GAMMA-RAY PRODUCTION IN MILLISECOND PULSAR BINARY SYSTEMS

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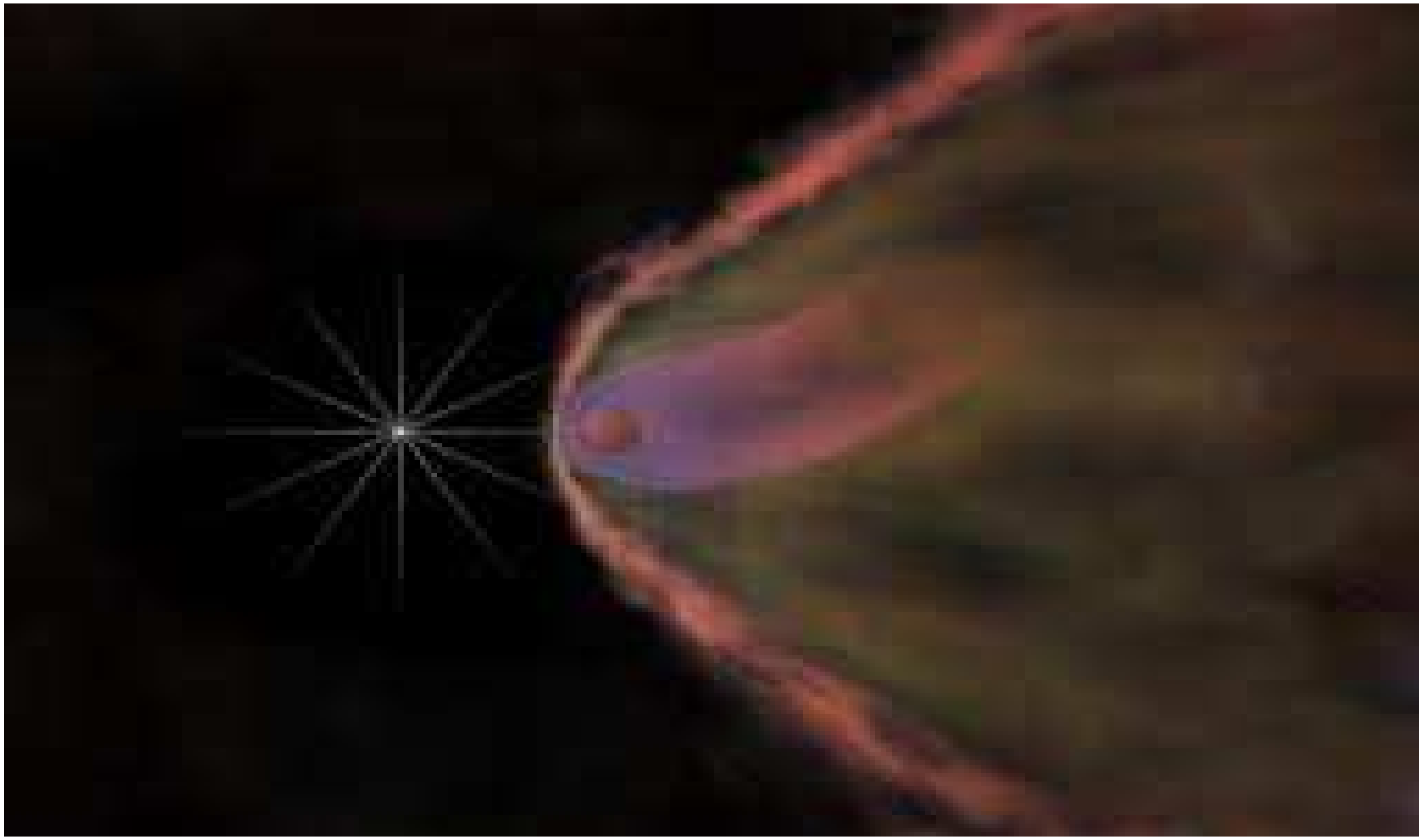
Considered scenarios for MSPs:

- Ejection phase
- Accretor phase

Predict high energy radiation from

- Leptons accelerated in the MS pulsar wind shock
- Leptons in the inner magnetosphere during accretion MSP

Ejecting MS pulsar within binary system

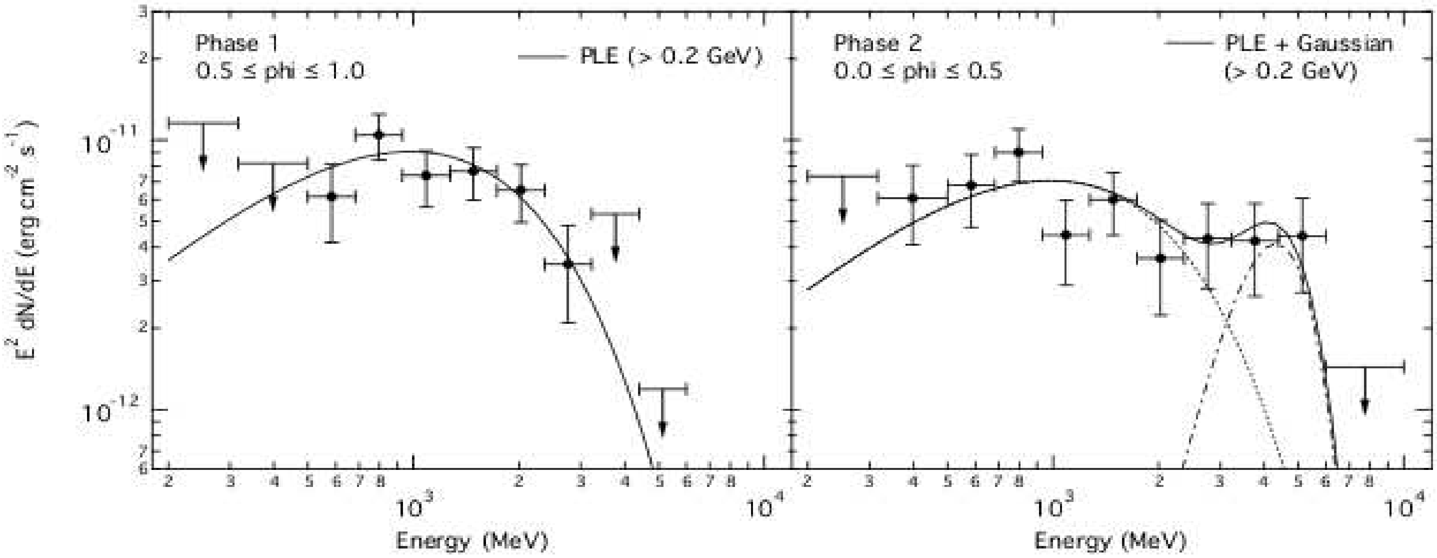


- Electrons accelerated on the shock (Harding & Gaisser 1990; Arons & Tavani 1993)
- Leptons accelerated by the pulsar ⇓
  Optical depths for electrons in the wind:

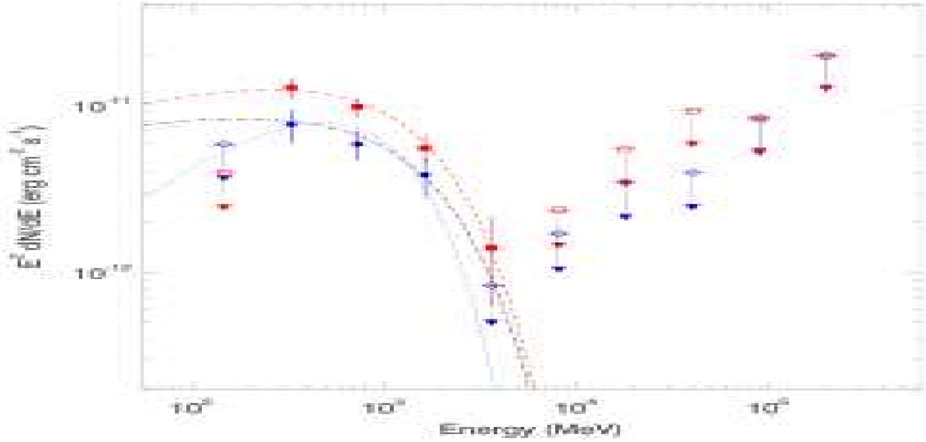
$$\tau_{\rm IC}^{\rm T} = n_{\rm ph}\sigma_{\rm T}R_{\star} \sim 0.1 T_4^3 R_{10}$$

Modulated γ-ray emission from MSP binaries

Black Widow PSR B1957+20 (Wu et al. 2012):

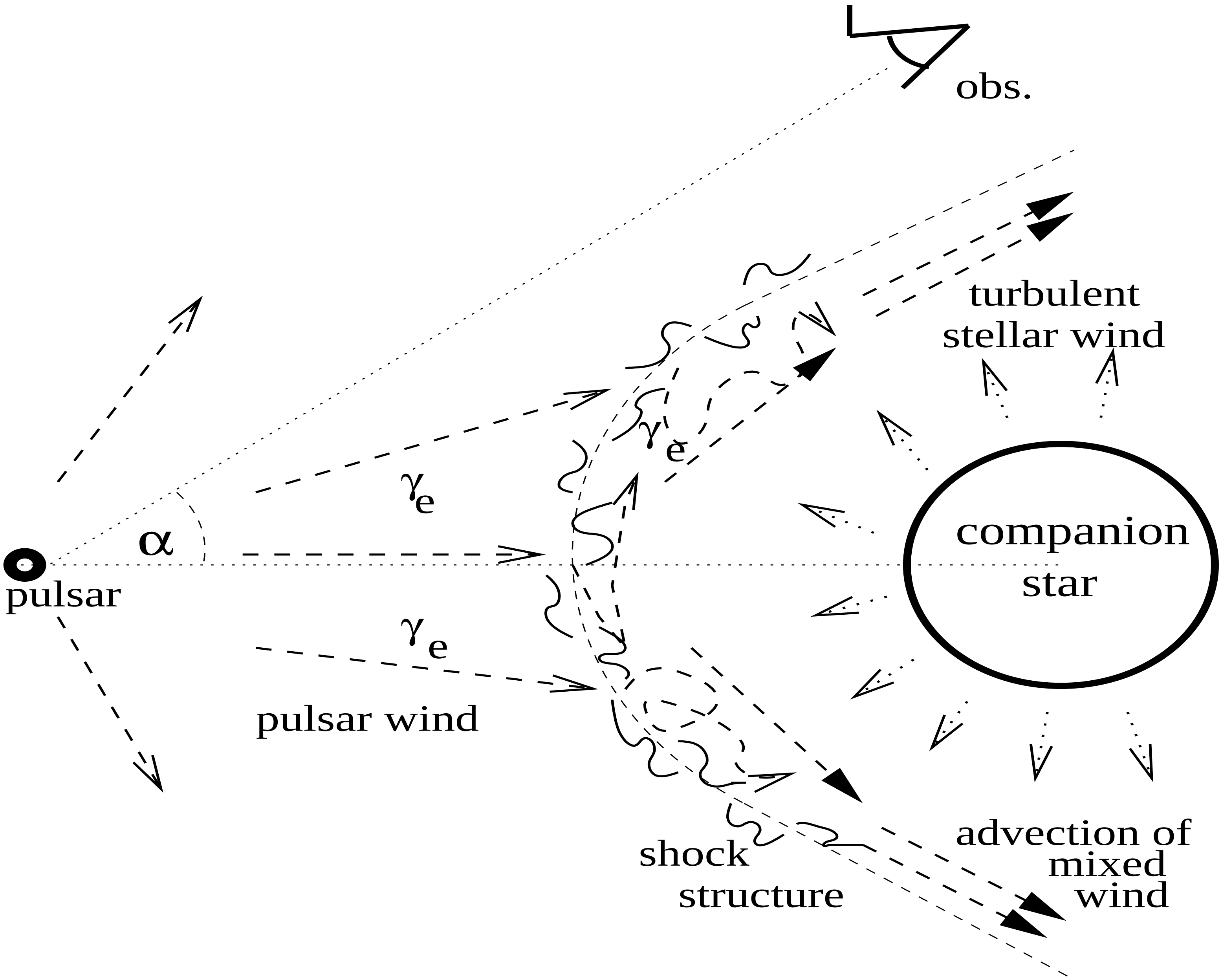


Black Widow PSR J1311-3430 (Xing & Wang 2015):



Inhomogeneous stellar wind can mix with the pulsar wind

(details in Bednarek 2014, A&A 561, A116)



- **Velocity of the mixed pulsar-stellar winds**

$$v_{\rm mix} = [\frac{2L_{\rm pul}\Delta\Omega_{\rm pul}}{\dot{M}_{\star}\Delta\Omega_{\star}}]^{1/2} \approx 1.2\times 10^9 (\frac{\chi_{-1}L_{35}}{M_{-10}})^{1/2} \quad {\rm cm\ s}^{-1} \qquad (1)$$

where $L_{\rm pul} = 10^{35}L_{35}$ erg $\rm s^{-1}$ is the power of the pulsar wind, $\dot{M} = 10^{-10}M_{-10}$ $\rm M_{\odot}$ $\rm yr^{-1}$ is the mass loss rate of the companion star, and $\chi = 0.1\chi_{-1}$ is teh ratio of solid angles of the winds at the shock.

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Optical depth enhanced by a factor as large as $c/v_{\rm mix} \sim 30$!

