Inverse Compton Emission from Gamma-ray Binaries: Pulsar Wind and Accretion Disk photons

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Gamma-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
★ γ-ray luminosity dominates spectrum (GeV/TeV)
★ The high energy emissions (X-rays/TeV) 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, LMC P3/CXOU J053600.0-673507 and PSR J2032+4127/MT91 213.

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

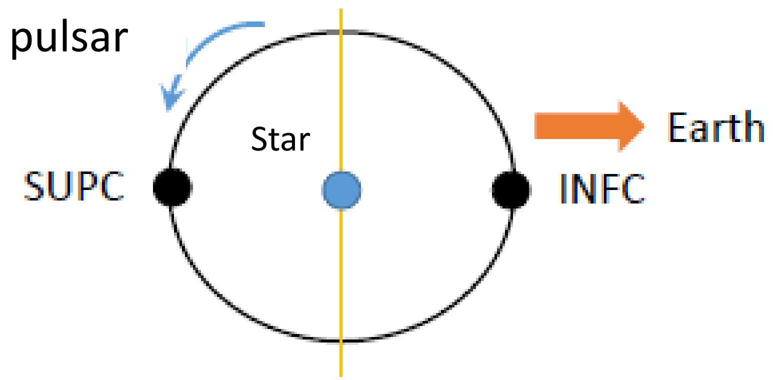
- Spin-modulated GeV emission is emitted from the accelerators inside the pulsar magnetosphere. It is unclear if this exists in all gamma-ray binaries except the long orbital PSR J2032+4127/MT91 213, in which spin-modulated gamma-rays are detected. It has a characteristic spectrum as

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

where E_c~GeV

Multi-wavelength emissions from pulsar binaries – orbital modulation

- The first orbital modulated gamma-ray emission is produced by IC between cold pulsar wind-stellar photons. The gamma-ray peak should occur at SUPC with energy around GeV.



- It has a characteristic spectrum as

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

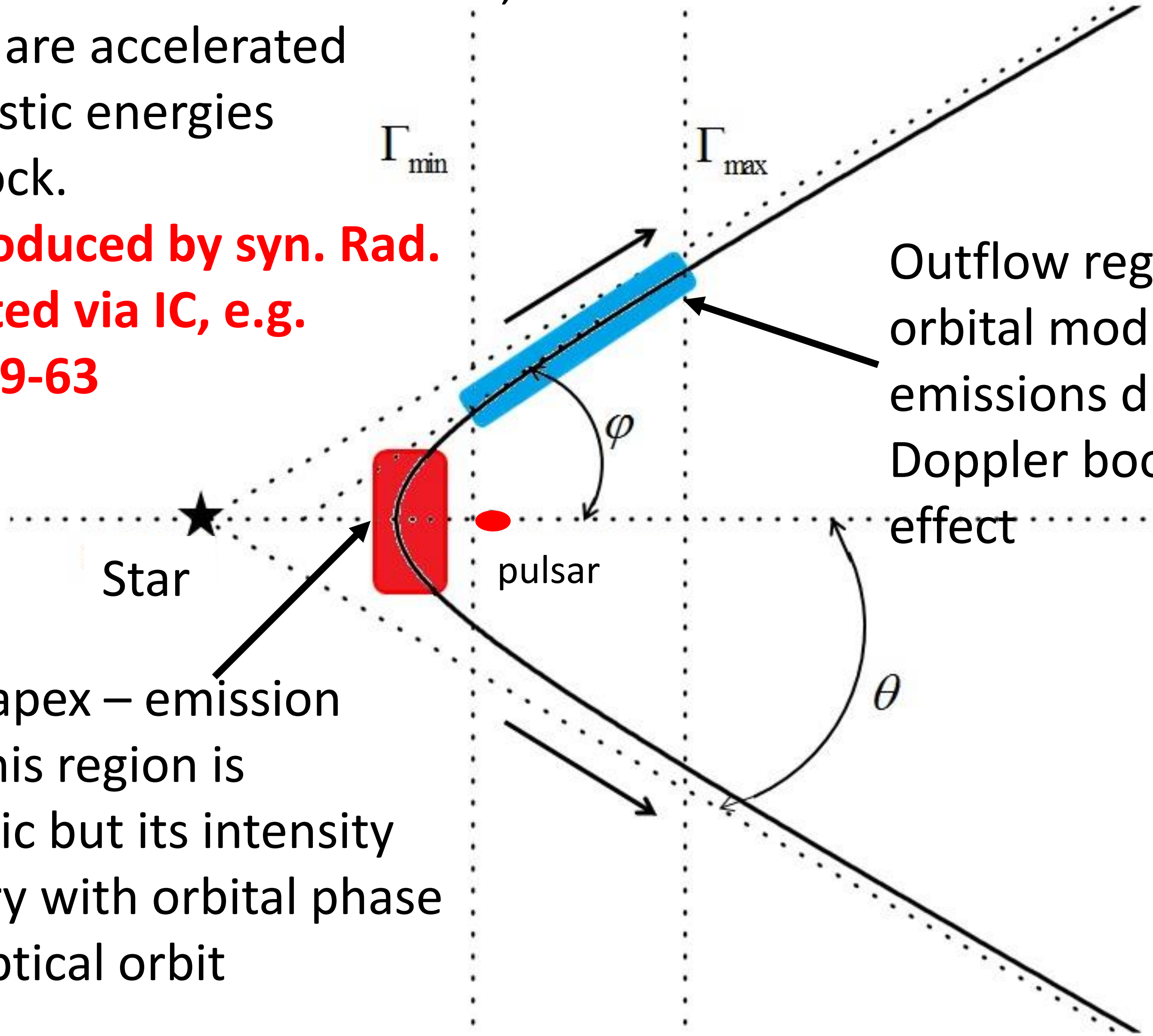
Pulsar wind contains nearly mono-energetic relativistic $e^\pm$ pairs

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. The orbital modulated GeV emission from LS5039 could be produced by this process (Takata et al. 2014)

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, e.g.
PSR B1259-63



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 GeV gamma-rays. In principle this process cannot produce orbitally modulated gamma-rays, e.g. in MSP binary 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 PSR B1259-63/LS2883. The characteristic spectrum is given by

