Neutron star mass and radius constraints from millisecond X-ray pulsars and X-ray bursters

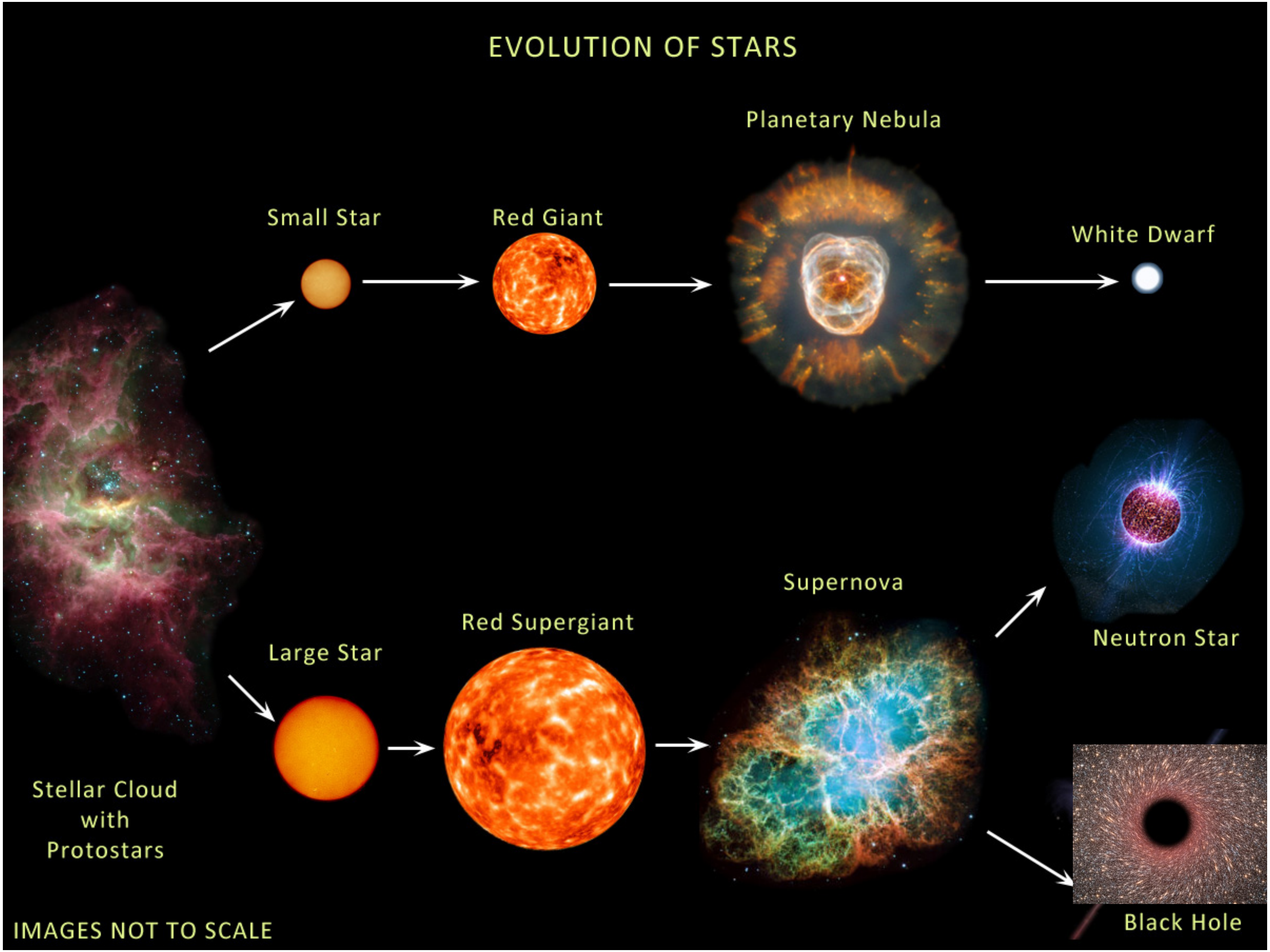
Juri Poutanen (University of Turku, Finland)

Collaborators:
Valery Suleimanov (Univ. Tübingen, Germany), Joonas Nättilä (Nordita, Stockholm), Tuomo Salmi, Jari Kajava (Univ. Turku, Finland), Andrew Steiner (Univ. Tennessee & Oak Ridge National Lab, USA), Erik Kuulkers (ESAC, Spain), Duncan Galloway (Monach Univ., Australia)

Saariselkä, April 2018

Plan

- Introduction
- Neutron star EoS – M/R relation
- How to measure M and R
- Methods: Timing, spectroscopy, X-ray polarization
- Objects, phenomena: radio pulsars, accreting ms pulsars, X-ray bursts


EVOLUTION OF STARS
Small Star
Red Giant
Planetary Nebula
White Dwarf
Large Star
Red Supergiant
Supernova
Neutron Star
Black Hole
Stellar Cloud with Protostars
IMAGES NOT TO SCALE

Neutron Star Zoo

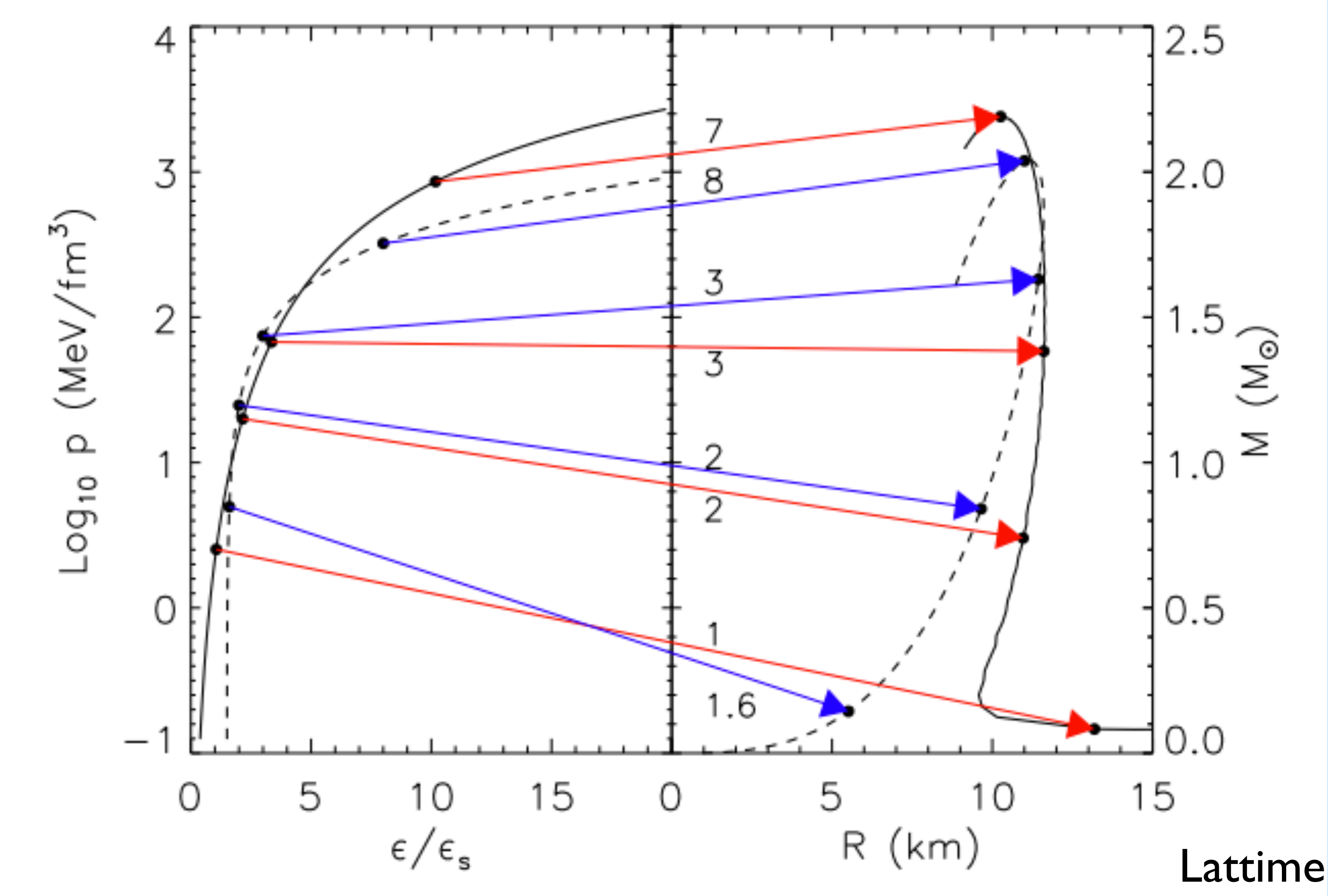
Rotation-powered
Radio pulsars
Radio millisecond pulsars
Gamma-ray pulsars

