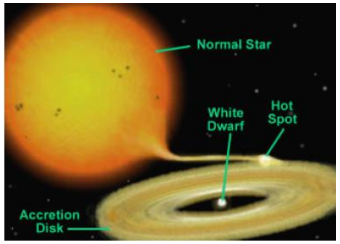
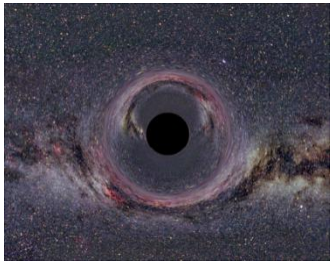
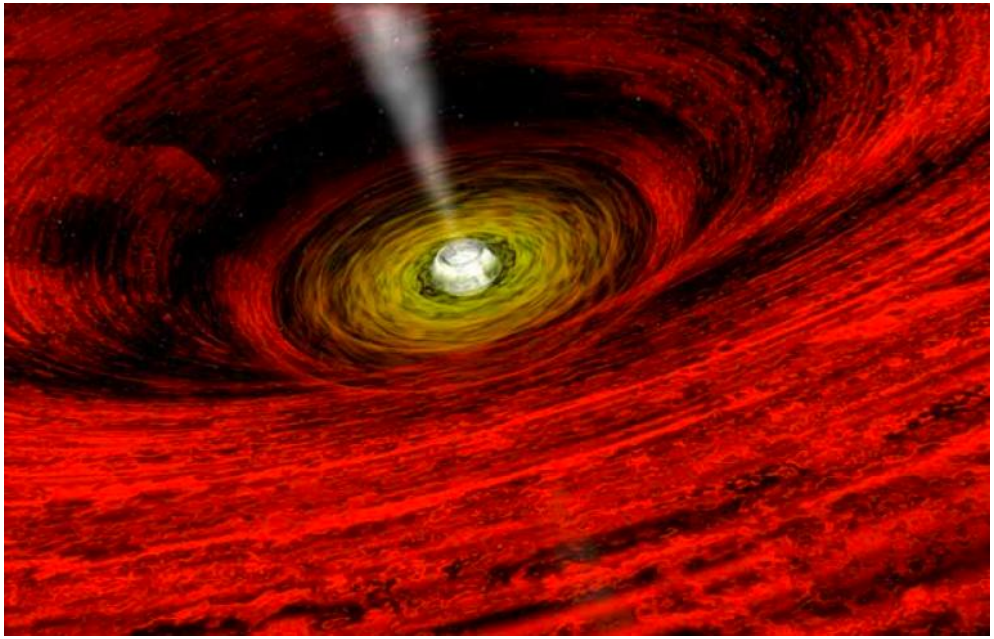
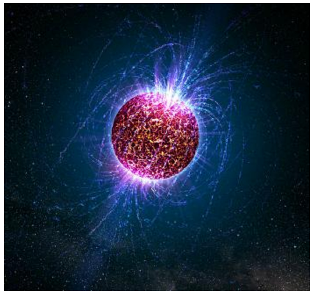
Neutron stars and black holes as strong gravity probes









Sudip Bhattacharyya

Tata Institute of Fundamental Research,
Mumbai, India

Outline

- Introduction: Motivation, X-ray astronomy
- Spectral tools
- Timing tools
- Conclusions

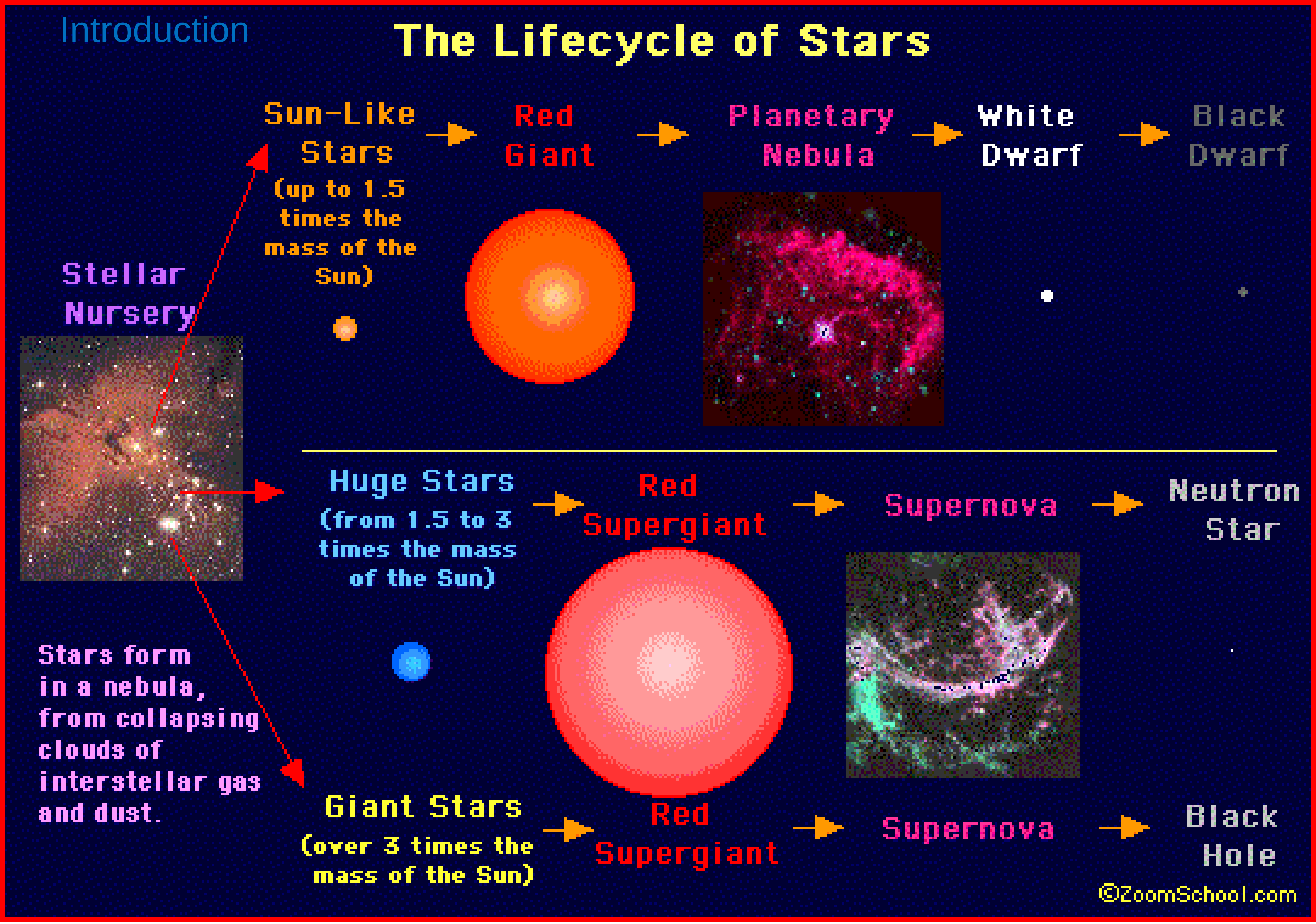
Why should we probe strong gravity?

1. It is natural to attempt to understand the unexplored extreme aspects of the universe using the current physical theories.

2. It is natural to attempt to test a fundamental law of physics (such as general theory of relativity) in an unexplored regime (such as strong gravity).

