The International X-ray Observatory

Probing strong gravity and dense matter in the next decade

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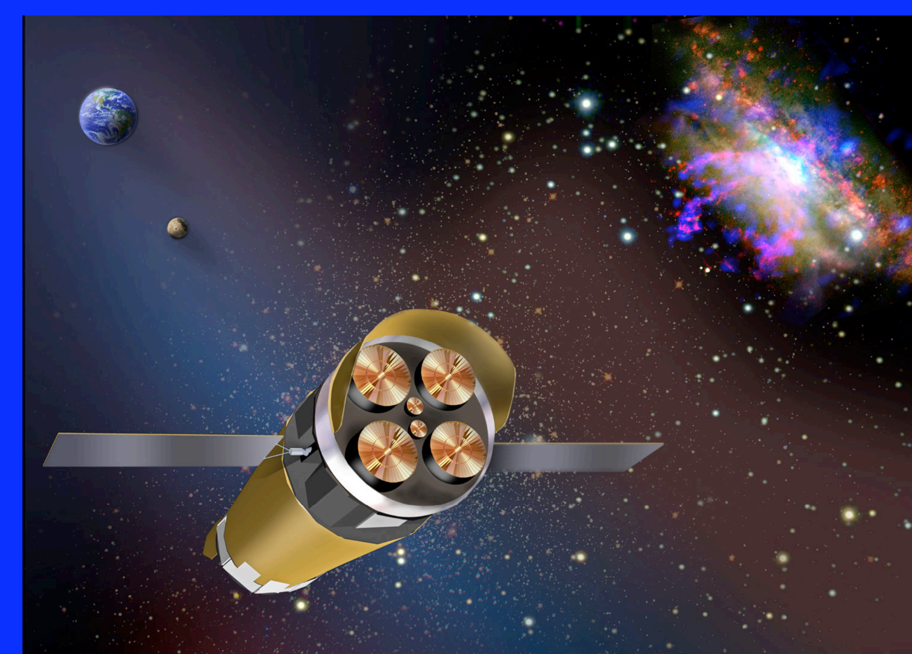
History

- The science case for a large X-ray observatory after XMM-Newton and Chandra is compelling:
  - ✓ 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

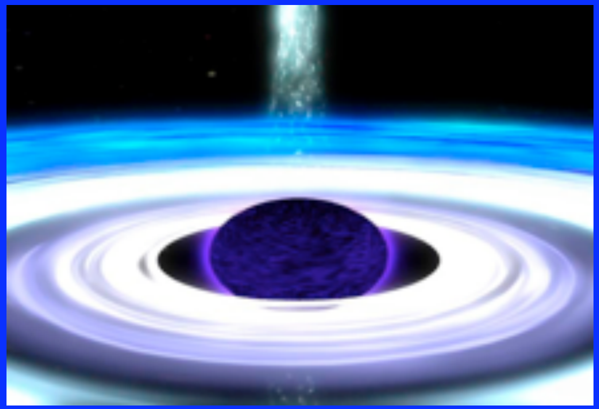


Recent events

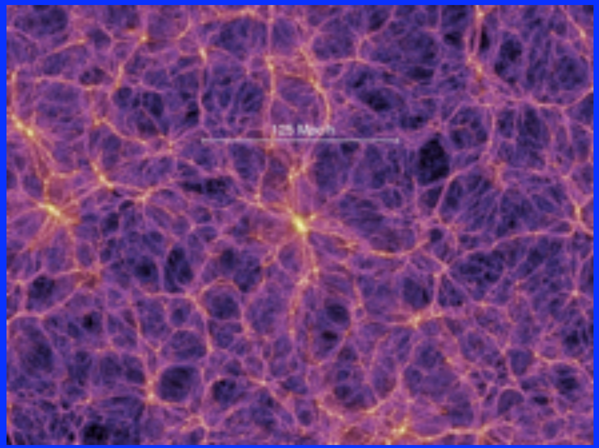
- In the spring of 2008, with ESA and NASA HQs, an effort began to see if the two missions could be merged
  - ✓ Which agency would lead a joint mission was NOT discussed
- An ESA/JAXA/NASA coordination group was formed and agreement was reached on a path forward, and was accepted at an ESA-NASA bilateral 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

Key science goals for IXO

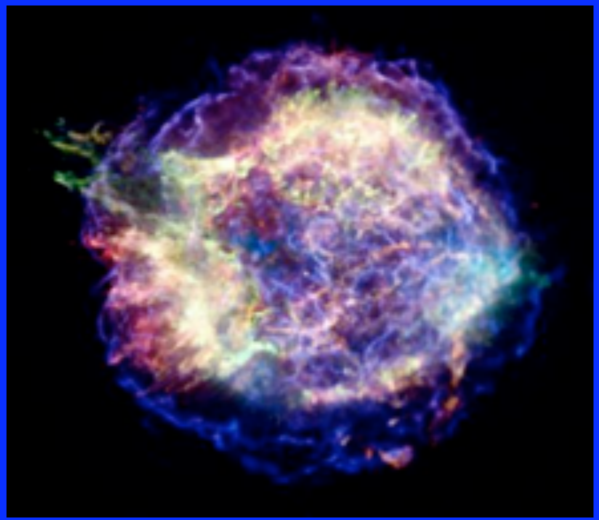
- Black holes and matter under extreme conditions



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

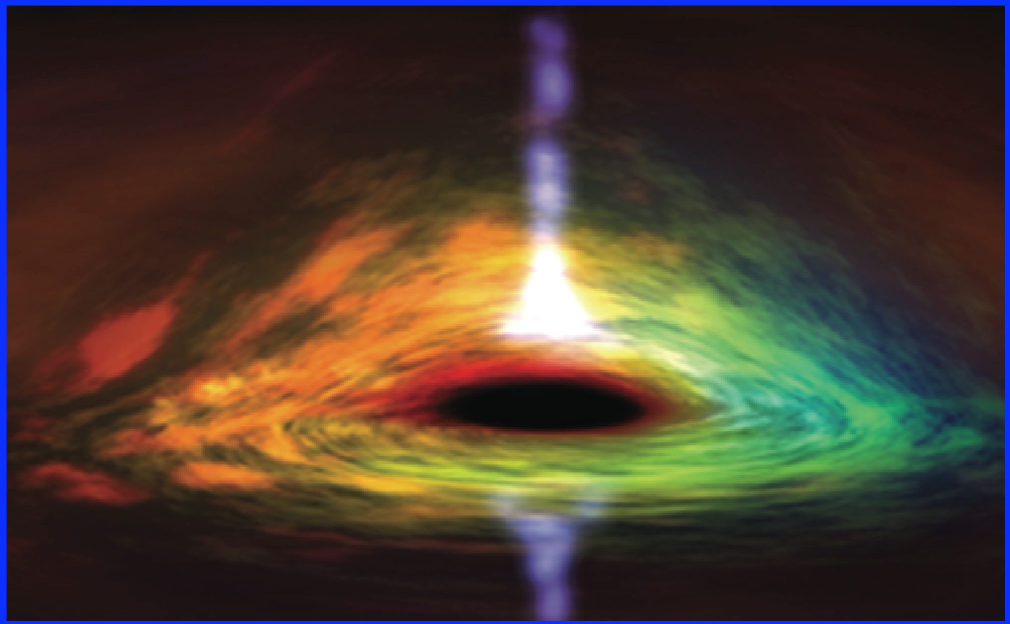


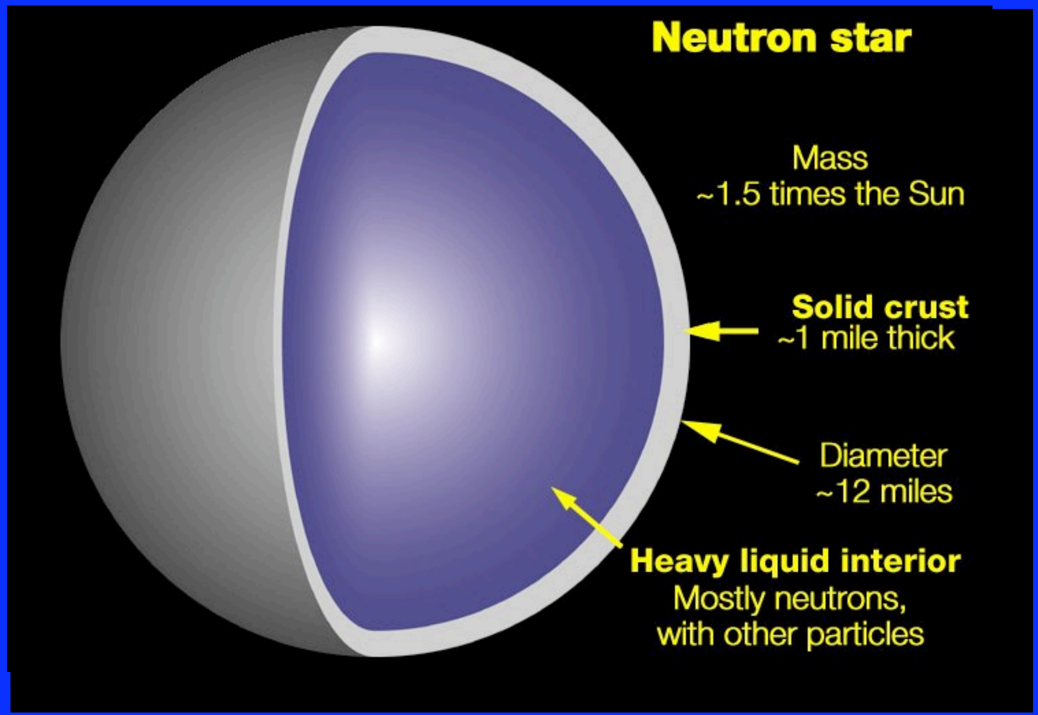
- Life cycles of matter and energy



Black holes & matter under extreme conditions

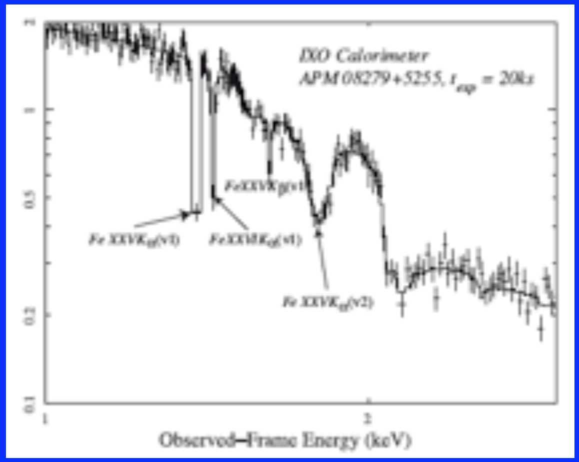
- How do supermassive black holes grow and evolve?
  - ➡ Complete census of AGNs of all kinds out to high redshifts
- Does matter orbiting close to a black hole event horizon follow the predictions of general relativity?
  - ➡ Time resolved spectroscopy of orbiting hot spots around black holes
- What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

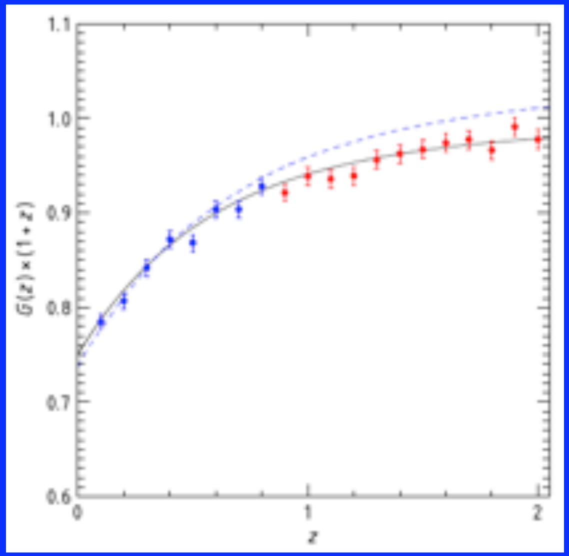


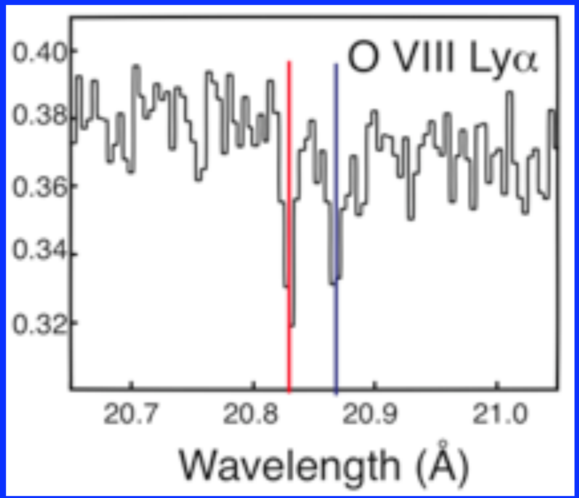


Galaxy evolution

- 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, in the cosmic web?
  - ➡ High resolution spectroscopy of OVII and OVII in absorption using background AGNs

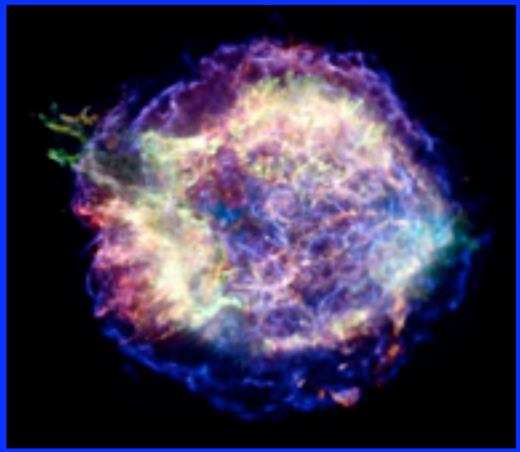


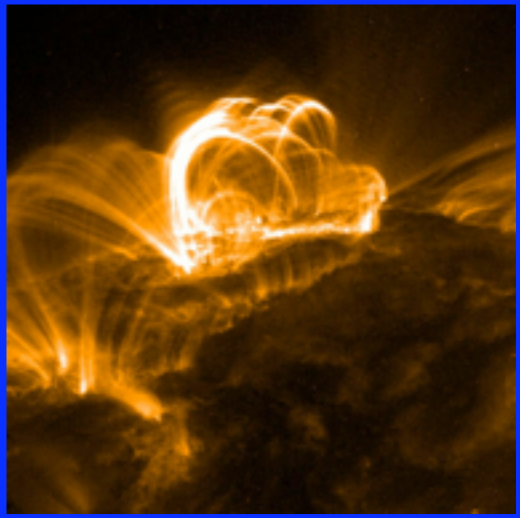




Life cycles of matter / energy

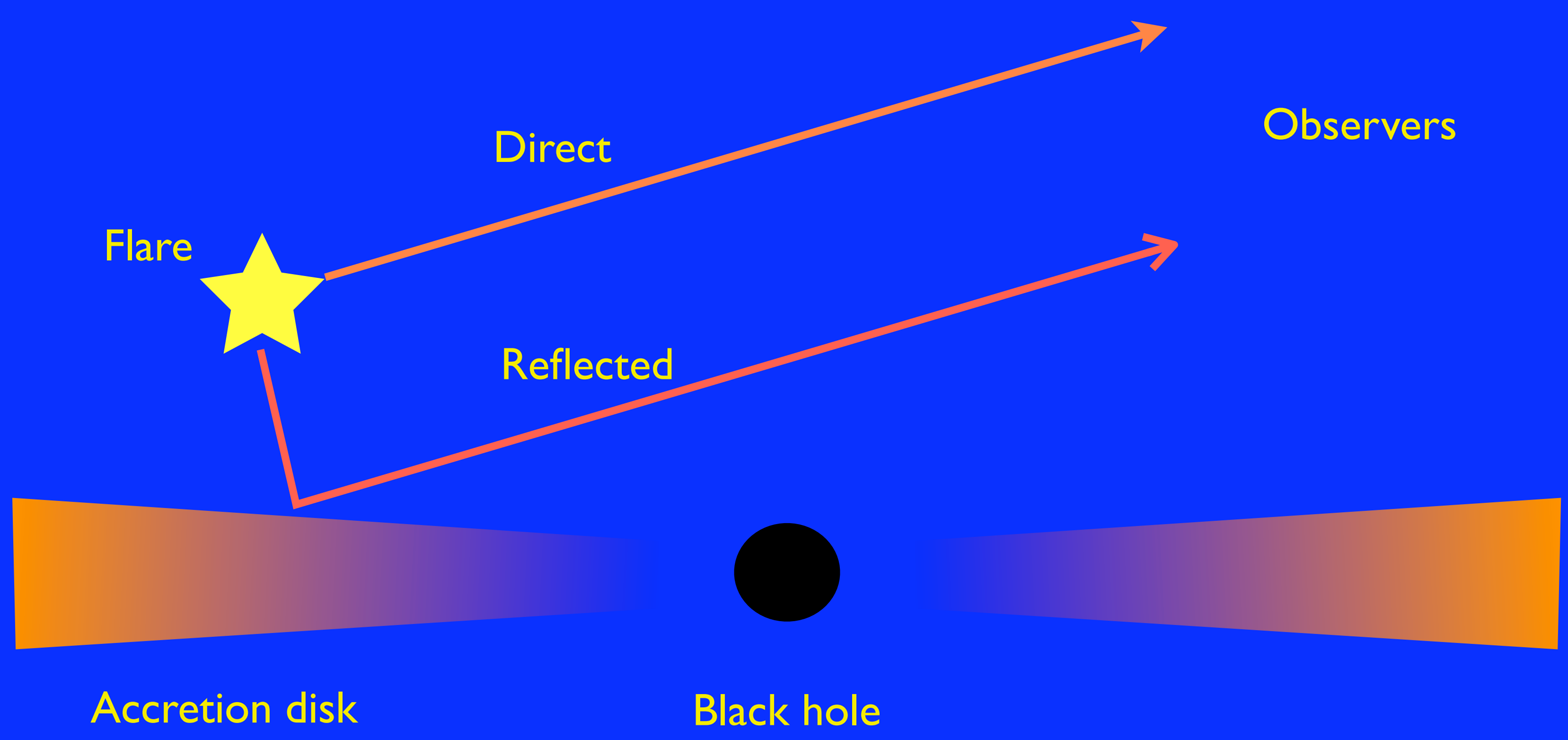
- When and how were the elements created and dispersed?
  - ➡ High resolution spectroscopy of SNe: CC versus type 1a
- How do high energy processes affect planetary formation and habitability?
  - ➡ Probing disks with reverberation mapping
- How do magnetic fields shape stellar exteriors and the surrounding 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

