Phase Resolved γ-ray Spectroscopy of Millisecond Pulsars

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Summary : Preliminary results of the phase resolved spectroscopy of the γ-ray emission of 11 bright millisecond pulsars with Fermi LAT data above 100 MeV.

Abstract

The Fermi LAT γ-ray observations have opened a new window onto particle acceleration in the compact magnetospheres of millisecond pulsars. With 3 to 4 years of observation, photon statistics, although not as high as for normal pulsars, allow a first spectral analysis of the emission as a function of rotational phase. We studied 11 of the brightest millisecond pulsars that exhibit different light curve morphologies with single or double peaks. We obtained spectra for the leading and trailing sides of the peaks and the inter-peak and off-pulse intervals.

We detected significant DC emission for 4 objects.

For the pulsed emission, the second peak appears to be often harder than the first peak, both in cut-off energy and in apex energy. The hardness evolves through the first peak, with trailing sides harder than the leading ones. This evolution is less marked in the second peak where both sides often exhibit similar spectra.

The sample is small, but starts to show spectral trends from one pulsar to another, with spin-down power and phase lag between the first radio and γ-ray peaks. For both γ-ray peaks, the cut-off energy and spectral index tend to increase with spin-down power and to correlate with each other. The apex energy does not relate to the rotational power. Its small variation with the radio lag needs confirmation as it would sign a dependence on pulsar geometry.

Analysis Method

- Data : we used 38 to 44 months of LAT data in the energy band between 100 MeV and 300 GeV.
- Software : we used the maximum likelihood analysis **gtlike** package to perform the spectral fits and **Tempo2** for the phase-folding of photons.
- Ephemerides : we used the most recent γ−ray and radio ephemerides from the Pulsar Search Consortium.
- Individual analysis :
- ✧ We selected phase intervals according to the light-curve shapes and photon statistics.
- ✧ We tested the existence of DC emission in the off-pulse interval. We consider a firm detection above a TS=25 threshold.
- ✧ We performed spectral analyses for 3 spectral shapes : *Power Law* and *Power Law with a Simple* or Super *Exponential Cut-off*.
- ✧ We performed the spectral analyses for the whole phase and for each phase interval
- ✧ The maximum-likelihood values did not favour a *Super Exponential Cut-off* over a *Simple* one at a significant level, so the results below are presented with the latter.

Two Examples

We present the individual results for only PSR J1231-1411 and J2124-3358. They illustrate different types of lightcurves with a double or single peak(s).

The ***apex energy*** is the energy corresponding to the maximum of the spectral energy distribution (Illustration in Fig. 5.)

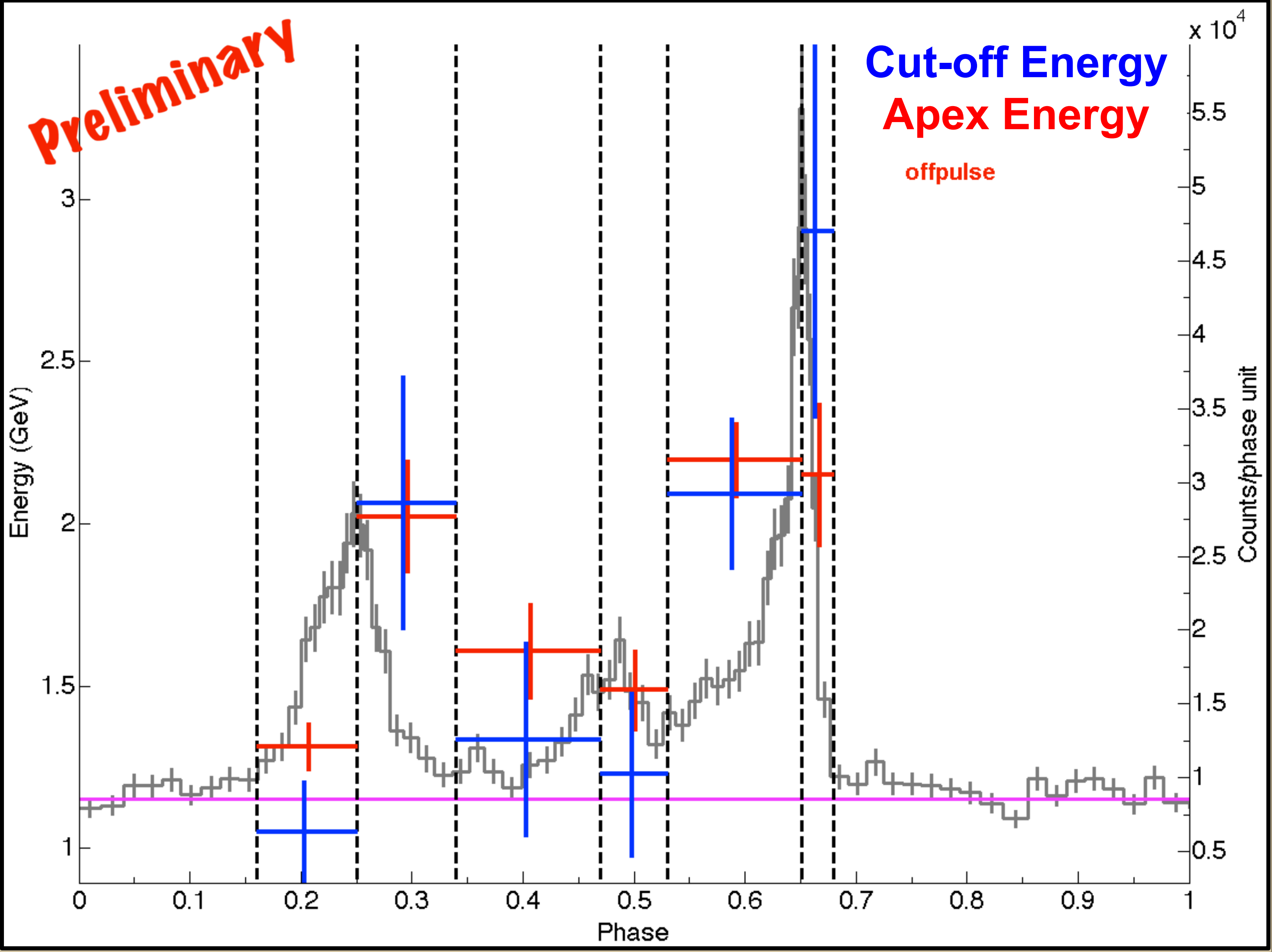


Fig. 1 *Changes in apex and cut-off energies with phase, displayed over the* γ*-ray lightcurve of PSR J1231-1411 (fixed count binning with 164 photons per bin).*

- First peak : higher apex energy on the trailing side than on the leading one
- Second peak : uniform apex energy
- All phase : cut-off energy and spectral index vary similarly with phase

