Exploring gravity in the strong field regime with high throughput X-ray measurements

Luigi Stella
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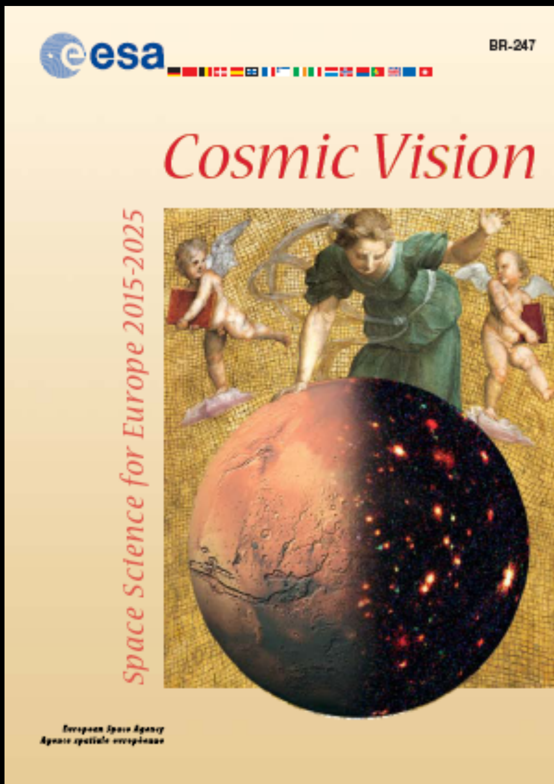
ESA's Cosmic Vision program



3. What are the fundamental physical laws of the Universe?

3.1 Explore the limits of contemporary physics

Use stable and weightless environment of space to search for tiny deviations from the standard model of fundamental interactions

3.2 The gravitational wave Universe

Make a key step toward detecting the gravitational radiation background generated at the Big Bang

3.3 Matter under extreme conditions

Probe gravity theory in the very strong field environment of black holes and other compact objects, and the state of matter at supra-nuclear energies in neutron stars

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

MOTION OF MATTER CLOSE TO THE EVENT HORIZON

ASTROPHYSICS NEAR BLACK HOLES: STRONG FIELD EFFECTS

- Inner Stable Circular Orbit
- Orbital motion near ISCO
- Frame dragging, light deflection, Shapiro effect

ASTROPHYSICAL IMPACT

- Black hole spins
- AGN feedback
- Relativistic jets
- Accretion physics

X-RAY DIAGNOSTICS:

- Precision measurements near the event horizon
  - Strong field motions: orbital & epicyclic
- Fe line spectral timing
  - Reverberation
  - Doppler tomography

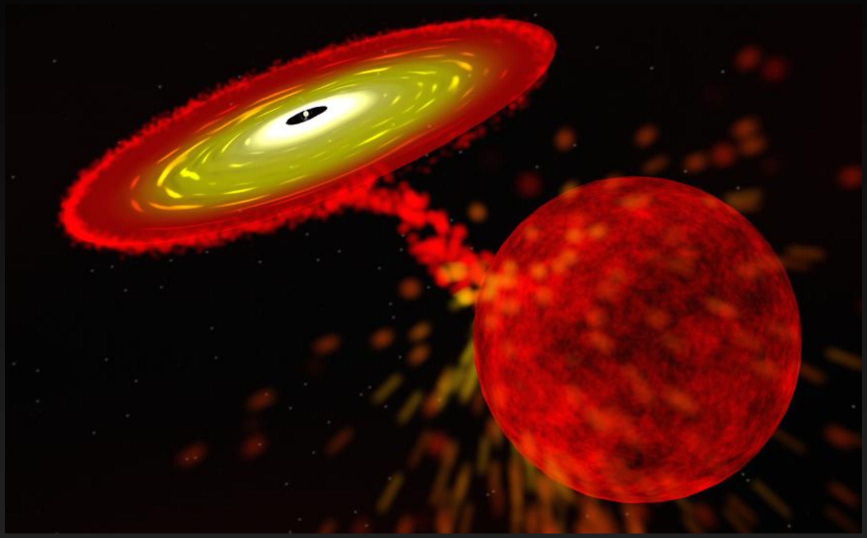
Current best tests of General Relativity: millisecond radiopulsars

RELATIVISTIC EFFECTS ARE SMALL PERTURBATIONS

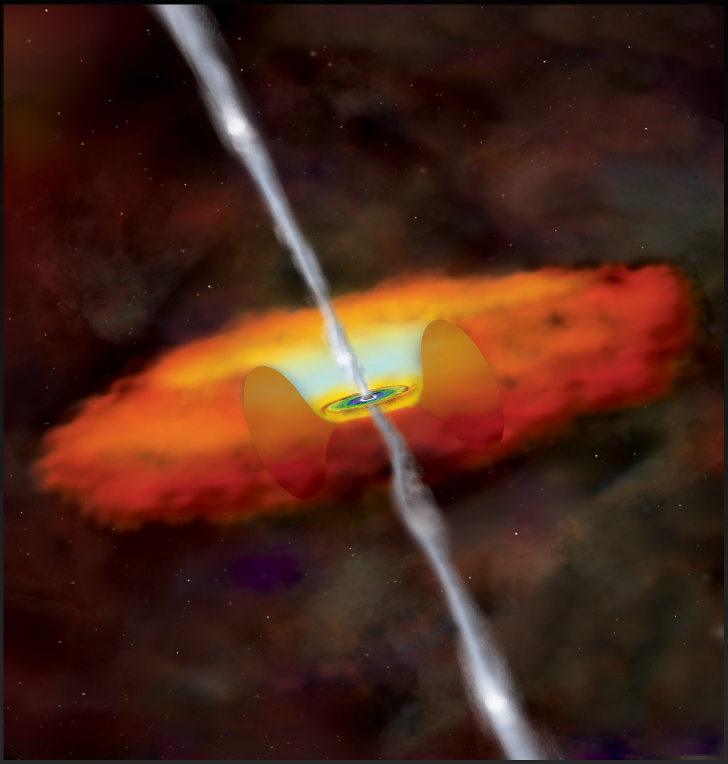
FACTOR 100,000 CLOSER TO THE BLACK HOLE

- VERIFY GENERAL RELATIVITY
- TEST ALTERNATIVE THEORIES

Accreting Black Holes



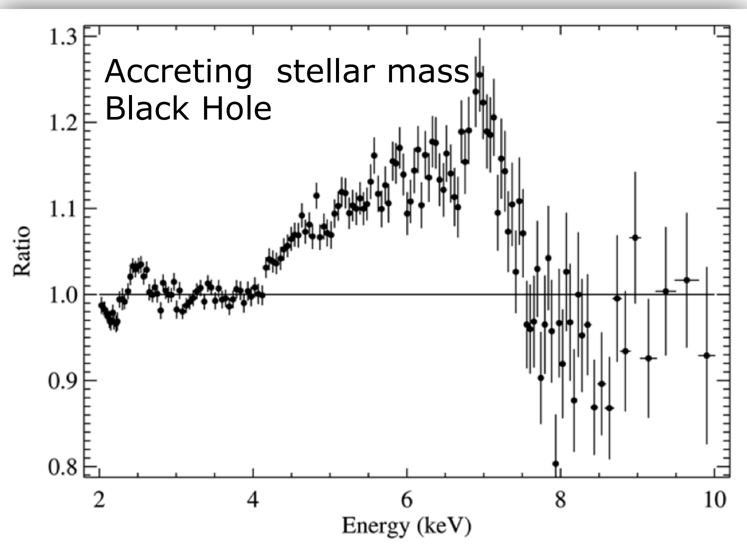
Stellar mass Black Holes in X-ray binaries

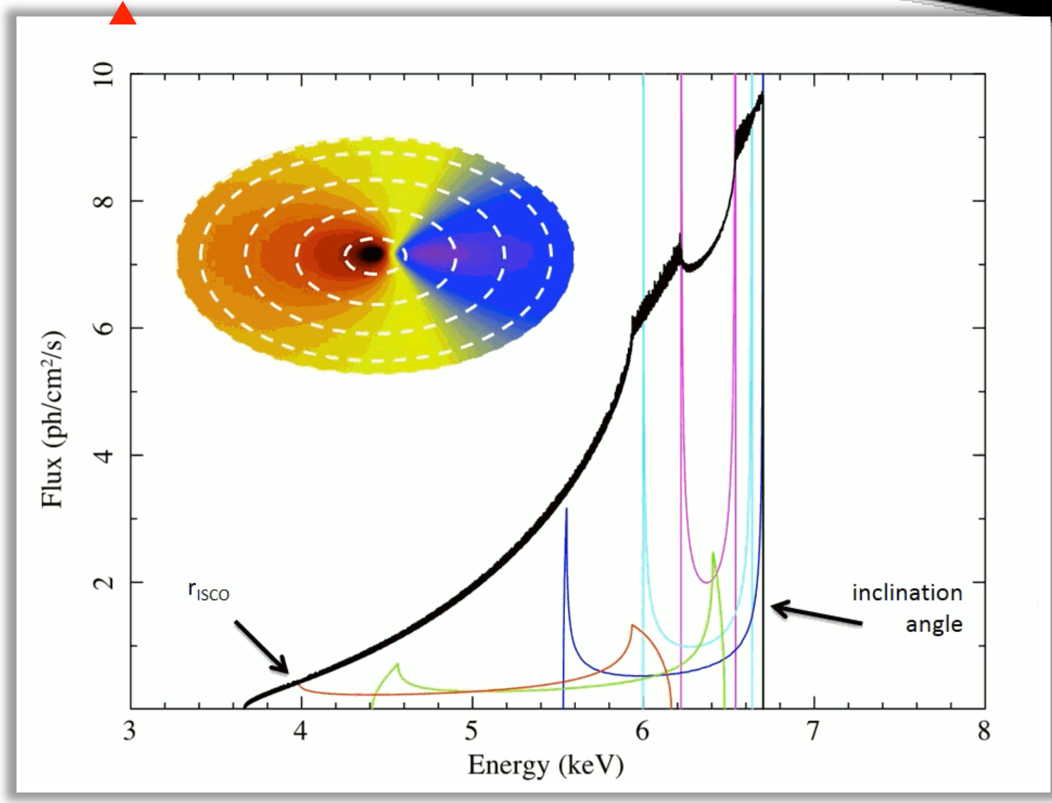


Supermassive Black Holes in nuclei of active Galaxies (AGN)

- Accretion-released energy leads to powerful X ray emission from the innermost disk regions
- X-ray flux is often very variable and spectra are complex

Iron line diagnostic probes relativistic velocity and redshift map

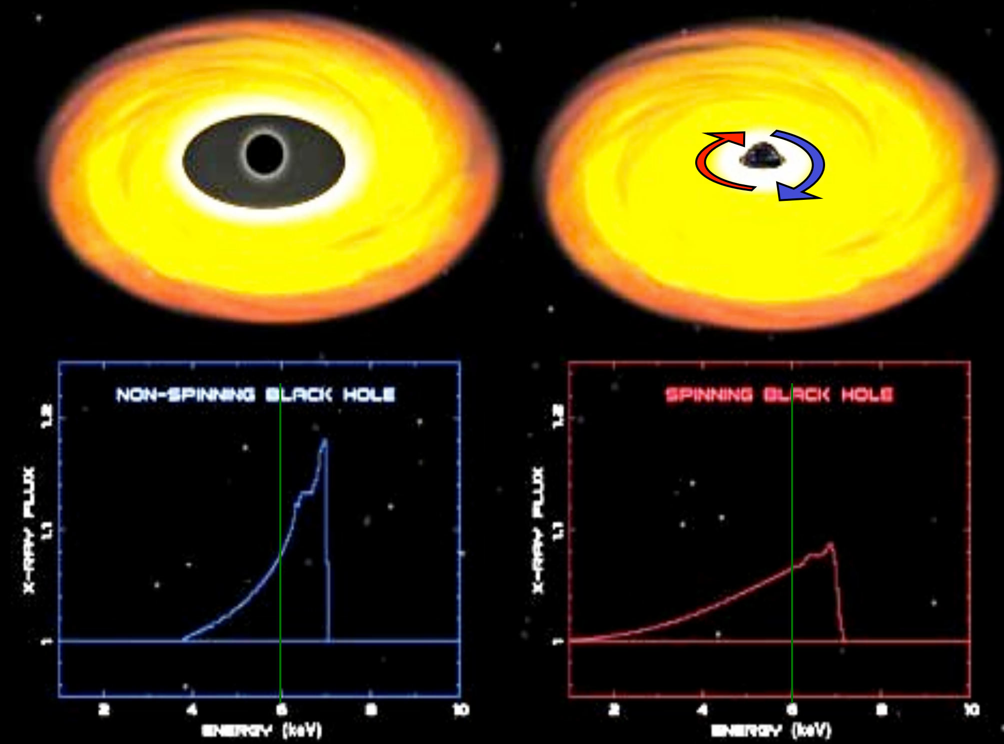




Line profile integrated over entire flow encodes:

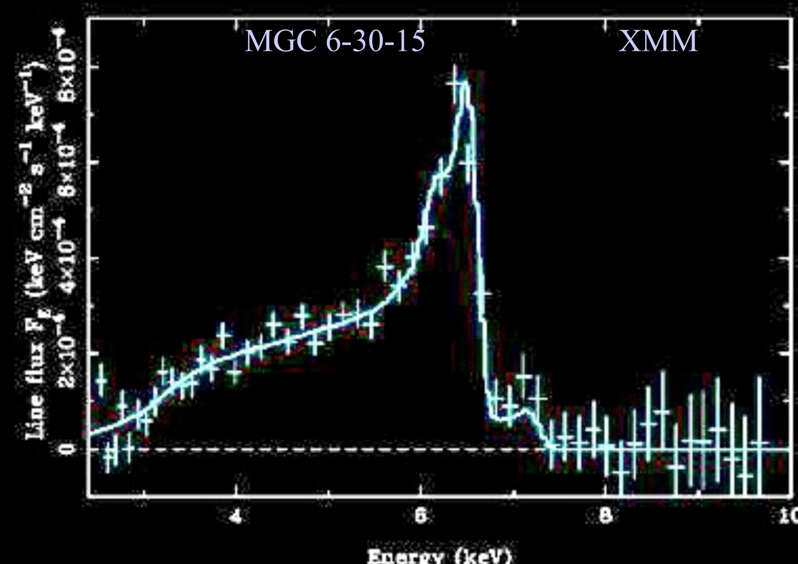
- Strong field relativistic effect: Doppler shifts and boosting, gravitational redshift, strong field lensing

Fe-lines from accretion disks around supermassive black holes in AGNs



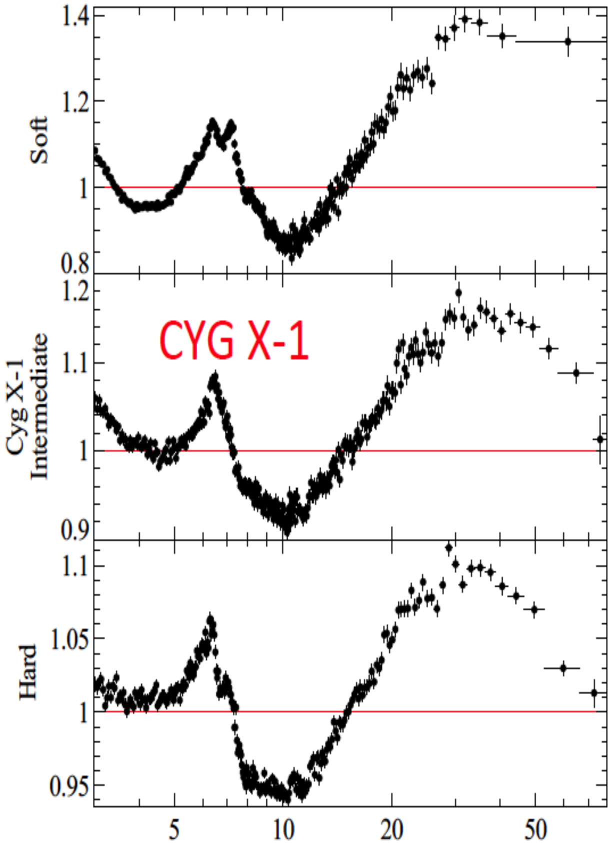
Fe-lines probe strong field gravity
(~few Rg)

