Gamma-Ray Emission from Compact Binary Systems

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Rikkyo University (Tokyo)

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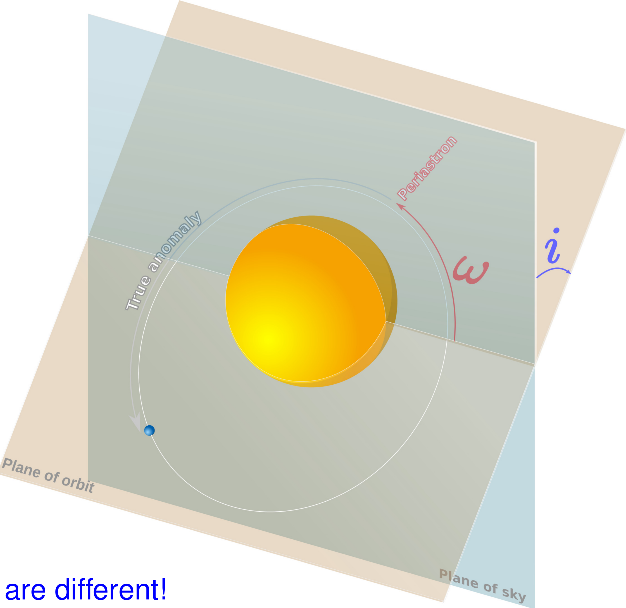
What are the Binary Systems emitting γ-rays?

OUTLINE

- A short introduction
  - ☞ Gamma-ray emitting binary zoo
- Gamma-ray binaries as multi-TeV sources
  - ☞ Why the acceleration process may go beyond a few TeV
- What is the nature of the most extreme gamma-ray binaries
  - ☞ Recent hints from X-ray observations
- Do we expect multi-component acceleration in gamma-ray binaries?
  - ☞ Analysis of the Crab Nebula spectrum

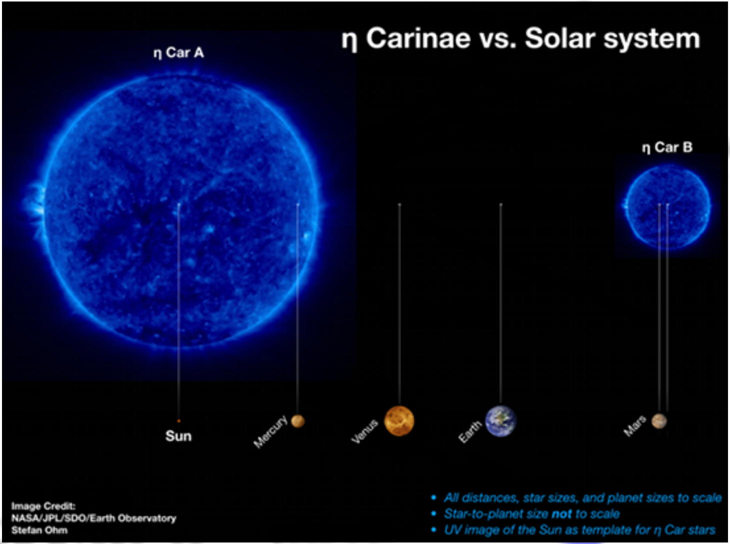
What are the Binary Systems emitting γ-rays?

- Orbit orientation
  - ✔ Inclination
  - ✔ Longitude of periastron
  - ✔ Node orientation
- Orbit geometry
  - ✔ Major semiaxis
  - ✔ Eccentricity
  - ✔ Period
- Stars
  - ✔ Compact, Luminosity, Dwarf
  - ✔ Accretion, Wind, Jet
- Emission site
  - ✔ Mechanism
  - ✔ Location
  - ✔ Doppler boosting



All binaries are different!

What are the Binary Systems emitting γ-rays?



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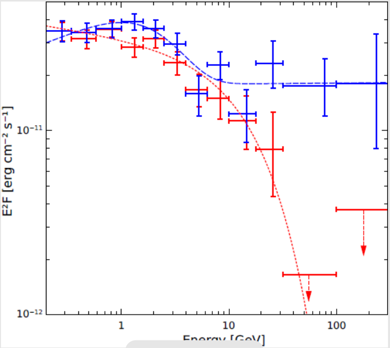
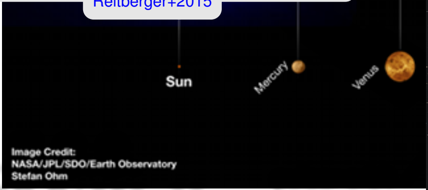
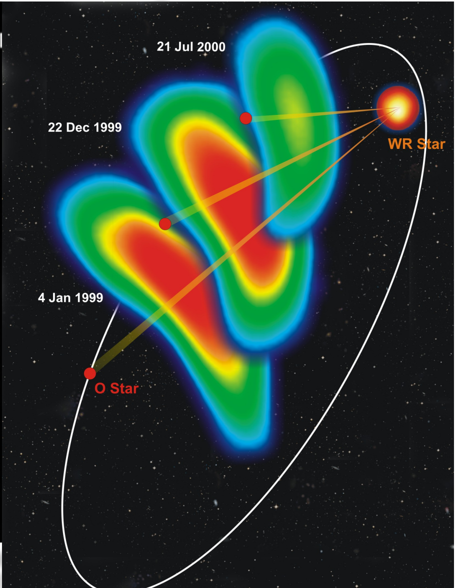