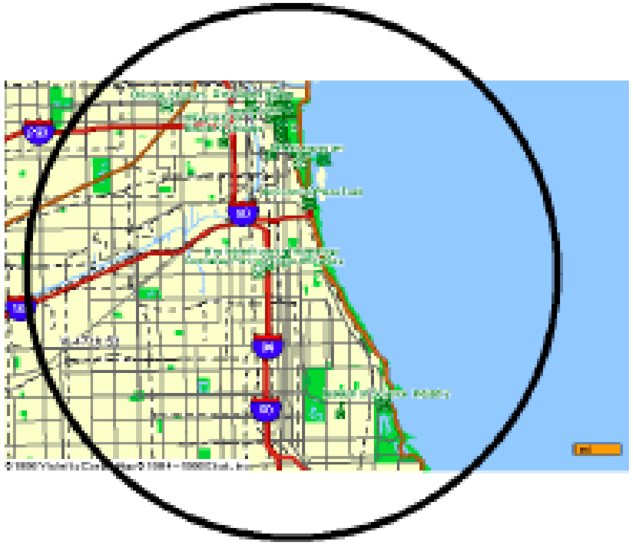
Note: (a) There is no fundamental reason why GR should be more acceptable than its alternatives.
(b) All historical tests of GR have been performed in our solar system, which has a weak gravity.
(c) GR fails in Planck scale.

Introduction



Courtesy: M. N. Vahia

Neutron star vs. a city

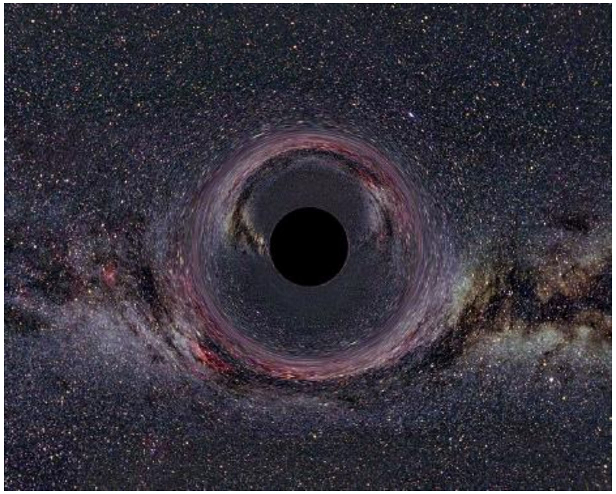


Courtesy: M. C. Miller

Extreme Objects

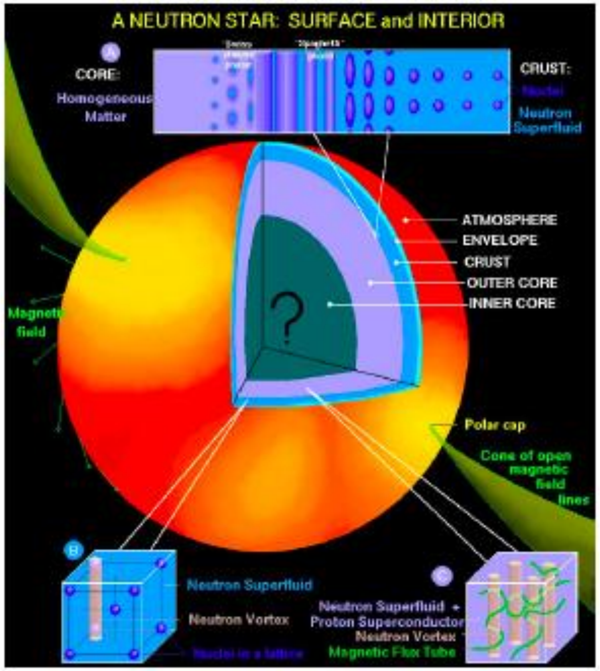
Radius ~ 10 - 20 km
Mass ~ 1.4 - 2.0 solar mass
Core density ~ 5 -10 times the nuclear density
Magnetic field ~ 10^7 - 10^{15} G

