# High Throughput X-ray Astronomy

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## eXTP Themes

- Dense matter
- Accretion in strong field gravity
- Strong magnetism
- Observatory science

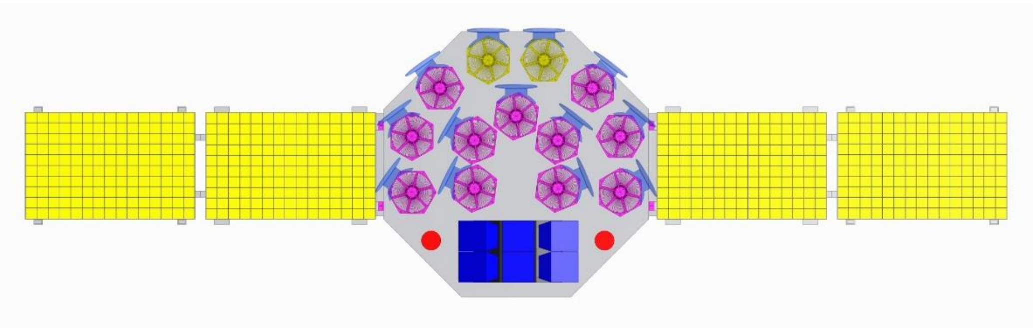
# eXTP: enhanced X-ray Timing and Polarimetry

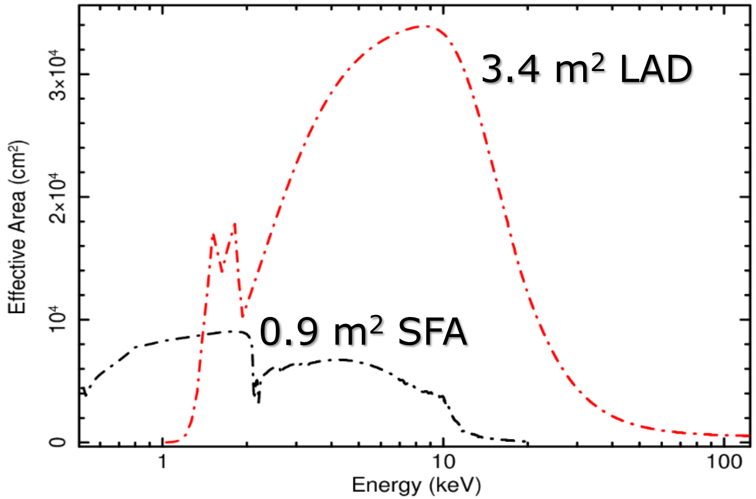
SFA - Spectroscopy Focusing Array

11 X-ray SGO optics, **0.9 m² @1 keV**, **0.6 m² @6 keV**, 1′ PSF, SDD, 0.5-10 keV, <100 μs

LAD
Large Area Detector

**3.4 m²** "LOFT" SDD detectors, 2-30 keV, 250 eV @ 6 keV






PFA – Polarimetry Focusing Array

2 X-ray Ni optics, **1100 cm² @6 keV**, 4.5m FL, 15″ PSF, GPD polarimeters, 2-10 keV

WFM
Wide Field Monitor

3 units, 2-50 keV, **4 sr FoV**, 80 cm²/unit, 5′ angular resolution

# eXTP Themes

Dense matter

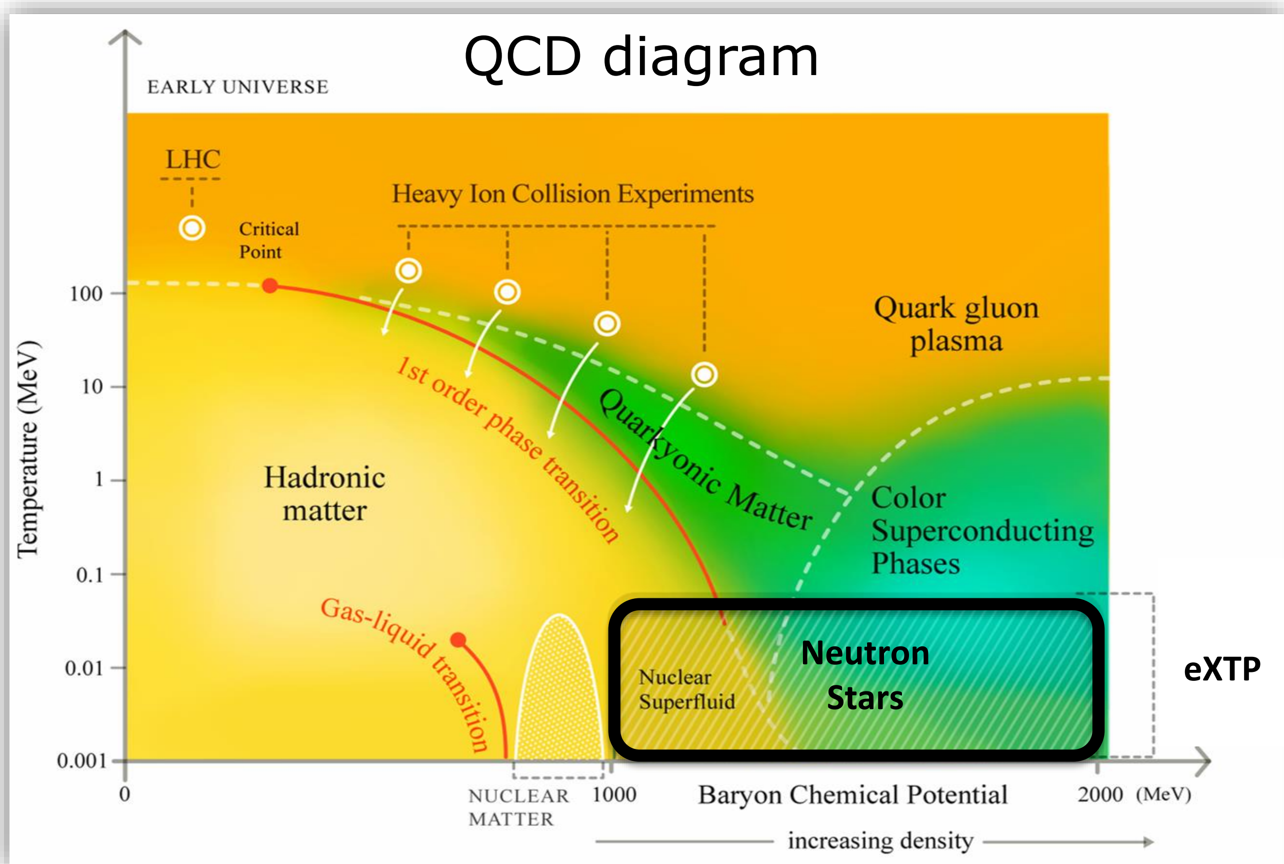
Accretion in strong field gravity

Strong magnetism

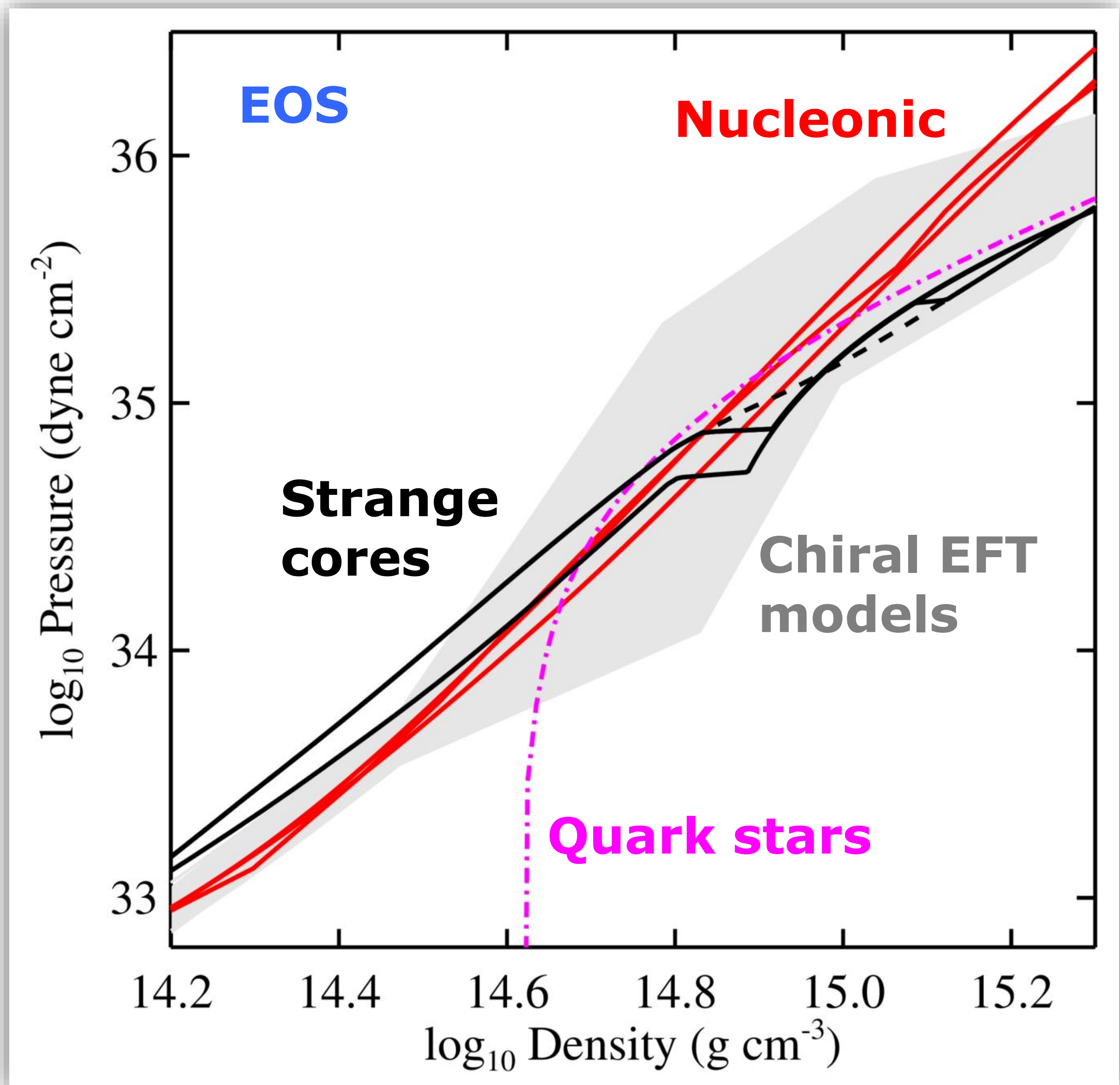
Observatory science

## The strong force determines the state of nuclear matter from atomic nuclei to neutron stars:

- a major open problem in modern physics
- progress driven by experiment and obervation

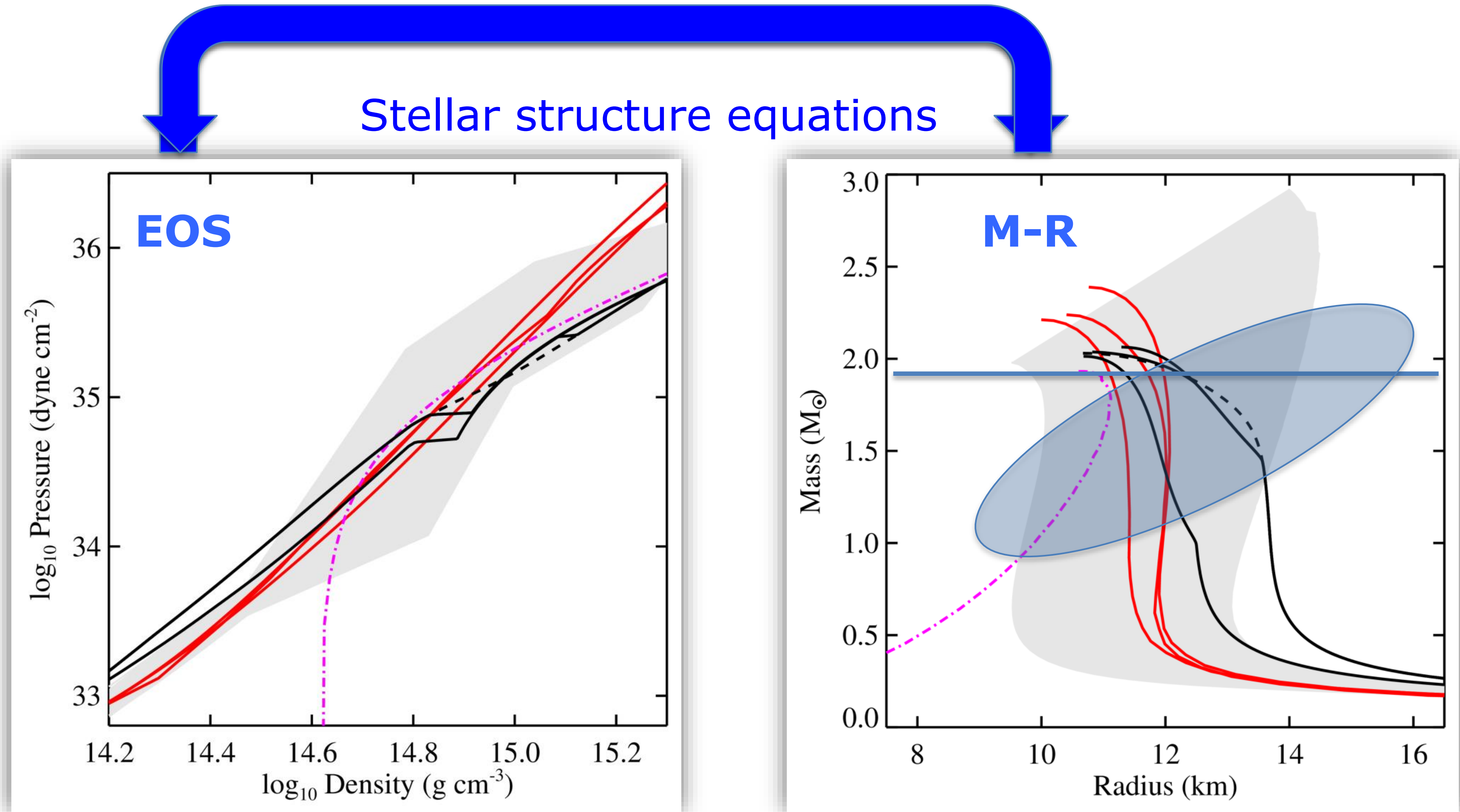



Neutron stars contain the **densest** and most **neutron-rich** matter **in the Universe**.



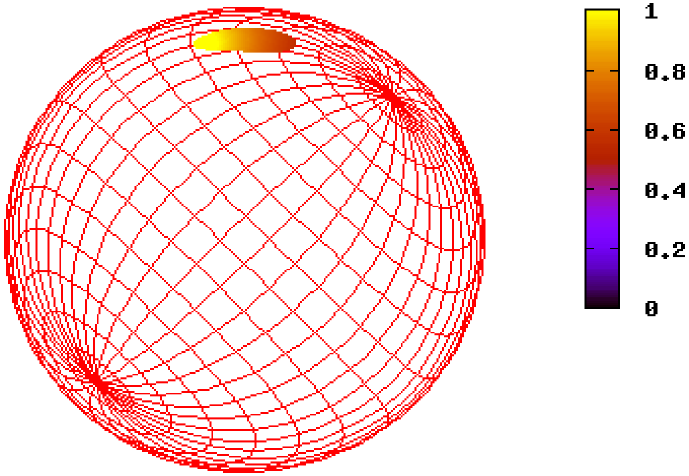

The strong force determines the 'stiffness' of neutron star matter.

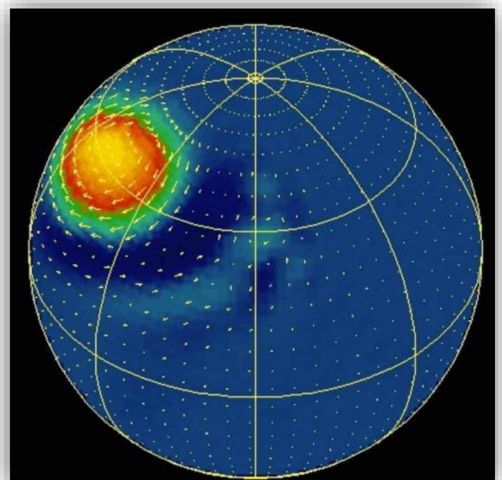
This is encoded in the **EQUATION OF STATE**.

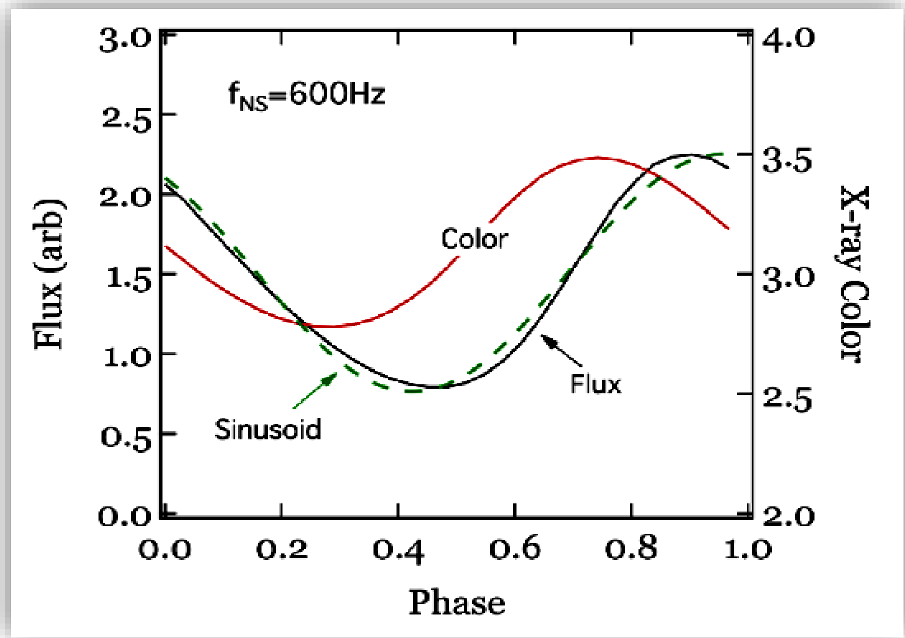



MUST MEASURE **BOTH M AND R** TO **HIGH PRECISION**
(LOW STATISTICAL AND SYSTEMATIC ERRORS) FOR A **RANGE OF M**.

# Pulse profile modelling



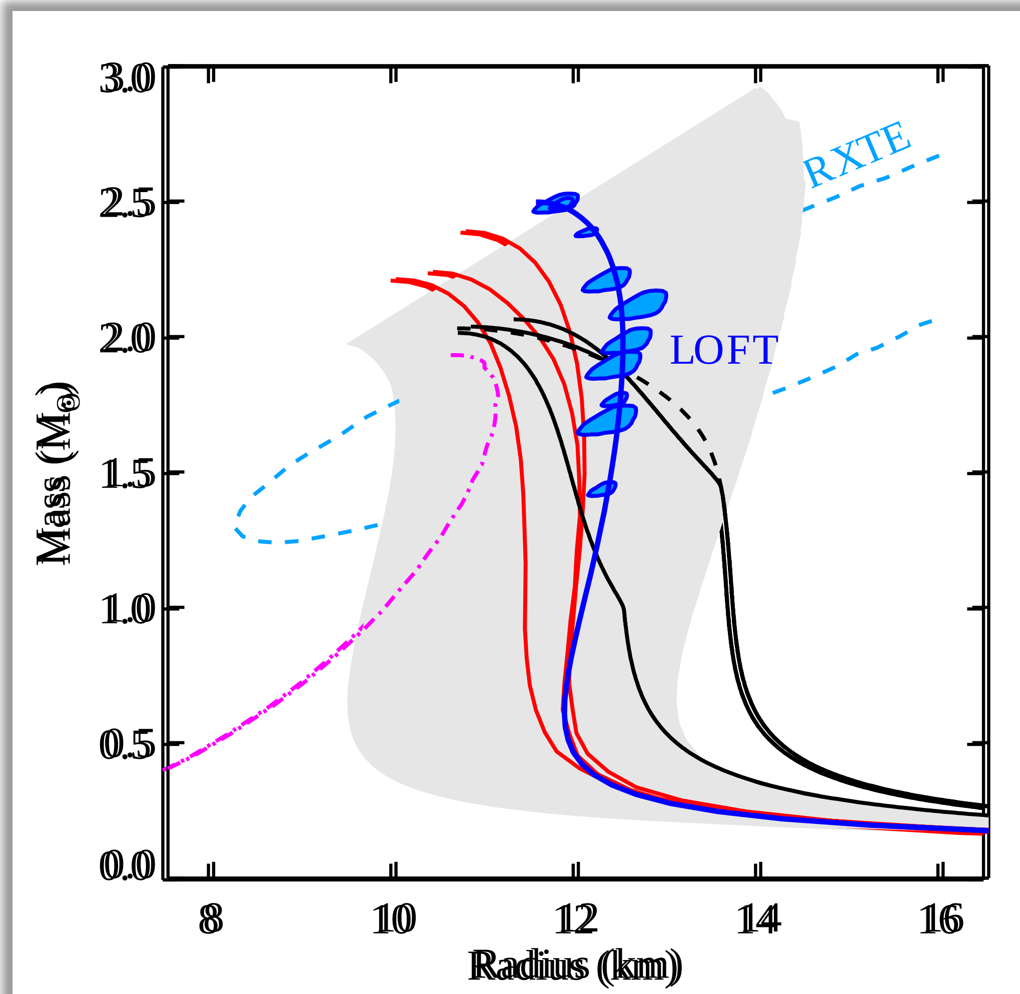






Hotspots on accreting neutron stars generate pulsations whose properties depend on M and R.

**EXTP CAN RECOVER M AND R SIMULTANEOUSLY BY FITTING THE PHOTON ENERGY-DEPENDENT PULSE PROFILE.**

Spitkovsky/ Morsink/Lo




For thermonuclear hotspots (burst oscillations) spectrum and emissivity are well understood.

Errors of a several % are achievable

Independent cross-checks further reduce risk of systematic errors.

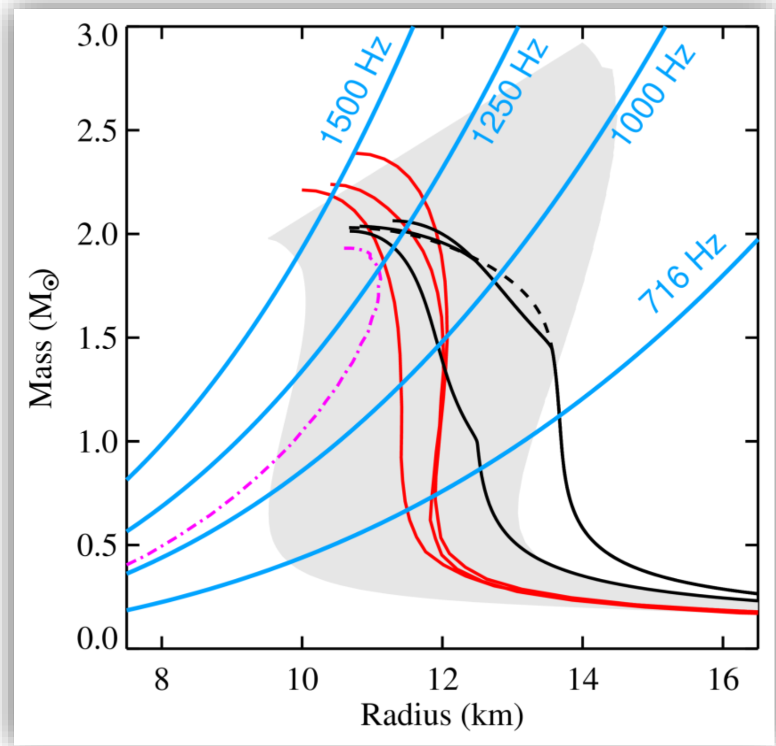
**Using only known sources, eXTP's pulse profile modelling measurements will map the EOS.**

Watts

- Neutron stars spin up via accretion.