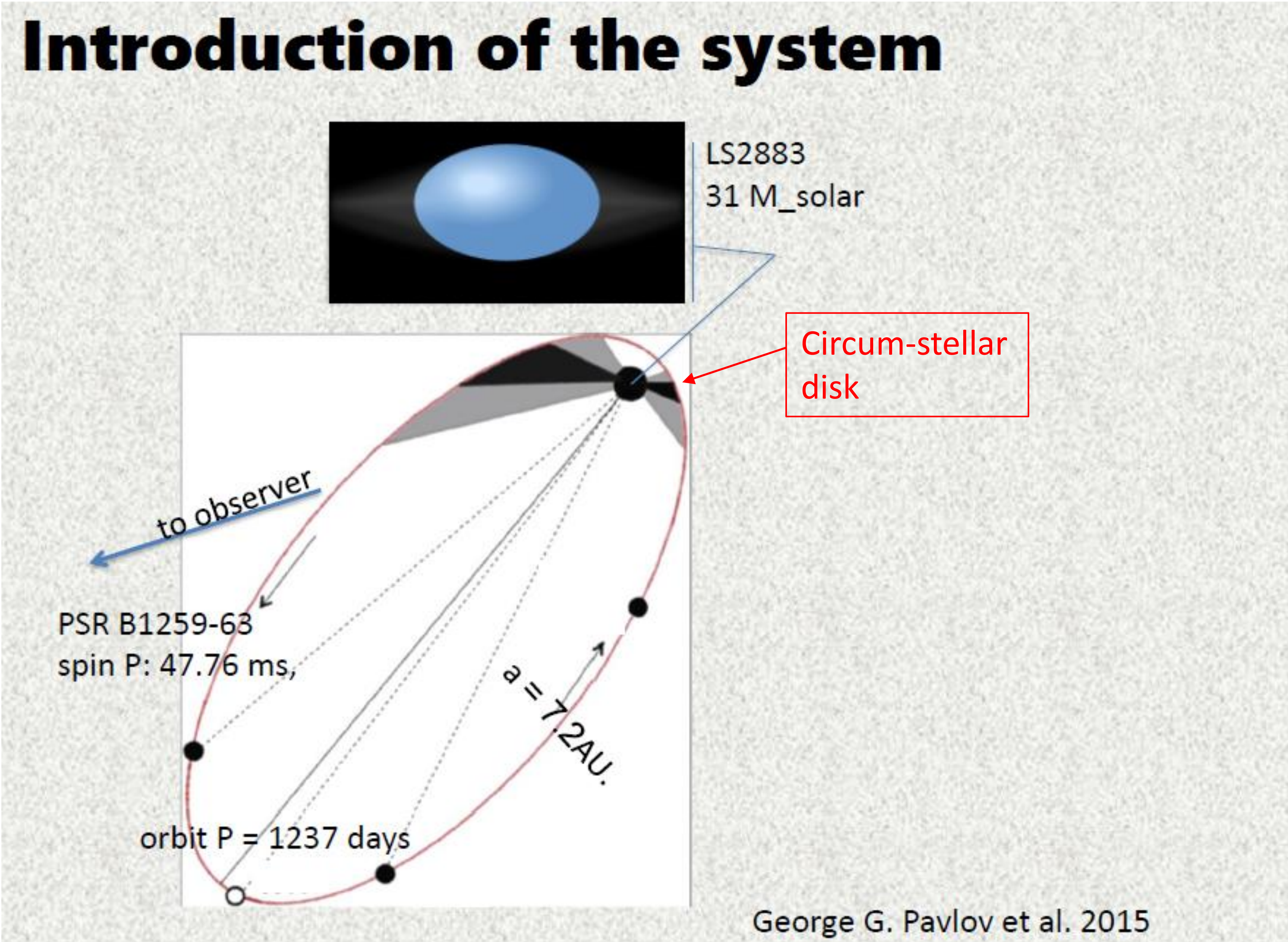
$$F_\gamma \propto \int dT_d(t)\,\exp(-(\frac{E_\gamma - \Gamma_w{}^2 kT_d}{\sigma_w^2})^2)$$

where $T_d(t)$ is the temperature of the transient disk at time t. This will give rise a broader spectrum.

IC emission process from some gamma-ray binaries

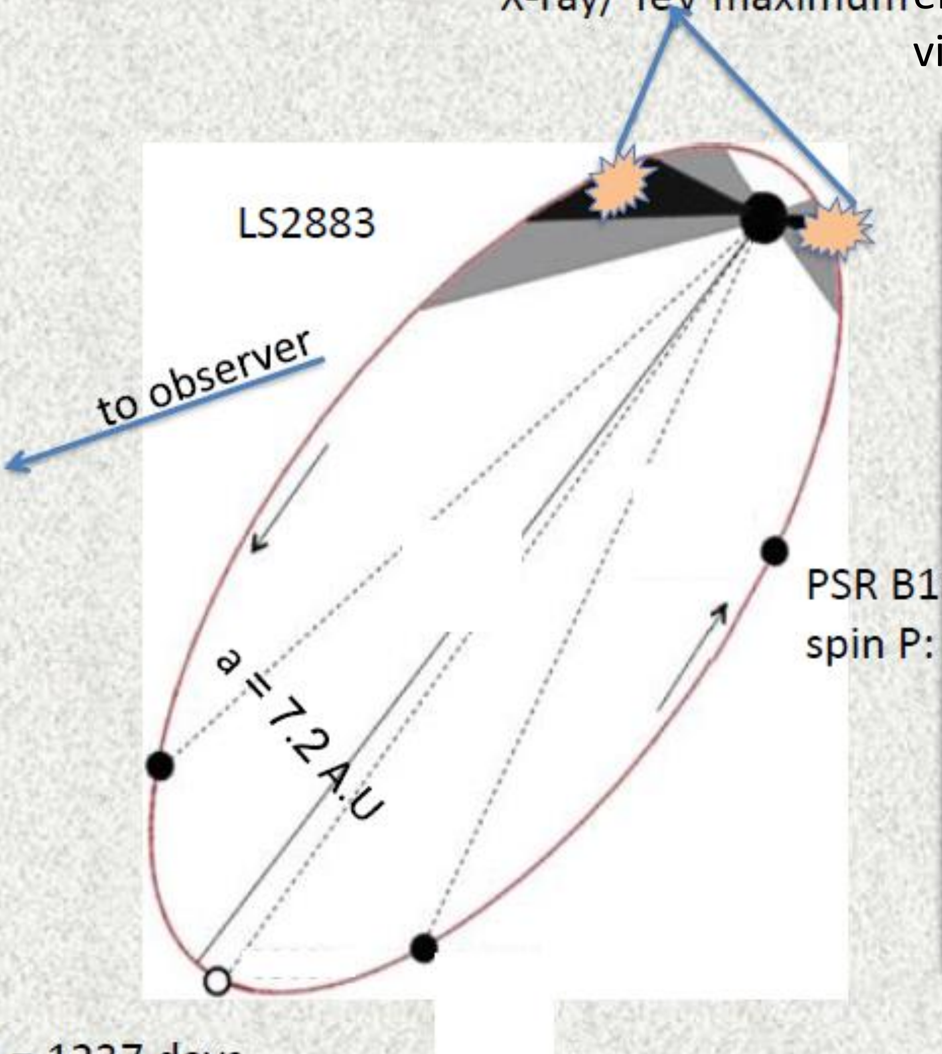
- PSR B1259-63/LS2883; PSR J2032+4127/MT91 213 ; HESS J0632
- MSP binary - PSR J1023.4+0038

