Theoretical Approaches to Modelling the Polarization from Accreting Millisecond Pulsars

Vladislav Loktev
University of Turku, University of Helsinki

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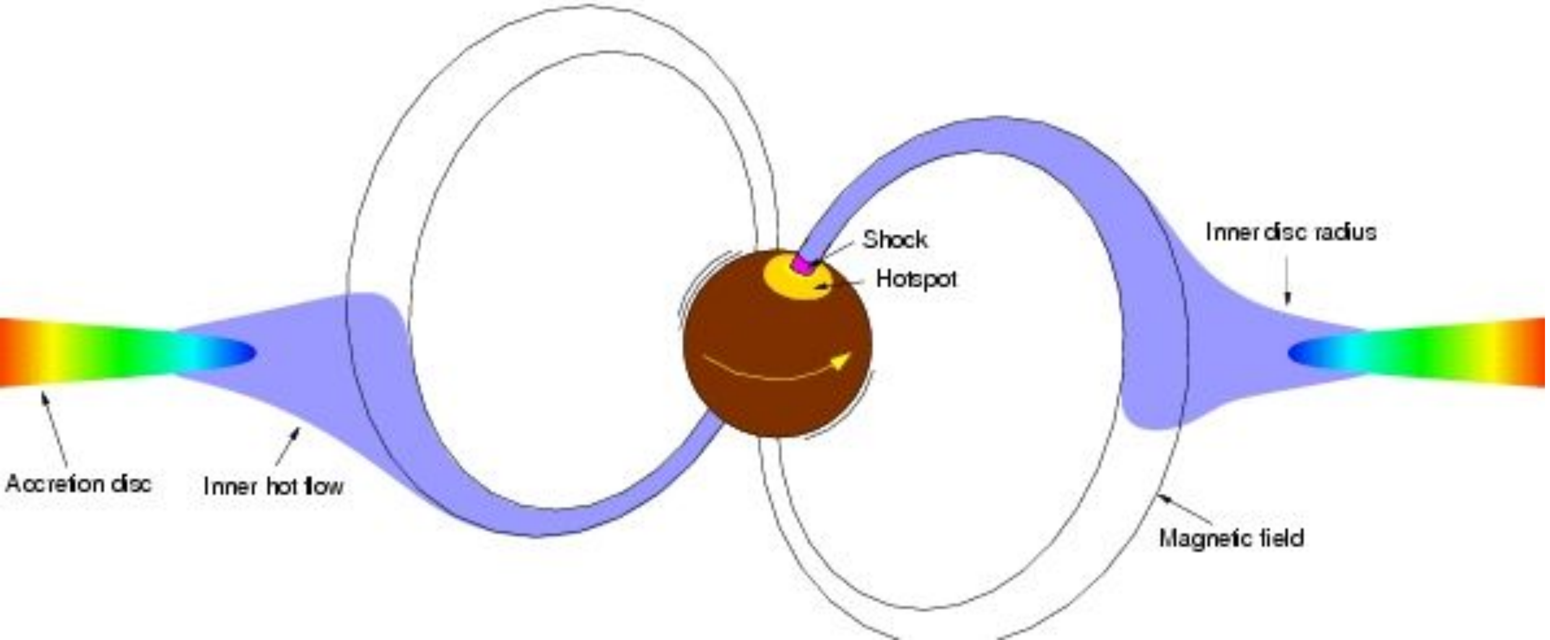
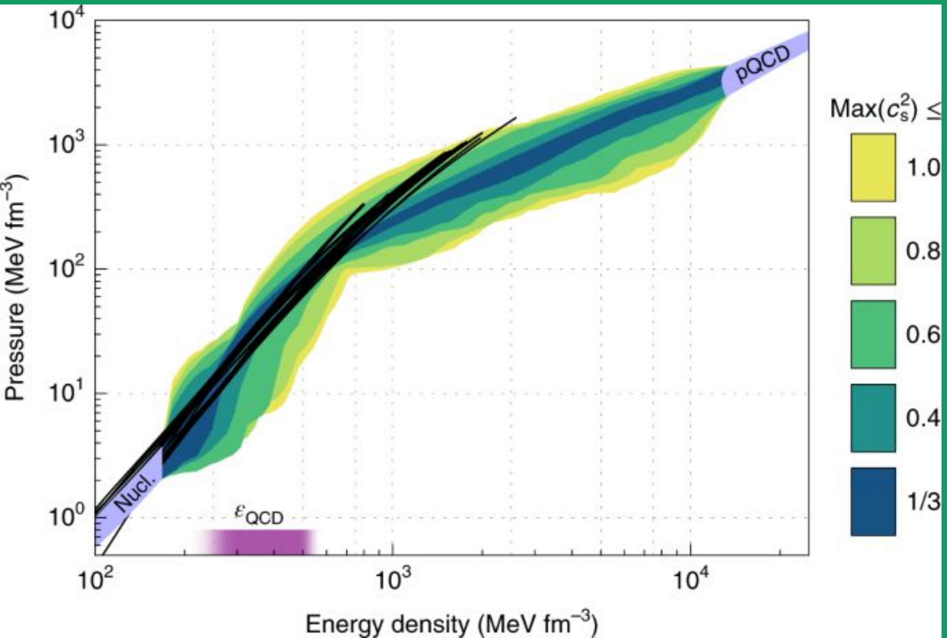
Accreting millisecond X-ray pulsars

