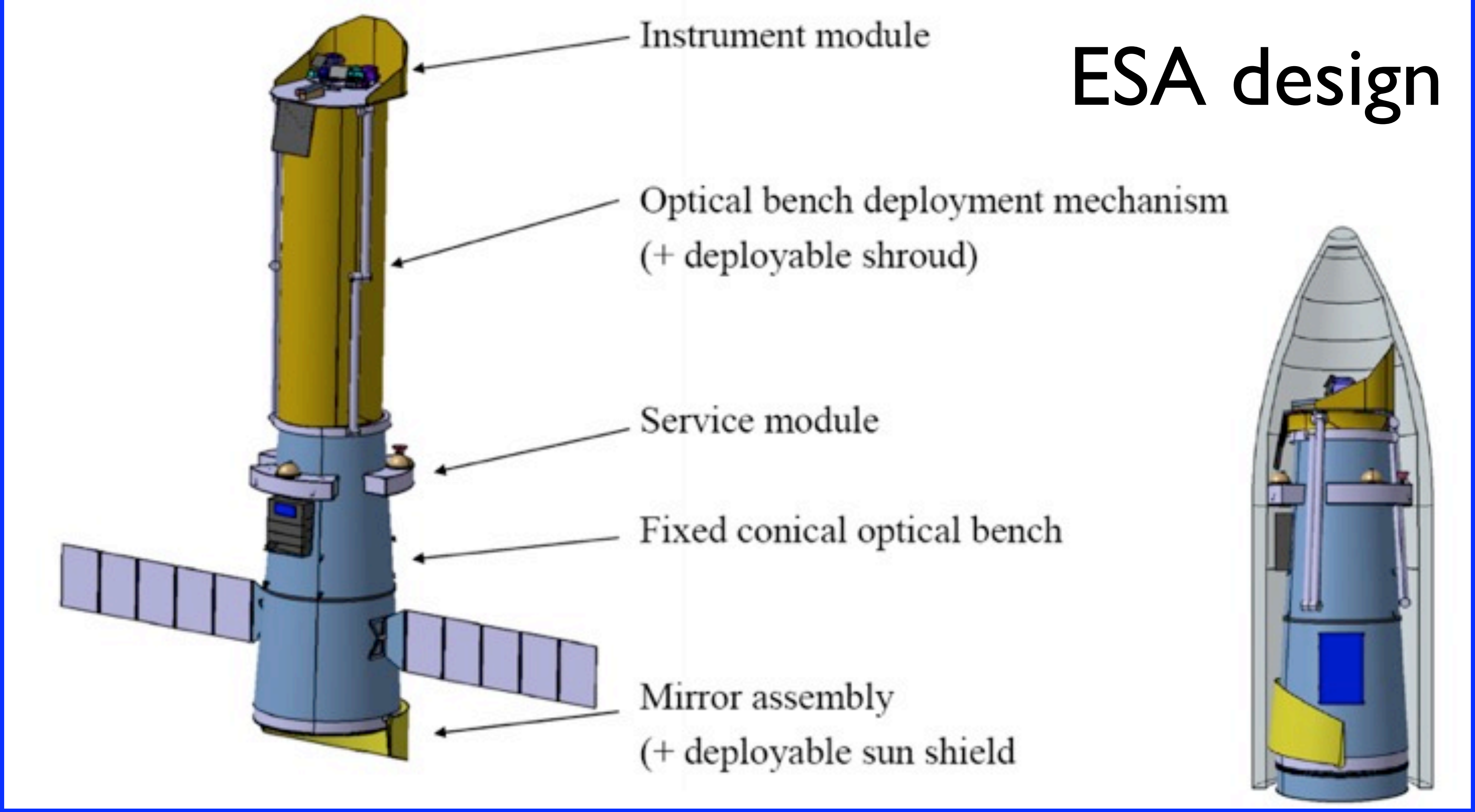
The IXO payload

- Large X-ray mirrors: 3 m^2 at 1 keV with 5" PSF
- 20 m focal length
- Science payload:
  - X-ray Micro-calorimeter Spectrometer (XMS) - 2.5 eV with 5 arc min FOV
  - X-ray Grating Spectrometer (XGS), R=3000 with 1,000 cm^2
  - Wide Field Imager (WFI) and Hard X-ray Imager (HXI) , 18 arc min FOV with 120 eV resolution - 0.3 to 40 keV
  - High Time Resolution Spectrometer (HTRS), 10^6 counts/s with 150 eV resolution - 0.3-40 keV
  - X-ray Polarimeter (X-POL)



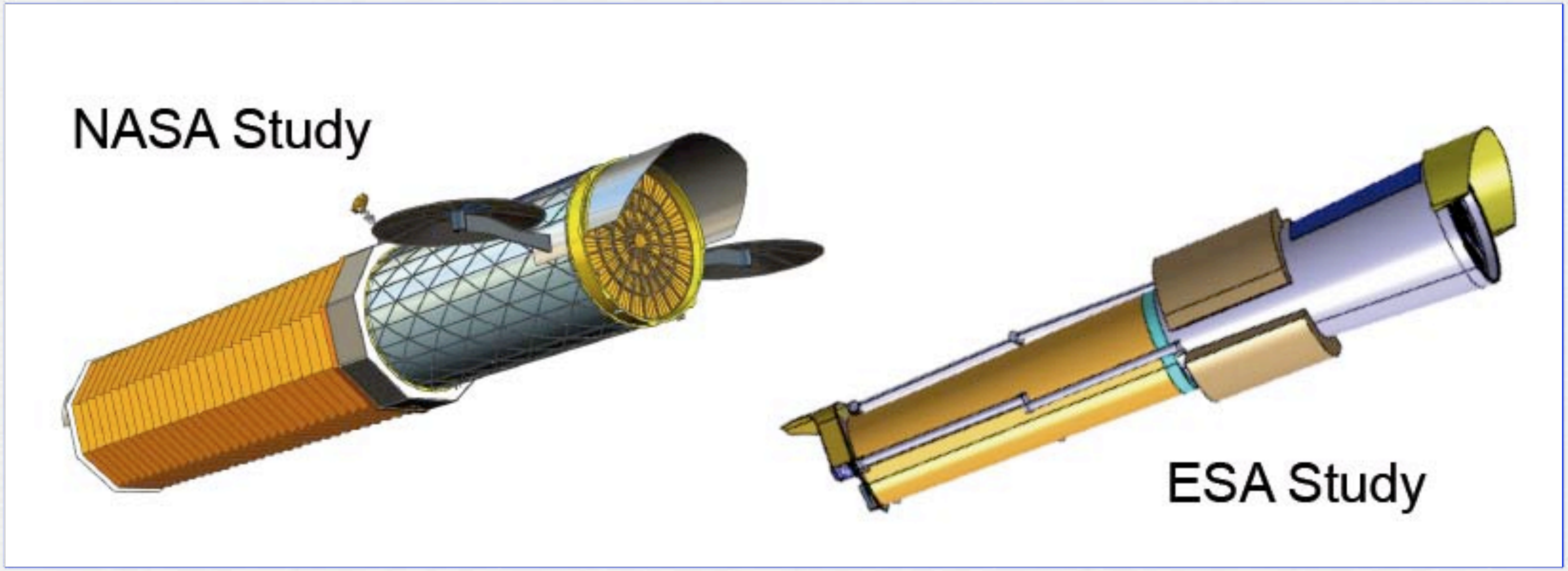
Mission designs

- The IXO concept is compatible with both Ariane V - Atlas V
  - ✓ 6 ton spacecraft
  - ✓ Target orbit: direct launch into L2
  - ✓ 5 Year mission (with consumables sized for a 10 year mission)



Mission design

- Separate ESA and NASA mission studies demonstrate overall mission feasibility, with no show stoppers