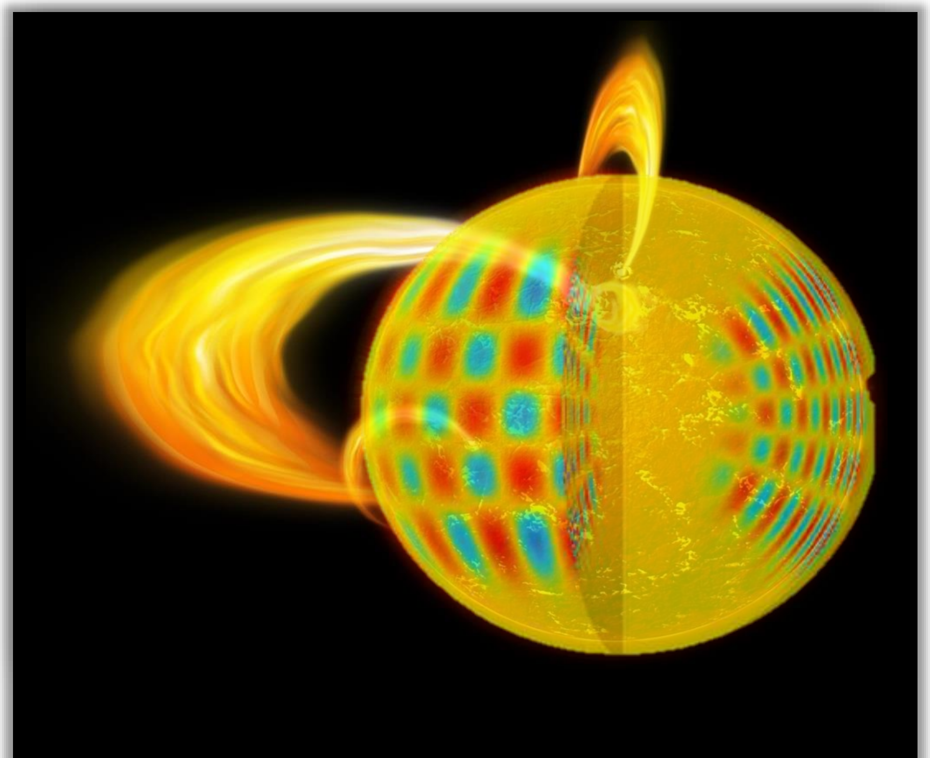
- Spin can be measured via pulsations, which are mostly weak/intermittent.

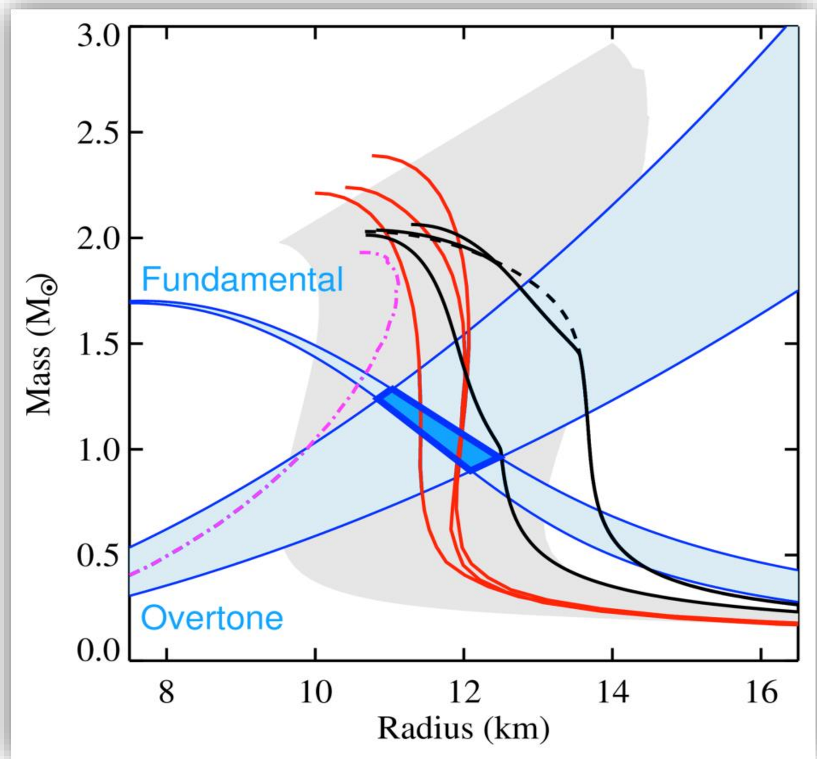
- Spin rates constrain EOS, e.g. via mass-shedding limit.




**eXTP will allow full characterization of the spin distribution of accreting neutron stars.**

# Magnetar Seismology



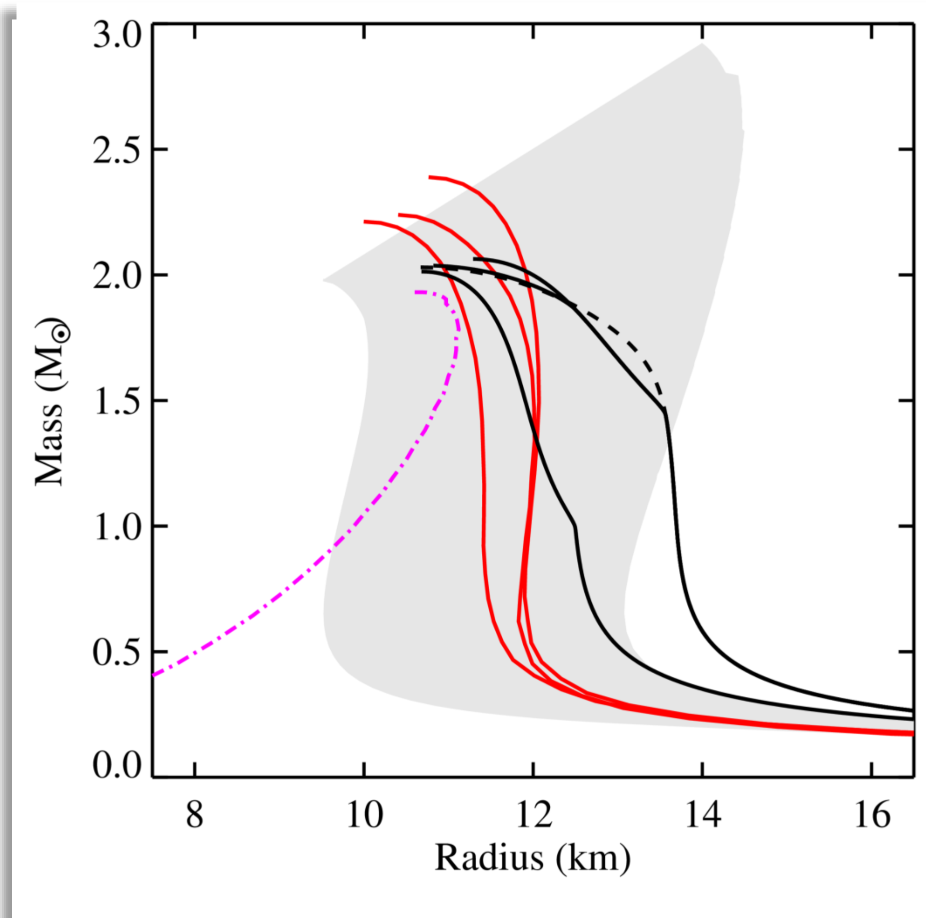



Starquakes on magnetars trigger global seismic vibrations.
At present we have data from only the rarest, most energetic events.

Seismic models depend on M and R. Frequencies constrain the EOS.

**eXTP WILL BE SENSITIVE TO SEISMIC VIBRATIONS FROM SMALLER STARQUAKES, DRIVING THE EMERGING FIELD OF NEUTRON STAR ASTEROSEISMOLOGY.**

# Equation of state with eXTP




- **measures both M and R**.
- **minimises statistical error** with its large effective area.
- **minimises systematic error** with complementary methods and same source cross-checks.
- Different approach to EoS than NUSTAR, SKA, LIGO/Virgo

# eXTP Main Themes

Dense matter

Accretion in strong field gravity

Strong magnetism

Observatory science

## Astrophysics near black holes: strong field effects

- Innermost Stable Circular Orbit
- Orbital motion near ISCO
- Orbital and epicyclic frequencies
- Frame dragging, light deflection, Shapiro effect

## Astrophysical impact

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

Tests of General Relativity
with binary millisecond radiopulsars:

Relativistic effects are small perturbations

## X-ray diagnostics:

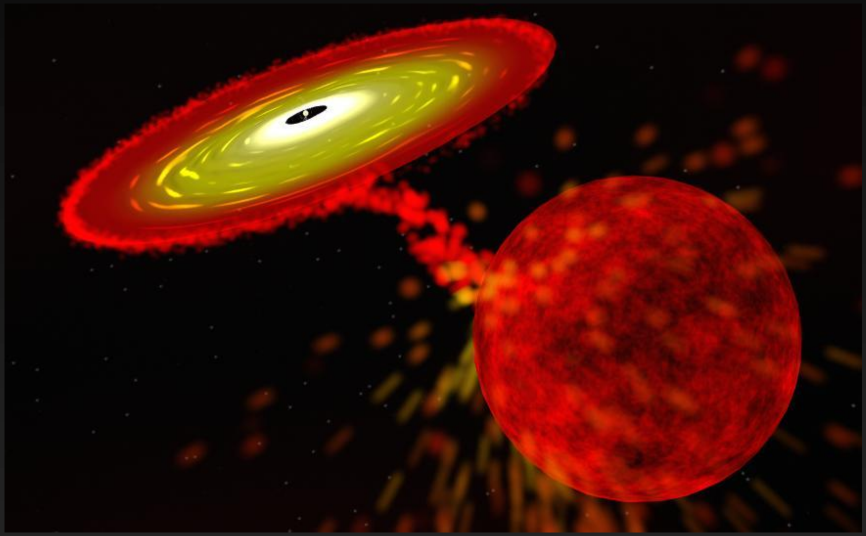
- Strong field motions:
  orbital & epicyclic
- Spectral/timing/polarimetry
  - Reverberation
  - Doppler tomography

Strong Gravity in stationary Spacetimes (complementary to dynamical spacetimes of GWs sources)

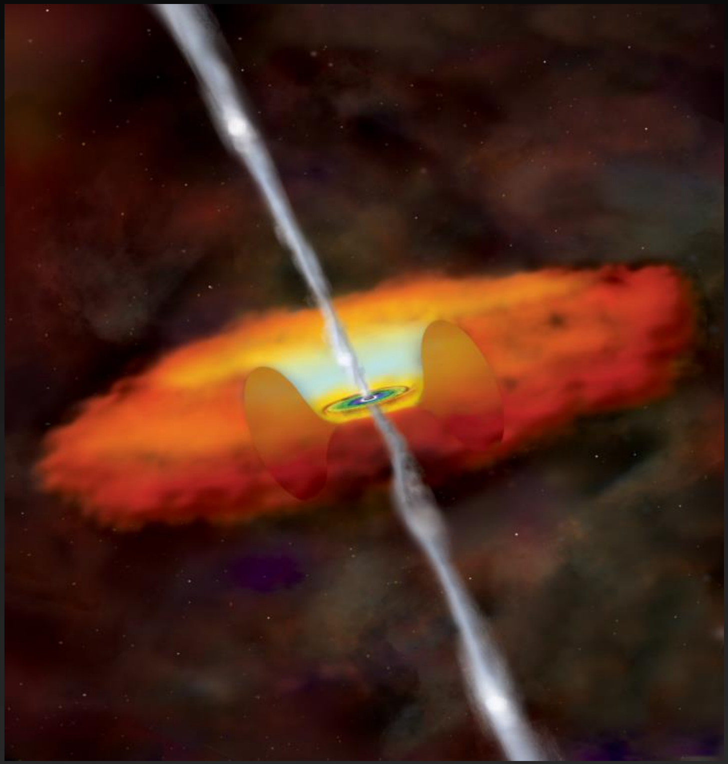
Factor 100,000 closer to the black hole

eXTP: near the event horizon
relativistic effects are large !

# Accreting Black Holes



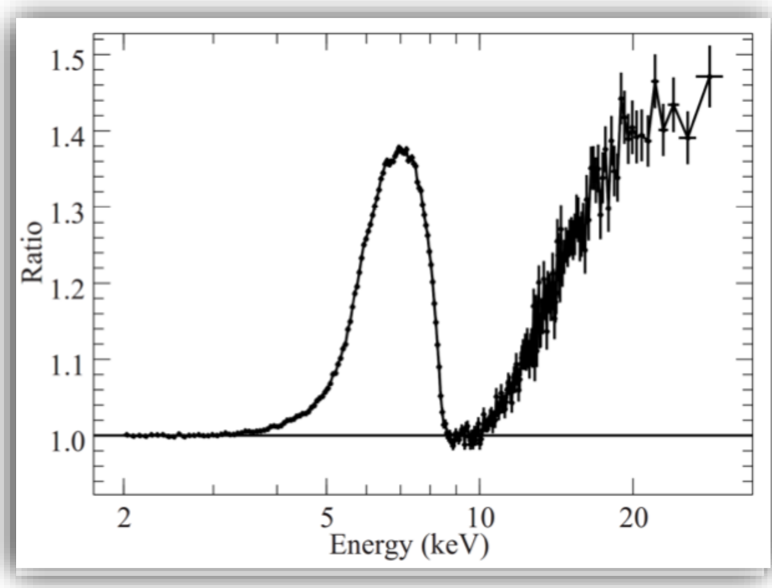
Stellar mass Black Holes in X-ray binaries



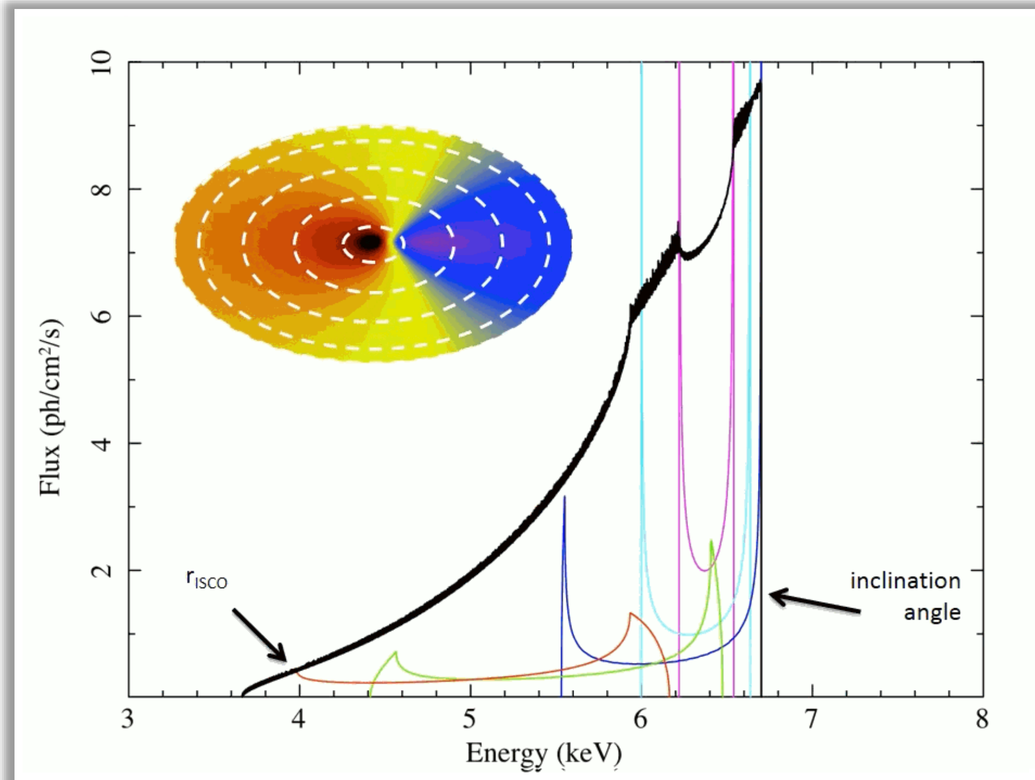
Supermassive Black Holes in nuclei of active Galaxies (AGN)

- 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

# Fe-line diagnostics




eXTP-LAD simulation of
black hole X-ray binary
1ks integration
$a^* = 0.967 \pm 0.003$




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, black hole spin
- Observed in both Active Galactic Nuclei and X-ray binaries

**Moreover: X-ray polarimetry diagnostics of accretion disk**

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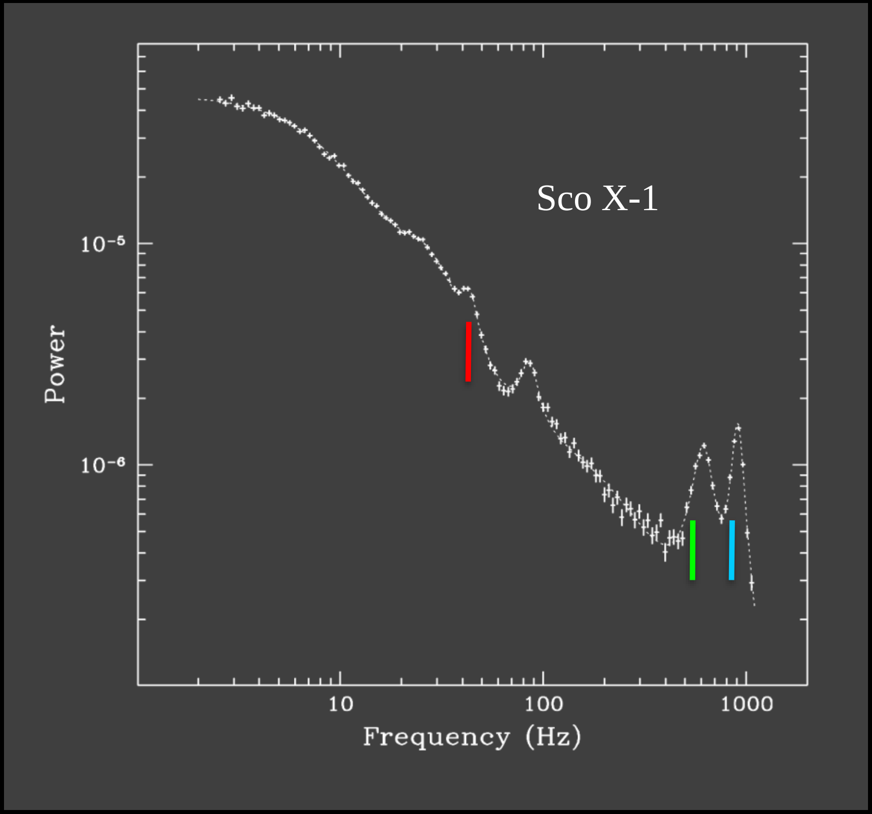
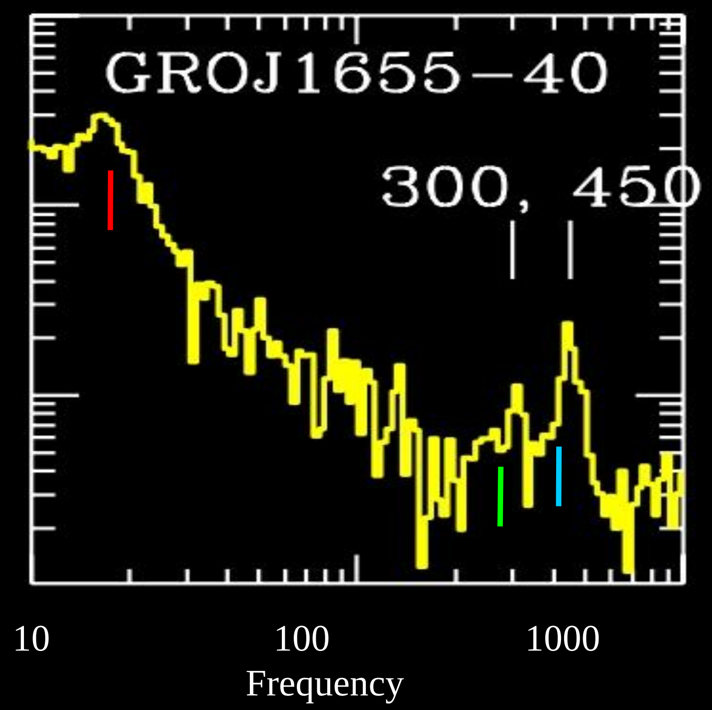
# Strong Field Diagnostic: Fast variability and Quasi Periodic Oscillations

## Accreting neutron stars

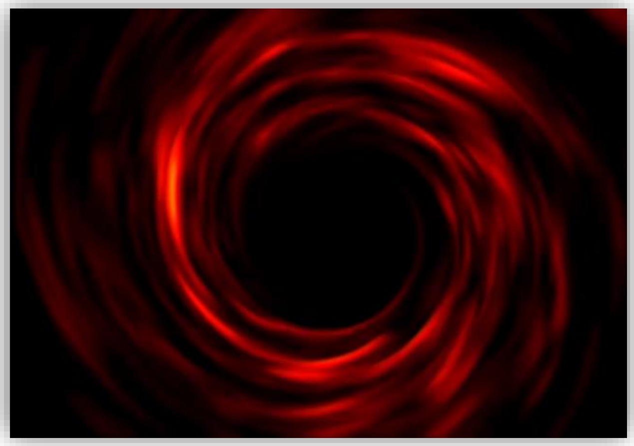


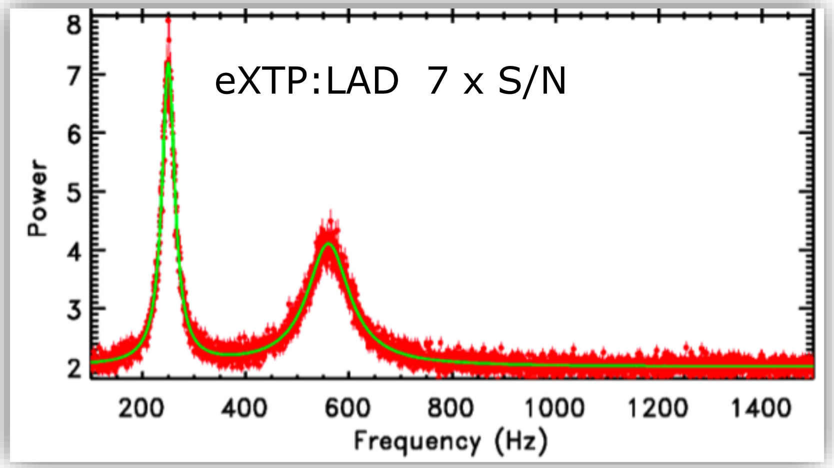

## Accreting black hole candidates



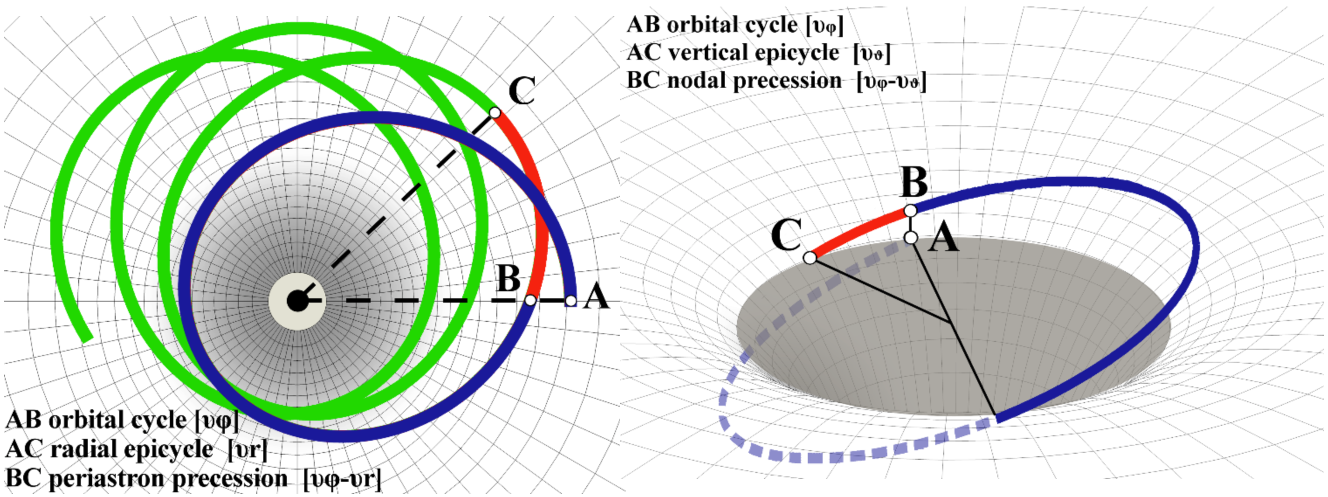
Strong field gravity diagnostics: Fundamental frequencies of motion in strong gravity

