UNIVERSITAT DE BARCELONA
Libertas Perfundet Omnia Luce

ICCUB
Institut de Ciències del Cosmos

Jets and outflows from microquasars and pulsar binaries and their emission

Josep M. Paredes

ALMA/NAASC 2012 Workshop
Outflows, Winds and Jets: From Young Stars to Supermassive Black Holes
Charlottesville, Virginia, March 3 – 6, 2012

OUTLINE

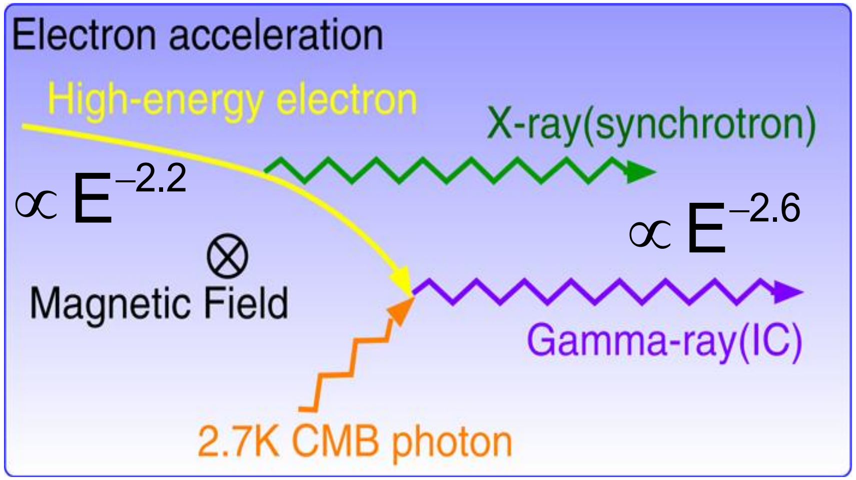
1. Binaries as sources of HE and VHE γ-rays
2. Microquasars
3. Non-accreting pulsars
4. Unclassified sources
5. New cases
6. Final remarks

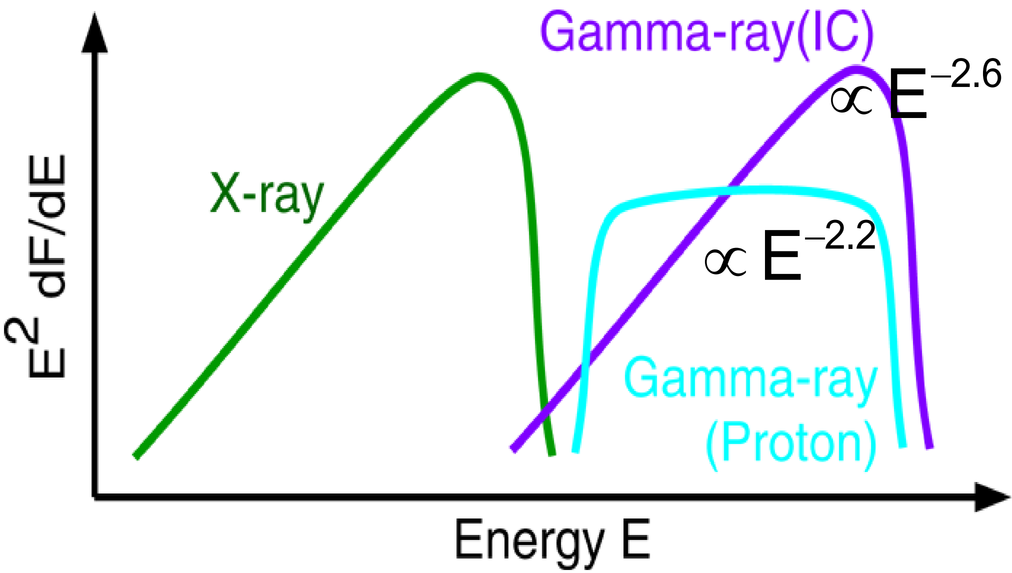
- 1. Accreting binaries
  - X-ray binaries
    - HMXRB
      - Be/X-ray transients
      - SG/obscure binaries
      - BH binaries
    - LMXRB
  - Microquasars
    - Relativistic jet
    - HM MQs
    - LM MQs

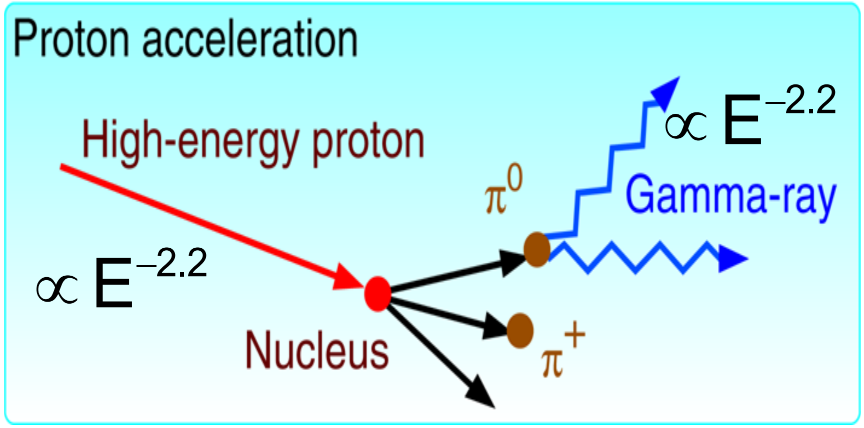
- 2. Non-accreting binaries
  - Colliding-wind massive binaries (OB+WR, OB+OB,WR+WR)
  - Pulsar wind binaries (e.g. PSR B1259-63)

Sources of relativistic particles → HE and VHE gamma-rays could be produced

Gamma-ray emission processes





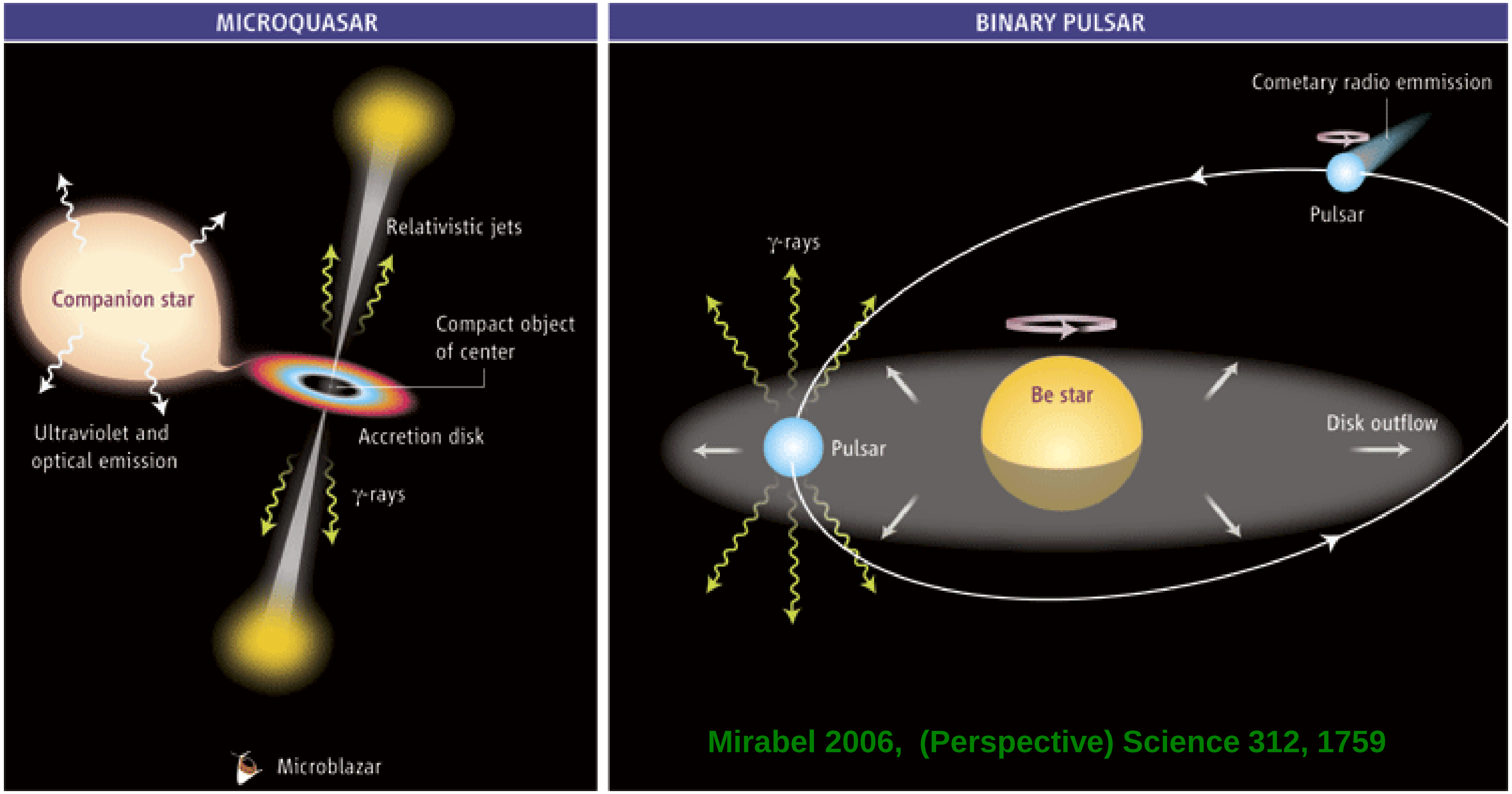


$$\left(\frac{dE}{dt}\right)_{\mathrm{I.C.}} = \frac{4}{3}\sigma_{\mathrm{T}} c \gamma_{\max}^{2} \mathrm{U}_{\mathrm{photon}}$$

$$\left(\frac{dE}{dt}\right)_{\mathrm{Sync}} = \frac{4}{3}\sigma_{\mathrm{T}} c \gamma_{\max}^{2} \frac{B^{2}}{2}$$

Microquasars and Non-accreting pulsar scenarios

GeV/TeV emitting XRBs: Accretion vs non-accretion



Cygnus X-1, Cygnus X-3

PSR B1259-63

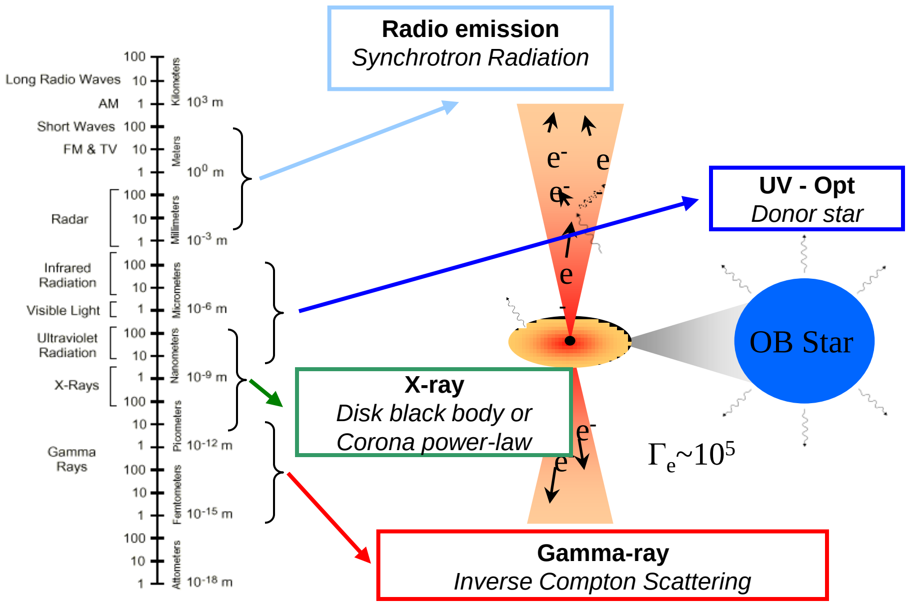
LS 5039 ?
LS I +61 303 ?
HESS J0632+057 ?
……1FGL J1018.6-5856 ?
……………. AGL J2241+4454 ?

Possible scenarios

Microquasar

- An accretion disk is formed by mass transfer.
- Display bipolar jets of relativistic plasma.
- The jet electrons produce radiation by synchrotron emission when interacting with magnetic fields.
- VHE emission is produced by inverse Compton scattering when the jet particles collide with stellar UV photons, or by hadronic processes when accelerated protons collide with stellar wind ions.

