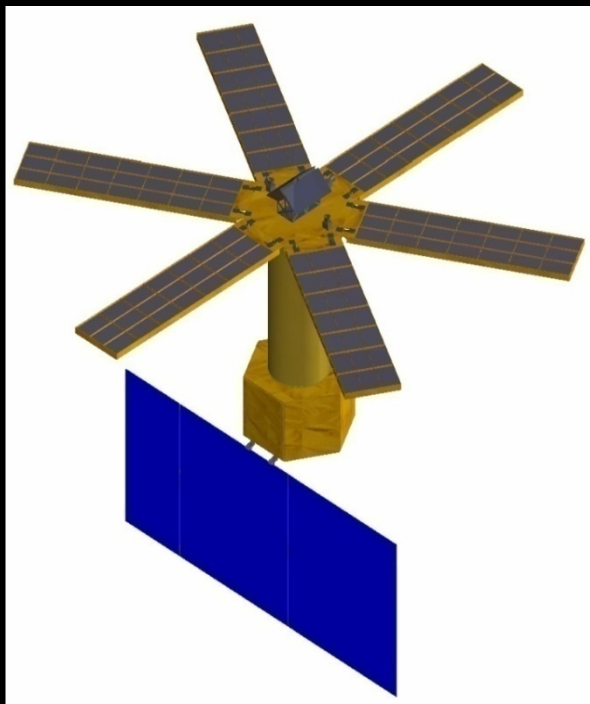
LOFT

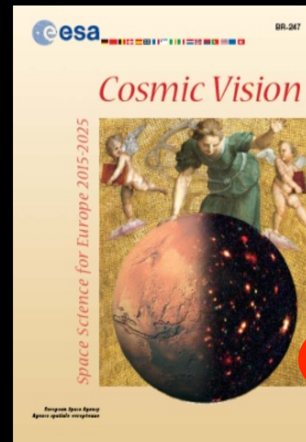
the Large Observatory For x-ray Timing

Luigi Stella

on behalf of the LOFT Consortium

LOFT: the **L**arge **O**bservatory **F**or x-ray **T**iming





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

LOFT Science Team composed of scientists from:

Australia, Brazil, Canada, CzechRepublic, Denmark, Finland, France, Germany, Greece, Ireland, Israel, Italy, Japan, theNetherlands, Poland, Spain, Sweden, Switzerland, Turkey, United Kingdom, USA

LOFT Consortium: national representatives:

Jan-Willem den Herder	SRON, the Netherlands
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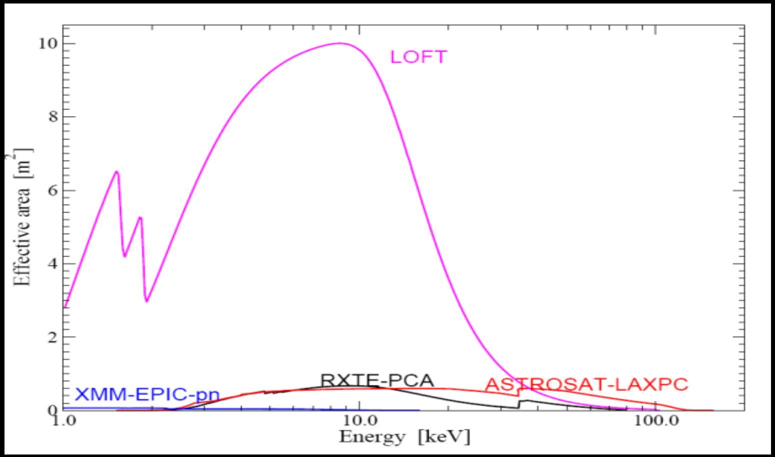
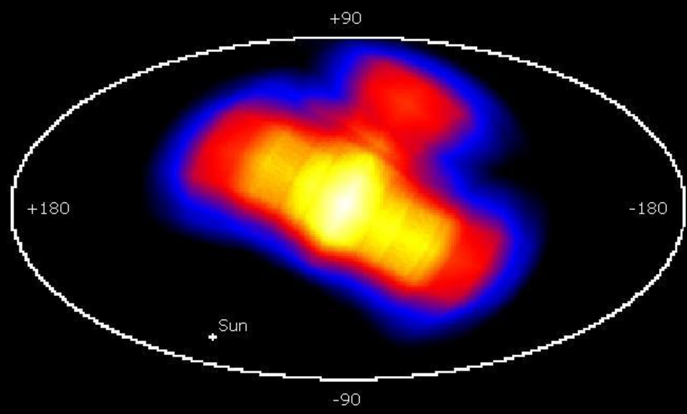
Andrea Santangelo	Univ. Tuebingen, Germany
Didier Barret	IRAP, Toulouse, France
Renè Hudec	CTU, Czech Republic
Andrzej Zdziarski	N. Copernicus Astron. Center, Poland
Juhani Huovelin	Univ. of Helsinki, Finland
Paul Ray	Naval Research Lab, USA
Joao Braga	INPE, Brazil
Tad Takahashi	ISAS, Japan

LOFT Instruments





LAD – Large Area Detector	
Effective Area	4 m^2 @ 2 keV 8 m^2 @ 5 keV 10 m^2 @ 8 keV 1 m^2 @ 30 keV
Energy range	2-30 keV primary 30-80 keV extended
Energy resolution FWHM	260 eV @ 6 keV 200 eV @ 6 keV (45% of area)
Collimated FoV	1 degree FWHM
Time Resolution	10 μs
Absolute time accuracy	1 μs
Dead Time	<1% at 1 Crab
Background	<10 mCrab (<1% syst)
Max Flux	500 mCrab full event info 15 Crab binned mode

WFM- Wide Field Monitor	
Energy range	2-50 keV primary 50-80 keV extended
Active Detector Area	1820 cm^2
Energy resolution	300 eV FWHM @ 6 keV
FOV (Zero Response)	180°x90° + 90°x90°
Angular Resolution	5' x 5'
Point Source Location Accuracy (10-σ)	1' x 1'
Sensitivity (5-σ, on-axis) Galactic Center, 3 s Galactic Center, 1 day	 270 mCrab 2.1 mCrab
Standard Mode	5-min, energy resolved images
Trigger Mode	Event-by-Event (10μs res) Realtime downlink of transient coordinates

Mission class and Programmatics

- ESA Medium Class mission (M3 candidate) – currently in Assesment study

- ESA Member States currently involved in the payload development:

Italy, UK, France, Germany, Switzerland, Spain, Denmark, Netherlands, Poland, Czech Republic, Finland

- International support: US, Japan, Brazil, India

- Launch date: 2022-2024 timeframe

- Soyuz launcher; low earth equatorial orbit (< 2 deg)

- 4+1 years mission lifetime

- ESA M3 mission: study to end-2013; selection early 2014

LOFT and ESA's Cosmic Vision program

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

→ Strong Gravity

→ Dense Matter

Dense Matter

- Properties of matter at supranuclear densities
  - Equation of State
  - Gravitational wave signal from coalescing binaries
    - neutron star - neutron star
    - neutron star - black hole
  - SNe and Gravitational Collapse
- Physics of strong force
  - QCD Diagram

Determining neutron star masses and radii with a very large area X-ray instrument

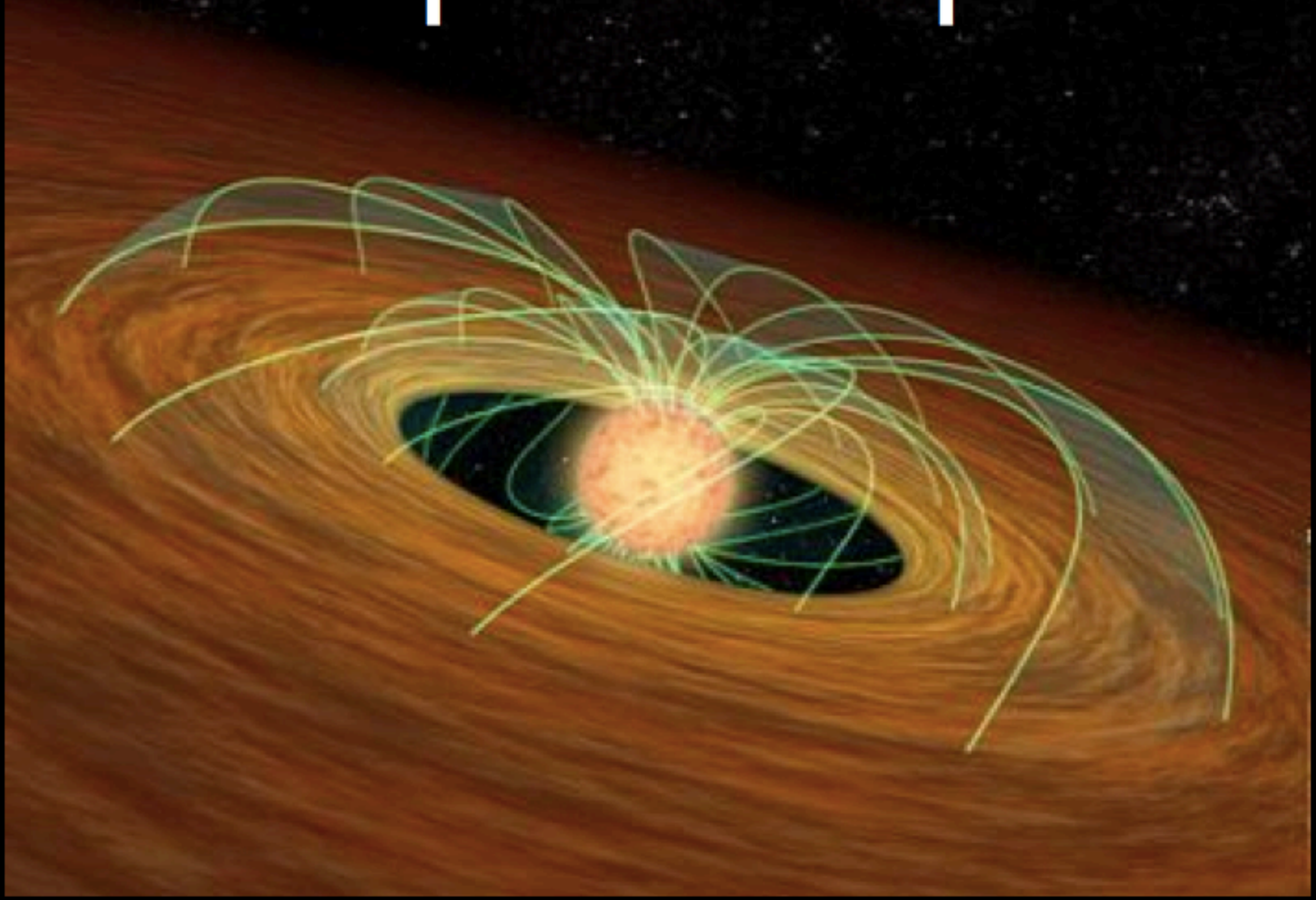
Timing

- Coherent pulsations
- Pulsations during type I bursts (rise and decay)
- Seismic oscillations during magnetar flares
- Neutron star spin frequency

Energy Spectra

- Iron lines Fe-lines from accretion disk
- Absorption lines during type I bursts