**Inhomogeneities in inner disk**

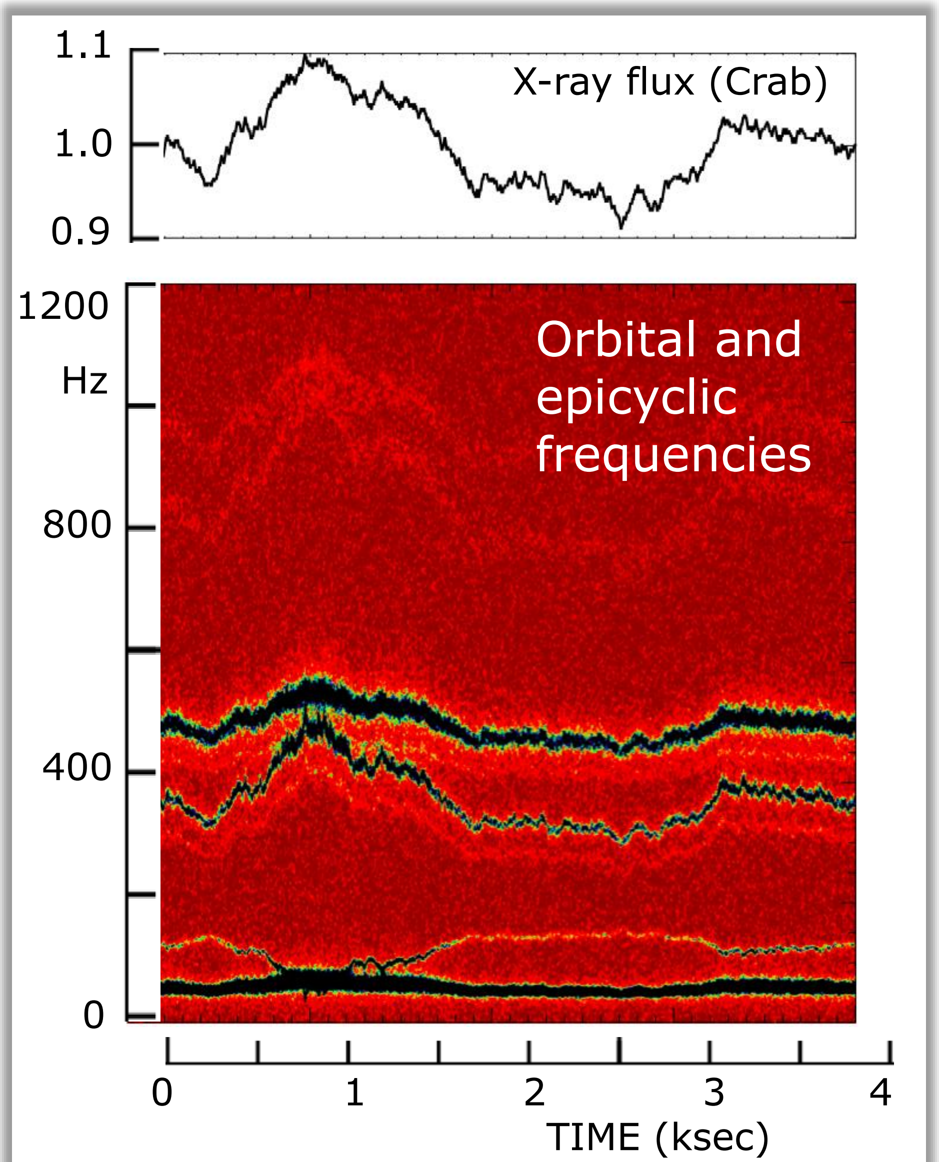


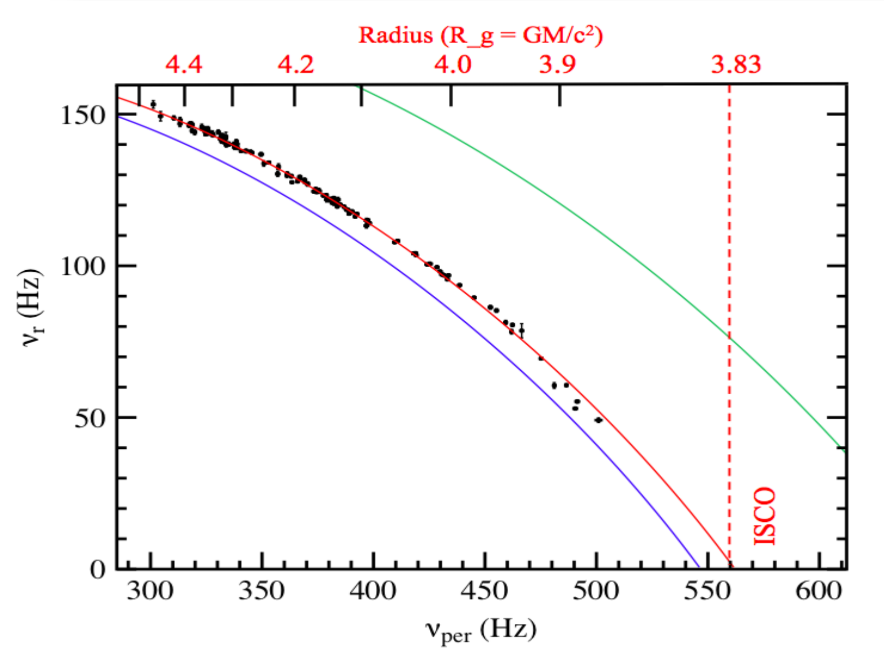



GR orbital, epicyclic and precessional frequencies



# Timing diagnostics: relativistic epicyclic motion

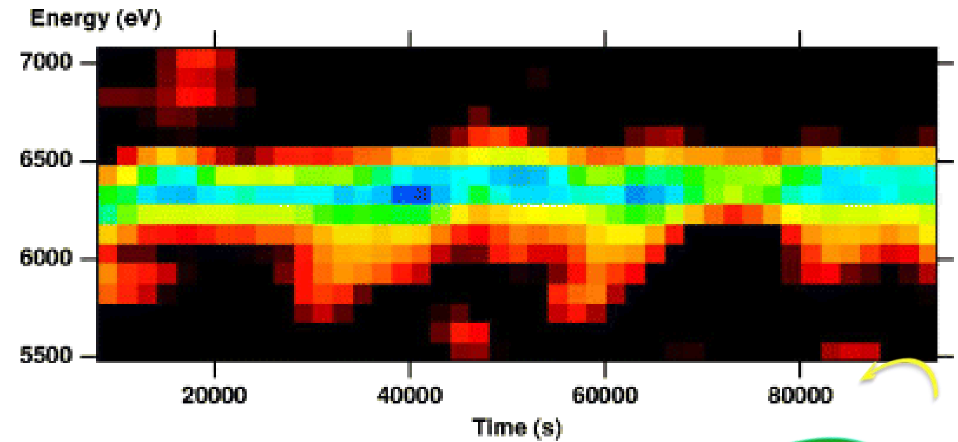


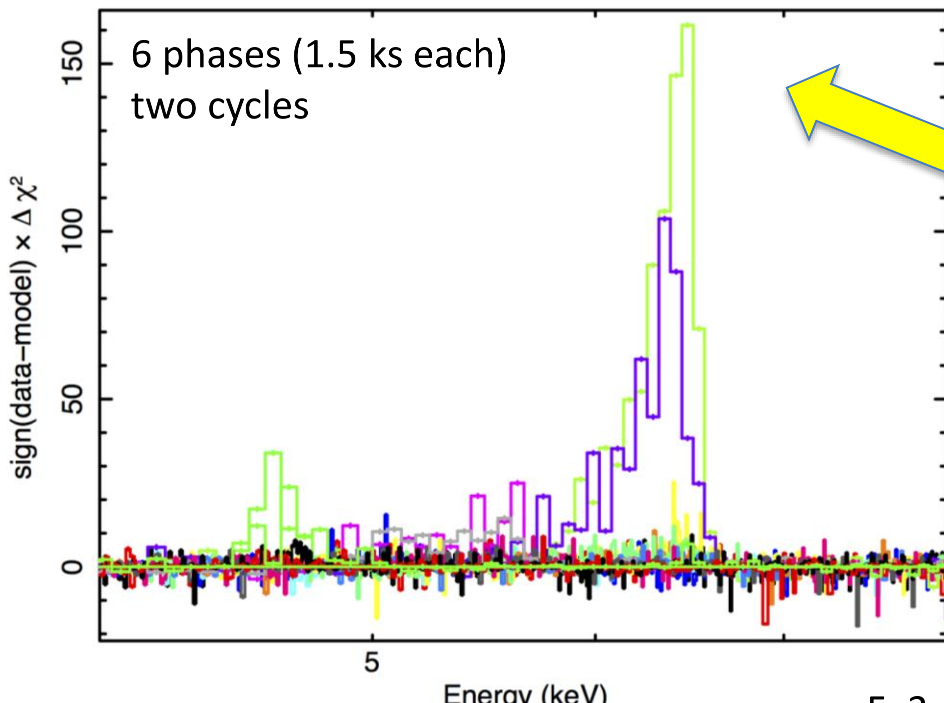



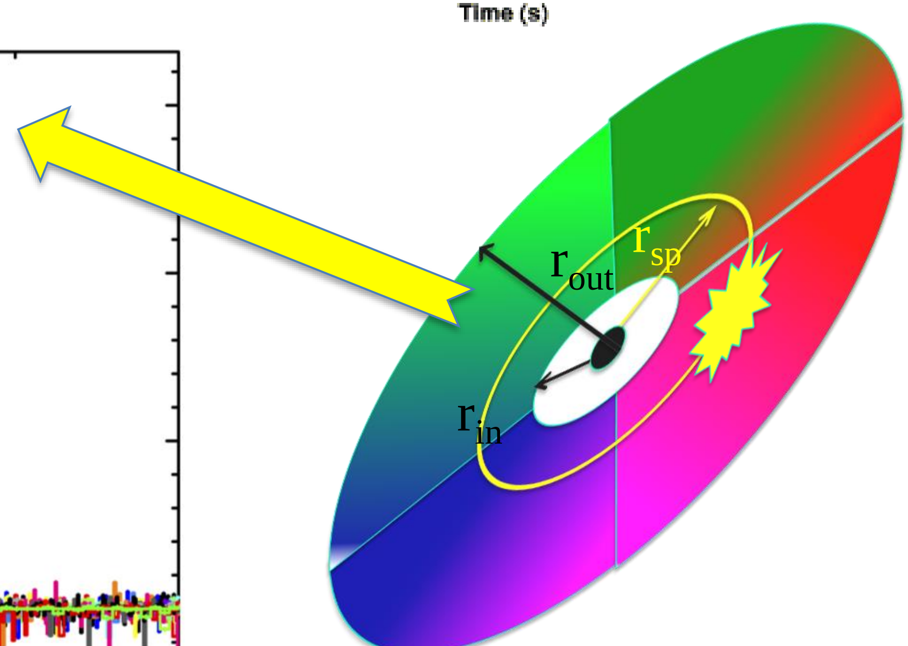

- Precisely measure orbital and epicyclic frequencies at each radius
- Compare to GR predictions
- Measure black hole mass and spin to < 0.3 % precision

# Spectral-Timing diagnostics
# Doppler tomography: orbital motion in AGNs

Orbiting spot:
XMM observations of NGC3516




F=3mCrab, EW=30 eV, a=0.5, $r_{in}$=1$r_g$, $r_{out}$=100$r_g$,
**M=3-4 $10^6$ $M_{sun}$, a=0.4-0.6**

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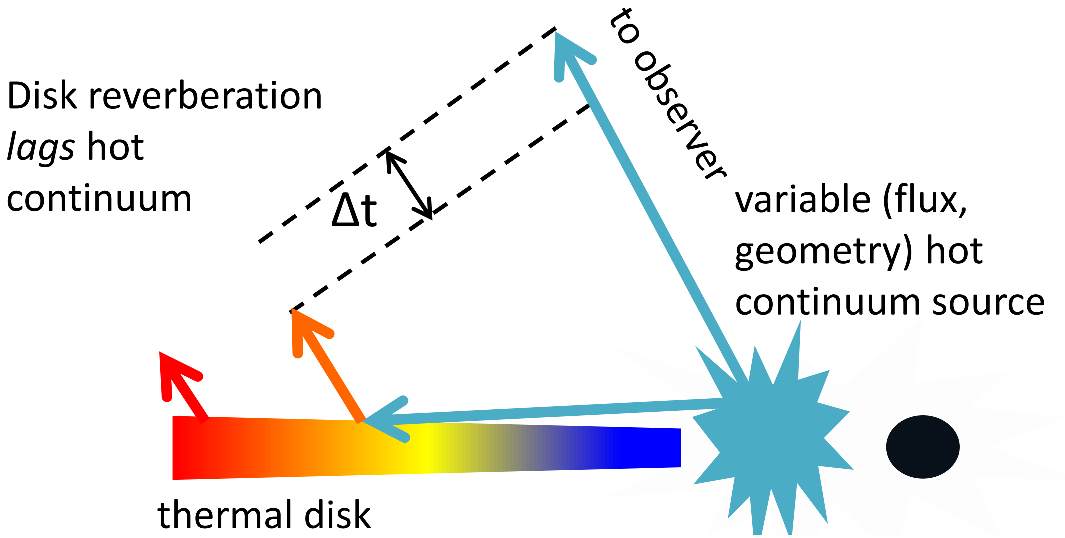
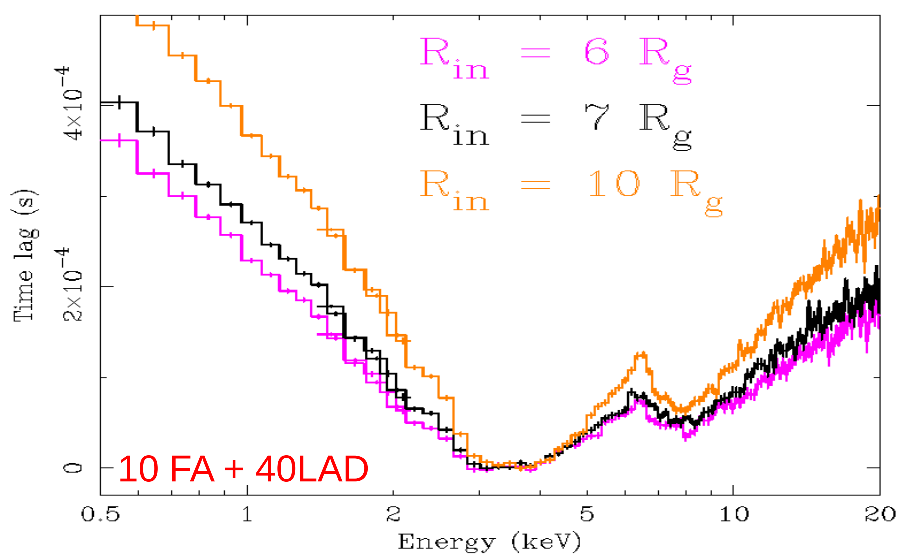
# Spectral - Timing diagnostics
# Reverberation: energy resolved light echoes




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




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!**

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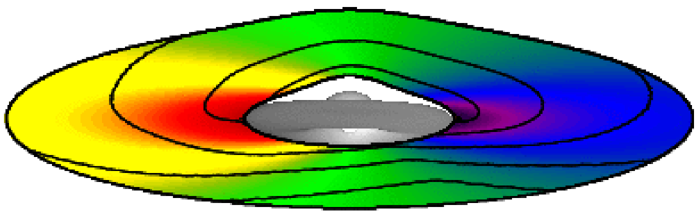
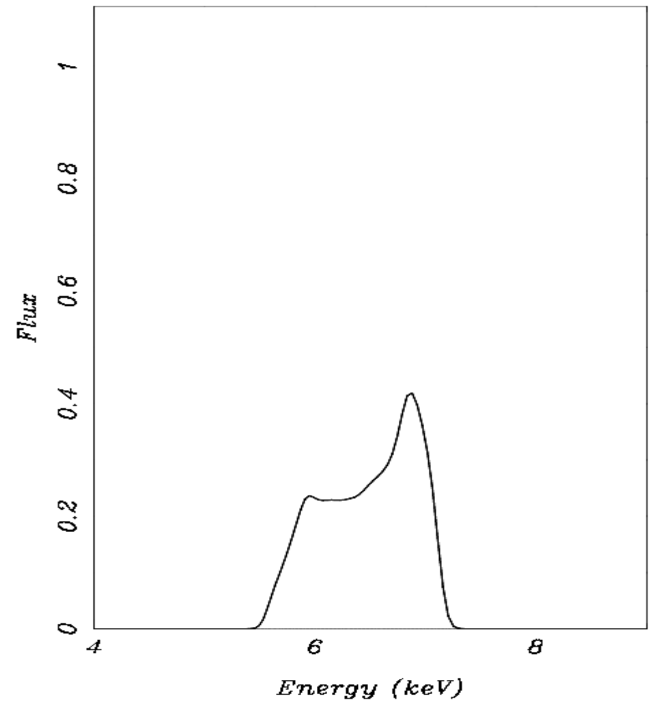
# Frame dragging nodal precession

Precessing hot torus:
reverberation



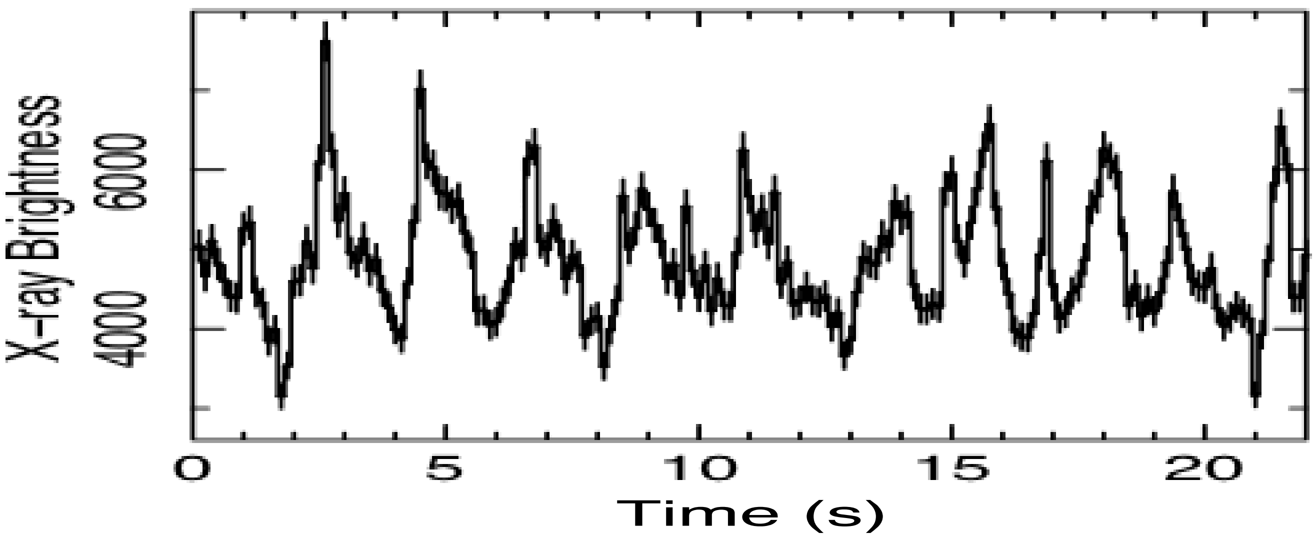


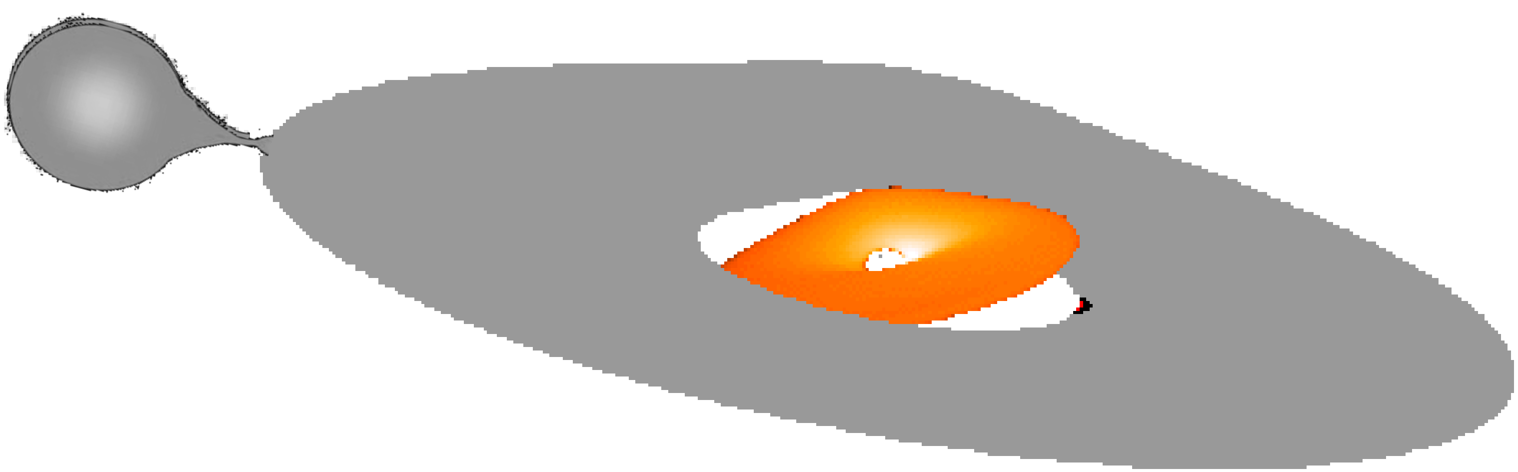

- Frame dragging: central hot torus <u>precesses</u>
- Hard radiation sweeps around over disk
- Reflection line profile varies periodically
- eXTP tracks the line profile, probing the disk velocity and redshift map

