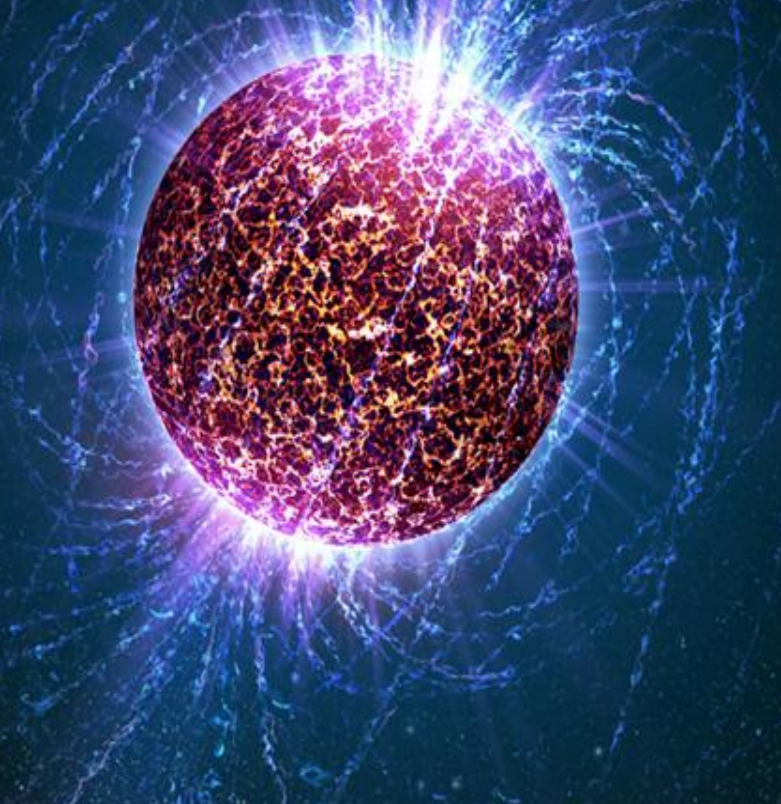
X-Ray Observations of Neutron Stars: future prospects



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Roma Tre

Outline

- Why do we study NS?