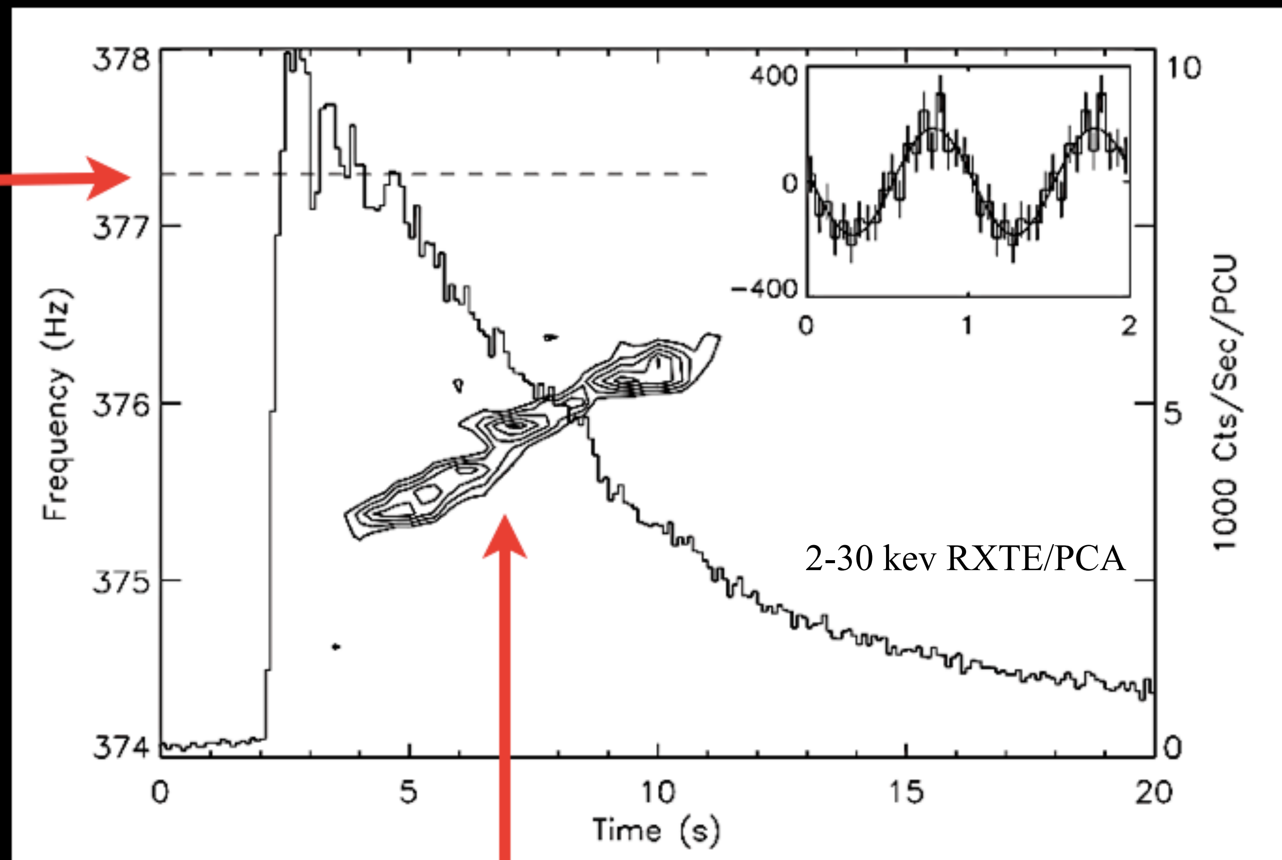
Accretion-powered pulsations



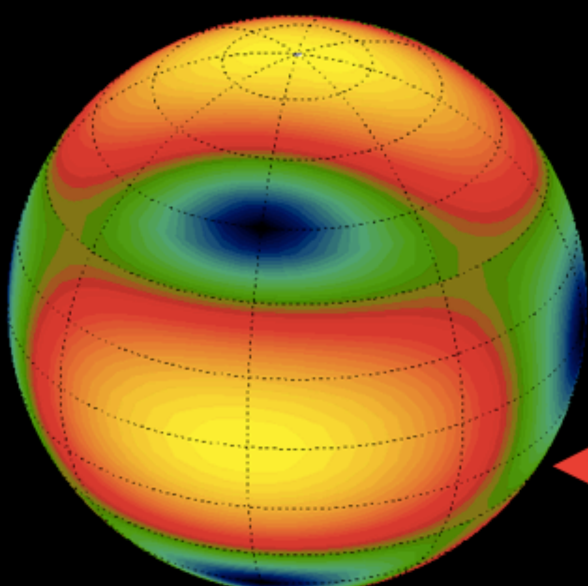
Matter channeled onto NS - *surface hotspot* and accretion shock contribute to pulsed emission.

Thermonuclear burst oscillations

Spin frequency



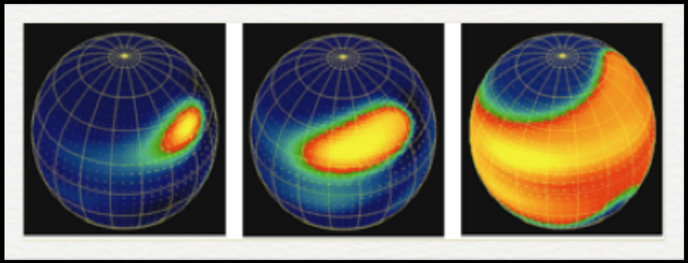
Watts et al. 2009

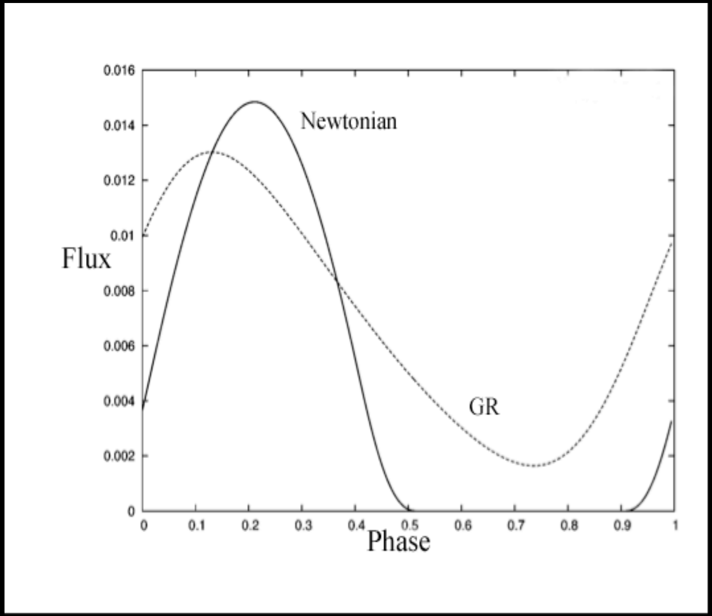


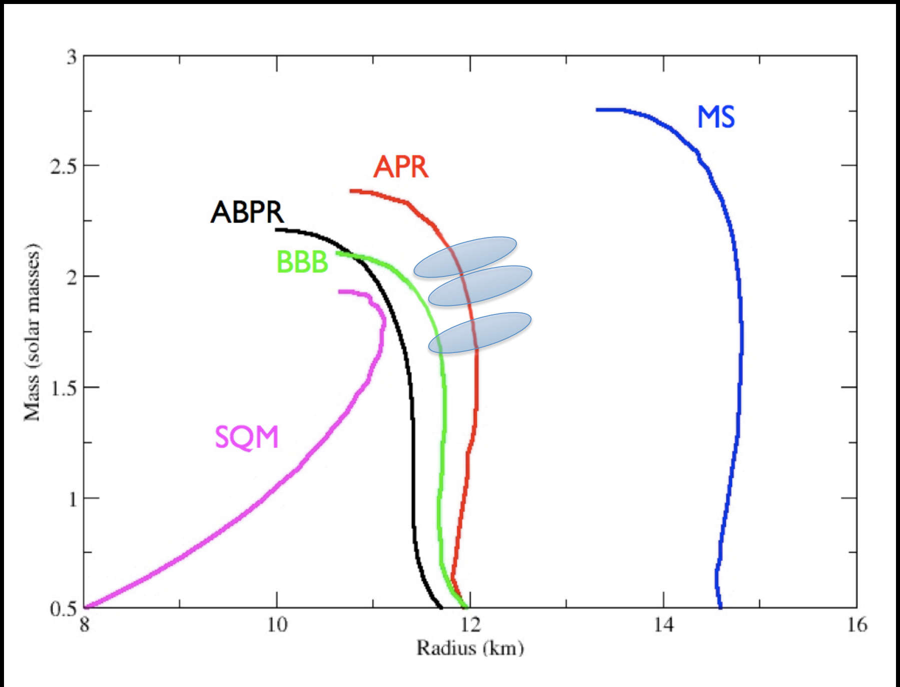
Drifting hotspot

Dense matter:
Neutron Star Structure and Equation of State of ultradense matter

X-ray oscillations are produced by hot spots rotating at the NS surface.
Modeling of the pulses (shape, energy dependence) taking into account Doppler boosting, time dilation, gravitational light bending and frame dragging will constrain the M/R of the NS.

