Gamma-ray emission from stellar binary systems

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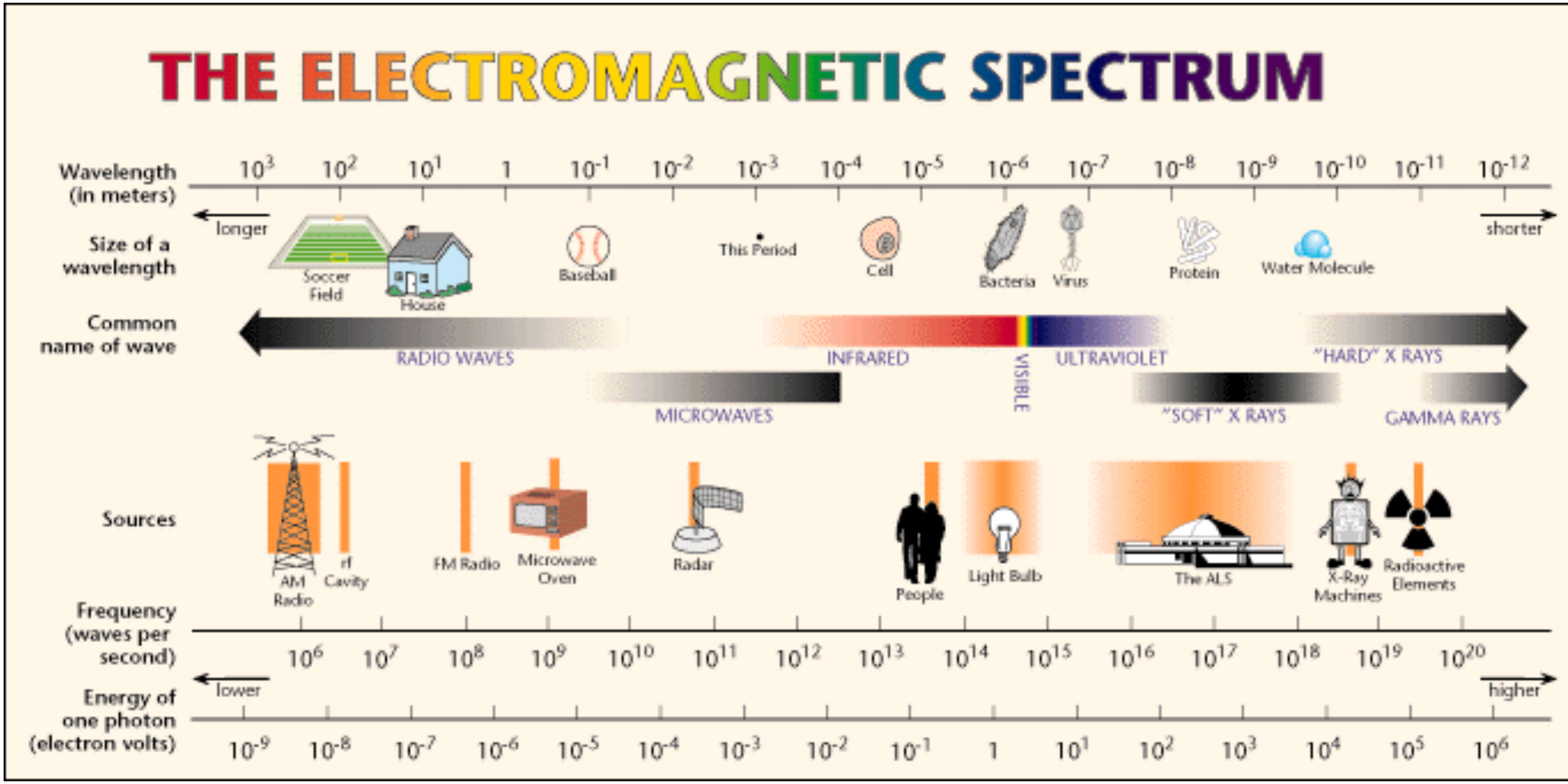
DUBLIN SUMMER SCHOOL ON HIGH ENERGY ASTROPHYSICS
University College Dublin (UCD). Dublin, Ireland, 4th - 15th July 2011

OUTLINE

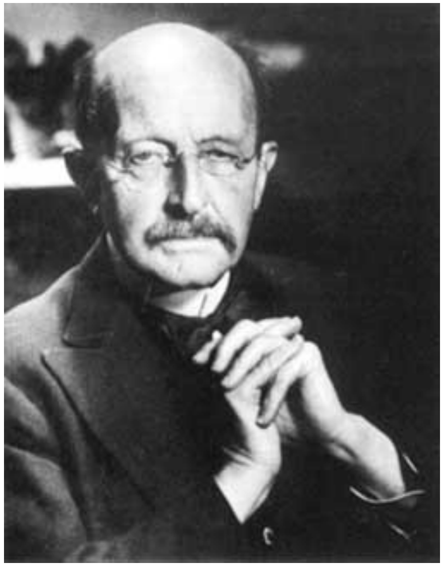
1. Introduction
2. Non-thermal emission processes
3. How to detect the HE and VHE γ–ray emission
4. The gamma-ray sky
5. X-ray binaries / Microquasars
6. Gamma-ray binaries
7. Colliding wind binaries (CWB)
8. Symbiotic binaries
9. Summary