Accretion-powered
X-ray pulsars
X-ray millisecond pulsars
X-ray bursters

Magnetically powered=Magnetars
Anomalous X-ray pulsars
Soft gamma-ray repeaters

Thermally powered = central compact objects

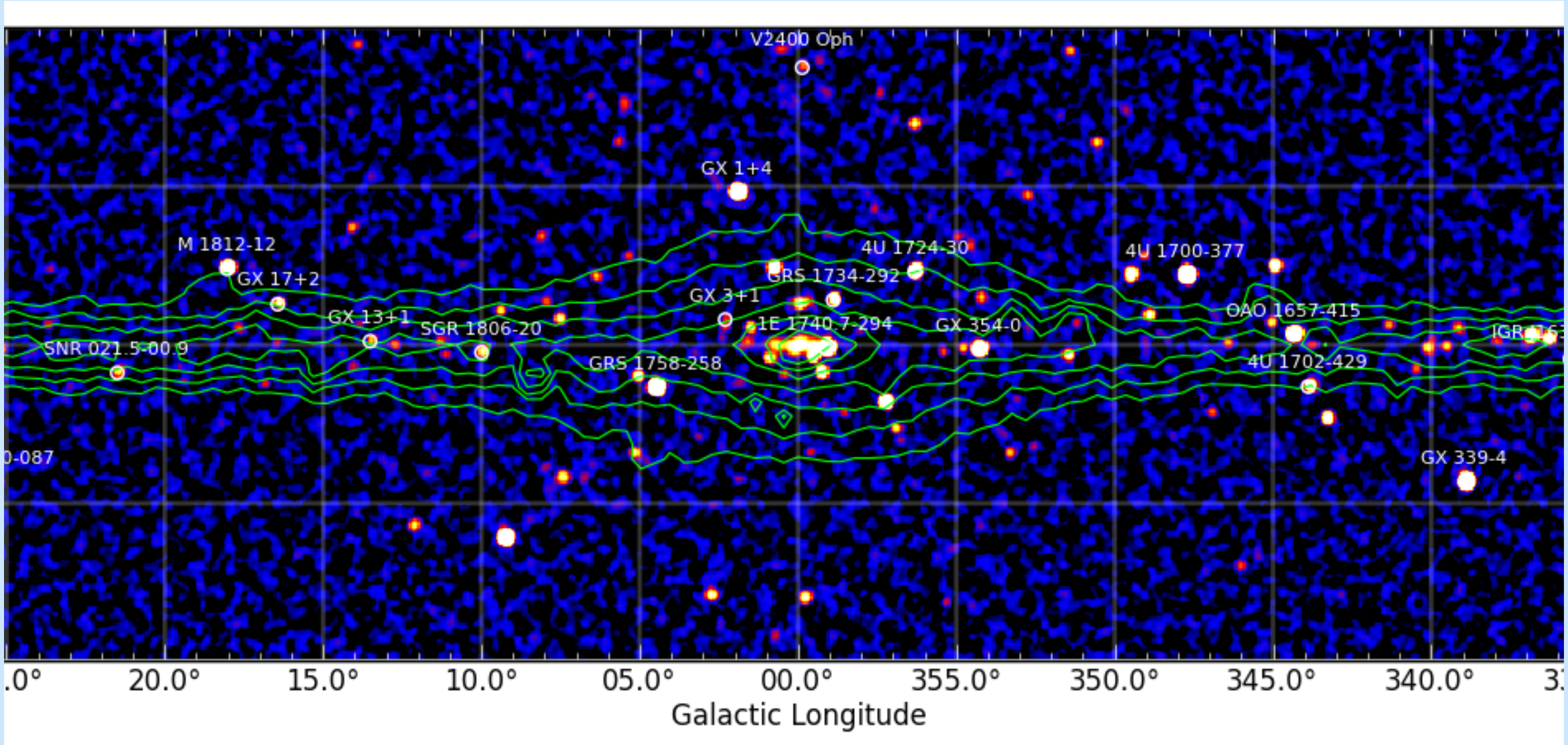
EoS vs
neutron star M-R

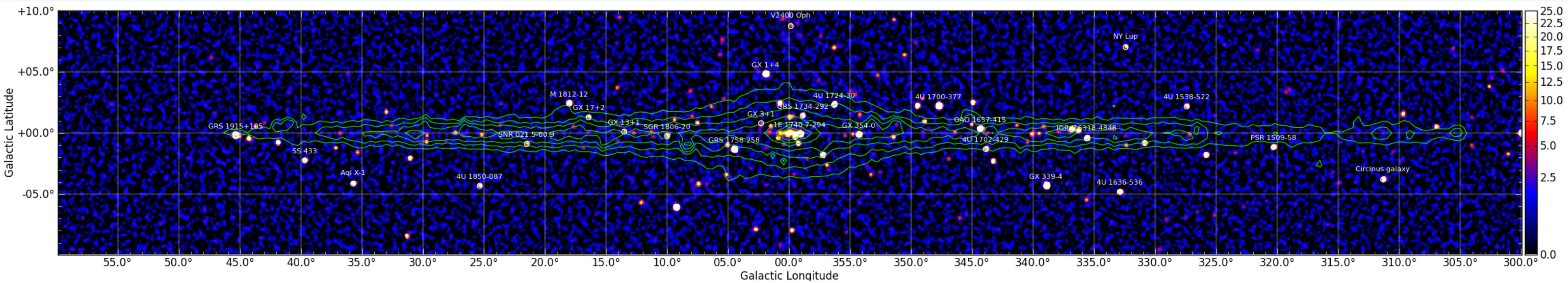


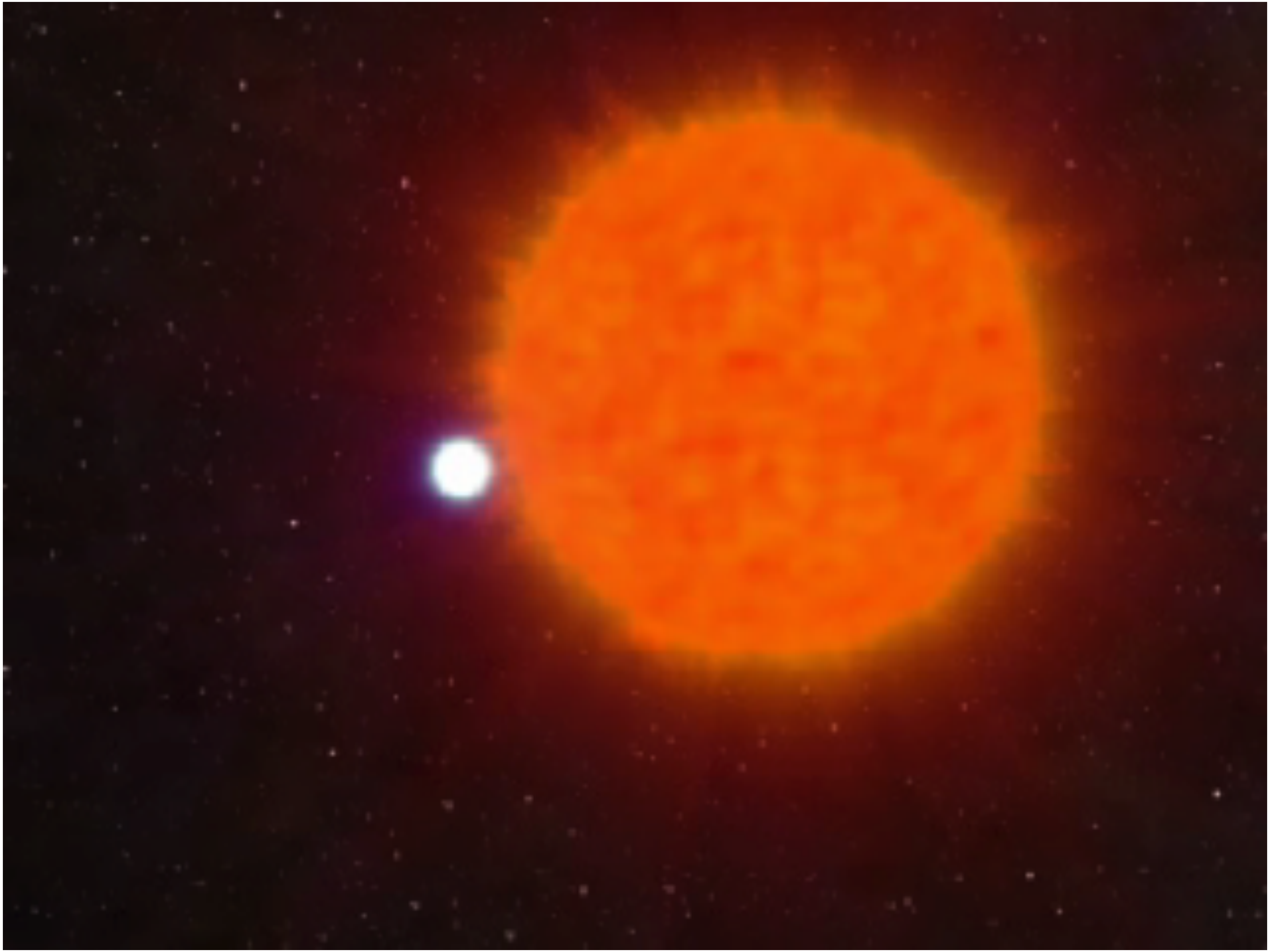
Lattimer 2012

Neutron stars in binaries

INTEGRAL 9-year survey in 35-80 keV





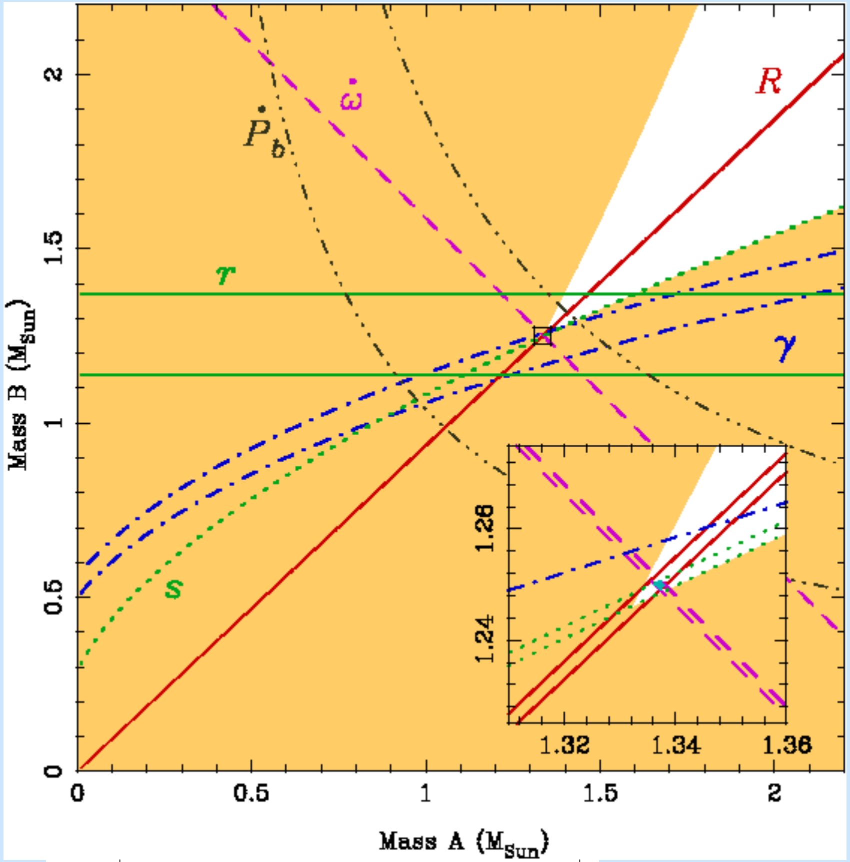


Timing of radio pulsars

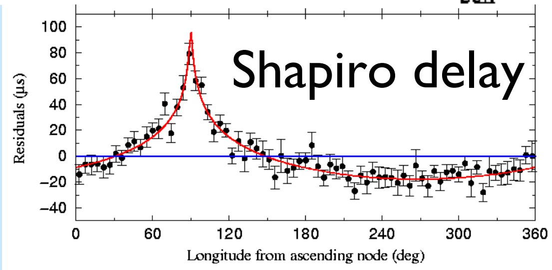
The Double Pulsar PSR J0737-3039

Radio timing yields

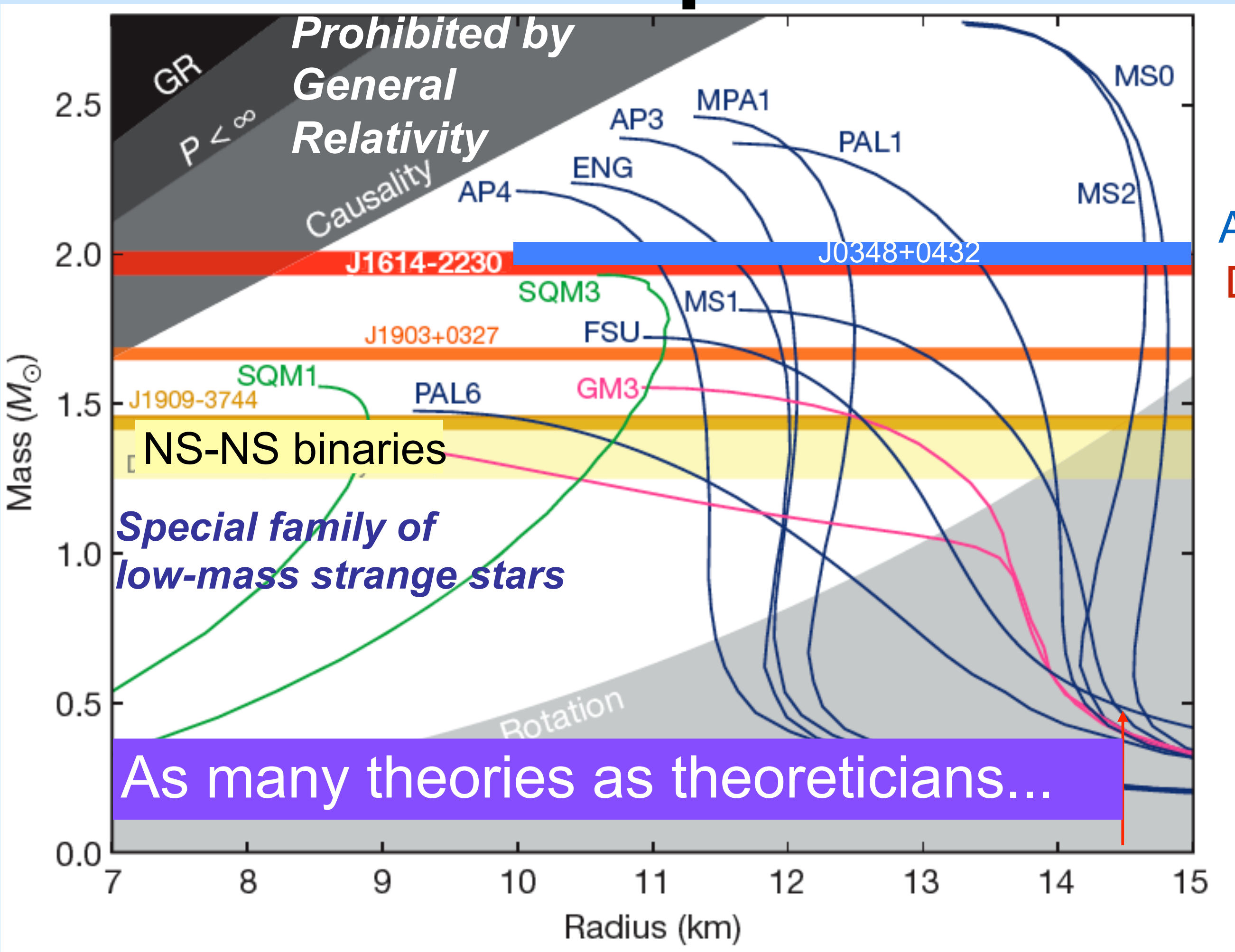
- P_B – binary period
- x – projected semi-major axis
- e – eccentricity
- ω – longitude of periastron
- T_0 – epoch of periastron



- Orbital period P_b = 2.4 h, e = 0.088
- P_A = 22.7 ms, P_B=2.8 s
- M_A= 1.337 $M_\odot$, M_B= 1.250 $M_\odot$



Zoo of equations of state

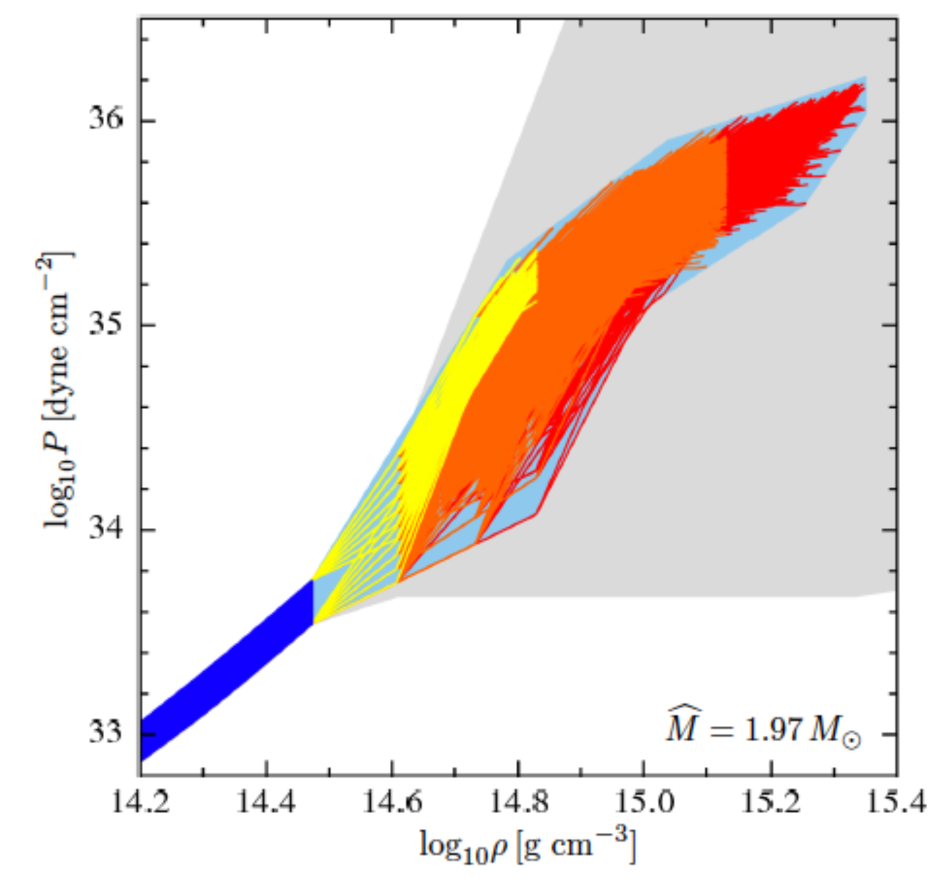


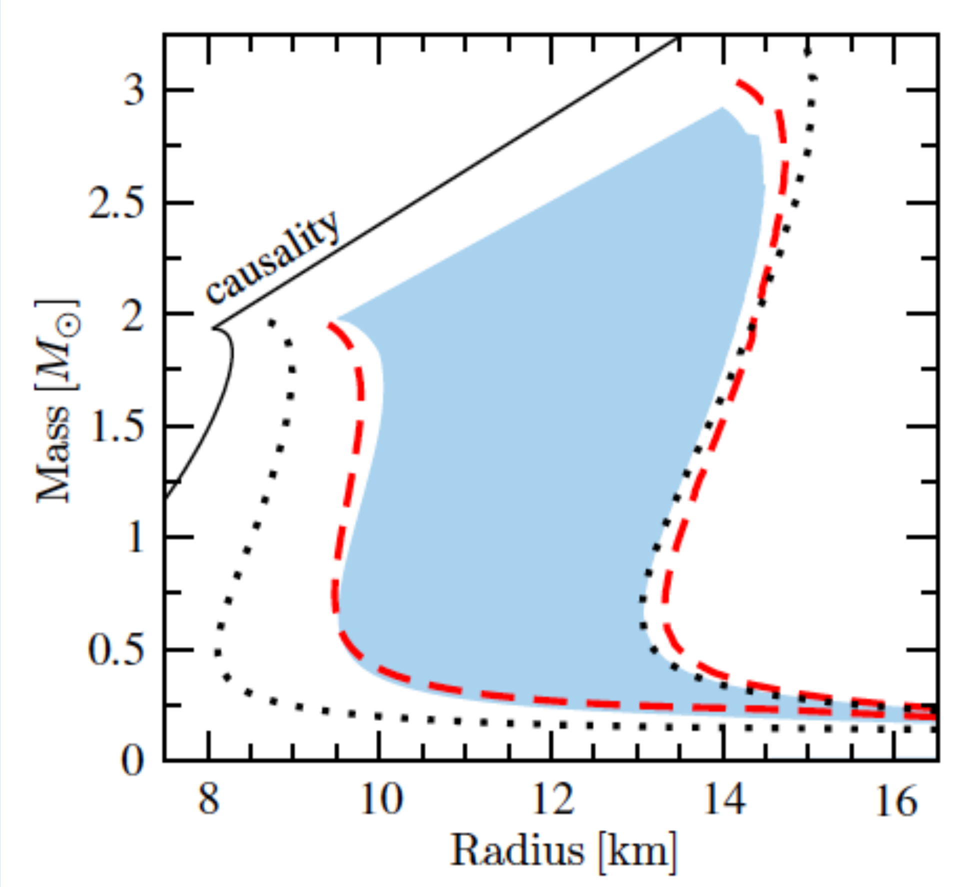
Antoniadis et al. 2013

Demores et al. 2010;
Fonseca et al. 2016

Every EoS gives a different M-R dependence.
M and R should be determined from observations.