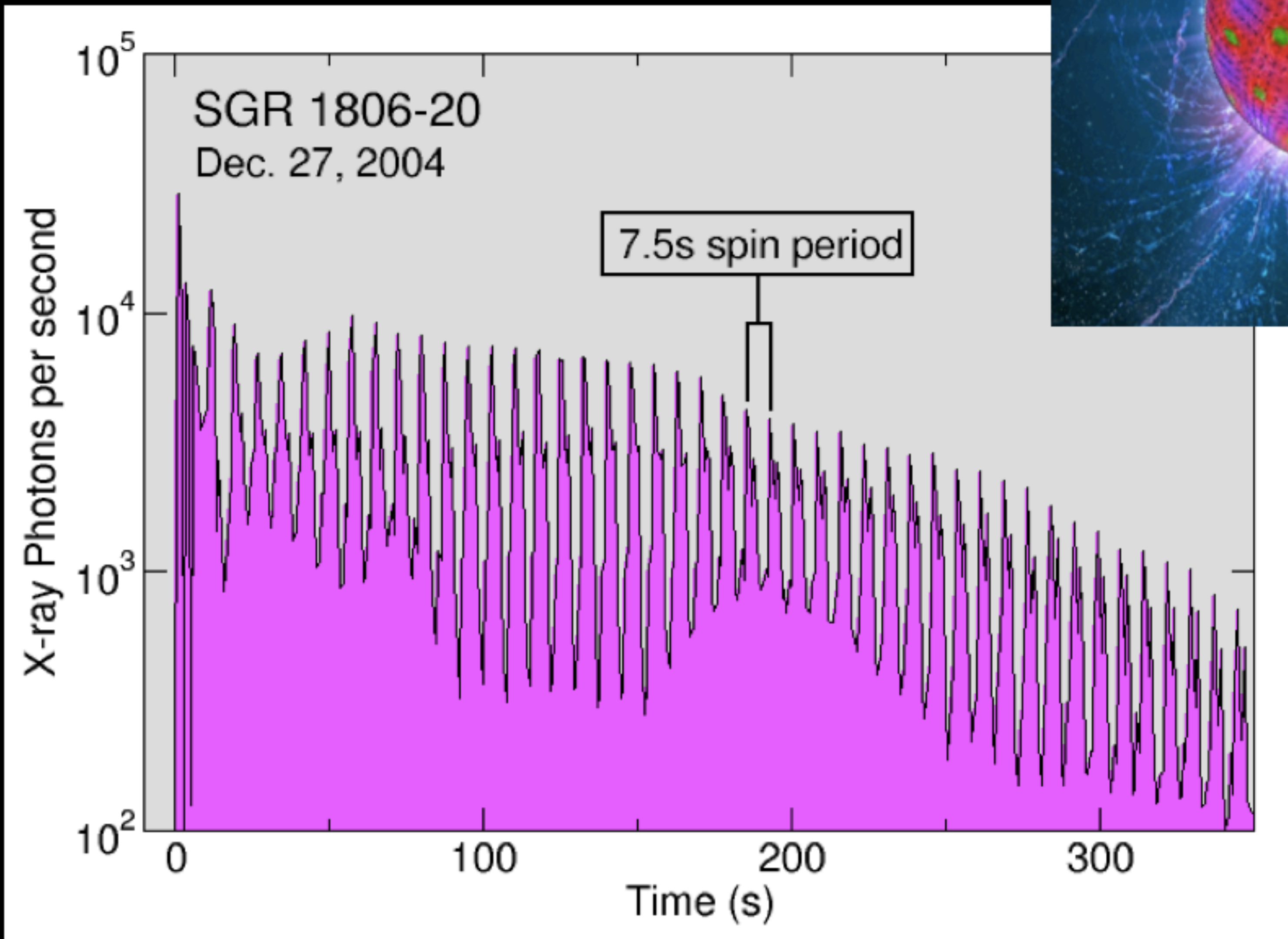


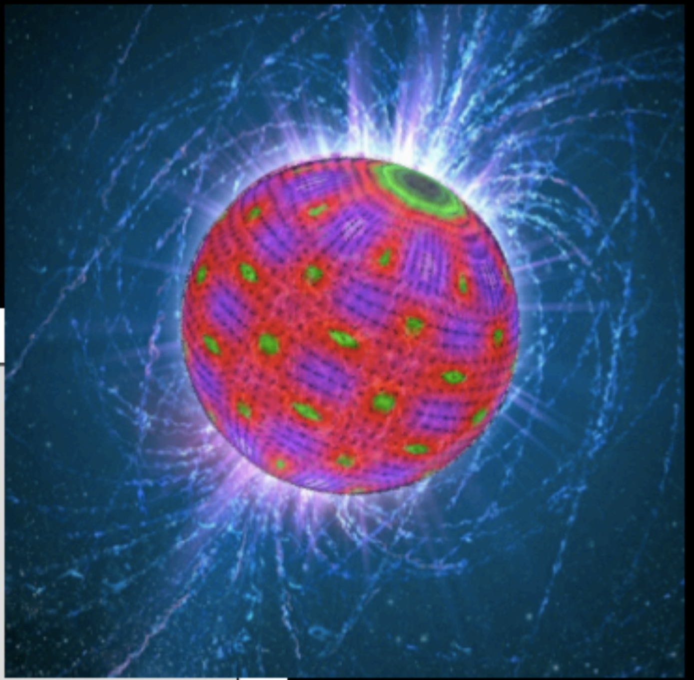




Morskink 2012; Watts 2012

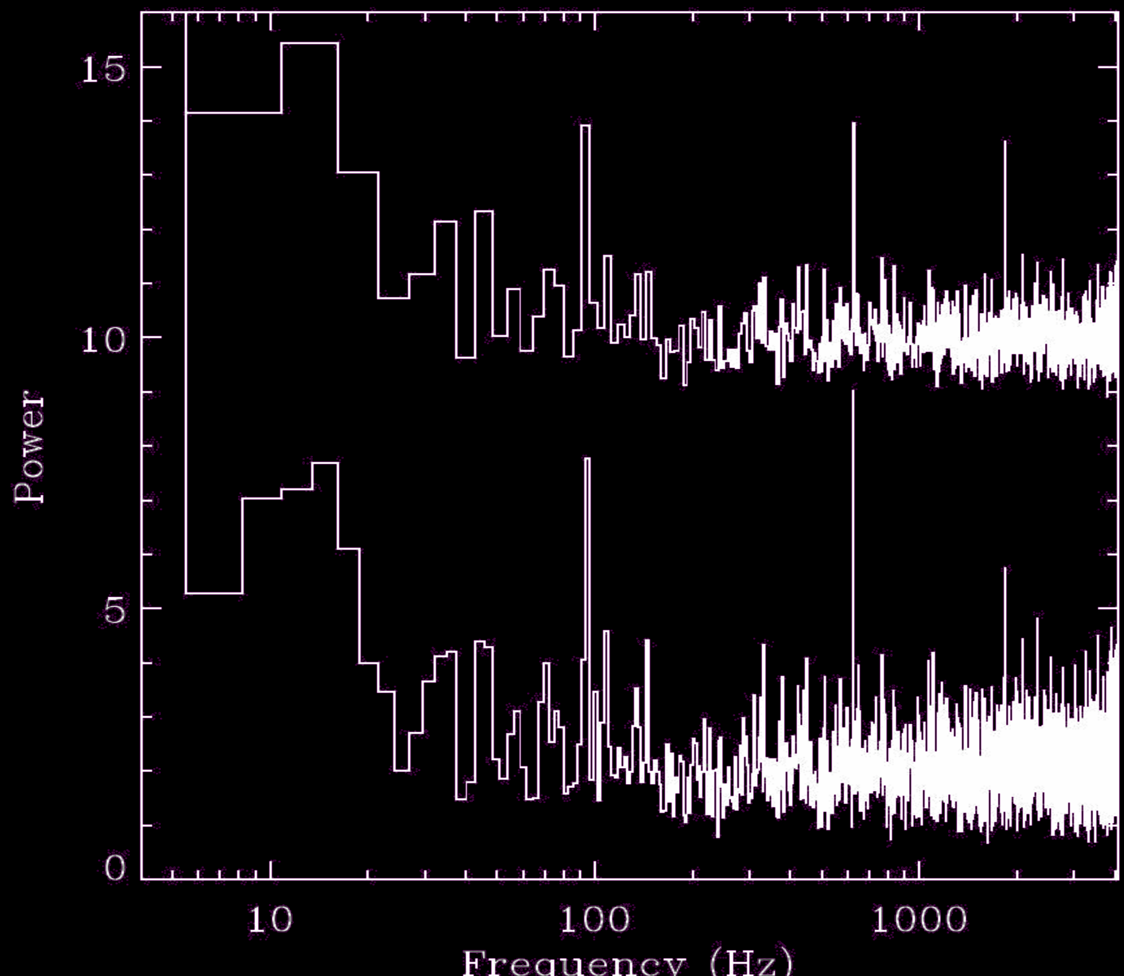
Magnetar seismology





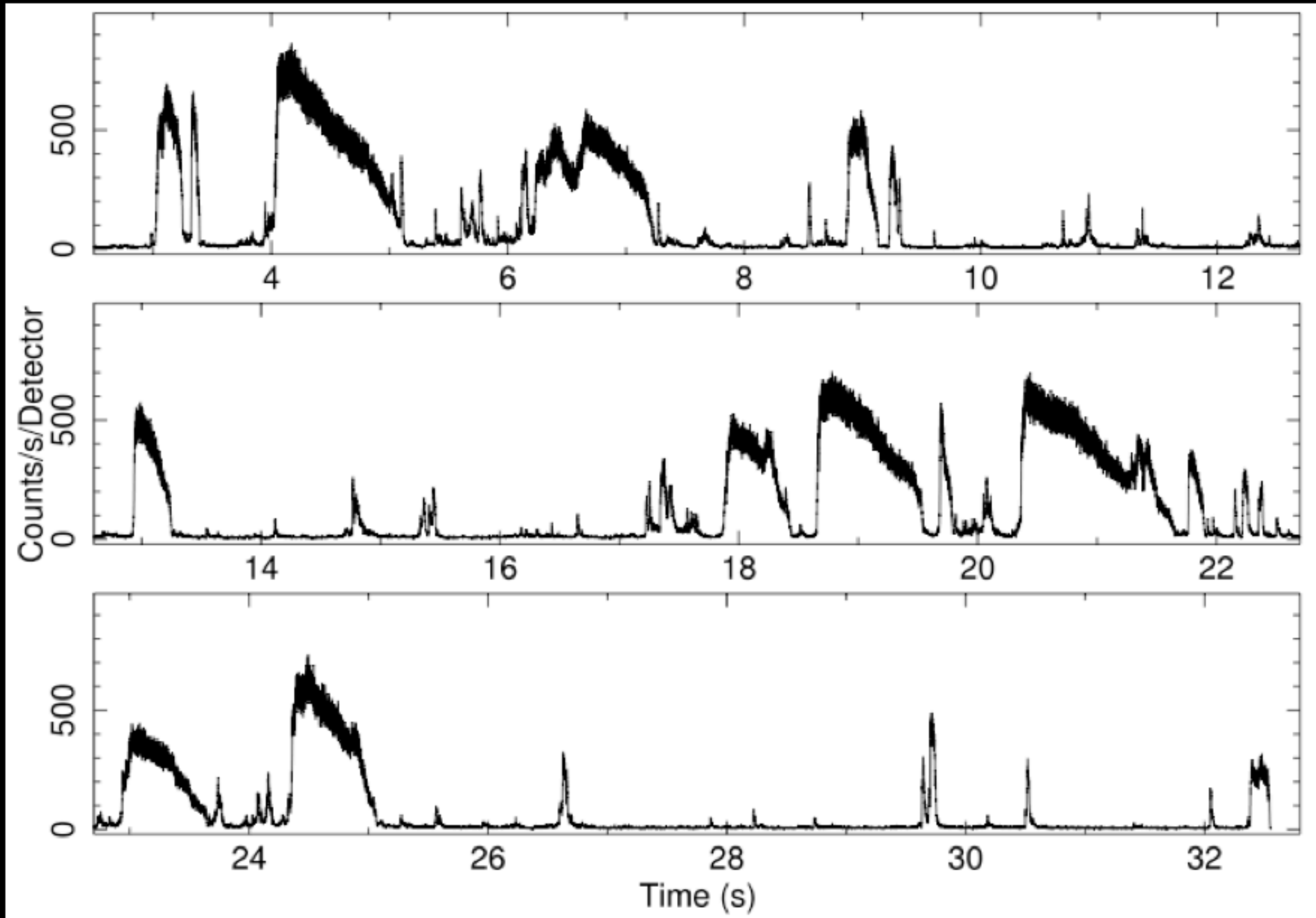
Transient Quasi Periodic Oscillations

QPOs detection confirmed by RHESSI obs.
Additionally… transient QPOs at 720 and 976 Hz.
Moreover 625 and 1840 Hz were detected.

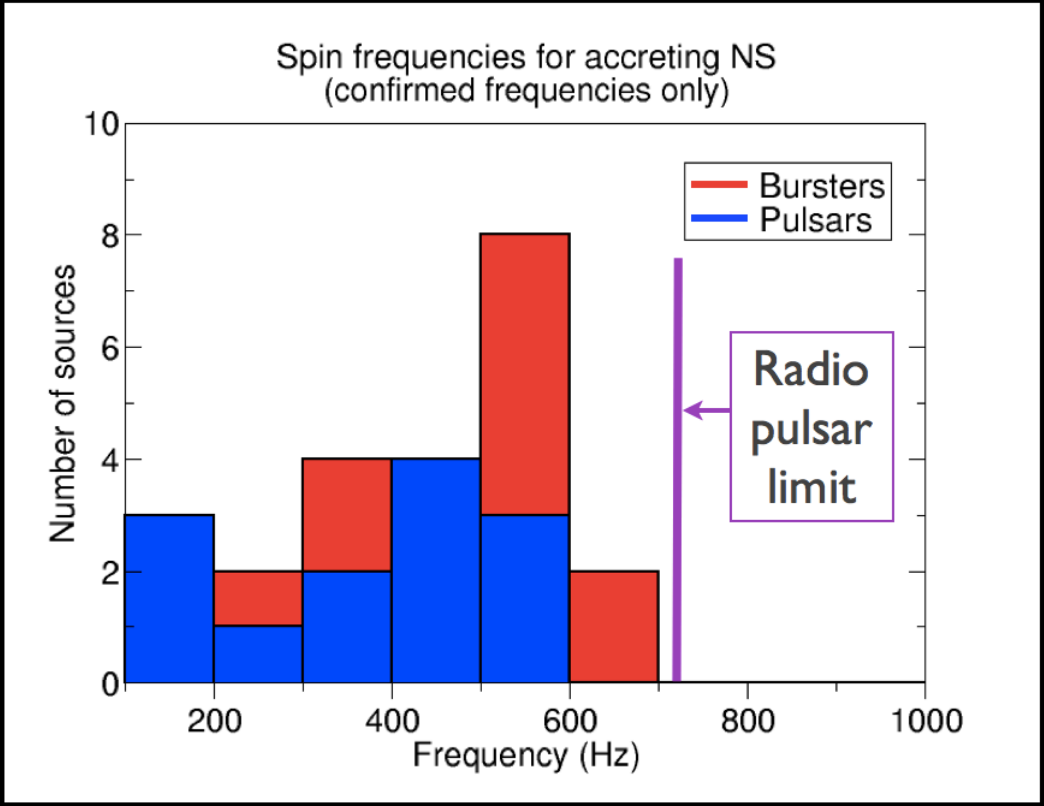


SGR1806-20

Courtesy G.L. Isreal



SGR 1900+14 burst storm including several intermediate flares, Israel et al. 2008



LOFT – LAD sensitivity to pulsations:

- pulsations down to 0.4% (2%) rms for a 100 mCrab (10 mCrab) source in 100 s,
- oscillations during type I bursts down to 1% (2.5%) rms in the burst tail (rise) among 35 NS covering a range of luminosities, inclinations and binary orbital phases.