e.g. MCG 6-30-15:
- Kerr BH required to fit line profile

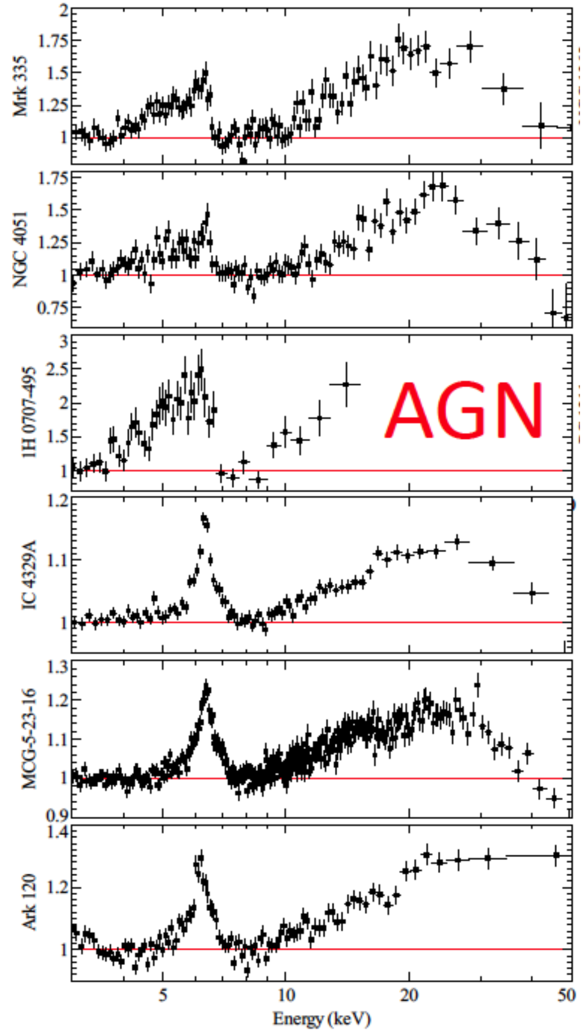


Iron lines probe Relativity predicted velocity and redshift map

XMM + NUSTAR



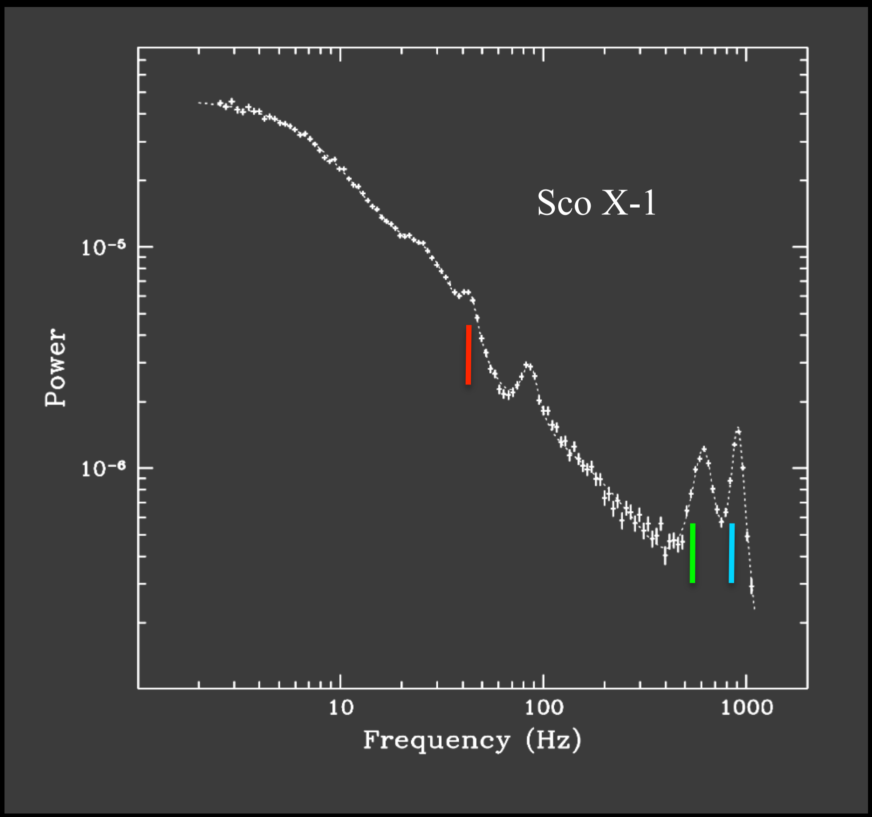
Parker, Tomsick+



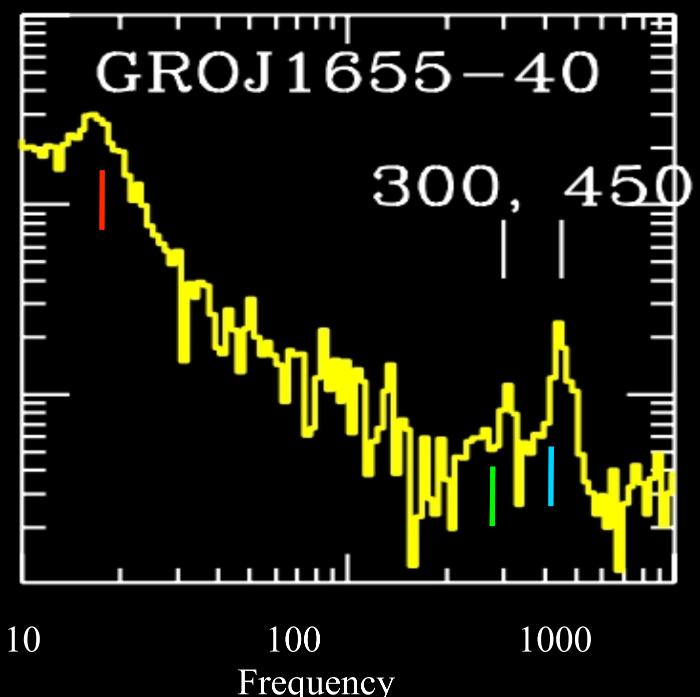
Parker, Matt+

Stong Field Diagnostic: Quasi Periodic Oscillations

Accreting neutron stars

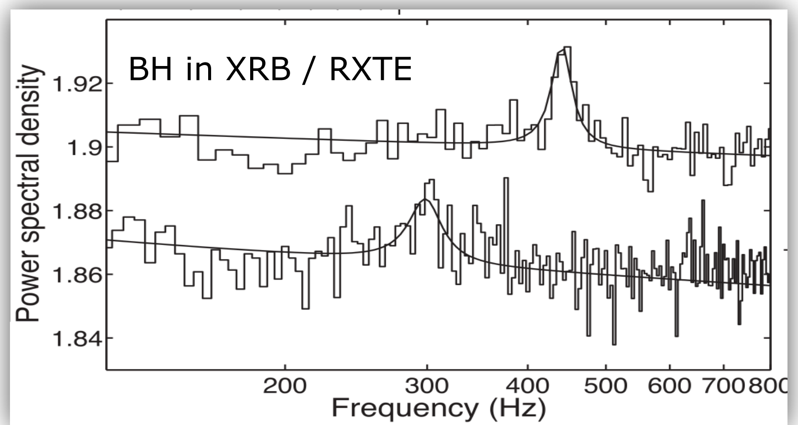


Accreting black hole candidates

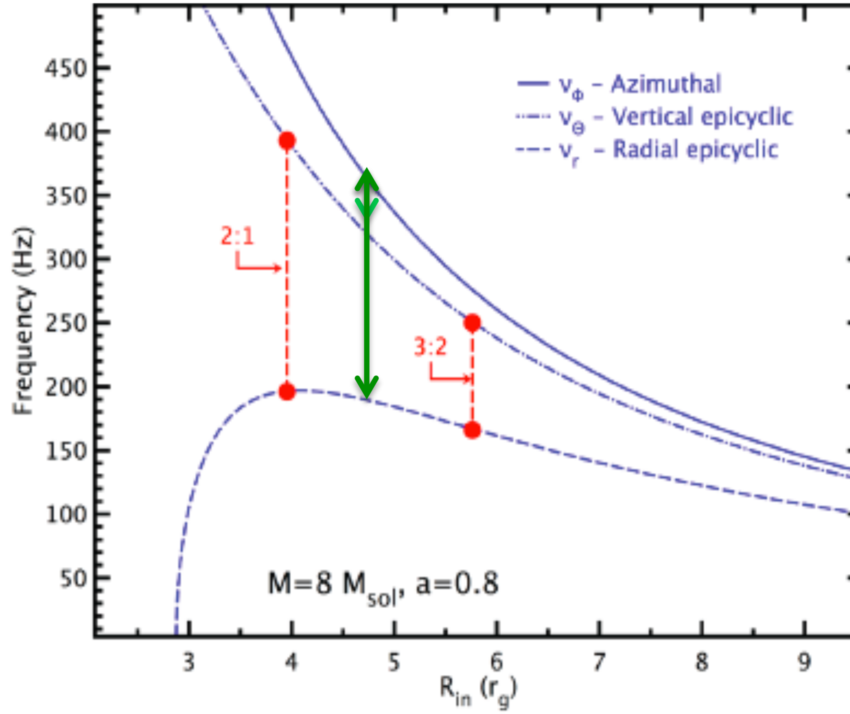


+ few AGN

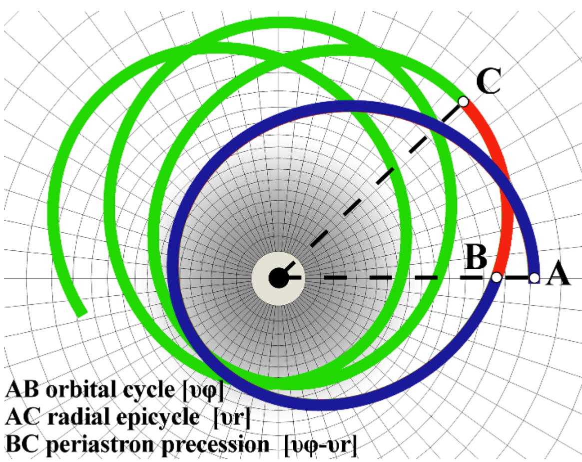
Frequencies of motion in strong gravity

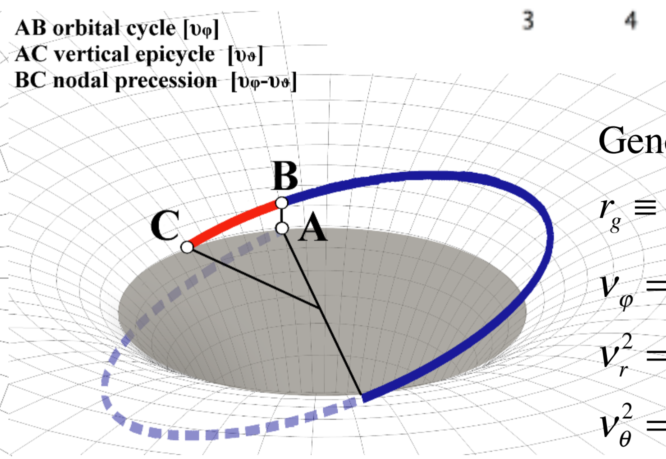


- Epicyclic Resonance (fixed r)
- Relativistic Precession: nodal and periastron



GR orbital, epicyclic and precessional frequ





General relativity:

$$r_g \equiv GM/c^2 \qquad j \equiv Jc/GM^2$$

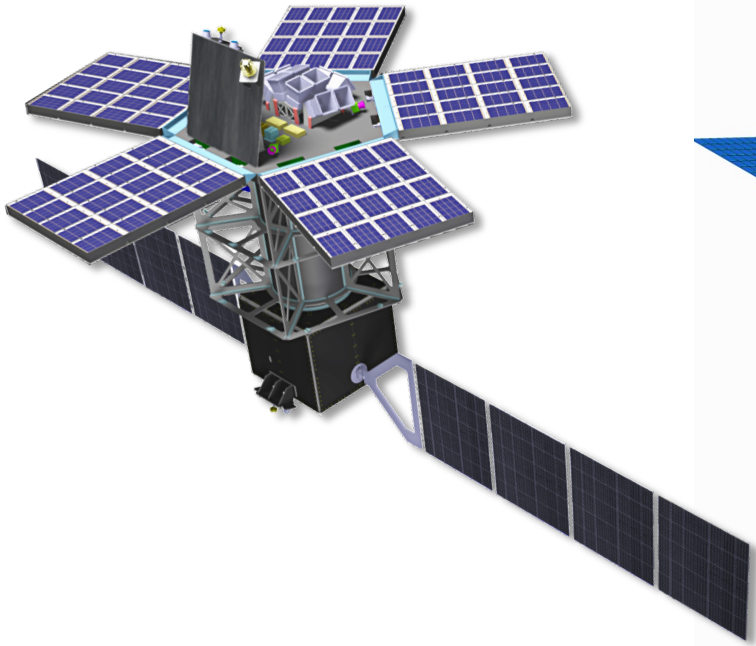
$$\nu_\varphi = \sqrt{GM/r^3}\,/\,2\pi(1 + j(r_g/r)^{3/2})$$

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

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

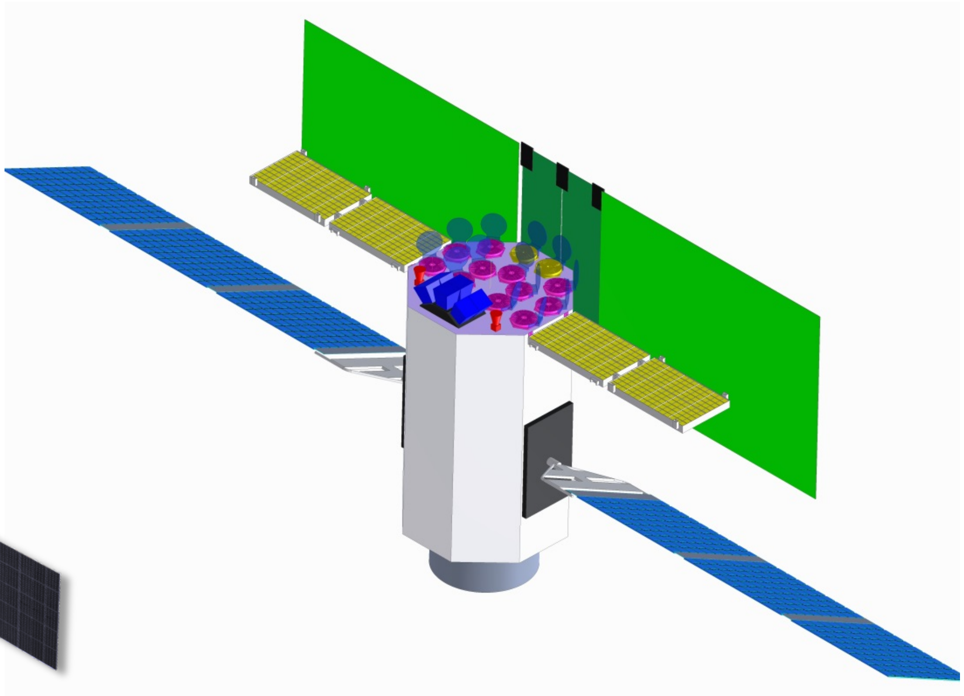
Two possible mission approaches

LOFT
Large Observatory For x-ray Timing (ESA)



Bright sources:
Large Collimated Area

eXTP
enhanced X-ray Timing and Polarization mission (CAS)

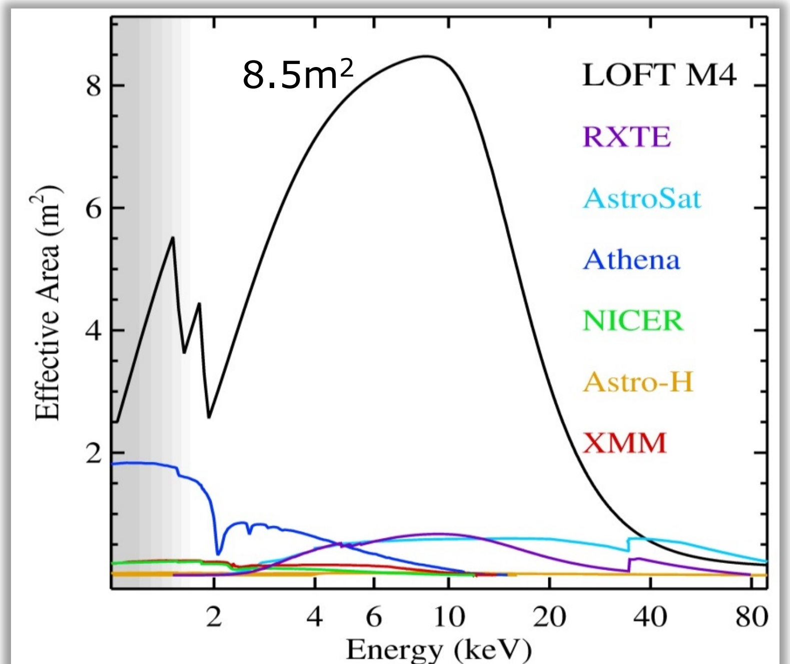


Weak/soft sources:
Collimated + Focused Area

Two possible mission approaches

LOFT

Large Observatory For x-ray Timing (ESA)



Bright sources:
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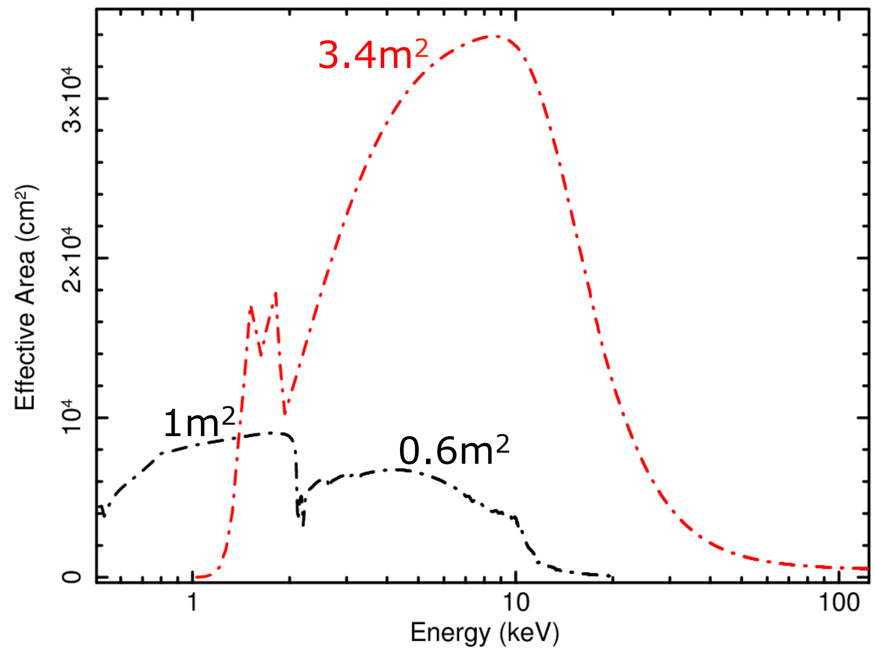
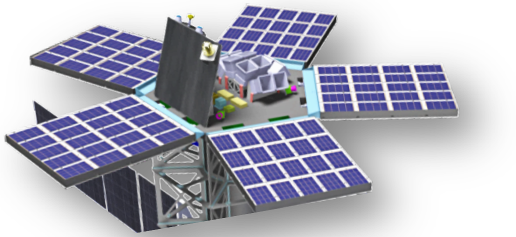
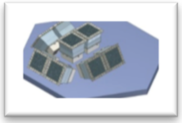


Weak/soft sources:
Collimated + Focused Area



LAD - Large Area Detector

EFFECTIVE AREA	3.4 m^2 @ 2 keV 8.5 m^2 @ 8 keV 0.8 m^2 @ 30 keV
ENERGY RANGE	2-30 keV (30-80 keV ext.)
ENERGY RESOLUTION FWHM	200 eV @ 6 keV
COLLIMATED FOV	1 deg FWHM
ABSOLUTE TIME ACCURACY	1 μs