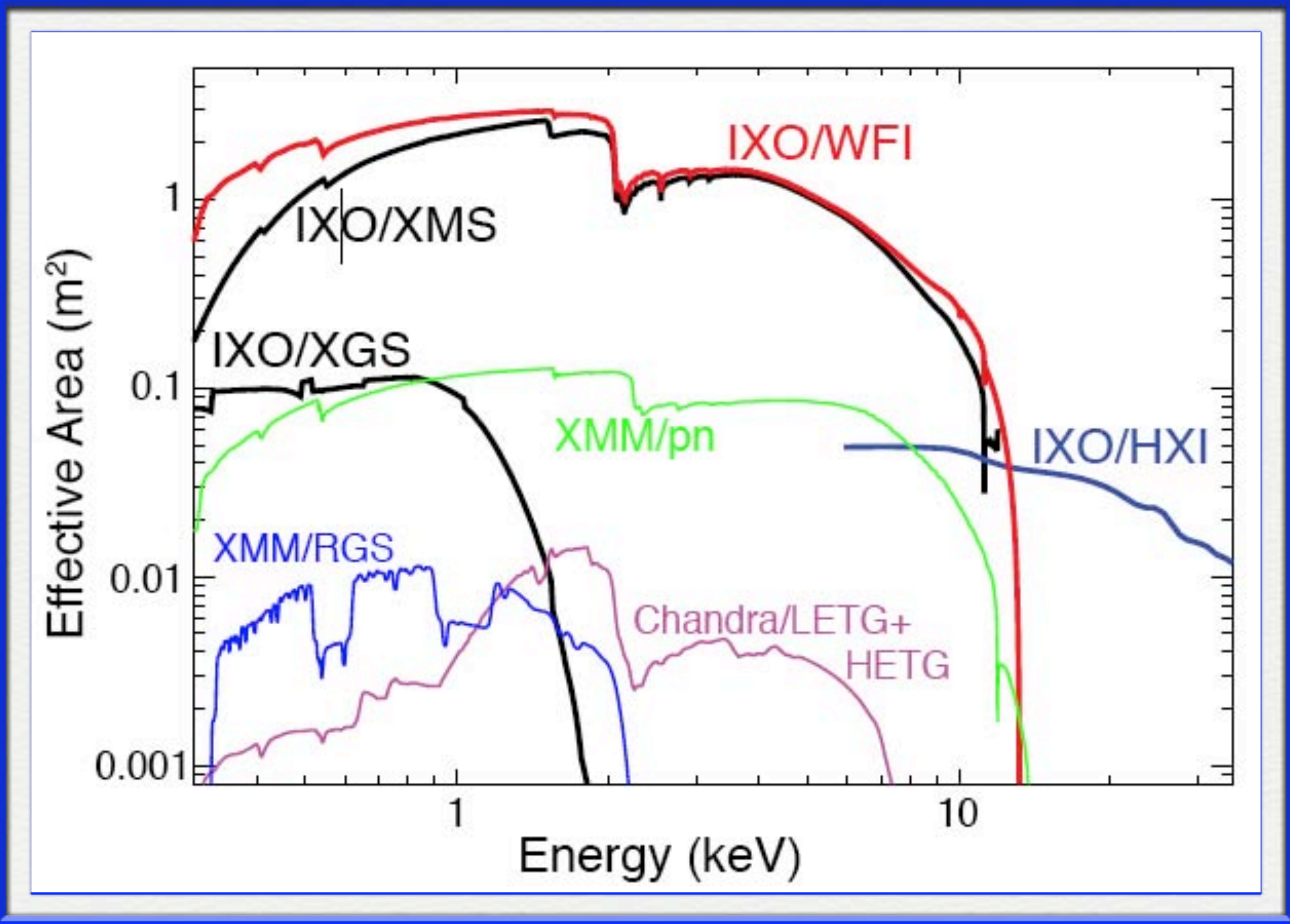


IXO getting deployed - NASA movie

- Deployable shroud & rotating focal plane

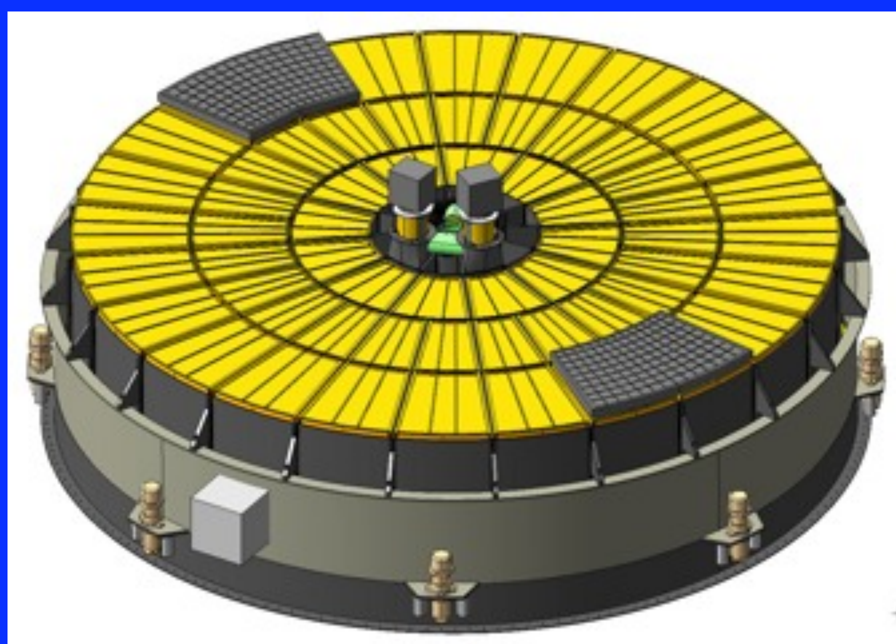
Effective area

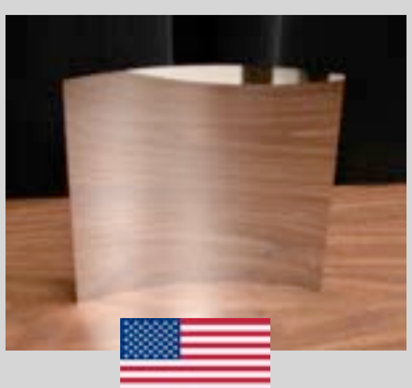
- 30 times the effective area of XMM-Newton EPIC-PN
- Effective area (HXI) underneath the WFI comparable to Simbol-X



The IXO payload

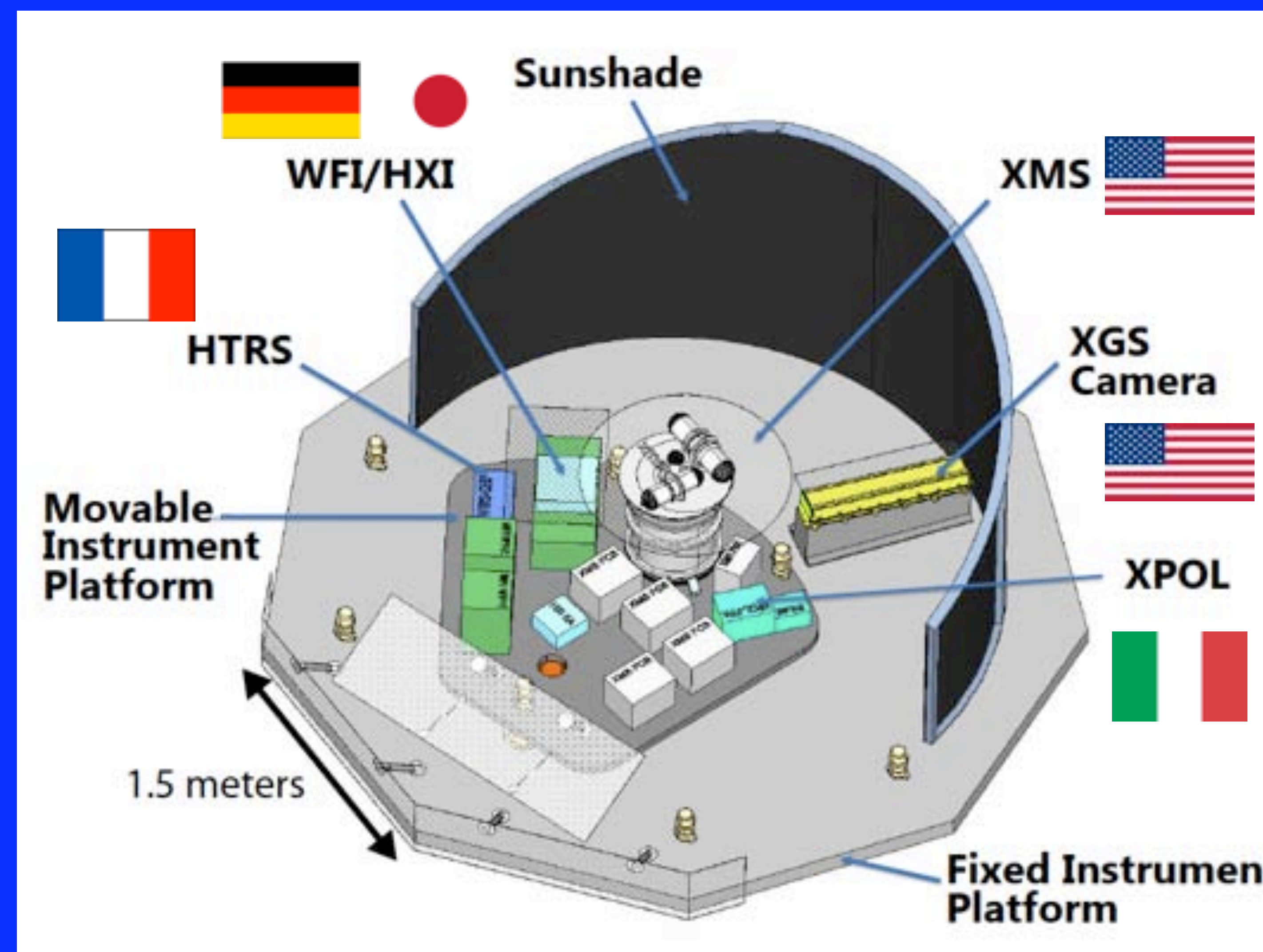
- Competitive mirror technologies - need light optics
- Distributed payload - nothing formalized yet