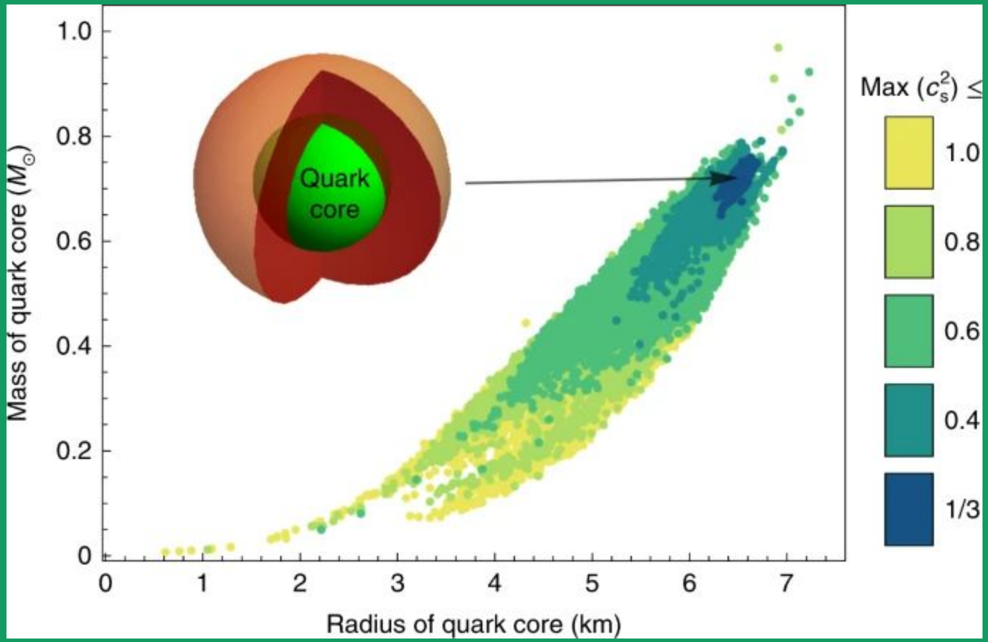
- NS in Low mass X-ray binary
- predominantly accreting matter onto magnetic poles
- The hot spots around the poles produce X-ray
- Very fast rotating causes pulsations with periods of few milliseconds



Candidates to help constraining EoS in NS core

- Millisecond pulsars exhibit strong GR effects that help constrain the size
- In binary system the mass is partly constrained from gravitational interaction with the component





To build a complete model of AMP pulse

- Understand the mechanism of X-ray emission at the surface of the NS
- Account for all relativistic effects
  - Light bending in the strong gravity
  - Doppler boosting by the relativistic rotation of the star
- Geometry of the problem
  - The shape of the emitting region
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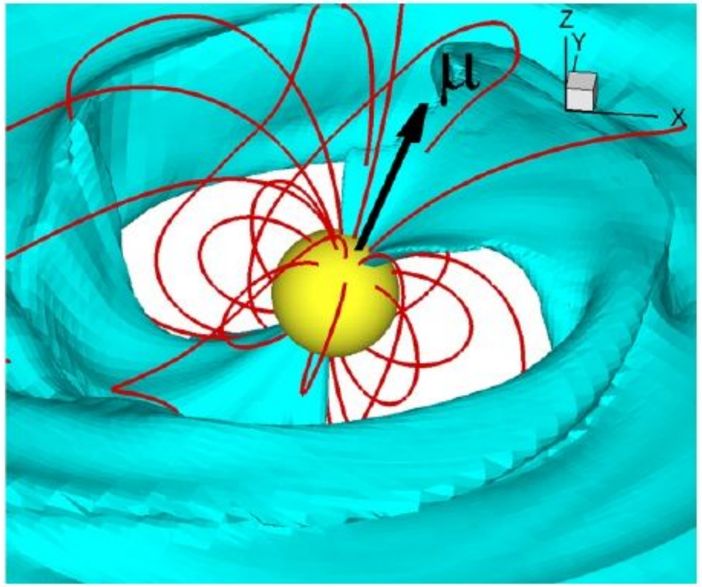
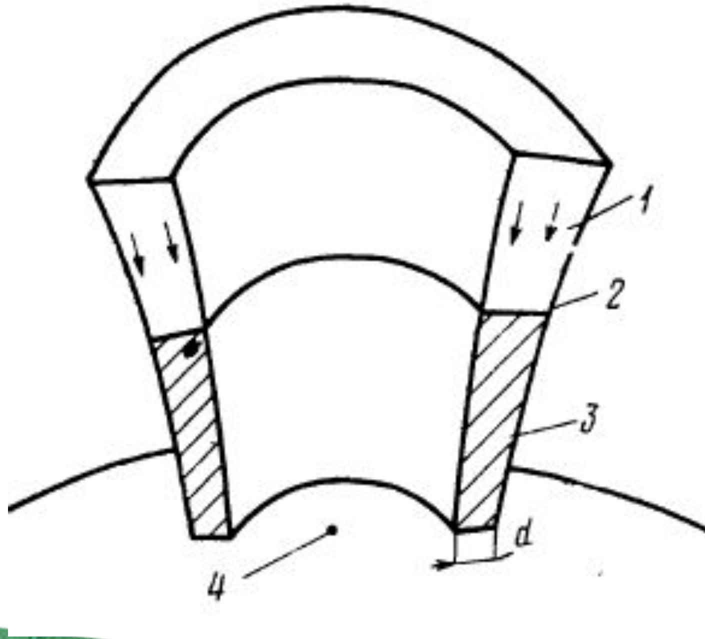
Emission region and mechanism

