Gravity in the strong field regime
&
Matter at supra-nuclear density

Science topics for a large area X-ray Telescope

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On behalf of

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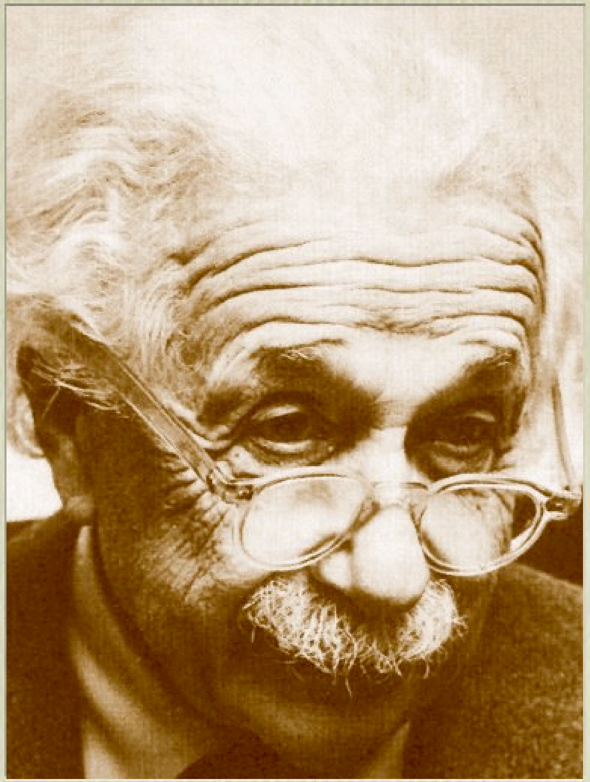
Part I

Gravity in the strong field regime

General Relativity

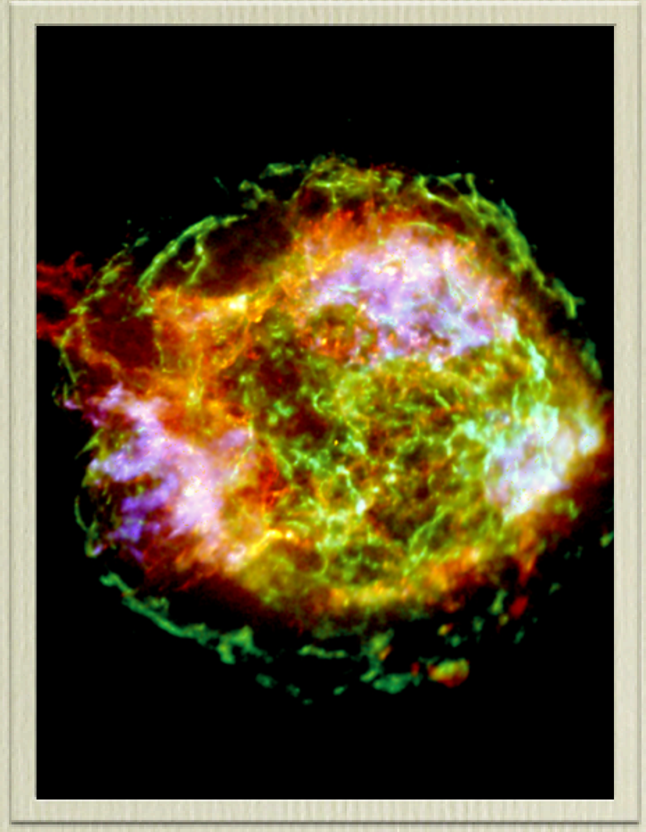
- After one century, General Relativity (GR) remains the best ever formulated theory of gravitation
- Yet GR cannot be the final theory of gravitation - one major step towards quantum gravity
- GR has been successfully tested in the weak field regime (e.g. around the earth)
- Several fundamental predictions of GR in the strong field regime have yet to be tested - The only tool we have in the Universe are compact objects



Compact objects:
Neutron stars and Black holes

- Stellar compact objects:
  - End-points of stellar evolution
  - Their formation is associated with the most violent phenomena seen in the Universe - Supernovae, Gamma-Ray Bursts
  - Their formation is also responsible for the enrichment of the Universe in heavy elements
- Supermassive black holes in galactic nuclei

