Neutron star mass and radius constraints from X-ray bursts, accreting millisecond pulsars and X-ray polarization

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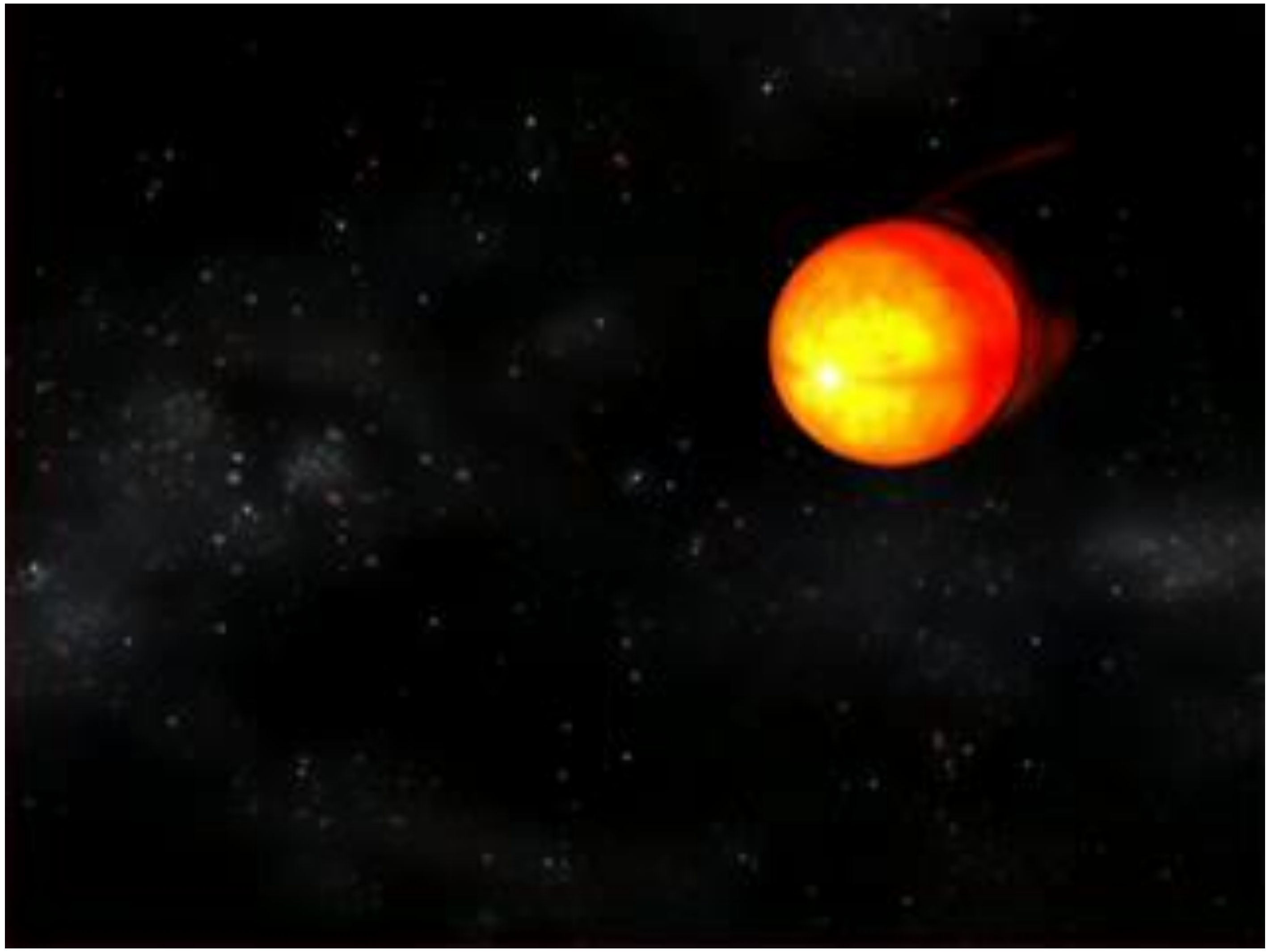
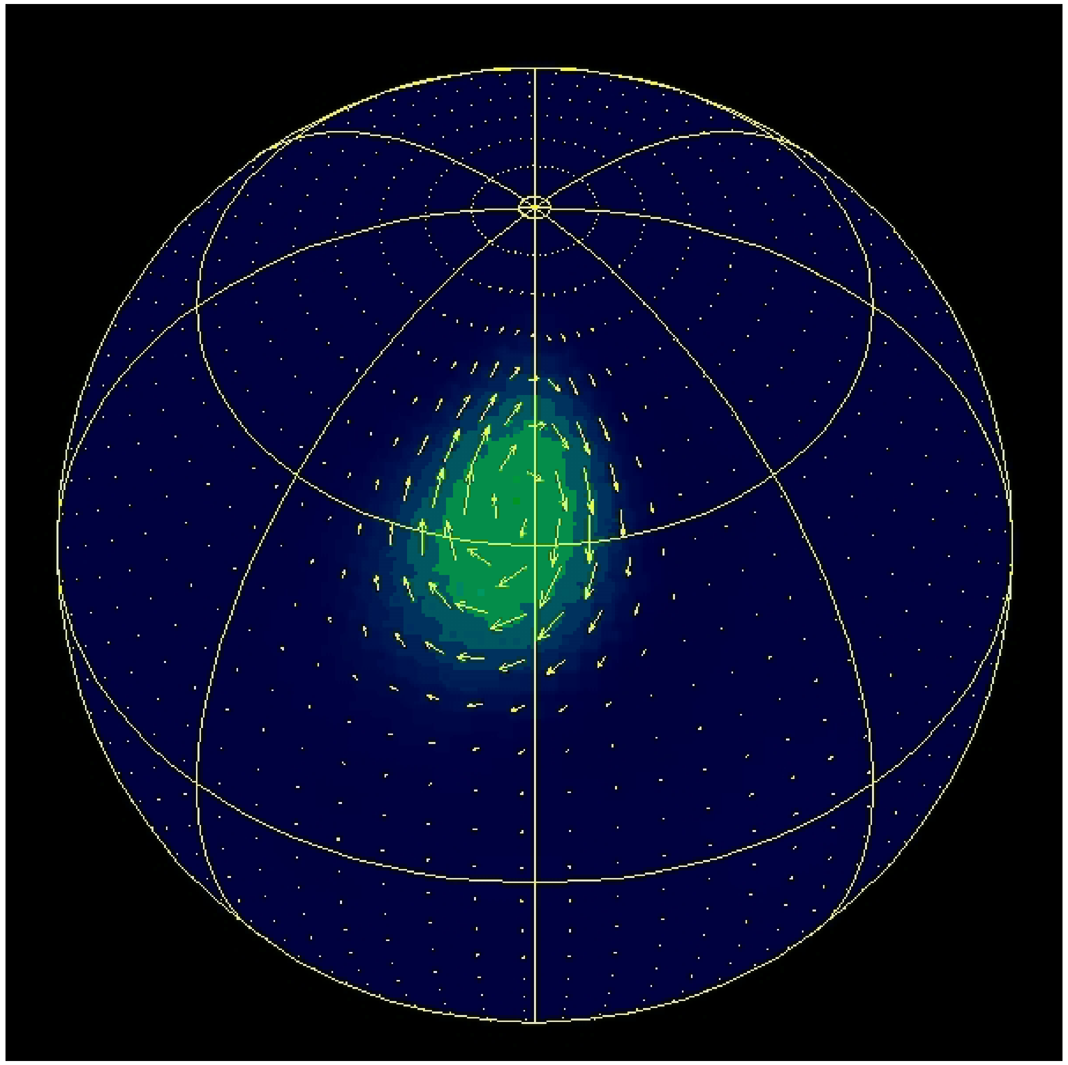
1. Using X-ray bursts to measure NS radii
2. Pulse profiles of accreting millisecond pulsars
3. Prospects with measuring polarization



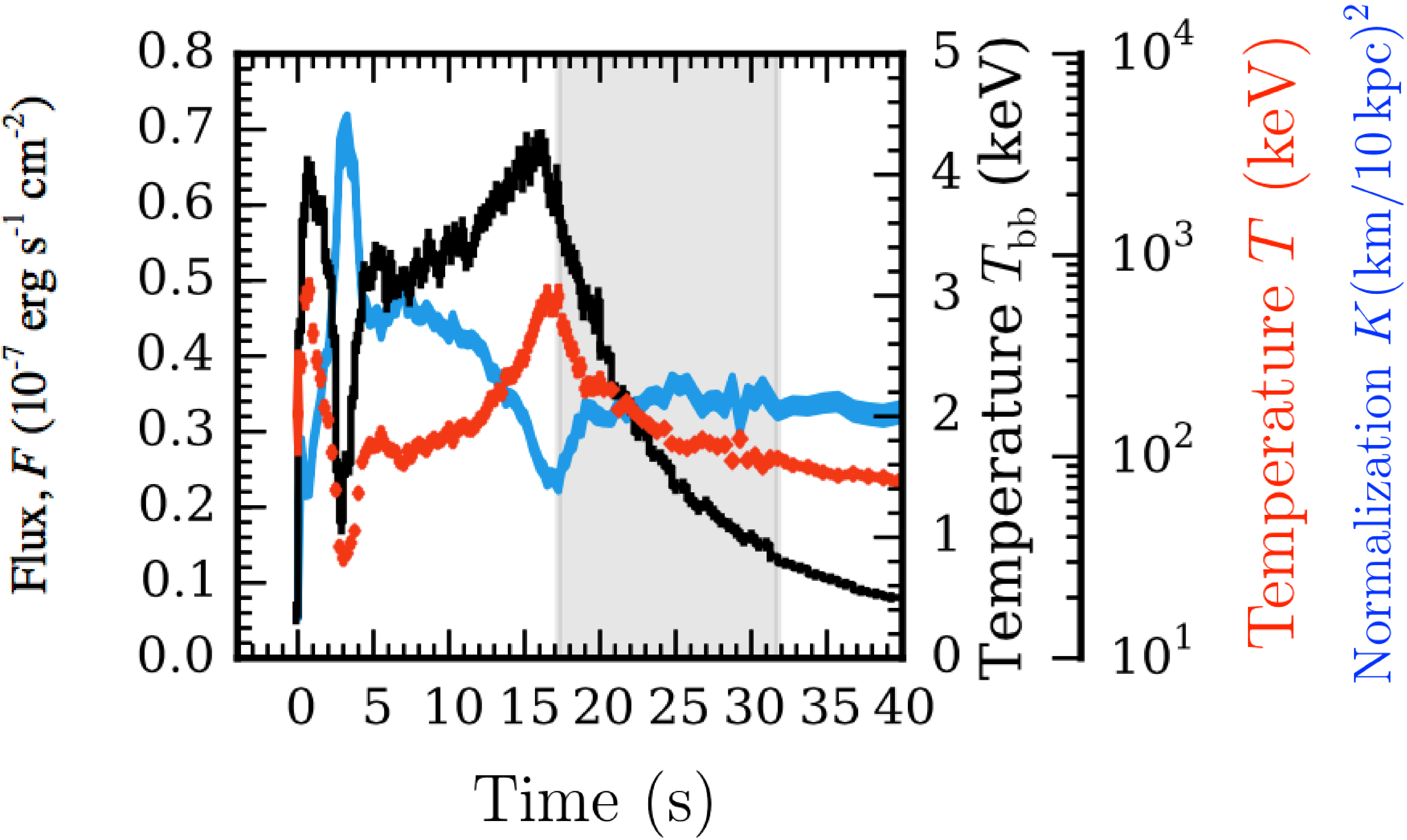


Determining NS parameters

- Thermal spectra from type I X-ray bursts
- Pulse profiles of persistent pulsations in accreting ms X-ray pulsars (AMPs).
- Pulse profiles of X-ray bursts oscillations (possibly with eXTP).

- Polarization can break degeneracy between parameters and improve the constraints.
- The best strategy is to observe AMPs which show PRE bursts.