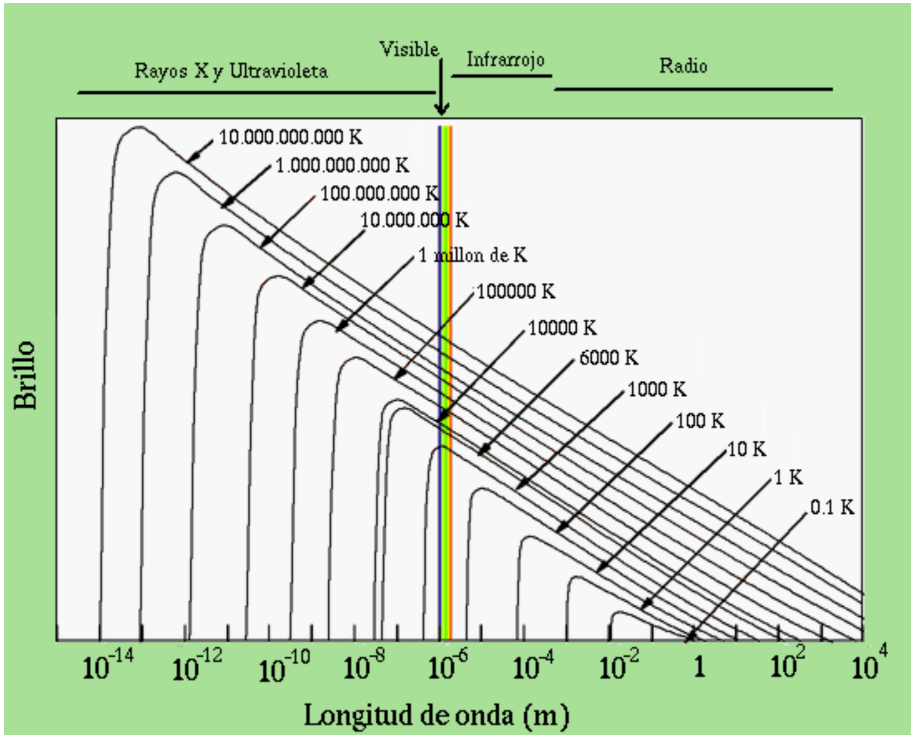
Introduction

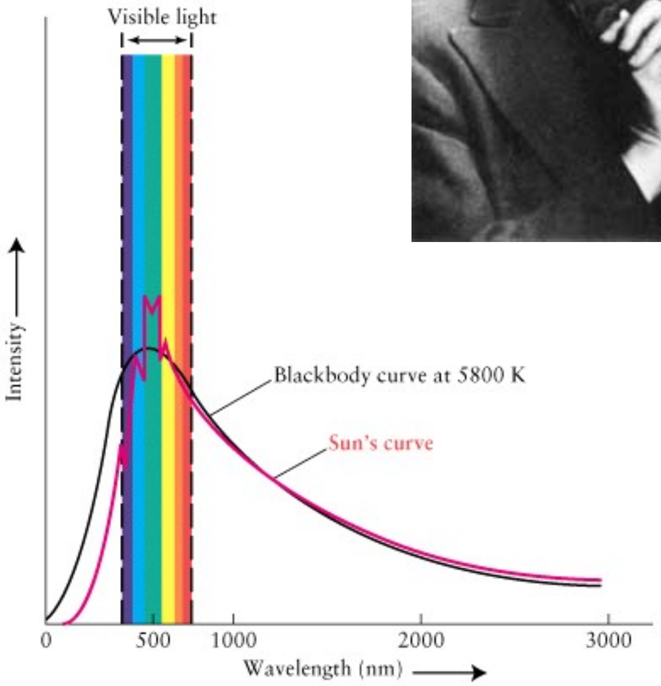


Max Planck

Radiation law for a Black Body (1900)
Physics Nobel Prize (1918)