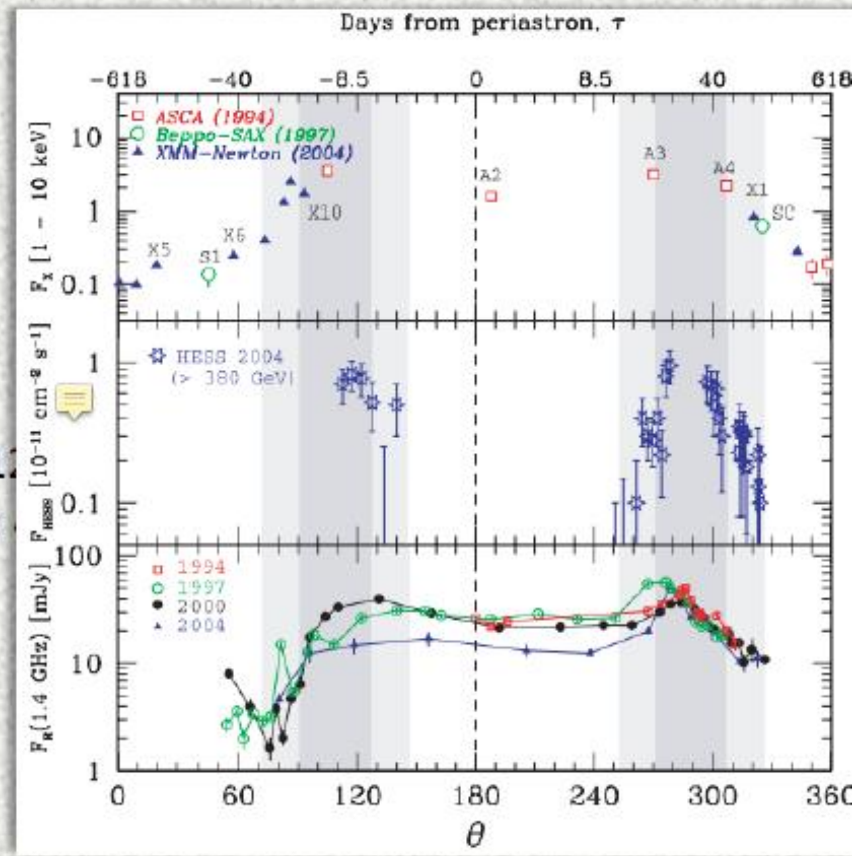
PSR B1259-63/LS2883



X-ray/TeV emission

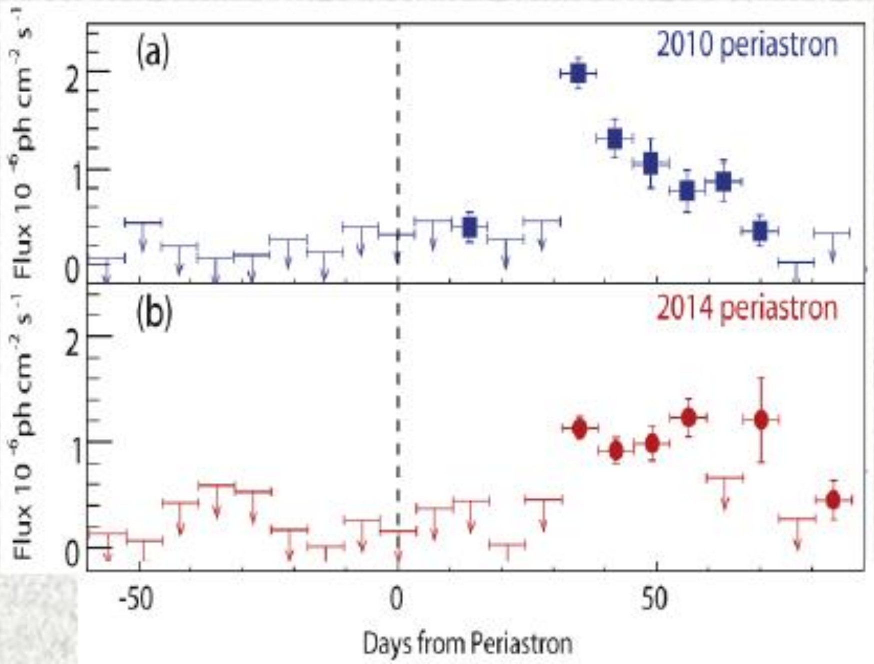
X-ray/ TeV maximum emitted by the shocked relativistic electrons via Syn. and IC respectively

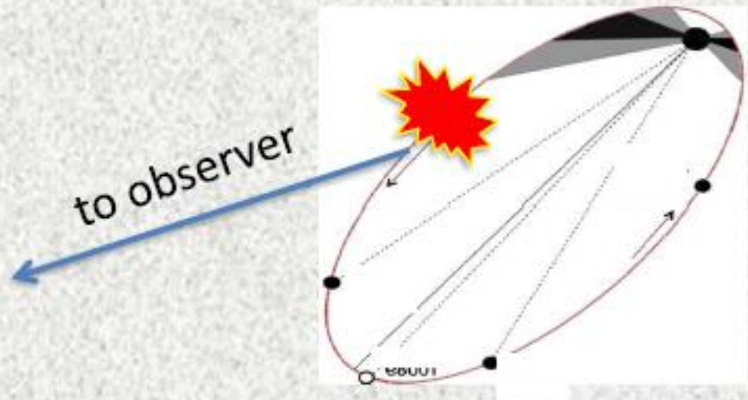




orbit P = 1237 days

Emission in 100 MeV-100 GeV





GeV flare at un-expected orbital phase

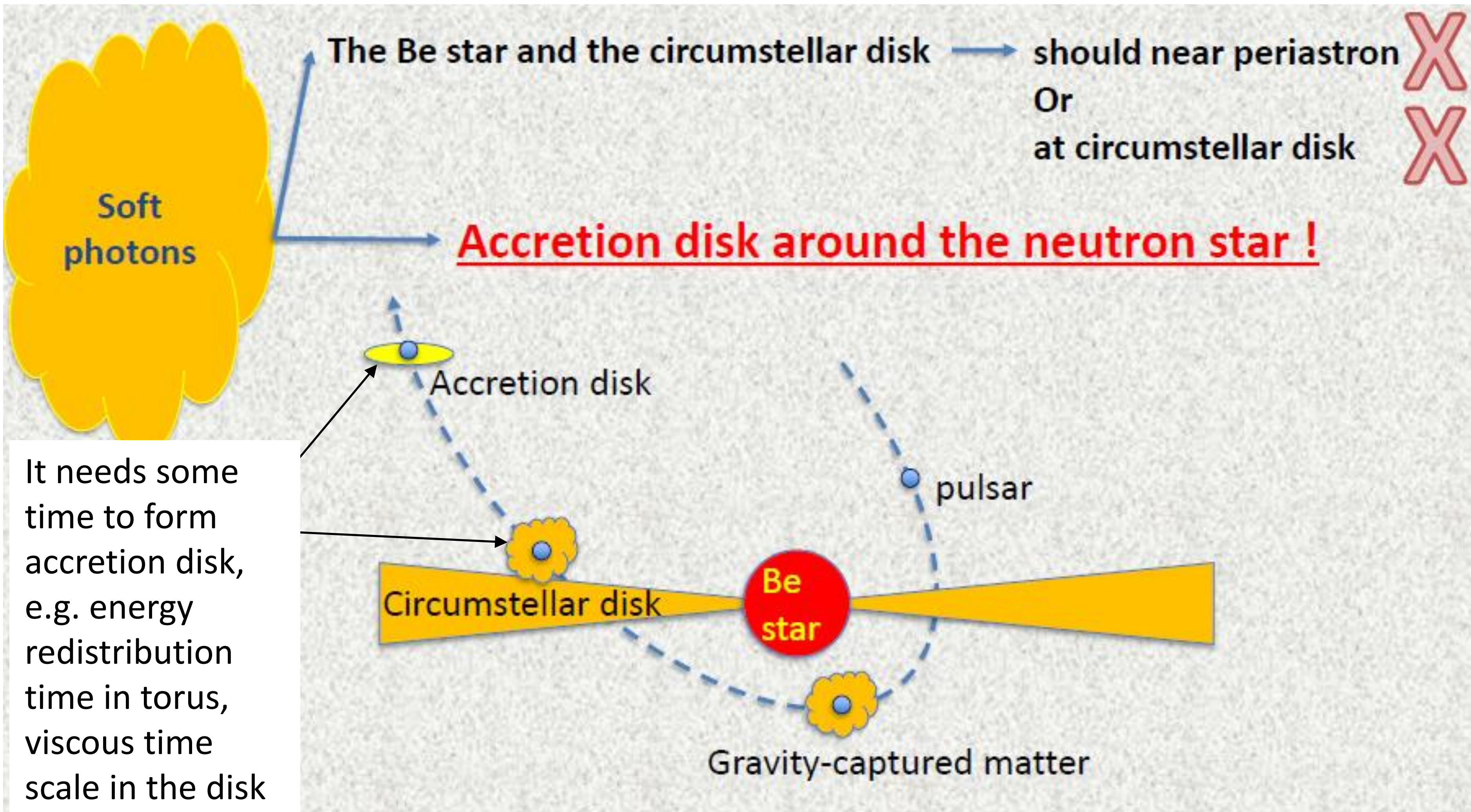
Tam 2011, Abdo 2011, Caliandro 2015

The next periastron passage occurs around September this year, we expect another GeV-flare should happen.