Reitberger+2015

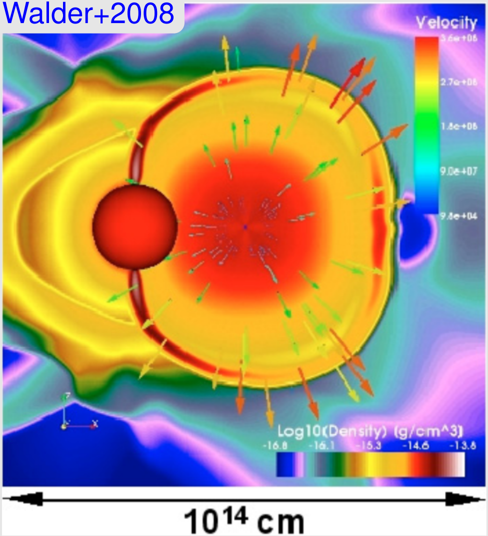




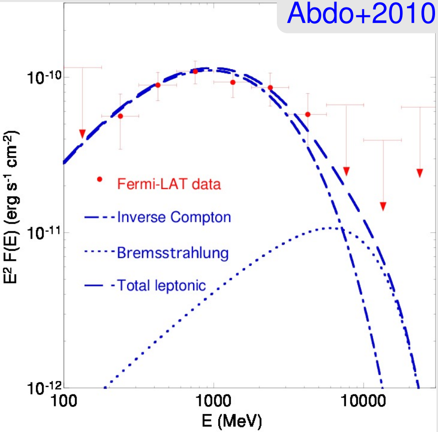
WR140 (Dougherty+2014)

What are the Binary Systems emitting γ-rays?

Walder+2008

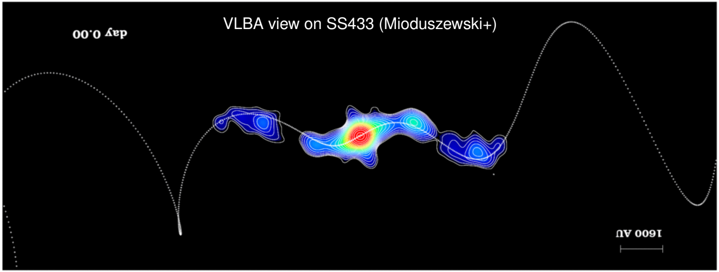


Abdo+2010

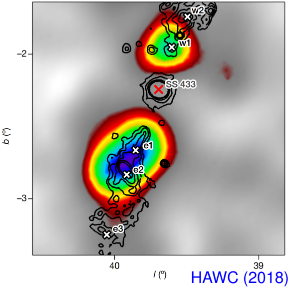


Symbiotic recurrent nova V407 Cyg: powered by accreting white dwarf

What are the Binary Systems emitting γ-rays?



- ✔ **SS433**: Microquasar with bright non-thermal radio and X-ray emission (Feldman+1978, Marshall+1978, Mirabel&Rogríguez 1999)
- ✔ Microquasar **SS433** features the most powerful Galactic jets with $L_{\rm kin} = 10^{39}\,{\rm erg/s}$
- ✔ These jets are subrelativistic ($v \sim 0.26c$)



HAWC (2018)

Gamma-Ray Binary Systems

BS with detected γ rays

System	Star	Star*	P	VHE	HE	X-ray
PSR B1259-63/LS2883	p	O/Be	1237d	periodic	variable	periodic
LS 5039	?	O	3.9d	periodic	periodic	periodic
LS I +61+303	?	Be	27d	variable	periodic	variable
HESS J0632+057	?	Be	320d	variable	—	variable
1FGL J1018.6-5856	?	O	17d	variable	periodic	variable
PSR J2032+4127/MT91 213	p	Be	50yr	variable	—	variable
LMC P3	?	O	10d	periodic	periodic	variable
Cyg X-3	bh	WR	4.8h	—	flare	—
Cyg X-1	bh	O	5.6d	flare	—	—
SS433	bh	A	13d	—	steady	steady
V407 Cyg	WD	RG	40yr	—	flare	flare
η Car	BG	WR	5.5yr	variable(?)	variable	variable

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HESS J0632+057	?	Be	320d	variable	—	variable
1FGL J1018.6-5856	?	O	17d	variable	periodic	variable
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Gamma-Ray Emitting BS

System	Star	Star*	P	VHE	HE	X-ray
Cyg X-3	bh	WR	4.8h	—	flare	—
Cyg X-1	bh	O	5.6d	flare		—
SS433	bh	A	13d	—	steady	steady
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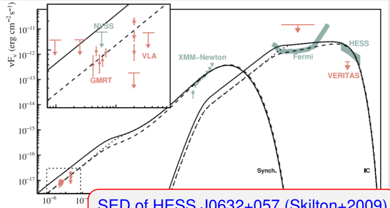
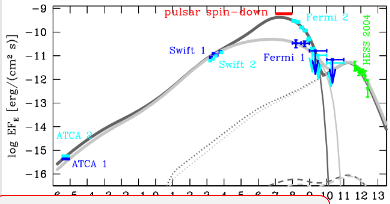
γ-ray binaries

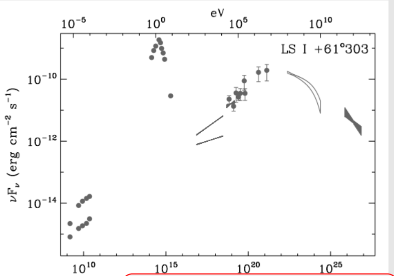
Gamma-Ray Binary Systems



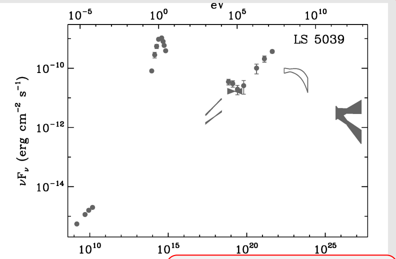
SED of HESS J0632+057 (Skilton+2009)



SED of PSR B1259-63/LS2883 (Abdo+2011)