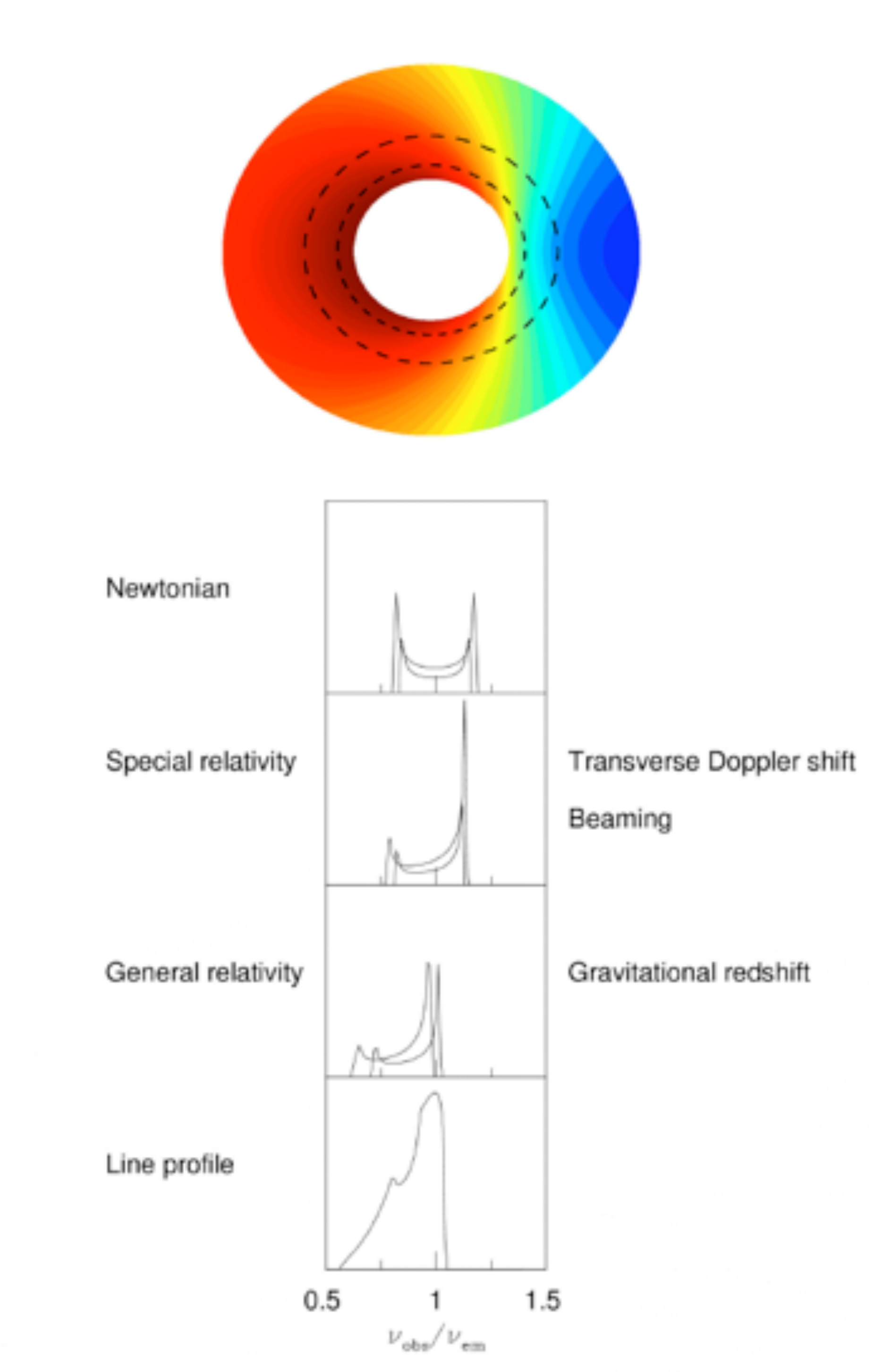




Using the Iron line to probe black holes

Reflexion on the accretion disk





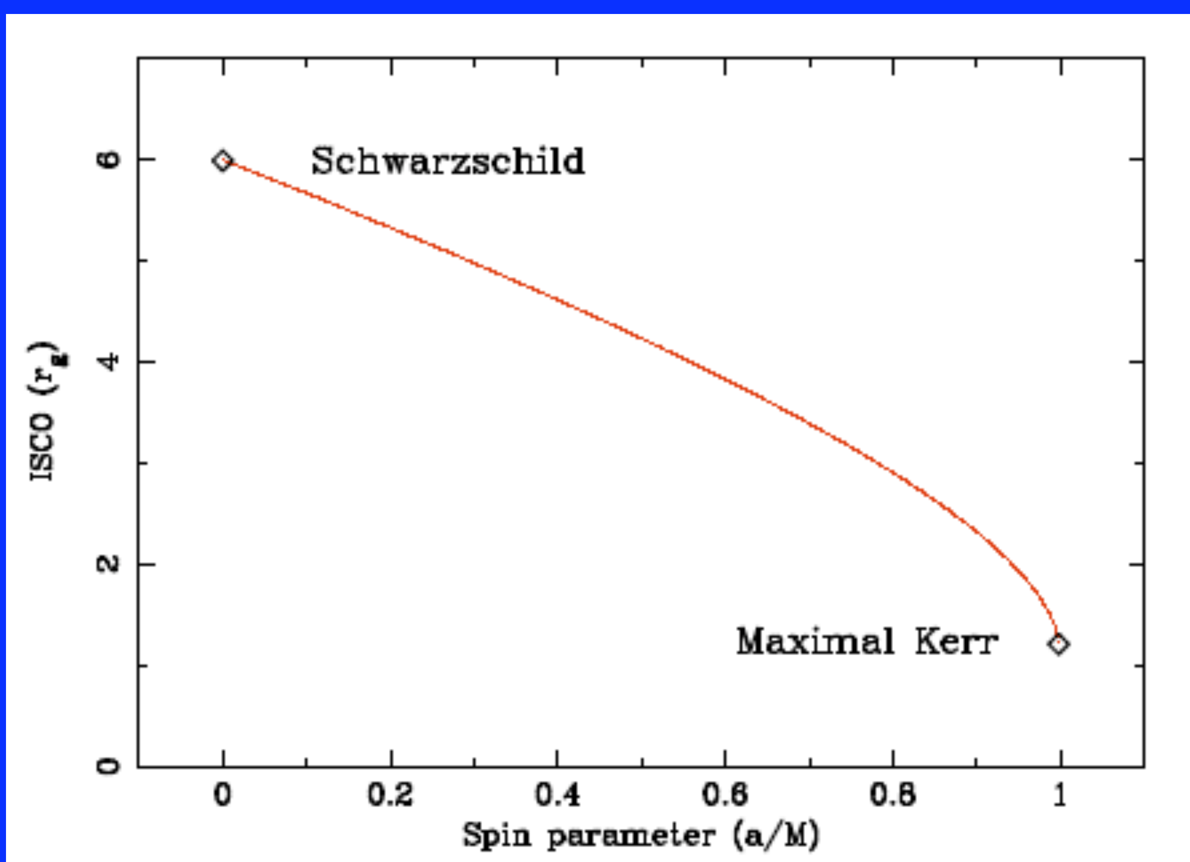
Fabian et al. (2000)

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

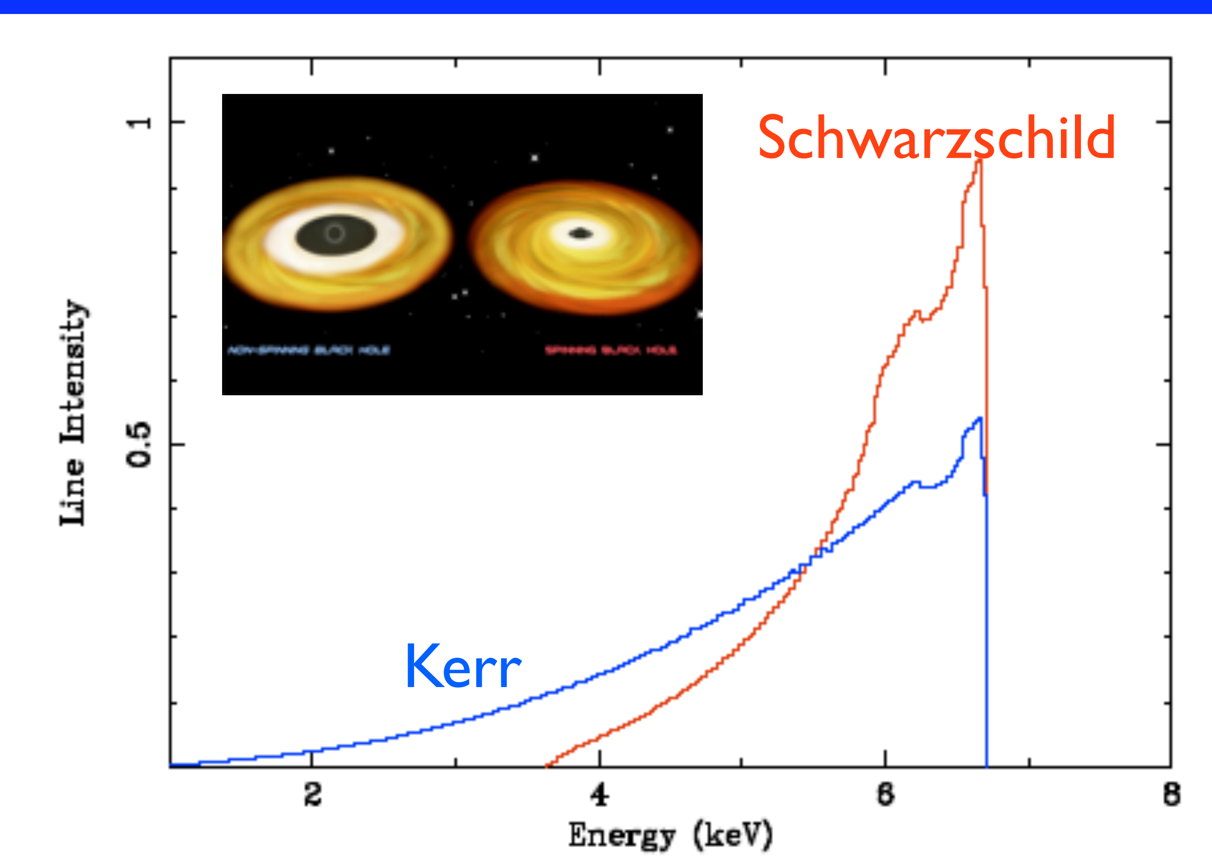
Spin constraints from the Iron line

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

Radius of the innermost stable circular orbit versus spin

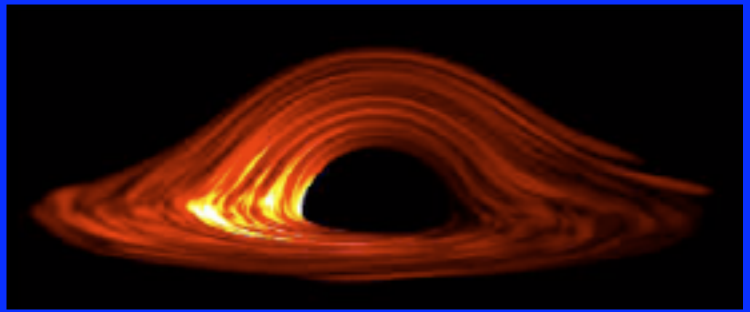


Iron line profile versus spin

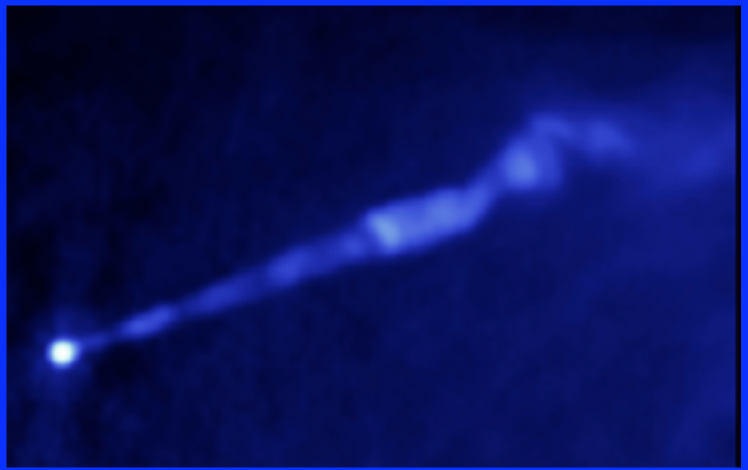


Why care about BH spins?

- Accretion efficiency scales with spin from 10% for non spinning up to 42% for maximally rotating black holes
  - ✓ The ionizing flux is 10-50% that from stars
  - ✓ 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



