# Evaluating the Influence of Light-Bending in the Timing Analysis of Soft X-ray Pulses from Magnetars

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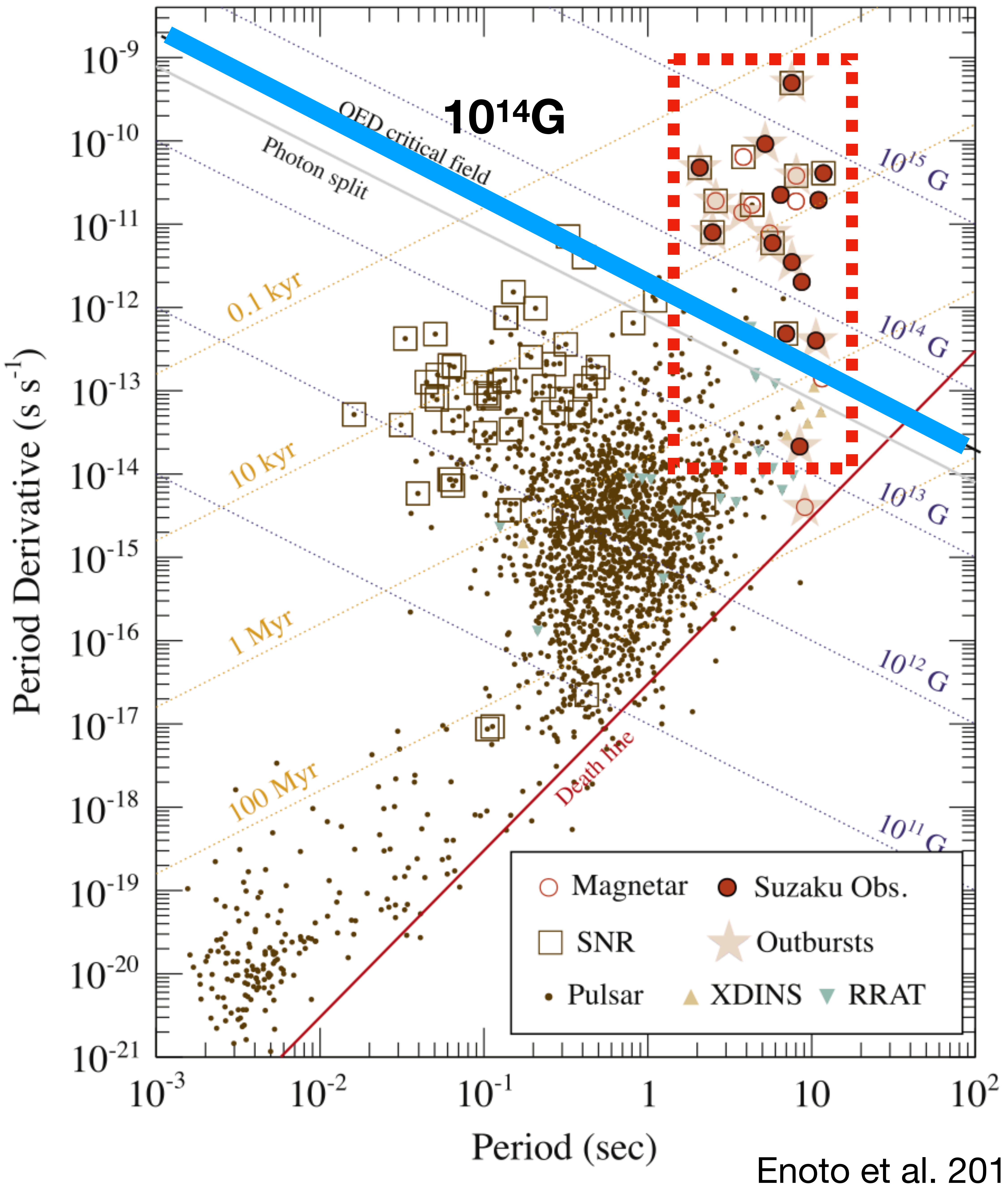
# Magnetars (SGR/AXP)

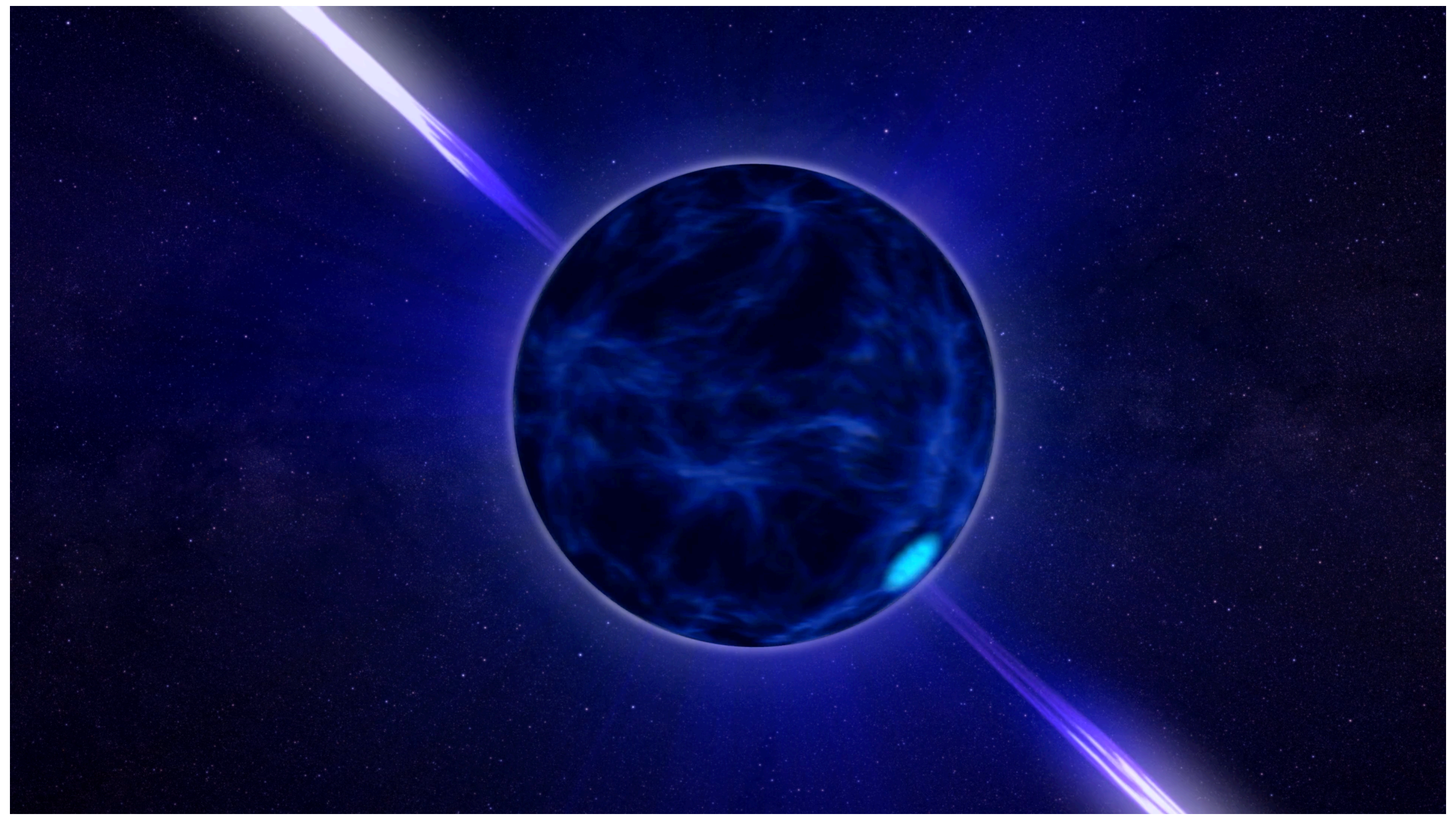
- $L_X \sim 10^{33} - 10^{35}$ erg/s $> \dot{E}_{rot}$
- Long period & Fast decay
  $P \sim$ 2-12s $\quad \dot{P} \sim 10^{-13}$-$10^{-10}$ s/s
- Strong magnetic field
  $B_{surf} \sim 10^{14}$ G - $10^{15}$ G
- 30+ confirmed