To build a model that accounts to all geometric and relativistic effects first and foremost we must understand the local radiation properties at the surface of the star

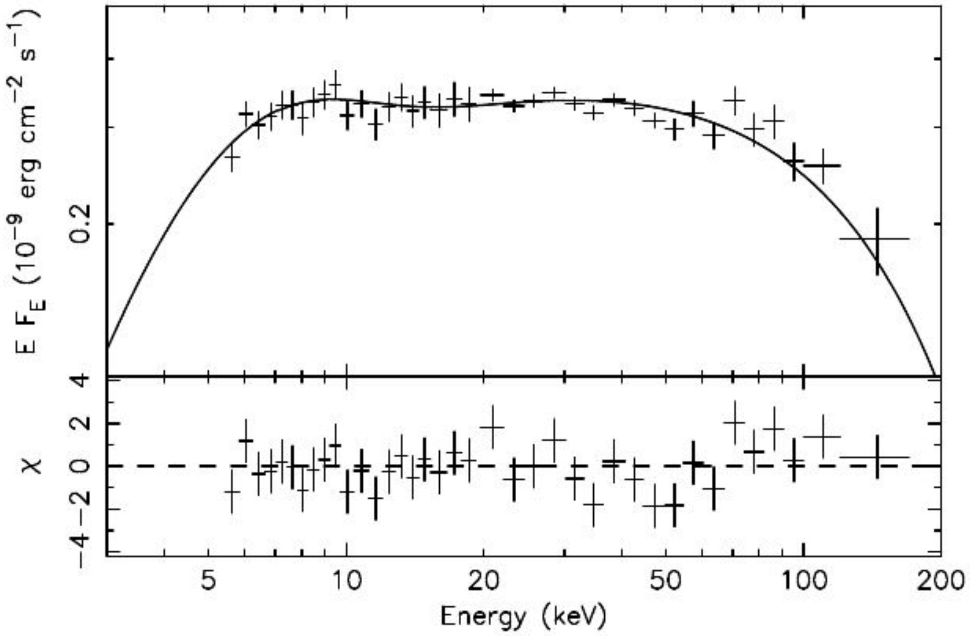


The matter piles up near the poles and forms a high temperature "shock" that produces hard X-rays through Comptonization



Comptonizing atmospheres of the hot spots

- The emission from the shock produced by thermal Comptonization of soft photons can be fitted with COMPPS model, the solution to Comptonization problem expanding over scattering orders
- But there are degeneracies in geometric parameters and spectral parameters in soft X-rays
- We then add polarization to this consideration