Photospheric Radius Expansion X-ray bursts

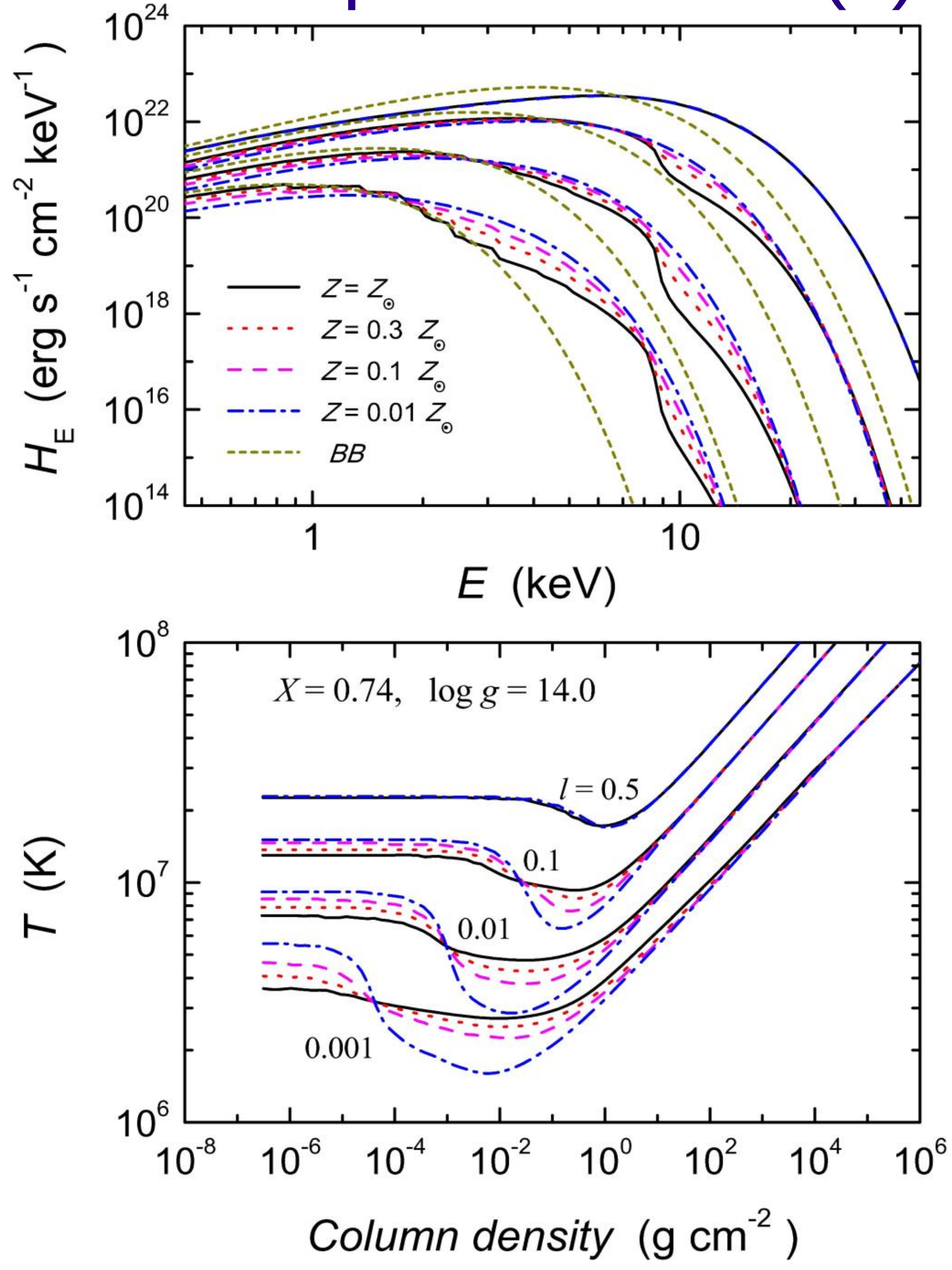


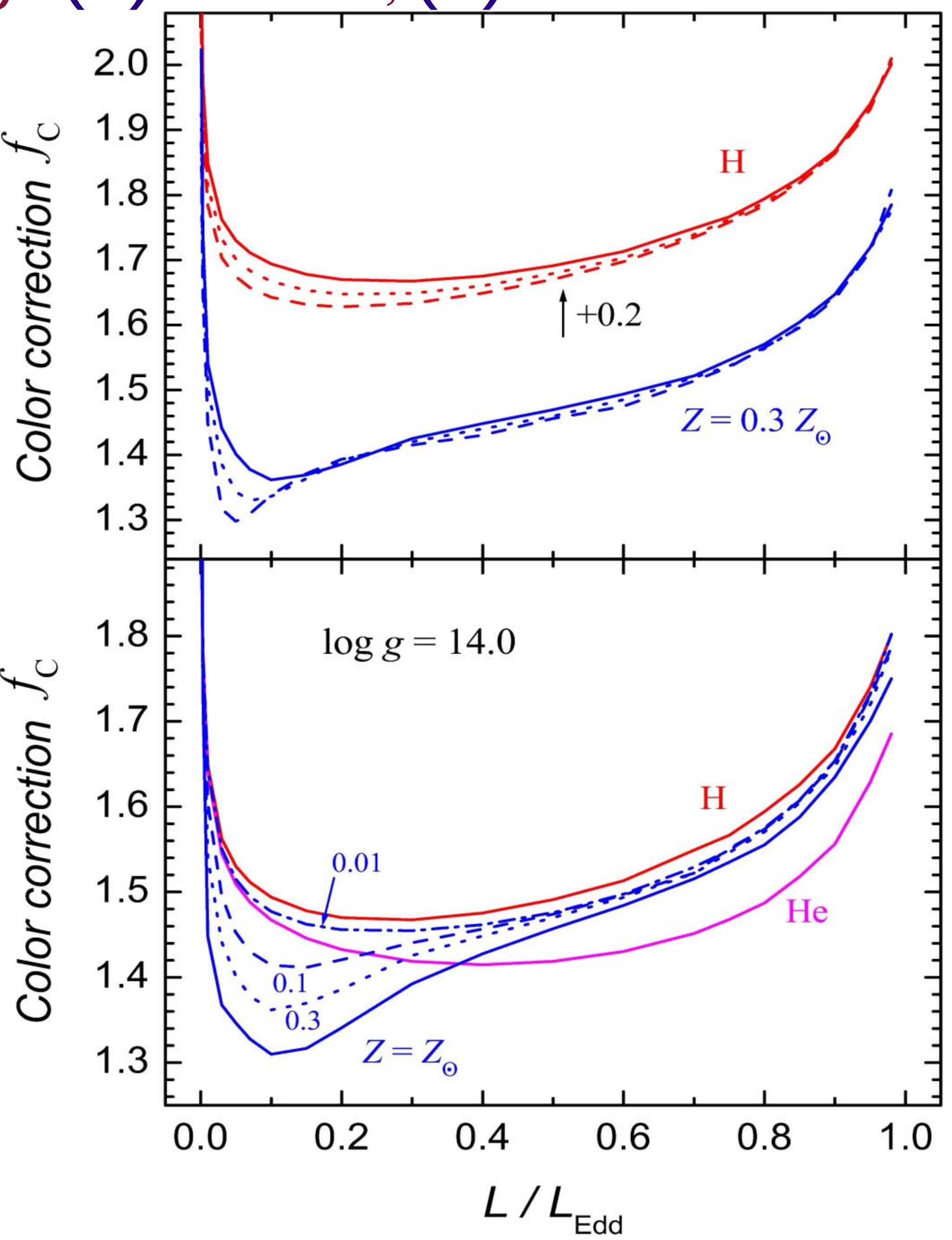
Neutron star atmosphere models helping to interpret burst spectral evolution

A large set of atmosphere models is computed

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

main parameters : (1) $\log g$ (2) $L/L_{\rm Edd}$, (3) chemical composition





Direct spectral fitting

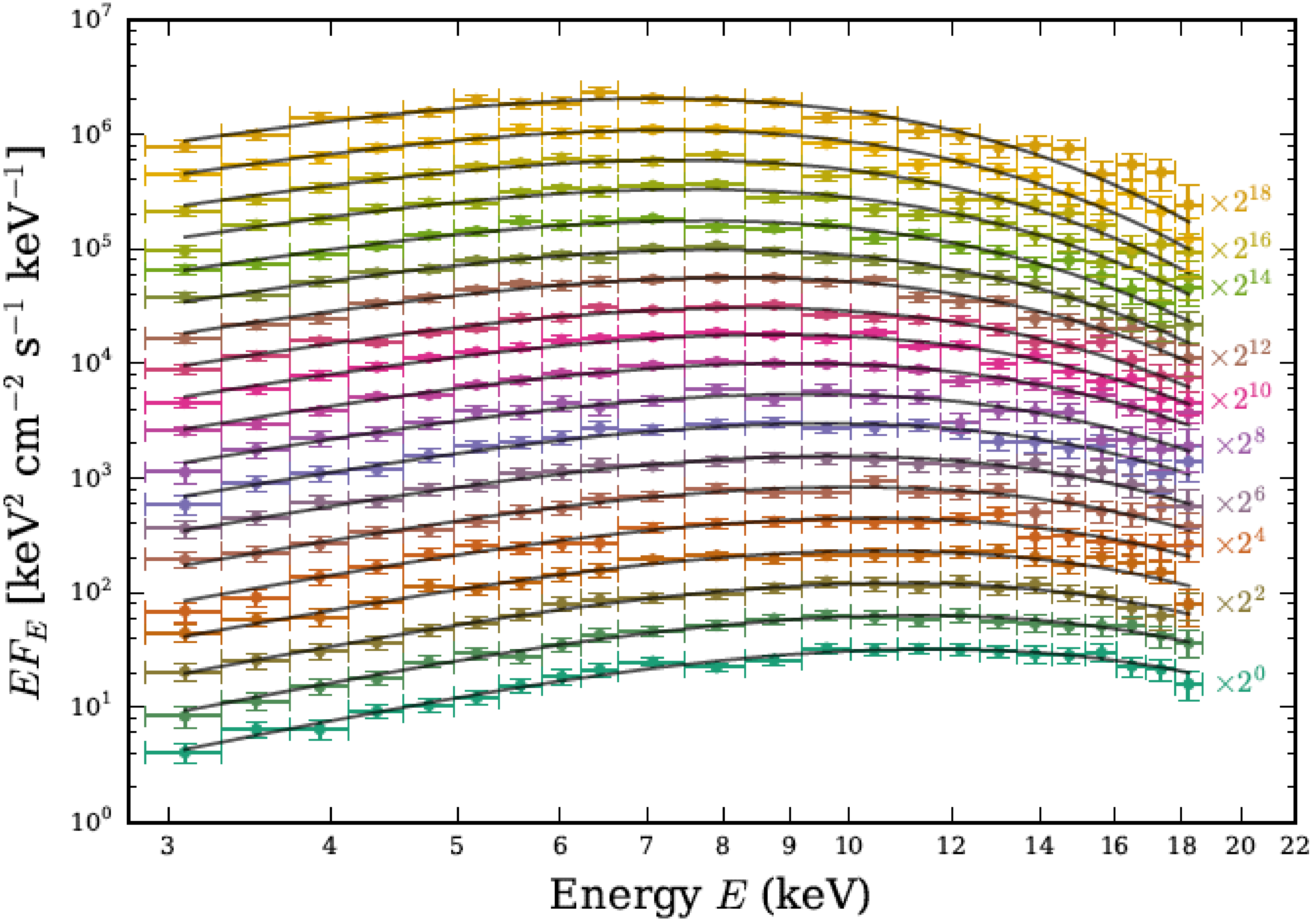
1. Most (all?) previous attempts to measure NS *M* and *R* from burst spectra rely on the blackbody fits. Thus plenty of information gets lost.

2. The computer power now allows to directly fit all the burst spectra from the same source simultaneously with the atmosphere models using MCMC.

