Fast Rotation of Neutron Stars

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in collaboration with
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Neutron Star Day
LUTh, Meudon, 27 June 2007

Motivation

- Theoretical
    - maximum frequency of the rotating NS
    - allowable masses of the fast rotating NS
    - signatures of the *exotic states* of matter
- Observational (2006)
    - discovery of the 716 Hz pulsar (24 years after 641 Hz pulsar)
    - suggestion of the observation of 1122 Hz pulsar

It is worth to study the consequences of the existence of submillisecond pulsars

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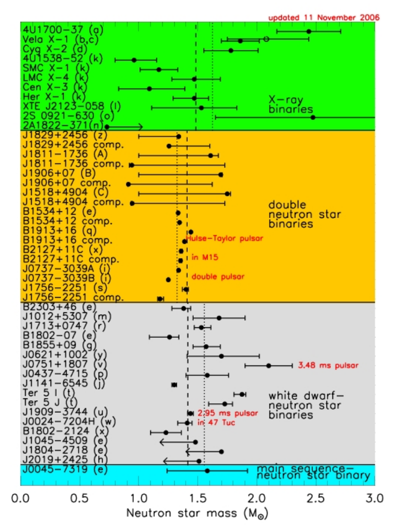
Masses of Neutron Stars

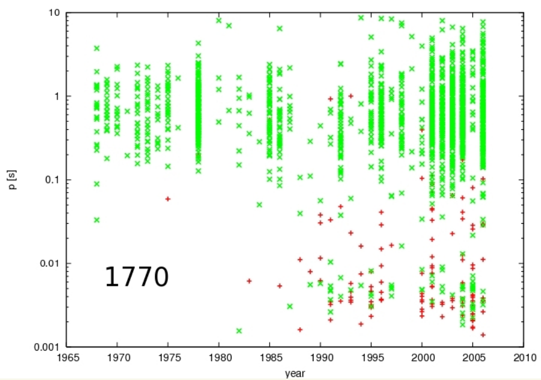


- bounds on the Equation of State
- large mass → soft matter excluded

Prakash - 2007

Periods of Pulsars

- Australia Telescope National Facility Pulsar Catalogue
- P - period
- $\dot{P} = dP/dt$ - period derivative
- in binary systems
- Millisecond pulsars



http://www.atnf.csiro.au/research/pulsar/psrcat/
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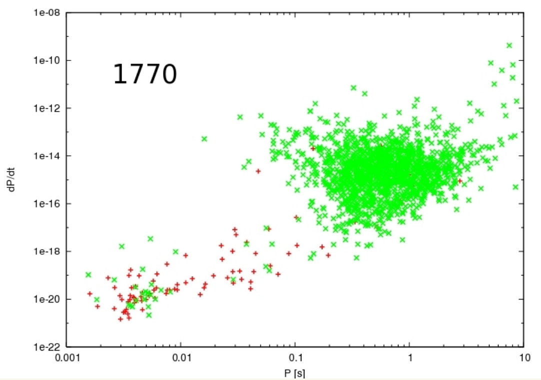

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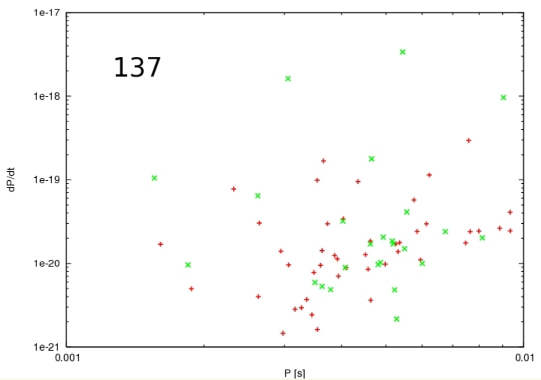