Ingram

# Frame dragging nodal precession: timing (QPO) diagnostics

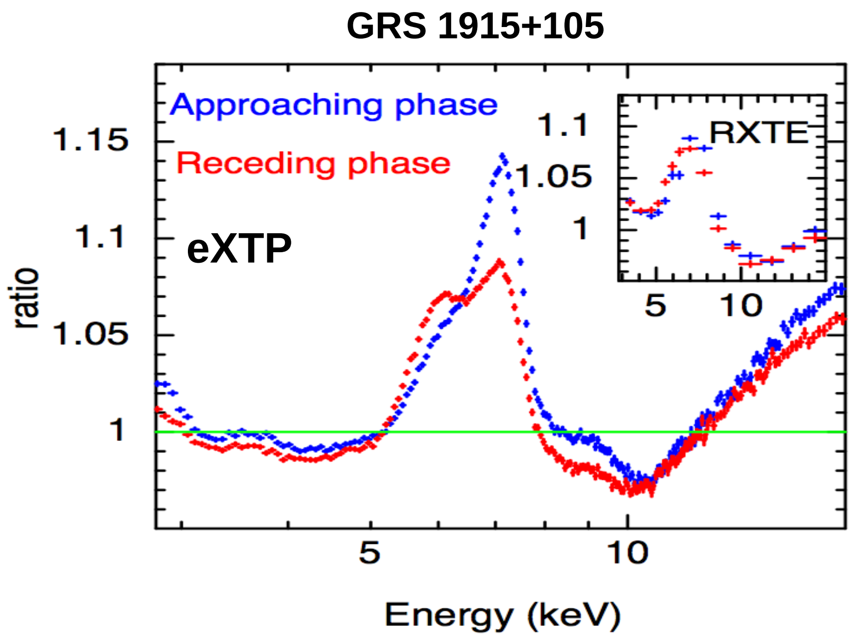
H 1743-322 – XMM

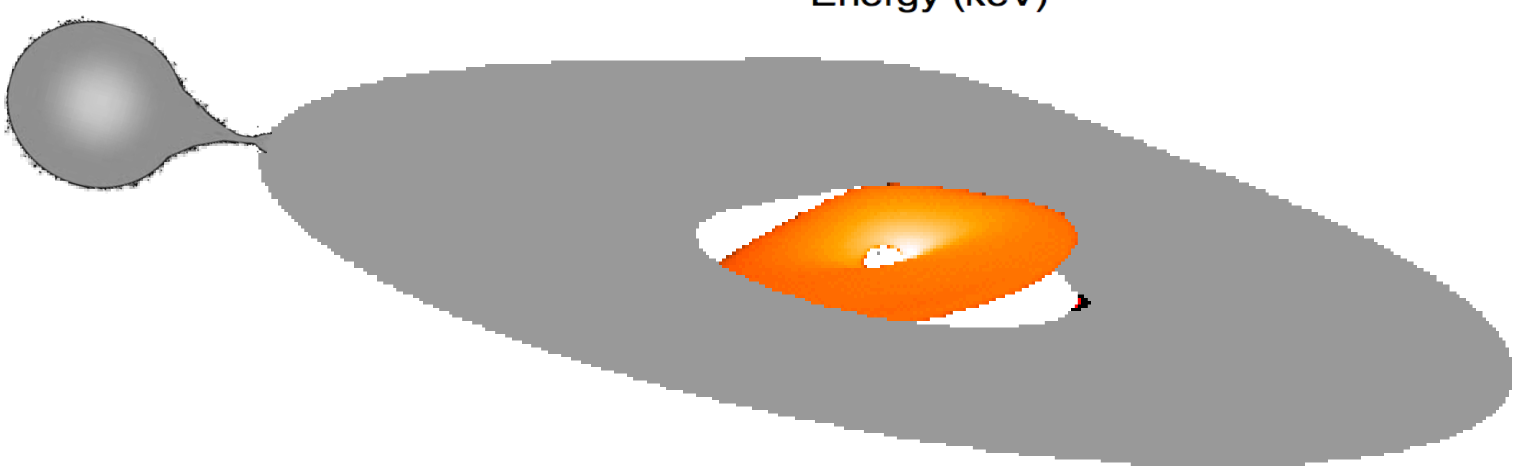


Ingram

# Frame dragging nodal precession: timing-spectral (Fe-line) diagnostics

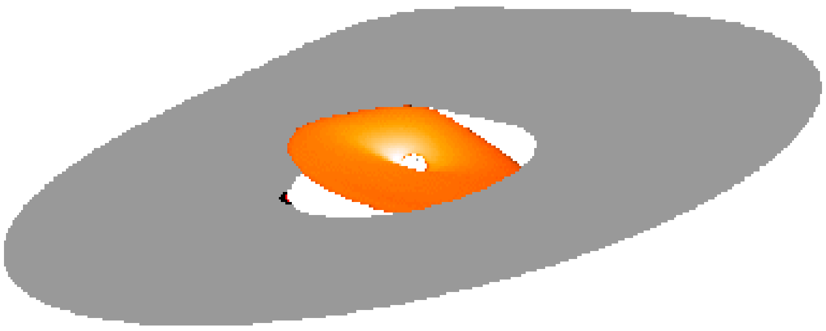


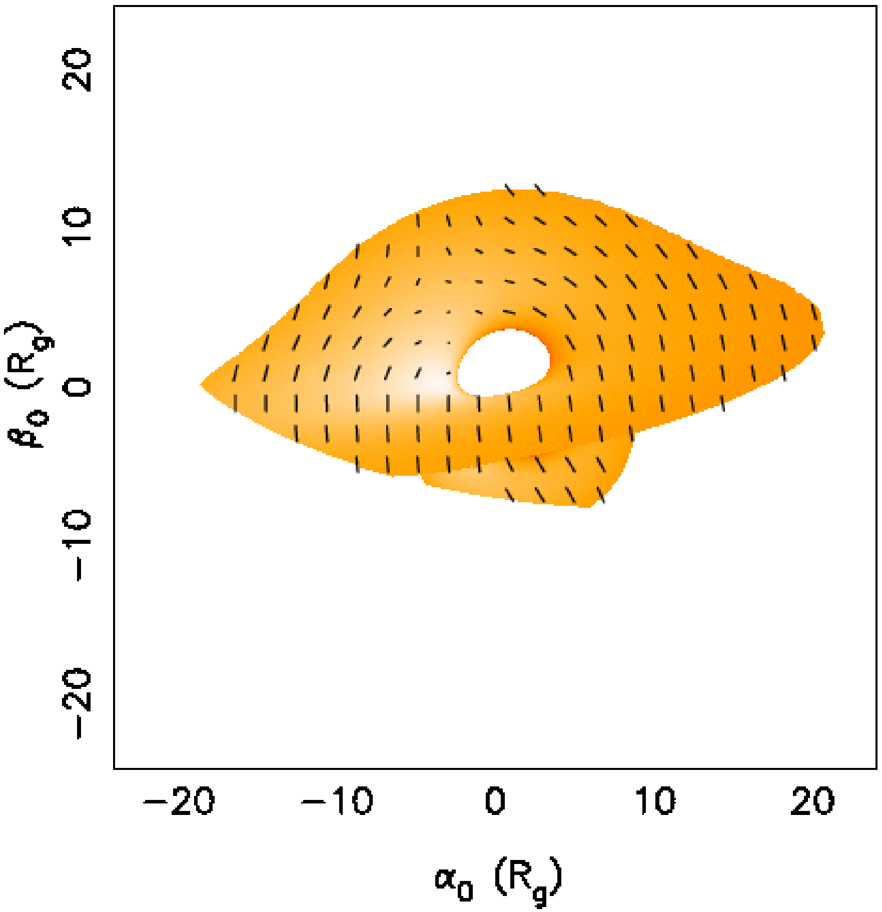



Ingram

# Frame Dragging: timing-polarisation diagnostics

$R_o$=20$R_g$, a=0.98

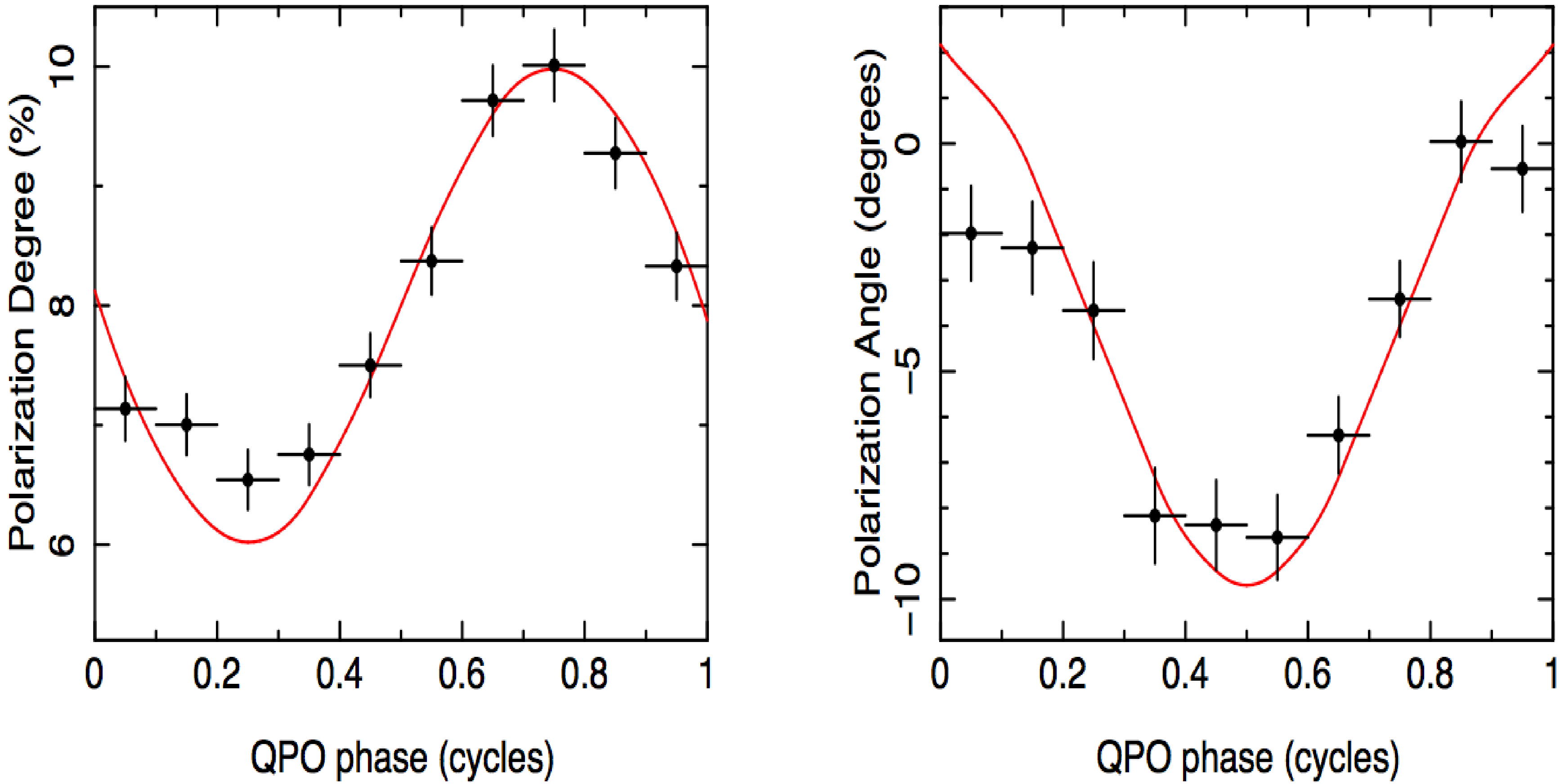





- polarization degree and angle affected by strong field light bending
- precession changes geometry and thus modulates polarization

Ingram

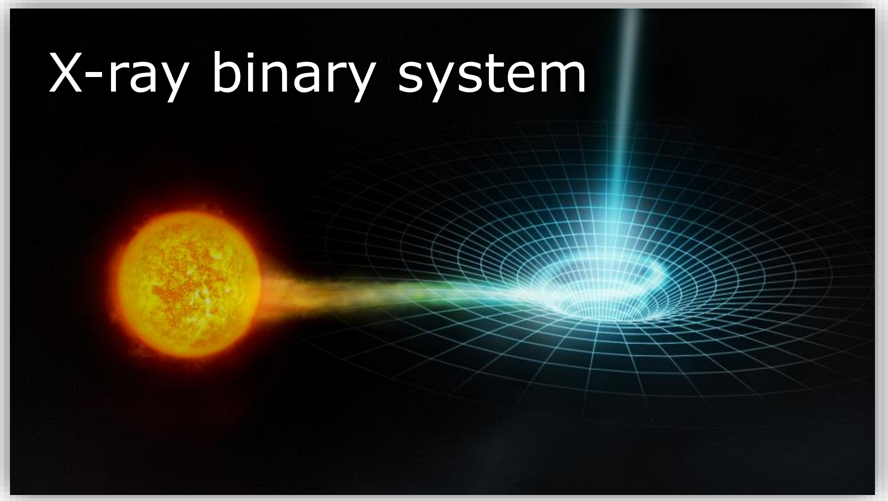
# Frame dragging: eXTP polarization measurements

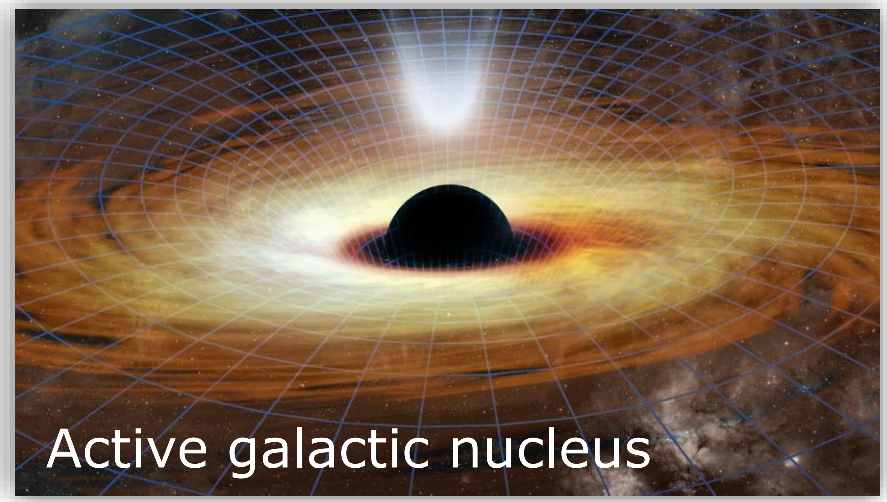



**Only eXTP can study frame dragging through the combination of Timing-Spectral-Polarimetry**

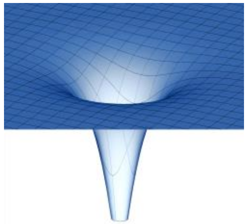
Ingram

# Accretion in strong field gravity: mass range



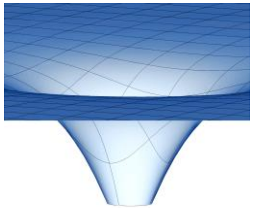




eXTP covers a very wide mass range in uniform setting



Stellar mass black hole
(or neutron star)

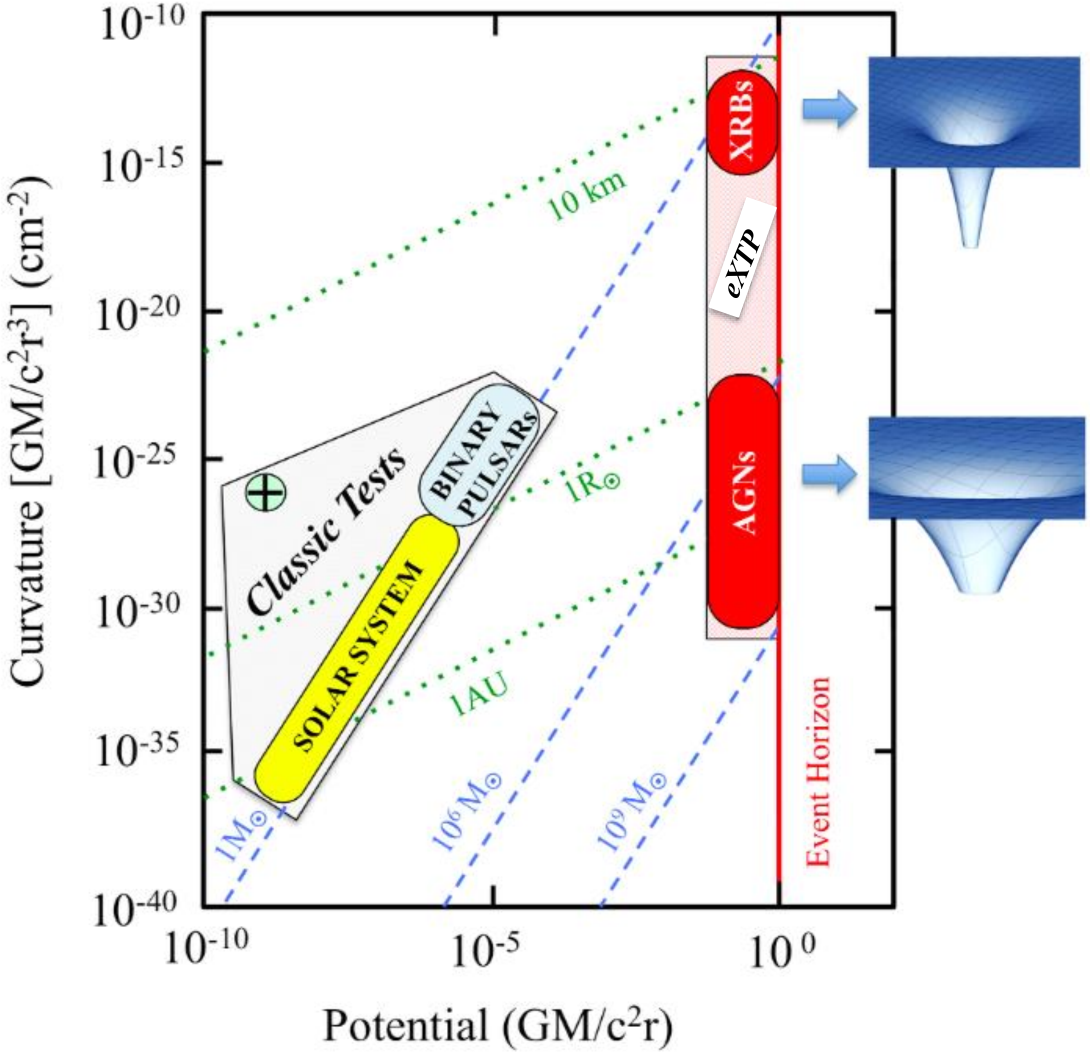
Strongly curved spacetime.
($10^{16}$ times Solar)



Supermassive black hole

Weakly curved spacetime
(~Solar)

COMPLEMENTARY TO GRAVITATIONAL WAVE EXPERIMENTS:
eXTP PROBES STATIONARY SPACETIMES




factor $10^{12}$ in curvature

factor $10^{5}$ in field strength

Test/constrain alternative theories of gravity that differ from GR only in the strong field regime, through X-ray diagnostics like Fe-lines and QPOs

Maselli

# eXTP Themes

Dense matter

Accretion in strong field gravity

Strong magnetism

Observatory science

# Strong Magnetism

- Polarization in accreting magnetic neutron stars
- Physics of magnetars
- QED effect: vacuum birifringence in high B-fields
  - different index of refraction in O-mode and X-mode
  - X-ray linear polarisation bosted by QED effect

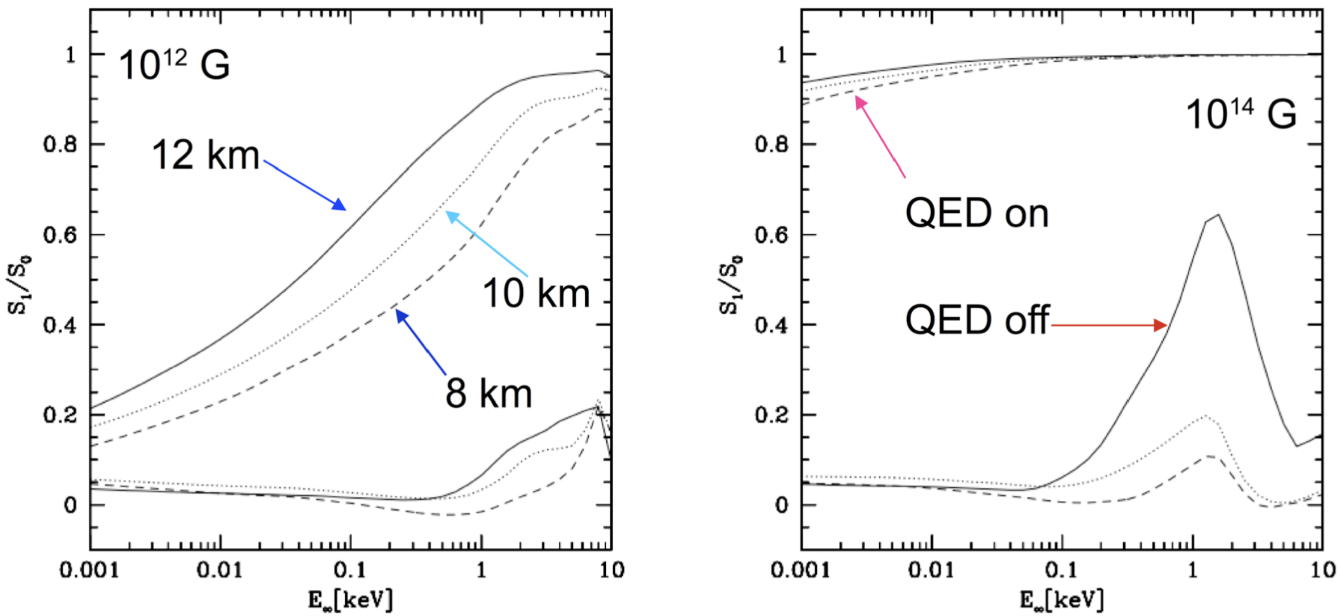



Figure 15: The expected fraction of linear polarization from the surface of strongly magnetized neutron stars with hydrogen atmospheres and effective temperatures of $10^{6.5}$ K. (from Heyl et al. 2005).

# eXTP Themes

Dense matter

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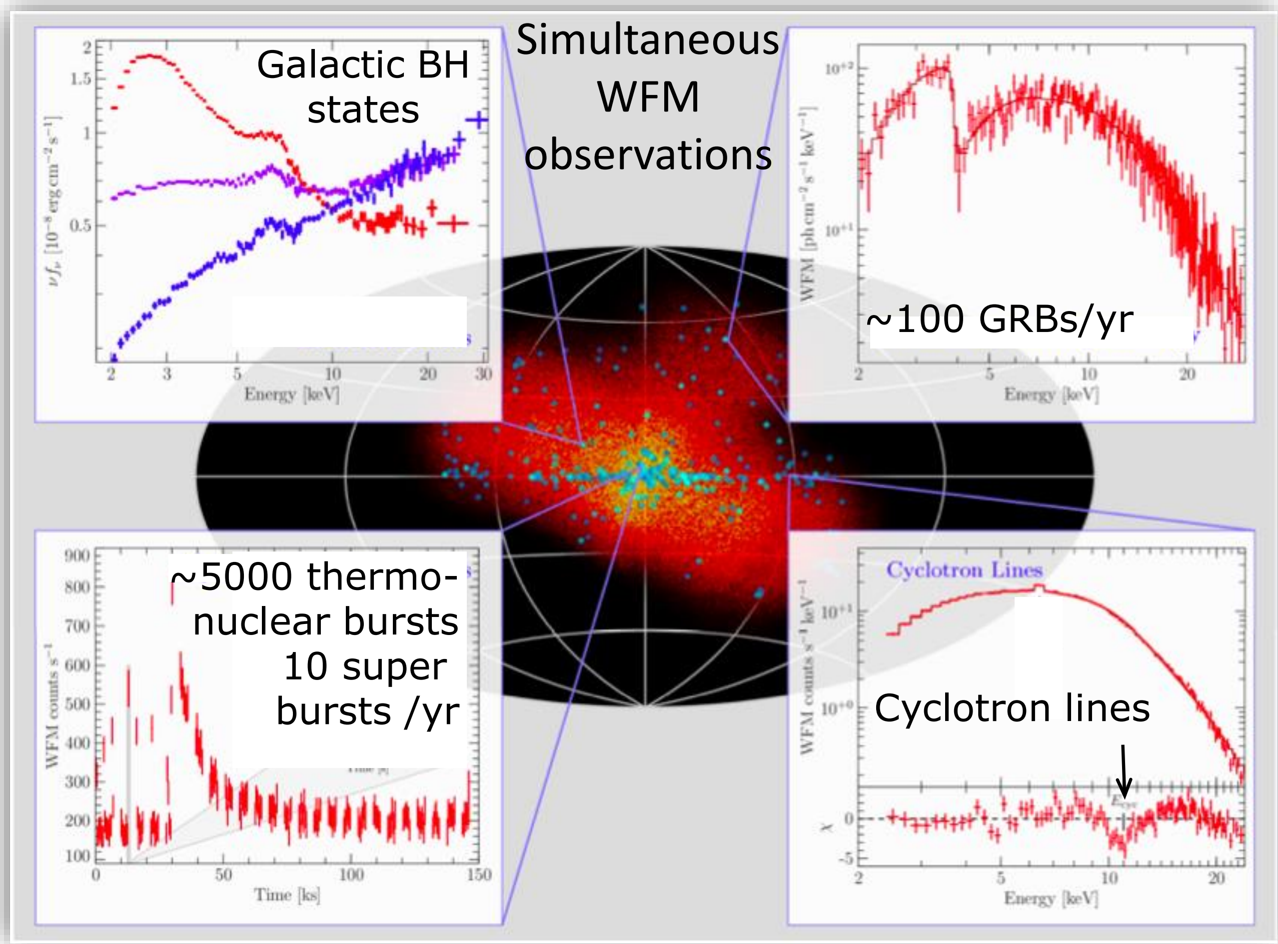
Strong magnetism

Observatory science

# Observatory science: Wide Field Monitor

Very wide field (4 ster) monitoring of the sky




**-> Search for X-ray Counterparts of LIGO/Virgo Gravitational Wave events**

# Conclusions

- **High throughput X-ray spectral/timing with polarimetric capabilities are unique features of eXTP**

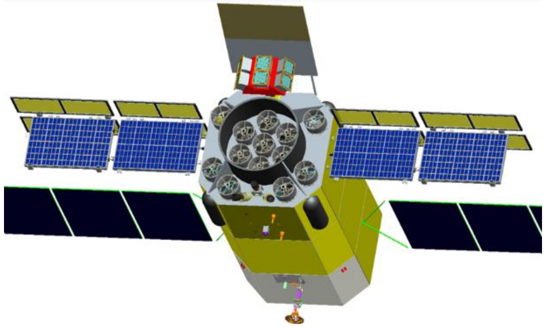
- Huge potential for **transformational advances in dense matter, strong field accretion and strong magnetism studies**.