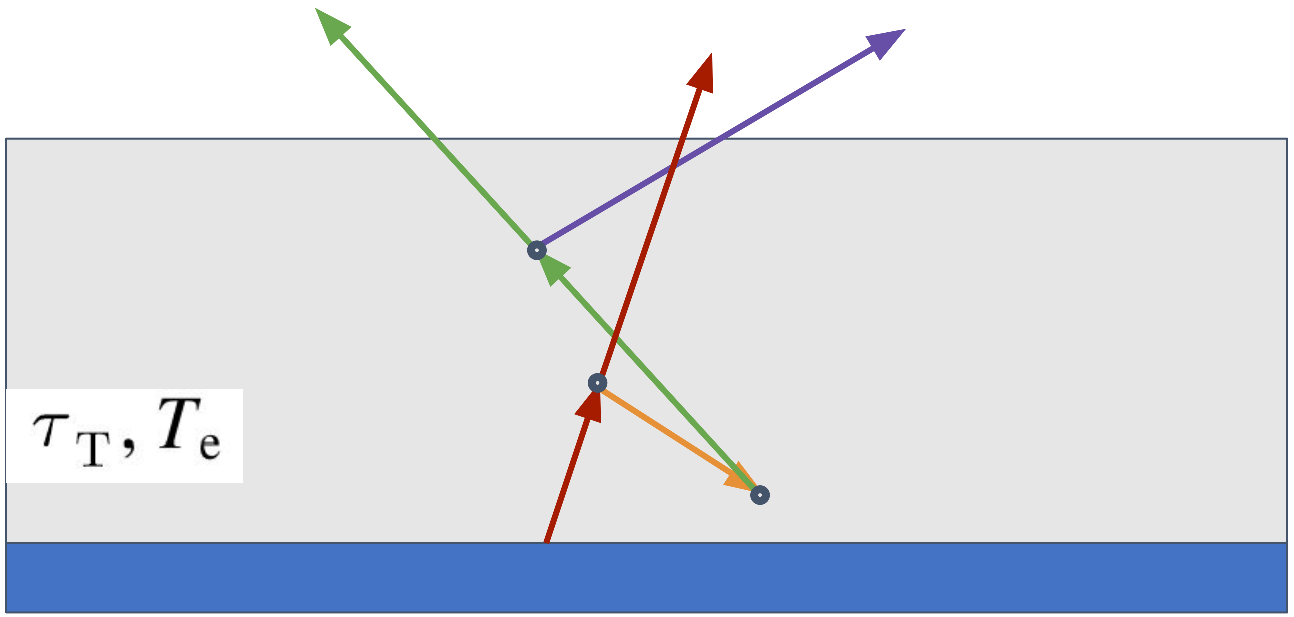


$N_{\rm H}(10^{22}{\rm cm}^{-2})$	0.28 (f)
$kT_{\rm e}$ (keV)	49^{+2}_{-6}
$kT_{\rm seed}$ (keV)	$1.49^{+0.16}_{-0.32}$
$\tau_{\rm T}$	$1.12^{+0.04}_{-0.07}$
$A^a_{\rm seed}$ (km^2)	$20.7^{+12.6}_{-4.5}$
$\cos\theta$	$0.60^{+0.06}_{-0.09}$
χ^2/dof	44/37
$L^a_{1-300\,{\rm keV}}$ (10^{36} erg s^{-1})	3.7