Modern constraints on EoS and NS mass-radius relation from M=2M$_\odot$





Hebeler et al. 2013

In order to constrain the EoS, neutron star radii are needed.

Astrophysical measuments of NS radii

- Thermal spectra from lonely NS (Valery's talk)
- Cooling NSs after accretion disc outbursts in transient sources
- Cooling NSs after X-ray (thermonuclear) bursts (Joonas' talk)
- X-ray burst oscillations
- Pulse profiles of accreting ms pulsars
- X-ray polarization
- Gravitational waves during mergers

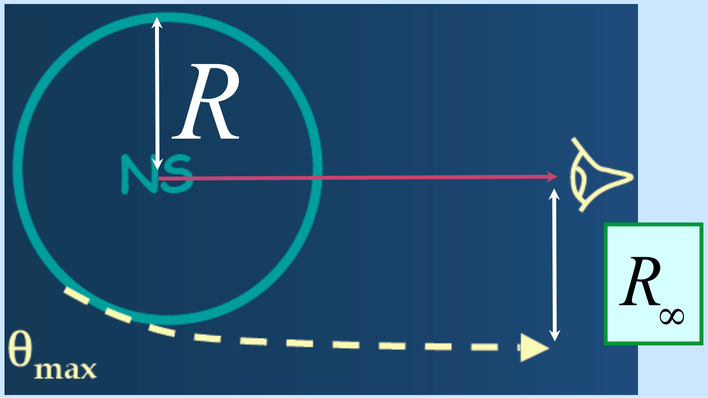
Neutron star mass-radius relation using blackbody radius at "infinity"

Fitting the bursts spectra with the blackbody we get the temperature T_{bb} and normalization K

$$F_{\rm bol} = \sigma_{\rm SB} T_{\rm bb}^4 K, \quad K = \frac{R_{\rm bb}^2}{D^2}$$

If the distance is known, we can determine apparent radius, which is related to R and M of the neutron star.

$$R_{\rm bb} = R_\infty = R_*(1+z) = R_*(1 - R_{\rm S}/R_*)^{-1/2}$$



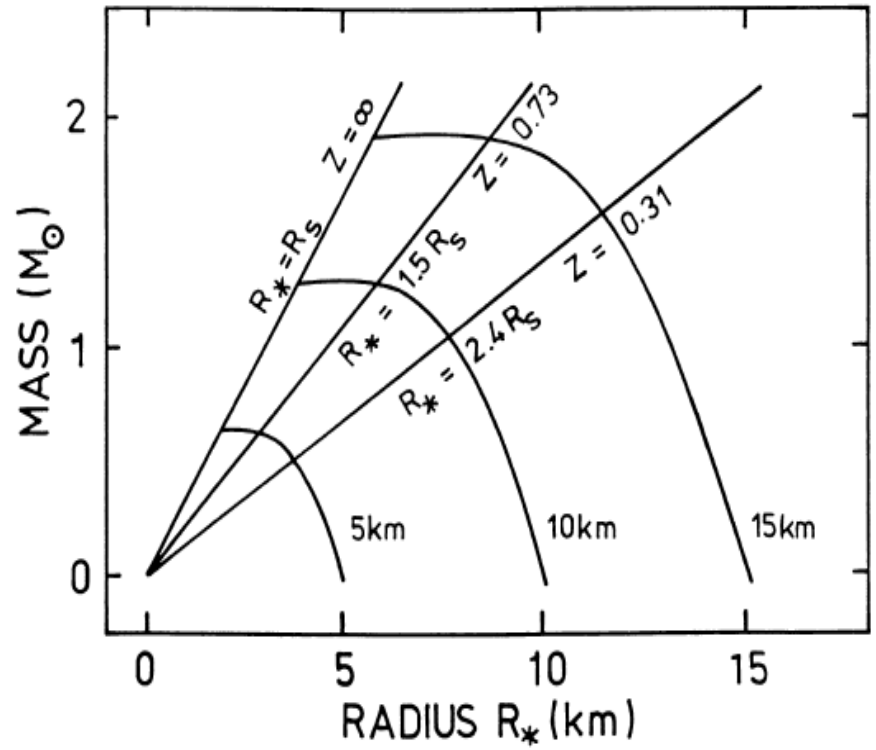
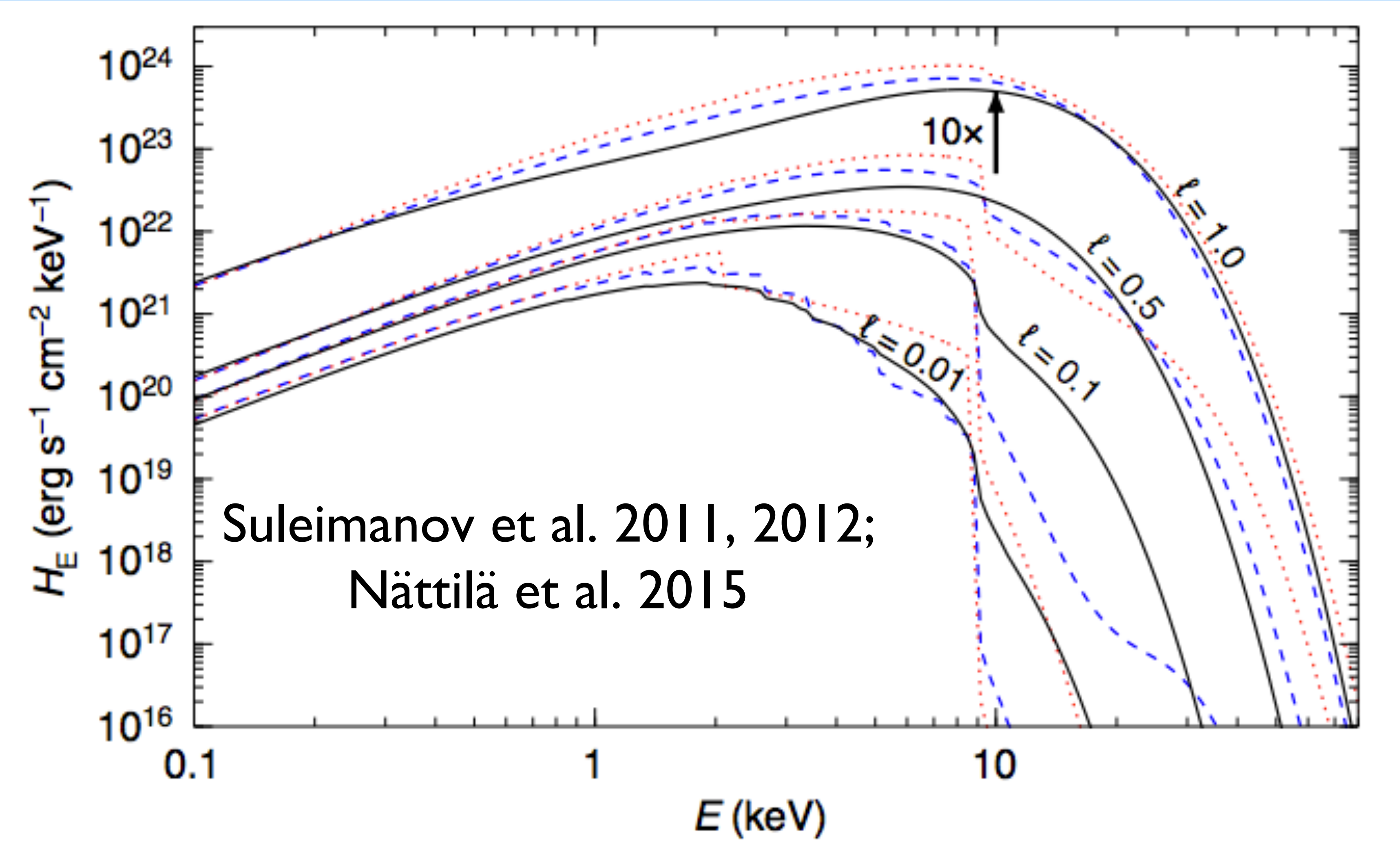


Fig. 4.3. Mass-radius relation for three hypothetical values of the blackbody radius R_∞ (5, 10, and 15 km). For clarity, we have not indicated error regions resulting from the uncertainties in the measurements. The straight lines indicate radii R_*, equal to the Schwarzschild radius R_S, 1.5 R_S, and 2.4 R_S (in the text we use R_g instead of R_S). The latter could, for example, result from an analysis of a burst with radius expansion (see text), or from the determination of the gravitational redshift of an observed spectral feature. For a given mass, the observed blackbody radius, R_∞, has a minimum value (1.5 $\sqrt{3}$) R_g; conversely, for a given blackbody radius R_∞ the mass cannot be larger than R_∞ (km)/7.7 $M_\odot$.

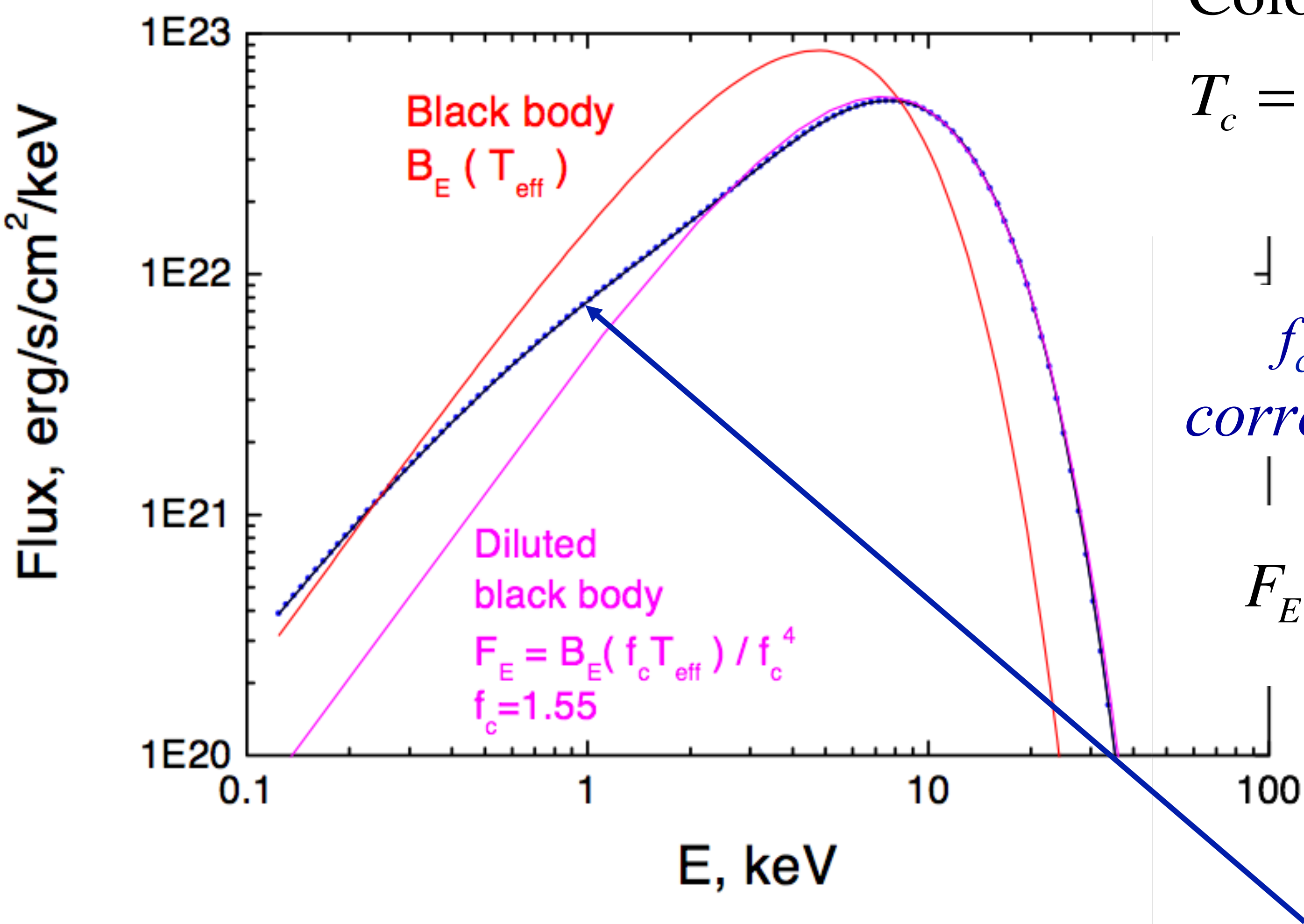
$$R_{\rm S} = 2GM/c^2 = 3\ {\rm km}\ (M/M_{\rm Sun}) \quad \text{Schwarschild radius}$$

Atmosphere models: emerging spectrum



Suleimanov et al. 2011, 2012;
Nättilä et al. 2015

Spectrum from a NS atmosphere



Color temperature

$$T_c = f_c\, T_{eff}$$

f_c - color correction factor

$$F_E \approx \frac{1}{f_c^4} B_E\left(f_c T_{\rm eff}\right)$$

Comparison of the theoretical X-ray burst spectrum (blue curve) with the black body (red) of the same effective temperature.