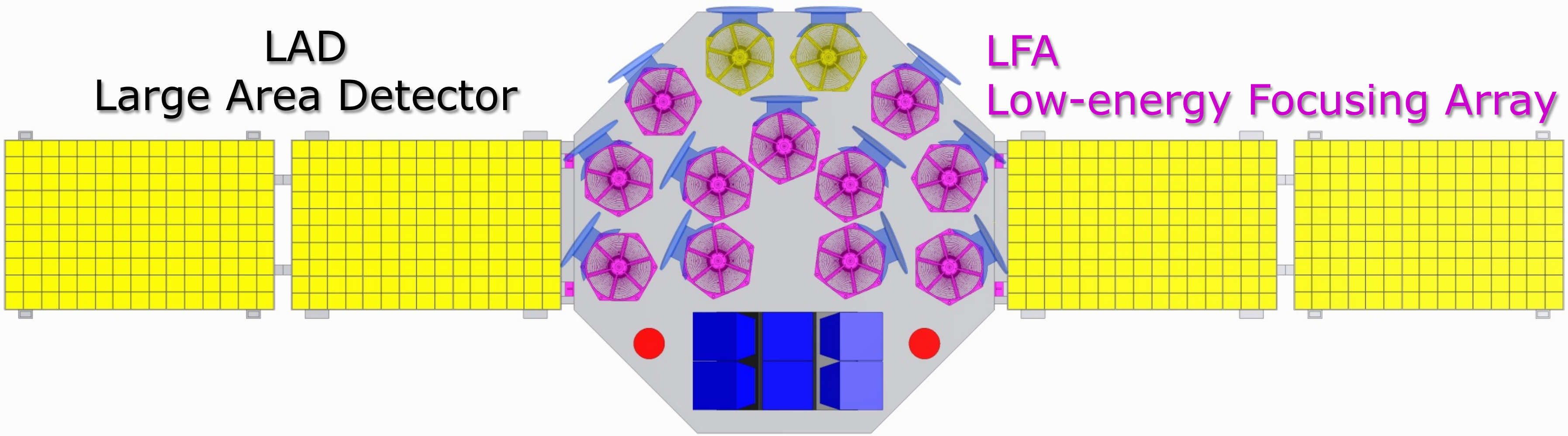


WFM – Wide Field Monitor

FIELD OF VIEW	5.5 steradian
POSITION ACCURACY (10Σ)	1 arcmin
ENERGY RANGE	2-50 keV
ENERGY RESOLUTION	300 eV @ 6 keV
COLLECTING AREA	1460 cm^2
TIME RESOLUTION	10 μs (trigger) ~minutes (images)
SENSITIVITY (5σ, GALACTIC CENTER)	330 mCrab (3s) 2.1 mCrab (1day)
GROUND TRANSMISSION OF GRB COORDINATES	< 30s

11 X-ray optics, 6200 cm^2 @6 keV, 4.5m FL, 1′ PSF, SDD (or CCD), 0.5-10 keV, <100 μs

2 X-ray optics, 1100 cm^2 @6 keV, 4.5m FL, 15″ PSF, GPD polarimeters, 2-10 keV

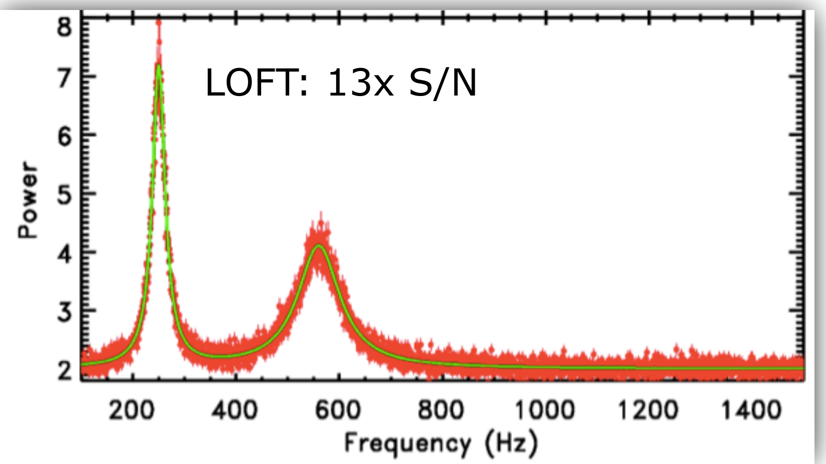


3.4 m^2 "LOFT" SDD detectors, 2-30 keV, <300 eV @ 6 keV

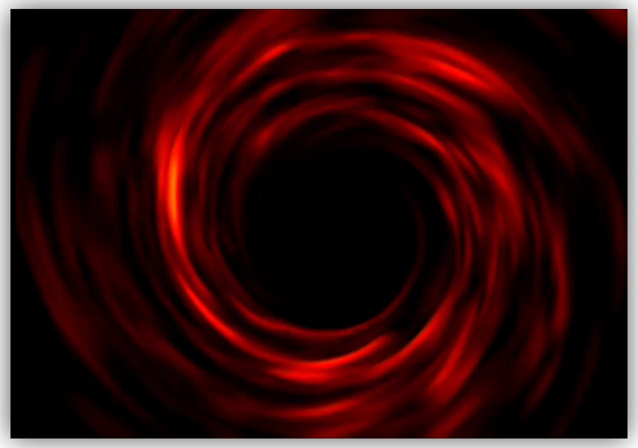
3 units, 2-50 keV, 4 sr FoV, 80 cm^2/unit, 5′ angular resolution