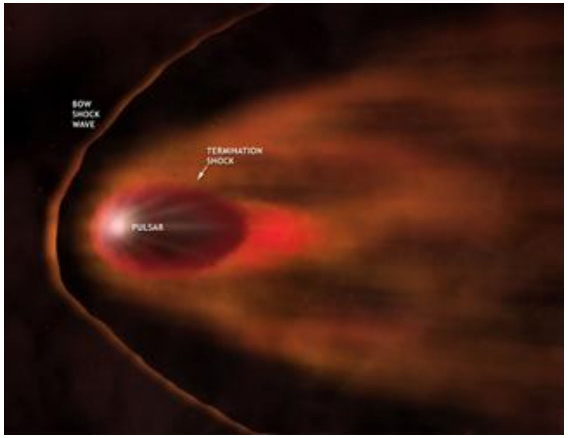
[Bosch-Ramon et al. 2006, A&A, 447, 263; Paredes et al. 2006, A&A, 451, 259; Romero et al. 2003, A&A, 410, L1]



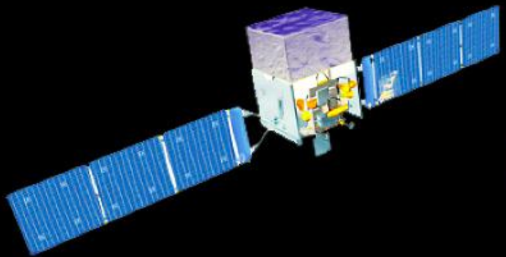
Non-accreting pulsar

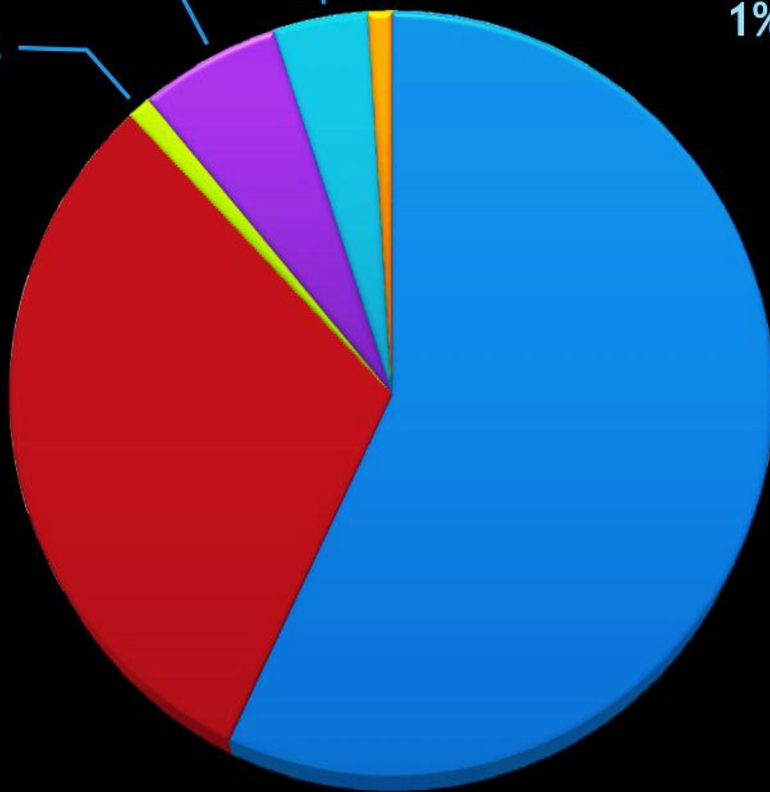
- The relativistic wind of a young (ms) pulsar is contained by the stellar wind.
- Particle acceleration at the termination shock leads to synchrotron and inverse Compton emission.
- After the termination shock, a nebula of accelerated particles forms behind the pulsar.
- The cometary nebula is similar to the case of isolated pulsars moving through the ISM.

[Maraschi & Treves 1981, MNRAS, 194, P1; Dubus 2006, A&A, 456, 801; Sierpowska-Bartosik & Torres 2007, ApJ, 671, L145]



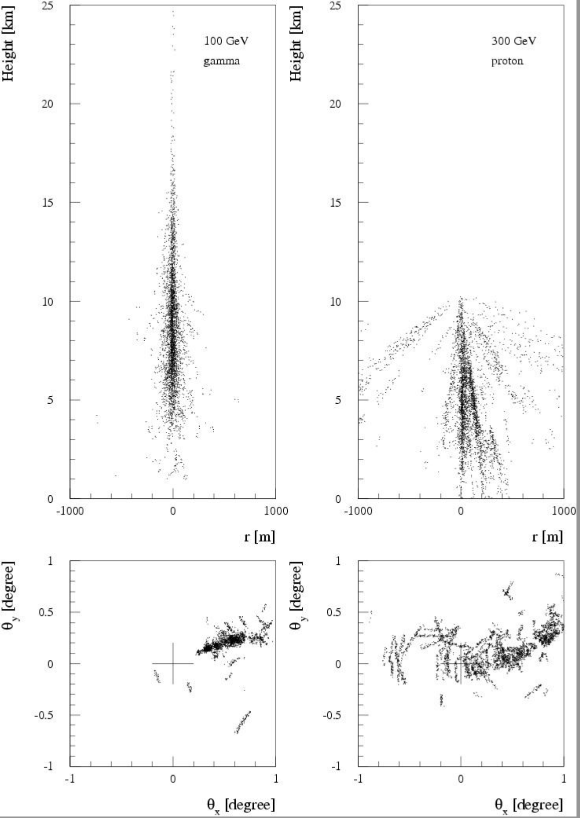
What has Fermi found: The LAT two-year catalog

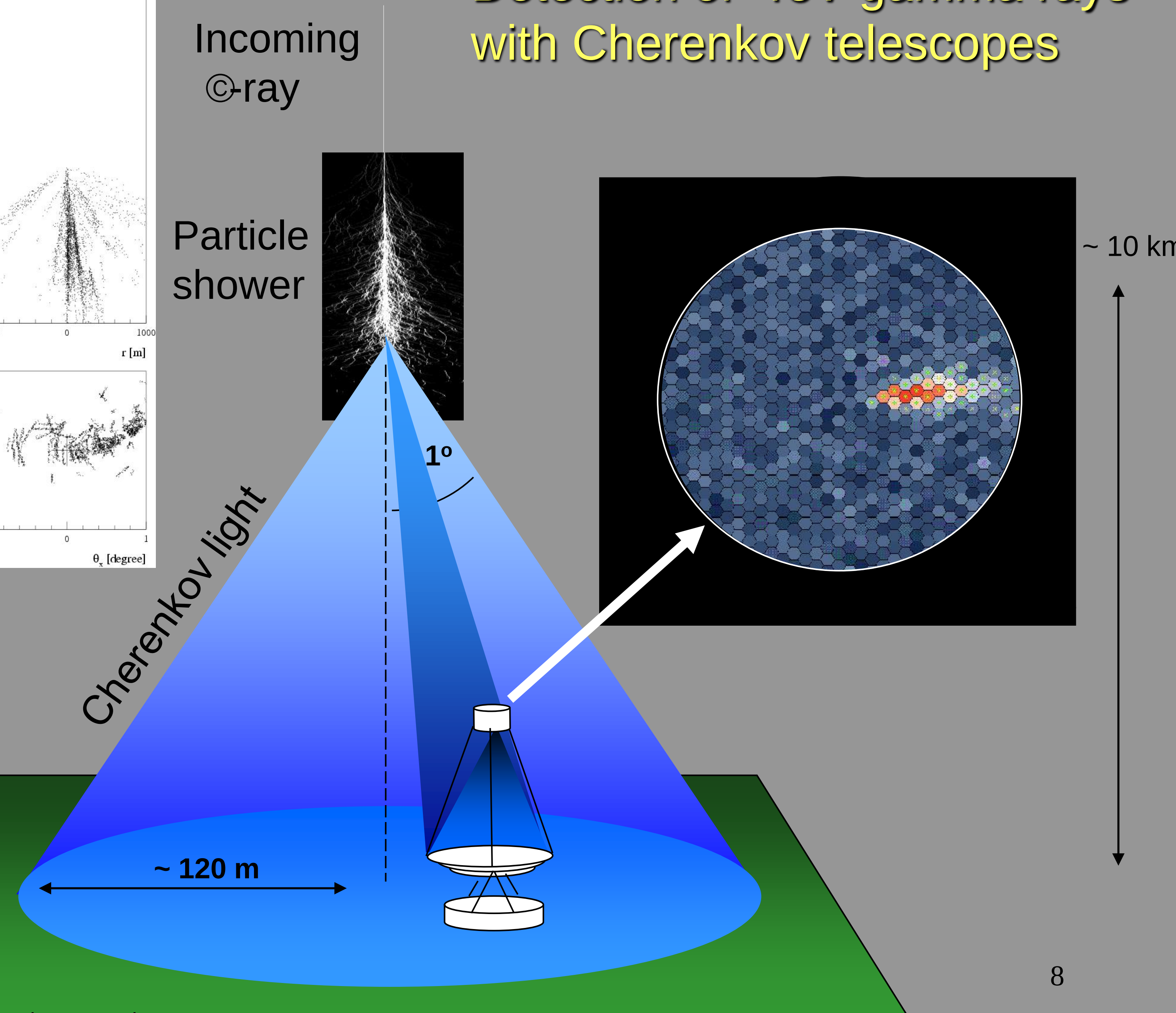




Credit: NASA/Goddard Space Flight Center

Detection of TeV gamma rays with Cherenkov telescopes





VHE - ground instruments

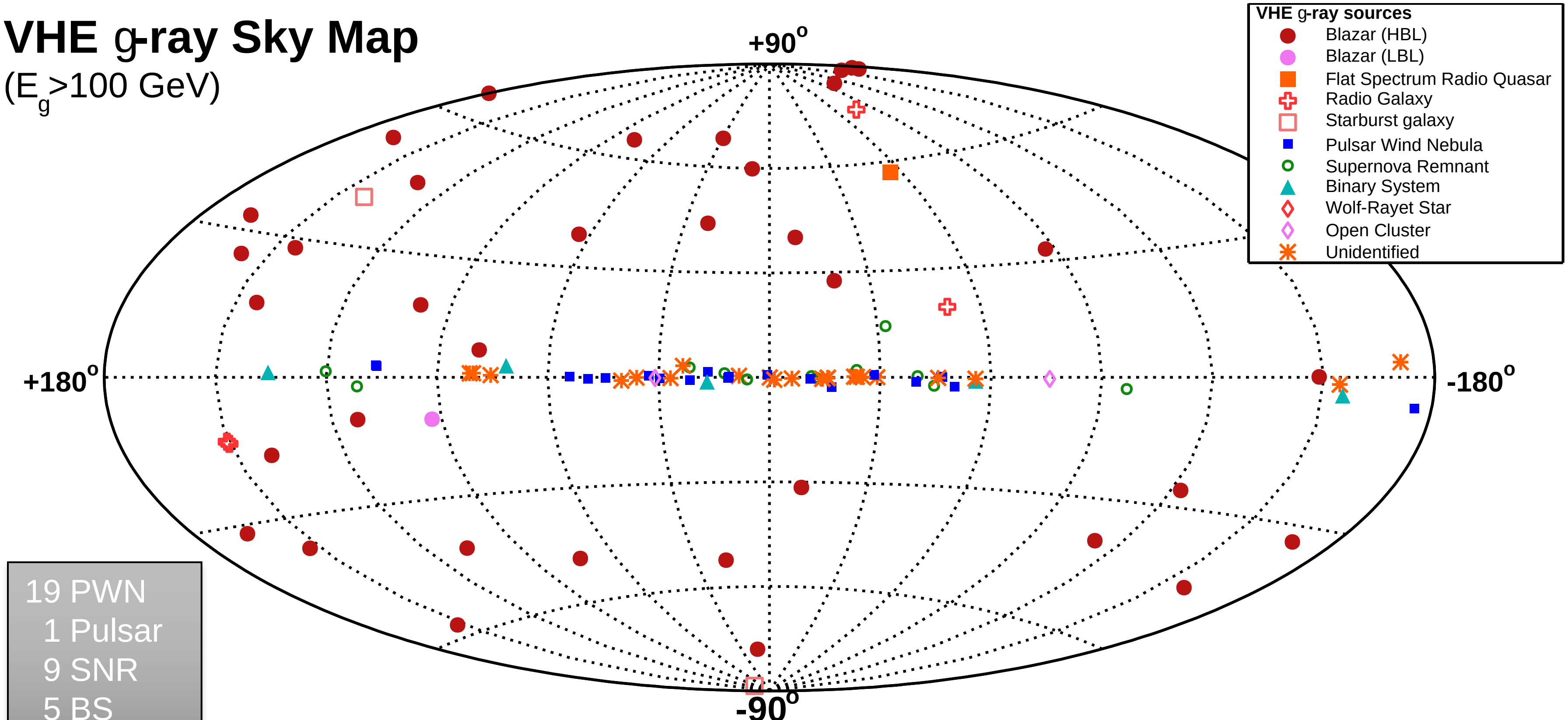
The gamma-ray sky

46 extragalactic

61 galactic

VHE γ-ray Sky Map

(E_γ>100 GeV)