P-Pdot Diagram



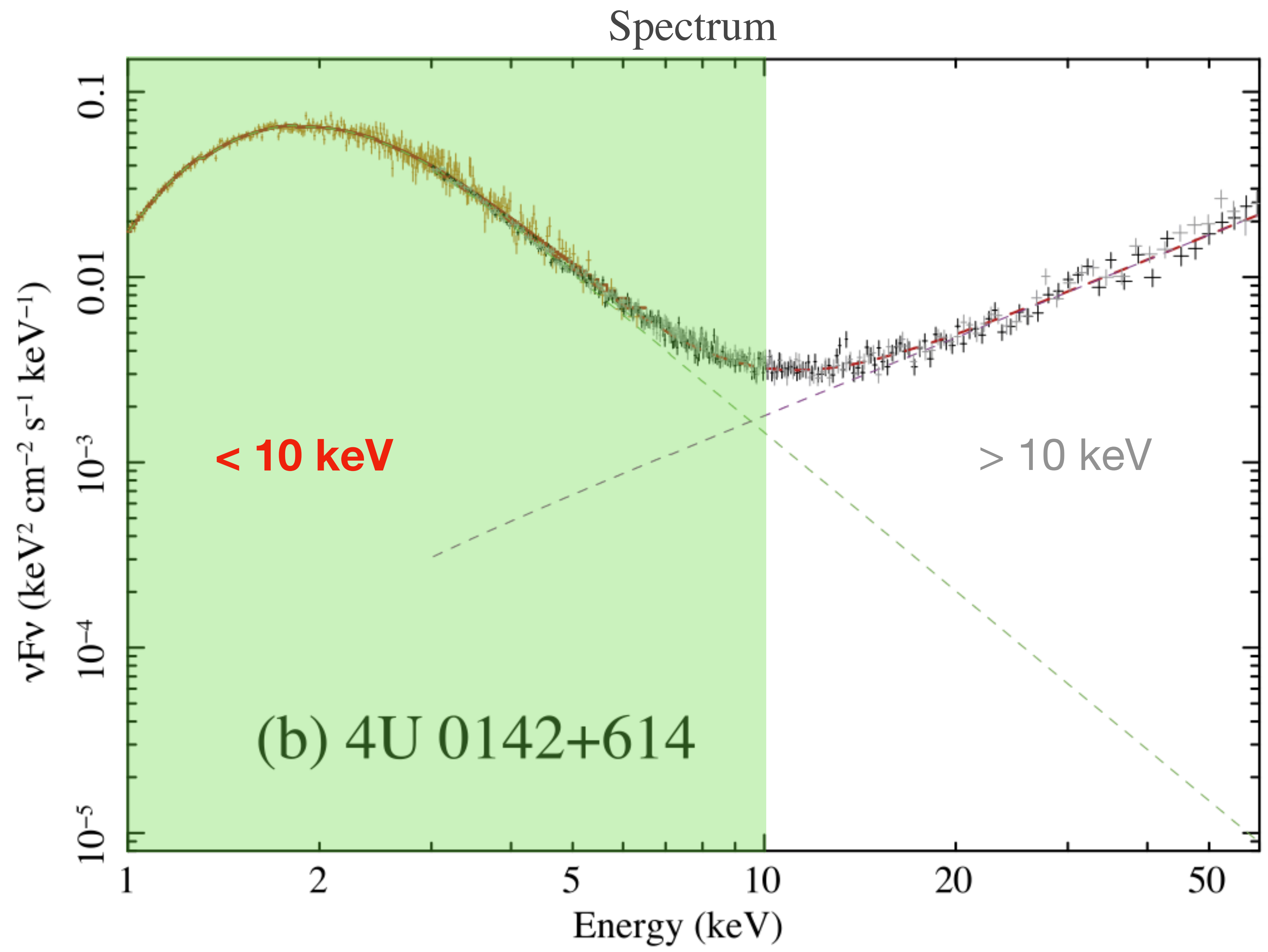

Enoto et al. 2017

# X-ray emission of Magnetars



## Soft X-ray Component (SXC)

From hot NS surface

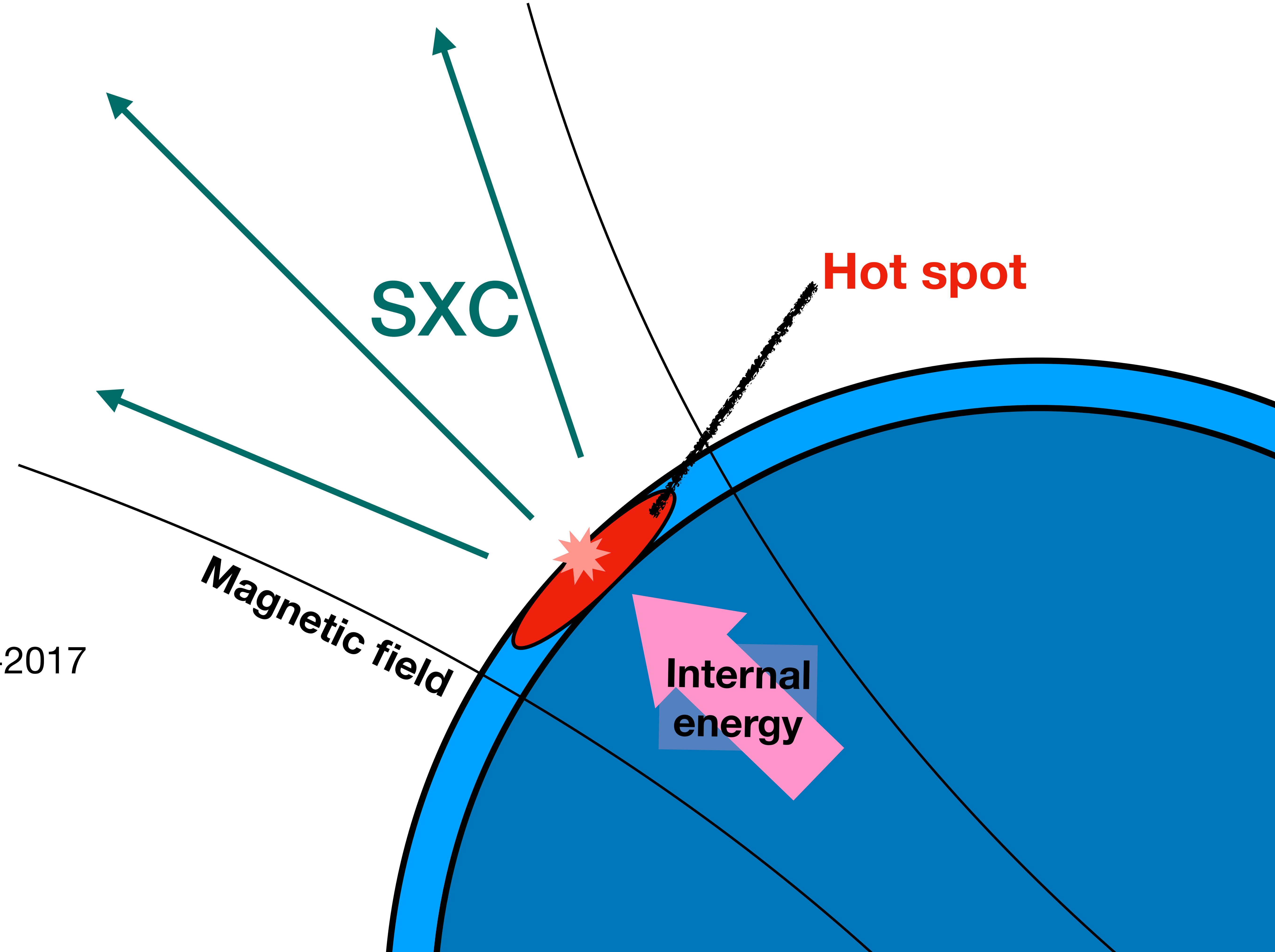



Enoto+2017

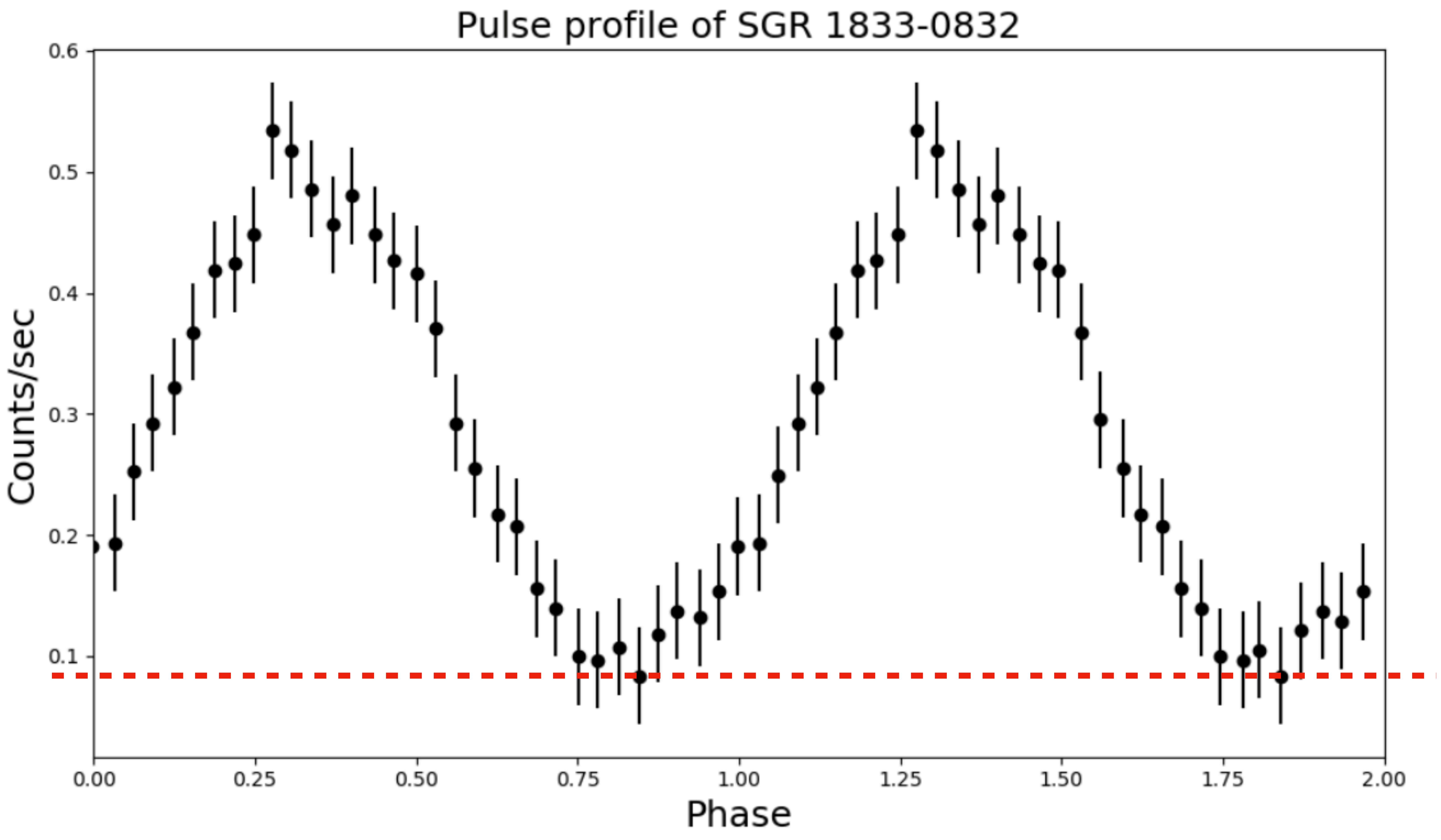
Distribution of hotspot

↓

Distribution of magnetic field

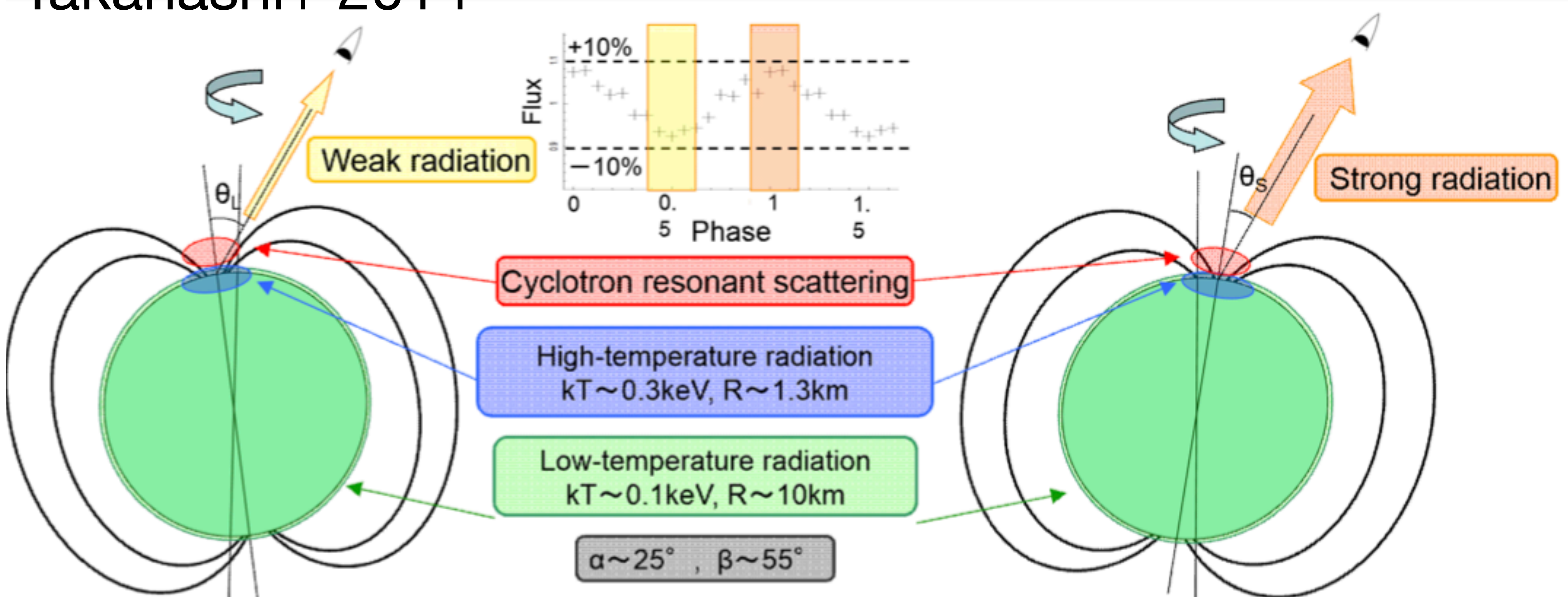


# How to explain the offset? SGR 1833-0832

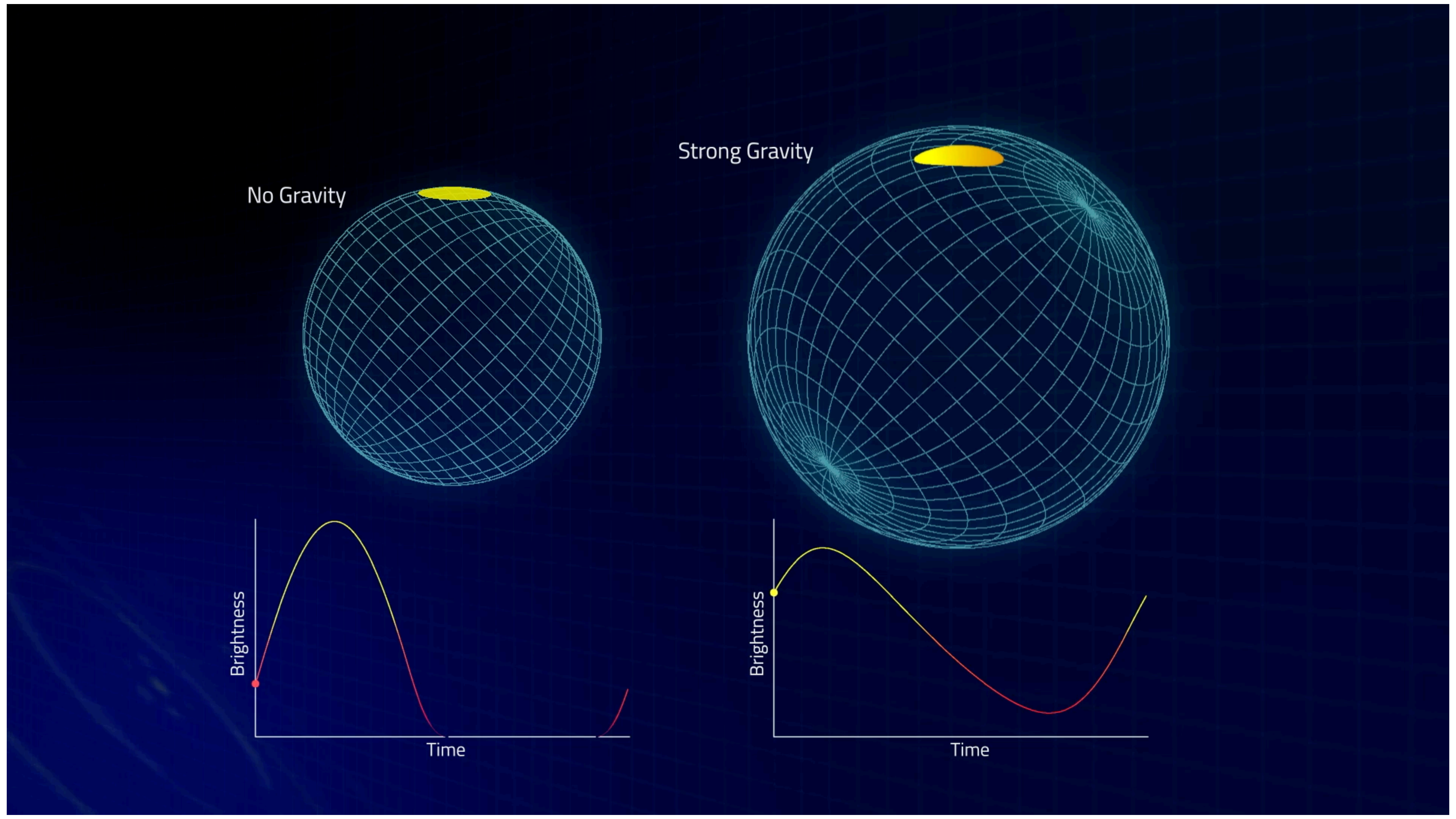


# How to explain the offset? SGR 1833-0832

Takahashi+ 2014




Credits: NASA NICER Group



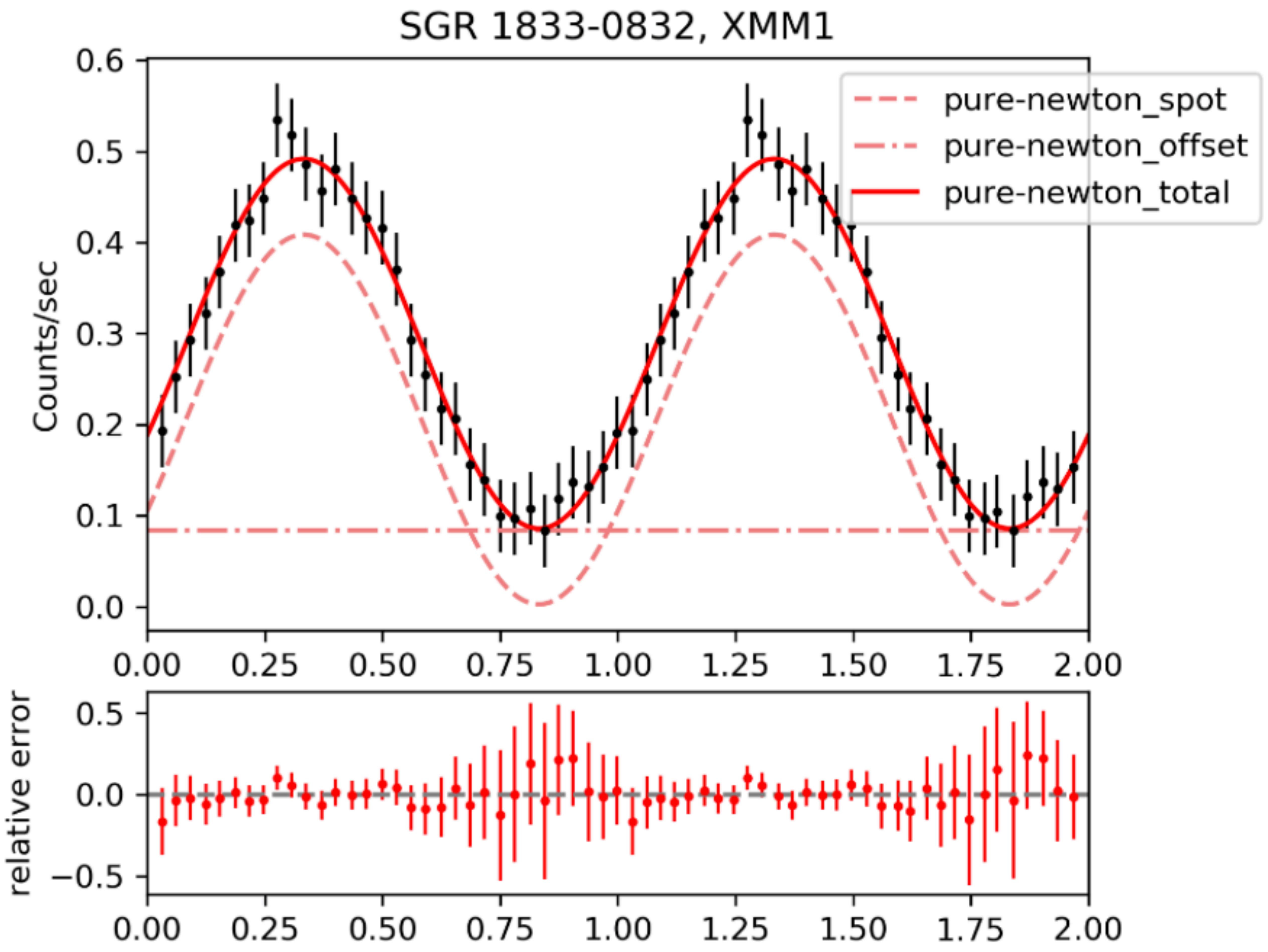