- **Non-thermal X-rays from MSP binaries (e.g. ~ 8 keV from B1957+20)**

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Electrons have to have Lorentz factors above

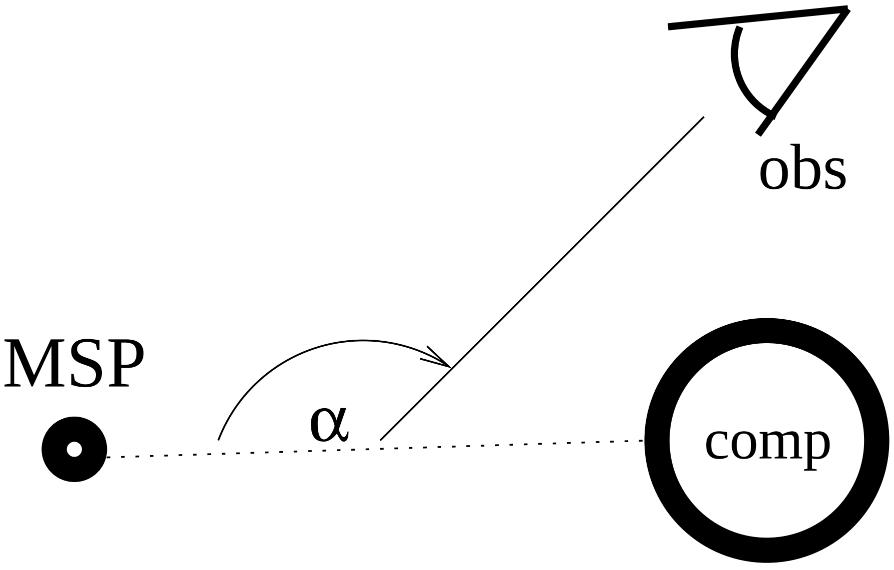
$$\gamma \sim 5\times 10^5 P_2 \rho_{11}^{1/2}/(\sigma_{-2}^{1/4}B_8^{1/2})$$

Electrons accelerated in turbulent wind collision region:

- Electron maximum energy: $E_{\rm syn}^{\rm max} \approx 10^6 P_2 \rho_{11}^{1/2} / (\sigma_{-2}^{1/4} B_8^{1/2}) \quad \mathrm{MeV}$,

(electron energy gains ($\chi \sim (v_{\rm mix}/c)^2 \sim 10^{-3}$) versus synchrotron losses)

- Spectrum of electrons: $\propto E_{\rm e}^{-2}$
- Gamma-rays: IC scattering of stellar radiation by isotropised electrons
- Gamma-ray spectra depend on the angle α ($\Delta(\cos\alpha) \pm 0.1$)



Parameters of considered MSP binary systems

Table 2. Basic parameters of millisecond pulsars and their binary systems: radius of the companion star ($R_\star$) and its surface temperature ($T_\star$), semimajor axis of the orbit (a), distance of the shock from stellar surface $R_{\rm sh}$, pulsar energy loss rate ($L_{\rm pul}$), distance to the binary system (D), and the X-ray luminosity from the binary system.

Name	$R_\star$ (cm)	$T_\star$ (K)	a (cm)	$R_{\rm sh}$ ($R_\star$)	$L_{\rm pul}$ (erg/s)	D (kpc)
B1957+20	10^{10}	8×10^3	1.7×10^{11}	5	1.6×10^{35}	2.5
J1023+0038	3×10^{10}	6.65×10^3	1.7×10^{11}	2	1.2×10^{35}	0.6-1.3
J1816+4510	8.4×10^9	2×10^4	1.2×10^{11}	4	10^{35}	2.4
J1810+1744	1.4×10^{10}	8×10^3	9.3×10^{10}	3	4×10^{34}	2.

Example calculations of synch. and TeV γ-ray emission

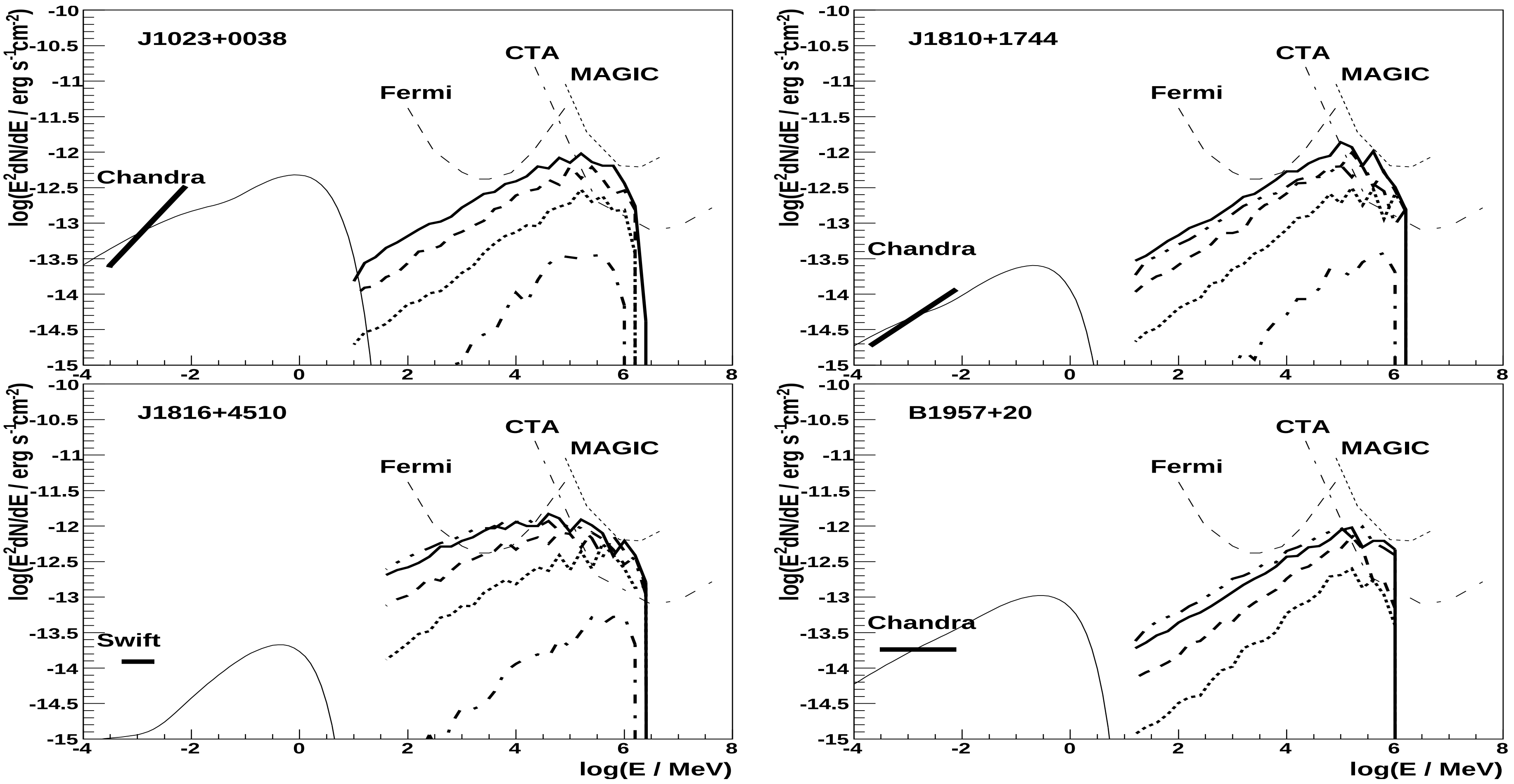


Figure 1: Comparison of the high-energy emission expected from the MSP binary systems with the sensitivities of Fermi-LAT, MAGIC and CTA, for different ranges of observation angles: $0.9 \leq \cos\beta \leq 1.0$ (dot-dashed, away from the companion star), $0.5 \leq \cos\beta \leq 0.6$(dotted), $-0.1 \leq \cos\beta \leq 0.$ (dashed), $-0.5 \leq \cos\beta \leq -0.4$ (solid), $-1.0 \leq \cos\beta \leq -0.9$ (dot-dot-dashed). The spectra are normalized to the X-ray fluxes observed from PSR B1957+20 (Huang et al. 2012), PSR J1023+0038 (Bogdanov et al. 2011), PSR J1810+1744 (Gentile et al. 2013). For PSR J1816+4510, the upper limit derived from the Swift data (Kaplan et al. 2012).