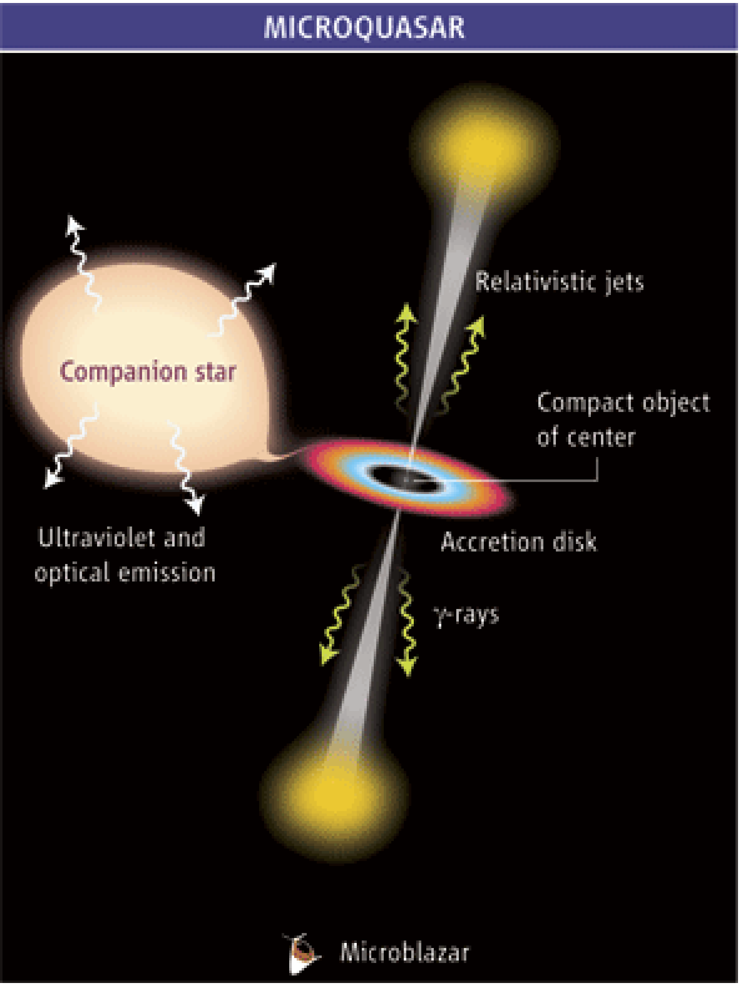
2011-01-08 - Up-to-date plot available at http://www.mpp.mpg.de/~rwagner/sources/

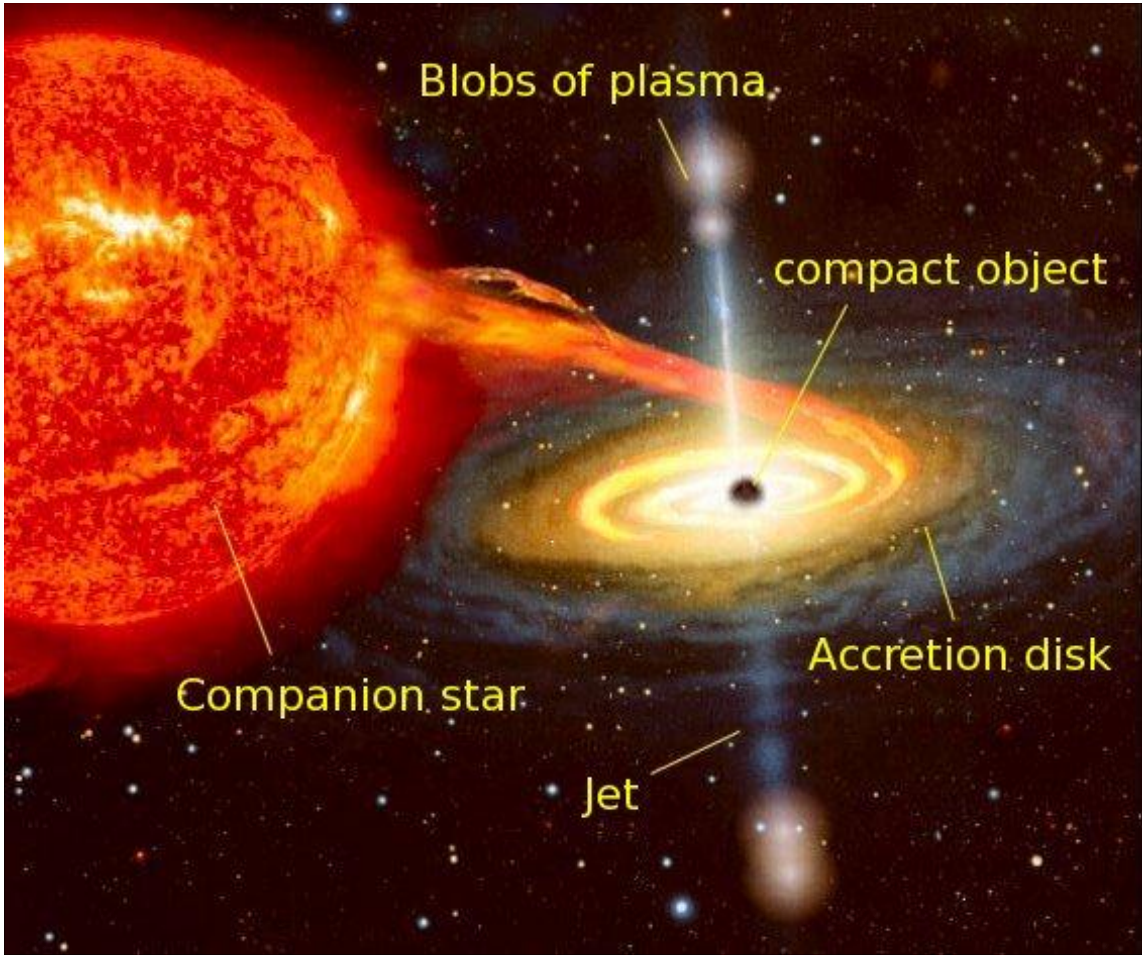
19 PWN
1 Pulsar
9 SNR
5 BS
1 WR
1 OC
GC
24 UNID

http://www.mppmu.mpg.de/~rwagner/sources/
(see also http://tevcat.uchicago.edu/)

Source	System Type	Orbital Period (d)	Radio Structure (AU)	Radio	X-ray	GeV	TeV
PSR B1259-63	O9.5Ve + NS	1237	Cometary tail ~ 120	P	P	T	P
LS I +61 303	B0Ve + ?	26.5	Cometary tail? 10 – 700	P	P	P	P
LS 5039	O6.5V((f)) +?	3.9	Cometary tail? 10 – 1000	persistent	P	P	P
HESS J0632+057	B0Vpe + ?	321	Elongated (few data) ~ 60	V	P	?	P ?
1FGL J1018.6-5856	O6.5V((f)) +?	16.6	?	P	P	P	?
Cygnus X-1	O9.7I + BH	5.6	Jet 40 + ring	persistent	P	T ?	T?
Cygnus X-3	WR + BH?	4.8h	Jet	Persistent & burst	P	P	?

Microquasars





At least 20 microquasars

Maybe the majority of RXBs are MQs
(Fender 2001)

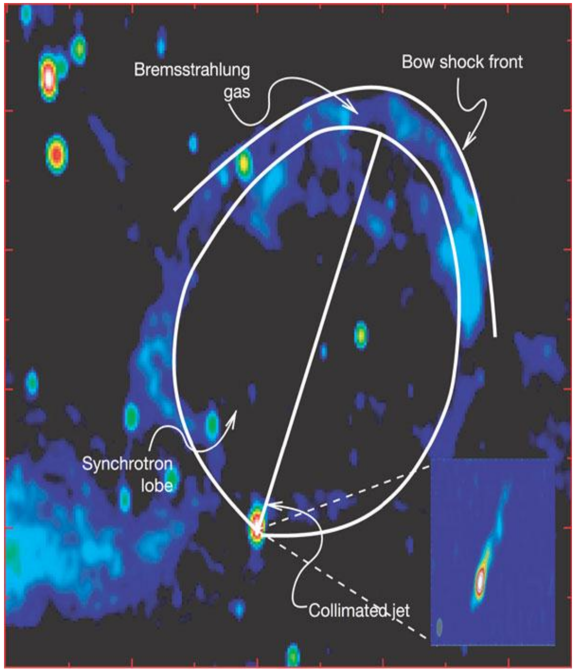
Cygnus X-1

- HMXB, O9.7I+BH

Stellar Mass Black Hole

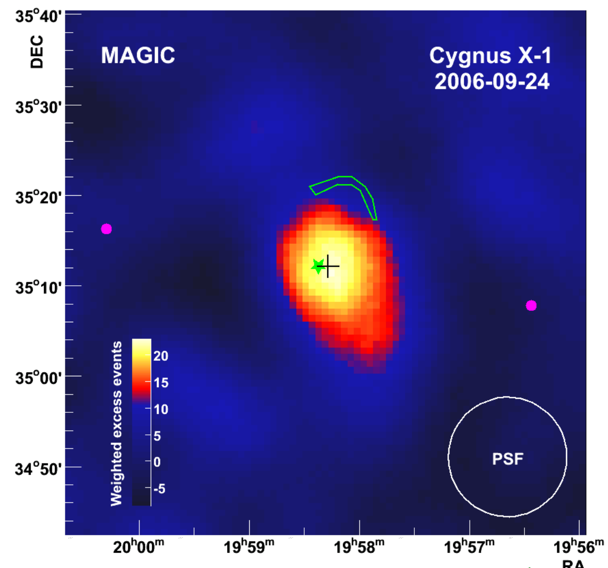
Detection (?) of VHE Gamma-rays

WSRT

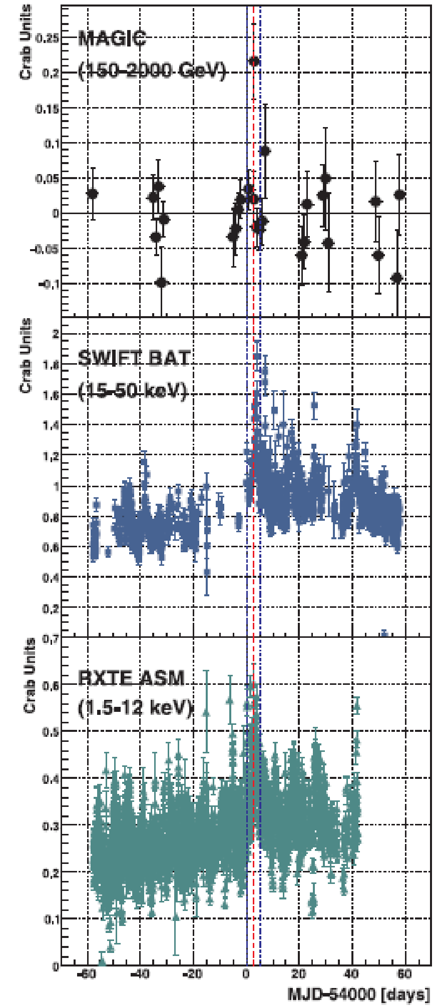


Gallo et al. 2005, Nature 436, 819

5 pc (8') diameter ring-structure of bremsstrahlung emitting ionized gas at the shock between (dark) jet and ISM



Albert et al. 2007, ApJ 665, L51



- Strong evidence of intense short-lived flaring episode
- Orbital phase 0.9 -1.0, when the BH is behind the star and photon-photon absorption should be huge: flare in the jet?

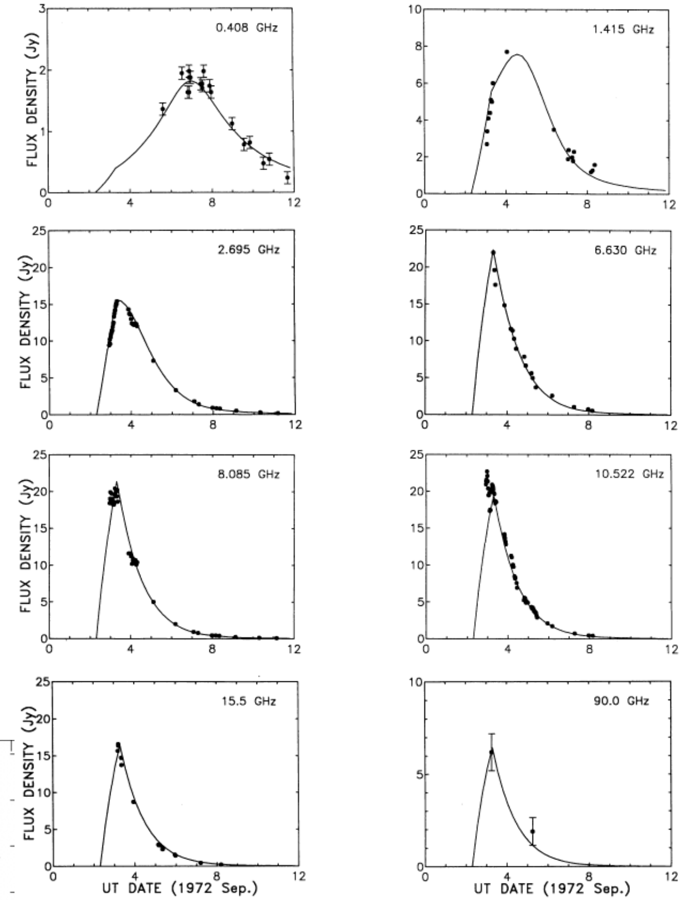
- A jet-cloud interaction?. Protons in the jet interact with ions in a cloud of a clumpy wind from the companion, producing inelastic p-p collisions and pion decay which produces a flare in TeV gamma rays (Araudo et al. 2009, A&A 503, 673)