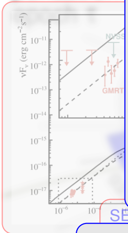


SED of LS I +61+303 (Dubus+2013)

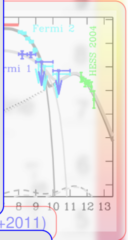


SED of LS 5039 (Abdo+2009)

Gamma-Ray Binary Systems



SED of HESS J0632+057 (Skilton+2009)



SED of PSR B1259-63/LS2883 (Abdo+2011)

Criteria for Gamma-Ray Binary:

- **Hard non-thermal X-ray emission**
- **Detected TeV emission**
- **Contains luminous star**
- **SED is dominated in gamma-rays**
- **Contains non-acreting pulsar**

System	VHE	X-ray	Star	SED	PSR
PSR B1259-63/LS2883	✔	✔	✔	✘	✔
LS 5039	✔	✔	✔	✔	✘
LS I +61+303	✔	✔	✔	✔	✘
HESS J0632+057	✔	✔	✔	✘	✘
1FGL J1018.6-5856	✔	✔	✔	✔	✘
PSR J2032+4127/MT91 213	✔	✔	✔	✔	✔
LMC P3	✔	✔	✔	✔	✘

Note that ✔ means **YES**; ✘ means **we don't know**

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PSR B1259-63/LS2883	✔	Why is that important?	✔	✘	✔
LS 5039	✔		✔	✔	✘
LS I +61+303	✔		✔	✔	✘
HESS J0632+057	✔		✔	✘	✘
1FGL J1018.6-5856	✔		✔	✔	✘
PSR J2032+4127/MT91 213	✔		✔	✔	✔
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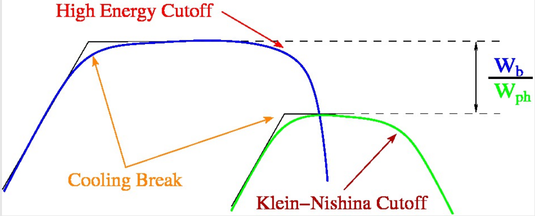
Energy Distribution of Electrons in Binary Systems

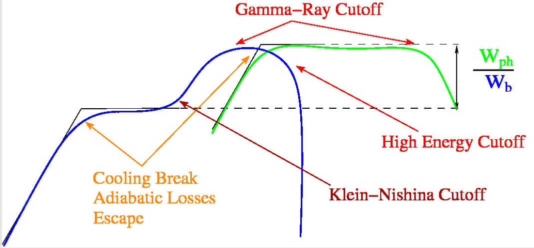


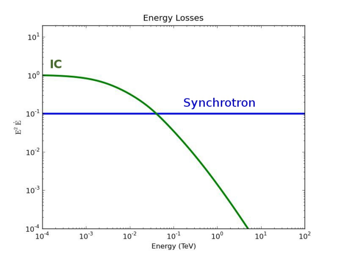
Steady electron distribution:

$$\frac{dN_e}{dE} = \frac{1}{\dot{E}} \int_{E}^{\infty} dE' \, Q(E)$$

$$\dot{E} = \dot{E}_{syn} + \dot{E}_{ic} + \dot{E}_{ad}$$

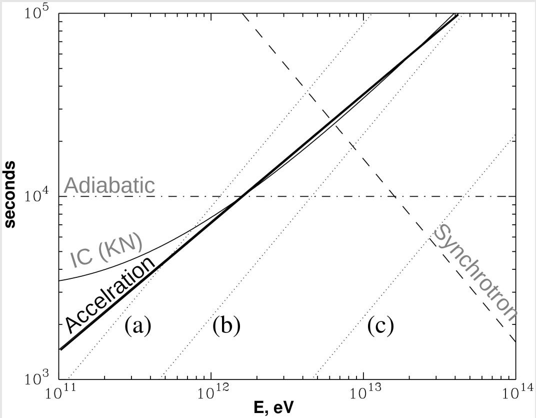
$$\dot{E}_{syn/ad/thomson} \propto E^{-\alpha}$$





Hard X-ray spectrum: leptonic source with dominant hot photon field

Particle acceleration in γ-ray binary systems



- Radiation dominated environment
  - ✔ K-N losses do not prevent acceleration
  - ✔ Converter Mechanism (Derishev+2000)
- $\gamma\gamma$ absorption
  - ✔ Max at 100GeV ($T \sim 3 \times 10^4$ K)
  - ✔ Transparent for 10 TeV γ-rays
- IC scattering
  - ✔ Nearly isotropic for 10 TeV γ-rays
- Sources of Multi-TeV γ-rays?
  - ✔ If the acceleration is efficient enough

What are the most efficient Galactic accelerators? **PWNe**

Gamma-Ray Binary Systems

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SED of PSR B1259-63/LS2883 (Abdo+2011)

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SED of LS I +61+303 (Dubus+2013)

Gamma-Ray Binary Systems

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PSR B1259-63/LS2883	✔	✔	✔	✘	All contain PSR?
LS 5039	✔	✔	✔	✔	
LS I +61+303	✔	✔	✔	✔	
HESS J0632+057	✔	✔	✔	✘	
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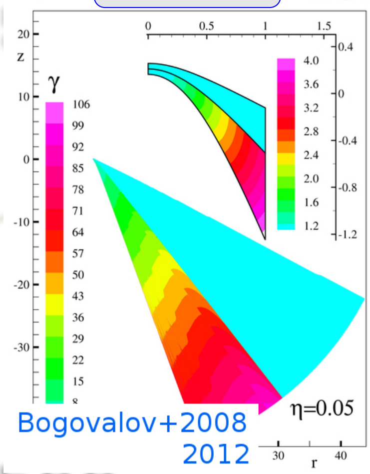
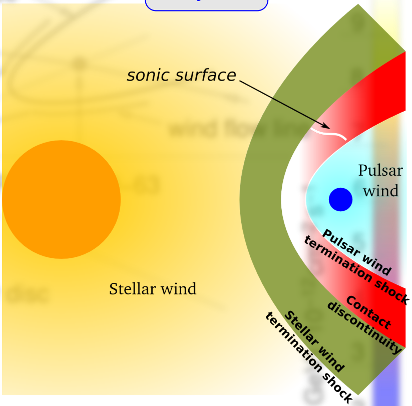
Hydrodynamics of wind interaction