Strong Gravity

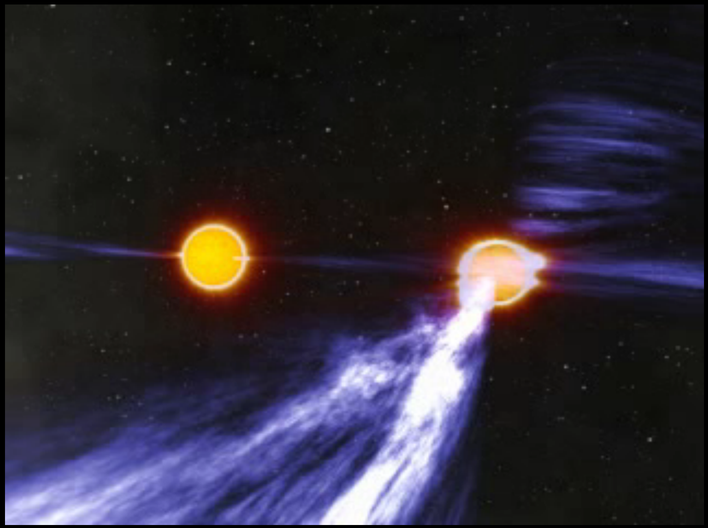
Relativistic Binary pulsars
with at least 1 post-newtonian parameter measured

- periastron advance,
- orbital decay,
- time-dilation and gravitational red-shift parameter,
- sin of the inclination of the orbit (equal, in GR, to the shape parameter of the Shapiro delay)
- mass of the companion star (equal, in GR, to the range parameter of the Shapiro delay)

* Accurate test of gravity; several GR effects confirmed with very good accuracy

(Possenti Burgay 2011)

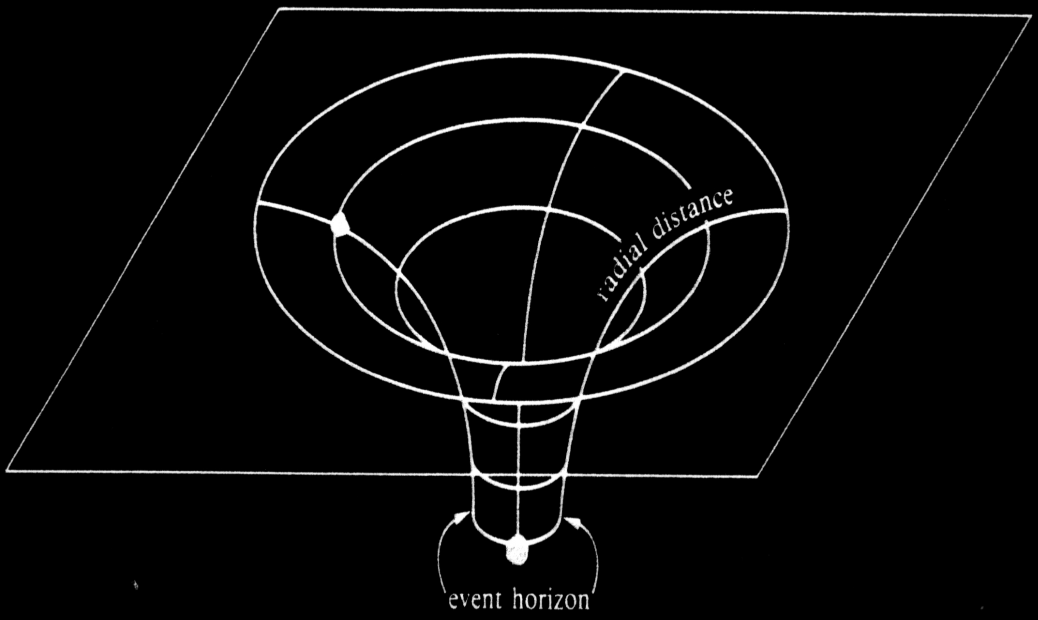
* BUT: direct measurements only at large radii ($R \sim 10^6$ Schwarzschild radii)



PSR
J0024-7204H*
J0024-7204J*
J0045-7319
J0437-4715**
J0514-4002A*
J0621+1002
J0737-3039A
J0737-3039B
J0751+1807
J0823+0159
J1022+1001
J1023+0038**
J1141-6545
J1518+4904**
J1537+1155
J1600-3053
J1603-7202
J1614-2230
J1623-2631*, **
J1640+2224
J1713+0747
J1740-3052
J1748-2021B*
J1750-3703A*
J1750-3703B*
J1756-2251
J1802-2124
J1804-0735*
J1811-1736
J1823-1115
J1829+2456
J1857+0943
J1903+0327
J1906+0746
J1909-3744**
J1915+1606
J1959+2048**
J2019+2425
J2051-0827
J2129+1210C
J2145-0750**
J2305+4707

Strong Field Effects

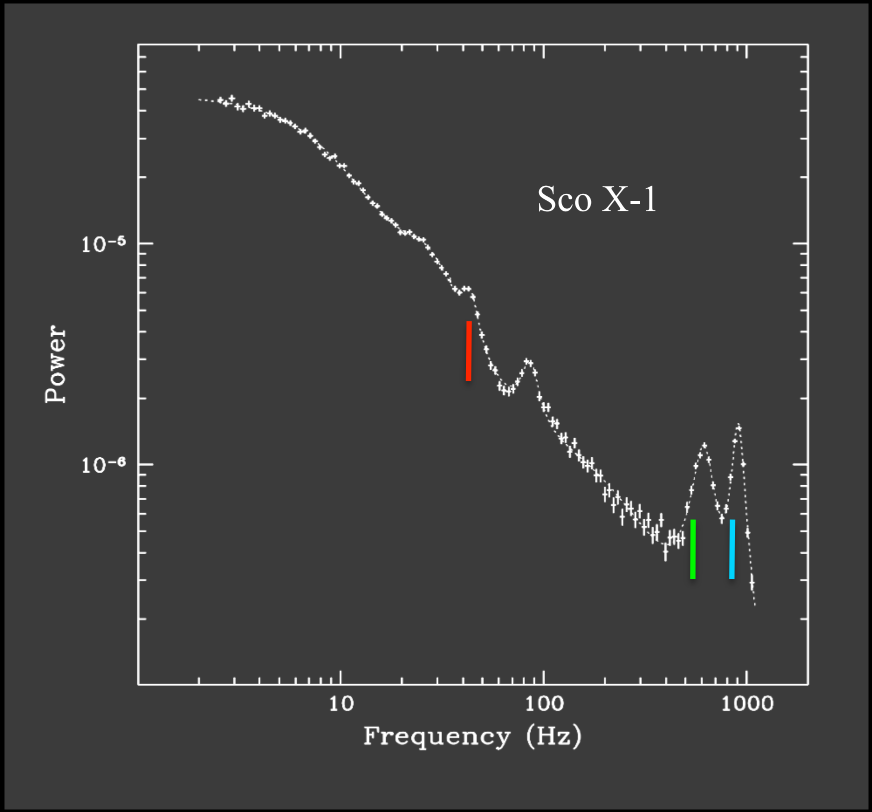
Need to sample Radii close to the horizon ($R_g \sim GM/c^2$): matter accretion into black holes and neutron stars provides the best tool.



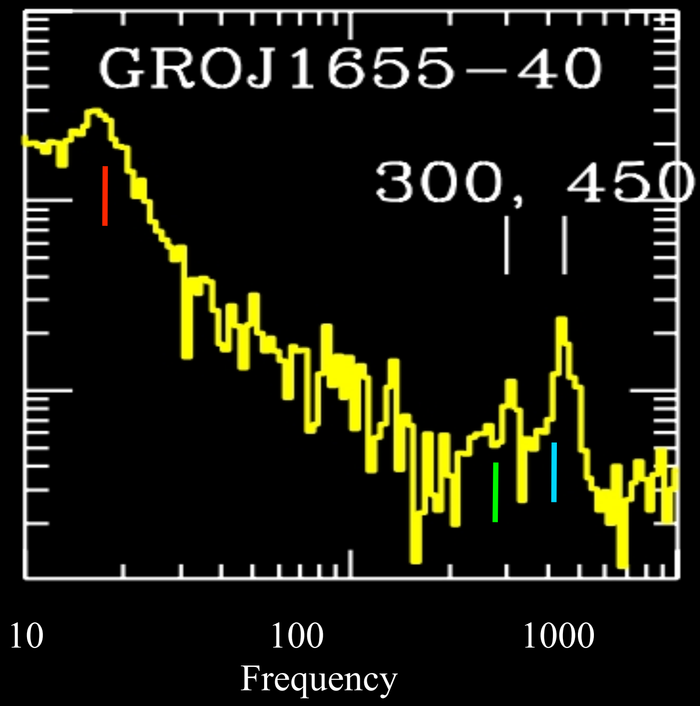
- Last Stable Circular orbit, aka ISCO (6 R_g -> 1 R_g)
- Particle motion around ISCO and fundamental frequencies of motion
- Dragging of inertial frame
- Strong field light deflection
- Black hole mass and spin

Stong Field Diagnostic: Quasi Periodic Oscillations

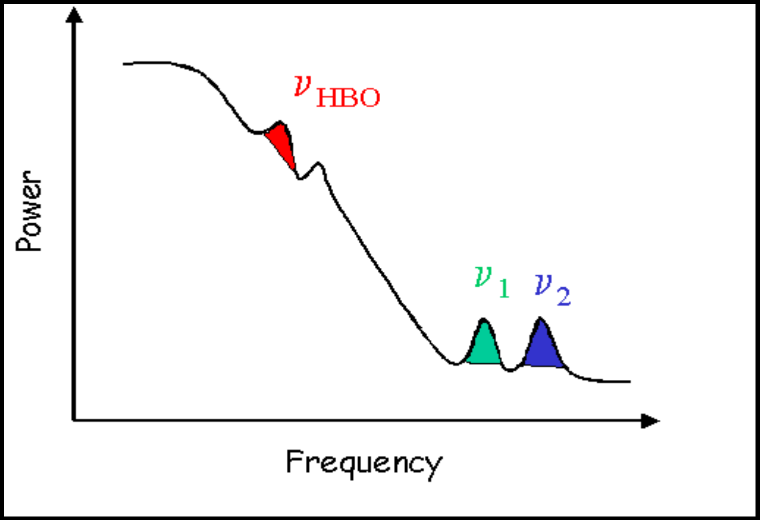
Accreting neutron stars

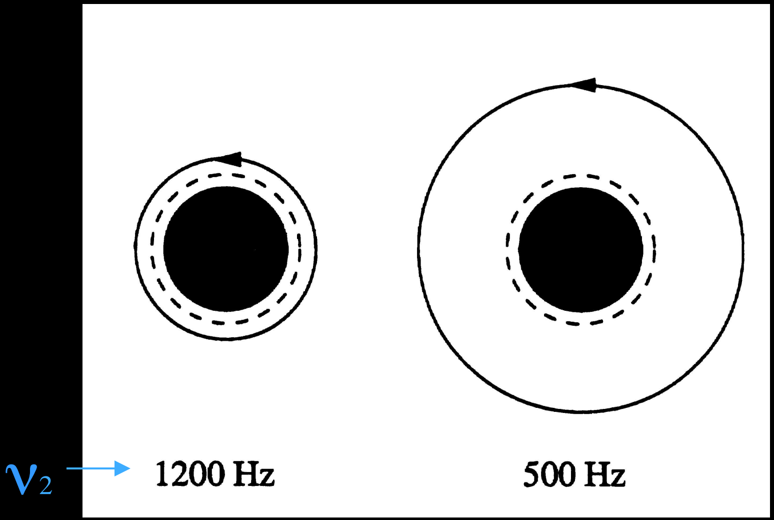


Accreting black hole candidates



Generic Model for higher frequency kHz QPOs





A 10 km radius, 1.4 M ⊙ neutron star with the corrisponding innermost circular stable orbit (ISCO; dashed circle) and orbits (drawn circles) corresponding to orbital frequencies of 1200 and 500 Hz, drawn to scale.