- Spin is thought to reflect the growth history of supermassive BH

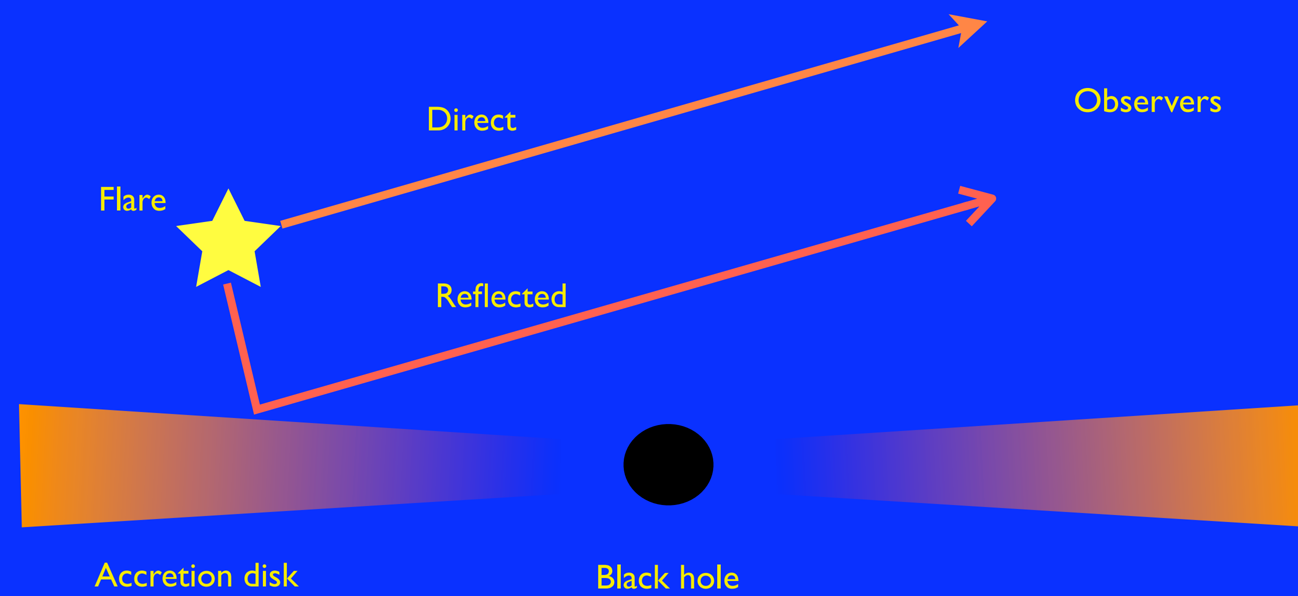
Broad line in the AGN 1H0707-495


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

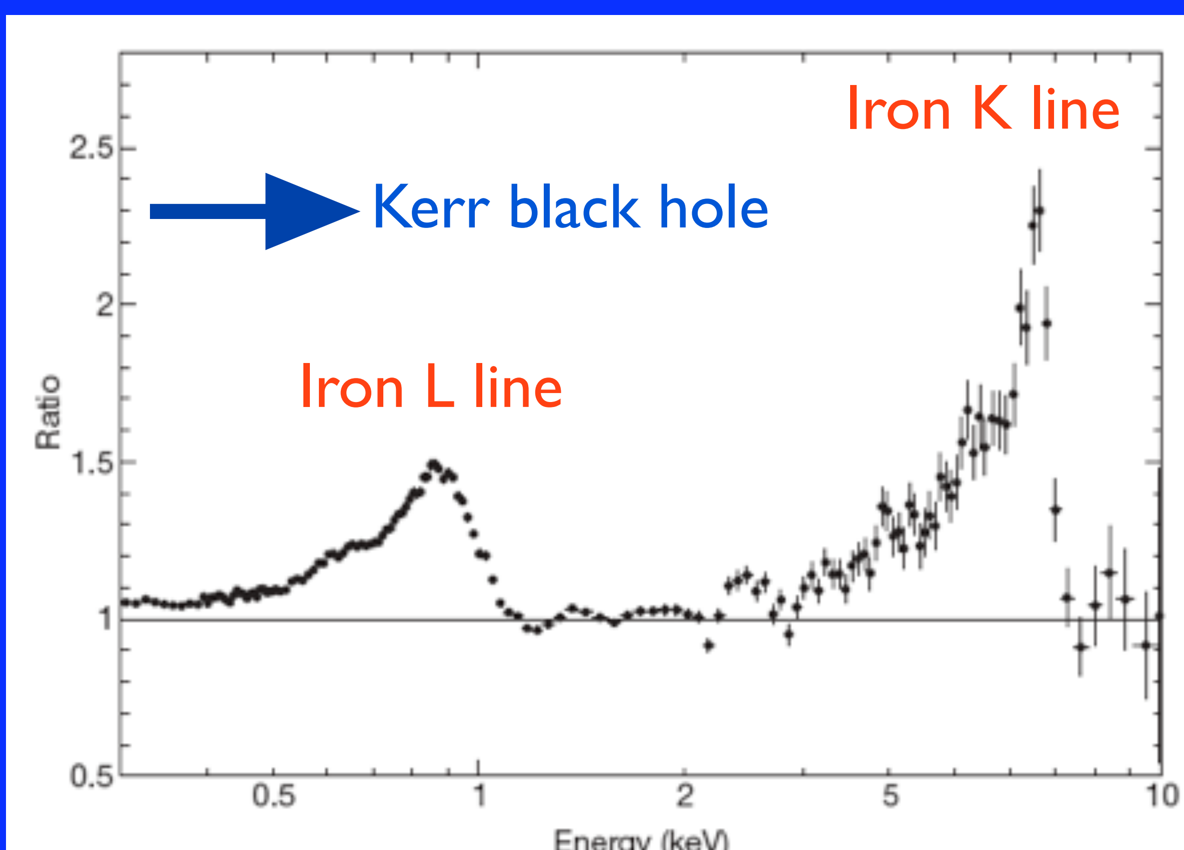
LETTERS

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

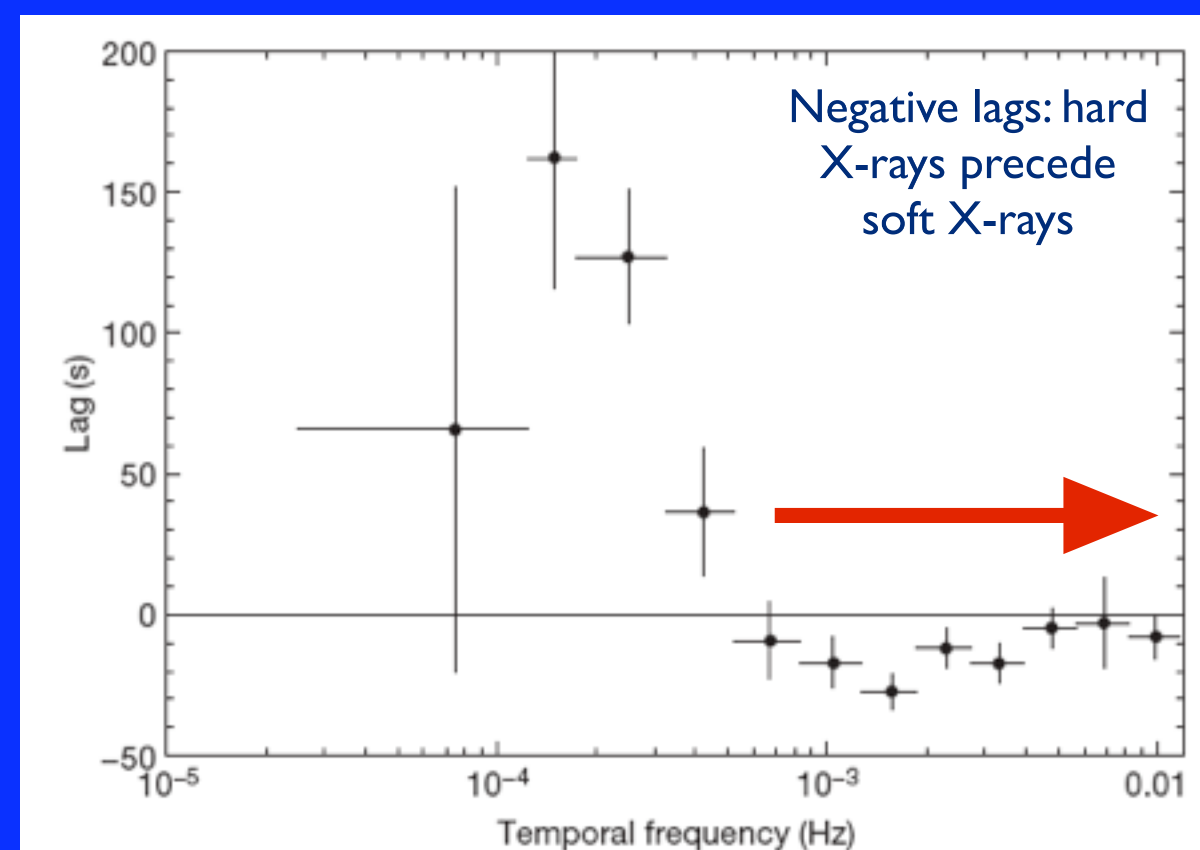
A. C. Fabian[1], A. Zoghbi[1], R. R. Ross[2], P. Uttley[3], L. C. Gallo[4], W. N. Brandt[5], A. J. Blustin[1], T. Boller[6], M. D. Caballero-Garcia[1], J. Larsson[1], J. M. Miller[7], G. Miniutti[8], G. Ponti[9], R. C. Reis[1], C. S. Reynolds[10], Y. Tanaka[6] & A. J. Young[11]



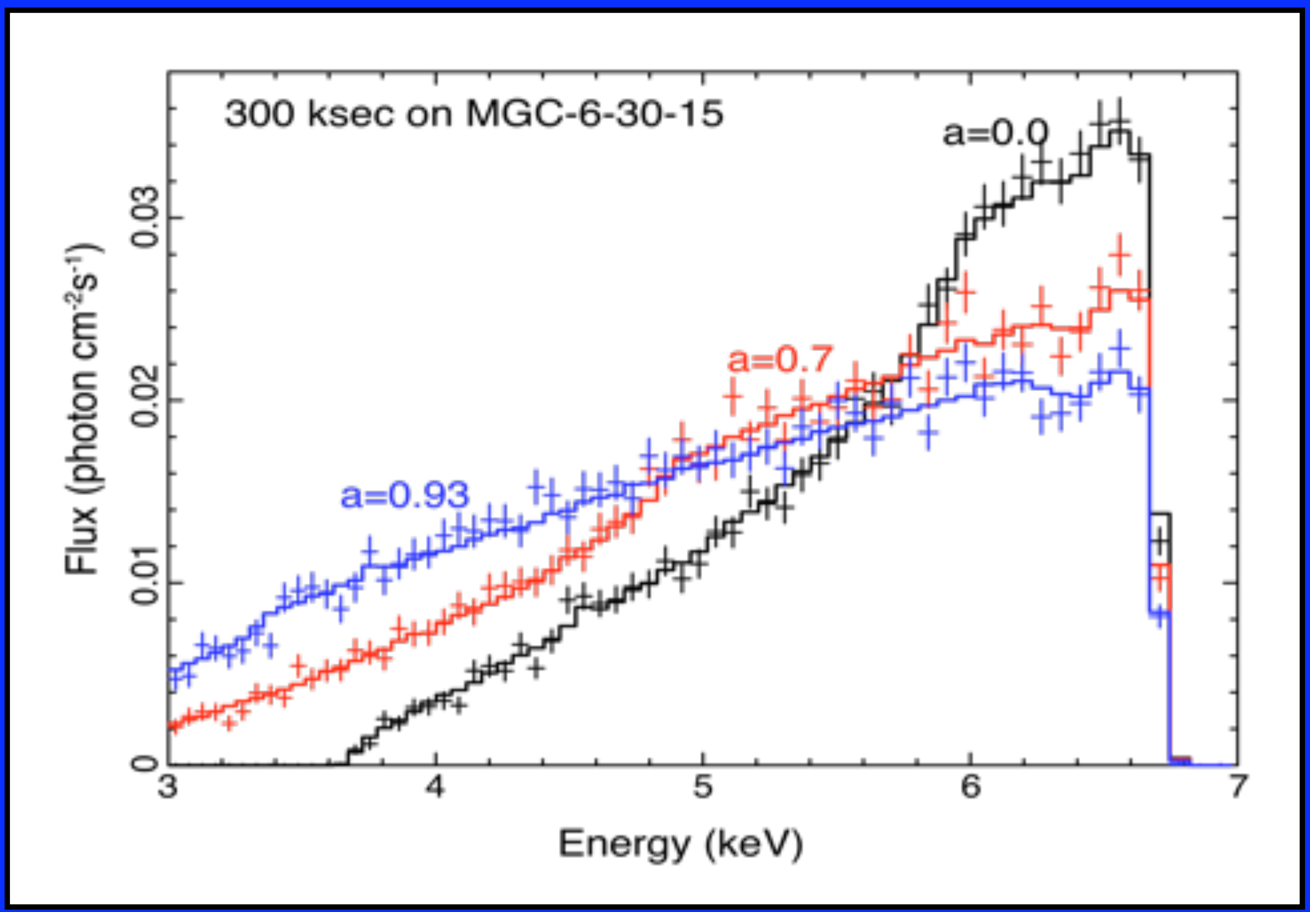
Residual X-ray spectrum



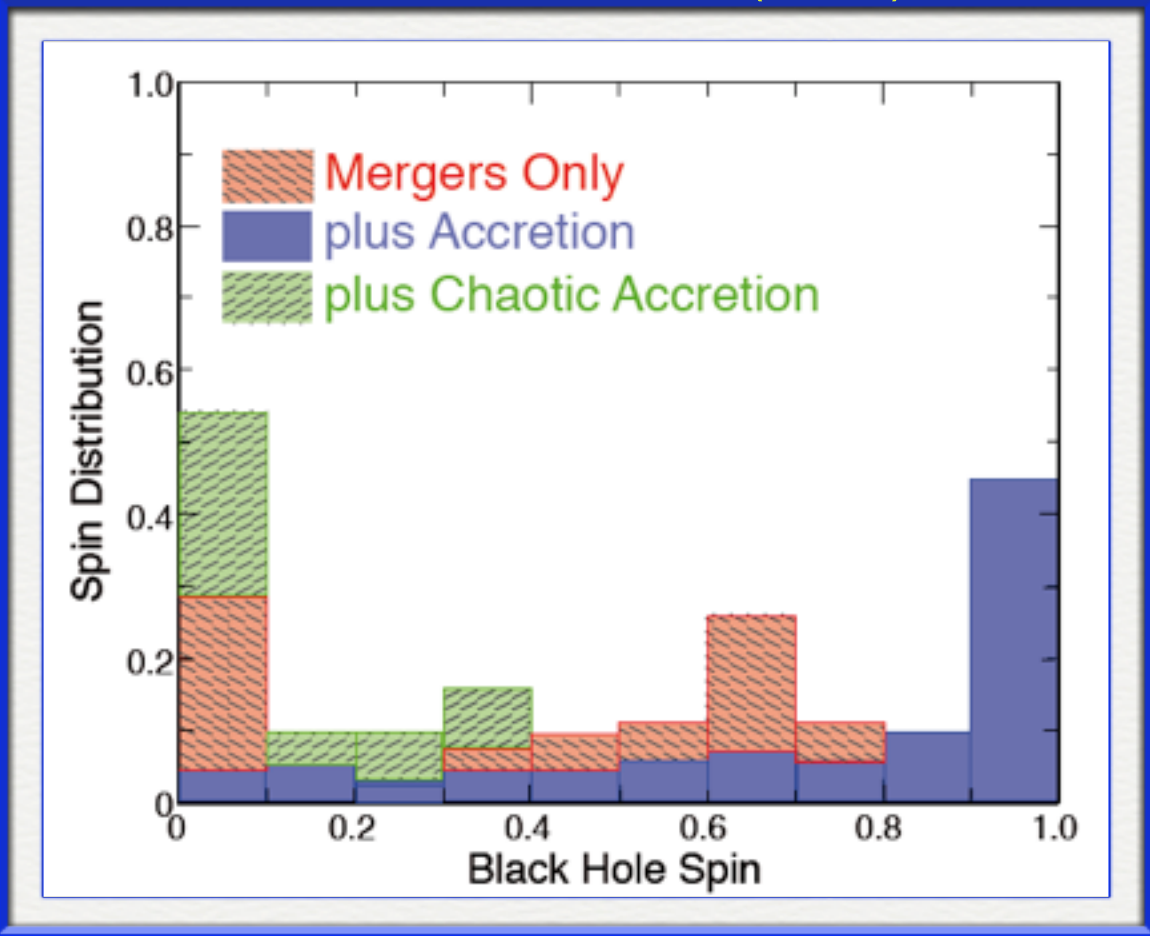
Lag spectrum between the 0.3–1-keV and 1–4-keV bands



Black hole spins and growth



Berti & Volonteri (2008)

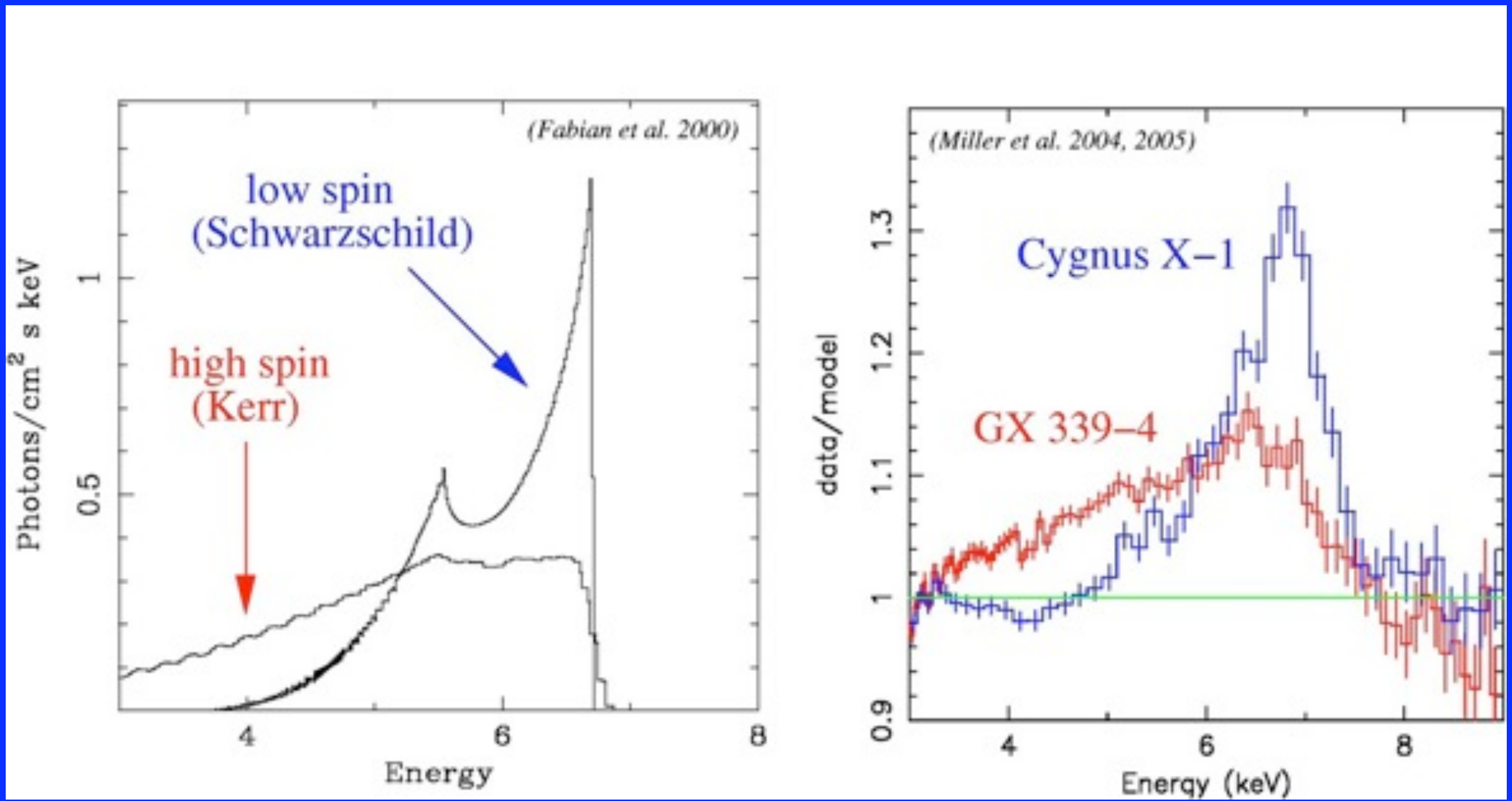


- IXO will use the relativistic Fe K line to determine the black hole spin for 300 AGN within $z < 0.2$ to constrain the super massive black hole merger history

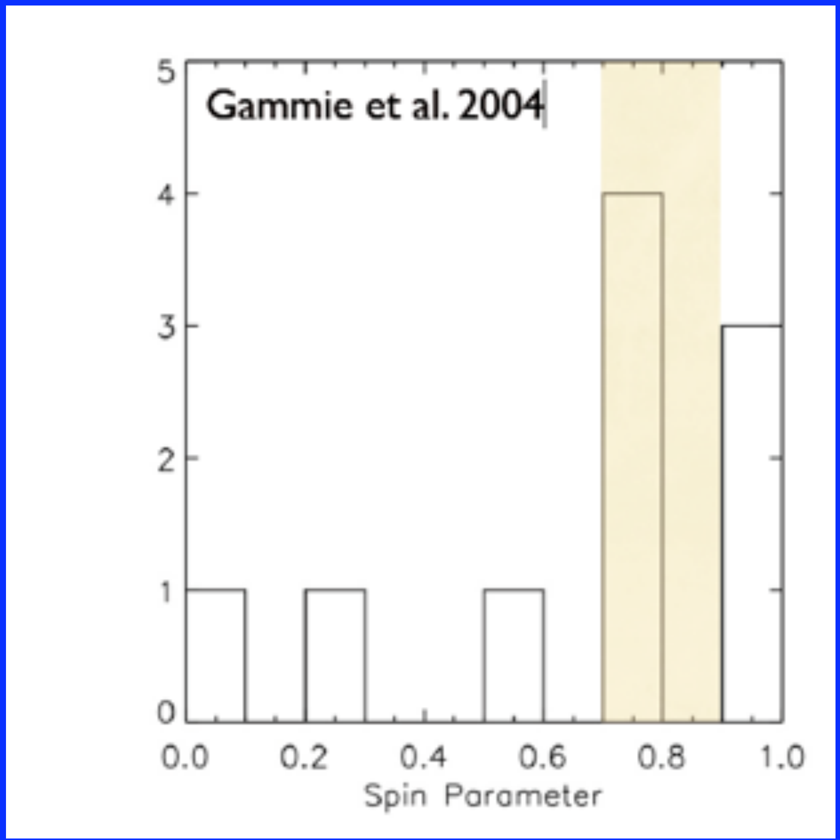
Low statistics numbers

- A sample of 10 stellar mass black holes only - slightly larger spins preferred

Miller (2009)