**Hot spot + Emission from entire surface**

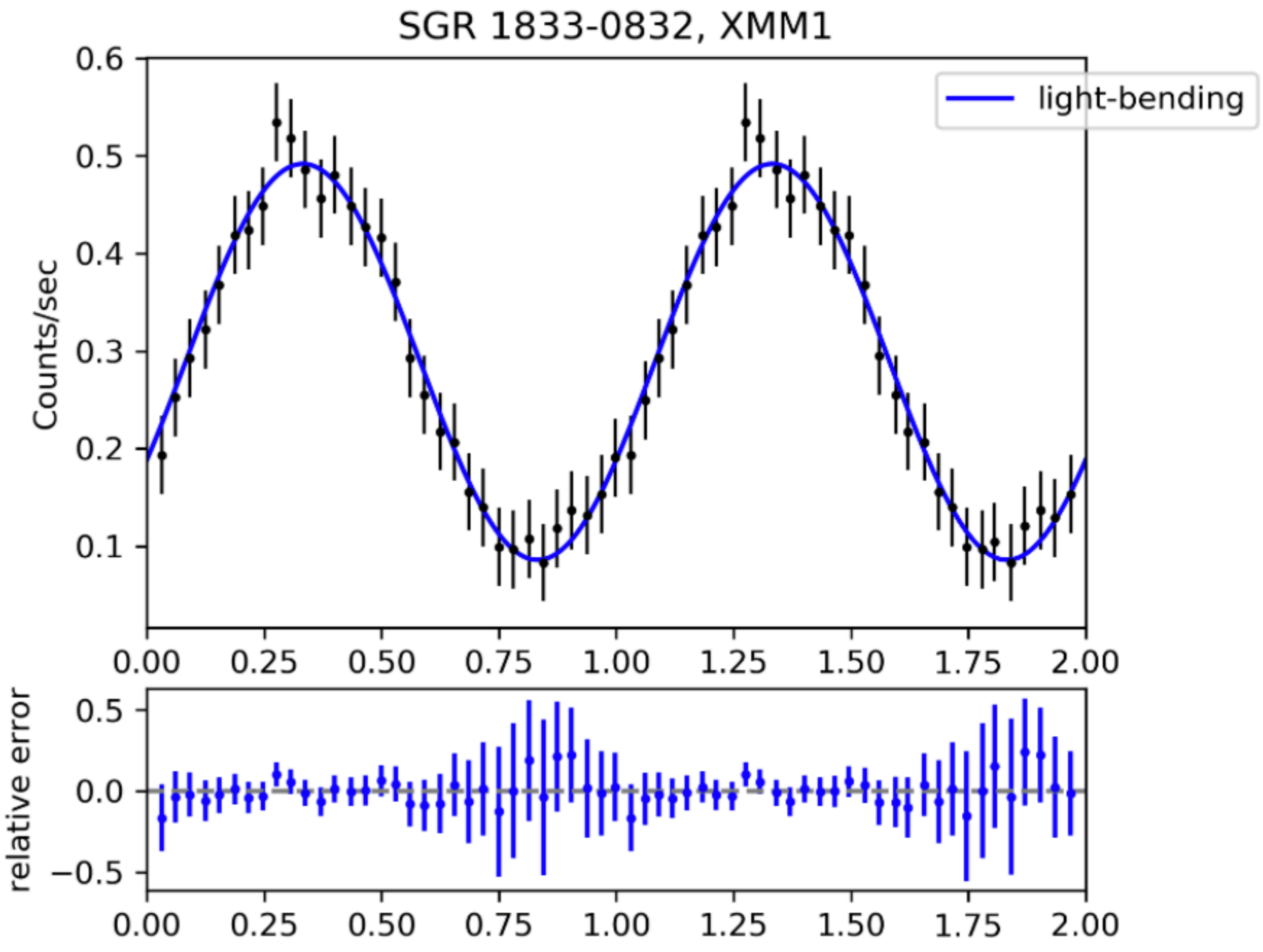
**Newtonian**

**Hot spot only**

**Light bending**

# How to explain the offset? SGR 1833-0832



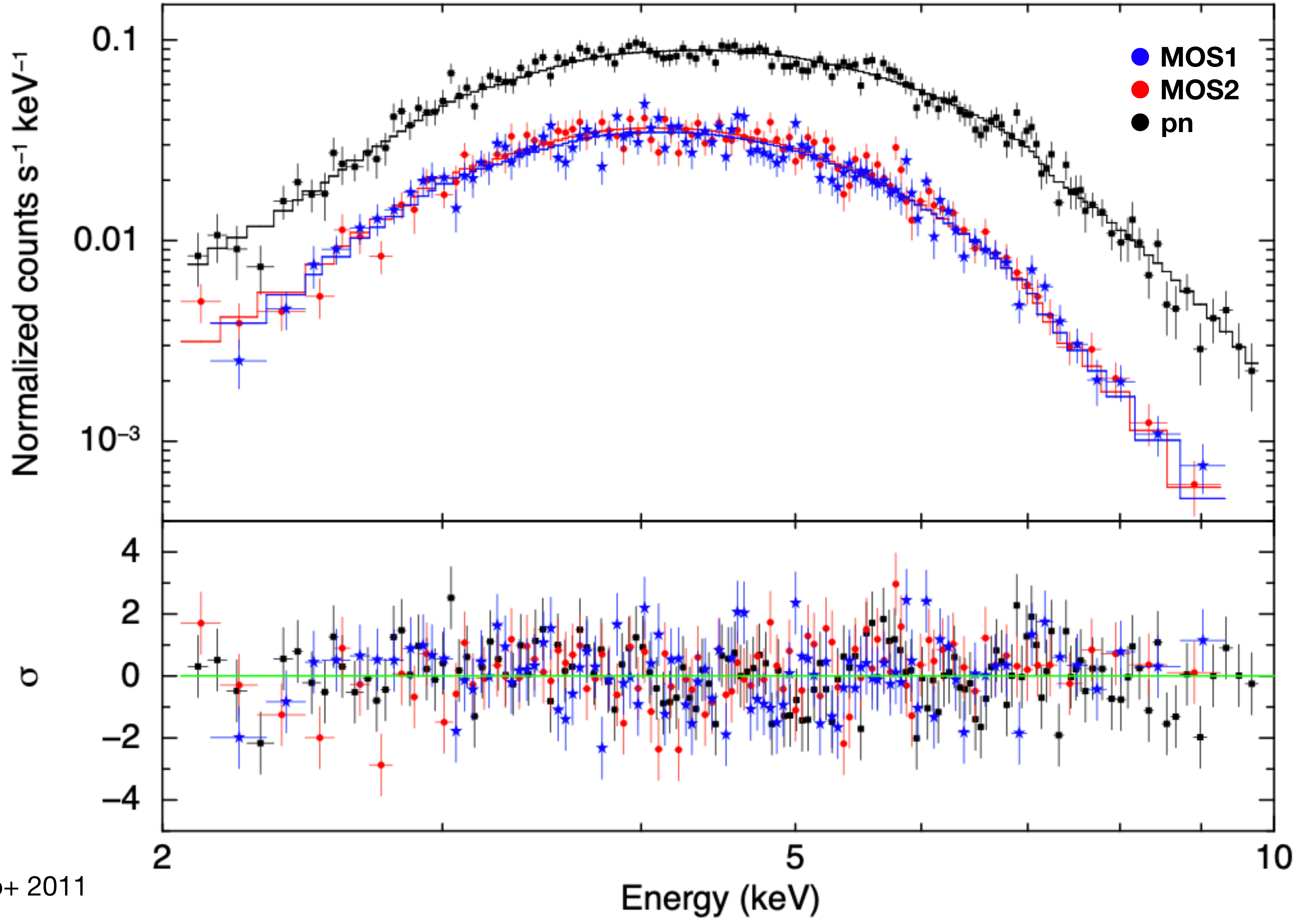

**Hot spot＋Emission from entire surface**

**Newtonian**

**Hot spot only**

**Light bending**

# How to explain the offset? SGR 1833-0832

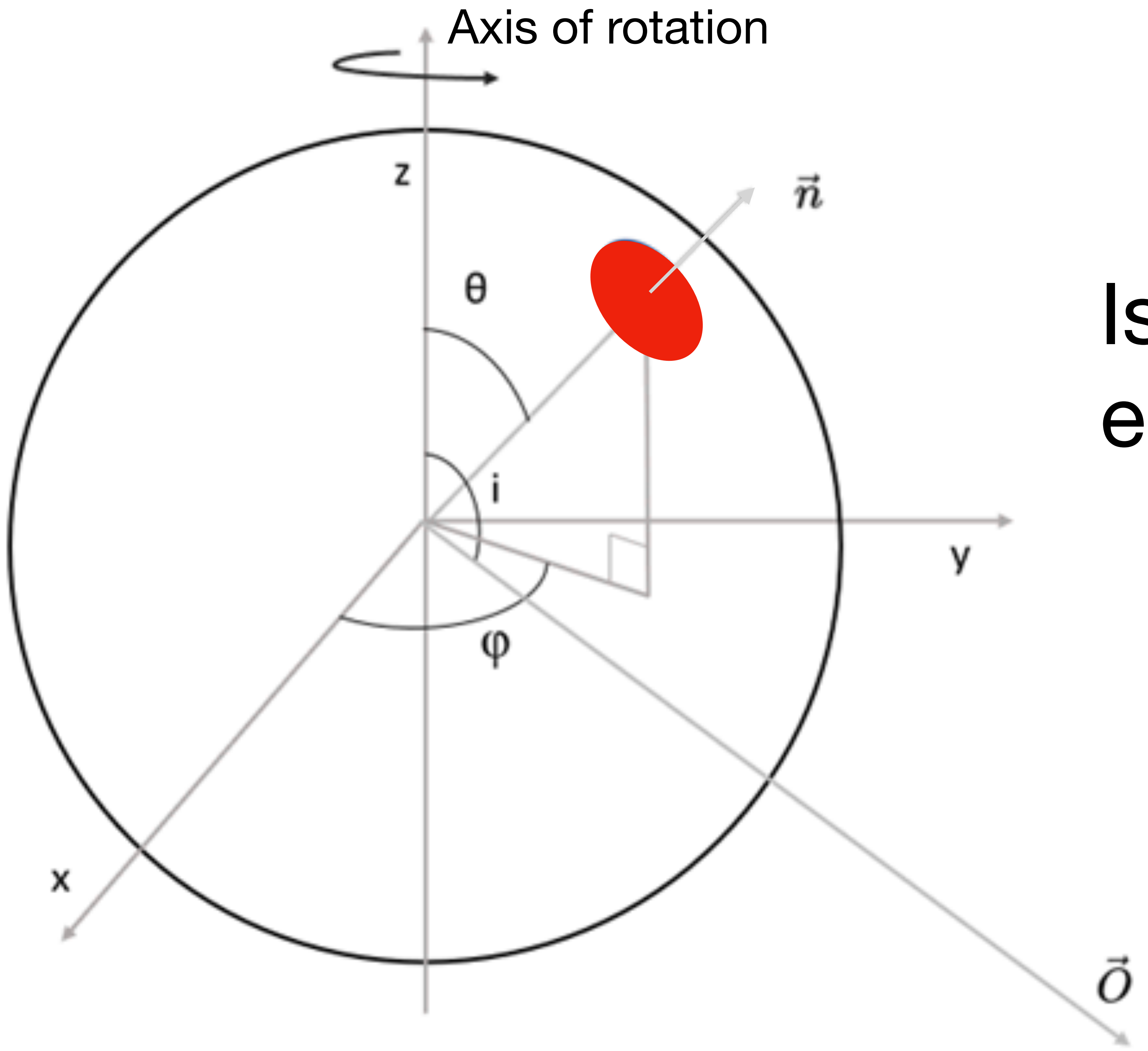



Esposito+ 2011

Spectrum fit by a single blackbody component

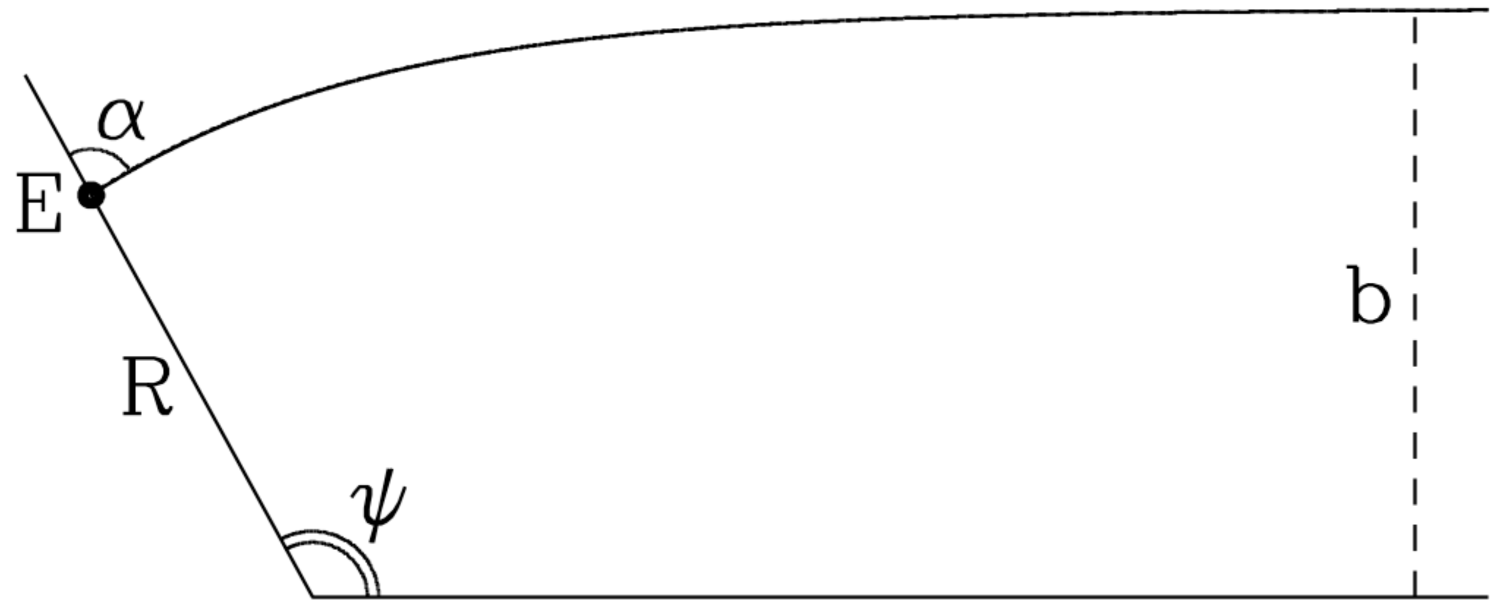
# Hot spot emission - Flux

$$\frac{r_g}{R} = \frac{1}{3}$$




Observer

Isotropic emission




Beloborodov 2002