Global parameters: *M, R, D* (+ chem. comp.) Local: F/F_{Edd} for each spectrum

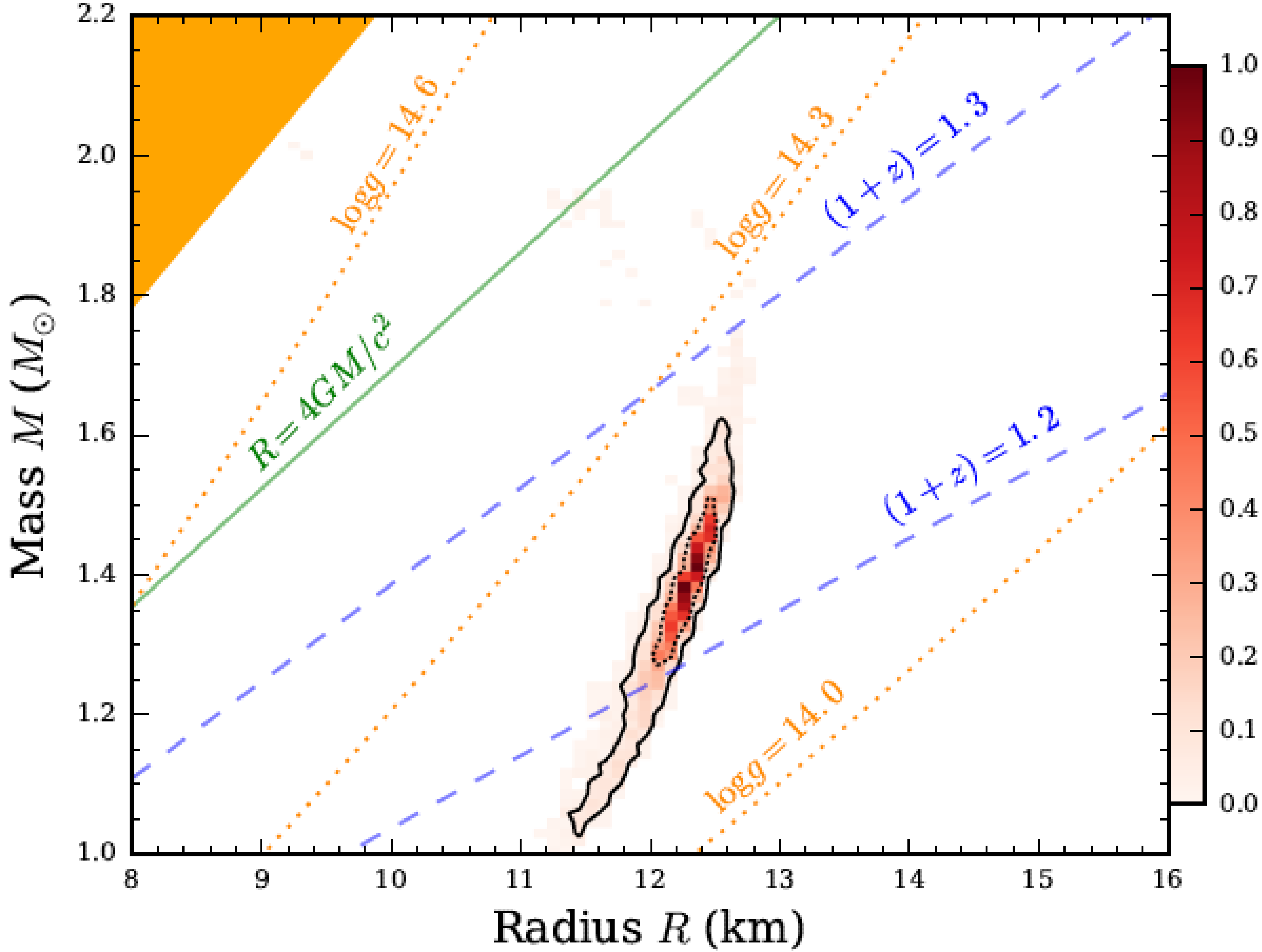
Direct spectral fitting

Fits to the spectra of 4U 1702-429



Direct spectral fitting

M-R constraints for 4U 1702-429

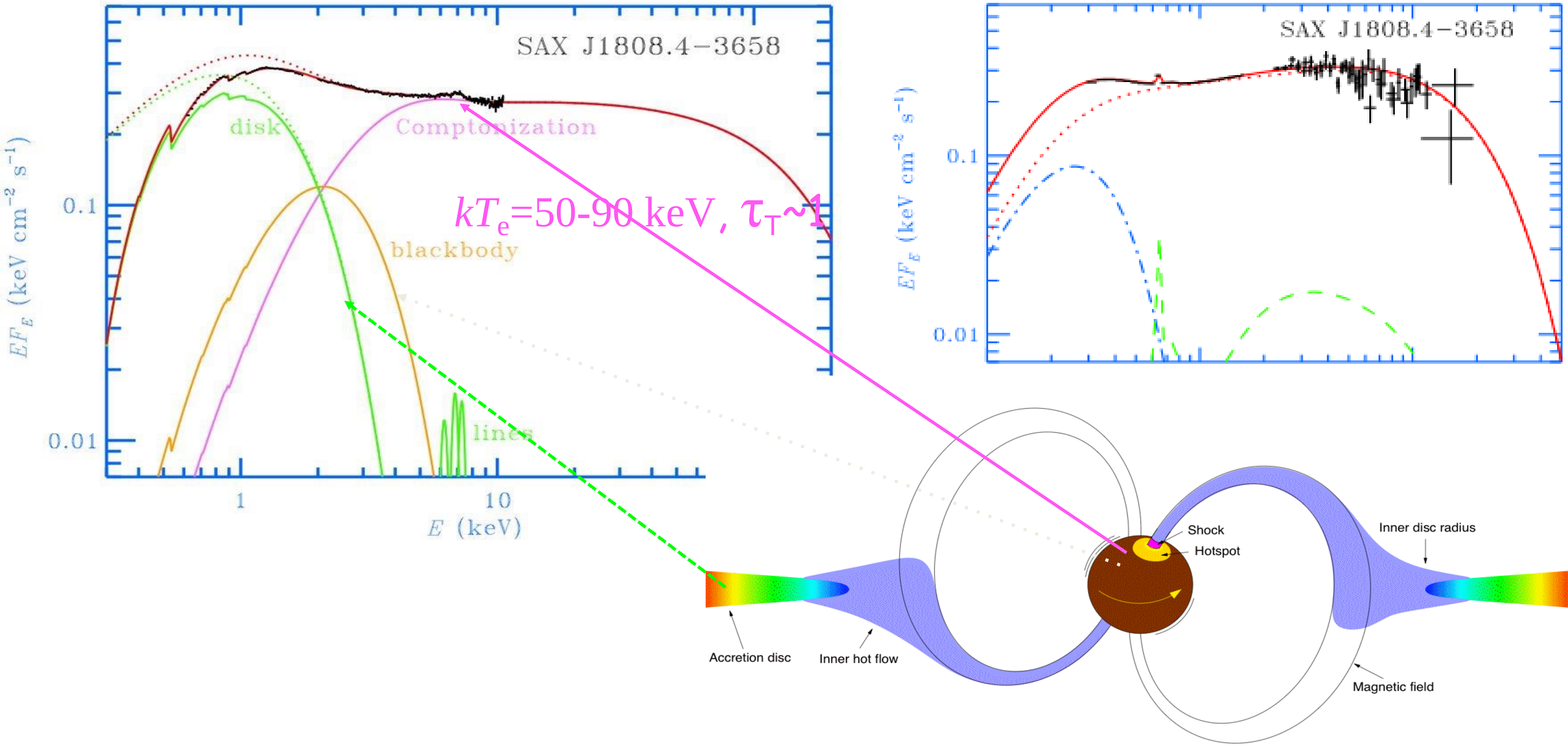


Nättilä et al. 2017

Accreting millisecond pulsars for eXTP

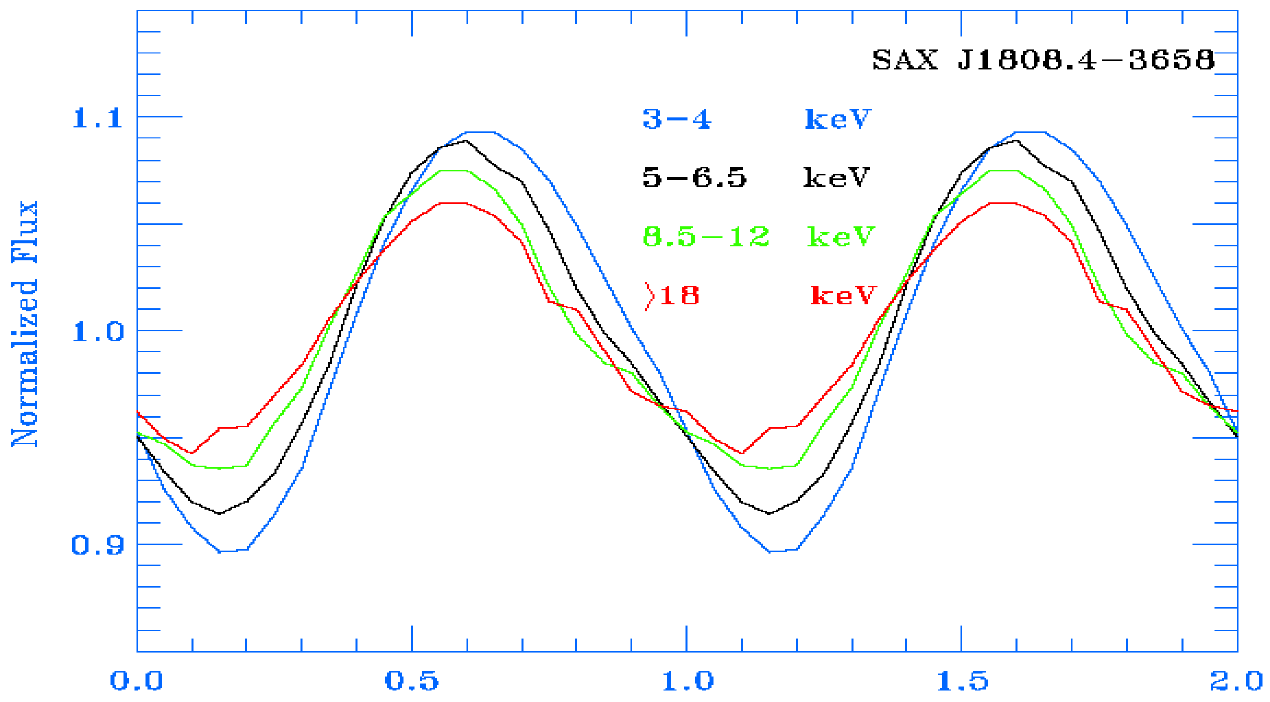
Source	Spin Hz	2-8keV flux in outburst	Outbursts every	Duration of desired state; comment
1. SAX J1808.4-3658	401	1E-09	2-3 years	single peak pulse profile over 2 weeks; PRE bursts
2. XTE J1751-305	435	1E-09	~ 4 yr	typically short duration (even 2d)
3. IGR J00291+5934	599	4E-10	3-4 yr	15d
4. NGC6440 X-2	206	1E-10	1 month	3-5d
5. Swift J1749.4-2807	518	1E-10	?	7d; eclipsing
6. XTE J1814-338	314	4E-10	20 yr ?	Long 50 day outbursts; bursts
7. XTE J0929-314	185	3E-10	?	>52d
8. XTE J1807-294	190	1E-09	?	120d
9. SWIFT J1756.9-2508	182	3E-10	~2 yr	14d
10. SAX J1748.9-2021	442	1E-09	4 yr	
11. IGR J17511-305	245	6E-10	?	10d
12. IGR J17498-2921	401	4E-10	?	15d
13. IGR J18245–2452	254	3E-10	?	
14. HETE J1900.1-2455	377	6E-10	quasi-persistent	long ~10yr outburst
15. MAXI J0911-655	340	2E-10		>100 d long outburst

