Gamma-ray Binaries

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High mass γ-ray binaries

- ★ Binary system contains a massive O/B star and a compact star
- ★ Orbits are usually highly elliptical and periods range from 3.9 days to 50 years
- ★ -ray luminosity dominates spectrum (GeV/TeV)
- ★ The high energy emissions are mainly produced by the interaction between stars, and their fluxes vary with orbital phase
- ★ Binary population synthesis study predicted the existence of ~ 30 gamma-ray binaries
- ★ Currently, 7 such systems have been discovered, they are 1FGL J1018.6-5856, HESS J0632+057, LS I +61° 303, LS 5039, PSR B1259-63, a newly discovered one LMC P3/CXOU J053600.0-673507 and PSR J2032+4127/MT91 213 with longest orbital period.

Low mass γ-ray binaries

★ Binary system containing a low mass companion star (WD/MS) and a millisecond pulsar

★Circular orbit with periods 0.1-1 day

★ -ray luminosity dominates spectrum similar to HMGBs but no TeV

★ The GeV gamma-ray emissions are mainly emitted from pulsar magnetosphere or in its vicinity, which do not show orbital modulation. Emissions produced by the interaction between stars are weak and their X-ray flux modulate with orbital phase.

★ Currently, 17 low mass gamma-ray binaries are detected.

Multi-wavelength emissions from pulsar binaries – non-orbital modulation

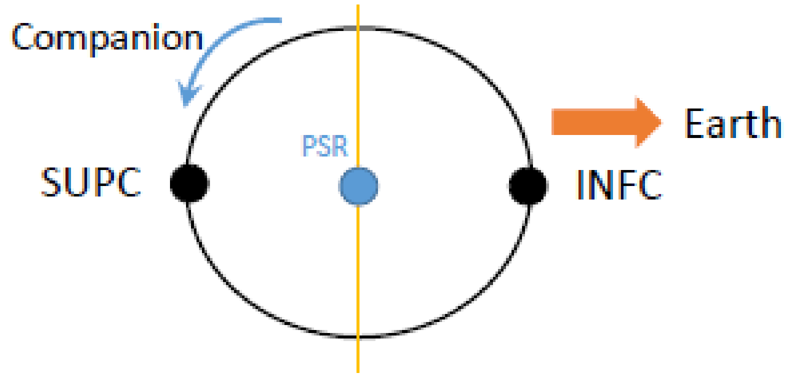
- Spin-modulated emission – this component is emitted from the accelerators inside the pulsar magnetosphere. All low mass gamma-ray binaries exhibit this component but it is unclear if this exists in high mass gamma-ray binaries except the long orbital HXGB PSR J2032+4127/MT91 213, in which spin-modulated gamma-rays are detected. It has a characteristic spectrum as

$$F_\gamma \propto E_\gamma^{-\alpha} \exp(-\frac{E_\gamma}{E_c})$$

where E_c~GeV

Multi-wavelength emissions from pulsar binaries – orbital modulation

- The first orbital modulated gamma-ray emission produced by IC between pulsar wind-stellar photons. The gamma-ray peak should occur at INFC/SUPC.



- It has a characteristic spectrum as

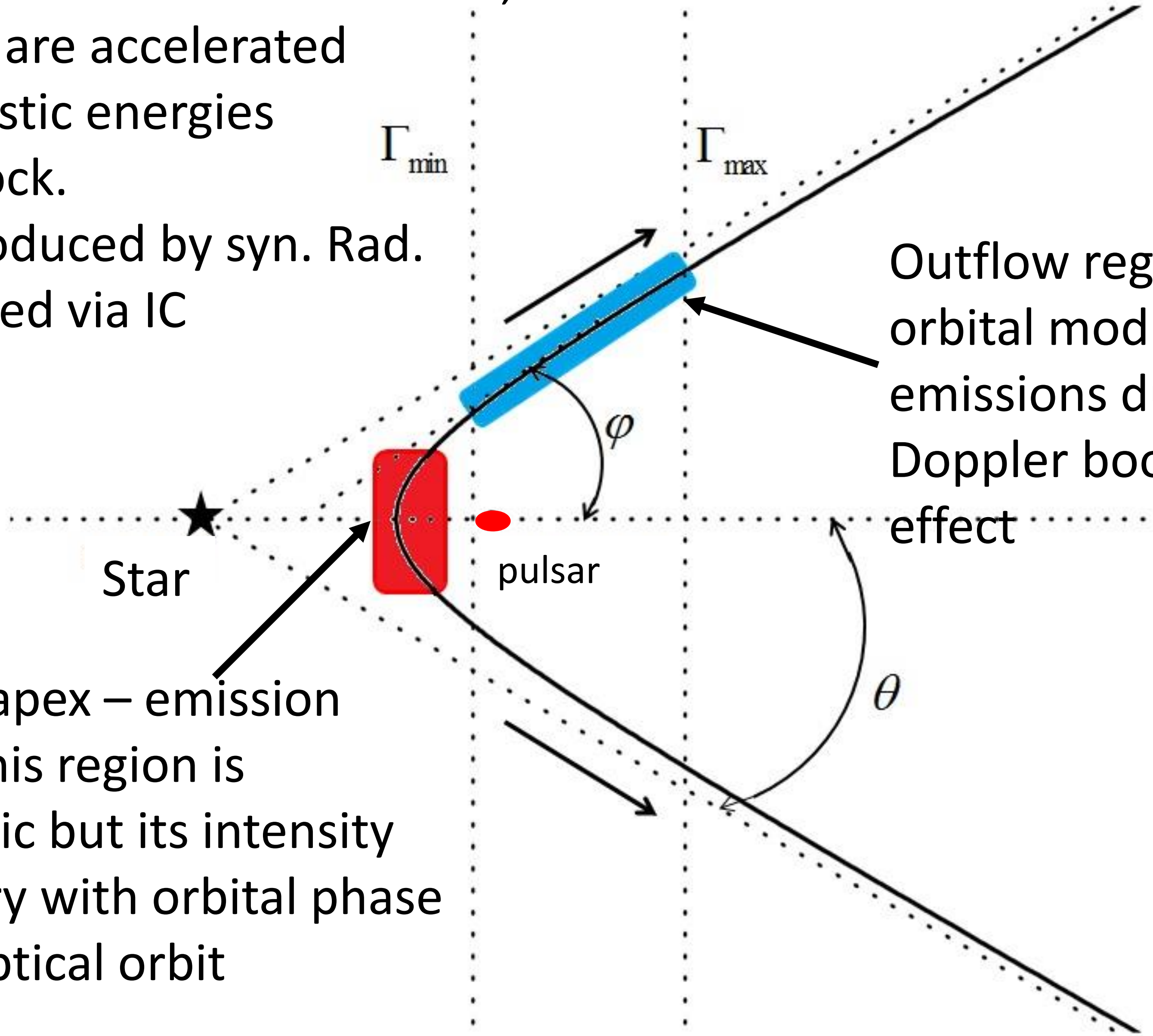
$$F_{\gamma} \propto \exp(-(\frac{E_{\gamma} - \Gamma_{w}{}^{2}kT_{c}}{\sigma_{w}^{2}})^{2})$$

Pulsar wind contains nearly mono-energetic relativistic $e^{\pm}$ pairs

where T_c is the temperature of the companion star, $\Gamma_w \sim 10^4$ is the Lorentz factor of the PW and σ_w is the energy spread in PW.

Second orbital modulated emission results from the interaction of the pulsar wind and the stellar wind, which forms a termination shock.

Electrons are accelerated to relativistic energies in the shock.
X-rays produced by syn. Rad.
TeV emitted via IC



Outflow region - orbital modulated emissions due to the Doppler boosting effect

Shock apex – emission from this region is isotropic but its intensity can vary with orbital phase for elliptical orbit

Emissions produced by IC between disk photons and PW – non-orbital/orbital modulation

- The (transient) accretion disk can be formed in some gamma-ray binaries which can also provide soft photons. IC between these soft photons and PW can also produce gamma-rays. In principle this process cannot produce orbitally modulated gamma-rays, e.g. in LMGB PSR J1023.4+0038. However if the life time of the disk is shorter than the orbital period, the gamma-ray signal exhibits orbital variation, e.g. in HMGB PSR B1259-63/LS2883. The characteristic spectrum is also given by

$$F_\gamma \propto \exp(-(\frac{E_\gamma - {\Gamma_w}^2 kT_d}{\sigma_w^2})^2)$$

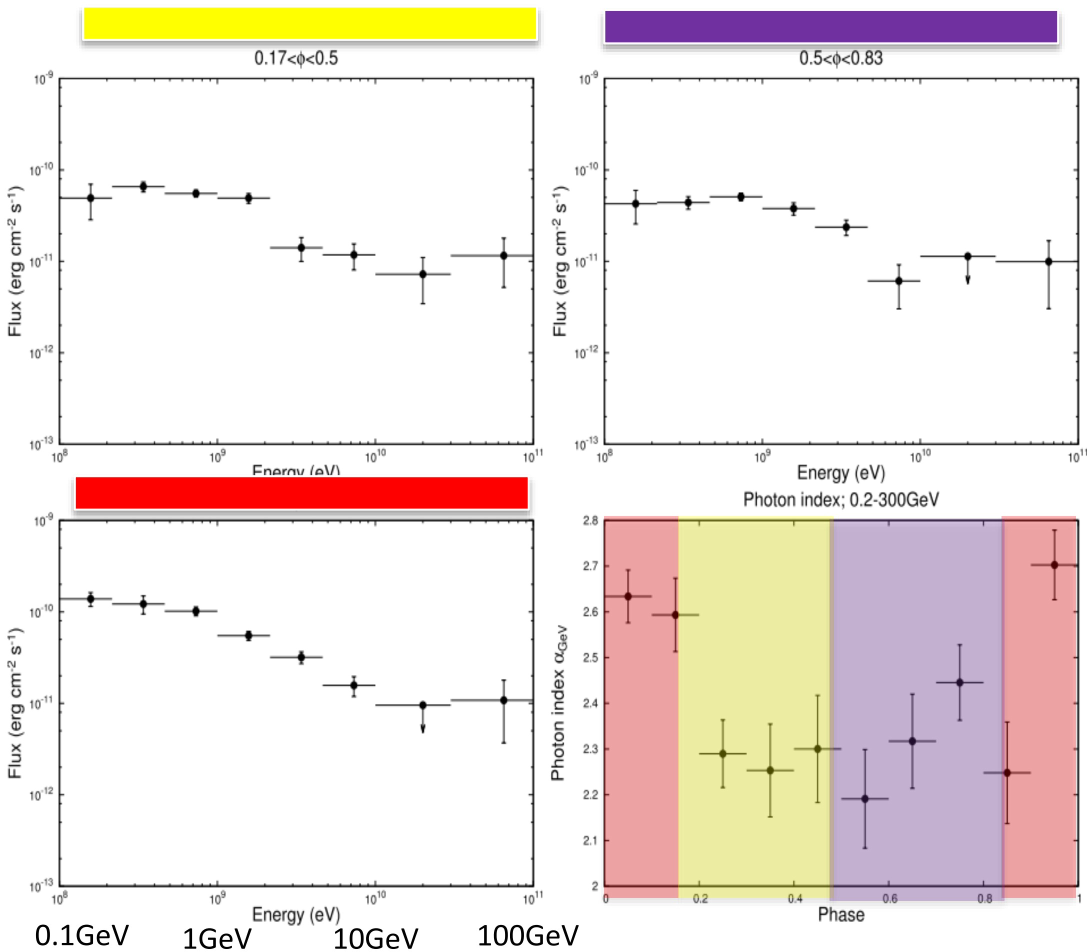
where T_d is the temperature of the disk.