$$1 - \cos\alpha = (1 - \cos\psi)(1 - \frac{r_g}{R})$$

$$x^k = (t, r, \theta, \psi)$$

$$u^k = \frac{dx^k}{d\lambda}$$

$$\psi = \int_R^\infty \frac{-u^\psi}{u^r} dr = \int_R^\infty \frac{dr}{r^2}[\frac{1}{b^2} - \frac{1}{r^2}(1 - \frac{r_g}{r})]^{-1/2}$$

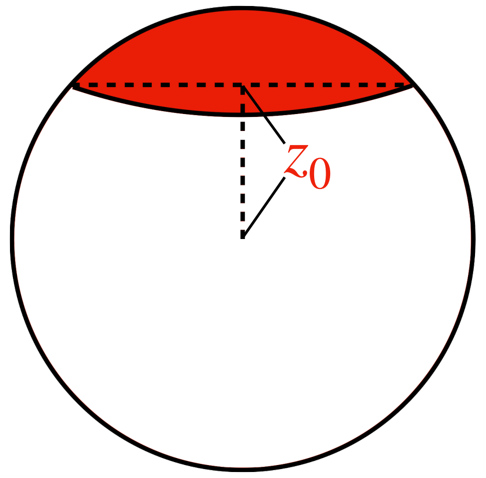
$$\sin\alpha = \frac{b}{R}\sqrt{1 - \frac{r_g}{R}}$$

$$dF = \frac{Ib}{R^2}\left|\frac{db}{d\cos\psi}\right|\frac{dS}{D^2} = (1 - \frac{r_g}{R}) I_0(\alpha)\cos\alpha \frac{d\cos\alpha}{d\cos\psi}\frac{dS}{D^2}$$

$i$: inclination (viewing angle)

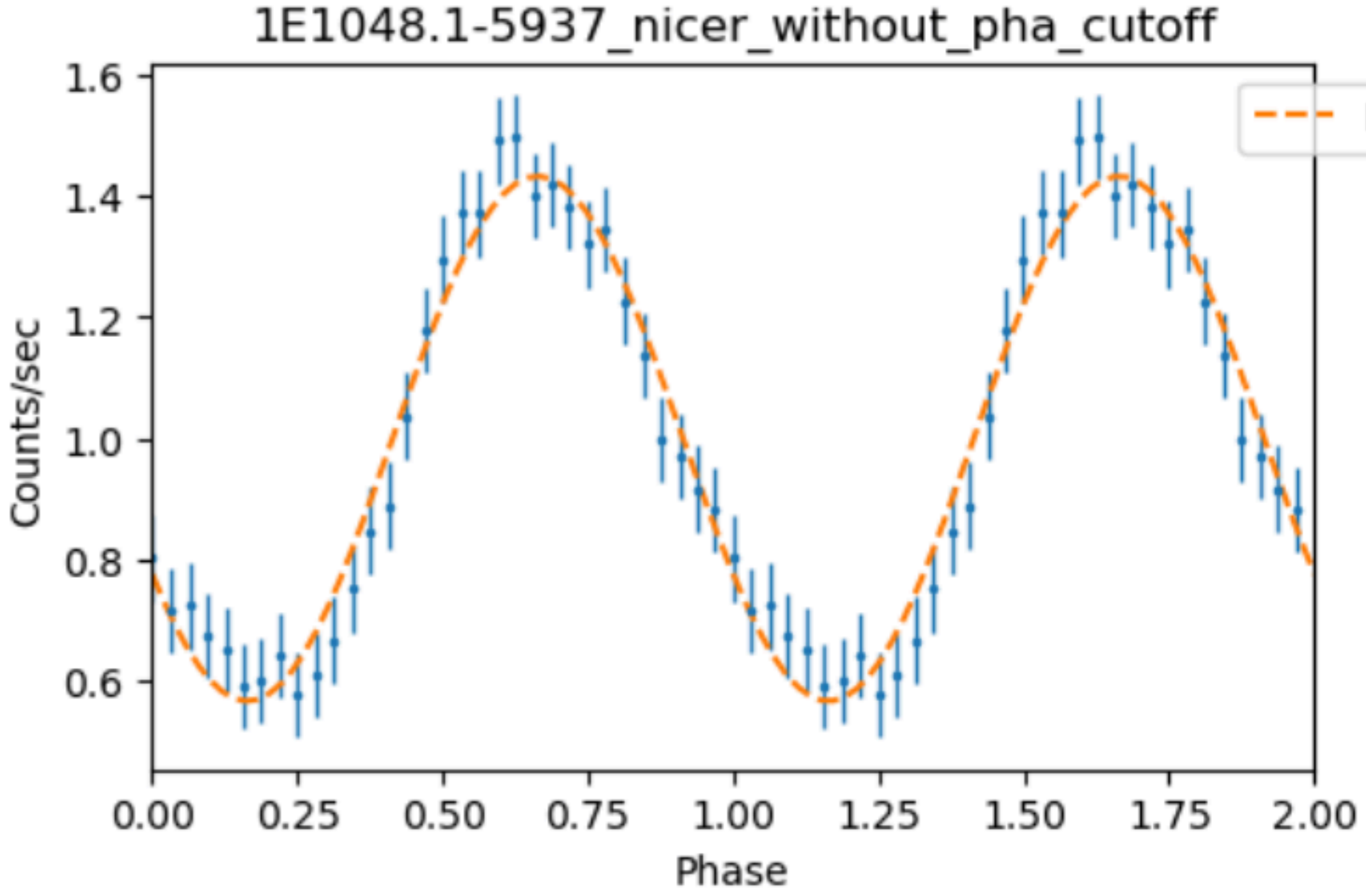
$\theta$: colatitude  $\varphi$: longitude