TeV γ-ray light curves

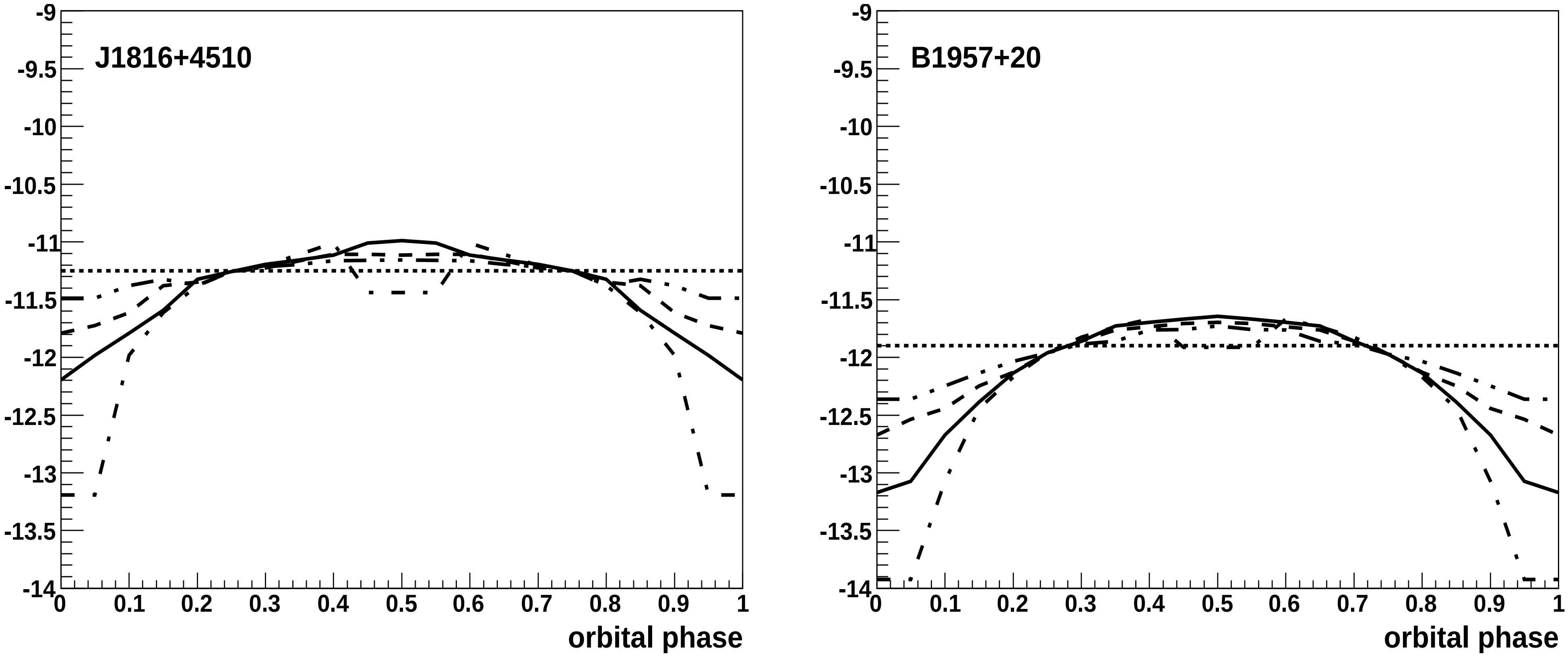


Figure 2: The γ-ray light curves in the TeV energies (>100 GeV) expected from considered MSP binary systems: PSR J1816+4510 (left), and PSR B1957+20 (right). Specific curves show the results for different inclination angles of the binary systems: $i = 0°$ (dotted), 30° (dot-dot-dashed), 45° (dashed), 60° (solid), and 90° (dot-dashed). The phase is counted from the location of the MSP in front of the companion star. The parameters of the companion stars and the binary systems are reported in Table. 1. It is assumed that the MSP moves in a circular orbit around the companion star. The parameters describing the spectrum and escape of electrons are the same as in Fig. 3. The injection place of electrons is assumed to be at the apex of the collision region (described by $R_{\rm sh}$ in Table 1). The γ-ray fluxes are collected in the range of phases with the width equal to 0.05.

Summary

- MSP induce stellar wind from the companion star
- MSP and stellar winds mix efficiently in the collision region
- Leptons accelerated in the collision region to TeV energies
- Leptons comptonize stellar radiation producing γ-rays

Conclusions

- Synchrotron and TeV γ-rays can be produced by leptons
- TeV fluxes expected within sensitivity of CTA
- Maximum TeV γ-ray emission when MSP behind the companion

(details in Bednarek 2014, A&A 561, A116)

Transition states in MSP binary systems

- Three (four) redback MSP binaries have been caught in the transition

PSR J1023+0038 (Archibald et al. 2009)
PSR J1824-2452 (Papitto et al. 2013)
PSR J1227-4853 (de Martino et al. 2014; Roy et al. 2014)
(1RXS 3154439.4-112820, Bogdanov & Halpern 2015) (?)

- Rotation powered state: radio and γ-ray pulsar
- Accretion powered state: no radio, enhanced X-rays and γ-rays
- X-ray pulsations with pulsar period in the accretion state

⇓

Evidence for accretion of matter onto NS surface !