What are the emission mechanism for GeV-photons?

- Synchrotron emission with Doppler boosting effect from shock or IC between lower energy shocked electrons and circumstellar disk photons
- These two possibilities should make GeV peak at the same orbital phase as X-rays/TeV
- If IC is still the emission mechanism of GeV photons, new lower energy relativistic electrons other than the shocked relativistic electrons and new soft photons are necessary.

Model for GeV-flare from PSR B1259-63/LS2883 (Yi & Cheng 2017)

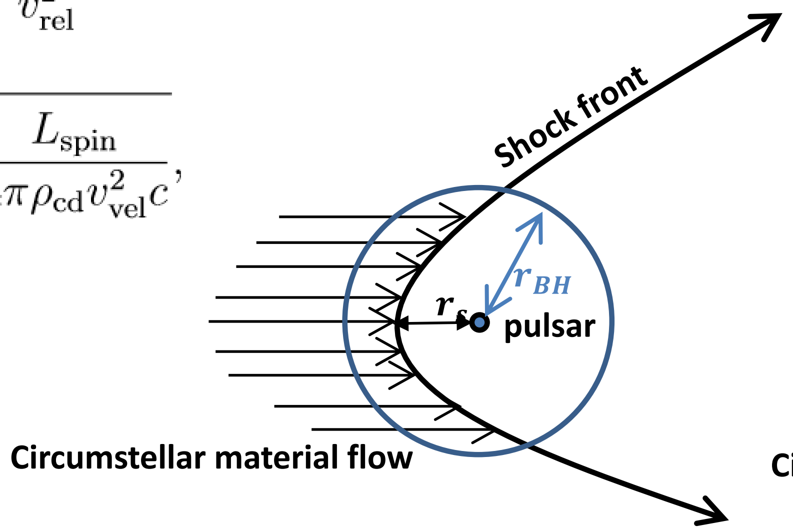


Condition of mass transfer from optical companion

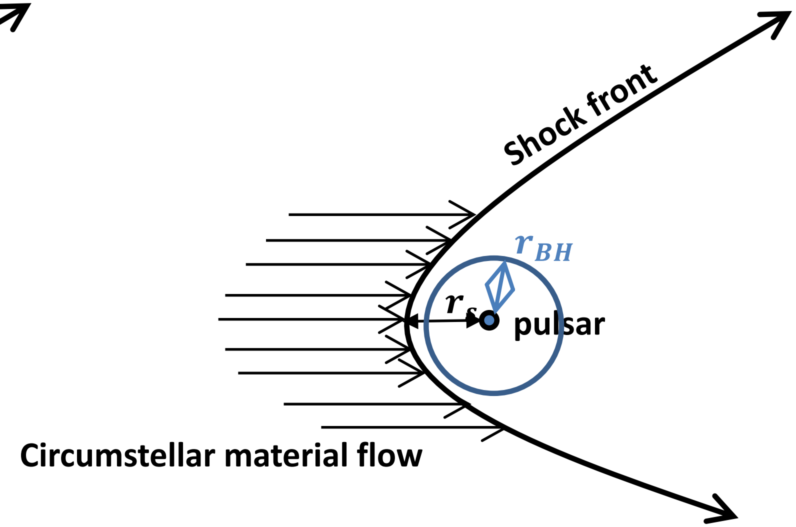
Shock from should inside the Bondi-Hoyle sphere

$$r_{\rm BH} = \frac{2GM_{\rm p}}{v_{\rm rel}^2},$$

$$r_{\rm s} = \sqrt{\frac{L_{\rm spin}}{4\pi\rho_{\rm cd}v_{\rm vel}^2 c}},$$

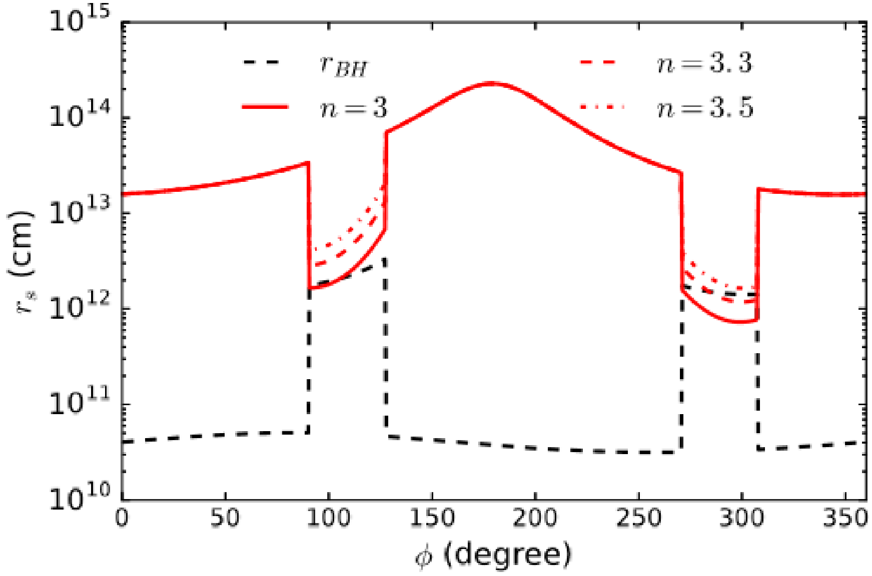


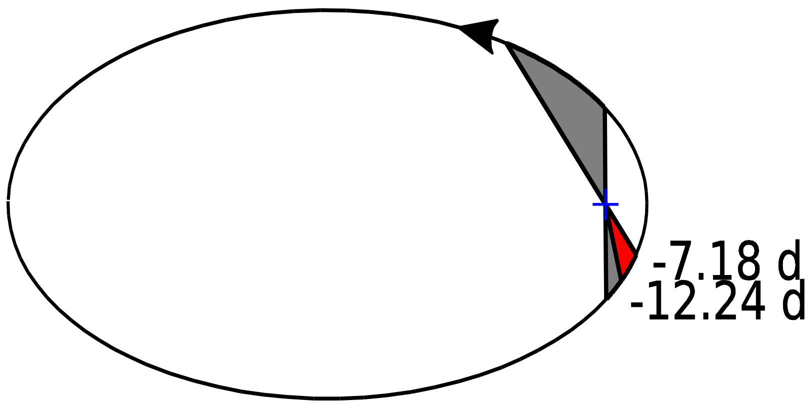
Mass can transfer



Mass can NOT transfer

Location of the circumstellar disk, and phases of mass transfer





n represents the density profile
of the circumstellar disk

Condition of the formation of accretion disk

- The transferred material should have enough specific angular momenta: $r_{circ} > r_{lc}$
- $r_{circ} = \frac{l^2}{GM_p}$
- The angular momenta of the transferred material are due to the density and velocity gradient of the circumstellar disk.

$$l(t) = \frac{(GM_{\rm p})^2}{v_{\rm rel}^3}\left(\frac{|\nabla v_{\rm vel}|}{v_{\rm rel}} + \frac{|\nabla \rho_{\rm cd}|}{\rho_{\rm cd}}\right).$$

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 (viscous time)
- The optical/UV emission is gradually increasing with time as the disk moves in and decreasing with time after reaching the Alfven radius (cf. Fig.1)
- GeV gamma-ray emission via IC between PW and disk photons (Fig. 2 and 3)