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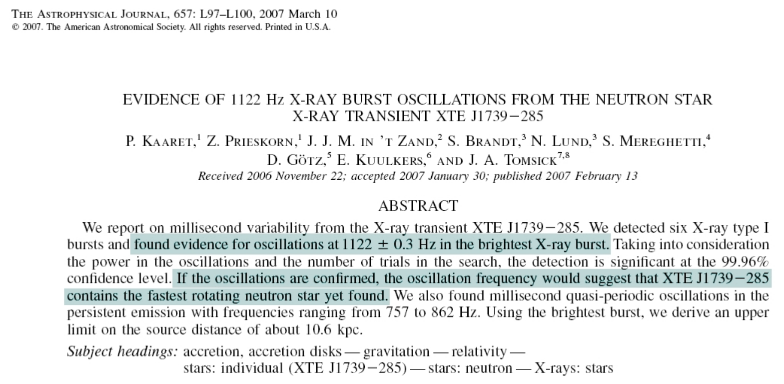
Frequencies of pulsars

- The rotation frequency
$$f = \Omega/2\pi$$
- PSR 1937+214 $f = 641$ Hz, $P = 1.558$ ms (1982) - first millisecond pulsar
- PSR 1748-2446 $f = 716$ Hz, $P = 1.397$ ms (2006)
- XTE J1739-285 $f = 1122$ Hz, $P = 0.89$ ms (2006) ?

1122 Hz pulsar - observation



The Astrophysical Journal, 657: L97–L100, 2007 March 10

EVIDENCE OF 1122 Hz X-RAY BURST OSCILLATIONS FROM THE NEUTRON STAR X-RAY TRANSIENT XTE J1739−285

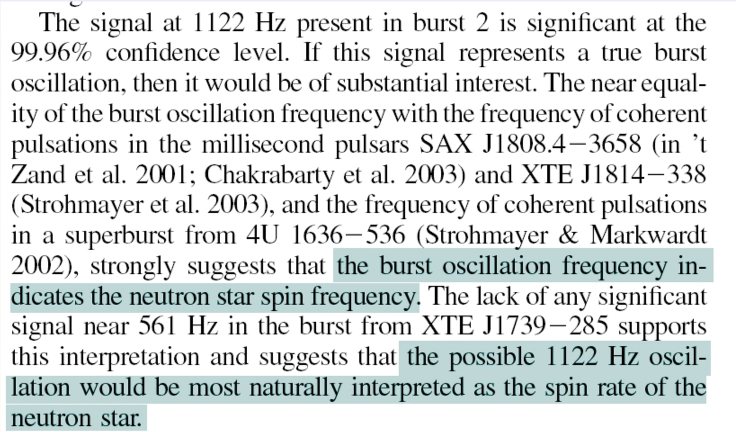
P. Kaaret,[1] Z. Prieskorn,[1] J. J. M. in 't Zand,[2] S. Brandt,[3] N. Lund,[3] S. Mereghetti,[4]
D. Götz,[5] E. Kuulkers,[6] and J. A. Tomsick[7,8]
Received 2006 November 22; accepted 2007 January 30; published 2007 February 13

ABSTRACT

We report on millisecond variability from the X-ray transient XTE J1739−285. We detected six X-ray type I bursts and found evidence for oscillations at 1122 ± 0.3 Hz in the brightest X-ray burst. Taking into consideration the power in the oscillations and the number of trials in the search, the detection is significant at the 99.96% confidence level. If the oscillations are confirmed, the oscillation frequency would suggest that XTE J1739−285 contains the fastest rotating neutron star yet found. We also found millisecond quasi-periodic oscillations in the persistent emission with frequencies ranging from 757 to 862 Hz. Using the brightest burst, we derive an upper limit on the source distance of about 10.6 kpc.

