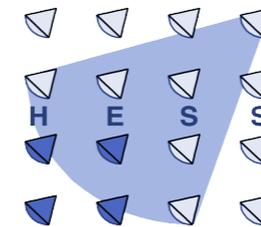


Emissione di raggi gamma in sistemi binari

Pol Bordas

Mera-TeV, Merate, Ottobre 2011

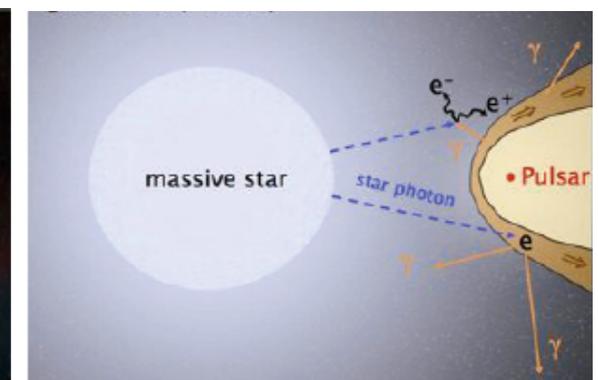
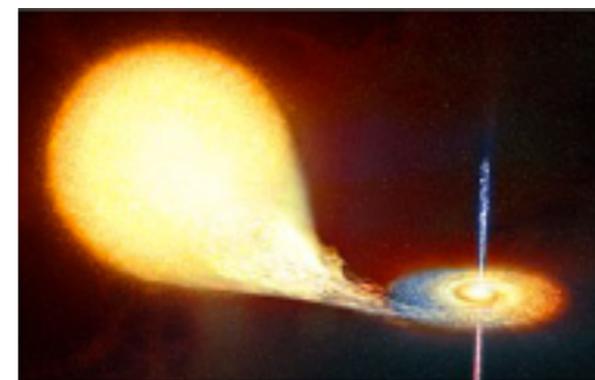
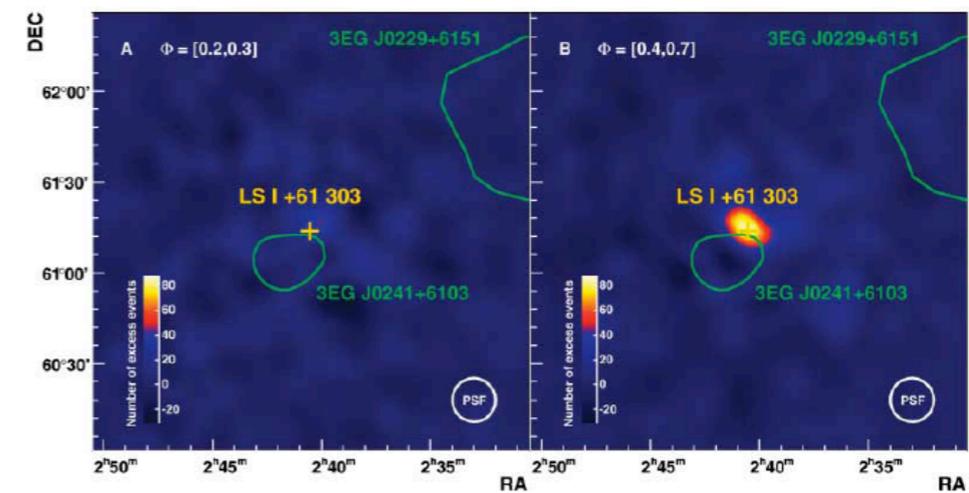
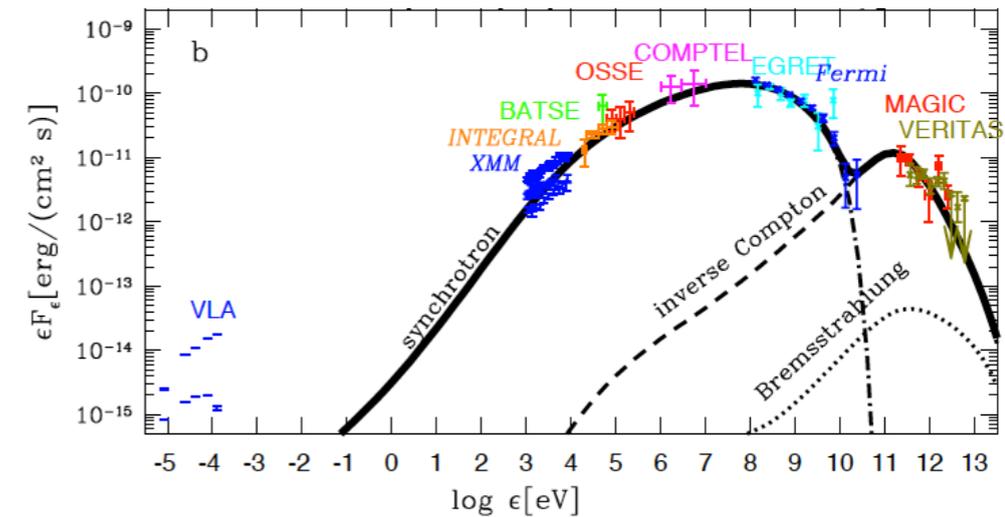


Emissione di raggi gamma in sistemi binari

- **Definizione, storia, catalogo**
- **Processi fisici nelle *γ -ray binaries***
 - accrescimento vs venti relativistici
 - accelerazione, radiazione, assorbimento
 - (alcuni) problemi non risolti
- **Dati attuali**
 - HE γ -rays: AGILE/*Fermi*
 - VHE γ -rays: MAGIC/H.E.S.S./VERITAS
- **Prospettive: CTA**

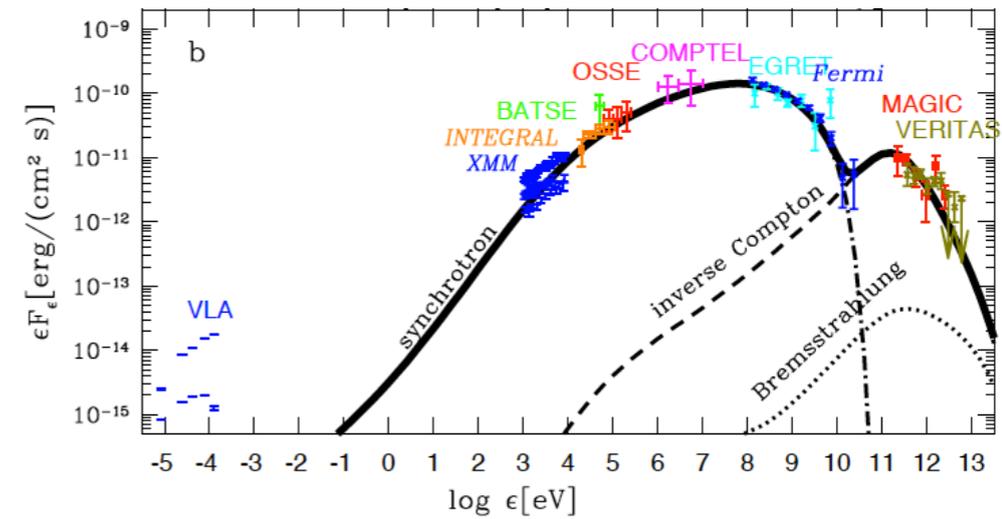
Definizione, storia, catalogo

- radiazione in tutto lo spettro e.m.
radio \rightarrow optical/UV \rightarrow X-rays \rightarrow γ -rays
(massimo a energie $>$ MeV, ma non sempre)
- sorgenti puntiformi e γ -variabili
- modulazione orbitale, ma anche *flares*
- Costituenti: stella massiccia (Be, O, oppure Wolf-Rayet) + oggetto compatto (NS/BH)

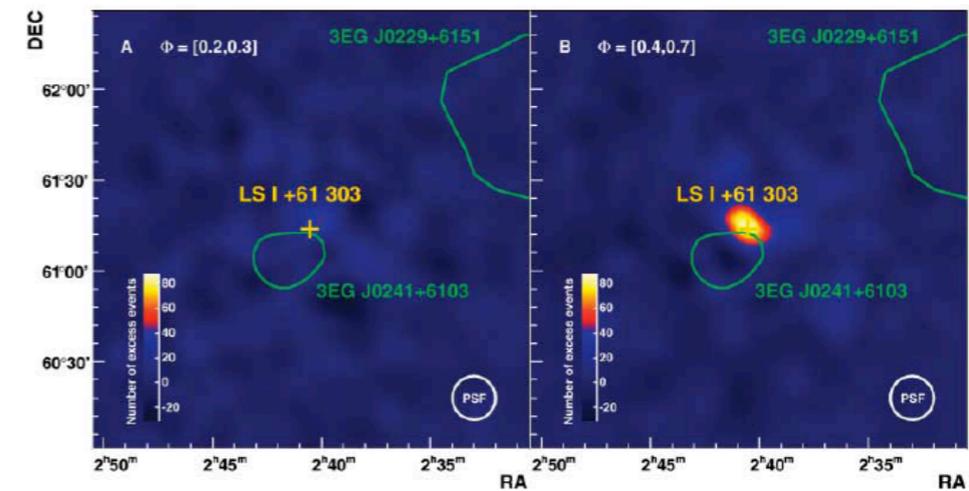


Definizione, storia, catalogo

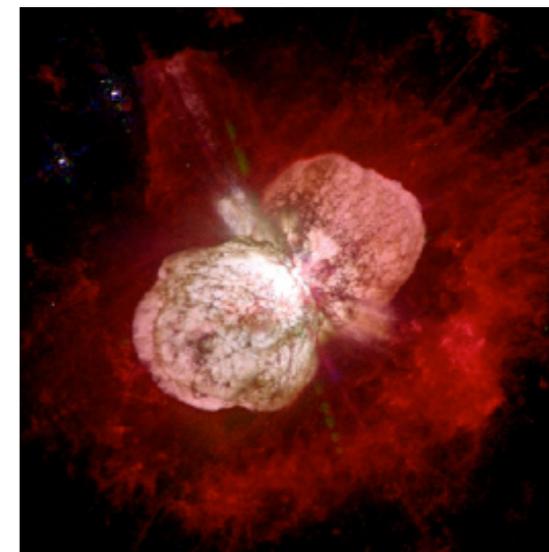
- radiazione in tutto lo spettro e.m.
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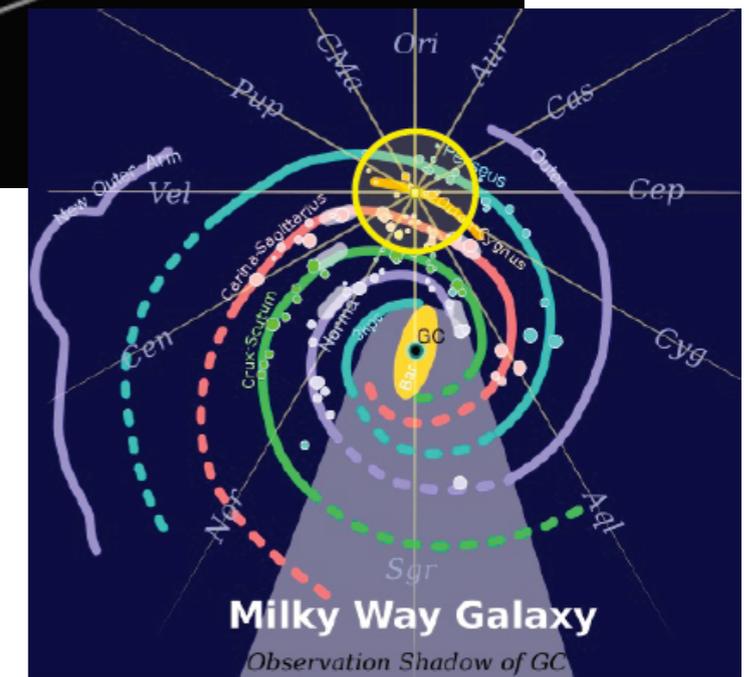
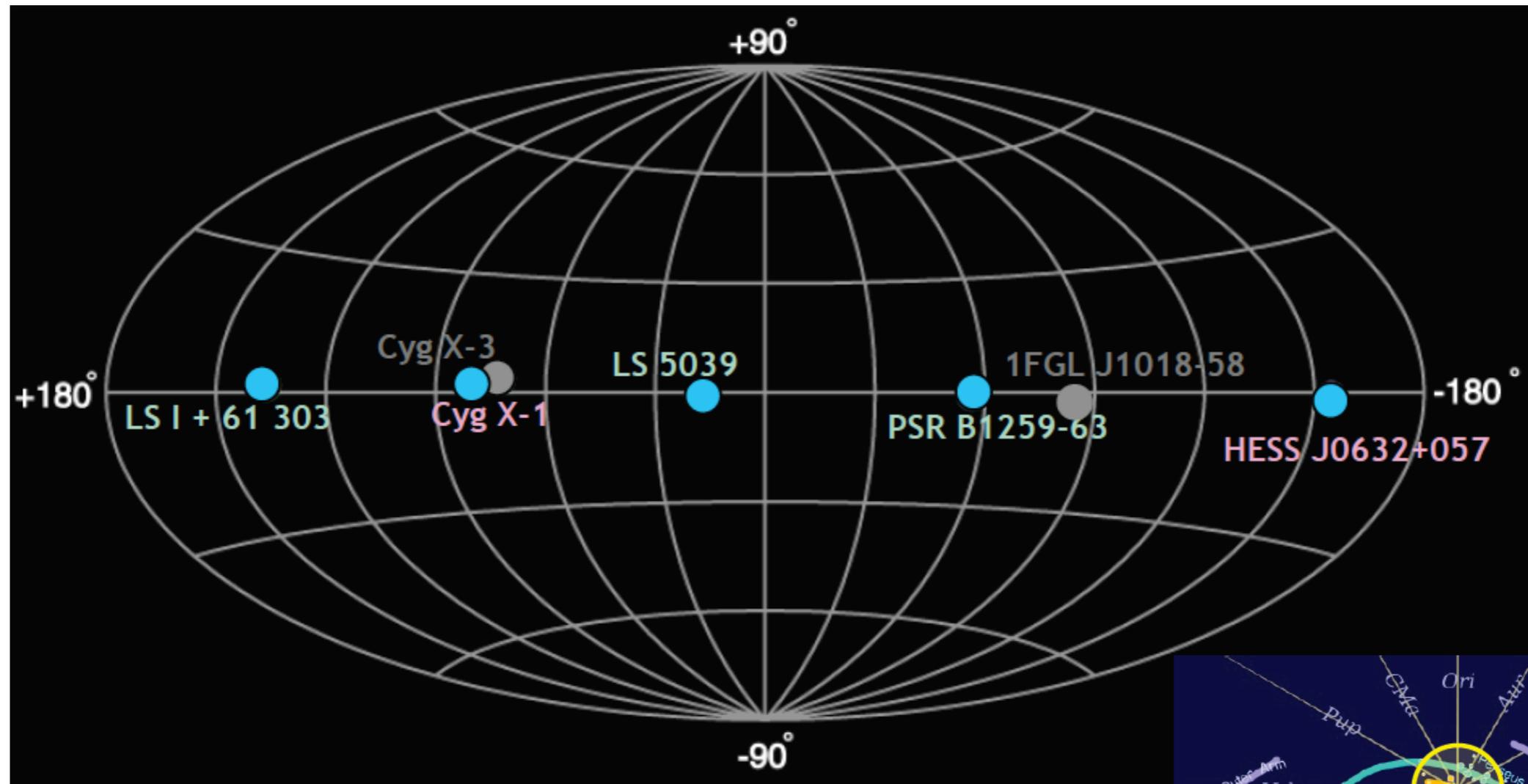
- Costituenti: stella massiccia (Be, O, oppure Wolf-Rayet) + oggetto compatto (NS/BH)
vedi però η Carinae !



Definizione, storia, catalogo

- Pulsars in sistemi binari : emissione HE
(Bignami et al. 1977, Vestrand & Eichler 1982 - Cyg X-3; Maraschi & Treves 1981 - LS I 61 303)
- Emissione di TeV-PeV γ -ray (!) => motivazione VHE Cherenkov astronomy
Her X-1, Vela X-1, Cyg X-3 e.g. Chadwick et al. (1985) - mai confermate - e.g. Weekes (1992)
- Assorbimento di raggi γ nelle vicinanze della stella compagna
Protheroe & Stanev (1987), Moskalenko et al. (1993)
- Binarie in GeV (?) -entro le barre di errore di *EGRET*
LS 5039 (Paredes et al. 2000), Cyg X-3 (Mori et al. 1997), LS I 61 303 (Thompson et al. 1995)
- Cascade anisotropiche Inverse Compton di copie e^\pm
Bednarek, (2000), Zdziarski et al. (2004), Dubus (2006)
- Scoperta di emissione γ a energie TeV
(PSR1259 - Aharonian et al. 2005; LS 5039 - Aharonian et al. 2005; LS I 61 303 - Albert et al. 2006)
- Nuovi modelli di emissione di raggi γ in sistemi binari
Bosch-Ramon et al. (2005); Romero (2003), Bednarek (2005), Böttcher et al. (2007)

Definizione, storia, catalogo



- tutte “locali”: non centro/anticentro bias
- $\sim 10 \times$ in più con proprietà similari nella Galassia

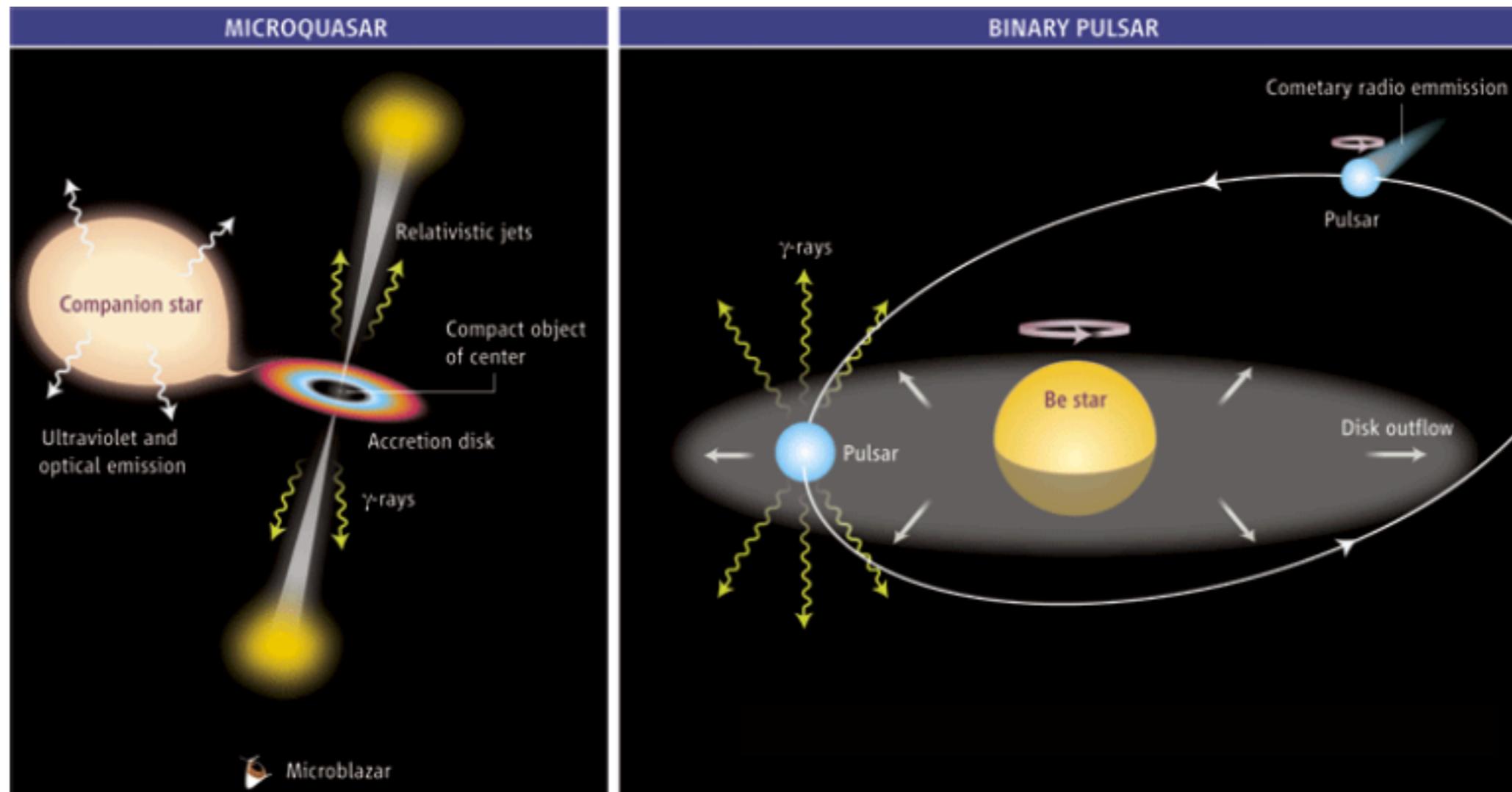
Definizione, storia, catalogo

detected

detected + orbital variability

system	BH/NS comp	Porb	radio	X-ray	GeV	TeV
PSR B1259-63	NS	1237				
LS 5039	?	3.9				
LS I +61 303	?	26.5				
HESS J0632+057	?	320			⊥	
1FGL J1018.6-5856	?	16.6				
Cyg X-1	BH	5.6				?
Cyg X-3	?	4.8h				⊥
Eta Carina	0	5.4y				?

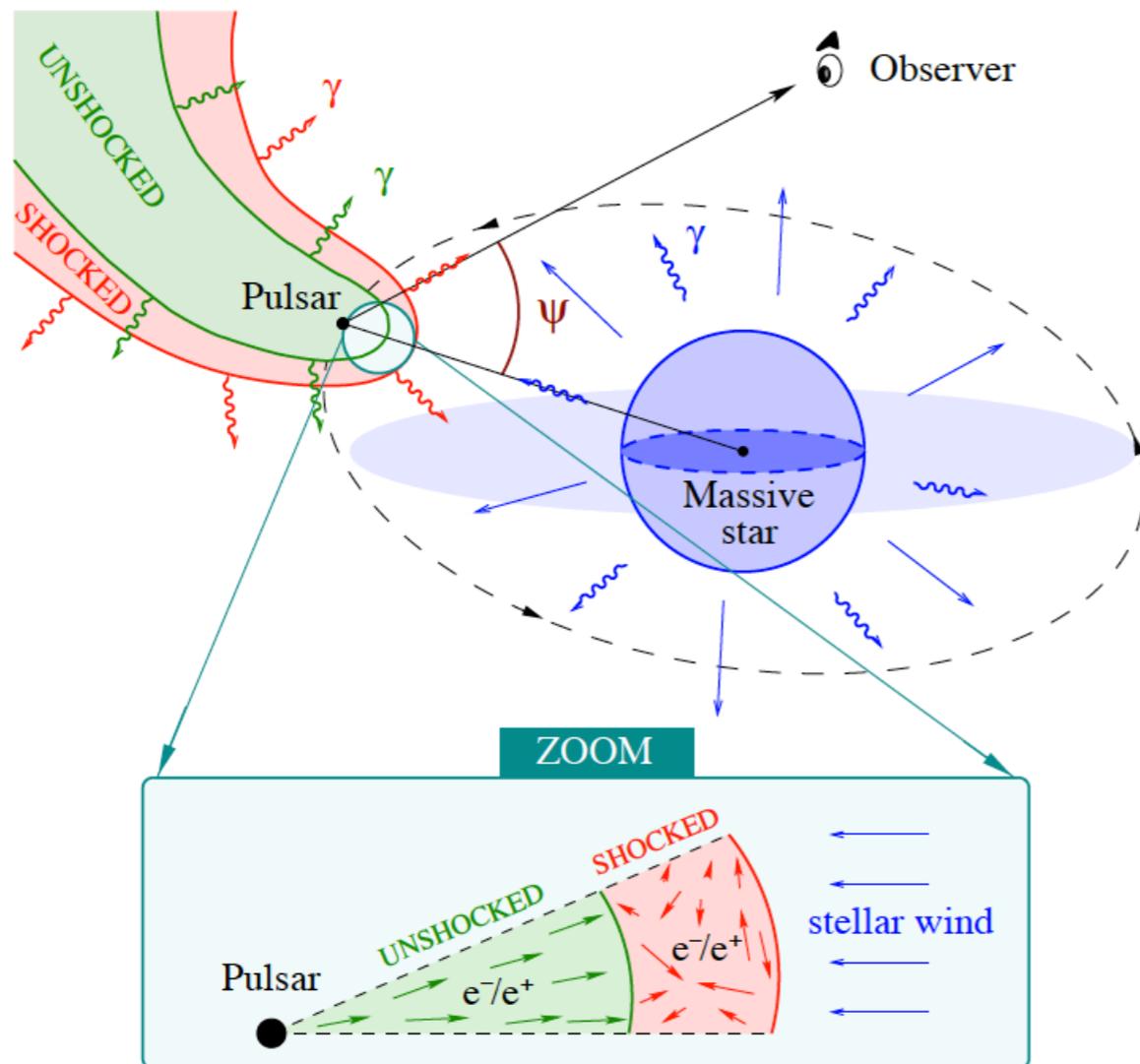
• **Processi fisici nelle γ -ray binaries**



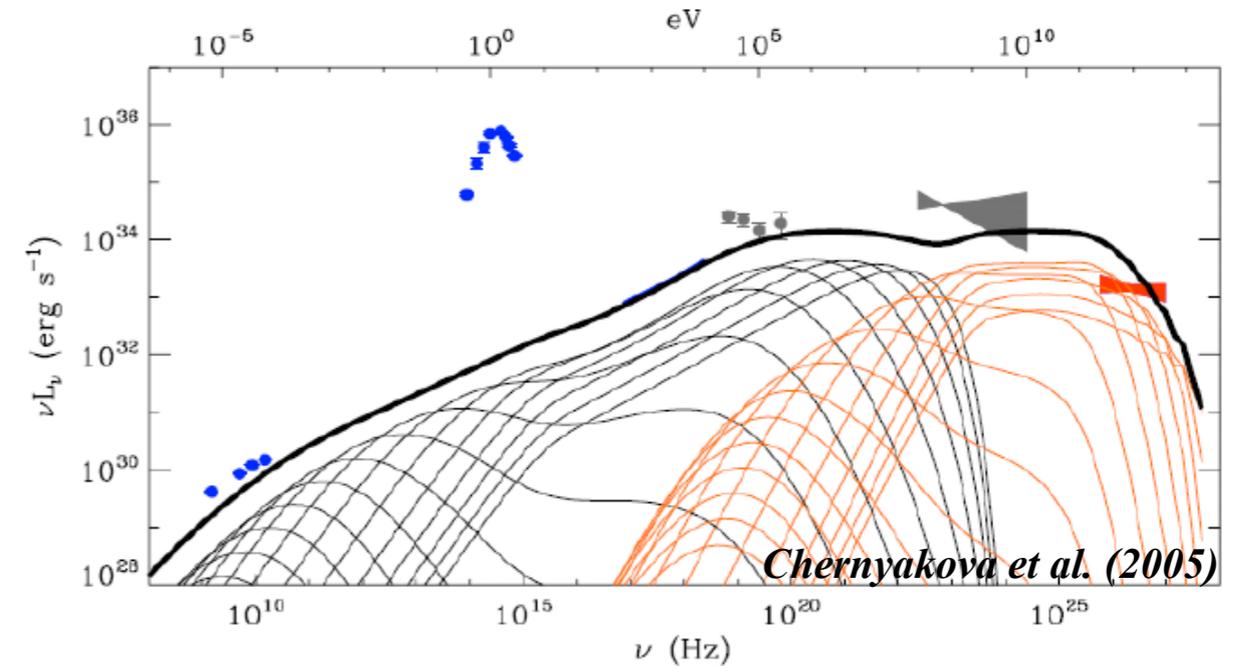
adattato da Mirabel et al. (2006)

Processi fisici nelle γ -ray binaries

1 - binary pulsar



adattato da Cerutti (2011)



- accelerazione e^{\pm} @ “*termination shock*”
popolazione non-termica $\sim N(E) \propto E^{-p}$, $p \approx 2$
- + $\mathbf{B} \Rightarrow$ radiazione sincrotrone (radio \leftrightarrow X-rays)
- + **campo fotoni UV** \Rightarrow IC \rightarrow γ -rays
(+ perdite scapamento/adiabatiche)