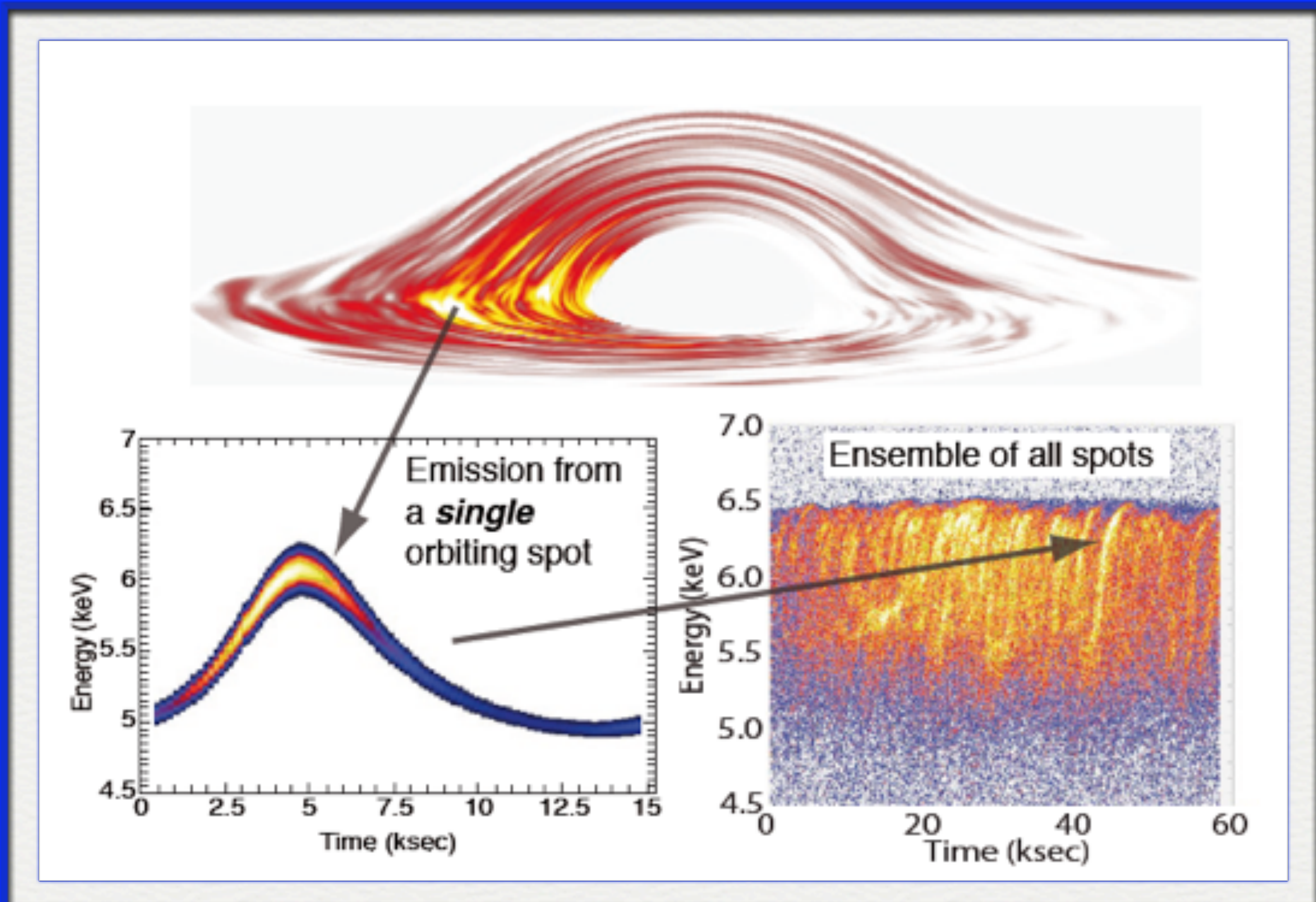


Spins from collapsar compared to observations



Miller (2009)

Plunging into the black hole



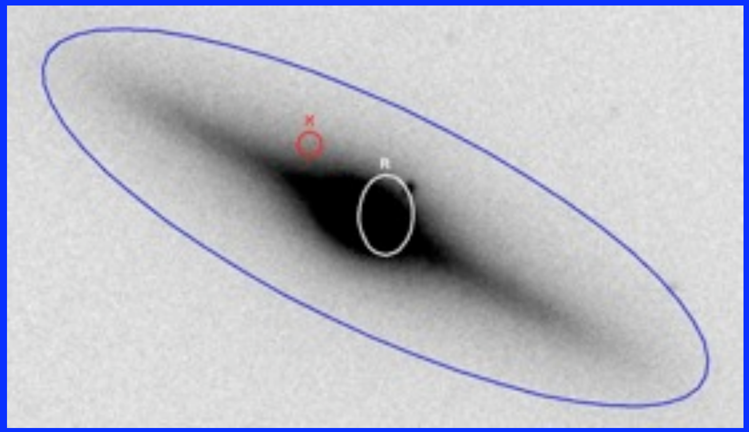
Best done with AGNs - 10^{2}-10^{3} lower count rates than XRBs but 10^{5}-10^{8} more massive, hence 10^{2}-10^{6} more counts per orbital timescale

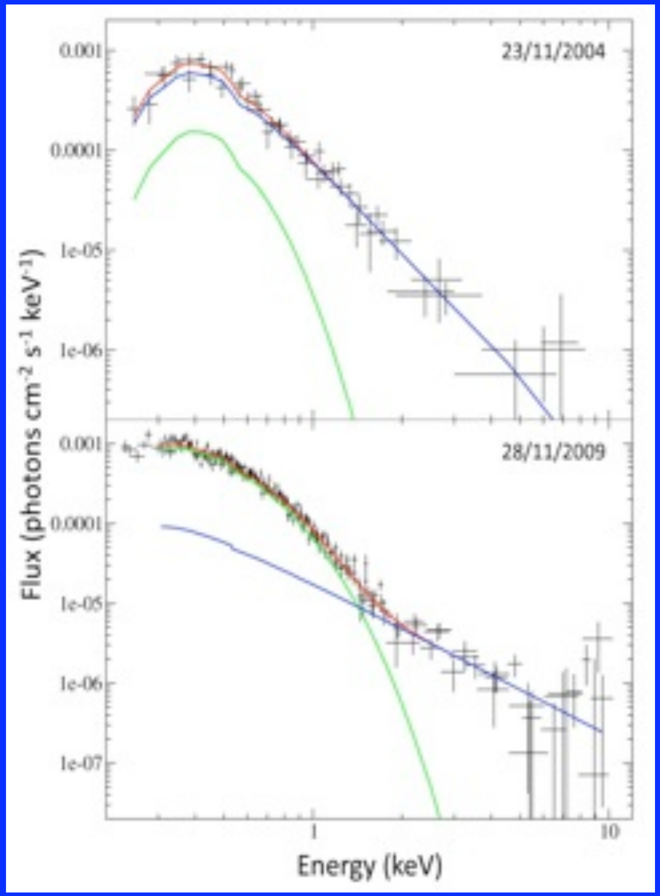
Can still be done with XRBs by averaging over many more orbital timescales than possible with AGNs

- 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

What about intermediate mass BH?

- New ultra luminous X-ray source (ULX) discovered in 2XMM catalog with unabsorbed max LX ~ 10^{42} erg s^{-1}
  - ➡ Beats previous record holder by factor 5 in LX
  - ➡ No radio source
  - ✓ 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 and intermediate mass black hole with mass ~500 – 100,000 Msol





Farrell, et al., 2009, Nature, in press

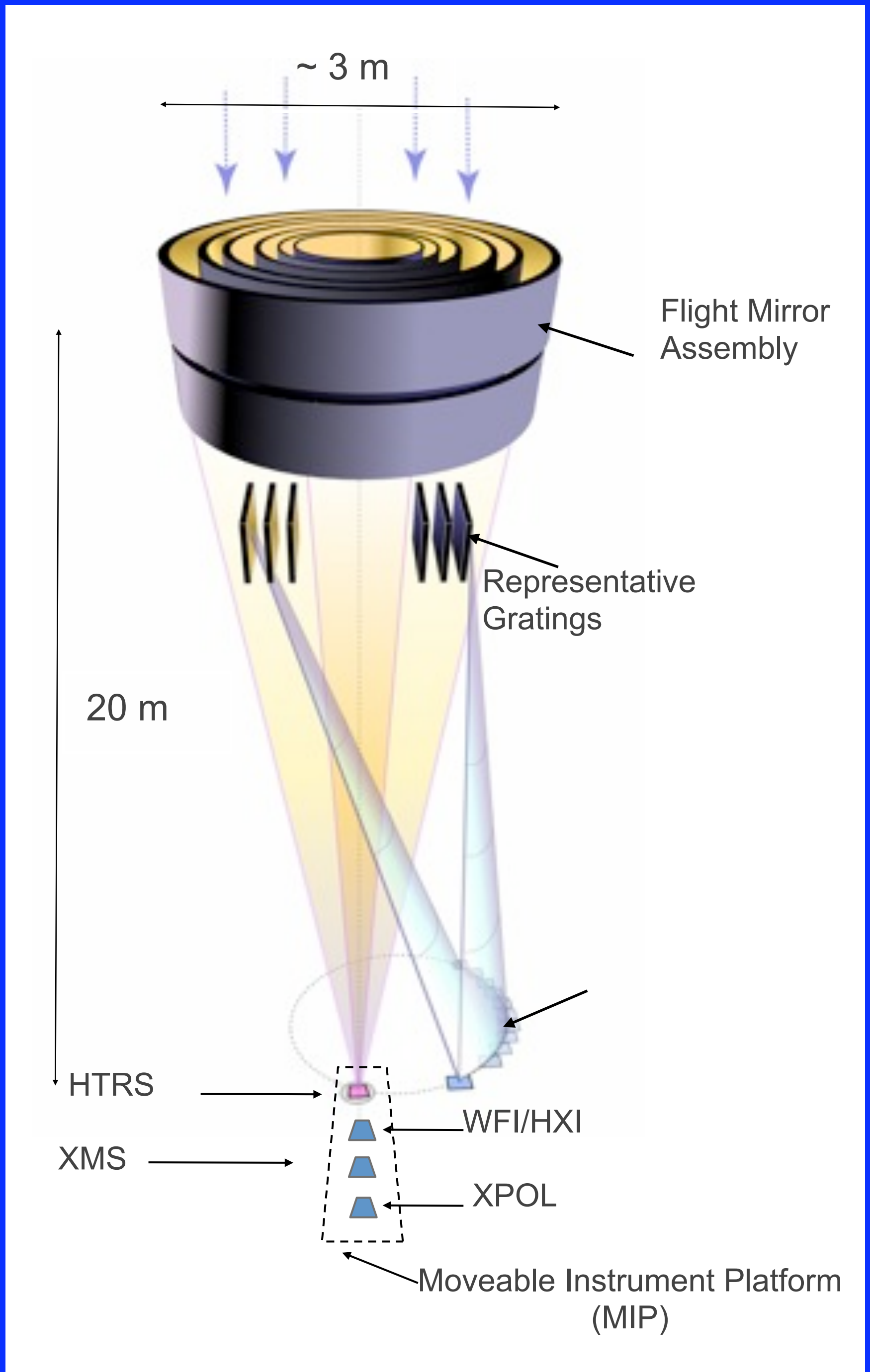
The IXO mission

IXO in a nutshell

- IXO configuration includes:
  - ✓ A single large X-ray mirror assembly compatible with both pore optics and slumped glass technology
  - ✓ An extensible optical bench to reach F=20 to 25m + ways to maximize effective area above 6 keV
    - ➡ No formation flying
  - ✓ A payload module with 5 complementary instruments
- The IXO concept is compatible with both Ariane V and Atlas V 551 launchers
  - ✓ Target orbit: direct launch into L2
  - ✓ 5 Year mission (with consumables sized for a 10 years mission)
  - ✓ Launch ≈ 2020-2021

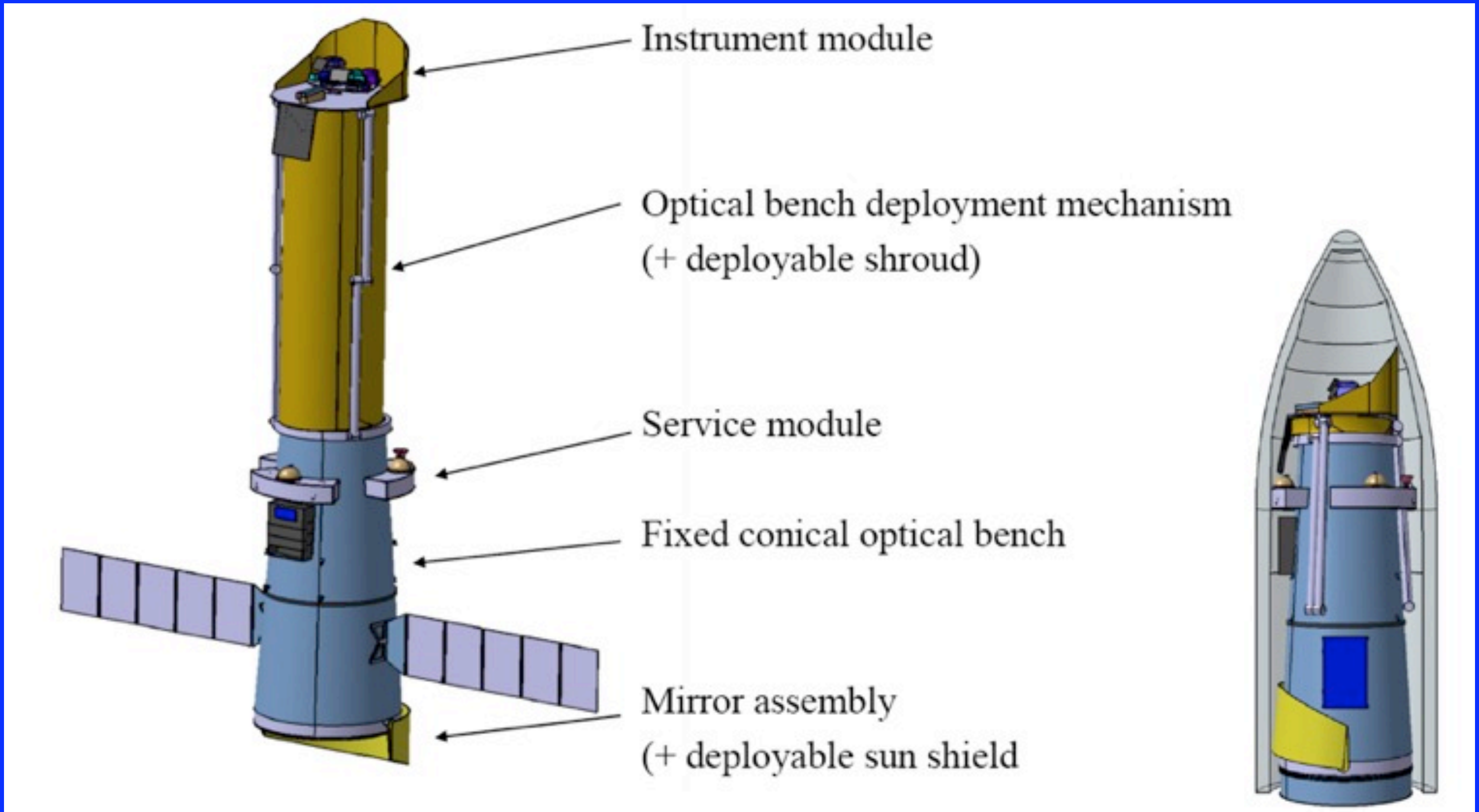
The IXO payload

- Flight Mirror Assembly
  - ✓ Highly nested grazing incidence optics, 3 m^2 @ 1.25 keV, with a 5″ PSF
- Instruments:
  - ✓ 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)



ESA mission design

- Observatory Mass ~6100 kg - 2 tons for the mirrors
- Very similar to the NASA design



ESA mission design

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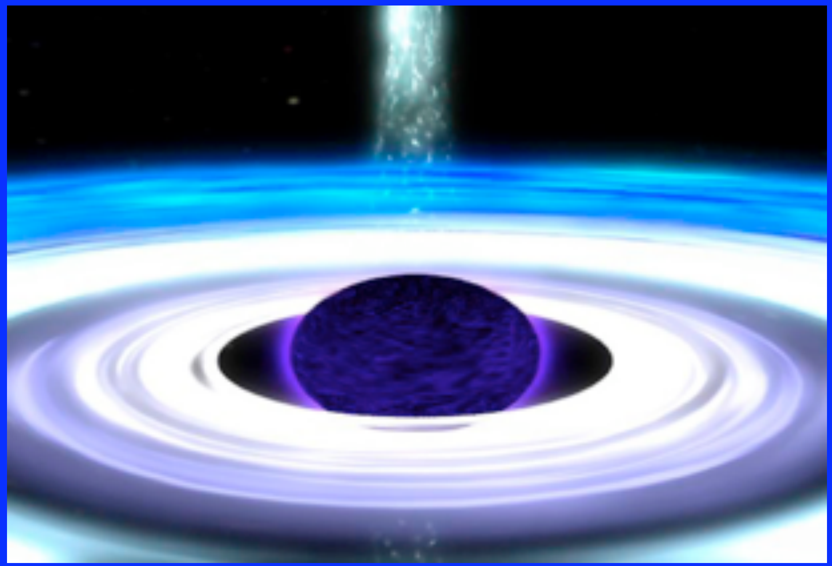
The HTRS