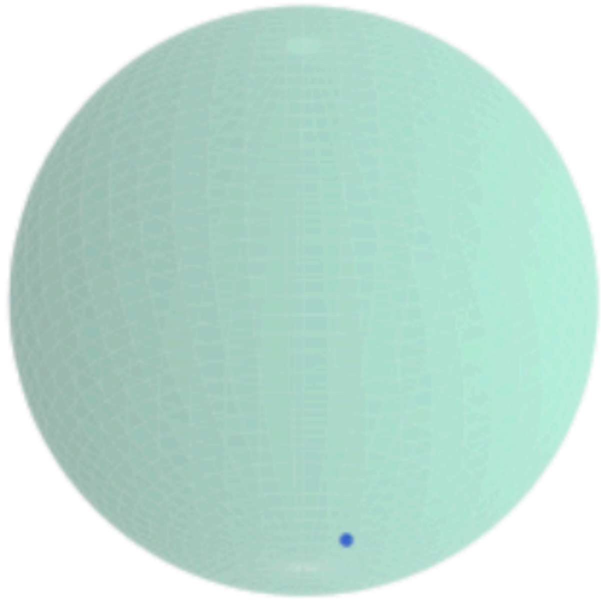
$z_0$: size of hot spot



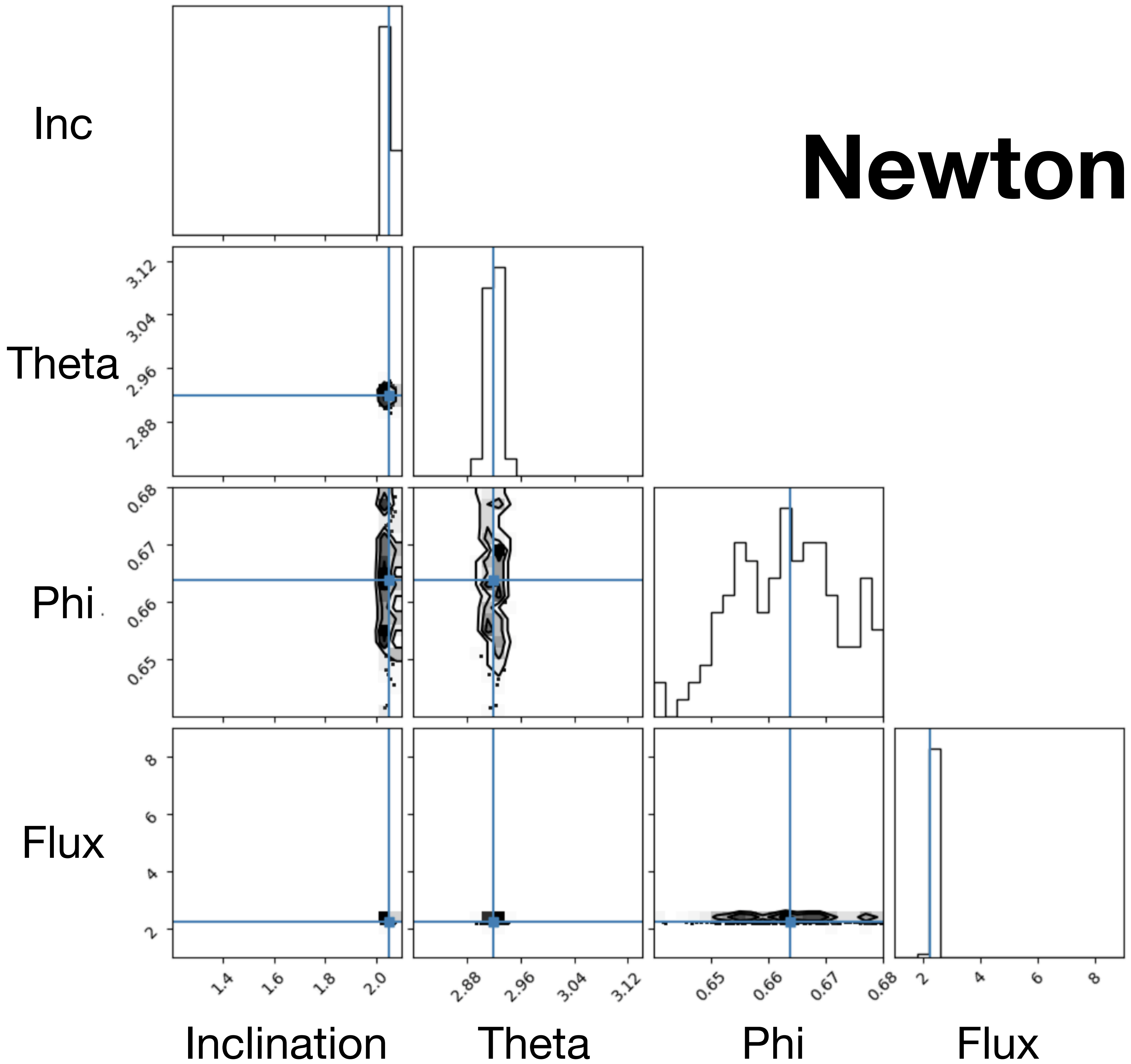

$$\mu(t) = \sin\theta\sin i\cos\Omega t + \cos\theta\cos i$$

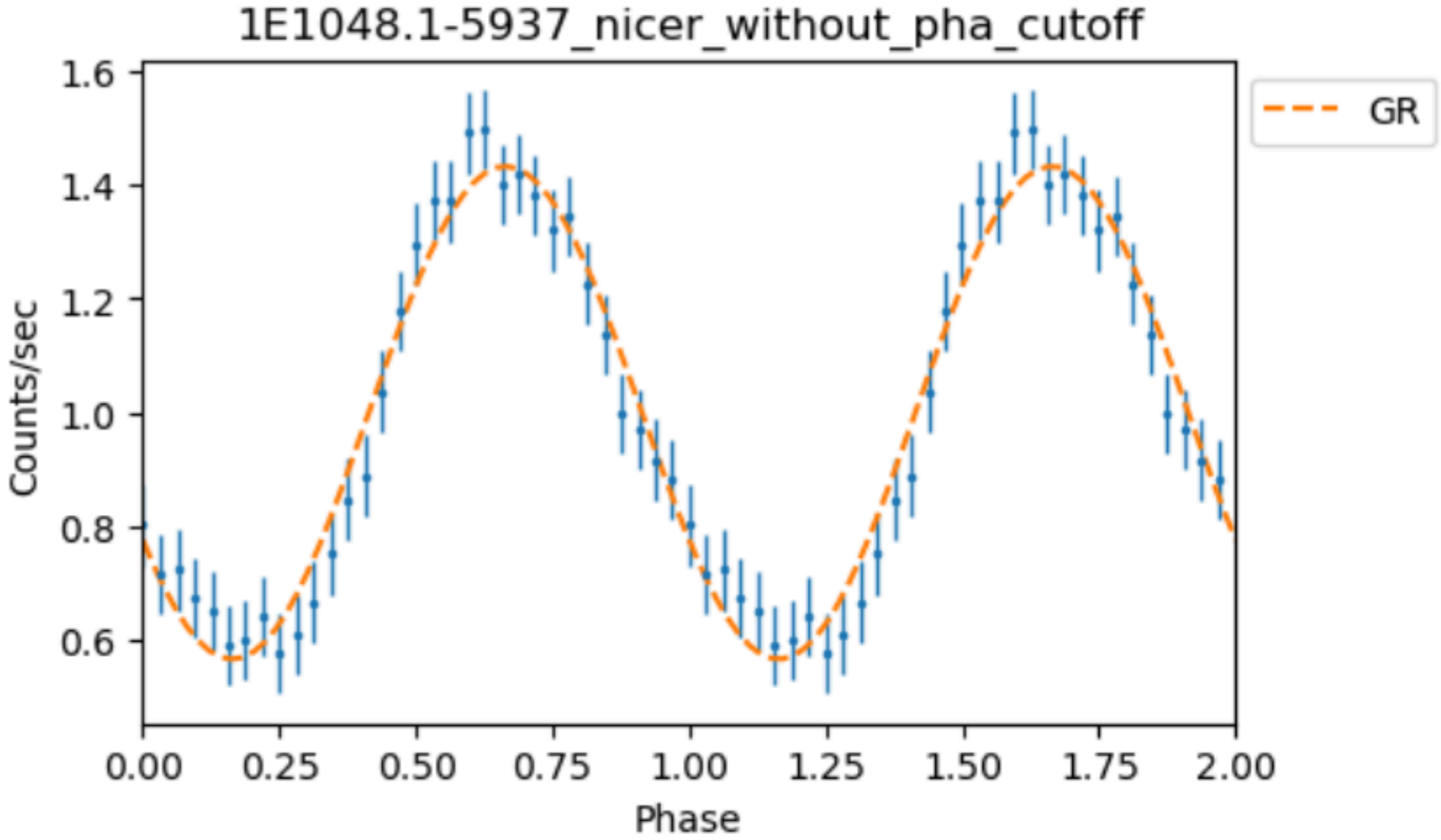
$$F = \mu(i, \theta, \varphi)(1 - \frac{r_g}{R}) + \frac{r_g}{R}$$