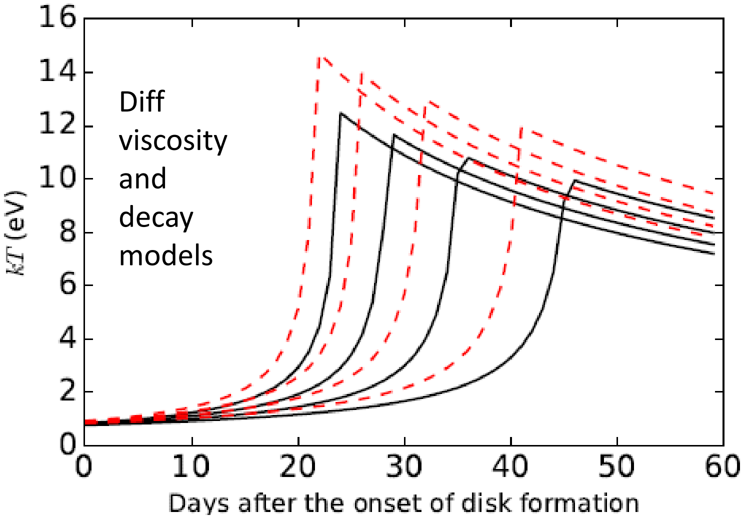


Fig. 1 Time for the peak T depends on α

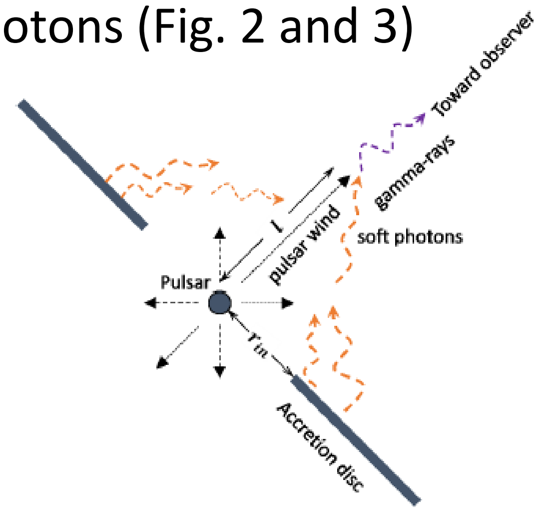


Fig. 2

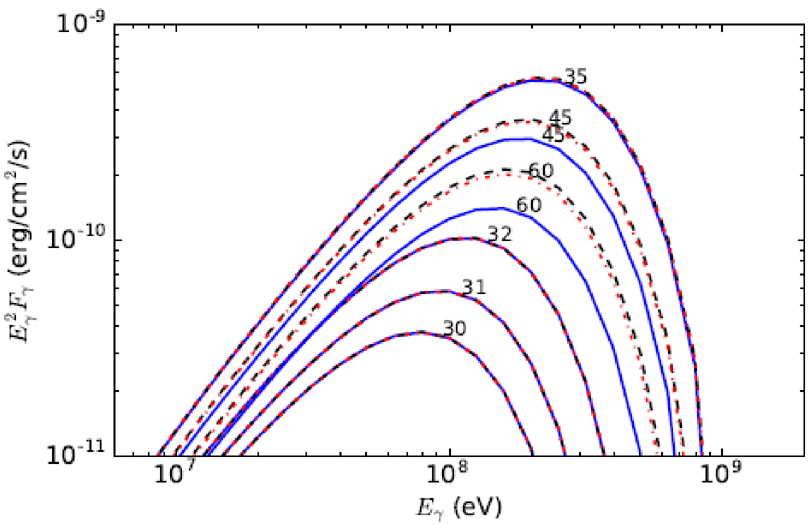
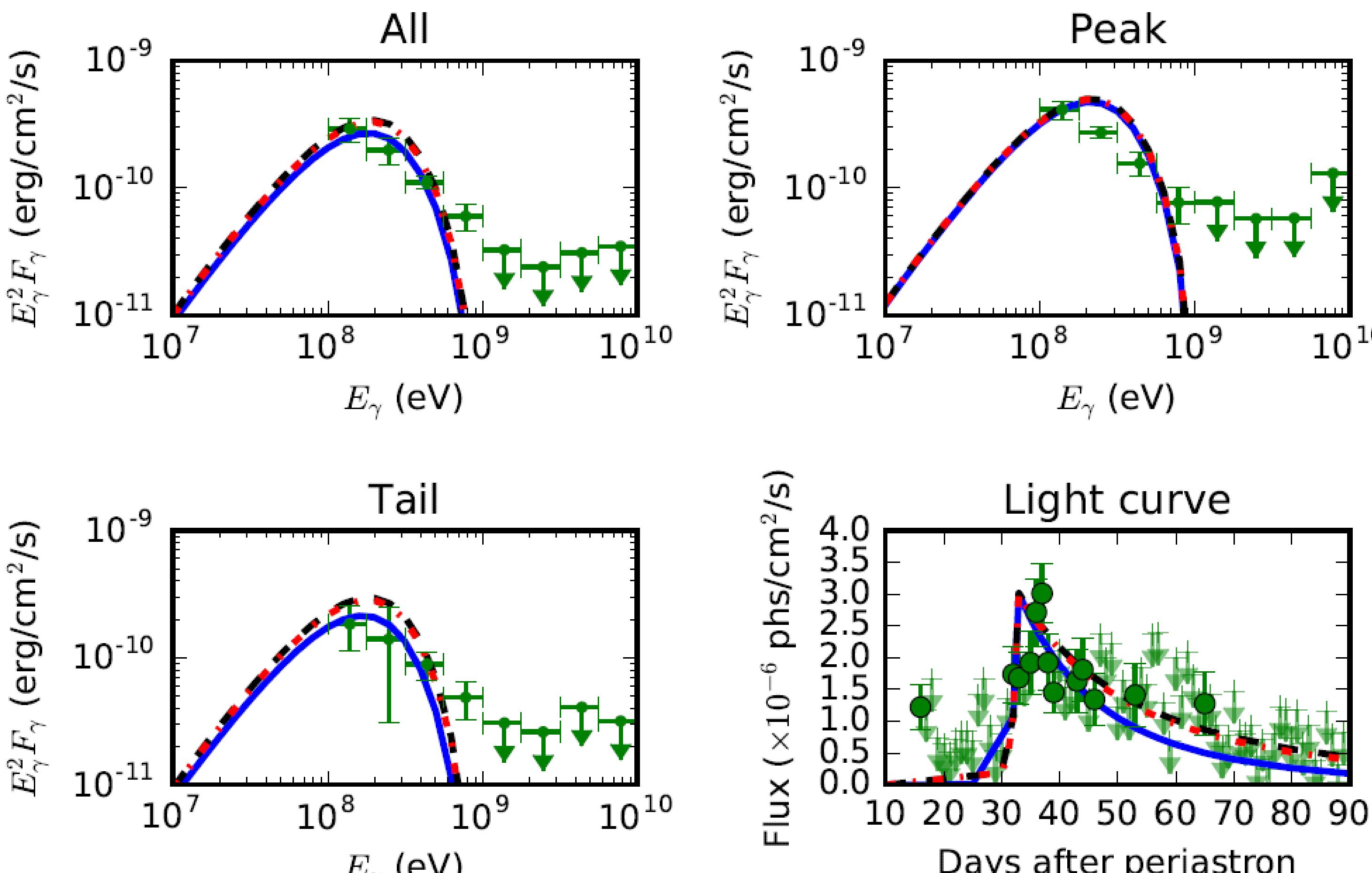