Neutron star mass-radius relation using blackbody radius at "infinity"

$$F_{\mathrm{bol}} = \sigma_{\mathrm{SB}} T_{\mathrm{bb}}^4 \frac{R_{\mathrm{bb}}^2}{D^2} = \sigma_{\mathrm{SB}} T_{eff}^4 \frac{R_\infty^2}{D^2}$$

$$K = \frac{R_{\mathrm{bb}}^2}{D^2}$$

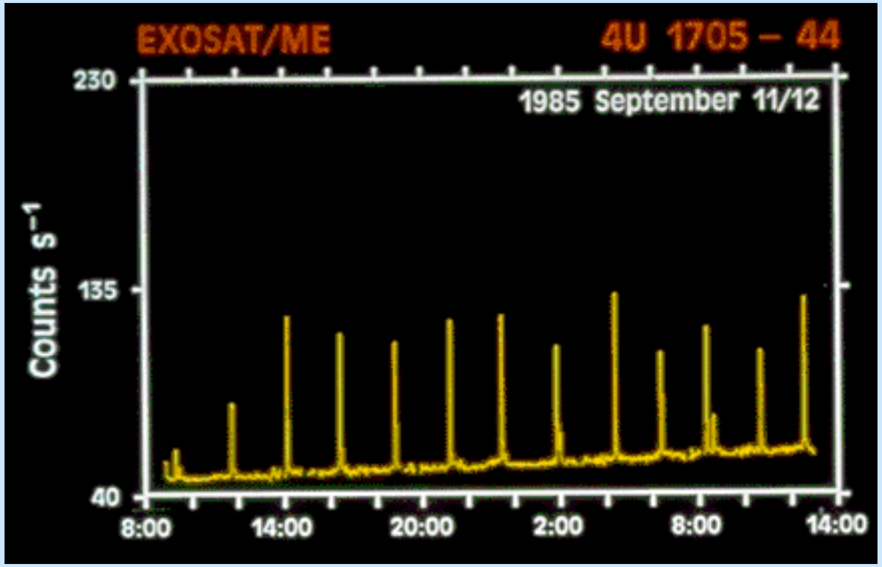
$$R_\infty = R_{bb} f_c^2 = D_{10}\sqrt{K} f_c^2$$

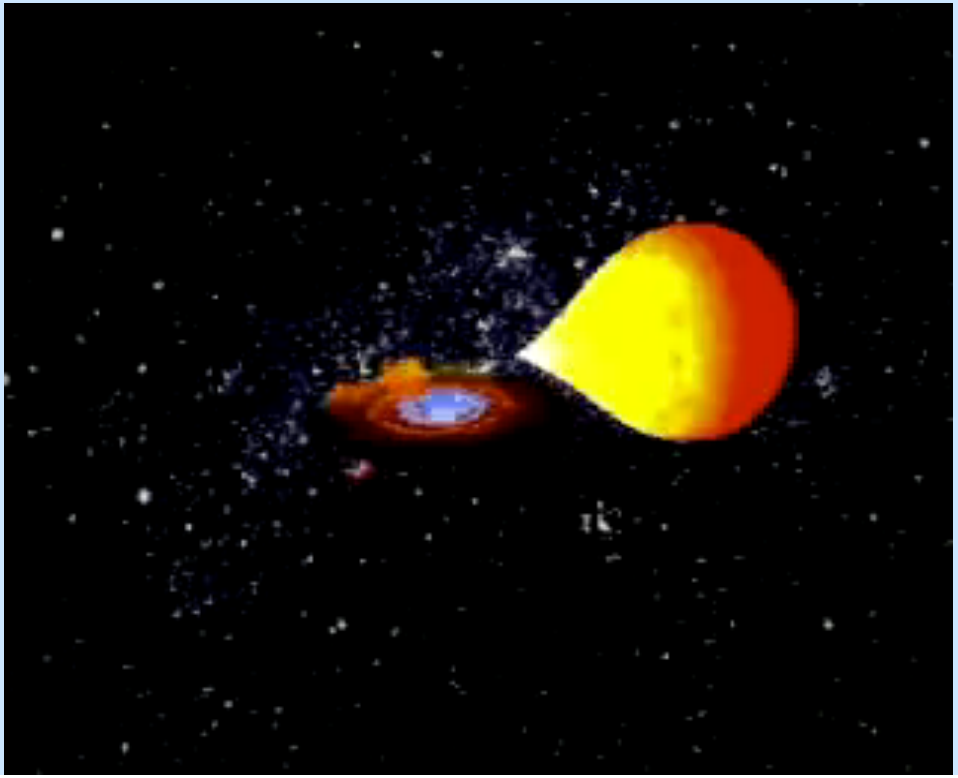
$$f_c = T_{bb} / T_{eff,\infty}; \quad K = \frac{R_{\mathrm{bb}}^2}{D^2}; \; D_{10} = D / 10\mathrm{kpc}$$

You need to know: blackbody normalization, color correction (from theory) and distance.

X-ray bursts

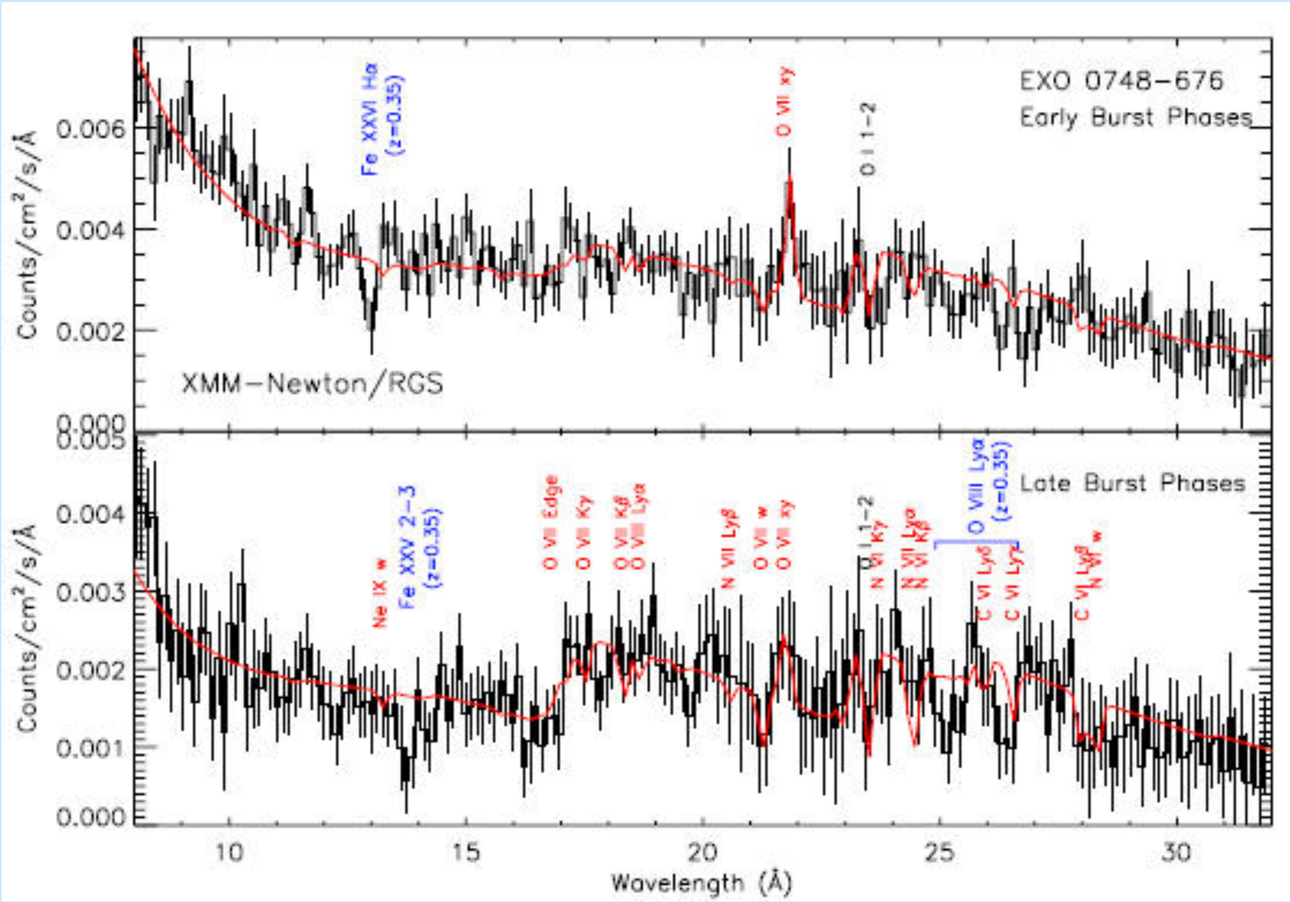
1. Discovered in the middle of 1970s (e.g. Grindlay et al. 1976).
2. Last for 10-1000 s. Sometimes reach Eddington limit.
3. Originate from accreting neutron stars in low-mass binary systems (LMXBs). About 70 known.
4. Thermonuclear unstable burning of H and He (and maybe C) accreted from the companion in the surface layers of neutron stars.





Atomic line shifts in X-ray burst

- Cottam et al (2002, Nature) observed with XMM-Newton bursts from EXO 0748-676
- Candidate Fe XXVI lines seen at redshift z = 0.35



Atomic line shifts in X-ray burst

- Observed redshift would strongly constrain the *M* and *R* of the neutron star (even if the distance to the source is not known; Ozel 2006).

- Unfortunately, in the existence of the lines is controversial:

(1) they were not seen in other bursts (Cottam et al. 2008);

(2) they are predicted to be much weaker and the lines of a different ion of Fe should be observed (Rauch et al. 2008), and finally

(3) the source was later observed to pulsate at 552 Hz (Galloway et al. 2009), and such rotation would smear all the lines.

- Thus, the current thinking is that no atomic lines have been observed from X-ray burst atmospheres.

Rossi X-ray Timing Explorer

Revolutionized X-ray timing. Discovered millisecond oscillations in X-ray bursts and pulsations in accreting transients.
Produced time-resolved spectra of X-ray bursts.

Three scientific instruments,:

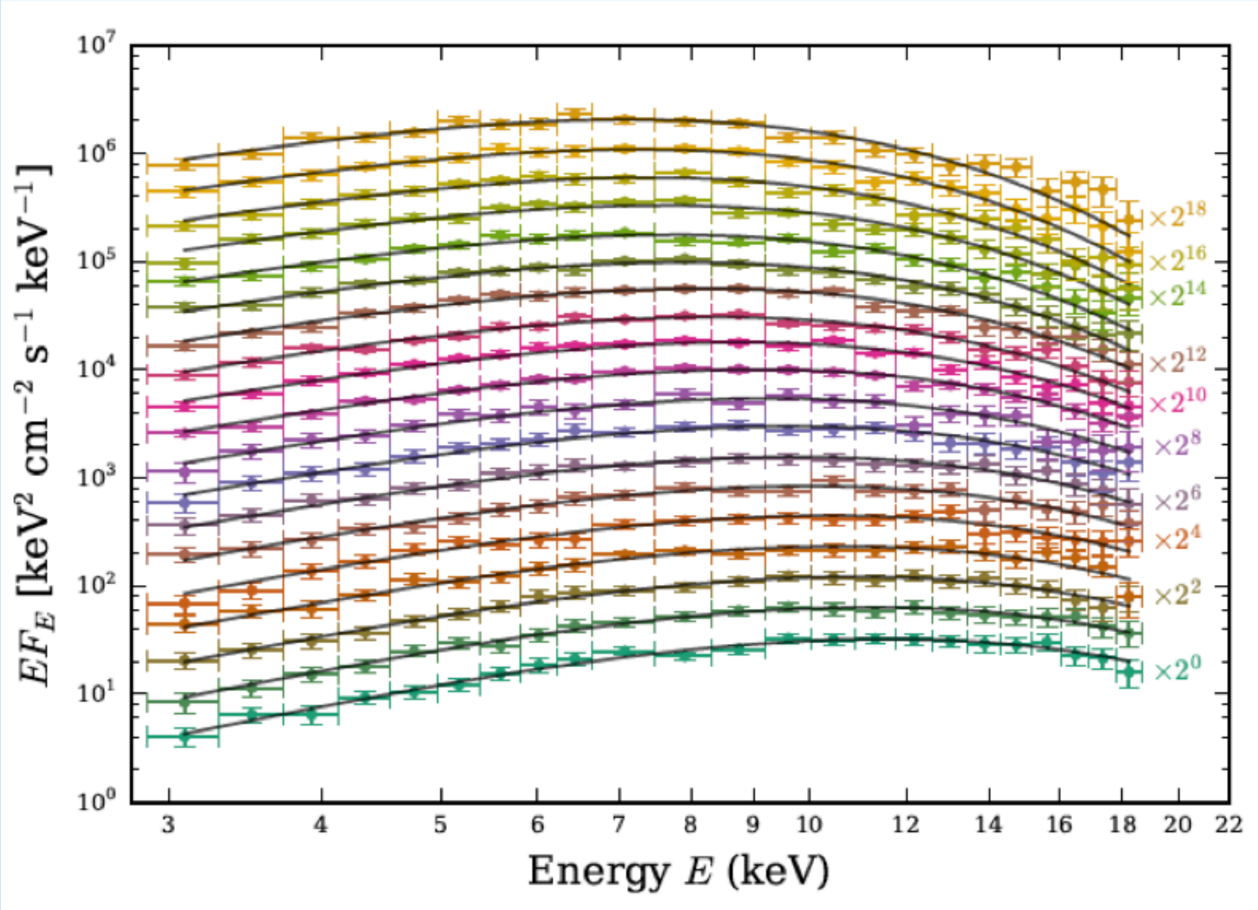
1. Proportional Counter Array (PCA), 2-60 keV. Small deadtime, high time resolution.

2. High Energy X-ray Timing Experiment (HEXTE), 20-200 keV

3. All-Sky Monitor (ASM), 1.5-12 keV

M-R constraints from 4U 1702-34

Direct fits to the X-ray burst spectra with the NS atmosphere models.