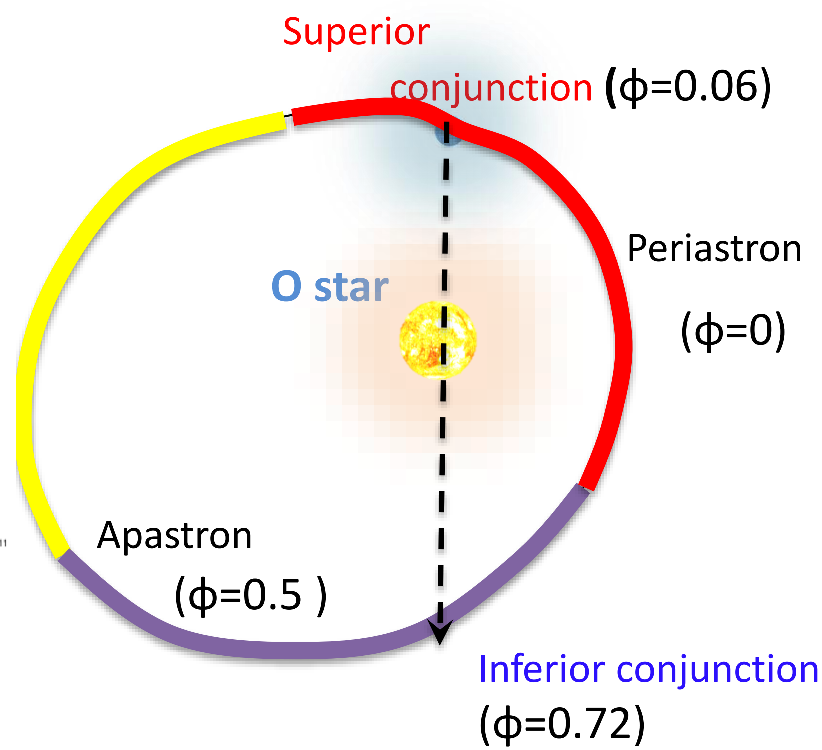
Applications to various gamma-ray binaries

- HMGBs - LS5039, PSR 1259-63 and PSR J2032+4127/MT91 213
- LMGBs –PSR J1023.4+0038 (RB)

LS 5039 (3.9 day elliptical orbit) (Takata et al. 2014)

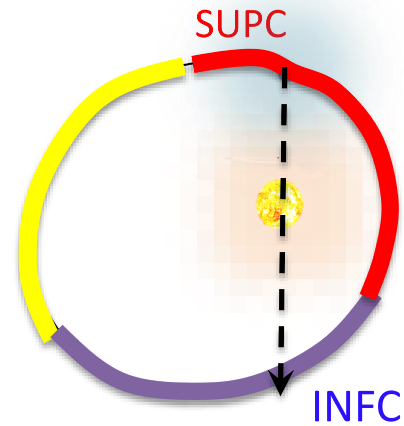
Orbital phase resolved spectra

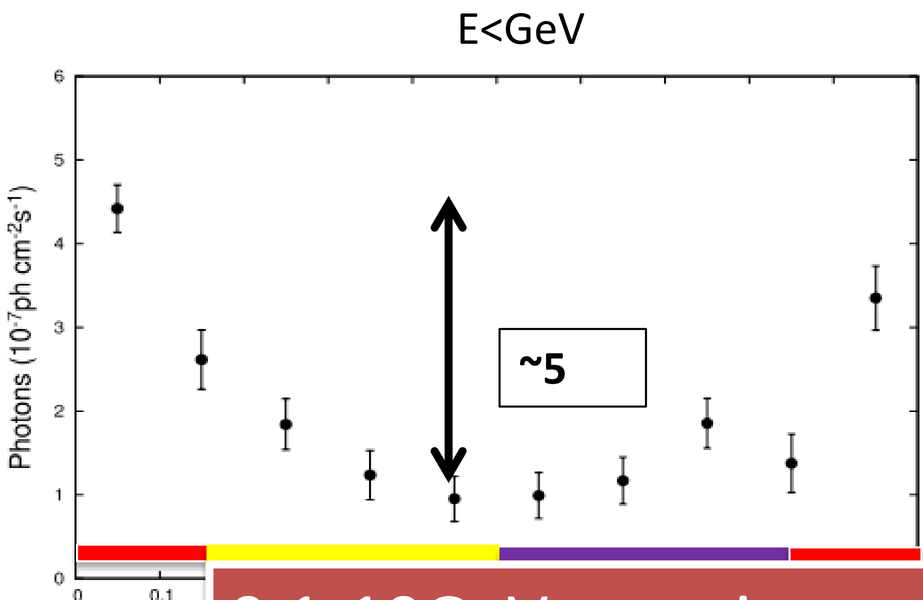


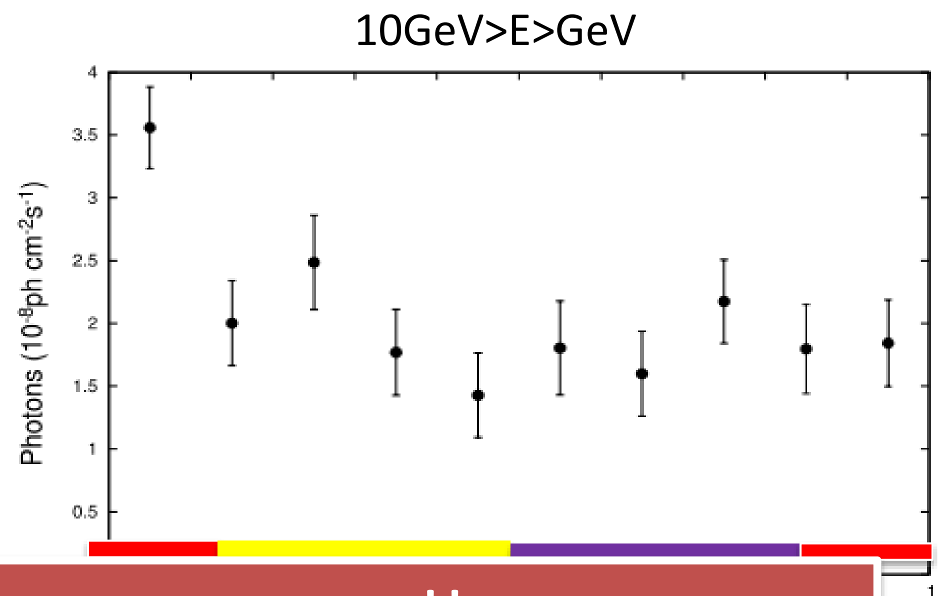


We can see that the spectral properties vary with orbital phase.

- Photon counts vs. orbital phase





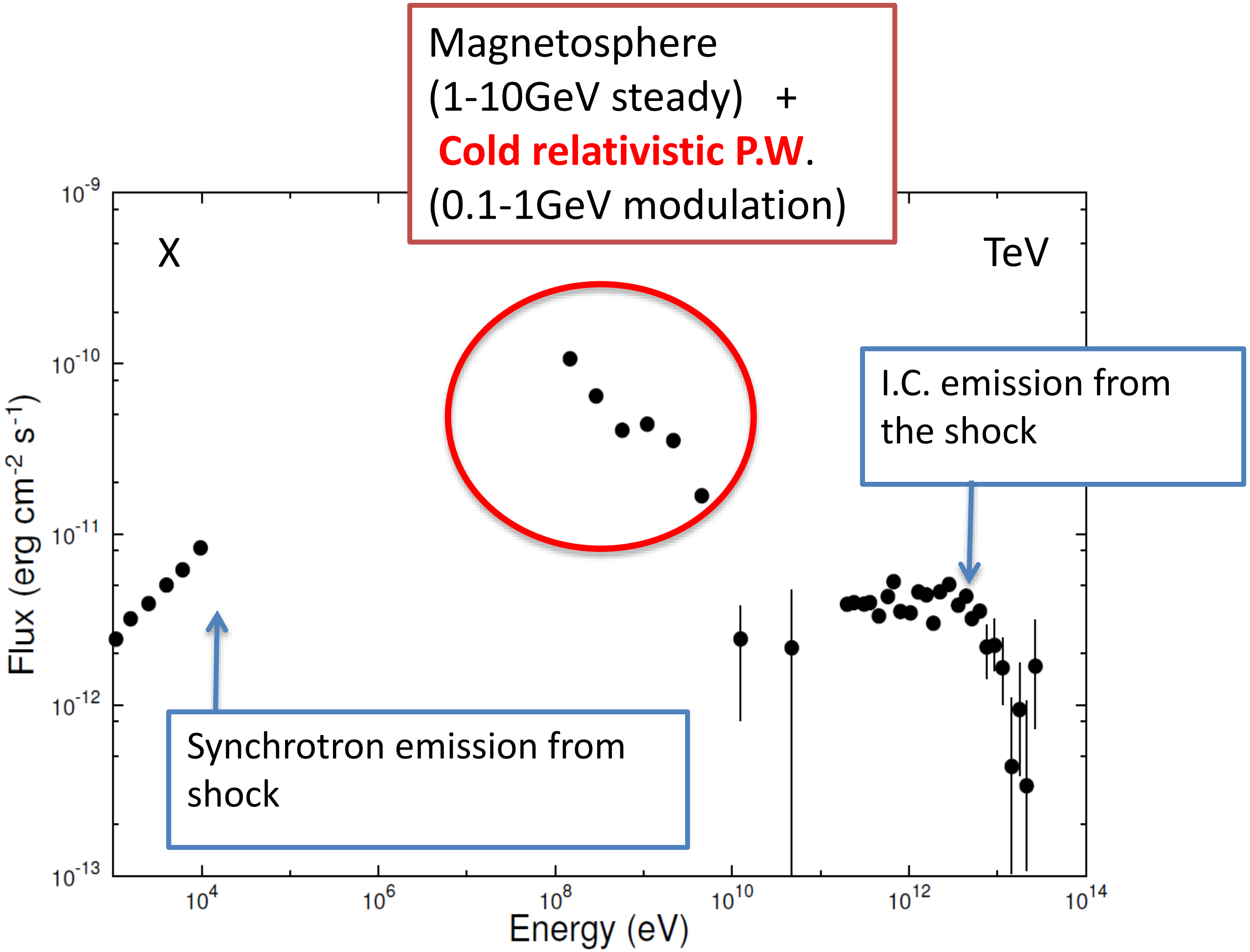


0.1-10GeV contains two components!!