$\nu_2 = \nu_\varphi(r_i)$ = Keplerian (φ) frequency at inner disk radius r_i

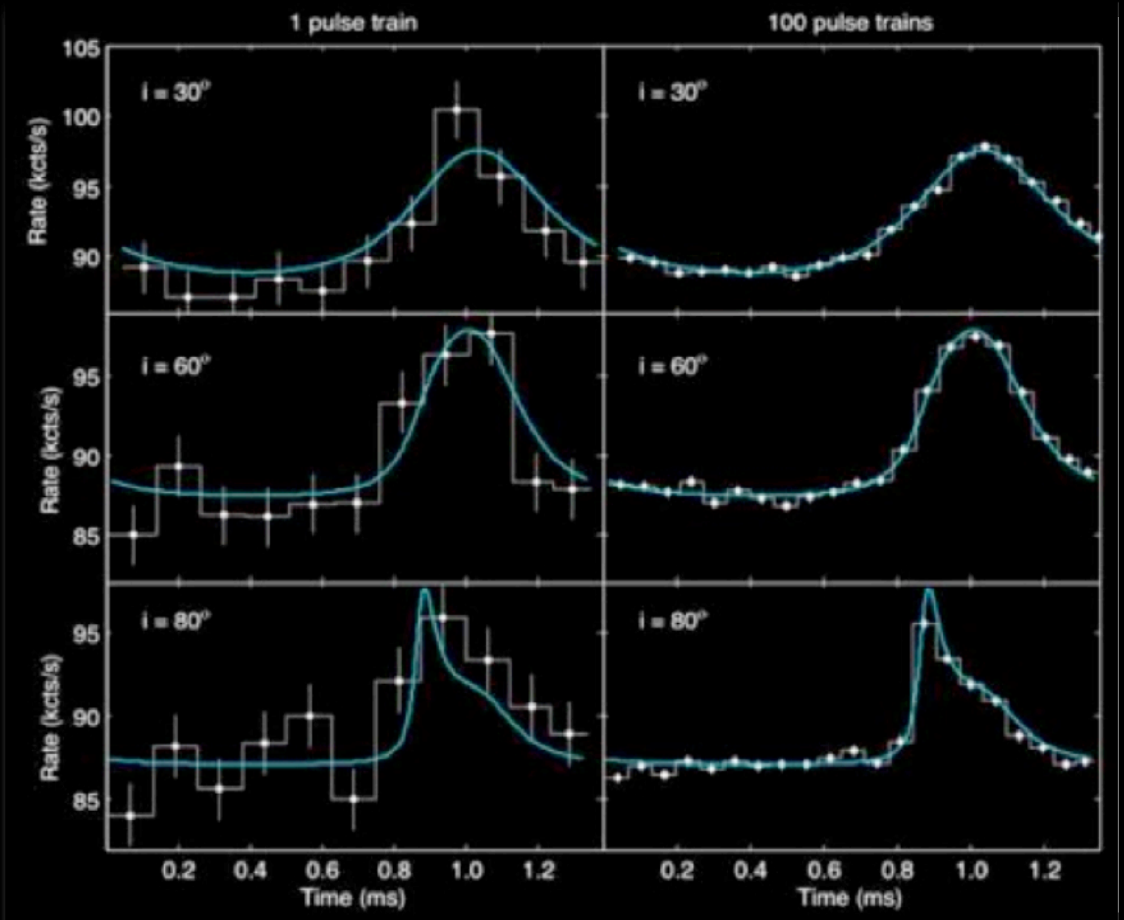
$$r_i \cong 15 \; (M/M_\odot) \; (\nu_2 / 1000 \text{ Hz})^{-2/3} \text{ km}$$

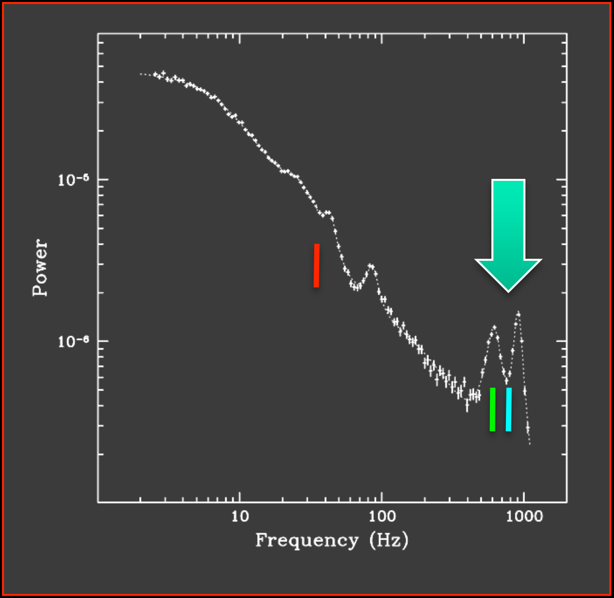
$r_i = f(\dot{M})$ to explain frequency variations

(Alpar, Shaham 1985;
Strohmayer et al. 1996;
Lamb et al. 1985;
Miller et al. 1997)

kHz QPOs in Time Domain with LOFT

300 mCrab, 5%, Q=100

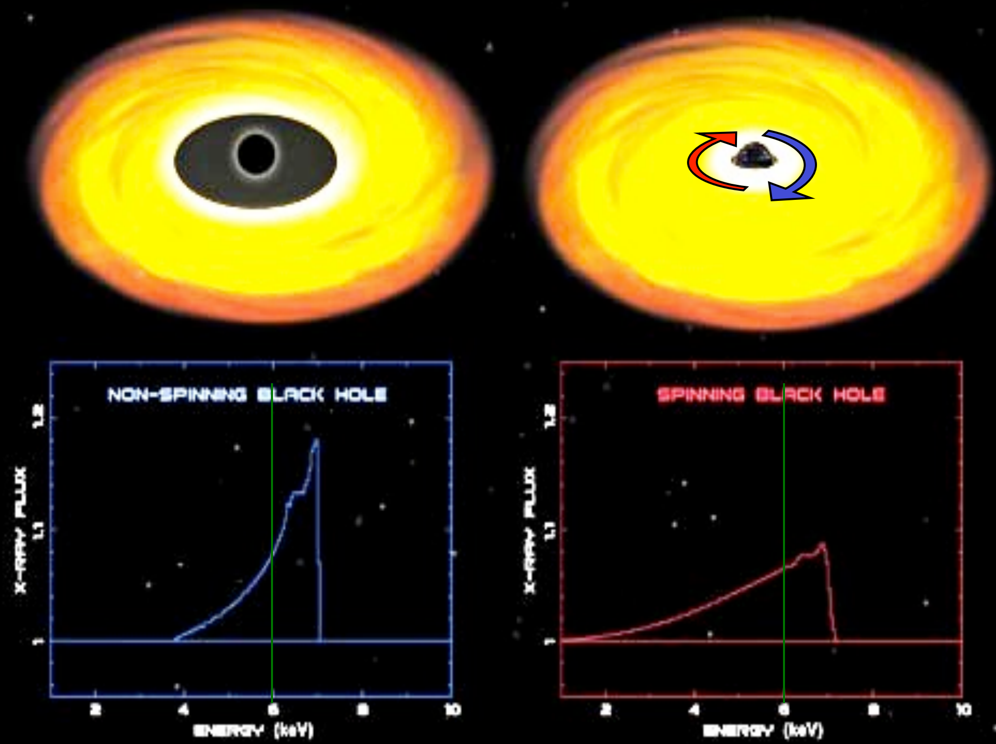




Strong Gravity diagnostic
Fe-lines from accretion disks

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

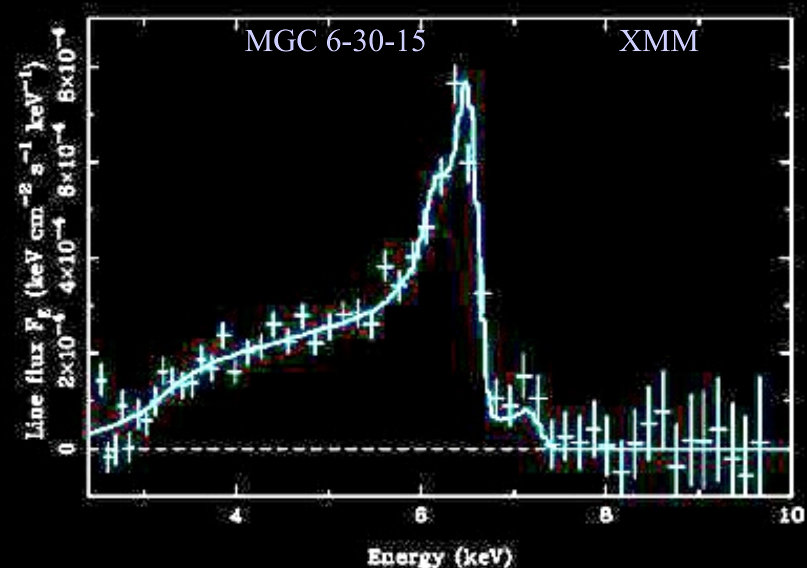
- Observed in many Active Galactic Nuclei and X-ray binaries