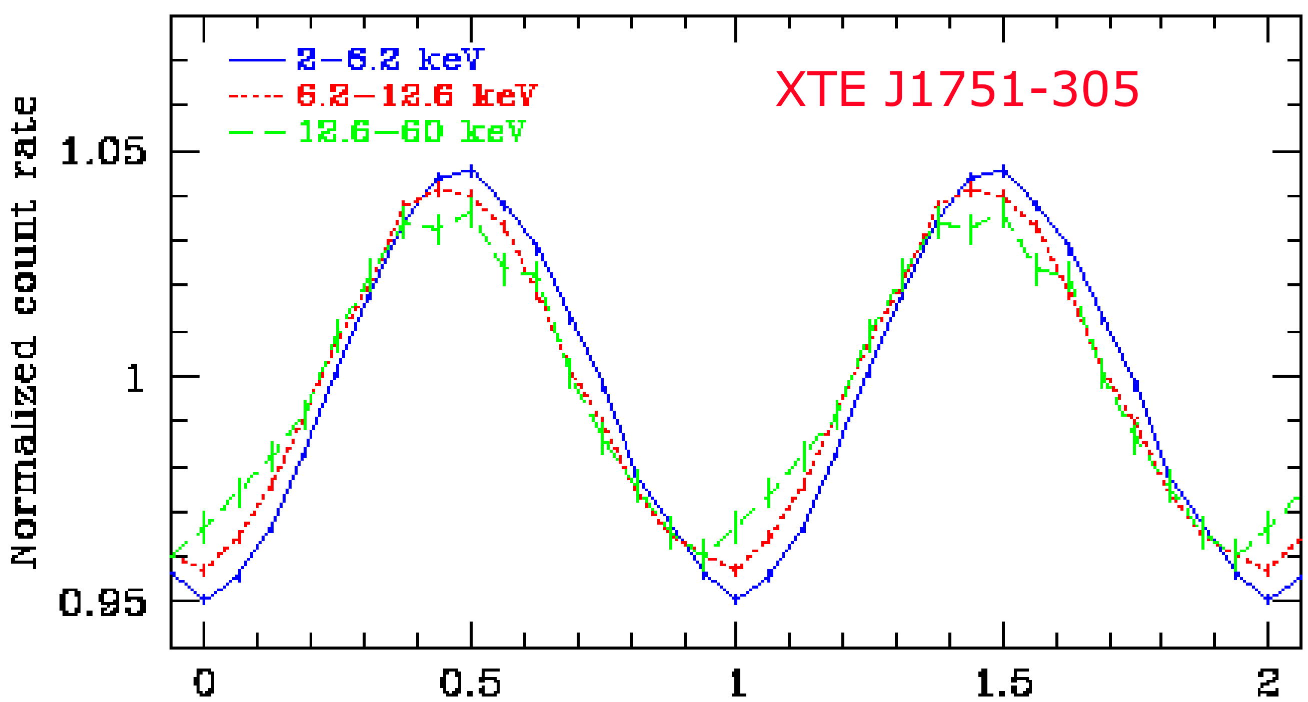
Accreting millisecond pulsars

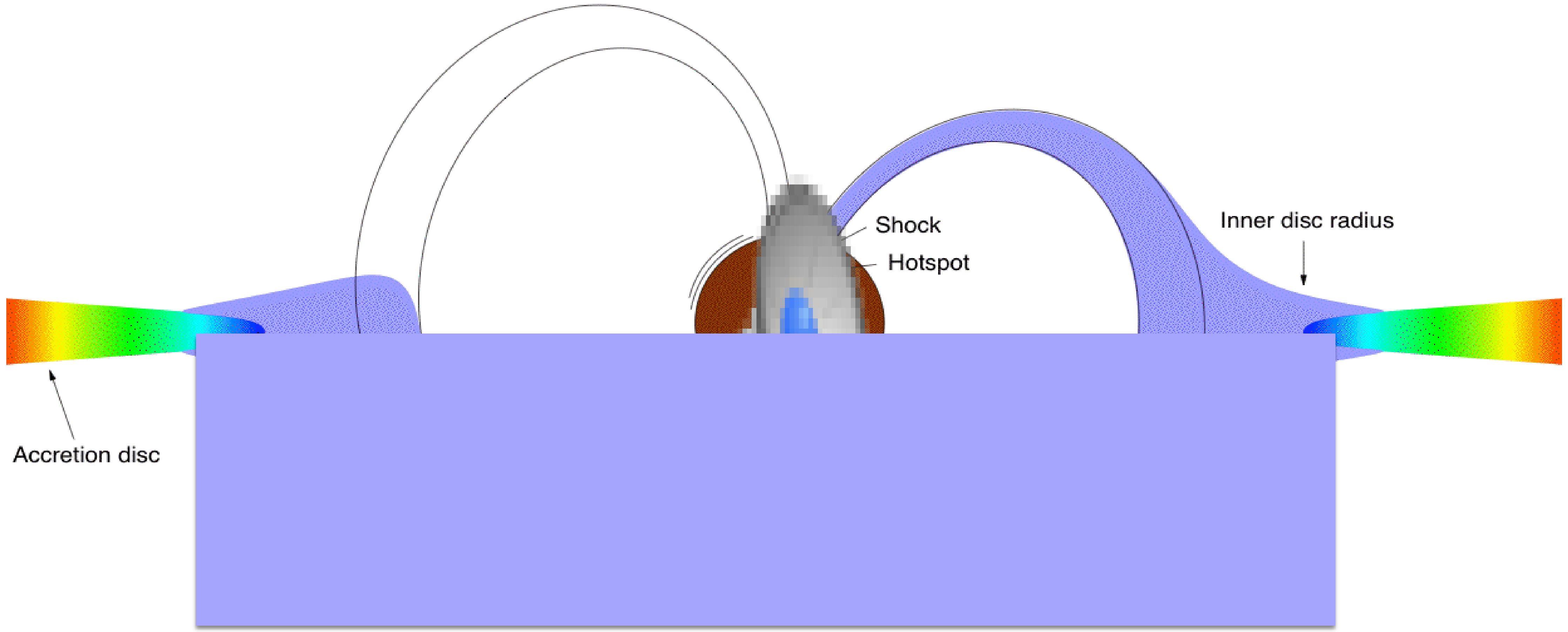


- Hard X-ray component pulsates ❾ produced probably at the shock.
- The blackbody also pulsates ❾neutron star surface
- Low-energy `blackbody’ is not pulsating ❾accretion disk

Pulse profiles



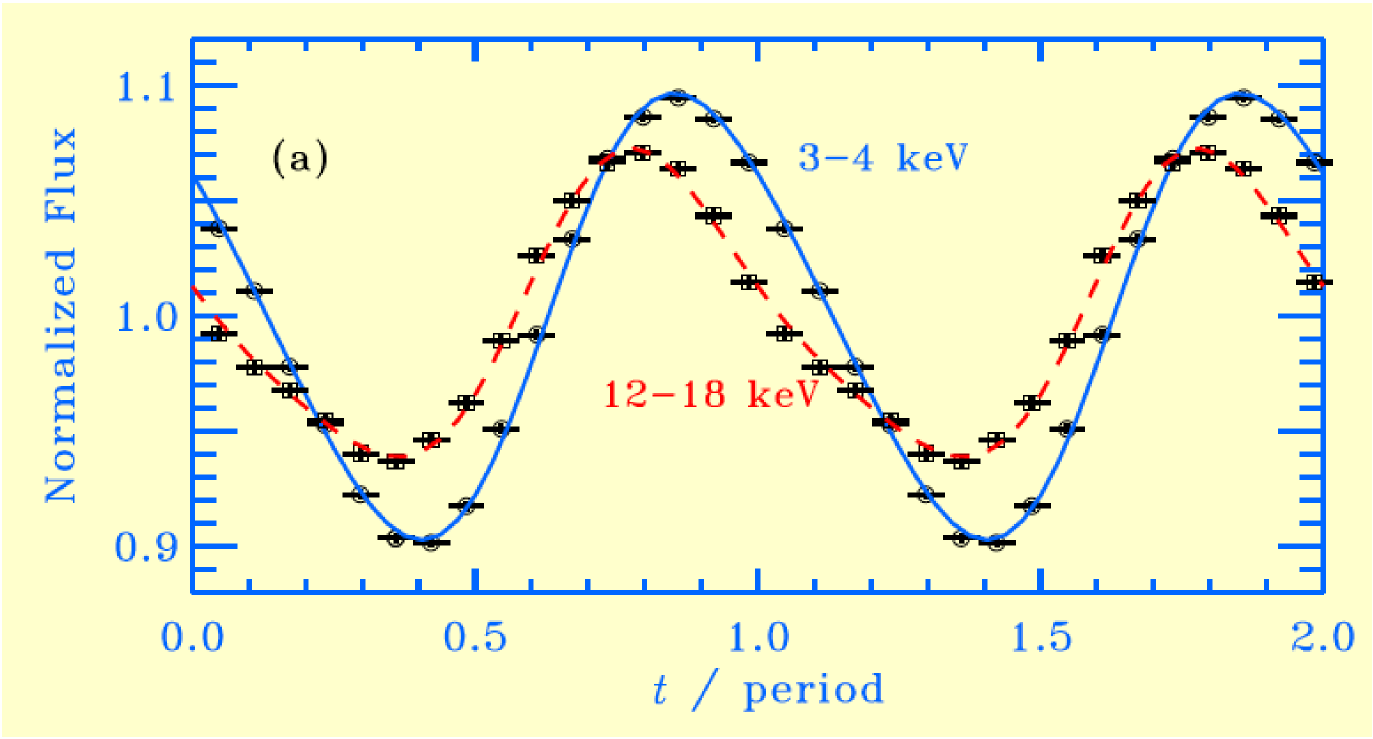


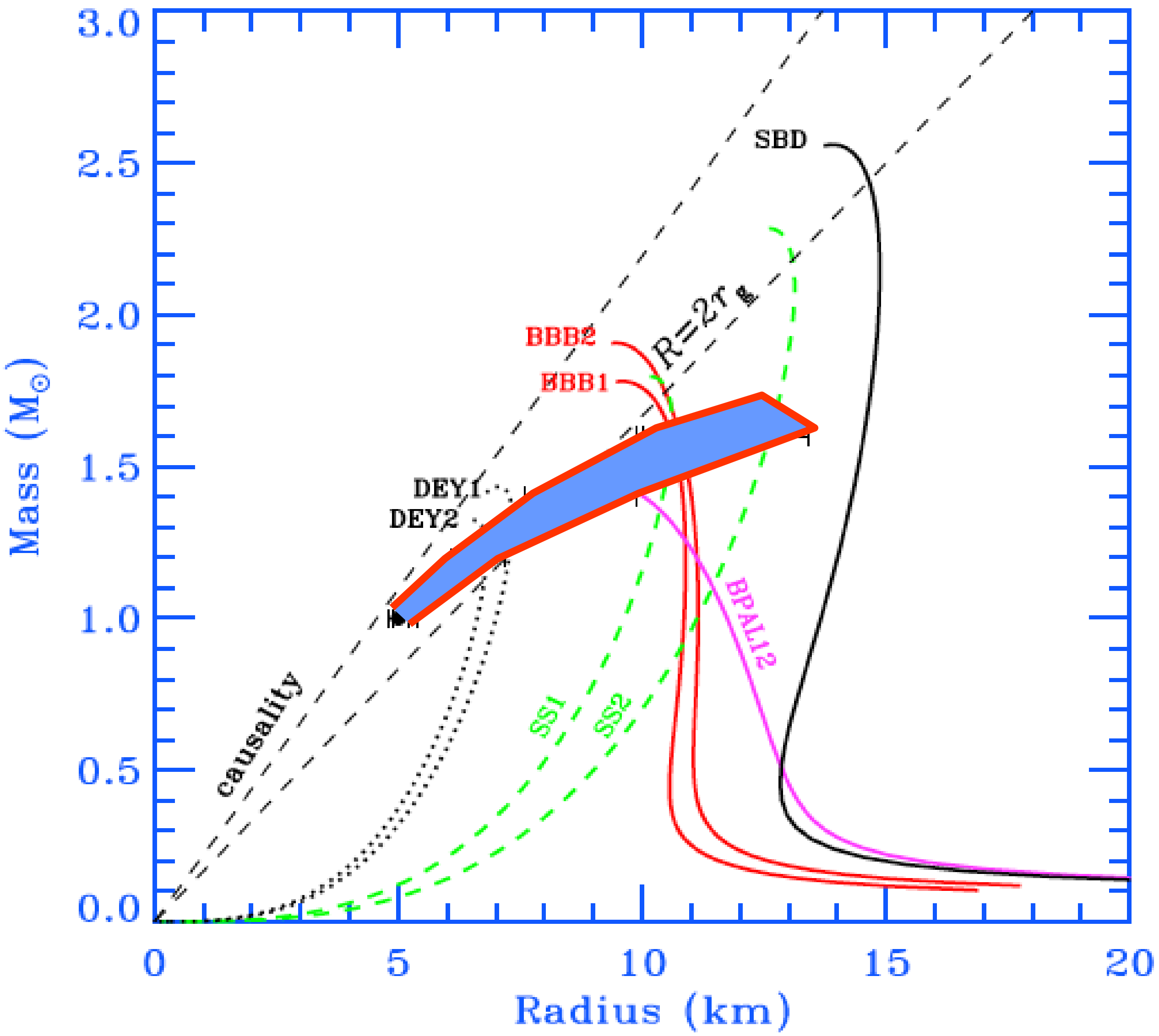


Constraints on the EoS from pulse profiles

Pulse profiles depend on NS compactness (light bending) and radius (Doppler effect).