Processi fisici nelle γ -ray binaries

1 - binary pulsar

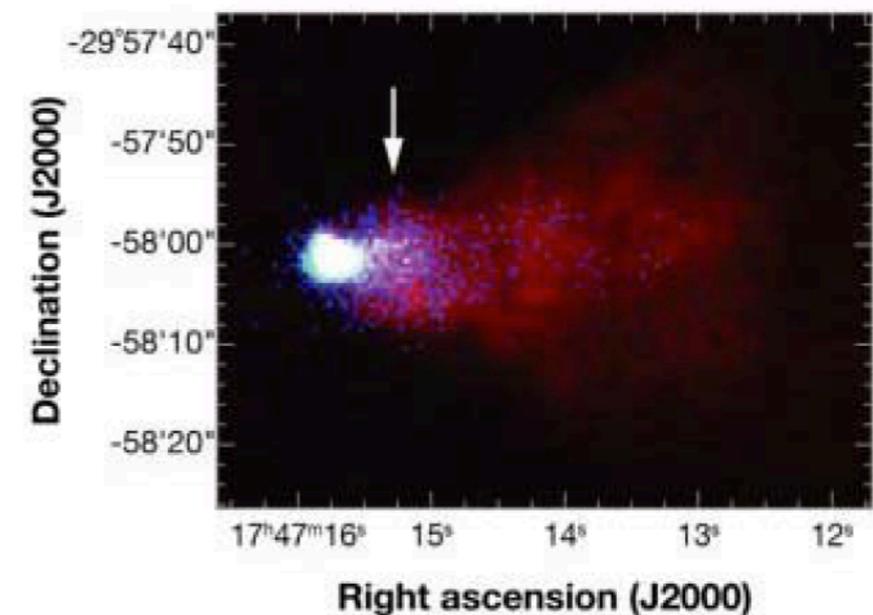
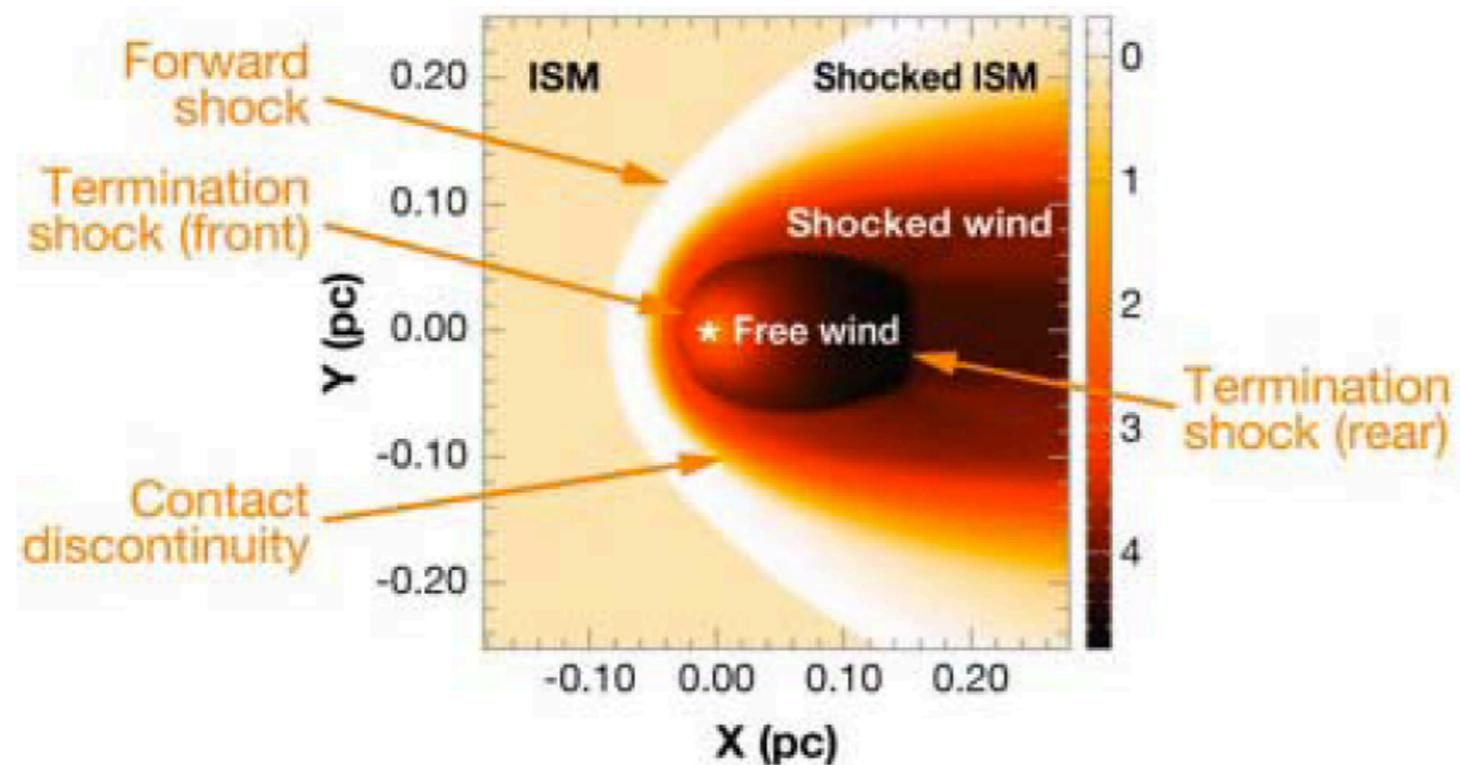


figure di Dubus et al. (2006)

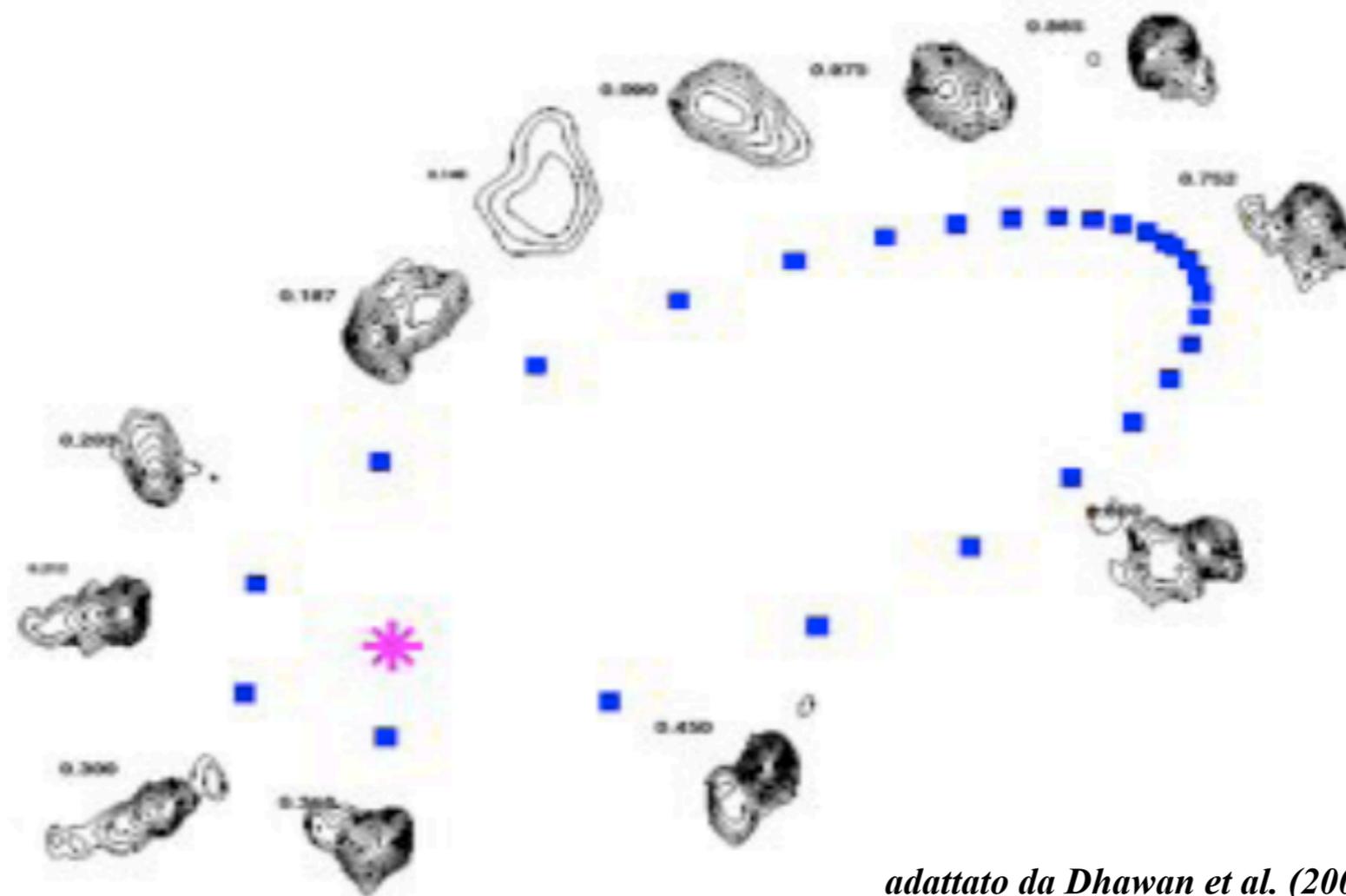
- modello *Pulsar Wind Nebulae* (PWN) applicato a γ -ray binary pulsar:
interazione vento relativista pulsar + ISM \rightarrow **vento pulsar + vento compagna**
- “*stagnation point*” si trova **dentro** del sistema binario
flusso di particelle con $v_i \approx c/3$ formano una “cometary tail” \Rightarrow **modulazione orbitale**

Processi fisici nelle γ -ray binaries

1 - binary pulsar

milliarcsecond scales show comet-like behaviour

Dhawan+ 2006, Albert+ 2008 (LS I +61 303); Ribó+ 2008 (LS 5039); Moldón+ 2011 (PSR B1259)



adattato da Dhawan et al. (2006)

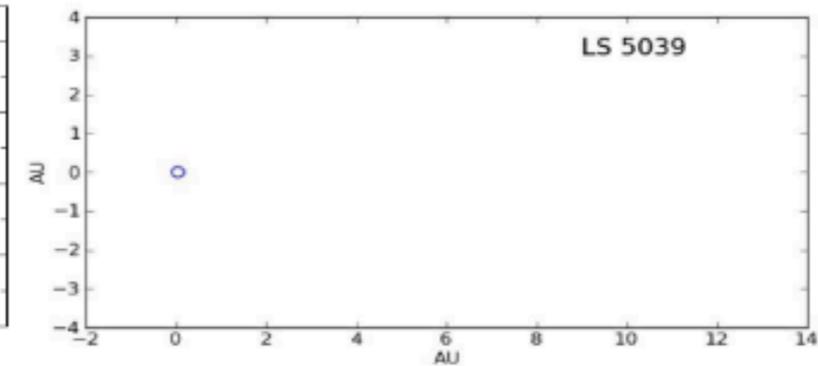
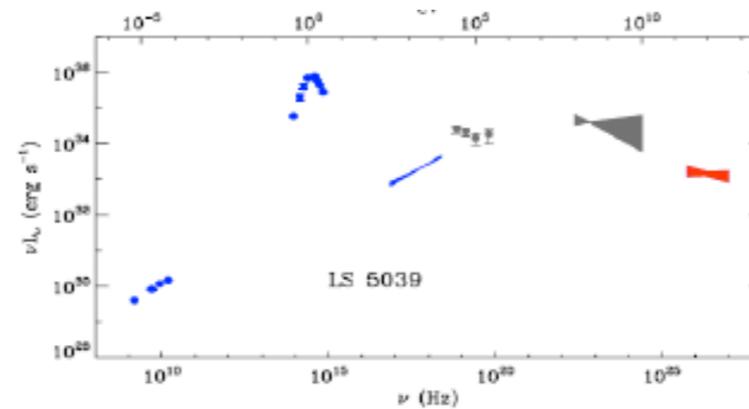
Processi fisici nelle γ -ray binaries

1 - binary pulsar

- pulsar in sistemi binari \Rightarrow emissione radio pulsata?

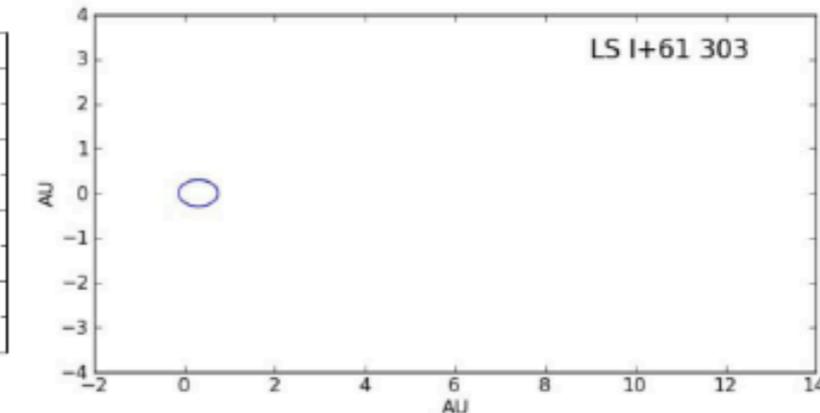
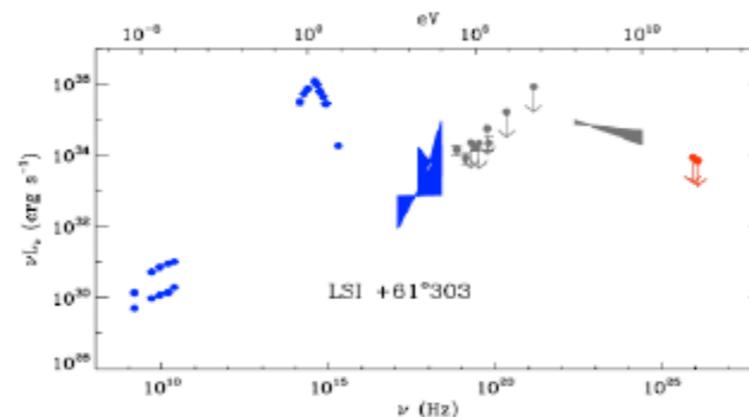
LS 5039

$P_{\text{orb}} = 3.9$ day
O6.5 V + ?



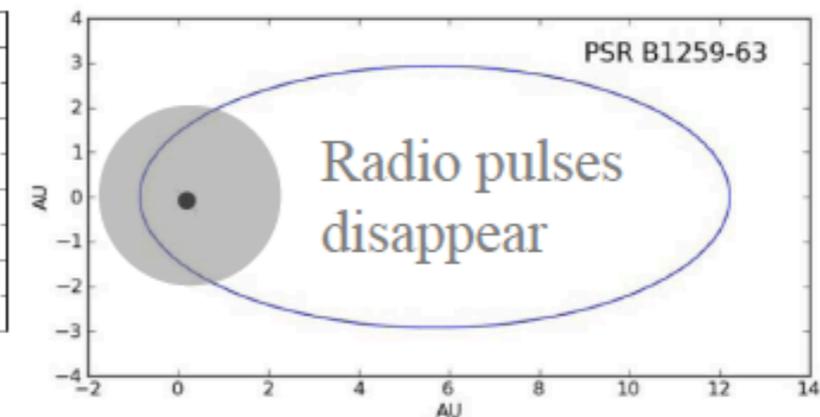
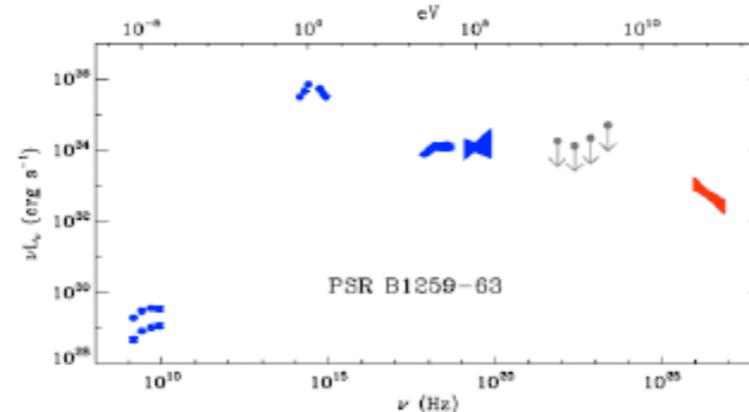
LS I +61 303

$P_{\text{orb}} = 26.5$ day
B0Ve + ?



PSR B1259-63

$P_{\text{orb}} = 3.4$ yr
O8.5Ve + pulsar



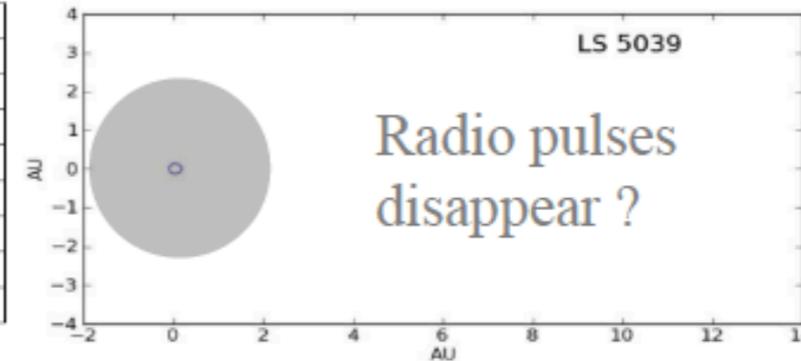
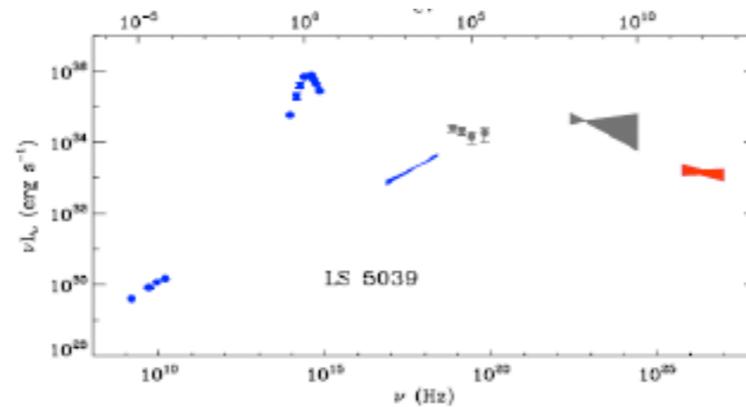
Processi fisici nelle γ -ray binaries

1 - binary pulsar

- pulsar in sistemi binari \Rightarrow emissione radio pulsata?

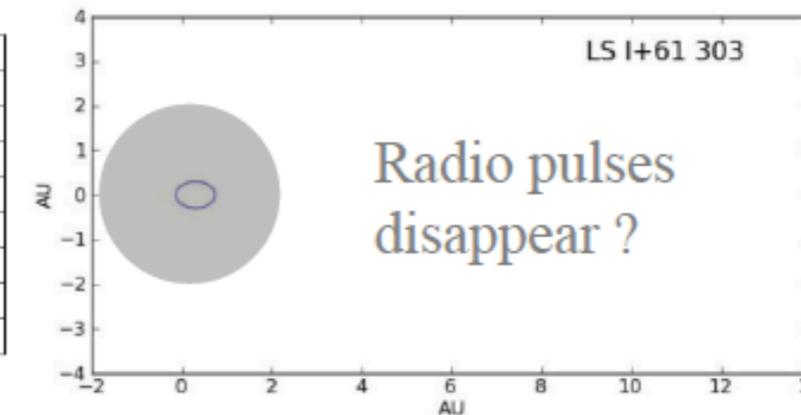
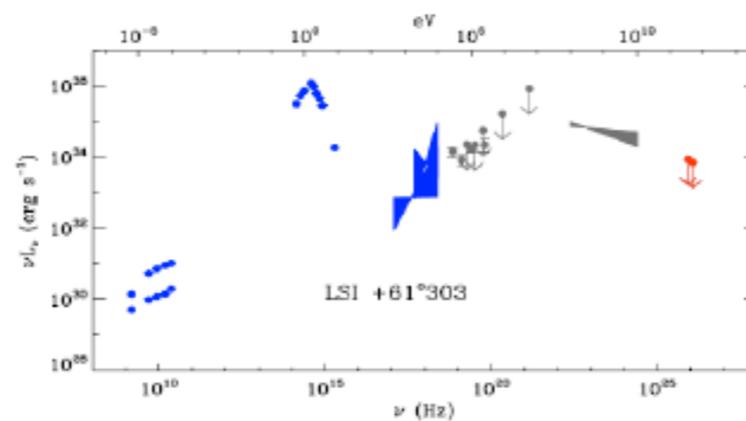
LS 5039

$P_{\text{orb}} = 3.9$ day
O6.5 V + ?



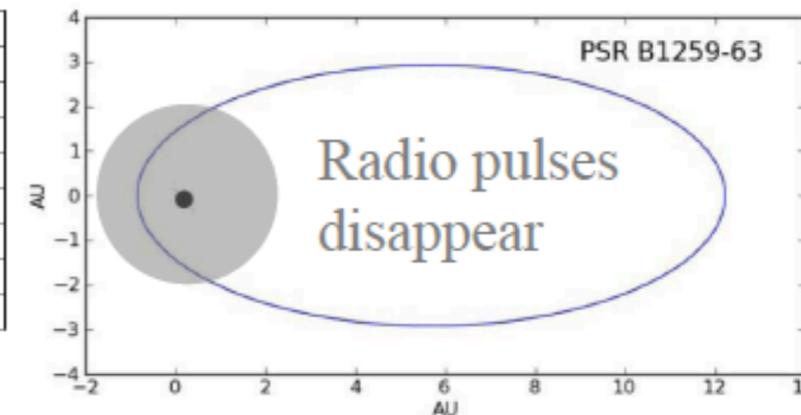
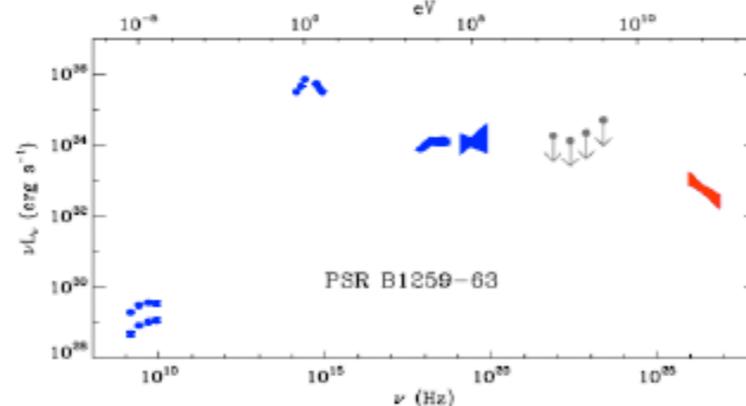
LS I+61 303

$P_{\text{orb}} = 26.5$ day
B0Ve + ?



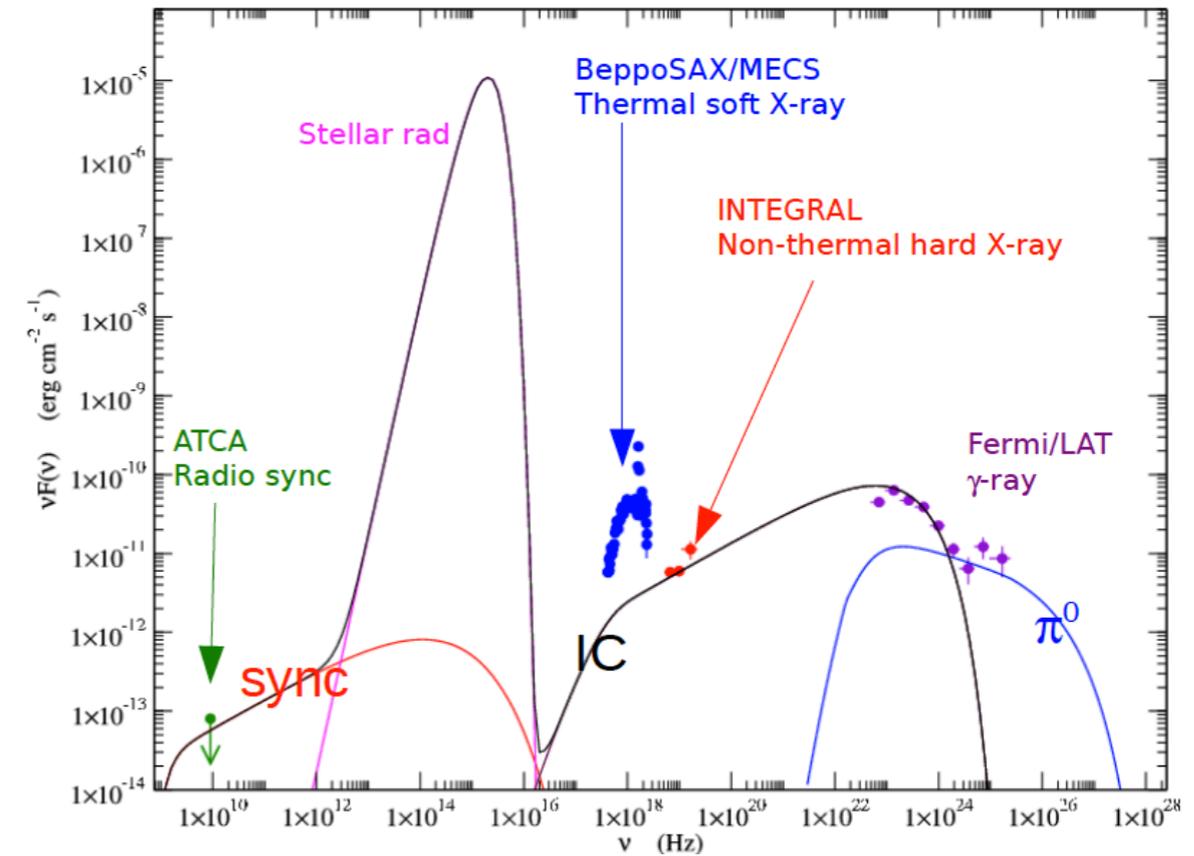
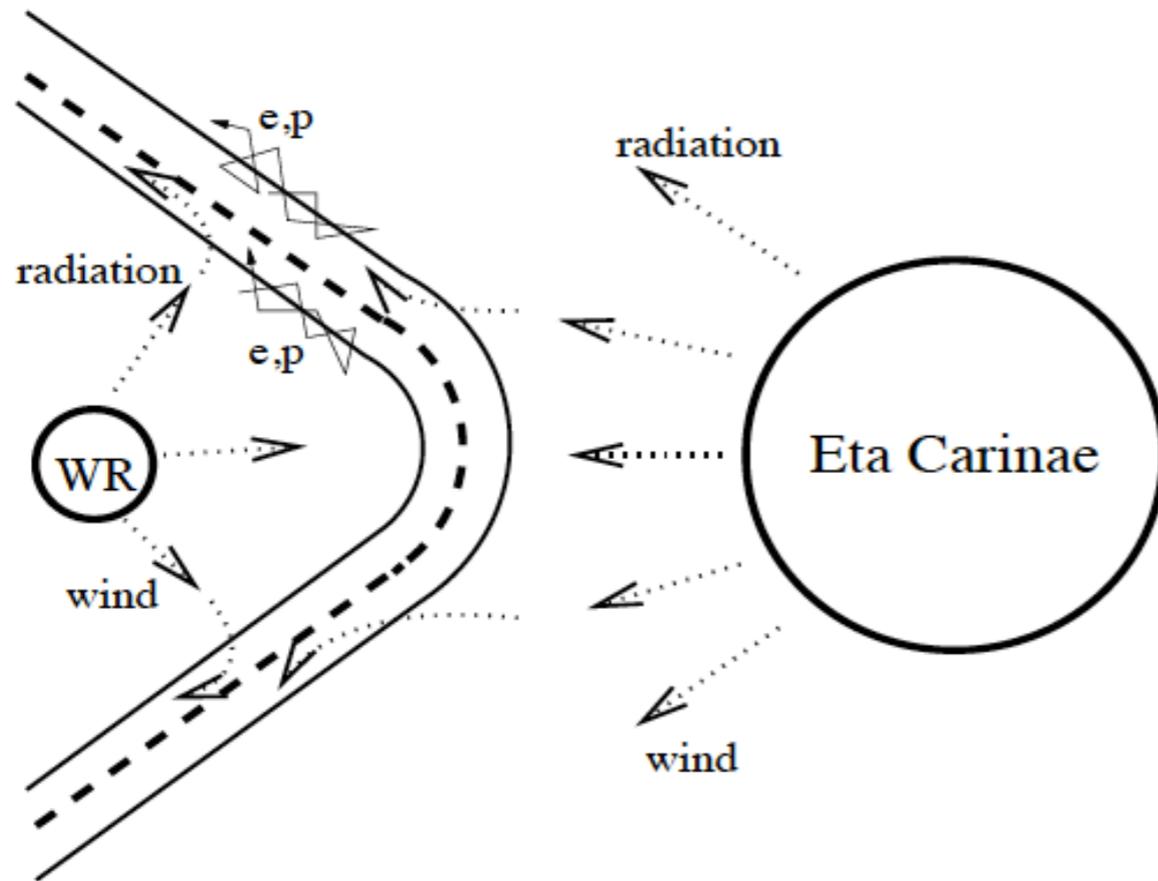
PSR B1259-63