Subject headings: accretion, accretion disks — gravitation — relativity —
stars: individual (XTE J1739−285) — stars: neutron — X-rays: stars

1122 Hz pulsar - observation

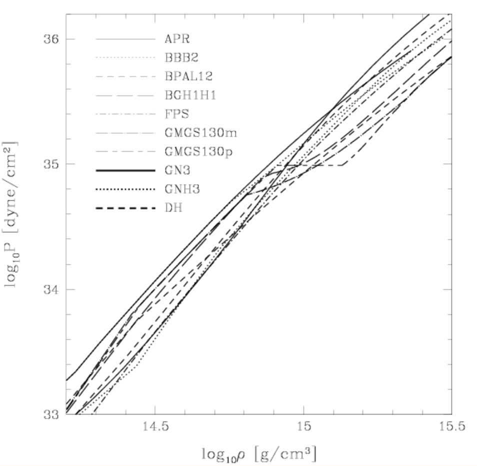


The signal at 1122 Hz present in burst 2 is significant at the 99.96% confidence level. If this signal represents a true burst oscillation, then it would be of substantial interest. The near equality of the burst oscillation frequency with the frequency of coherent pulsations in the millisecond pulsars SAX J1808.4−3658 (in 't Zand et al. 2001; Chakrabarty et al. 2003) and XTE J1814−338 (Strohmayer et al. 2003), and the frequency of coherent pulsations in a superburst from 4U 1636−536 (Strohmayer & Markwardt 2002), strongly suggests that the burst oscillation frequency indicates the neutron star spin frequency. The lack of any significant signal near 561 Hz in the burst from XTE J1739−285 supports this interpretation and suggests that the possible 1122 Hz oscillation would be most naturally interpreted as the spin rate of the neutron star.

EOSs - nuclear matter

$P(\rho)$ - Equation Of State

- BPAL12 *Bombaci 1995* - soft limit
- GN3 *Glendenning 1985* - stiff limit
- FPS *Pandharipande & Ravenhall 1989*
- BBB2 *Baldo et al. 1997*
- DH *Douchin & Haensel 2001*
- APR *Akmal et al. 1998*



EOSs - softened matter

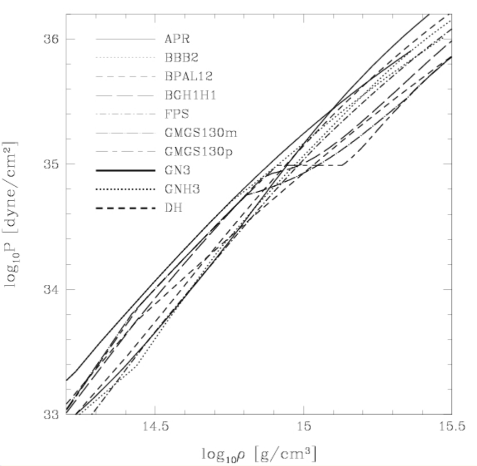
$P(\rho)$ - Equation Of State

matter softened by the appearance of hyperons

- GNH3 *Glendenning 1985*
- BGN1H1 *Balberg & Gal 1997*

matter softened by the phase transition to kaon condensated phase *Pons et al. 2000*

- GMGSp -first order phase transition between pure phases
- GMGSm - phase transition through mixed phase



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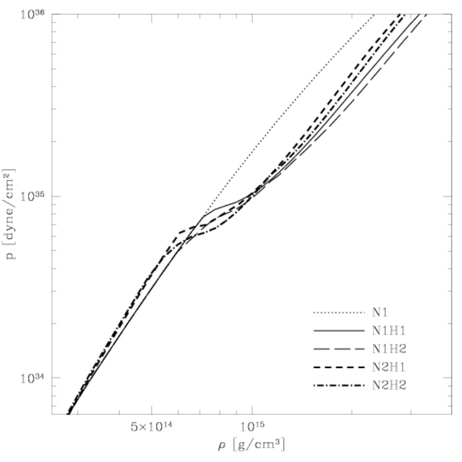


Methods of solution

Numerical methods

- Rigid rotation, one parameter EOS: $P(\rho)$
- solution of the Einstein equations for stationary, axially symmetric metric
- LORENE library - http://www.lorene.obspm.fr
- spectral methods
- more accurate than finite difference methods
- problems with non-continuous quantities - the problem is solved in domains