Nättilä et al. 2017

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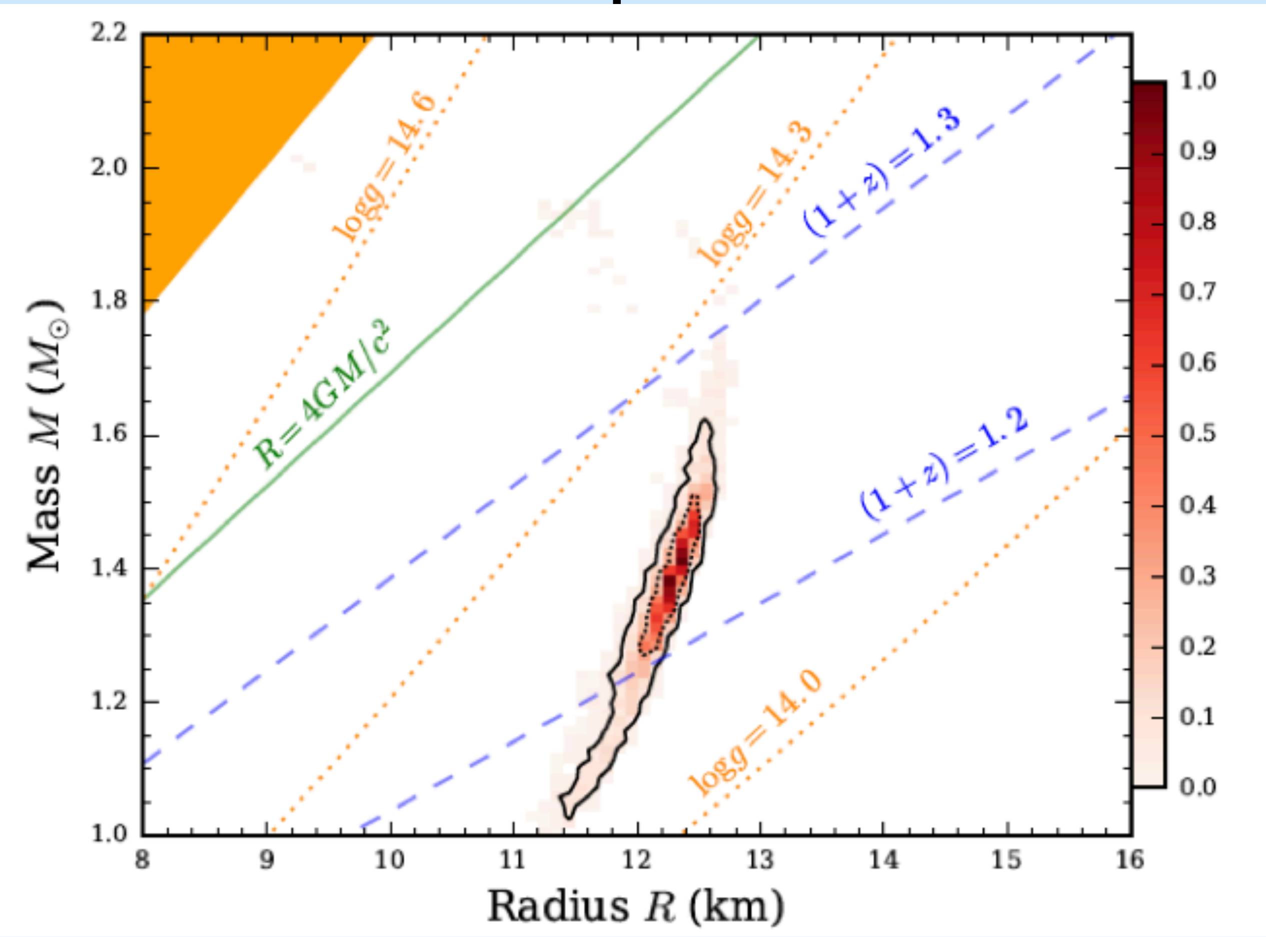
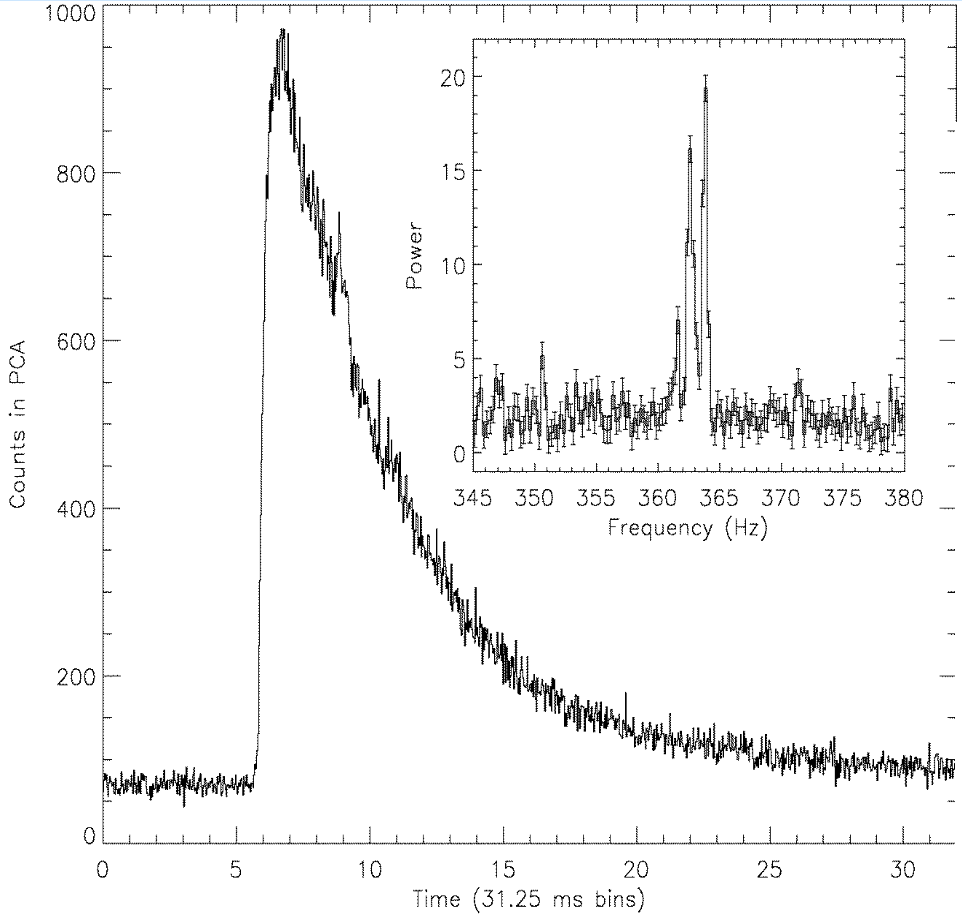


Nättilä et al. 2017

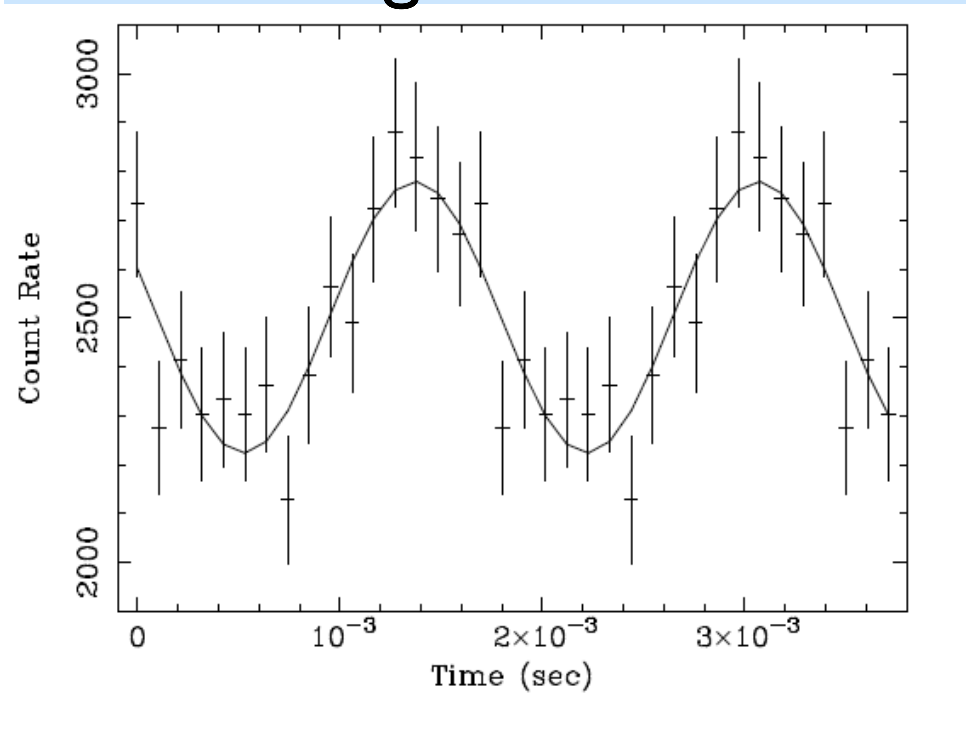
Millisecond oscillations during X-ray bursts

4U 1728-34



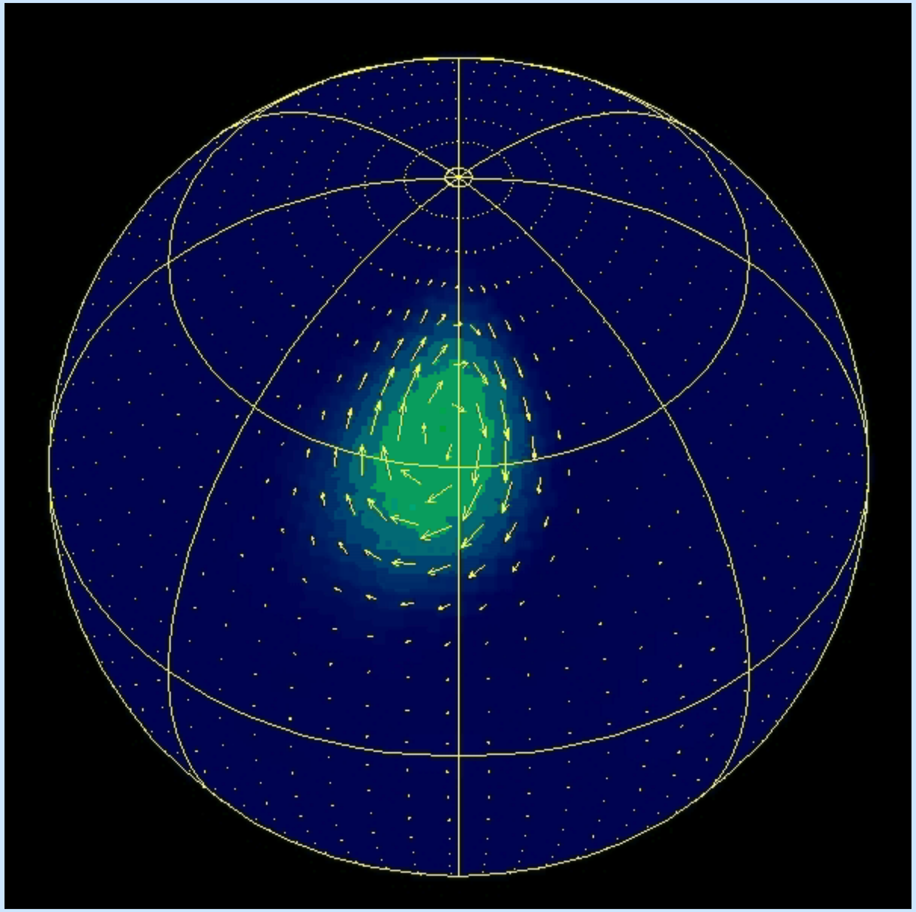
Time (s)

Light curve



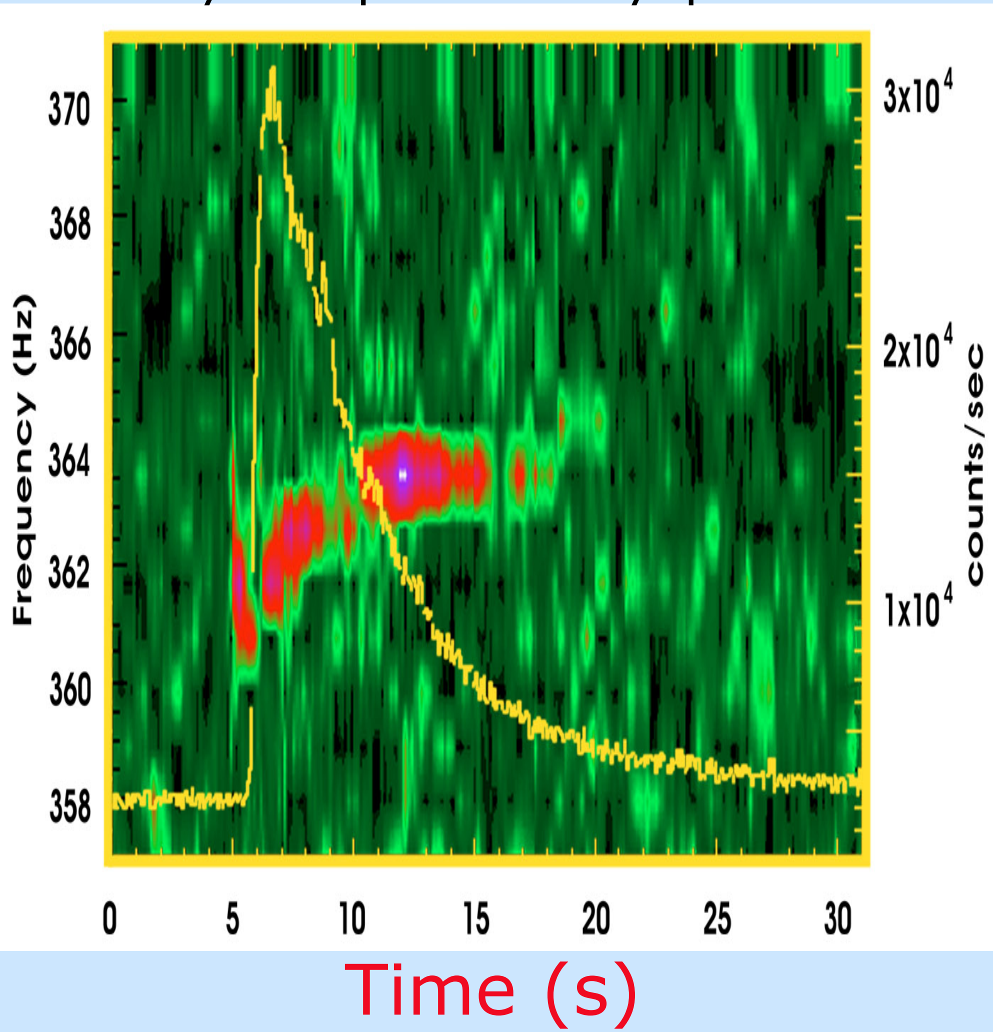
Strohmayer et al (1996, 1997)