$P_{\text{orb}} = 3.4$ yr
O8.5Ve + pulsar



Processi fisici nelle γ -ray binaries

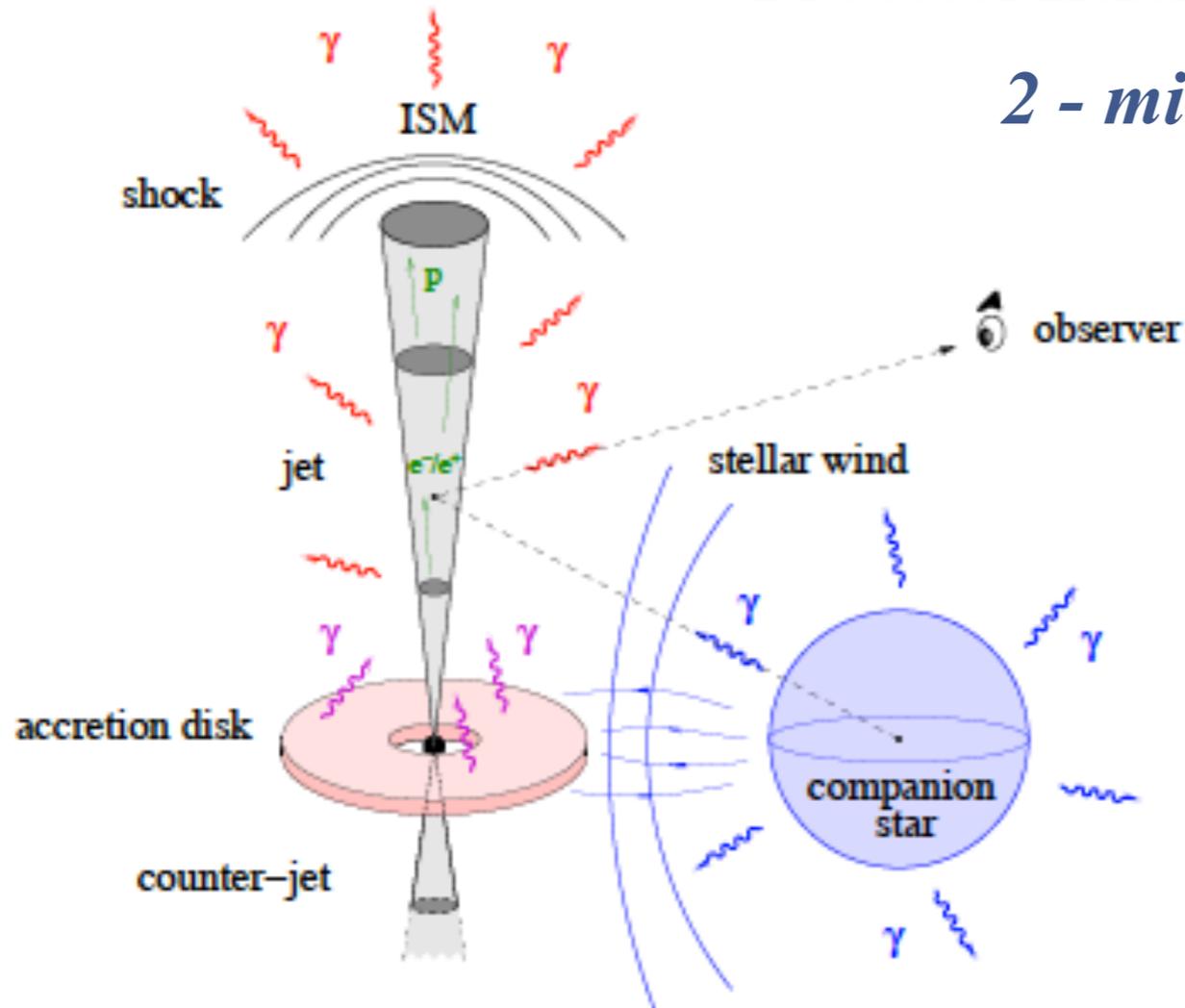
“1b” - η Carinae



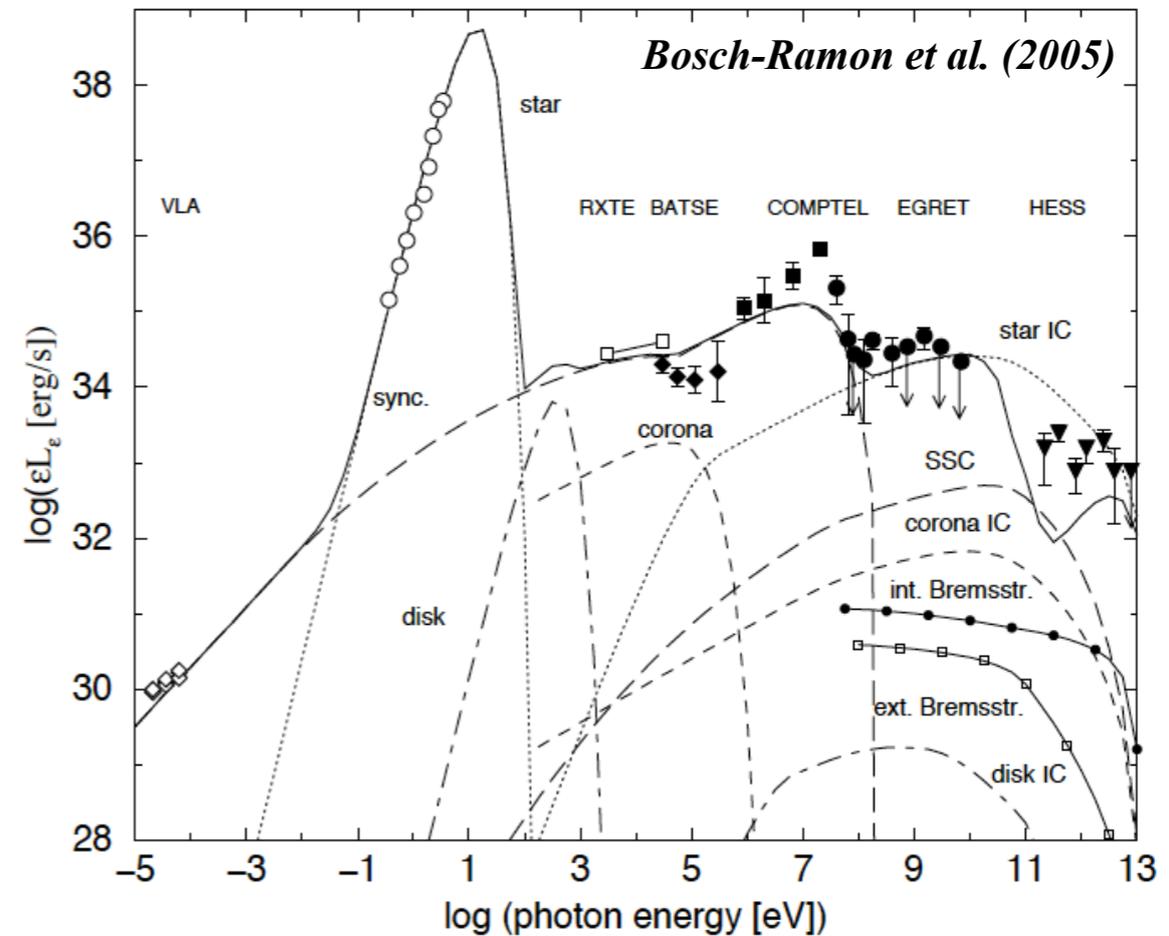
- accelerazione $e^{+/-}$ nel forward/reverse shock fra i venti stellari?
 + $\mathbf{B} \Rightarrow$ radiazione sincrotrone (radio \leftrightarrow X-rays)
 + **campo fotoni UV** \Rightarrow IC \rightarrow γ -rays
- interazioni hadroniche $pp \rightarrow \pi^0 \rightarrow \gamma$ -rays ?

Processi fisici nelle γ -ray binaries

2 - microquasars



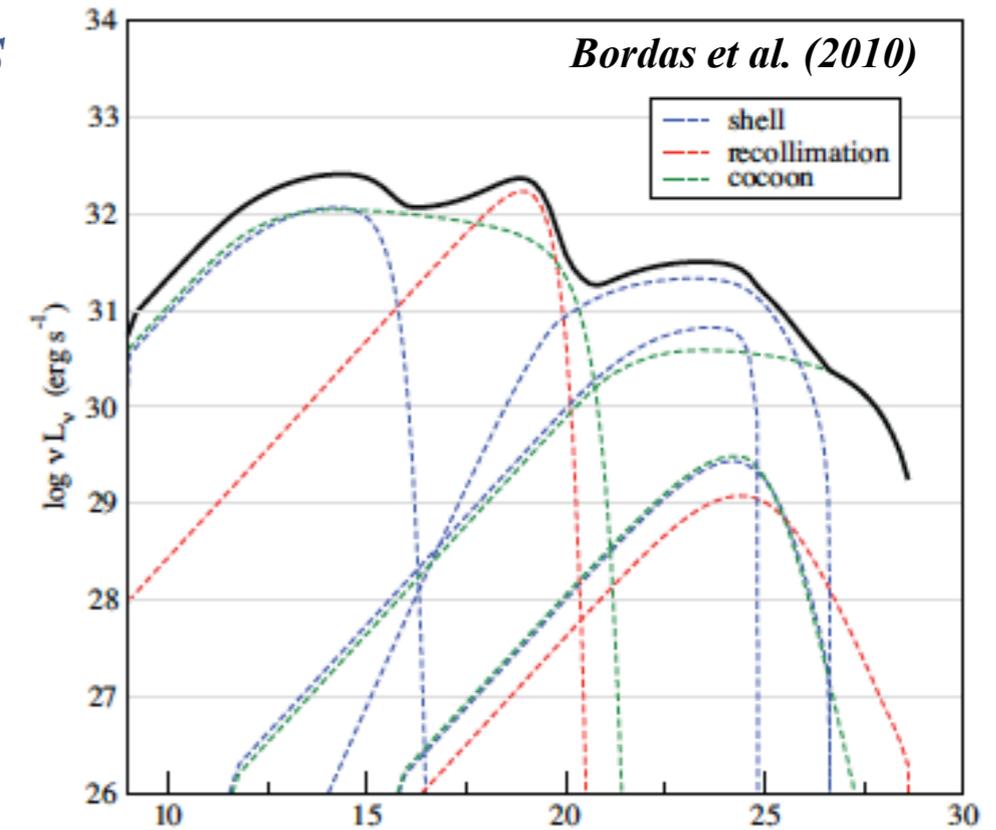
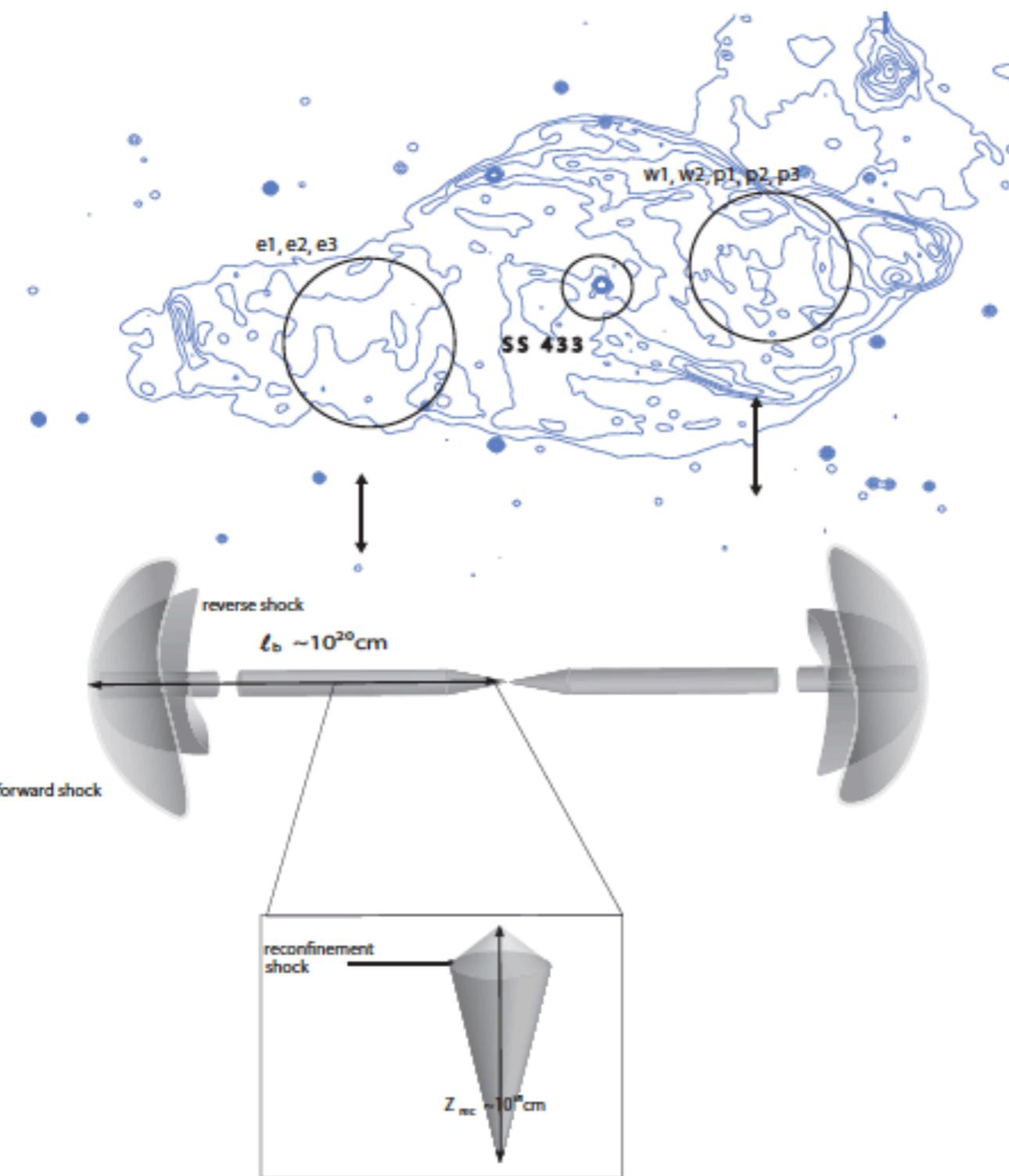
adattato da Cerutti (2011)



- **accrescimento** stella compagna \rightarrow oggetto compatto (Roche overflow/vento stellare)
- formazione di **jets relativistici** simili a quelli presenti in AGN e GRBs - scale "galattiche"
 - + **B** \Rightarrow radiazione sincrotrone (radio \leftrightarrow X-rays??)
 - + **campo fotoni UV** \Rightarrow IC \rightarrow γ -rays / interazioni pp \rightarrow $\pi^0 \rightarrow$ γ -rays

Processi fisici nelle γ -ray binaries

2 - microquasars



Self-similar growing

- Self-similar parameter: $\mathcal{R} \equiv l_{jet} / r_{jet}$
- Source basic parameters:
 - Source age $t_{\mu Q} \sim 10^4 - 10^5$ yr
 - Energy injection rate $Q_{jet} \sim 10^{36} - 10^{37}$ erg s⁻¹
 - Medium density $n_{ISM} = 0.1 - 1.0$ cm⁻³

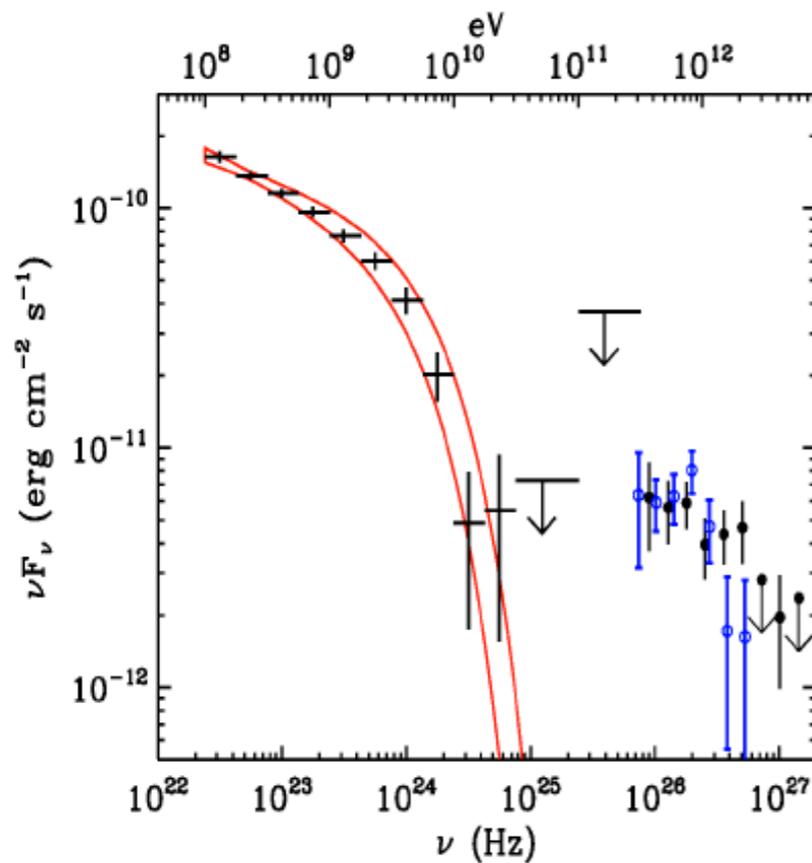
• Characteristic length: $l_0 = \frac{Q_{jet}^2}{\rho_{ISM}^2 c^6 (\Gamma_{jet} - 1)^3}^{1/4}$

given $l_{jet} \gg l_0$, then $\left\{ \begin{array}{l} l_{bow} = 1.5 \left(\frac{Q_{jet}}{\rho_{ISM}} \right)^{1/5} t_{MQ}^{3/5} \\ v_{bow} = \frac{d}{dt}(l_b) = \frac{3l_b}{5t_{MQ}} \\ r_{bow} = l_b / \mathcal{R} \end{array} \right.$

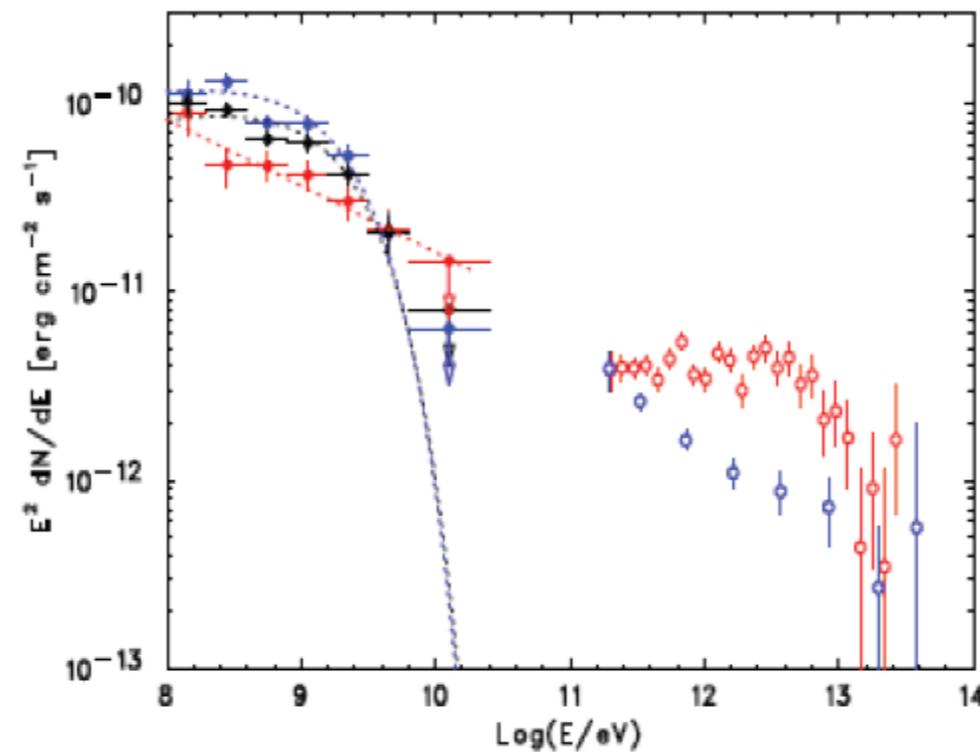
Processi fisici nelle γ -ray binaries

(alcuni) problemi non risolti

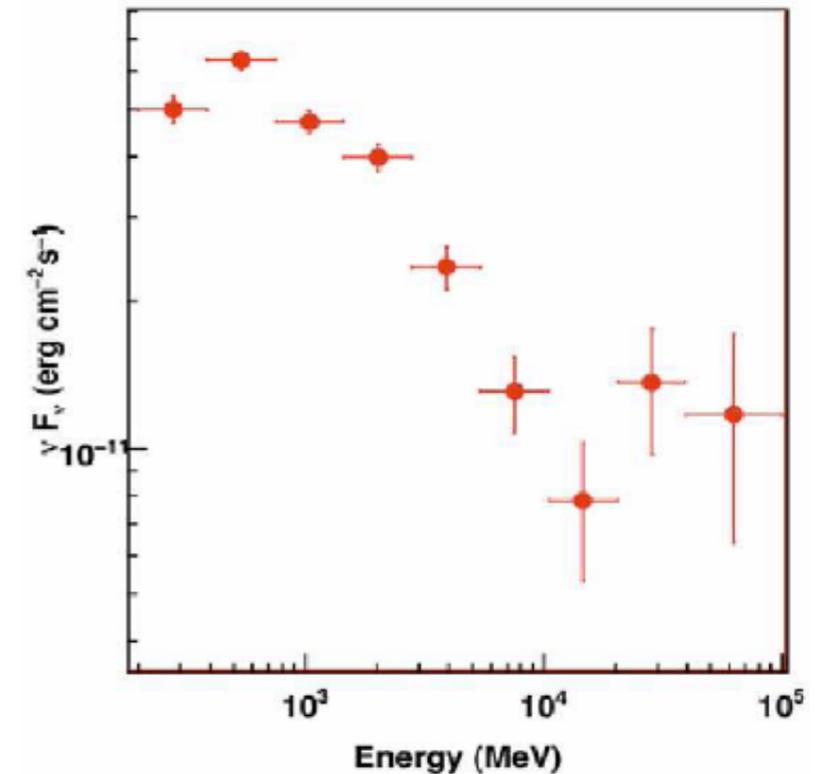
- diverse popolazioni? Cutoff esponenziale \Leftrightarrow emissione magnetosferica pulsar ?



LSI +61 303



LS 5039

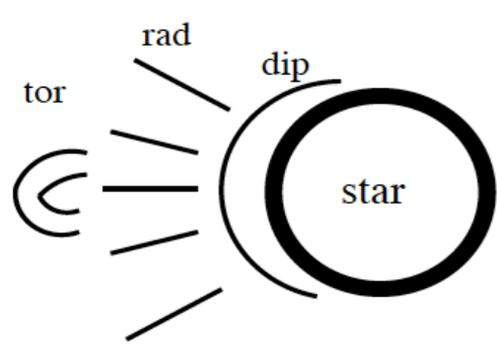


η Carinae

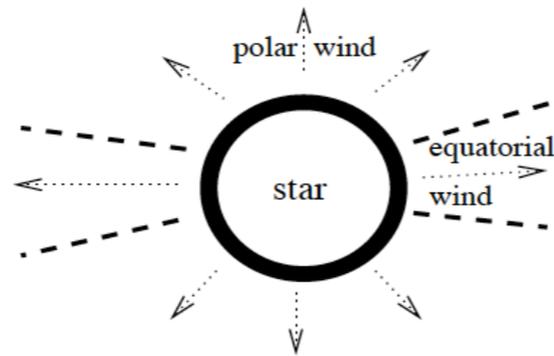
Processi fisici nelle γ -ray binaries

(alcuni) problemi non risolti

- struttura campo magnetico/vento stellare?

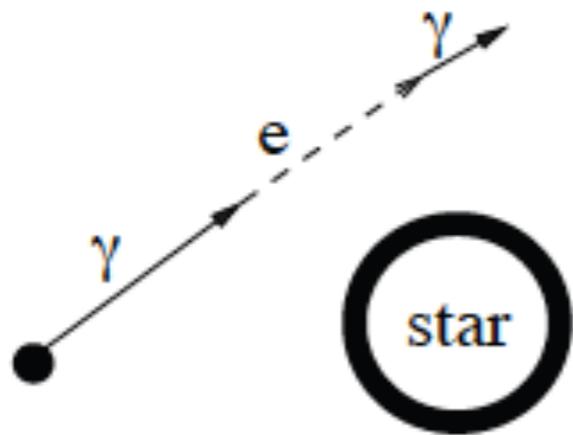
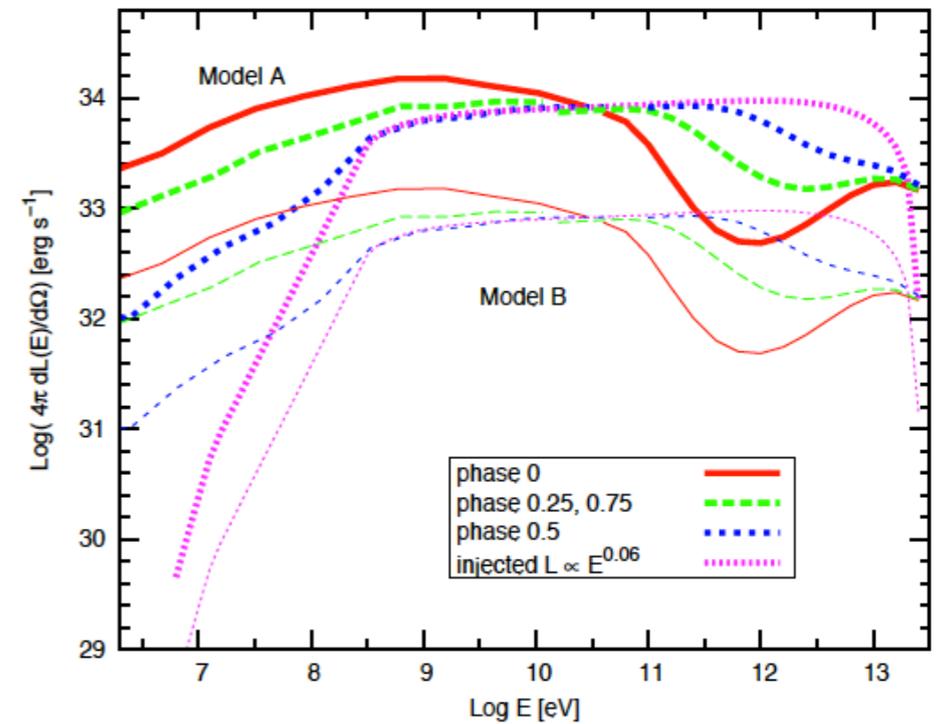


$B(R) \propto R^{-3}$ (dip),
 $\propto R^{-2}$ (rad), $\propto R^{-1}$ (tor)

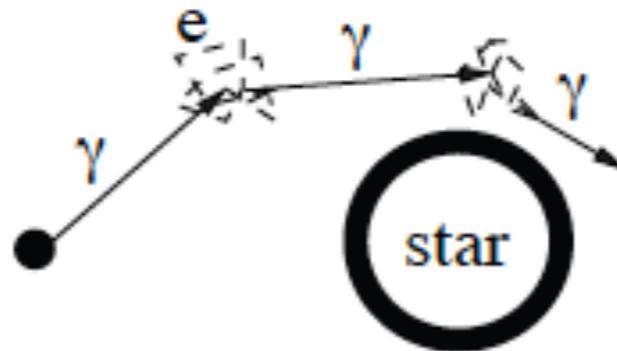


polare: $v \sim 10^3$ km/s
 equatoriale: $v \sim 10-100$ km/s

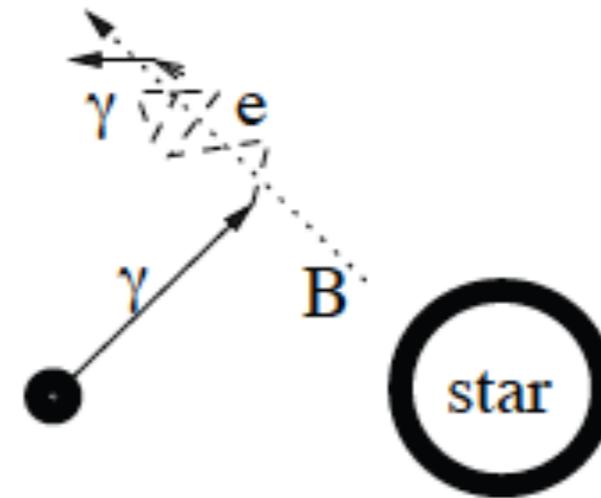
- sviluppo dettagliato delle cascate?