HD (MHD) simulations



Binary Pulsar



Binary environment implies differences from usual PWNe; relativistic nature of the pulsar wind makes differences to CWB

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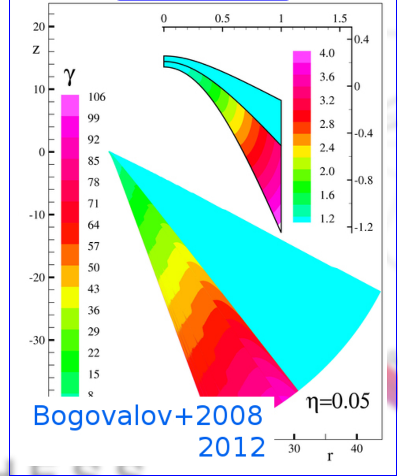
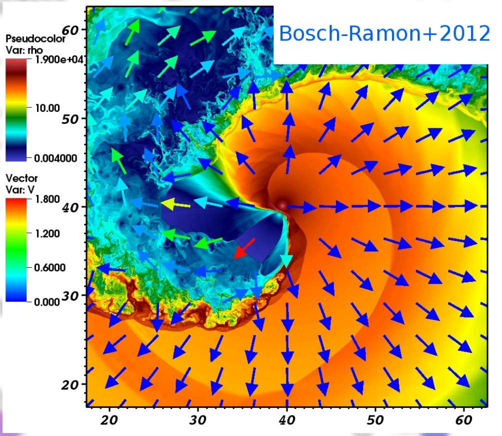
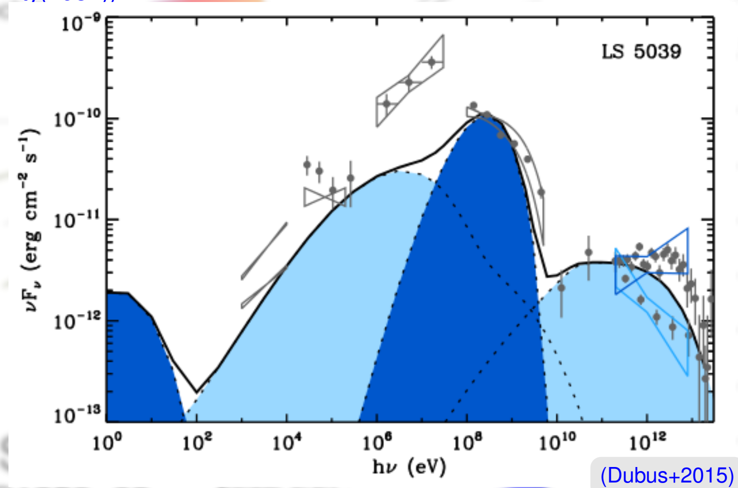




Relativistic effect: Coriolis force created shock

LS5039: More detailed simulations

Coupled hydro-kinetic modeling of binary pulsar (approach similar to Kennel&Coronity(1984))



(Dubus+2015)

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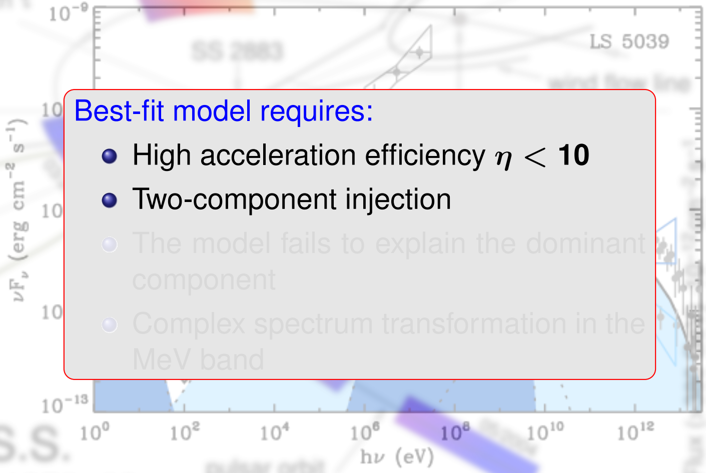

Best-fit model requires:

- High acceleration efficiency $\eta < 10$
- Two-component injection
- The model fails to explain the dominant component
- Complex spectrum transformation in the MeV band

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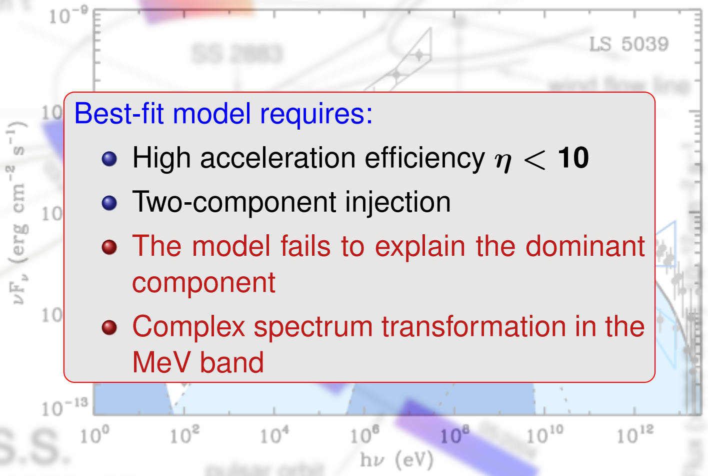

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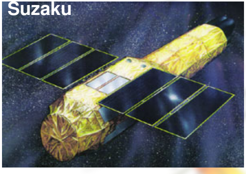
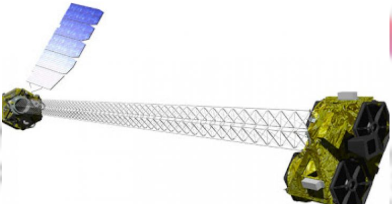
Does this confirms or disproves the underlying model? How to prove presence of a pulsar in LS5039?