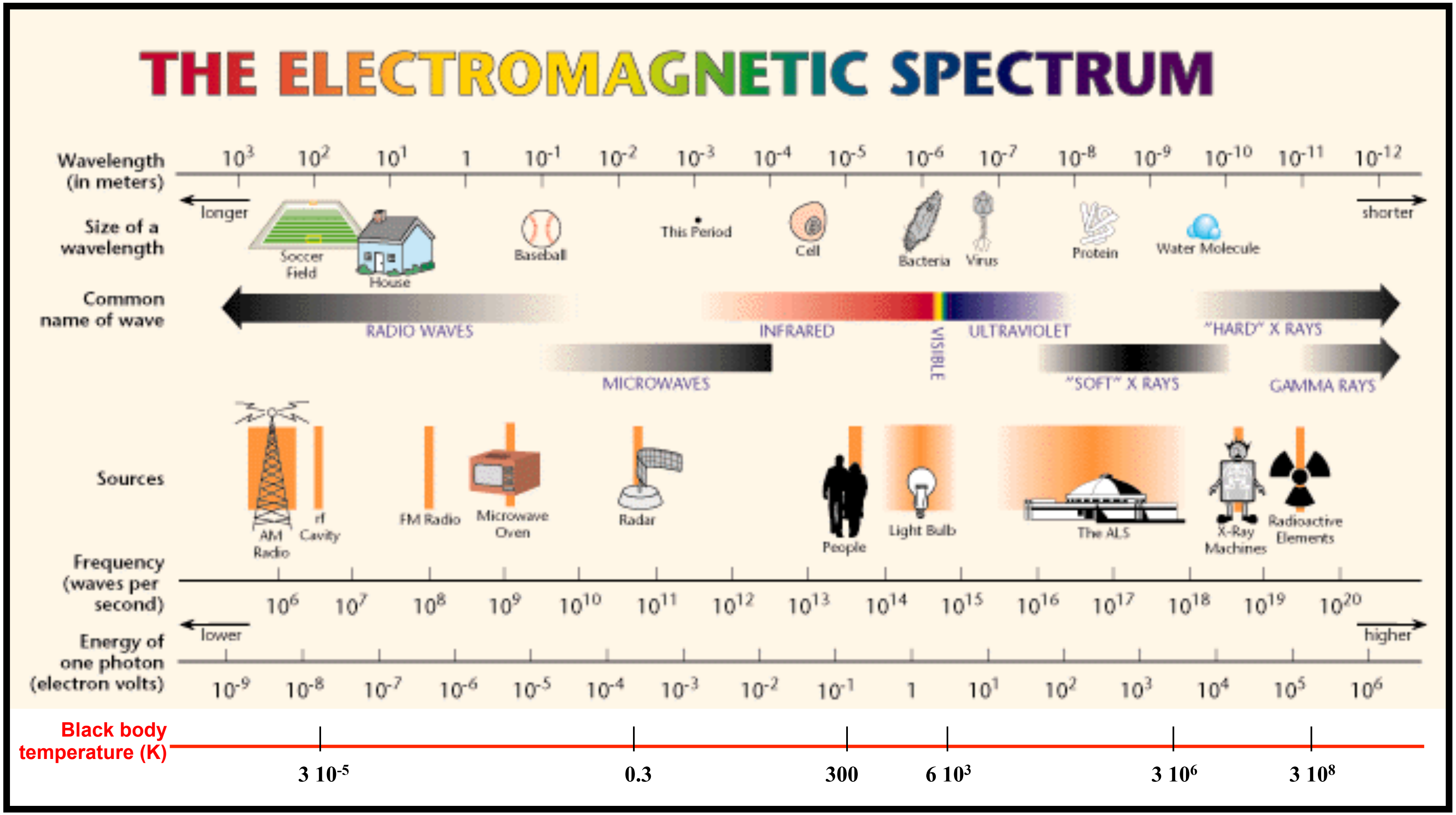






- Energy output α T^4
- A BB at temperature T has the maximum of the emission at a wavelength :

$$\lambda = 0.29/T$$ Wien's law



No BB emission. No bodies with T < 3 K (background radiation)

The cosmic radio emission is ciclotron sincrotron, free-free, ...

Thermal emission

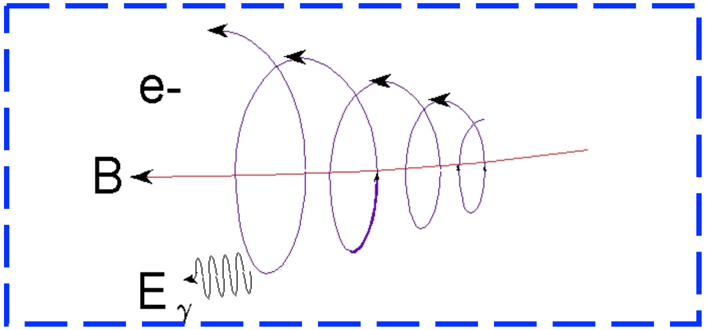
No BB emission

No bodies so hots...

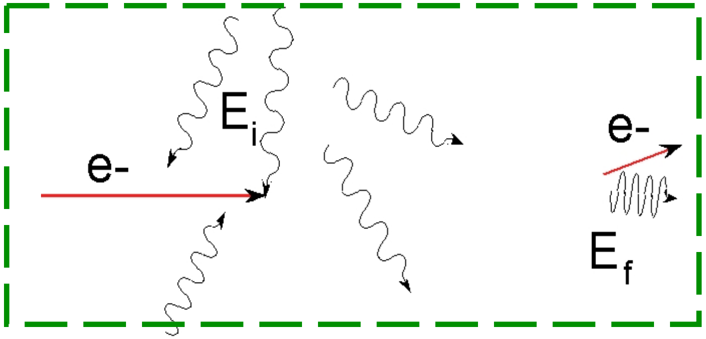
Gamma-ray emission processes

- **Electromagnetic Processes**:

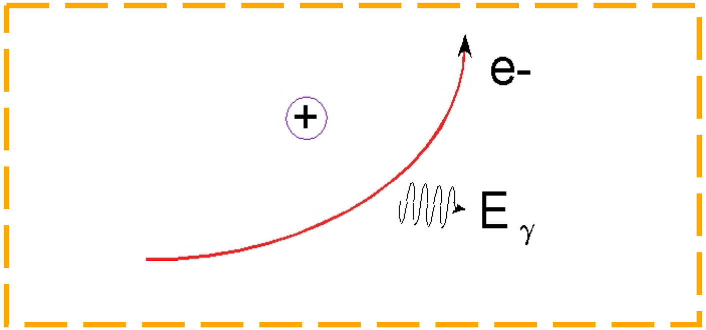
  Synchrotron Emission:
  Probes Magnetic Field, Electron Energy



  Inverse Compton Scattering:
  Probes Photon Field, Electron Energy



  Bremmstrahlung:
  Probes Matter Density, Electron Energy



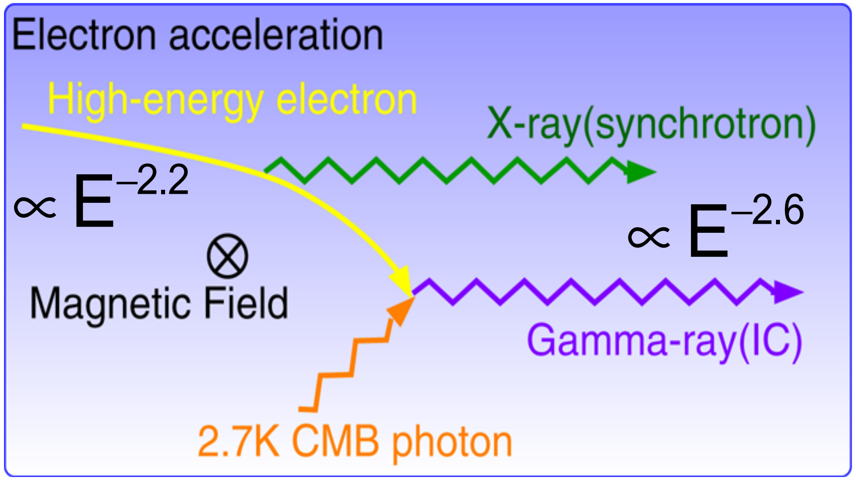
- **Hadronic Cascades**:

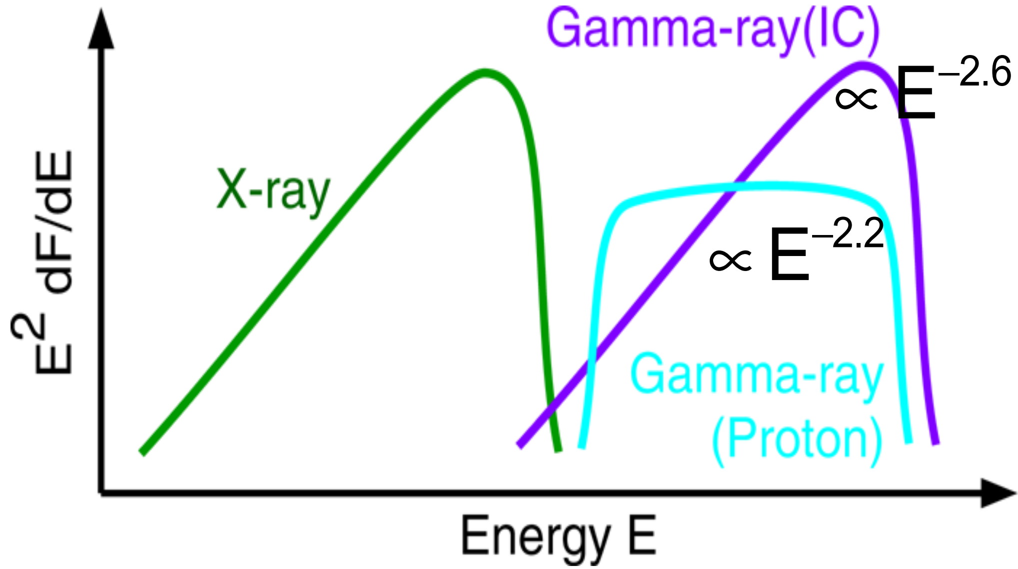
  $p + \gamma \rightarrow \pi^{\pm} + \pi^{o} + \ldots \rightarrow e^{\pm} + \nu + \gamma + \ldots$

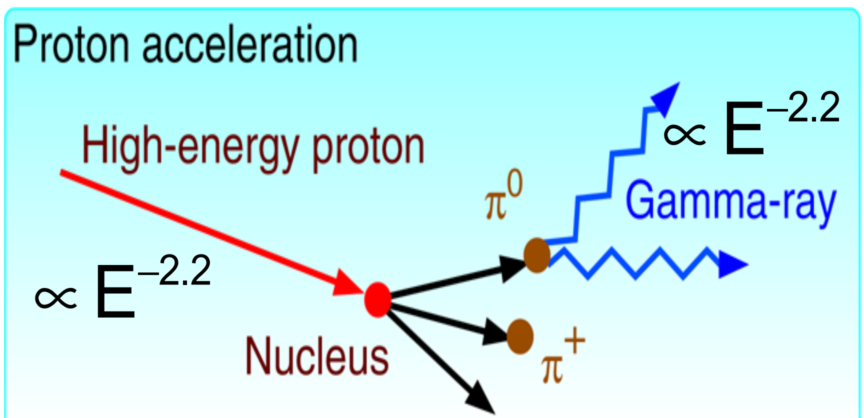
  $p + p \rightarrow \pi^{\pm} + \pi^{o} + \ldots \rightarrow e^{\pm} + \nu + \gamma + \ldots$