cascade lineale



isotropizzate

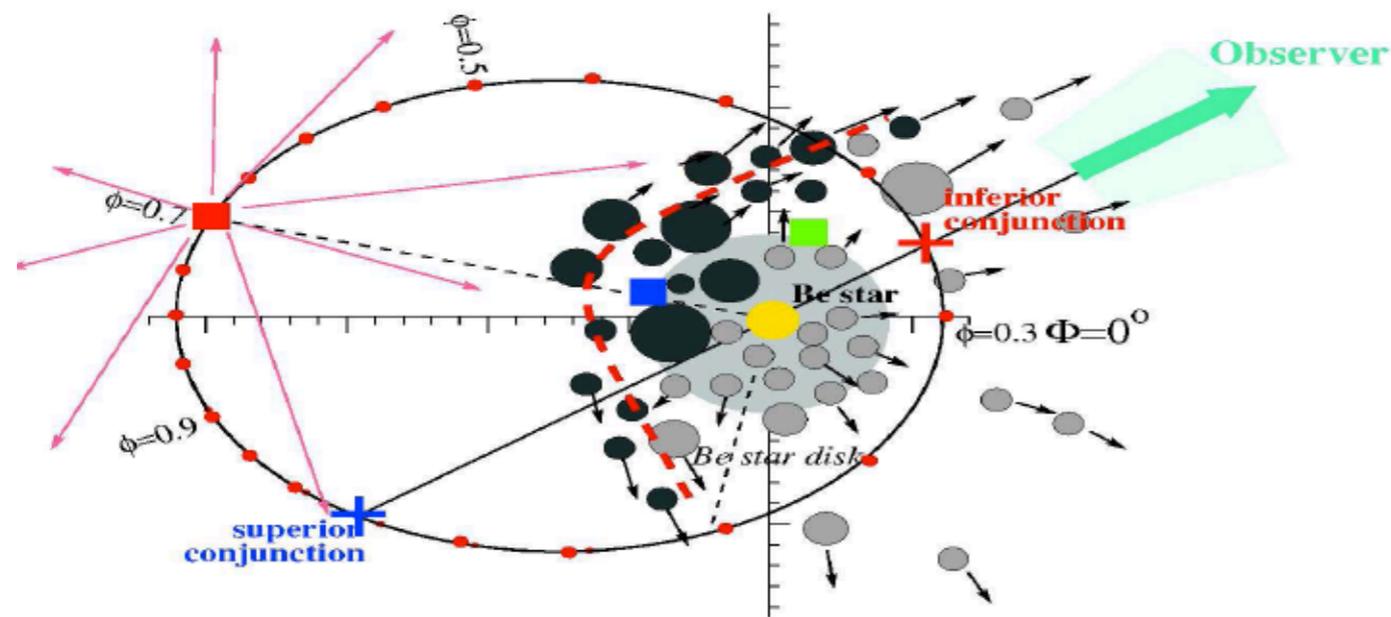


magnetico-dominante

Processi fisici nelle γ -ray binaries

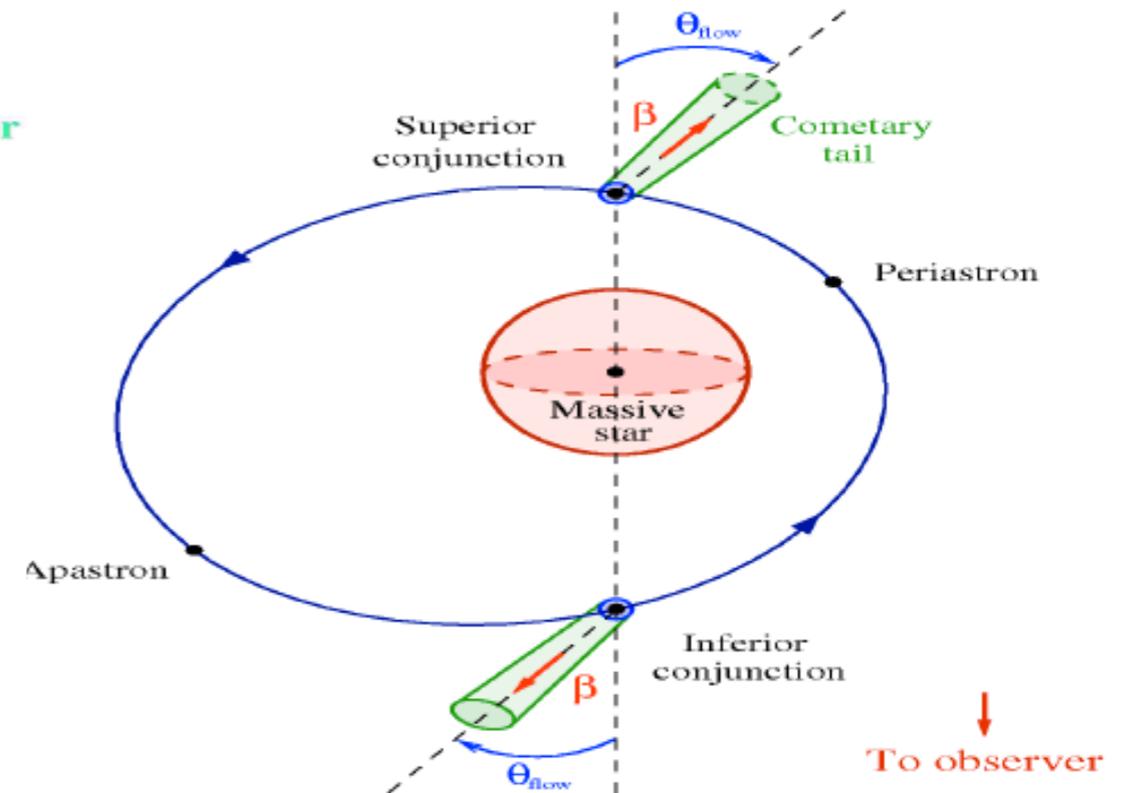
(alcuni) problemi non risolti

- Effetto di un vento stellare inhomogeneo ?



adattato da Zdziarski et al. (2010)

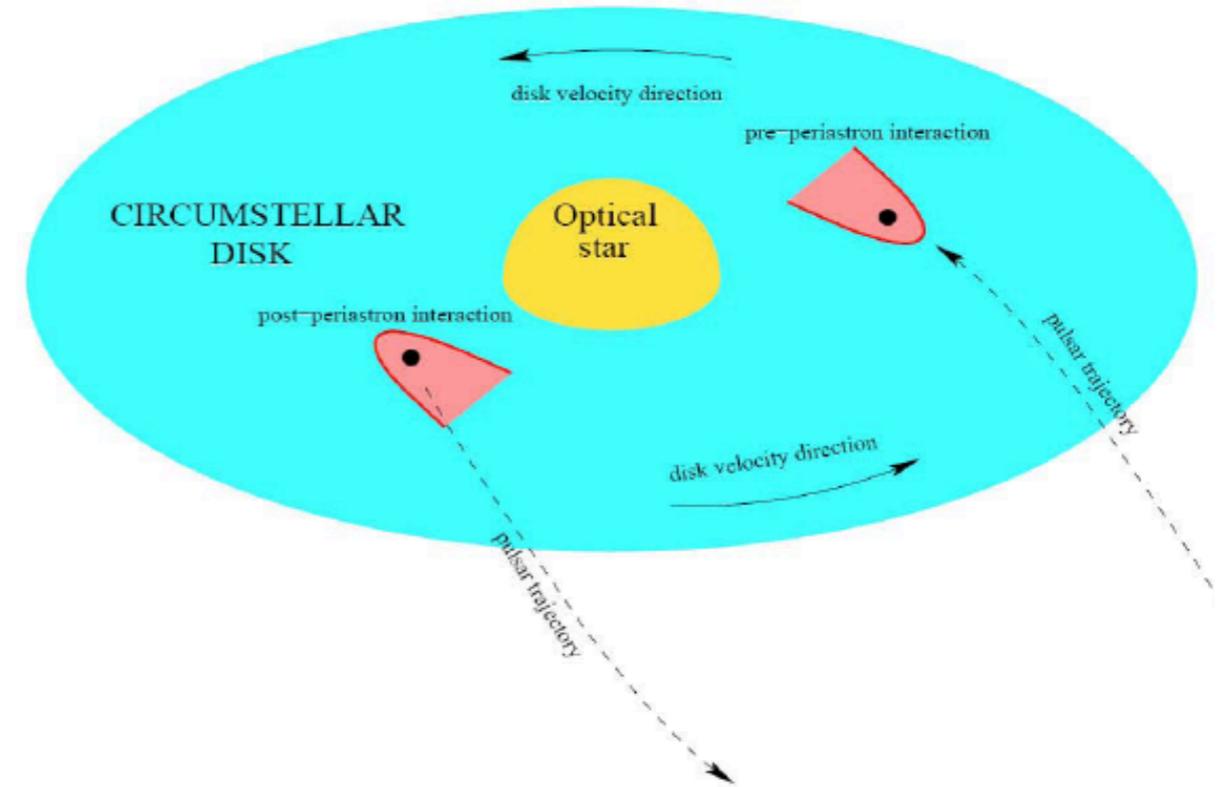
- Doppler boosting dei flussi di particelle relativistiche in binarie con pulsar?



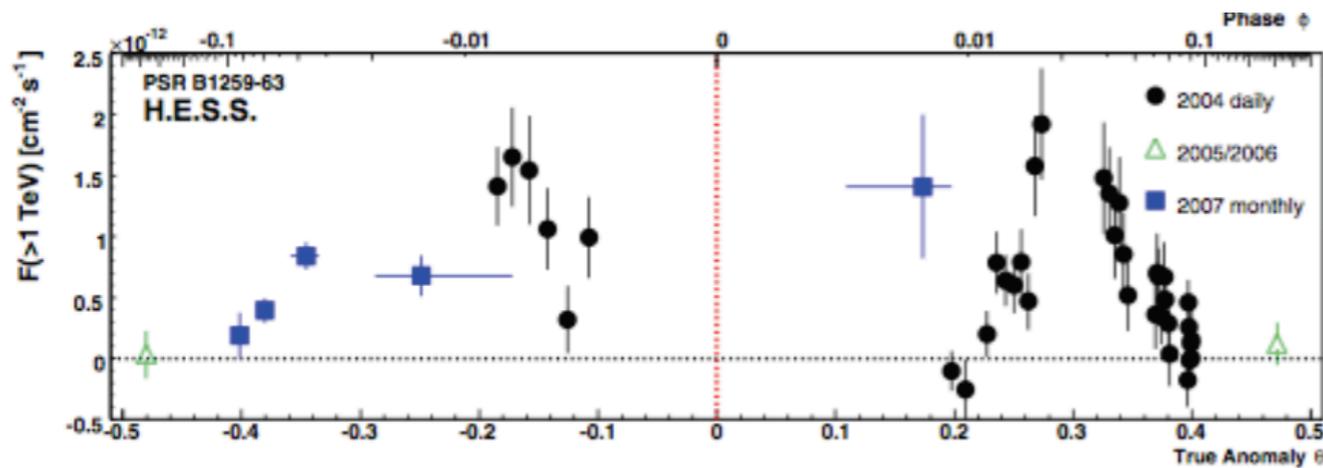
adattato da Dubus et al. (2009)

PSR B1259-63

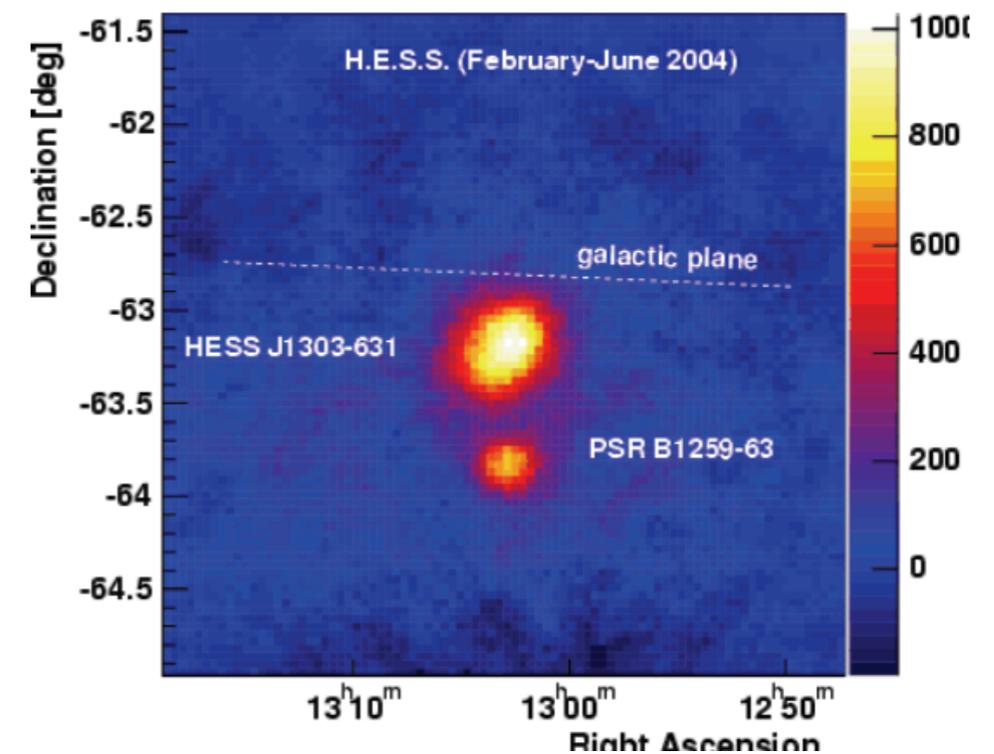
- $P_{\text{orb}} = 3.4$ anni; $P_{\text{pulsar}} = 48$ ms
- compagna: O9.5Ve $\sim 30 M_{\text{sun}}$
- pulsazioni osservate in radio
- emissione radio stesa recentemente scoperta



VHE γ -rays HESS - Aharonian et al. (2004, 2007)

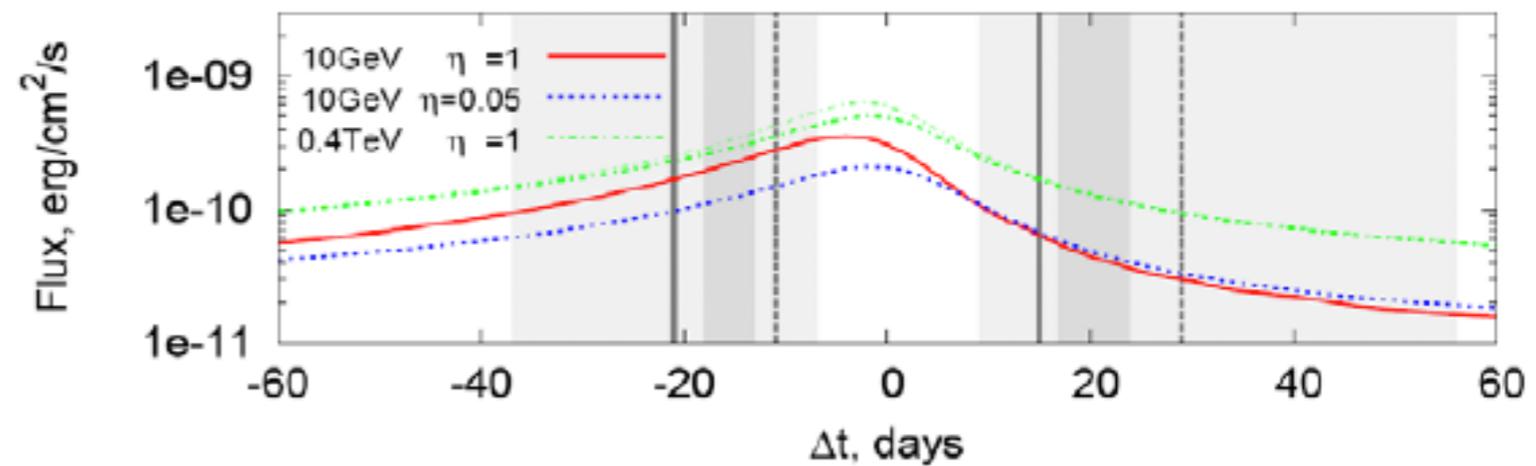
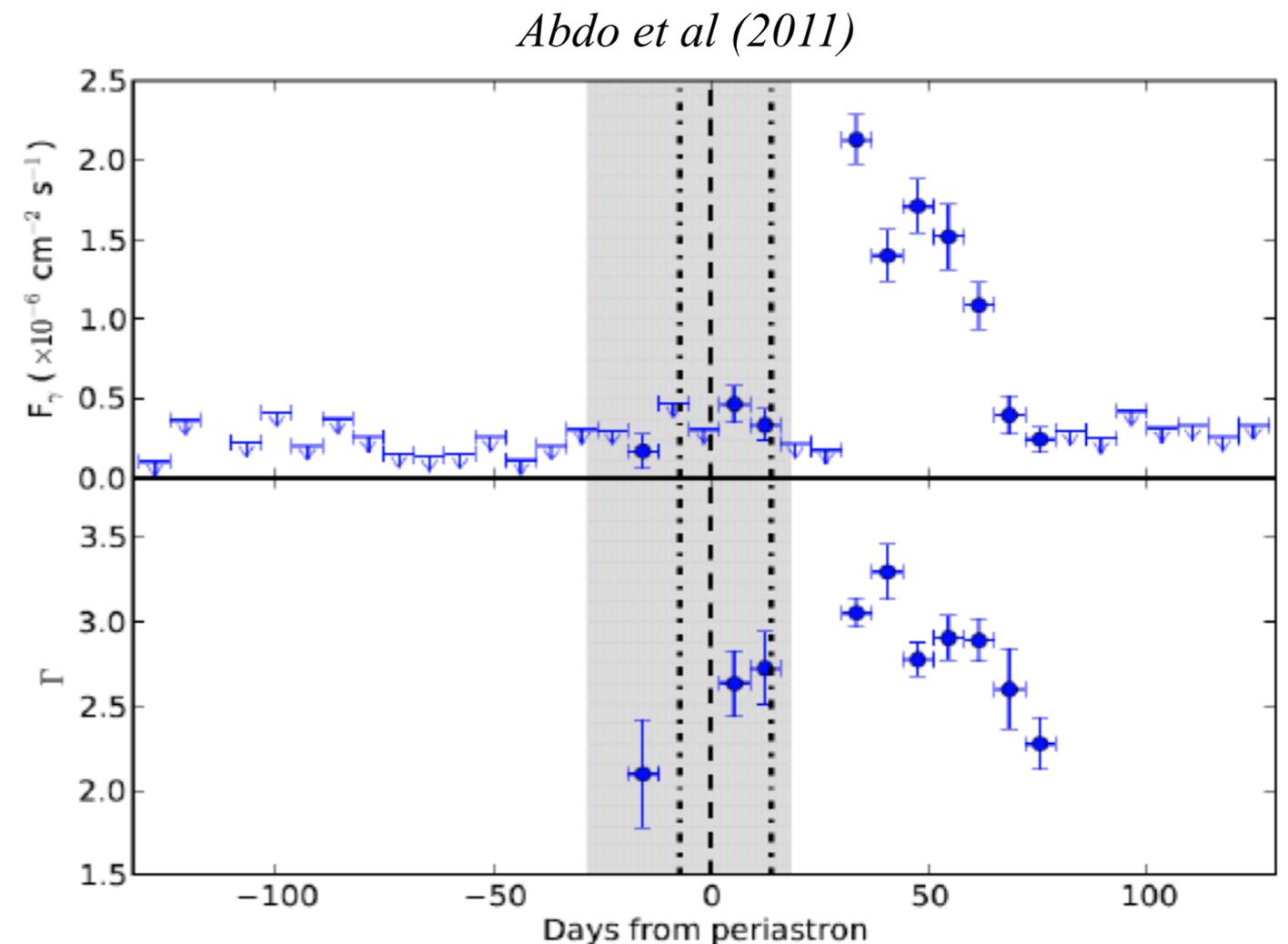
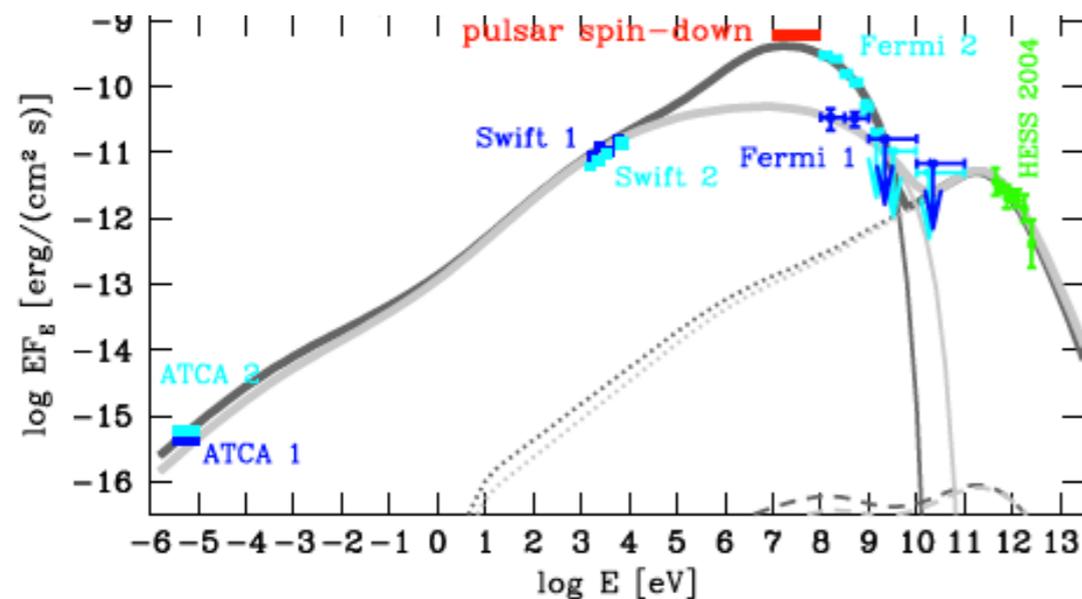


Aharonian et al (2007)



PSR B1259-63

- GeV flares dopo periastro
 - effetti IC non isotropico?
 - cambio condizioni fisiche nel emissore?
 - nuova componente?
- L_γ isotropica $\approx 8 \times 10^{35}$ erg/s
- L_γ spin down $\approx 8.3 \times 10^{35}$ erg/s

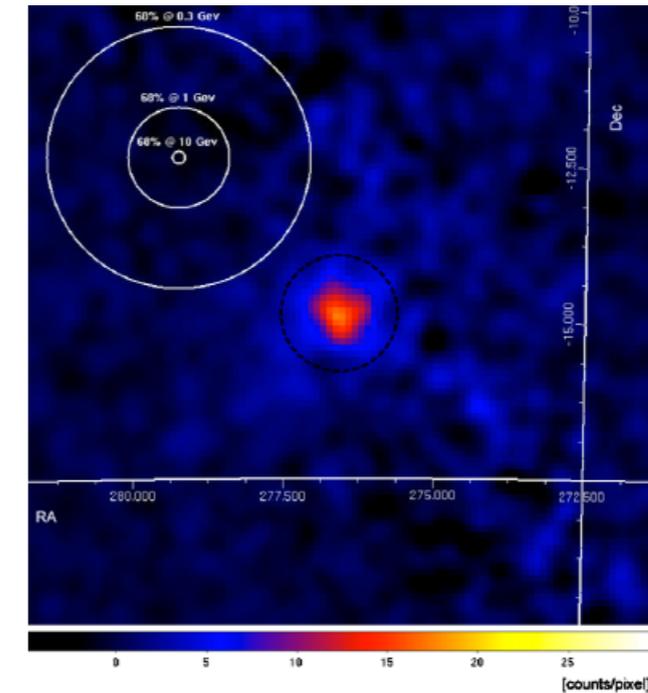


Khanguyan et al (2011)

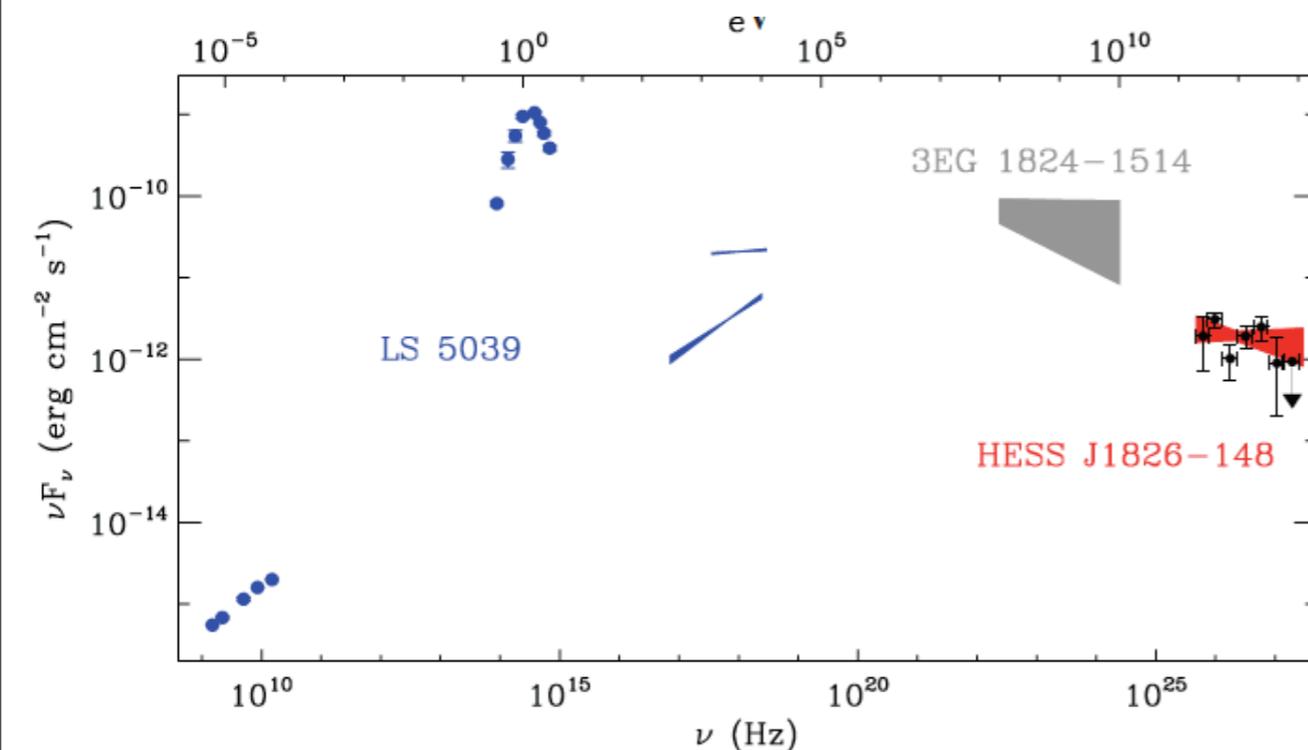
LS 5039

- $P_{\text{orb}} = 3.9$ days
- compagna: O6.5V, $\sim 20 M_{\text{sun}}$
- oggetto compatto: $3.7 (+1.3/-1.0) M_{\text{sun}}$
- Eccentricità moderata
- emissione radio stesa (jets?/PWN?)
- associata a 3EG J1824–1514 (Paredes et al. 2000)
- prima binaria @ TeV (Aharonian et al. 2005)

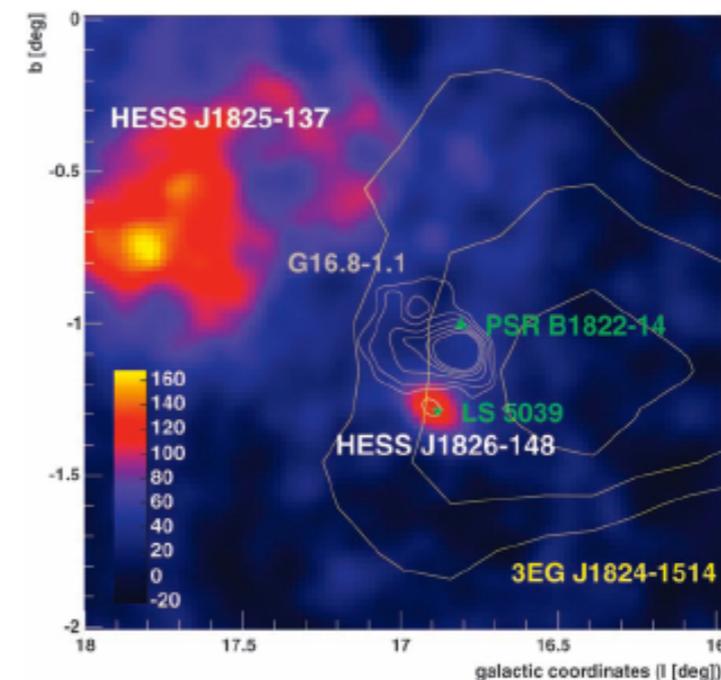
HE γ -rays *FERMI.* - Abdo et al. (2009)