→① Above 1GeV, steady emissions +

② Below 1GeV, modulating emissions

Theoretical Model (assuming the compact companion is a pulsar)



4) Model parameters

- Spin down power $\boldsymbol{L_{sd} = 2 \times 10^{36} \mathrm{erg/s}}$

(determined by observed flux)

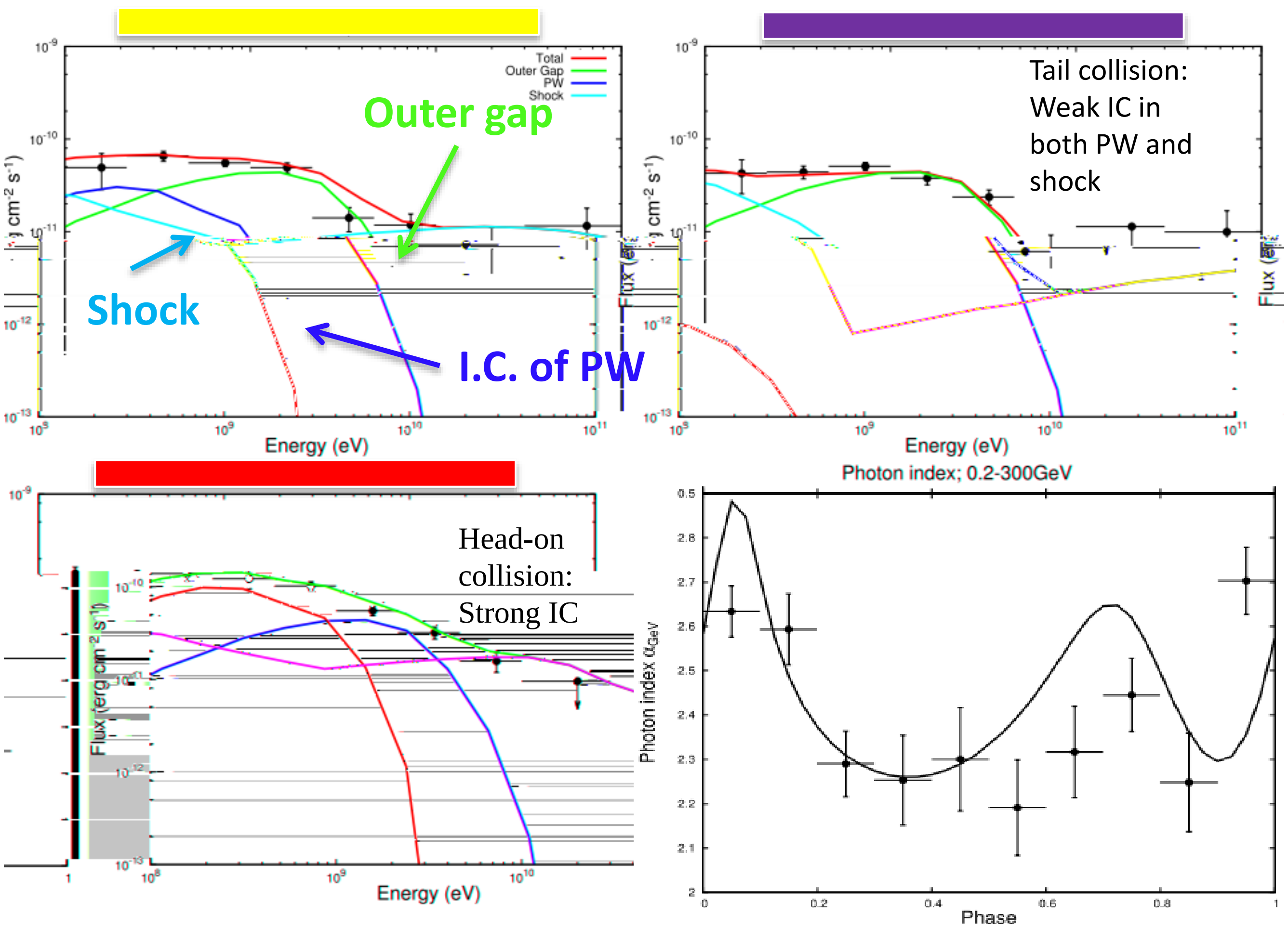
- Lorentz factor of cold-relativistic pulsar wind $\Gamma_{cpw} \sim 10^4$

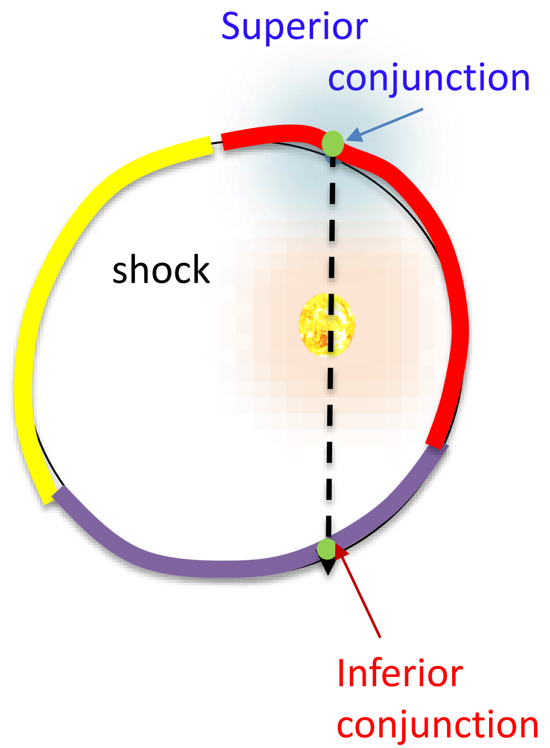
(determined by the Fermi data fitting)

- Earth viewing angle measured from the perpendicular to the orbital plane $i \sim \mathbf{60\ degree}$

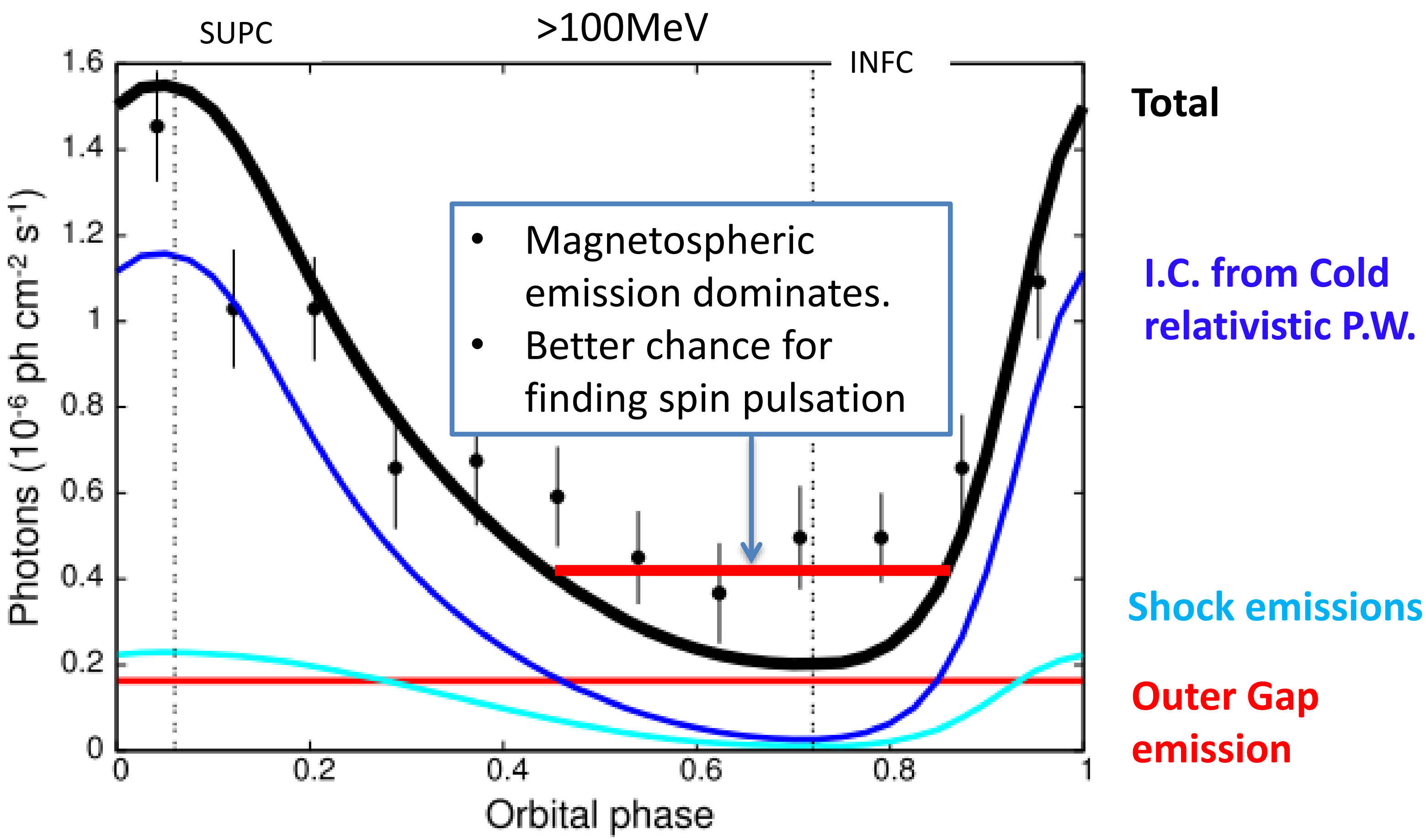
(determined by observed orbital modulation)