Fig. 3 Time evolving spectrum

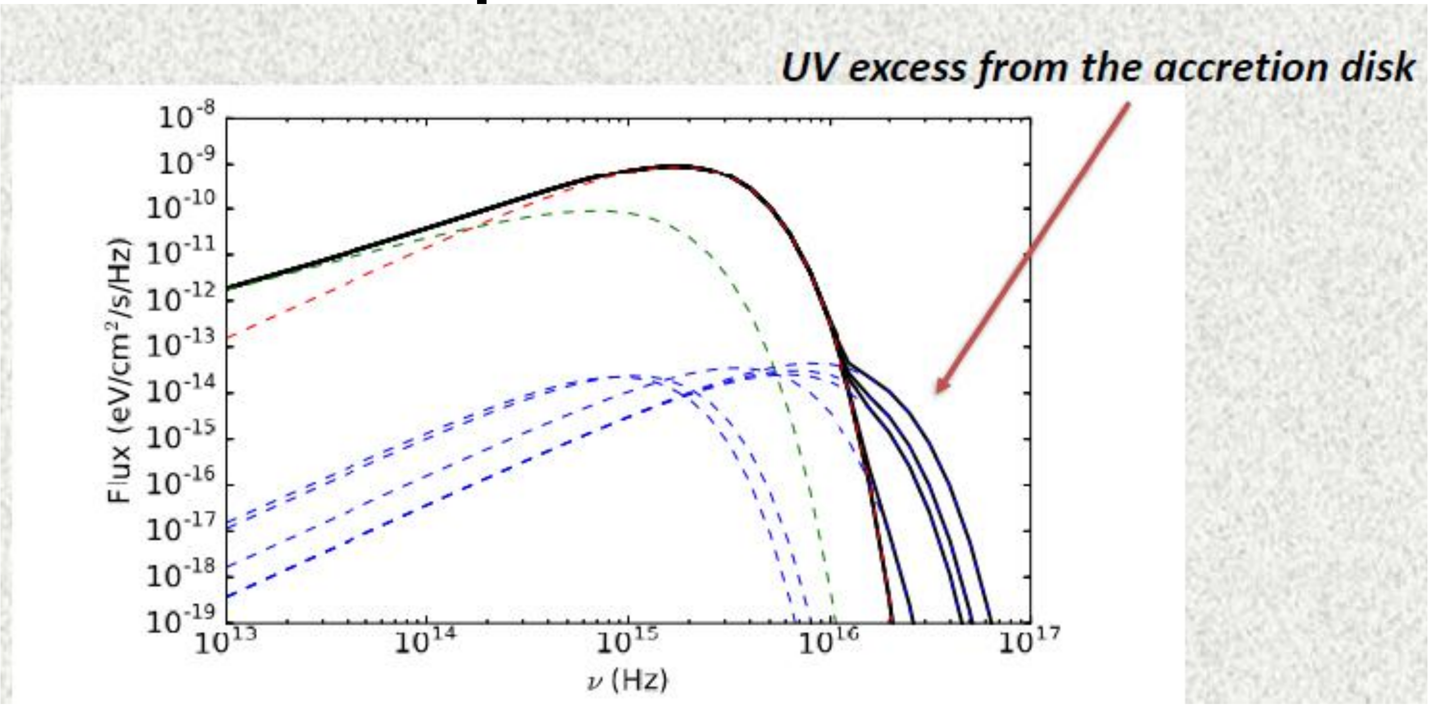
Transient gamma-ray emission via IC between the accretion disk photons and PW

Data : Caliandro et al. (2015)



Model predictions

- UV

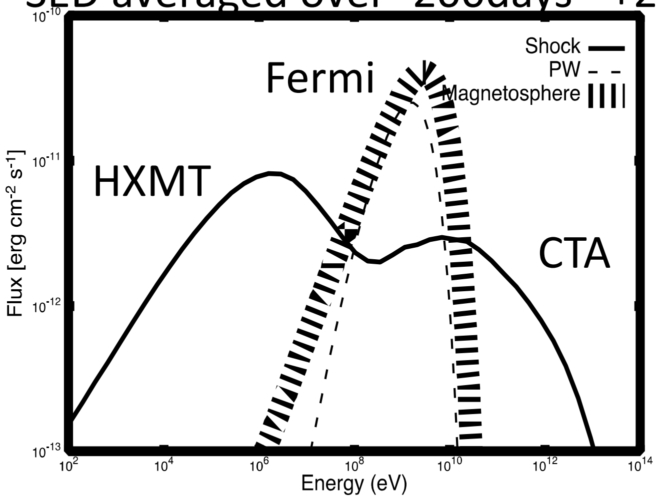


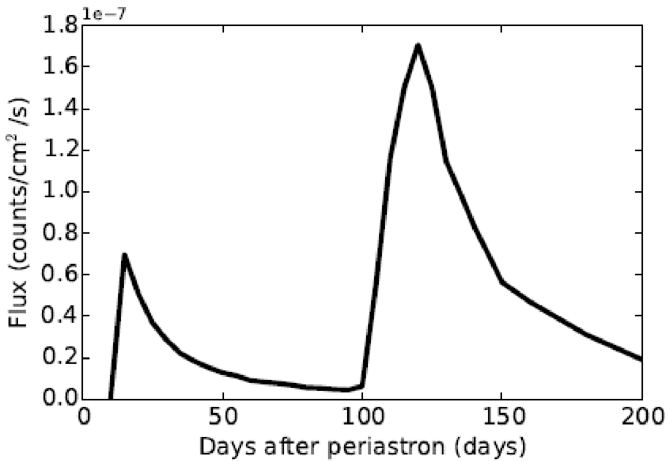
- The disk also produces addition spin-down torque and hence $\dot{P}$ should be larger during the GeV-flare phase
- Hα emission line

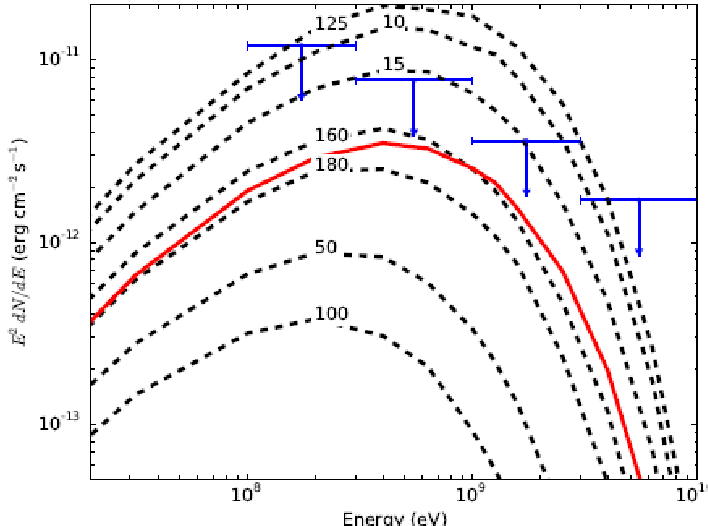
Predicted GeV flux for other gamma-ray binaries with CD but not yet with GeV detection

- PSR J2032+4127/MT91 213 – Takata et al. 2017 have predicted that an accretion disk will be formed and GeV-flare should occur after the passing through the CD, which is near the periastron.
- HESS J0632 – the predicted SED and light curve(Yi et al. 2017b)