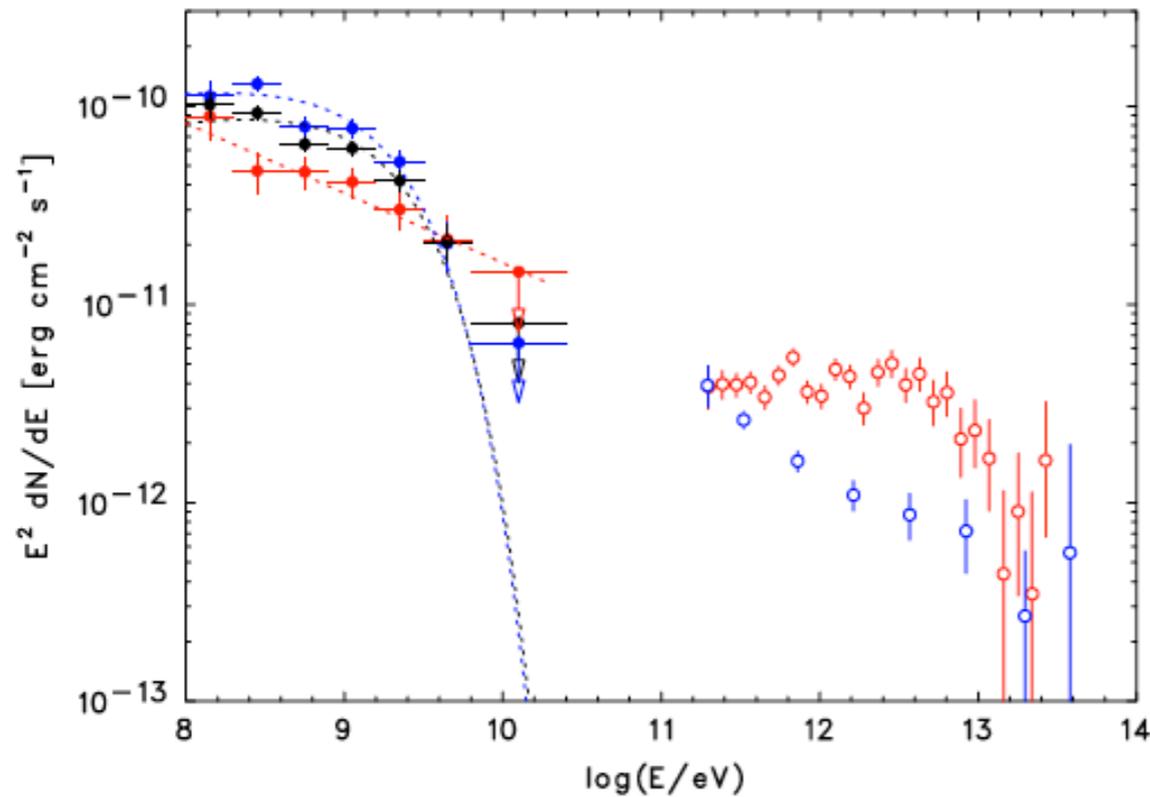
VHE γ -rays *H.E.S.S.* - Aharonian et al. (2006)



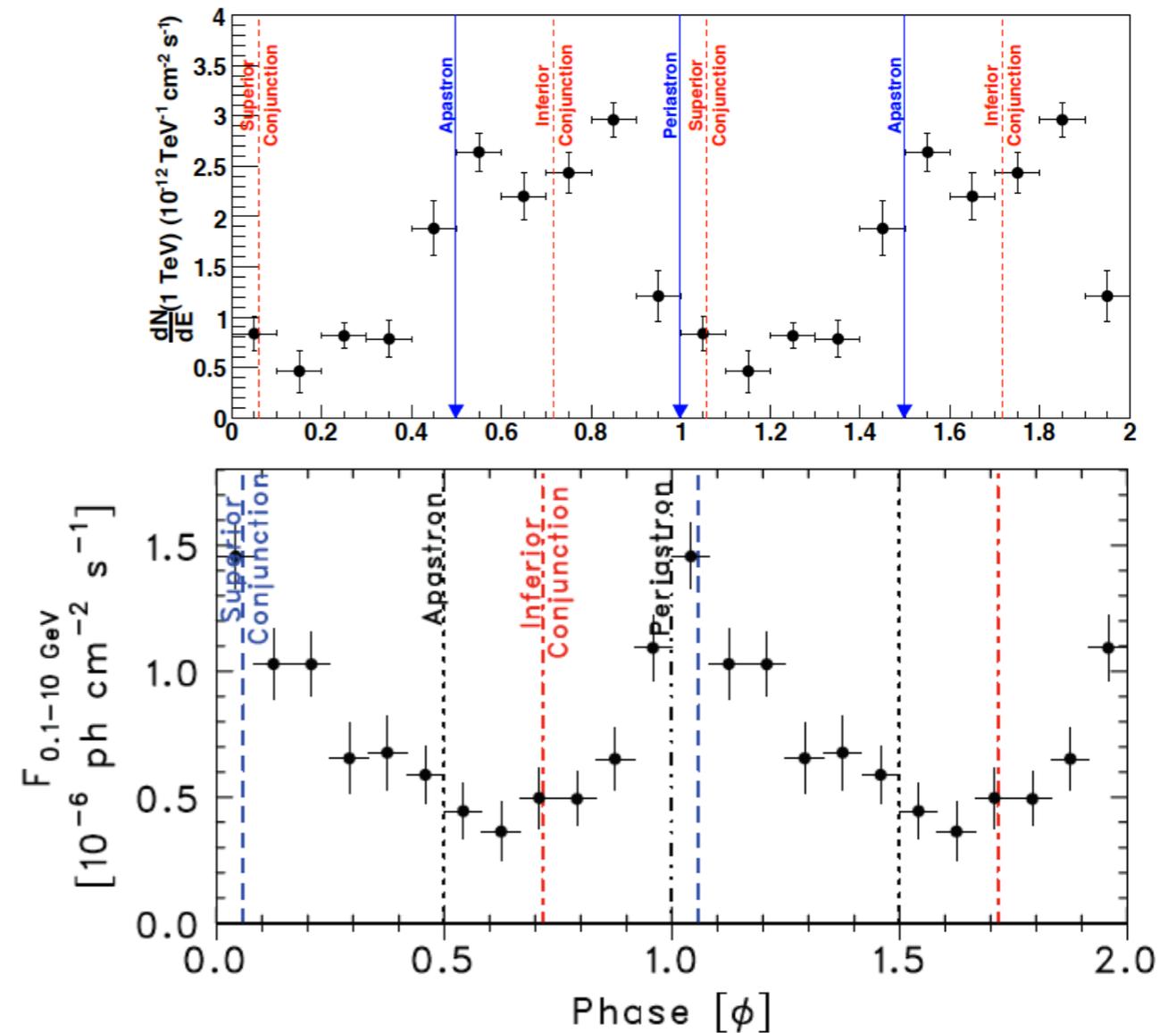
estratto di Aharonian et al. (2006)



LS 5039



Abdo et al (2009)

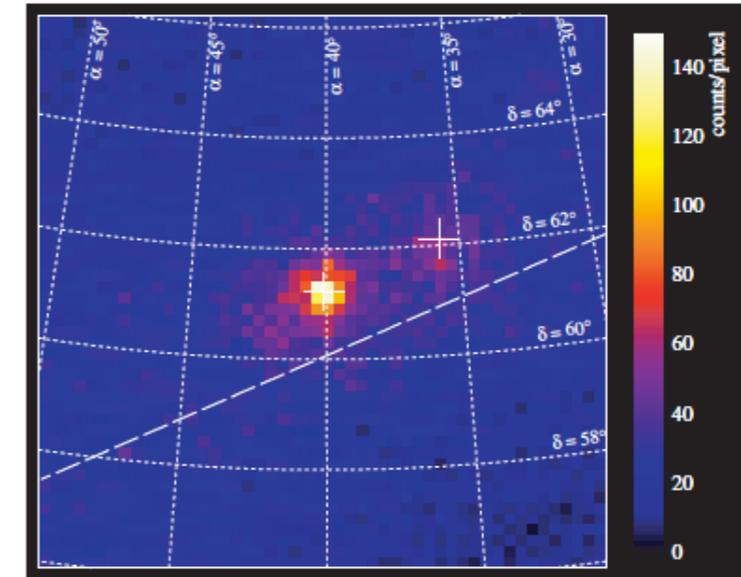


- HE massimo: $\Phi = 0.06$ (conj. sup.). VHE massimo: $\Phi = 0.72$ (conj. inf) \Rightarrow **OK: assorbimento**
- Cutoff a energie di alcuni GeV \Rightarrow **differenti popolazioni di $e^{+/-}$?**
 \Rightarrow **emissione magnetosferica? (ma c'è modulazione orbitale!)**

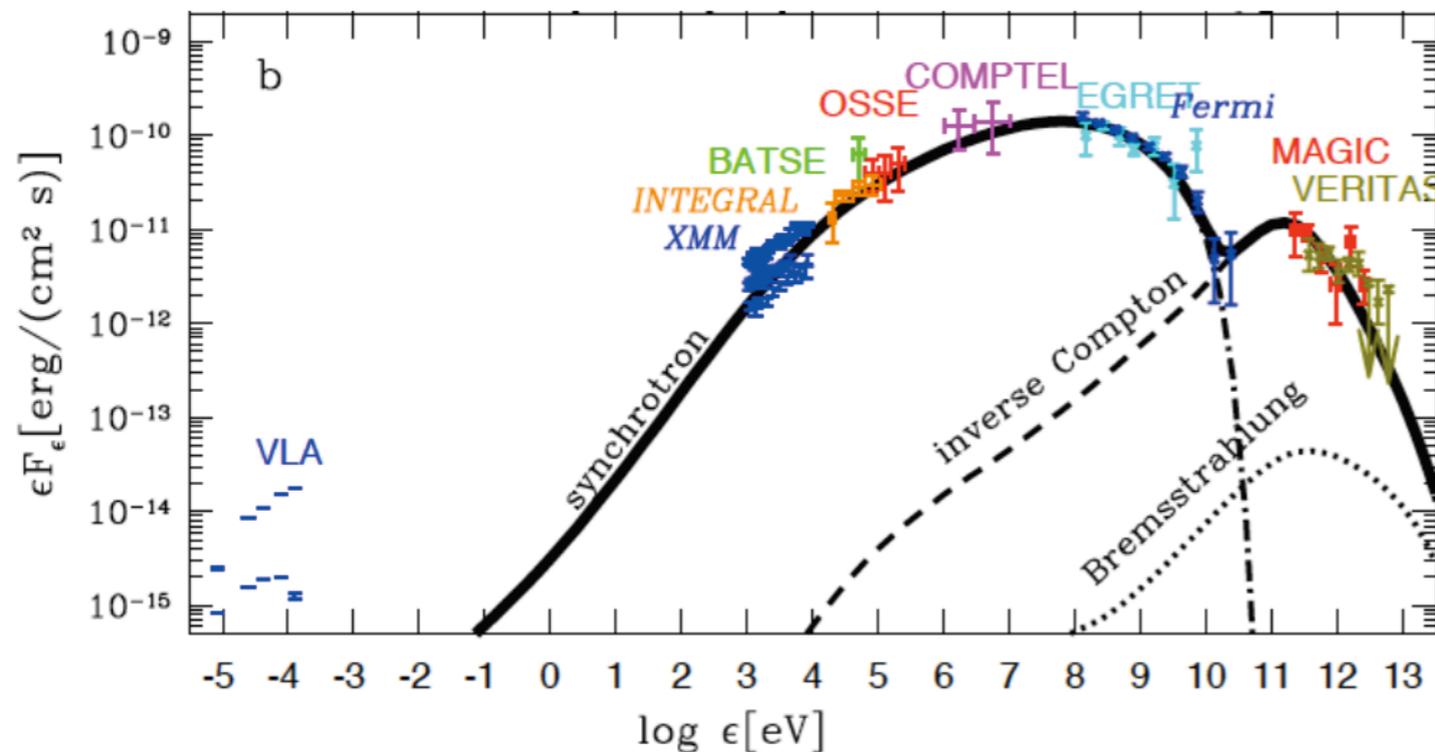
LS I +61 303

- $P_{\text{orb}} = 26.5$ days
- compagna: Be, $\sim 20 M_{\text{sun}}$
- oggetto compatto: $(1.4 - 3) M_{\text{sun}}$
- Eccentricità alta ($\epsilon = 0.55$)
- emissione radio stesa (jets?/PWN?)
- associata a *COS B* 2CG135+01 (Hermsen et al. 1977)
- prima binaria @ TeV (Aharonian et al. 2005)

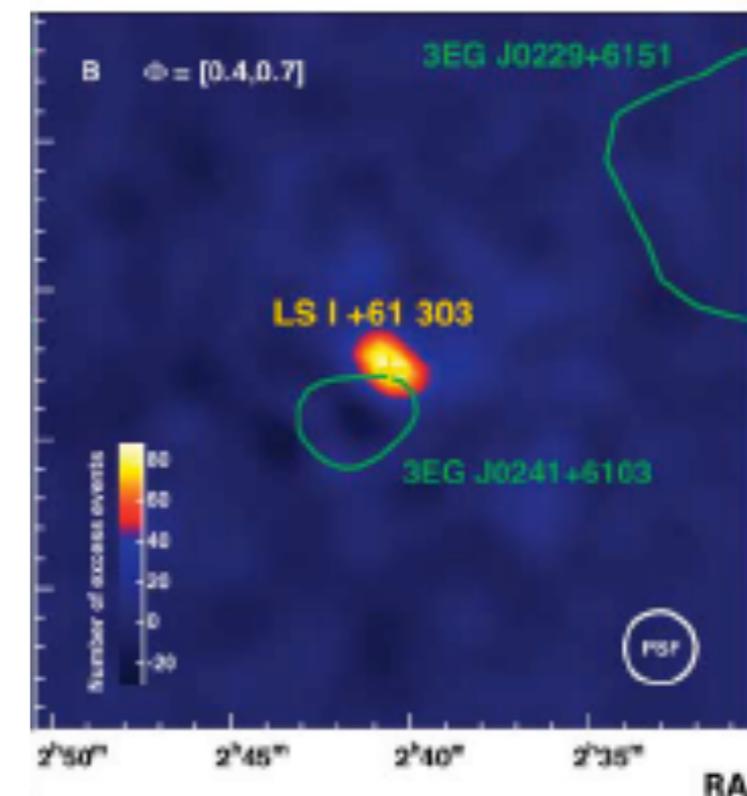
HE γ -rays *Fermi* - Abdo et al. (2009)



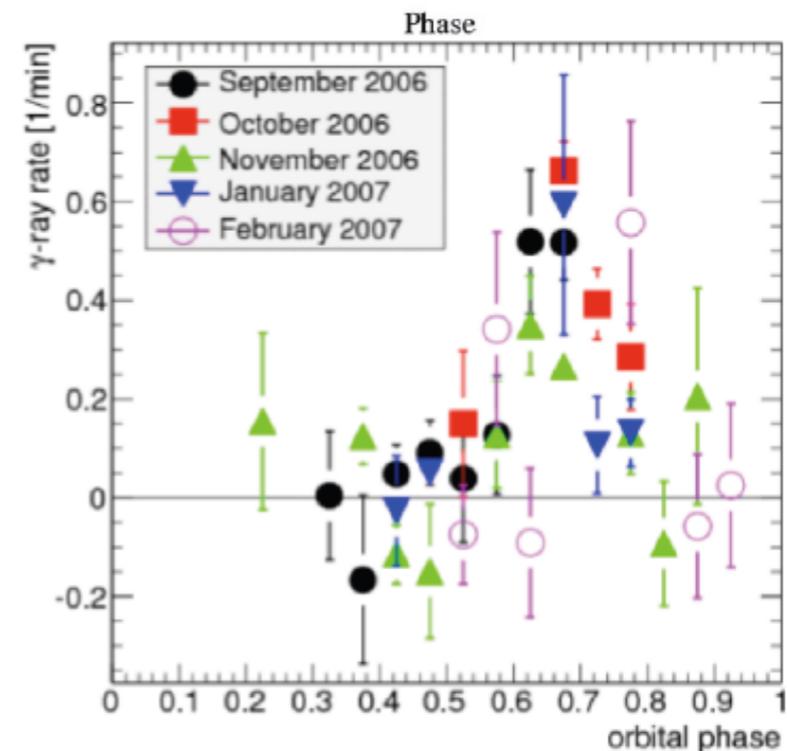
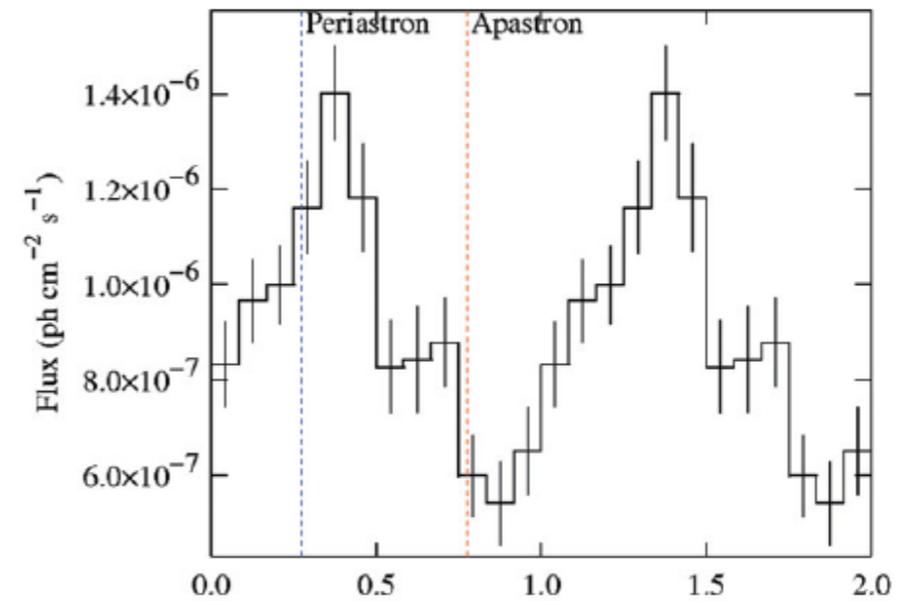
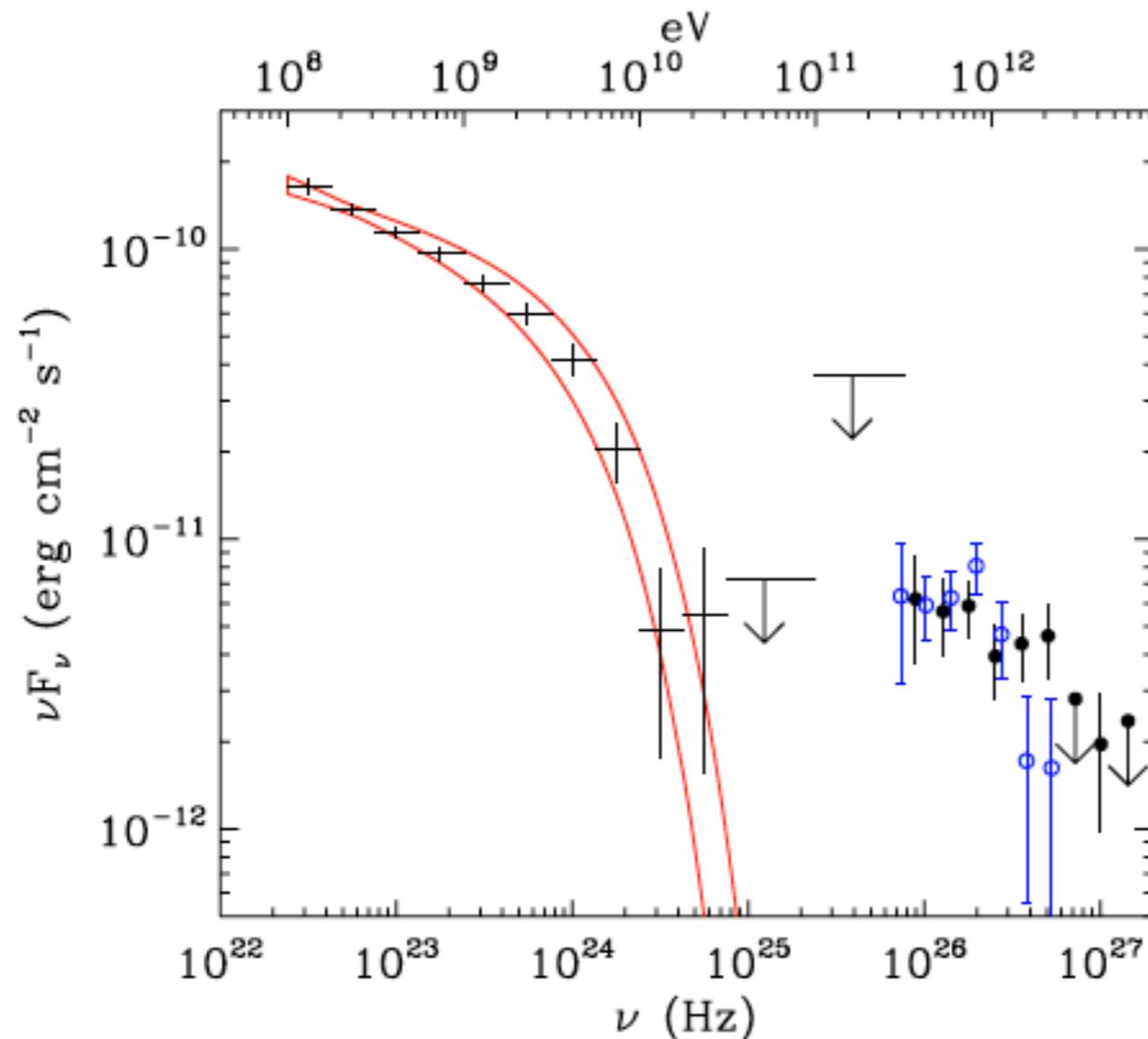
VHE γ -rays *MAGIC* - Albert et al. (2006)



adattato da Zdziarski et al. (2010)



LS I +61 303



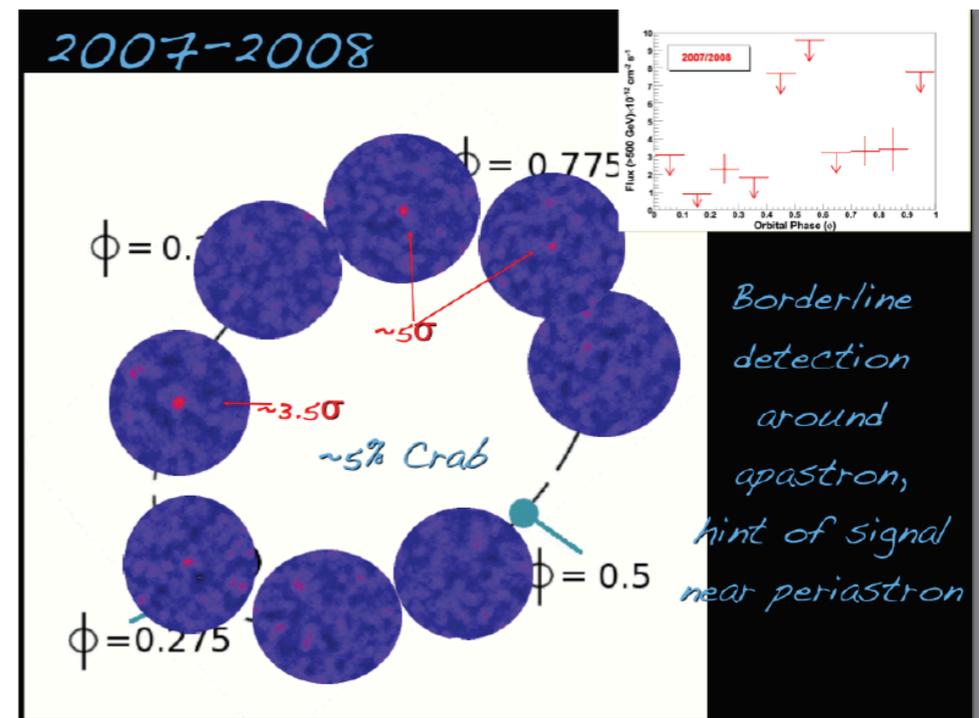
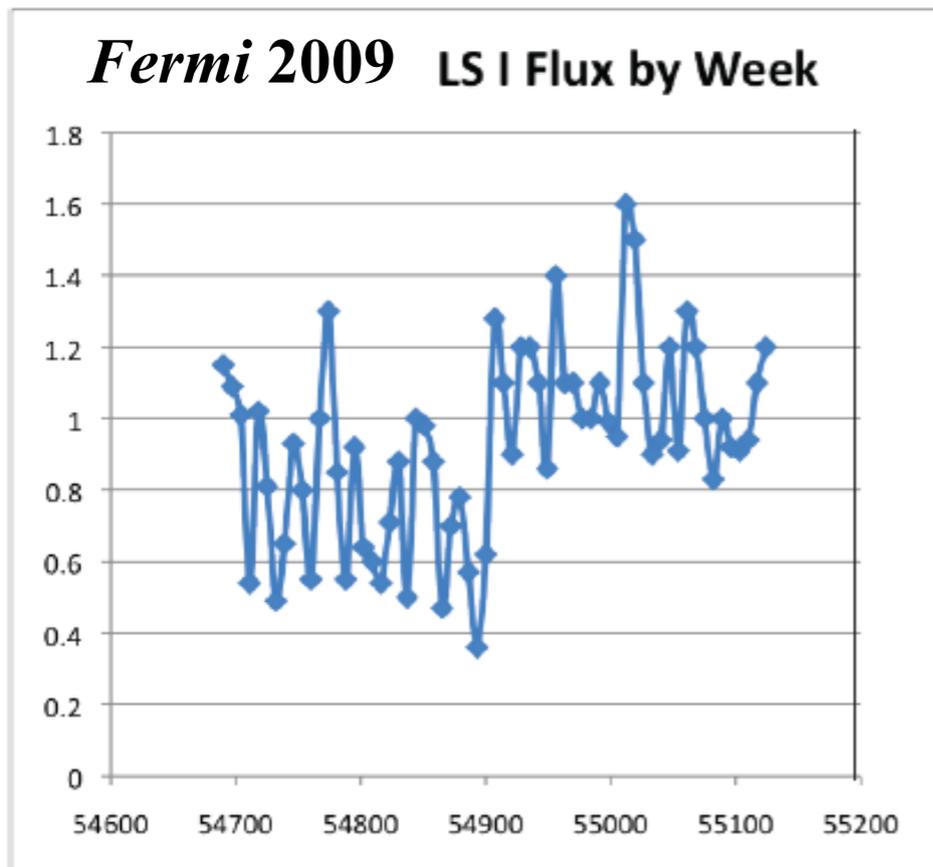
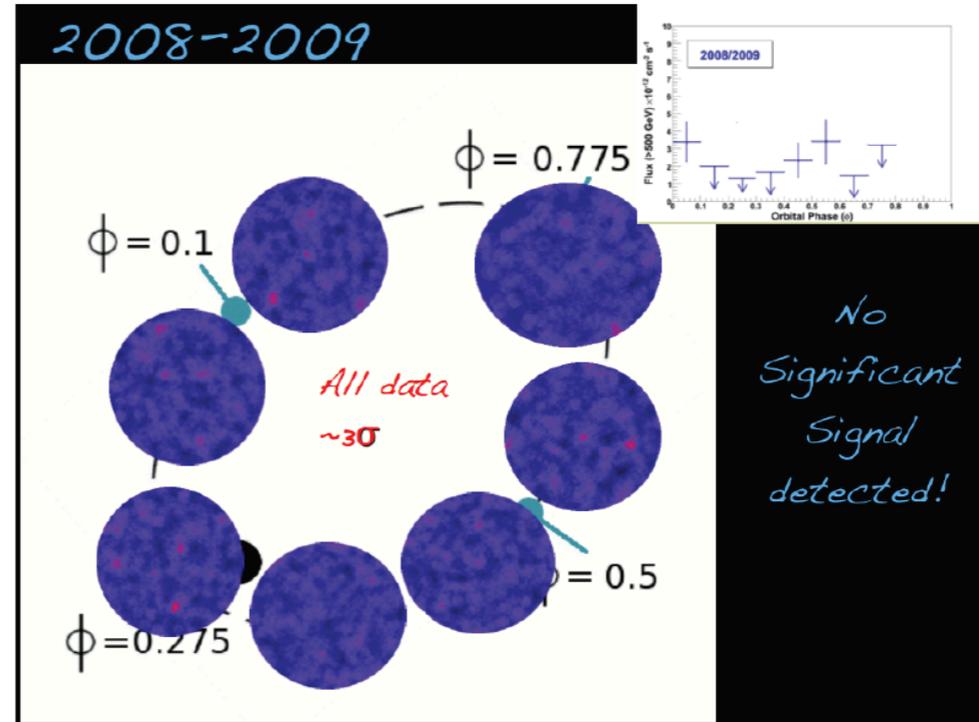
- HE massimo: periastro ($\sim \Phi$ conj. sup.). VHE massimo: apastro ($\sim \Phi$ conj. inf) \Rightarrow **OK: assorbimento**
- Cutoff a energie di alcuni GeV \Rightarrow **differenti popolazioni di $e^{+/-}$?**
 - \Rightarrow disco della compagna Be \Rightarrow interazione hadroniche?
 - \Rightarrow **emissione magnetosferica? (ma c'è modulazione orbitale!)**