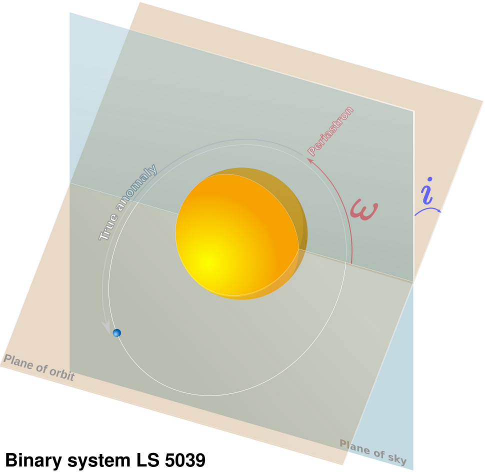
Gamma-Ray Binary System LS5039

LS 5039 was observed with Suzaku and NuSTAR





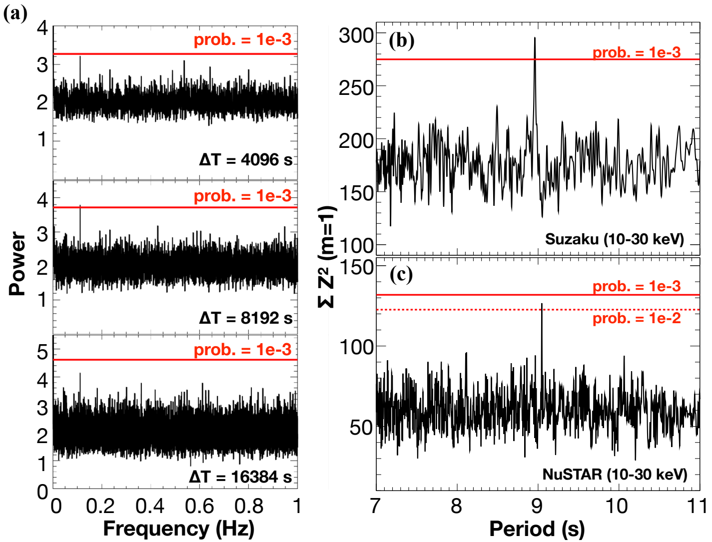
NuSTAR



Binary system LS 5039

Hard X-ray instruments give a unique chance to detect pulsed emission from compact binary systems

Search for pulsed emission from LS 5039



Yoneda+(PRL submitted)

Search for pulsed emission from LS 5039

It was shown that (Yoneda+, PRL submitted)

- Analysis of the Suzaku data suggests pulsation with $P = 8.96\mathrm{s}$
- Analysis of the NuSTAR data suggests pulsation with $P = 9.045\mathrm{s}$
- The period difference implies NS slowing down $\dot{P} = 3 \times 10^{-10}\mathrm{s\,s^{-1}}$
- This information can shed light on the nature of LS 5039
  - ✔ The compact object is a neutron star
  - ✔ The compact object is magnetar
  - ✔ Magnetic field decays very quickly in this source

Magnetar in LS 5039

One needs at least $10^{36}\,\mathrm{erg\,s^{-1}}$ to explain the emission from the source

1. **Spin-down Luminosity**

$$L_{\rm LD} = \frac{(2\pi)^2 I \dot{P}}{P^3} \sim 10^{34}\ \mathrm{erg\ s^{-1}}$$

2. **Accreting Pulsar**
   - Pulse period is increasing
   - No fast time variability like accreting object

3. **Stellar Wind**

$$L_{\rm w} \sim \frac{1}{2}\dot{M}_{\rm w} v_{\rm w}^2 \times \frac{\pi R_{\rm A}^2}{4\pi D_{\rm sep}^2} < 6\times 10^{31}\ \mathrm{erg\ s^{-1}}$$

4. **Decay of strong magnetic field**

$$L_{\rm BF} = \frac{B_{\rm NS}^2 R_{\rm NS}^3}{6\tau} \sim 10^{37} \times \left(\frac{B_{\rm NS}}{10^{15}\ \mathrm{G}}\right)^2 \left(\frac{R_{\rm NS}}{10\ \mathrm{km}}\right)^3 \left(\frac{\tau}{500\ \mathrm{yr}}\right)^{-1}\ \mathrm{erg\ s^{-1}}$$