Line profile and time variability
black hole mass and spin

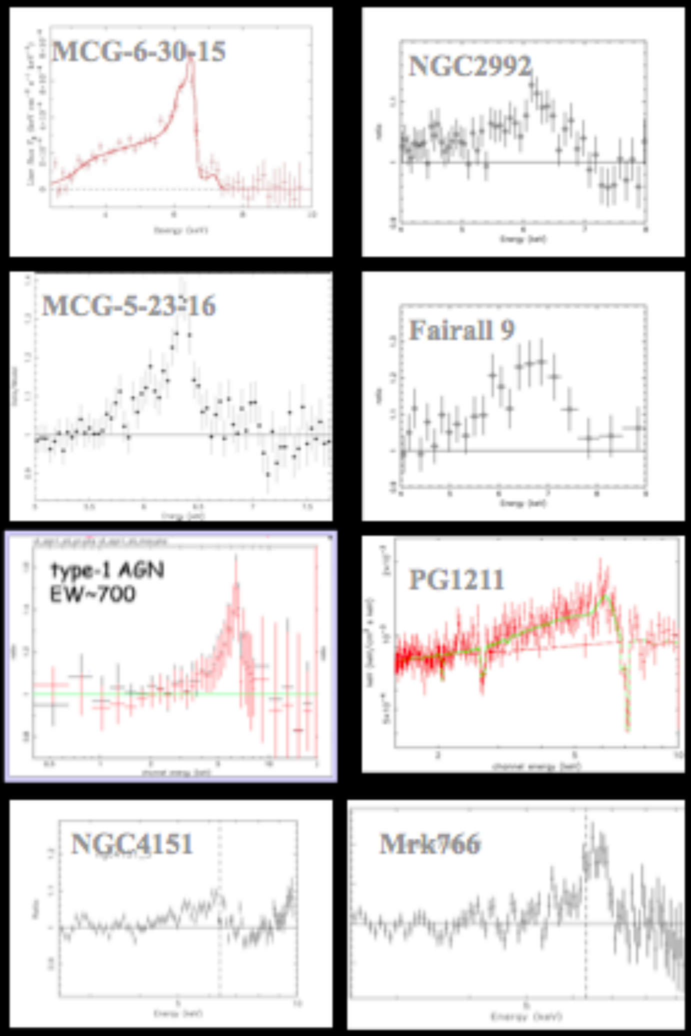
In situ probing of strong field gravity
(~few Rs)

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

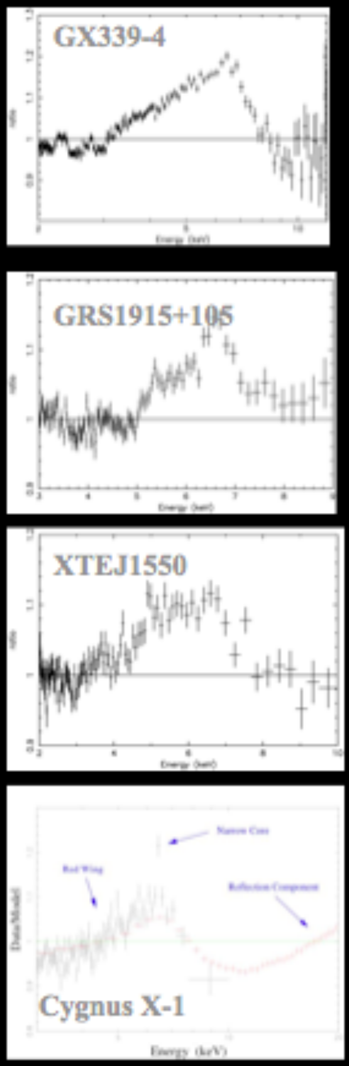


Very Broad Fe-K line profiles in :

AGNs

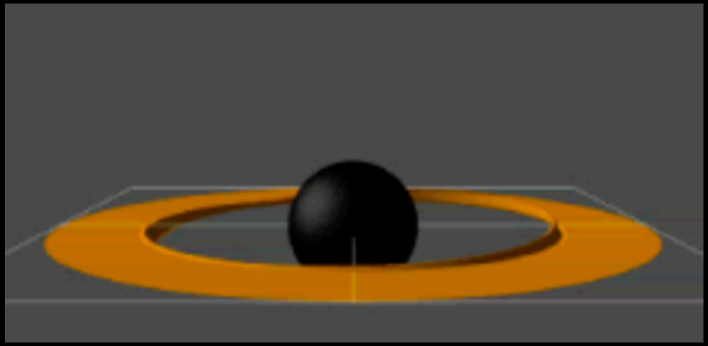


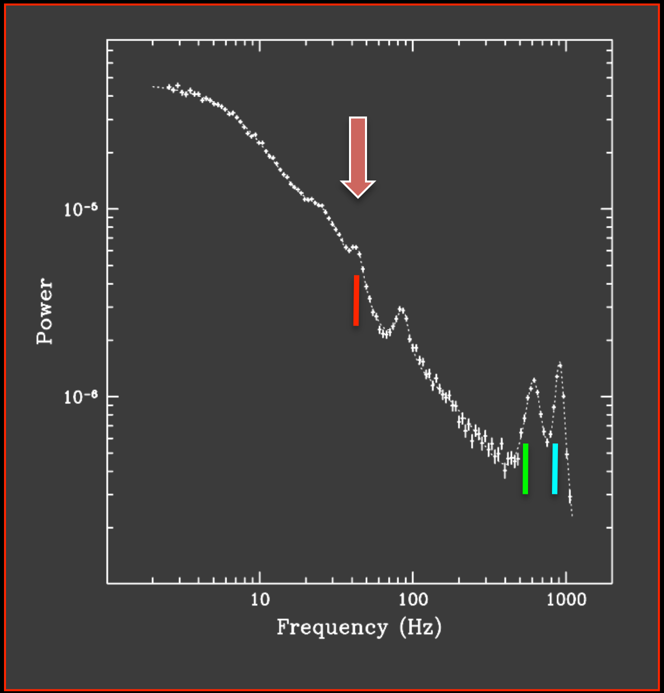
X-ray Binaries



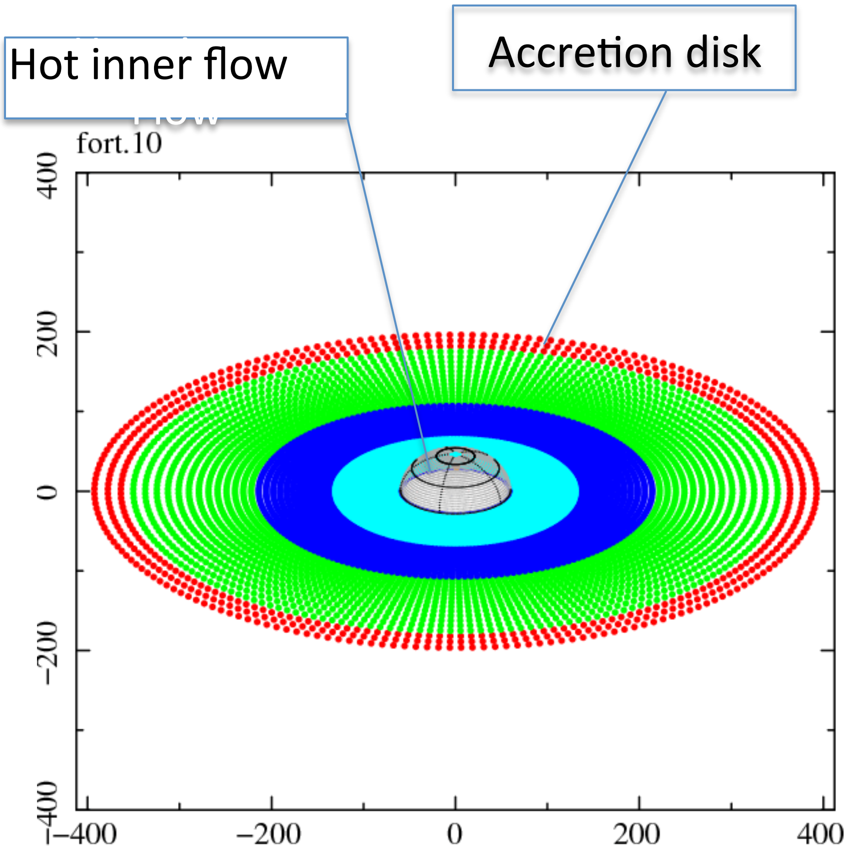
Low Frequency QPOs

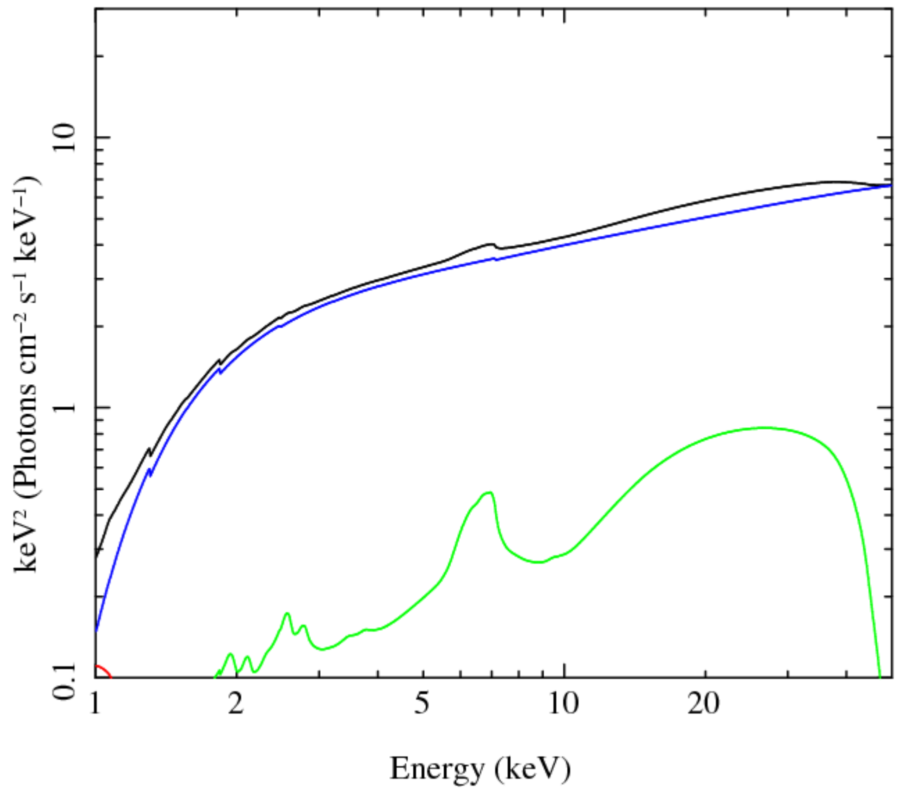
Relativistic nodal precession
(from frame dragging)
of the innermost disk regions ?

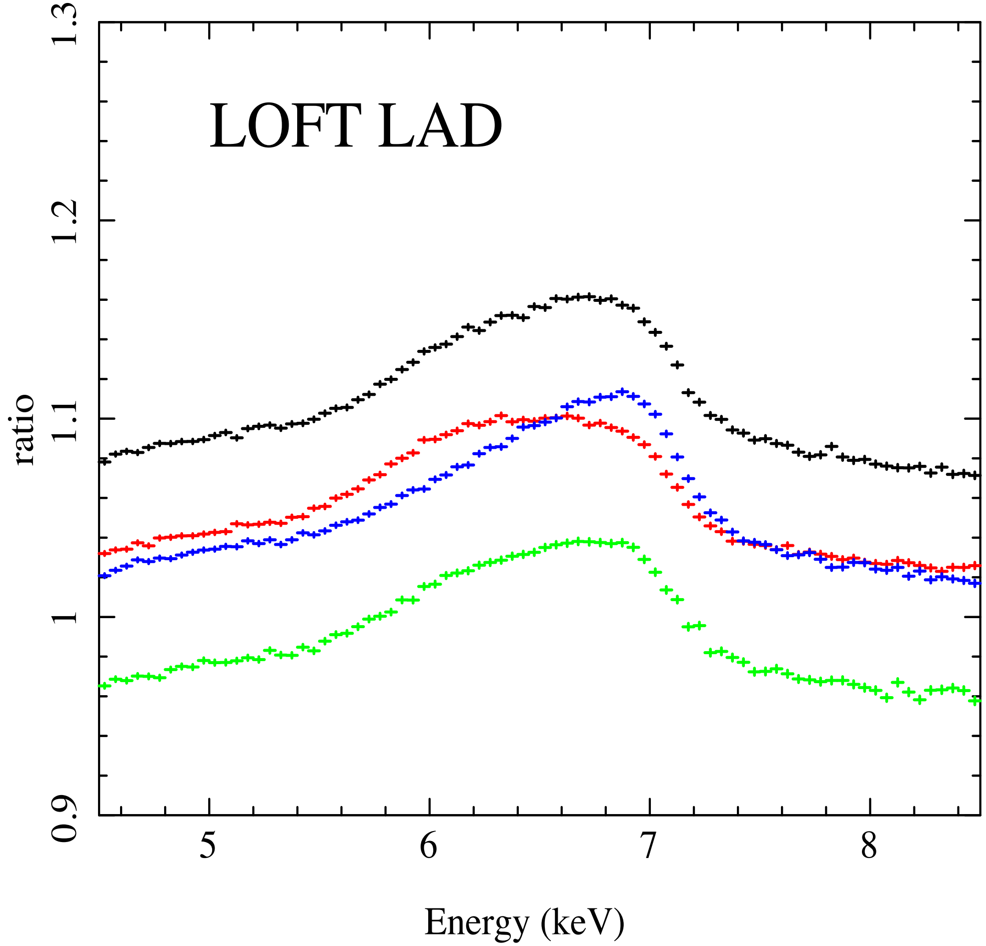




Relativistic nodal precession (from frame dragging) of the innermost disk regions
(Ingram & Done 2012)