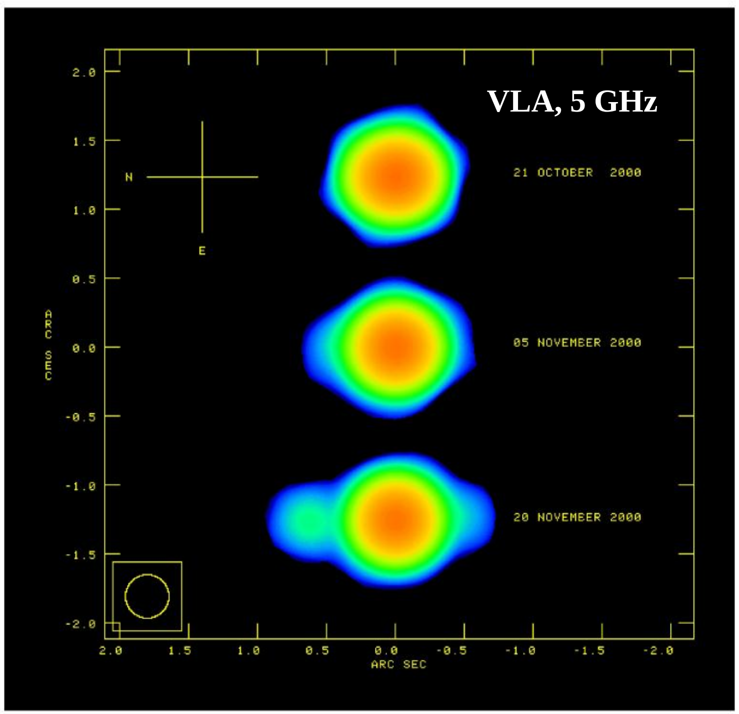
- Detected (>100 MeV) by *AGILE* (Sabatini et al. 2010, ApJ 712, 10; ATel ♯2715)
  but not by *Fermi*/LAT (Abdo et al. 2010, ATels and *Fermi*/LAT blog)

Cygnus X-3

Strong radio outbursts

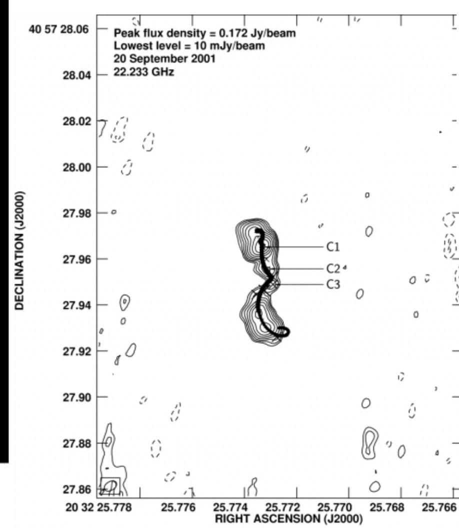
- HMXB, WR+BH?
- Exhibits flaring to levels of 20 Jy or more
- Modelling Cyg X-3 radio outbursts: particle injection into twin jets   Martí et al. 1992, A&A 258, 309

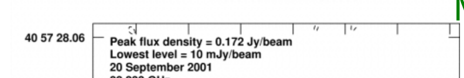




Development of arcsecond radio jets in CYGNUS X-3

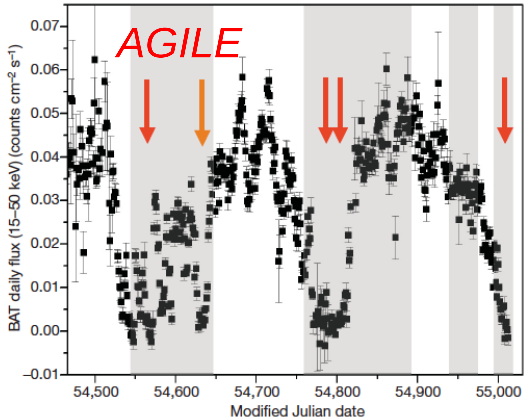
Martí et al. 2001, A&A 375, 476





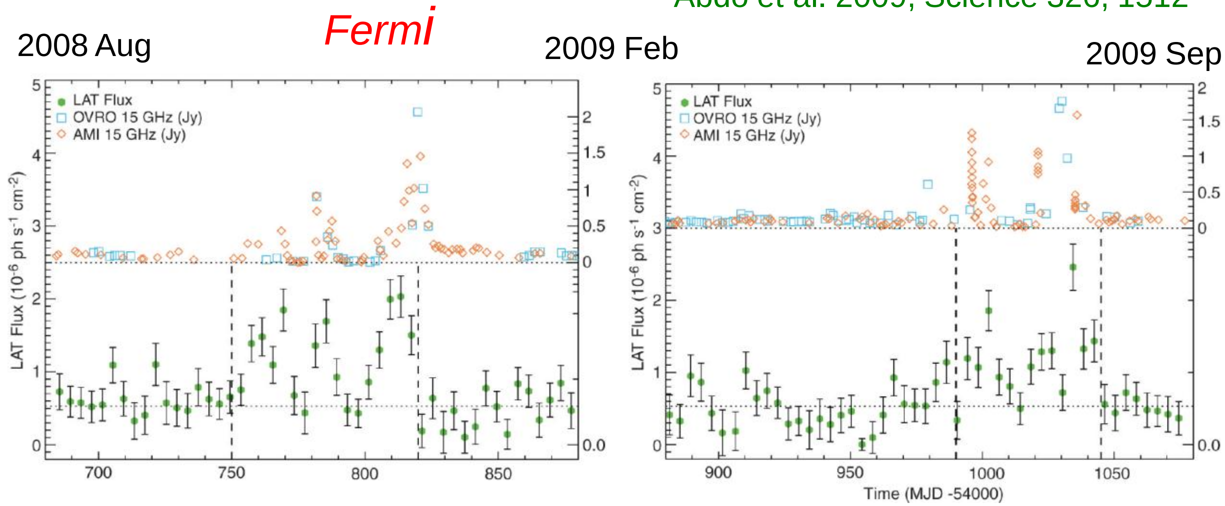
Miller-Jones et al. 2004, ApJ 600, 368

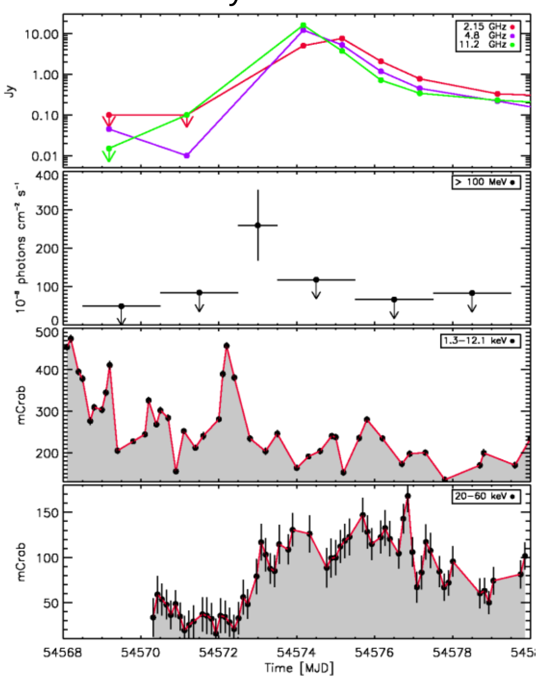
Cygnus X-3 Detection of HE Gamma-rays



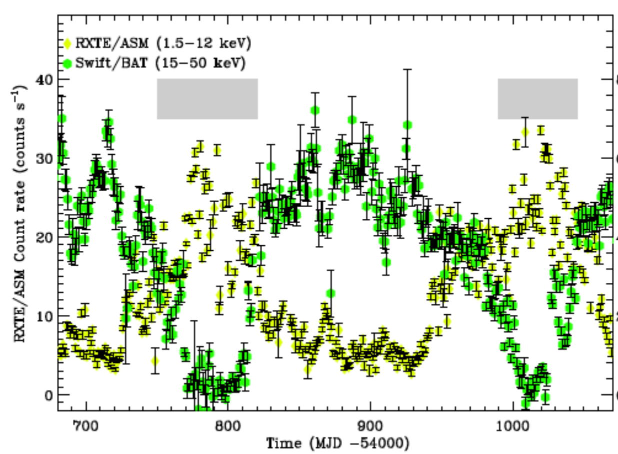
Gamma-ray flares occur only during soft X-ray states or their transitions to or from quenched hard X-ray states