Millisecond oscillations during X-ray bursts



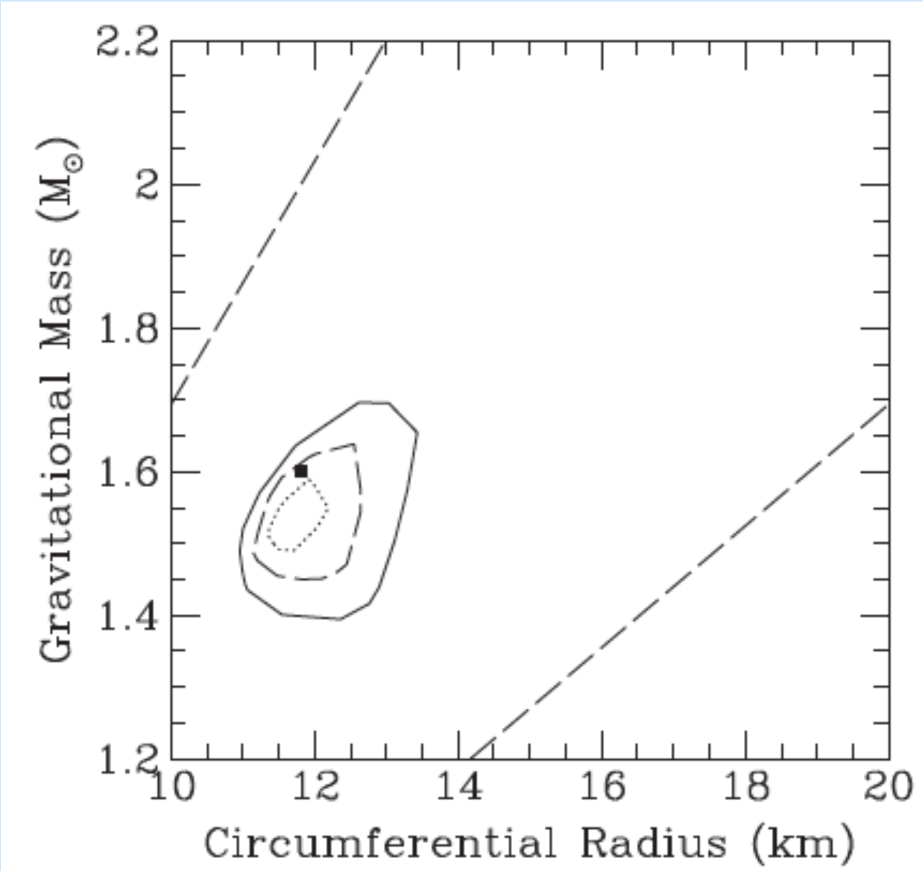
simulations by A. Spitkovsky

Contours:
Dynamic power-density spectra



Millisecond oscillations during X-ray bursts

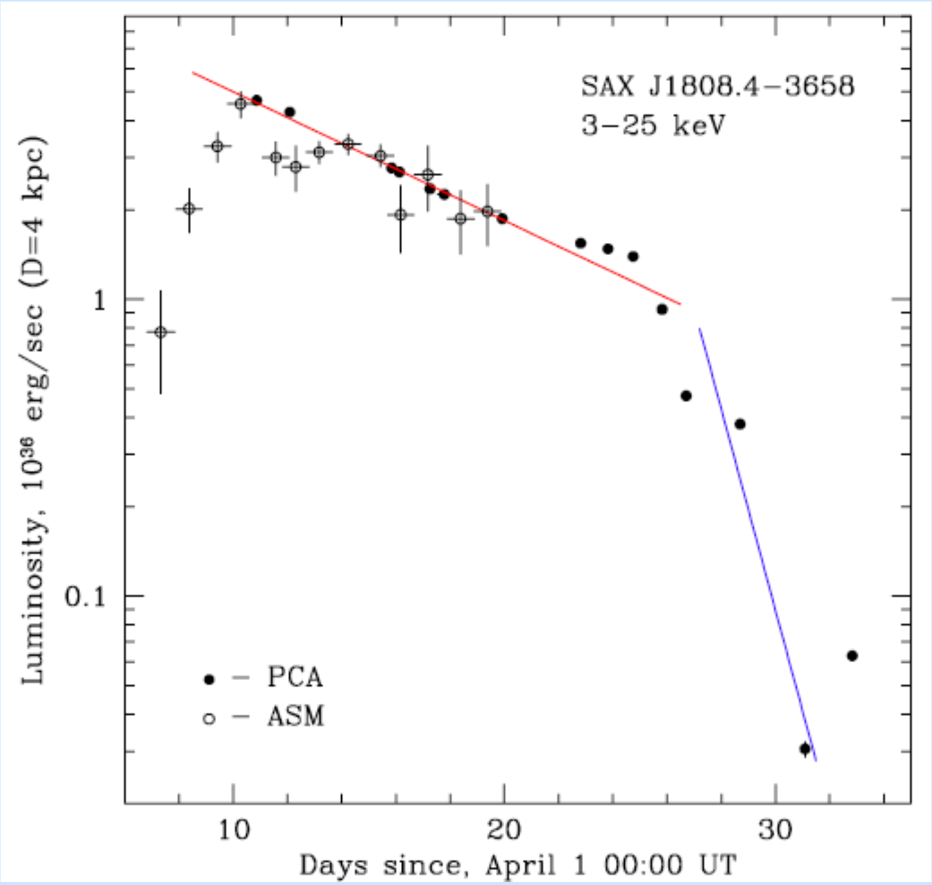
Potentially can be used to determine M-R with high-quality pulse profiles from future large-area X-ray observatories (eXTP, STROBE-X)



Mliller & Lamb 2015

X-ray ms pulsars

1998: discovery of 2.5 ms pulsations in persistent emission from a weak transient source SAX J1808.4-3658 by Wijnands & van der Klis (1998) using RXTE data



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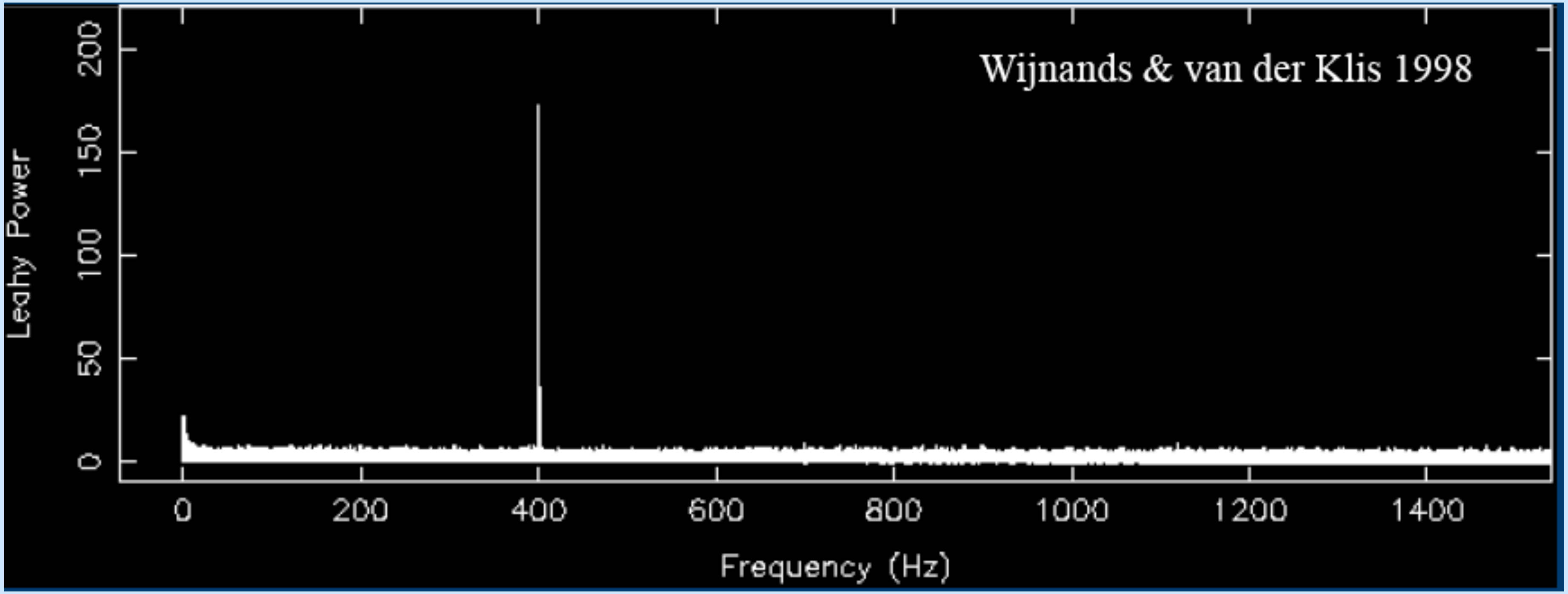
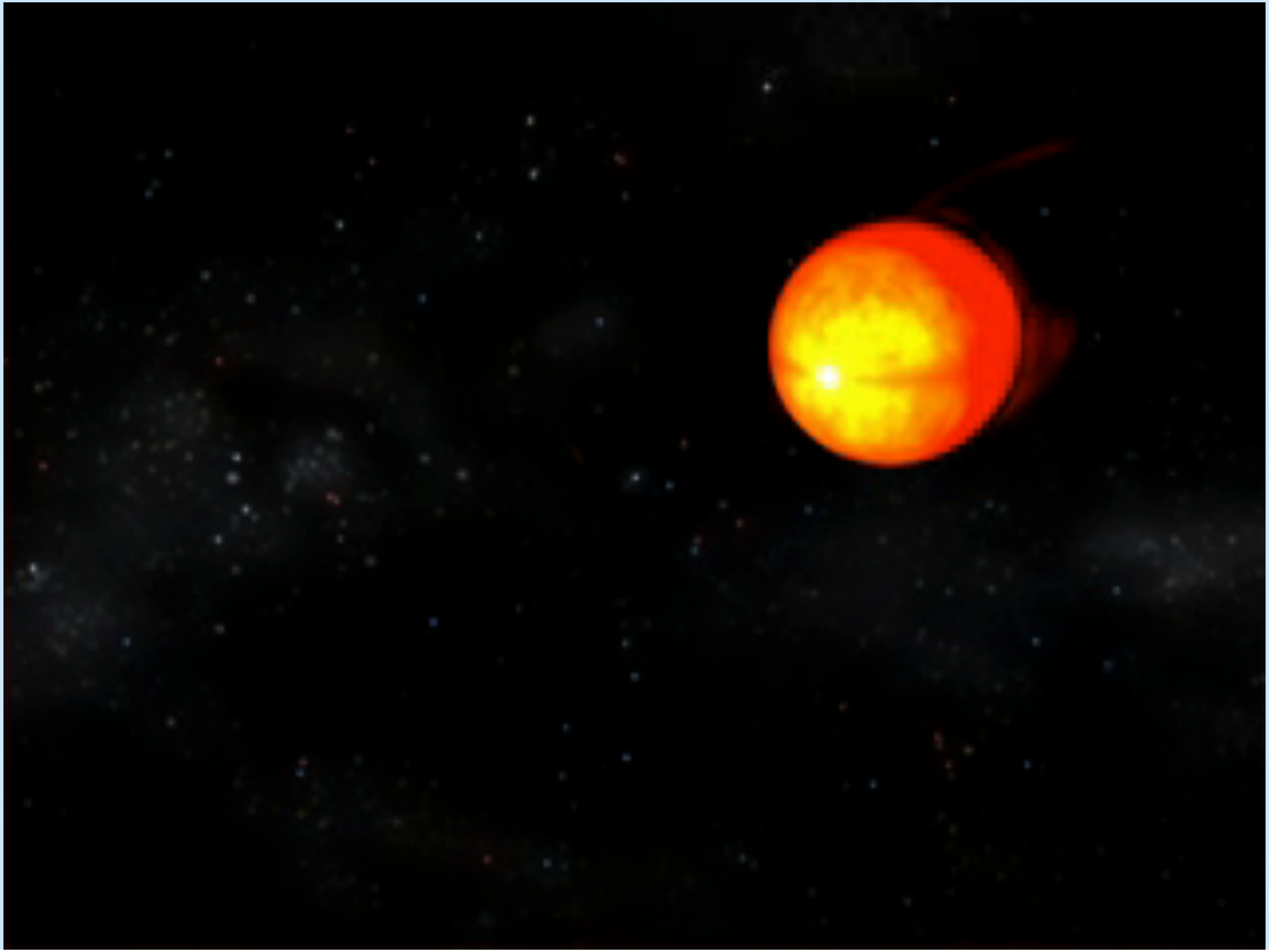
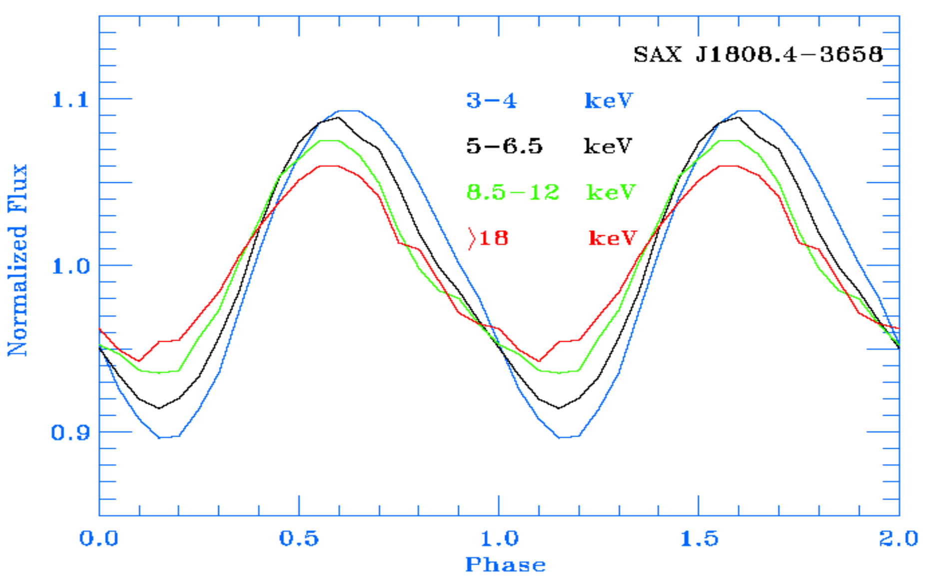
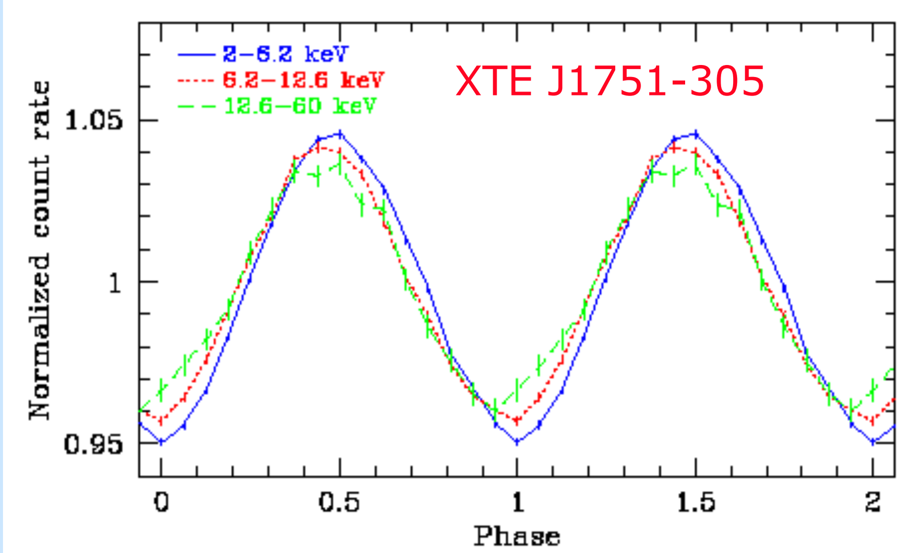