Strong field gravity diagnostics: Fundamental frequencies of motion

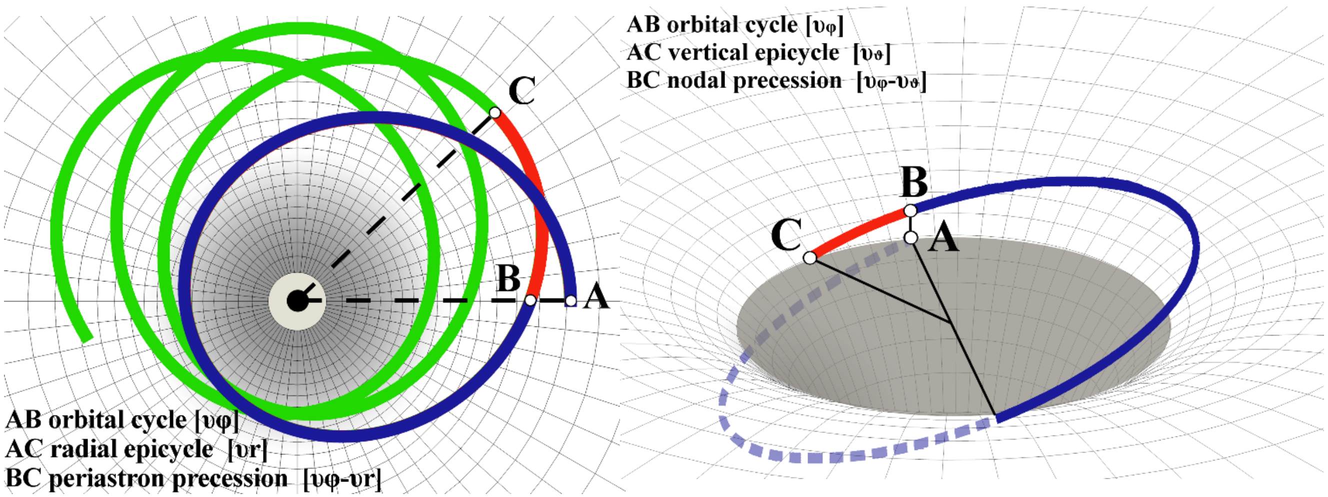
Frequencies of motion in strong gravity

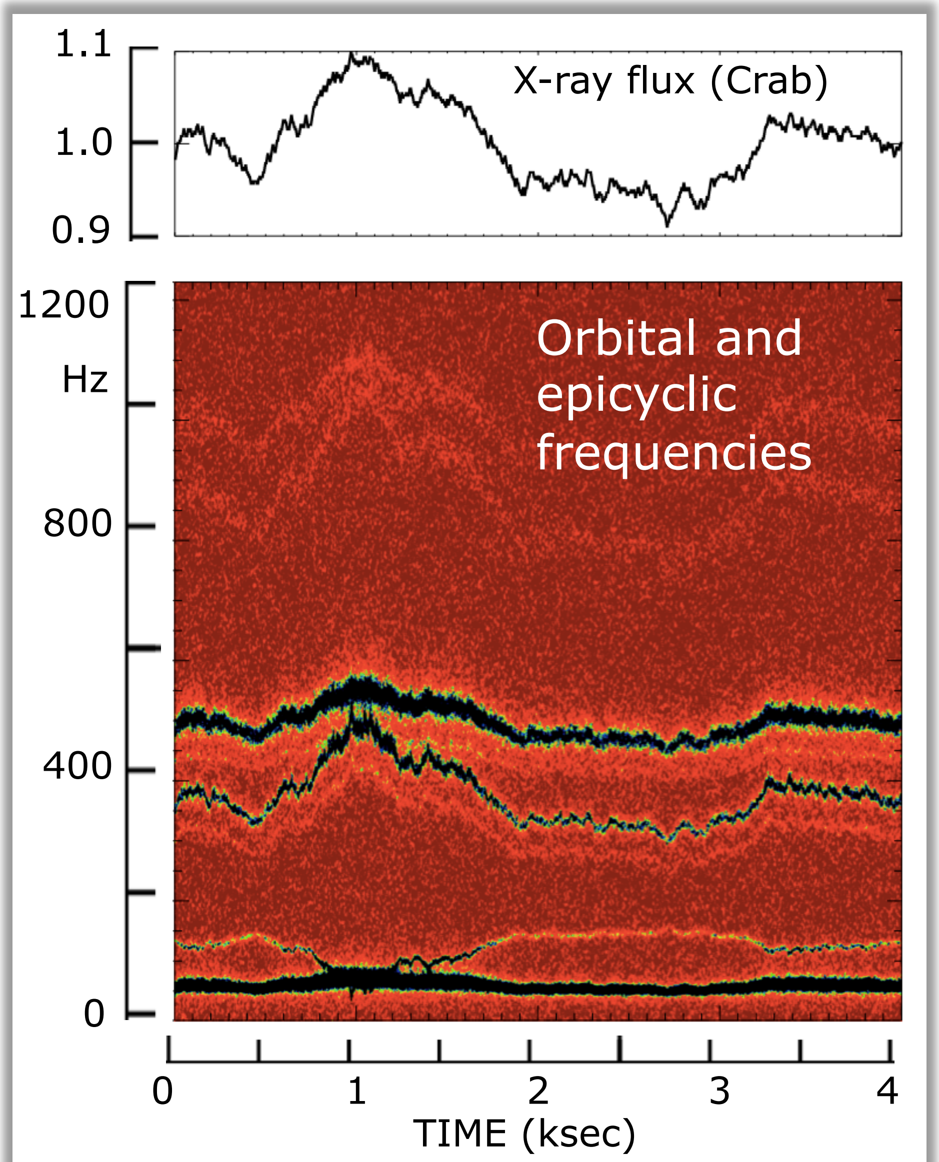


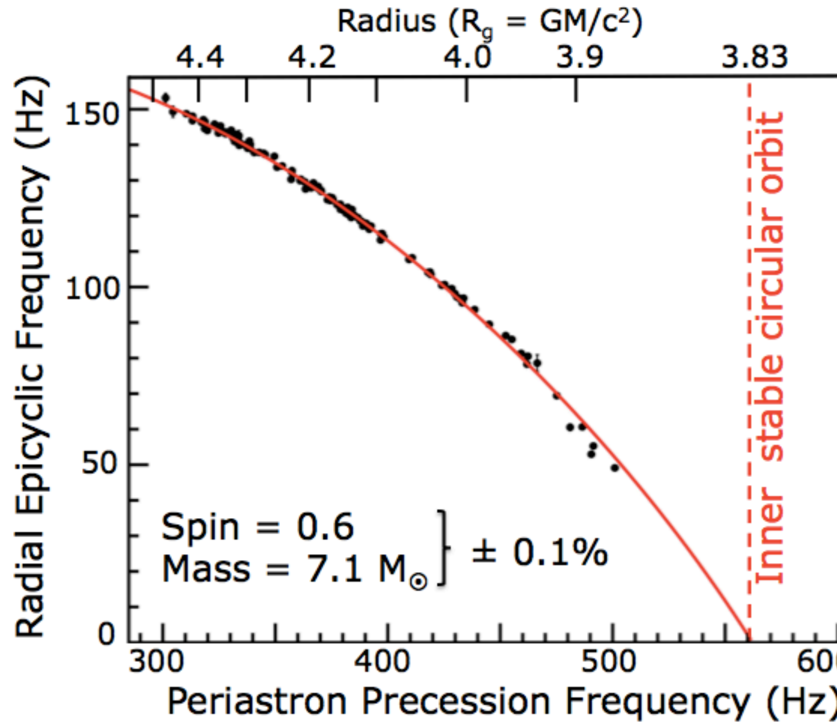
Inhomogeneities in inner disk



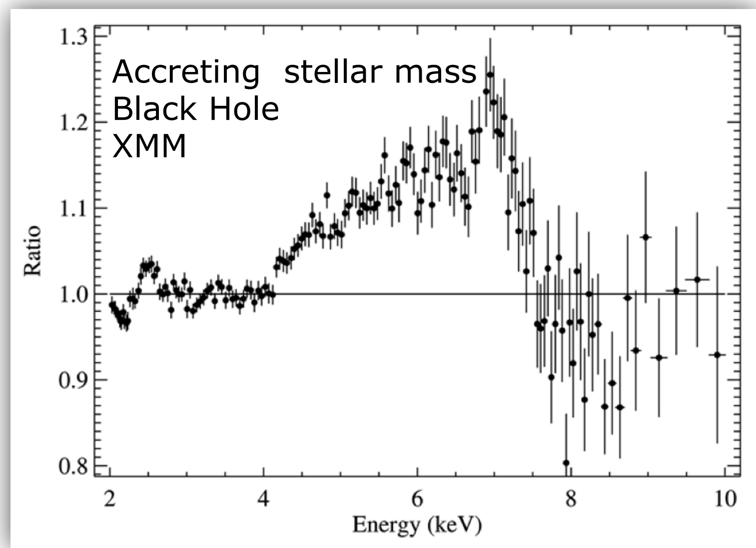
GR orbital, epicyclic and precessional frequencies

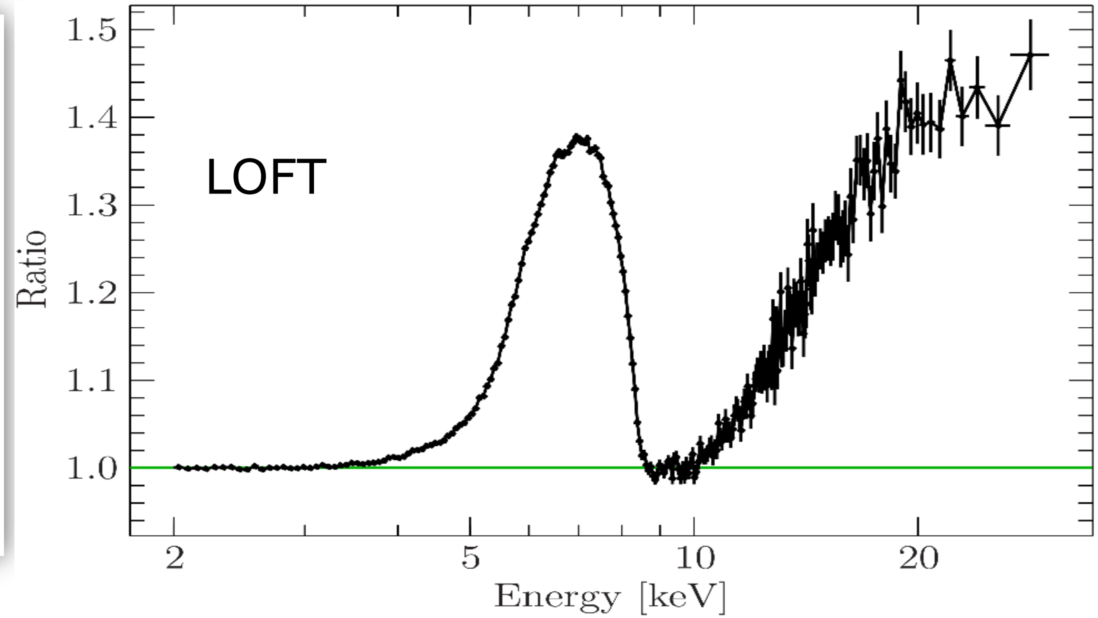






- Precisely measure orbital and epicyclic frequencies at each radius
- Compare curve to GR predictions
- Measure black hole mass and spin to 0.1% precision



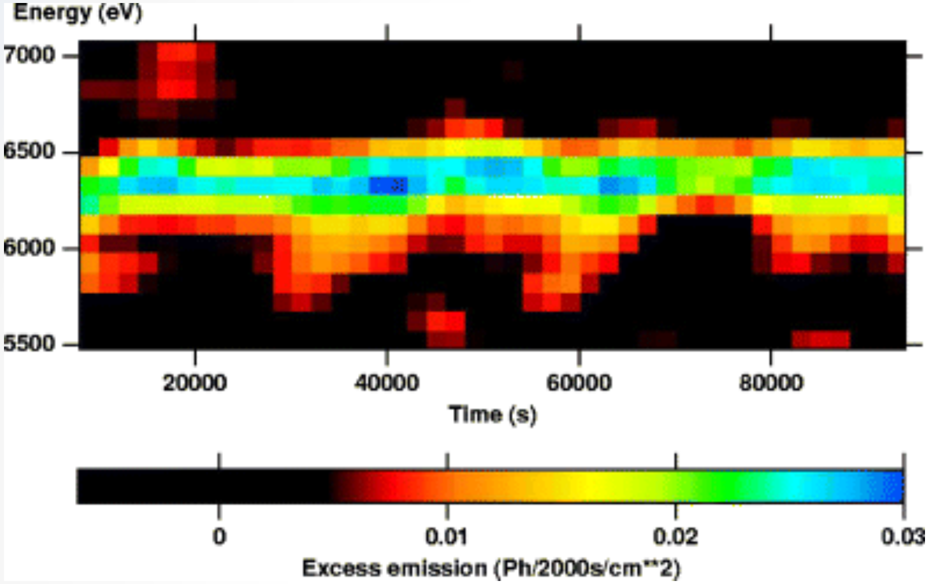


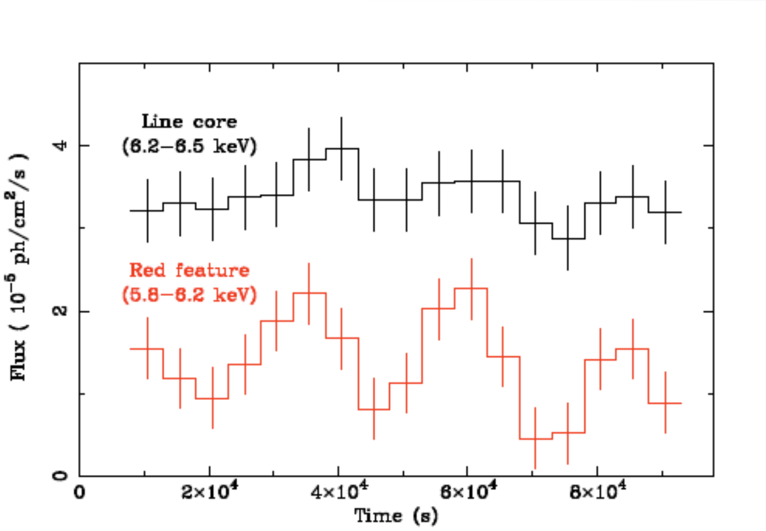
General relativity predicted velocity and redshift map of the accretion disk

Line profile integrated over entire flow encodes:

- Strong field relativistic effect: Doppler shifts and boosting, gravitational redshift, strong field lensing
- Observed in Active Galactic Nuclei and X-ray binaries

Combining spectral and timing measurements:
Orbiting spot: XMM observations of NGC3516

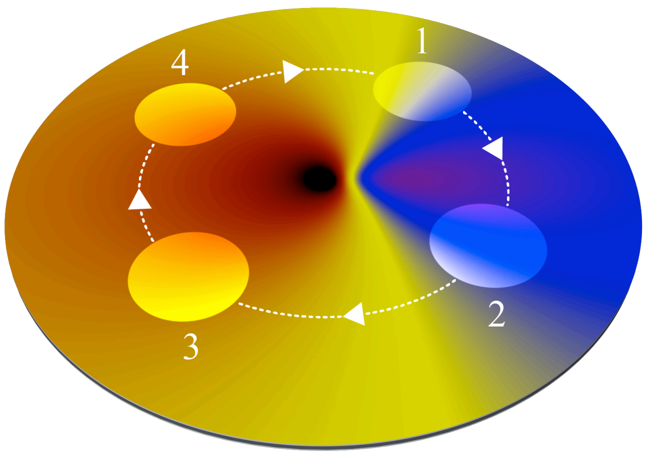




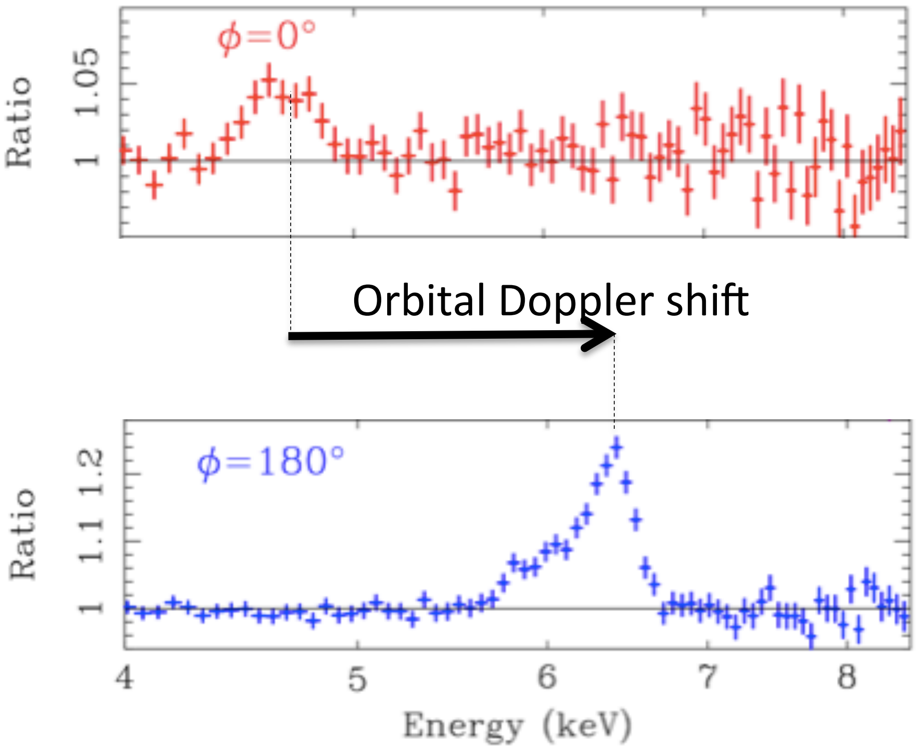
The excess emission map in the time–energy plane. The pixel size is 2 ks in time and 100 eV in energy. 4 cycles 25 ks orbital period at 9 Rg (XMM - Iwasawa+2004, Turner+2006)