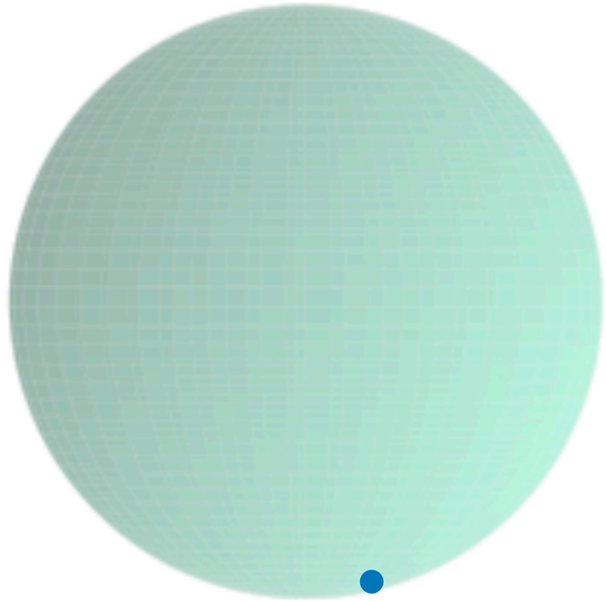


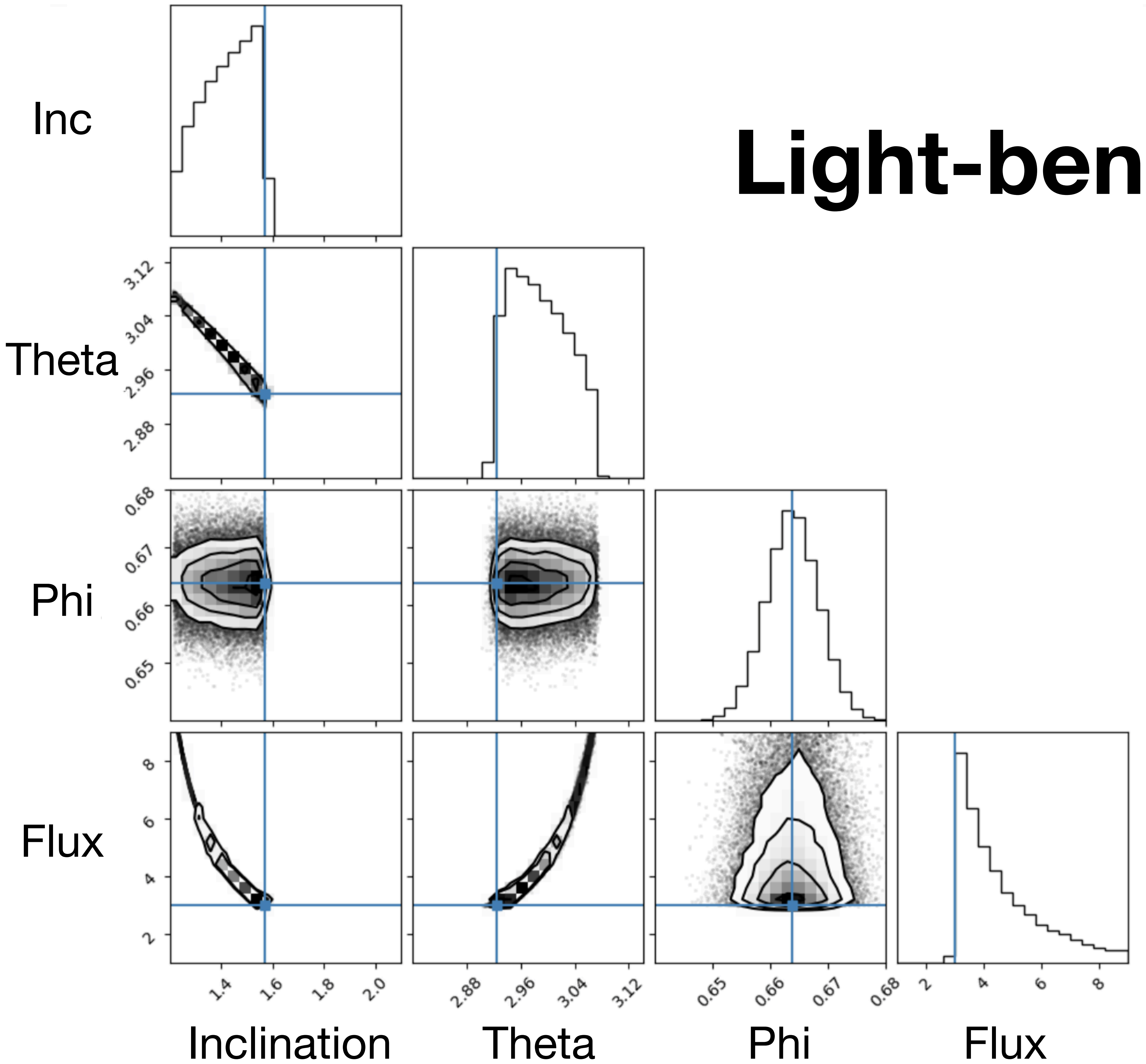
# Newtonian



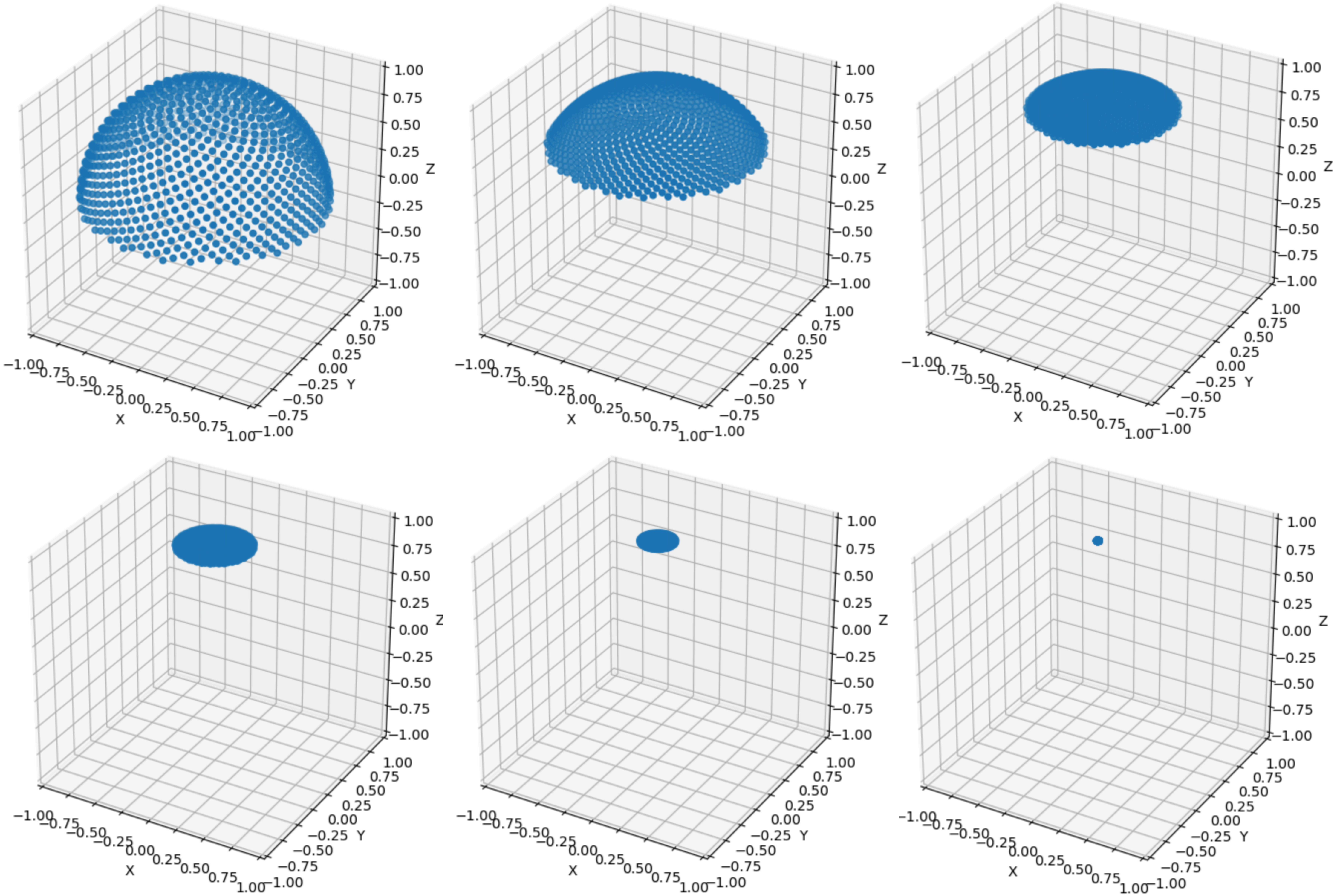



# Light-bending



# Estimate the size of hot spot

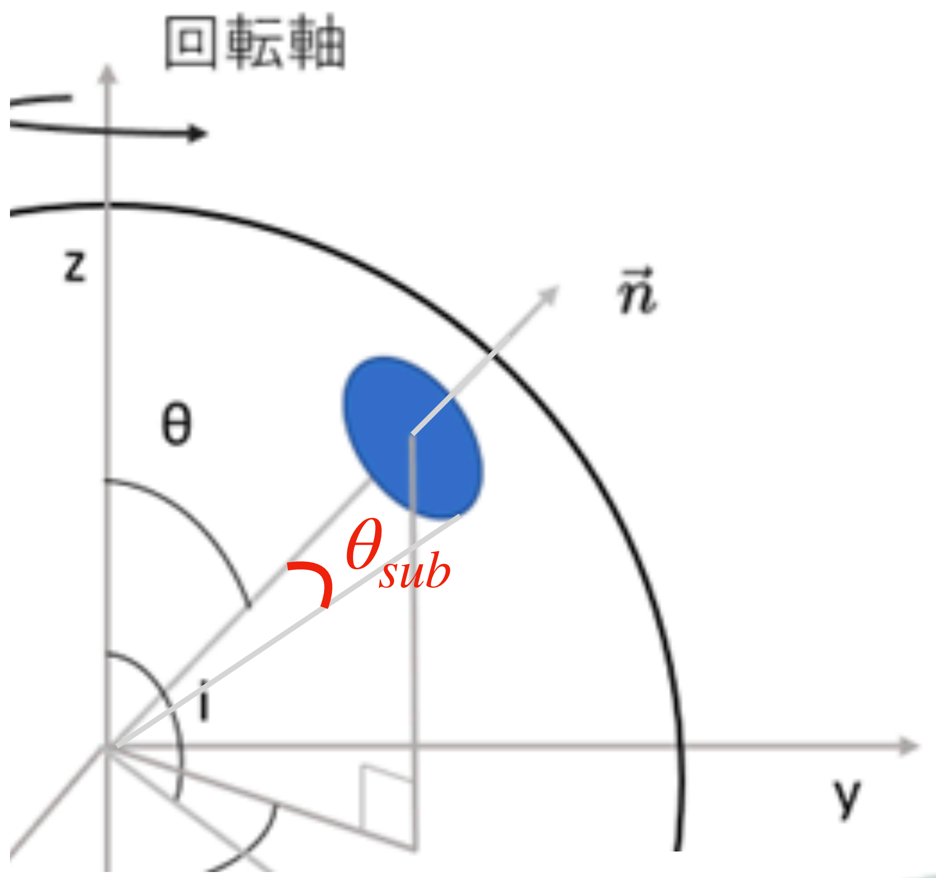


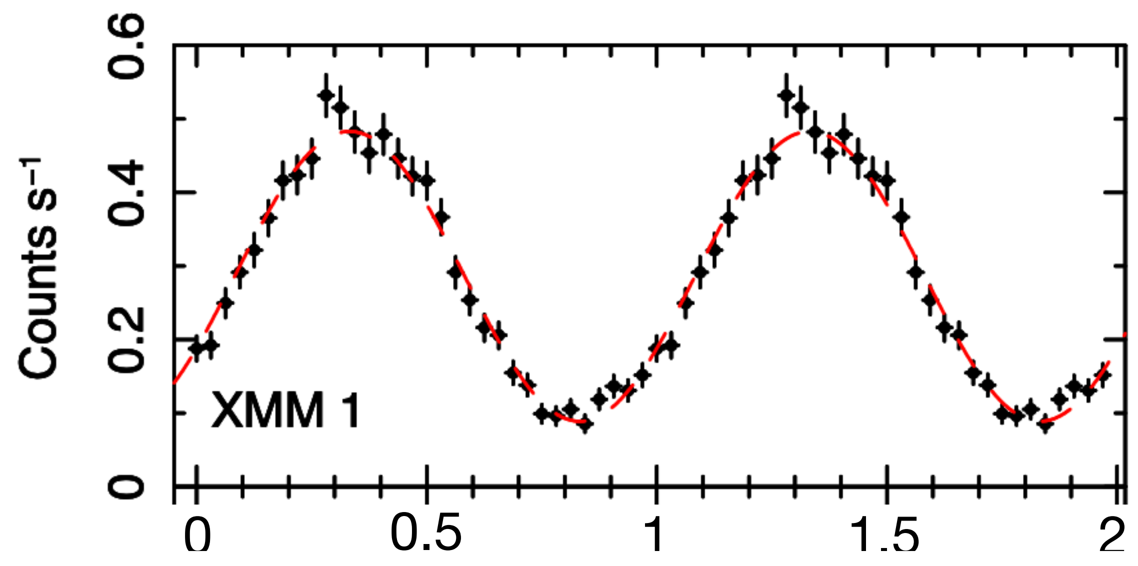

**Uniform temperature**

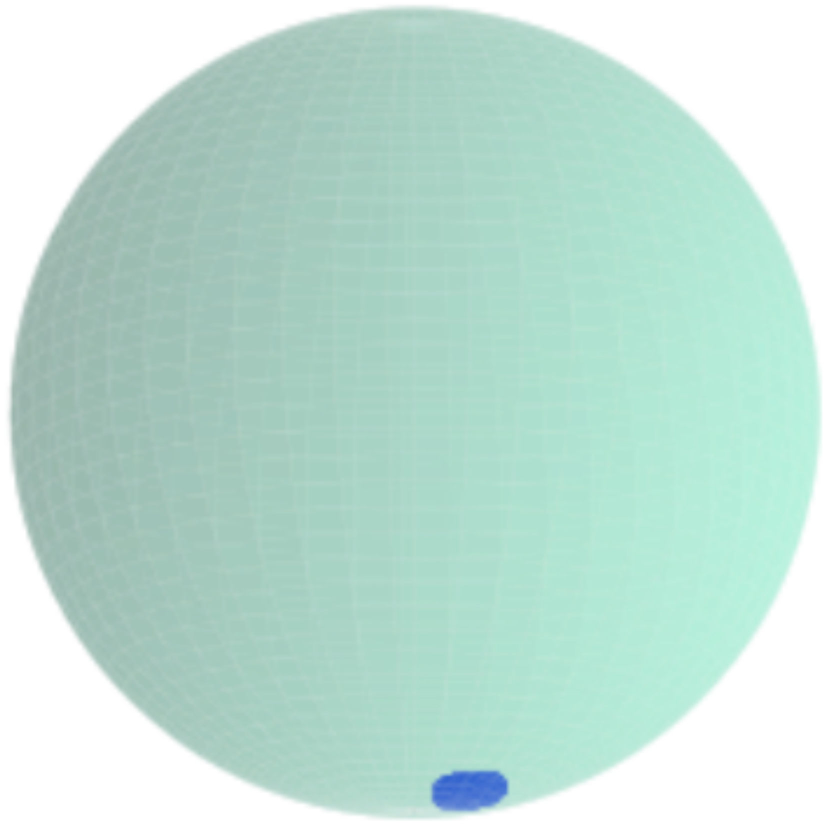