SED averaged over -200days - +200days

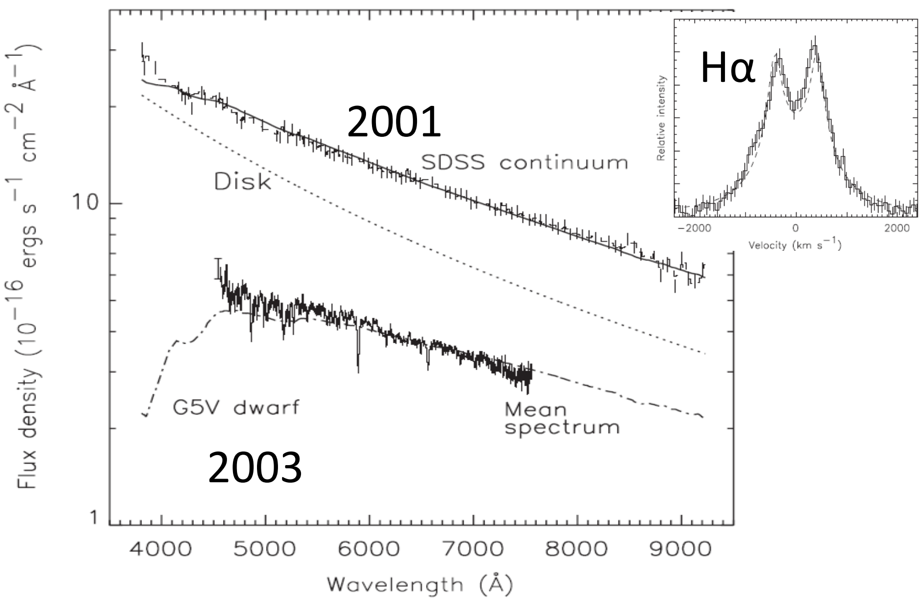




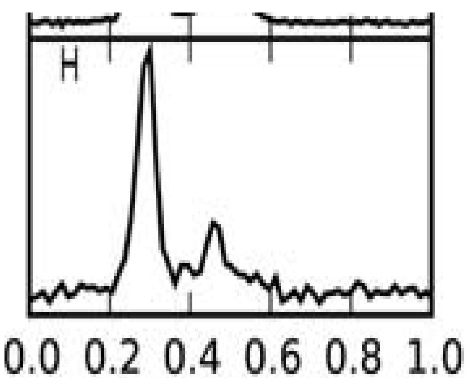


Fermi upper limit (Caliandro et al. 2013)

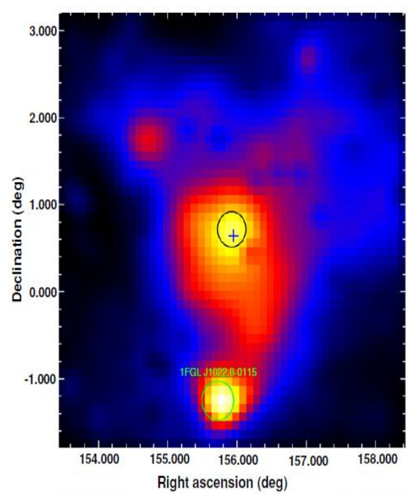
PSR J1023.4+0038 (MSP/low mass MS binary: a circular orbit with 4.75 hr period)



- 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*)



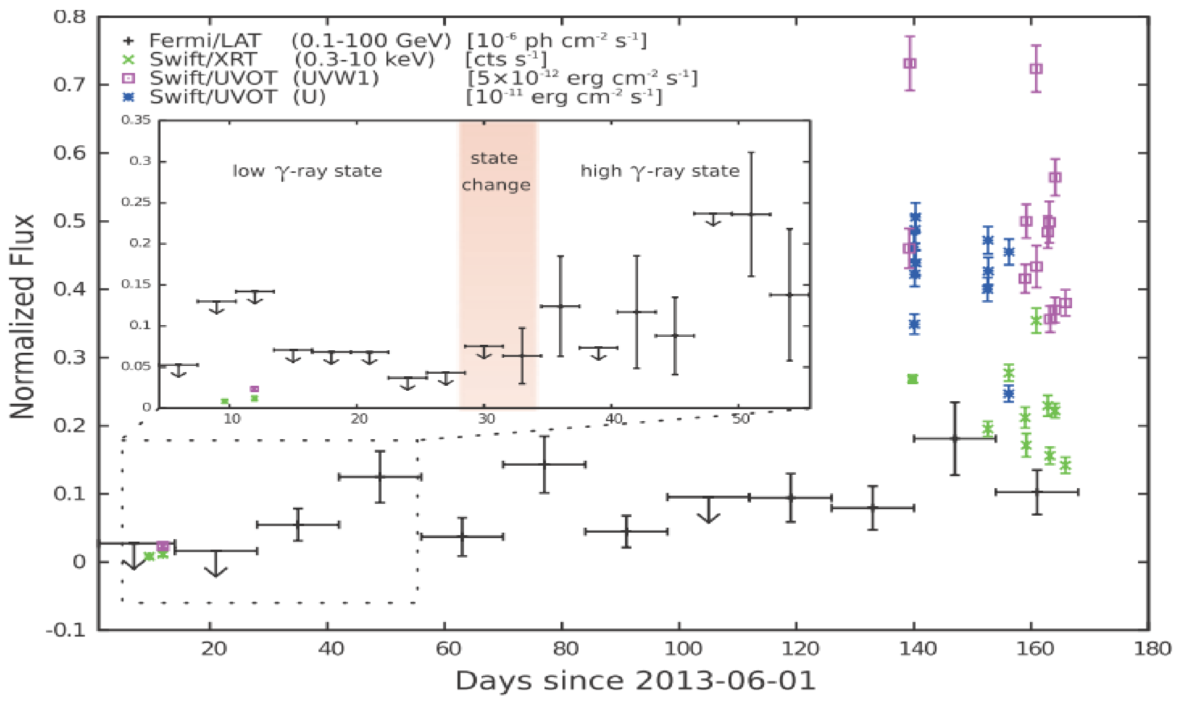
Radio pulse profile



Test-Statistical map of 2FGL J1023

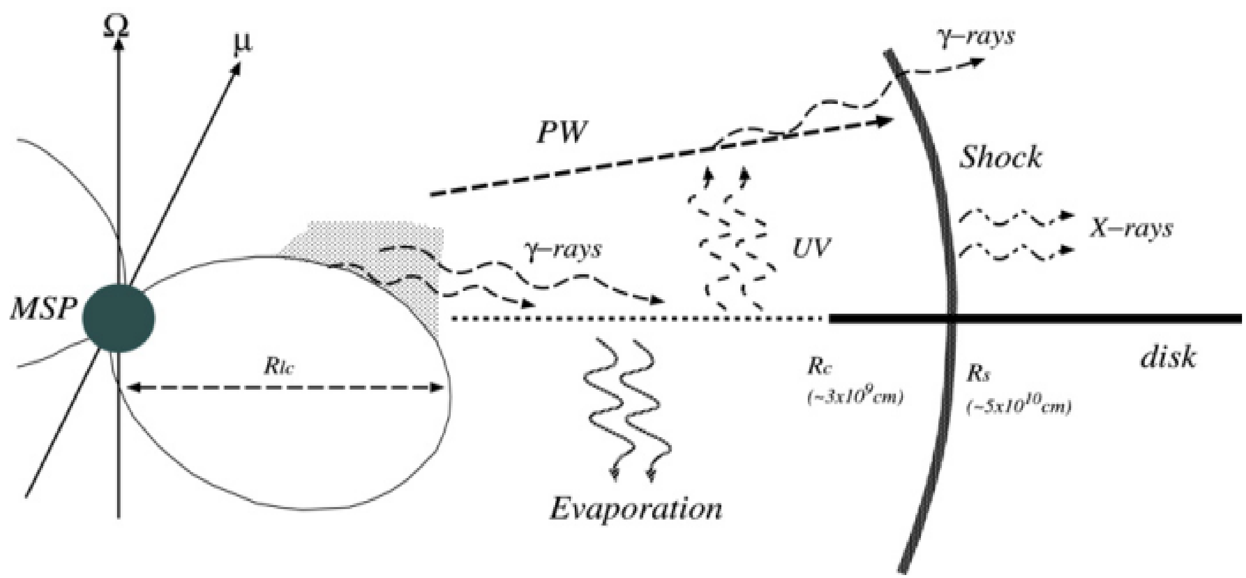
New stage J1023.4+0038

- Between 2003 and June 2013, pulsed radio is detected and no evidence of disk
- 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