Theory - Sorkin, Friedman, Ipser 81,82,88

Assumptions

- two-parameter family of uniformly rotating stellar models based on a one-parameter EOS $P = P(\rho)$
- the sequence of models labeled by a parameter x (e.g. ρ_c or P_c)

$$\mathrm{d}M = \Omega \mathrm{d}J + \gamma \mathrm{d}M_B$$

$J = const$

$$\left(\frac{\partial M}{\partial x}\right)_{J=const} = 0$$

$$\left(\frac{\partial M_B}{\partial x}\right)_{J=const} = 0$$

$M_B = const$

$$\left(\frac{\partial J}{\partial x}\right)_{M_B=const} = 0$$

$$\left(\frac{\partial M}{\partial x}\right)_{M_B=const} = 0$$

$M = const$

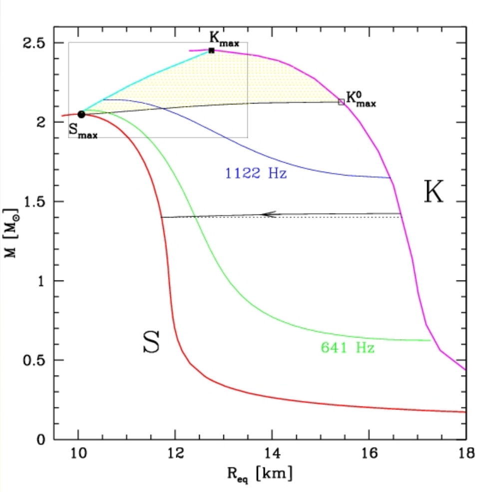
$$\left(\frac{\partial J}{\partial x}\right)_{M=const} = 0$$

$$\left(\frac{\partial M_B}{\partial x}\right)_{M=const} = 0$$

$M(R)$ for rotating NS

Bounds on rotating stars

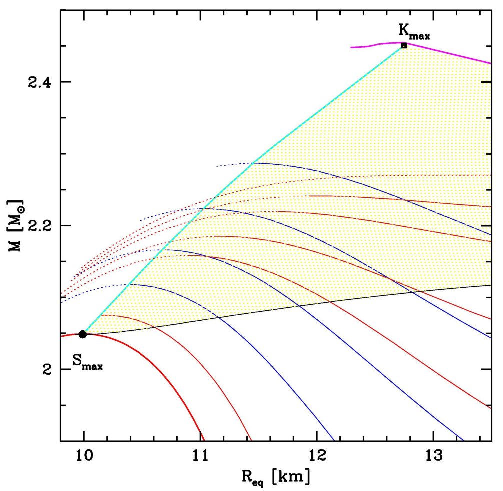
- S - Static models
- K - Keplerian rotation
- Instability line
- supramassive configurations



Stability and maximum mass of rotating neutron stars

$J = const$ total angular momentum fixed

$f = \Omega/2\pi = const$ (angular) rotational frequency fixed

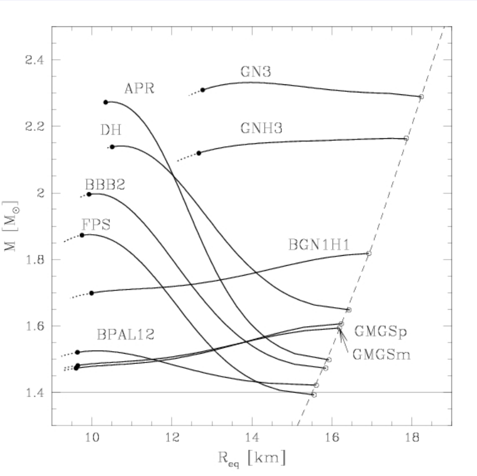


1122 Hz pulsar

- significant reduction of the allowed masses
- realistic models involving only nucleons (FPS,BBB2,DH,APR) - monotonic dependence of *tilda-like* shape $M(R)$