The HTRS

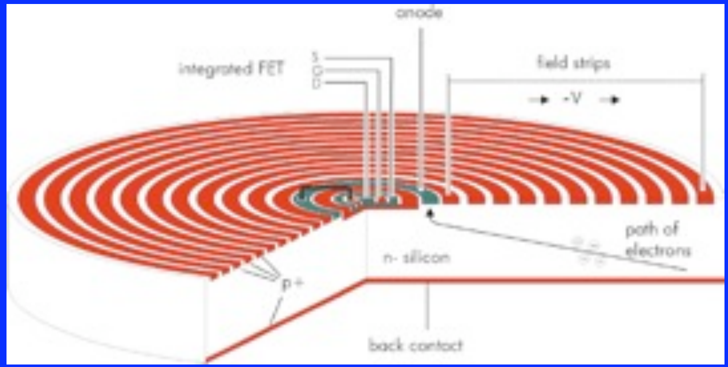
- The High Time Resolution Spectrometer (HTRS) will provide IXO with the capability to observe bright X-ray sources
  - ✓ accreting neutron star and black hole X-ray binaries, including X-ray bursters
- Two science goals, under the *matter under extreme conditions* topic:
  - ✓ Accretion in strong gravity
  - ✓ The equation of state of dense matter



The HTRS characteristics

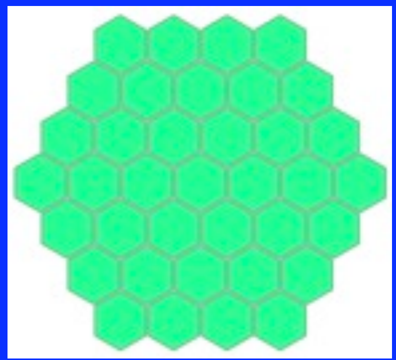
- HTRS is based on Silicon Drift Detectors (SDD)
  - ✓ The main advantage of SDD is their small physical size and consequently the small capacitance of the anode, which translates to a capability to handle very high count rates simultaneously with good energy resolution.
  - ✓ The HTRS is an array of 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

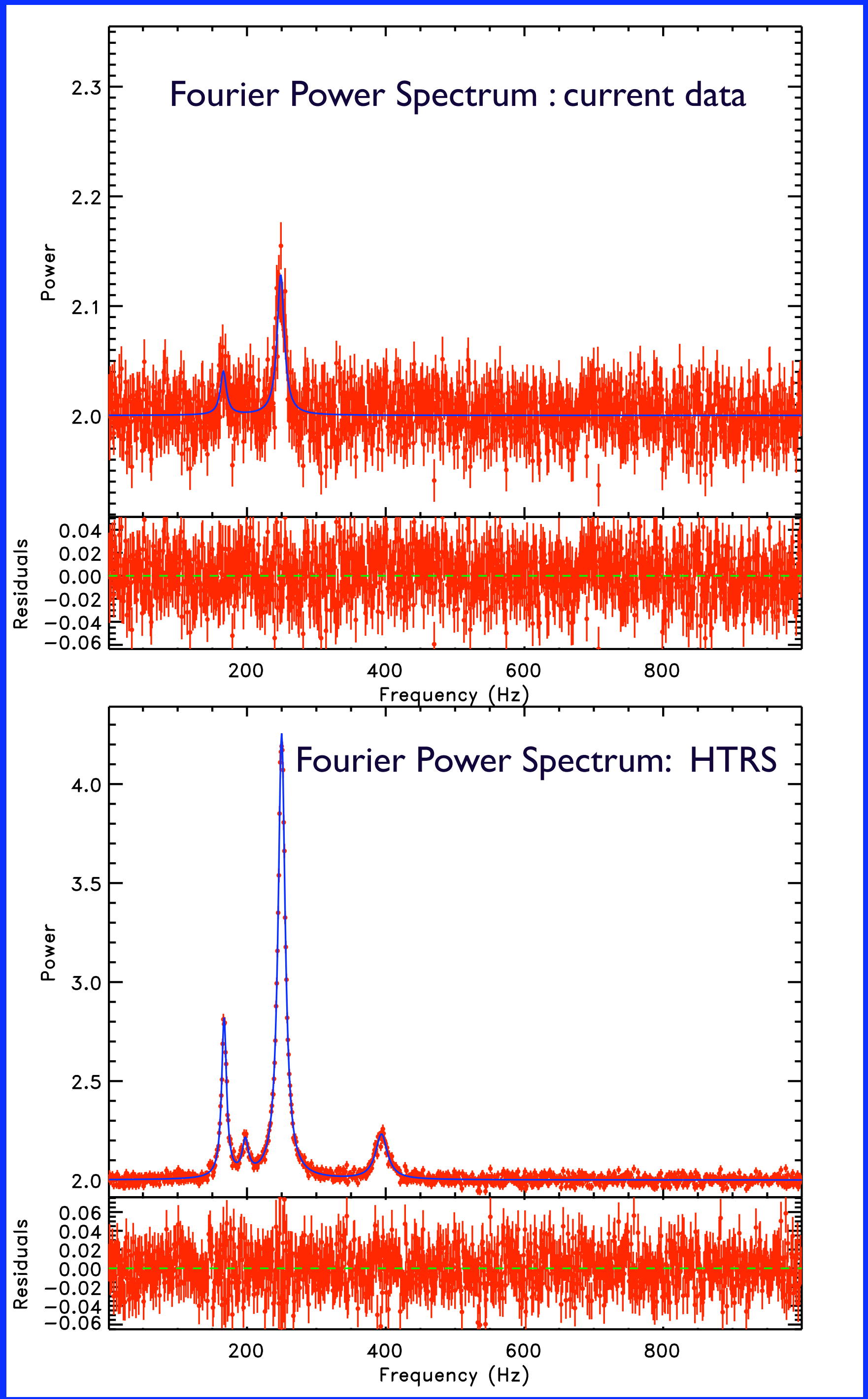
Energy range	0.3-20 keV
Time resolution	10 micro-seconds
Energy resolution	<150 eV @ 6 keV (-20C)
1 Crab count rate	~200 000 counts/s
Count rate capability	> 10 Crab
Deadtime & pile-up	<1% @ 1 Crab
Overall detector size	~ 2 cm^2
Readout time	50-75 ns



The SDD array

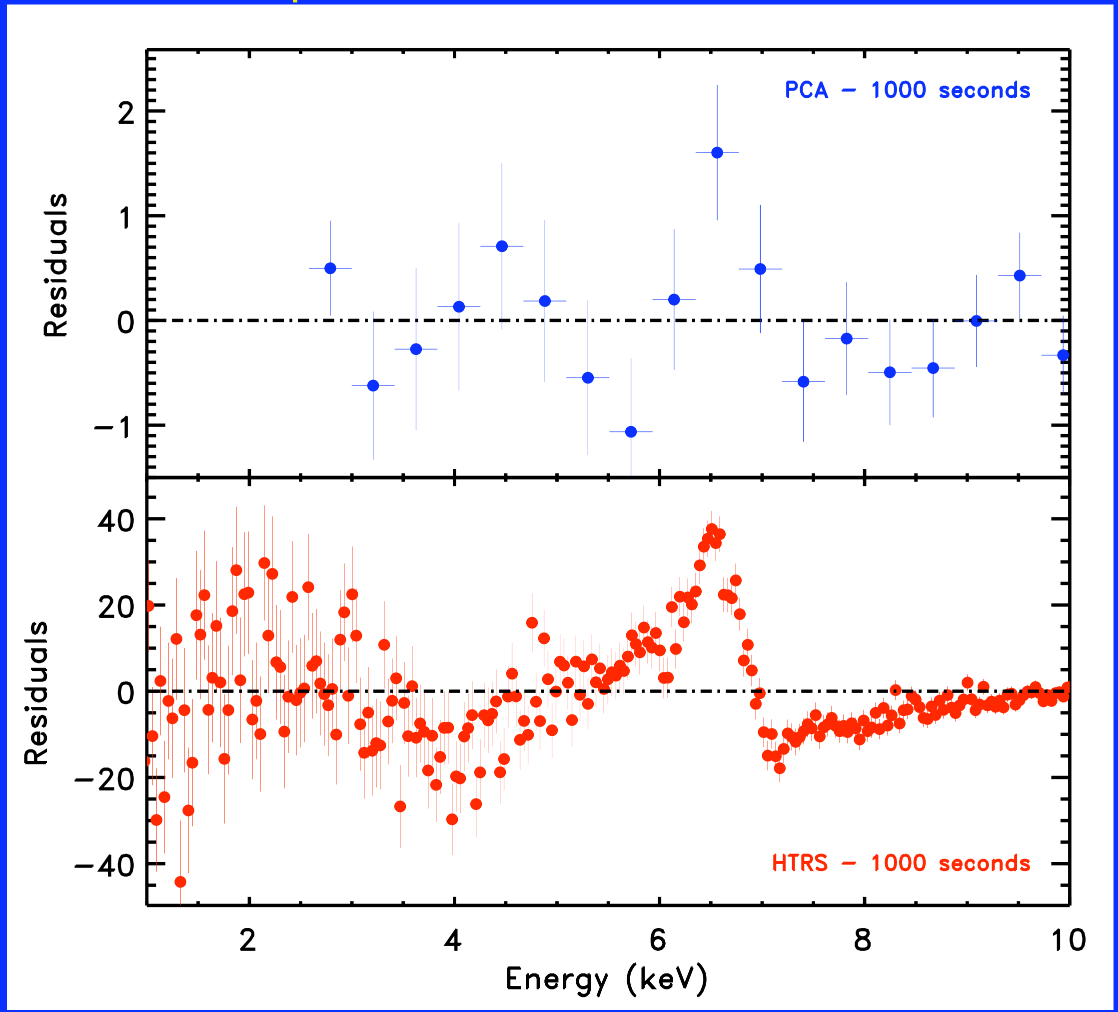
The gain with the HTRS

Gain in count rates



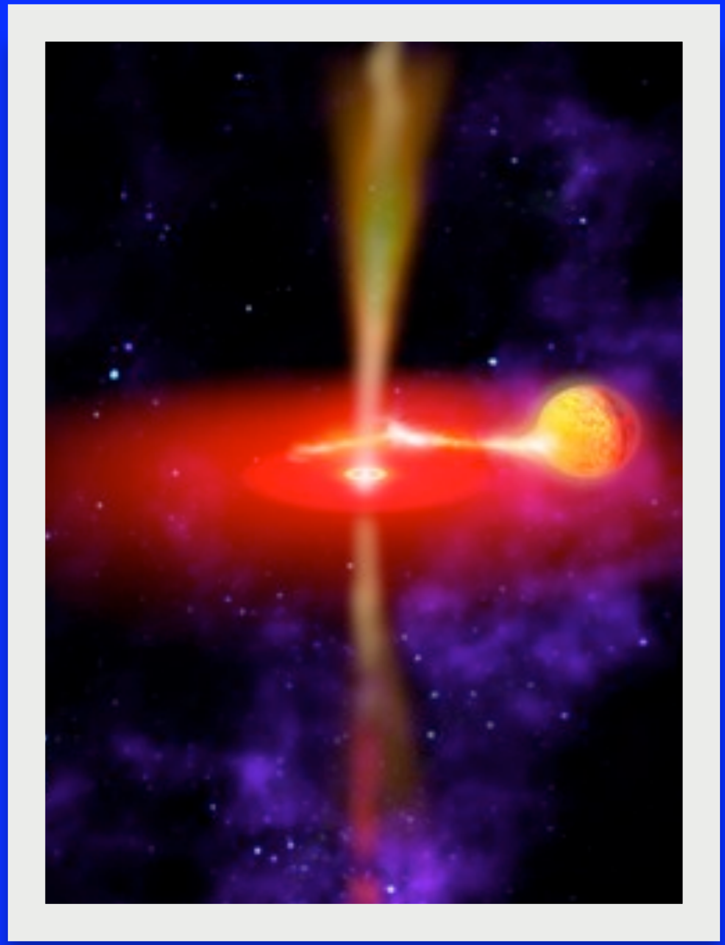
- Combining fast timing and spectroscopy
  - ✓ Larger count rates (x 10-20)
  - ✓ Improved energy resolution
    - ➡ Two types of instruments in one !

Gain in spectral resolution with the Iron line



HTRS targets

- HTRS will perform high time resolution spectroscopy of galactic compact objects:
  - ✓ powered by accretion
    - ➡ Over a wide range of accretion rates, e.g. x-ray novae, microquasars
  - ✓ powered by thermonuclear burning
    - ➡ type I X-ray bursters
  - ✓ powered by magnetic energy
    - ➡ Over a wide range of magnetic fields, e.g. from millisecond pulsars to magnetars
  - ✓ powered by internal energy
    - ➡ Over a wide range of ages, e.g. cooling neutron stars

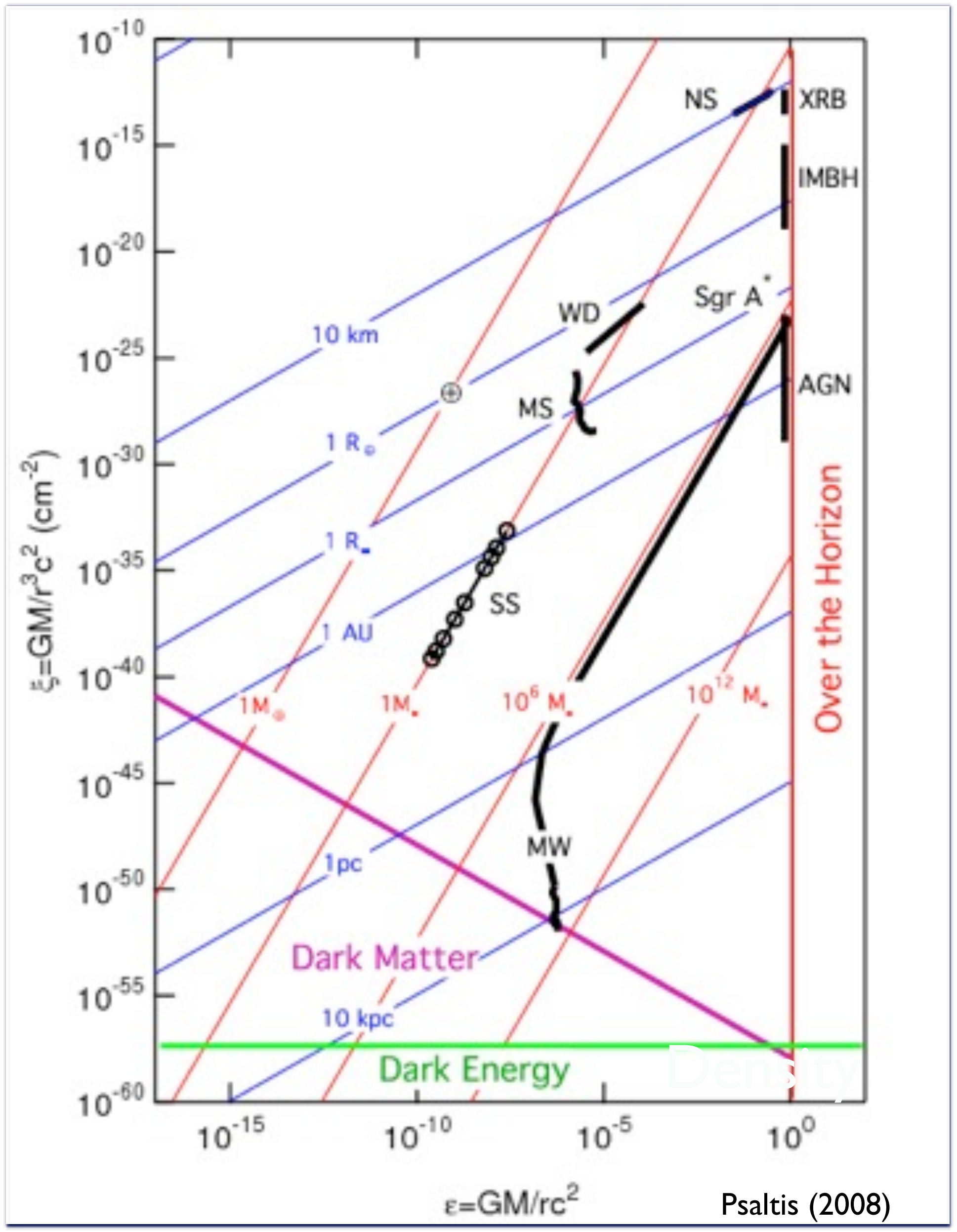


Probing strong gravity

X-ray binaries probe the strongest gravitational fields and the most extremely curved spacetimes

$$\xi = \frac{GM}{c^2 r^3}$$

Curvature



Potential

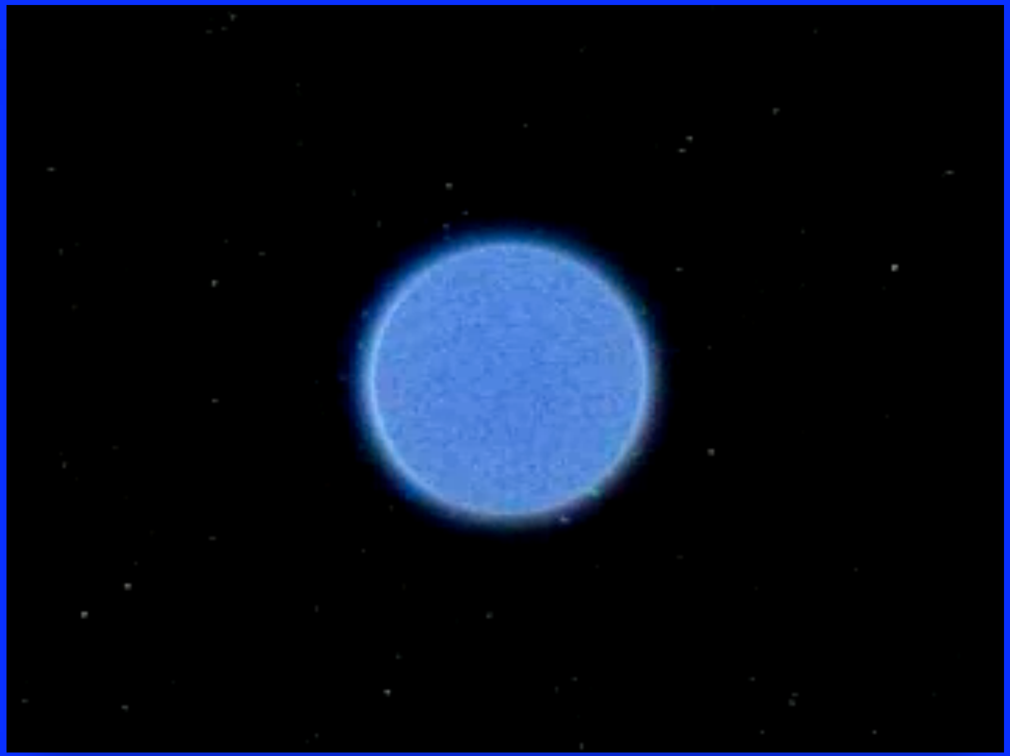
$$\epsilon = \frac{GM}{c^2 r}$$

Psaltis (2006)