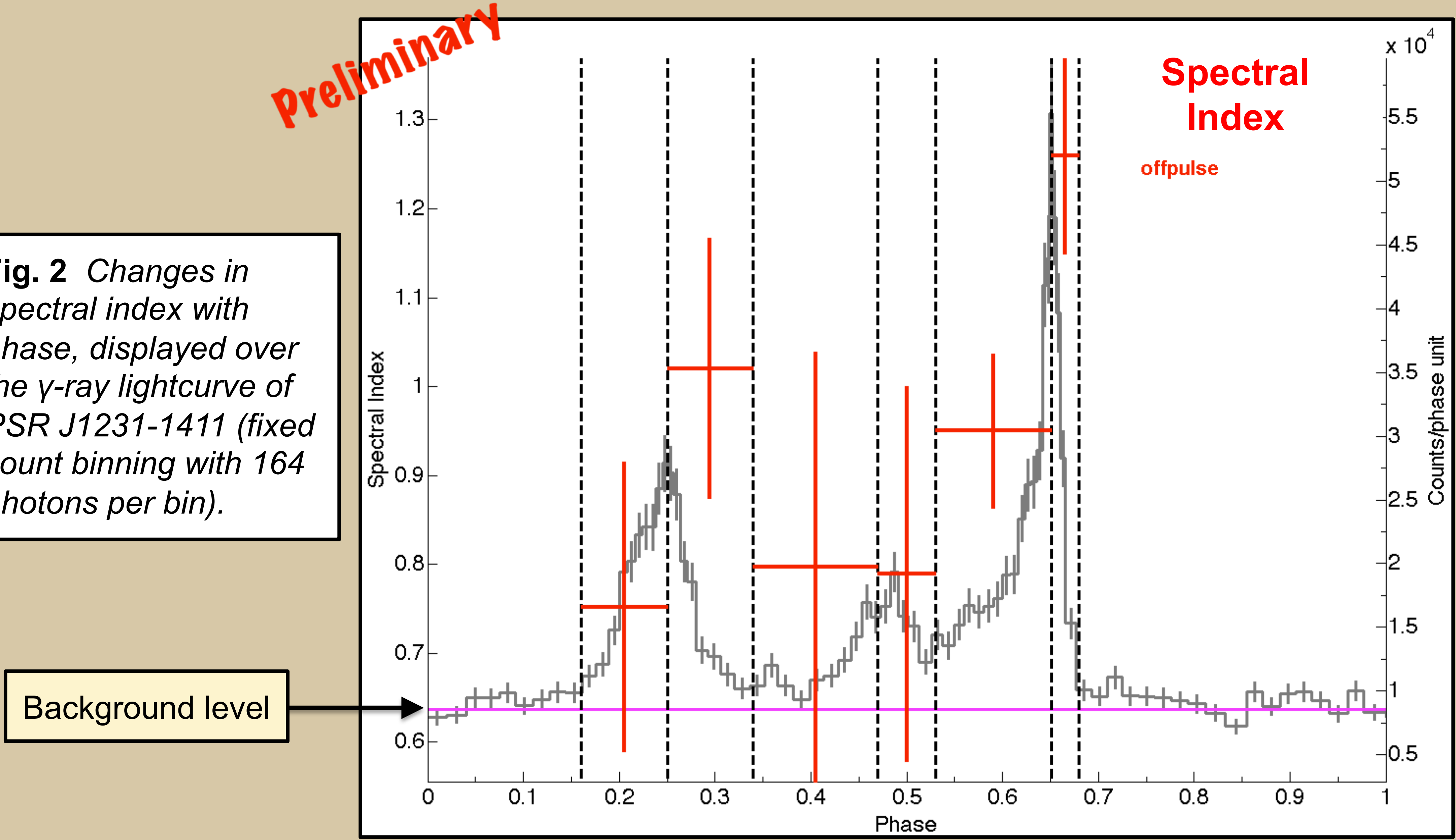


Fig. 2 *Changes in spectral index with phase, displayed over the γ-ray lightcurve of PSR J1231-1411 (fixed count binning with 164 photons per bin).*

Trends in observations :

- First peak : shift to higher energy from leading to trailing sides
- Second peak : comparable spectral shapes for leading and trailing sides