Model fitting of Fermi data



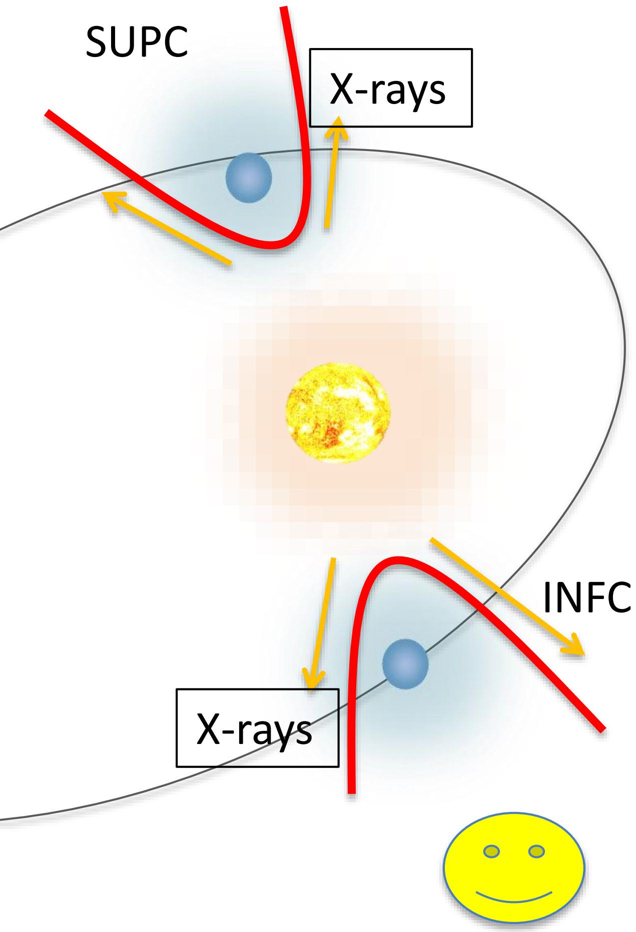


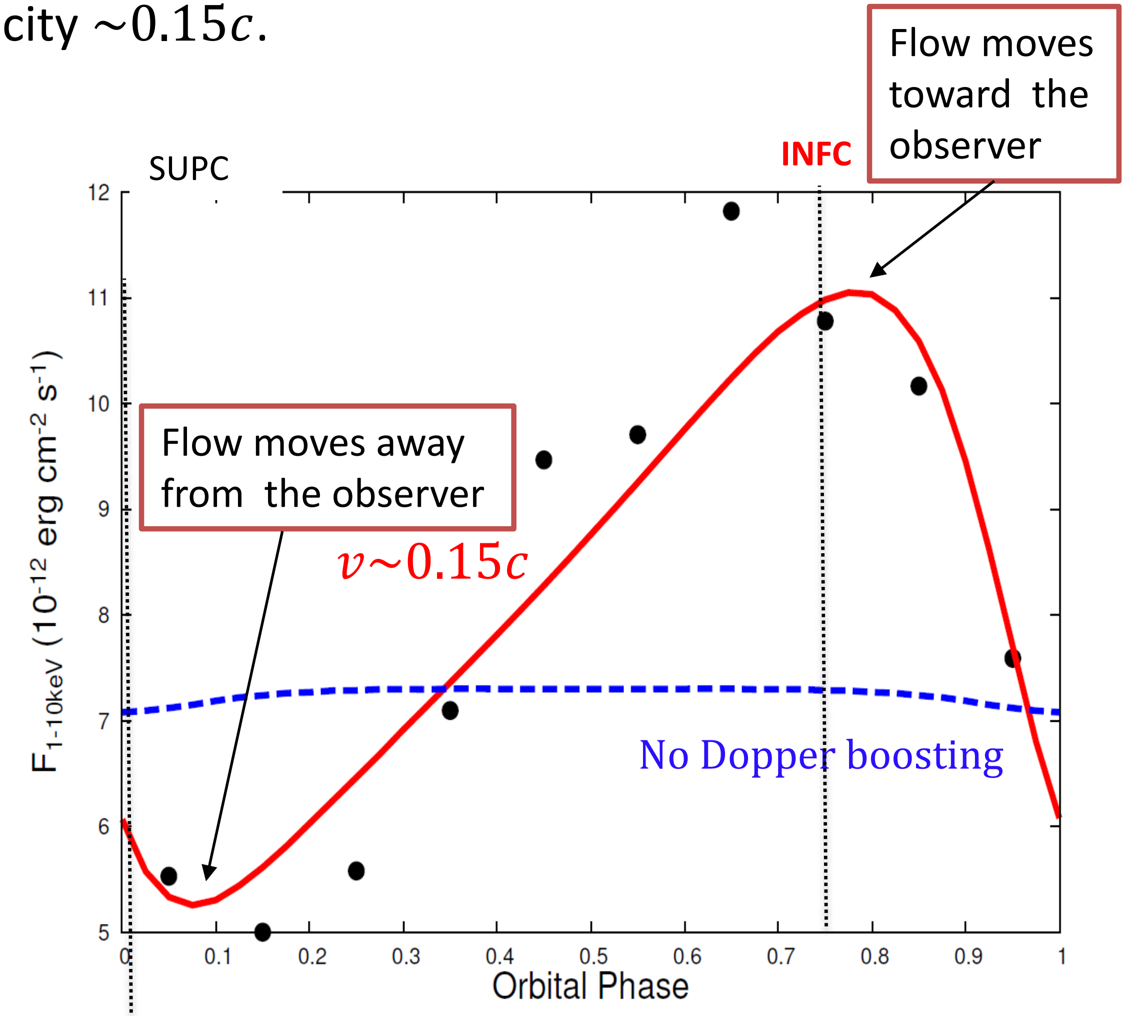
>100MeV light curves



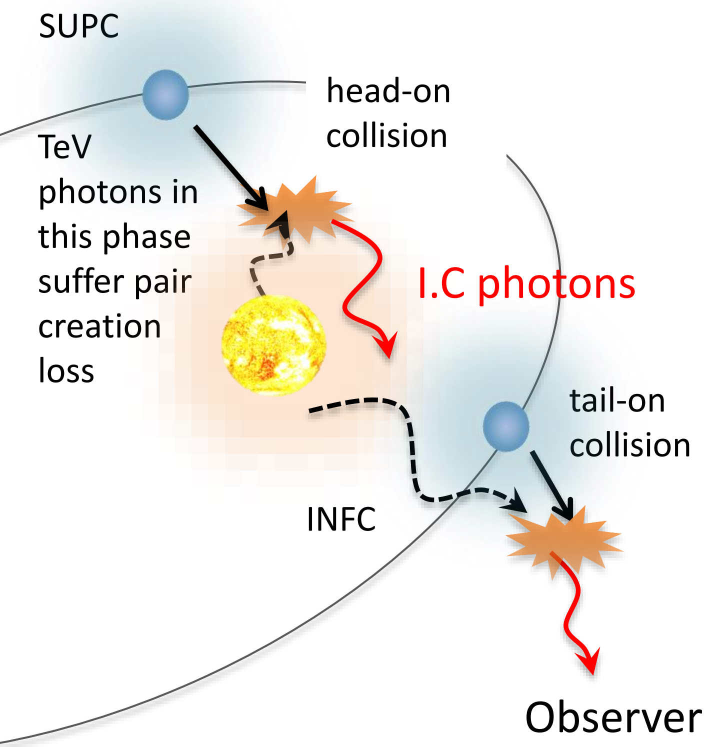
X-ray light curves

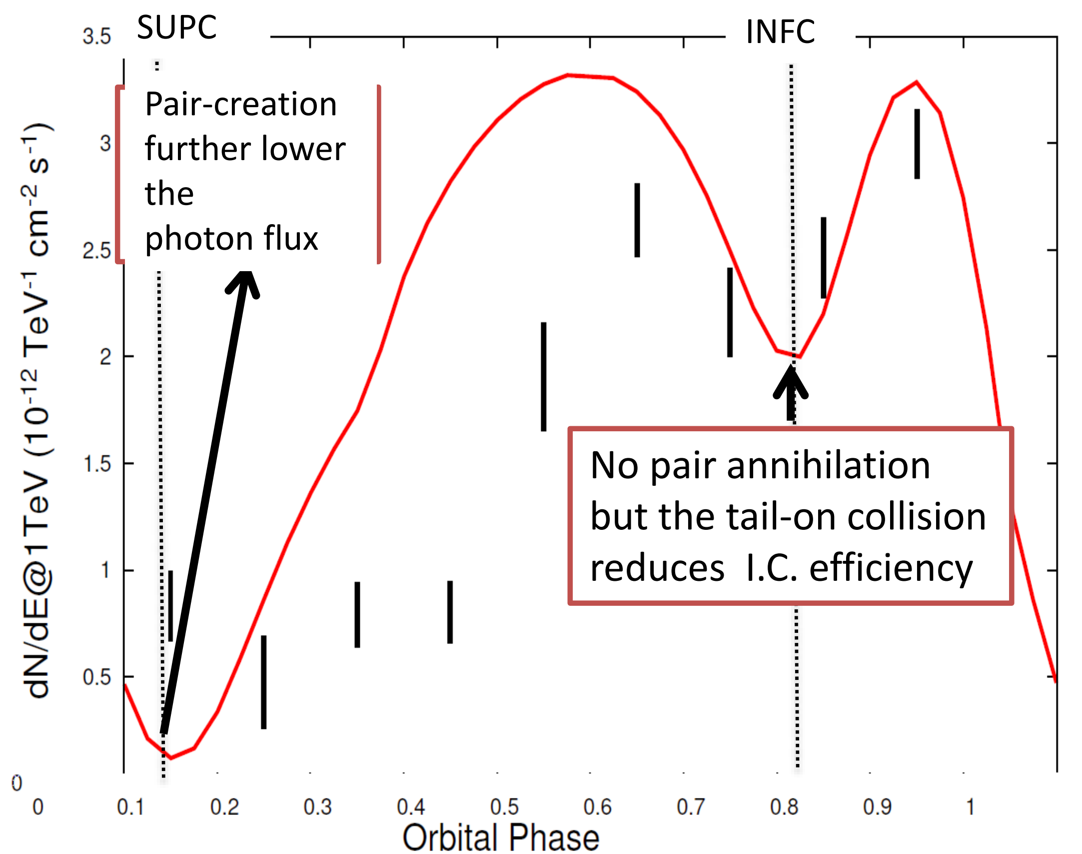
- Amplitude is explained by the effect of the Doppler boosting with the shocked pulsar wind velocity $\sim 0.15c$.