Slumped Glass
5″ HEW
~270 kg/m²

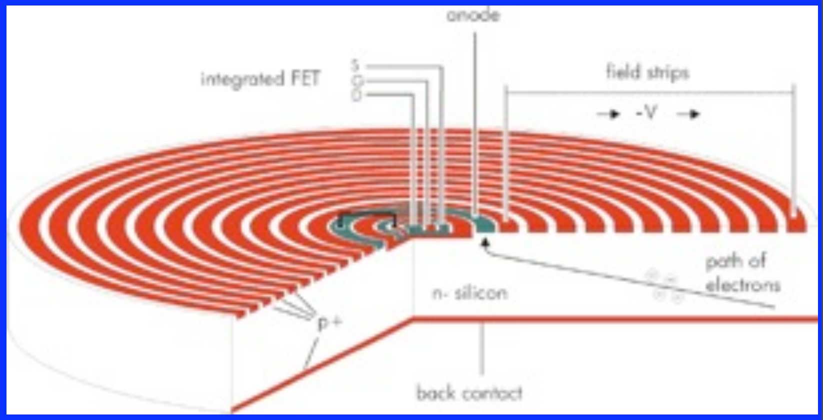
Si-HPO
5″ HEW
~200 kg/m²



The HTRS characteristics

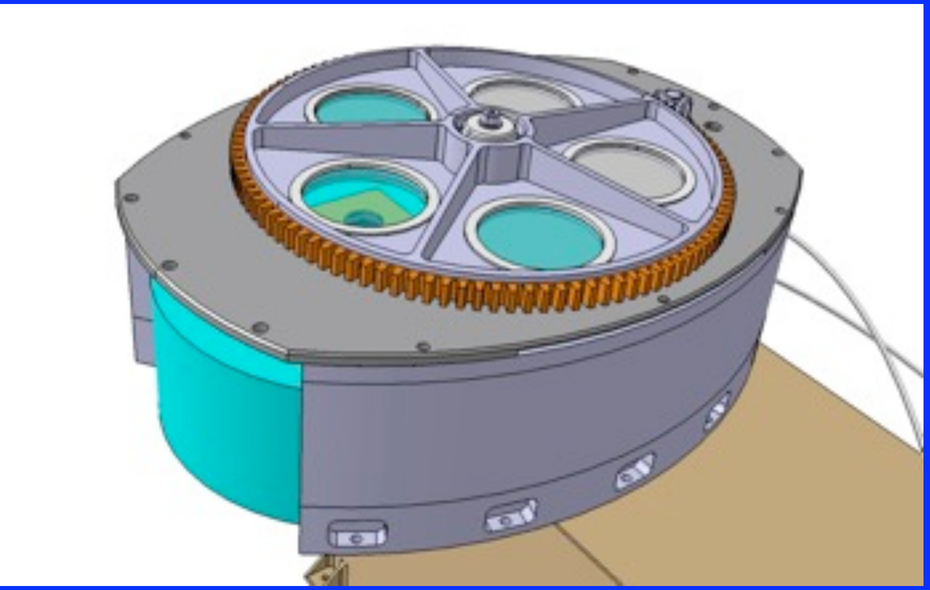
- HTRS is based on Silicon Drift Detectors (SDD)
  - ✓ The main advantage of SDD is their small physical size and consequently the small capacitance of the anode, which translates to a capability to handle very high count rates simultaneously with good energy resolution.
  - ✓ The HTRS is an array of 37 hexagonal SDDs, placed out of focus, such that the focal beam from the IXO mirror is spread over the array.

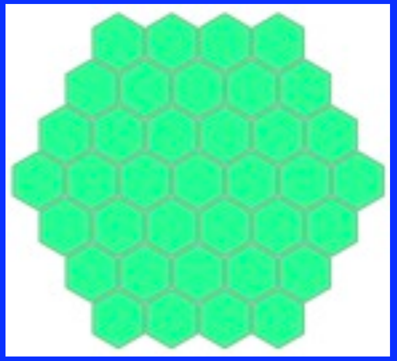
Courtesy of Peter Lechner & Lothar Strueder



Single SDD

Energy range	0.3-20 keV
Time resolution	10 micro-seconds
Energy resolution	<150 eV @ 6 keV (-20C)
1 Crab count rate	~200 000 counts/s
Count rate capability	> 10 Crab
Deadtime & pile-up	<1% @ 1 Crab
Overall detector size	~ 2 cm^2
Readout time	50-75 ns