Theoretical interpretation

- **Propeller model (Papitto et al. 2014):**

Electrons accelerated in the turbulent transition region of the inner disk

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comptonize synchrotron radiation

- **Truncated disk model (Takata et al. 2014):**

Leptons in the pulsar wind

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comptonize optical radiation from the disk truncated at $\sim 10^{10}$ cm
(i.e. above the light cylinder radius)

Redback MSP binary: PSR J1227-4853

- Existing accretion disk disappeared in 2012
  (in optical → de Martino et al. (2014)
- Discovery of radio pulsar (1.69 ms, PSR J1227-4853)
  (Roy et al. 2014)
- Discovery of γ-ray flux (Fermi) decreased by a factor of ~ 2
  (Xing & Wang 2014, Johnson et al. 2015)
- Redback binary MSP with companion ($0.06 - 0.12\ M_\odot$), period 6.9 hrs
  (de Martino et al. 2014)
- X-ray (0.3-10 keV) luminosity during accretion state: 5×10^{33} erg s^{-1},
  modulated X-ray emission with the pulsar period
  (Papitto et al. 2014)

Emission stages of PSR J1227-4853

disk state

rotation powered state

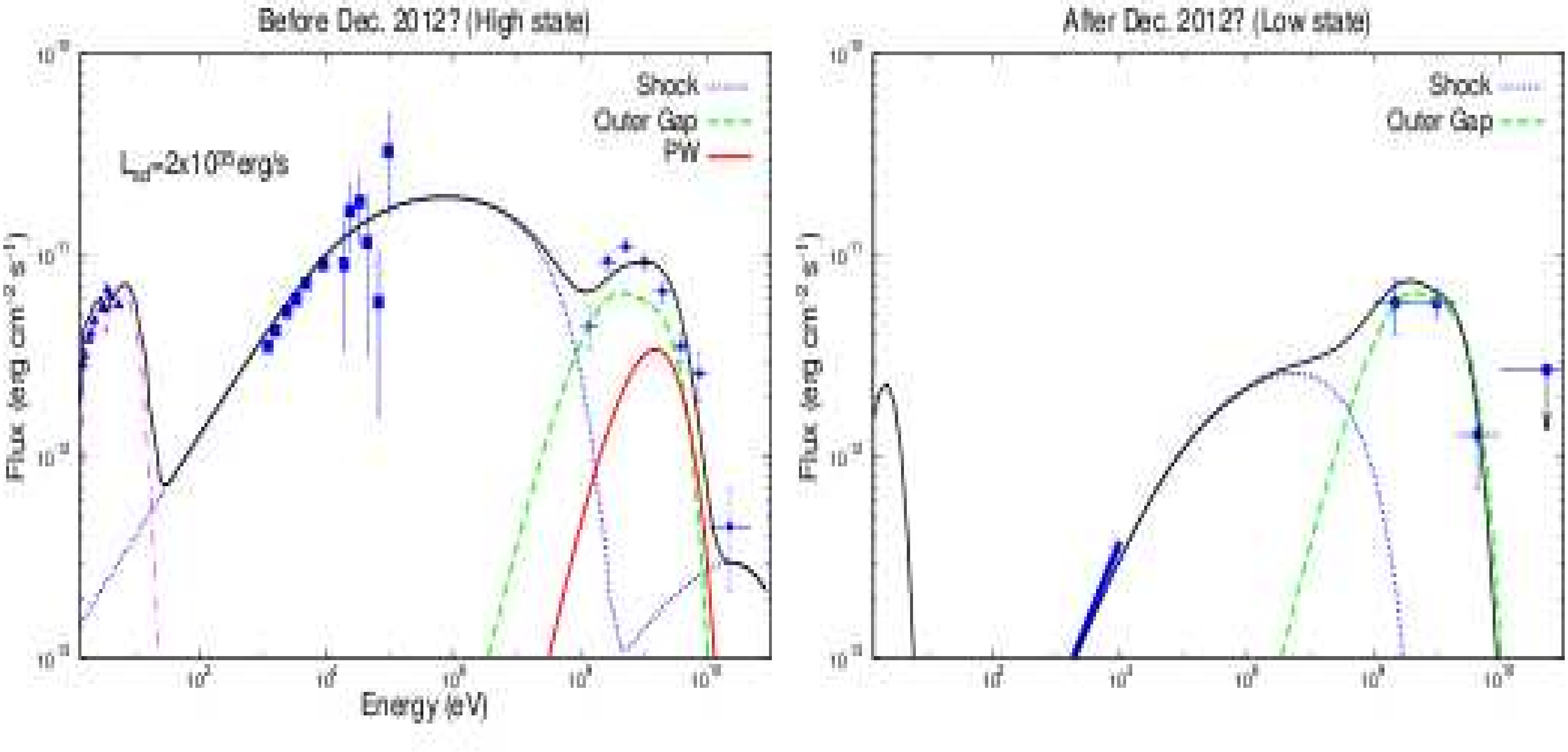


Figure 3: Spectrum of PSR J1227-4853 in rotation and accretion-powered states (from Tam et al. 2014).

Gamma-ray emission stages of PSR J1227-4853

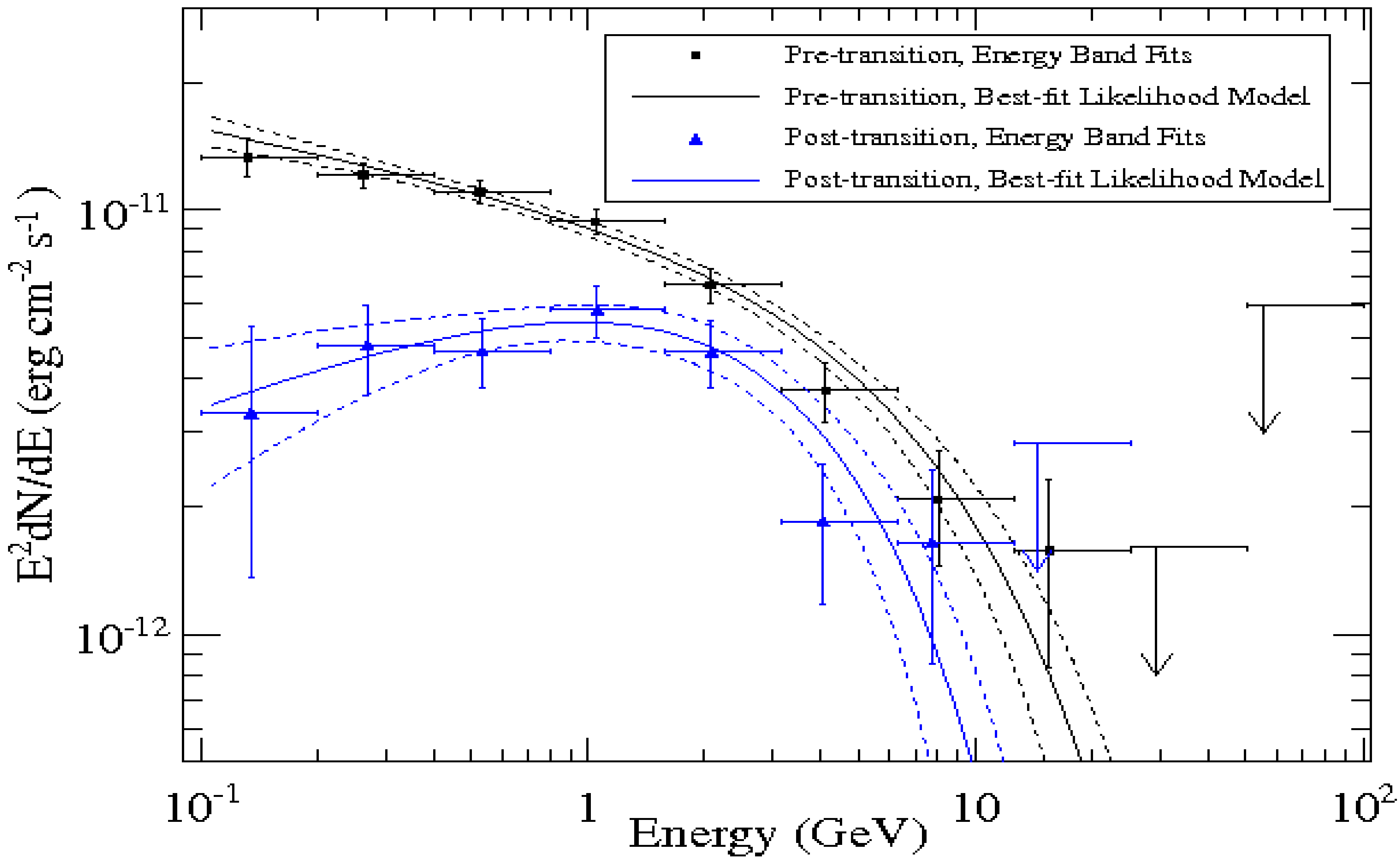


Figure 4: Gamma-ray spectra of PSR J1227-4853 in different states (from Johnson et al. 2015).