- **Observatory science programs** (many based on WFM data)

-

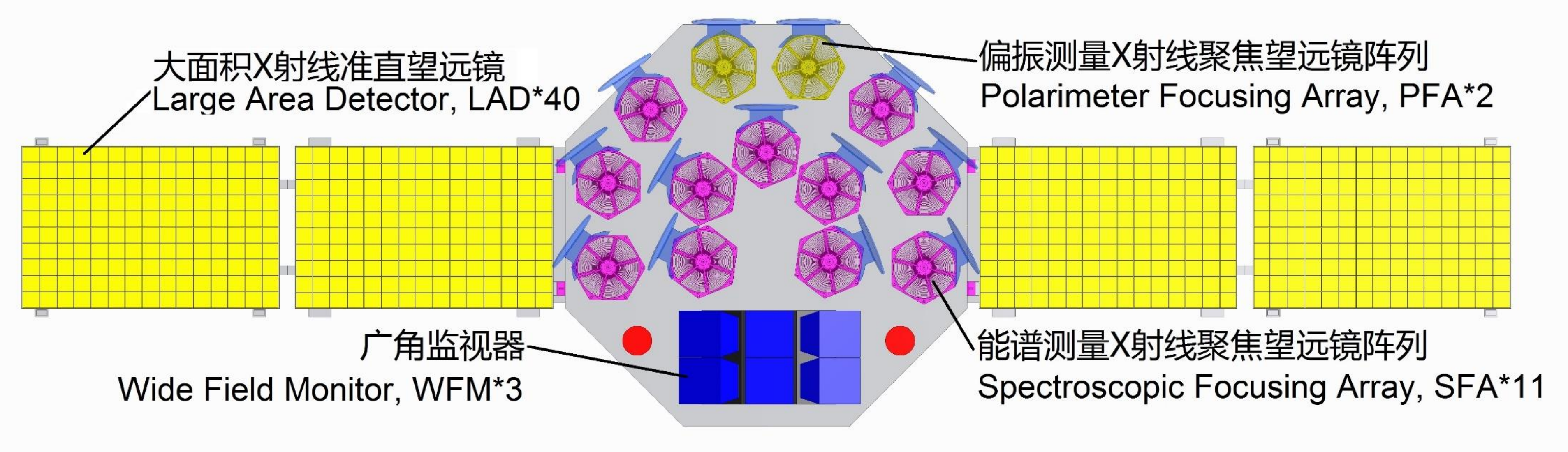
# eXTP

## enhanced X-ray Timing and Polarimetry



Payload characteristics

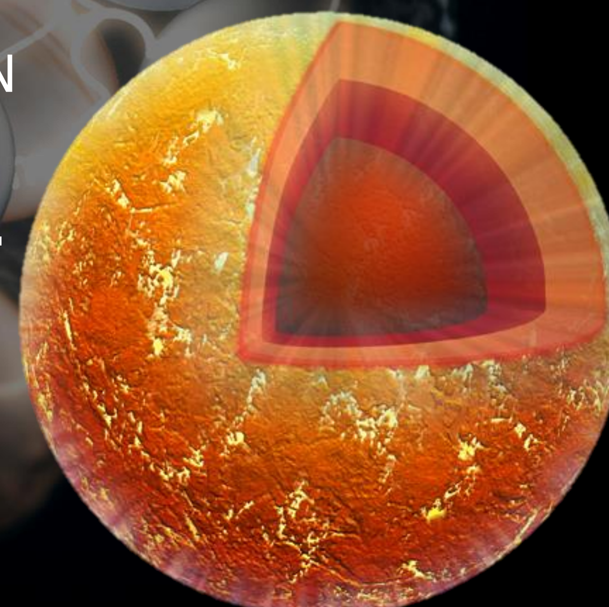
- Short focal-length for multiple modules
- Deployable panel for collimated modules
- Polarimeter with imaging capability
- Wide field monitor



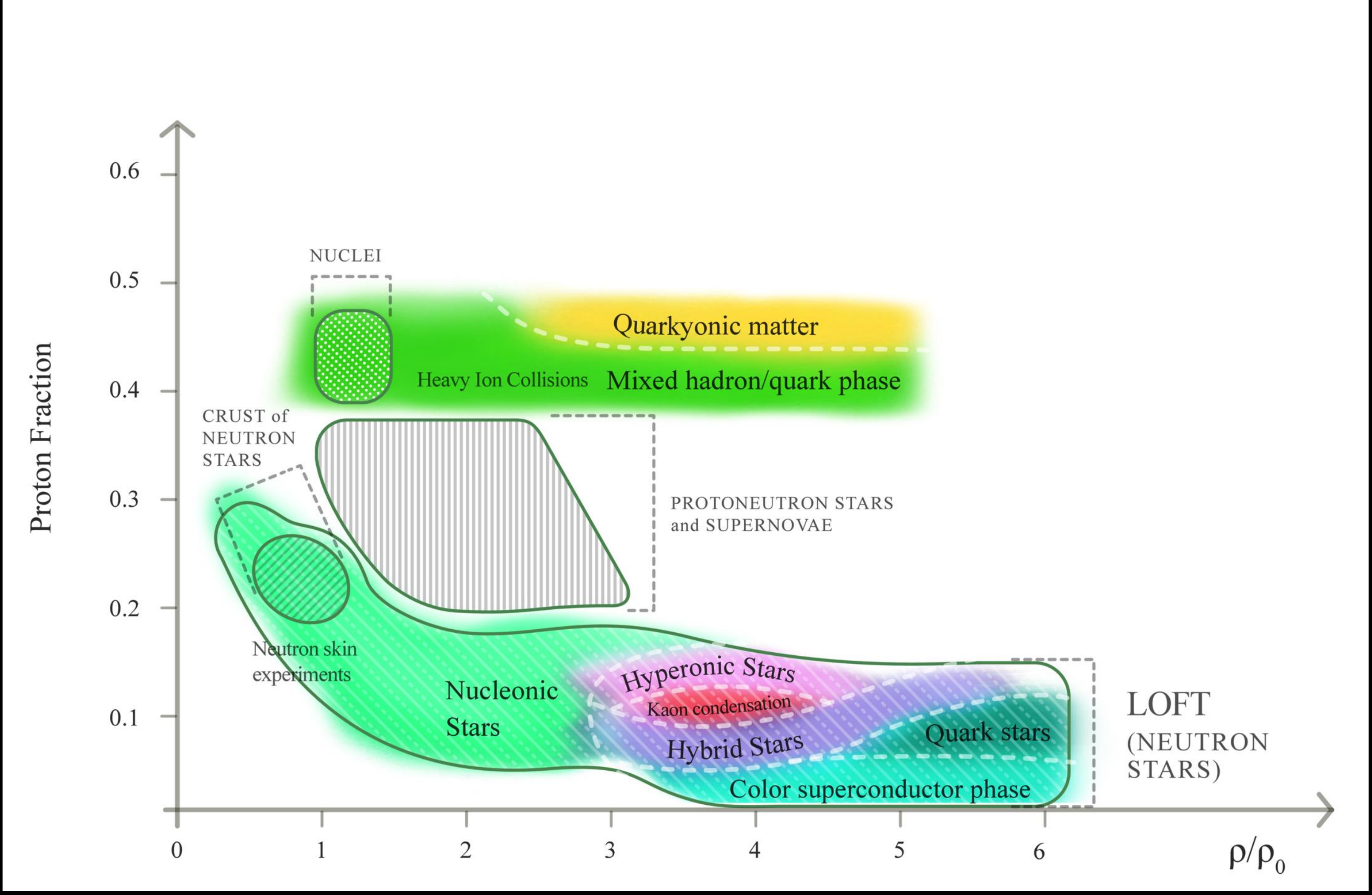
The strong force determines the state of nuclear matter - from atomic nuclei to neutron stars.

It is a major problem within modern physics.

PROGRESS IS DRIVEN
BY **EXPERIMENT**
AND **OBSERVATION**.

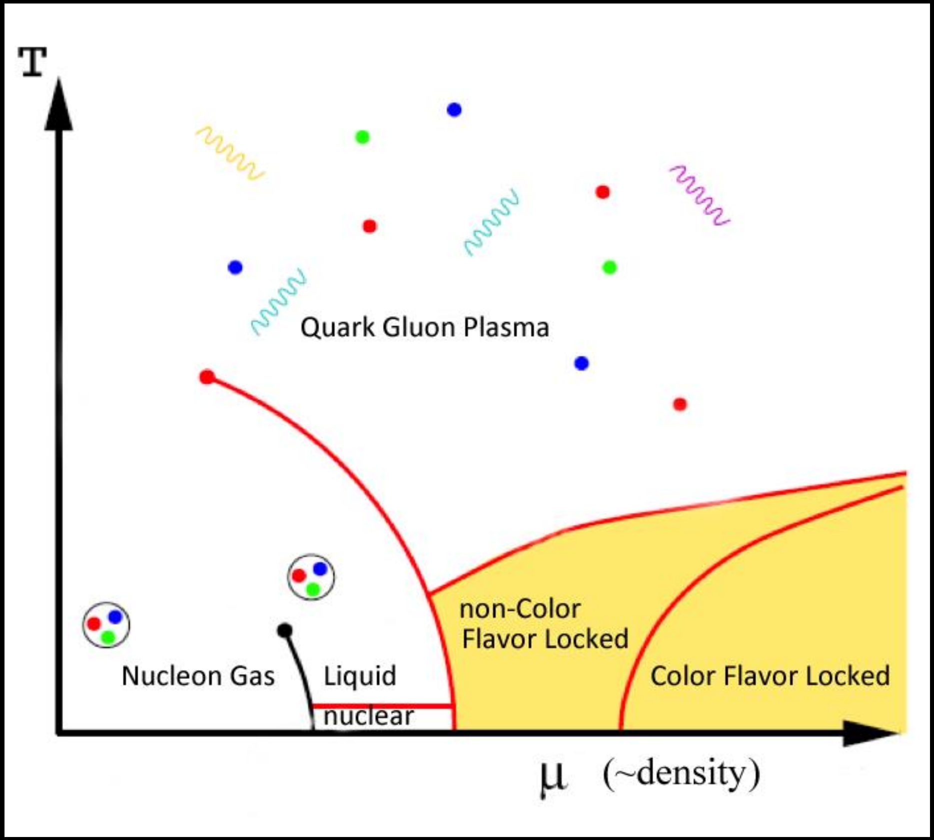


# Role of weak interactions



# QCD Phase Diagram

- Little known on the properties of bulk matter at supernuclear densities
- Color Flavor Locked (CFL) phase expected asymptotically (high mu)
- Quark Gluon Phase at high T and mu
- Gas and liquid phases of nuclei at low mu
- Normal Quark phase or other exotic Phases in between (e.g. two-flavor color superconducting phase(2SC), gapless 2SC phase)




Heavy ion collision experiment sample the high-energy regime (> 100 GeV/nucleon, i.e. high T in the diagram)

**Low energy regime can only be studied through compact stars**

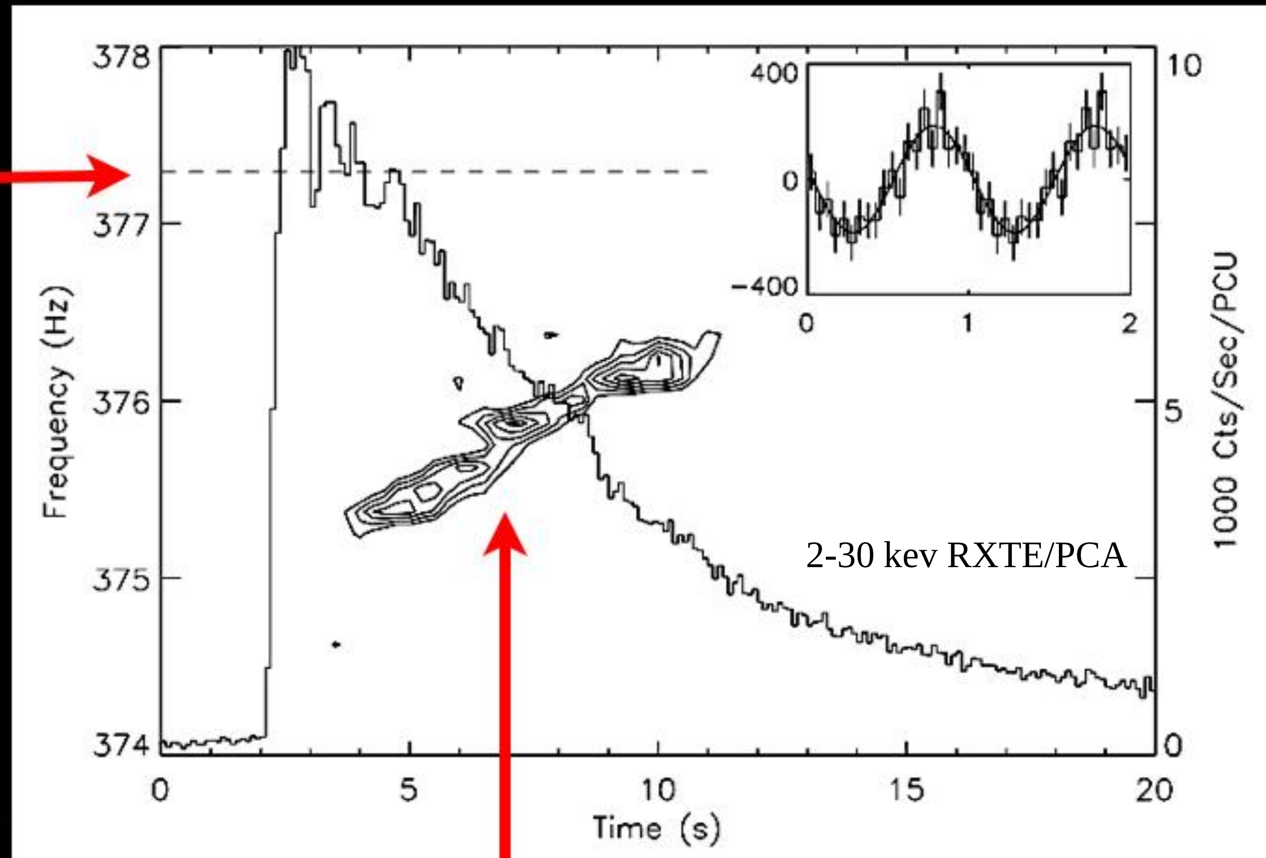
# Dense Matter

- 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

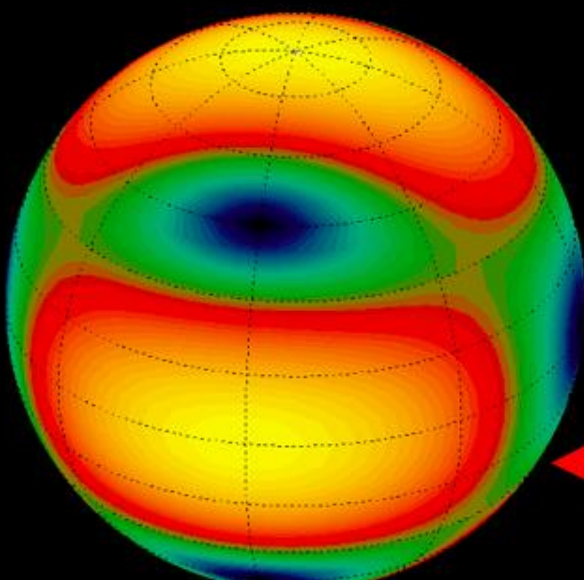
- Physics of strong force
  - QCD Diagram

# Thermonuclear burst oscillations

Spin frequency

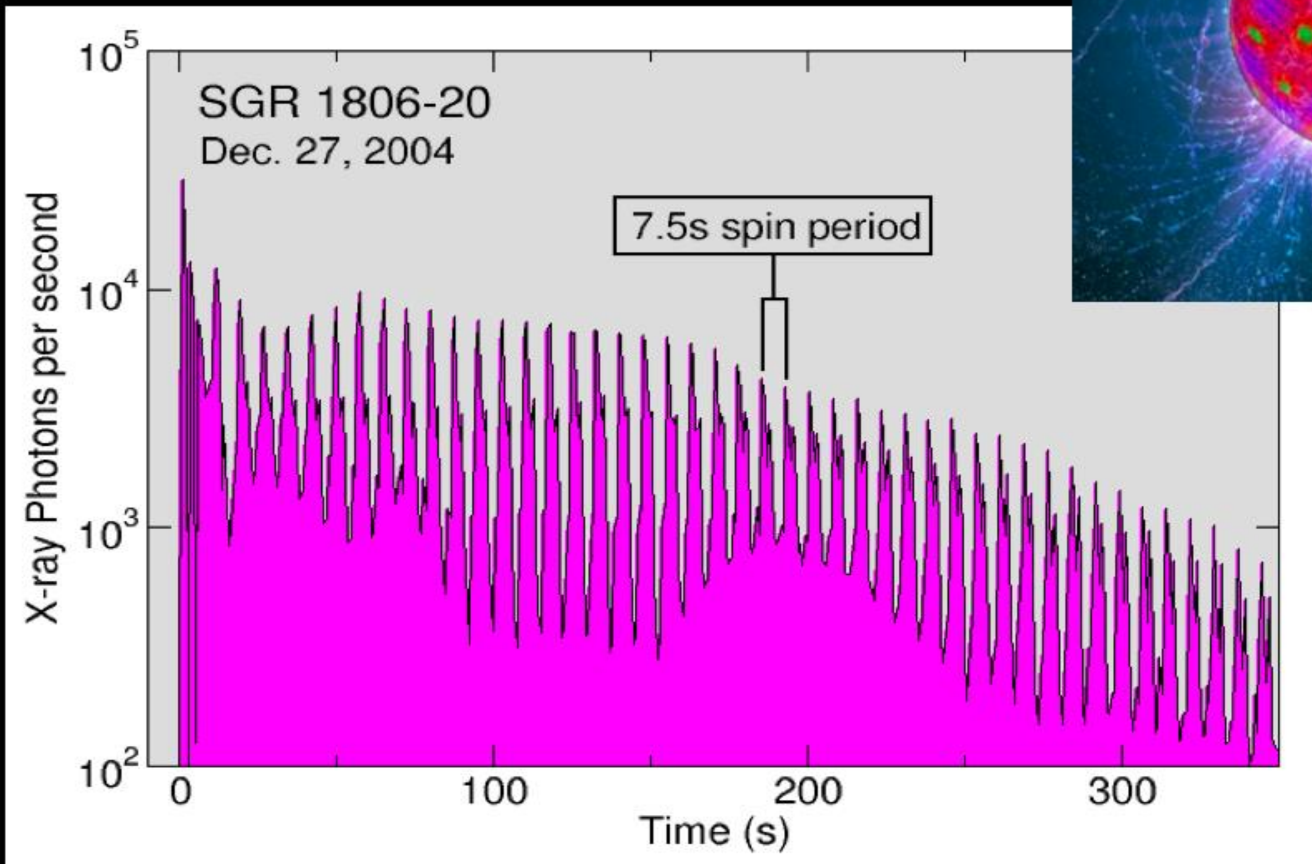


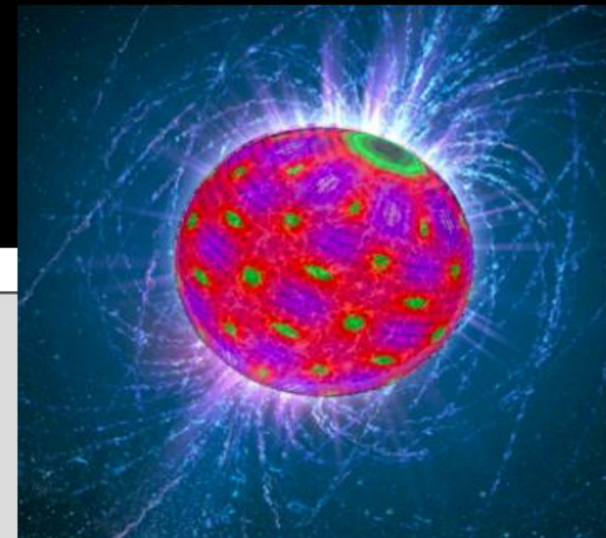

Watts et al. 2009



Drifting hotspot

# Magnetar seismology



# Strong Field 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)
- relativistic precession

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

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

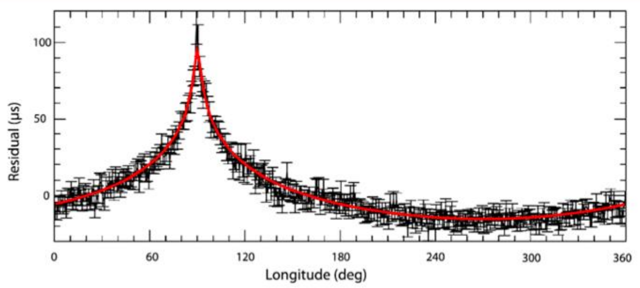
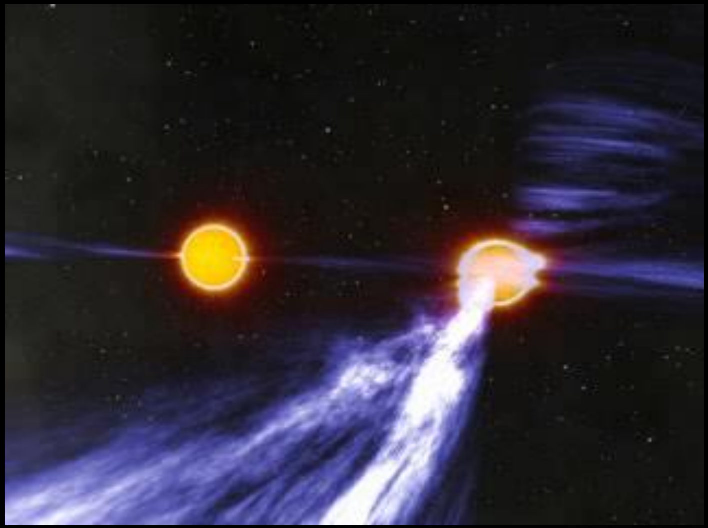


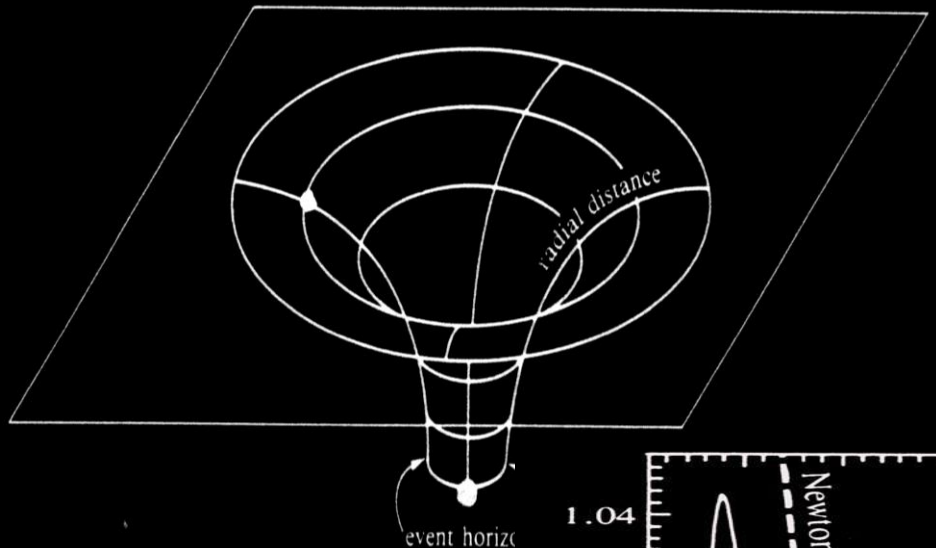

Figure 2.4: The Shapiro time delay measures the relativistic time delay experienced by the pulses from one of the pulsars in the double pulsar system PSR J0737-3039A as they pass through the strong gravitational field of the other neutron star. The red line shows the predicted delay based on General Relativity, and the agreement is within 0.013% of the theory, providing one of the best tests in the strong-field limit (From Kramer et al. 2006, Science 314, 97).



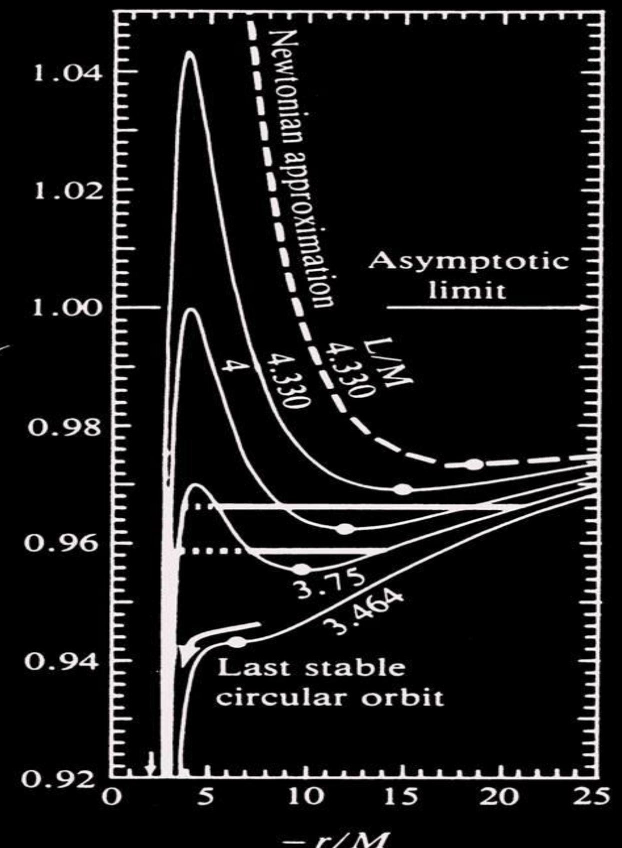
| PSR |
|---|
| J0024-7204H* |
| J0024-7204J* |
| J0045-7319 |
| J0437-4715** |
| J0514-4002A* |
| J0621+1002 |
| J0737-3039A |
| J0737-3039B |
| J0751+1807 |
| J0823+0159 |
| J1022+1001 |
| J1023+0038** |
| J1141-6545 |
| J1518+4904** |
| J1537+1155 |
| J1600-3053 |
| J1603-7202 |
| J1614-2230 |
| J1623-2631*, ** |
| 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.