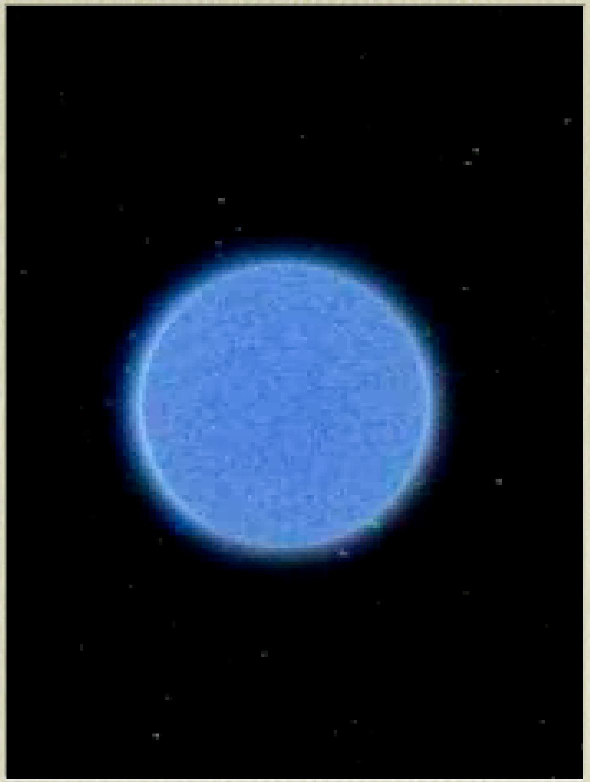
Great appeal to the grand public!



Cas A: supernova remnant in X-rays

X-rays probing the strong field region

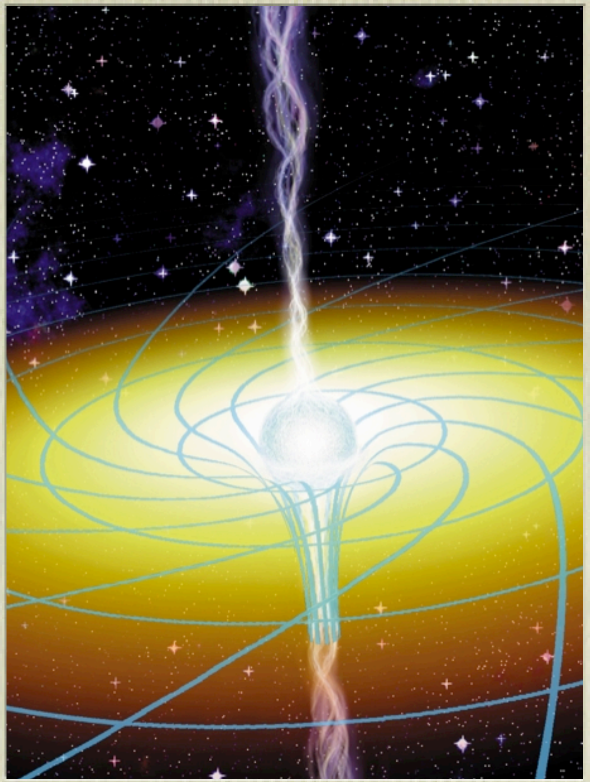
- Matter falling onto a compact star will shine predominantly in X-rays
- Compact objects are surrounded by regions of extreme spacetime curvature
- X-rays can be used to track the motion of matter in the strongly curved spacetime and test some of the most fundamental GR predictions



Accretion flow around a black hole

Observable X-ray signatures of strong gravity

- Gravitational redshifts: gravity stealing energy from photons
- GR fundamental predictions:
  - Innermost stable circular orbit
  - Strong dragging of inertial frames: spinning compact objects twisting spacetime like a tornado
  - Event horizon



Frame dragging

Diagnostics of strong gravity

Searched for with space instrumentation using broad band X-ray spectroscopy and timing (e.g. with Newton and Rossi):