Understanding how strong gravity works and testing our understanding of General Relativity require observations of X-rays generated, close to the horizon of the black hole or the surface of the neutron star, in the sub-ms time domain

Accretion powered X-rays

- Accretion produces X-rays through the release of gravitational potential energy
- For a 10 km compact object size, 90% of the energy is radiated within the last 100 km
- Accretion proceeds through a disk in which the azimuthal velocity is close to the Keplerian velocity
  - ✓ Characteristic velocities ~0.5c
  - ✓ Dynamical timescales 2 ms at 100 km (10 Msol)

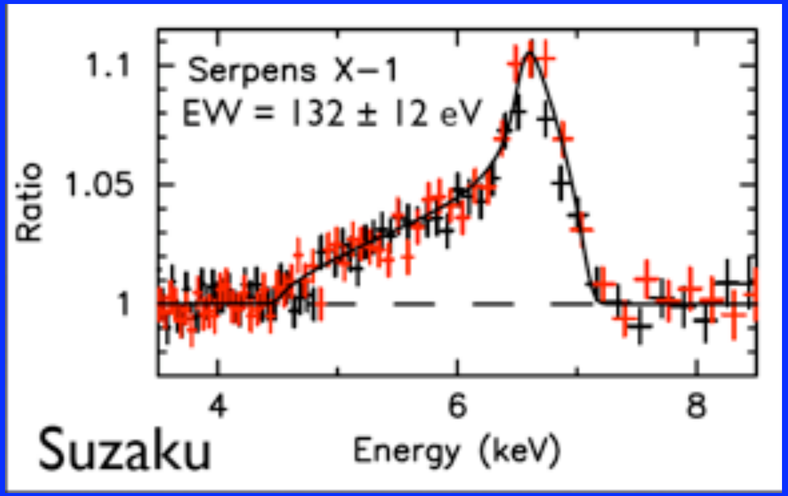


Two approaches:
- Timing
- Spectroscopy

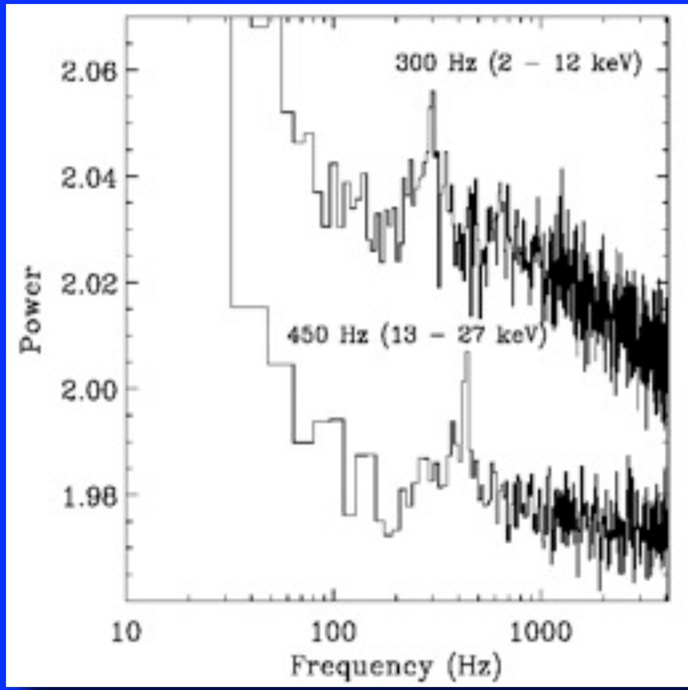
Strong gravity features in X-rays

- Secured (but yet to be fully exploited):
  - ✓ Relativistically smeared iron line tracing matter moving close to the compact objects: seen in black hole systems and in neutron stars
- To be confirmed:
  - ✓ Redshifted absorption lines from radiation emitted at the surface of a neutron star
  - ✓ The innermost stable circular orbit (from timing and spectroscopy)
  - ✓ Epicyclic frequencies (from timing)
  - ✓ Lense-Thirring precession (from timing)
  - ✓ The black hole event horizon
    - ➡ The HTRS has the potential to confirm the above findings and to use them to probe strong field GR

Broad iron lines in NSs
Cackett et al. (2008)

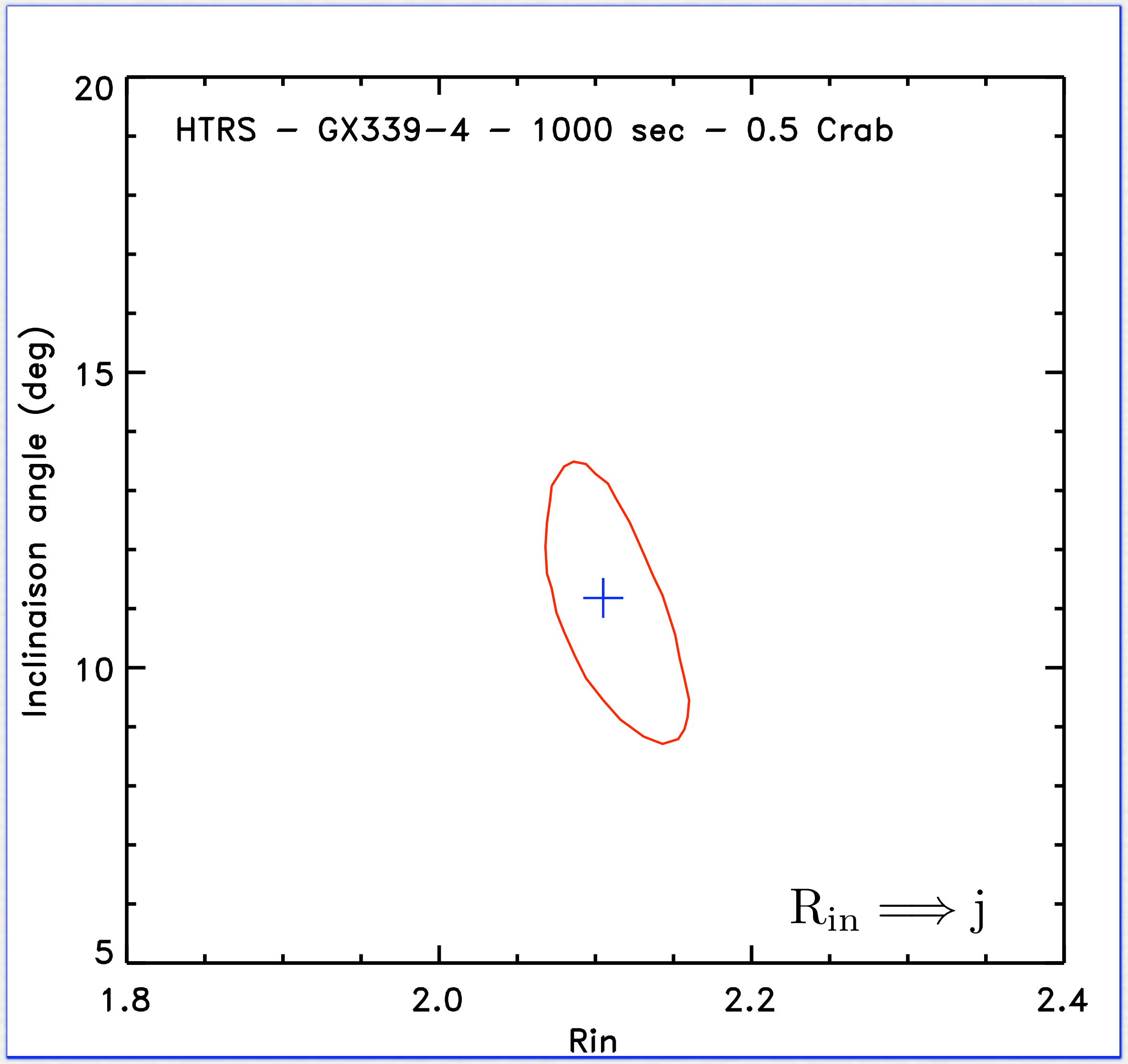


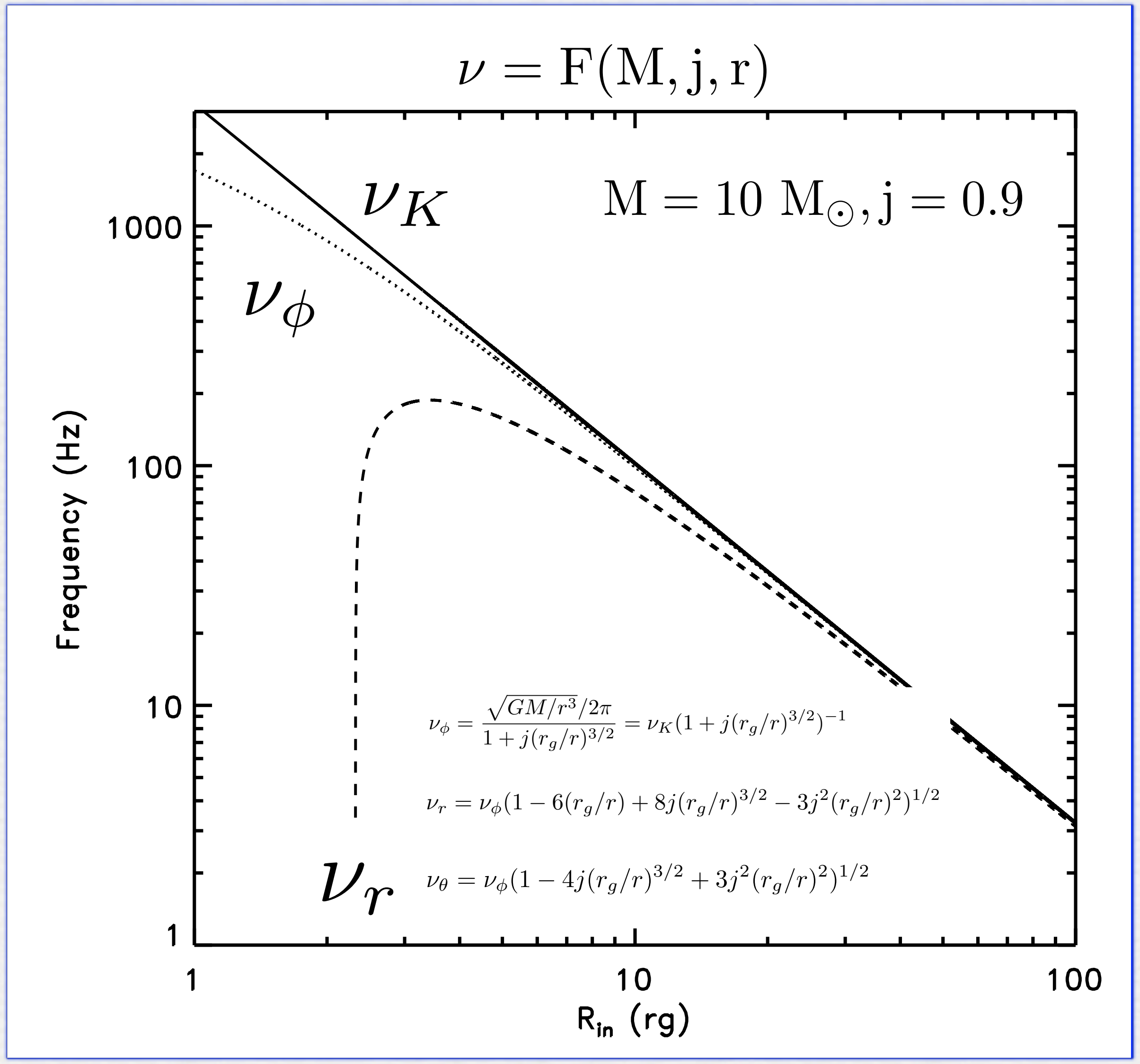
Black hole high frequency QPOs
Remillard (2006)



Combining energy and Fourier spectra

The confidence contours of the inclination versus inner disk radius (parameters from Miller et al. (ApJ).