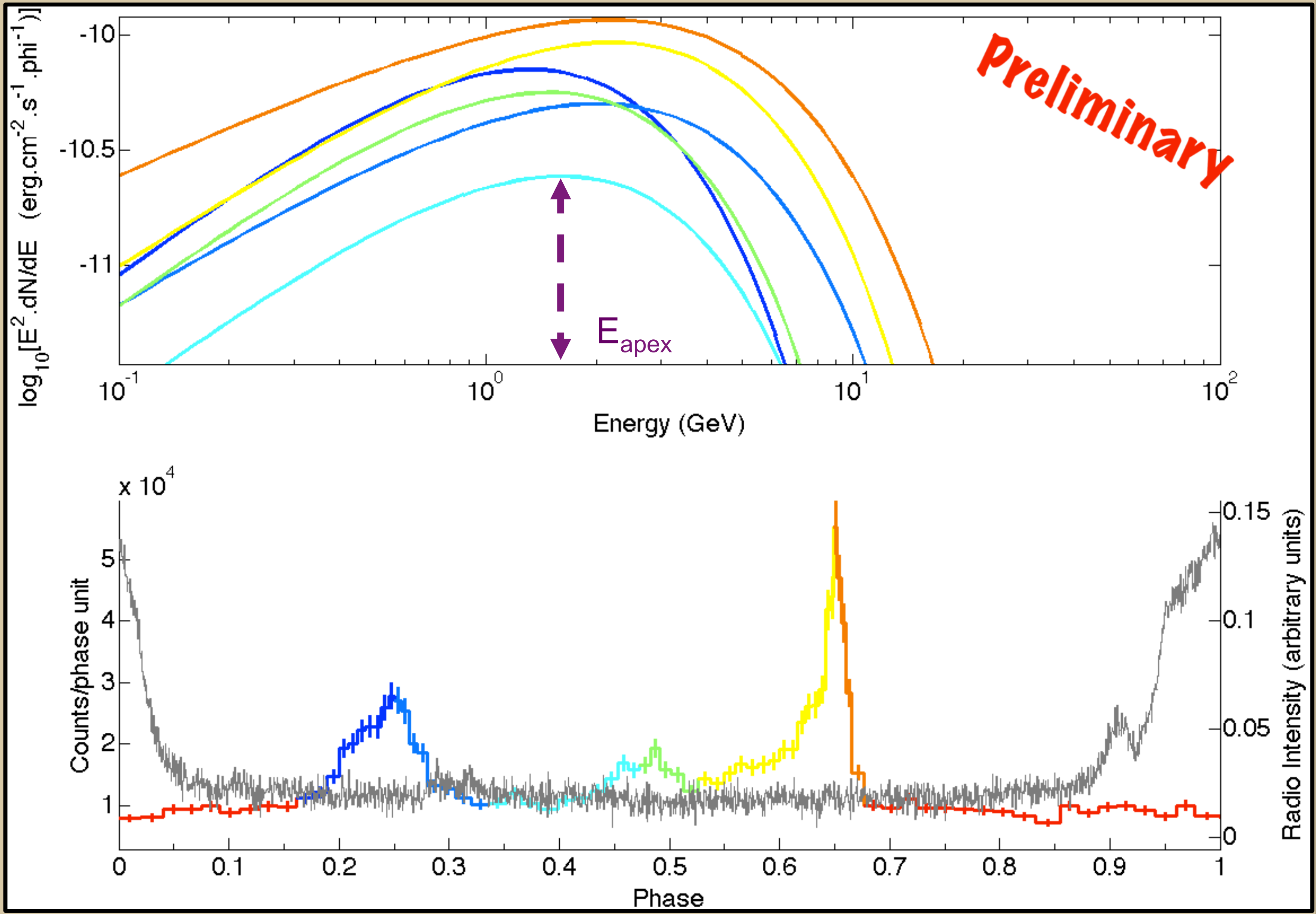
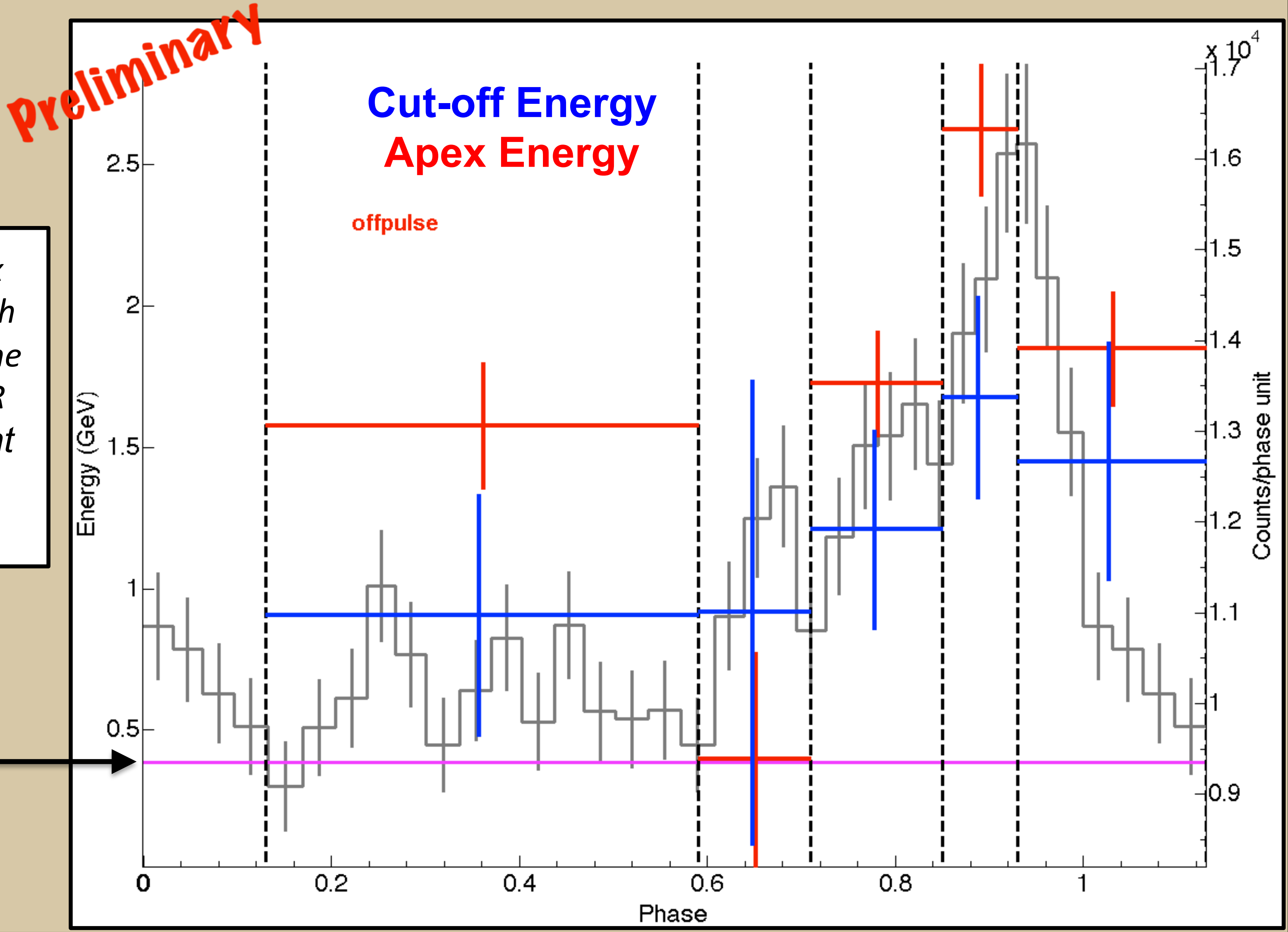


Fig. 3 Spectral evolution with phase for PSR J1231-1411. Each phase interval in the the γ-ray lightcurve is coded in colour. The spectra correspond to the best-fit solutions. The radio lightcurve at 1.4 GHz is shown in grey.

- Off-pulse : DC emission detected with TS = 160
- Continuous change in apex energy across the broad peak
- Stable cut-off energy through the broad peak

Fig. 4 *Changes in apex and cut-off energies with phase, displayed over the γ-ray lightcurve of PSR J2124-3358 (fixed count binning with 341 photons per bin).*

Background level



- Rather uniform spectral index, but large error bars.

For our light-curves, we selected only photons within $\theta \leq \max(1.0 - 2.0 * \log(E_{GeV}), 1.5°)$ from the pulsar position