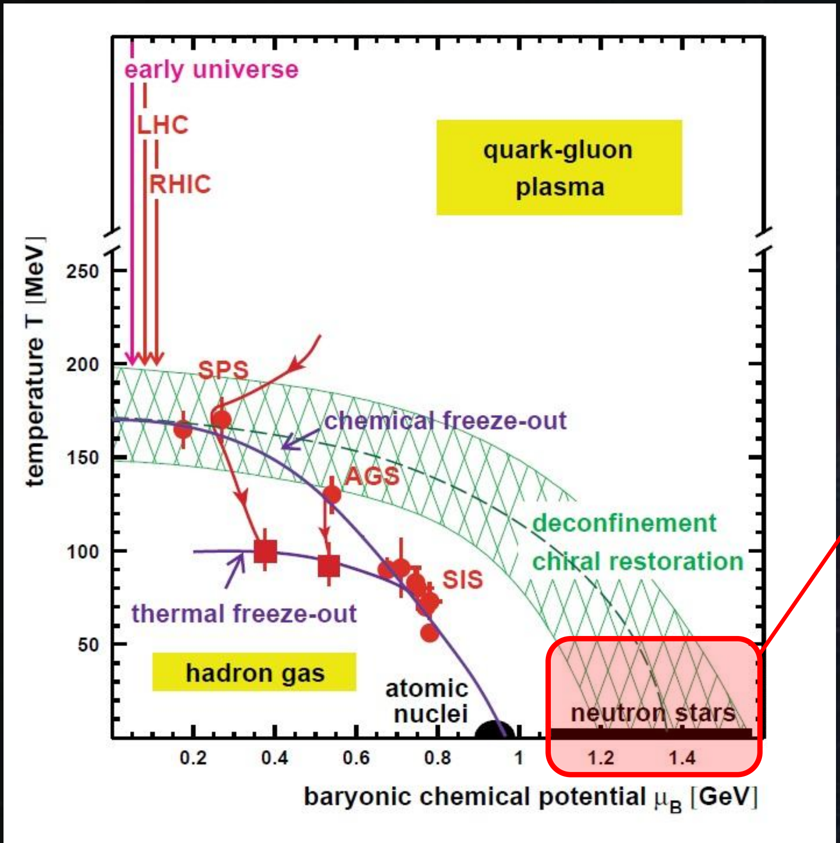
- NS equation of state

- Current status of observations:
  - the case of EXO0748-646

- Future prospects:
  - X-rays spectroscopy
  - X-rays polarimetry

- How and when

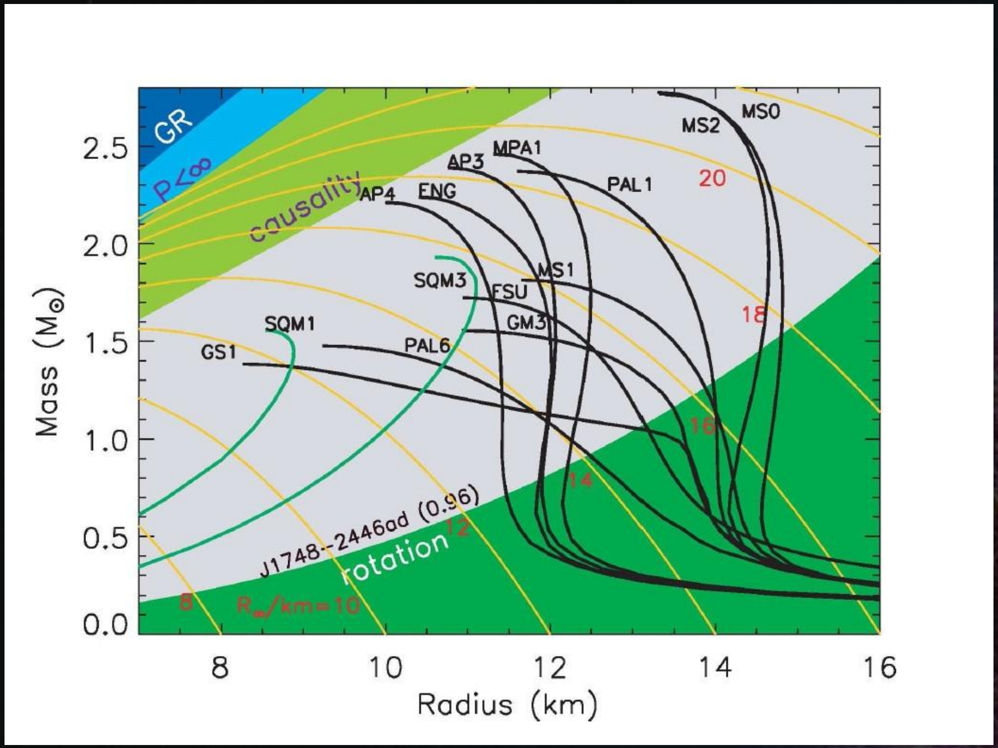
Why do we study NS?

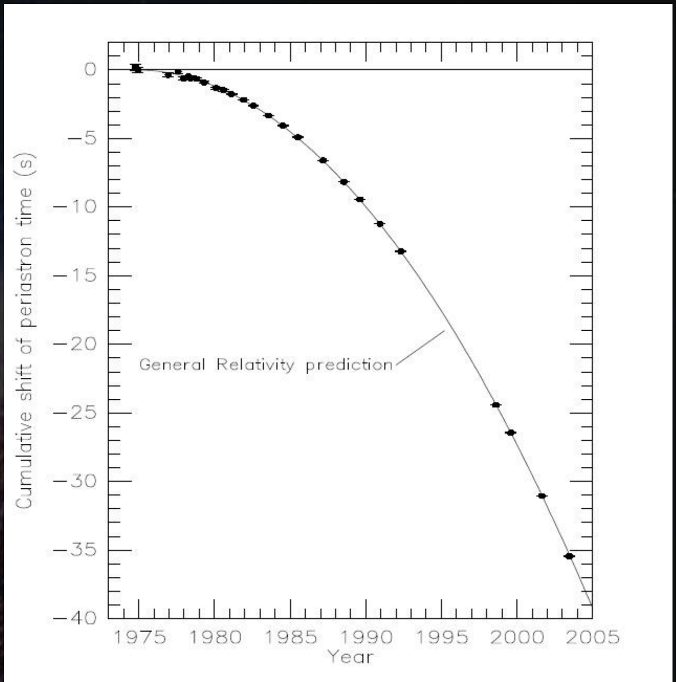


$\rho \sim 3 \times 10^{14}$ g cm^{-3} :

… exotic excitations (hyperons), Bose condensates of pions and kaons, transition to strange quark matter

NS equation of state





Hulse & Taylor – Nobel Price 1993

Radio observations ⇨ only precise mass determination

In order to have both <u>mass</u> and <u>radius</u> simultaneously, we have to look at the photospheric emission, whose natural wavelenght band is the **X-ray band**!