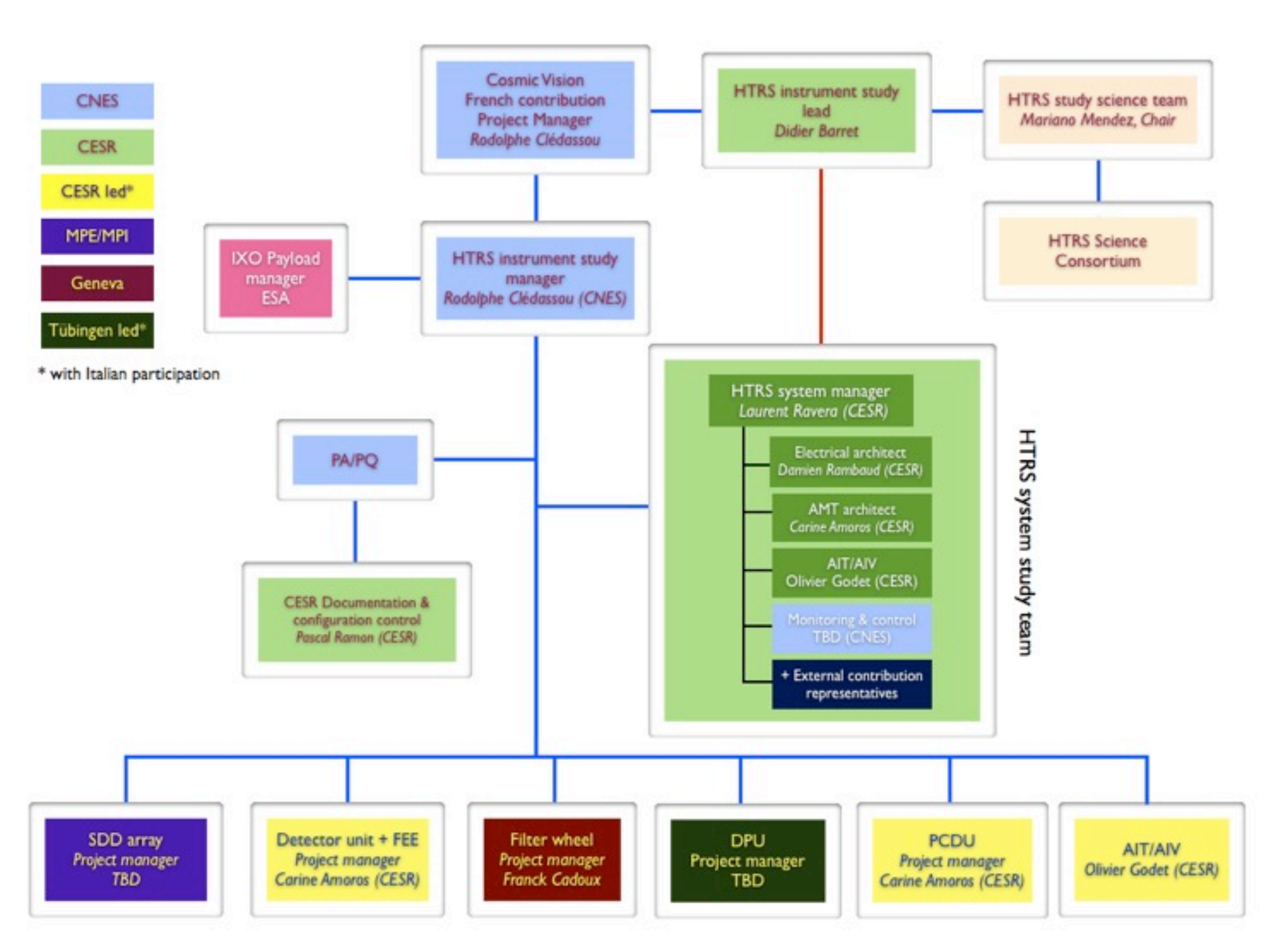




The SDD array

The HTRS phase A study team

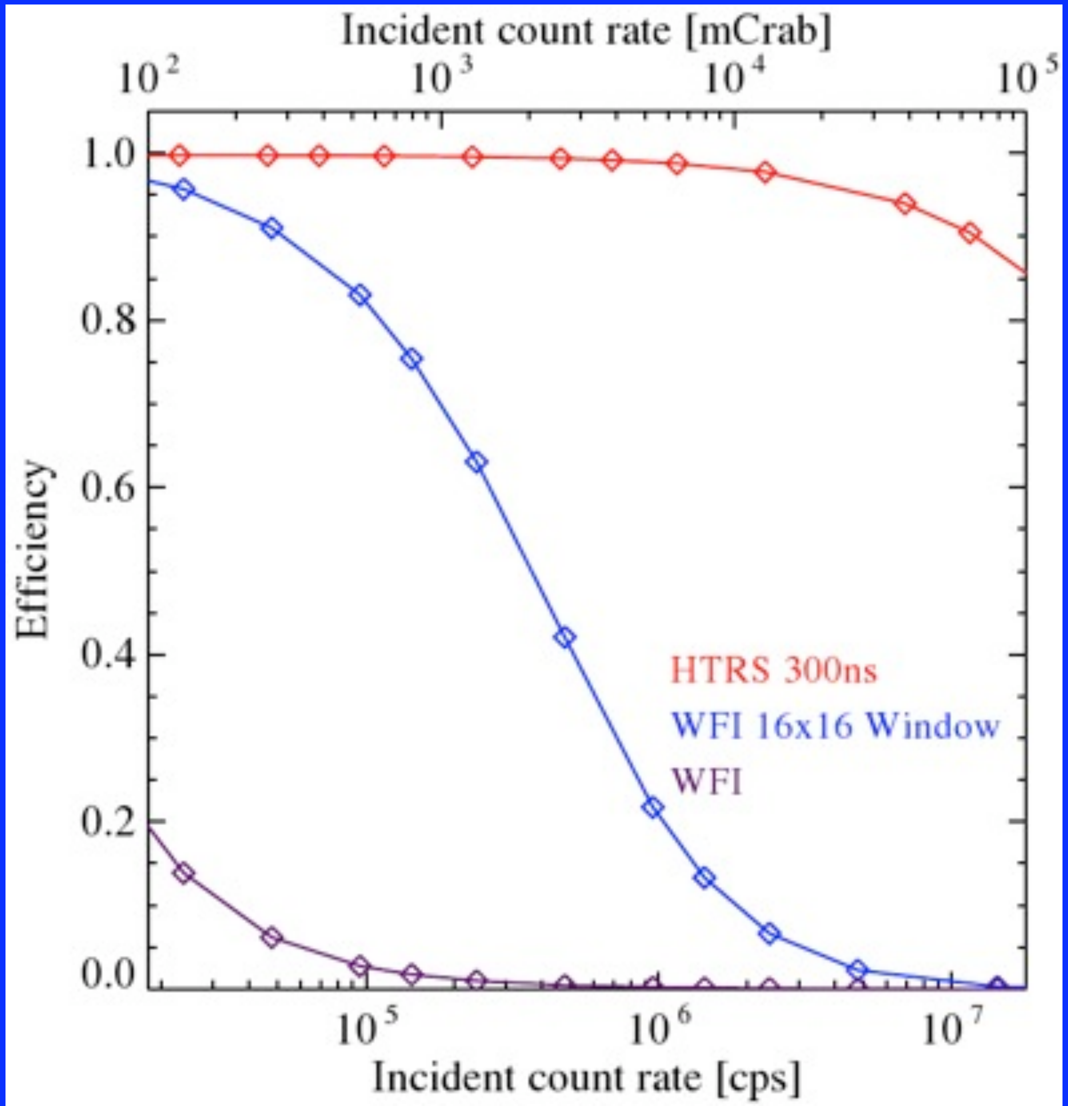
- CNES: project management - CESR HTRS system manager



Count rate capability

- The HTRS will be the only IXO instrument capable of coping with extreme count rates

Comparison with the other fast instrument on IXO: The Wide Field Imager in window mode

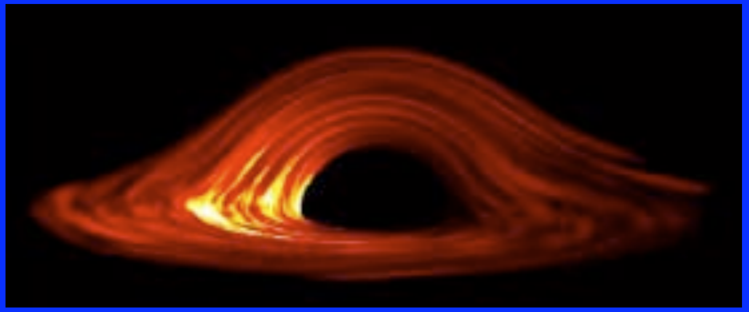


- Combine fast timing and spectroscopy
  - ✓ Larger count rates (x 10-20)
  - ✓ Improved energy resolution
    - ➡ with no energy pile-up and deadtime

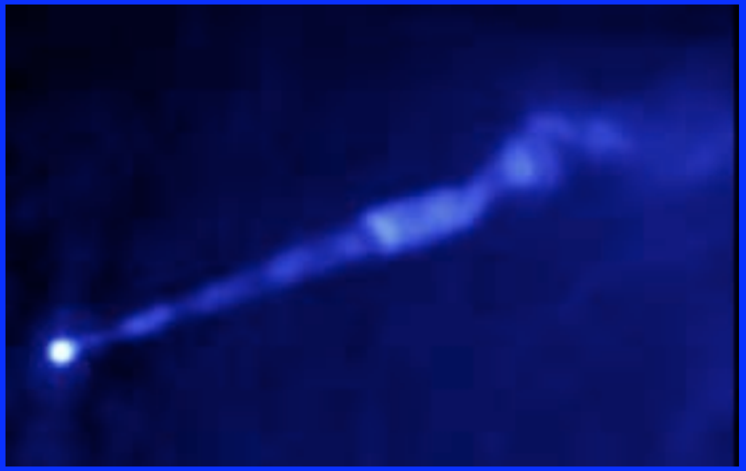
Science with the HTRS

- The High Time Resolution Spectrometer (HTRS) will provide IXO with the capability to observe bright X-ray sources
  - ✓ accreting neutron star and black hole X-ray binaries, including X-ray bursters
- Two science goals, under the *matter under extreme conditions* topic:
  - ✓ Accretion in strong gravity
    - ➡ Measuring the spin distribution of stellar mass black hole and probing strong field GR
  - ✓ The equation of state of dense matter
    - ➡ Tracking X-rays from the surface of NSs to determine their radii

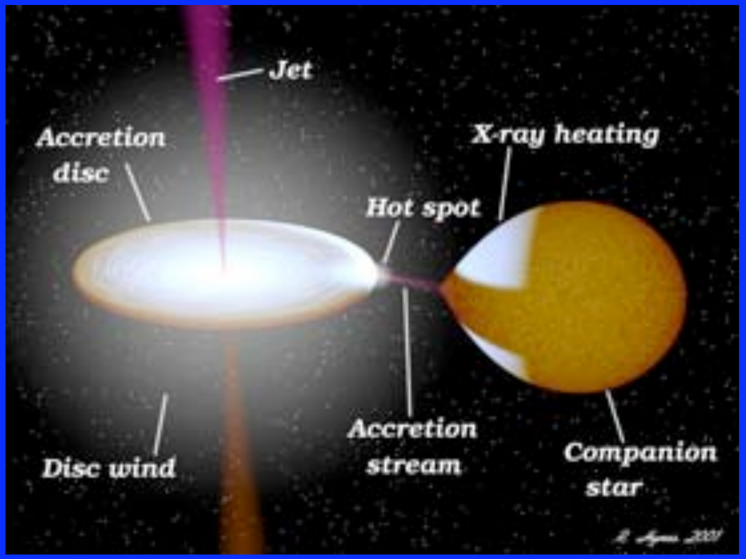
Why care about BH spins?



- Accretion efficiency scales with spin from 10% for non spinning up to 42% for maximally rotating black holes



- BH launch jets which can shape galaxies, clusters
  - ✓ Tied to BH spins

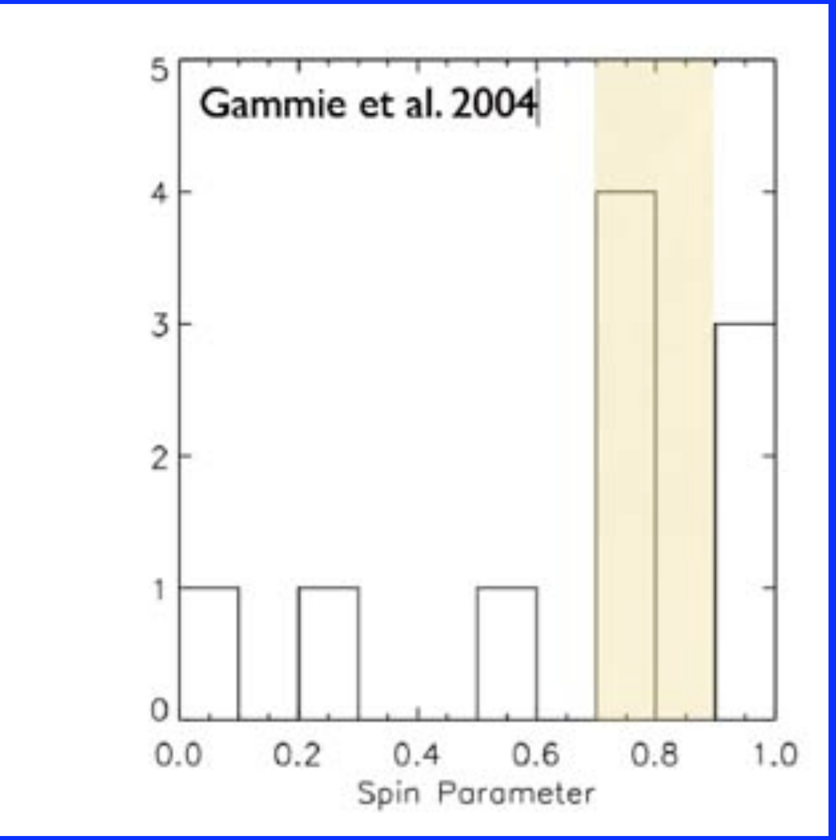


- From a zero spin to a maximal spin, a black hole must double its mass
  - ✓ Not possible in a stellar binary
    - ➡ Current spin reflects that imparted at birth
    - ➡ A unique window on SNe/GRBs and the first BHs
- Put in the AGN context, spin may reflect the growth history of supermassive BHs