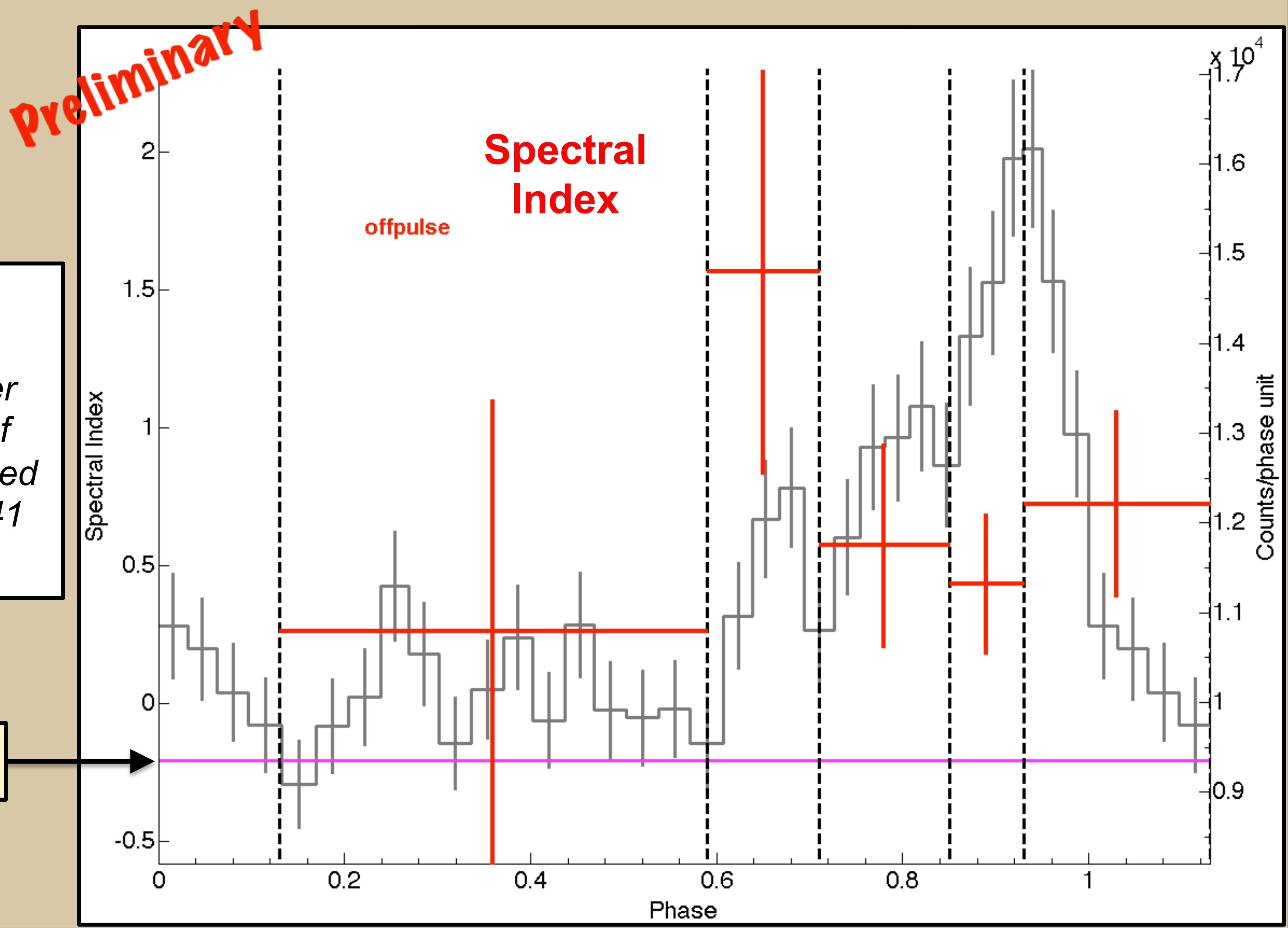


Fig. 5 *Changes in spectral index with phase, displayed over the γ-ray lightcurve of PSR J2124-3358 (fixed count binning with 341 photons per bin).*

Trends in observations :

- Single peak : gradual hardening on the leading side and softening on the trailing side

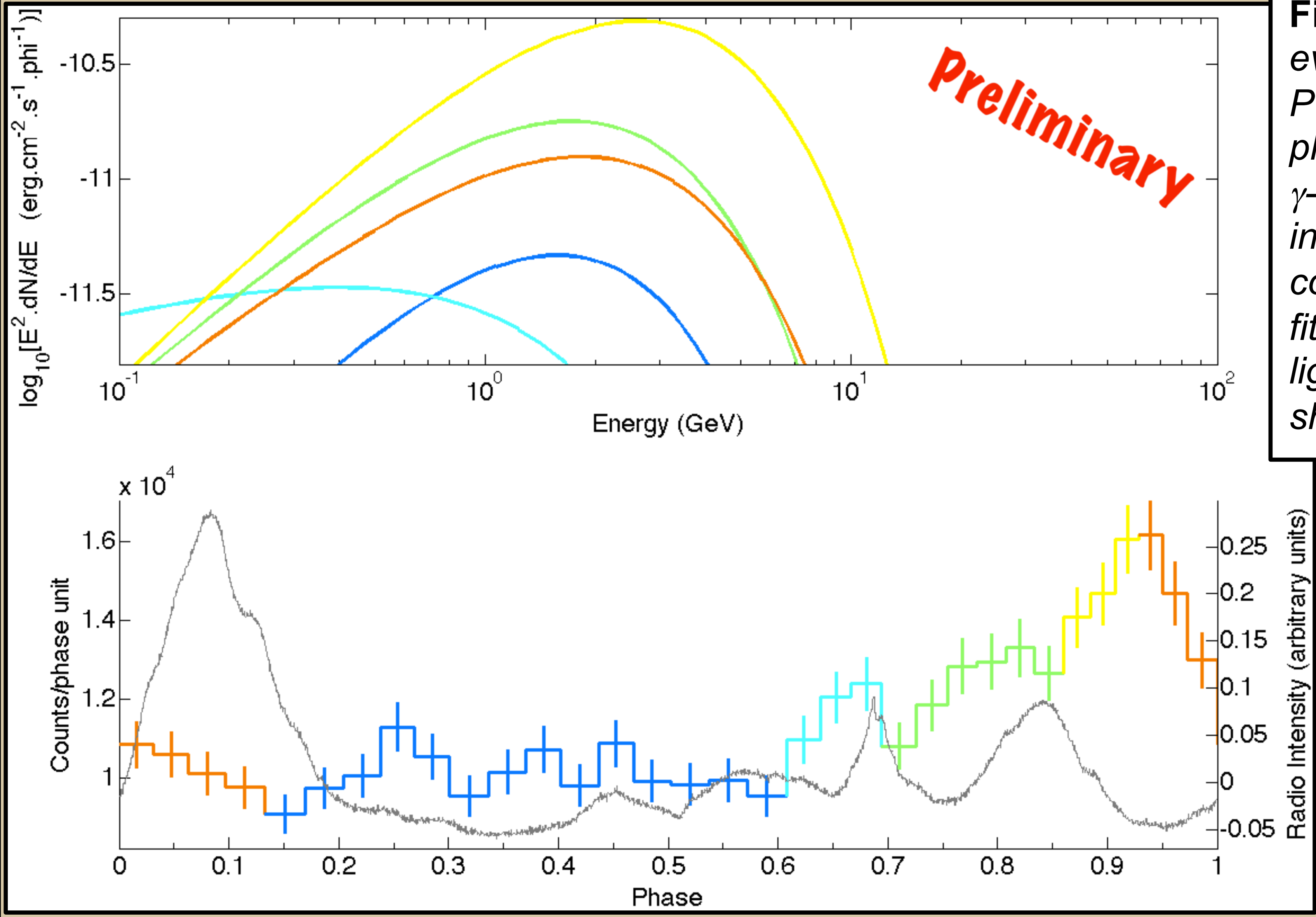
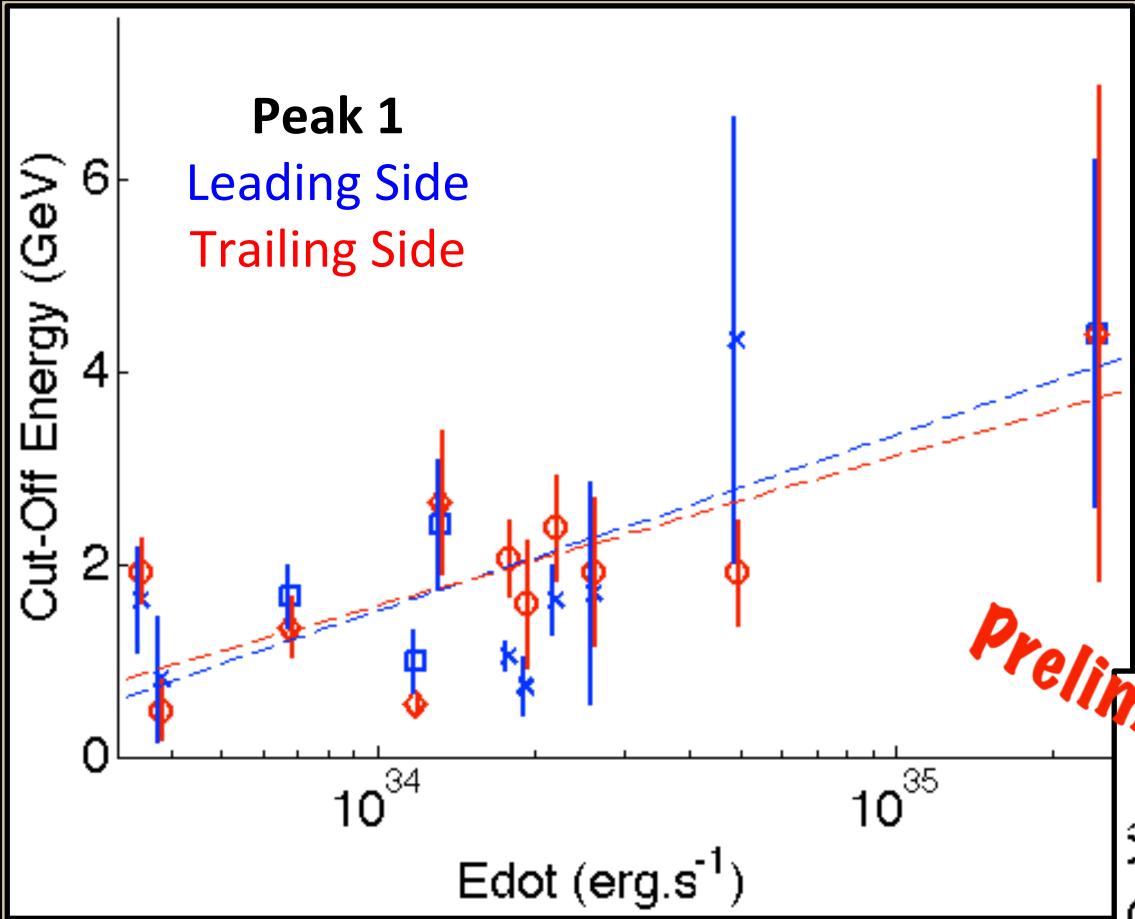