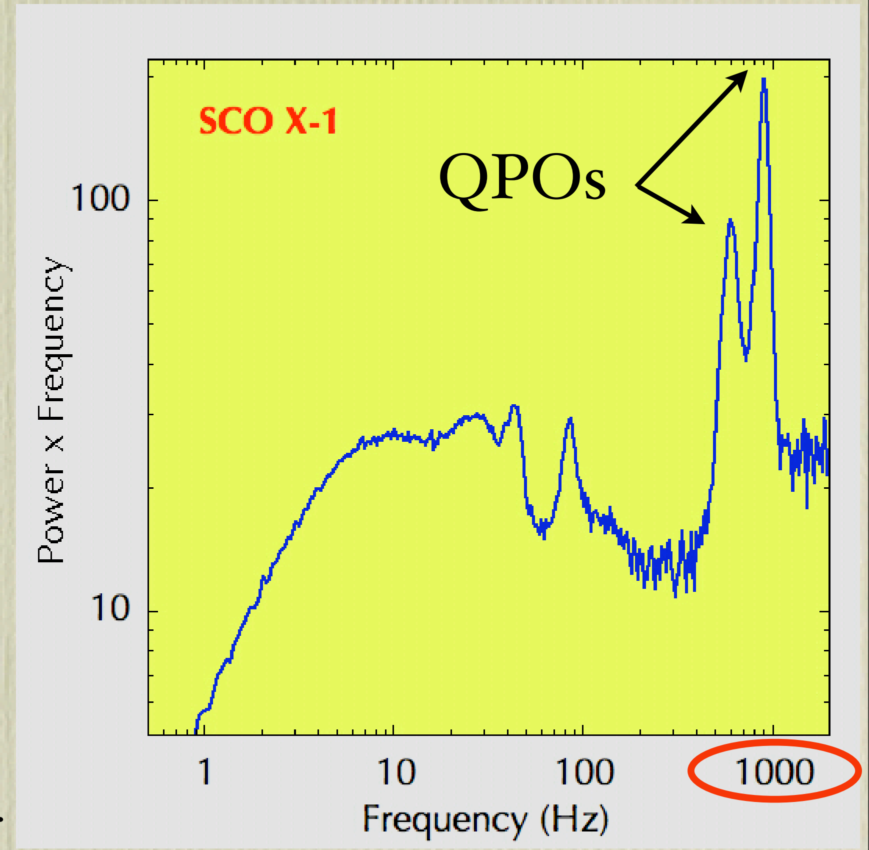
- Secured: Relativistically smeared iron line tracing matter moving close to the black hole event horizon - Redshifted absorption lines from radiation emitted at the surface of a neutron star

- Tantalizing evidence for:
  - The innermost stable circular orbit
  - The event horizon
  - *Orbital motion in the strong field region around black holes and neutron stars - Matter moving close to the innermost stable circular orbit*

Strong field orbital motion

- Structured variability on the dynamical timescales of the accretion flow revealed as Quasi-Periodic Oscillations
- If related to orbital motion: 800 Hz ⇔ 20 km
- Effective probes of the strong field region where GR *must* play a role - most models involve epicyclic motions
- Great potential to test GR, to constrain the mass, radius and spin of compact objects