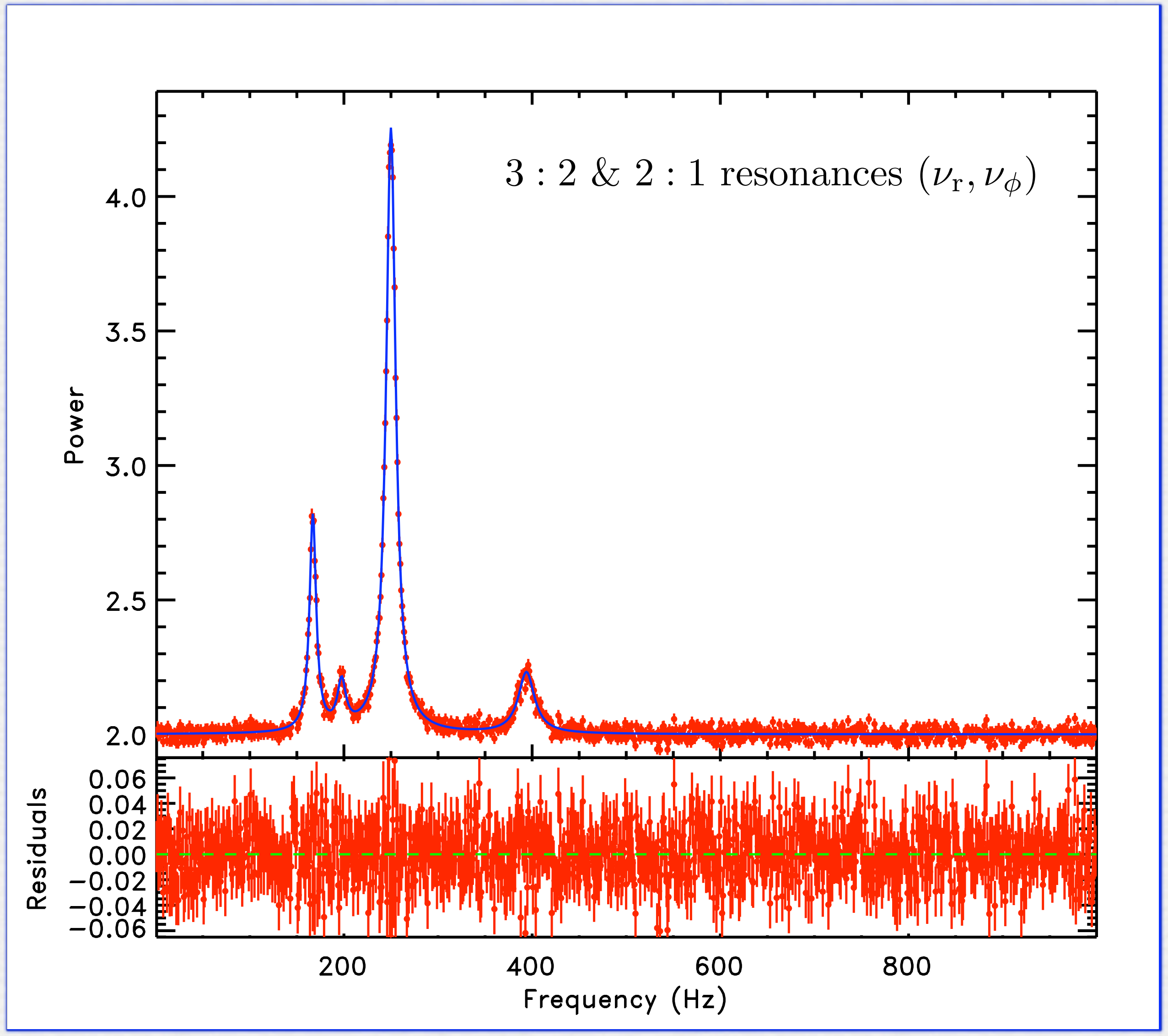


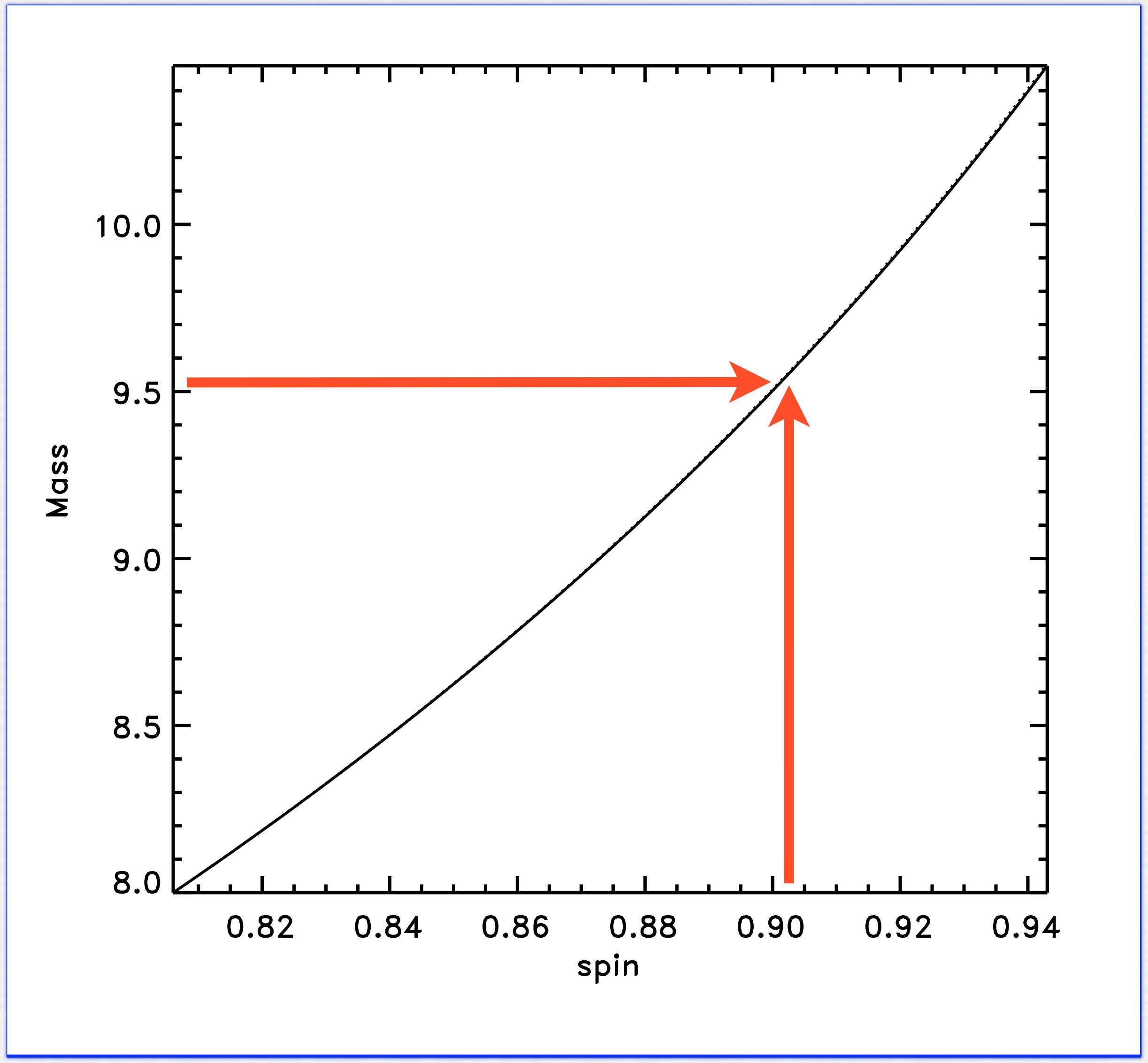


Orbital frequency, radial and vertical epicyclic frequencies depend on radius, mass and spin

Mass constraints

Four QPOs simulated with radial and vertical epicyclic frequencies in a 2/3 and 1/2 ratios.



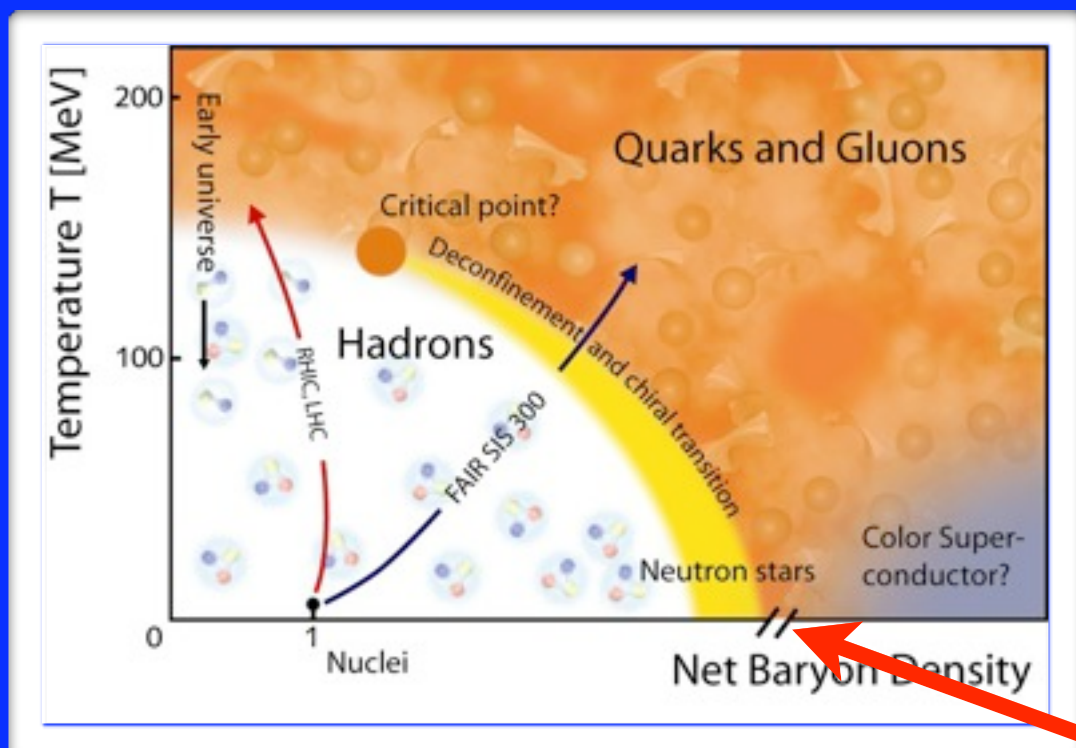


Identifying two QPO frequencies with General Relativistic frequencies constrains M and j.

Equation of state of cold matter

Neutron stars probe the low temperature-large density region of the QCD phase diagram

Temperature



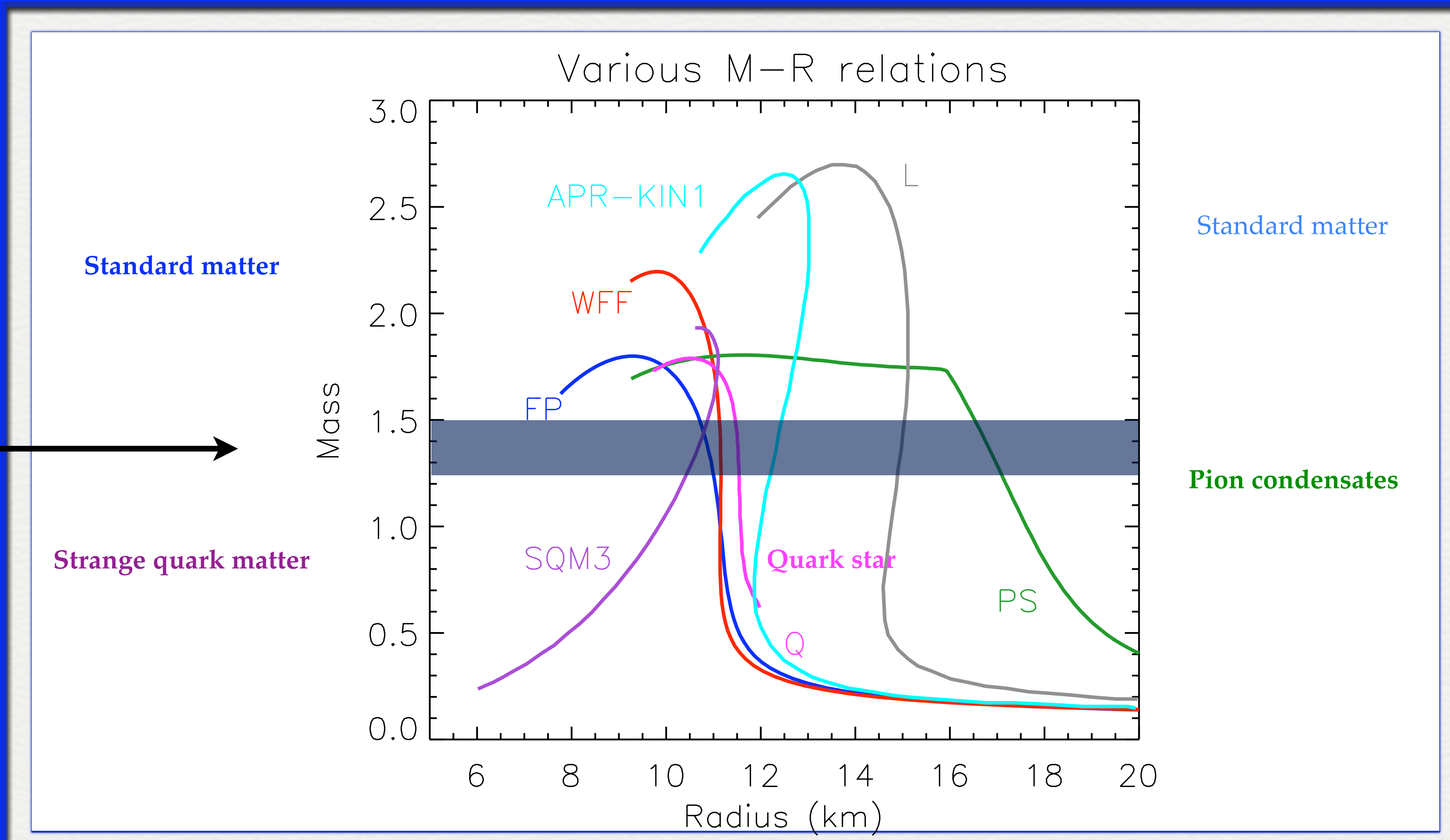
Density

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.

The equation of state

- The interactions between the particles that constitute stars determines the equation of state (EOS), a relation between pressure and density
  - ✓ that can be translated into a mass-radius relation
    - ➡ What is really needed is radii

NS masses from binary pulsars

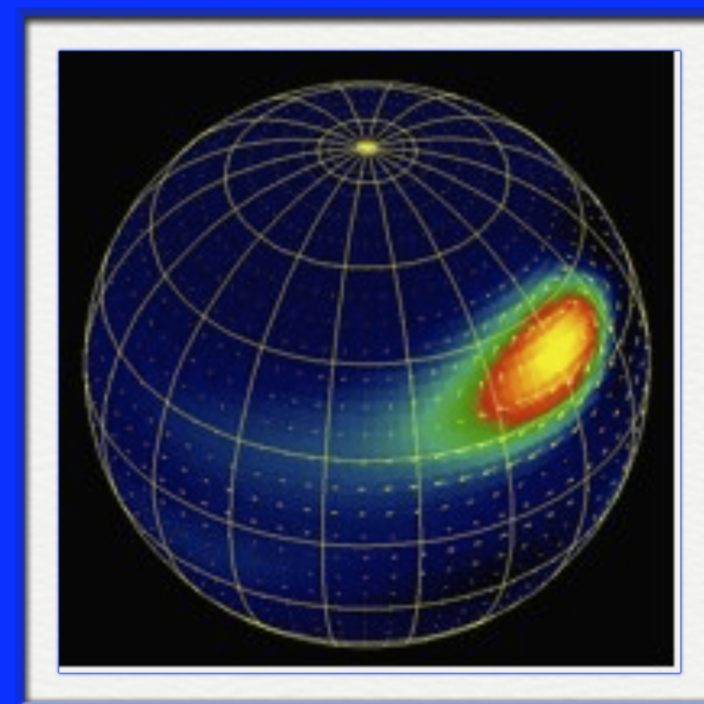


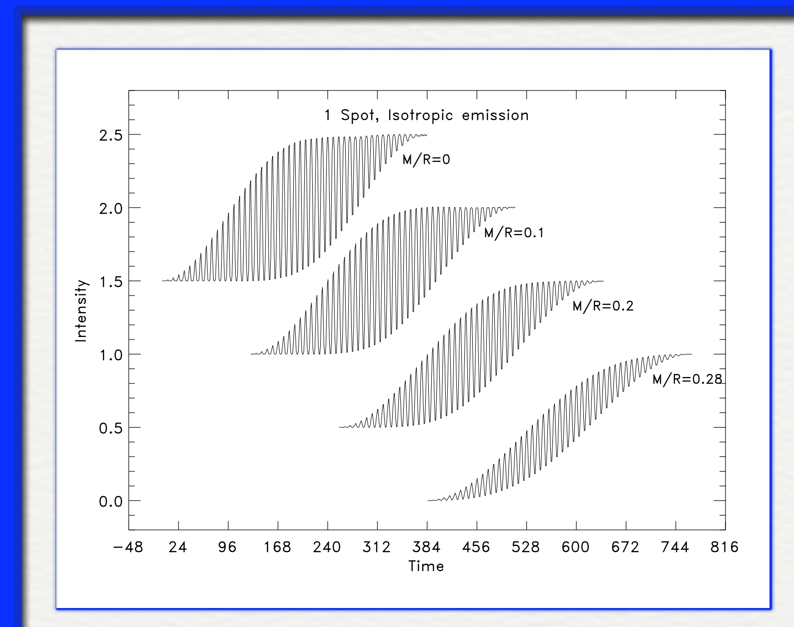
Constraining the NS EoS

- 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, ...

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

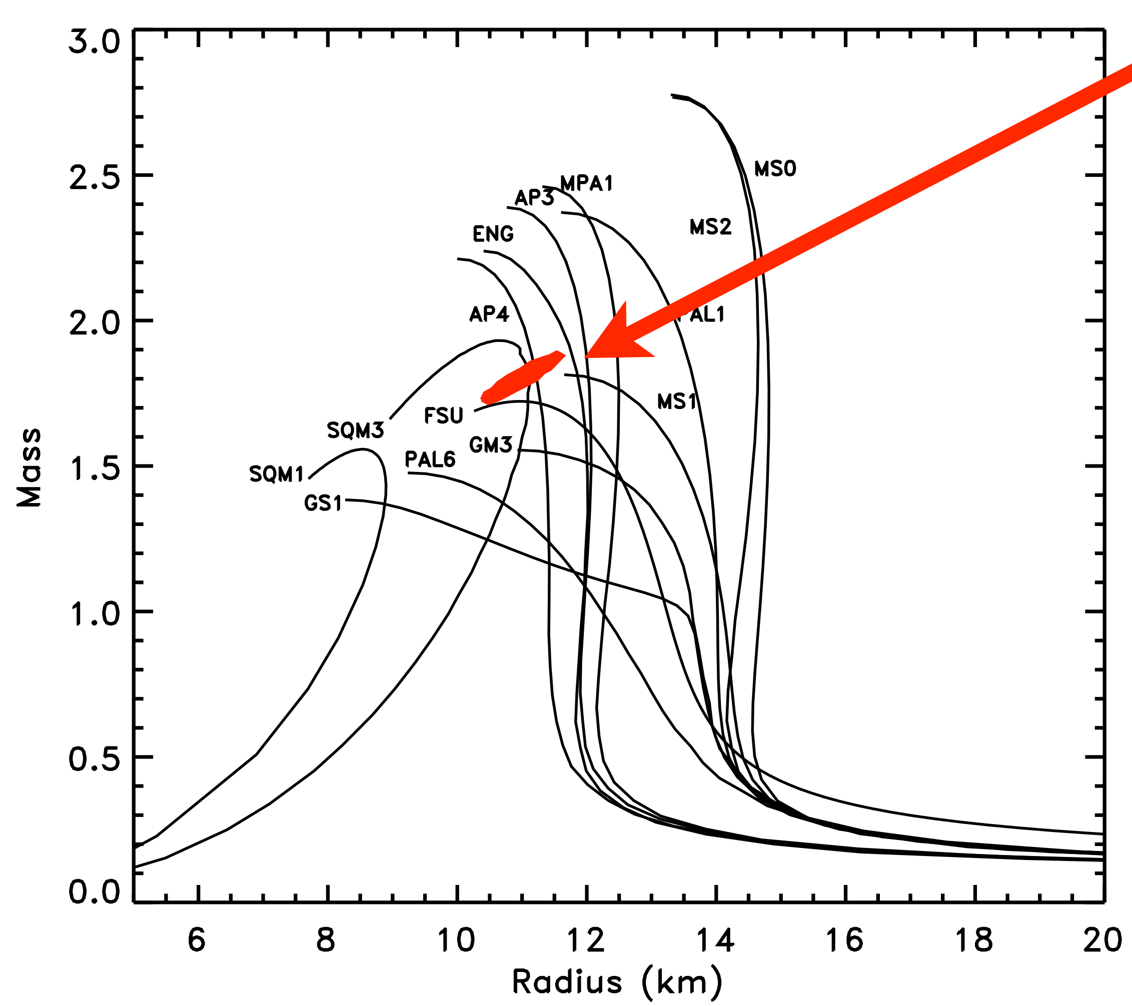




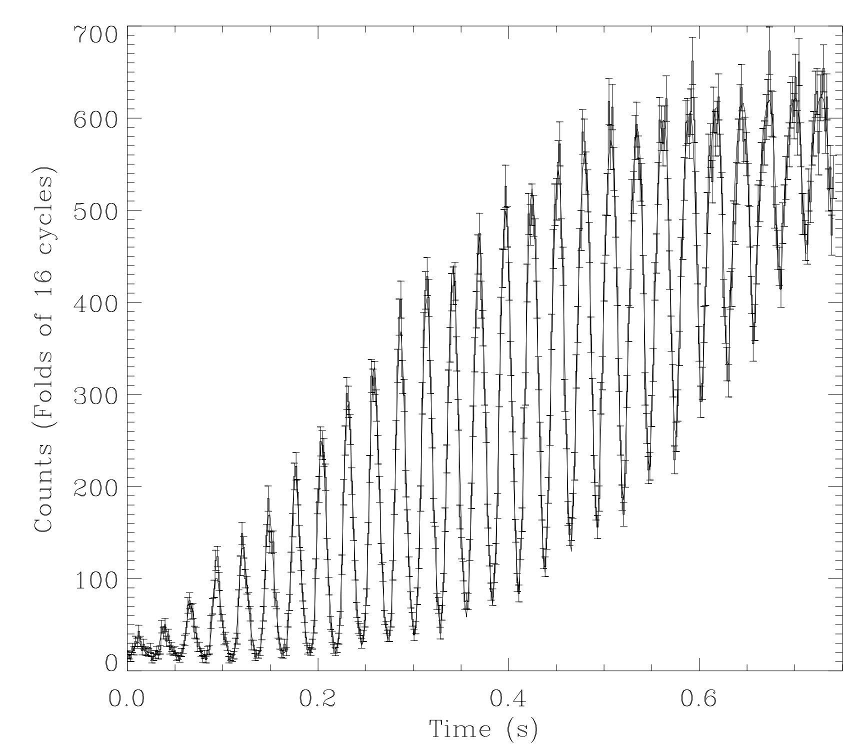
Poutanen & Gierlinski (2004)

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.