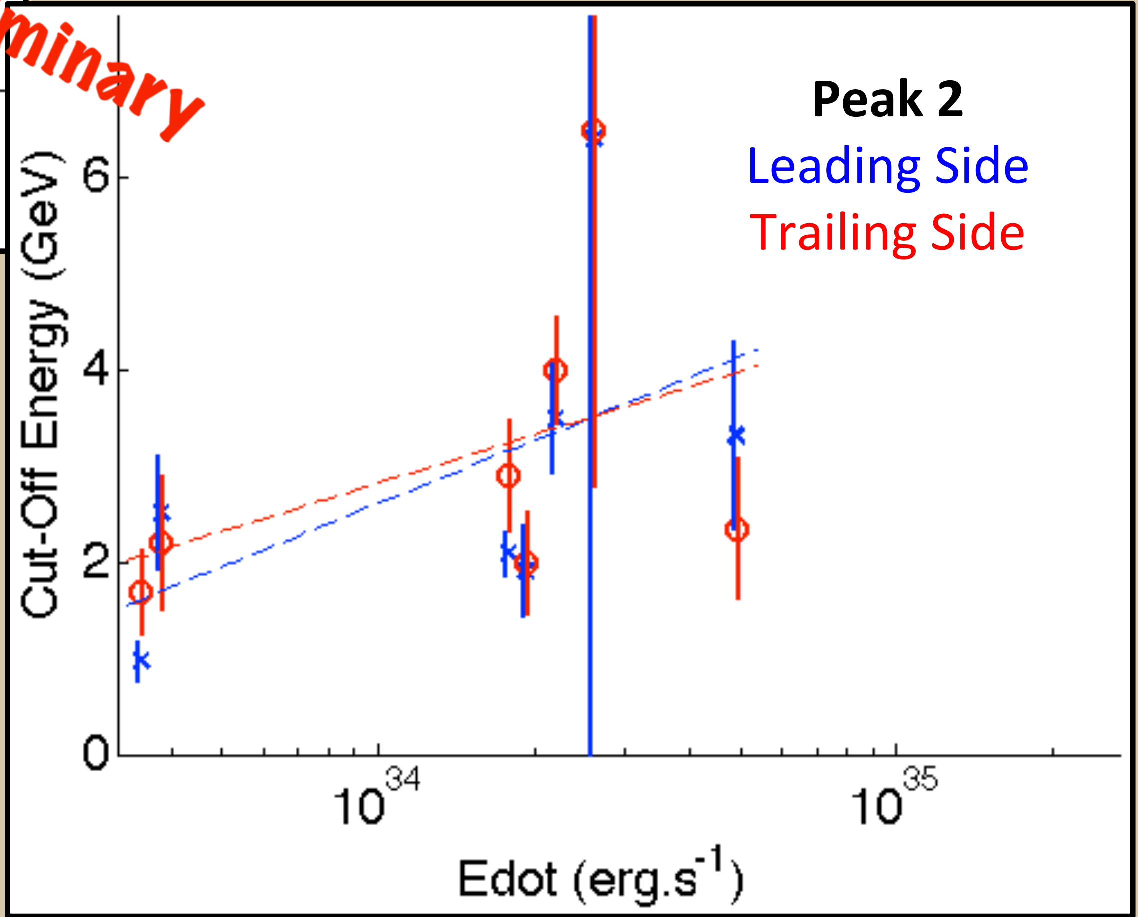
Fig. 6 *Spectral evolution with phase for PSR J2124-3358. Each phase interval in the the γ-ray lightcurve is coded in colour. The spectra correspond to the best-fit solutions. The radio lightcurve at 1.4 GHz is shown in grey.*