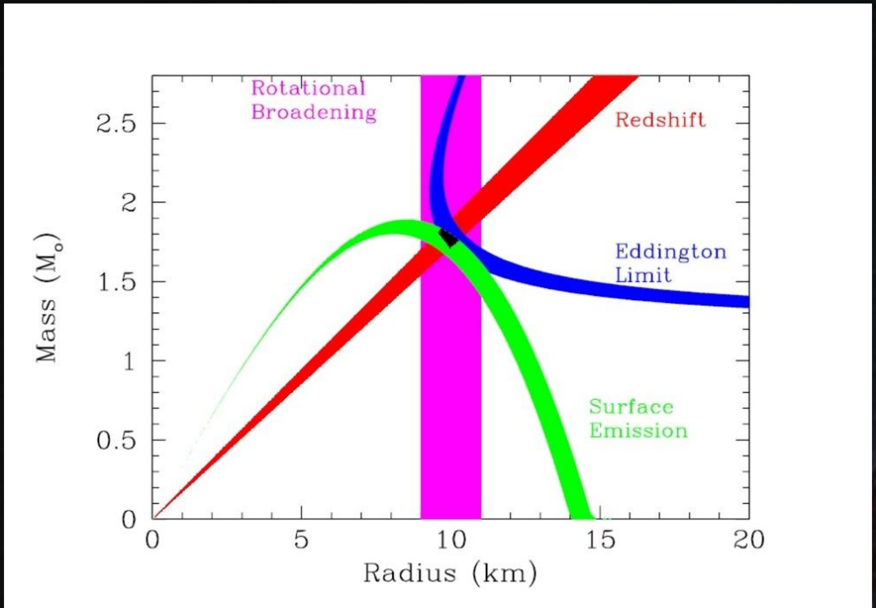
Current status

EXO0748-646, accreting NS

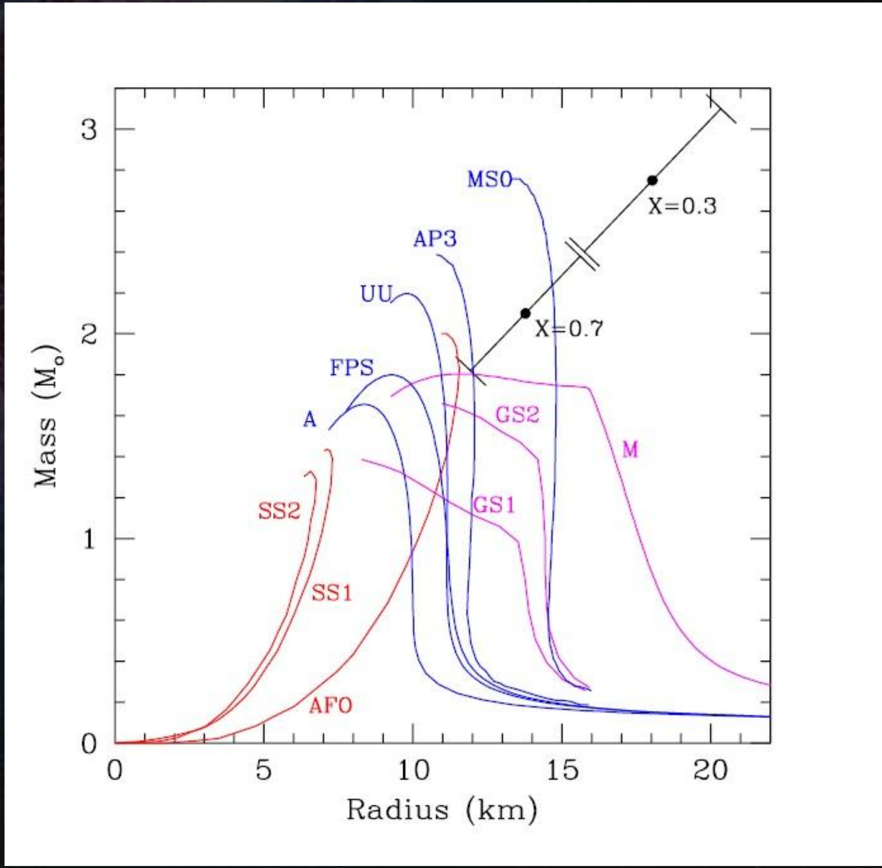
Observable	Measurement	Dependence on NS Properties
$F_{\rm Edd}$	$(2.25 \pm 0.23) \times 10^{-8}$ erg cm^{-2} s^{-1}	$\frac{1}{4\pi D^2}\frac{4\pi GMc}{\kappa_{\rm es}}\left(1-\frac{2GM}{c^2R}\right)^{1/2}$
z	0.35	$\left(1-\frac{2GM}{Rc^2}\right)^{-1/2}-1$
$F_{\rm cool}/\sigma T_c^4$	1.14 ± 0.10 (km/kpc)^2	$f_\infty^2 \frac{R^2}{D^2}\left(1-\frac{2GM}{Rc^2}\right)^{-1}$

NS Property	Dependence on Observables	Constraint
M	$\frac{f_\infty^4 c^4}{4G\kappa_{\rm es}}\left(\frac{F_{\rm cool}}{\sigma T_c^4}\right)\frac{[1-(1+z)^{-2}]^2}{(1+z)^3}F_{\rm Edd}^{-1}$	$2.10 \pm 0.28 M_\odot$
R	$\frac{f_\infty^4 c^2}{2\kappa_{\rm es}}\left(\frac{F_{\rm cool}}{\sigma T_c^4}\right)\frac{1-(1+z)^{-2}}{(1+z)^3}F_{\rm Edd}^{-1}$	13.8±1.8 km
D	$\frac{f_\infty^2 c^2}{2\kappa_{\rm es}}\left(\frac{F_{\rm cool}}{\sigma T_c^4}\right)^{1/2}\frac{1-(1+z)^{-2}}{(1+z)^3}F_{\rm Edd}^{-1}$	9.2±1.0 kpc

Ozel, 2006


Rotational Broadening
Redshift
Eddington Limit
Surface Emission
Mass (M$_\odot$)
Radius (km)
0
0.5
1
1.5
2
2.5
0
5
10
15
20