Power density spectrum of Sco X-1 X-rays



Turning diagnostics into tests

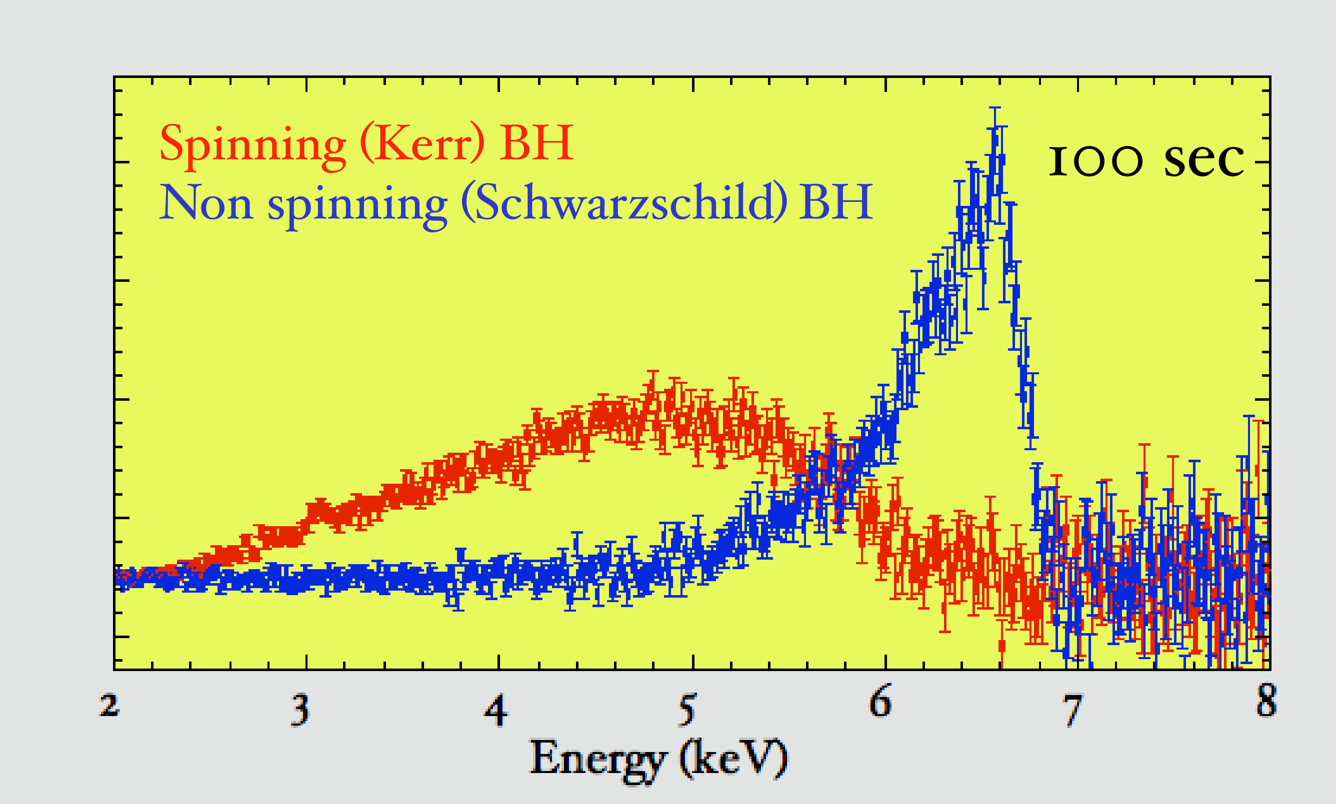
- A 10 m^2 class X-ray mission is required to convert these diagnostics of GR into true tests of GR

- 10 m^2 collecting area will provide better than one order of magnitude improvement in photon statistics - spectral and timing signals will be observed on their characteristic lifetimes - e.g. X-ray flares from an AGN accretion disk - QPOs on their coherence time

- The instrumentation will have to combine:
    - broad band spectral coverage (up to ~100 keV)
    - high-throughput fast timing capabilities (microsecond timing)
    - good energy resolution

Measuring the spin and mass

Simulations of stellar mass accreting black hole spectra seen by a 10 m^2 X-ray telescope: Relativistically smeared iron line



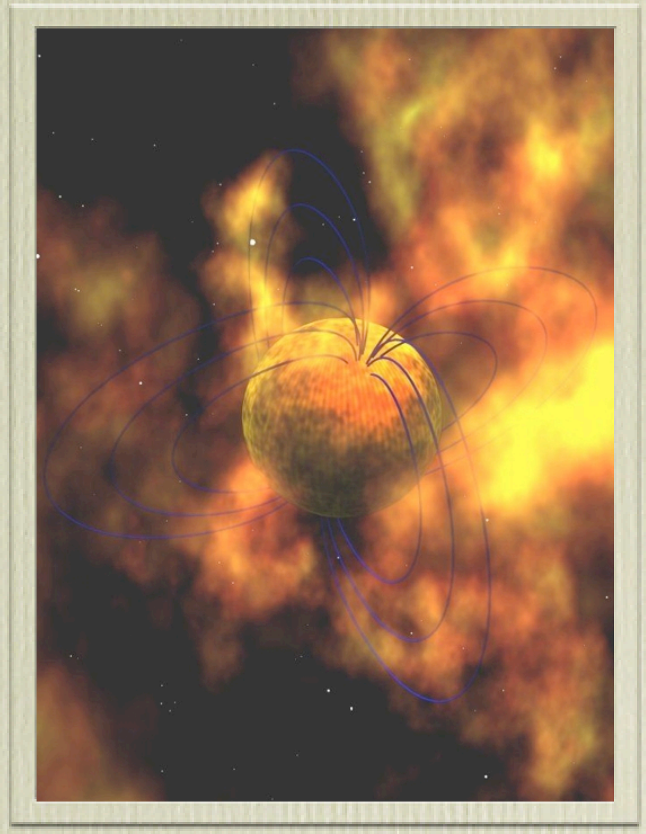
Relevance to understand how black holes form and evolve, accretion flow physics and the link between accretion and ejection taking place over a wide range of objects