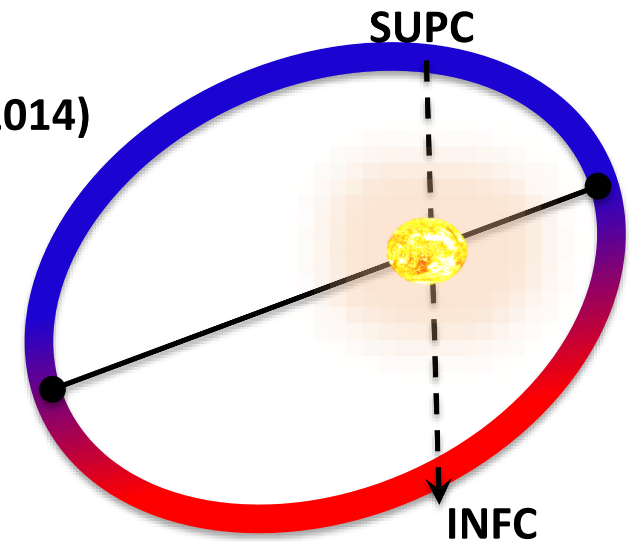
TeV light curves

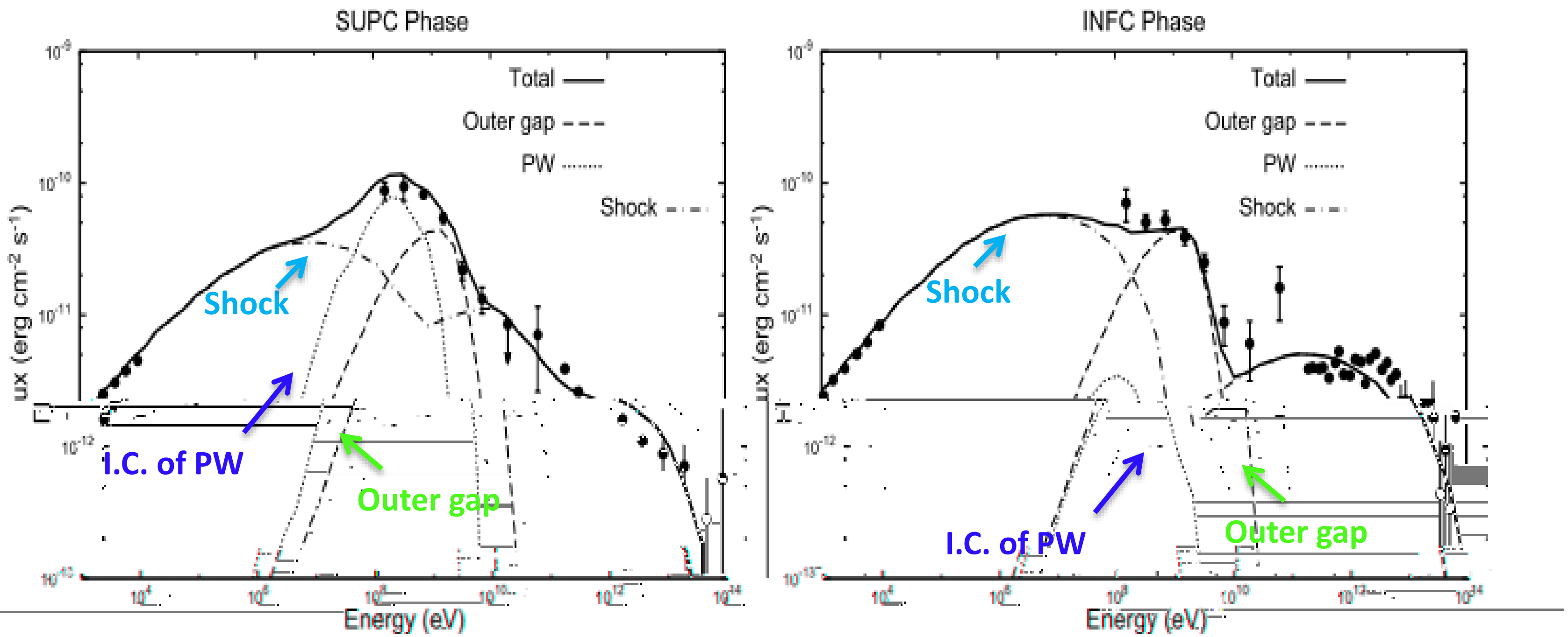




■ Multi-wavelength spectra **(Takata etal. 2014)**

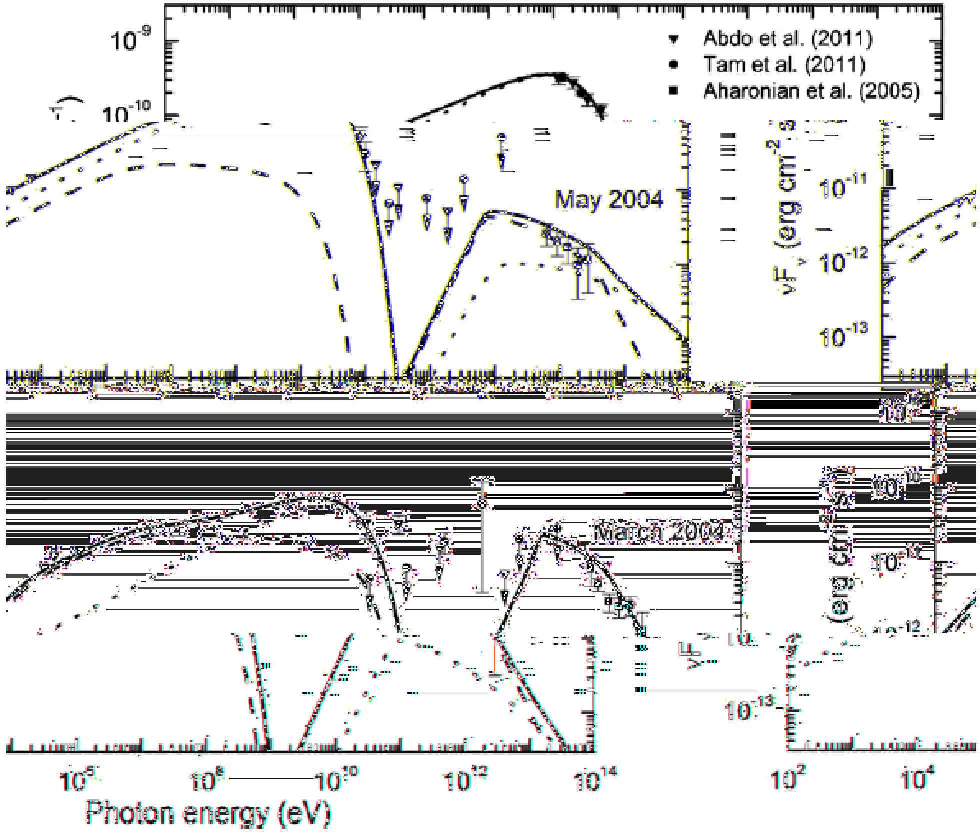
(1)In INFC both X-ray and TeV are enhanced significantly, this results from Doppler boosting effect
(2)PW component is strong in SUPC and is weak in INFC due to effective low soft photon density and tail-collision

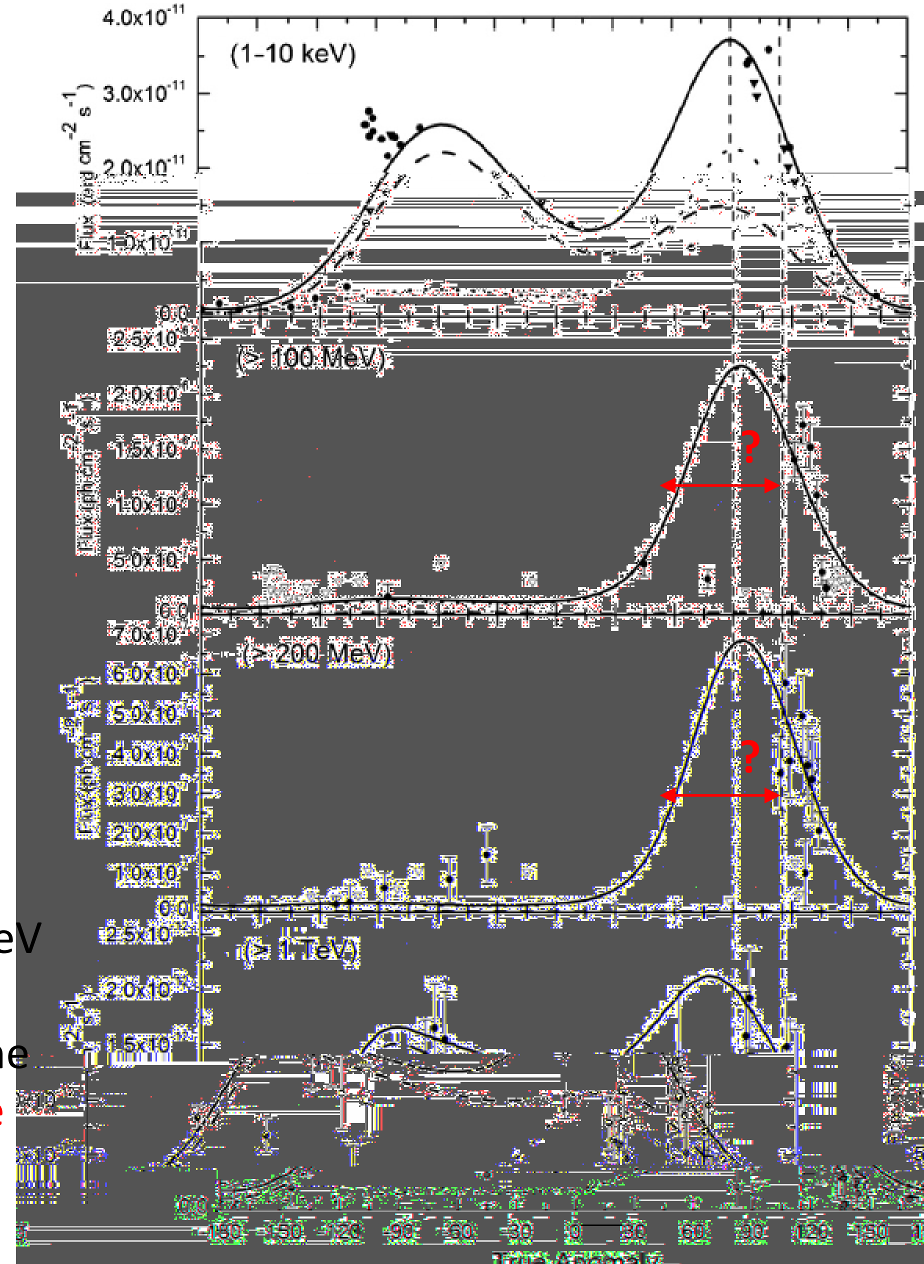




X-ray and TeV spectra only available in two orbital phases

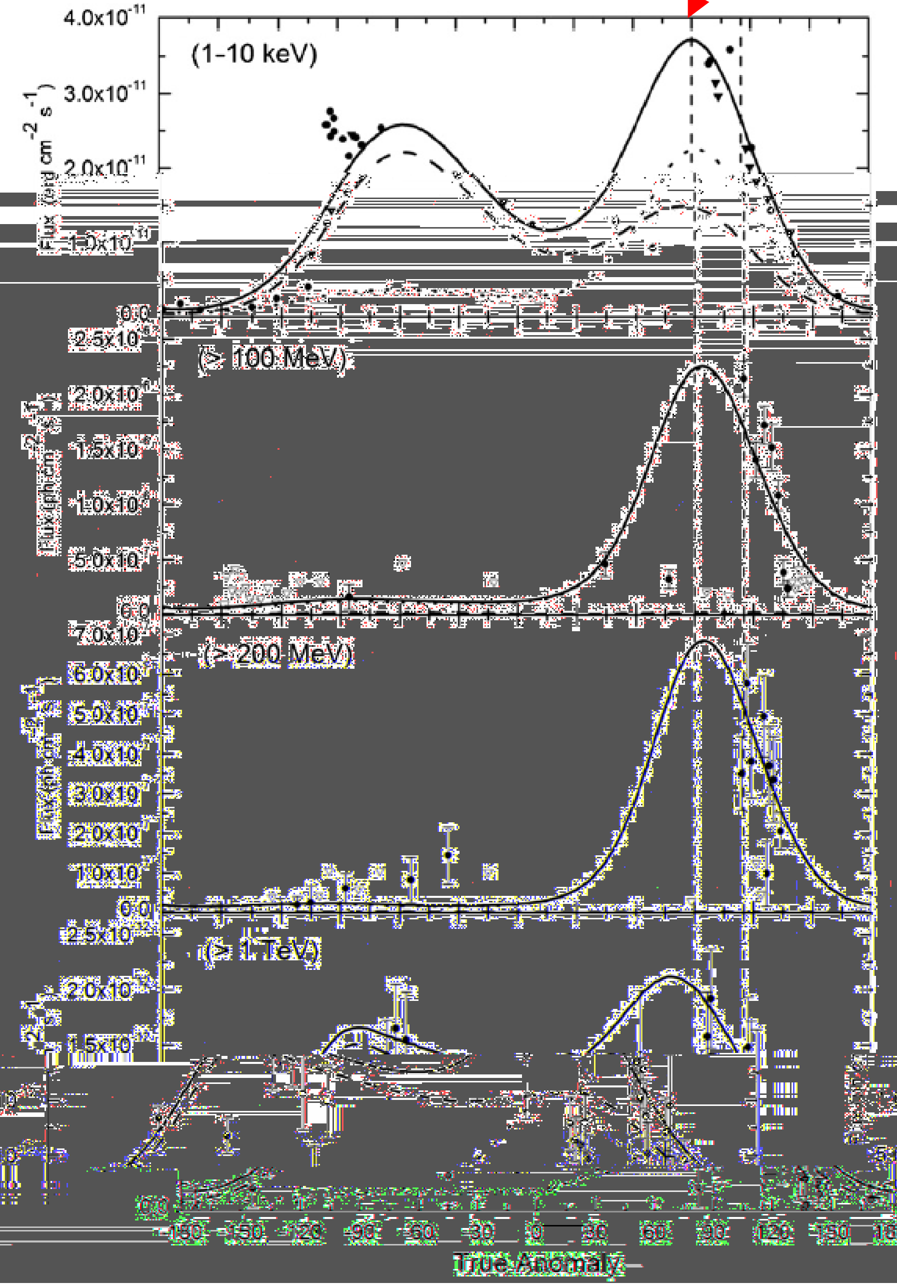
PSR 1259-63 (pulsar+Be star, T_{orb}=1236days): Orbital dependent spectra and light curves