Formation of ms pulsars

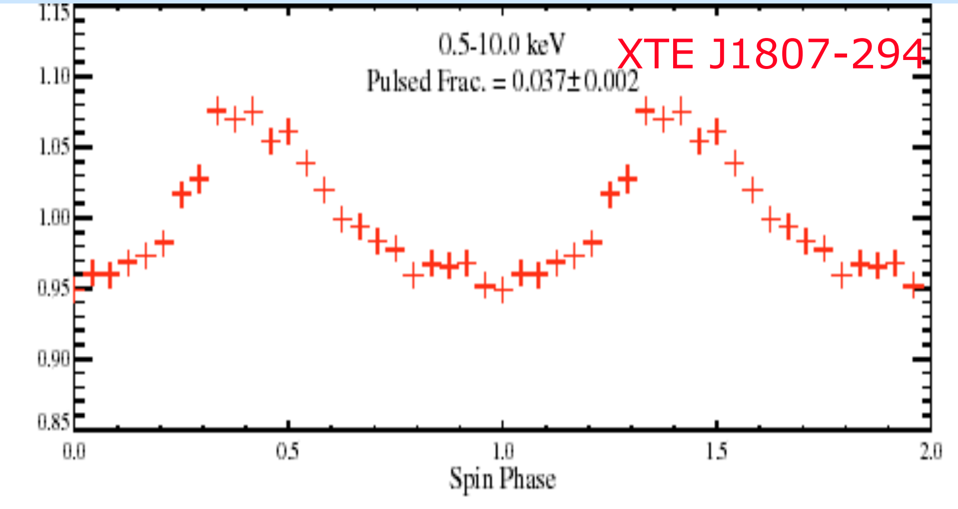


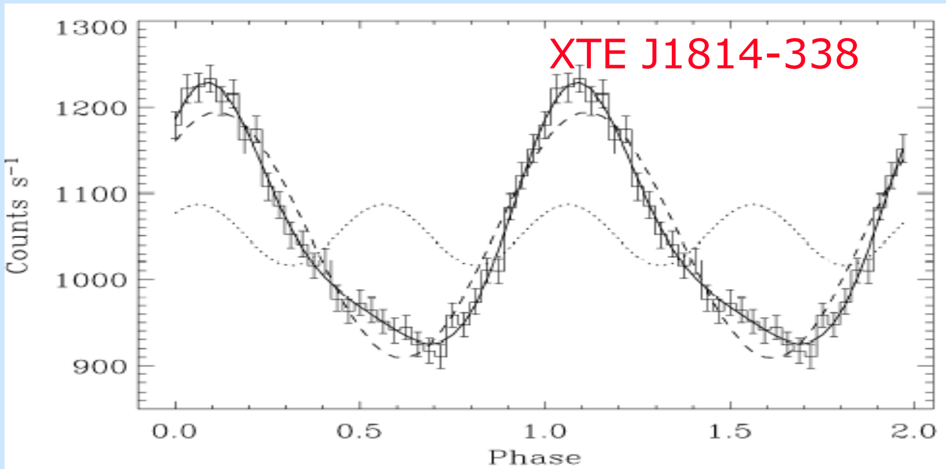
Pulse profiles of X-ray ms pulsars





Gierlinski & Poutanen 2003





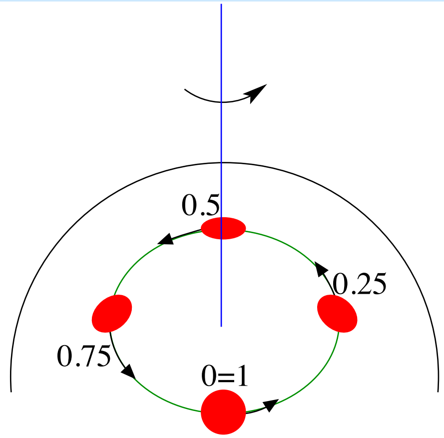
Solid – persistent emission; histogram - X-ray bursts. Strohmayer et al. (2003).

Kirsch et al. (2003)

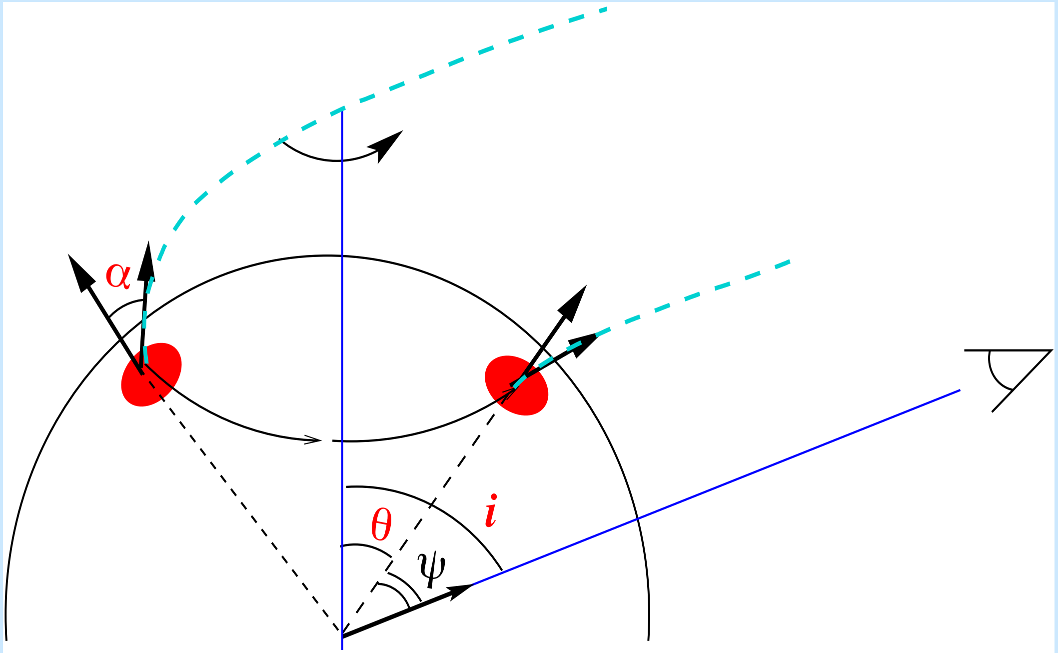
Doppler effect, aberration and light bending

In ms pulsars, rotational velocities are high (b=v/c ~0.1), the Doppler effect plays an important role

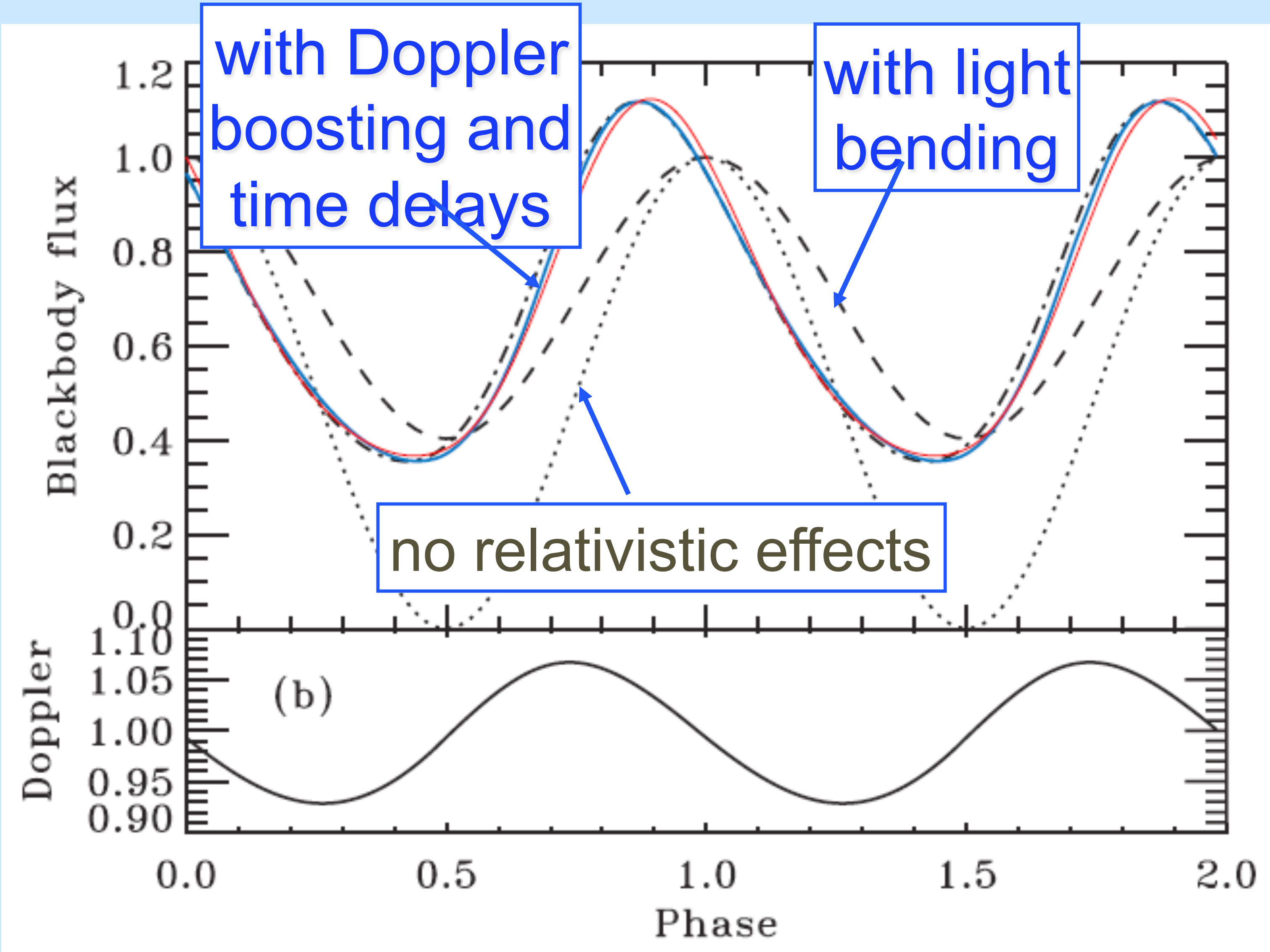
Light emitted from the NS surface can be deflected by 45-60 degrees (for 1.4-1.6 solar mass and 10-12 km NS). We see more than ½ of the surface.



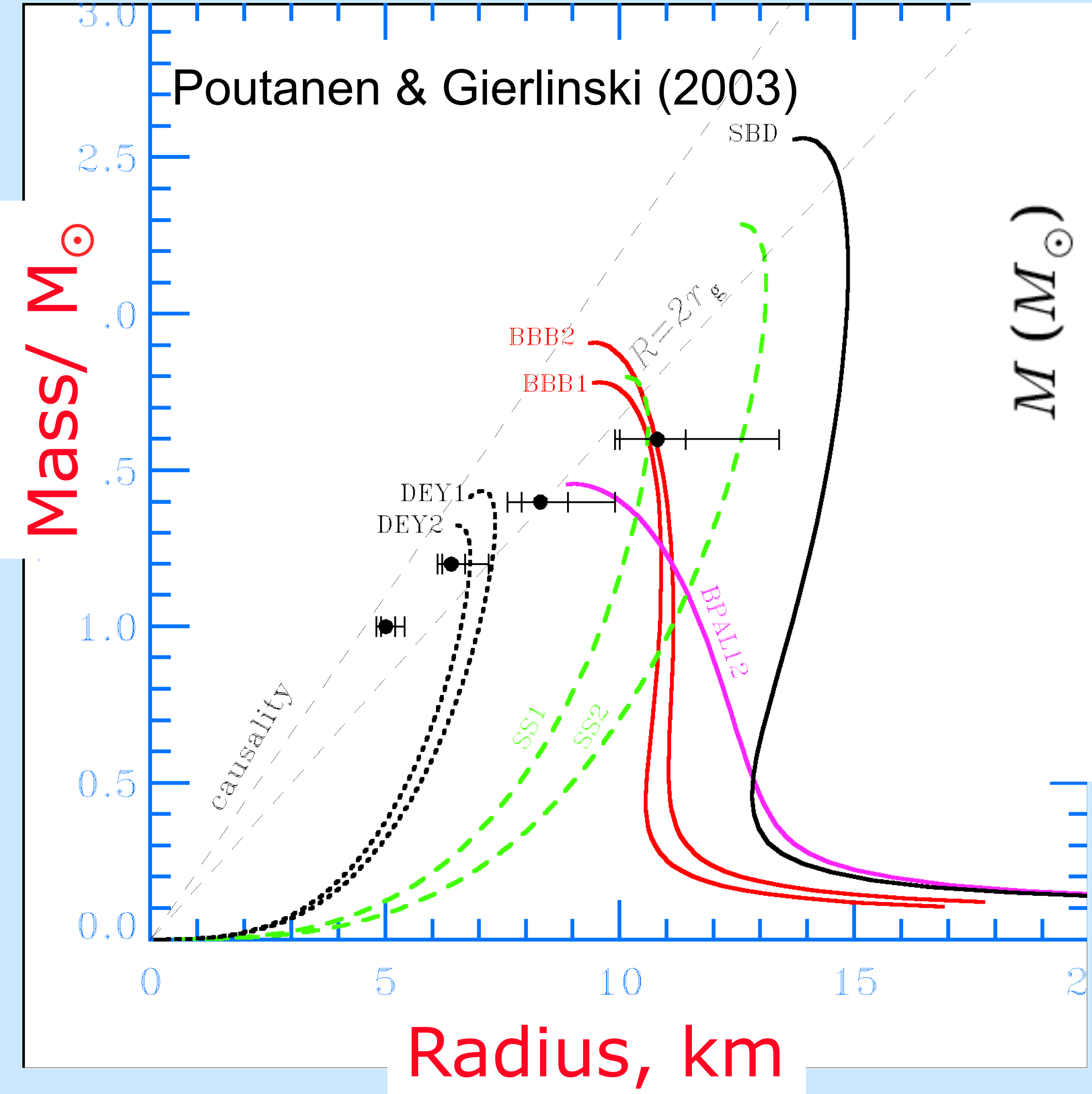
PHASE	AREA	PROJECTED VELOCITY
0=1	LARGEST	~0
0.25		LARGEST NEGATIVE
0.5	SMALLEST	~0
0.75		LARGEST POSITIVE