Abdo et al. 2009, Science 326, 1512

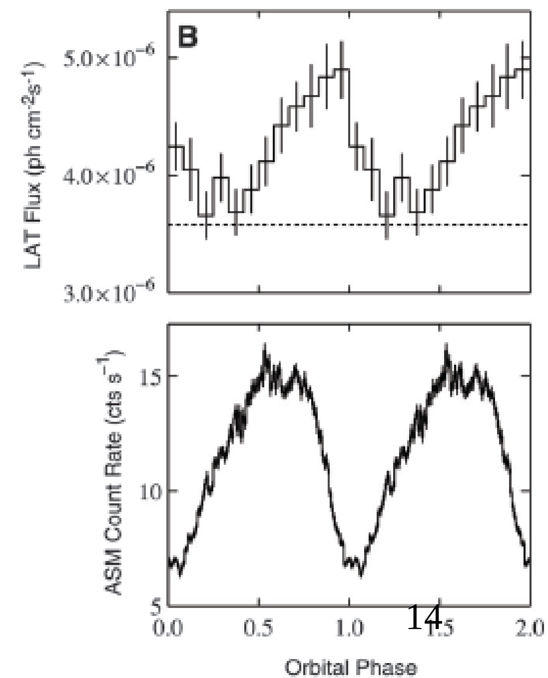




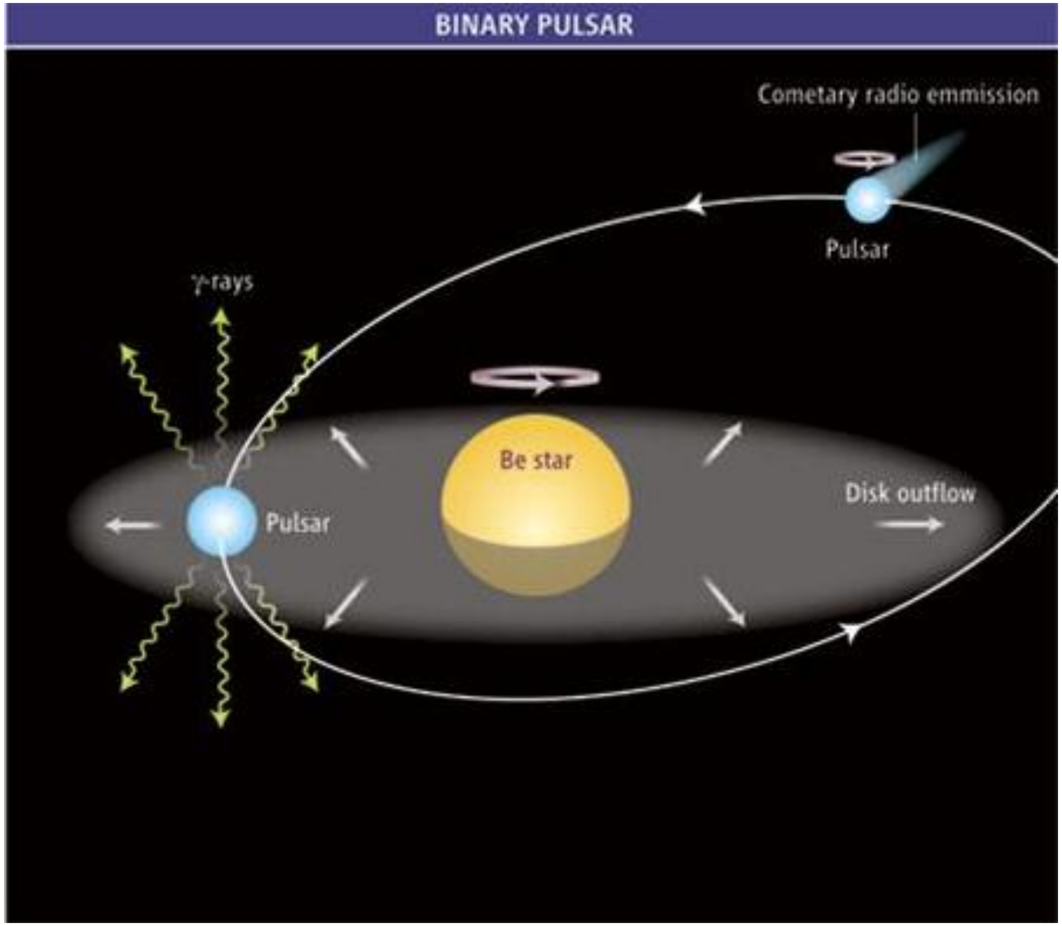
Tavani et al. 2009, Nature 462, 620



Active gamma periods in the soft X-ray states

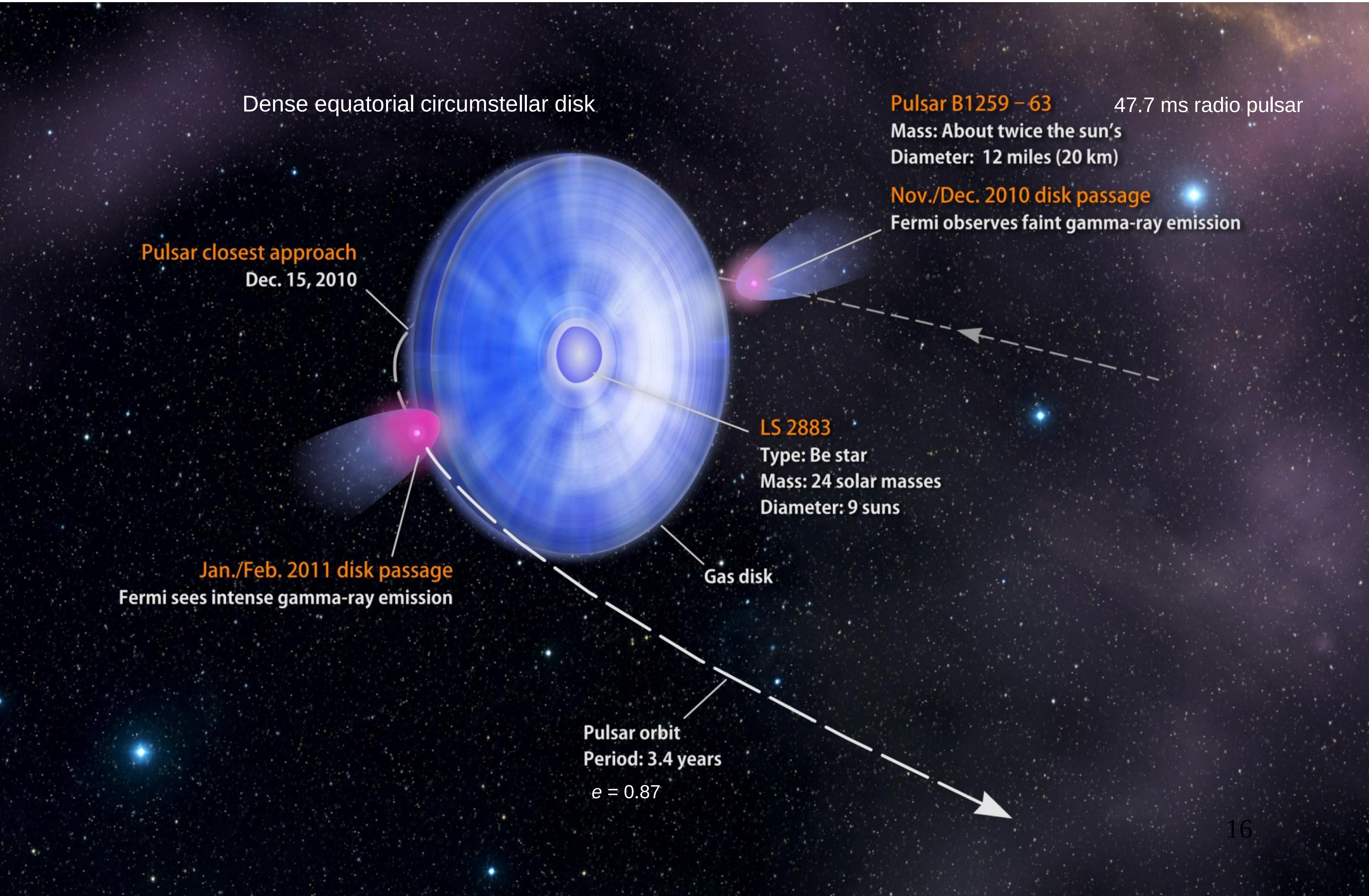


Binary pulsar systems



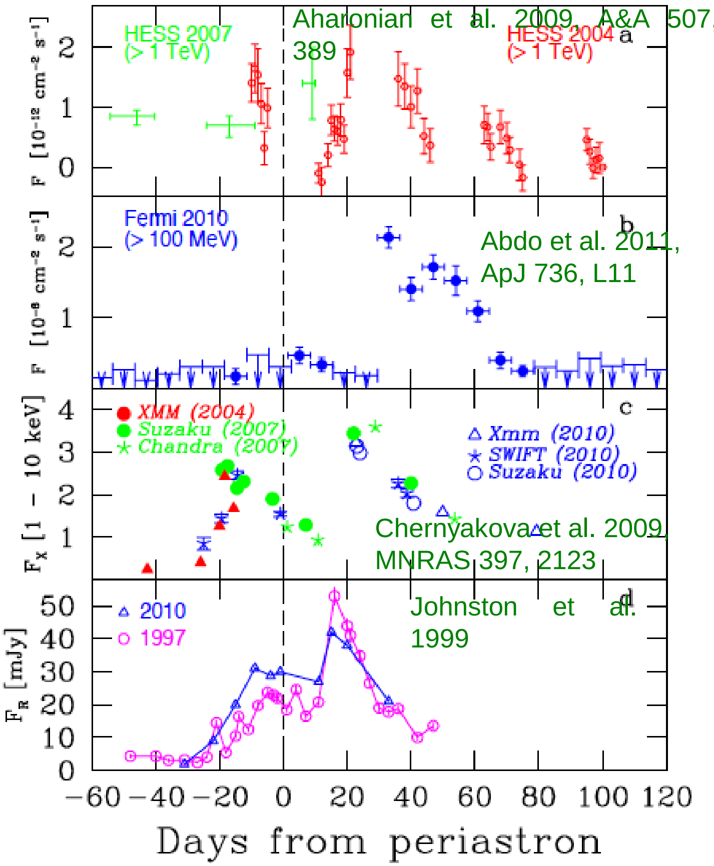
PSR B1259-63 *Young pulsar wind interacting with the companion star*

The first variable galactic source of VHE

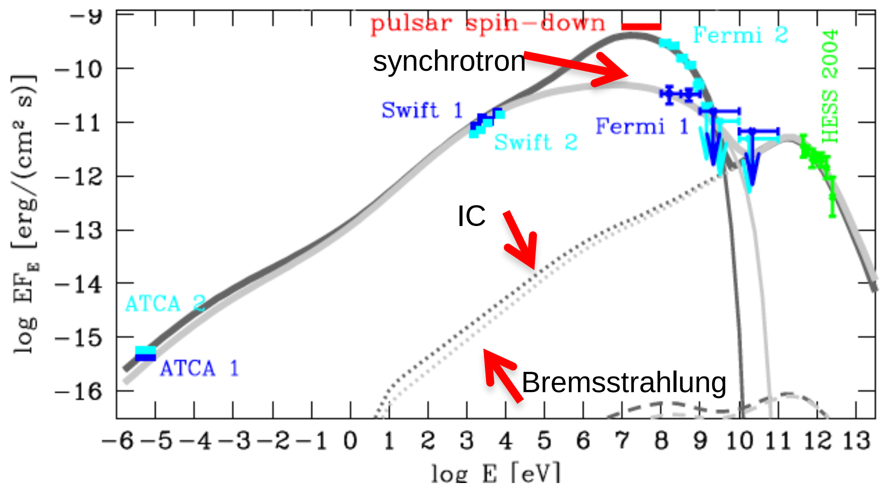


PSR B1259-63 / LS 2883: O8.5-9 Ve (Negueruela et al. 2011, ApJL, 732, L11)

- ✧ Orbital plane of the pulsar inclined with respect to the disk (Melatos et al. 1995, MNRAS 275, 381; Chernyakova et al. 2006, MNRAS 367, 1201)
- ✧ Tavani & Arons 1997, ApJ 477, 439 studied the radiation mechanisms and interaction geometry in a pulsar/Be star system
- ✧ The observed **X-ray/soft gamma-ray** emission was consistent with the shock-powered high-energy emission produced by the pulsar/outflow interaction



PSR B1259 / LS 2883

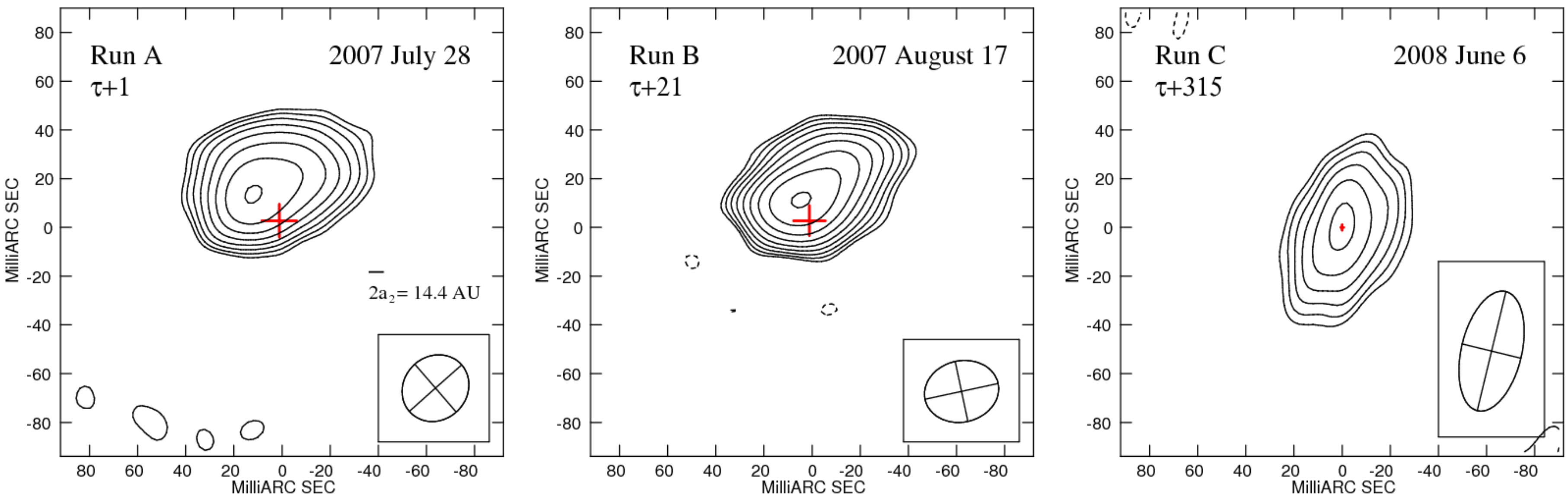


PSR B1259-63. Nearly all the spin-down power is released in HE gamma rays (Abdo et al. 2011). Doppler boosting suggested (Tam et al. 2011), but very fine tuning is needed(!).

Australian Long Baseline Array (LBA)
2.3 GHz

Extended radio structure

Moldón et al. 2011, ApJ 732, L10



Total extension of the nebula: ~ 50 mas, or 120 ± 24 AU

The red crosses marks the region where the pulsar should be contained in each run

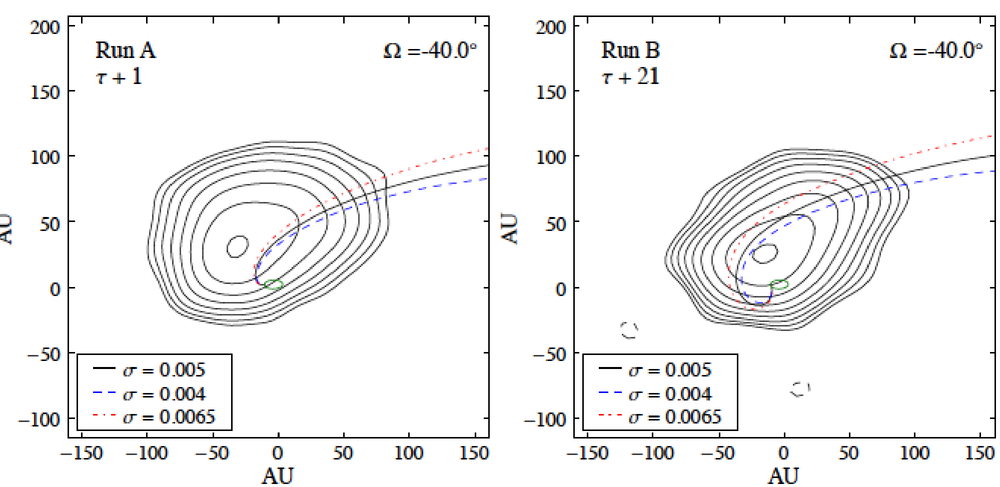
Kinematical model Moldón et al. 2011, ApJ 732, L10

This is the first observational evide[...]
stars can produce variable extende[...]

Shock between the relativistic pulsar wind and a spherical stellar wind (Dubus 2006, A&A 456, 801)

Run				
A	19.9±1.4	10.4±0.2	50	120±
B	46.7±1.0	32.7±0.4	55	132±
C	3.0±0.4	2.8±0.4	<2.8	<6.7±

The evolution of the nebular flow after the shock is described in Kennel & Coroniti (1984)



PSR B1259 / LS 2883

Unclassified sources:

Microquasar or pulsar scenario ?