LOFT LAD
ratio
1.3
1.2
1.1
1
0.9
5
6
7
8
Energy (keV)

Preliminary observing program breakdown

4-years Breakdown: 21 Ms driving science + <u>30 Ms for observatory science</u>

Source Type	TOO	Sources	Pointings	Total Time (ks)	Science Goal
BH transient outbursts	Yes	4	800	2400	SFG1,2,4
Persistent BH	No	2	400	1600	SFG 1,2,4
AGN	No	30	50	8000	SFG 5
Msec pulsar outburst	Yes	3	250	1000	EOS1, SFG2,3
NS transient bright outburst	Yes	3	250	1800	EOS 1,2 SFG 3
Persistent bright NS	No	12	350	4800	EOS 1,2 SFG 2,3
NS transient weak outburst	Yes	6	6	120	EOS 2
Persistent weak NS	No	14	14	280	EOS 2
Bursters	Yes	10	40	1000	EOS 2

A 4 year mission will guarantee a 99% probability to detect single Black Hole Transient with fast QPOs (2: 94%)

ESA Cosmic Vision Theme:
Matter under extreme conditions

- 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?

LOFT Science

Strong Gravity

Dense Matter

Observatory Science
(~50% of the time)

(an incomplete)

Observatory Science Matrix

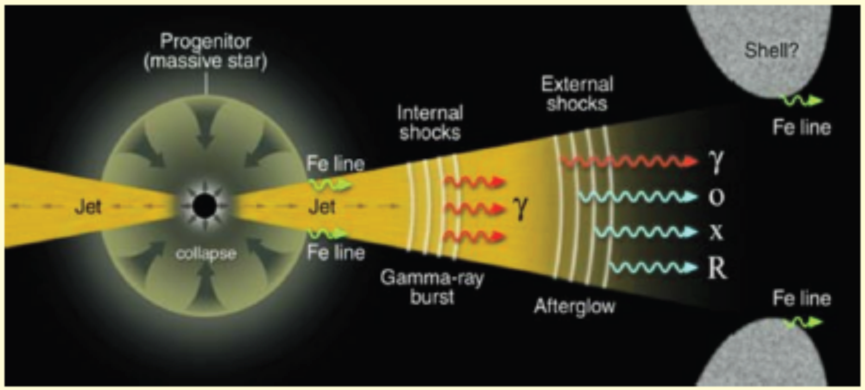
($F_x > 0.3$ mCrab ~ 7×10^{-12} erg/cm^2/s)

L = LAD W=WFM

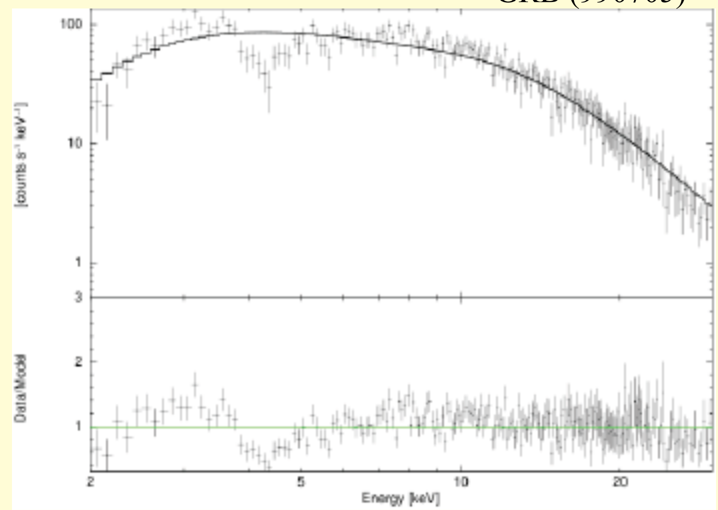
	Accretion Ejection	Magnetic fields	Cosmology	Evolution	Transient Sky
X-ray Bursters	L W	L		L W	L W
Low Mass X-ray Binaries	L W	L		L W	L W
High Mass X-ray Binaries	L W	L W		L W	L W
Isolated Neutron stars	L	L		L	
Magnetars		L W		L W	L W
Flare Stars		L W			W
Gamma Ray Bursts	W		W	W	W
Tidal Disruption Events	L W		L W		L W
Nearby Galaxies (MCs, M31)	L W	L W			L W
Bright AGNs (Seyferts, Blazars)	L W				L W
X-ray Bkgd Fluctuations			L	L	

LOFT- Observatory science

Gamma-Ray Bursts



GRB (990705)



Amati et al. (2000)

13 s WFM (J. in't Zand)

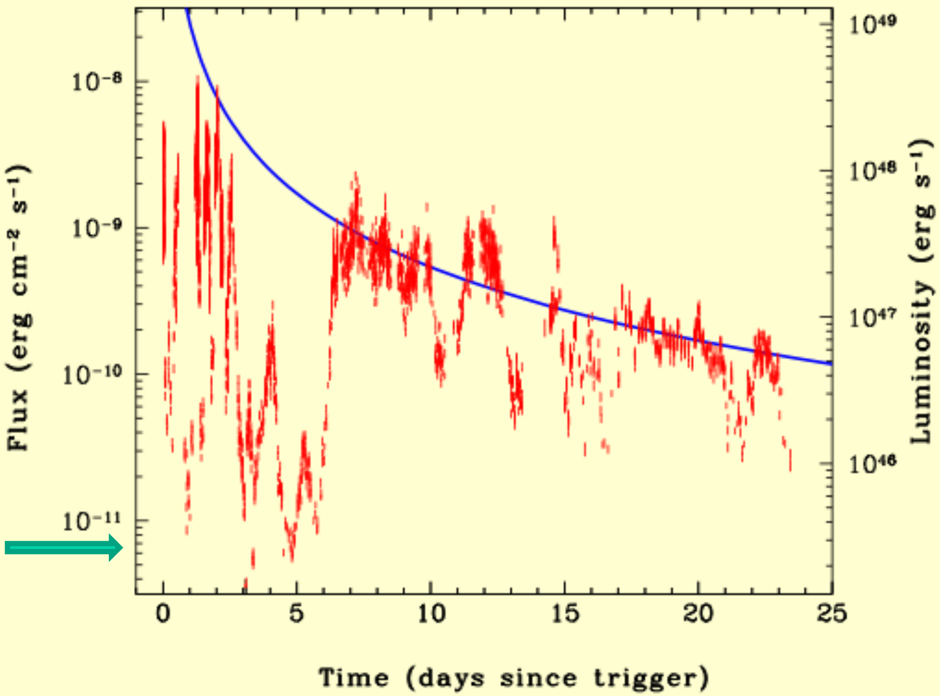
WFM Breakthrough science:

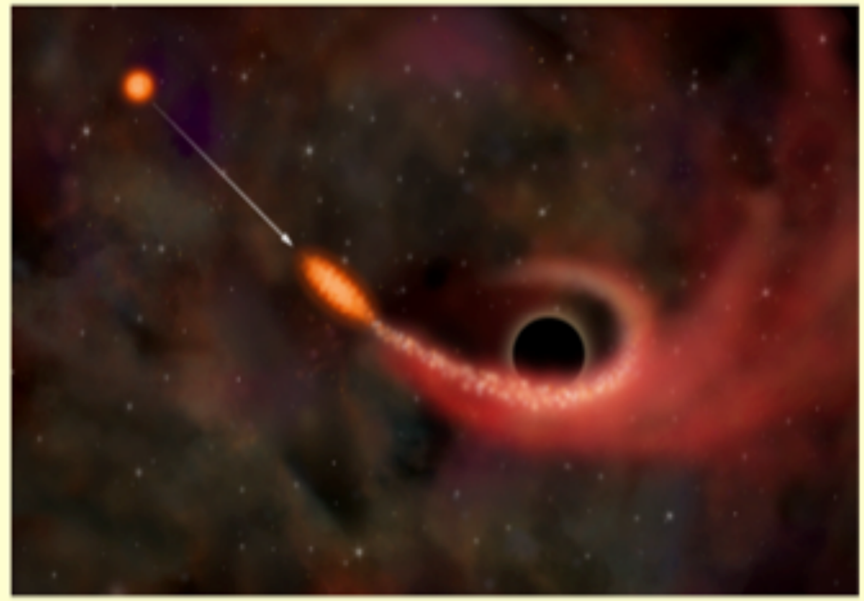
prompt emission down to 2–3 keV with WFM

incl. spectral evolution, abs./emiss. features from metal-rich environment, very high *z* GRBs [pop III stars!]

(courtesy Wilms)

Tidal Disruption Events





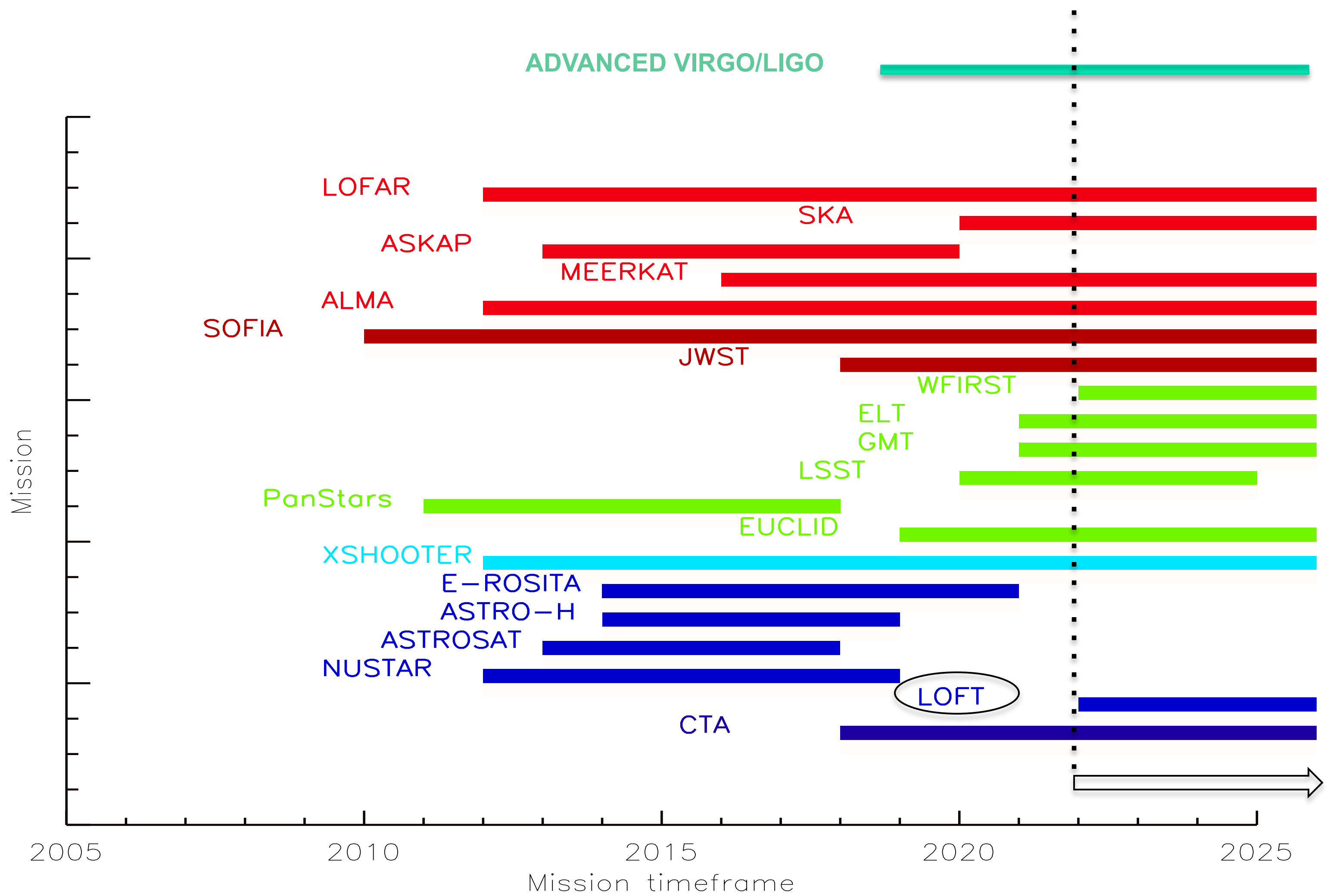
(Komossa et al., 2004, Fig. 1)