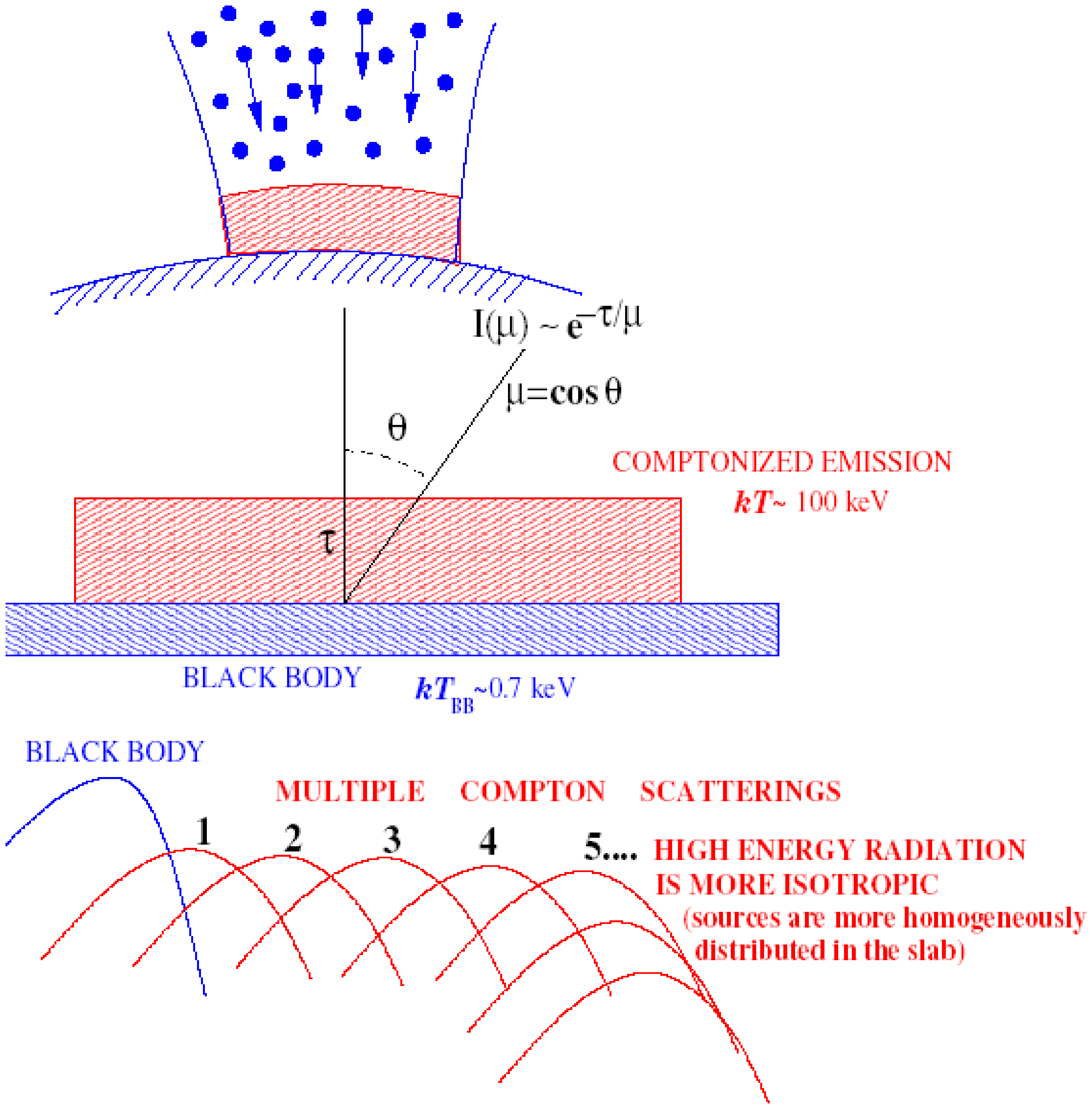
Fitting profiles provide constraints on M and R.





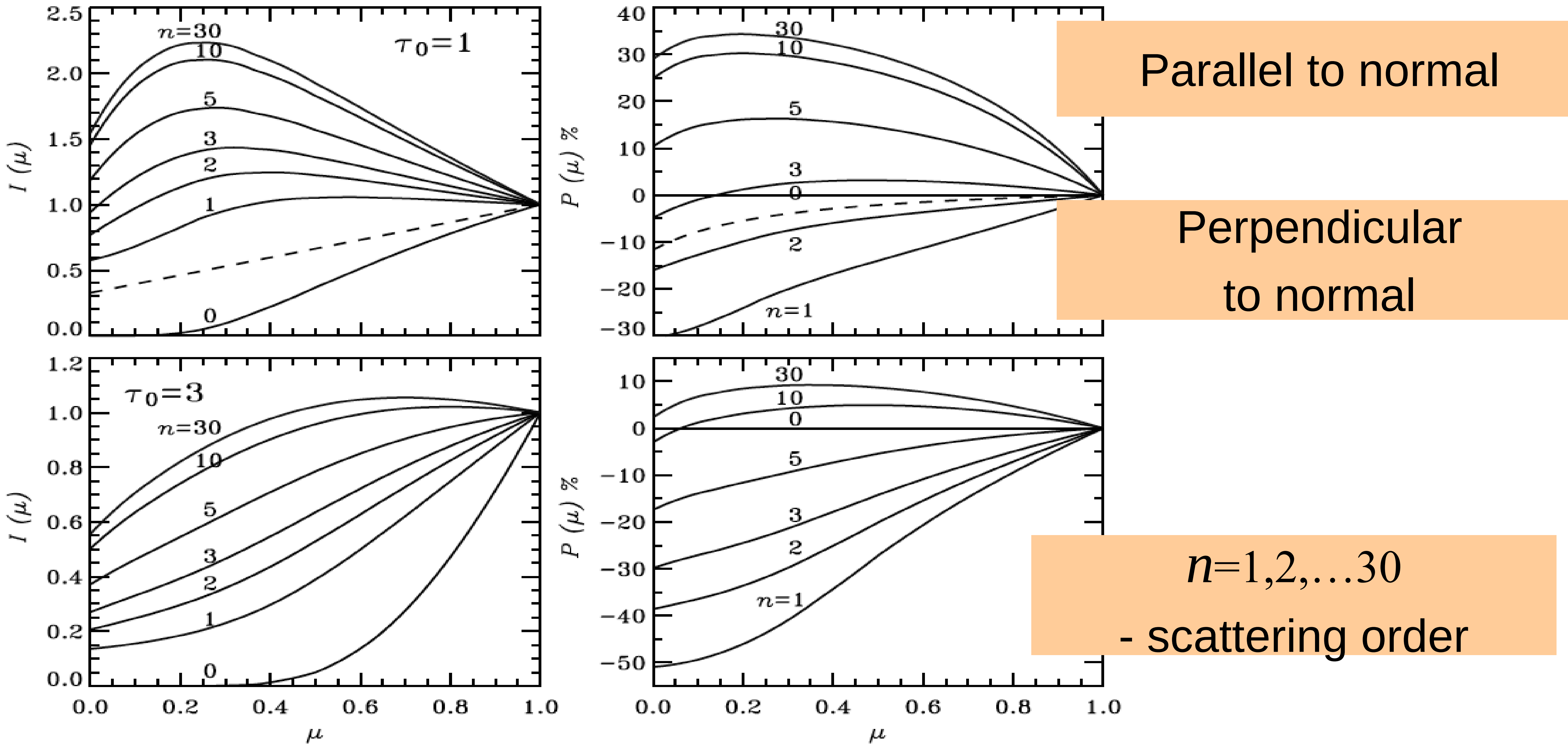
Poutanen & Gierliński (2003)

Comptonization in a shocked region



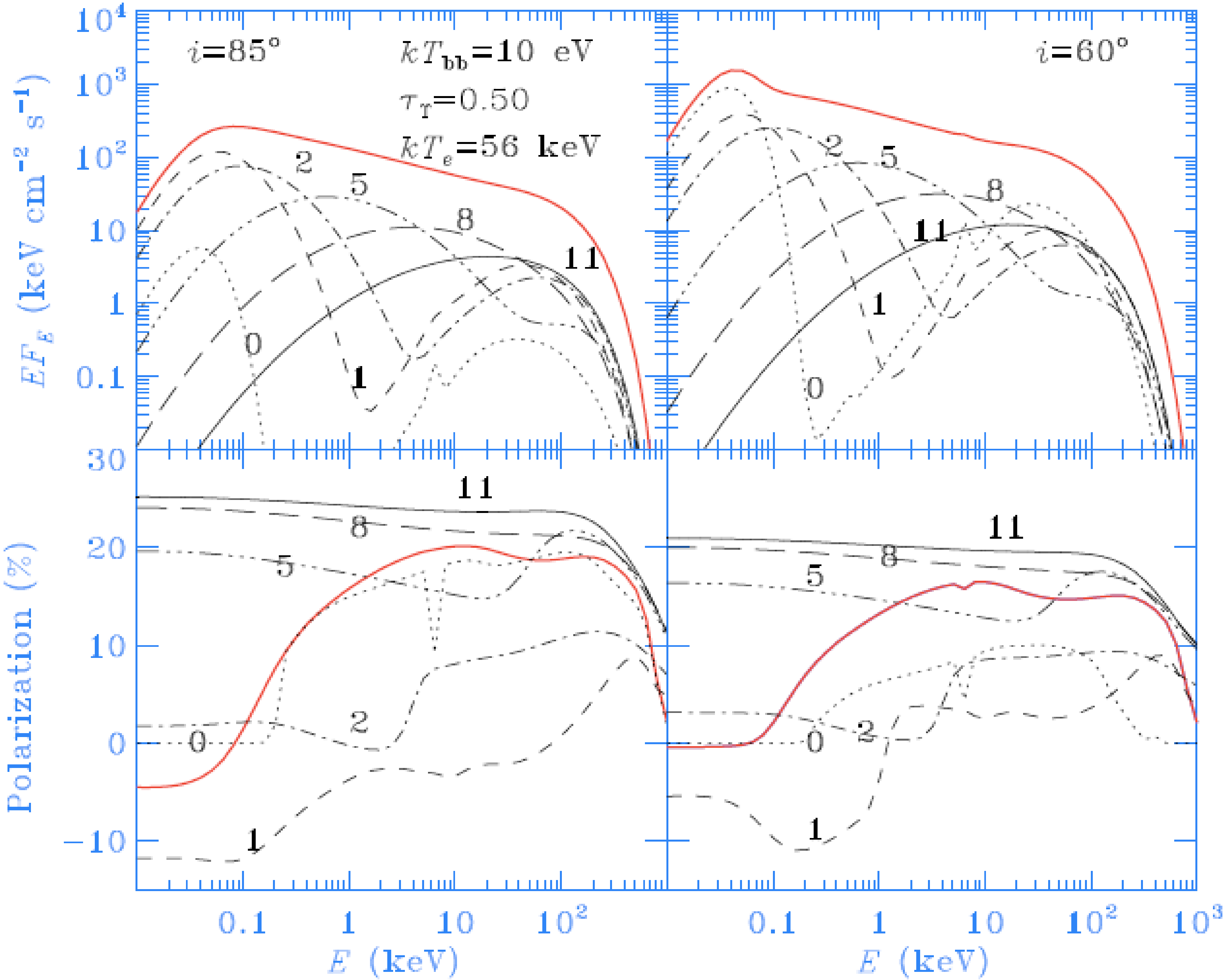
Polarization from a shocked region

Intensity and polarization as a function of cosine inclination for different scattering orders.