LS I +61 303

- VERITAS non detection 2008-2009
- Fermi riporta incremento flusso > 40 %

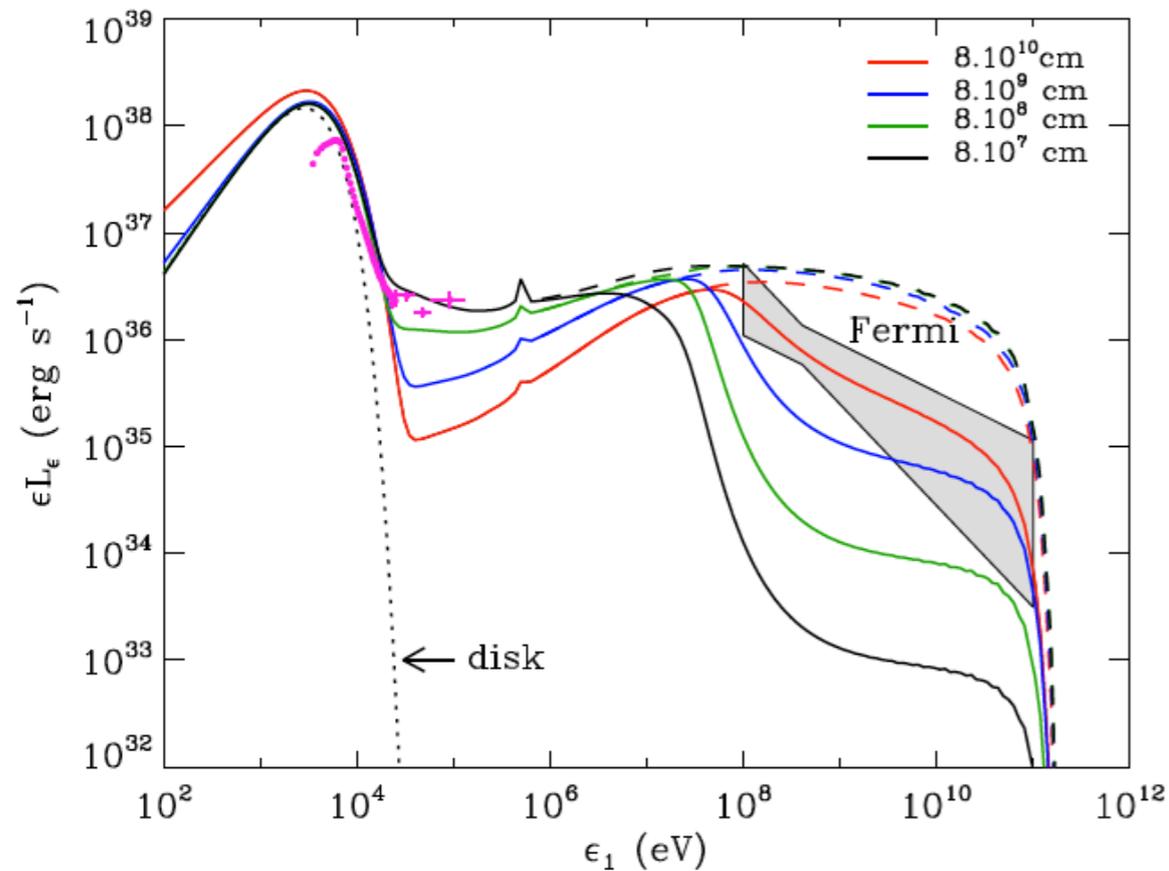
vento compagna + interazione disco
 “decrescimento” stella compagna Be :

- => variazioni orbitali? (e.g., non in LS 5039)
- => emissione di *flares*? (in radio, X-rays & GeV)

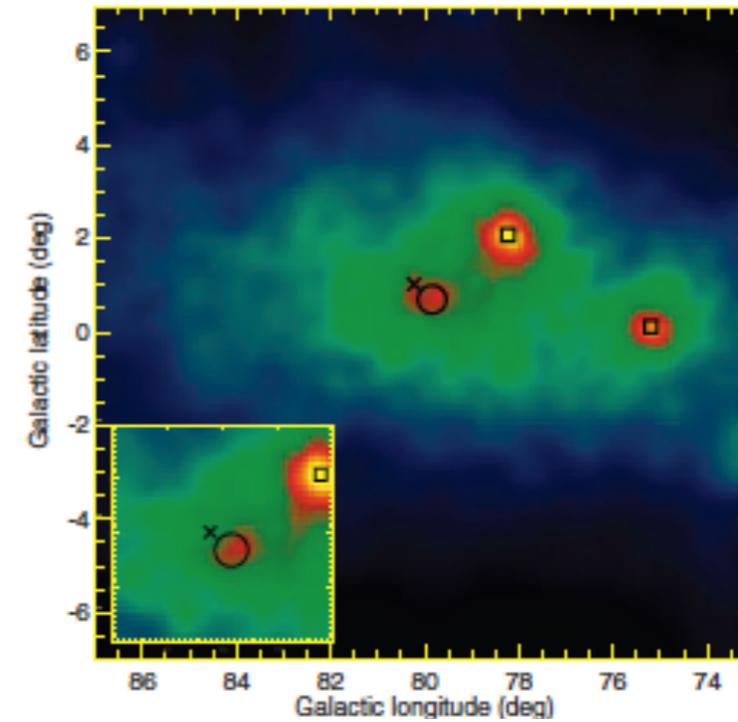


Cyg X-3

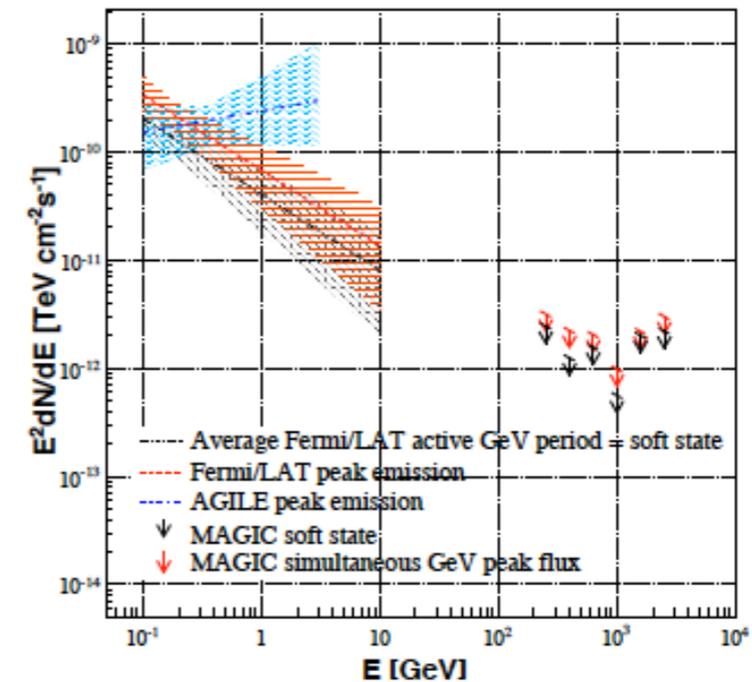
- $P_{\text{orb}} = 4.8$ h
- compagna: Wolf-Rayet con forte vento
- oggetto compatto (probabilmente BH?)
- piu brillante XRB in radio (*flares*: $\times 1000$!)
- Emissione $> \text{TeV}$ osservata negli 80's ?



HE γ -rays AGILE - Tavani et al. (2009)

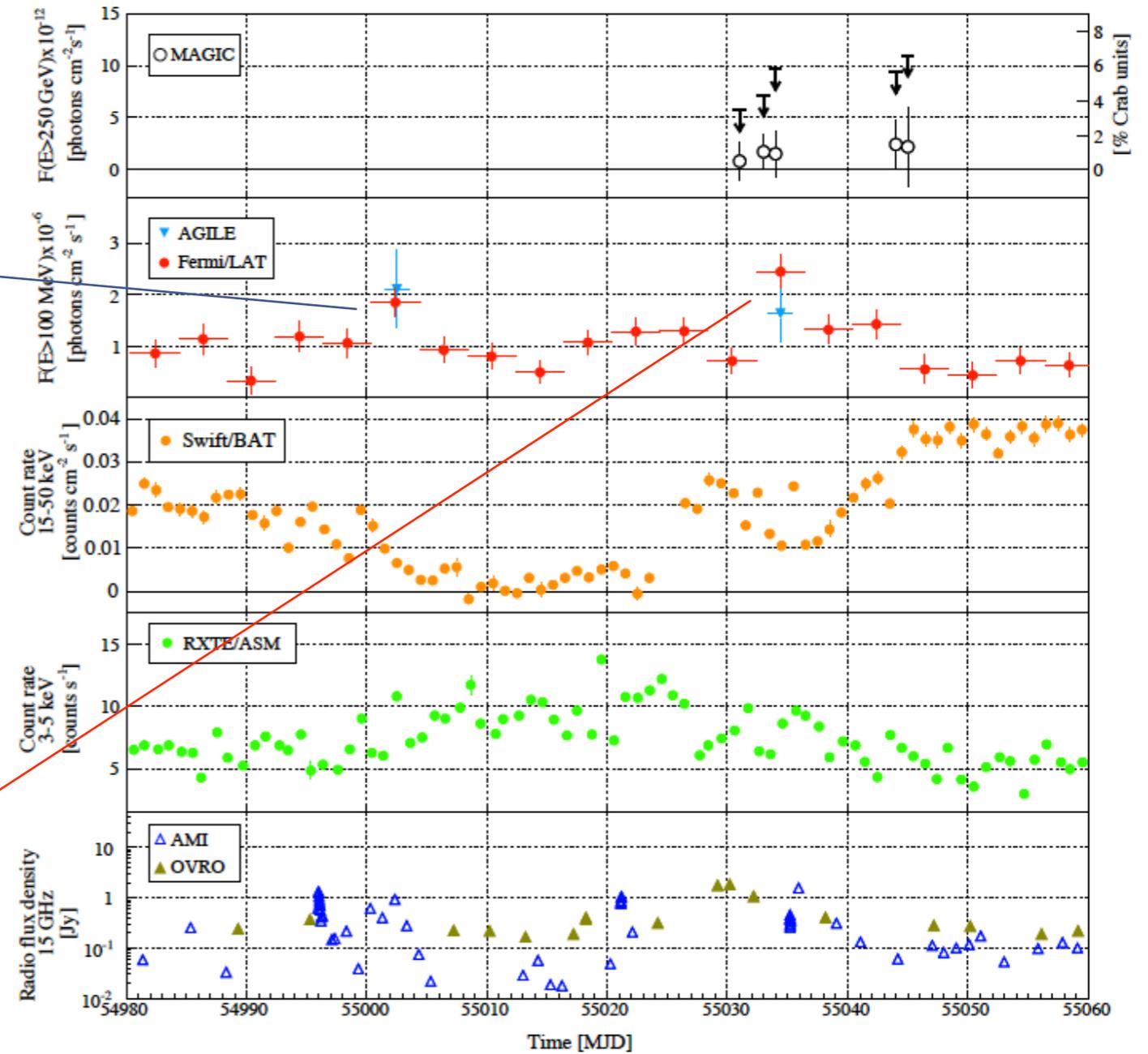
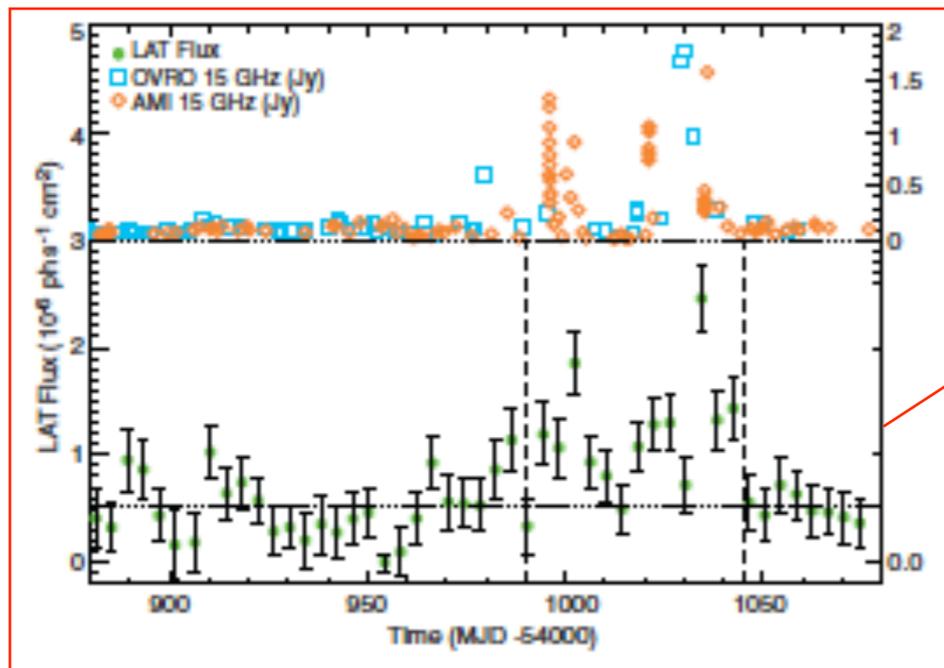
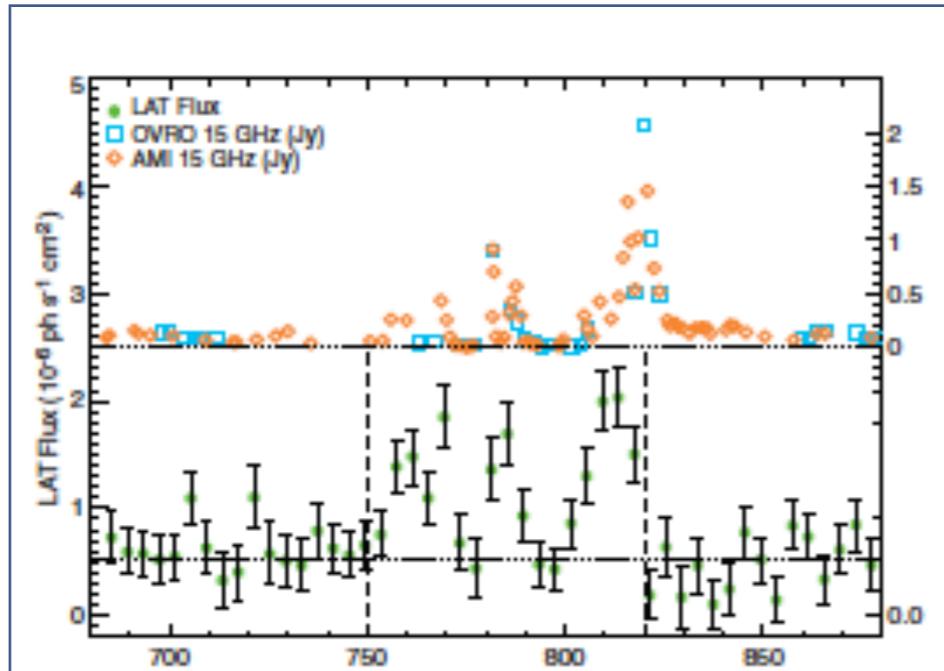


VHE γ -rays MAGIC - Aleksic et al. (2010)



Cyg X-3

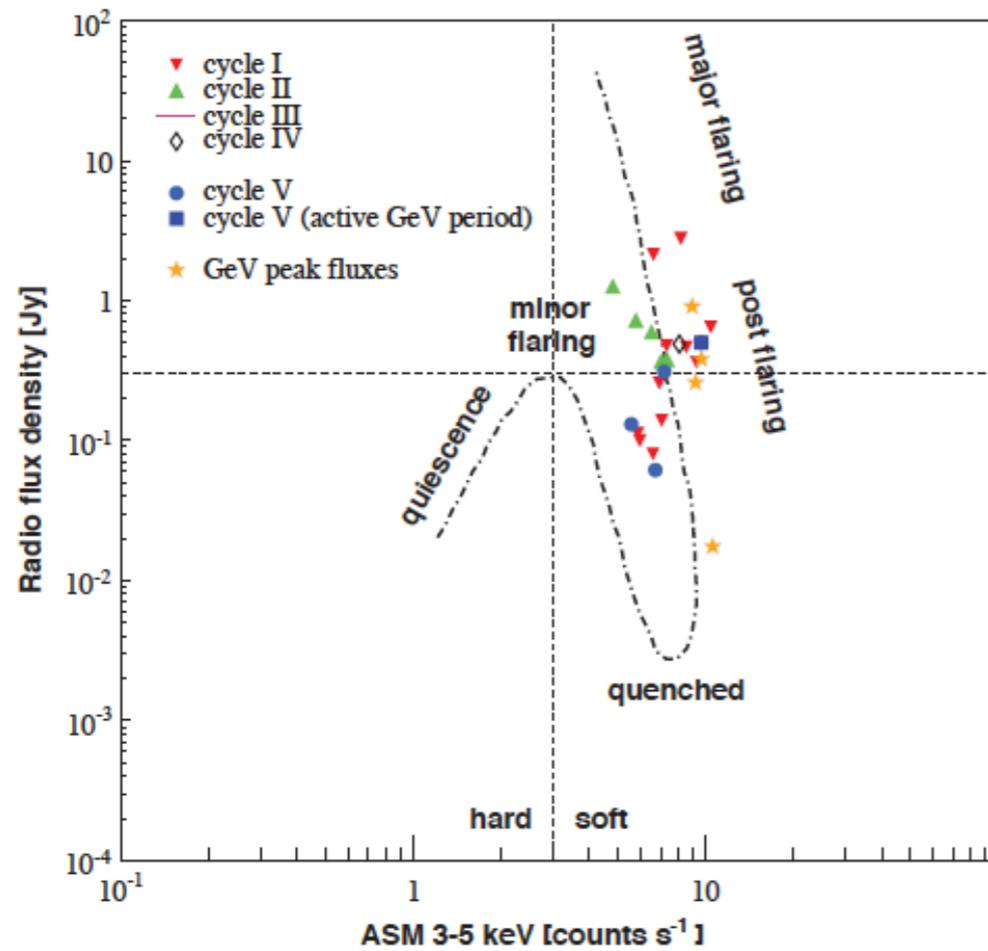
- Due periodi di attività riportati in GeV (*Fermi* & *AGILE*) $\sim L_\gamma > 10^{35}$ erg/s



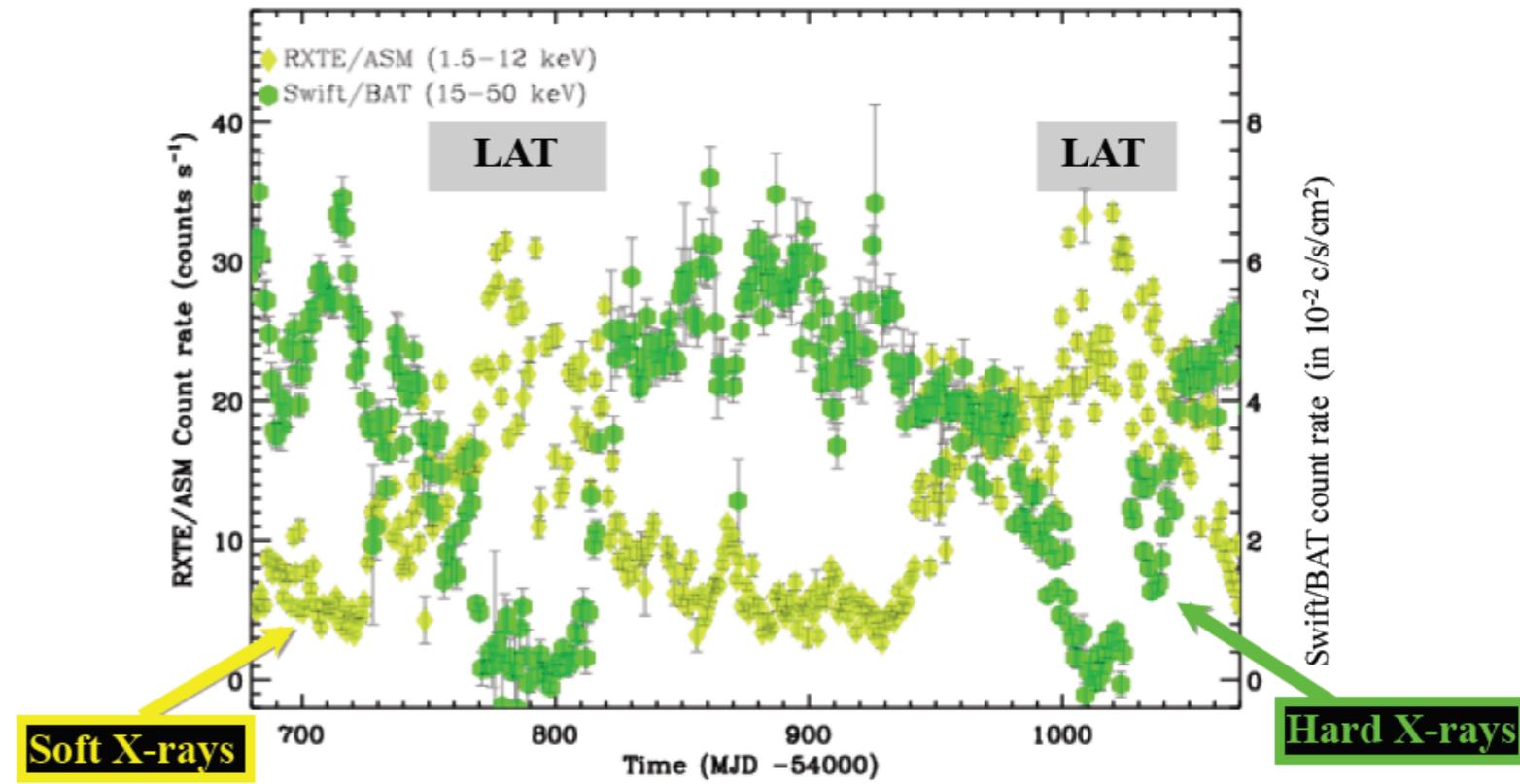
... MAGIC riporta upper limits in osservazioni simultanee

Cyg X-3

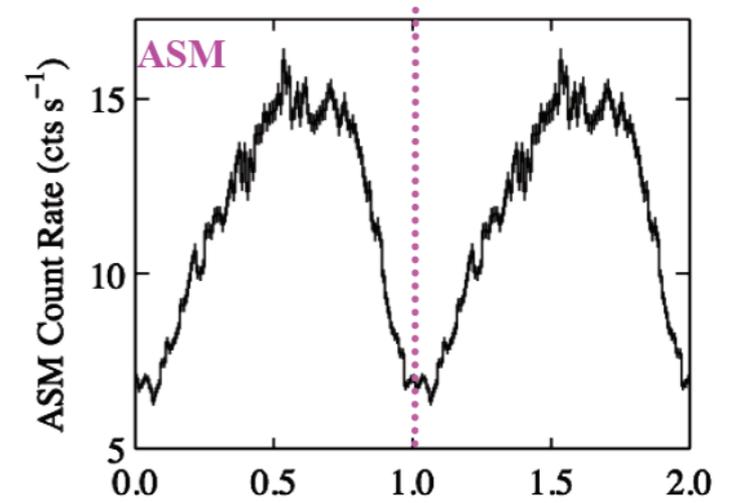
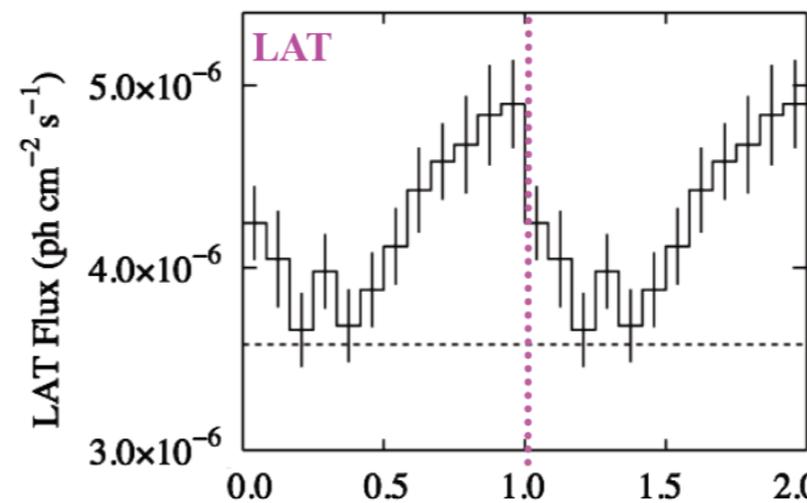
- radio flares simultanei appaiono dopo il “quenched state”



- GeV flares durante X-ray soft states solamente



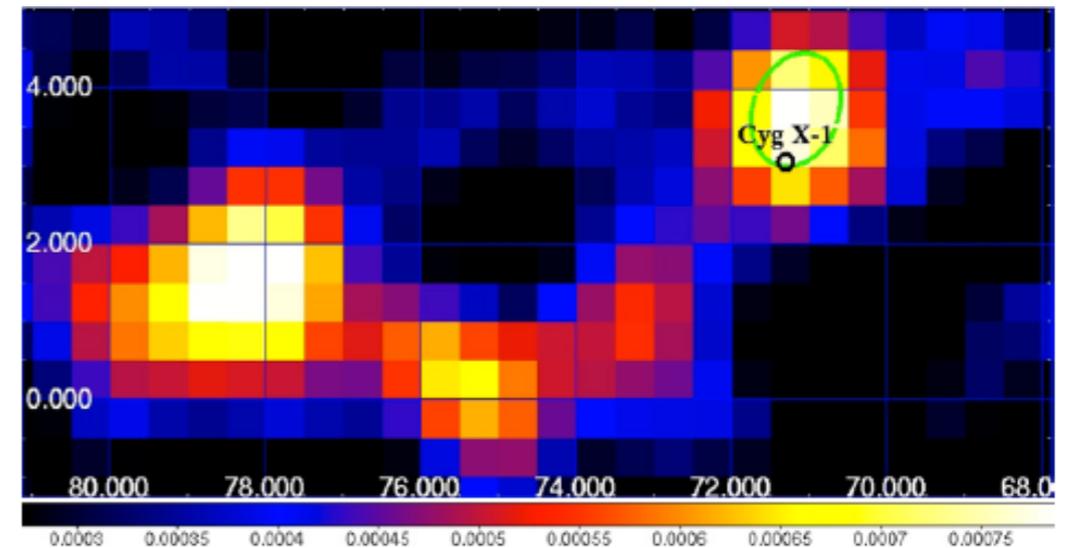
- GeV avanti di $\sim 0.3 \Phi$ rispetto X-rays



Cyg X-1

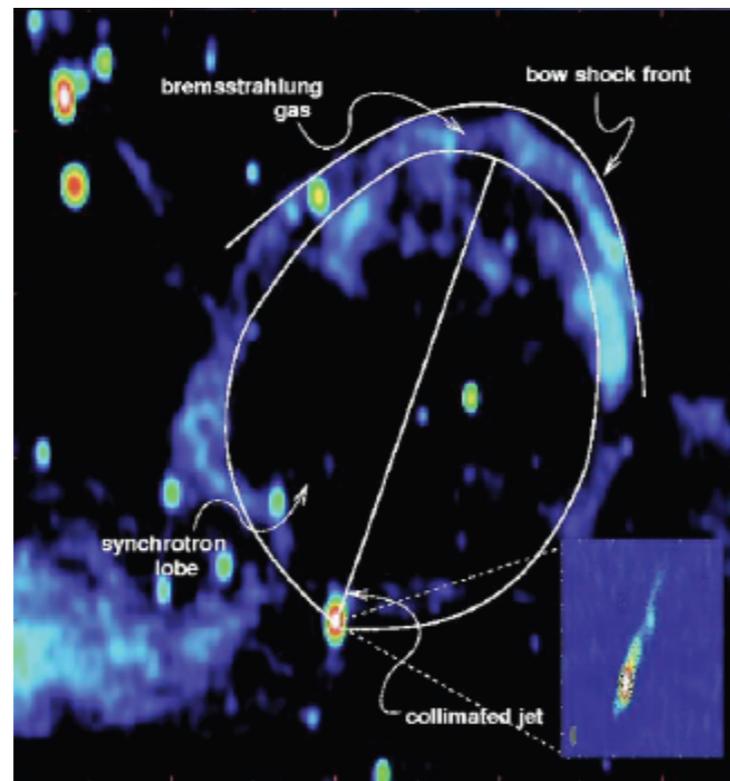
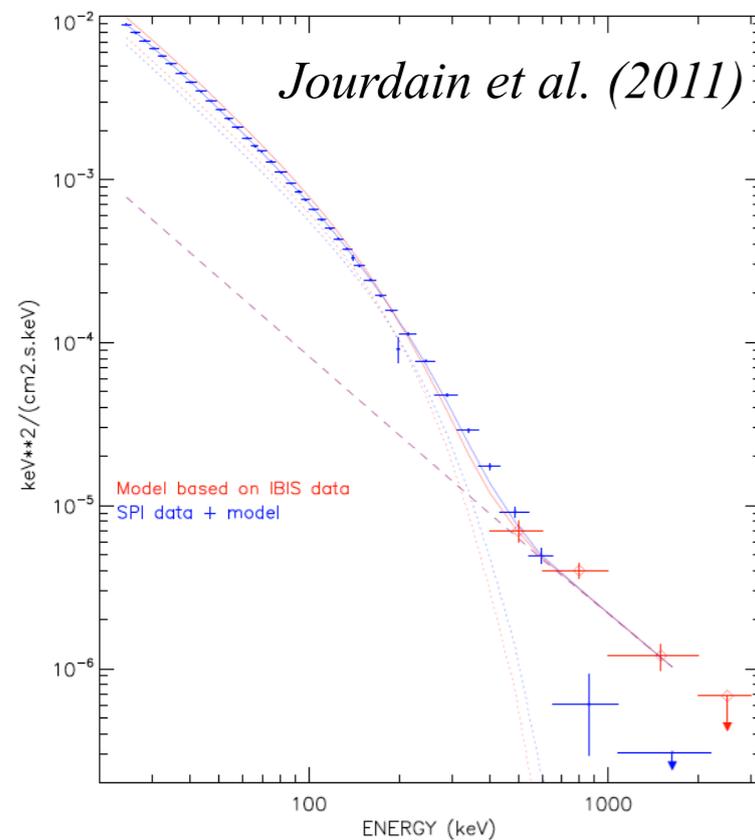
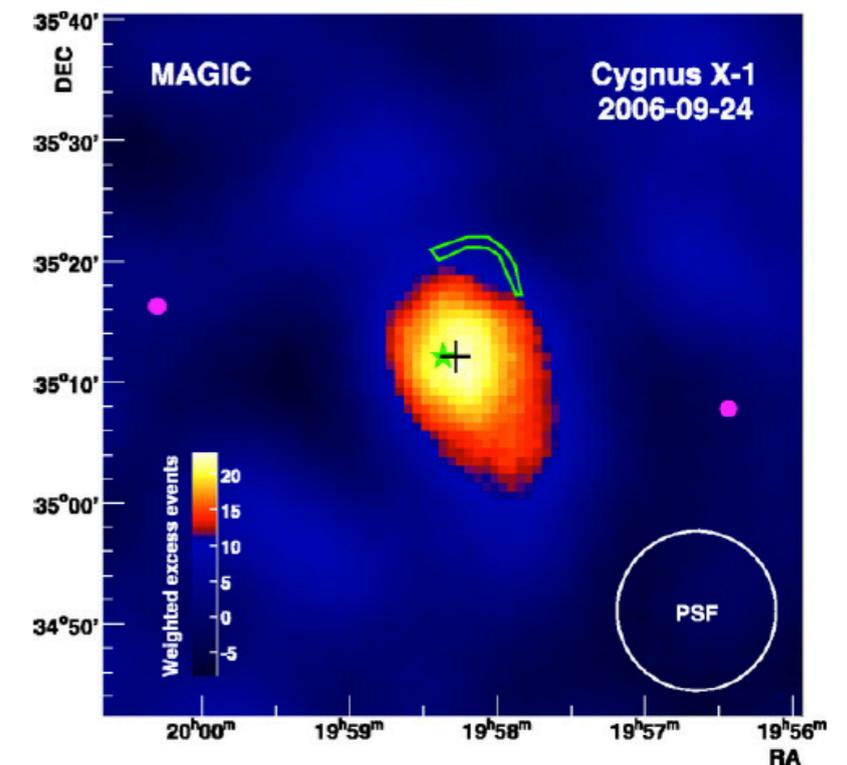
- $P_{\text{orb}} = 5.6 \text{ d}$
- compagna: O9.7Iab $\sim 30 M_{\text{sun}}$
- BHC ($> 13 M_{\text{sun}}$)
- one-sided jet \Rightarrow “microblazar”?
- bow-shock interazione col ISM
- emissione polarizzata dal jet???