# Consistency check: timing - spectrum

assuming a circular radiation area

## Estimating the size of hotspots from pulse profile



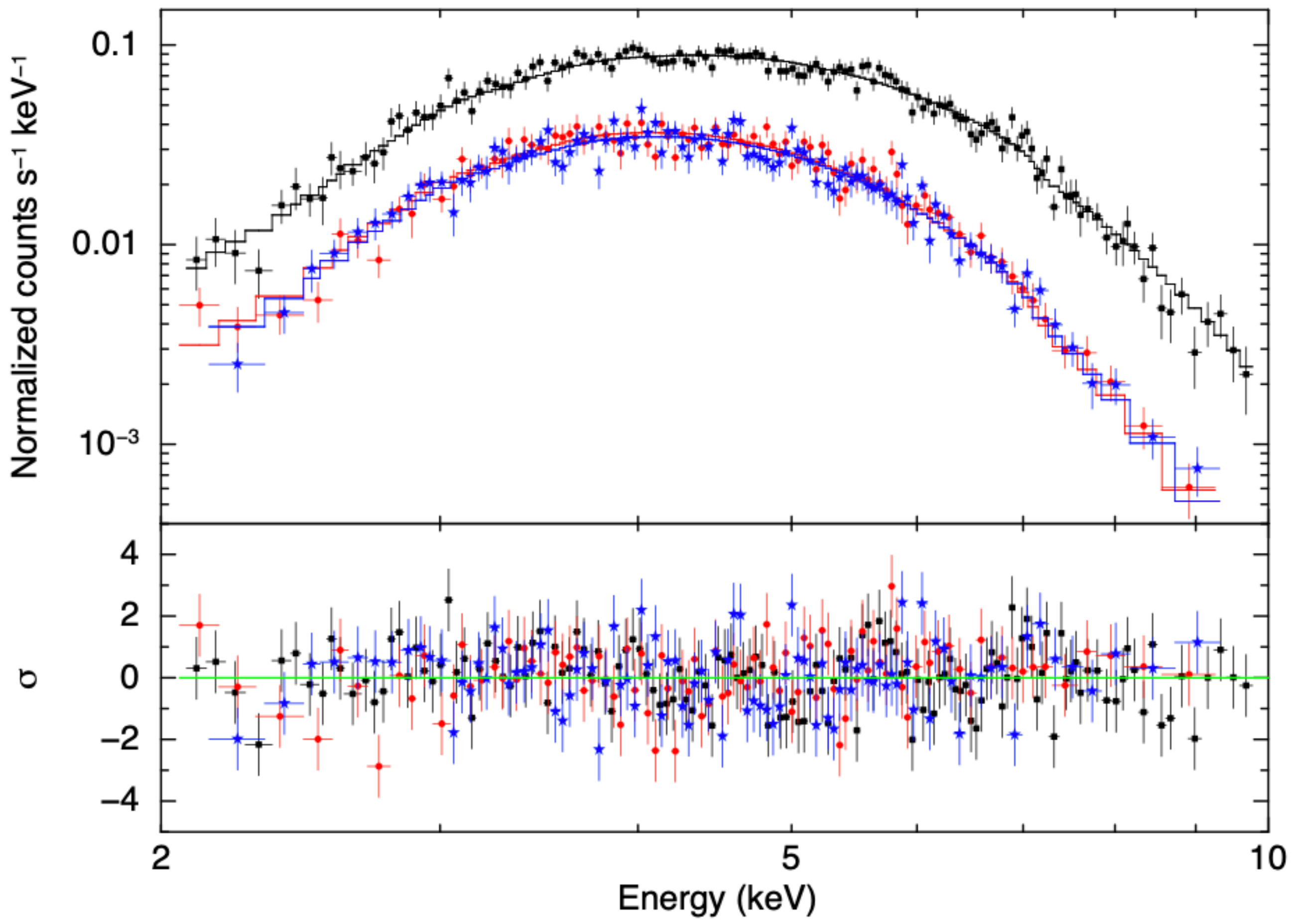



Radiation radius

## Estimating the size of hotspots from spectrum

$$L = S\sigma T^4$$

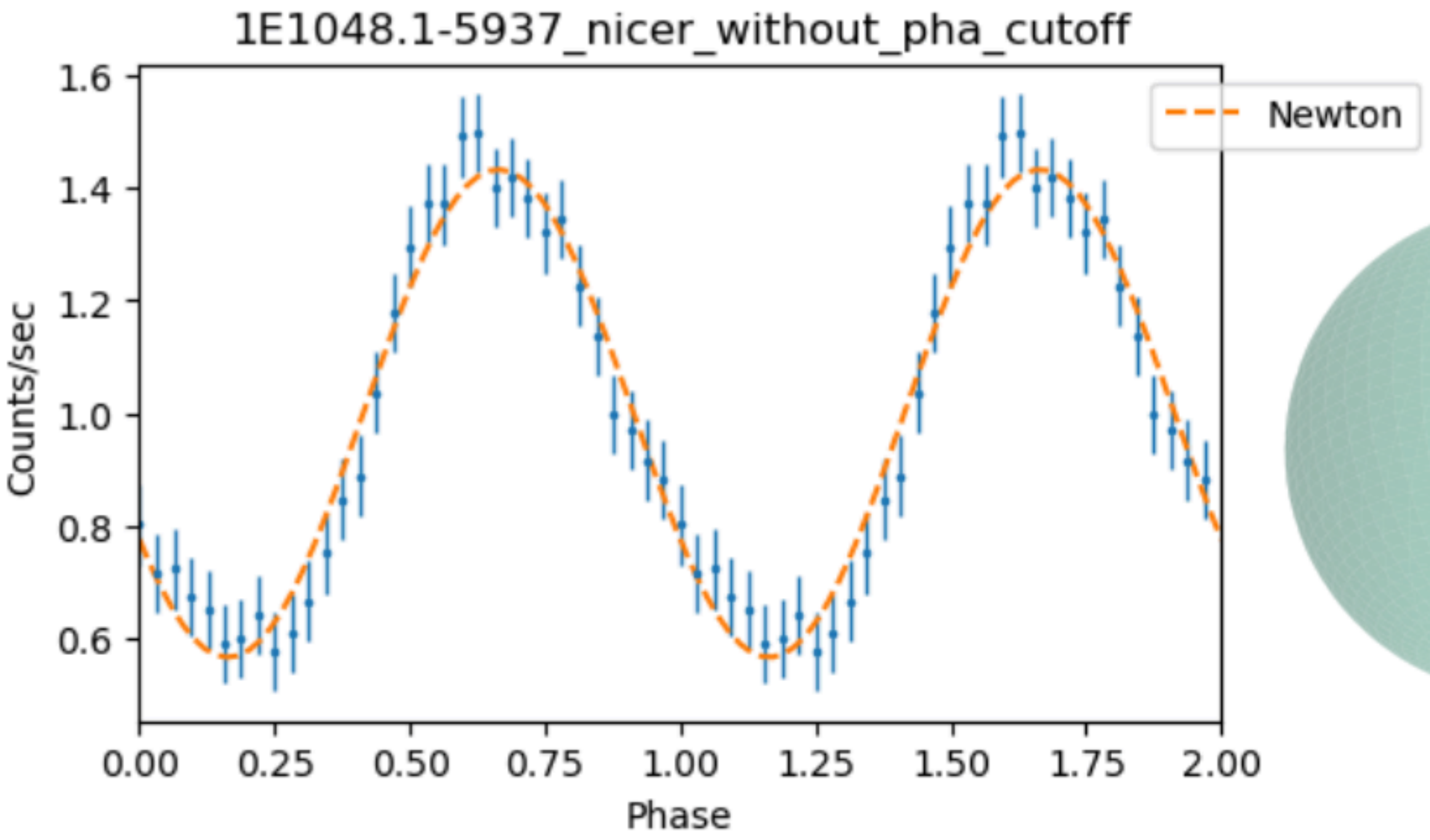
$$L_{obs} = \frac{S_{obs}}{4\pi D^2} L$$