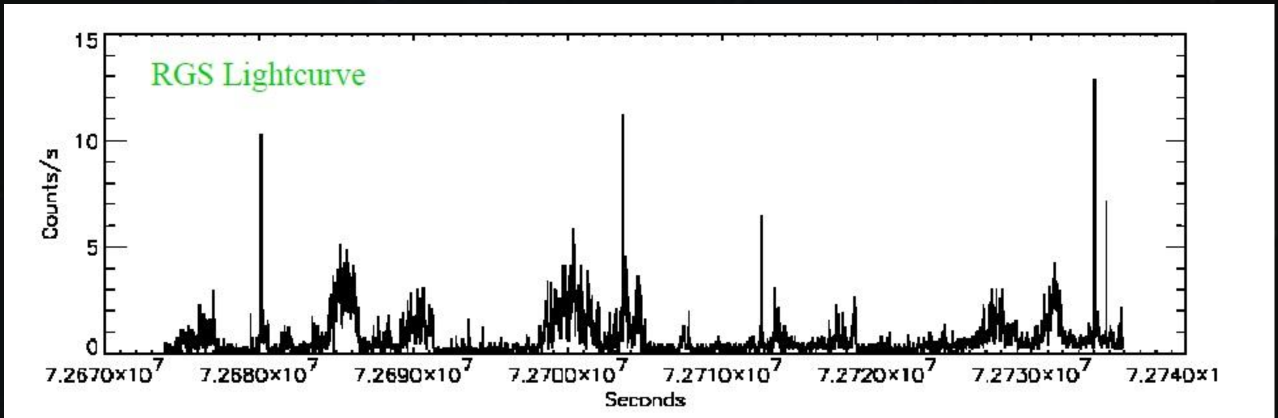
Ozel, 2006

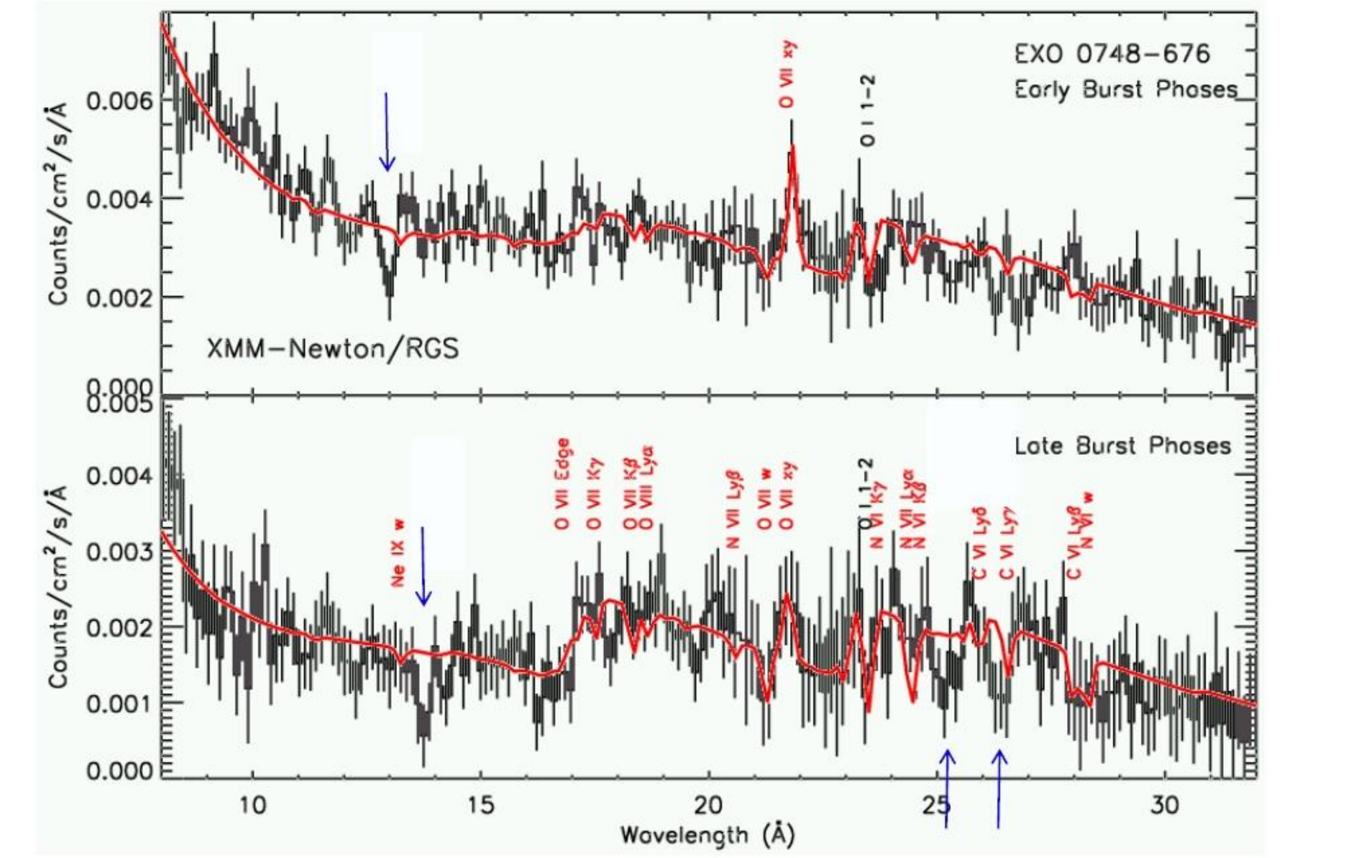

MS0
AP3
UU
FPS
A
GS2
M
GS1
SS2
SS1
AFO
X=0.3
X=0.7
Mass (M$_\odot$)
Radius (km)
0
1
2
3
0
5
10
15
20

EXO0748-646

RGS data for 28 bursts (3200 sec)

& simultaneous EPIC data for 3 bursts (250 sec)