Magnetar in LS 5039

One needs at ... **m the source**

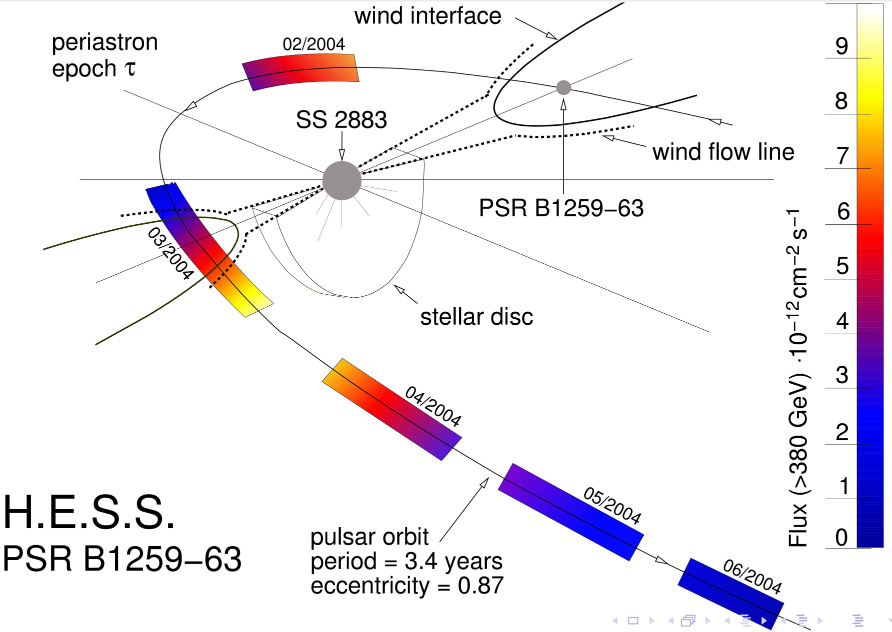
1. Spin-
2. Accre
   - Pu
   - No
3. Stella
4. Decay

L_{BF} = ... erg s^{-1}

This suggests interesting implications:

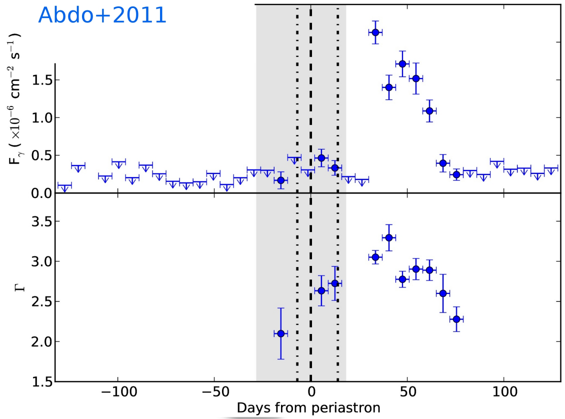
- ✔ nature of the compact object in the archetypal gamma-ray binary system (in all?)
- ✔ the first magnetar in binary system (very important for scenarios of magnetar formation)
- ✔ enable us to constrain the mass of the magnetar by solving the orbit (EOS)
- ✔ acceleration of particles by the decay of the super-strong magnetic field
- ✔ possible connection to other extreme astrophysical phenomena

Binary Pulsar System PSR B1259-63/LS2883



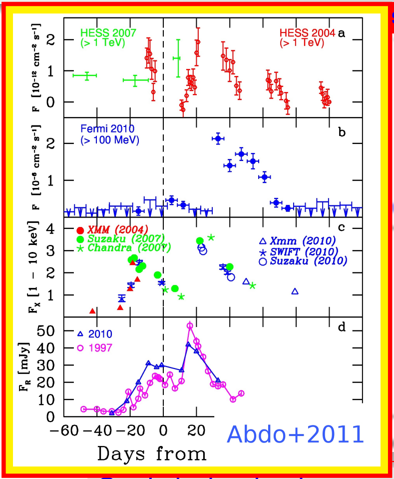
GeV Lightcurve

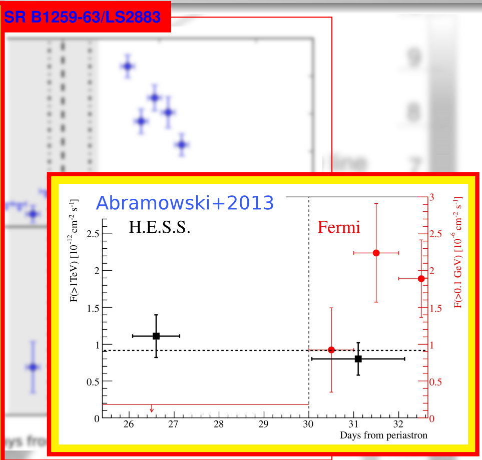
Flare from PSR B1259-63/LS2883



Fermi/LAT detected a bright flare with total duration of approx 1 month. Flare had a very sharp rise and the peaking luminosity exceeding $L_{\rm SD}$

GeV Lightcurve

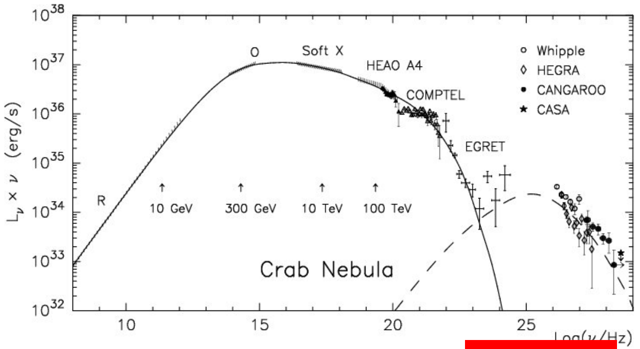




Such behavior has not been seen at other wavelengths. There is no explanation for this phenomena. Can it also be triggered by the magnetic field transformation?

PWN: Are multi component acceleration is required?