HE γ -rays (**4.0 σ**) AGILE - *Sabatini et al. (2010)*



VHE γ -rays (**4.1 σ**)

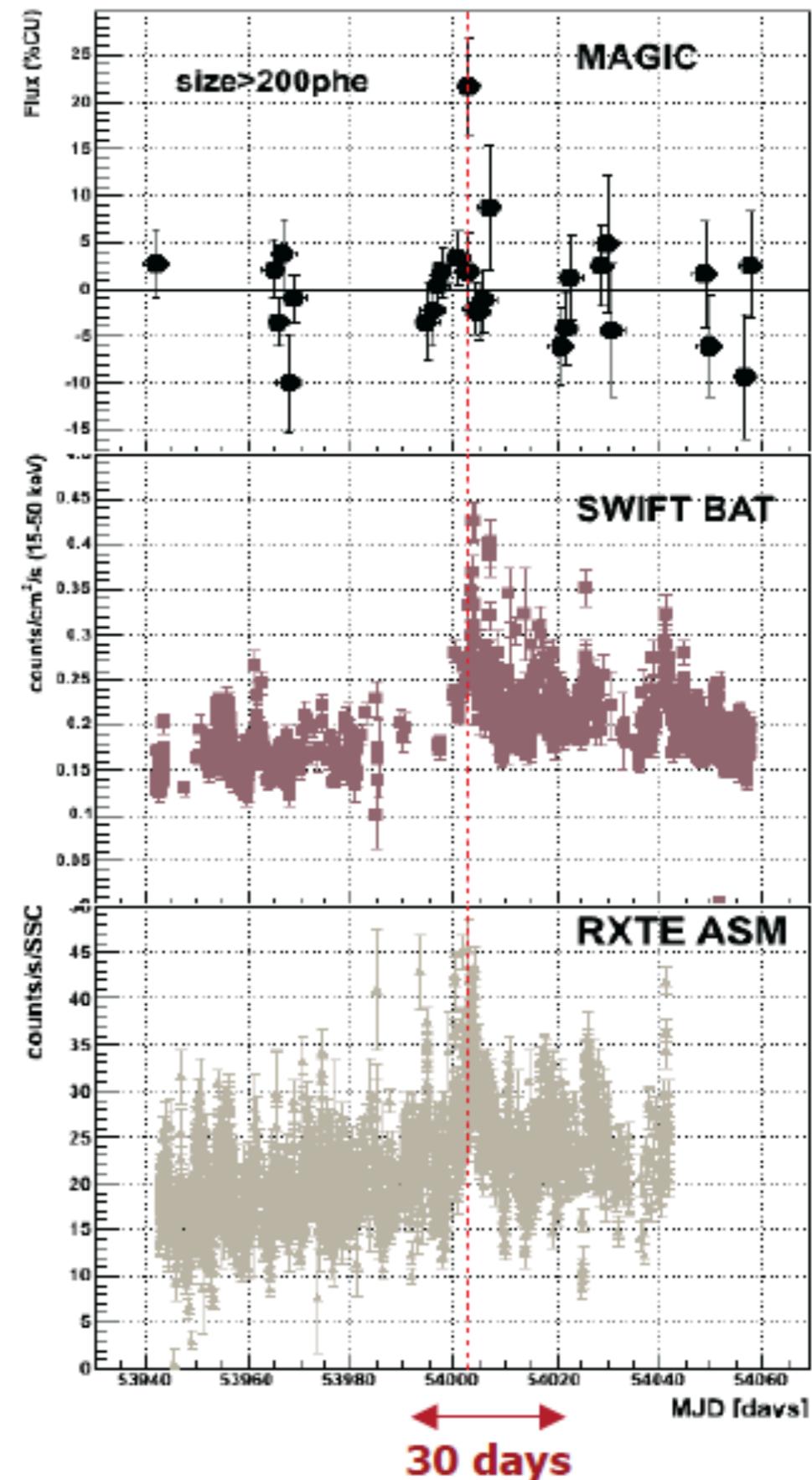
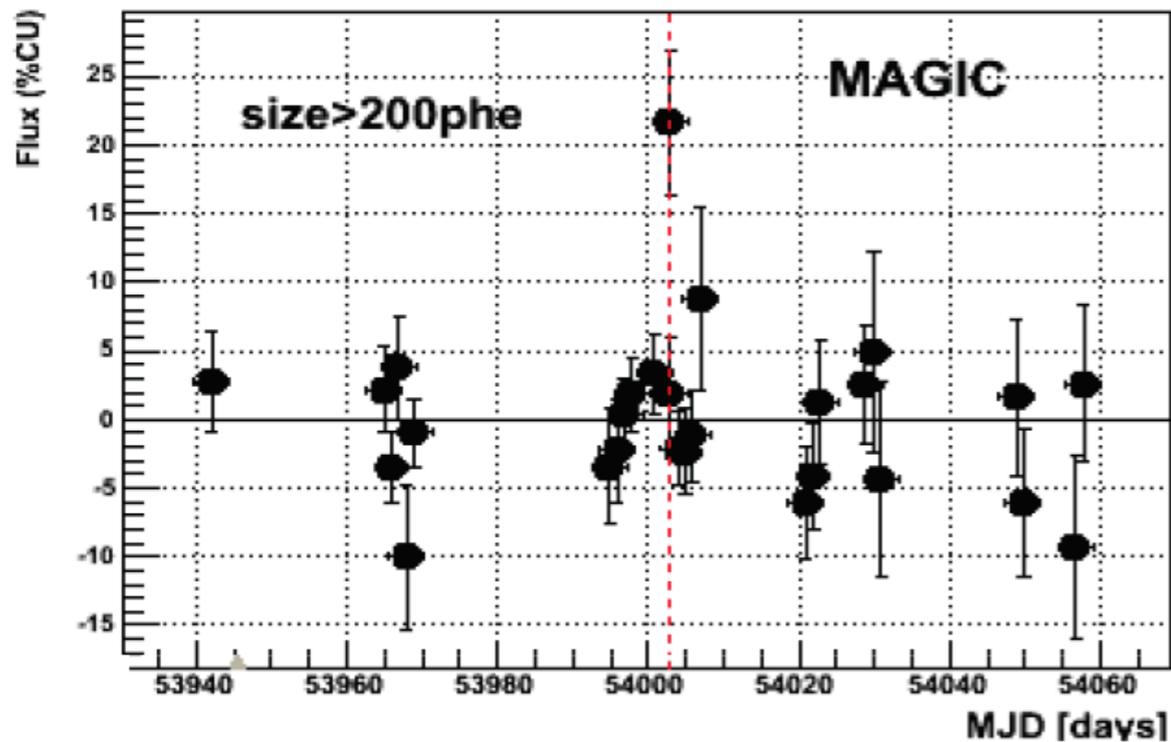
MAGIC - *Albert et al. (2007)*



Gallo et al (2005)

Cyg X-1

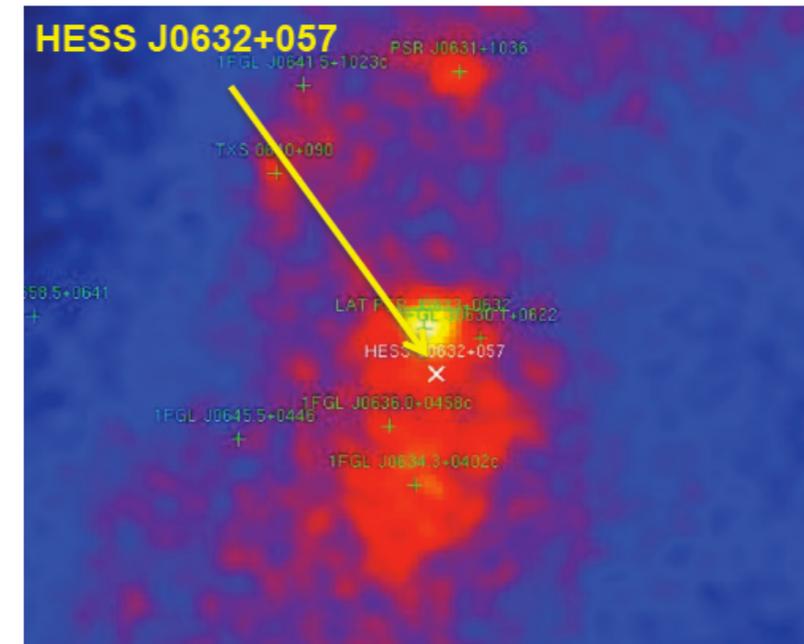
- senza segnale in 40h durante 2006
- detection in ~ 1 h durante Sept. 2006
- 4.9 pre-trial \Rightarrow 4.1 post-trial
- correlazione VHE e X-ray flares?
- conferma necessaria...



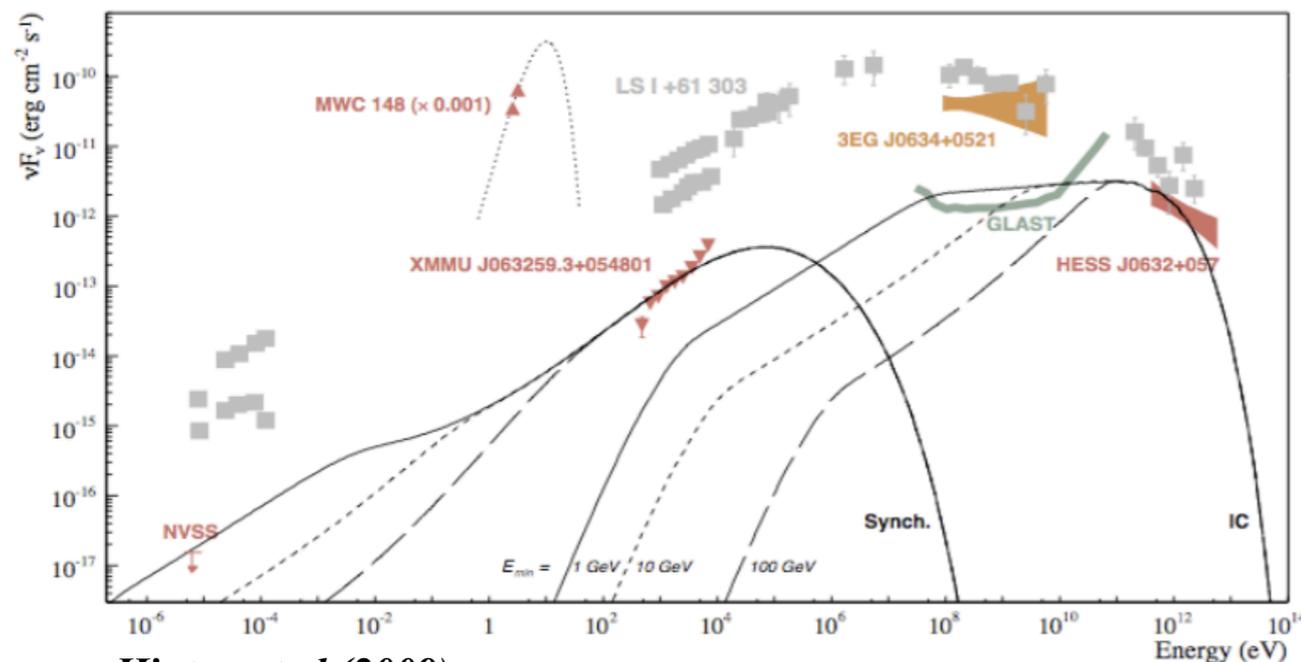
HESS J0632+057

- $P_{\text{orb}} = 3.9$ days
- compagna: O6.5V, $\sim 20 M_{\text{sun}}$
- oggetto compatto: $3.7 (+1.3/-1.0) M_{\text{sun}}$
- emissione radio stesa (jets?/PWN?)
- associata a 3EG J1824-1514 (Paredes et al. 2000)
- prima binaria @ TeV (Aharonian et al. 2005)

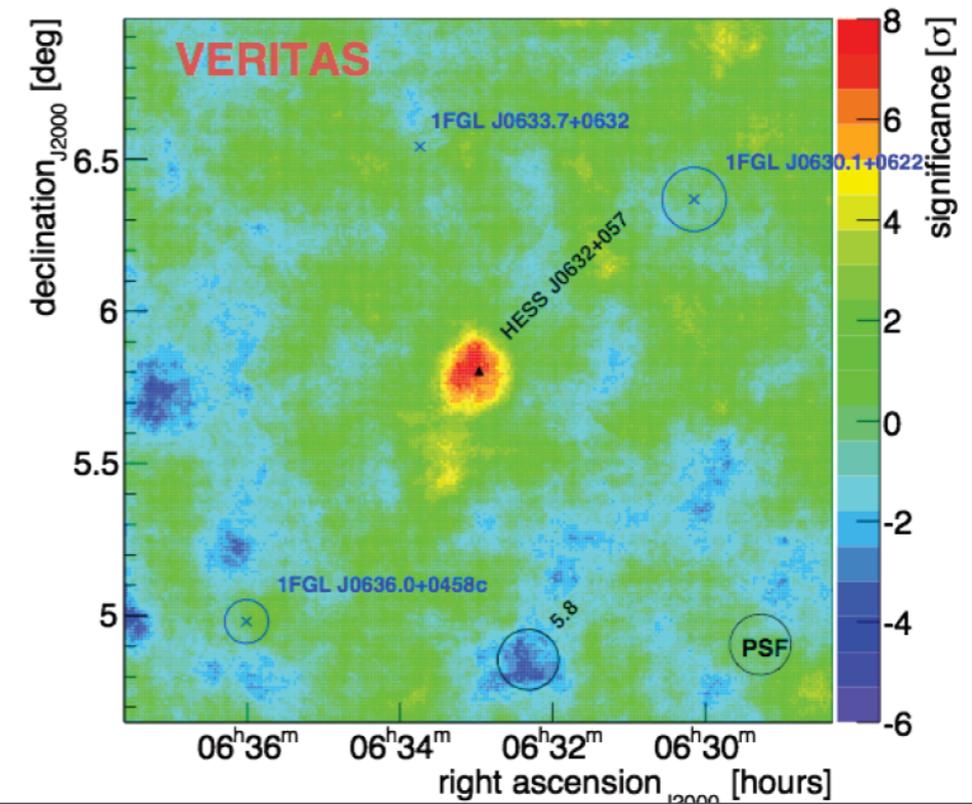
HE γ -rays Fermi - Dubois et al. (2010)



VHE γ -rays VERITAS - Aliu et al. (2010)



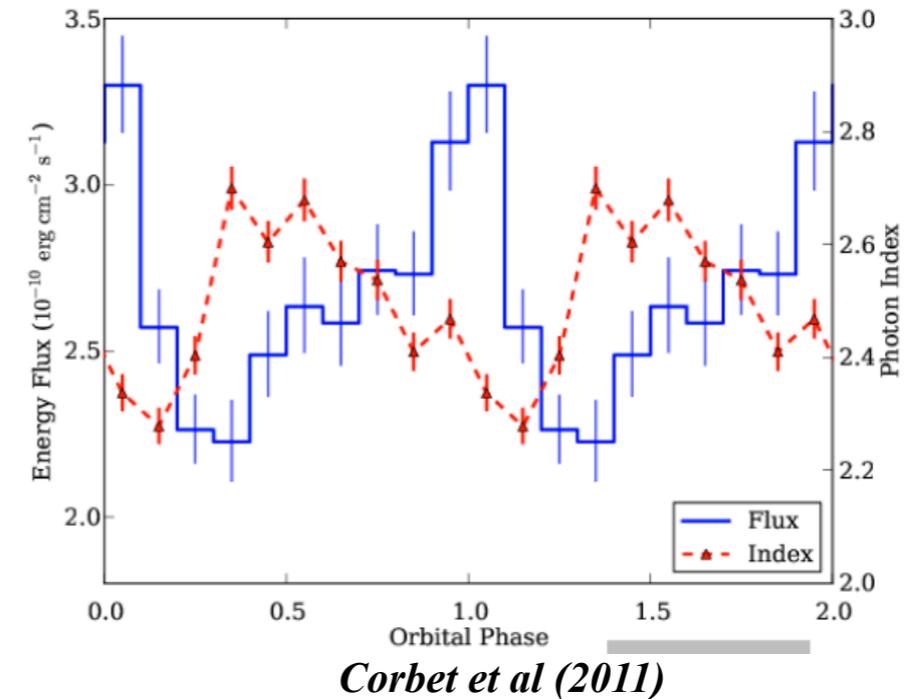
Hinton et al (2009)



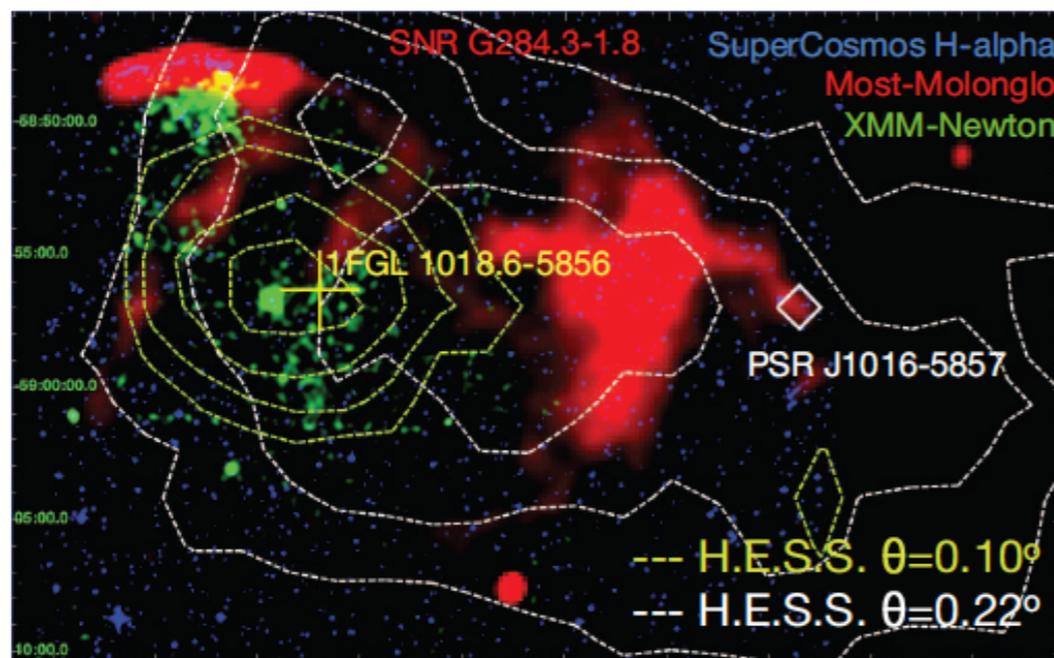
1FGL J1018.6-5856

- $P_{\text{orb}} = 16.58$ days
- compagna tipo O
- dati recenti (2011) : *Fermi* + X-rays + radio
- anche in VHE, ma periodicit  non riportata
- prima binaria scoperta originalmente @ GeV

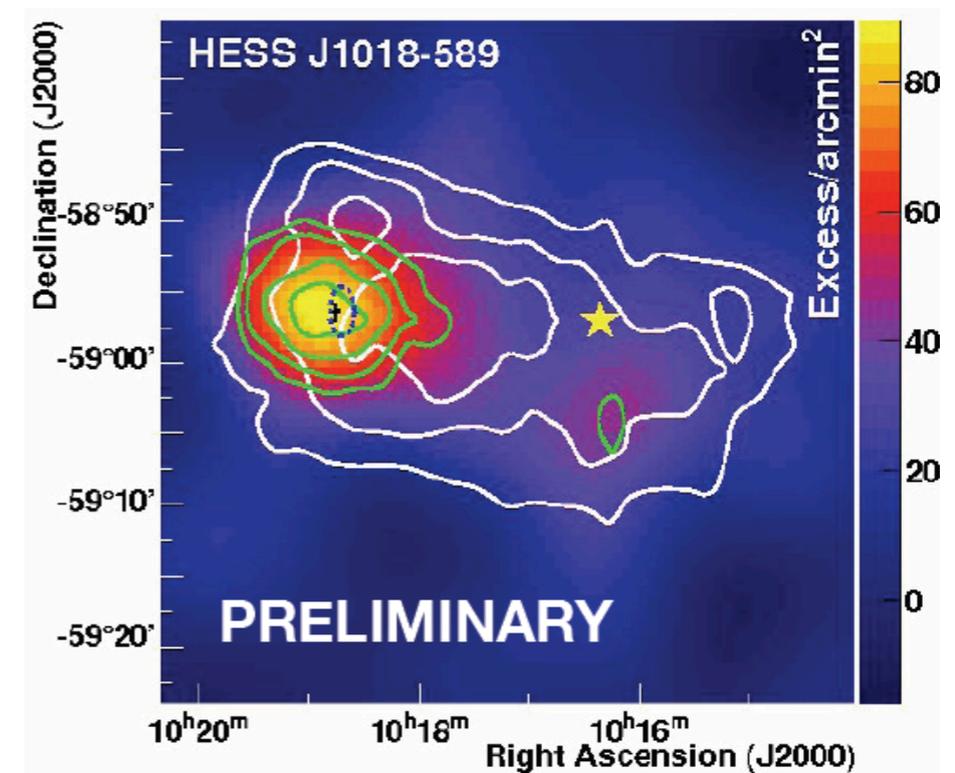
HE γ -rays *Fermi - Corbet et al. (2011)*



Radio & X-rays

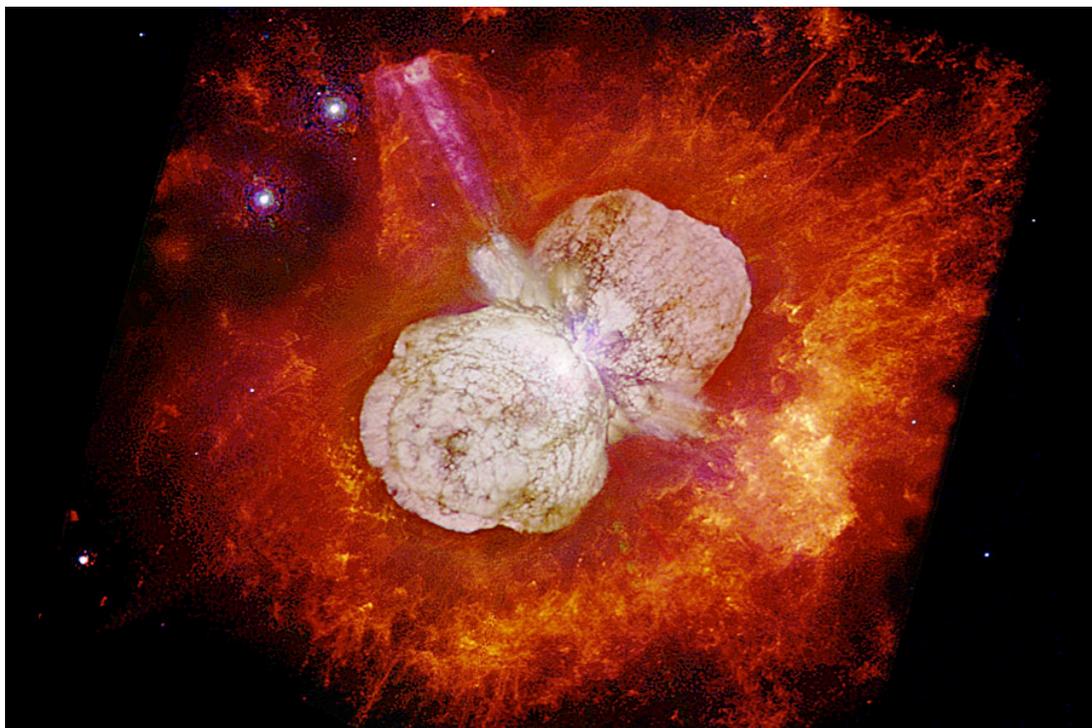


VHE γ -rays *H.E.S.S. - de Ona Wilhelmi et al. (2011)*



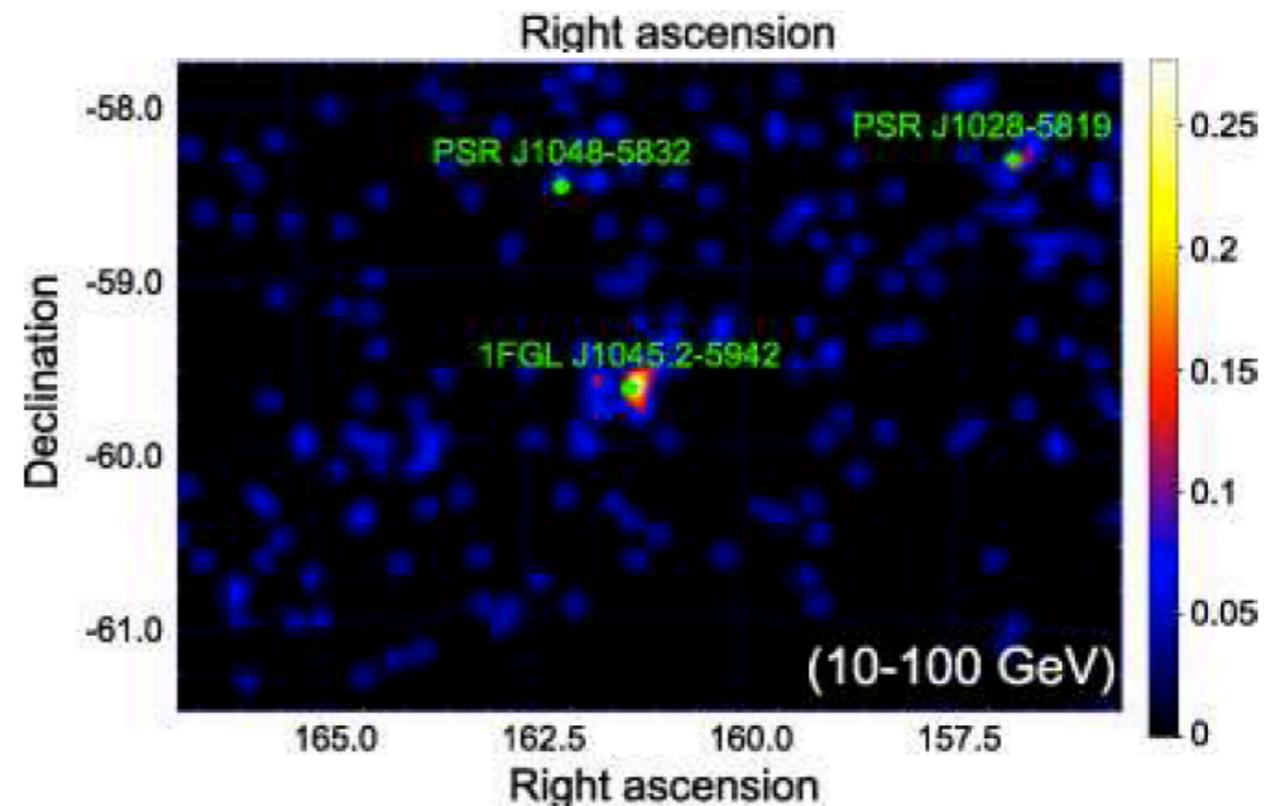
η Carinae

- unica binaria senza oggetto compatto!
- $P_{\text{orb}} = 5.4 \text{ y}$
- **primaria:** Luminous Blue Variable $> 80 M_{\text{sun}}$
 - mass-loss rate $\sim 5 \times 10^{-3} M_{\text{sun}}/\text{year}$!
 - vento $\sim 500 \text{ km/s}$
- **secondaria:** O oppure WR $\sim 30 M_{\text{sun}}$
 - mass-loss rate $\sim 10^{-5} M_{\text{sun}}/\text{year}$!
 - vento $\sim 3000 \text{ km/s}$