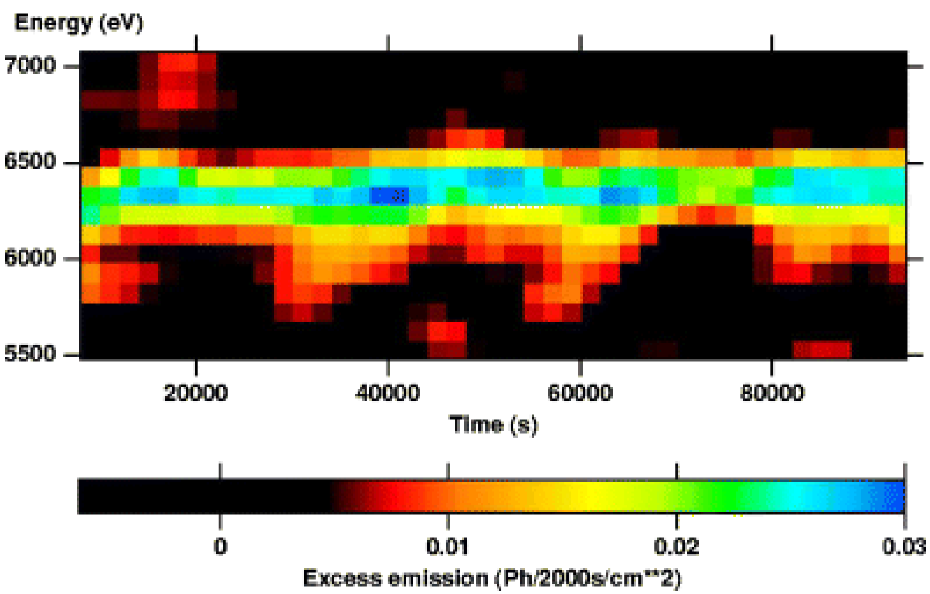


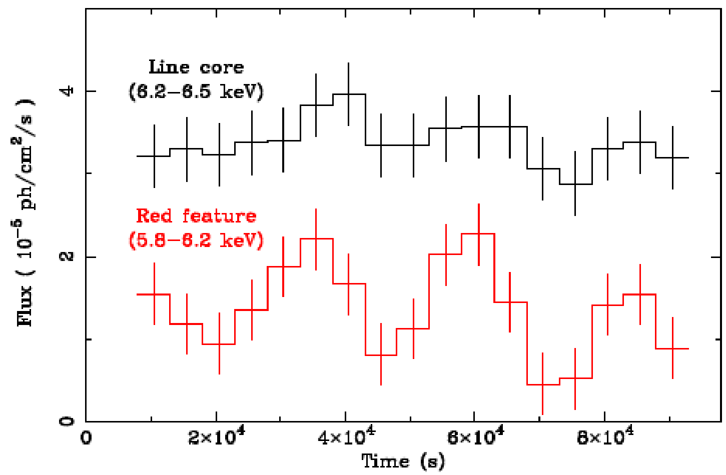

- Last Stable Circular orbit, aka ISCO ( 6 $R_g$ -> 1 $R_g$)
- Particle motion around ISCO and fundamental frequencies of motion
- Dragging of inertial frame
- Strong field light deflection
- Black hole mass and spin



# Combining spectral and timing measurements:

# Orbiting spot: XMM observations of NGC3516



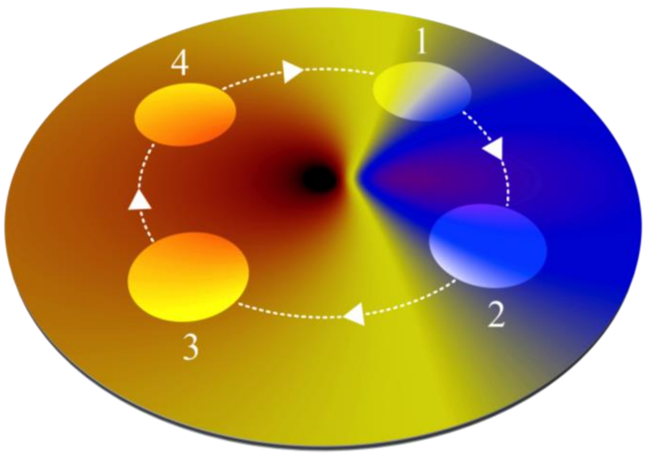




The excess emission map in the time–energy plane. The pixel size is 2 ks in time and 100 eV in energy. 4 cycles 25 ks orbital period at 9 Rg (XMM - Iwasawa+2004, Turner+2006)

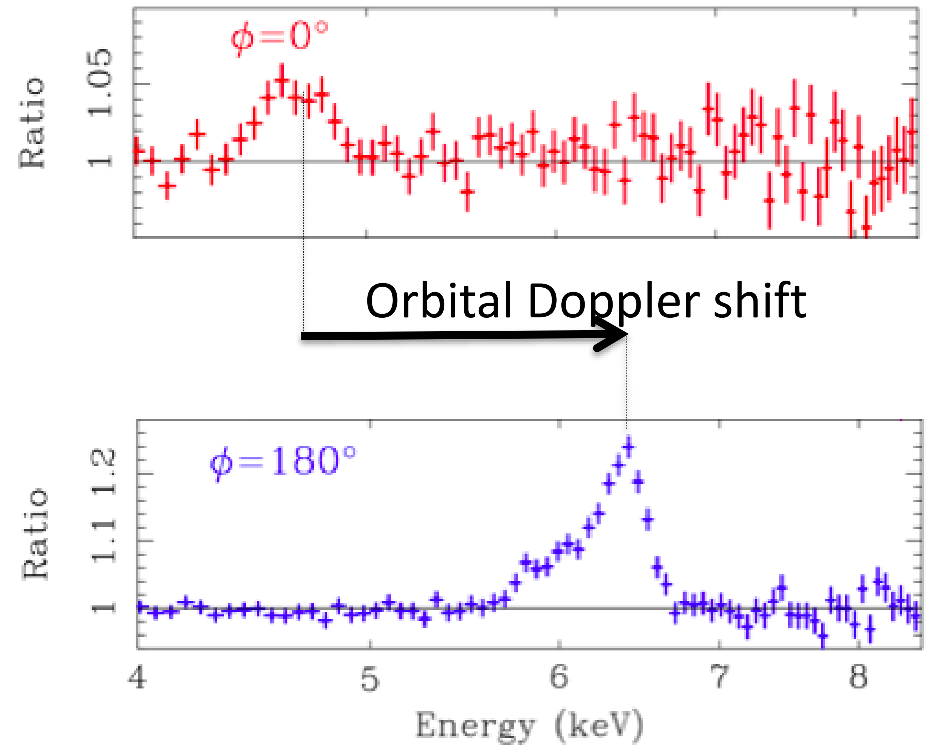
$M_{X\text{-}ray}$=1-5 $10^7$ $M_{sun}$ ; $M_{opt}$=1.68(0.33)$10^7$ $M_{sun}$

Orbital motion Doppler Tomography: AGN

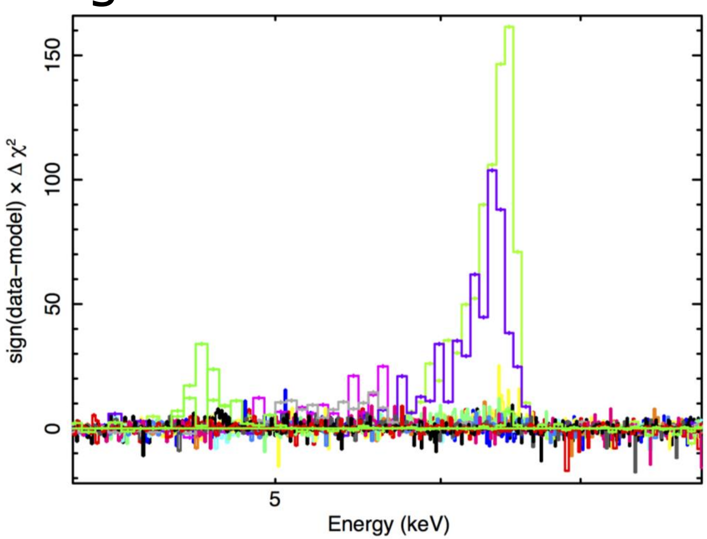
## Supermassive black hole




## LOFT 3 ks integrations



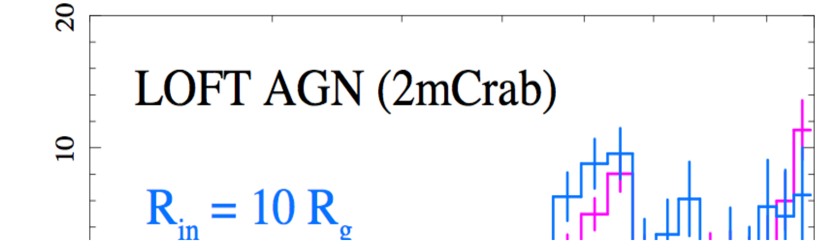

## eXTP 1.5 ks 2x integrations

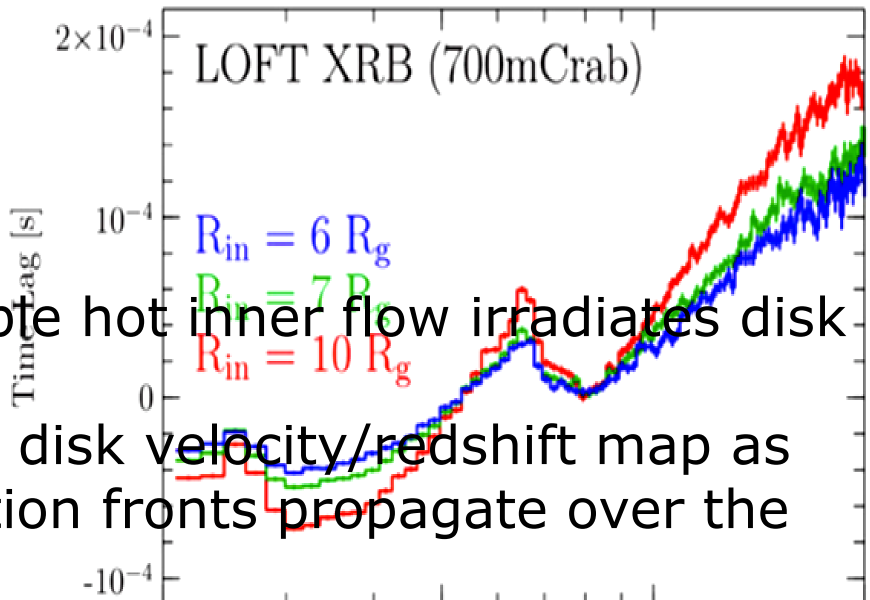



Doppler shifting for orbits closely around a <u>supermassive</u> black hole

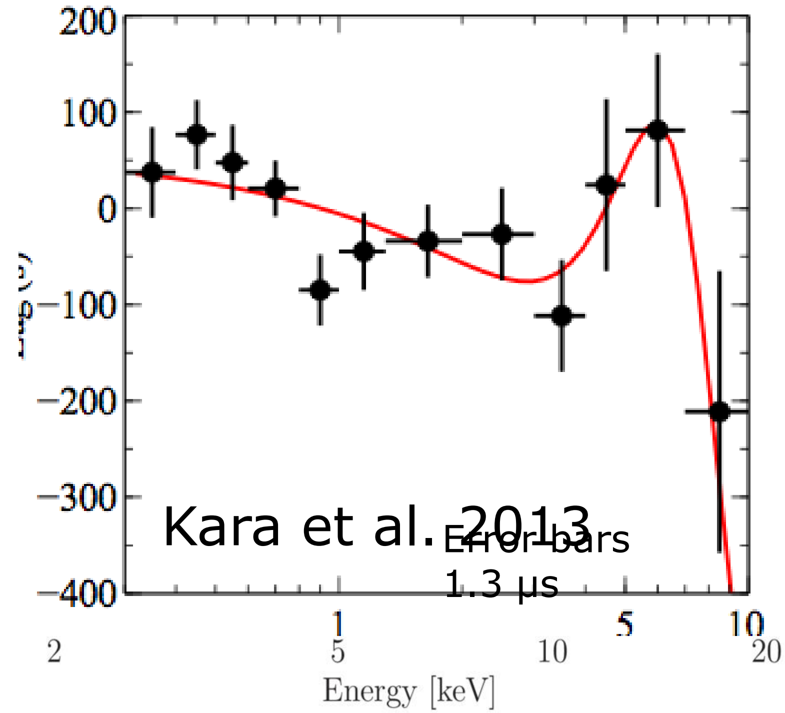
# Reverberation

refle
iron
*lags*
cont




- 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

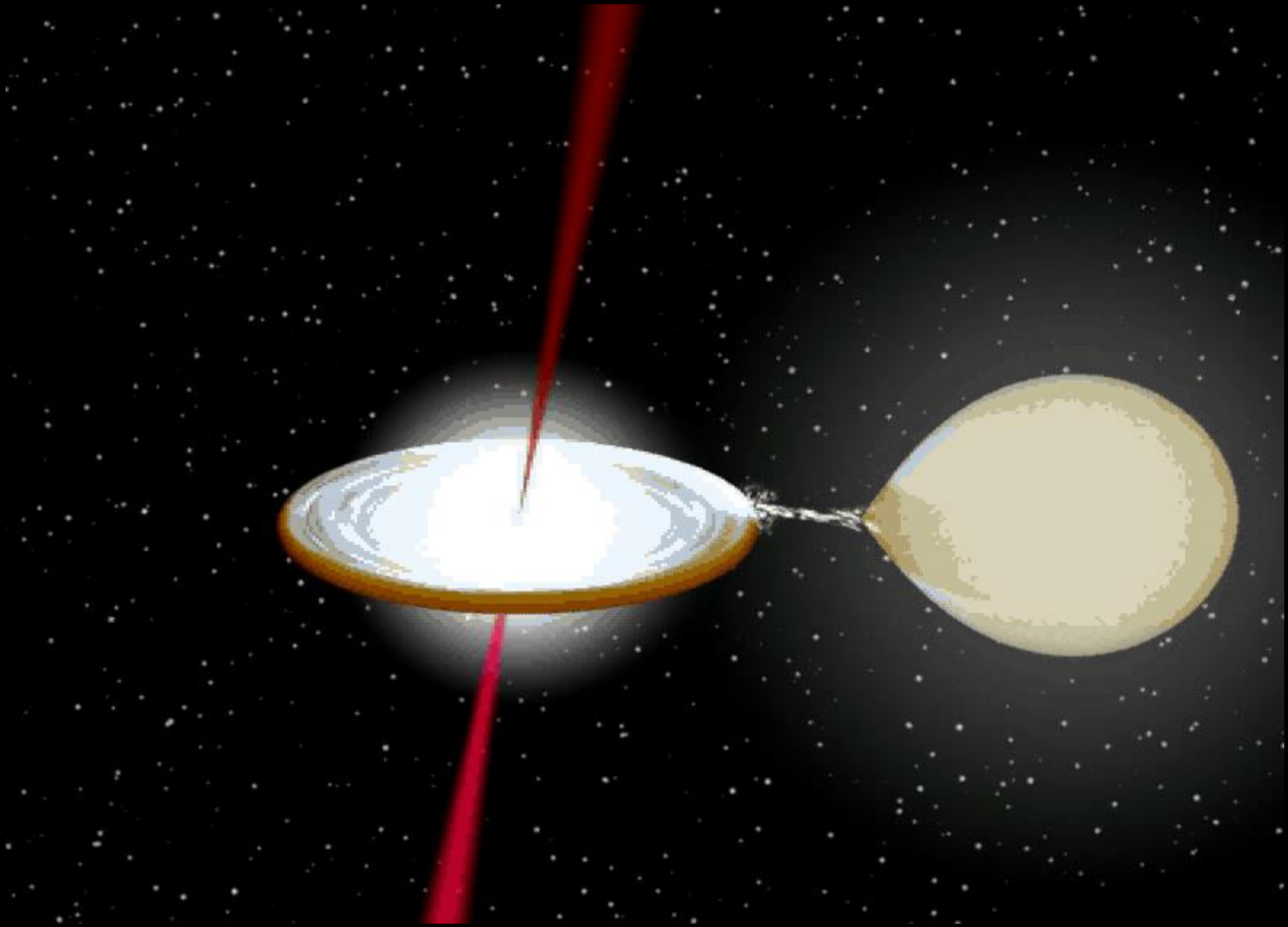



Kara et al. 2013

Error bars
1.3 μs

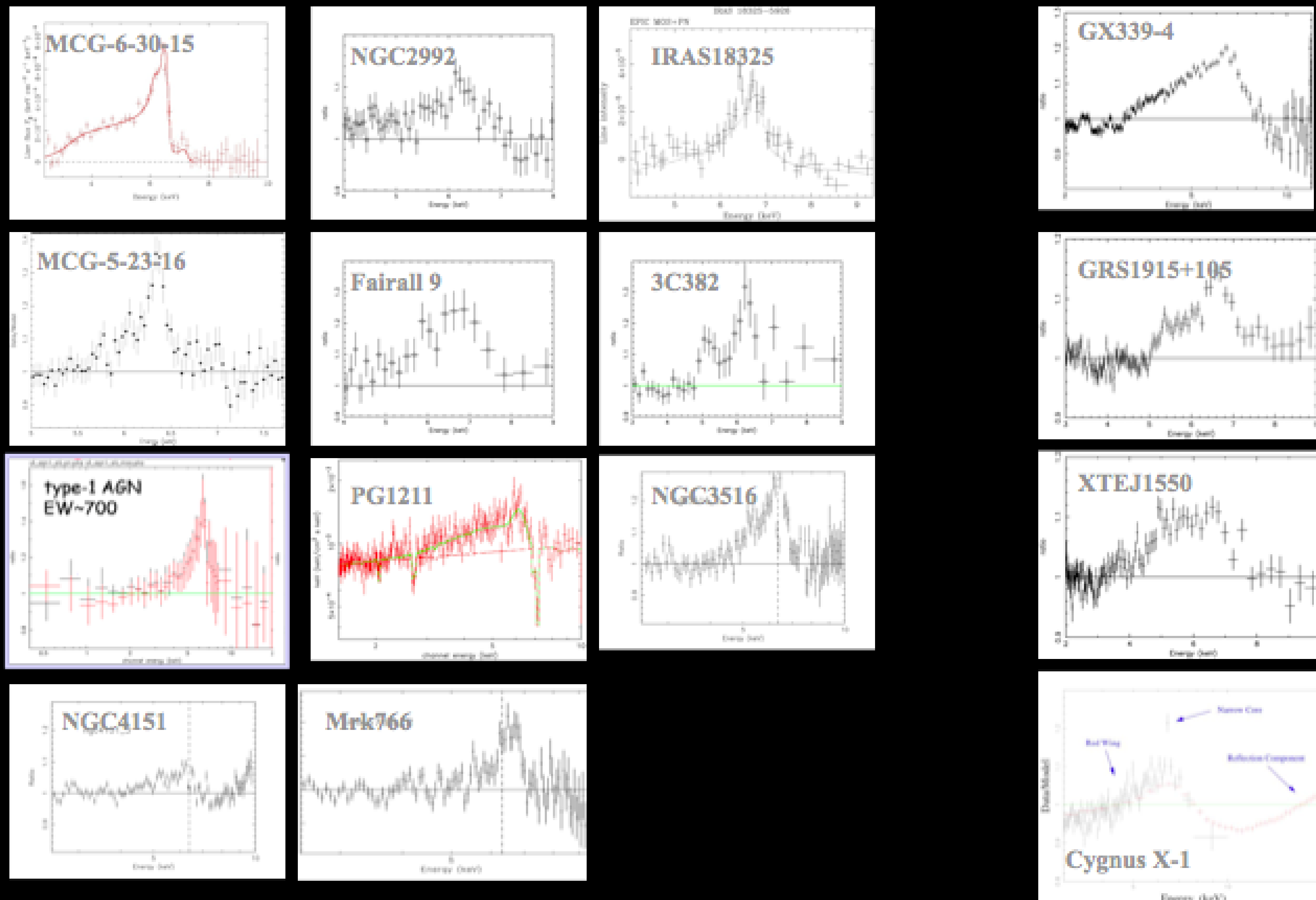
Reverberation (barely) detected in XMM data