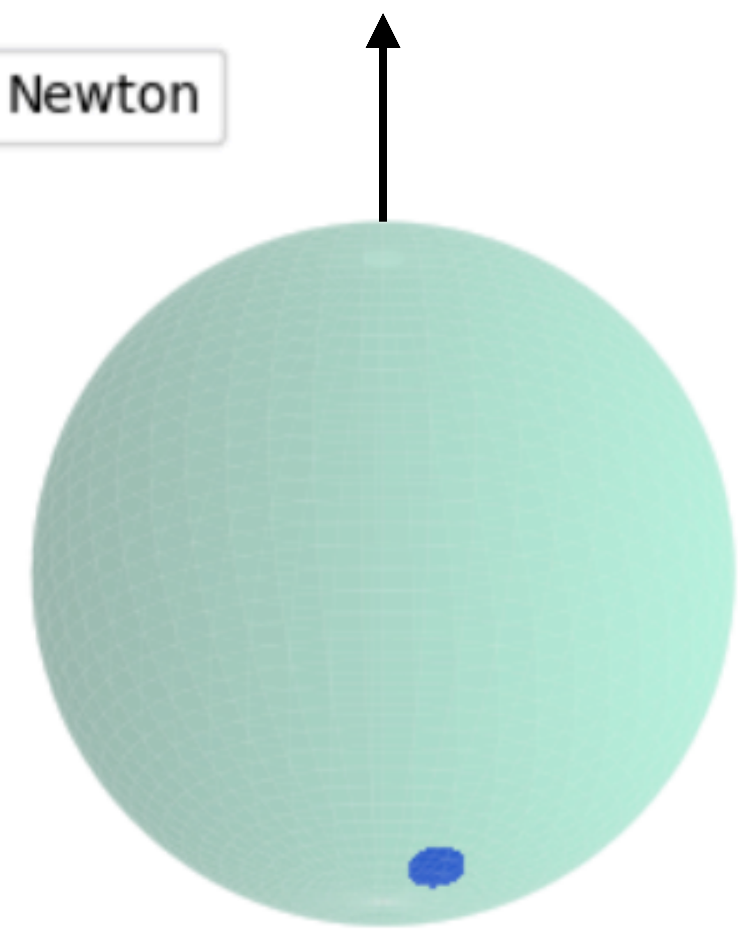


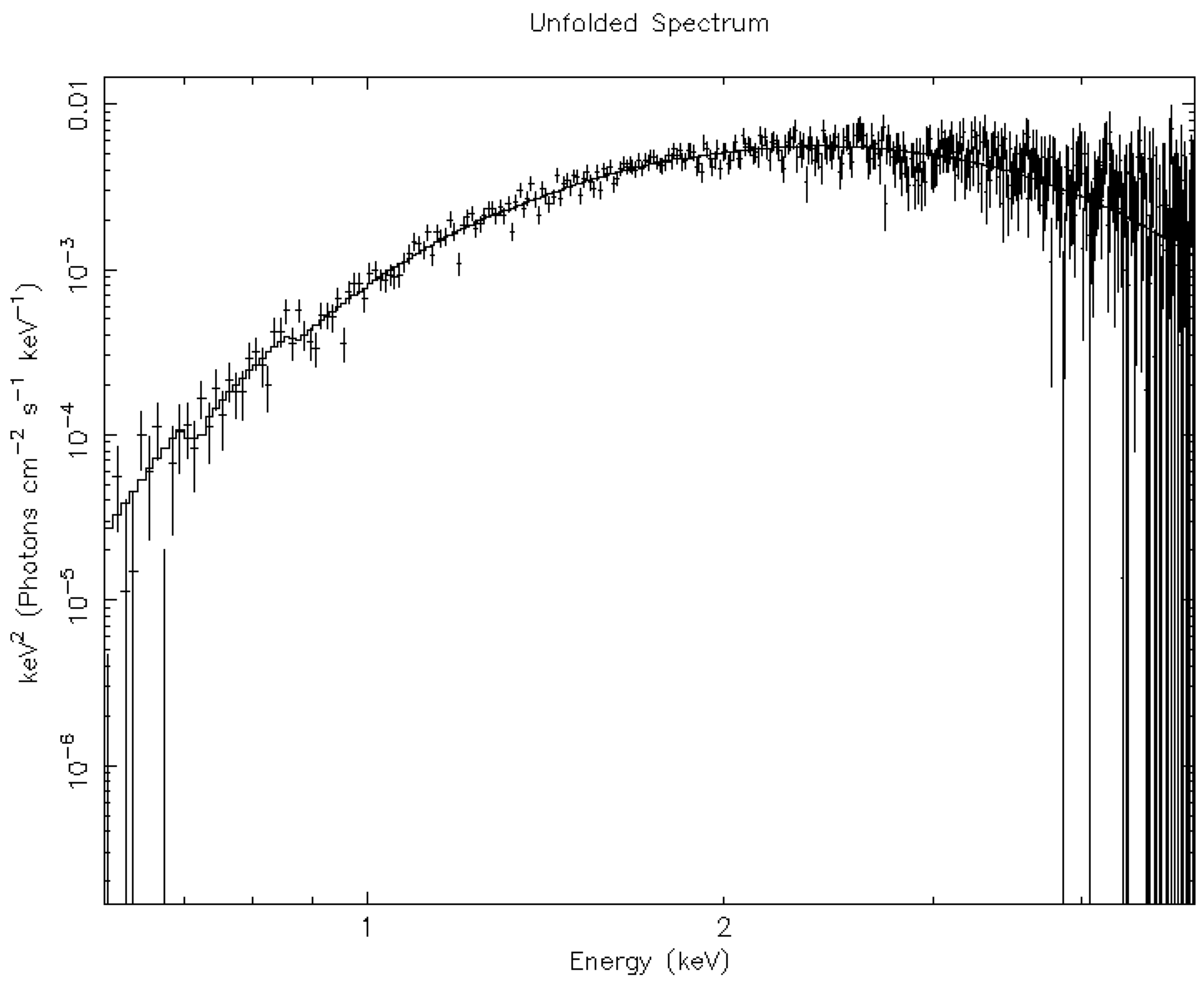

T: blackbody temperature
D: distance
S: emission area

Time-averaged projection of the radiation radius

# 1E 1048.1–5937





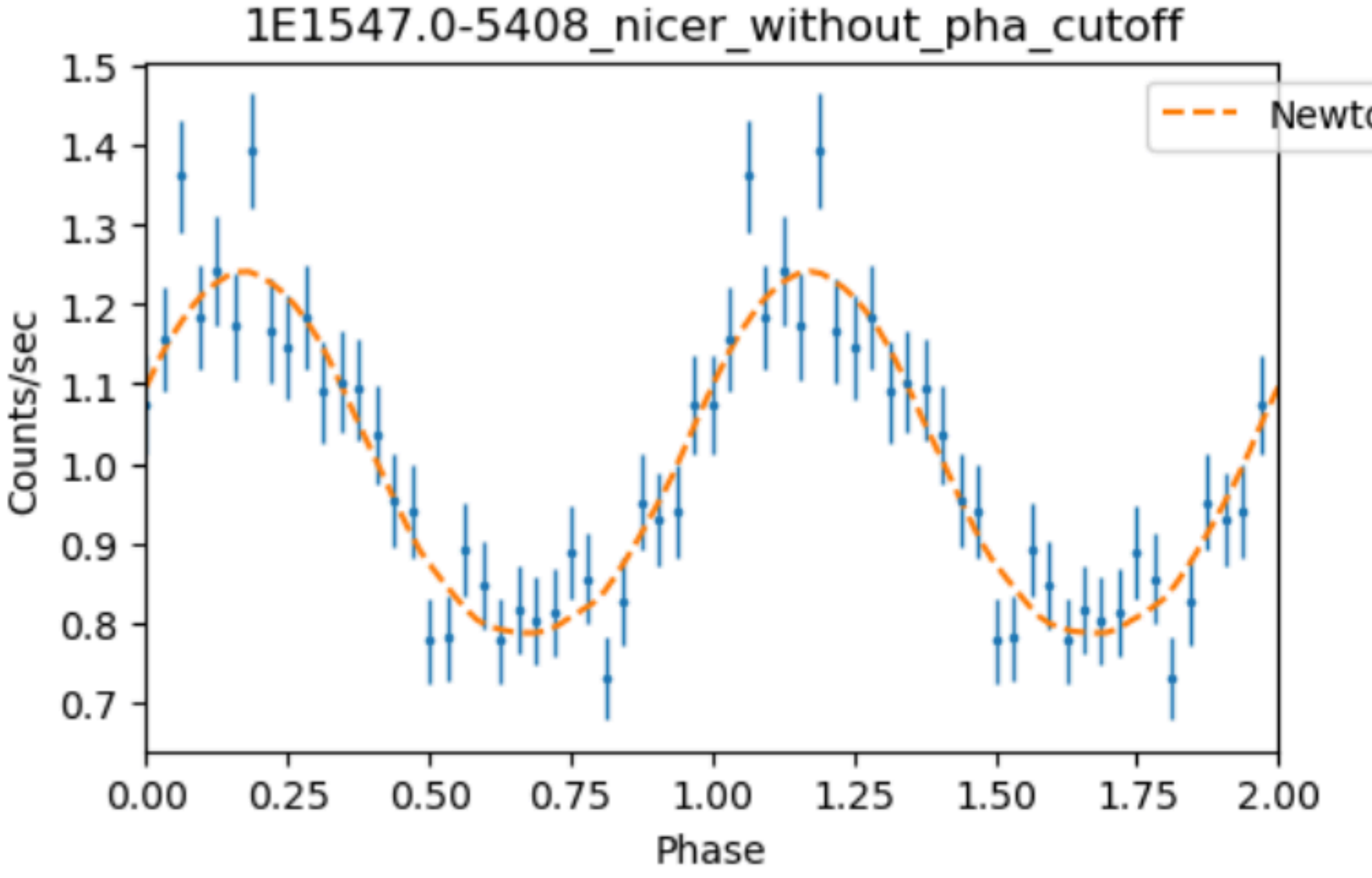

Timing: $R_{max} = 1.68\, km$

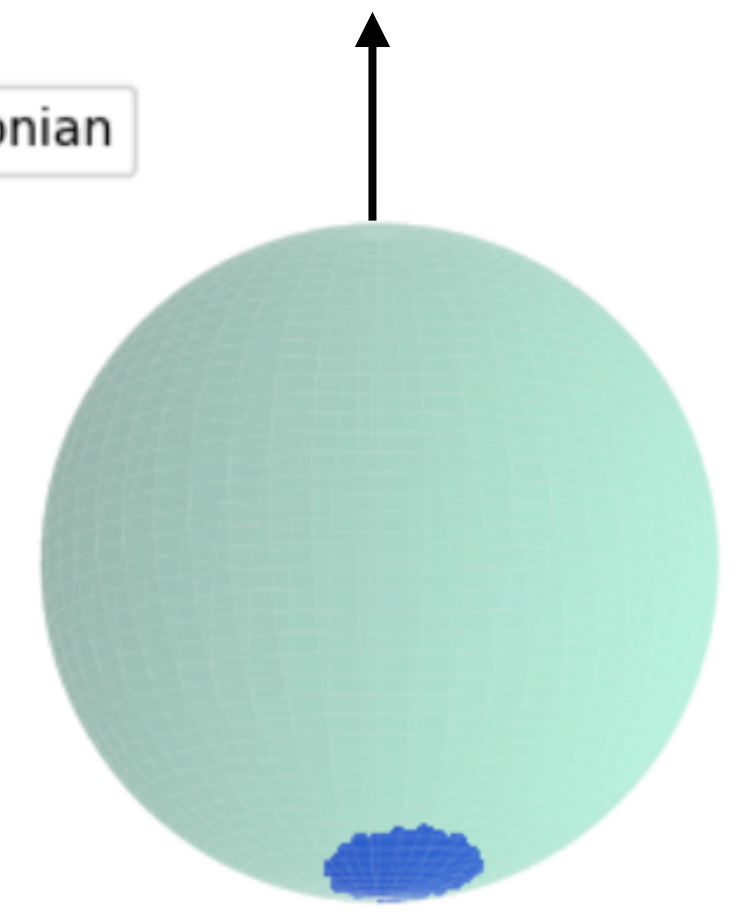
Spectral: $< R_{\perp} > = 3.1\, km$

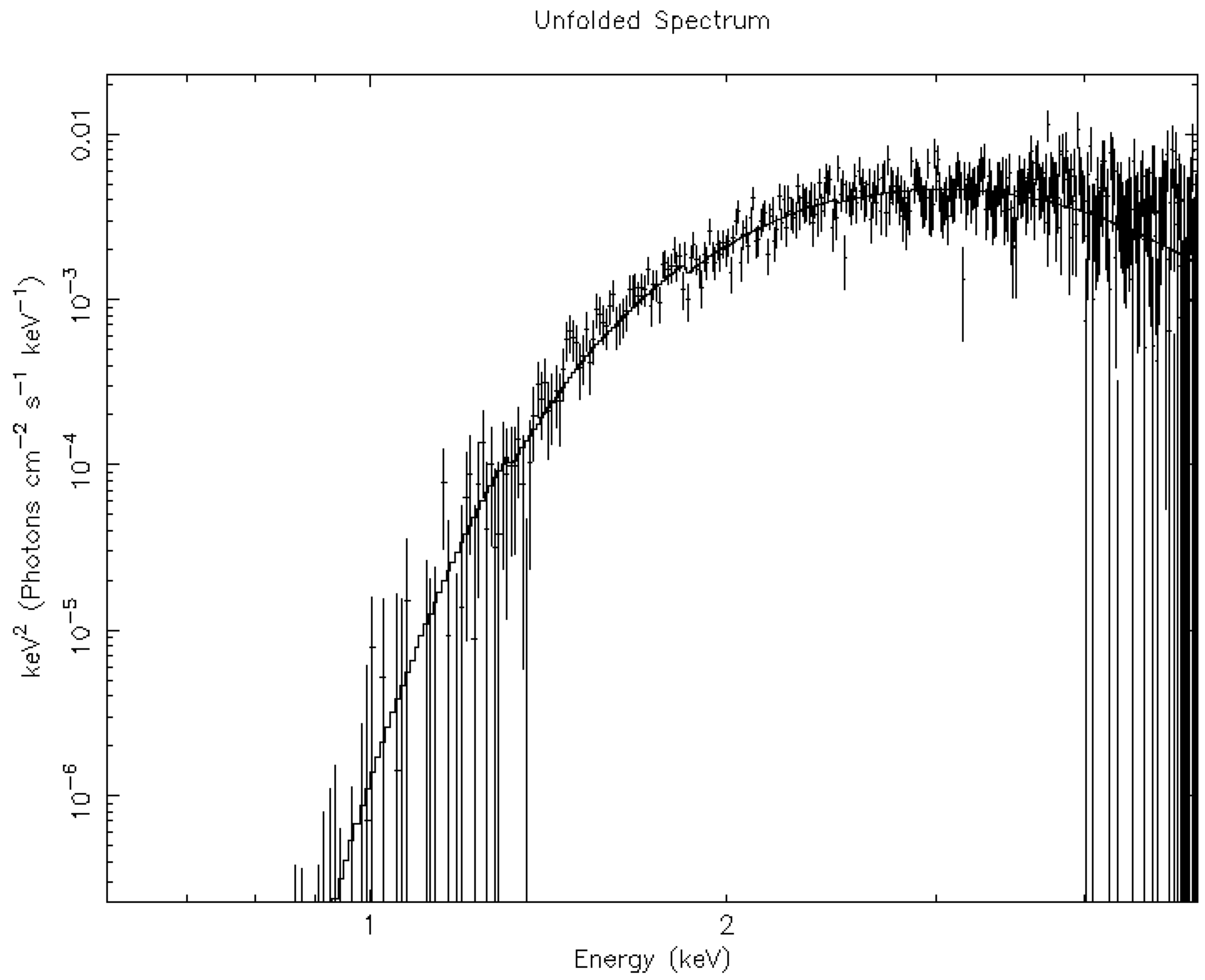
R = 12 km

Distance = 9.0 (1.7) kpc  Martin +2006

# 1E 1547.0–5937






Timing: $R_{max} = 2.57\, km$

Spectral: $< R_{\perp} > = 1.81\, km$

R = 12 km

Distance = 4.5(5) kpc

Tiengo +2010

# Summary

- Considering the light bending effect, it became possible to explain the pulse profiles using only hotspots, which is more natural
- Managed to check the consistency of hotspot parameters in Newtonian model

# Future work

- Taking into account of beaming effect
- Taking into account of different shapes of hotspots
- Developing spectrum analysis code incorporating the light bending effect
- Multi-peak pulse profile