Considered model: basic assumptions

(details in Bednarek 2015, MNRAS 451, L55)

- Accretion disk penetrates NS magnetosphere below the light cylinder radius
- The accretion disk builds up accumulating matter
- Magneto-spheric radius for the plasma in the inner disk reaches corotation radius of the pulsar
- Matter falls onto the NS surface
- Leptons accelerated in the slot gap of the pulsar magnetosphere
- Disk radiation creates additional target for secondary leptons in this gap

An accretion disk in the inner MSP magnetosphere

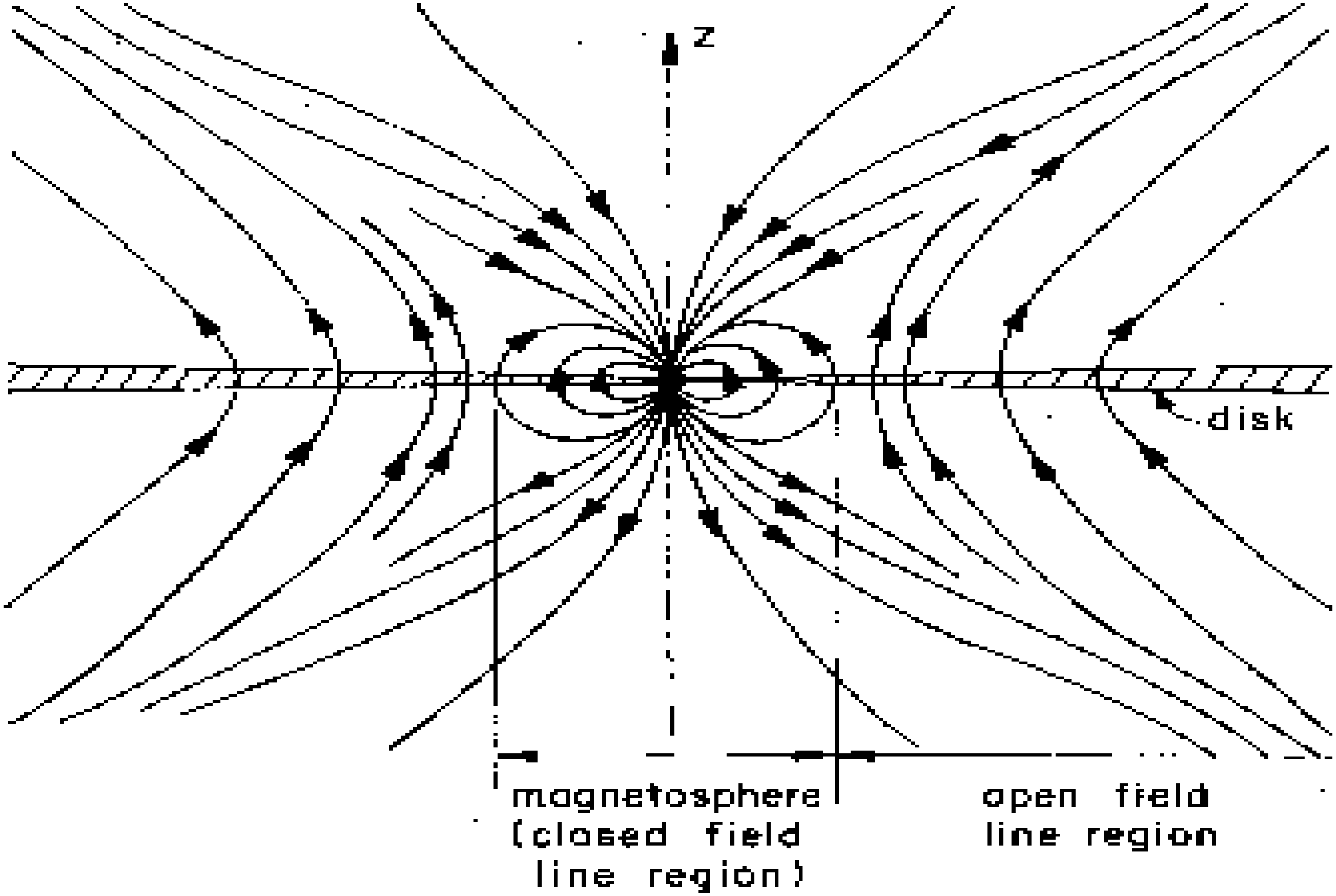
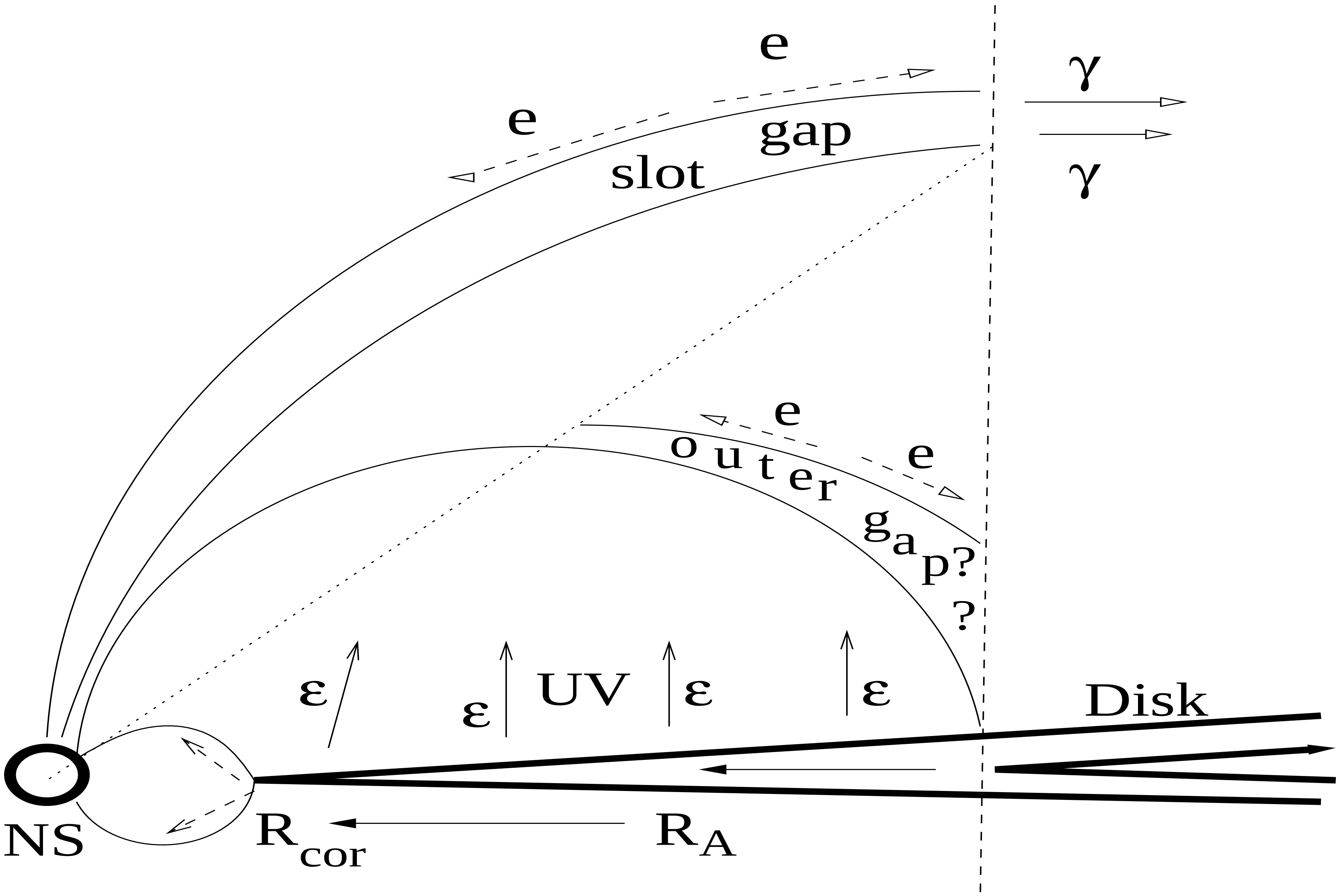