$$M(R_{min}) - M(R_{max}) \simeq$$

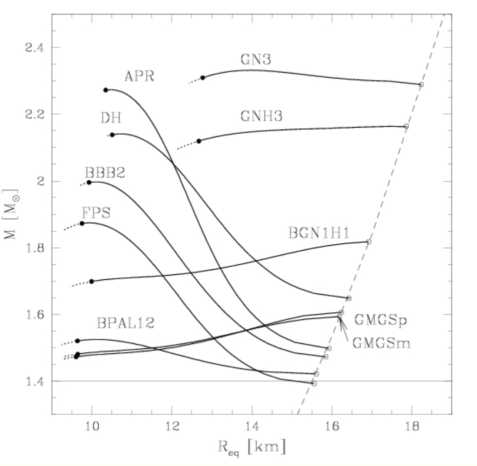
$$0.5 \div 0.8 M_{\odot}$$



Bejger, Haensel, Zdunik, (2007) AA 464, L49

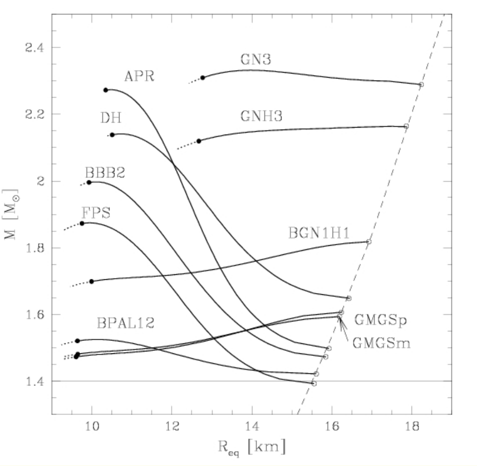
1122 Hz pulsar

- significant reduction of the allowed masses
- for EOSs softened at high density either by the appearance of hyperons (GNH3,BGN1H1) or a phase transition (GMGSm,GMGSp) - the range of allowed masses very narrow $\simeq 0.1 M_\odot$ and $M(R_{min}) < M(R_{max})$



1122 Hz pulsar, approximate formula

- $f_{\rm orb}^{\rm Schw.}(M, R_{\rm eq}) = 1122$ Hz
- $\frac{1}{2\pi}\left(\frac{GM}{{R_{\rm eq}}^3}\right)^{1/2} = 1122$ Hz
- $R_{\rm max} =$
  $$15.52\ \left(\frac{M}{1.4\ M_\odot}\right)^{1/3}\ \text{km}\ .$$



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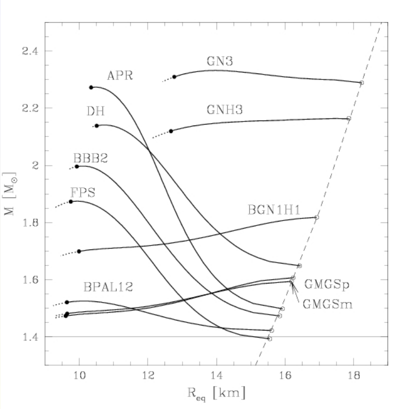
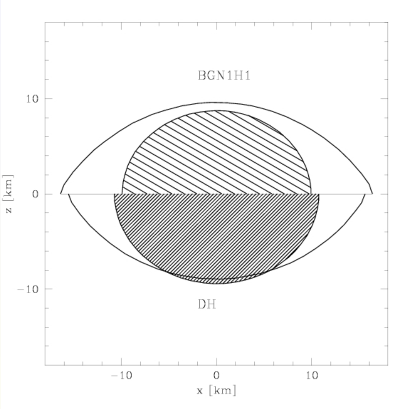
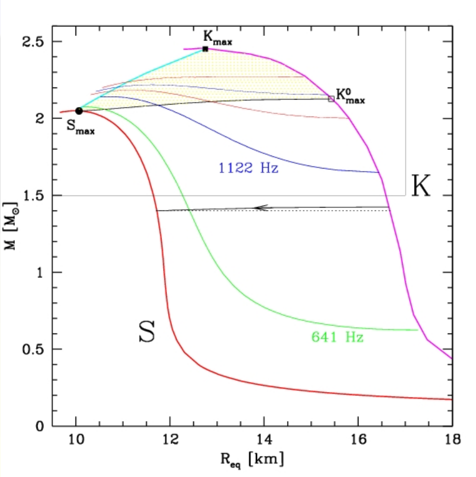




fast rotation - large oblateness of the star

Submillisecond pulsars

- Very fast rotation - $f > 1000$ Hz
- mass of rotating star quite well defined (very small range of the allowed masses)