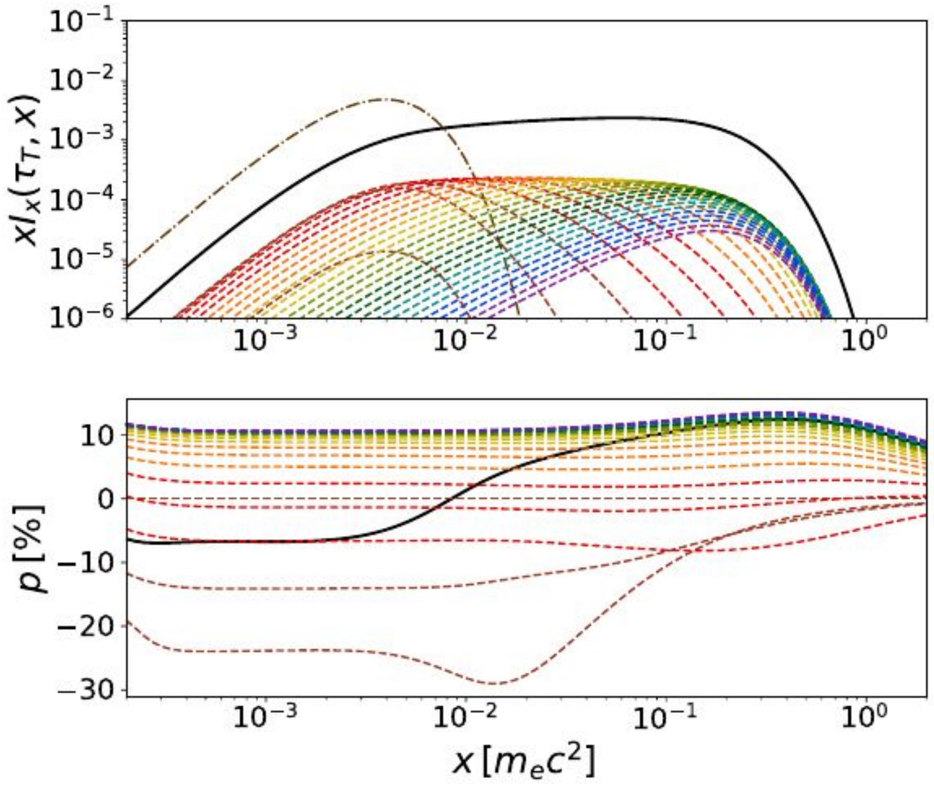
e.g. Falanga et al. 2005

Radiative transfer in the slab

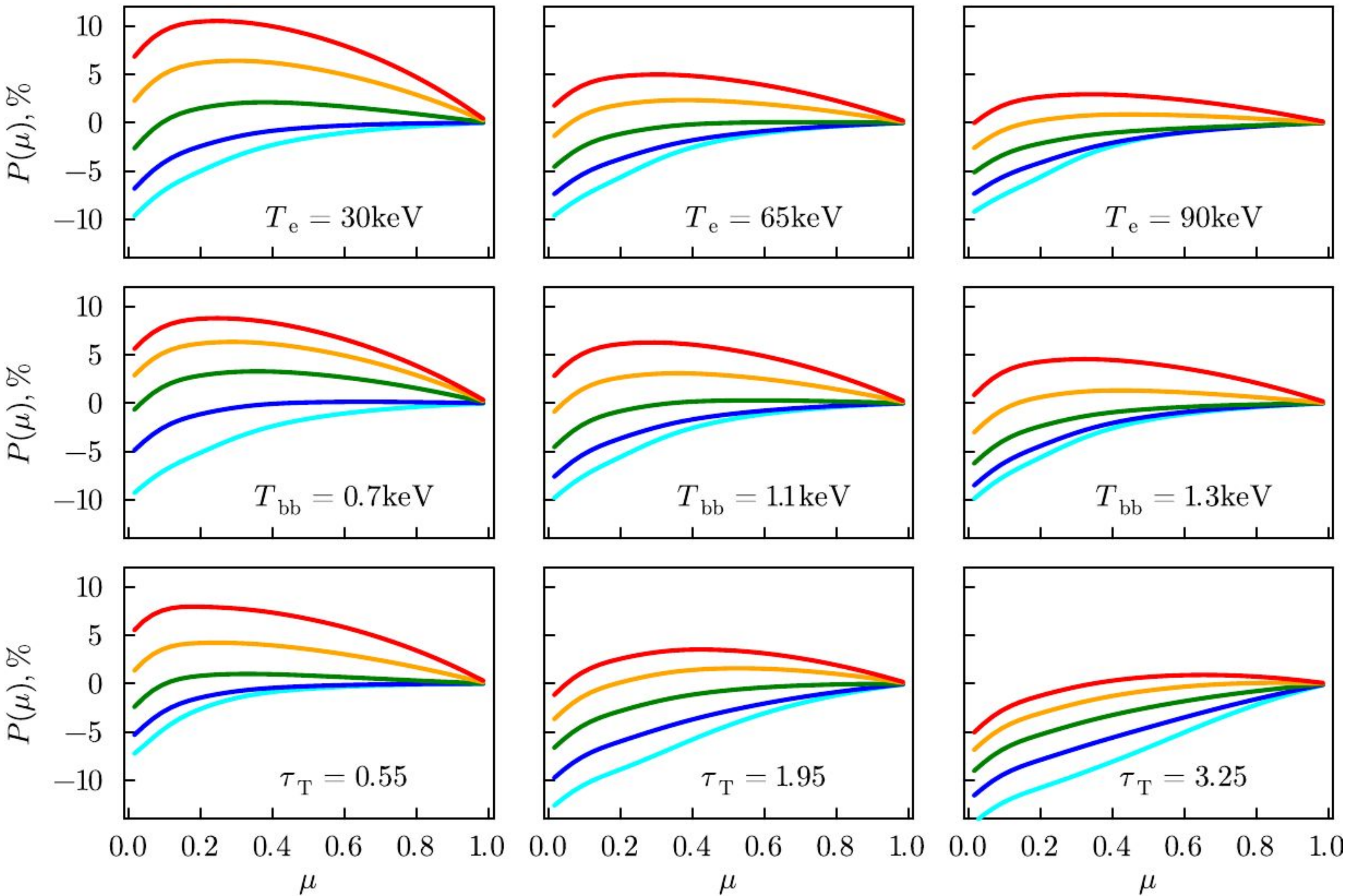
- Electrons scatter off hot electrons
- On average they gain energy
- And get polarized in the process



$$\mu \frac{\mathrm{d}\boldsymbol{I}(\tau, x, \mu)}{\mathrm{d}\tau} = -\sigma(x)\boldsymbol{I}(\tau, x, \mu) + \boldsymbol{S}(\tau, x, \mu),$$