  $E_\gamma \sim 0.1\ E_p$

Gamma-ray emission processes





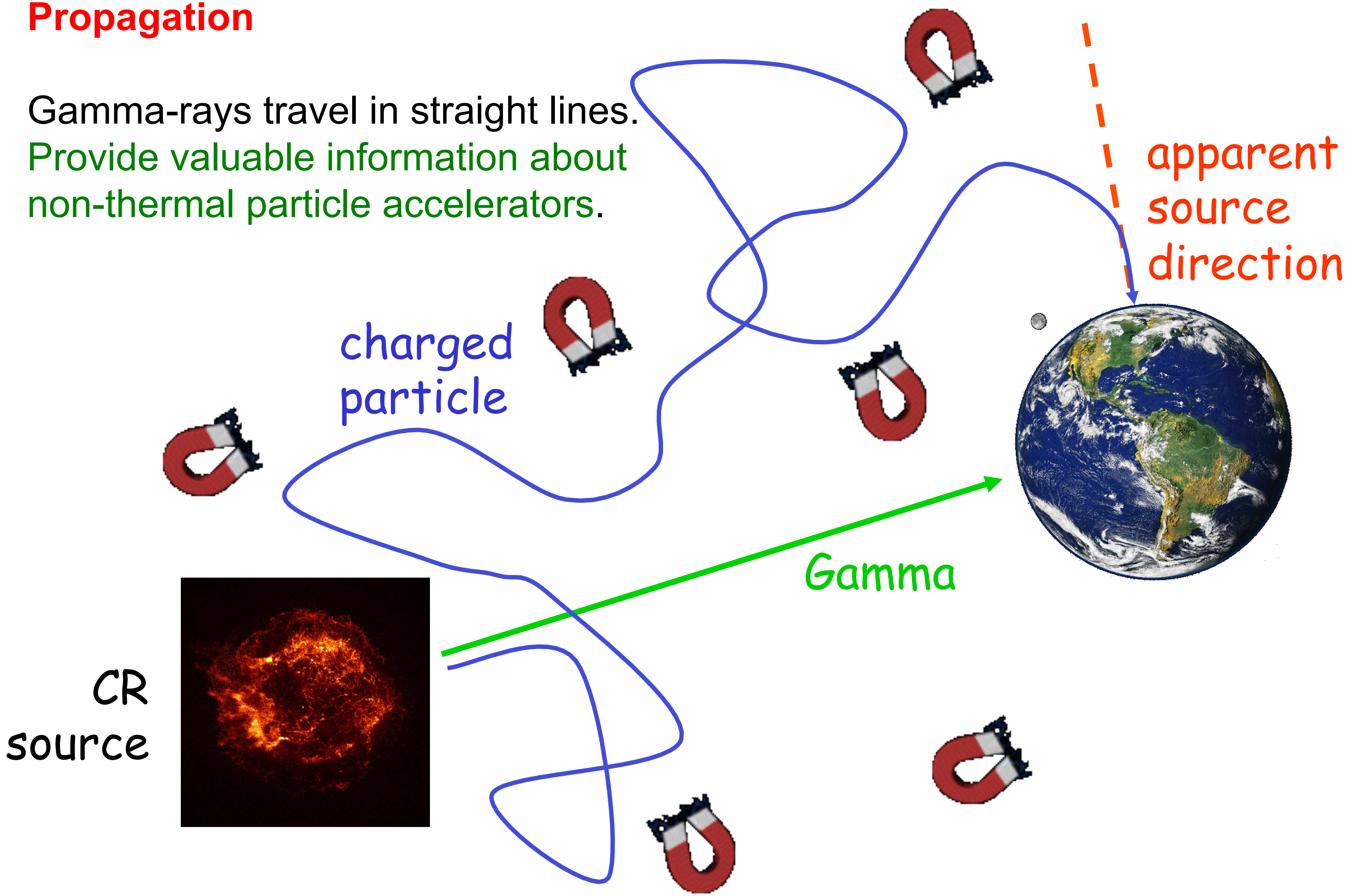


$$\left(\frac{dE}{dt}\right)_{\mathrm{I.C.}} = \frac{4}{3}\sigma_{\mathrm{T}} c \gamma_{\max}^{2} \mathrm{U}_{\mathrm{photon}}$$

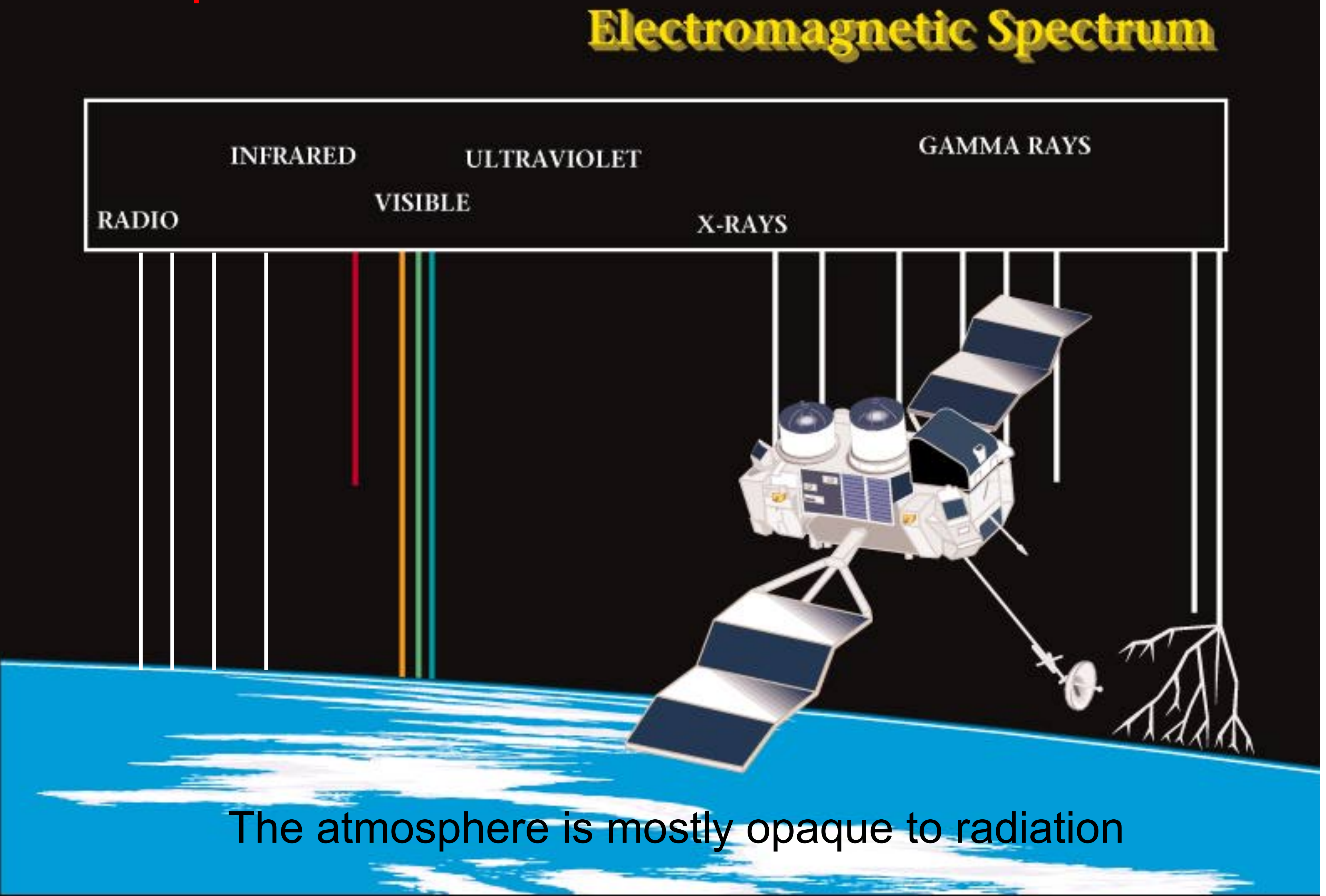
$$\left(\frac{dE}{dt}\right)_{\mathrm{Sync}} = \frac{4}{3}\sigma_{\mathrm{T}} c \gamma_{\max}^{2} \frac{B^2}{2}$$

Propagation

Gamma-rays travel in straight lines.
Provide valuable information about non-thermal particle accelerators.