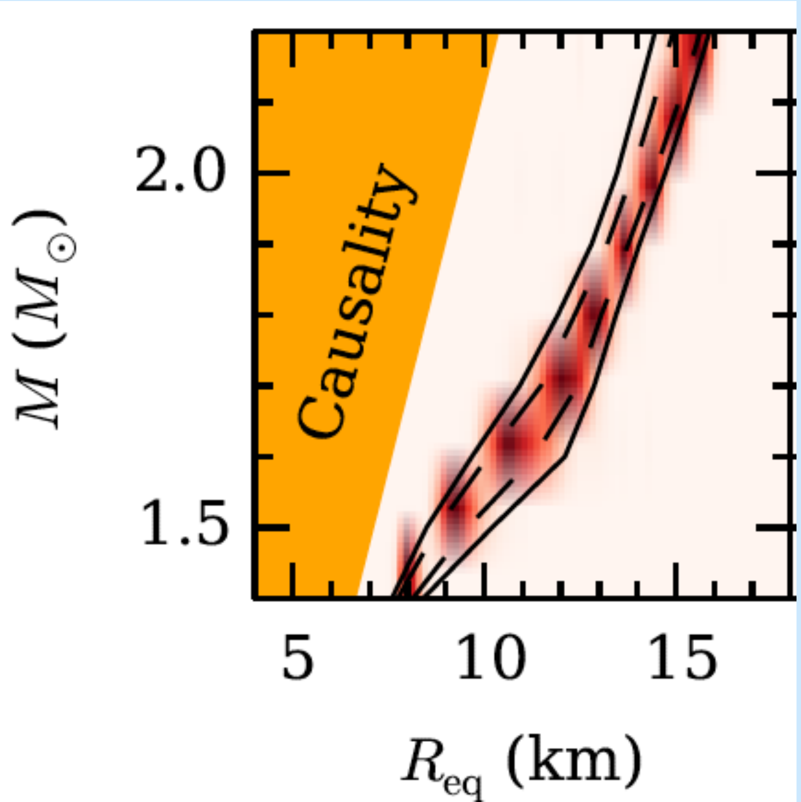


Light curves (blackbody, 400 Hz)



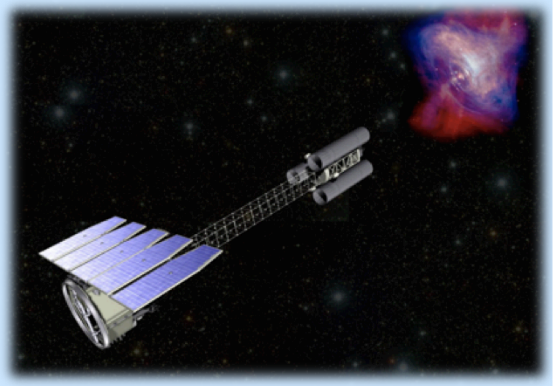
Constraining equation of state from pulse forms



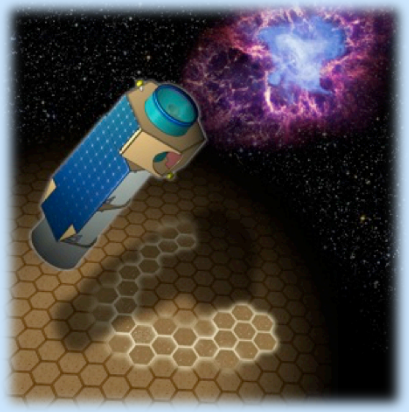


Salmi et al. 2018

Proposed X-ray Polarimetry Missions



Imaging X-ray Polarimetry Explorer (IXPE)
- **NASA** SMEX candidate (PI: M. Weisskopf)
- 175 M$
- Pre-selected in 2015 for Phase A study
- Selected as a SMEX mission in January 2017
- Launch Date: **2021**

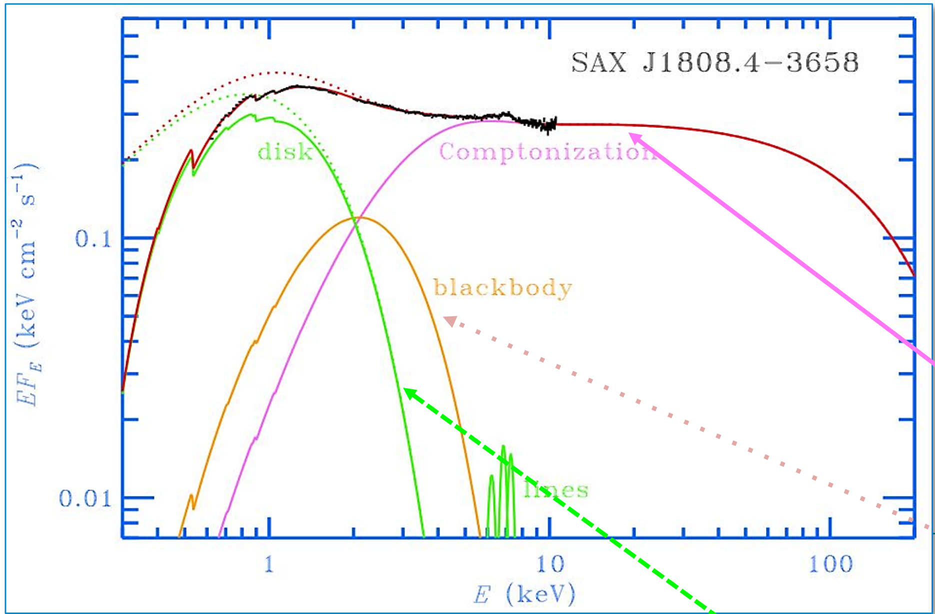


X-ray Imaging Polarimeter Explorer (XIPE)
- **ESA** M4 candidate (PI: P. Soffitta)
- 450 M€
- Pre-selected in 2015 for Phase A study
- Not selected

Enhanced X-ray Timing Polarimetry (eXTP)
- **CAS** mission candidate (PI. S. Zhang, M. Feroci)
- China+Europe (+ESA?)
- Selected by CAS in December 2016
- Launch Date: **2025-2026**

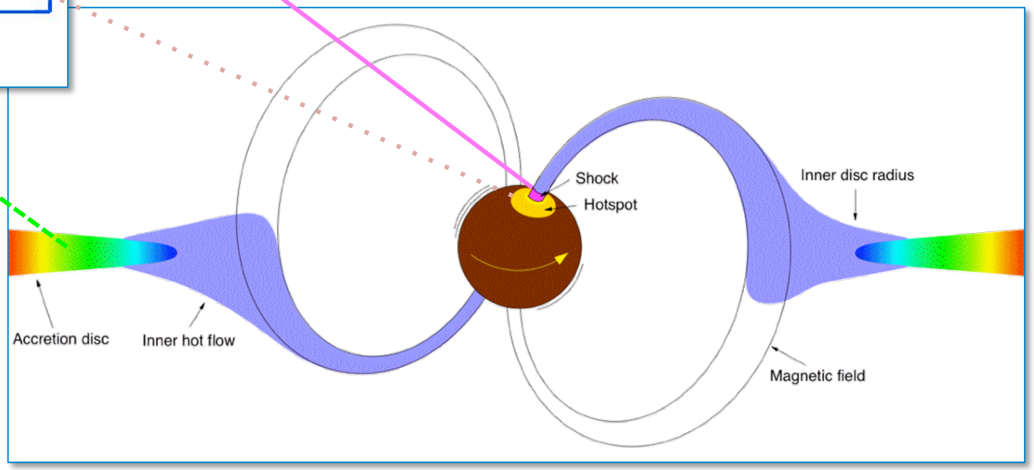
IXPE WILL MEASURE GEOMETRICAL PARAMETERS IN ACCRETING MILLISECOND PULSARS

IXPE
Imaging
X-Ray
Polarimetry
Explorer



In accreting millisecond pulsars (AMPs)

- **Hard X-ray component pulsates: produced in the hotspot**
- **The blackbody also pulsates: heated neutron star surface**
- **Low-energy "blackbody" is not pulsating: accretion disk**

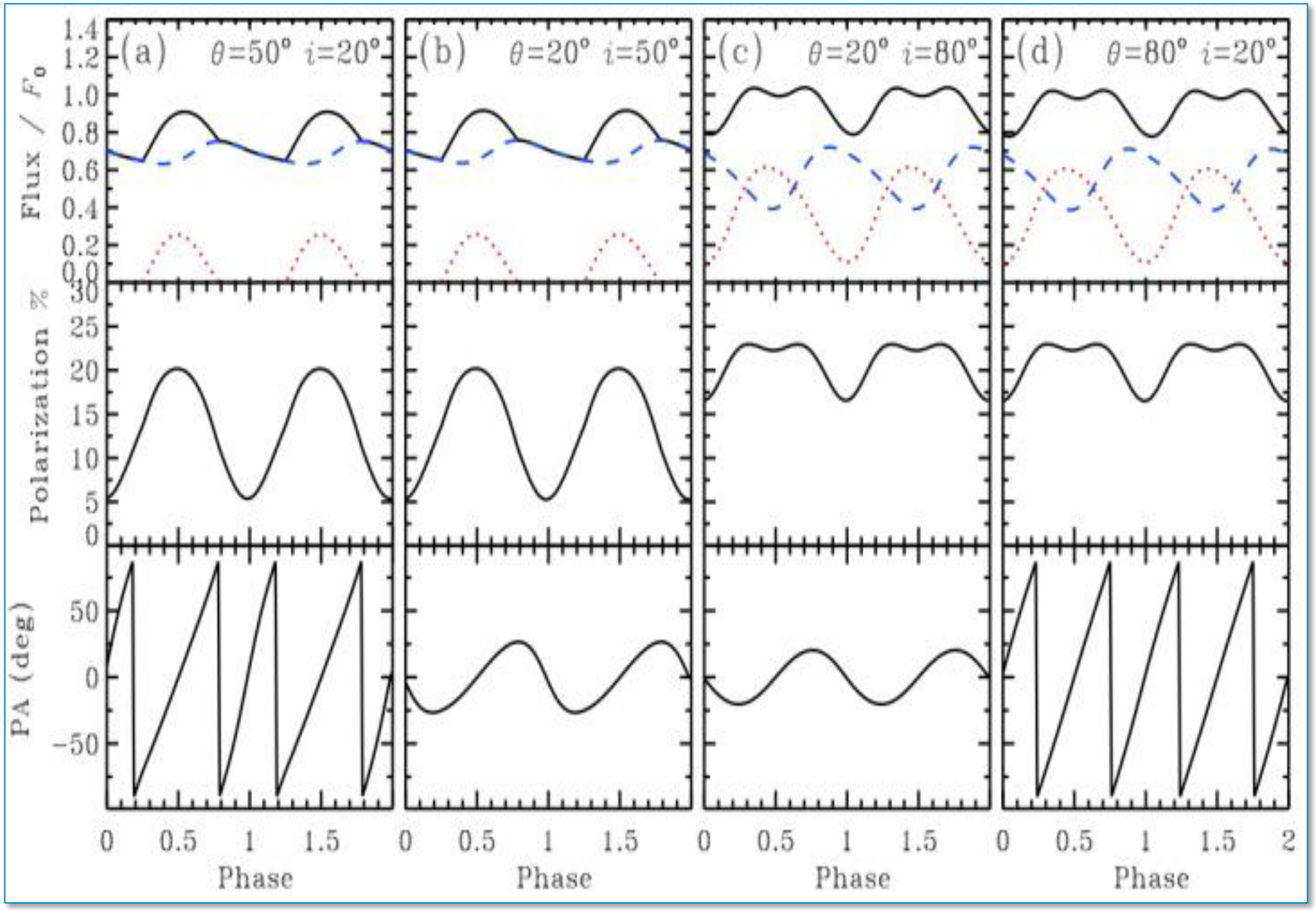


IXPE WILL MEASURE GEOMETRICAL PARAMETERS IN ACCRETING MILLISECOND PULSARS

Emission due to scattering in hotspots

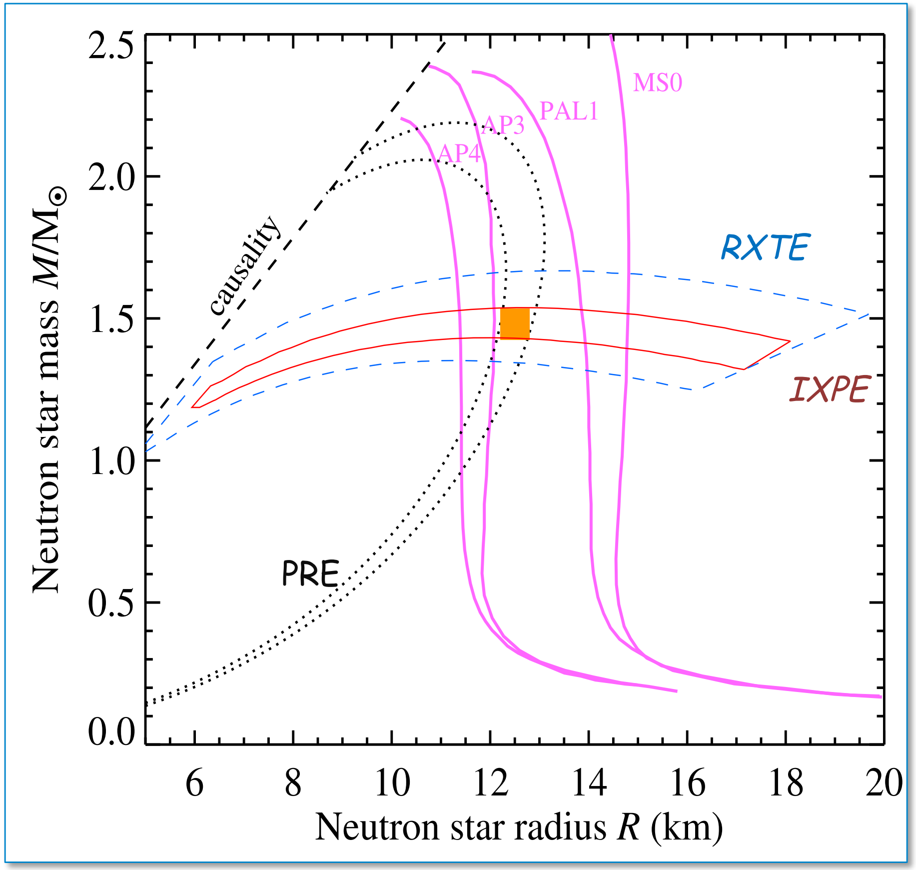
↓

Phase-dependent linear polarization



Polarization measurements constrain the geometrical parameters of the system.

IXPE CONSTRAINS THE EQUATION OF STATE



When combined with spectral measurements of the X-ray bursts, will give strong constraints on EoS (M-R within ~5%)

Conclusions

1. Determining EoS requires measurements not only of the neutron star mass (that one gets from radio pulsars) but also of its radius.

2. X-ray (thermonuclear) bursts are excellent tools to do the job. Current burst data (combined with existence of $2M_\odot$ NS) are consistent with the NS radii $11<R<13$ km, favoring rather stiff equation of state.

3. Pulse profiles from accreting ms pulsars provide an alternative to measure M-R.

4. Combining the data make constraints tighter.

5. Future X-ray polarization measurements will allow to further narrow down the range of parameters.