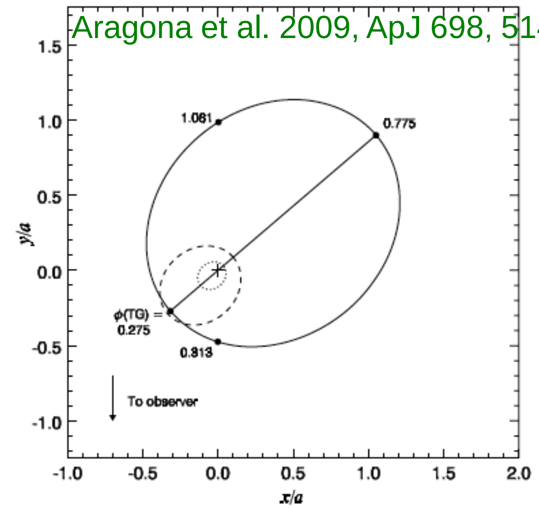
LS I +61 303

- HMXB, B0Ve+**NS?**

COS-B γ-ray source CG/2CG 135+01

Hermsen et al. 1977, Nature 269, 494

Aragona et al. 2009, ApJ 698, 514

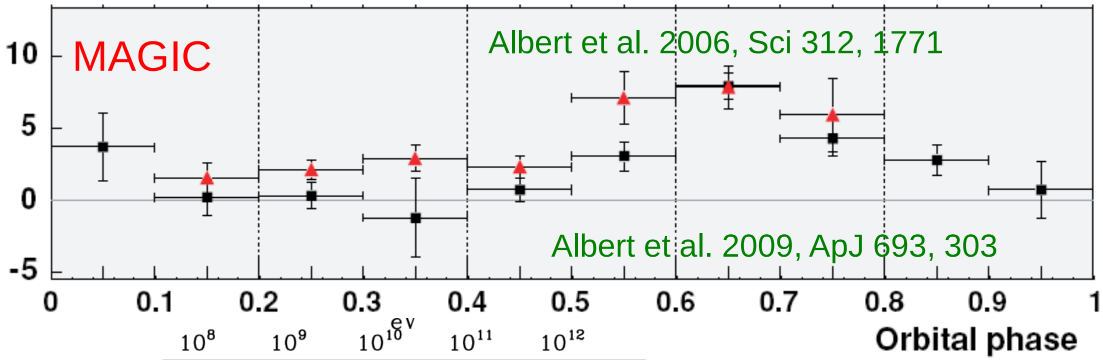


periodicity

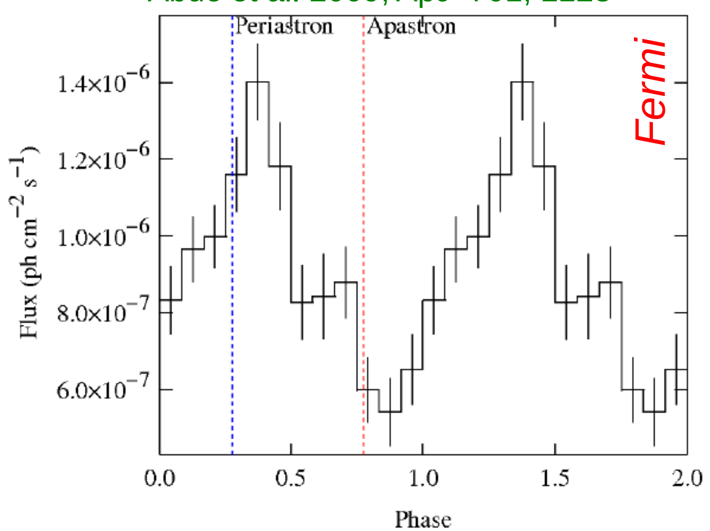
Radio (P=26.496 d) Taylor & Gregory 1982, ApJ 255, 210

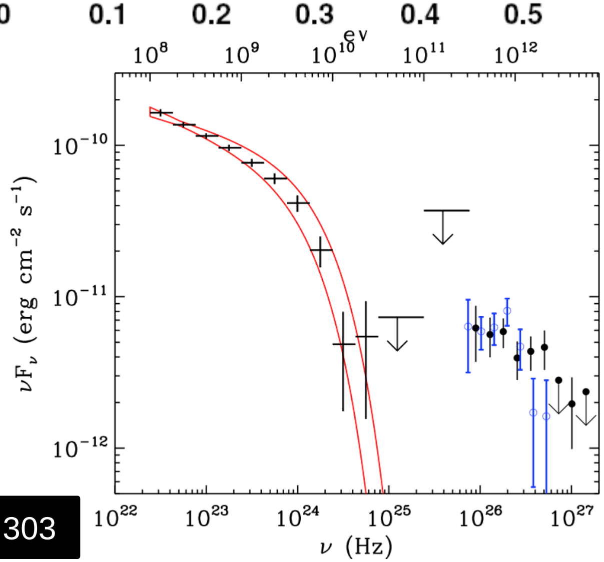
Optical and IR Mendelson & Mazeh 1989, MNRAS 239, 733; Paredes et al. 1994 A&A 288, 519

X-rays Paredes et al. 1997 A&A 320, L25; Torres et al. 2010, ApJ 719, L104



Abdo et al. 2009, ApJ 701, L123





Fermi

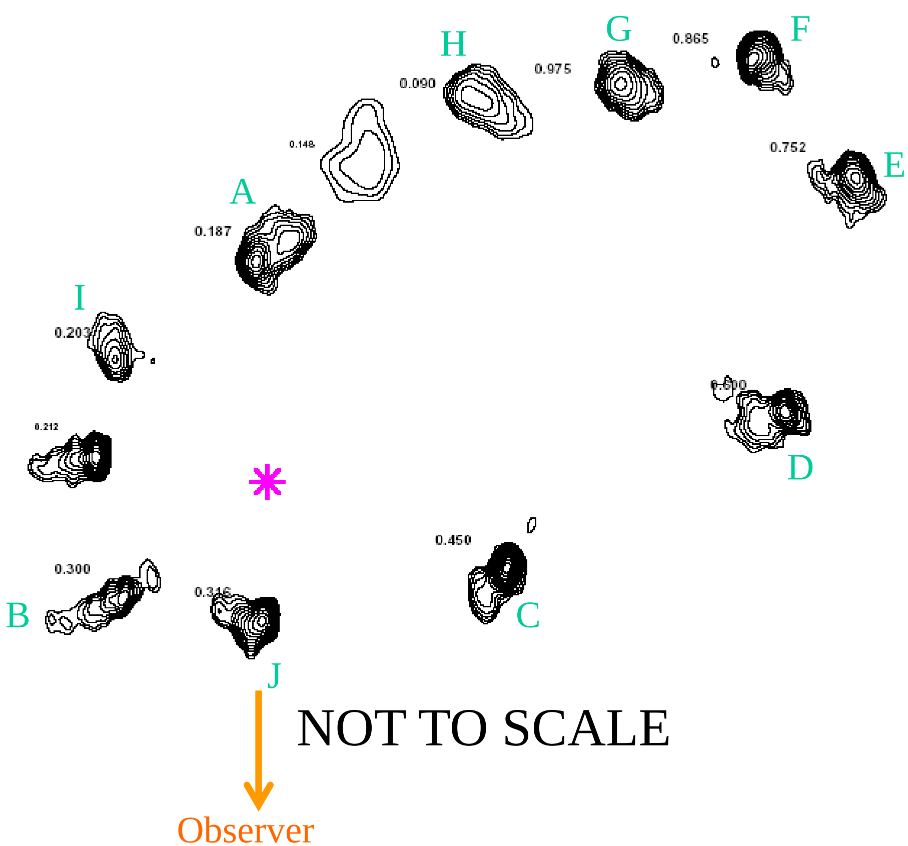
MAGIC blue, 0.5-0.7

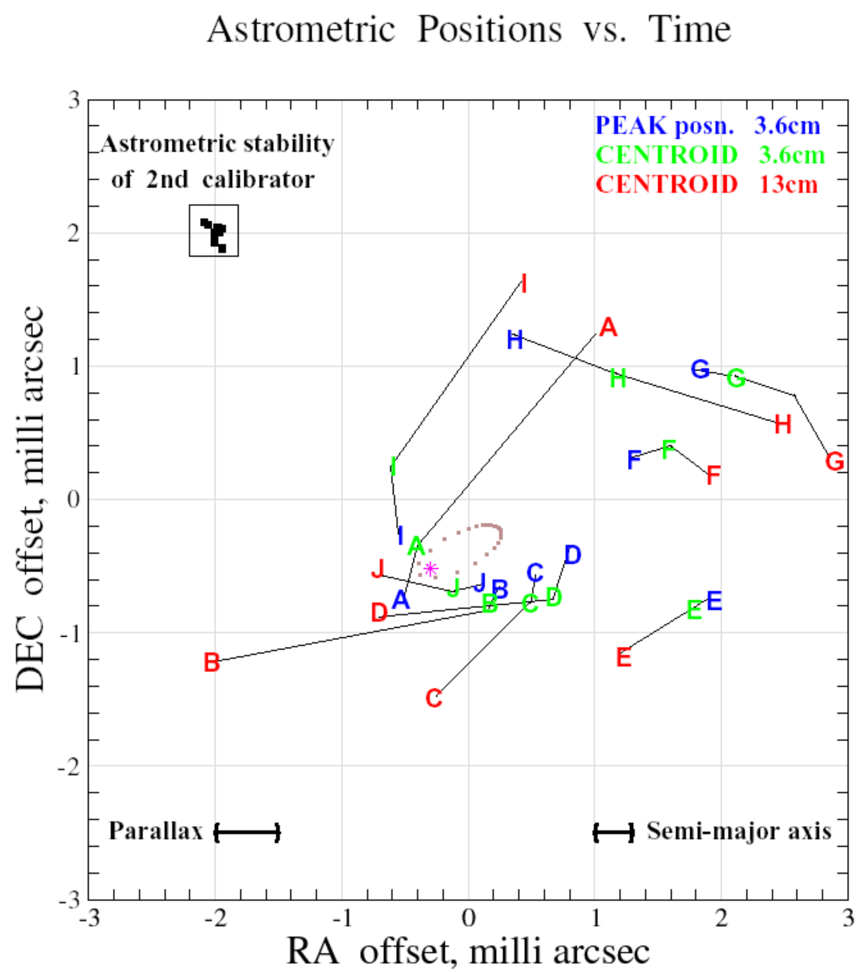
VERITAS black, 0.5-0.8

Link between HE and VHE γ-rays is nontrivial

VLBA

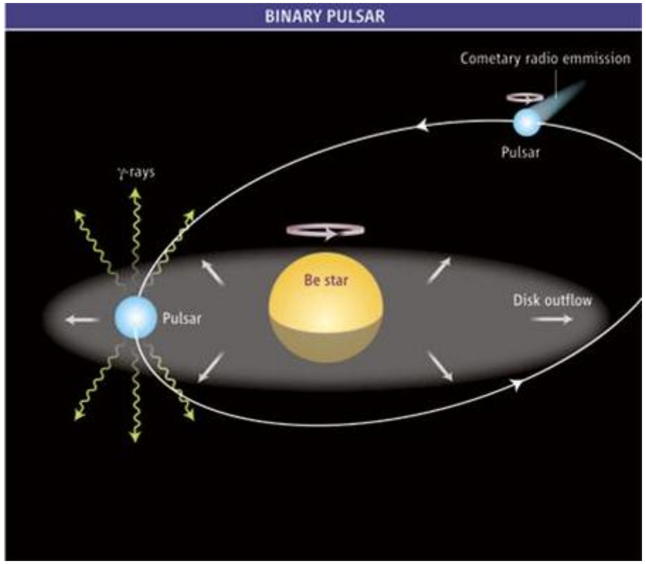
Jet-like features have been reported several times, but show a puzzling behavior (Massi et al. 2001, 2004). VLBI observations show a rotating jet-like structure (Dhawan et al. 2006, VI Microquasars Workshop, Como, Setember 2006)





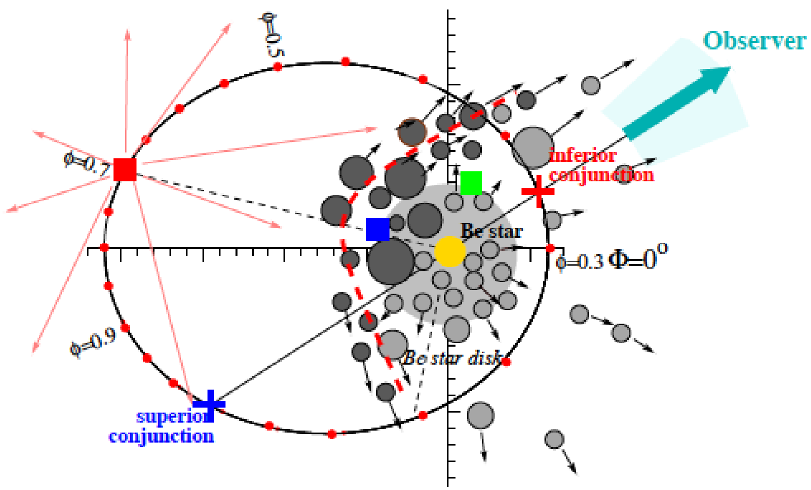
3.6cm images, ~3d apart, beam 1.5x1.1mas or 3x2.2 AU.
Semi-major axis: 0.5 AU