Black hole image: **simulated, not real**

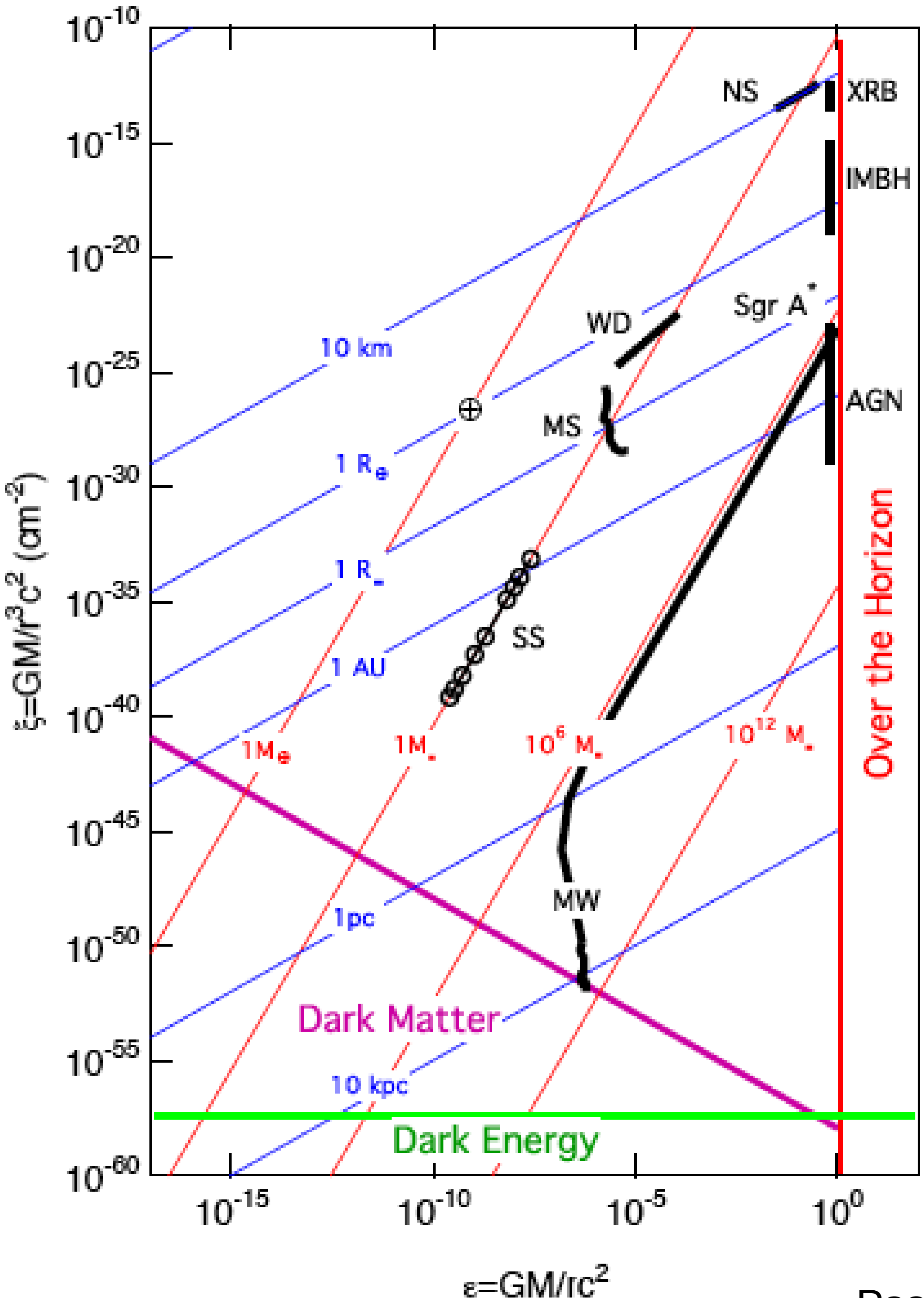


Stellar mass BH
~ 10 solar mass

Supermassive BH
~ 10^6-10^9 solar mass



Courtesy: D. Page



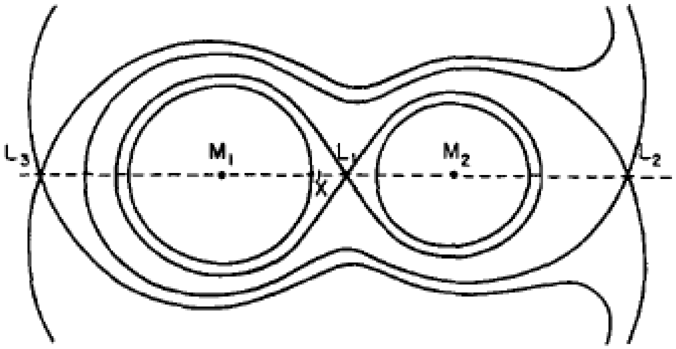
Psaltis (2008)

A parameter space quantifying the strength of a gravitational field.

$\xi \Rightarrow$ A measure of curvature
$\varepsilon \Rightarrow$ A measure of potential

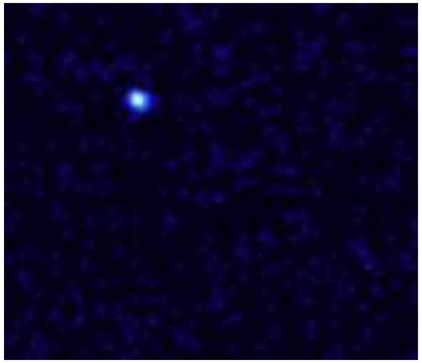
Stellar mass black holes (BH) and neutron stars (NS) give rise to the strongest gravity.

Low-mass X-ray Binary (LMXB)



Equipotential surfaces in a binary system
Courtesy: Bhattacharya & van den Heuvel (1991)

Artist's impression of a low-mass X-ray binary
Courtesy: NASA website



Chandra image of KS 1731-260
Courtesy: NASA website

Angular size ~ 10^{-10} arcsec
Best X-ray resolution ~ 1 arcsec

X-rays from inner accretion disk and neutron star surface.

Orbital period: minutes to days

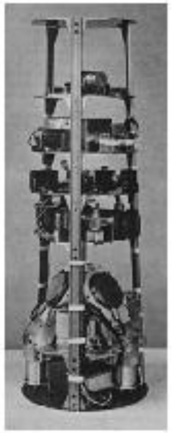
Age ~ Billion years

Neutron star magnetic field ~ 10^7 to 10^9 G

Neutron star spin ~ 300 to 600 Hz

X-ray astronomy

Riccardo Giacconi



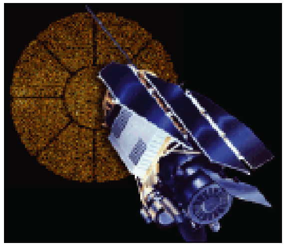
Experiment package that was flown on a rocket and discovered the first extra-solar X-ray source in 1962

$\Rightarrow$ Discovered the bright neutron star low-mass X-ray binary Sco X-1

X-ray instruments on a balloon: TIFR balloon facility

Uhuru: first dedicated X-ray satellite

Einstein: first fully X-ray imaging satellite



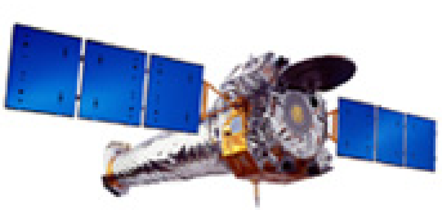
ROSAT: did the first X-ray all sky survey

Why is it extremely difficult to study low-mass X-ray binaries?

1. Cannot be spatially resolved. Information has to be extracted from spectral and timing analysis.
2. They are far away, typical distance ~ 10000 lightyears.
3. A particular source can be observed for a very limited time.

X-ray satellites

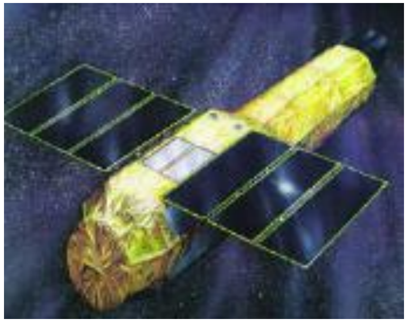
Some current satellites:



Chandra

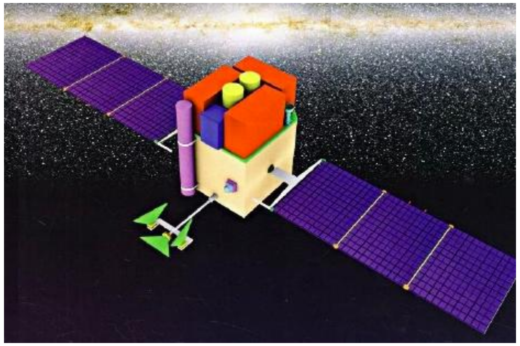
XMM-Newton

RXTE



Suzaku

Some future satellites:



Astrosat

International X-ray Observatory

What predictions of GR do we want to test in strong gravity regime?

Examples:

- Event horizon
- Innermost stable circular orbit (ISCO)
- Frame dragging
- Light bending / Lensing
- Gravitational redshift
- No-hair theorem (Kerr metric)