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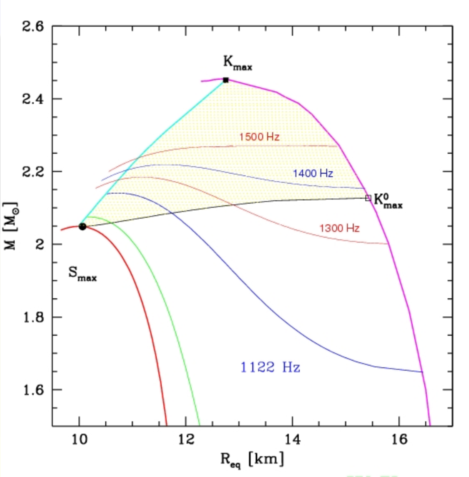
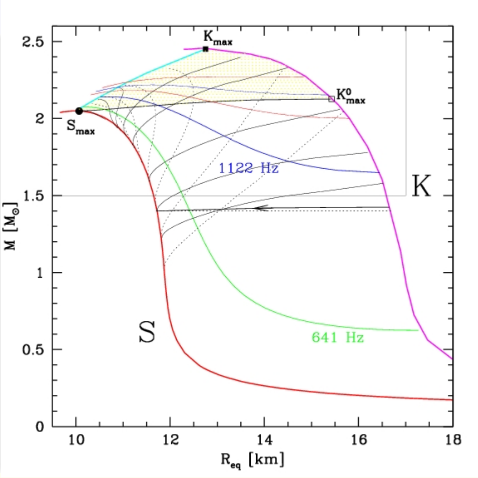


Submillisecond pulsars - accretion

- accretion from the last stable orbit (ISCO)
- simultaneous increase of the angular momentum and baryon mass of the star: $\mathrm{d}J = x_l l_{\mathrm{IS}}\ \mathrm{d}M_{\mathrm{B}}$,
- x_l the fraction of the angular momentum of the element of matter transferred to the star $x_l \leq 1$
- accretion:
  solid line - $x_l = 1$
  dashed line - $x_l = 0.5$



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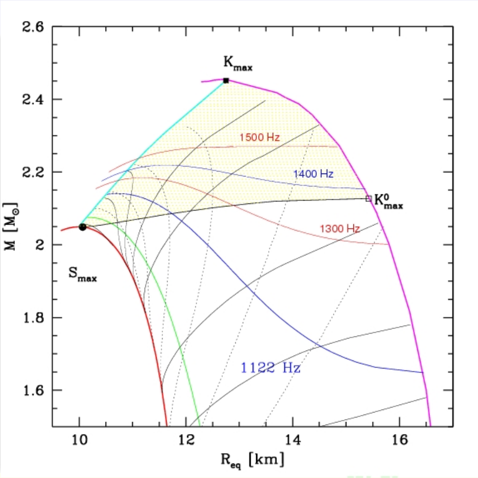
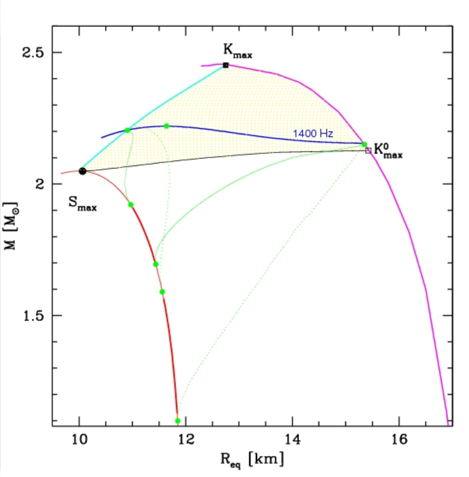