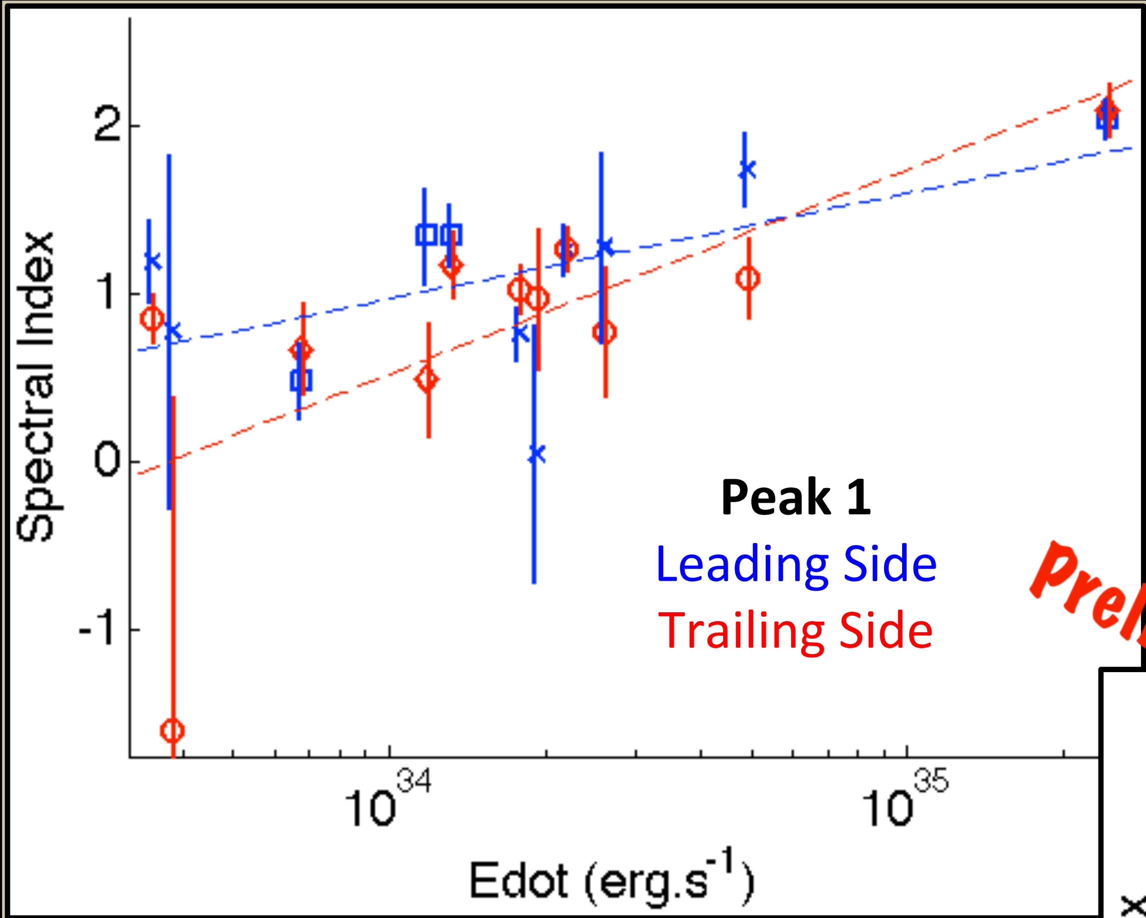
Preliminary

For both peaks :

- Significant apparent evolution of the cut-off energy with spin-down power
- No significant difference between leading and trailing sides



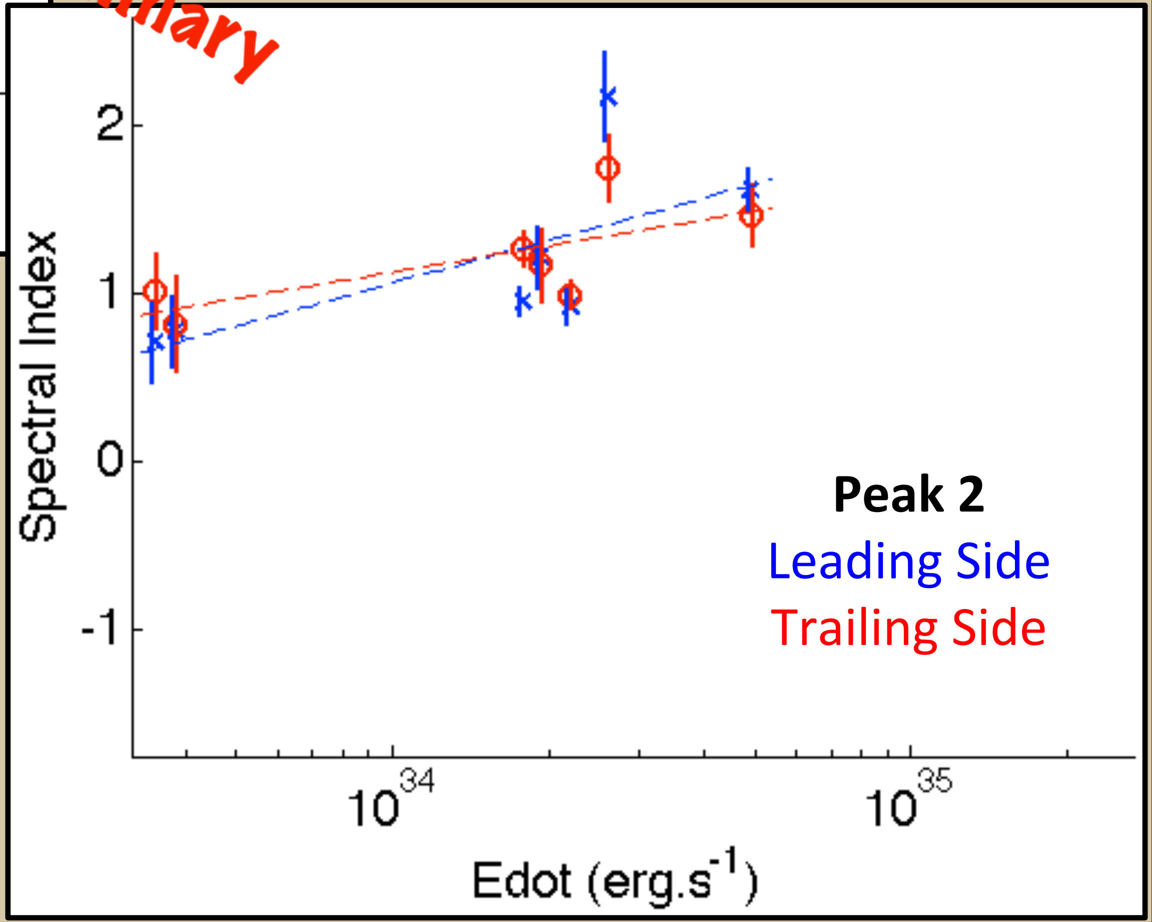
Spectral evolution with rotational power



For both peaks :