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

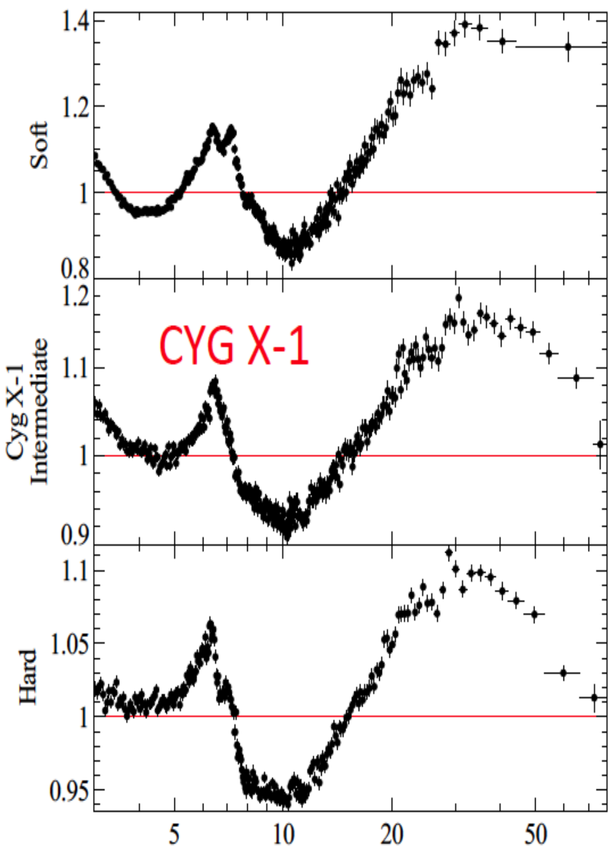


# Very Broad Fe-K line profiles

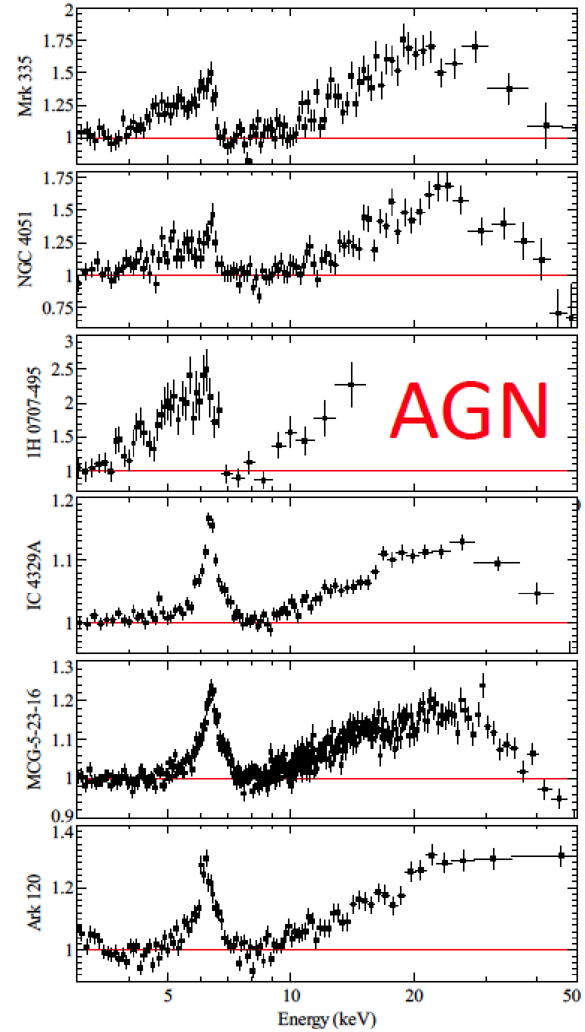
## AGNs X-ray Binaries



# XMM + NUSTAR

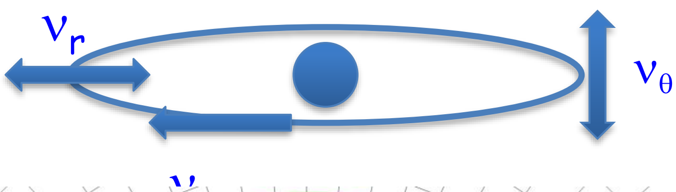


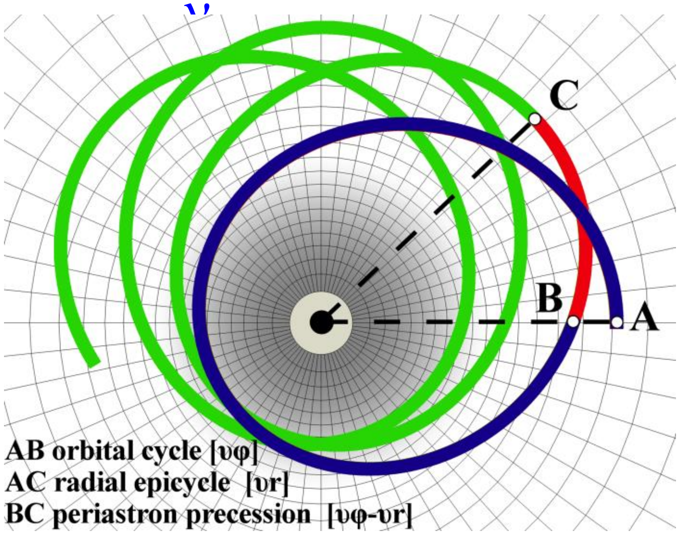

Parker, Tomsick+

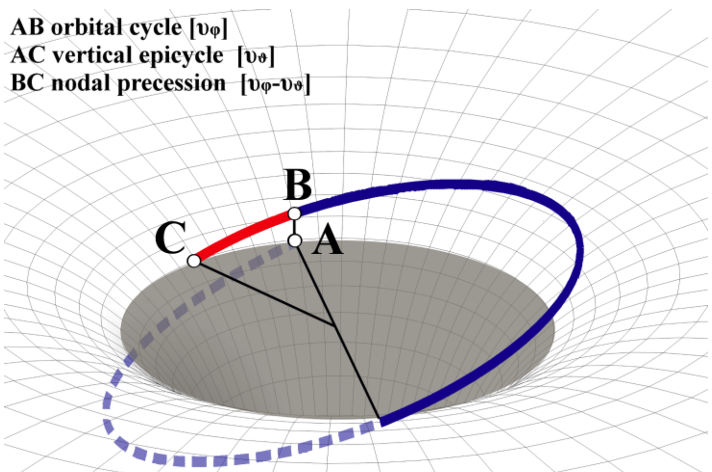



Parker, Matt+

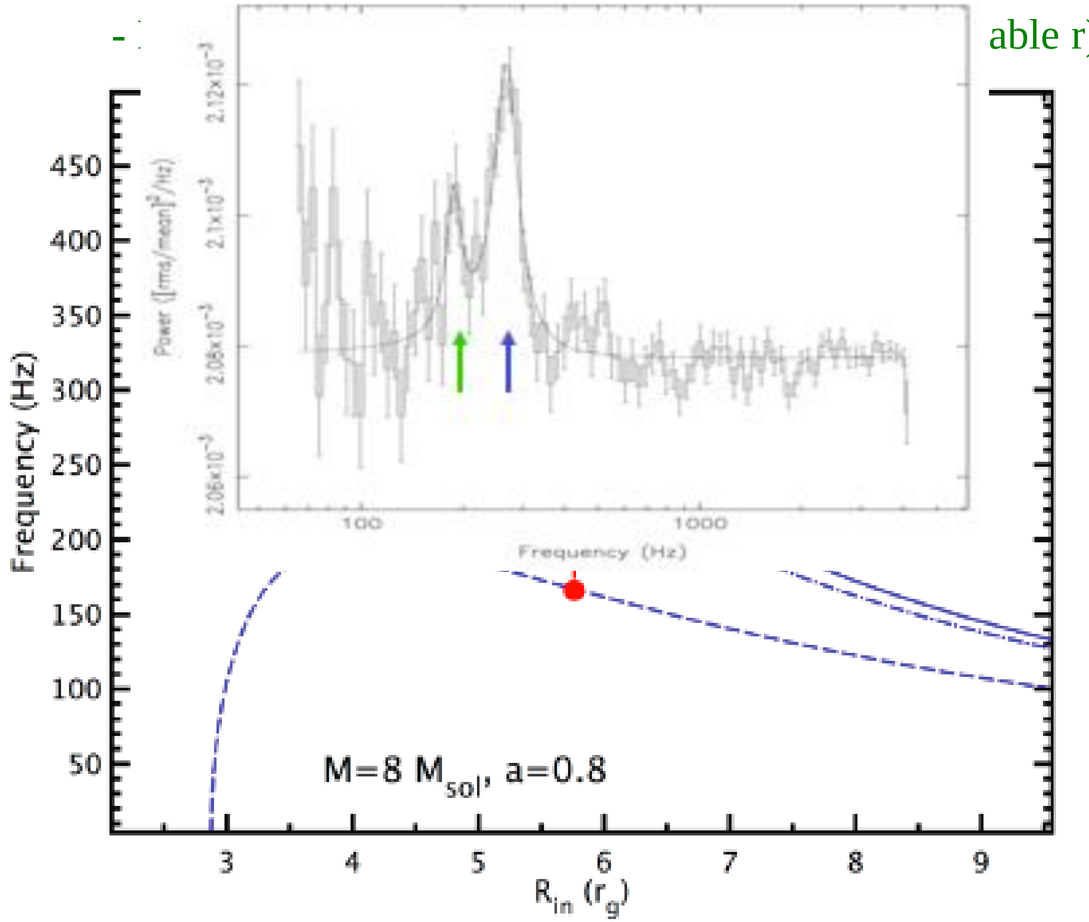
# Fundamental Frequencies of Particle Motion




able r)




General relativity:

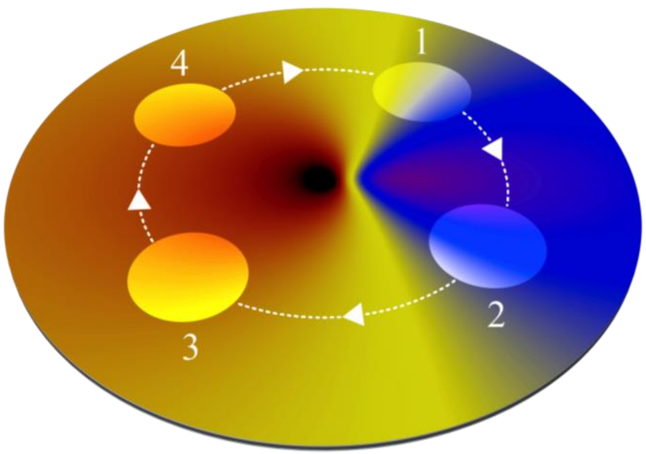
$$r_g \circ GM/c^2 \qquad j \circ Jc/GM^2$$

$$n_j = \sqrt{GM/r^3}/2p(1+j(r_g/r)^{3/2})$$

$$n_r^2 = n_j^2(1-6(r_g/r)+8j(r_g/r)^{3/2}-3j^2(r_g/r)^2)$$

$$n_q^2 = n_j^2(1-4j(r_g/r)^{3/2}+3j^2(r_g/r)^2)$$

# Stellar-mass black hole

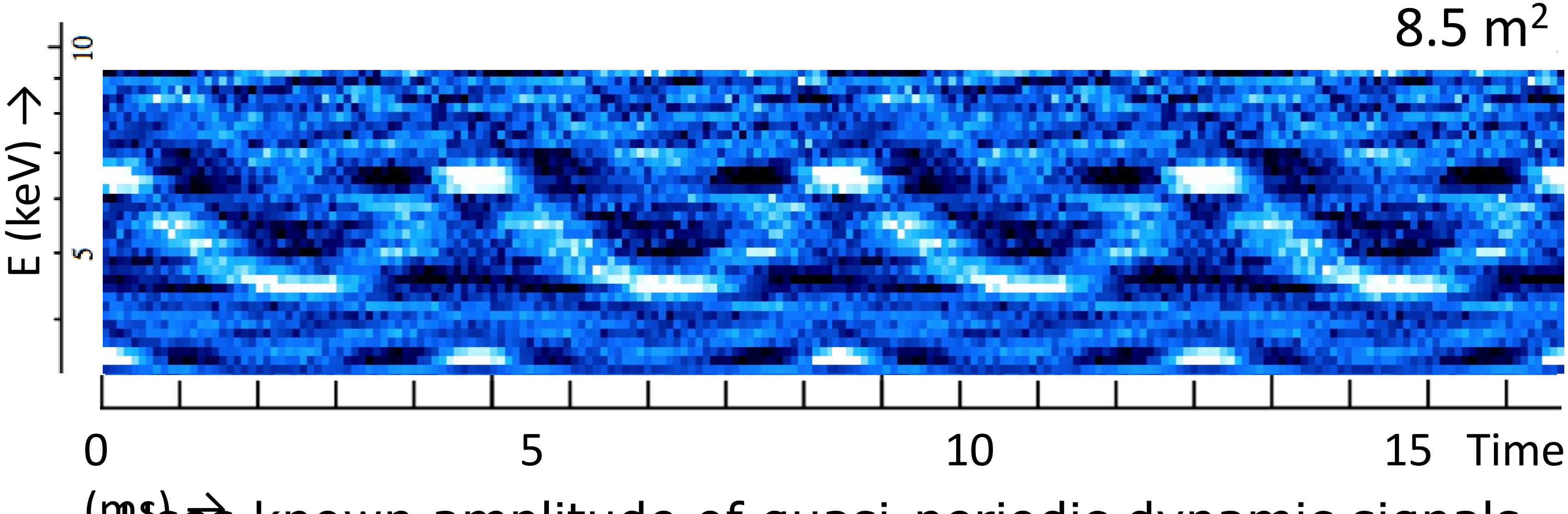


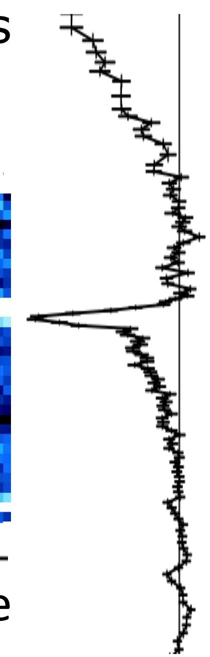

Orbital radial velocity curve at ISCO, closely around a <u>stellar mass</u> black hole

Doppler tomography of disk velocity & redshift map.

Typical precision 1.5% in 100 ks

8.5 $m^2$

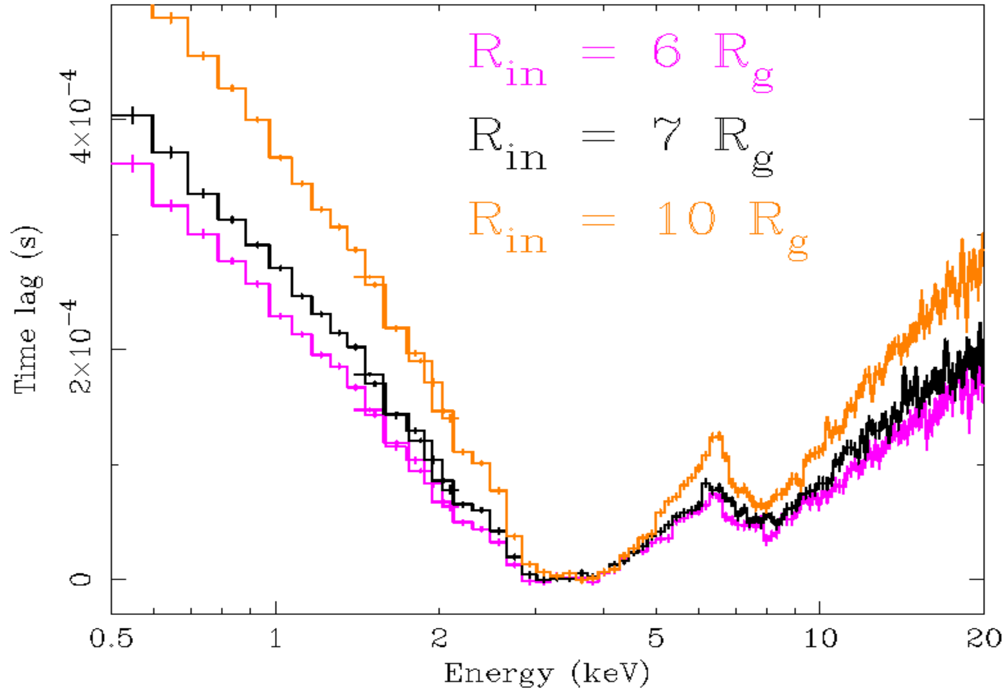


Uses <u>known</u> amplitude of quasi-periodic dynamic signals

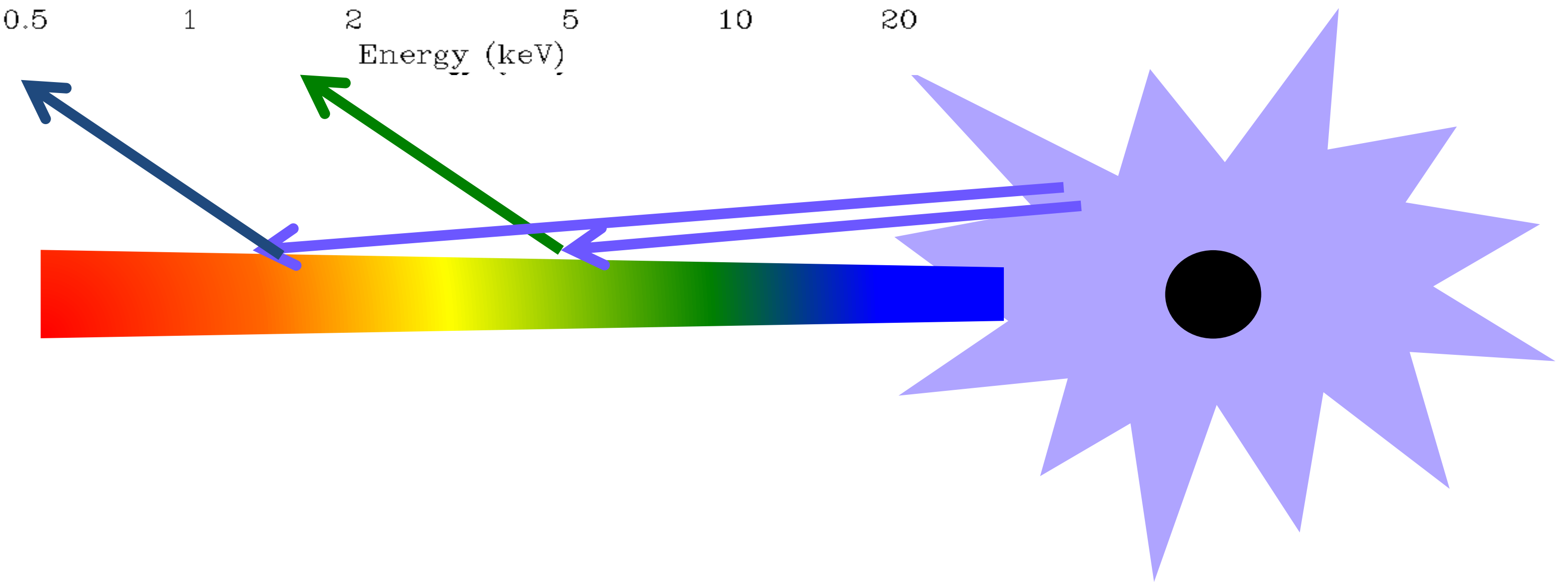
# Disc reverberation components

10 FA + 40LAD



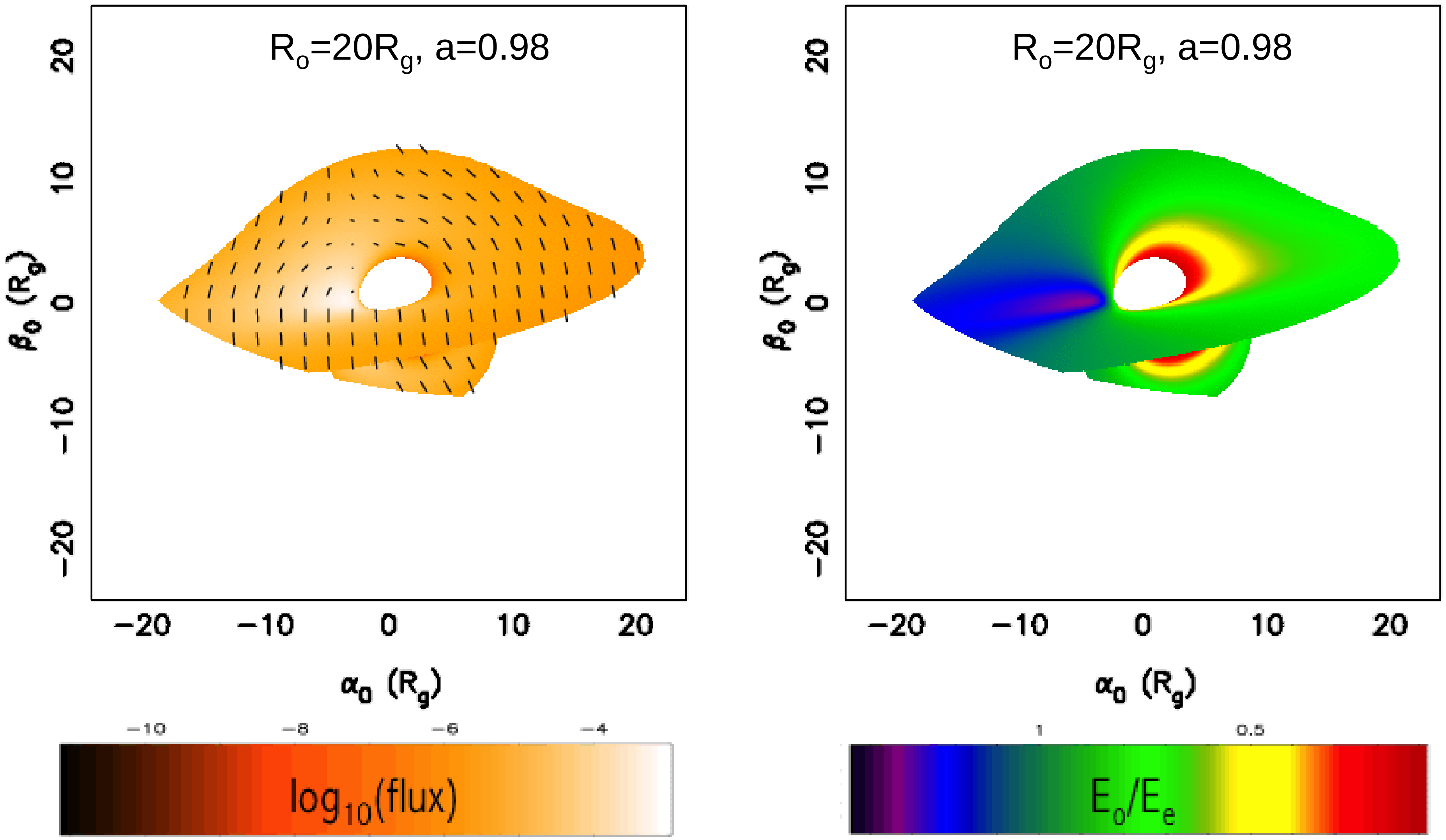

In addition to the iron line and reflection continuum, the absorbed flux is reradiated by the disc as thermal blackbody radiation

**eXTP can study all three components simultaneously!**



Uttley

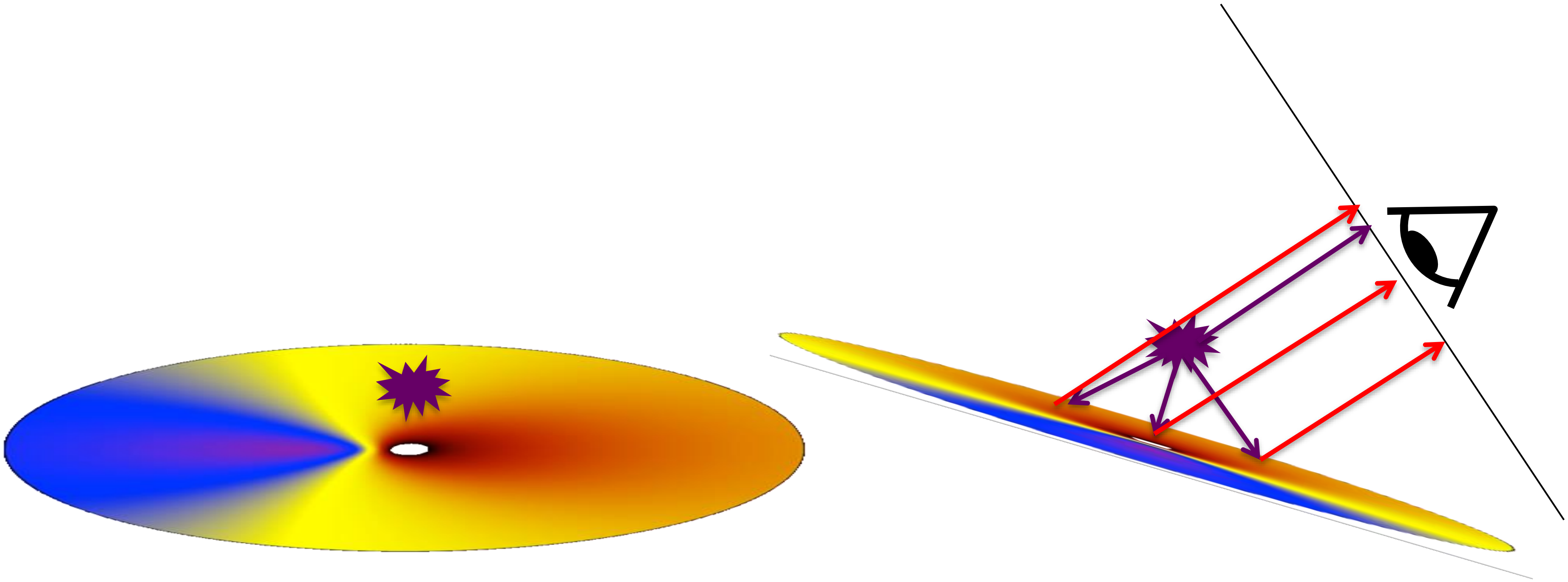
# Movies – high inclination (i=70°)

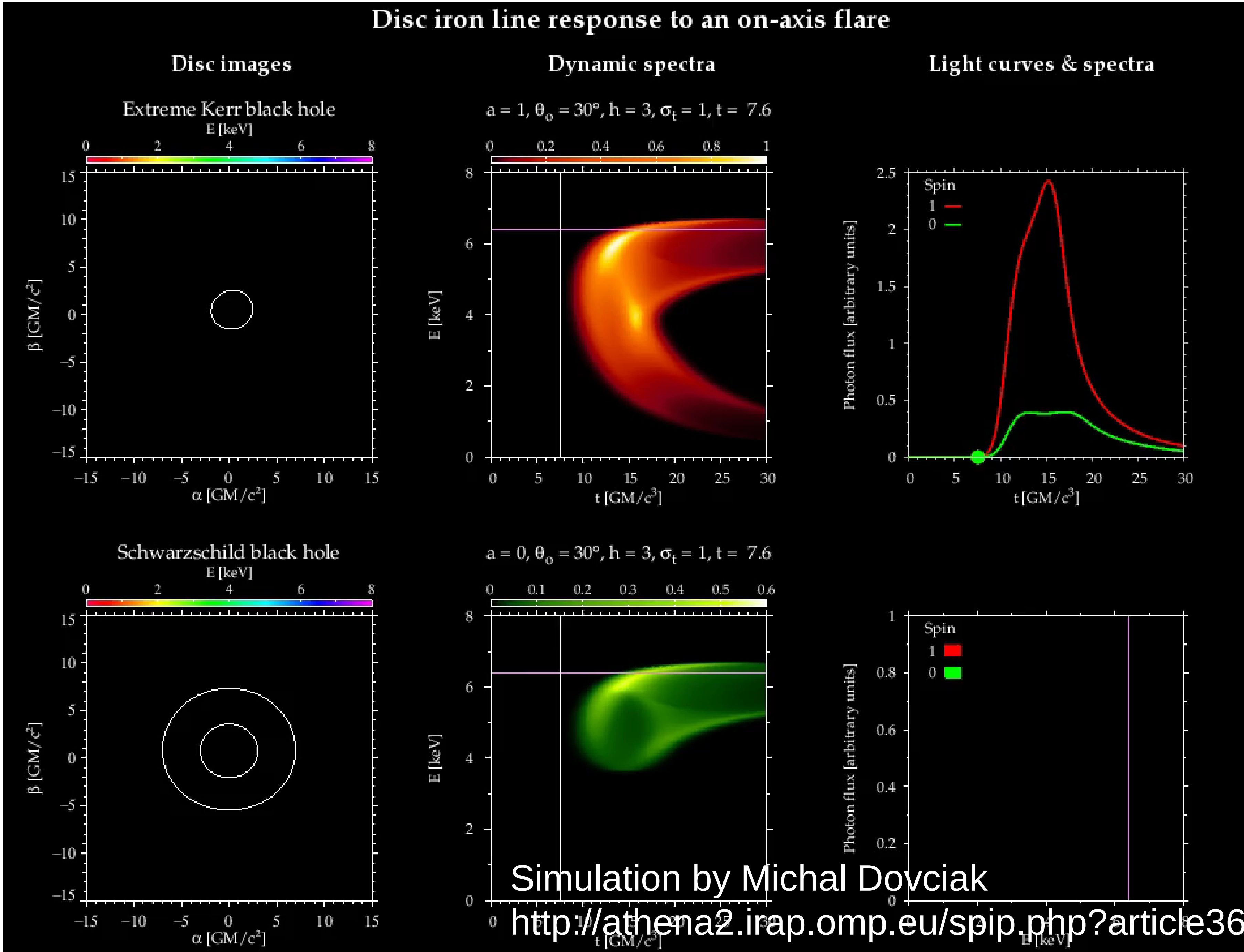



www.youtube.com/watch?v=ieZYYfCapJg&feature=youtu.be

Ingram et al (2015)