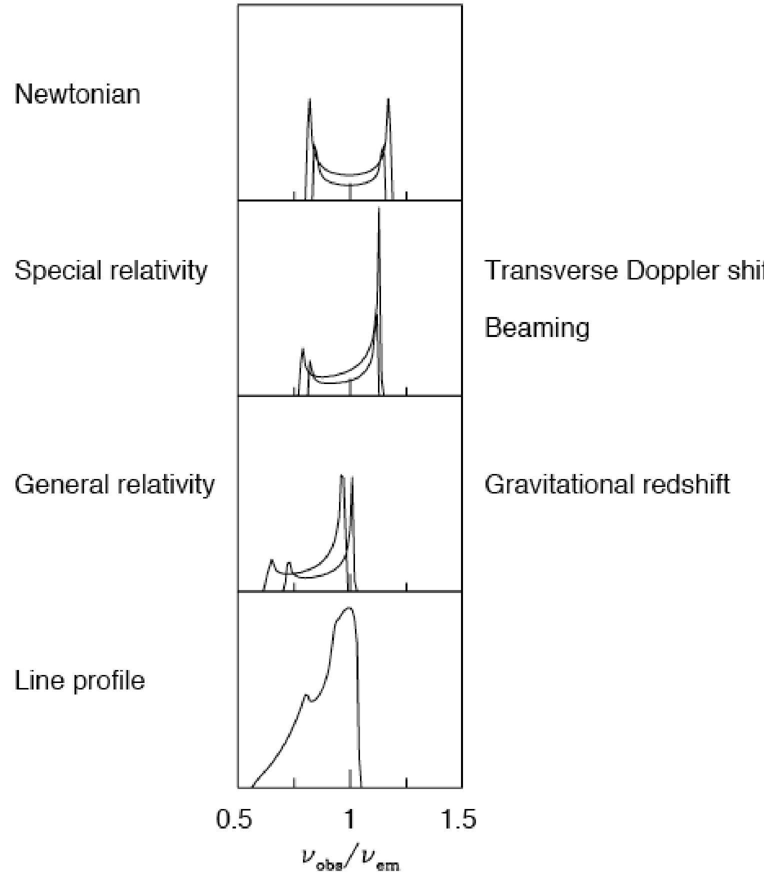
X-ray line spectrum of accretion disks

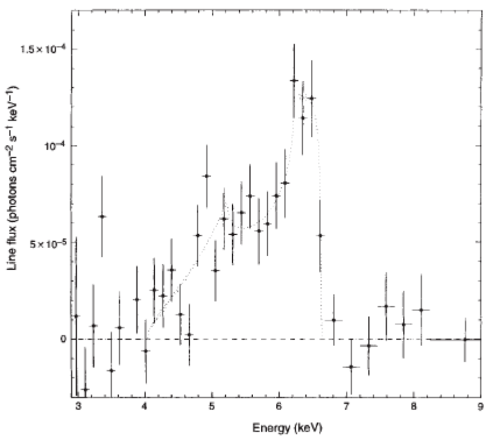
Fabian et al. (2000)

From black hole systems:

Broad asymmetric iron Kα emission lines are observed from supermassive black hole (AGN) and stellar-mass black hole (black hole LMXB) systems.

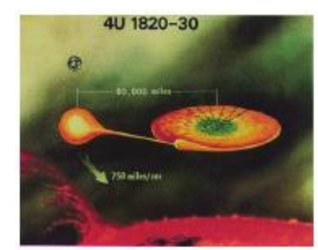
They originate from the inner part of the accretion disk.





Tanaka et al. (1995)

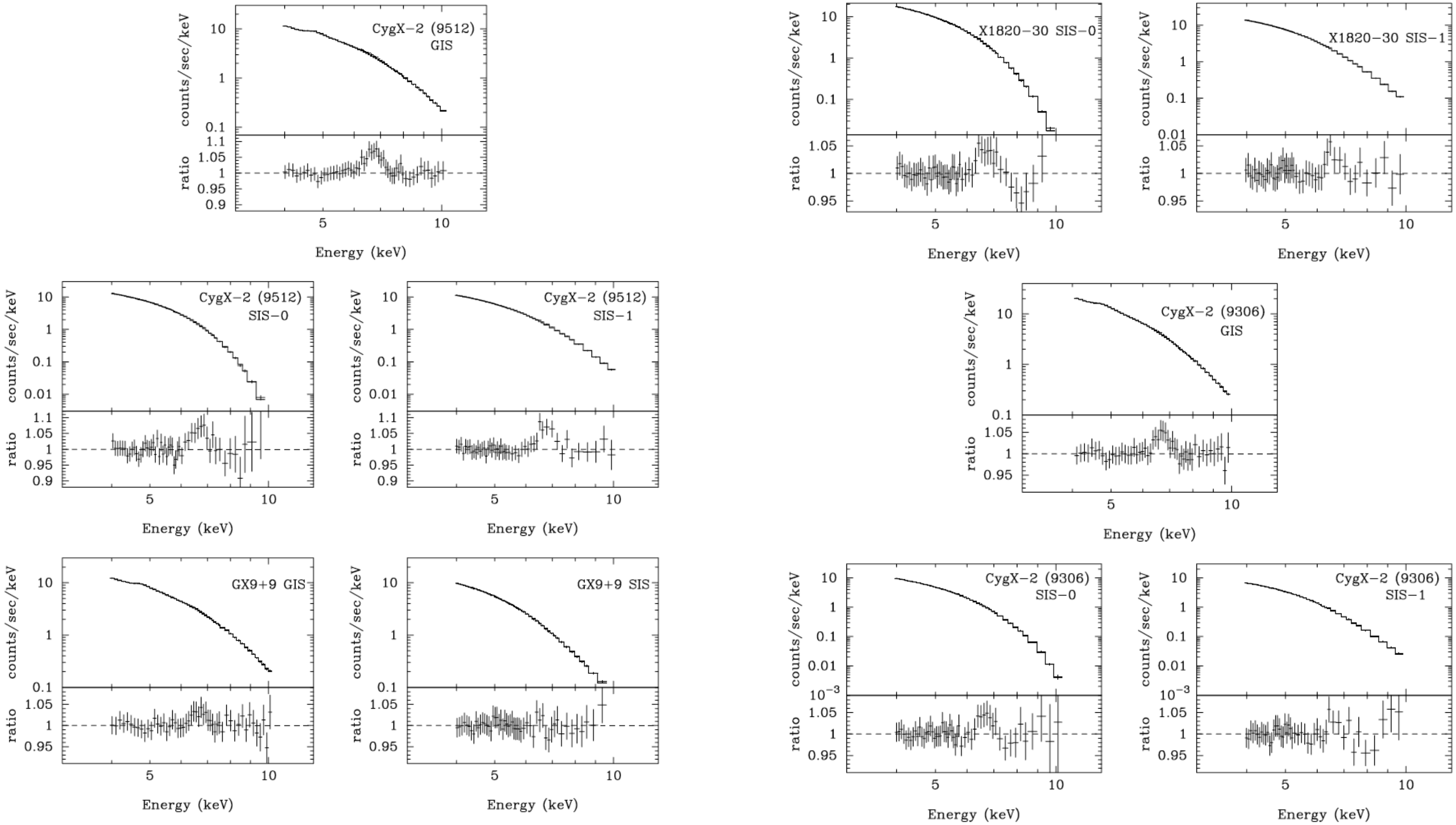
Measurement of the angular momentum parameter a/M (= J/M^2), if the disk inner edge radius is less than 6GM/c^2.



Nature-given tool to measure the black hole spin and to probe the strong gravity regime.

X-ray line spectrum of accretion disks (continued)

Broad Iron Lines from Neutron Star LMXBs



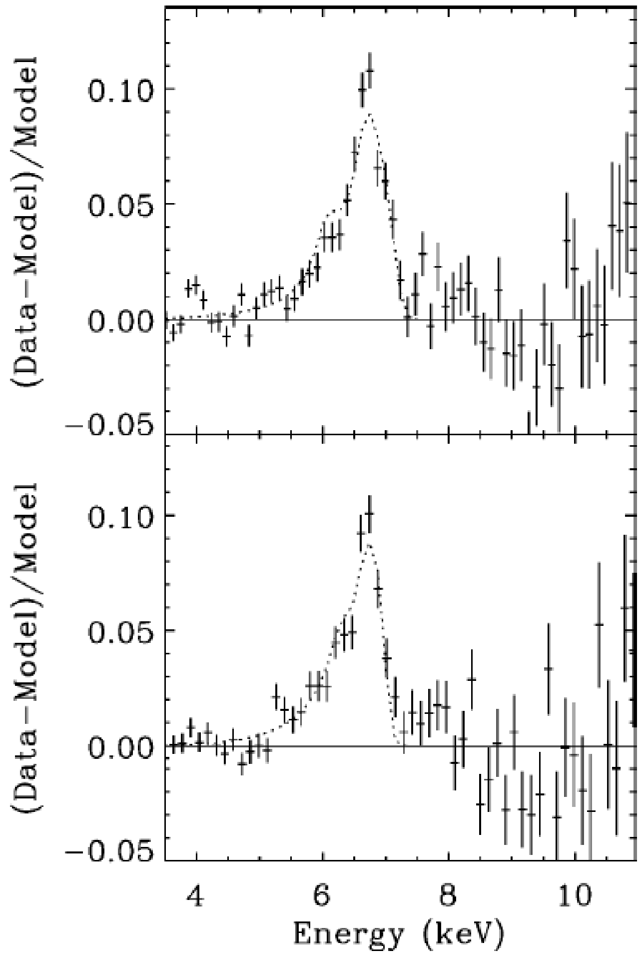
Asai et al. (2000)

The relativistic nature of broad iron lines from NS LMXBs was not established up to the end of 2006.