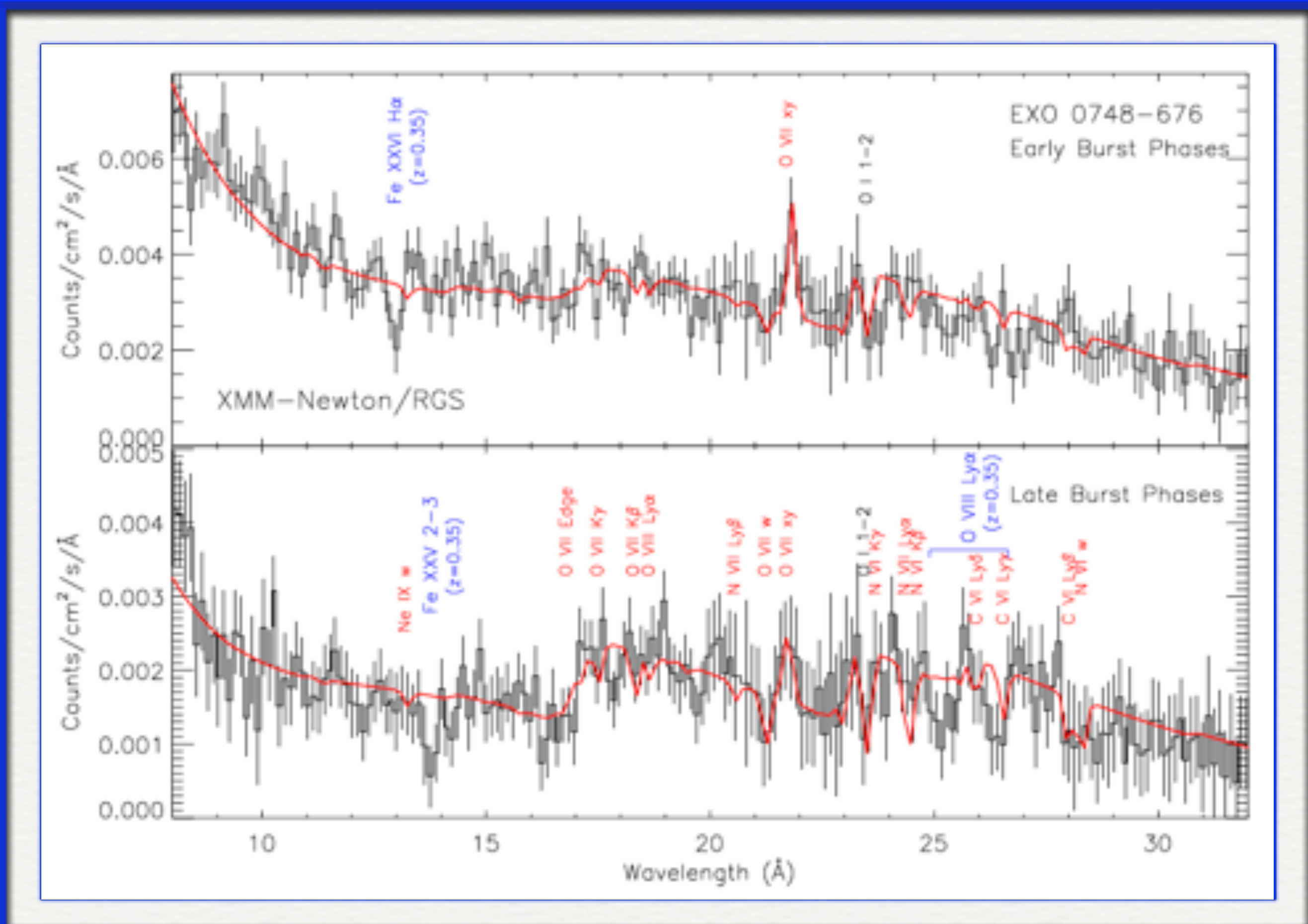


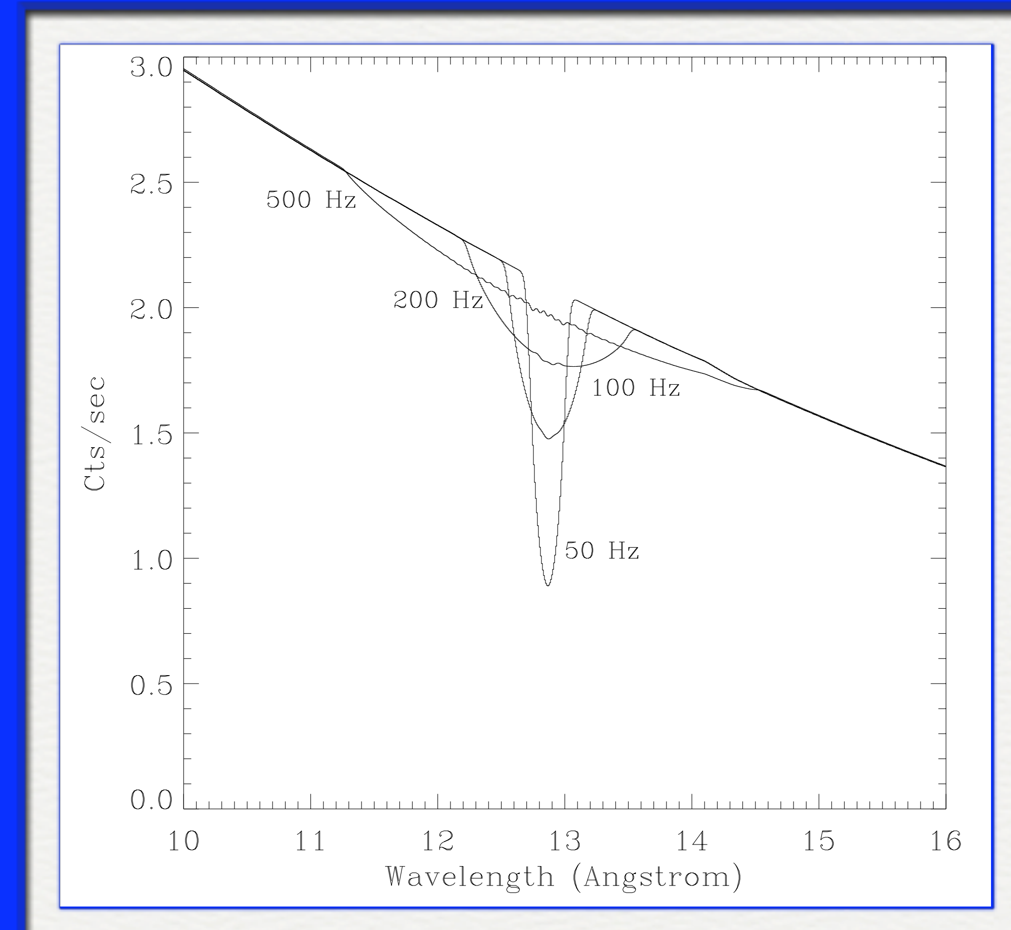
Constraints on mass and radius waveform fitting. The red ellipse shows the 95% confidence regions from 5 typical bursts. (Courtesy of Cole Miller).



X-ray burst spectroscopy

Cottam et al. (2002, Nature)





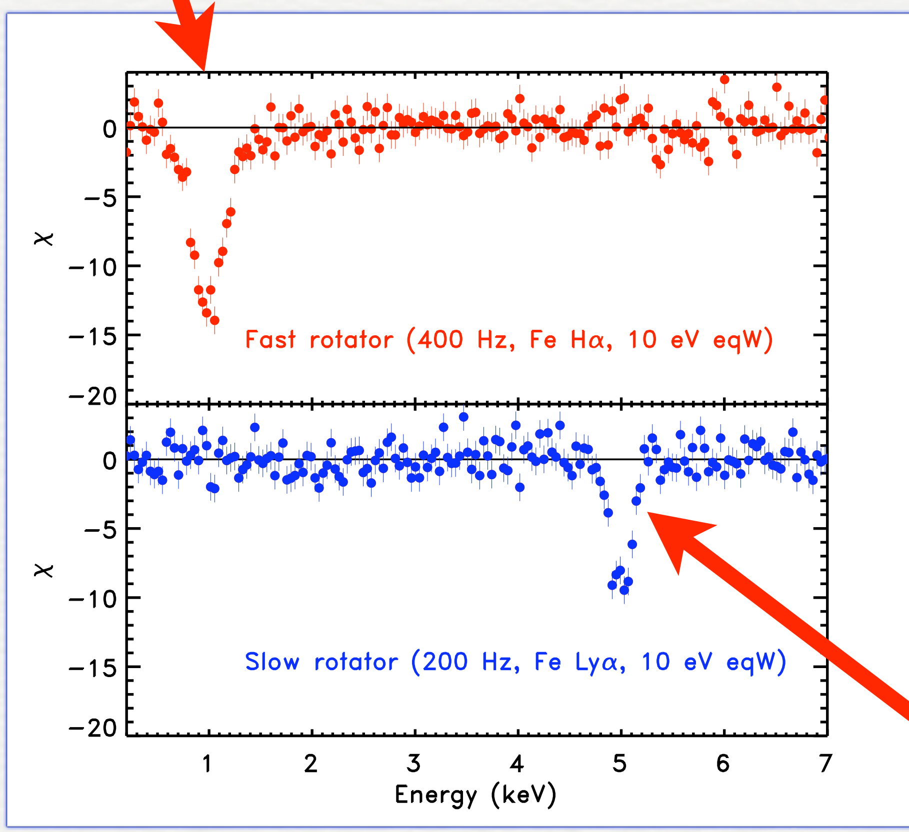
The XMM-Newton RGS spectra of EXO 0748-676 for 28 type I X-ray bursts. The red line is the empirical continuum, with additional O VII intercombination line emission, modulated by absorption in photoionized circumstellar material (Cottam et al., Nature).

Absorption line profiles from the surface of a rotating neutron star. The profiles produced by contributions from the entire neutron star surface are shown for several different rotation rates. The observer is assumed to be looking in the rotational equator

X-ray burst absorption features

HTRS will cope with bright X-ray bursts (Mcts/s) and 120-150 eV spectral resolution

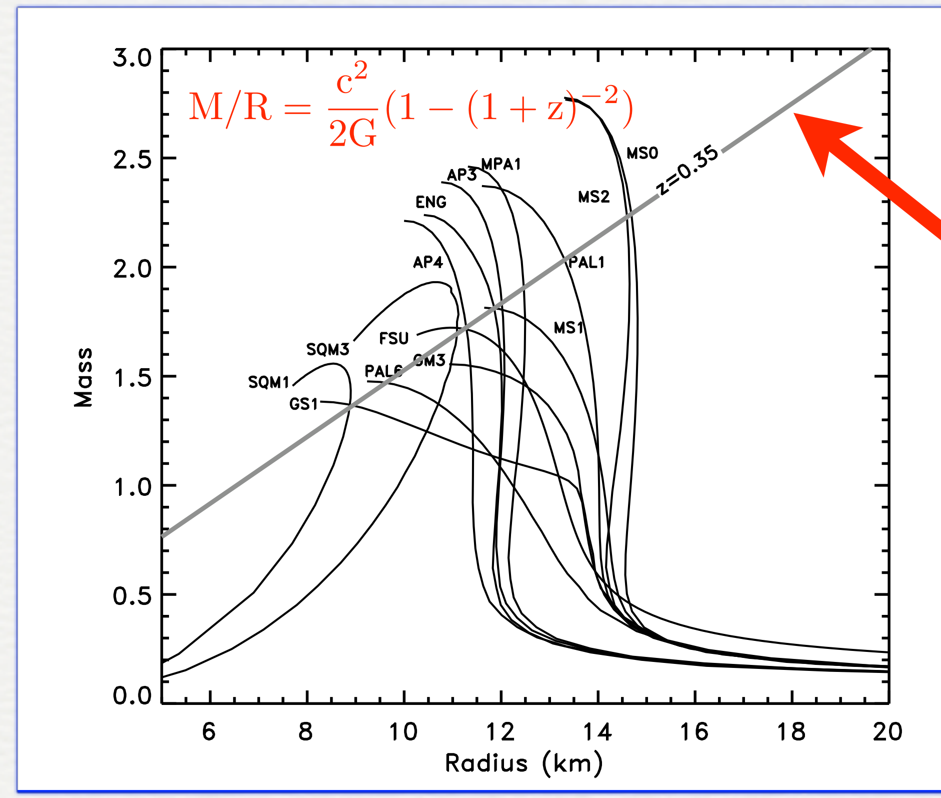
Residuals (chi²)



Energy (keV)

The residuals for a simulated redshifted (z=0.35) Fe Hα & Fe Lyα absorption lines (Chang et al.)

Mass

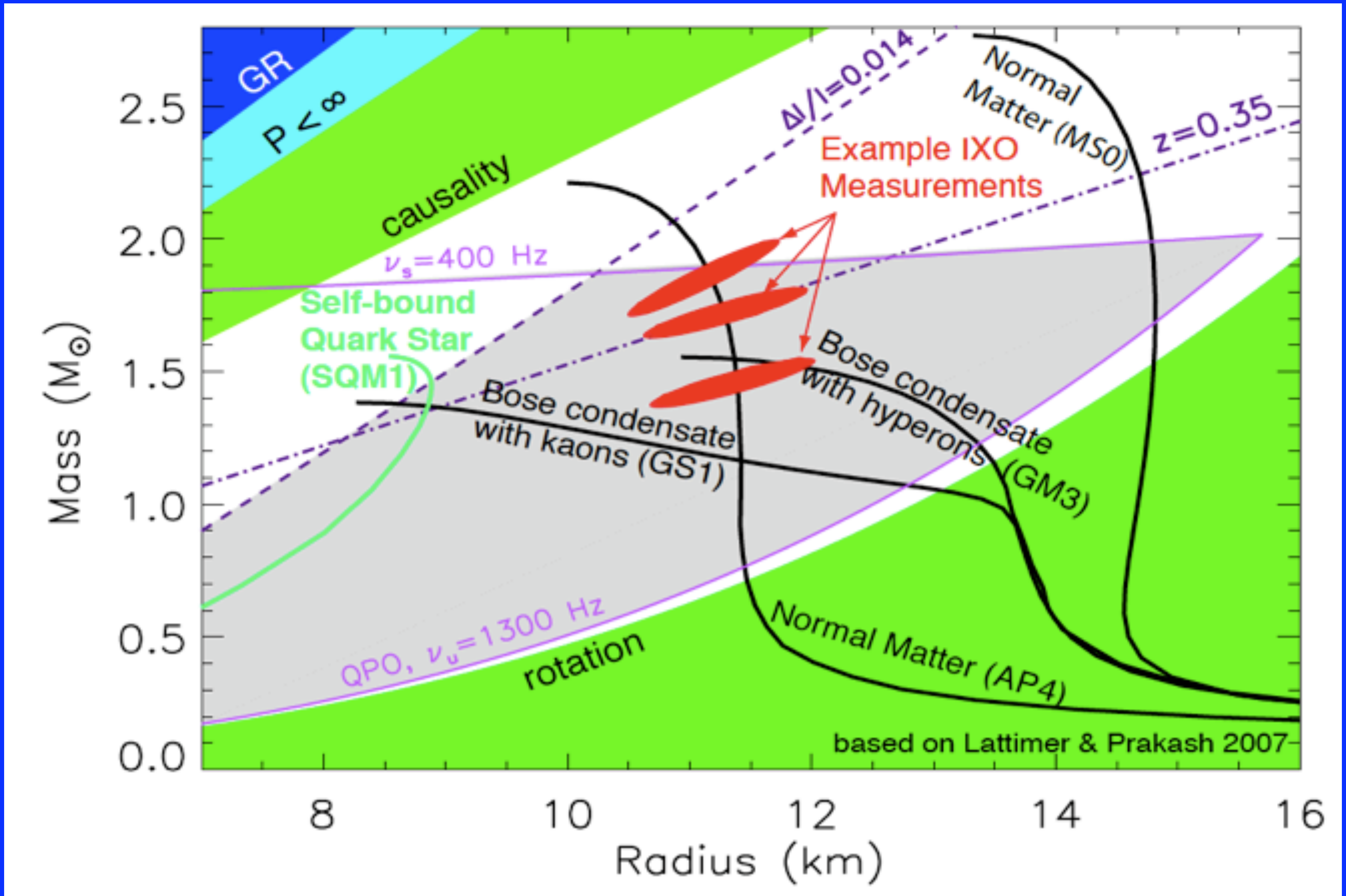


Radius

The constraints inferred from the redshift is shown as a continuous line (data are courtesy of J. Lattimer).

Determining the EoS

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



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
  - ✓ Probe 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 spin measurements with the HTRS (Barret et al. 2009)
- Similarly, determining the equation of state of the densest matter observable in the Universe appears for the first time within reach
  - ✓ Observe the bright phases of NSs with a high throughput spectrometer : the HTRS (Barret et al. 2009)

IXO in action (NASA design)