# Reverberation mapping close to the event horizon

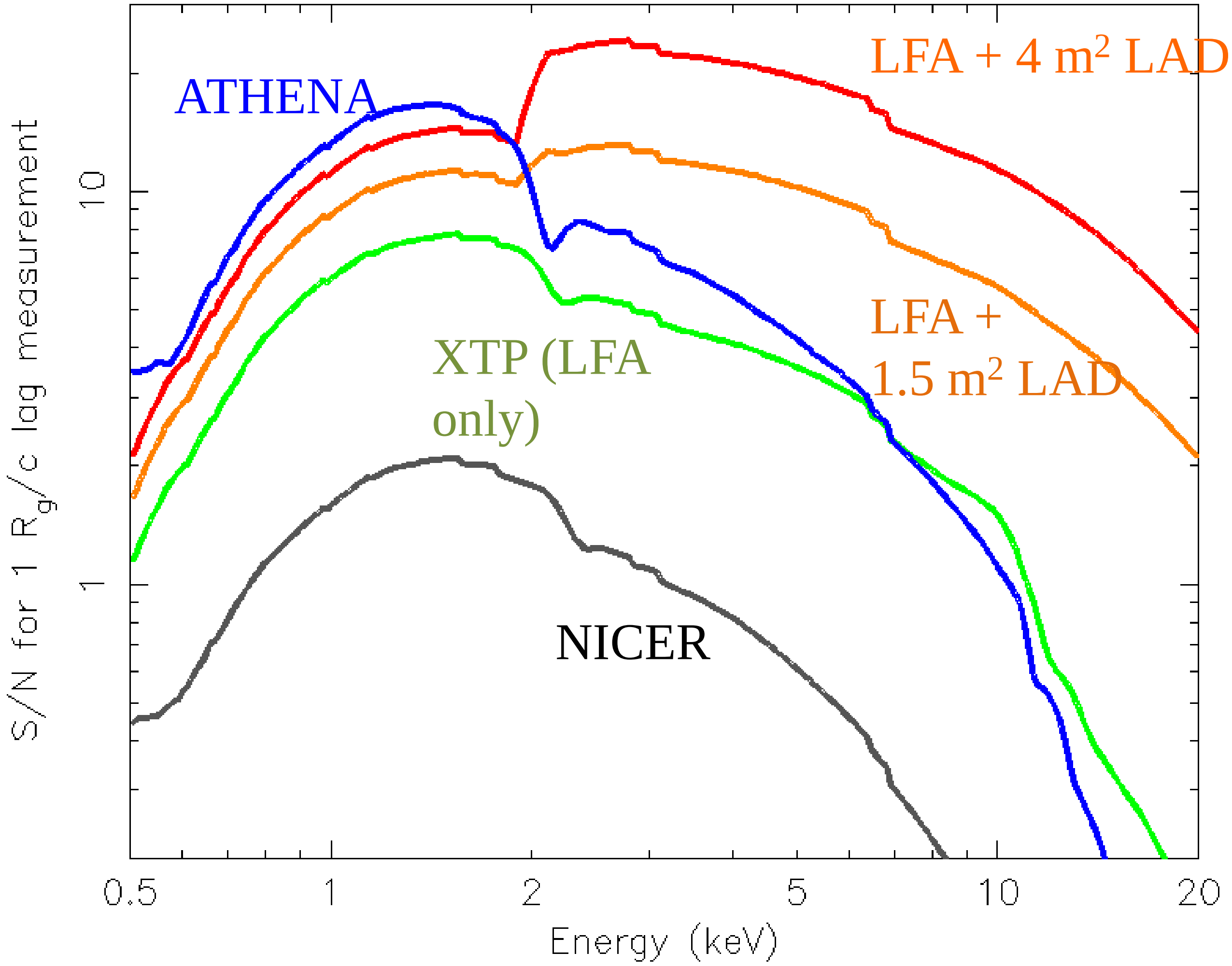





Simulation by Michal Dovciak

http://athena2.irap.omp.eu/spip.php?article36

# 100 ks 1 Crab XRB reverberation sensitivity: mission comparison

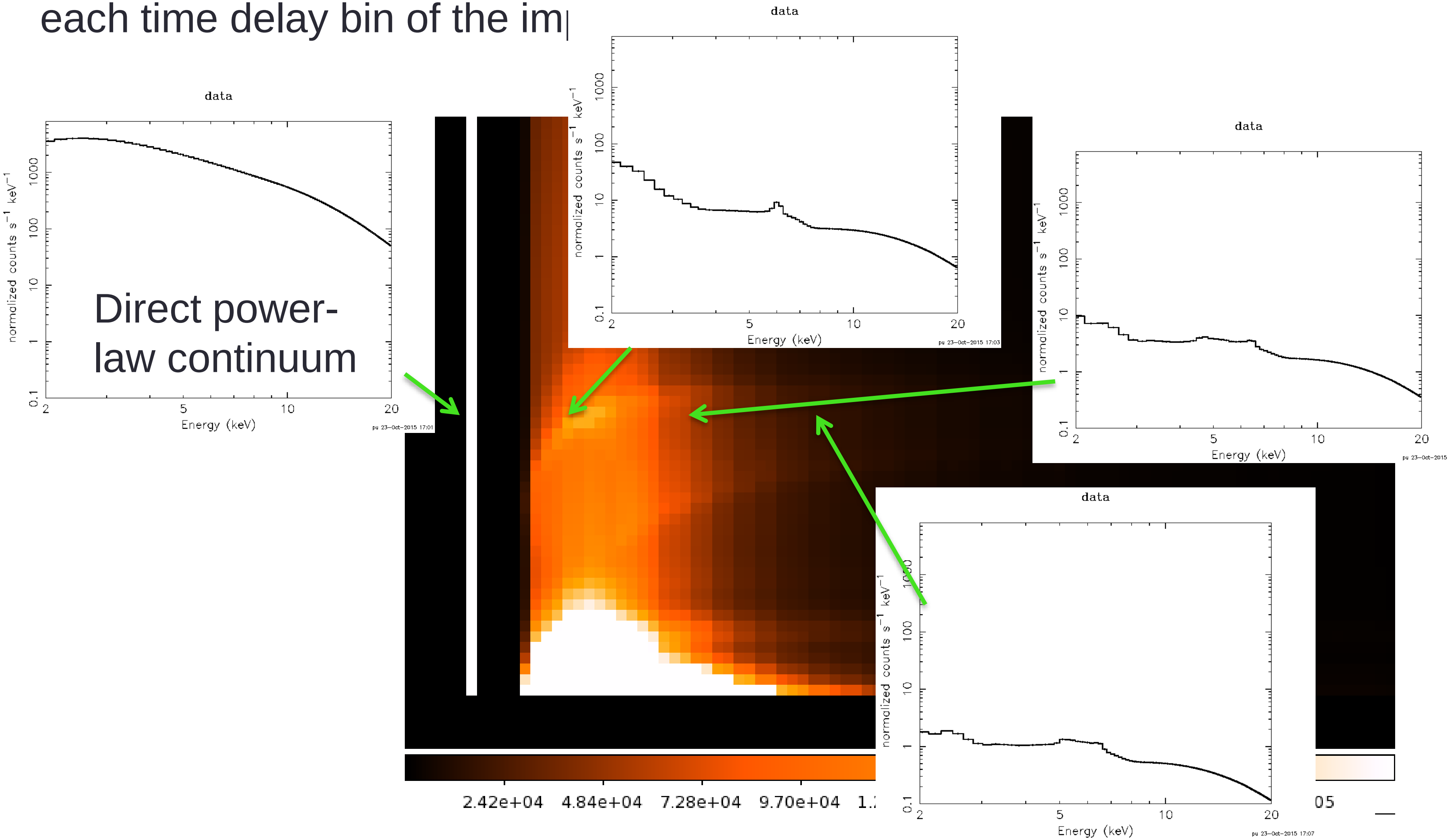



Note: eXTP sensitivity at low energies improves due to increased correlated ‘reference band’ rate from LAD

Uttley

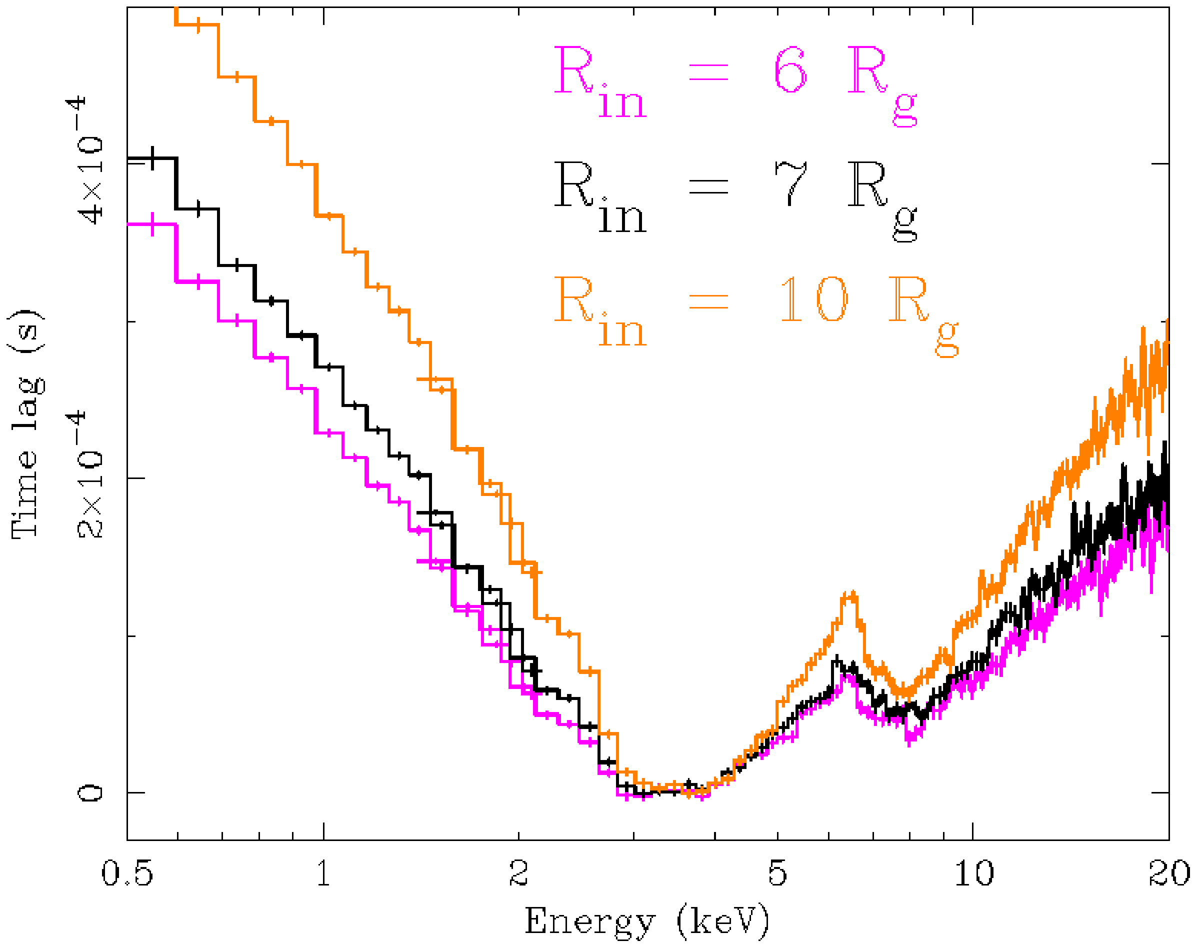
# Building the impulse response

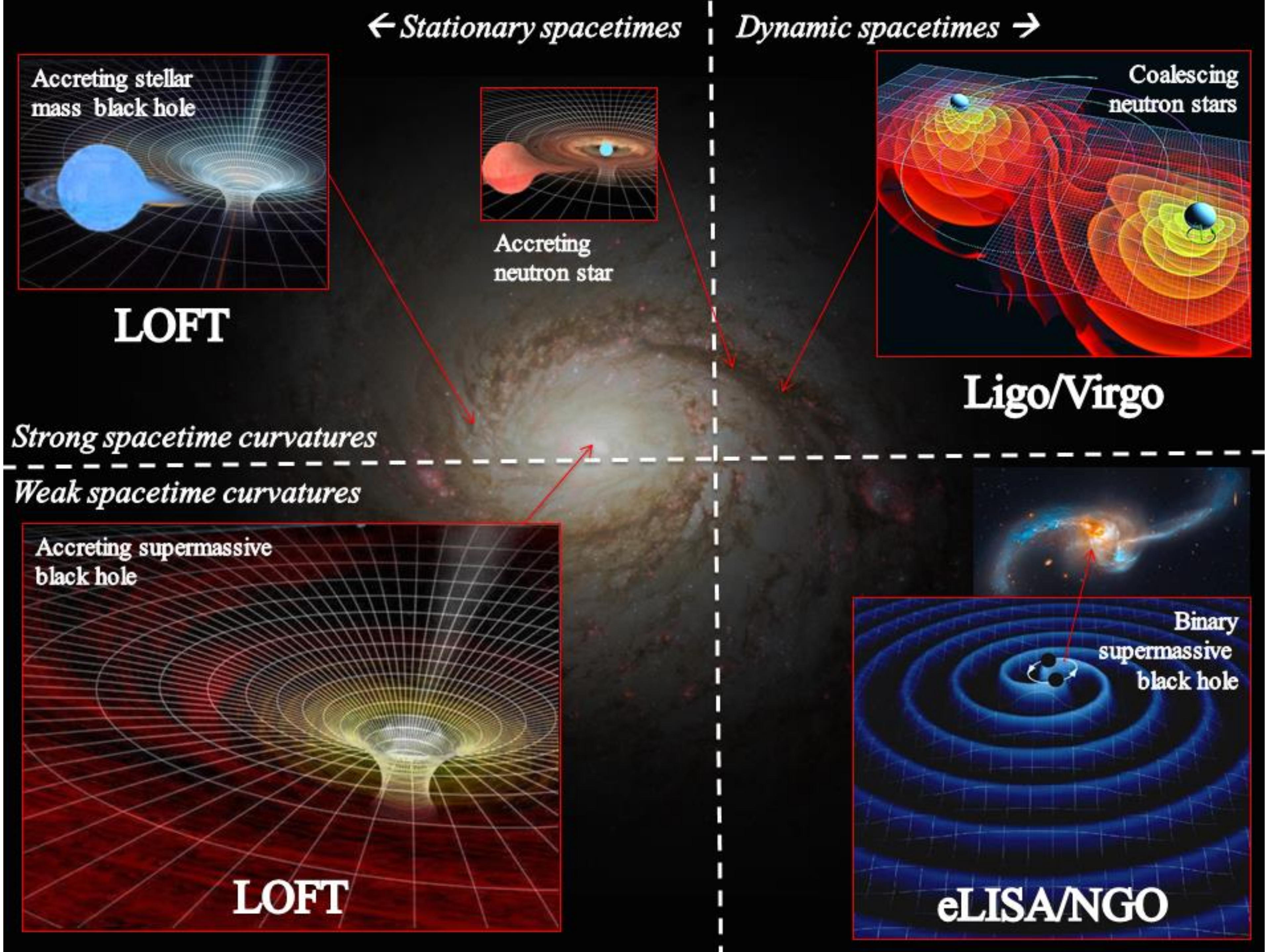
In practice we can make the impulse response for a given detector (e.g. LAD, 40 modules) by making a fake spectrum (xspec fakeit command) for each time delay bin of the im



# BH XRB: eXTP reverberation lag simulations

10 FA + 40LAD





← Stationary spacetimes
Dynamic spacetimes →
Accreting stellar mass black hole
LOFT
Accreting neutron star
Coalescing neutron stars
Ligo/Virgo
Strong spacetime curvatures
Weak spacetime curvatures
Accreting supermassive black hole
LOFT
Binary supermassive black hole
eLISA/NGO

# Testing strong-field GR with LOFT

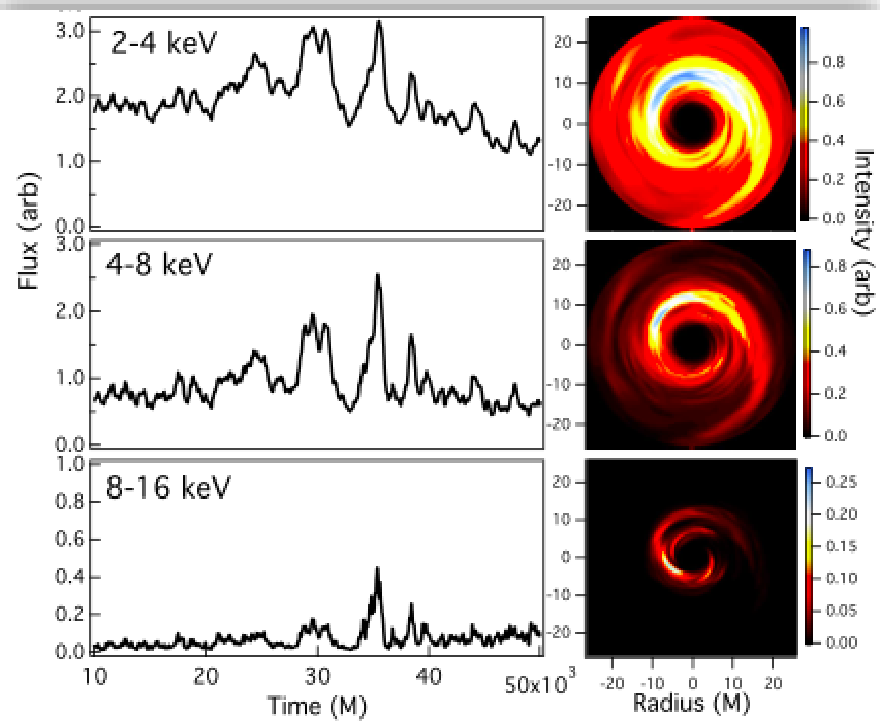
- The determination of the ISCO radius, and more generally of the epyciclic frequencies, would allow to test GR against alternative theories of gravity. For instance, in Chern-Simons gravity (a theory in which the Einstein-Hilbert action is modified by adding a parity-violating term, which couples to gravity via a scalar field), the ISCO frequency is modified by ~ 10^{-4} csi a*/M^5, where csi parametrizes the magnitude of the deviation from GR. Since present constraints on csi from solar system tests are very weak. Only an experiment probing the high-curvature region near the horizon of a stellar mass BH, such as LOFT, could significantly constrain the csi parameter, and then test GR against Chern-Simons gravity.

- More generally, many of the alternative theories of gravity which have been proposed, can be tested through the determination of the ISCO radius and frequency: from theories with quadratic curvature invariants coupled with scalar fields, to “F(R)” theories.

- A different approach to study deviations from general relativity consists in parametrizing the rotating BH spacetime in terms of a set of multipole momenta. GR predicts the Kerr solution, corresponding to a particular set of momenta; a different set of momenta would imply violation of the no-hair theorem, and then a deviation from GR. The epyciclic and phi-frequencies of geodesic orbits can be expressed in terms of the momenta of the BH. Therefore, if LOFT can measure the epyciclic frequencies, it will be possible to determine the multipole momenta, and then to reconstruct the BH solution, testing the no-hair theorem.

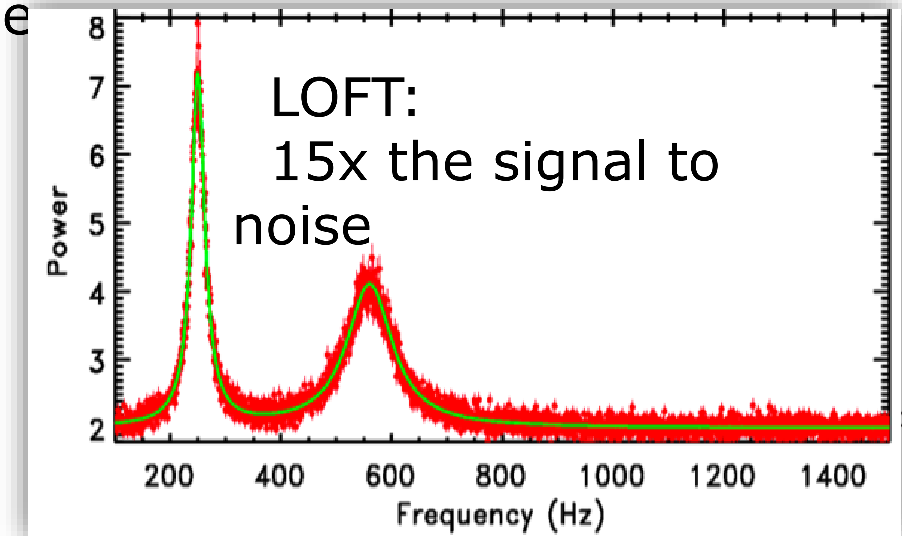
| | | NICER-SEXTANT | LOFT |
|---|---|---|---|
| **Energy band** | | 0.2-12 keV | 2-30 (+30-80) keV |
| **Effective area** | | 2 000 $cm^2$ @ 2 keV<br>600 $cm^2$ @ 6 keV | 40 000 $cm^2$ @ 2 keV<br>100 000 $cm^2$ @ 6 keV |
| **Available techniques** | | 1 | 3 |
| **Anticipated results** | | **Few % accuracy in R for 1 source. where the mass is known to ~10% from radio timing. Weaker constraints on other sources where mass is not known independently.** | **3-5% simultaneously in both M and R** for ~ **10 sources** |
| **Known potential candidate sources (by technique)** | Pulse profile modelling | PSRJ0437-4715 for which M is known from radio. May be possible for 2 additional bright isolated X-ray pulsars, however for these M is not known | 24 stars with burst oscillations and/or accretion-powered pulsations. |
| | Weak/intermittent pulsations | N/A | ~100 NS LMXBs. |
| | Seismology | N/A | 20 bursting magnetars. |
| **Model dependence for pulse profile modeling technique** | | Depends on poorly understood pulsar emission mechanism (see text) | Spectrum of burst oscillation sources understood to within 1% (§2.2.4.1). |
| **Opportunity for cross-checks using independent methods** | | N/A | 3 independent methods. Burst spectroscopy gives complementary constraint on the burst oscillation pulse profile modeling sources. Analysis using at least two different pulsation types for 70% of potential pulse profile modelling targets. |
| **Impact** | | CONSTRAINS EOS | RECONSTRUCTS EOS |

General Relativity predicts precise orbital and epicyclic frequencies at each radius




Wellons et al. 2013

Orbiting inhomogeneities make frequencies observable




- Strong gravity dynamical frequencies just detected in current (RXTE) data
- LOFT diagnoses strong field gravity very precisely by:
  - timing of the flux variations
  - time resolved spectroscopy

  at very high signal to noise
- Uses known phenomena

# SFG SciRQ

| Parameter | Performance Requirement SFA | Performance Requirement LAD | Science Objective |
|---|---|---|---|
| Effective area | 0.8*6000 $cm^2$ @ 6keV<br>0.8*9000 $cm^2$ @ 2keV | 3 $m^2$ @ 6 keV<br>1 $m^2$ @ 2 keV | Fe Line AGN&XRB reverberation QPOs/resolved |
| Energy resolution | <180 eV @ 6 keV | <300 eV @ 6 keV | AGN Fe line & tomography |
| BKG level/syst | 9e-4 cts/s/$arcmin^2$<br>2-10 keV | 240 cts/s (rescaled M4)<br>0.3% (as M4) | AGN doppler tomography |
| PSF (HPD) | <1 (0.85) arcmin | - | AGN Fe line/Doppler tomography |
| | | | |

# Conclusions

ulations predicted in polarization degree and angle
ving polarization angle should track rocking iron line
umber of possible techniques considered, phase folding explored
eline: easily detect predicted modulations for i>40 degrees
easily detect modulations half the predicted amplitude with half the
dicted average polarization degree
: more time makes up for less area due to Poisson scaling, but:
two independent detectors may be important for other methods
QPO properties change on timescales >~200ks
: more complex scaling for phase folding, since we need to determine
antaneous QPO phase (but different scaling may apply to different
nique)
n baseline signal to noise will allow us to do energy-resolved
rization timing