$M_{X\text{-}ray}$=1-5 10^7 M_{sun} ; M_{opt}=1.68(0.33)10^7 M_{sun}

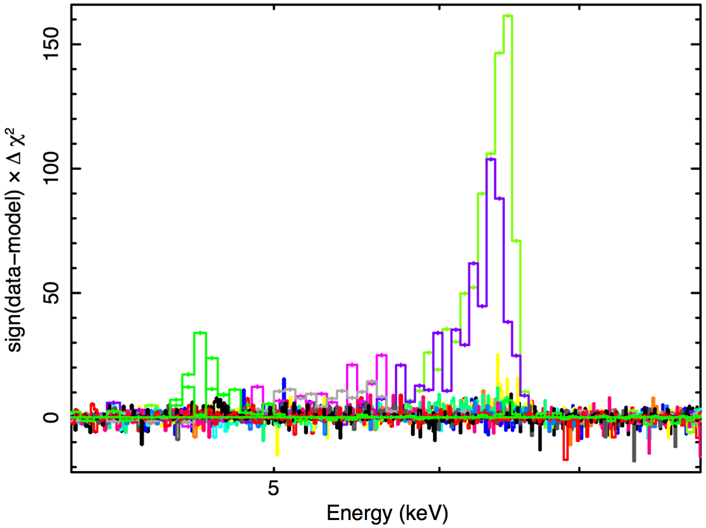
Supermassive black hole



LOFT 3 ks integrations

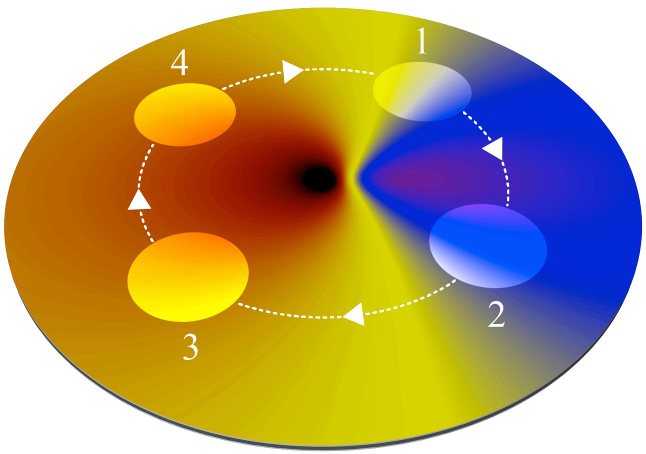


eXTP 1.5 ks 2x integrations



Doppler shifting for orbits closely around a <u>supermassive</u> black hole

Stellar-mass black hole

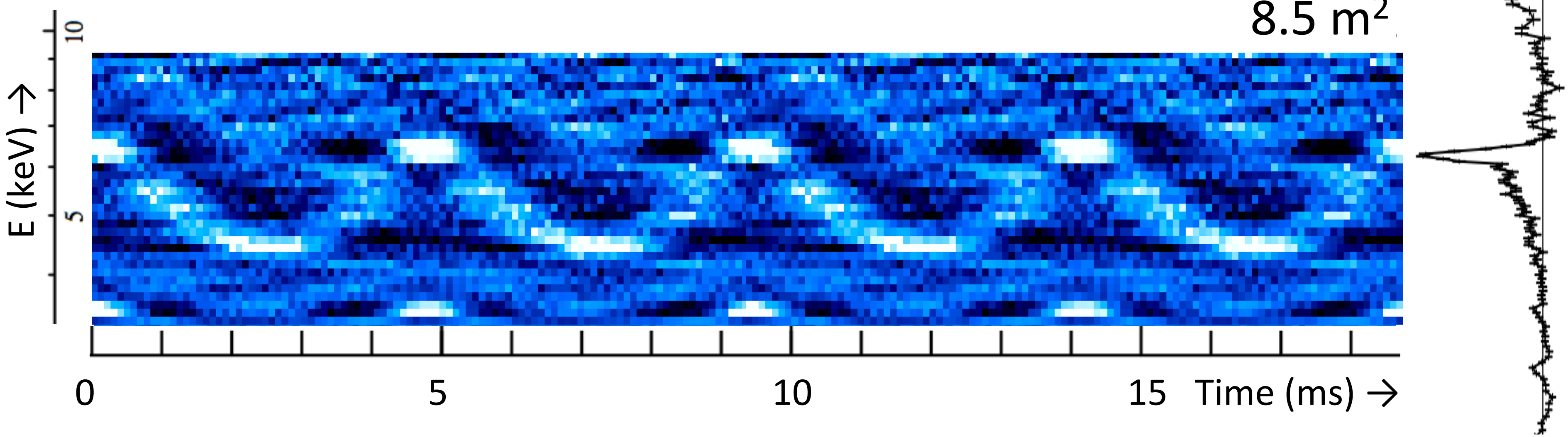


Orbital radial velocity curve at ISCO, closely around a stellar mass black hole

Doppler tomography of disk velocity & redshift map.

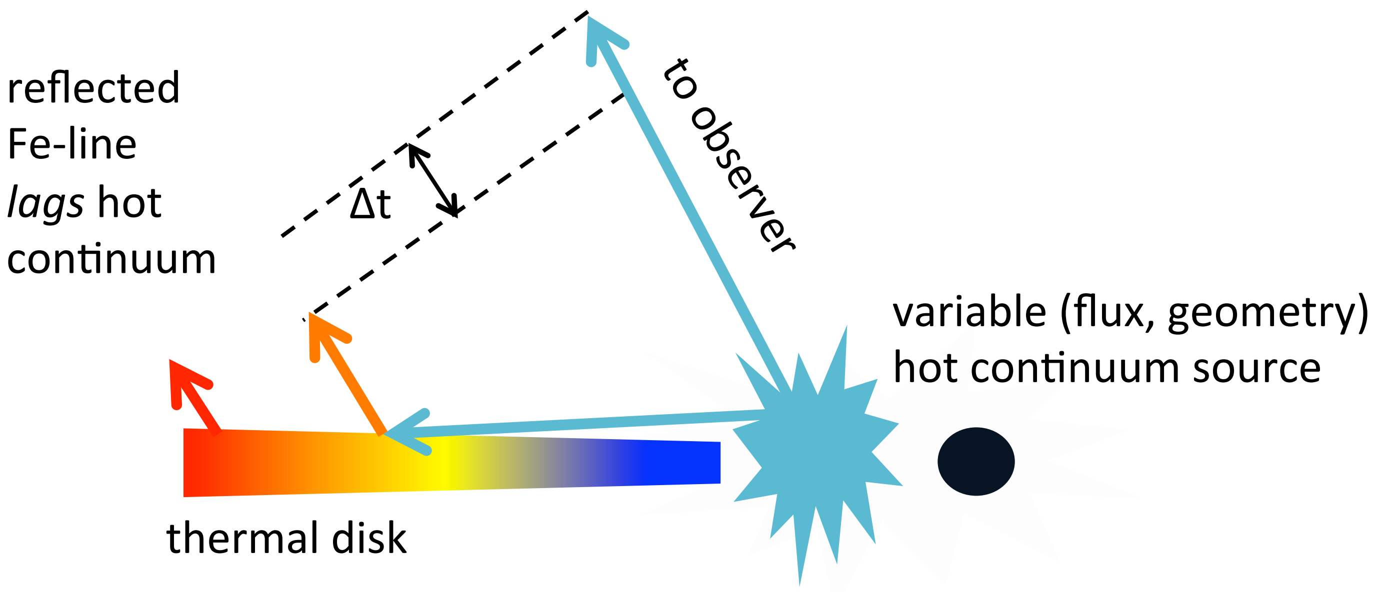
Typical precision 1.5% in 100 ks

8.5 m^2



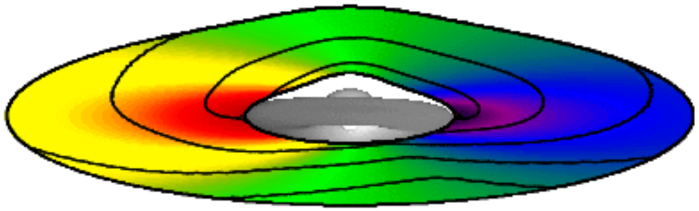
Uses known amplitude of quasi-periodic dynamic signals

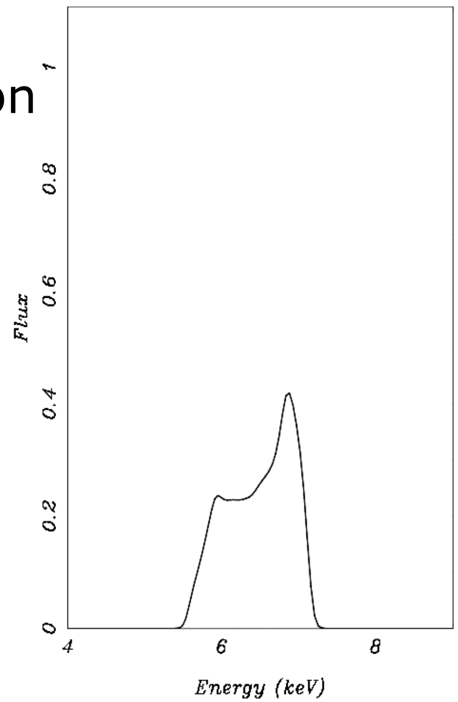
Reverberation: energy resolved light echoes

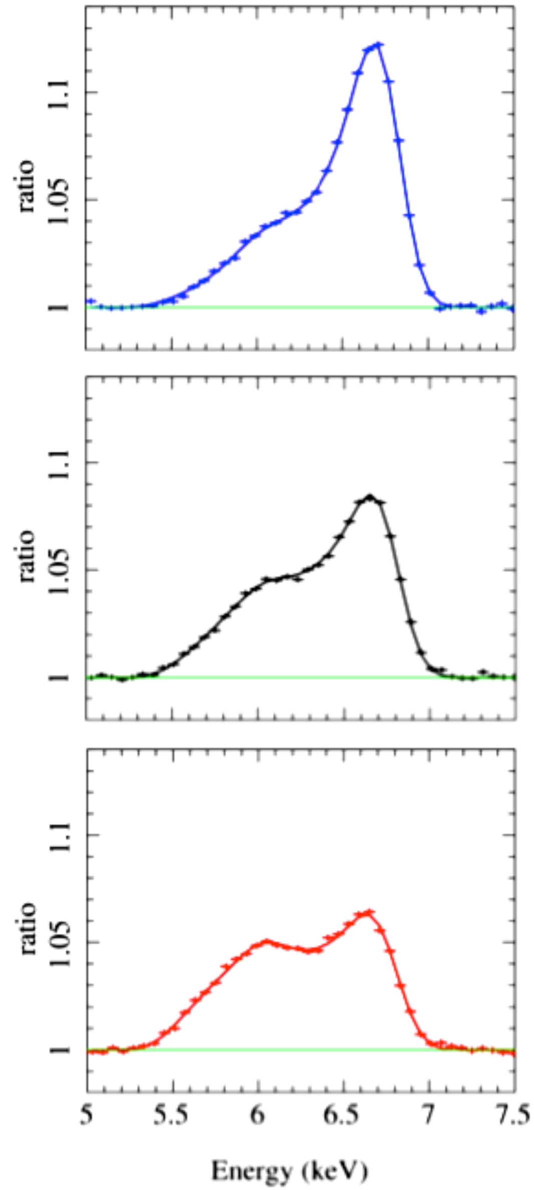


- Probe **disk velocity/redshift map** as radiation fronts propagate over the disk
- Relativistic effects as a function of **absolute radius** (e.g. km)