Absorption



The atmosphere is mostly opaque to radiation

How to detect the HE and VHE γ-ray emission

X rays

0.1-2 keV soft X rays	*ROSAT*
2-10 keV X rays	*XMM-Newton*, *Chandra*, *Swift*/XRT
10-100 keV hard X rays	*INTEGRAL*/IBIS, *Swift*/BAT

Gamma rays

0.1-1 MeV soft gamma rays	*INTEGRAL*/IBIS
1-100 MeV gamma rays	*CGRO*/COMPTEL

High Energy gamma rays (HE)

0.1-50 GeV *COS B*, *CGRO*/EGRET, *AGILE*, *Fermi*/LAT

Very High Energy gamma rays (VHE)

>50 GeV Imaging Atmospheric Cherenkov Telescopes

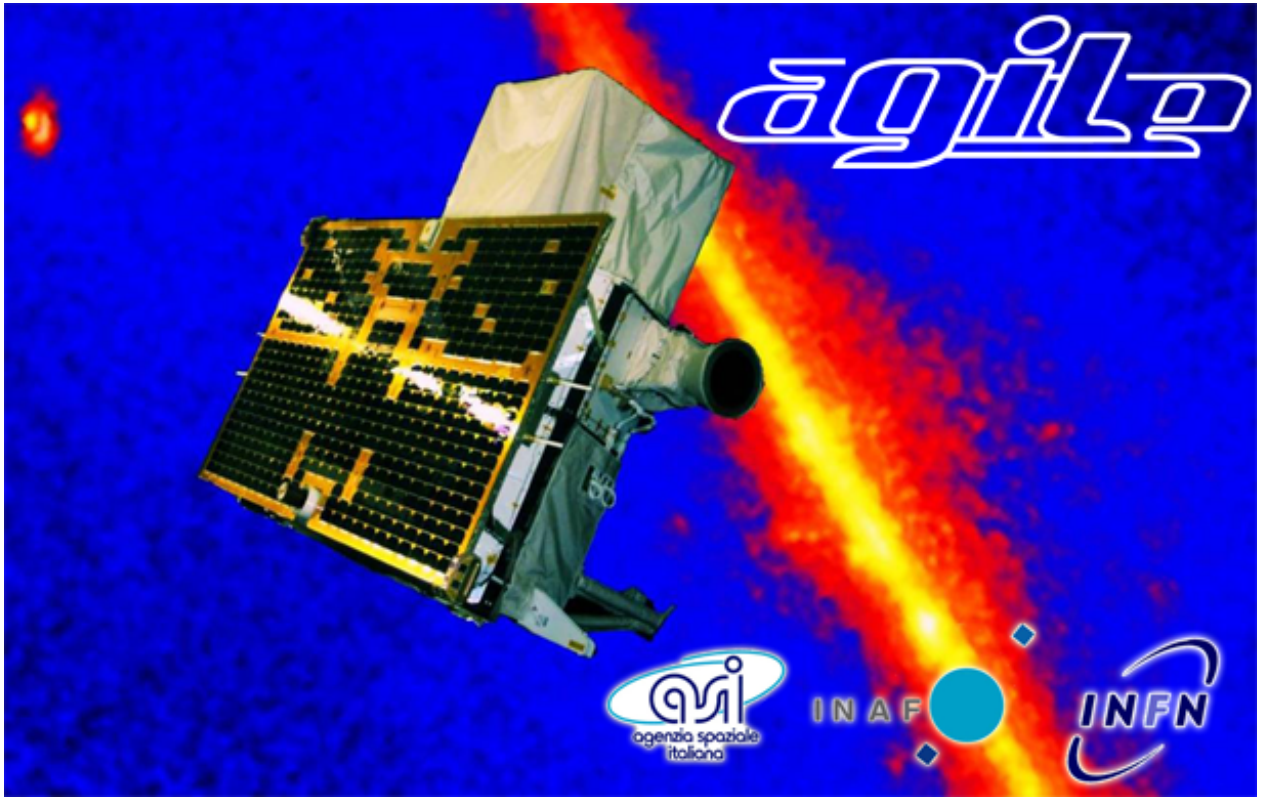
Whipple, HEGRA

CANGAROO, HESS, MAGIC, VERITAS

Water Cherenkov Telescopes

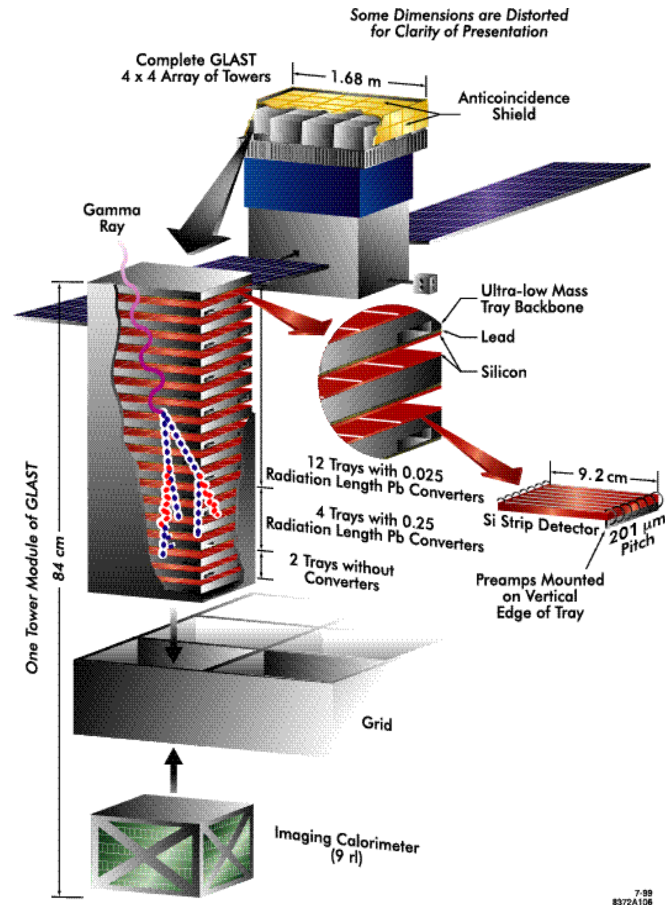
Milagro Gamma-Ray Observatory

AGILE



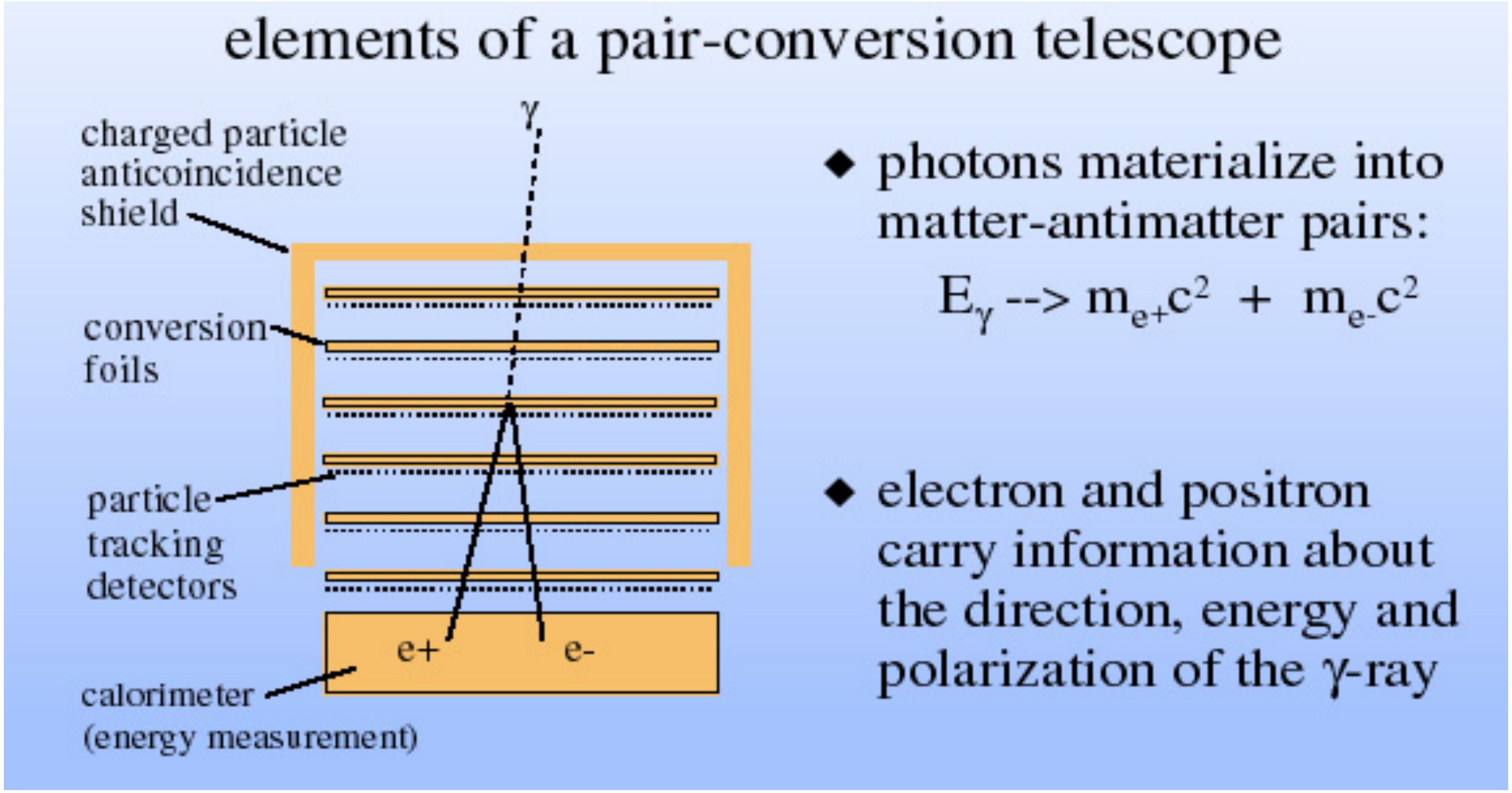
Fermi Gamma Ray Large Area Space Telescope (*GLAST* → *Fermi*)