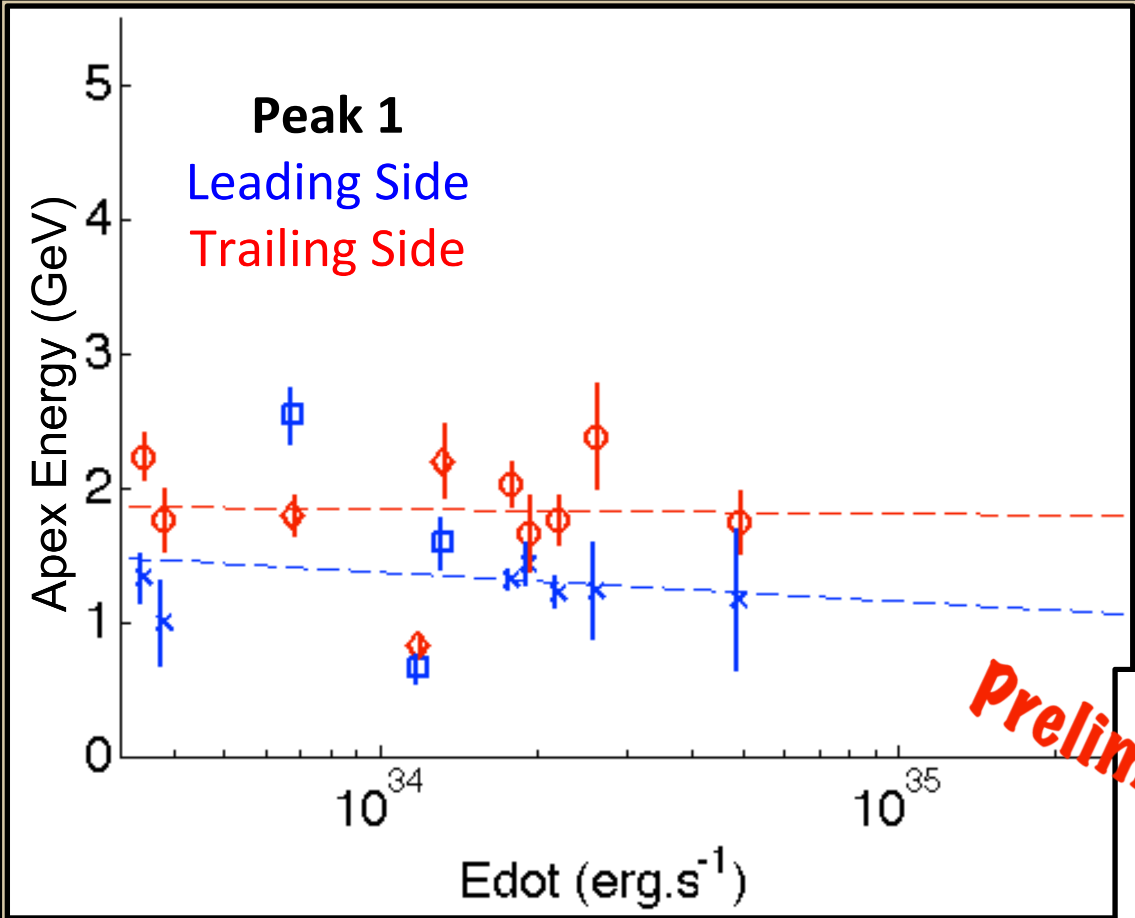
- Increase of spectral index with rotational power

Preliminary



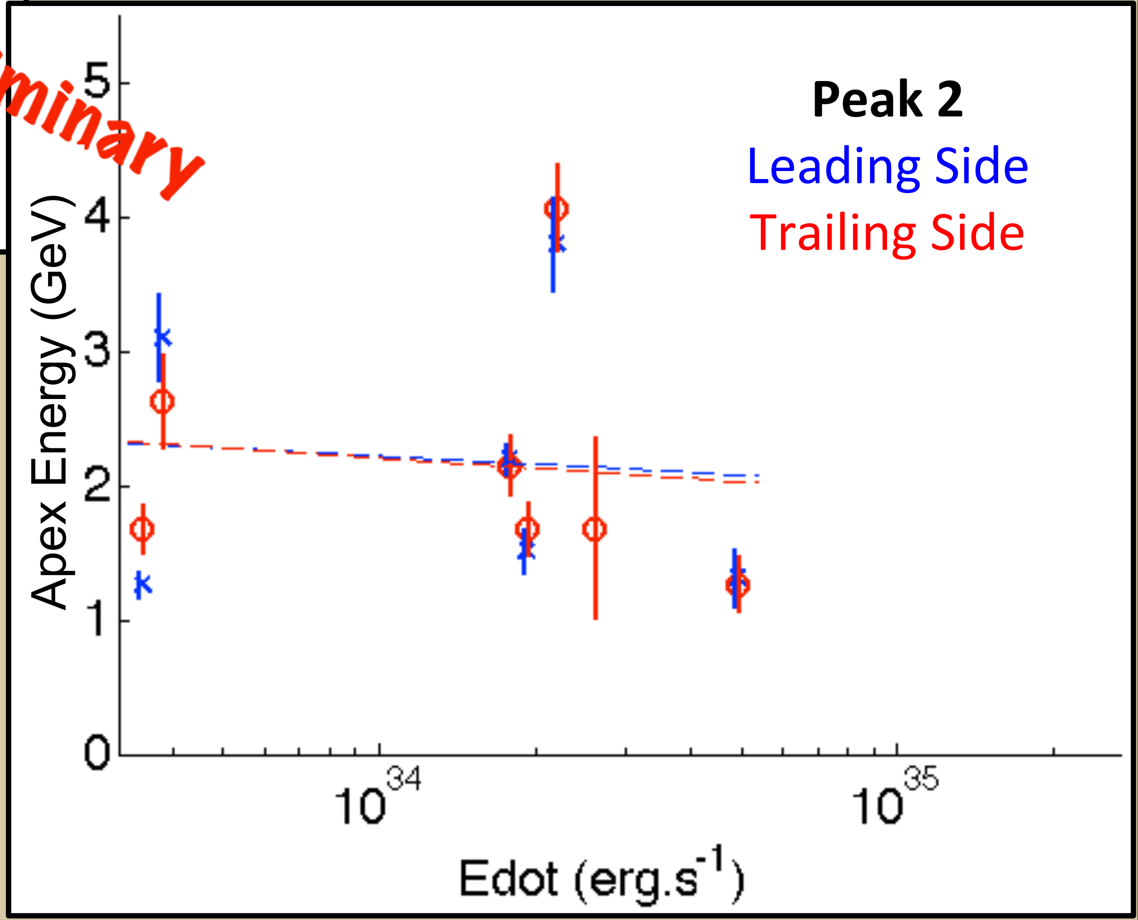
For both peaks :

- We find a correlated evolution of the cut-off energy and spectral index with rotational power