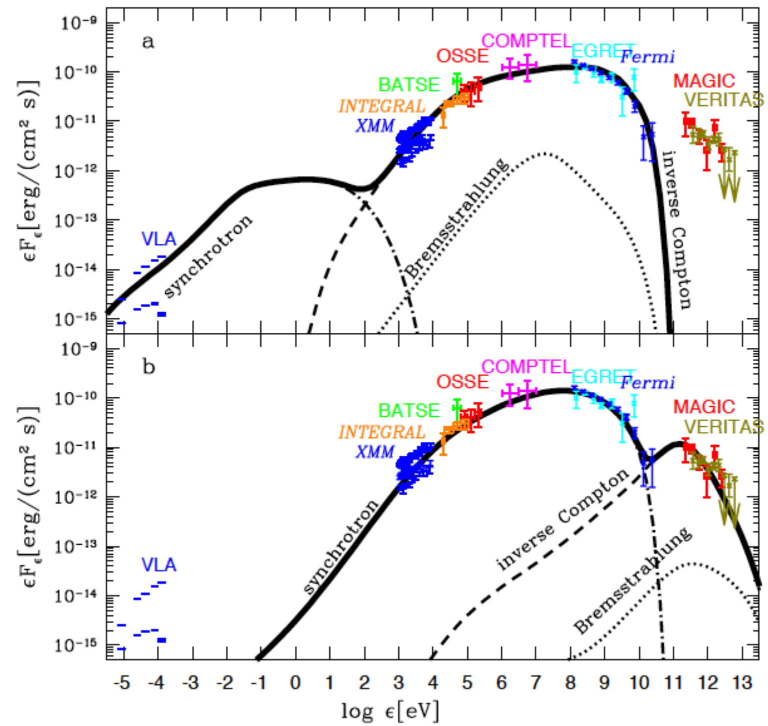
LS I + 61 303



Pulsar scenario: Interaction of the relativistic wind from a young pulsar with the wind from its stellar companion. A comet-shape tail of radio emitting particles is formed rotating with the orbital period. We see this nebula projected (Dubus 2006, A&A 456, 801). UV photons from the companion star suffer IC scattering by the same population of non-thermal particles, leading to emission in the GeV-TeV energy range

Zdziarski et al. 2010, MNRAS 403, 1873





Not resolved yet the issue of the momentum flux of the pulsar wind being significantly higher than that of the Be wind, which presents a problem for interpretation of the observed radio structures (as pointed out by Romero et al 2007, A&A 474, 15)

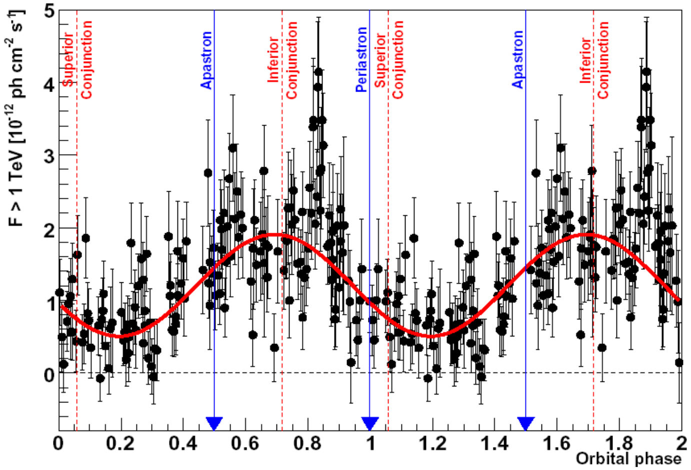
LS I + 61 303

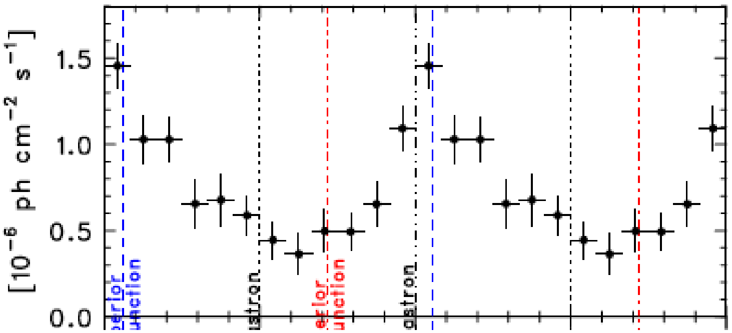
LS 5039

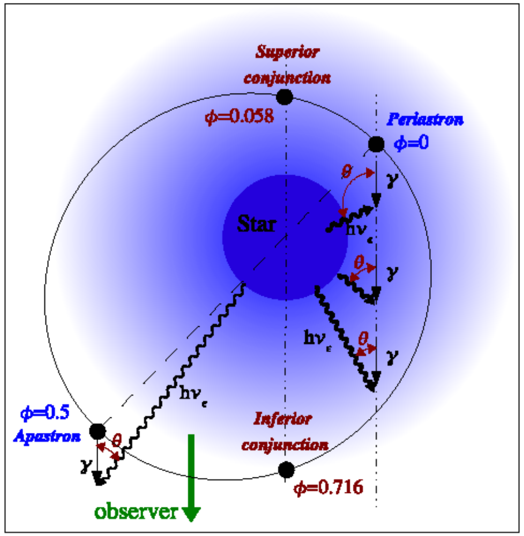
- HMXB, O6.5V+NS?

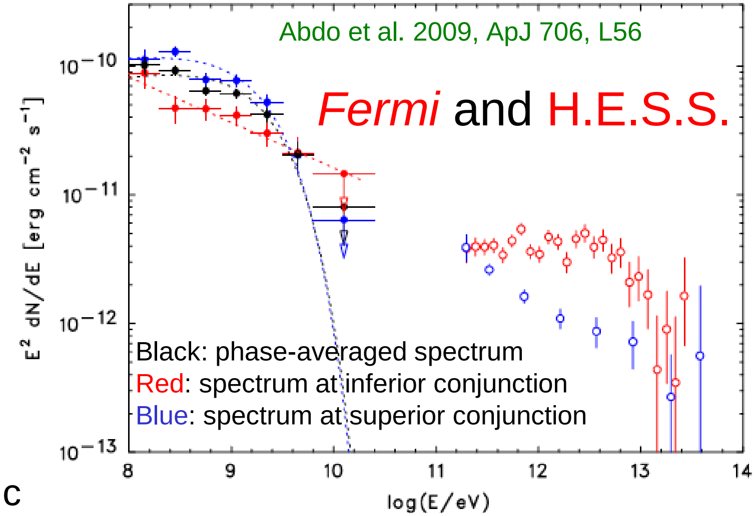
H.E.S.S.

Aharonian et al. 2006, A&A 460, 743









- IC scattering will vary with radiation density

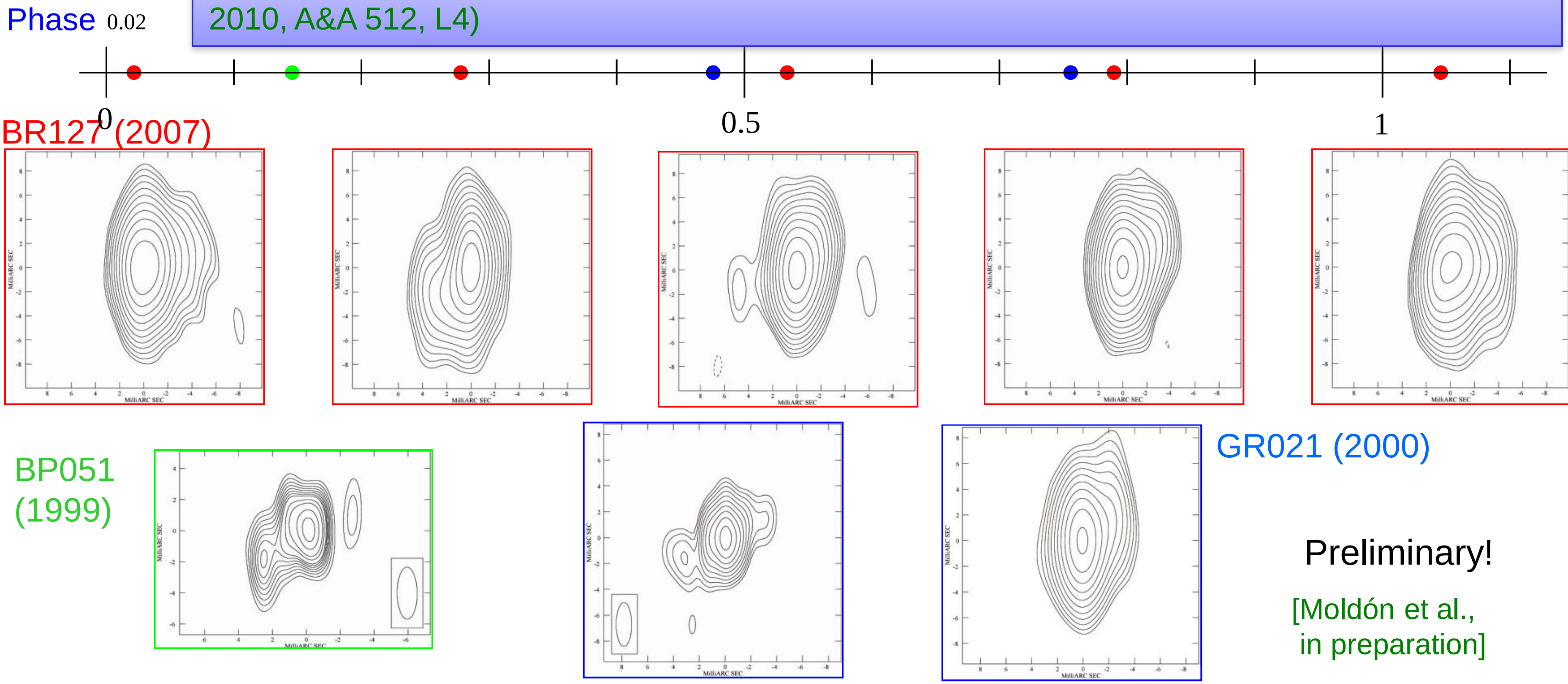
- The flux will also depend on the geometry seen by the observer because the source of seed photons is anisotropic (Khangulyan et al. 2008; Sierpowska-Bartosik&Torres 2008b)

- The emission is enhanced (reduced) when the highly relativistic e$^-$ seen by the observer encounter the seed photons head-on (rear-on), i.e., at superior (inferior) conjunction

- VHE absorption due to pair production will be maximum (minimum) at superior (inferior) conjunction

Radio

VLBA observations during a whole orbital cycle suggest that LS 5039 is a young non-accreting pulsar (Ribó et al. 2008; Moldón et al., in prep.) (see however Perucho et al. 2010, A&A 512, L4)



✧Yet unclear where the IC VHE emission is mainly produced (pulsar wind zone, wind collision region, beyond the system…?)

✧The γ-ray data require a location of the production region at the periphery of the binary system at ~10^{12} cm (Khangulyan et al. 2008, MNRAS 383, 467; Bosch-Ramon et al. 2008, A&A 489, L21)

✧SPH modeling reveals difficulties for the pulsar wind scenario to confine the particles in LS 5039 (Romero et al. 2010)

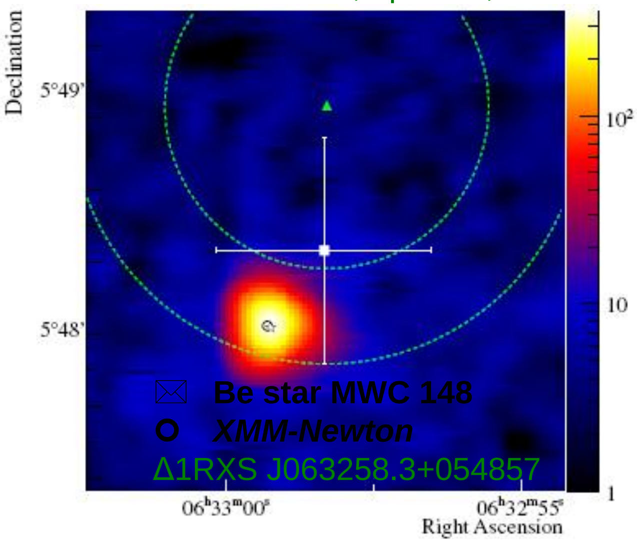
✧In gamma-ray binaries in general, the pairs created due to photon-photon interactions can contribute significantly to the core, and generate an extended structure (Bosch-Ramon & Khangulyan 2011, PASJ 63, 1023)