Precessing hot torus:
variable geometry reverberation



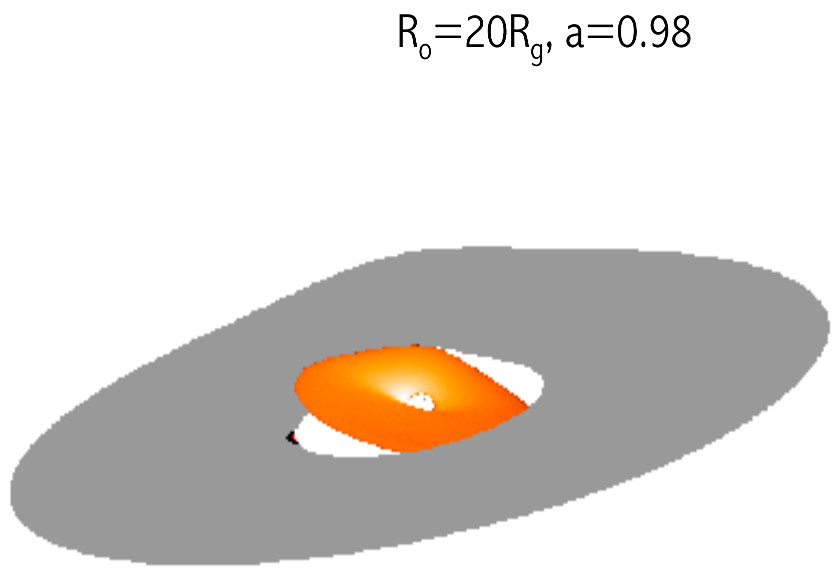


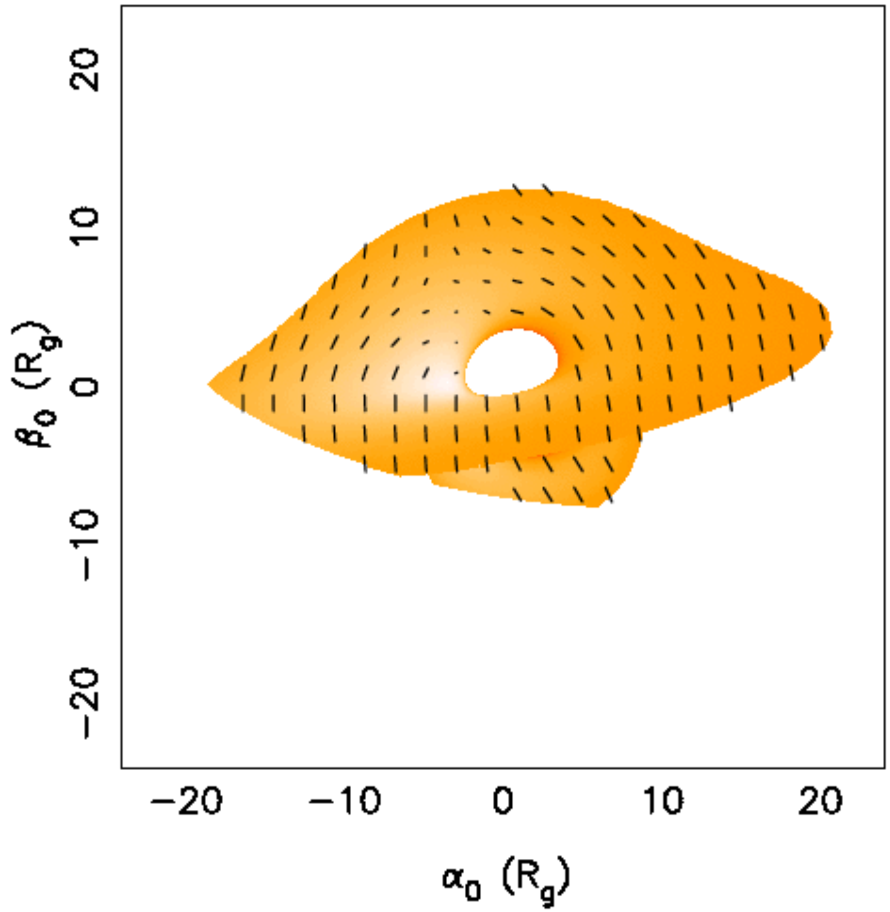


- Frame dragging: central hot torus <u>precesses</u>
- Hard radiation sweeps around over disk
- Reflection line profile varies periodically
- LOFT tracks the line profile, probing the disk velocity and redshift map
- Typical precision 0.3-3%

Stella Vietri 1998 ,Ingram+ 2009, 2012

Polarization of processing inner torus

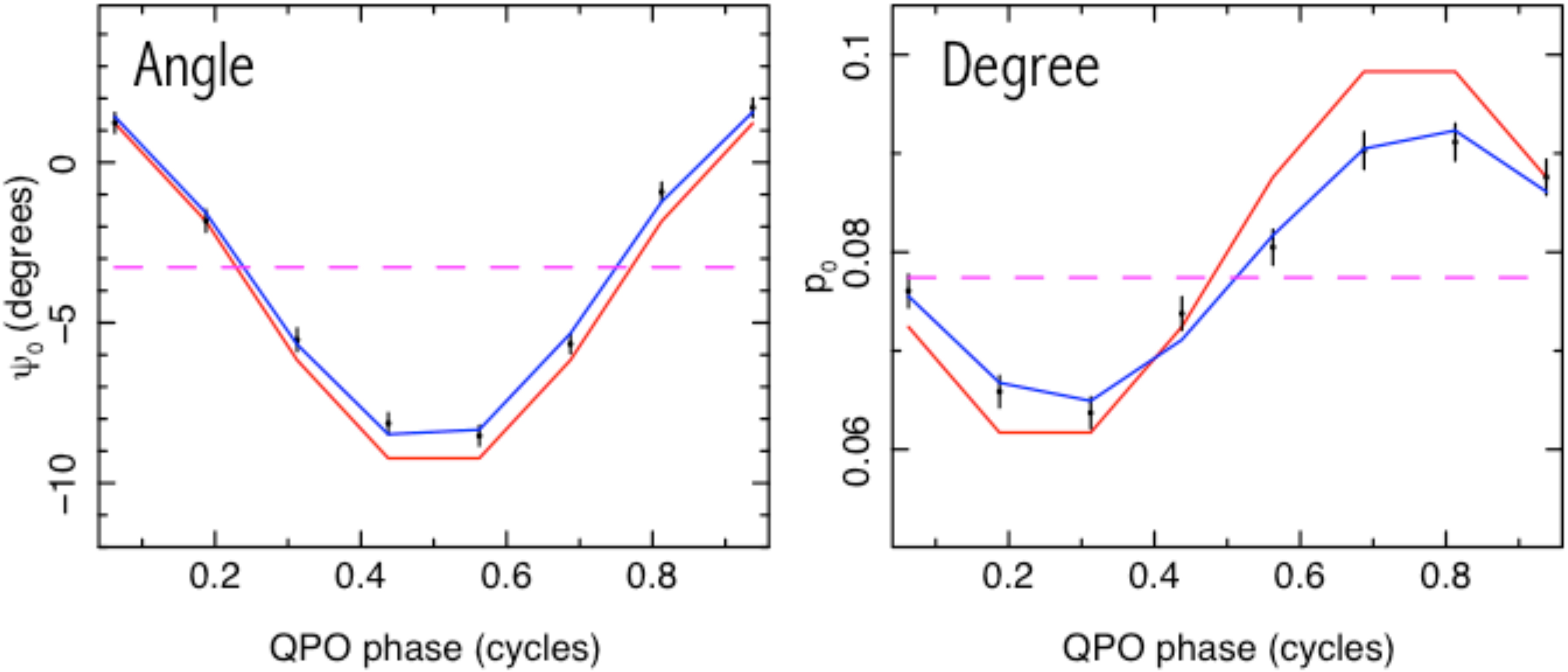




- polarization degree and angle affected by strong field light bending
- precession changes geometry and thus modulates polarization

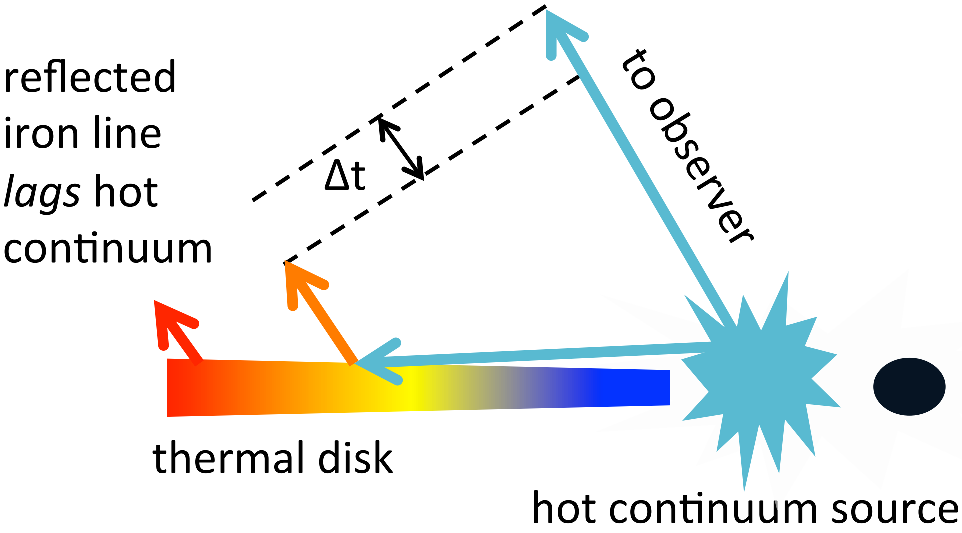
(Ingram+ 2015)

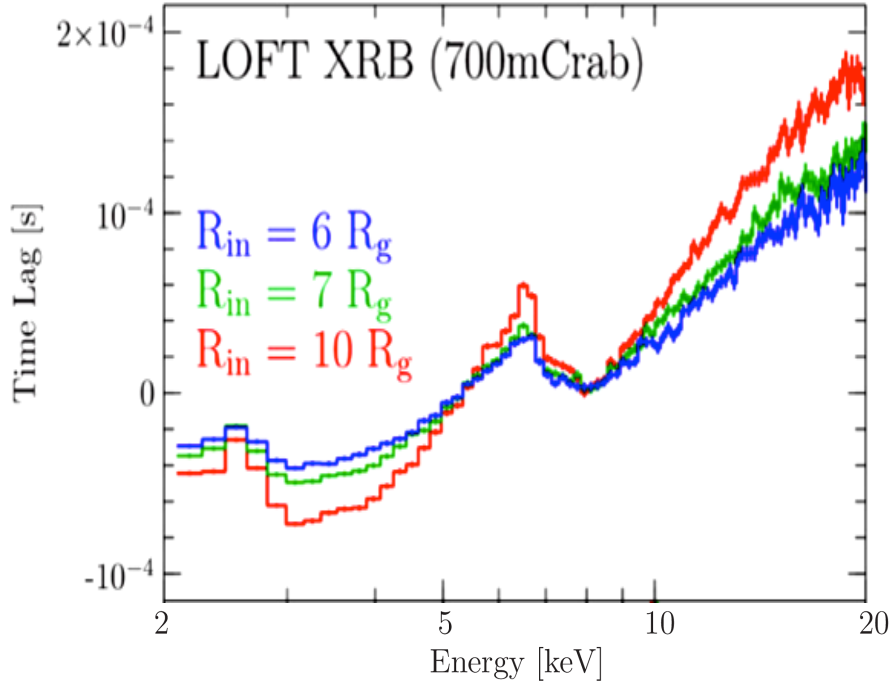
eXTP polarization measurements



- 32.768ks exposure
- $<p_0>=8\%$, $\sigma_{p_0}=1.4\%$, $<\psi_0>=-4$ degrees, $\sigma_{\psi_0}=4$ degrees
- Flux = 1 photon $cm^{-2}s^{-1}$ assuming absorbed power-law with $\Gamma=2$ and $N_h=1\times10^{22}cm^{-2}$
- 40 LAD modules, 2 GPD units

Variable Flux Reverberation





- Variable hot inner flow irradiates disk
- Probe **disk velocity/redshift map** as radiation fronts propagate over the disk
- Obtain strong field velocities and relativistic effects as a function of **absolute radius**

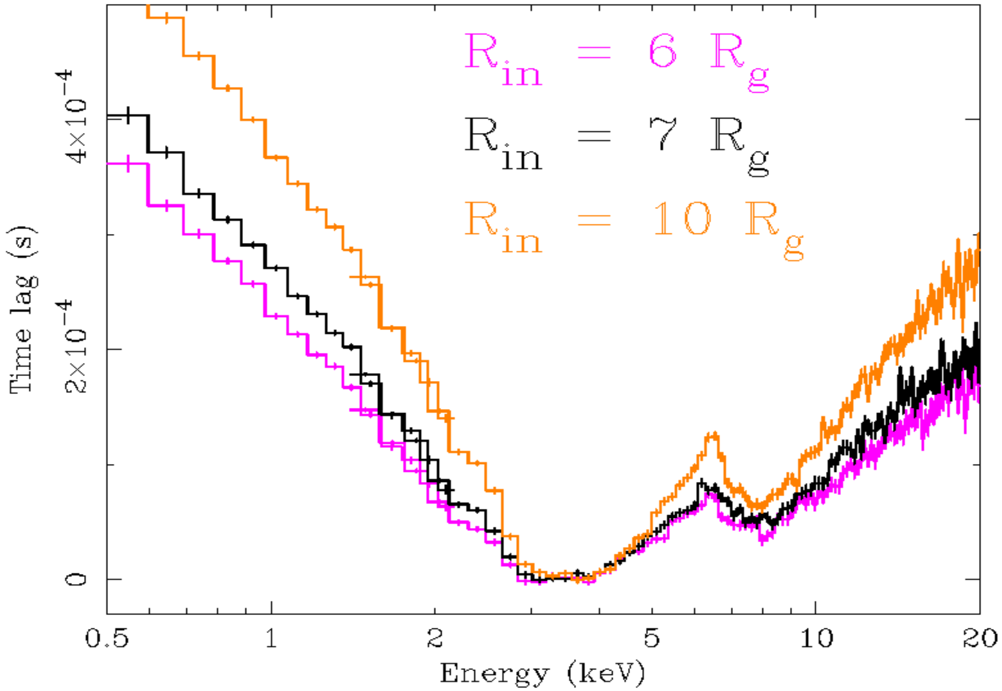
Reverberation detected in XMM data

LOFT improves S/N by
- factor ~6 in AGN
- factor >200 in X-ray binaries!