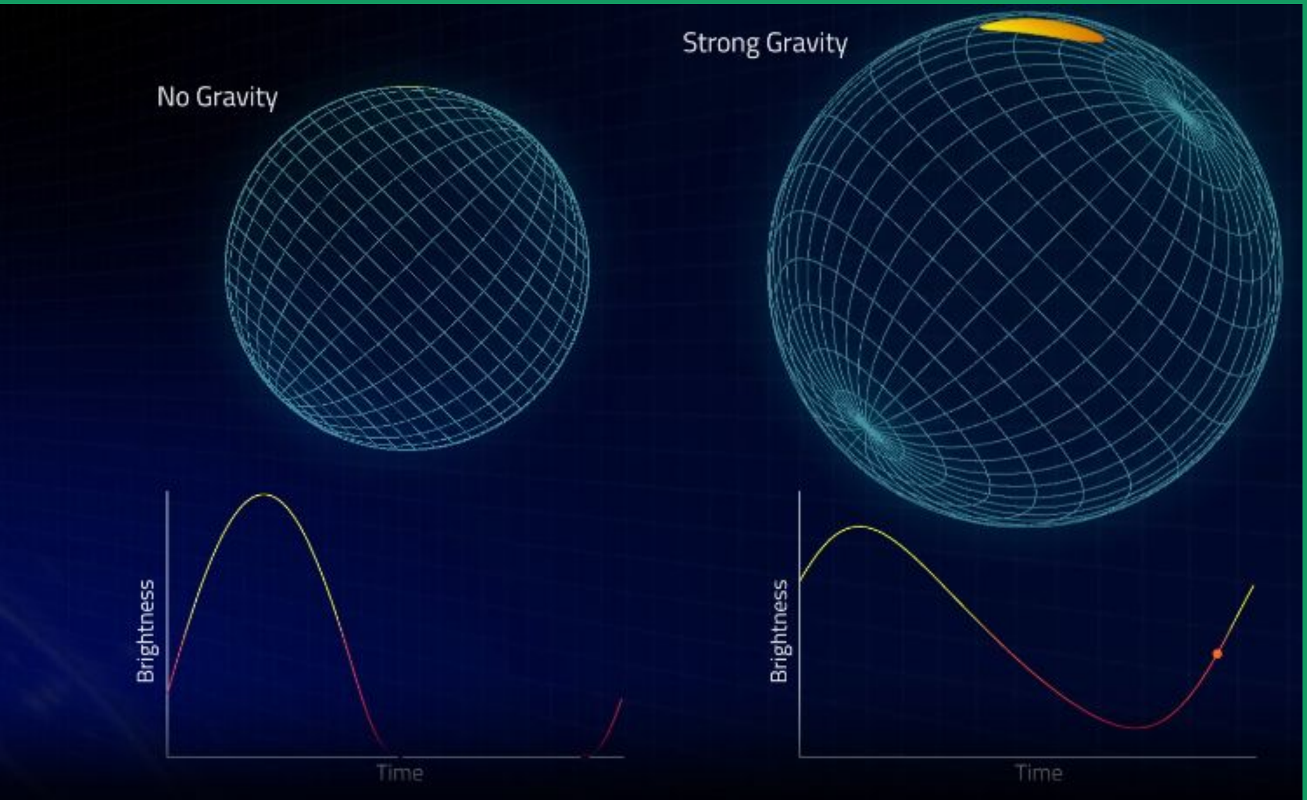
Resulting Comptonized spectrum model

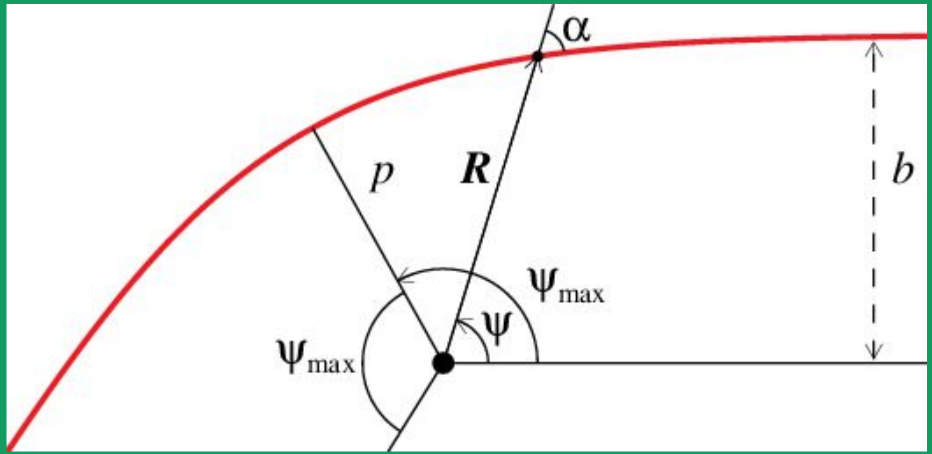


e.g. Bobrikova et al. 2023

Relativistic effects

- Light bending in strong gravity (adds the information about te compactness of the Neutron star into the pulse profile)
- We can use Schwarzschild metric to account for it



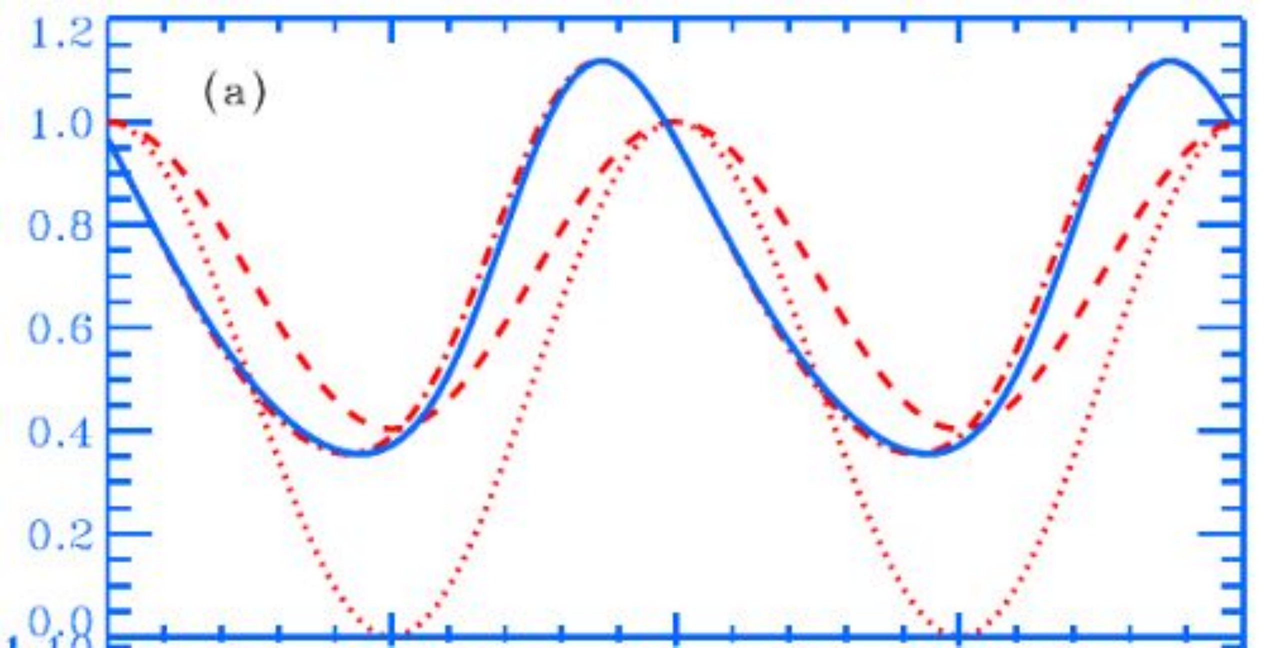


- Light trajectories are planar and polarization conserves

[NASA]

Relativistic effects

- Doppler boosting by relativistic motion of the surface (adds more information about the size of the star to the pulse profile)
- Further affects the pulse profile and also affects polarization through the change of the emission angle
- For fastest pulsars the equatorial surface velocity may reach 10-20% speed of light