Securing spin measurements

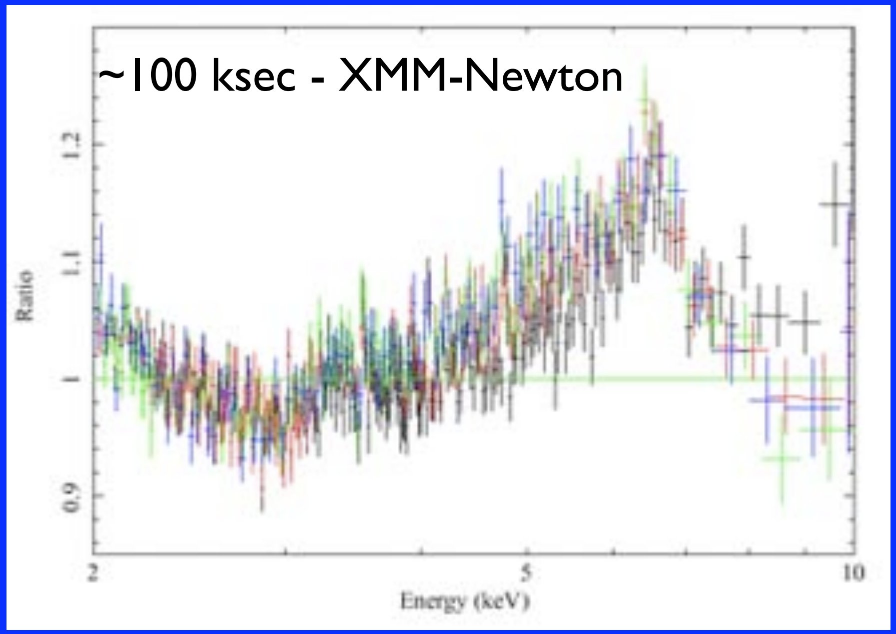
- ~10 stellar mass black holes only - slightly larger spins preferred
  - ✓ Addition 30-40 candidate black holes to be considered
- Securing the spin measurements by:
  - ✓ Sampling the source in multiple states with much better statistics
    - ➡ Test the robustness of the models
  - ✓ Correlating the spin inferred from energy spectra with timing (and even polarimetry) measurements
    - ➡ QPOs
    - ➡ Reverberation mapping
    - ➡ Low energy continuum spectroscopy

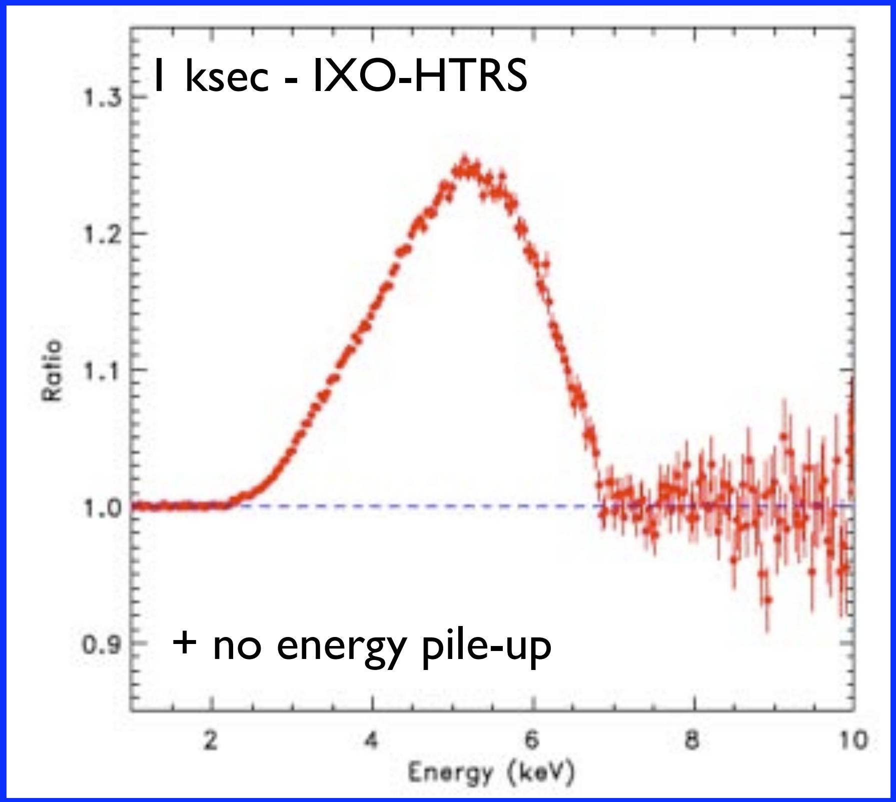
Spins from collapsar compared to observations

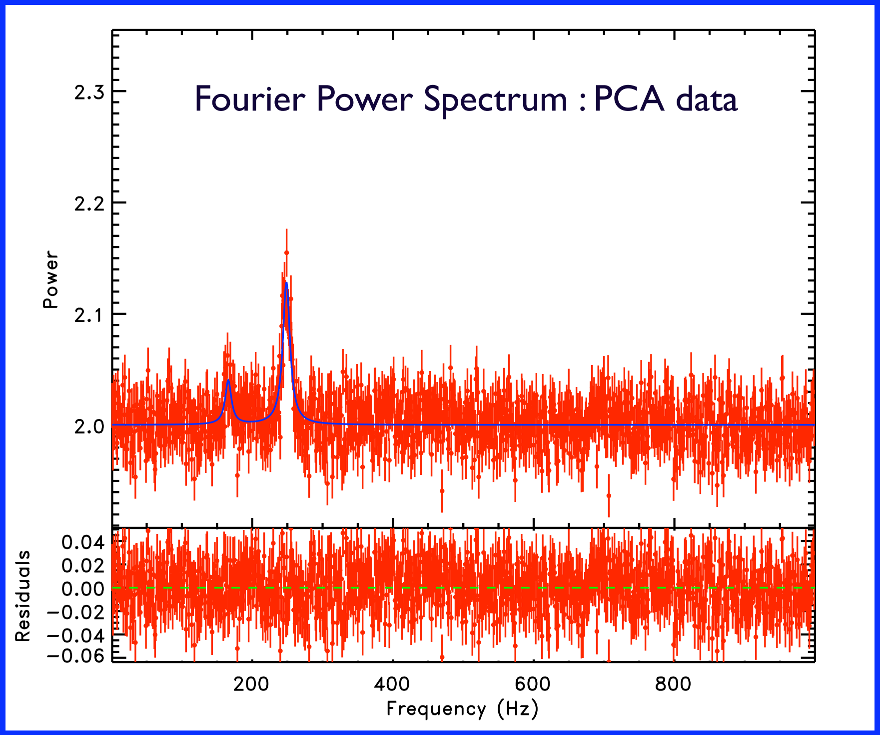


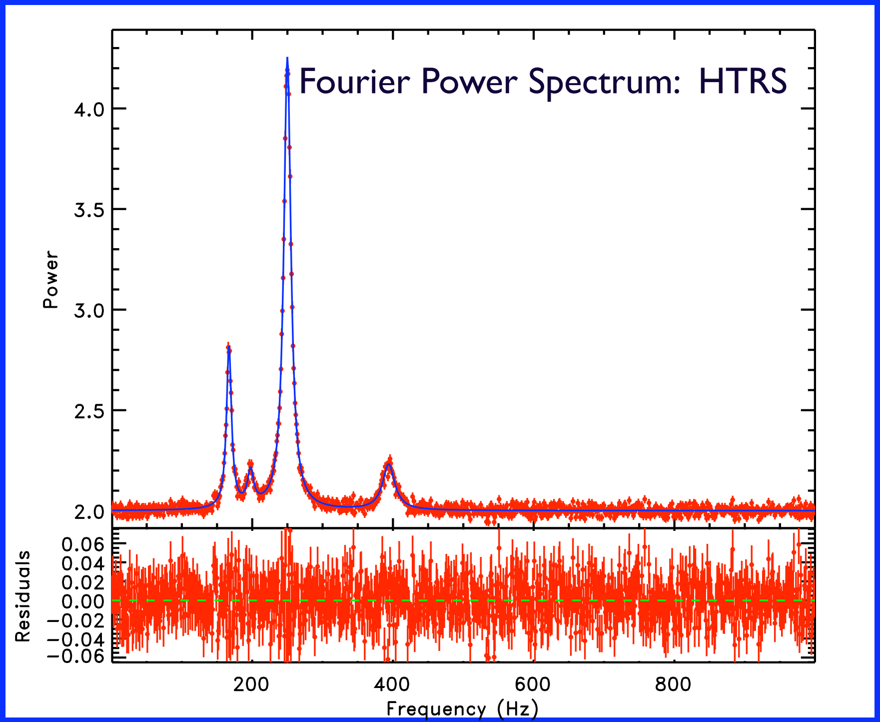
Miller (2009)