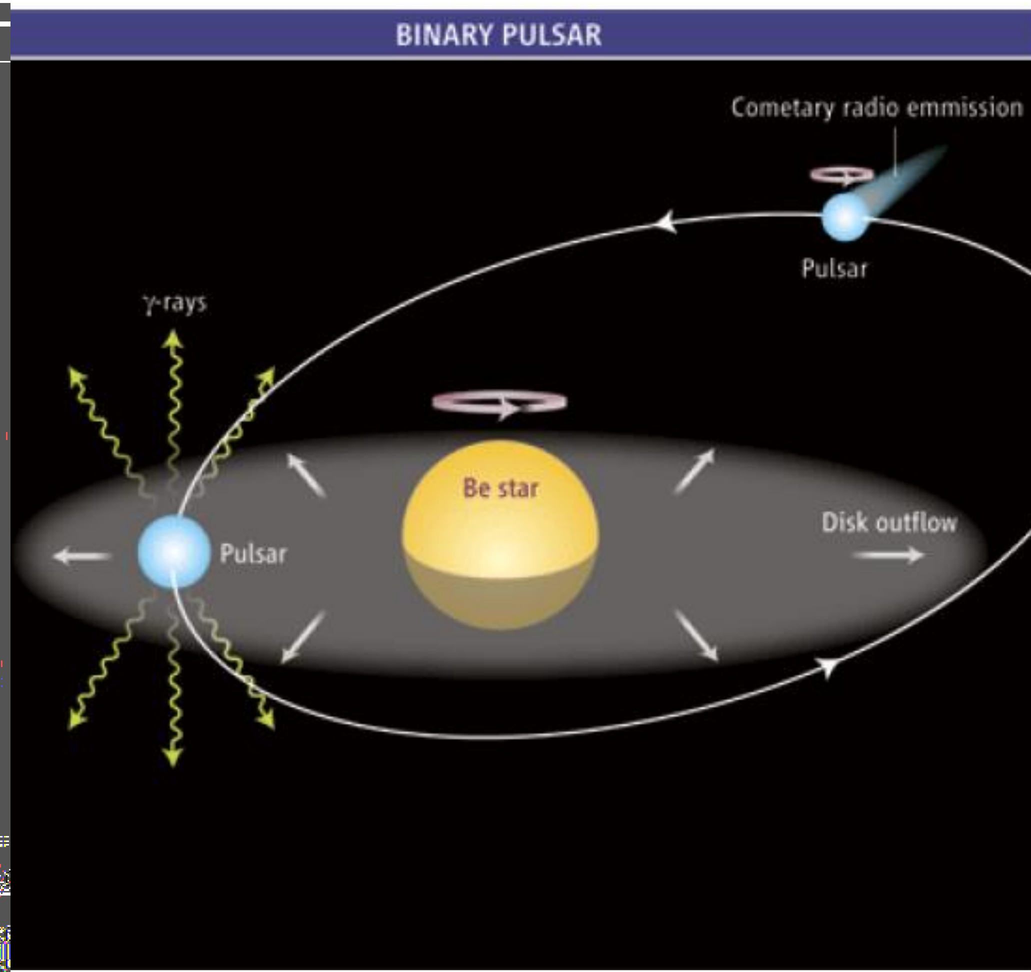


Kong et al. explained the X-rays and TeV via synchrotron and IC processes in shock,and the GeV result from Doppler Boosting effect because the stellar photon density is not enough to explain the GeV flux. However, the predicted GeV-light curve does not match the observed data between 60-120 degree

Stellar disk



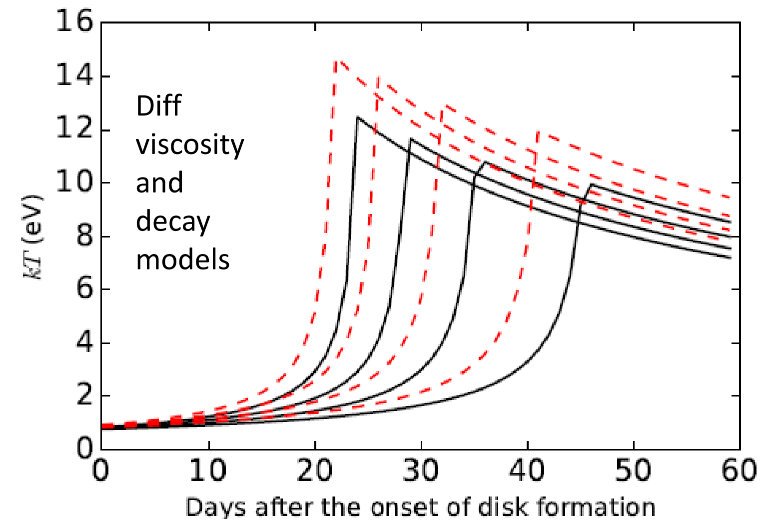
Accretion may take place in the stellar disk



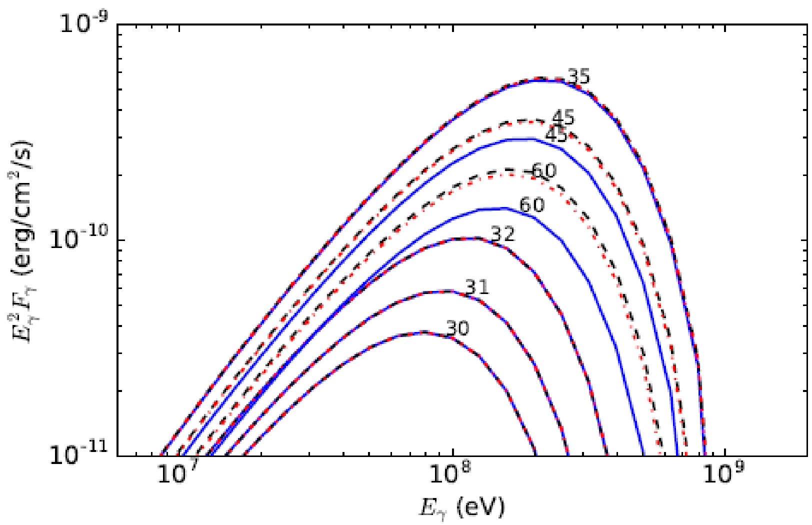
Formation of transient disk around NS during the passage of stellar disk

Yi and Cheng 2017

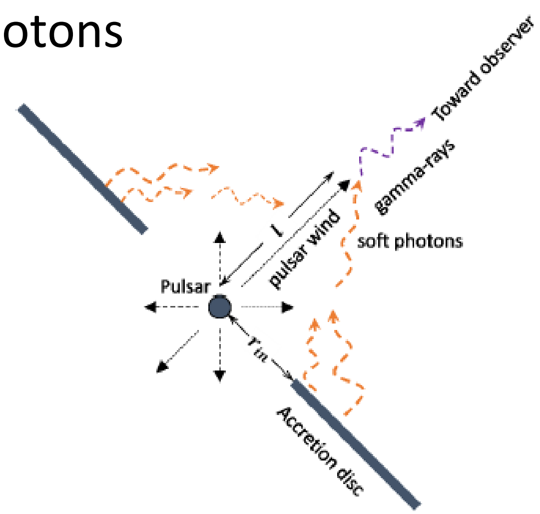
- Mass are captured by the gravity of NS during the passage of the stellar disk
- The capture matter spiral in to form an accretion disk surrounding the pulsar, which takes roughly a few tens days
- The optical/UV emission is gradually increasing with time as the disk moves in and decreasing with time after reaching the Alfven radius
- GeV gamma-ray emission via IC between PW and disk photons



Time for the peak T depends on α

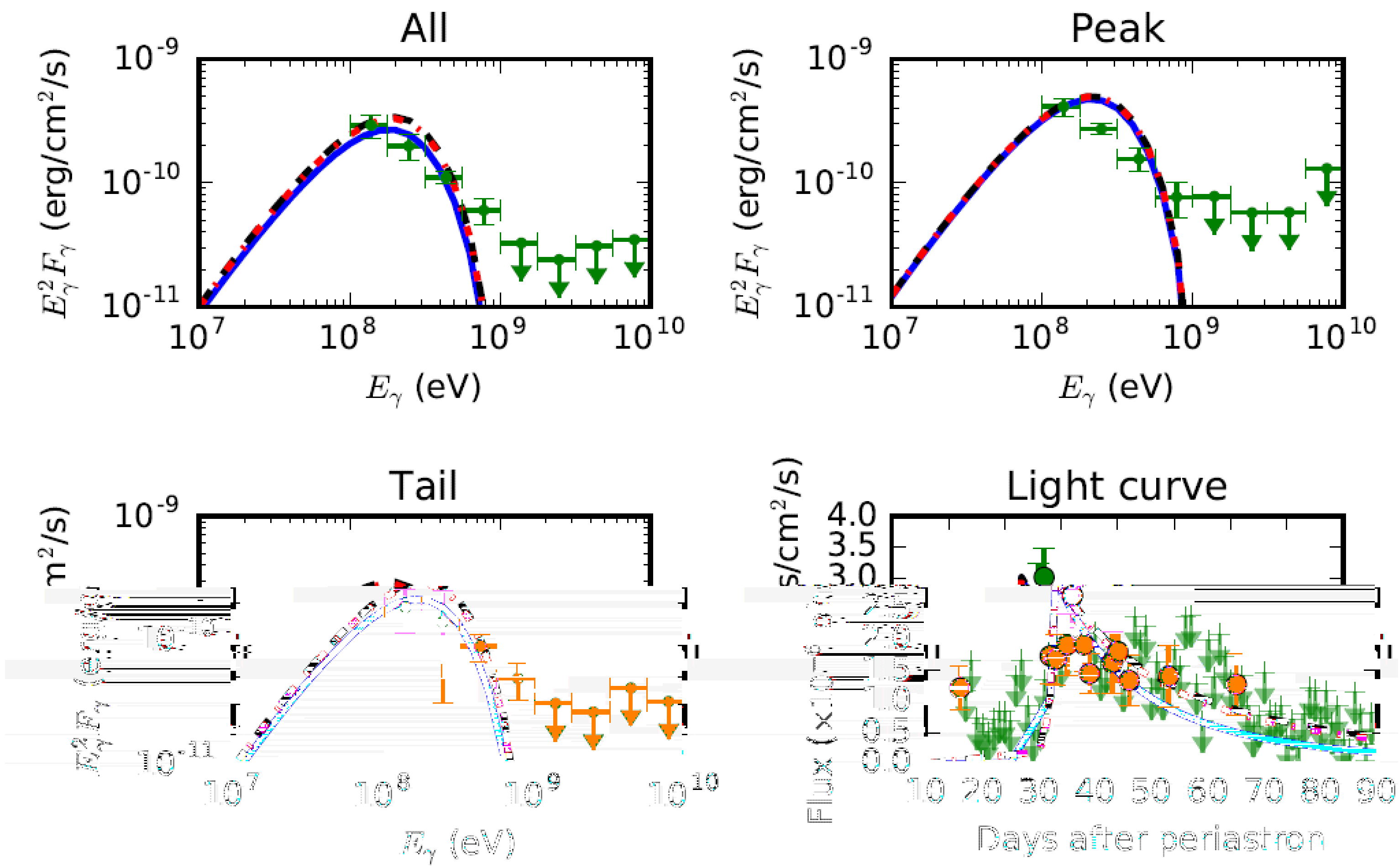


Time evolving spectrum



Transient gamma-ray emission via IC between the accretion disk photons and PW

Data : Caliandro et al. (2015)