X-ray line spectrum of accretion disks (continued)

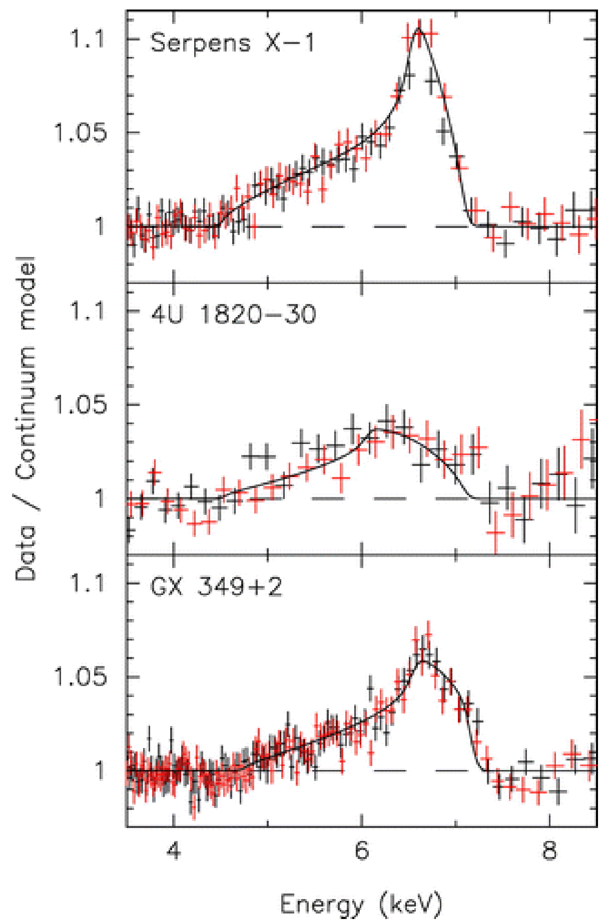
Relativistic nature at last!

Serpens X-1: XMM-Newton EPIC pn data



Bhattacharyya and Strohmayer (2007)

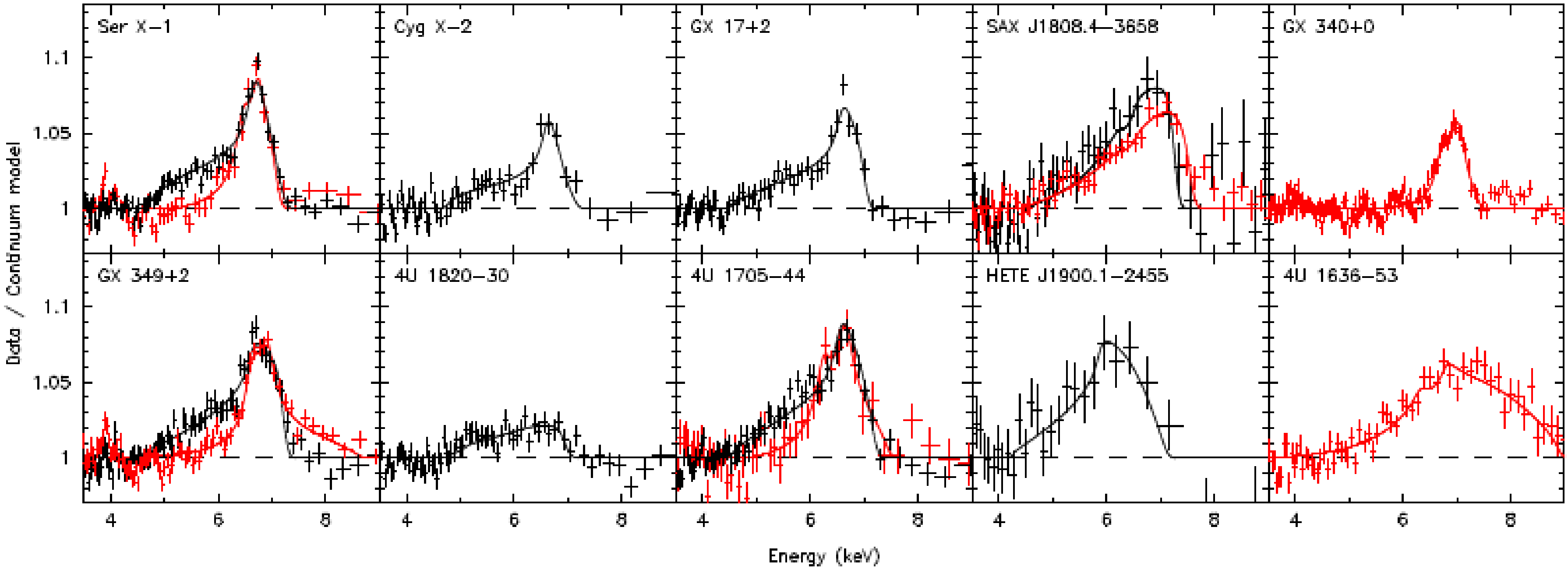
Suzaku data



Cackett, Miller, Bhattacharyya et al. (2008)

X-ray line spectrum of accretion disks (continued)

XMM-Newton data (red) and Suzaku data (black)



Cackett et al. (2009)

Since the first discovery in 2007, relativistic nature of broad iron lines has been confirmed for 10 neutron star LMXBs.

X-ray line spectrum of accretion disks (continued)

How disk line can be useful?

Measurement of ISCO radius and a/M can be useful to test several predictions of GR (we will also see later). The structure of the line may be directly used to constrain the spacetime metric. Various NS parameters, such as radius, angular momentum parameter, mass (using also kHz QPO), may be constrained, which may in turn be useful to constrain laws of gravitation.

Doubts / systematics:

1. In order to use the line as a diagnostic tool, the continuum spectrum must be known very accurately, and other relevant system parameters (e.g., inclination angle) must be measured independently.

2. NS disk line methods may involve additional systematics, because the disk may be truncated by one of the following effects: (1) ISCO, (2) magnetic field, (3) radiative pressure, (4) NS surface.

X-ray continuum spectrum of accretion disks

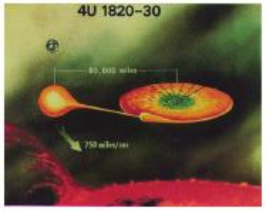
Modeling the BH continuum X-ray spectrum in soft state with an appropriate relativistic disk blackbody model plus a harder component can be useful to measure the ISCO radius (assuming the disk extends up to ISCO), and hence the angular momentum parameter (a/M) of the BH.

These two parameters are extremely useful to test the GR predictions.