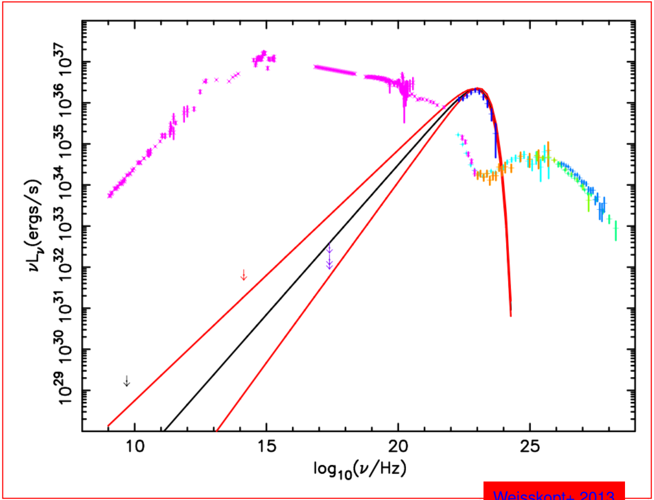
pre-Fermi/LAT SED of the Crab Nebula



Aharonian&Atoyan

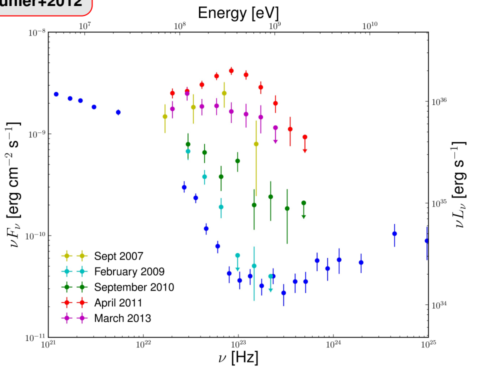
PWN: Are multi component acceleration is required?

post-Fermi/LAT SED of the Crab Nebula



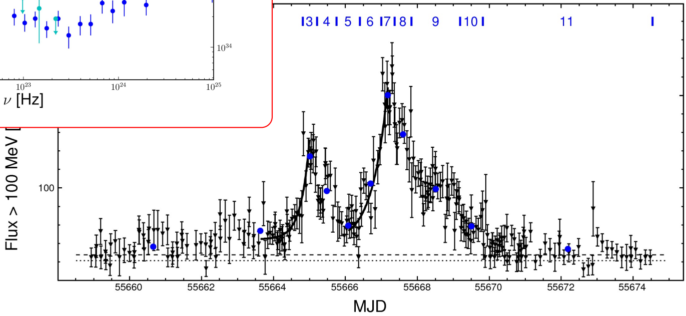
Weisskopt+ 2013

Crab Flares



$E_{\rm br} > 300\,{\rm MeV}$

Variability time: $t_{\rm var} \sim 12\,{\rm h}$



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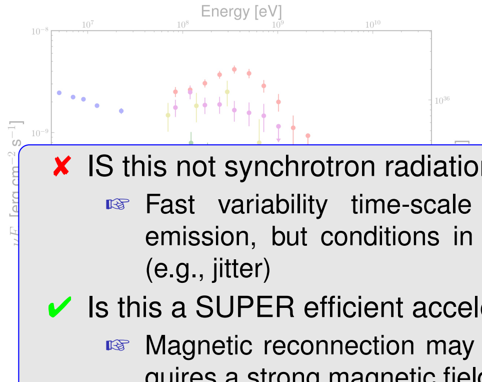
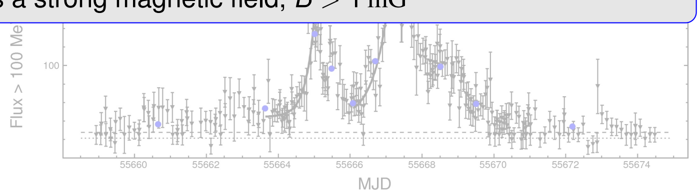
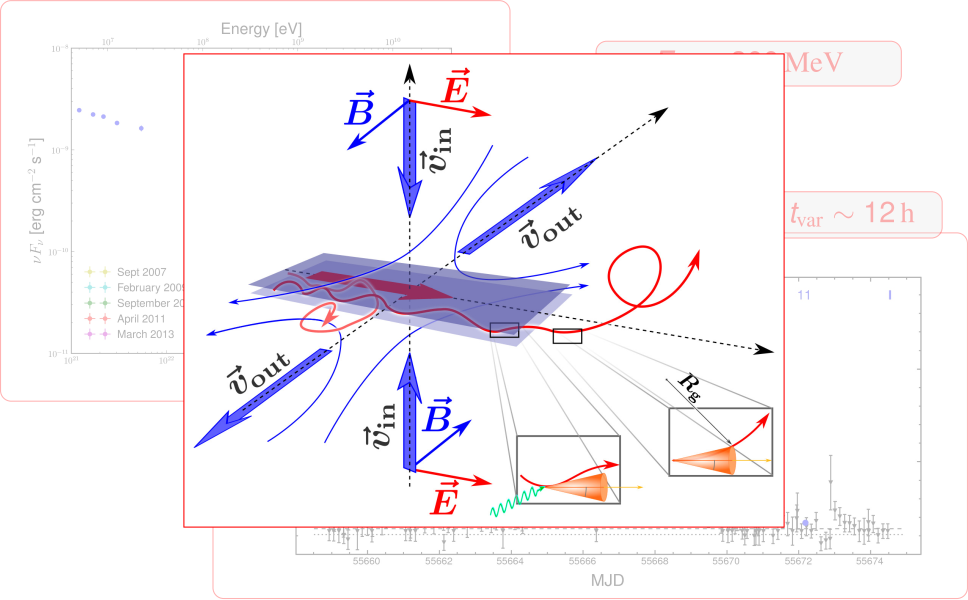


$E_{\rm br} > 300\,{\rm MeV}$

- ✘ IS this not synchrotron radiation?
  - ☞ Fast variability time-scale requires magnetobremsstrahlung emission, but conditions in the nebula exclude other regimes (e.g., jitter)
- ✔ Is this a SUPER efficient acceleration? (with $\eta < 1$)
  - ☞ Magnetic reconnection may provide a viable solution, but it requires a strong magnetic field, $B > 1\,{\rm mG}$