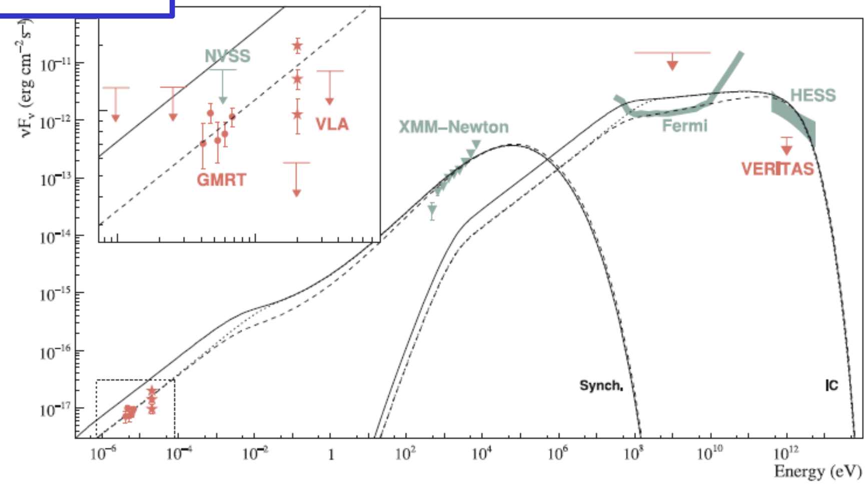
New cases

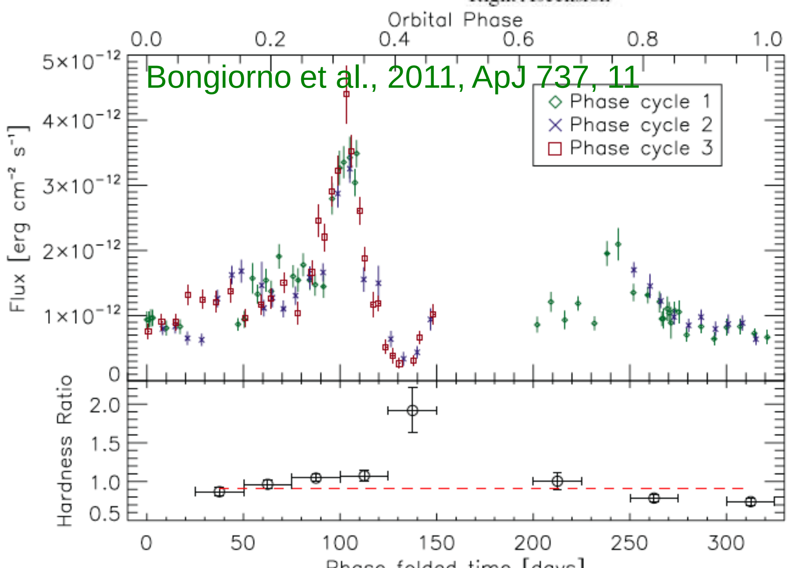
HESS J0632+057

Skilton et al. 2009, MNRAS 399, 317

Hinton et al. 2009, ApJ 690, L101







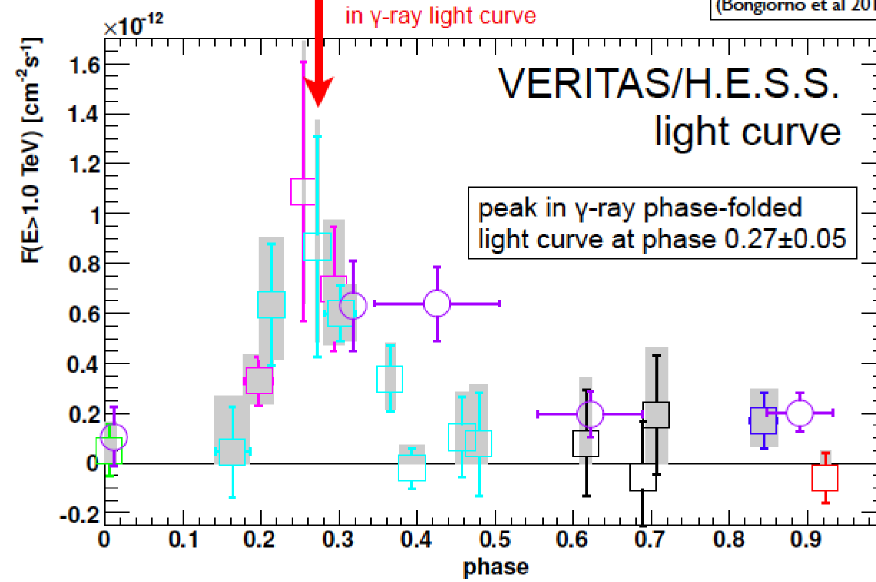
Swift X-ray periodicity: P=321 ± 5 days

→ strong evidence for binary nature

Maier and Skilton, 2011, 32nd ICRC2011

Phase folding values:
MJD$_0$ = 54857; Phase: 321 days
(Bongiorno et al 2011)

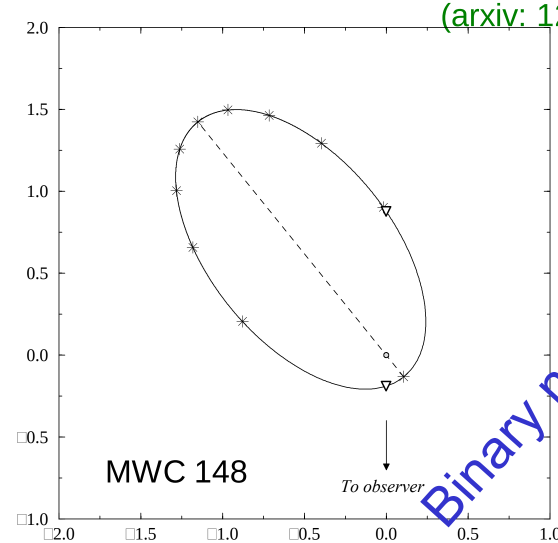
Position of maximum
in γ-ray light curve



Dates of VERITAS observations:
Dec 16 2006 - Jan 25 2007
Dec 30 2008 - Jan 03 2009
Jan 26 2009 - Jan 30 2009
Oct 18 2010 - Oct 30 2010
Feb 7 2010 - Mar 21 2010
Dec 14 2010 - April 5 2011

H.E.S.S. observations:
(2004-2010)

Casares et al., 2011, MNRAS (arxiv: 1201.1726)



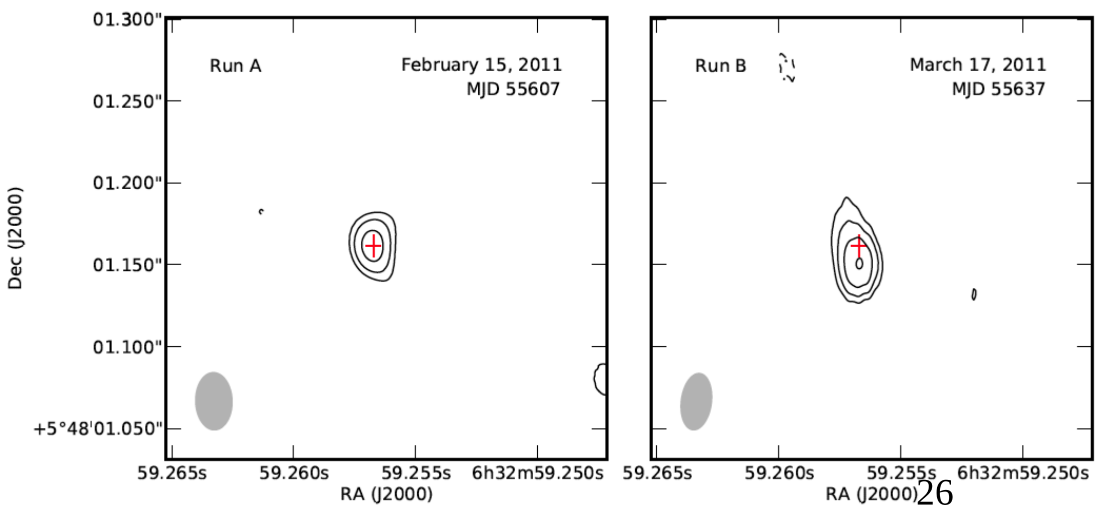
In Feb. 2011 *Swift* reported increased X-ray activity (Falcone et al. 2011, Atel # 3152)

VERITAS and MAGIC detected elevated TeV gamma-ray emission (Ong et al. 2011, Atel # 3153; Mariotti et al. 2011, Atel # 3161)

VLBI counterpart

(Moldón et al. 2011, Atel # 3180)

- Confirmed association with Be star
- Confirmed the non-thermal nature of the radio source
- Discovery of extended emission



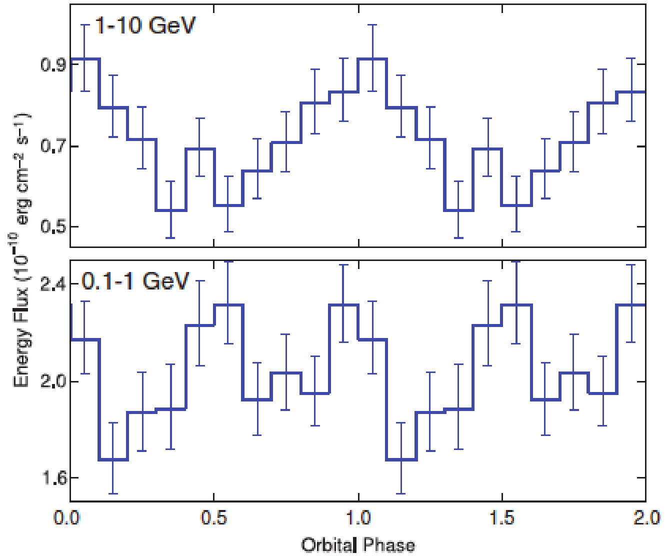
Moldón et al. 2011, A&A 533, L7

HESS J0632+057

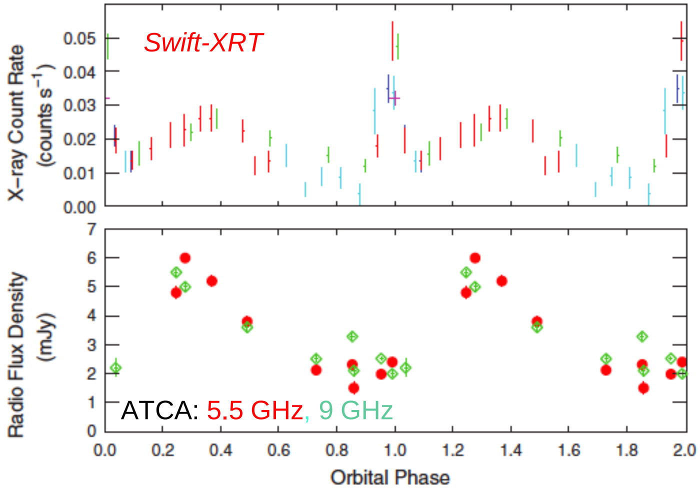
1FGL J1018.6-5856

Ackermann et al. 2012, Fermi Col., Science 335, 189

- 1FGL J1018.6-5856 is one of the brighter Fermi sources
- LAT spectrum similar to a pulsar - but no pulsations seen
- Optical counterpart ~O6V((f)), just like LS 5039



Flux modulated with a 16.6 d period



- X-ray flare-like behaviour near phase 0, coinciding with gamma-ray maximum
- An spatially coincident variable radio source
- **Radio structure ?**

Final remarks

Similarities expected in both scenarios

✧Radio-to-gamma-ray emission and radiation reprocessing (absorption of radio, X-rays and gamma-rays, IC cascades)

✧Periodic emission: environment changes, interaction geometry (IC, gamma gamma), distance between objects…

✧Extended non-thermal outflows (e.g radio, X-rays)

✧Outflow-medium interactions at small and large scales and related observational features (thermal, lines and non-thermal emission)

Differences	Favour **Pulsar**	Favour **MQ**	
No accretion X-rays (continuum or lines)	✔✔✔		BUT certain regimes of accretion and jet formation do not lead to strong thermal X-ray emission
γ-ray energy requirements	✔✔		BUT just slightly, since the large detected HE and VHE luminosities require very powerful pulsars
Variable radio morphology	✔		BUT stellar wind-jet interactions lead also to changing jet structures along the orbit, and γ-ray absorption and radio emission from the created pairs lead to similar changing morphological structures
No pulses observed		✔✔	BUT the stellar wind may absorb the radio pulsations, X-ray pulsations may be too weak, and γ-ray pulsations are difficult to be found in binaries due to timing confusion because of the orbital periodicity
γ-ray emitter location		✔	(not close to the compact object), BUT the pulsar scenario may accommodate such a requirement
No thermal stellar wind shock signatures		✔	BUT only applies to close systems with strong stellar winds
Sudden variability		✔	BUT the stellar wind could be structured which could induce variability in the γ-ray emission in the pulsar case

Summary

The MQs and Binary pulsar systems with HE and/or VHE gamma-ray emission

- Are (synchrotron) radio emitters
- Periodic at all wavelengths (?)
- Have a bright companion (O or B star) → source of seed photons for the IC emission
- Jet or Cometary-tail radio structures.
  - Non-accreting pulsars orbiting massive stars can produce variable extended radio emission at AU scales.
- Be circumstellar disk
  → target nuclei for hadronic interactions
  → and the pulsar wind play a role in the HE and VHE gamma-ray emission but the mechanisms are not well understood
- New microquasars can be detected while flaring
- VLBI radio observations are a common link, useful to understand the behavior of gamma-ray binaries. Can put constrains on physical parameters of the system.