Cottam et al. 2002

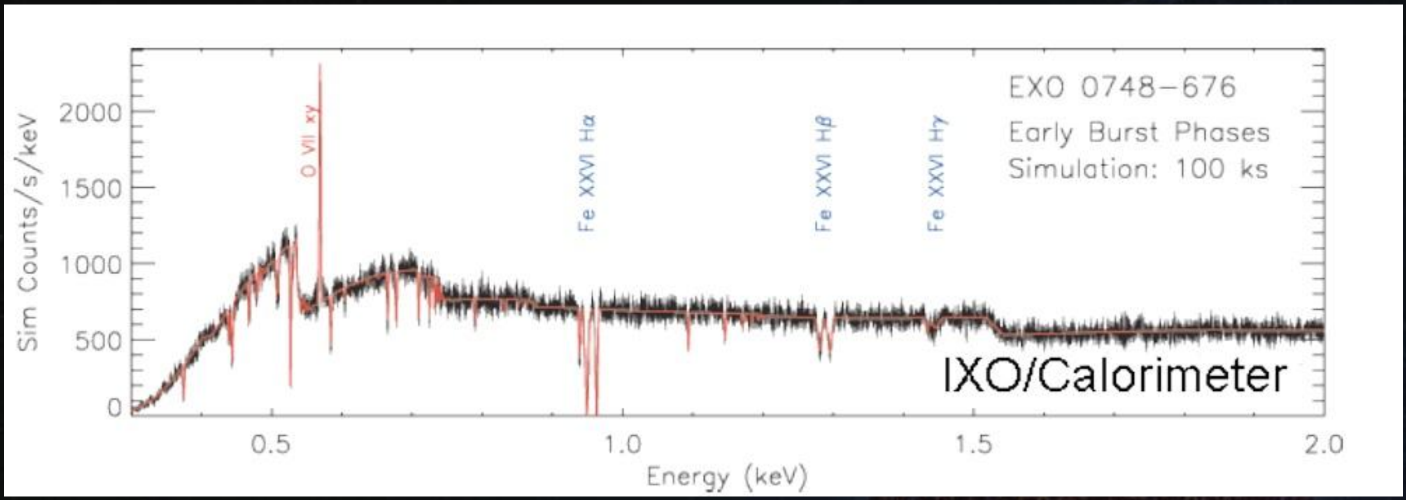
Fe XXVI n=2-3

Fe XXV n=2-3

O VIII Lyα

Z=0.35

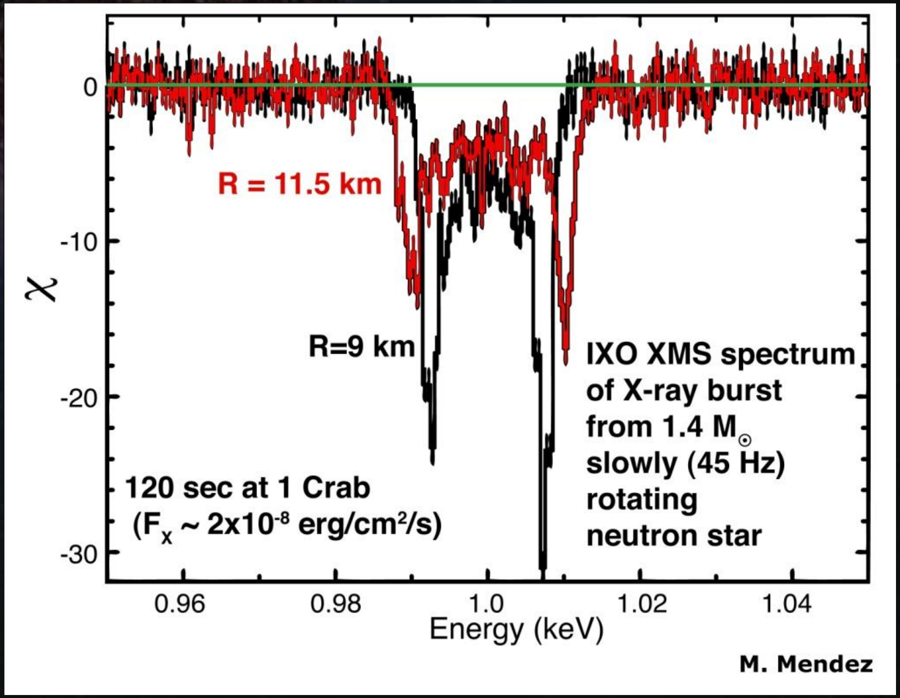
Future prospects
- X-ray spectroscopy -



IXO Science Investigations

Doppler broadening ⇨ direct measurement of stellar radius

(note that the magnetic field strenghts in LMXBs are small enough, $<10^9$ G, that Zeeman splitting is not important)



Future prospects
- X-ray polarimetry -

Radio pulsars

isolated, rotation-powered NS; strong electric fields and pair production in the very strong (up to few 10^{13} G) magnetic field result in beamed outflow of relativisticprticles and radiation (almost certainly "synchrotron radiation" in X-rays)

X-ray polarimetry could provide decisive information to test detailed models and to determine the emission site ("polar cap" vs "outer cap")