➔ Breakthrough capability 🡐

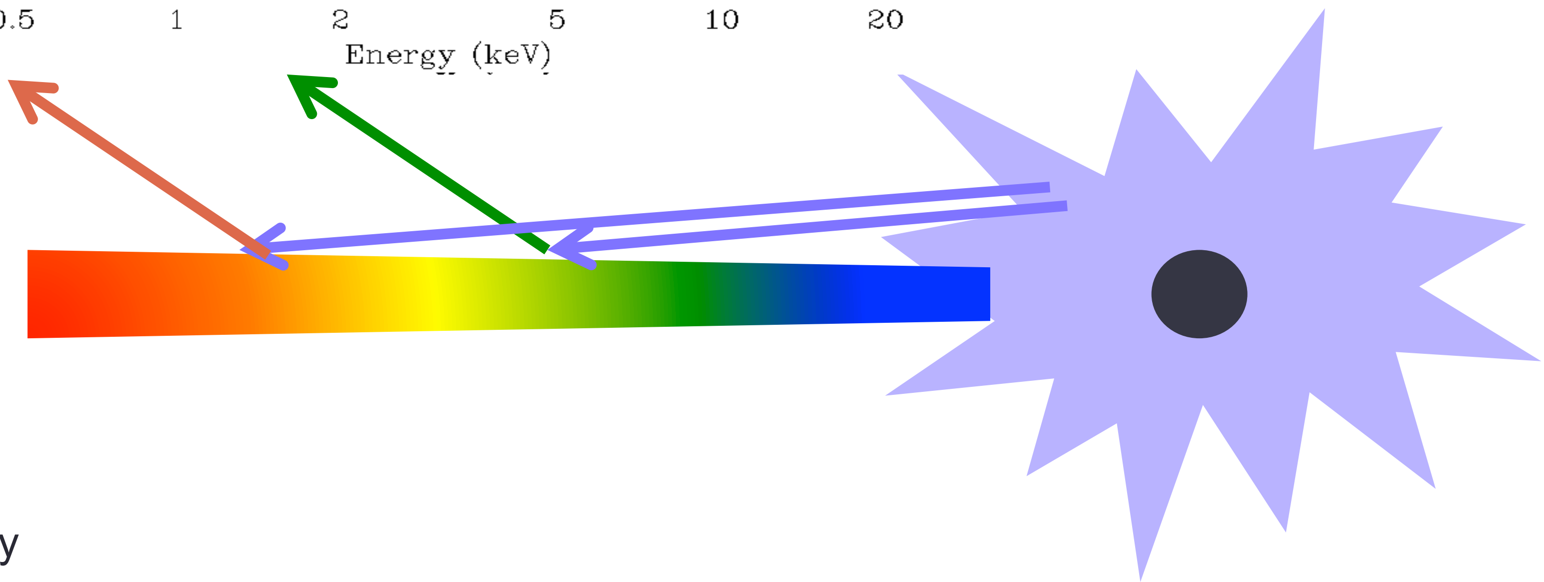
Disc reverberation components

10 FA + 40LAD



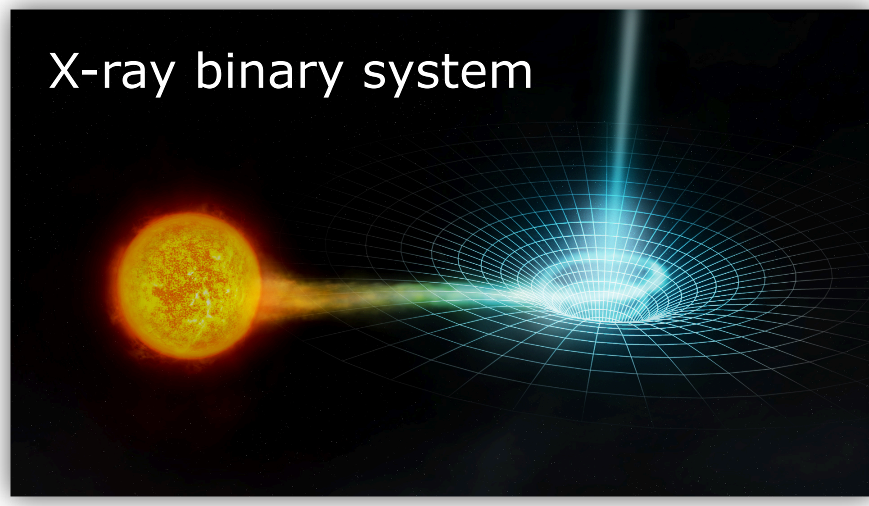
In addition to the iron line and reflection continuum, the absorbed flux is reradiated by the disc as thermal blackbody radiation

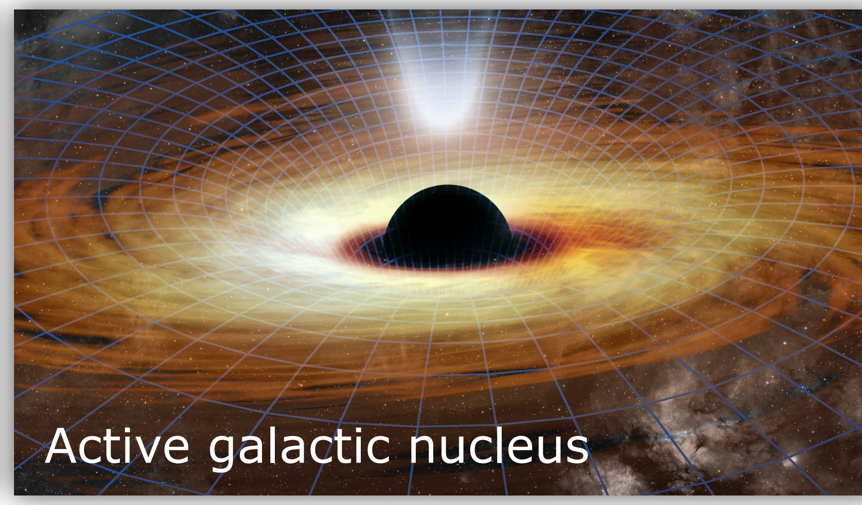
eXTP can study all three components simultaneously!



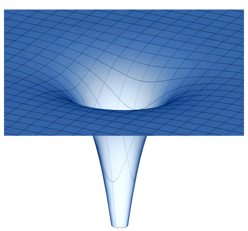
Uttley

LOFT's STRONG GRAVITY ARENA: ACCRETING BLACK HOLES



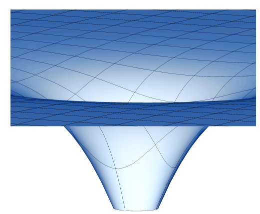


← LOFT and eXTP cover wide mass range in uniform setting →



Stellar mass black hole
(or neutron star)

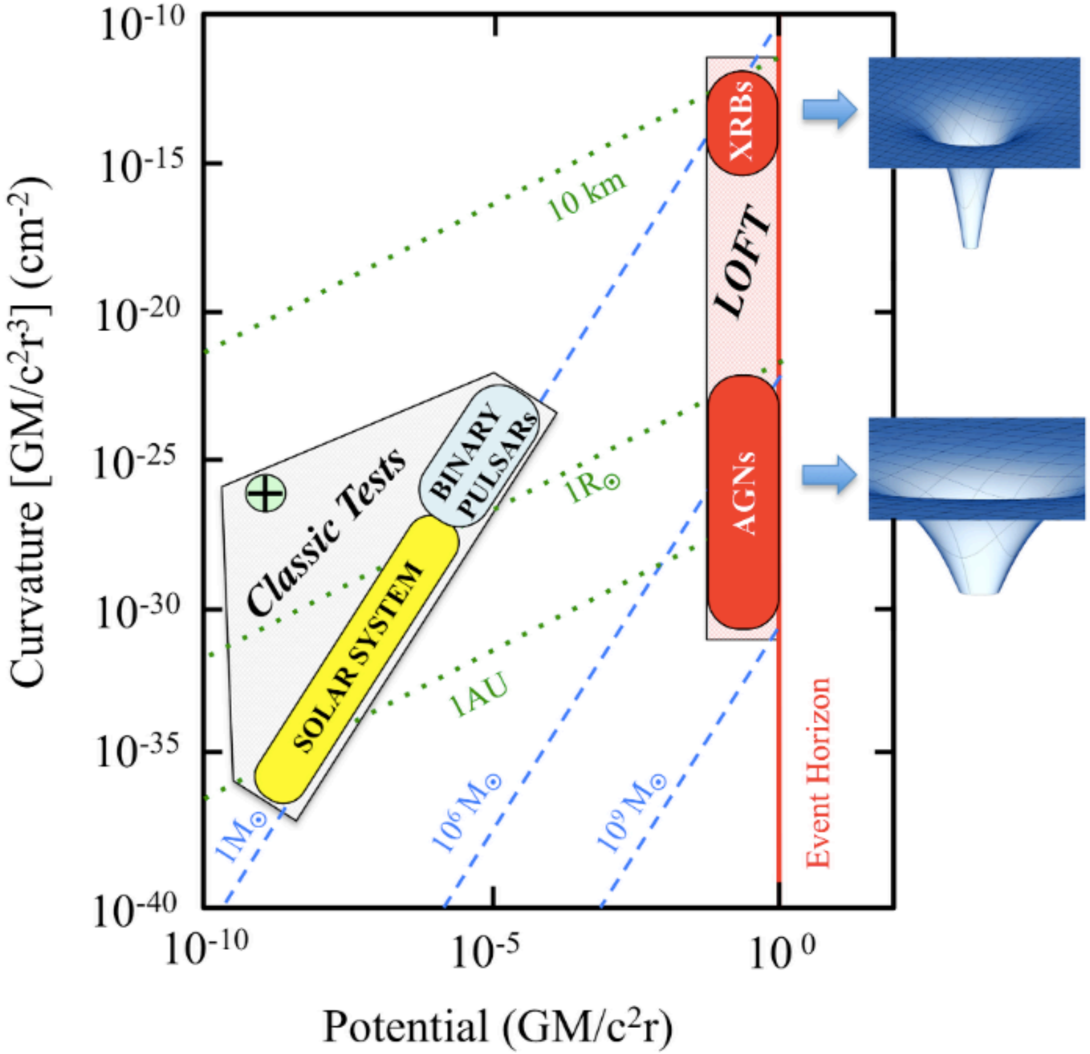
Strongly curved spacetime.
(10^{16} times Solar)



Supermassive black hole

Weakly curved spacetime
(~Solar)

COMPLEMENTARY TO GRAVITATIONAL WAVE EXPERIMENTS:
LOFT PROBES <u>STATIONARY</u> SPACETIMES



factor 10^{12} in curvature

factor 10^{5} in field strength

Test alternative theories of gravity through X-ray diagnostics like Fe-lines and QPOs

after Psaltis 2008

CONCLUSIONS

- X-ray timing, spectral and spectral/timing diagnostics of accreting black holes will allow us to:
  - verify for the 1st time key predictions of GR in the strong field regime
  - test or constrain some alternative theories of gravity

- Very high throughput combined with good spectral resolution is required: two different missions are being studied, LOFT and eXTP

THANK YOU