Improvements: spectra & timing



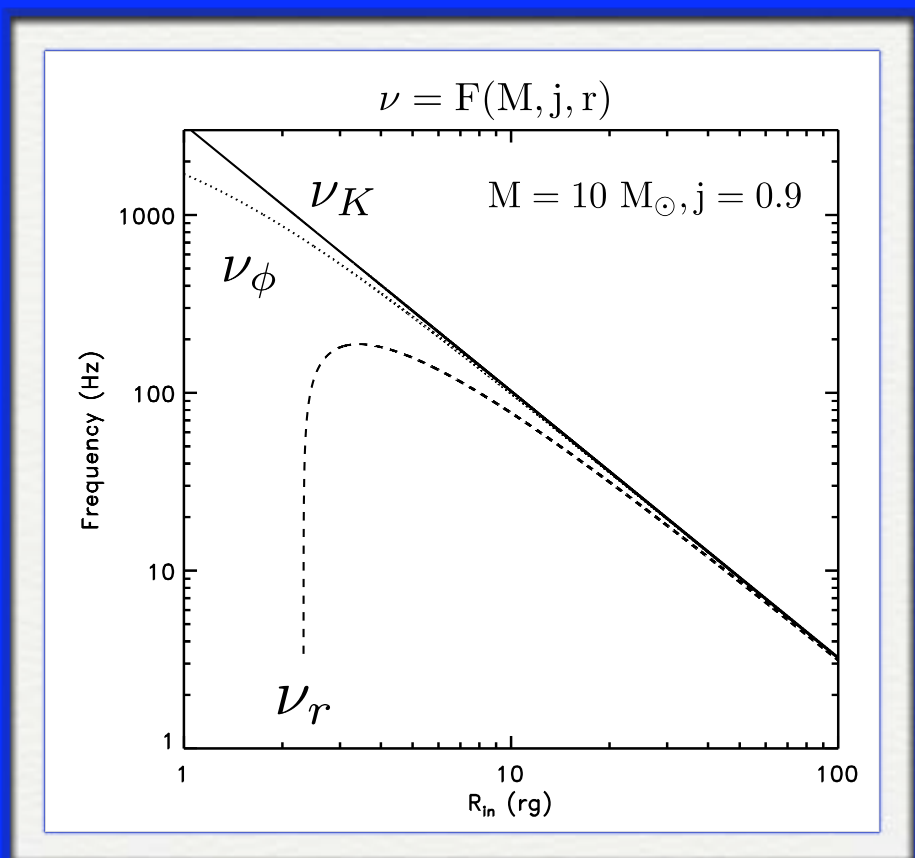






Multiple spin constraints

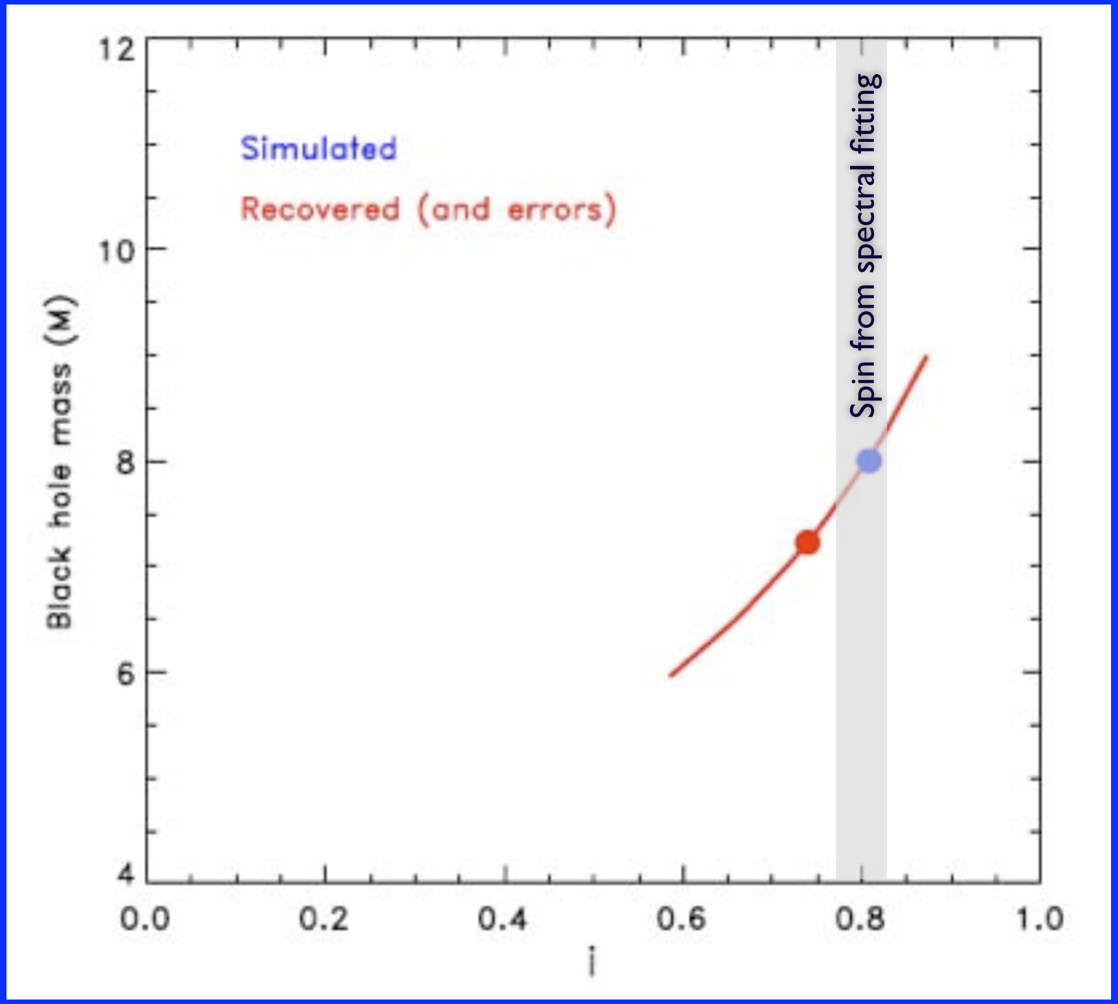
- From QPO pairs - resonance between epicyclic frequencies



$$\nu_\phi = \frac{\sqrt{GM/r^3}/2\pi}{1 + j(r_g/r)^{3/2}} = \nu_K(1 + j(r_g/r)^{3/2})^{-1}$$

$$\nu_r = \nu_\phi(1 - 6(r_g/r) + 8j(r_g/r)^{3/2} - 3j^2(r_g/r)^2)^{1/2}$$

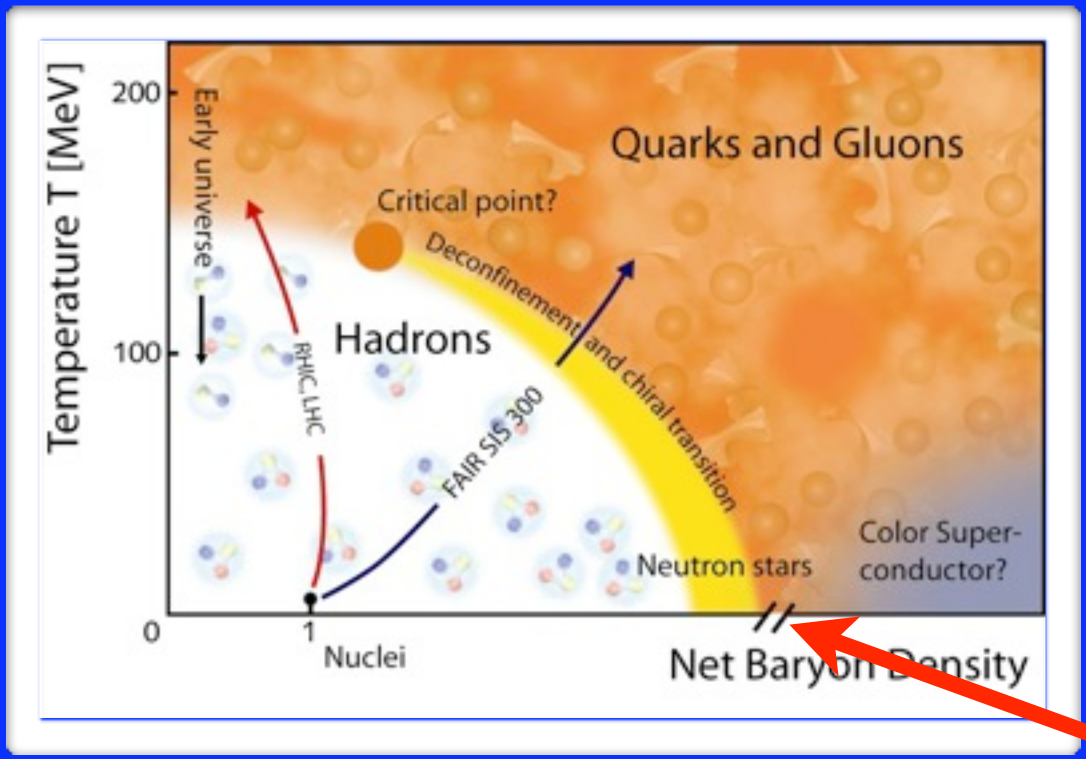
$$\nu_\theta = \nu_\phi(1 - 4j(r_g/r)^{3/2} + 3j^2(r_g/r)^2)^{1/2}$$