Polarimetry also offer an interesting opportunity to observe an exotic QED effect – **vacuum birefringence** – induced by a strong magnetic field:

$$n_{\parallel} \approx 1 + \frac{\alpha}{4\pi} \sin^2\theta \left[\frac{14}{45} \left(\frac{B}{B_{\mathrm{cr}}} \right)^2 - \frac{13}{315} \left(\frac{B}{B_{\mathrm{cr}}} \right)^4 \right]$$

$$n_{\perp} \approx 1 + \frac{\alpha}{4\pi} \sin^2\theta \left[\frac{8}{45} \left(\frac{B}{B_{\mathrm{cr}}} \right)^2 - \frac{379}{5040} \left(\frac{B}{B_{\mathrm{cr}}} \right)^4 \right]$$

$$B_{cr} = \frac{m^2 c^3}{e\hbar} \approx 4.4 \times 10^{13} G$$

when the de Broglie radius of a plasma electron becomes comparable to its Larmor radius

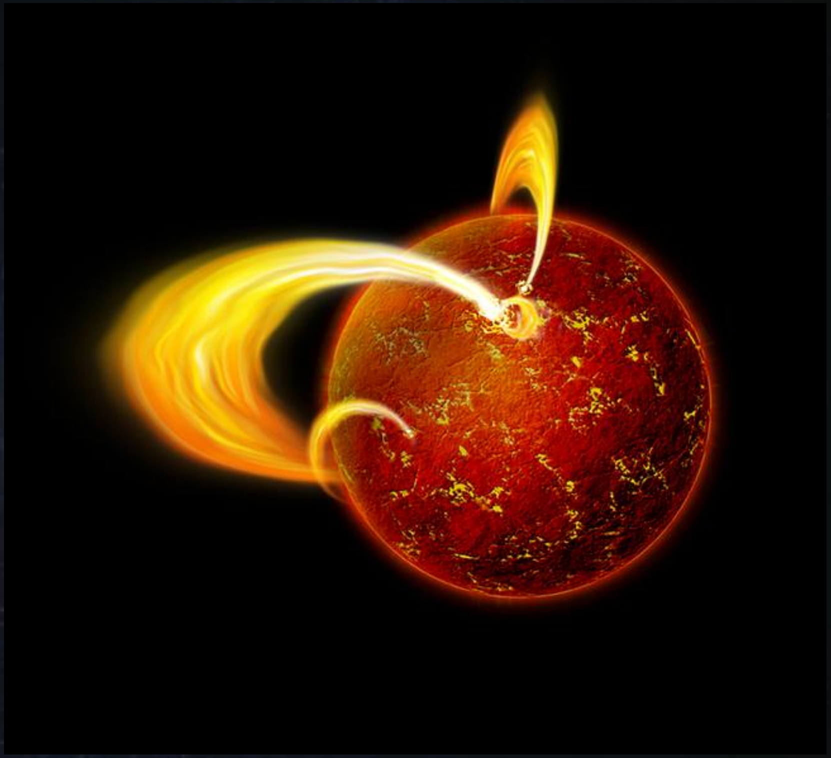
Quantization of electrons in “Landau levels” ⇨ $E_n = n \cdot 12\ \mathrm{keV} \cdot B_{12}$

Observation of these cyclotron lines thus provide a direct measurement of the NS magnetic field

Magnetars

isolated, magnetic-powered NS; SGRs and AXPs are likely to be magnetars, i.e. NS with extremely strong (10^{14-15} G) magnetic fields

Magnetically coupled seismic activity possibly results in high-energy radiation and plasma outflows, occasionally in extremely luminous (up to 10^{47} erg s^{-1}) giant flares. Radiation emitted in such superstrong magnetic fields is inevitably highly polarized



X-ray polarimetry could provide important data for understanding the nature of magnetars and for studying physical processes in extreme magnetic fields

X-ray binaries

system composed by a normal star accreting onto a NS; the behavior at the inner edge of the accretion disk depends on the NS's magnetic field (B):

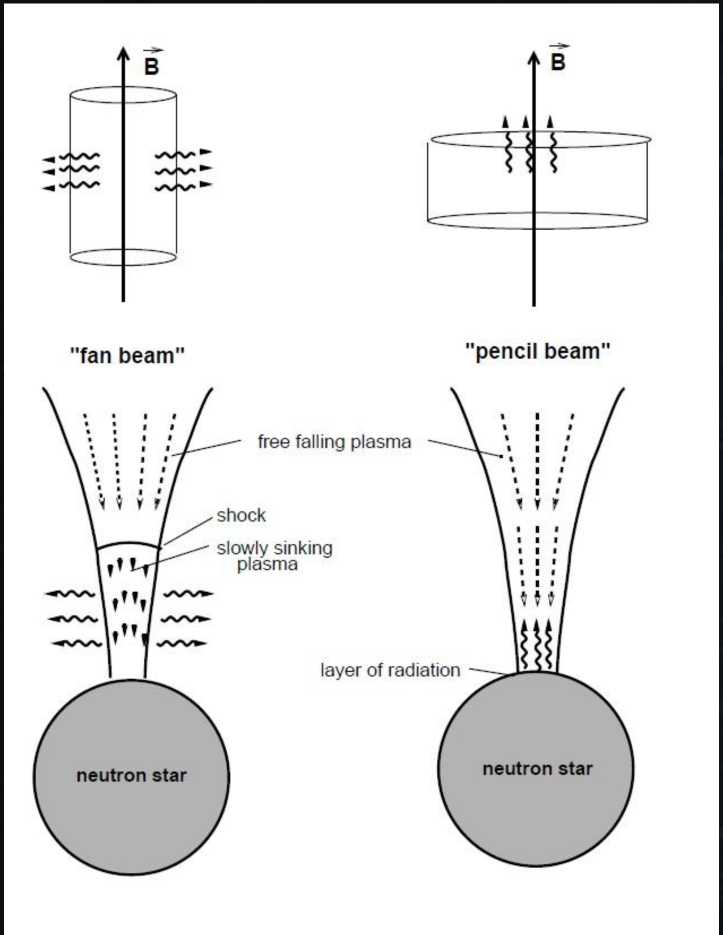
For strong B → "X-ray pulsar". Typically found in system where the donor is a young O/B-star; theese system are als called "High Mass X-ray Binaries" (HMXBs)