Doubts regarding this approach:

1. Is it rigorously shown that the BH spectrum in the soft state cannot be described with alternative models?
2. Even if this model is correct, the disk spectrum from near ISCO may be the harder part of the blackbody, which may be comparable to the harder component in those energies.
3. Zero-torque at ISCO?
4. Systematics due to various unknown parameters (e.g. e^- scattering).
5. More doubts?

These doubts should be studied systematically.



X-ray continuum spectrum of accretion disks (continued)

But at least the measured a/M from disk line (DL) and disk blackbody (DBB) should be consistent with each other. **They are not!**

Current status:

GRS 1915+105 : DL: a/M = 0.56±0.02 (Blum et al. 2009)
DBB: a/M = 0.98 - 1 (McClintock et al. 2009)

GRO J1655-40 : DL: a/M > 0.9 (Reis et al. 2009)
DBB: a/M = 0.65 - 0.75 (McClintock et al. 2009)

4U 1543-47: DL: a/M = 0.3 (+0.2,-0.3) (Miller et al. 2009)
DBB: a/M = 0.75 - 0.85 (McClintock et al. 2009)

Can this method be used for NSs? We need to use the data when the disk extends up to ISCO (may be determined from kHz QPOs, other means?). But for NSs, there will be more systematics due to magnetic field, strong radiative pressure, NS surface, etc.

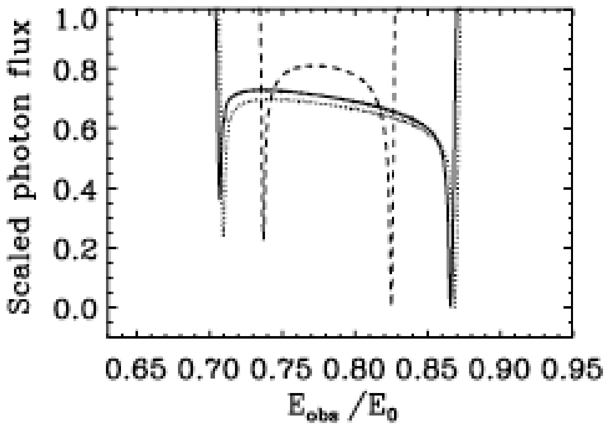
Line spectrum of rapidly spinning neutron stars

Surface line can be used as a tool to detect frame-dragging.

The ratio of low-energy flux deficit (area) to high-energy flux deficit (area) increases sharply with a/M (by 36% for the figure on the right). Like equivalent widths, these flux deficits depend only weakly on the detector's resolution.

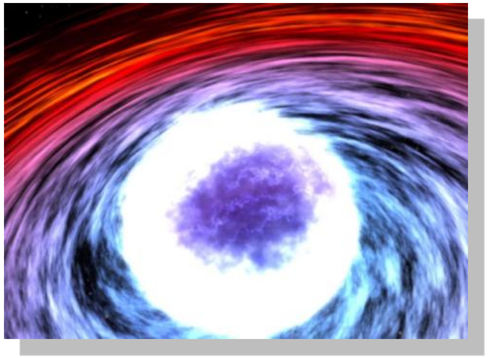
This same effect can be reproduced by changing the value of $\Omega_{spin}R$. sin θ . Sin i_{spin} (which changes the line-width), so we need to measure this parameter. There are other smaller systematics.

Bhattacharyya, Miller, Lamb (2006)



Solid curve: i_{spin} = 60^o, a/M = 0.0; dotted curve: i_{spin} = 60^o, a/M = 0.188; dashed curve: i_{spin} = 30^o, a/M = 0.0; other parameters are same including ν_{spin} = 400 Hz.

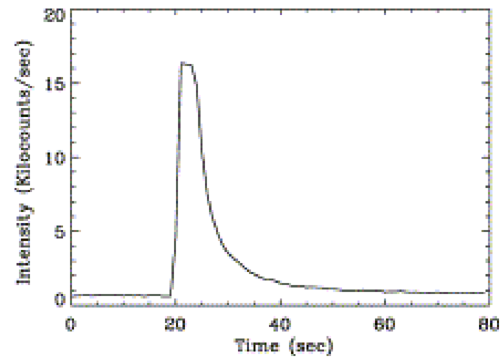
Thermonuclear X-ray Bursts



Accretion on neutron star

Unstable nuclear burning of accreted matter on the neutron star surface causes type I (thermonuclear) X-ray bursts.

Burst light curve



Rise time ≈ 0.5 - 5 seconds
Decay time ≈ 10 - 100 seconds
Recurrence time ≈ hours to day
Energy release in 10 seconds
≈ 10^{39} ergs

↓

Sun takes more than a week to release this energy.

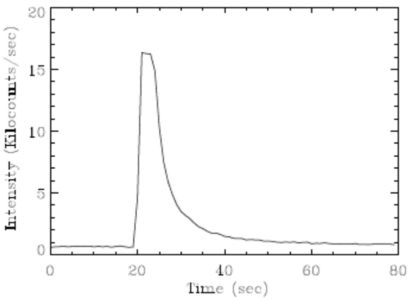
Why is *unstable* burning needed?

Energy release:
Gravitational ≈ 200 MeV / nucleon
Nuclear ≈ 5 MeV / nucleon

Accumulation of accreted matter for hours → Unstable nuclear burning for seconds ⇒ Thermonuclear X-ray burst.

Continuum spectrum of thermonuclear X-ray bursts

- Burst spectra are normally well fitted with a blackbody model.

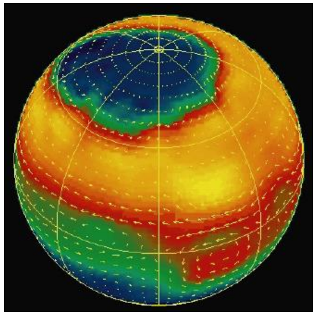


- In principle, neutron star radius can be measured from the observed bolometric flux (F_{obs}) and blackbody temperature (T_{obs}), and the known source distance (d):

$$R_{obs}=d.(F_{obs}/(\sigma T^4_{obs}))^{1/2}$$

- But there are systematic uncertainties:
  (1) unknown amount of spectral hardening;
  (2) effect of unknown gravitational redshift;
  (3) unknown distance;
  (4) if part of the surface emits.

$$T = T_{obs}.(1+z)/f \qquad R = R_{obs}.f^2/(1+z) \qquad \begin{cases} z > 0;\ f \sim 1.0 - 2.0 \\ 1+z = [1 - (2GM/Rc^2)]^{-1/2} \end{cases}$$



Atmospheric chemical composition, surface gravity, temperature $\Rightarrow$ f

Continuum spectrum of thermonuclear X-ray bursts (continued)

Can we use continuum burst spectrum to test GR?

May be when thermonuclear flame spreads.