(Burrows et al., 2011)

Prompt emission: e.g., GRB 110328A (=Swift J164449.3+573451)

Measurements in J1644 show relativistic jet activity caused by the violent accretion. *LOFT* will study these events in much deeper detail!

LOFT in its timeframe



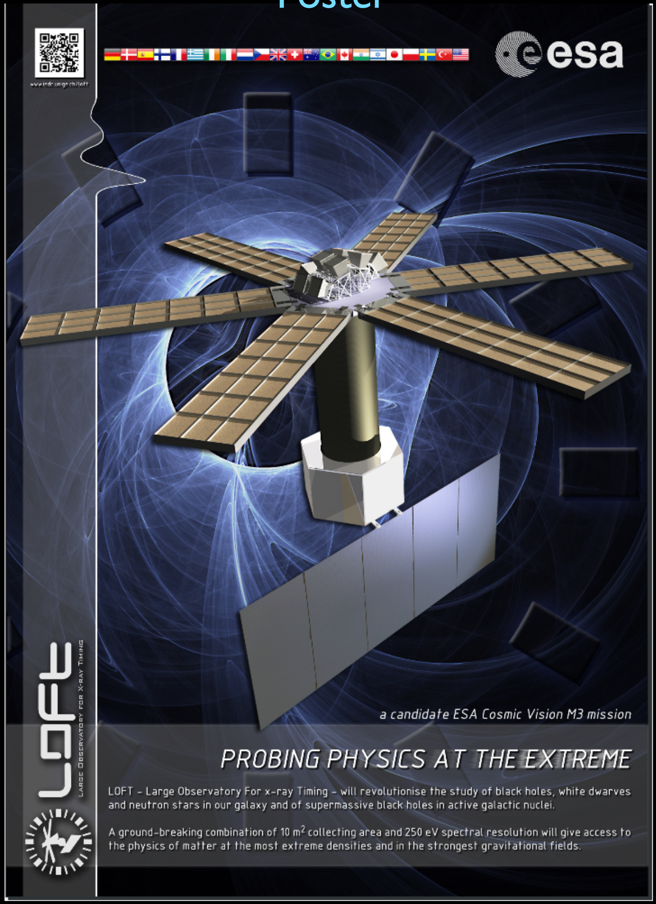
LOFT Web Page

Feroci et al. arXiv:1209.1497
http://www.isdc.unige.ch/loft/

http://www.isdc.unige.ch/loft

- Mission info
- Simulation Tools
- Project status updates
- Public Outreach
- Paper Model & Poster

Poster



Paper Model (1:32)

LOFT Science Coordination
Michiel van del Klis & Luigi Stella
Dense Matter Working Group
Anna Watts
Strong Gravity Working Group
Didier Barret
Observatory Science Working Group
Joern Wilms

LOFT International Support Team:
loft.webmaster@gmail.com

The LOFT Science WGs: Italian Members/Coordinators

L. Stella, 1 of 2 Science Coordinator

L. Amati, OS-GRB Coordinator
D. de Martino, OS-AWD Coordinator
M. Orlandini, OS-XRB Coordinator

Dense Matter WG: 6 / 39 members
Strong Gravity WG: 7 / 42 members
Obs. Science WG: 44 / 134 members

Participating Institutes/Institutions:

Bologna, Cagliari, Ferrara, Firenze, Milano, Napoli, Padova, Palermo, Pisa, Roma, Torino, Trieste

LOFT as an Observatory

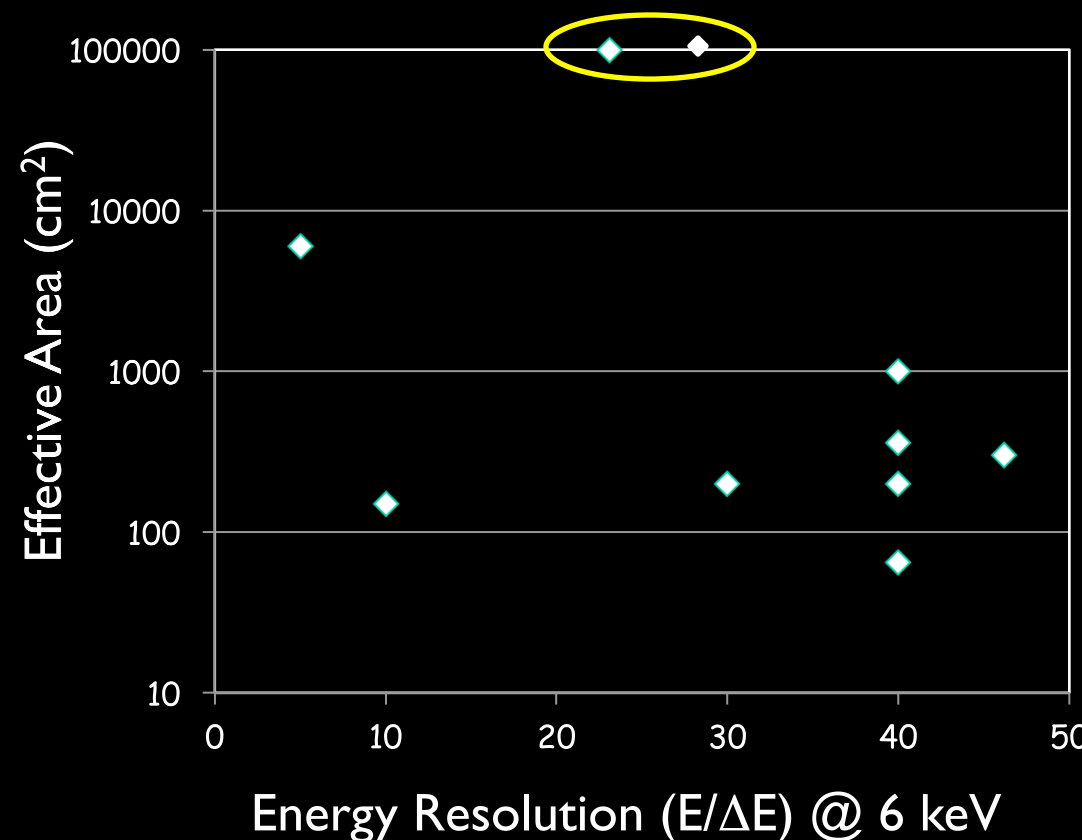
A (nearly-)"CCD"-class resolution with huge effective area.

(and a half-sky, arcmin, soft X-ray, 300 eV resolution WFM)

Access to spectroscopy on time scales unaccessible to other observatories and/or access to flux variability timescales simply still "unknown" (e.g., seconds in blazars).

LOFT/LAD in context:

ASCA
BeppoSAX
RXTE
Chandra
XMM
Swift
Suzaku
Astro-H



Top Level Objectives: Dense Matter

- EOS1 Constrain the Equation of State of supranuclear-density matter by the measurement, using three complementary types of pulsations, of mass and radius of at least 4 NS with an instrumental accuracy of 4% in mass and 3% in radius.

- EOS2 Provide an independent constraint on the EoS by filling out the accreting NS spin distribution through discovering coherent pulsations down to an amplitude of about 0.4% (2%) rms for a 100 mCrab (10 mCrab) source in a time interval of 100 s, and oscillations during type I bursts down to typical amplitudes of 1% (2.5%) rms in the burst tail (rise) among 35 NS covering a range of luminosities, inclinations and binary orbital phases.

- EOS3 Probe the interior structure of isolated NSs by observing seismic oscillations in Soft Gamma-ray Repeater intermediate flares with flux ~1000 Crab through high energy photons (> 20 keV).

Top Level Objectives: Strong Field Gravity

- SFG1 Detect strong-field GR effects by measuring epicyclic motion in high frequency QPOs from at least 3 black hole X-ray binaries.

- SFG2 Detect disk precession due to relativistic frame dragging with the Fe line variations in low frequency QPOs for 10 NSs and 5 BHs.

- SFG3 Detect kHz QPOs at their coherence time, measure the waveforms and quantify the distortions due to strong-field GR for at least 10 NSs covering different inclinations and luminosities.

- SFG4 Measure the Fe-line profile and carry out reverberation mapping of 5 BHs in binaries to provide BH spins to an accuracy of 5% of the maximum spin (a/M=1), constraining fundamental properties of stellar mass black holes and of accretion flows in strong field gravity.

- SFG5 Measure the Fe-line profile of 30 AGNs, and carry out reverberation mapping of the 8 AGNs most suitable for the latter purpose, to provide BH spins to an accuracy of 20% of the maximum spin (10% for fast spins) and measure their masses with 30% accuracy, constraining fundamental properties of supermassive black holes and of accretion flows in strong field gravity.

Science-related Mission Features

- Pointing:
  - 3-axis stabilized (LAD response stability)
  - LAD accessible sky fraction >50% (R), >75% (G)
  - Galactic Center visibility: >35% (R), >65% (G)
  - Up to 2 slews per orbit ("night-time" observations)
  - ToOs : within 8 hrs (working hours) and 24 hrs (otherwise)

- Low-Earth Orbit (equatorial: 550 km, <2°)
  - spectral resolution (reduce radiation damage)
  - reduce background (modulation)

- Data and Telemetry:
  - Downlink per orbit: 6.7 Gbit (X-band, Kourou and Malindi)
  - Flex TM share between LAD and WFM
  - Fast delivery of GRB/transient coordinates (VHF network)

The LOFT Mission

LOFT is specifically designed to exploit the diagnostics of very rapid X-ray flux and spectral variability in compact objects, yielding unprecedented information on strongly curved spacetimes and matter under extreme conditions of density and magnetic field strength.

LOFT will investigate variability from submillisecond QPO's to years long transient outbursts.

The LOFT LAD has an effective area ~20 times larger than any largest predecessor, uniquely combined with a "CCD-class" energy resolution.

The LOFT WFM has a few steradian field of view at soft X-rays to discover and localise X-ray transients and impulsive events and monitor spectral state changes, triggering follow-up observations and providing a wealth of science in its own.