For low mass donor → "Low Mass X-ray Binaries" (LMXBs); persistent pulsations are not observed and the accretion disk extends deep into the gravitational potential well, suggesting that the magnetic field is considerably weaker than that in HMXBs

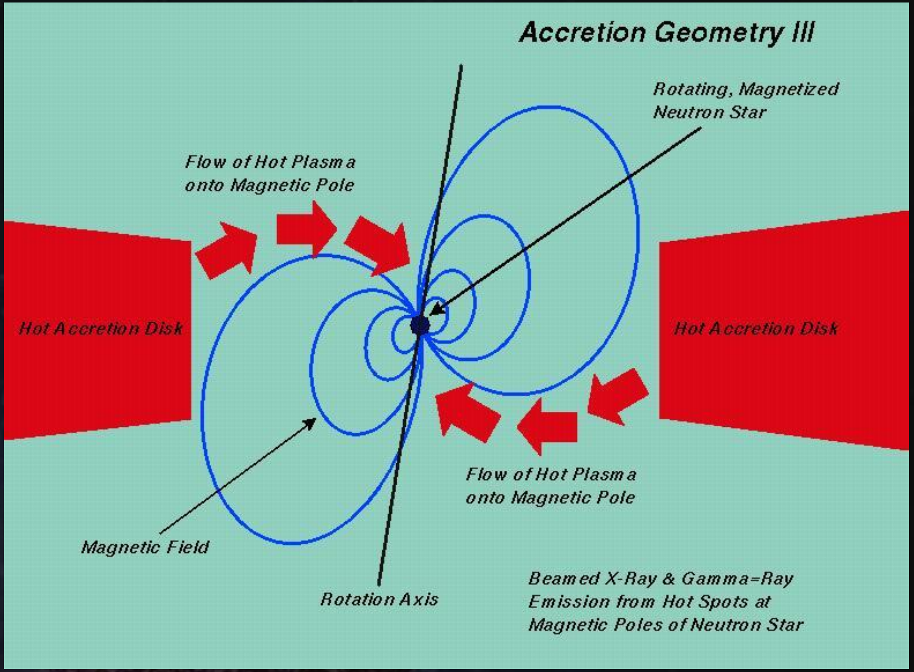
HMXBs $\xrightarrow[\text{time}]{\text{magnetic field decay}}$ LMXBs