Figure 5: (see Lavelace et al. 1995)

Accretion disk within the MSP pulsar magnetosphere



Accretion disk within the pulsar inner magnetosphere

- The kinetic energy of the disk matter balanced by the magnetic energy at the Alfven radius,
$$R_{\rm A} = 8.4 \times 10^4 (B_8^2/\rho)^{1/5} \quad {\rm cm}, \tag{2}$$
where $B = 10^8 B_8$ G is the surface magnetic field of MSP,
ρ is density of disk matter in grams/cm^3

- The disk inner radius expected to be at the magneto-spheric radius
$$R_{\rm m} = \chi R_{\rm A}, \tag{3}$$
where χ is argued to be in the range $\chi \sim$0.1-1
(Lamb, Pethick & Pines 1973)

- Matter flows onto NS when, $R_{\rm m} \approx R_{\rm cor}$, where
$$R_{\rm cor} = (GM_{\rm NS})^{1/3} (P_{\rm NS}/2\pi)^{2/3} \approx 1.7 \times 10^6 P_{\rm ms}^{2/3} \quad {\rm cm}. \tag{4}$$

- The light cylinder radius at $R_{\rm LC} = cP/2\pi \approx 4.8 \times 10^6 P_{\rm ms}$ cm

- Inner disk temperature ($L_\mathrm{D} = GM_\mathrm{NS}\dot{M}/2R_\mathrm{in} = 4\pi R_\mathrm{in}^2 T_\mathrm{in}^4$):

$$T_\mathrm{in} \approx 1.5 \times 10^6 L_{34}^{1/4}/P_\mathrm{ms}^{1/3} \quad \mathrm{K}, \tag{5}$$

  where disk luminosity $L_\mathrm{D} = 10^{34} L_{34}$ erg s^{-1}.

- Disk temperature profile (Shakura & Sunyaev 1973):

$$T(R) \approx T_\mathrm{in}(R_\mathrm{in}/R)^{3/4}. \tag{6}$$

Gamma-ray emission in the accretion state

- Secondary leptons produced in the slot gap from absorption of primary gamma-rays
- Leptons comptonize disk radiation
- Leptons have power law spectrum between 100 MeV and 100 GeV
- We simulate propagation of leptons in the disk radiation (synchrotron losses included, γ-ray absorption included)

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Gamma-ray spectra in the accretion state