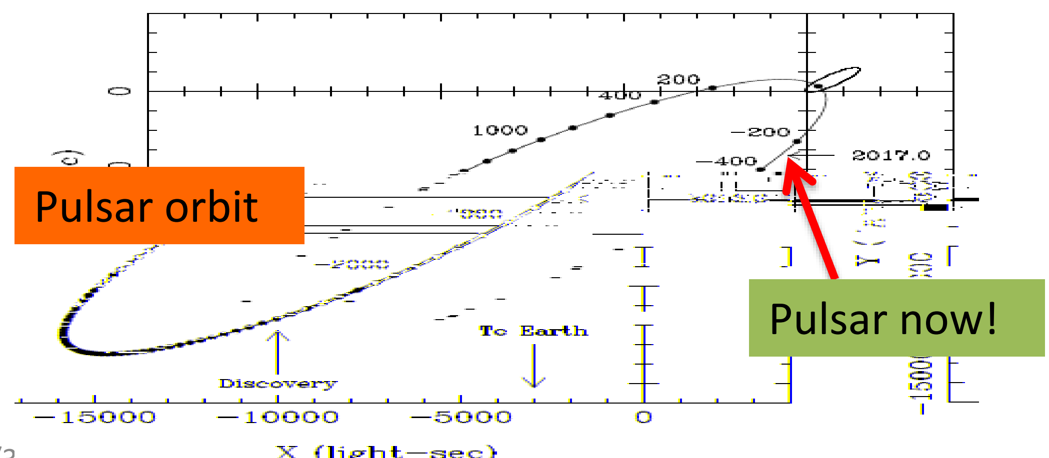
PSR J2032+4127/MT91 213

- Radio loud young pulsar/Be star
- Rotation pulsed emission in Radio/GeV (no orbital GeV yet)

$$P \simeq 143\ \mathrm{ms} \quad L_{\mathrm{sd}} \simeq 1.7 \times 10^{35}\ \mathrm{erg/s}$$

- Very long orbit binary: Po~50 years.

  (Lyne et al. 2015: Ho et al. 2016)
- Next periastron passage in late 2017.



Predicted spectra near periastron (Takata etal. 2017)

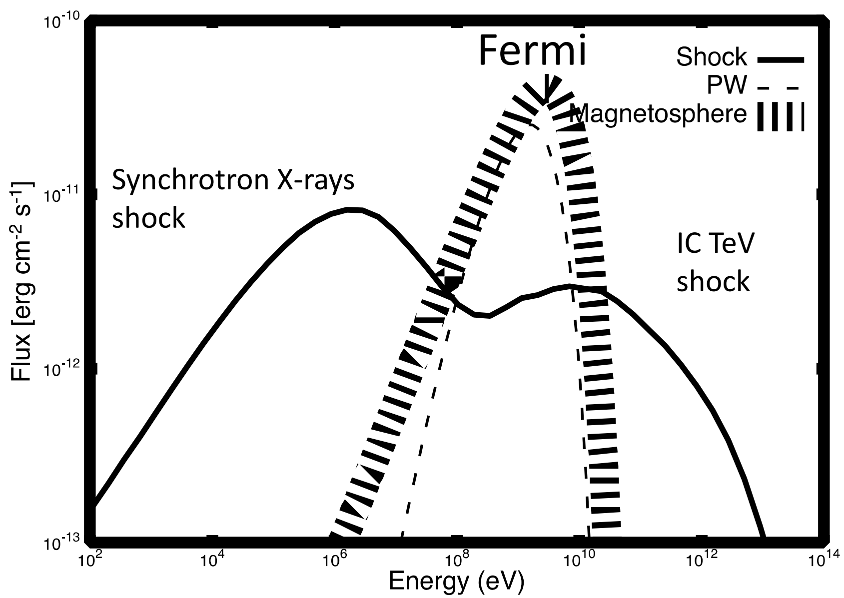
- IC on relativistic pulsar wind + shock

-- Pulsar will encounter the stellar disk to form an accretion disk around the periastron

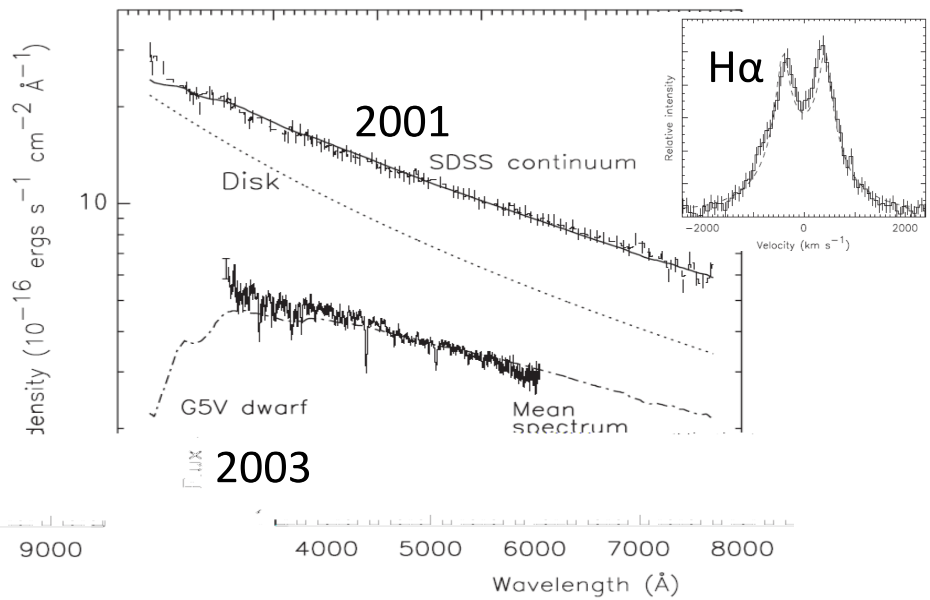
-- An additional GeV component is produced via I.C. scattering off the disk photons

-- Predicted flux ~10^{-10} ergcm^{-2}s^{-1} at periastron (IC flux~ magnetosphere flux).

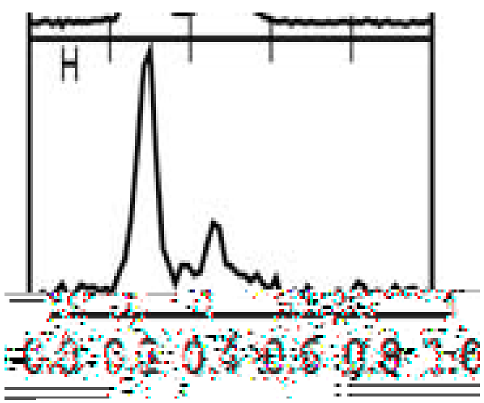
SED averaged over -200days - +200days



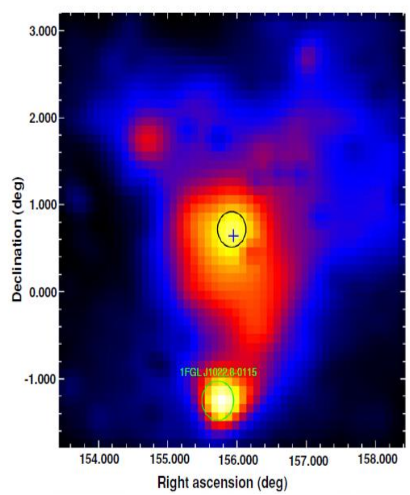
PSR J1023.4+0038 (MSP/low mass MS binary: a circular orbit with 4.75 hr period)



- Evidence (hydrogen and helium line emissions) of truncated accretion disk in 2001, and no pulsed radio emissions (Wang et al. 2009, *ApJ*)
- In 2003 pulsed radio emission was found with no disk (Archibald et al. 2009 *Sci*).
- We found weak non-thermal X-ray and gamma-ray emissions (2FGL J1023.6 + 0040; Tam et al. 2010, *ApJL*)