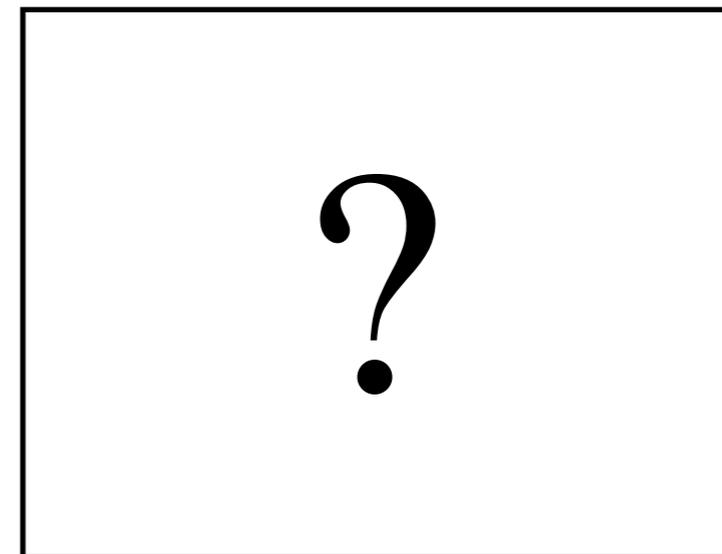


credits: N. Smith, J. A. Morse (U. Colorado) et al., NASA

HE γ -rays *Fermi.* - Abdo et al. (2010)



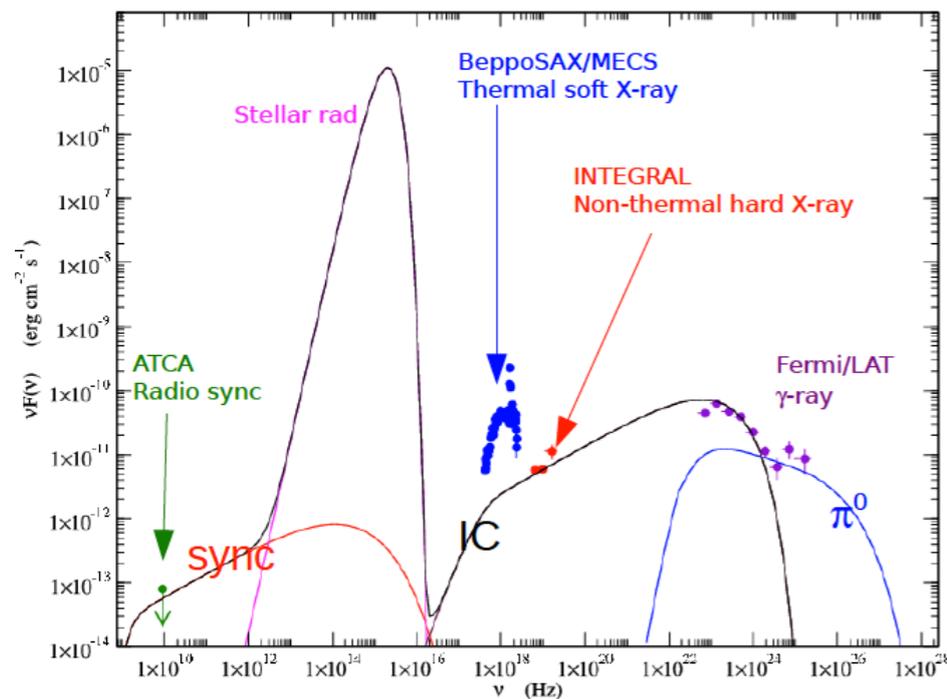
VHE γ -rays



η Carinae

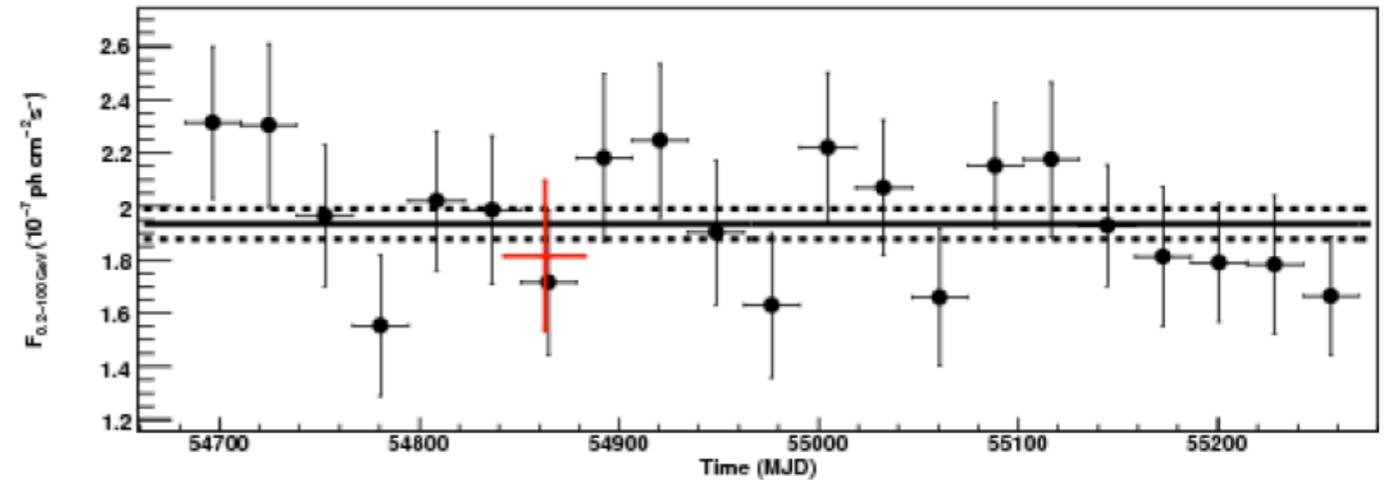
“ η Carinae: a large hadron collider” ?

- e \pm /- IC con intenso campo UV + interazioni pp nei venti stellari
 - pro: spiega X-ray & hard tail @ GeV
 - con: variabilità non trovata
- IC con IR da “Homunculus nebula”
 - pro: non variabilità spiegata
 - con: non hard tail!

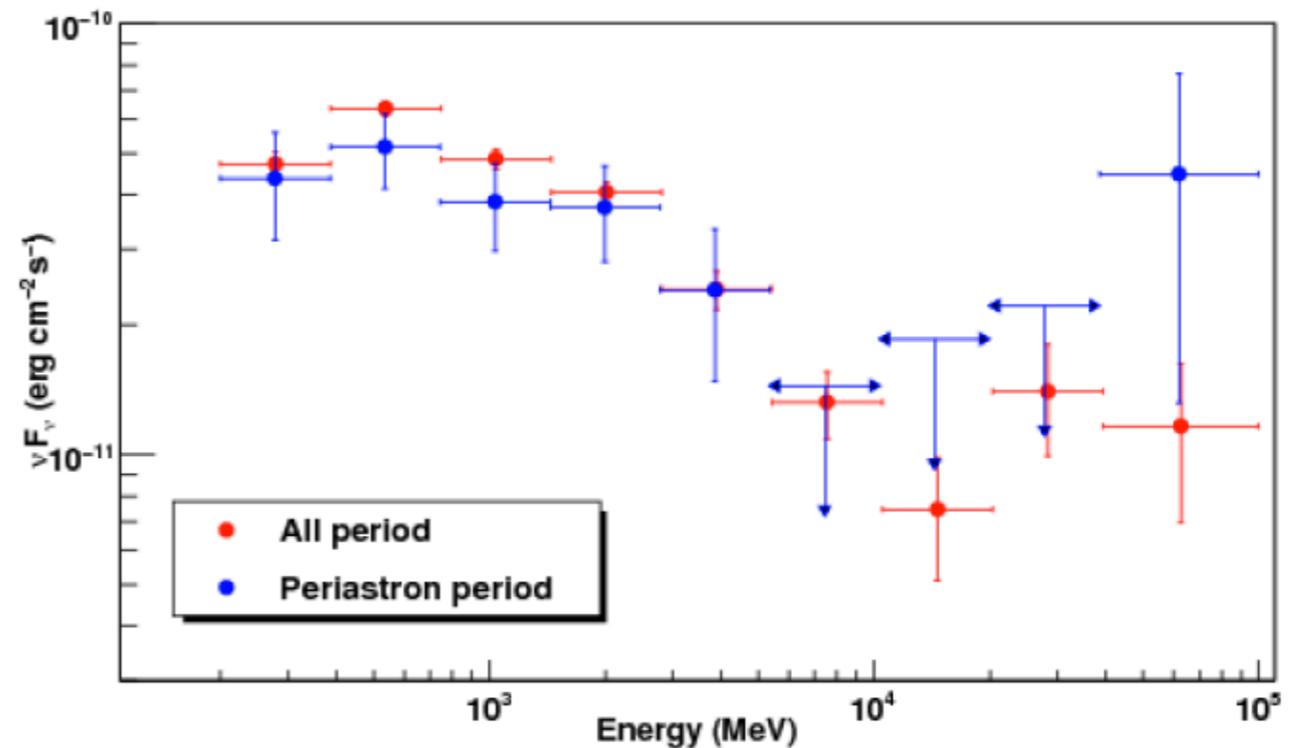


Abdo et al. 2010, Farnier et al. (2010)

- Flusso > 100 MeV \approx costante (alte energie poca statistica)



- exp. cutoff + componente hard: due popolazioni di particelle?



Prospettive: CTA

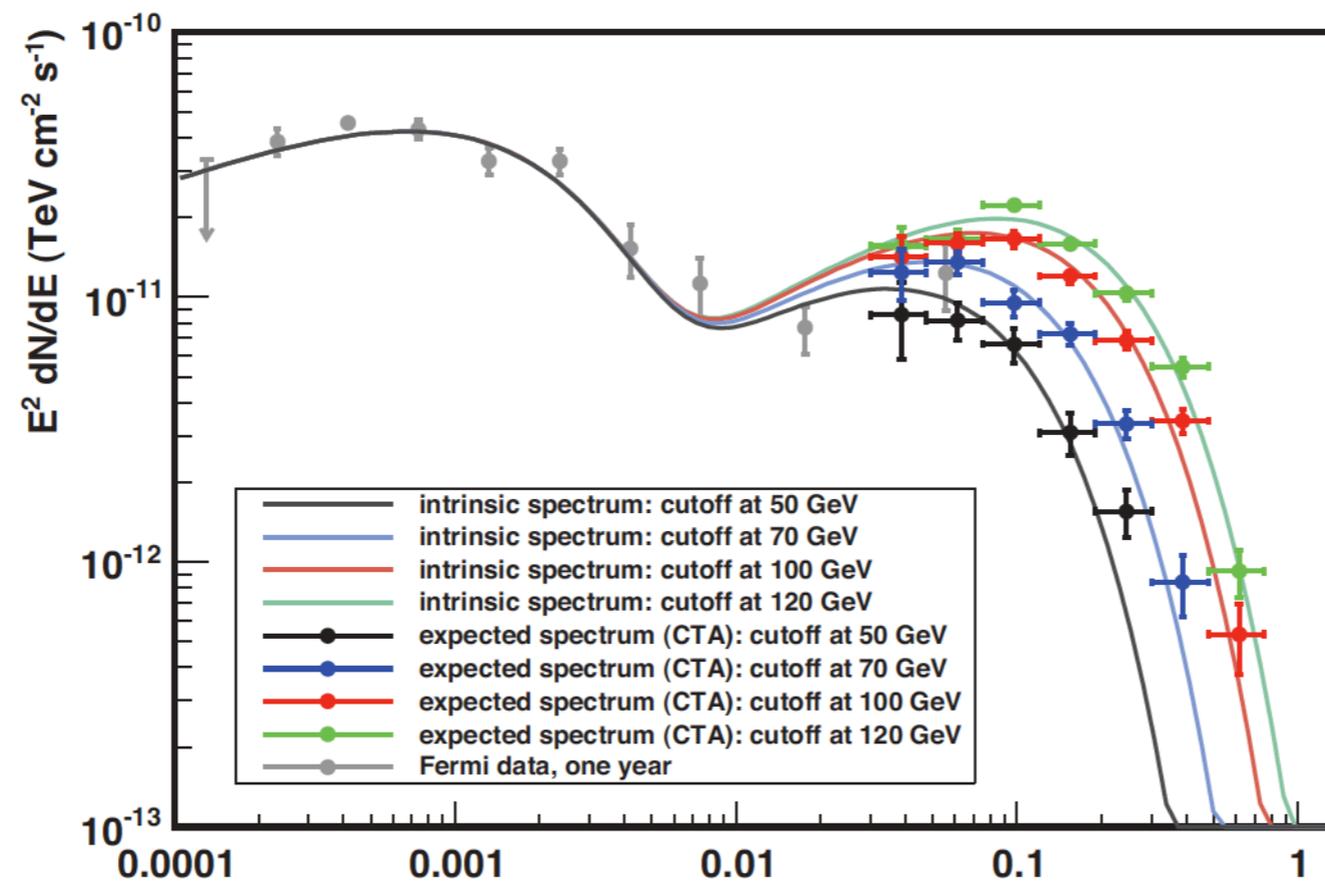
Binaries with the eyes of CTA

W. Bednarek^a, P. Bordas^b, V. Bosch-Ramon^c, E. De Cea del Pozo^o, G. Dubus^d, S. Funk^e, D. Hadasch^o, D. Khangulyan^f, S. Markoff^g, S. Nagataki^q, T. Naito^h, M. de Naurois^l, P. Munar^j, J.M. Paredes^{i,1,*}, G. Pedalletti^o, O. Reimer^{e,k}, M. Ribó^j, A. Szostek^{l,m}, Y. Terada^r, D.F. Torres^{n,o}, V. Zabalza^j, A.A. Zdziarski^p, for the CTA Collaboration

... to be submitted on September 2011 (!)

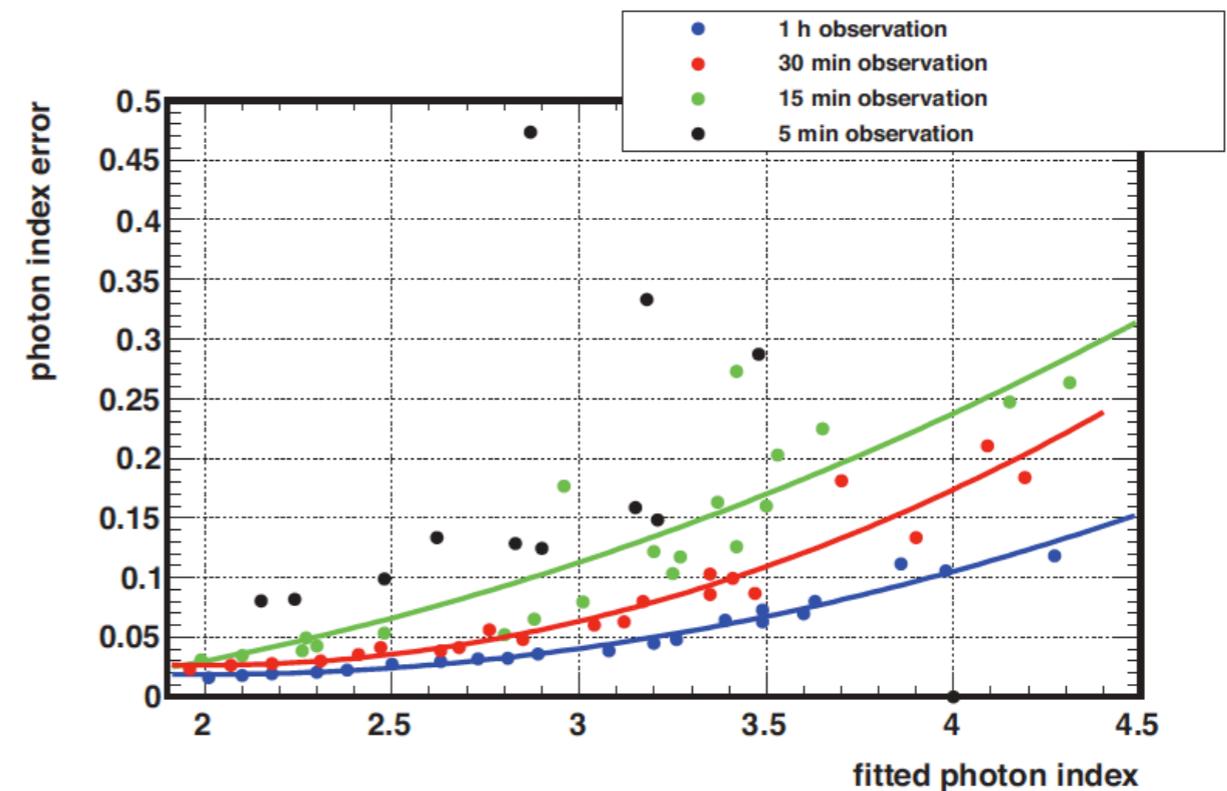
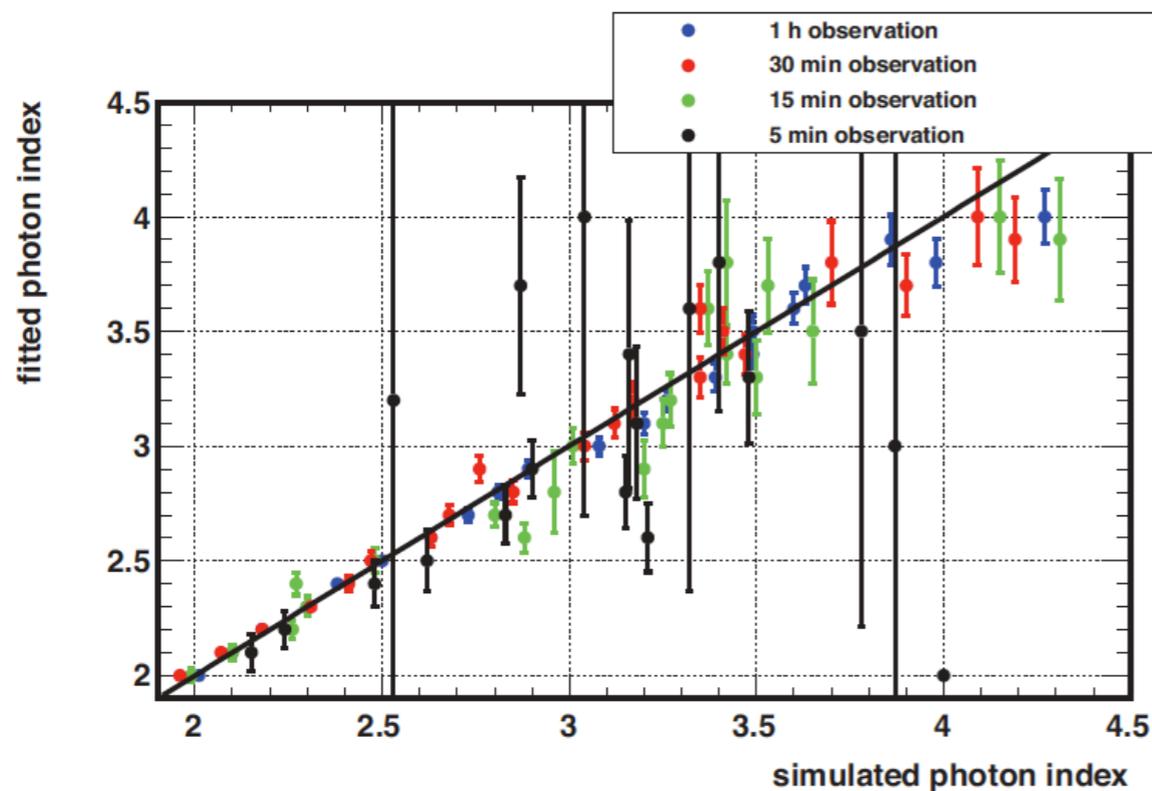
Prospettive: CTA

- Monitoraggio dell'attività di un gruppo di binarie γ ?
→ evitare “Target of Opportunity” infruttuosi (e.g. Cyg X-3, Cyg X-1...)
- Estensione VHE regime sotto le decine di GeV - sopra le decine di TeV
→ sorgenti con spettro soft (e.g. Cyg X-1, η Carinae...)



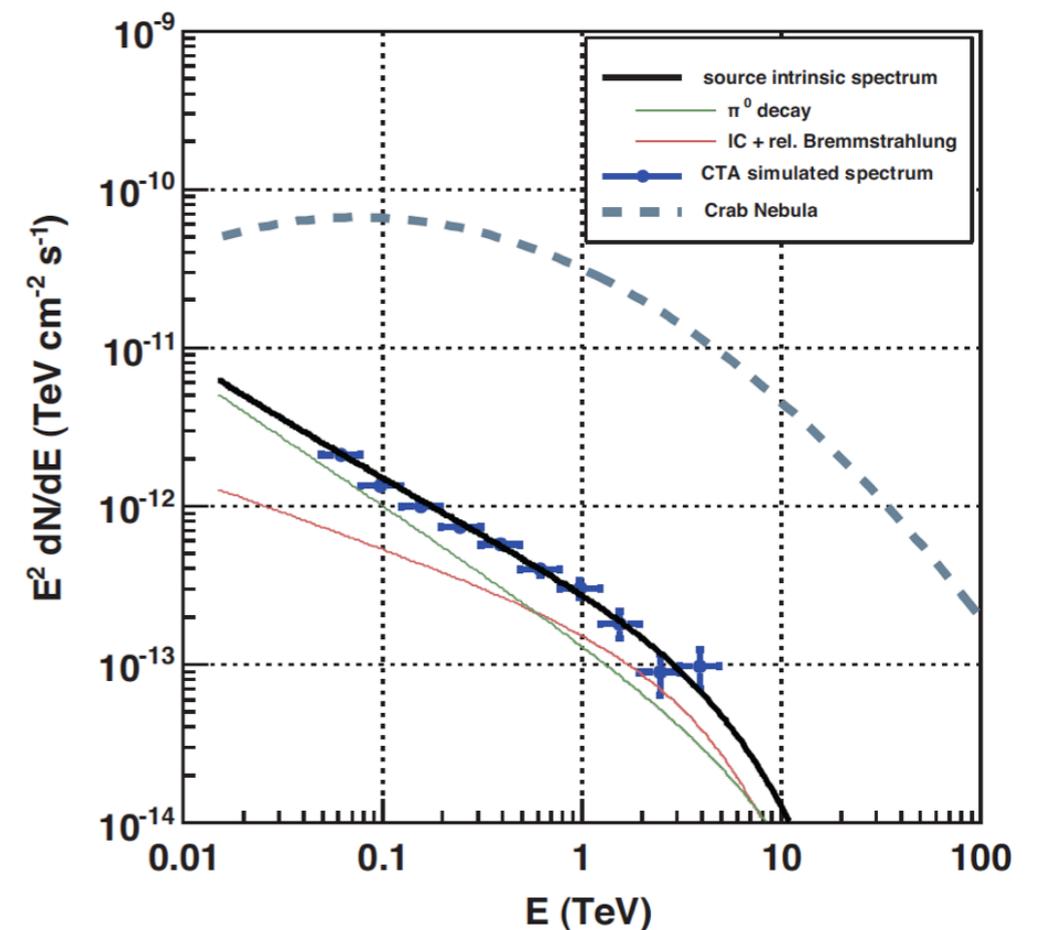
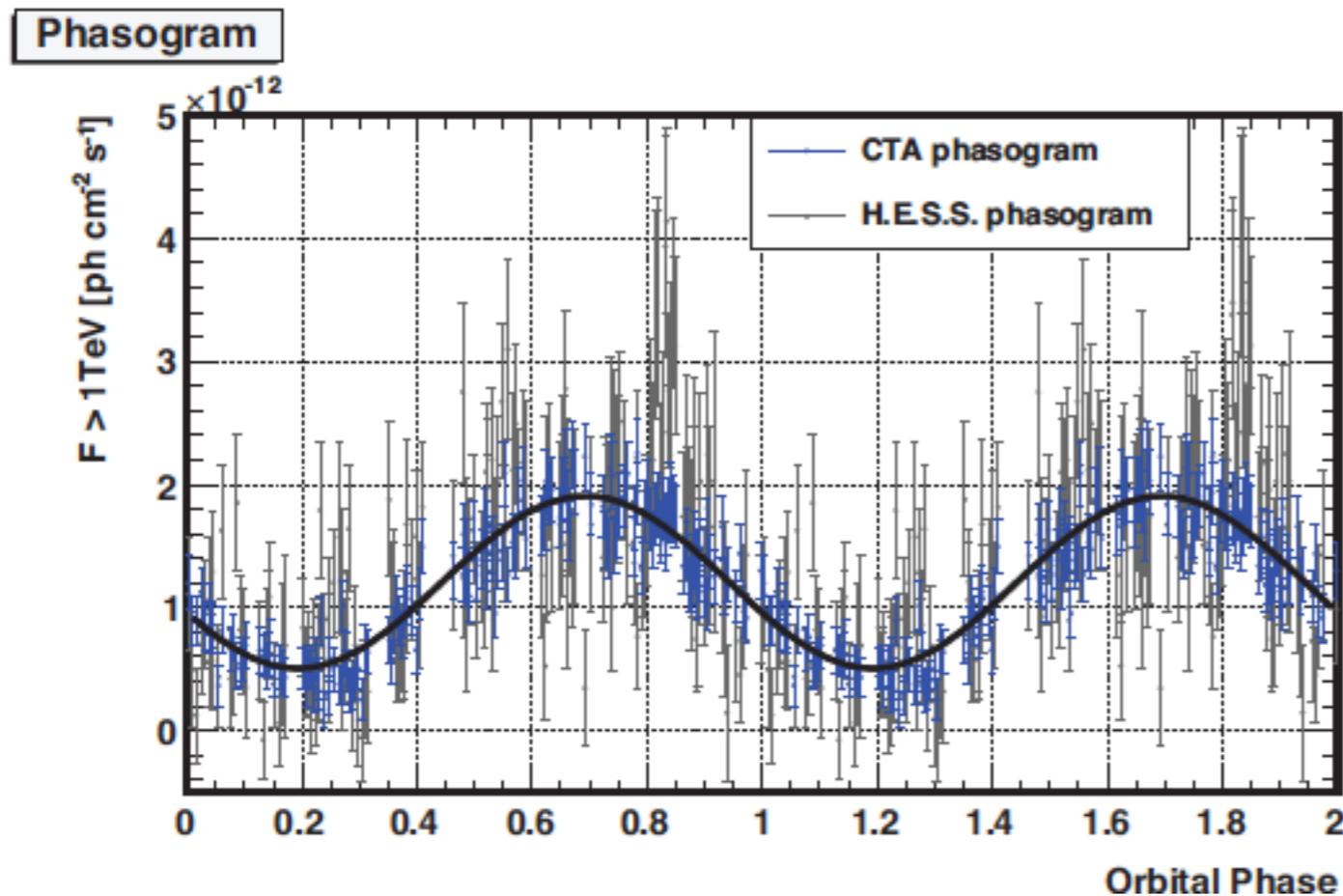
Prospettive: CTA

- Miglioramento sensitività + risoluzione spettrale
→ studio dettagliato delle variazioni spettrali col movimento orbitale/durante *flares*



Prospettive: CTA

- Risoluzione temporale/spaziale
 - studio preciso della variabilità durante *flares*
 - risolvere regione di emissione solo se fuori dal sistema binario (e.g. Cyg X-1?)



Conclusioni

siamo sicuri...

- **LS 5039, LSI +61 303, PSR B1259, Sistemi binari in raggi γ (forse con pulsar)**
- **Cyg X-3, Cyg X-1: Sistemi binari in raggi γ con *microquasar***

non siamo tanto sicuri...

- **LS 5039:** emissione TeV anche in superior conjunction... e l'assorbimento?
- **LSI +61 303:** fluttuazioni supra-orbitali @ TeV? flares?
- **HESS J0632:** periodico in TeV? sistema binario veramente? emissione GeV?
- **PSR B1259:** emissione GeV, massimo dopo periastro?
- **1FGL J1018:** periodico anche in TeV?
- **Cyg X-3:** emissione GeV solo in flares? TeV?
- **Cyg X-1:** un solo flare in TeV? *AGILE* si, *Fermi* no?
- **η Carinae:** acceleratore hadronico? Flusso GeV costante? TeV?

Conclusione

- *Sicuro?*
- “*Sicuro morì ai ponticini...!*”

(proverbio toscano)