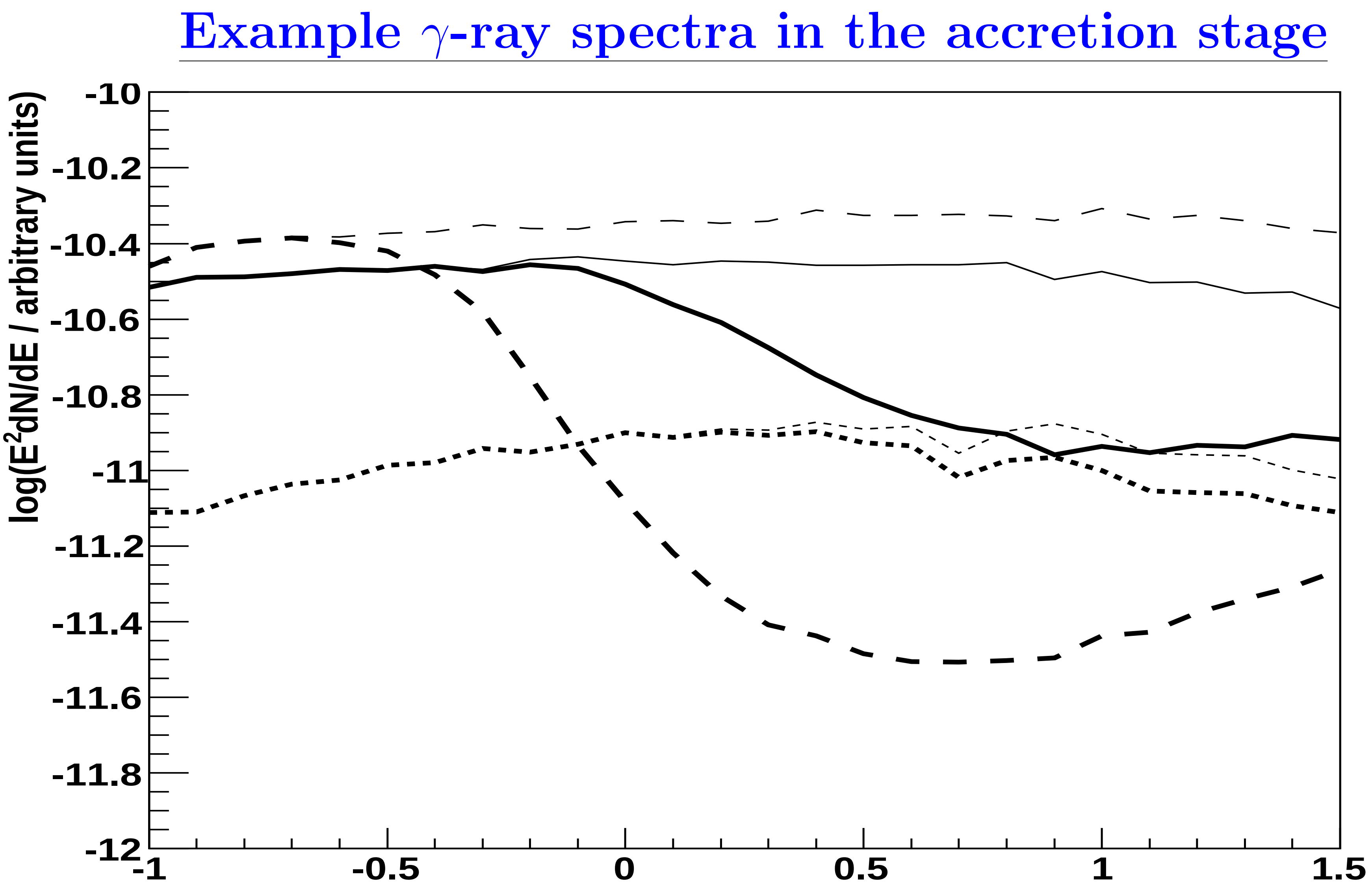

Figure 6: SED of γ-rays produced in the IC scattering of the accretion disk radiation by secondary leptons with the power law spectrum and spectral index equal to -2 between 100 MeV and 100 GeV (thin curves) and the spectra after absorption of γ-rays in the disk radiation (thick curves). Specific spectra are calculated for luminosities of the accretion disk $L_{\rm D} = 10^{33}$ erg s^{-1} (dotted), 10^{34} erg s^{-1} (solid), and 10^{35} erg s^{-1} (dashed). The disk extends up to the co-rotation radius and the period of the pulsar is equal to 1.7 ms (Bednarek 2015).

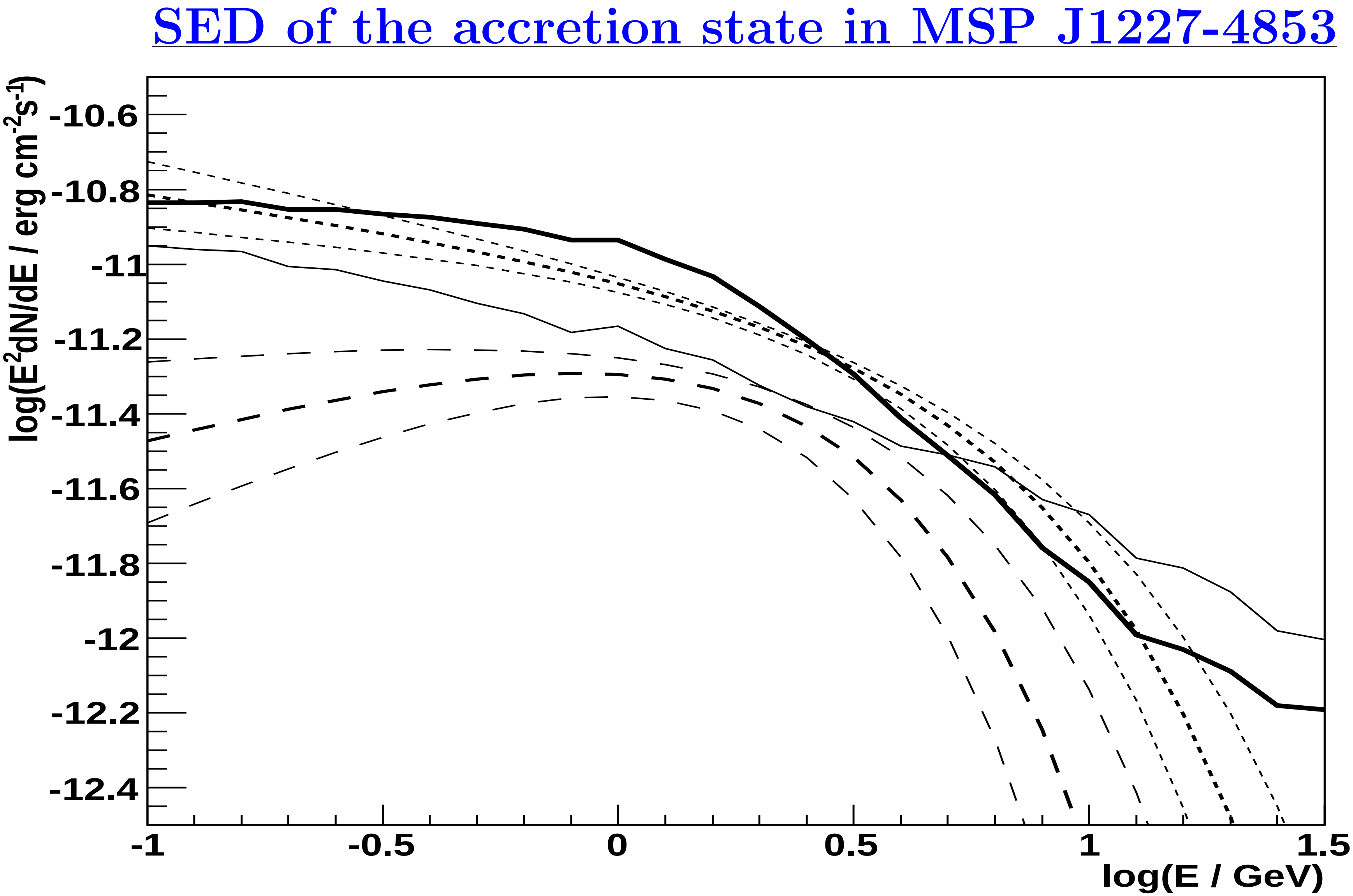

Figure 7: SED of the Redback type binary system containing MSP PSR J1227-4853. The approximation of the pre-transition and post-transition spectra from PSR J1227-4853 (dotted and dashed curves, see Johnson et al. 2015). The IC spectrum produced by secondary $e^{\pm}$ pairs which comptonize thermal radiation from the accretion disk, before (thin solid curve) and after absorption in the disk radiation (thick solid). It is assumed that the secondary $e^{\pm}$ spectrum is of a simple power law type with the spectral index -2.6 between 0.1-100 GeV. The accretion disk luminosity is assumed to be equal to $L_{\rm D} = 3 \times 10^{33}$ erg s^{-1} (Bednarek 2015).

Summary

- **We propose that accretion disk penetrates deep into the NS magnetosphere in the binary system PSR J1227-4853,**
- **The matter flows onto the NS surface in the accretion state of transiting MSPs,**
- **Pulsar mechanism is still active: acceleration of leptons in the slot gap,**
- **Secondary leptons comptonize disk radiation producing enhanced γ-rays**

Conclusions

- **γ-rays in accretion state might be also modulated with the NS period (?)**
- **Accretion disk emission should be observable at ~ 0.1 keV (UV)**
- **The presence of accretion disk might influence the geometry of the slot gap**

(more details in Bednarek 2015, MNRAS 451, L55)