- Time lags also make a small contribution

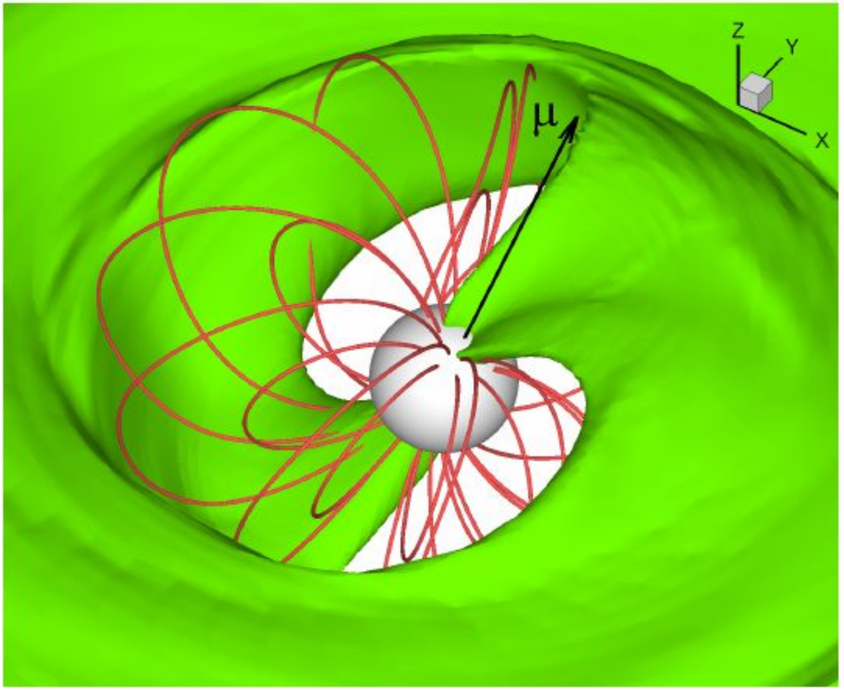
e.g. Poutanen 2006

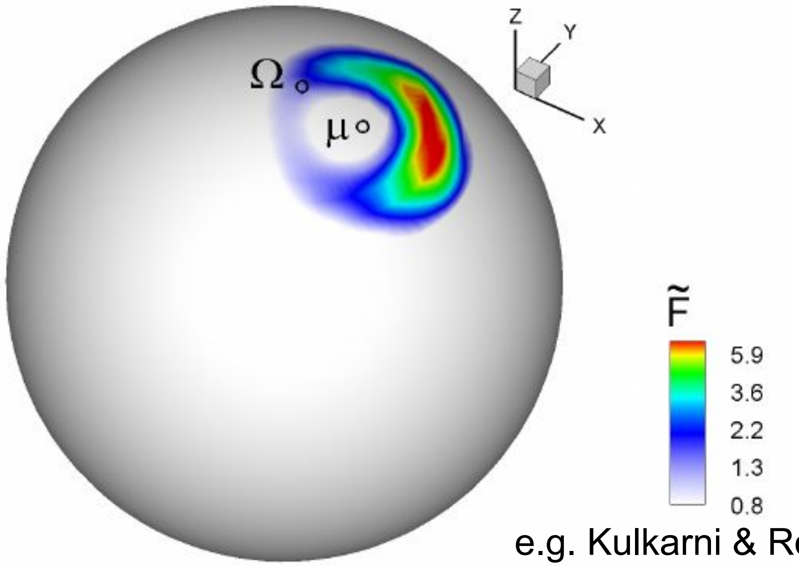
The shape of the spot

The simplest case of a circular spot is usually considered.

Simulation show how the shape of the spot can vary with magnetic obliquity

This can slightly affect the shape of the pulse

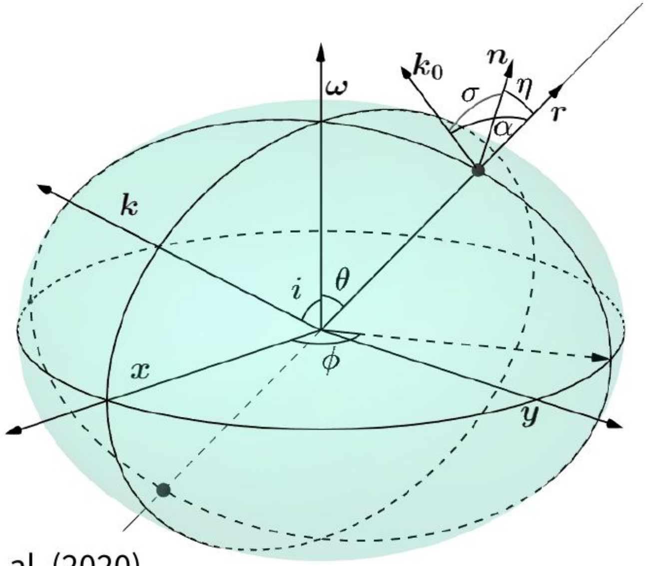




e.g. Kulkarni & Romanova 2013

The shape of the star

Millisecond period rotation causes the star to flatten under the influence of centrifugal forces.