Part II

The equation of state of matter at supra-nuclear density

Neutron stars

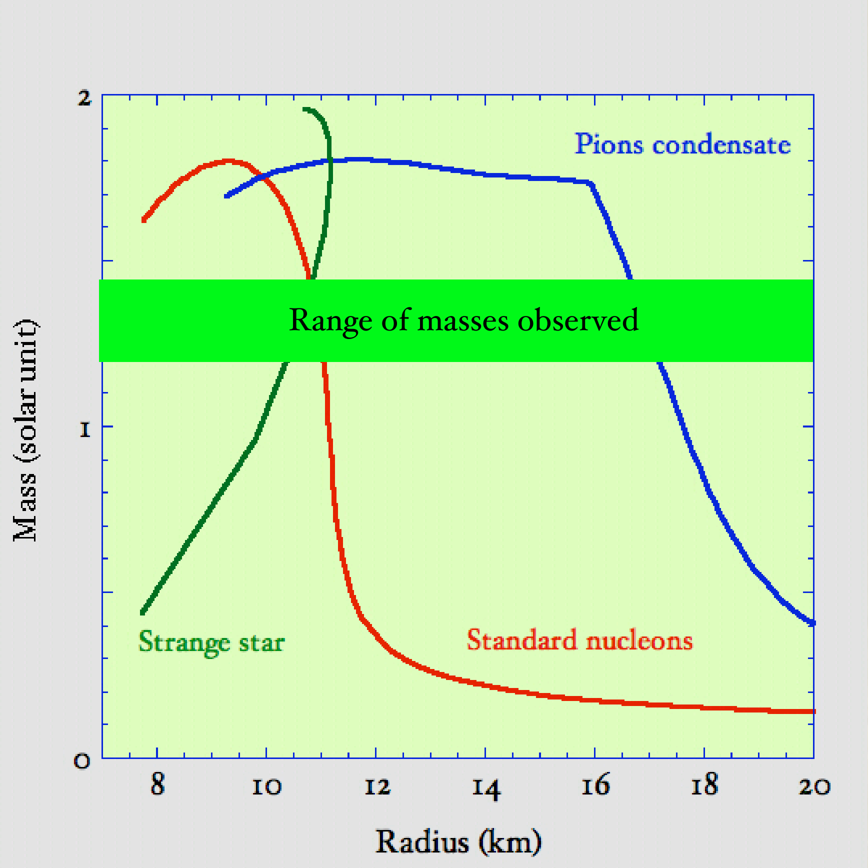
- Differ from black holes by the presence of a solid surface
- Magnetic fields can reach 10^{15} Gauss (strong field quantum electrodynamics)
- Millisecond spins (possible sources of gravitational waves)
- 1 solar mass packed in 10 km! The density can reach ten times the density of an atomic nucleus



Magnetized neutron star

Matter at supra-nuclear density

- The composition of neutron stars depends on the nature of strong interactions
- The structure of neutron stars is given by the equation of state (EoS) of dense matter
- Physics allows neutron stars to be made of exotic matter
- X-rays from neutron stars encode information about their masses and radii, allowing to constrain the EoS



Mass-radius relations for different EoS

What 10 m² could do!

Gravitational redshift (M/R)

combined with

Pressure broadening (M/R^2)