Sunyaev & Titarchuk 1985; Haardt & Matt 1993; Viironen & Poutanen 2004

Polarization from optically thin electron scattering-dominated atmosphere

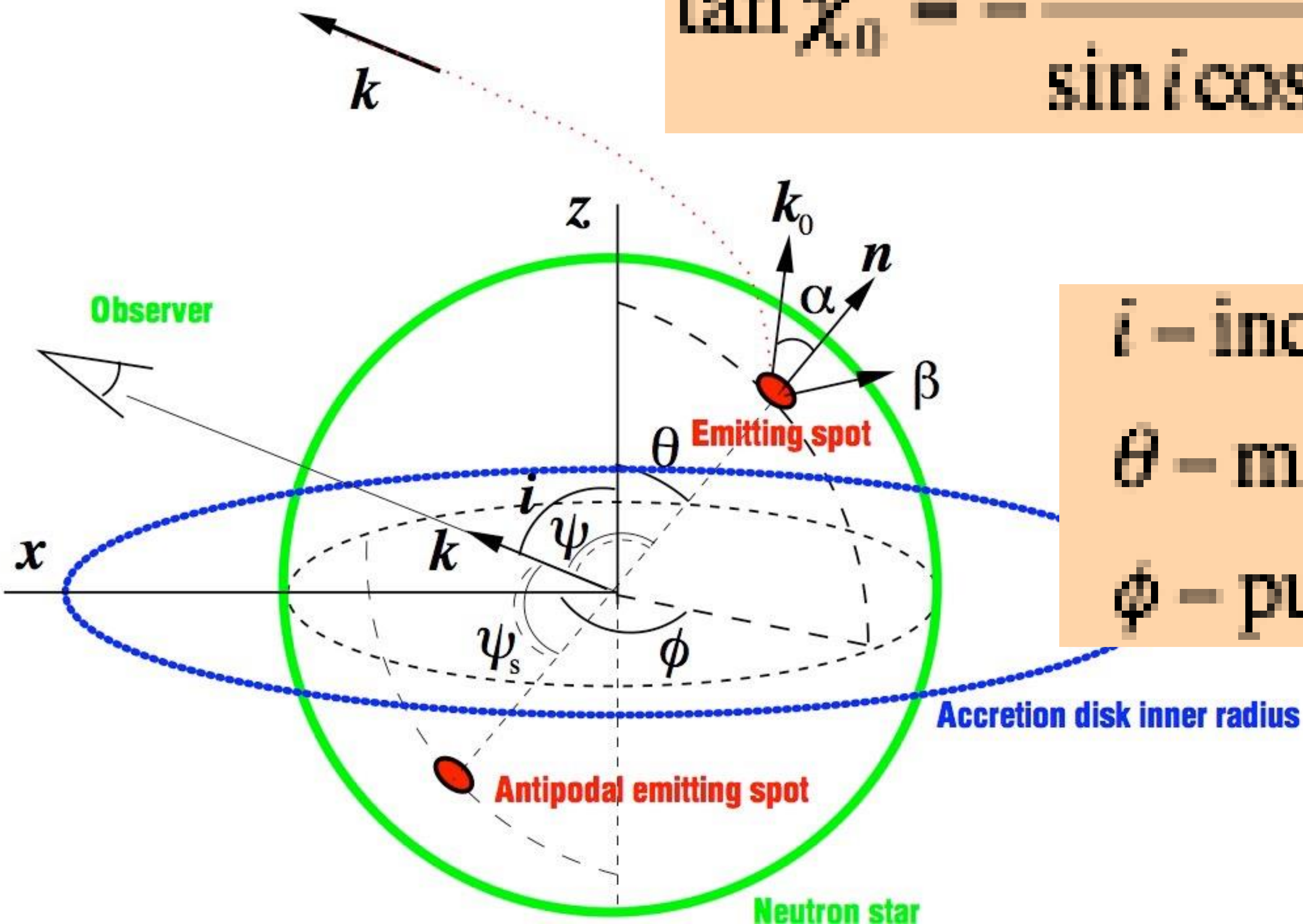


Poutanen & Svensson (1996)

Phase dependence of polarization angle

Rotating vector model, RVM
(Radhakrishnan & Cooke 1969)

$$\tan\chi_0 = -\frac{\sin\theta\sin\phi}{\sin i\cos\theta - \cos i\sin\theta\cos\phi}$$



i – inclination

θ – magnetic obliquity

ϕ – pulsar phase

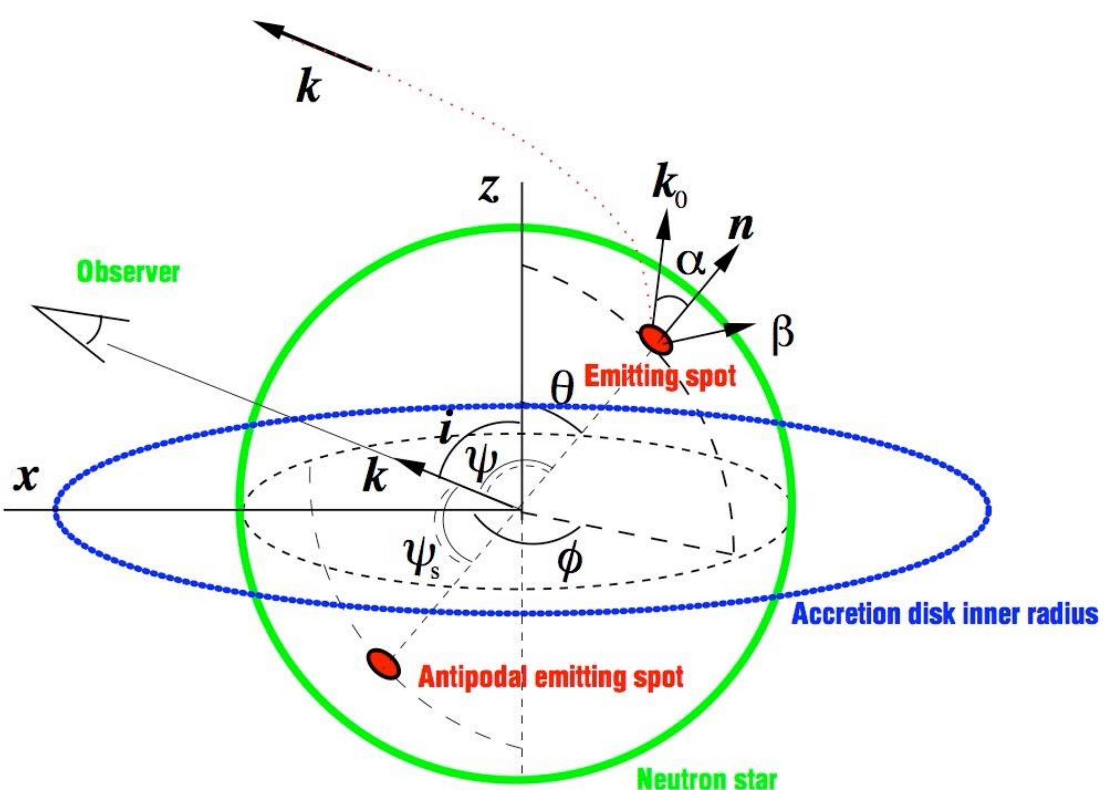
Phase dependence of polarization angle

- Relativistic RVM (Ferguson 1973, 1976) incorporates effects of special relativity.
- Relativistic RVM of Viironen & Poutanen (2004) includes GR (light bending) and special relativity effects which rotate polarization plane by angle $|_c$

$$\tan\chi_c = \beta_{eq}\sin\theta\cos\alpha\,\frac{\cos i\sin\theta - \sin i\cos\theta\cos\phi}{\sin\alpha\sin\psi + \beta_{eq}\sin\theta\sin i\sin\phi}$$

Polarization angle :