Submillisecond pulsars - limits on the mass

Example $f_{rot} = 1400$ Hz

- accretion from the last stable orbit (ISCO)
- x_l the fraction of the angular momentum of the element of matter transferred to the star $x_l \leq 1$
- accretion:
  solid line - $x_l = 1$
  dashed line - $x_l = 0.5$
- the limit for the initial mass of the accreting neutron star

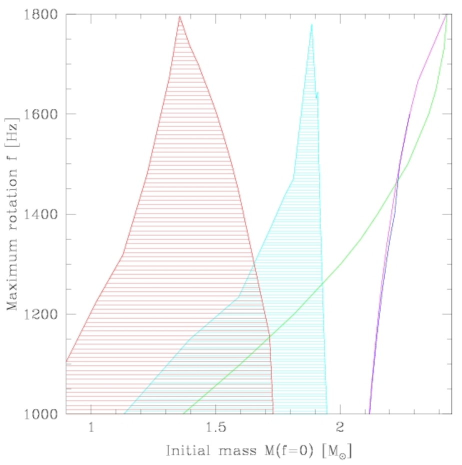


Submillisecond pulsars - limits on the mass

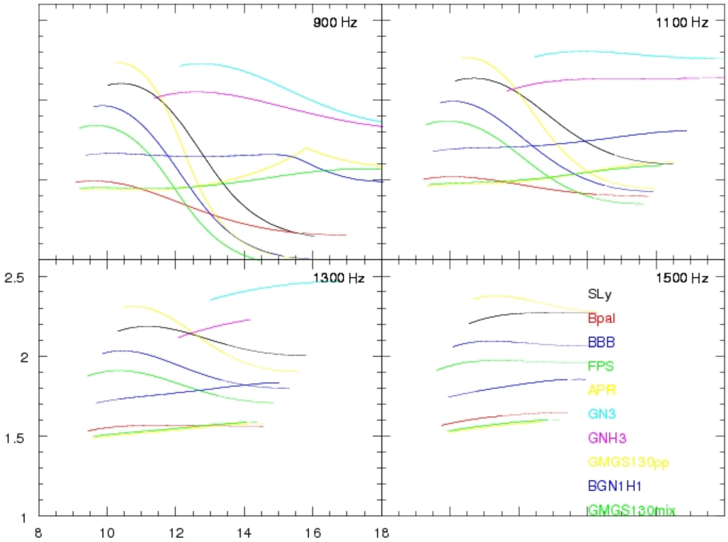
The initial mass of the accreting neutron star

- the fraction of the angular momentum of the element of matter transferred to the star $x_l = 0.5$
- the fraction of the angular momentum of the element of matter transferred to the star $x_l = 1$

The final mass very well defined for $f_{rot} > 1200$ Hz



Submillisecond pulsars - EOS dependence



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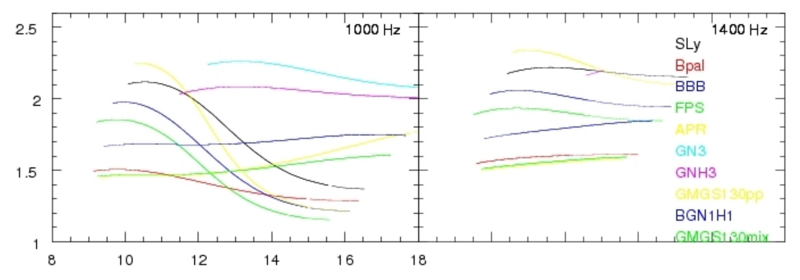
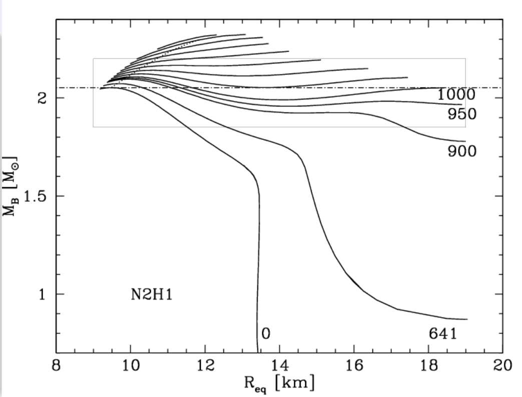