The physics of emission

Rothschild et al, 2009

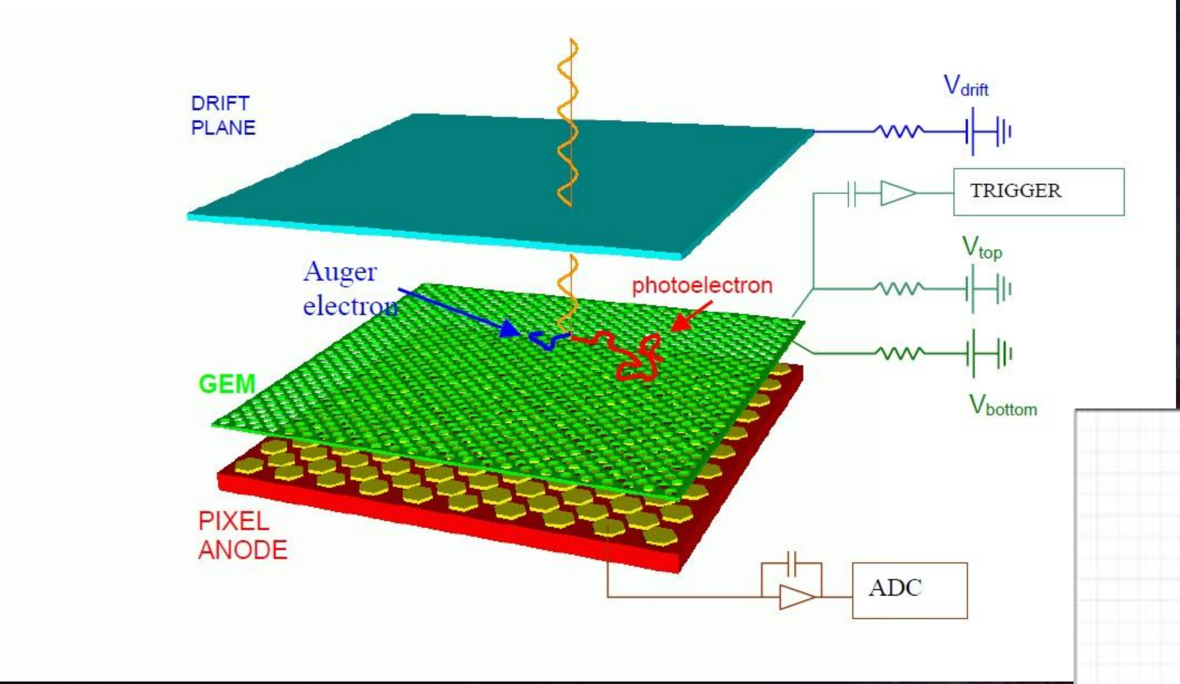


Basko & Sunyaev, 1976



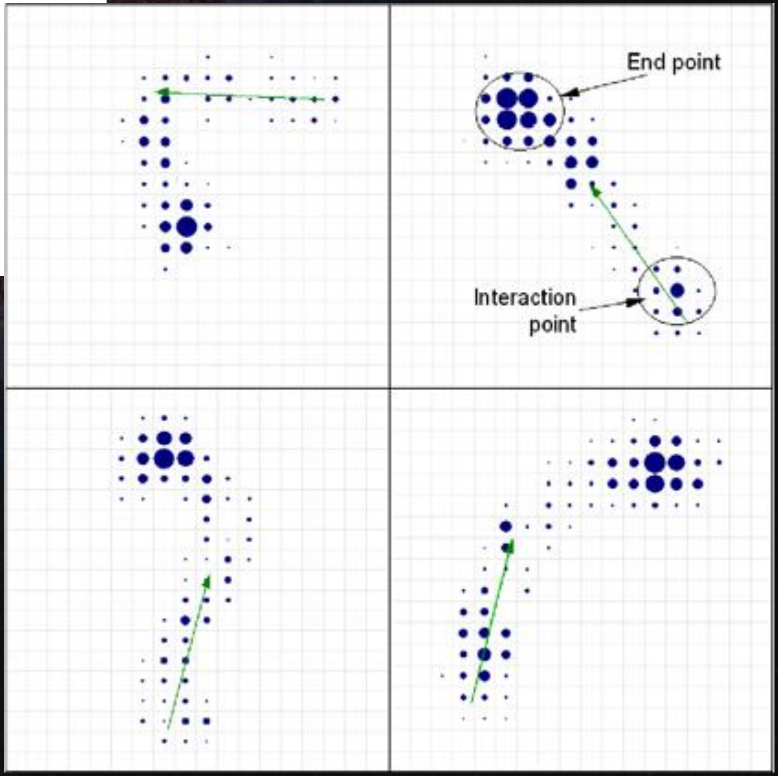
X-ray polarization measurements can test models and infer parameters of the accreting matter and of the NS.

How

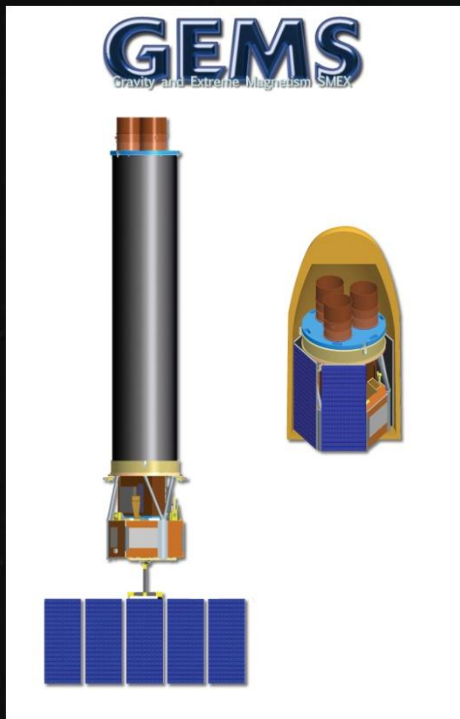


INFN Pisa – INAF/IASF Roma

Costa et al, 2001

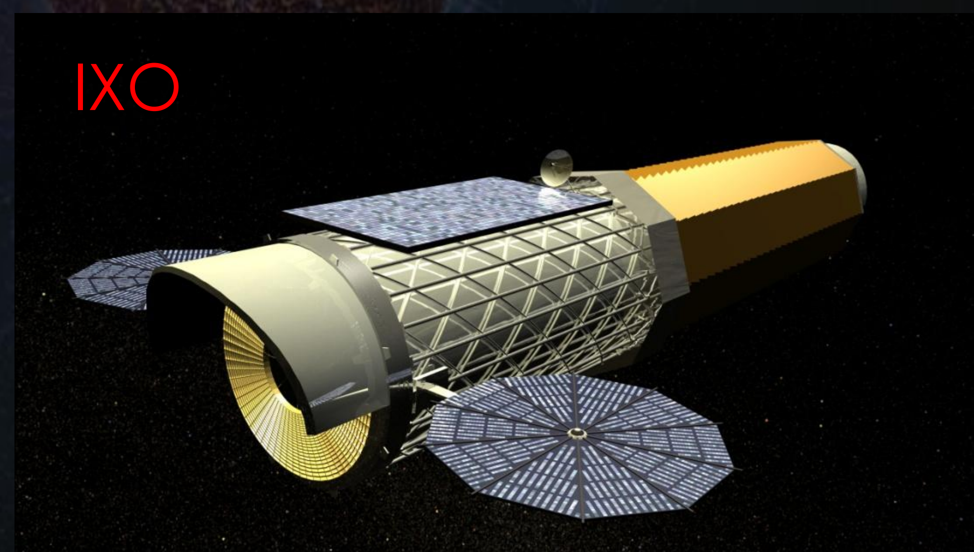


When



2014

2021



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