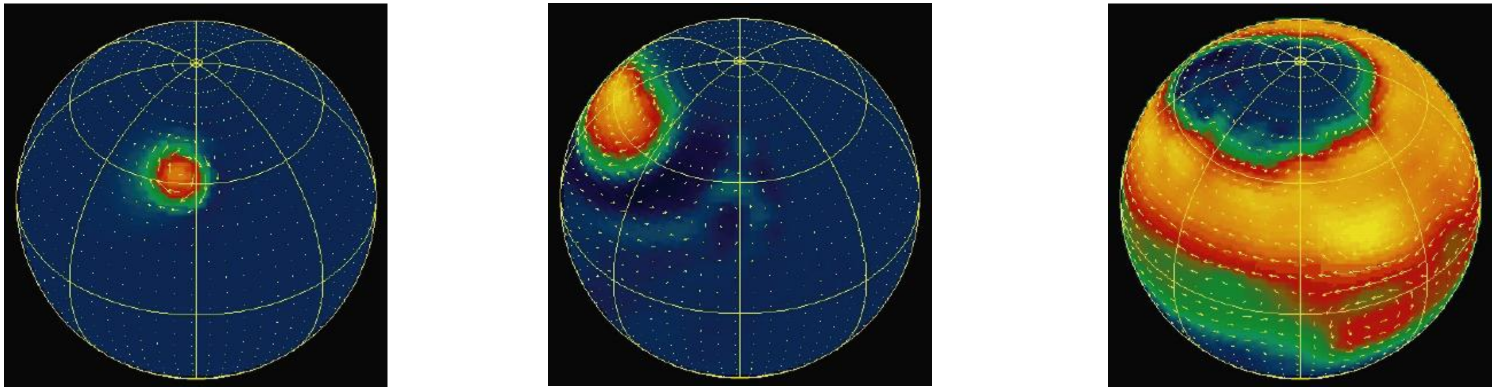


Figure courtesy:
A. Spitkovsky

The time-resolved and phase-resolved spectrum may be useful to probe light bending and gravitational redshift.

But, first we need to understand the flame-spreading observationally and theoretically.

Correlation among evolution of various spectral and timing properties during burst rise ⇒ Observational measurement of flame-spreading

We need a detector with large area, good time-resolution and less pile-up.

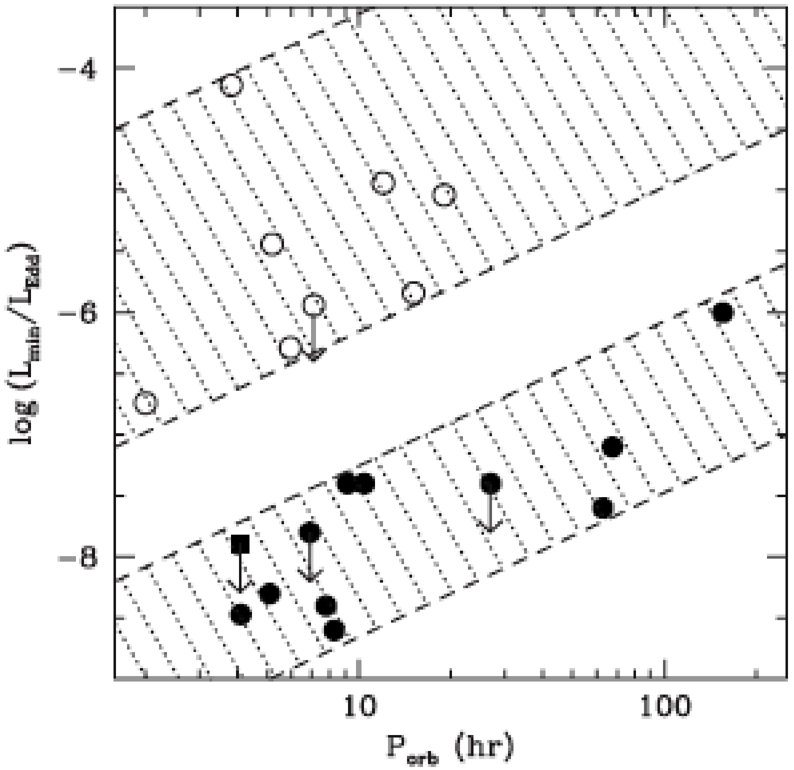
Testing event horizon

In quiescent state, NS luminosities are systematically higher than the BH luminosities.

A soft thermal spectral component is often found from quiescent NSs, most probably originated from the NS surfaces. This component is not found from quiescent BHs.

These indicate the existence of event horizon.

A rigorous study is needed.

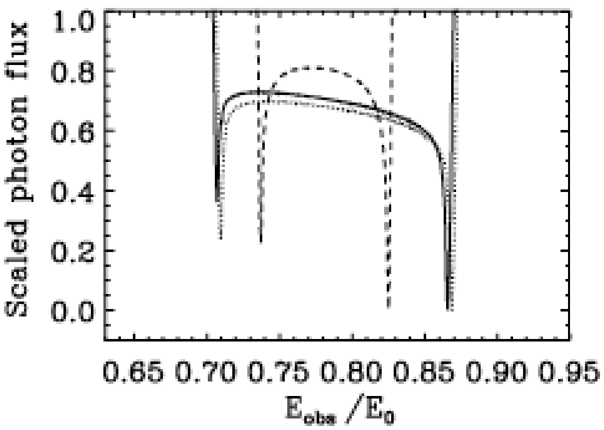


NS: open circles
BH: filled circles

McClintock, Narayan, Rybicki (2004)

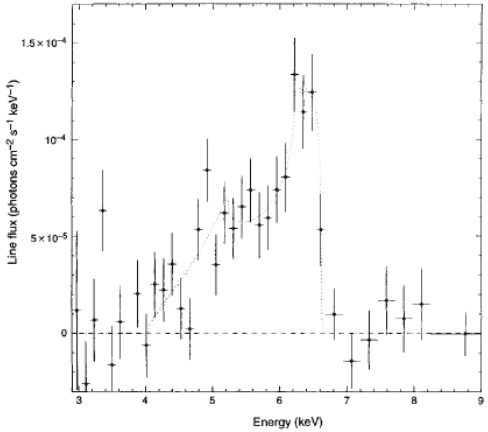
Testing the light bending effect

Double-peak / double-minimum depend on the flat-space geometry of the emitter / absorber, as well as on light bending.



The light bending effect is probably more critical for the NS surface geometry than for the disk geometry.

So both kinds of spectral lines can be usefull to test the light bending effect, but the surface lines will be more important.



When NS is compact enough, or the disk extends very close to the compact object, photons can reach the observer via various paths. The theoretical computation of this lensing should be compared with the observed lines.

Spectral tools

Testing the no-hair theorem

Kerr metric is a unique description of the spacetime outside a spinning black hole and is determined by only two parameters: M and a $\Rightarrow$ no-hair theorem

The exterior spacetime metric of a black hole can be expanded in multipoles, and the coefficients may be measured with observation.

For Kerr spacetime: quadrupole $q = -a^2/M^2$

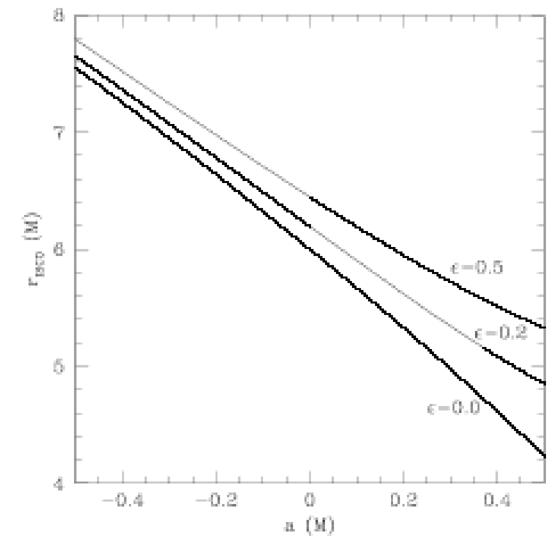
Now we assume that $q = -a^2/M^2 - \varepsilon$ (Glampedakis and Babak 2006), if ε is observationally found to be zero, then no-hair theorem is probably true.