Equation of state of cold matter

Neutron stars probe the low temperature-large density region of the QCD phase diagram - key goal of modern physics

Temperature



Density

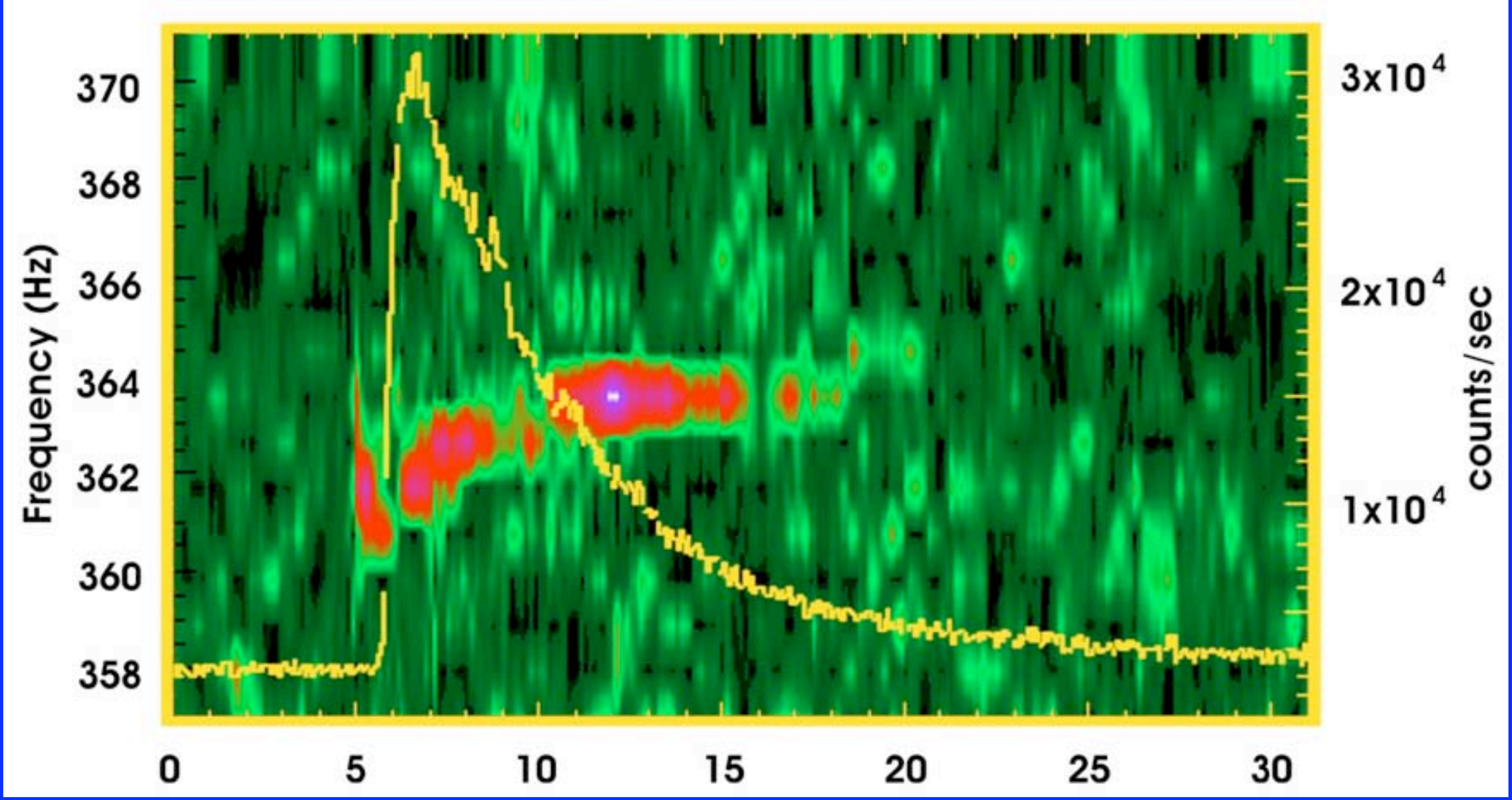
Determining the equation of state of cold matter requires measuring the mass-radius relation of neutron stars, using X-rays generated at their surface or their vicinity.

Constraining the NS EoS

- Thanks to its high throughput, the HTRS will provide direct constraints on the NS EoS:
  - ✓ by waveform fitting of X-ray burst oscillations & X-ray pulsations in accreting millisecond pulsars
  - ✓ by measuring predicted redshifted absorption lines in type I X-ray bursts and performing fine X-ray burst spectroscopy
  - ✓ by constraining the inner disk radius (hence the neutron star radius) from fast timing variability (kHz QPOs)
  - ✓ by waveform fitting of quasi-periodic oscillations
  - ✓ by detecting high-frequency QPOs from magnetars
  - ✓ by measuring neutron star spin distribution
- Additional constraints will be provided by the other IXO instruments, e.g. cooling neutron stars, quiescent neutron star low-mass X-ray binaries in GCs, ...

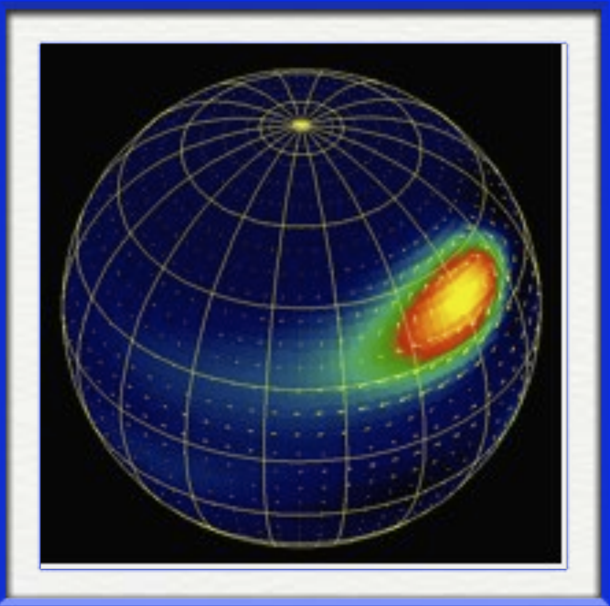
Burst oscillations

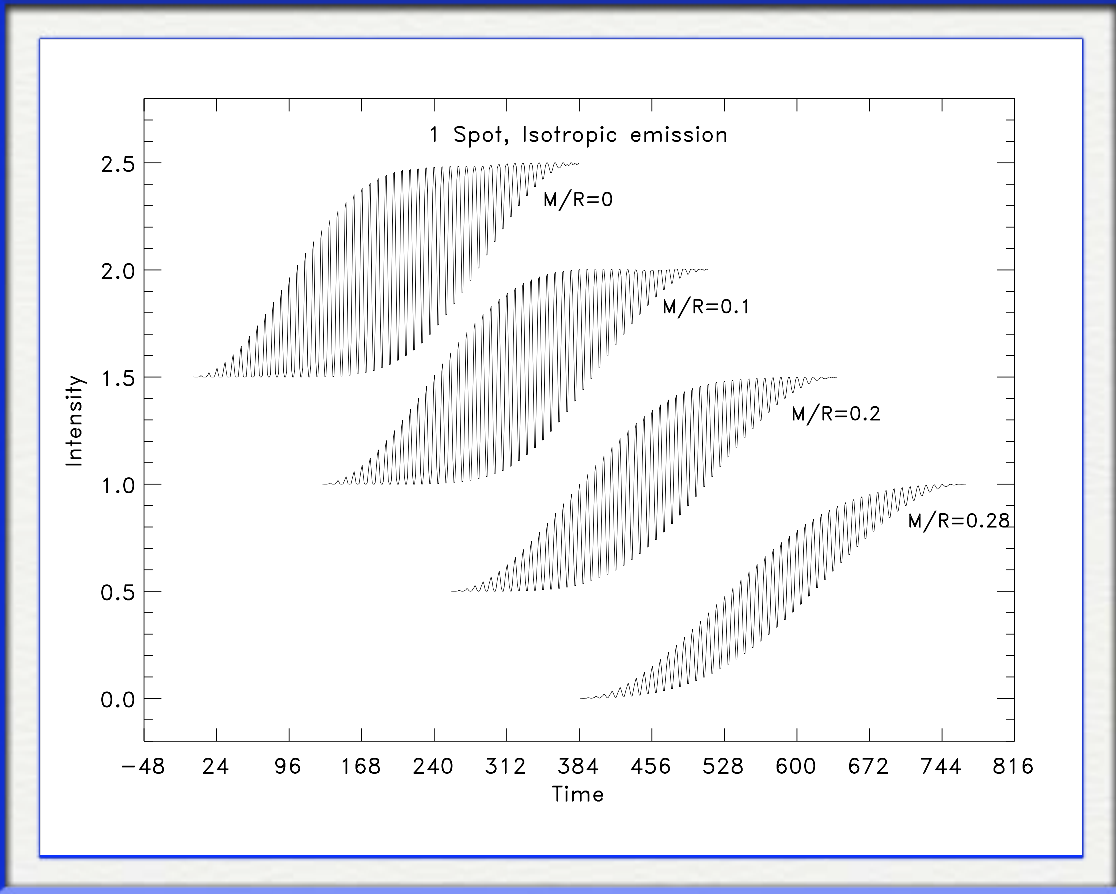
- Burst light curve and power density spectra