Loktev, V., et. al. (2020)

The shape of a neutron star

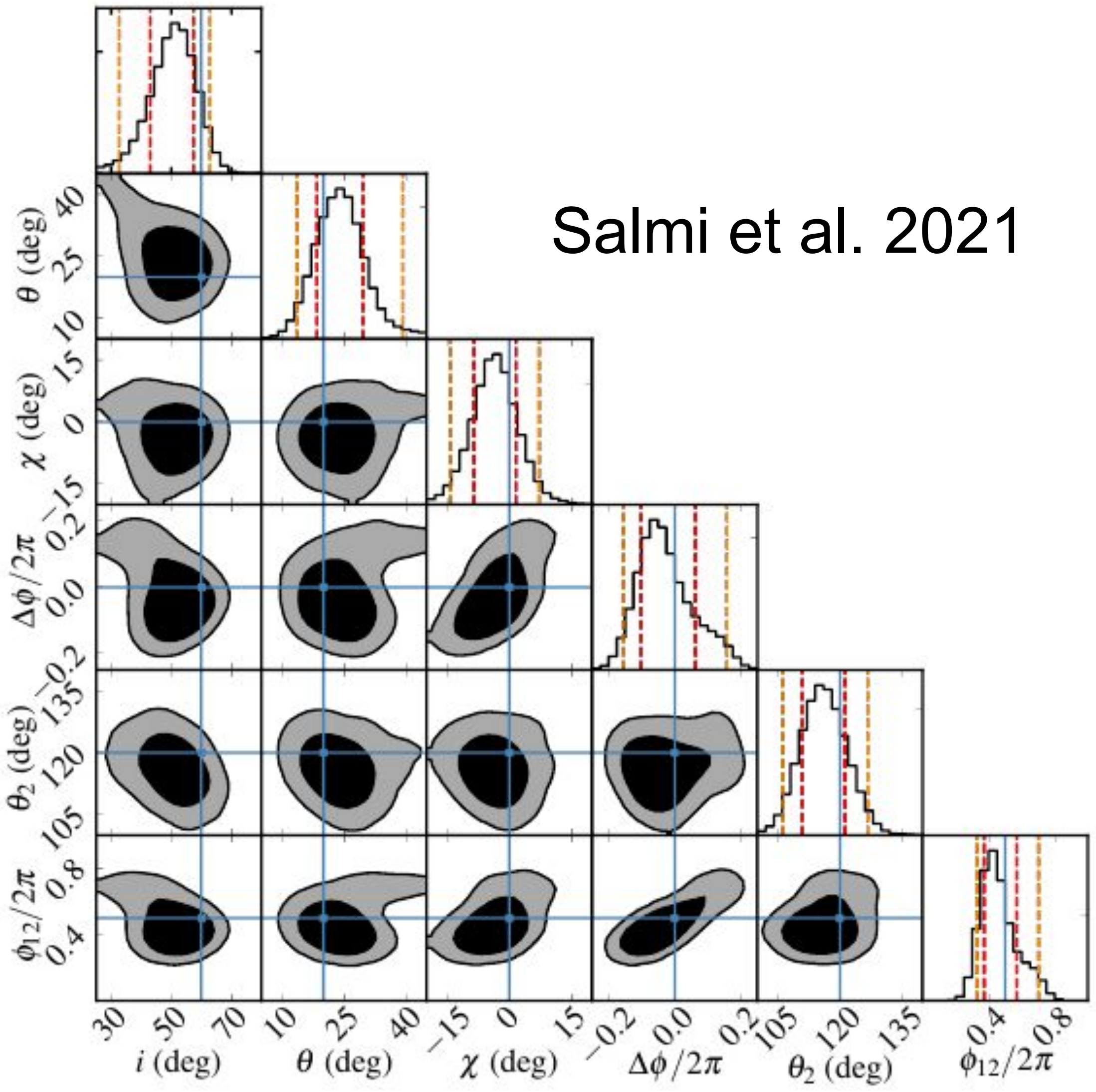
$$R(\theta) = R_e \left(1 + o_2(x, \bar{\Omega}) \cos^2 \theta\right)$$

see AlGendy & Morsink 2014

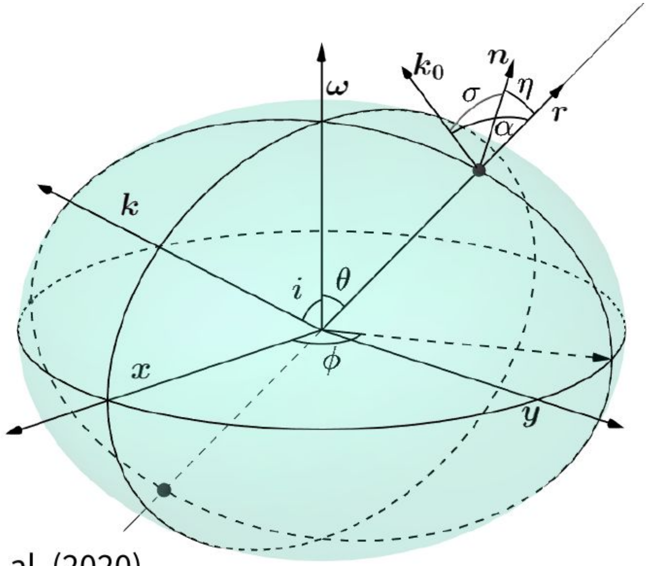
The shape of the star

Millisecond period rotation causes the star to flatten under the influence of centrifugal forces.

This introduces <u>biases</u> to location of the hot spots as opposed to spherical shape



Salmi et al. 2021



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The shape of a neutron star

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- Emission from the disk, other components of the accretion flow, (see Dorsman et al. 2025)
- Additional scatterings in the accretion funnel (see Ahlberg et al. 2024)