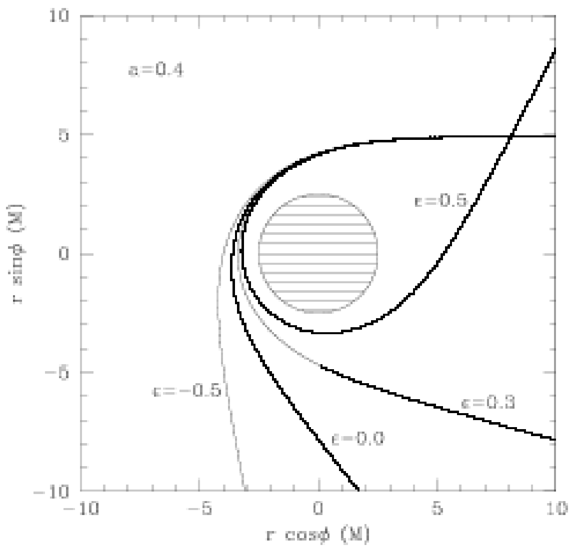
Methods:

(1) ISCO radius depends on ε (see figure on the right); but we need to measure ISCO radius (from disk line, etc.) and a/M independently.

(2) The speed of matter at ISCO depends on ε; speed of matter may be determined from the relative brightness of the blue and red wings of disk line.

(3) Photon orbits depend on ε (see figure on the right); imaging of black hole needed.

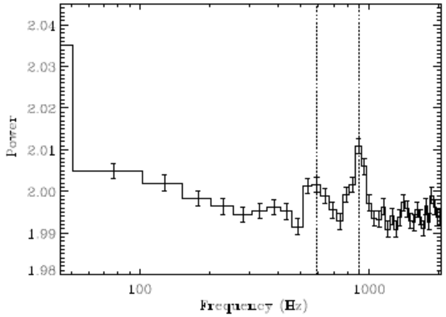




Psaltis and Johannsen (2009)

Timing tools

Kilohertz quasi-periodic oscillations (kHz QPOs)



KHz QPOs often appear in a pair in the power spectrum, in the 200-1200 Hz frequency range.

Fourier Transform

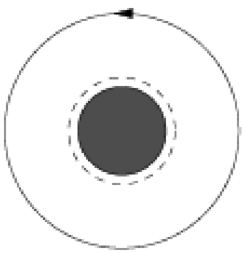
$$\hat{f}(\xi) := \int_{-\infty}^{\infty} f(x)\, e^{-2\pi i x \xi}\, dx.$$

$$f(x) = \int_{-\infty}^{\infty} \hat{f}(\xi)\, e^{2\pi i x \xi}\, d\xi$$

Power spectrum is the Fourier transform of the intensity vs. time curve.

This observationally robust timing feature have been detected from many neutron star LMXBs.

According to almost all the models, the uniquely high kHz QPO frequencies are either the following accretion disk frequencies, or the beating or resonances among them, or with the neutron star spin frequency ν_{spin}.



ν_ϕ : Orbital frequency

ν_r : Radial epicyclic frequency

ν_θ : Vertical epicyclic frequency

$\nu_\phi - \nu_r$: Periastron precession frequency

$\nu_\phi - \nu_\theta$: Nodal or `Lense-Thirring' precession frequency

Timing tools

Kilohertz quasi-periodic oscillations (kHz QPOs)

Accretion disk frequencies:

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

$$r_g \equiv GM/c^2$$

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

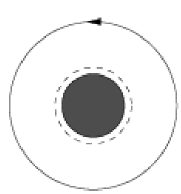
$$j \equiv Jc/GM^2$$

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

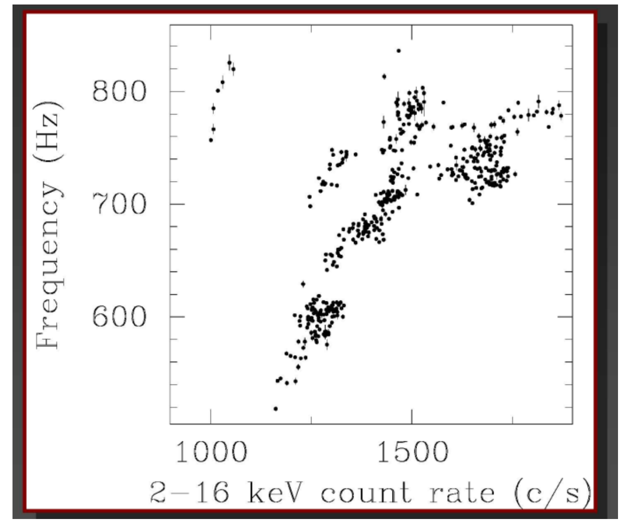
So when the correct model is identified, kHz QPOs can be used to measure the neutron star parameters M and J.

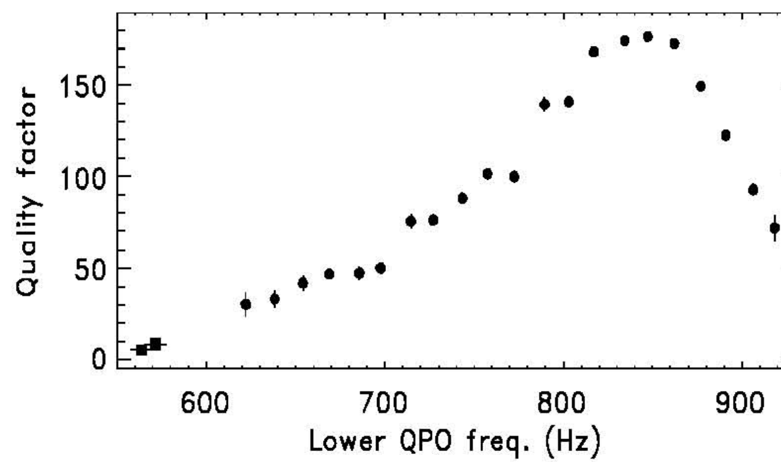
Apart from neutron star parameter measurement, KHz QPOs can be useful to study the matter flow in strong gravity region, and to test a law of gravitation.

For example, the general relativistic `Lense-Thirring' precision (frequency: ν_ϕ - ν_θ) has not yet been detected with certainty in strong gravity.



Signature of ISCO?





Barret et al. (Courtesy: M. Mendez)

Conclusions

1. **Probing strong gravity regime: Astrophysicists, general relativists, plasma physicists, and sometimes nuclear physicists have to work together.**

2. **General relativists have to formulate the theoretical framework for realistic strong gravity tests at the level of test particles.**

3. **Any strong gravity test would involve plasma physics (accretion, flame-spreading, etc.), so the entry of the plasma physicists.**

4. **Entry of the astrophysicists: theoretical computation of photon transfer, observations, data analysis and modeling, preparation of the science case for instruments/satellites, instrument building, etc.**

A unique multidisciplinary field!

Conclusions

1. **Probing strong gravity regime:** **Astrophysicists, general relativists, plasma physicists, and sometimes nuclear physicists have to work together.**

2. **General relativists have to formulate the theoretical framework for realistic strong gravity tests at the level of test particles.**

3. **Any strong gravity test would involve plasma physics (accretion, flame-spreading, etc.), so the entry of the plasma physicists.**

4. **Entry of the astrophysicists: theoretical computation of photon transfer, observations, data analysis and modeling, preparation of the science case for instruments/satellites, instrument building, etc.**

Thank you!

A unique multidisciplinary field!