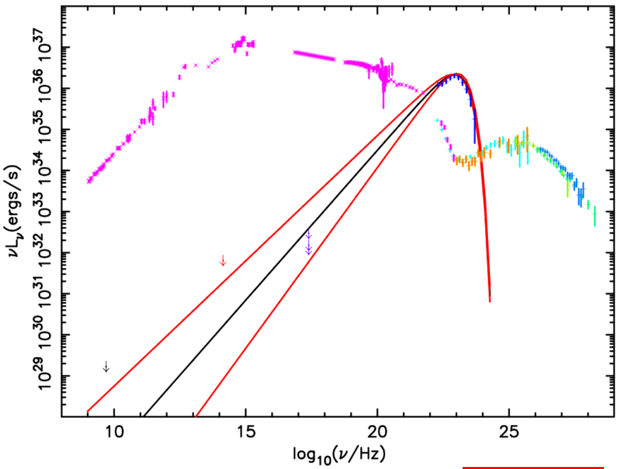
Crab Flares



Energy [eV]
νF_ν [erg cm^{-2} s^{-1}]
Sept 2007
February 2009
September 20
April 2011
March 2013
MeV
$t_{\rm var} \sim 12$ h
$\vec{B}$
$\vec{E}$
$\vec{v}_{\rm in}$
$\vec{v}_{\rm out}$
R_g
55660
55662
55664
55666
55668
55670
55672
55674
MJD

PWN: Are multi component acceleration is required?

The broadband emission is produced in a weak magnetic field, $B \simeq 125\,\mu\mathrm{G}$, and the flare is produced by strong magnetic field $B > 1\,\mathrm{mG}$.



Weisskopt+ 2013

PWN: Are multi component acceleration is required?

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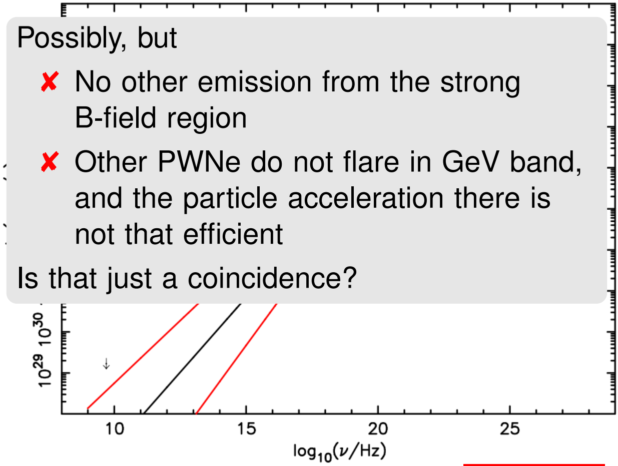


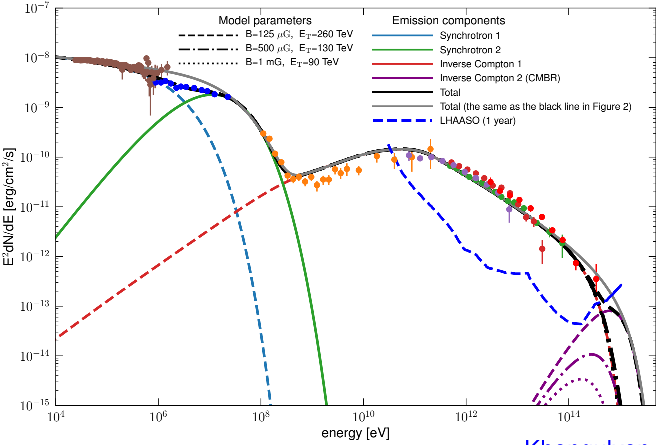
Possibly, but

- ✘ No other emission from the strong B-field region
- ✘ Other PWNe do not flare in GeV band, and the particle acceleration there is not efficient

Is that just a coincidence?

Weisskopt+ 2013

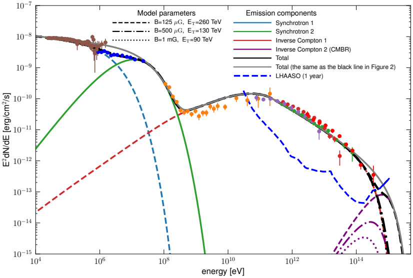
Multi-Component model



Khangulyan+(2020)

Multi-Component model

- Non-smooth transition @1MeV (Aharonian&Atoyan 1998)
- Gamma-ray data constrain electrons emitting below 1MeV
- Future observations in the MeV band (ASTROGAM, GRAMS) should define the spectral shape
- **Observation with LHAASO (in operation now), should constrain the magnetic field responsible for production of multi-MeV synchrotron photons**



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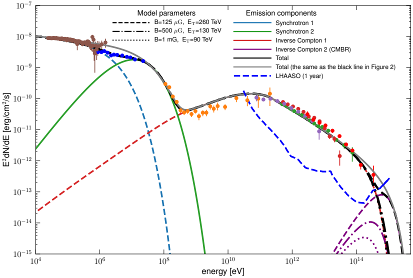

It cannot be excluded a priory that multi-MeV photons are produced in environments with stronger magnetic field. Future observations in the MeV and UHE bands should shed light on the conditions at the MeV emitter in the crab nebula.

Summary

- Gamma-ray emitting binaries represent a small, but very diverse group of gamma-ray sources
- The majority of them have apparently the same nature (based on 5 criteria)
- These objects might be efficient multi-TeV particle accelerator, so LHAASO should be able to see a few of them and to constrain the acceleration process efficiency
- Detailed analysis of the Suzaku and NuSTAR data enabled one to find pulsations in the hard X-ray spectrum of LS 5039
- Pulse period and its time derivative constrains the nature of the brightest component in LS 5039: it must be due to the dissipation of the magnetar magnetic field
- Multi-component particle acceleration seen in gamma-ray binaries might be also operating in the Crab Nebula
- Observations with LHAASO (and also in MeV band) will bring a lot of new information, even in the case of the Crab Nebula (a very well studied source)