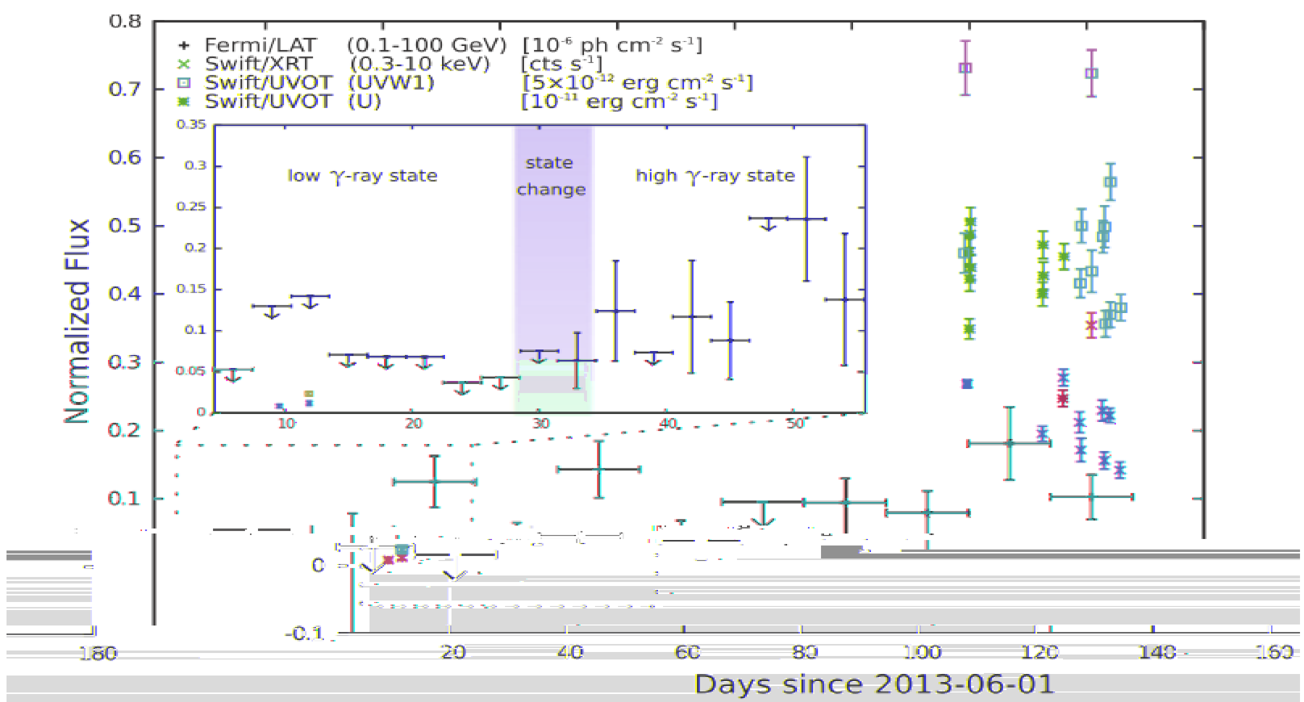
Radio pulse profile



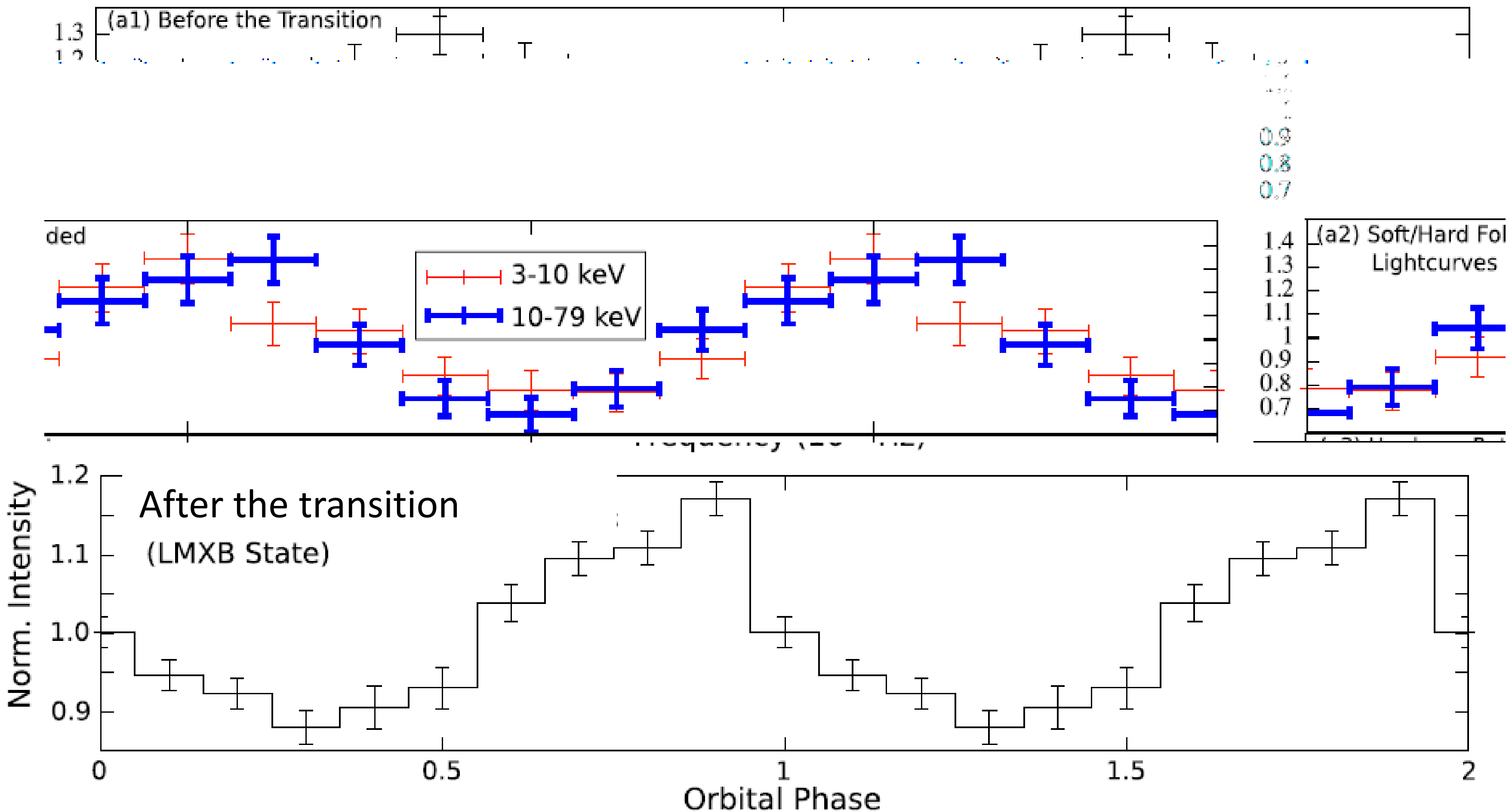
Test-Statistical map of 2FGL J1023

New stage J1023.4+0038

- After June, 2013, the pulsed radio emissions disappeared
- X-rays (up by factor 20) and gamma-rays (up by factor 5) increases.
- Evidence of the accretion disk (Hα emission) around the pulsar



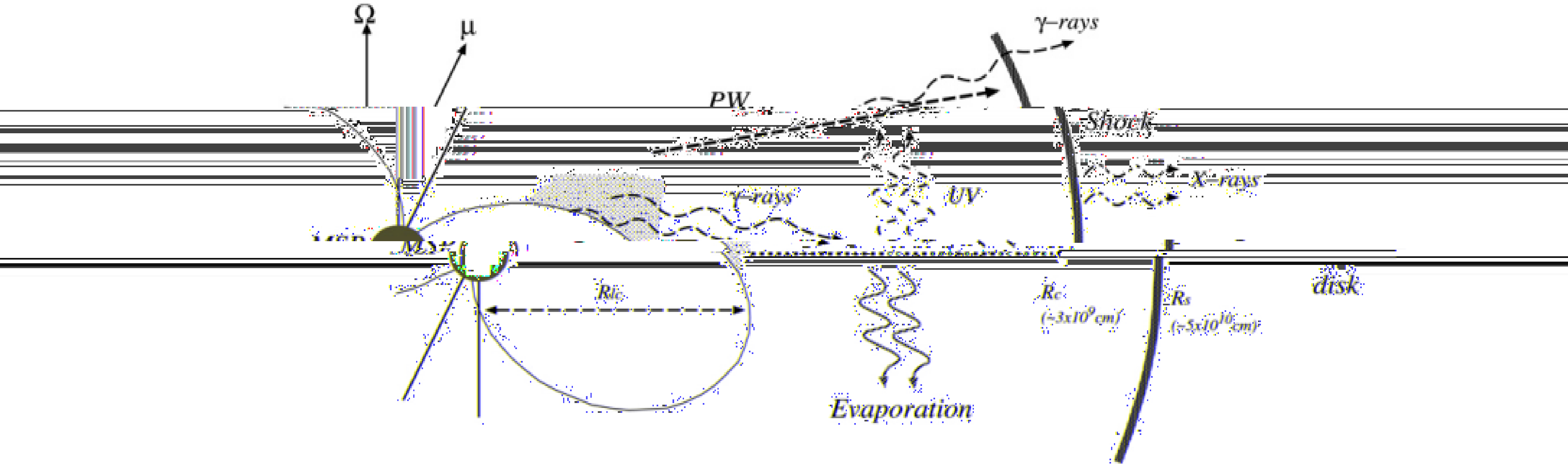
Change of X-ray light curves



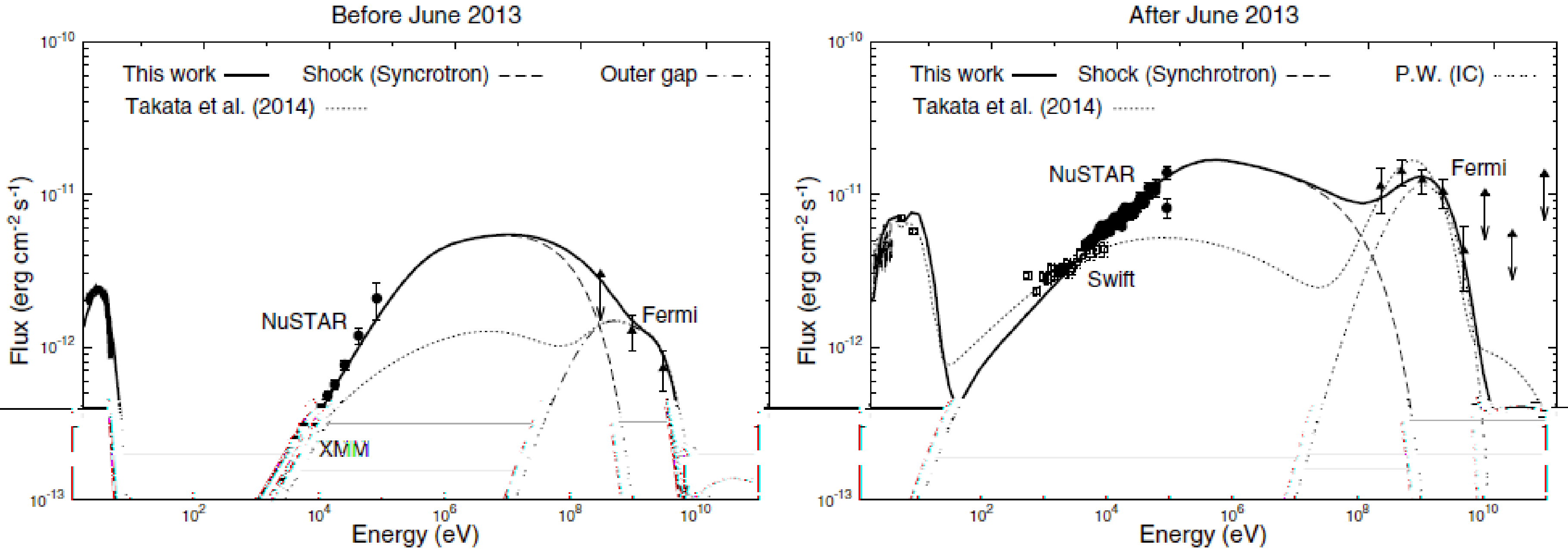
INFC SUPC

Emission model after the state change (Takata et al. 2014)

- Emissions from the disk can be up-scattered by the pulsar wind to produce stronger gamma-rays.
- The formation of disk implies the stellar wind becomes stronger, the shock front is pushed toward to the pulsar instead of toward the star. Consequently the energy injection into the shock is larger and, the X-ray flux increases and its peak occurs at SUPC instead of INFC.
- The disk emission contribute to optical and UV



Model Spectral Fitting (Li et al. 2014)



The synchrotron component is Doppler Boosted we expect this component has orbital modulation. On the other hand GeV is contributed by magnetospheric and IC on PW, both do not have orbital modulation.

Summary

- Gamma-ray binaries are detected in wide range of spectrum. The radiation processes between HMGBs and LMGBs share many similarities. Their observational differences mainly result from the spin-down power and companion star properties.
- For HMGBs: the orbital modulated X-ray and TeV emissions are likely from the shock regions via synchrotron and IC processes respectively. On the other hand shock accelerated electrons cannot emit photons in GeV regime, IC between PW and soft photons either from the companion star or accretion disk surrounding the pulsar can produce GeV-emission.
- For LMGBs: GeV flux can be produced by pulsar magnetospheric emission and IC between disk photons and PW but no orbital modulation in these two processes. Orbital modulated X-rays comes from synchrotron radiation of the shock. TeV is too weak to be detected. A weak orbital modulated GeV-component could occur at SUPC/INFC resulting from IC between PW and companion stellar photons.