Waveform fitting

- X-ray oscillations are produced by hot spots rotating at the neutron star surface
- Modeling of the pulses (shape, energy dependence) taking into account:
  - ✓ Doppler boosting
  - ✓ Relativistic aberration
  - ✓ Gravitational light bending in the Schwarzschild spacetime
- Can be used to constrain the star compactness (M/R)
  - ✓ e.g. the higher the compactness, the lower the modulation amplitude

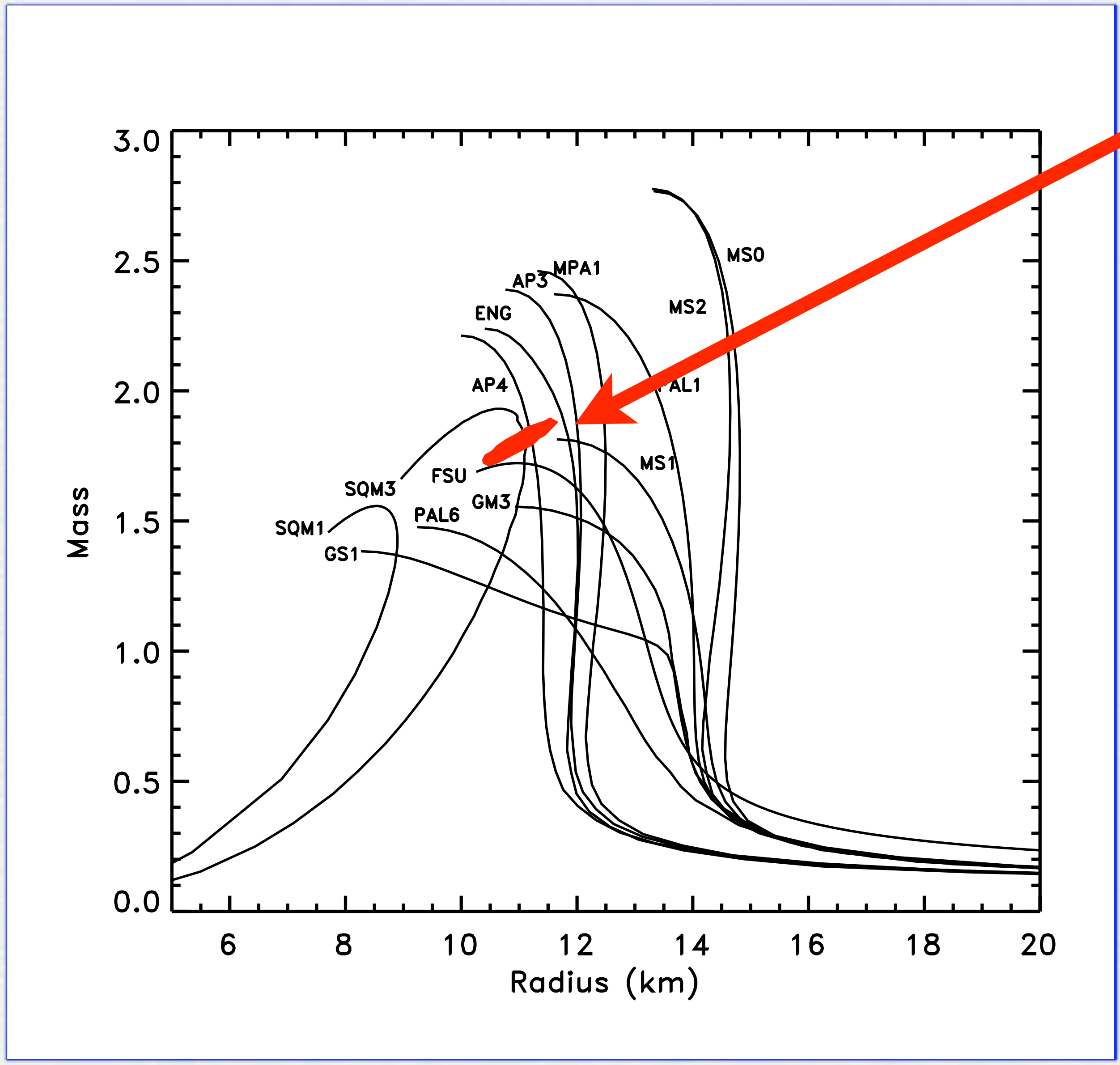




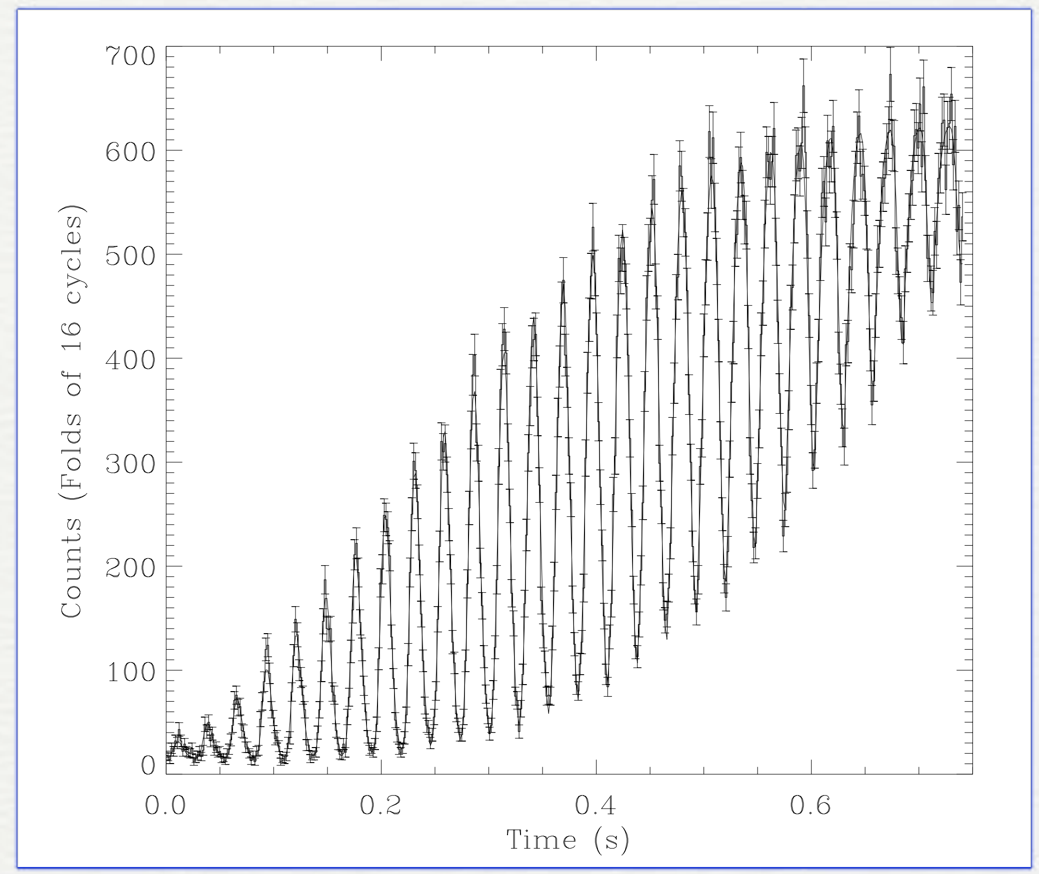
Poutanen & Gierlinski (2004)

Burst oscillation waveform fitting

The energy response of the HTRS (**0.5-10** keV) is optimized for type I X-ray bursts. Burst oscillations will be detected within 1 cycle (>1000 counts/cycle, 2 Crab, 300 Hz) - between 20 and 40 times larger count rates than the PCA.



Constraints on mass and radius waveform fitting. The red ellipse shows the 95% confidence regions from 5 typical bursts. (Courtesy of Cole Miller).



Conclusions

- IXO is the natural successor to Chandra (~2600 users) and XMM-Newton (~3000 users)
  - ➡ Separate studies by ESA and NASA demonstrate that the mission implementation for a 2021 launch is feasible
  - ➡ Part of Astro2010 Decadal Survey and ESA Cosmic Visions program
- Understand how black holes form, evolve, work, influence their surroundings is a key science goal of IXO
  - ✓ by probing BHs at all scale under a wide range of conditions: from stellar mass BHs to the first BHs formed in the Universe - emphasis put on stellar mass BH spin measurements with the HTRS
- Similarly, determining the equation of state of the densest matter observable in the Universe appears for the first time within reach
  - ✓ by observing the brightest phases of NSs with the HTRS