$$\chi = \chi_0 + \chi_c$$



i – inclination

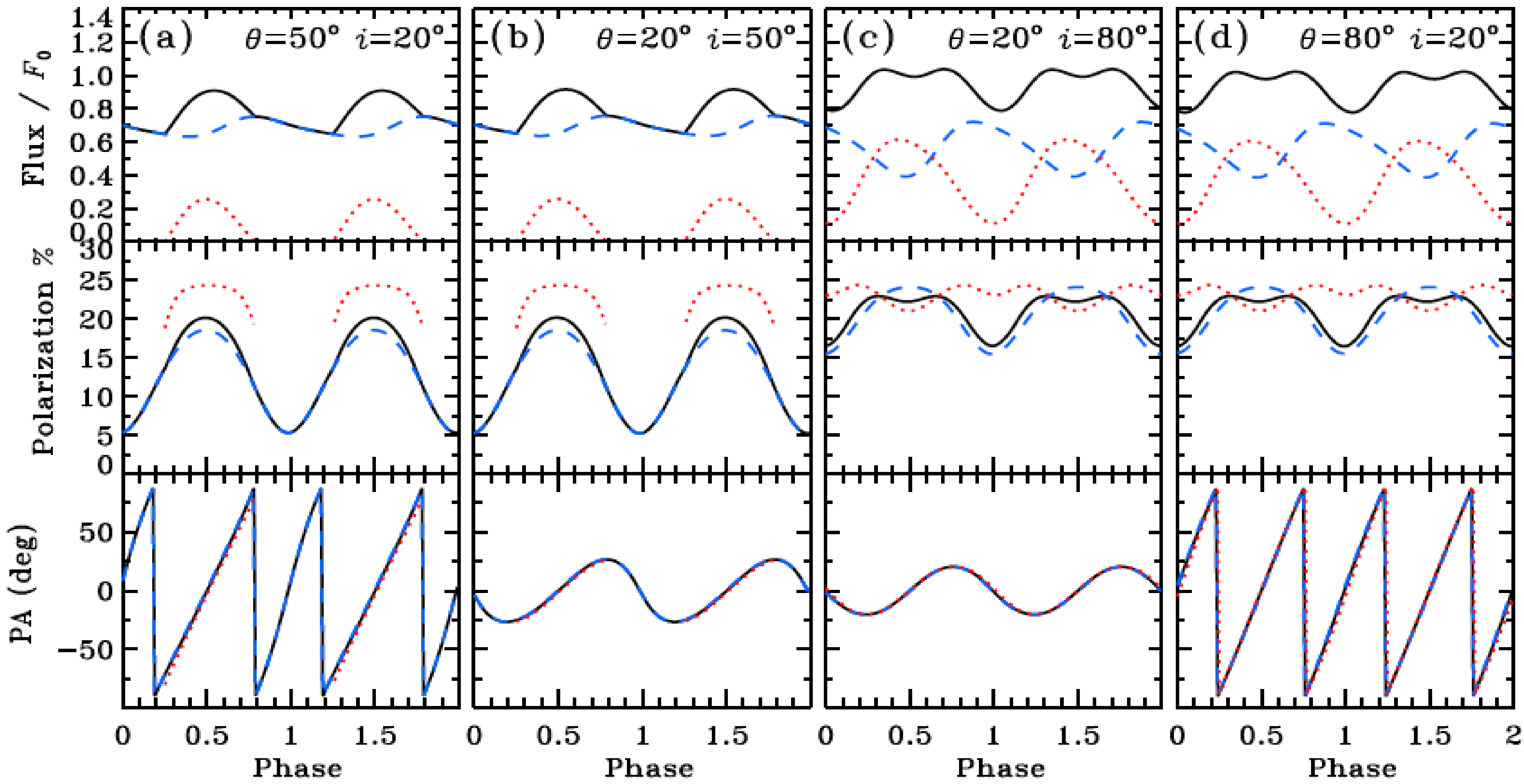
θ – magnetic obliquity

ϕ – pulsar phase

$\beta_{eq} = v/c$ – equatorial velocity

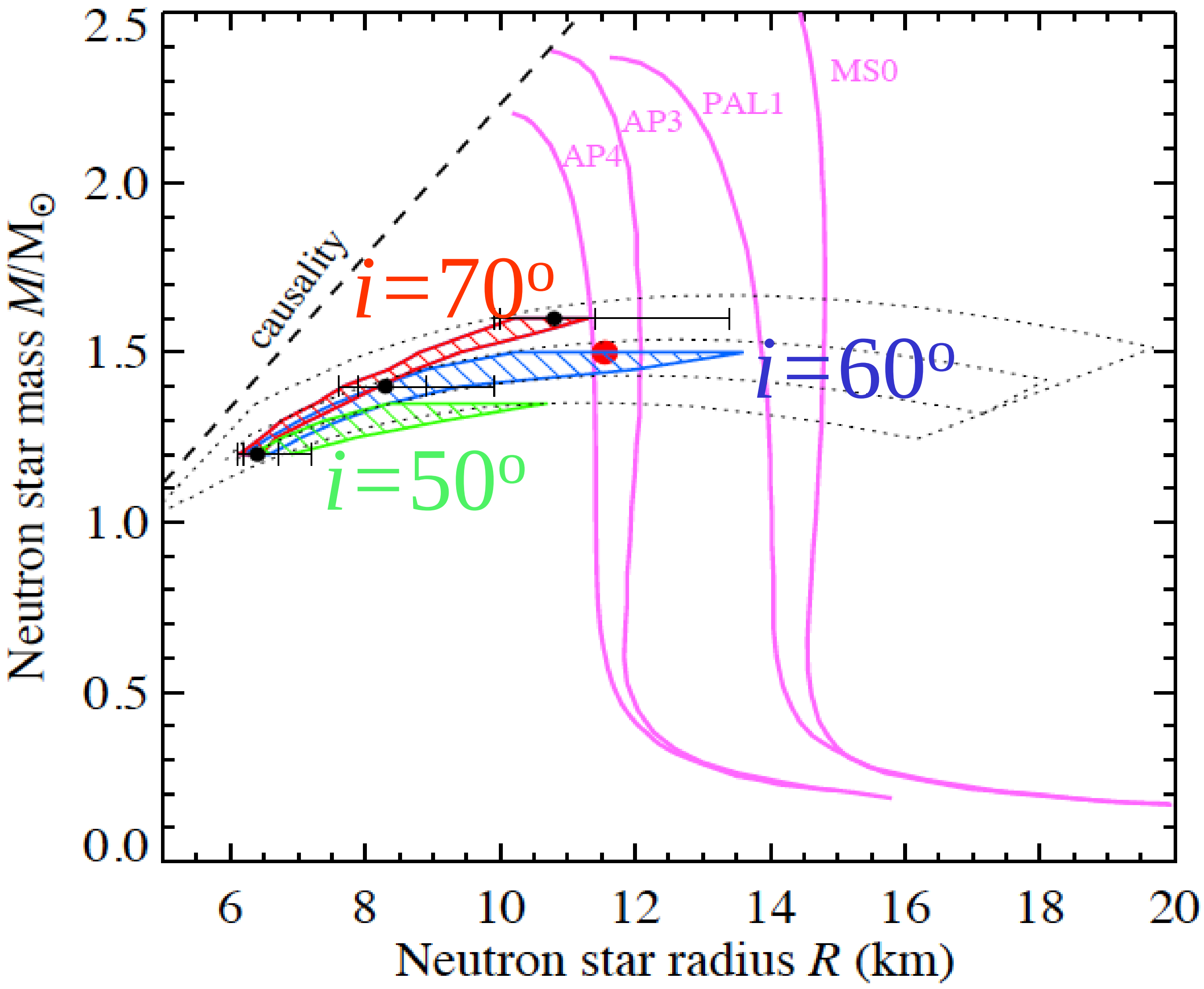
X-ray polarization

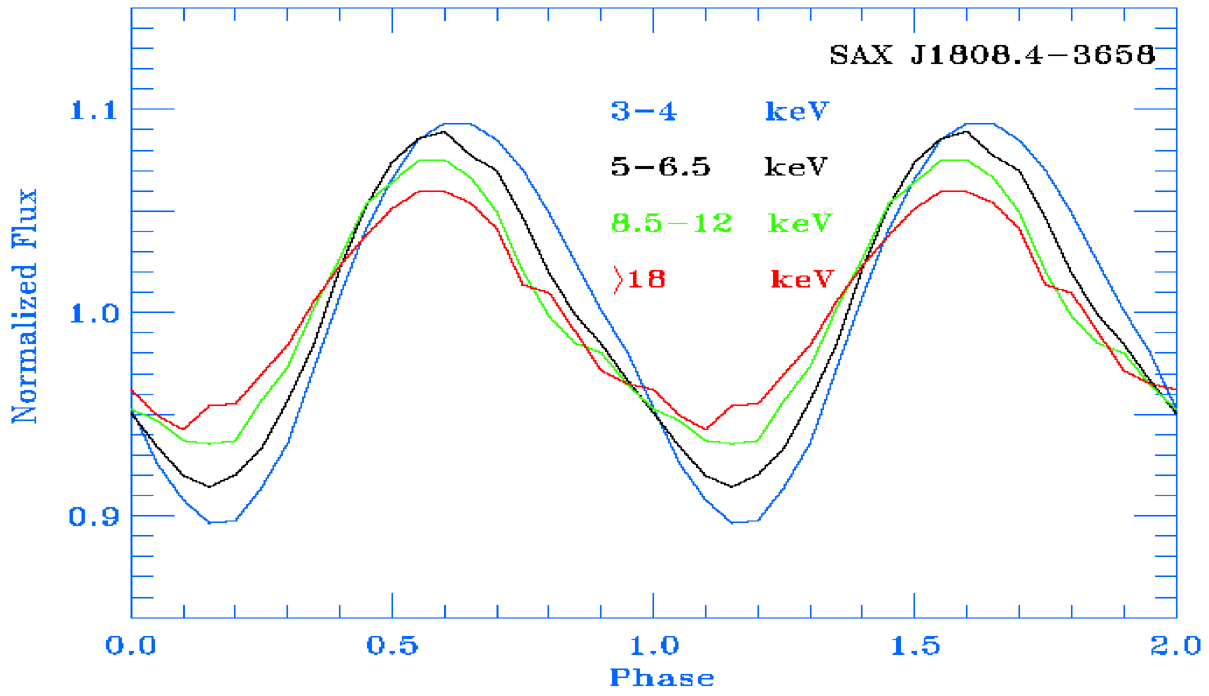
Polarization information allows to break degeneracy between



Viironen & Poutanen (2004)