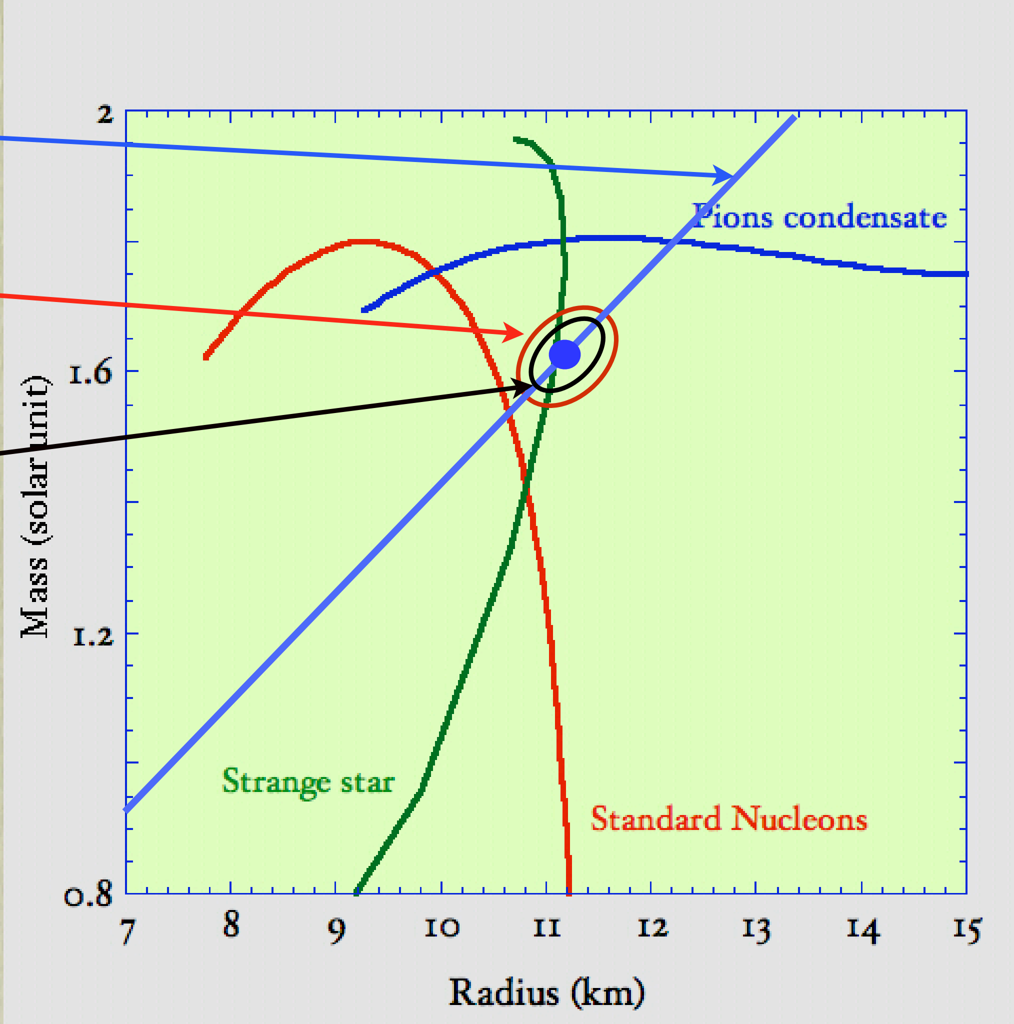
combined with

Waveform modeling of rotating hot spots (M/R)

Additional constraints

Waveform modeling of Kilo-Hz QPOs (M/R)

X-ray continuum spectrum fitting (R and magnetic field)

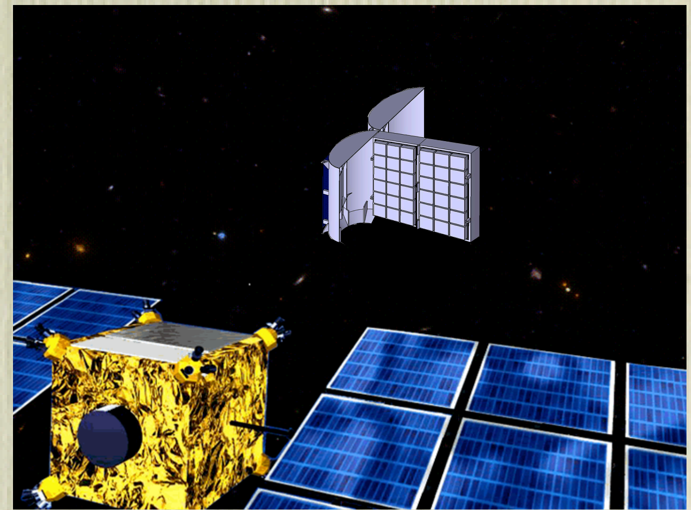


A bright future ahead

- Compact objects are the best laboratories for extreme physics
- X-rays are effective probes of the motion of matter in the strong field region
- The first diagnostics of strong field gravity have been recently obtained in X-rays
- These signals must now be used to test physics under extreme conditions
- X-rays generated at the neutron star surface hold great potential for constraining the equation of state of matter at supra-nuclear density

With a European leadership

A New Generation X-ray Telescope with a 10 m^2 collecting area combining broad band spectral coverage, fast timing capabilities and good energy resolution is now required (e.g. XEUS)



With its technology development plan (e.g. light weight optics) and great heritage in high energy astronomy, ESA has the potential to take the lead in this field with support from a broad European and worldwide community