- for high rotational frequency mass of the star almost fixed
- the mass for given f_{rot} depends on the EOS
- the masses for different models of matter are separated

Back-bending - signature of the softening of EOS

- at fixed rotation frequency $f = \Omega/2\pi$ - non-monotonic behavior possible without loosing stability of the star
- the existence of the inflexion point - the signature of the back-bending phenomenon
- back-bending - spin-up of the star by the angular momentum loss J



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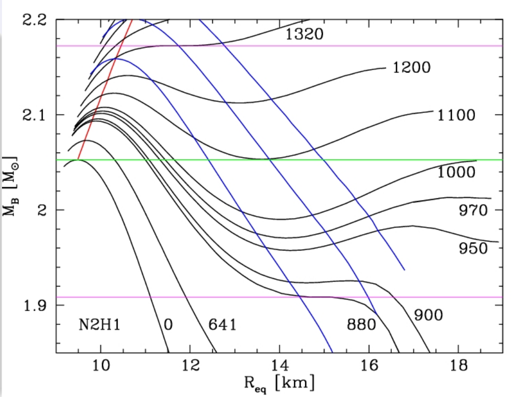

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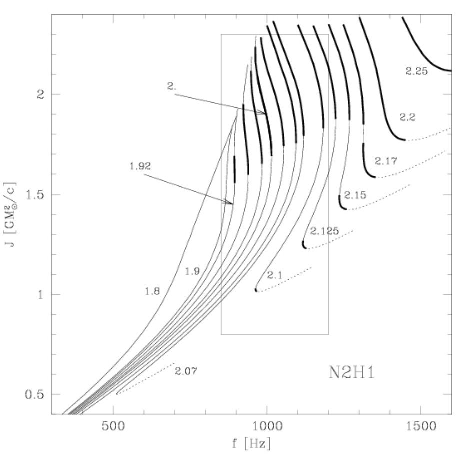

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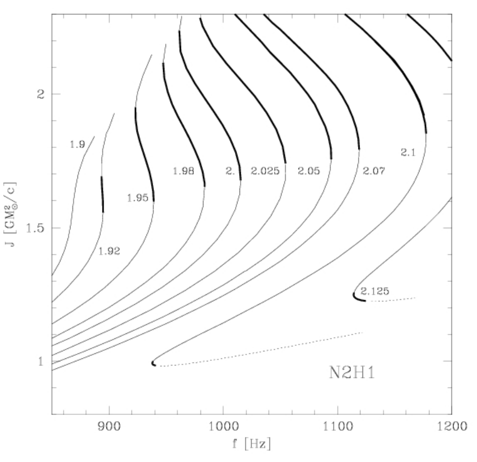
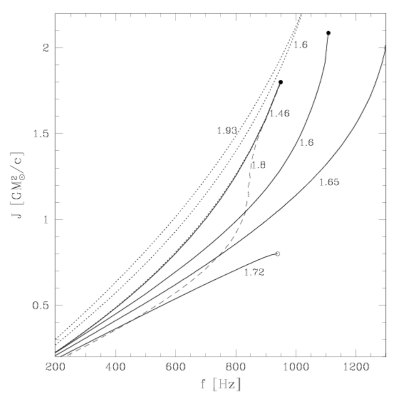
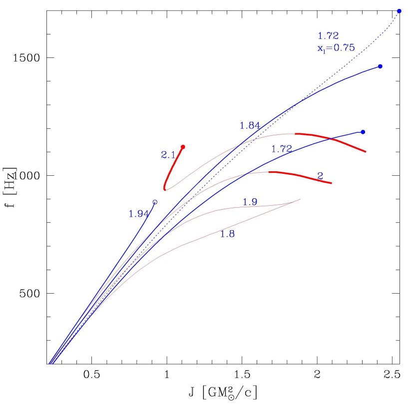


Accretion kills BB





The absence of the back-bending phenomenon for the accreting neutron star