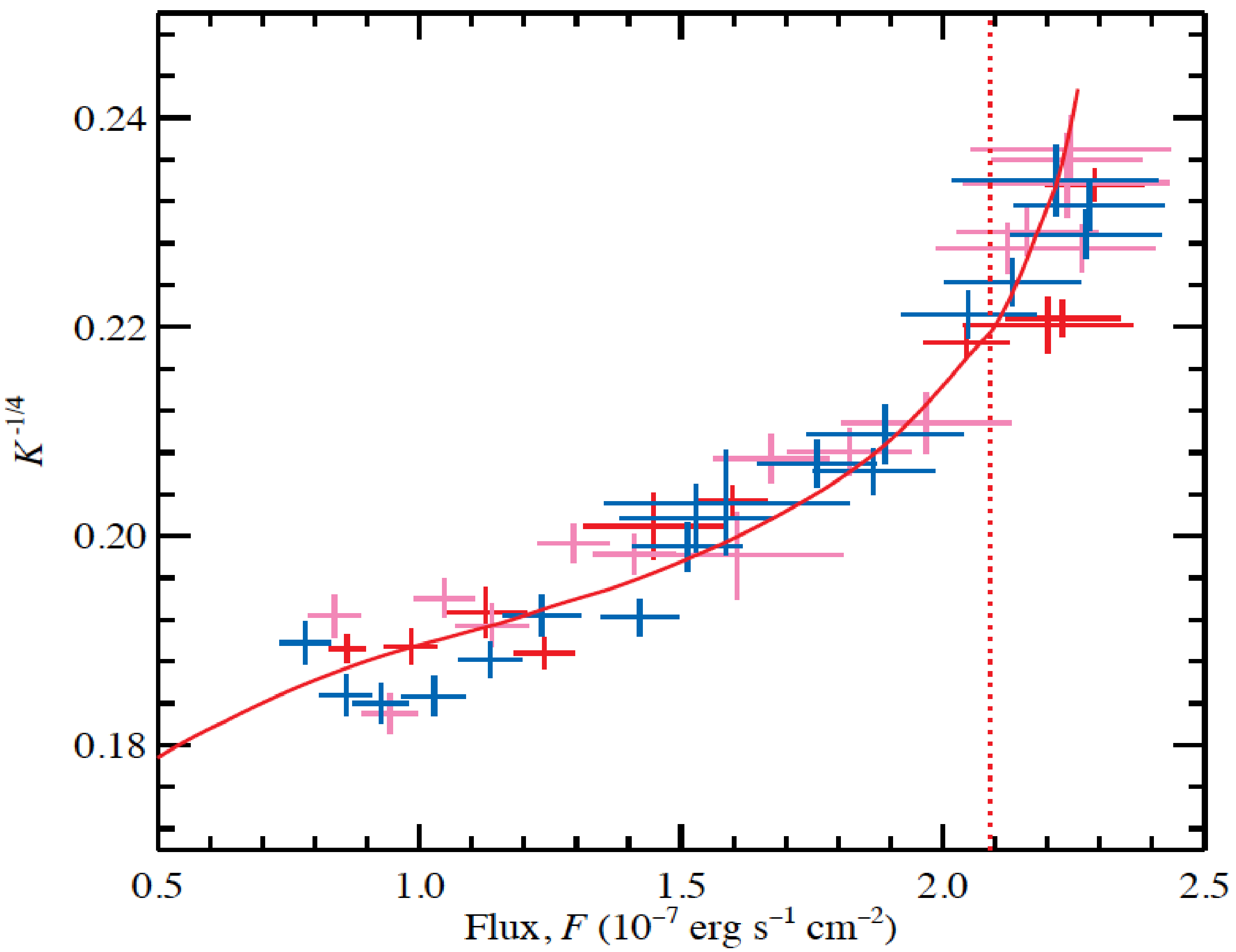
eXTP/IXPE/XIPE constraining NS EoS

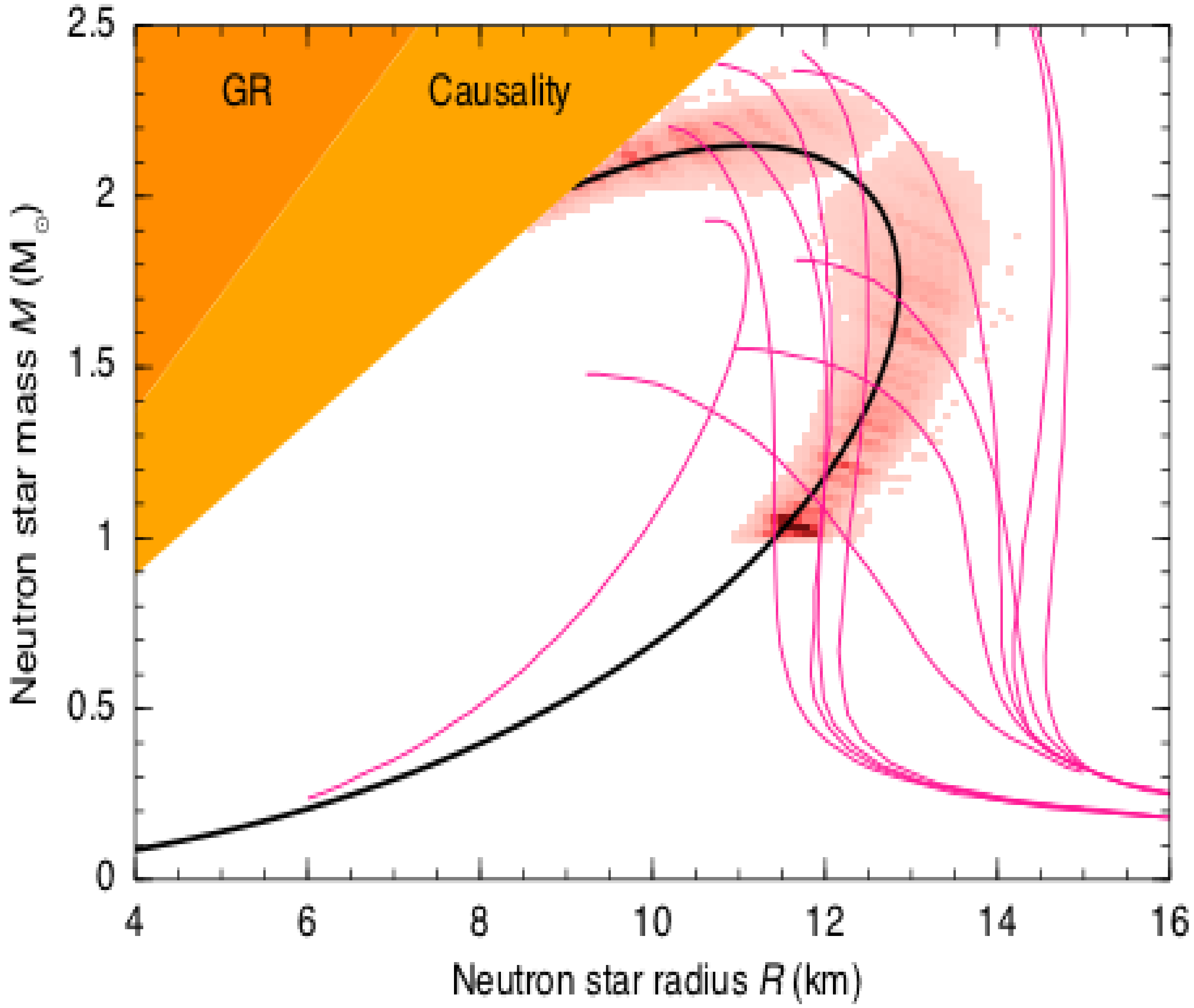




- Black dots: constraints on M/R from 2 weeks of *RXTE* data.
- Contour plots: constraints for fixed inclination obtained from the polarization data.

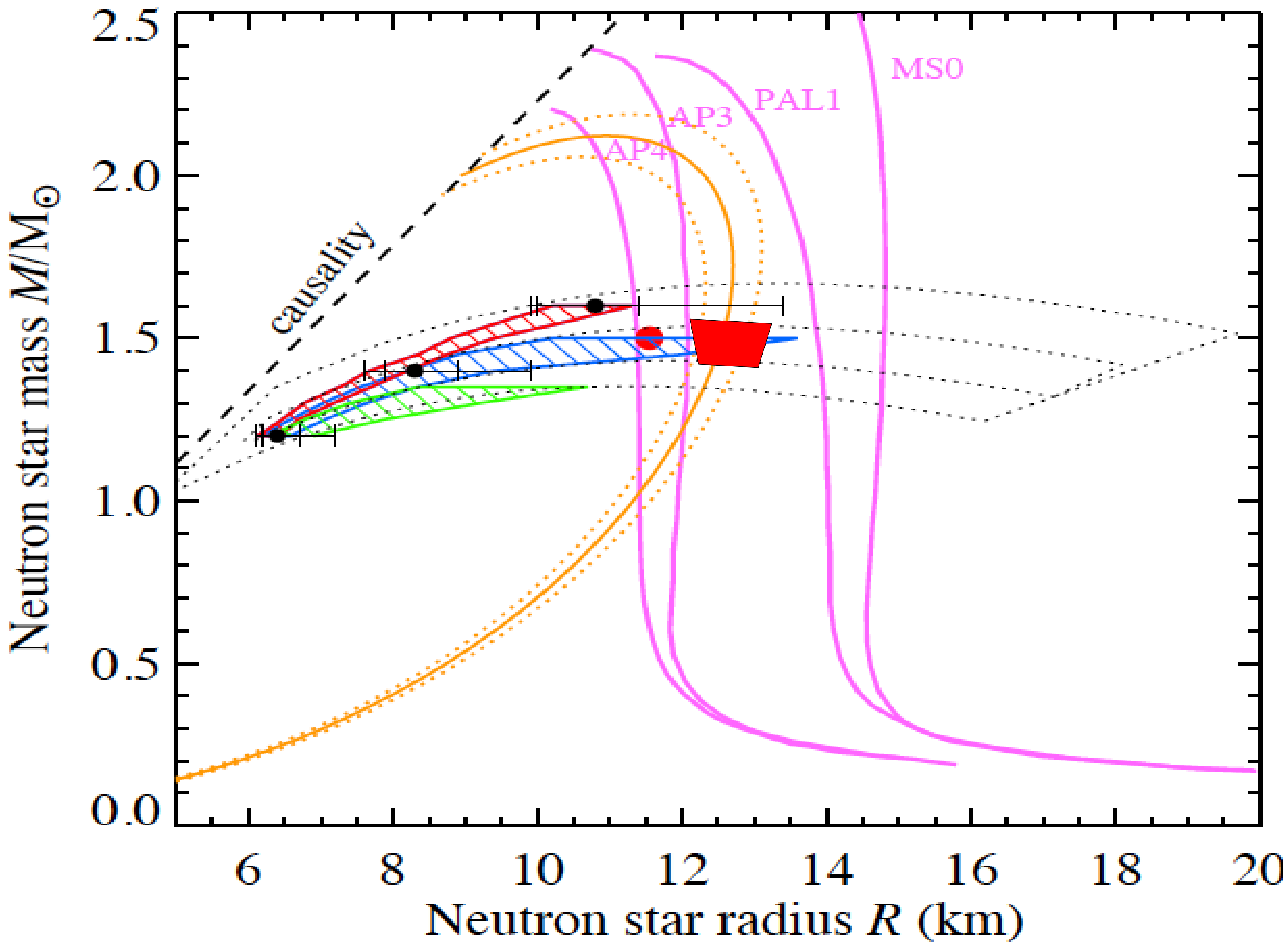
Constraints on SAX J1808.4-3658 from PRE bursts





Three PRE bursts observed by *RXTE* showing similar evolution

Combined constraints on SAX J1808.4-3658

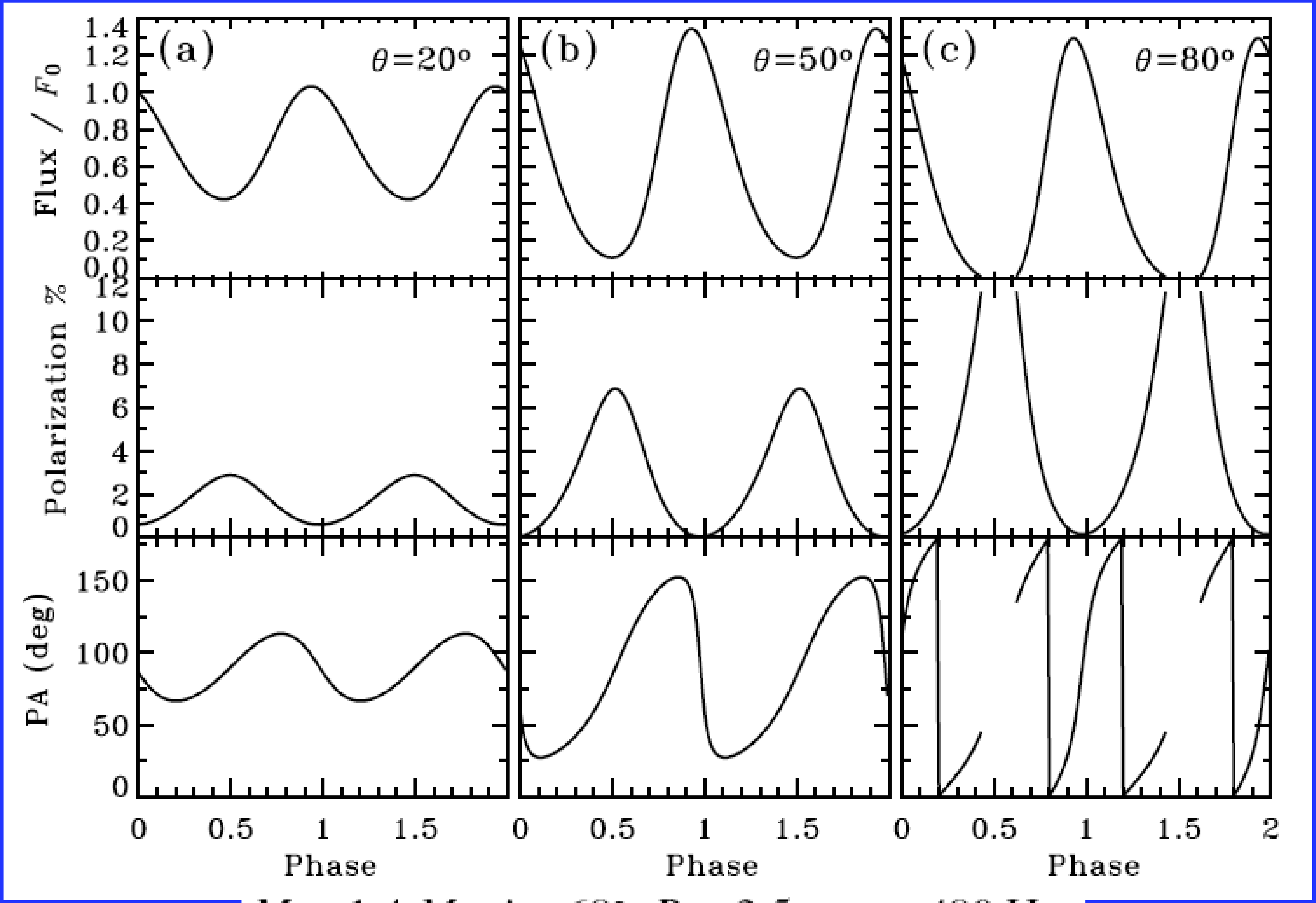


Combining pulse profiles modeling with inclination obtained from polarization and spectral evolution in PRE bursts will give very accurate determination of M-R.

Conclusions

1. Determining EoS requires not only neutron star mass M but also its radius R.
2. X-ray (thermonuclear) bursts with photospheric radius expansion are excellent tools to do the job.
3. Current burst data are consistent with the NS radii $11<R<13$ km, favoring rather stiff equation of state.
4. Pulse profiles of accreting millisecond pulsars provide perpendicular constraints on M and R.
5. X-ray polarization will allow to obtain geometrical parameters and to reduce the uncertainties.

NMSP: spectra and polarization



$M = 1.4\,M_\odot$, $i = 60°$, $R = 2.5 r_g$, $\nu = 400$ Hz.

Viironen & Poutanen 2004

- Phase dependence of polarization degree and polarization angle strongly depend on the spot position and inclination
- Oscillation amplitude together with polarization properties strongly constrain the geometry