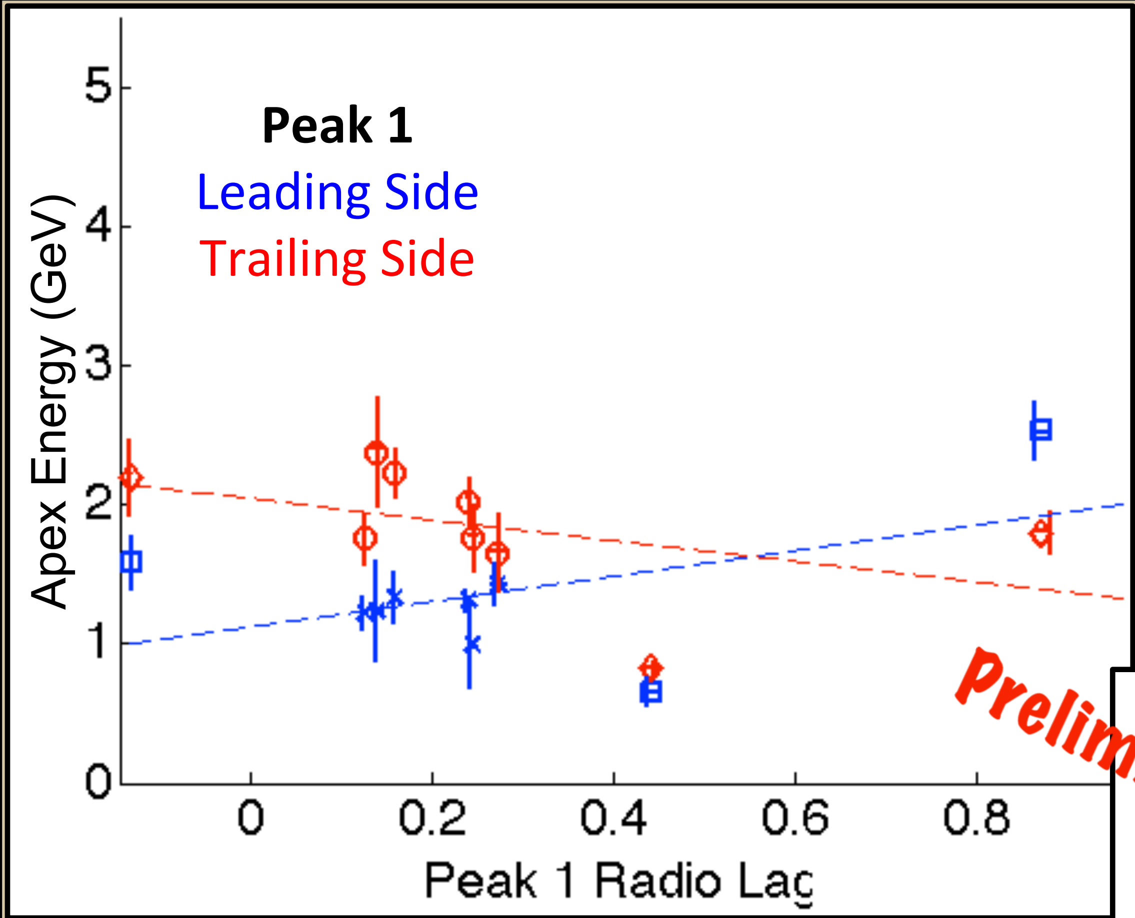
- Peak 1 : Apex energy generally higher on trailing side than on leading one
- Peak 2 : apex energy generally comparable on both sides of the peak

Preliminary



For both peaks :

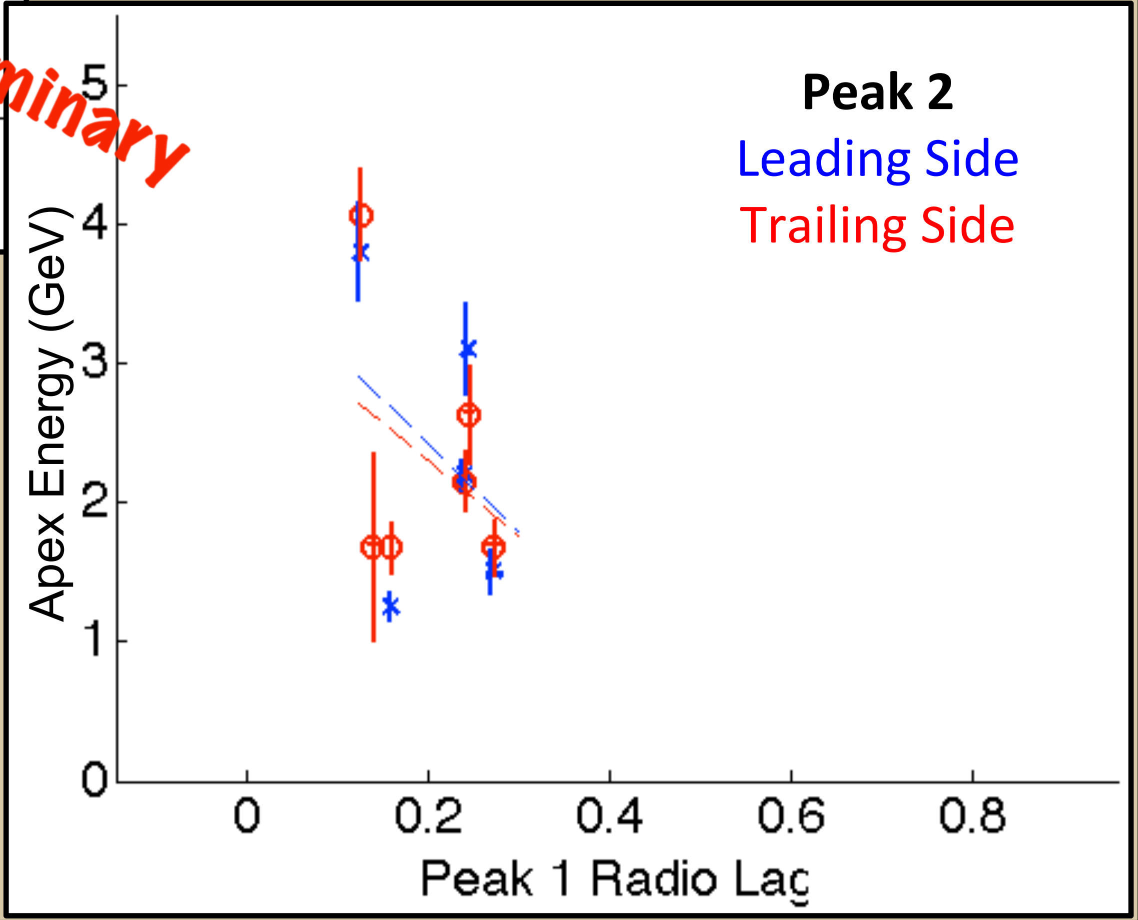
- No apparent evolution of the apex energy with spin-down power (as opposed to the significant evolution of the cut-off energy)



For both peaks :

- Hint of a variation of the apex energy with the radio lag
- Since the apex energy does not evolve with the spin-down power, the small (at best) variation may be related to the magnetic obliquity

Preliminary



Scatter plots Diamonds and squares indicate single-peaked pulsars whereas circles and crosses indicate double-peaked pulsars.

The **peak 1 radio lag** is the phase separation between the first radio peak and the first γ-ray peak.