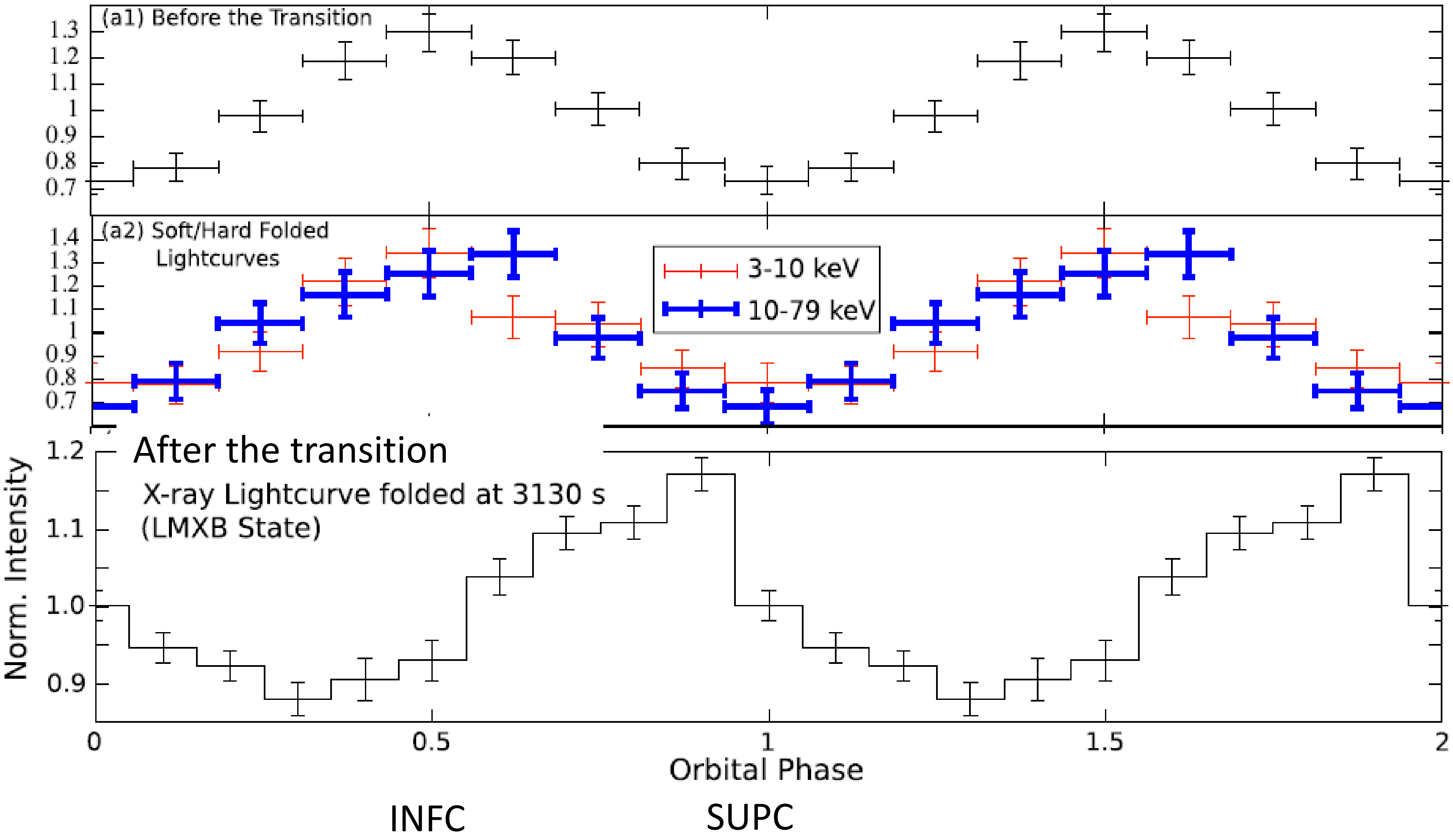


Emission model after the state change (Takata et al. 2014)

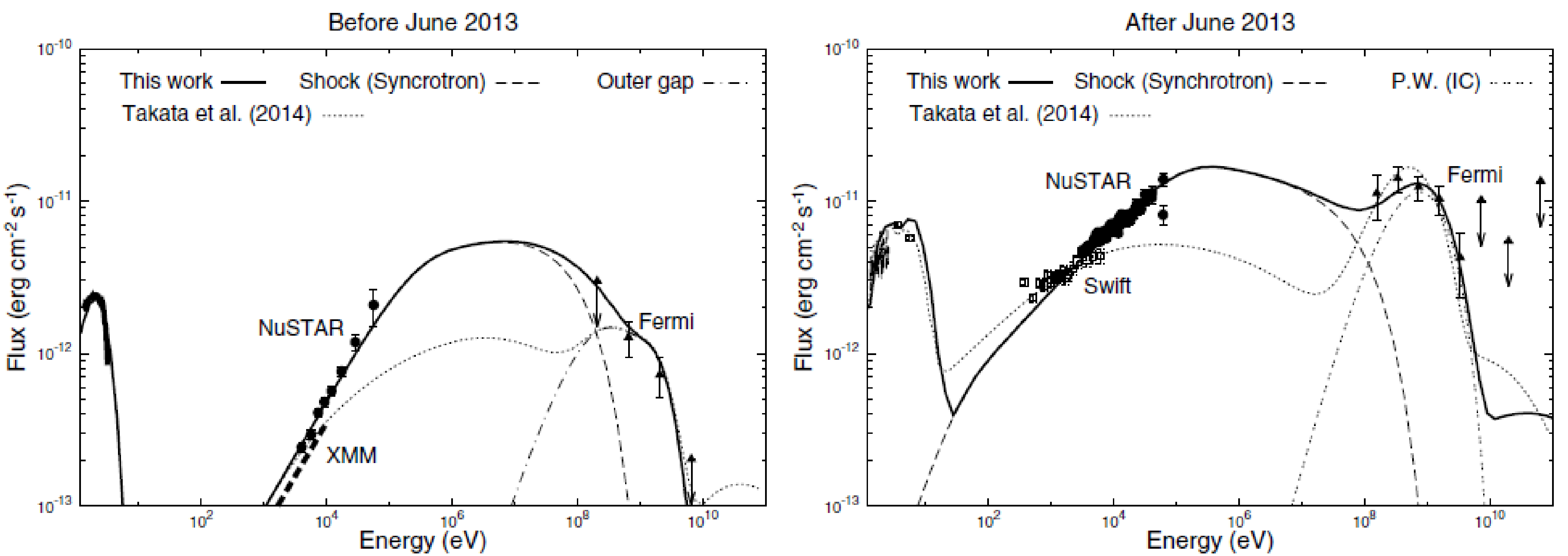
- Accretion is formed after June 2013, the disk photons can be up-scattered by the pulsar wind to produce stronger gamma-ray flux.
- The formation of disk implies the stellar wind becomes stronger, the shock front is pushed toward to the pulsar instead of toward the star. Consequently the energy injection 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



Change of X-ray light curves (stronger wind and support the formation of disk after June 2013



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 GBs and MSPBs share many similarities. Their observational differences mainly result from the spin-down power and companion star properties.
- We suggest that once a transient disk is formed around the pulsar a new component in GeV range should be produced via IC between the cold pulsar wind and the disk soft photons
- The existence of disk can be confirmed by Hα emission line, UV excess and larger $\dot{P}$.