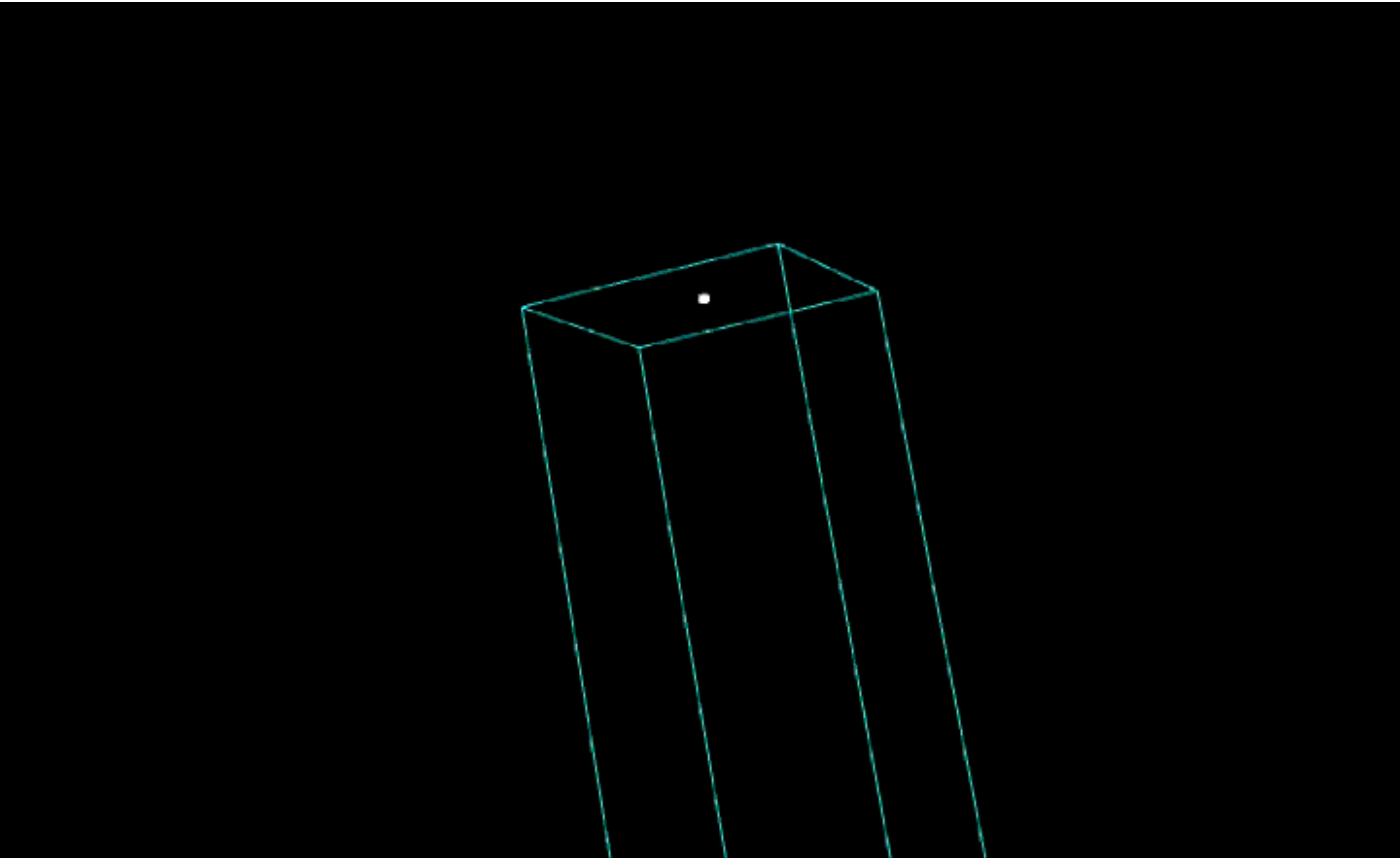
- Launch in 2008
- 20 MeV to 300 GeV



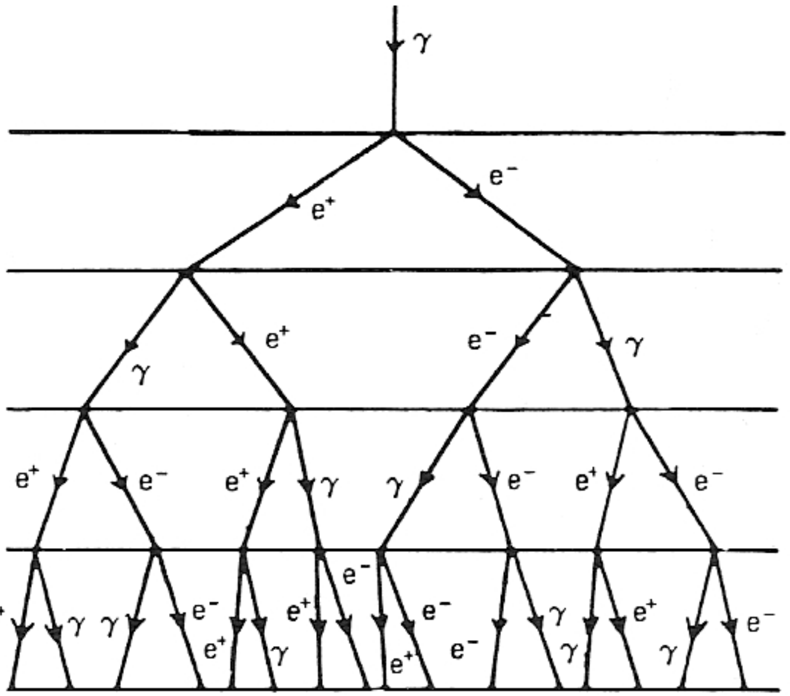
HE - Spaceborne instruments

Fermi design





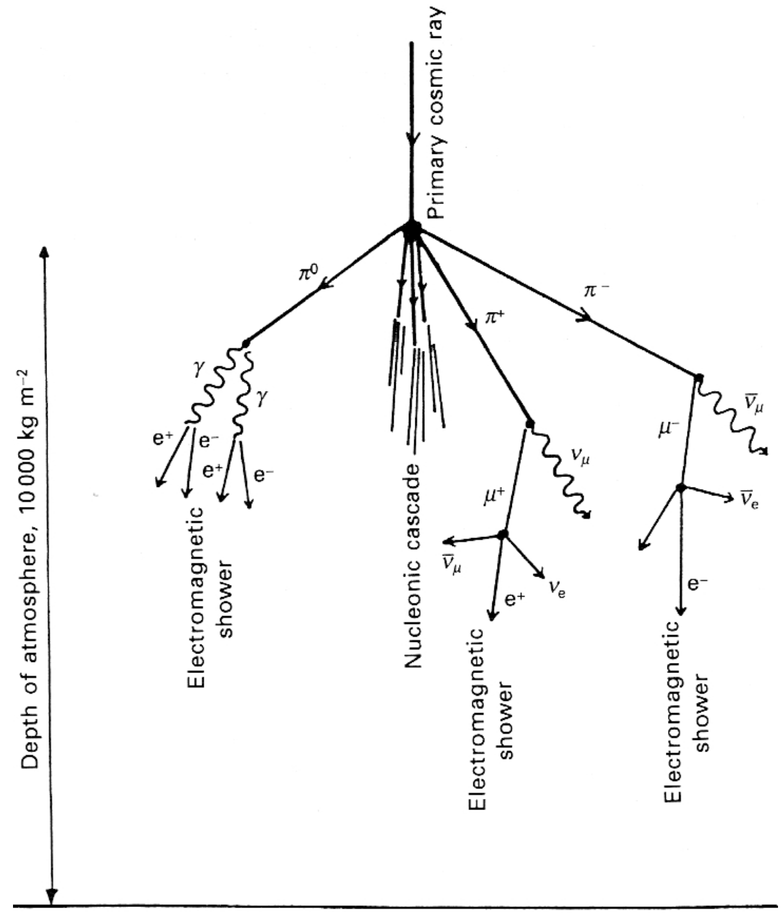
Electromagnetic cascade
Electrons, positrons and photons
Hierarchical and Compact structure



$v_{light} = c/n$,   n index of refraction

If e^{-+} move faster than the light in the medium, a flash is produced…

Hadronic cascade
All kinds of particles
Complex and Extended structure

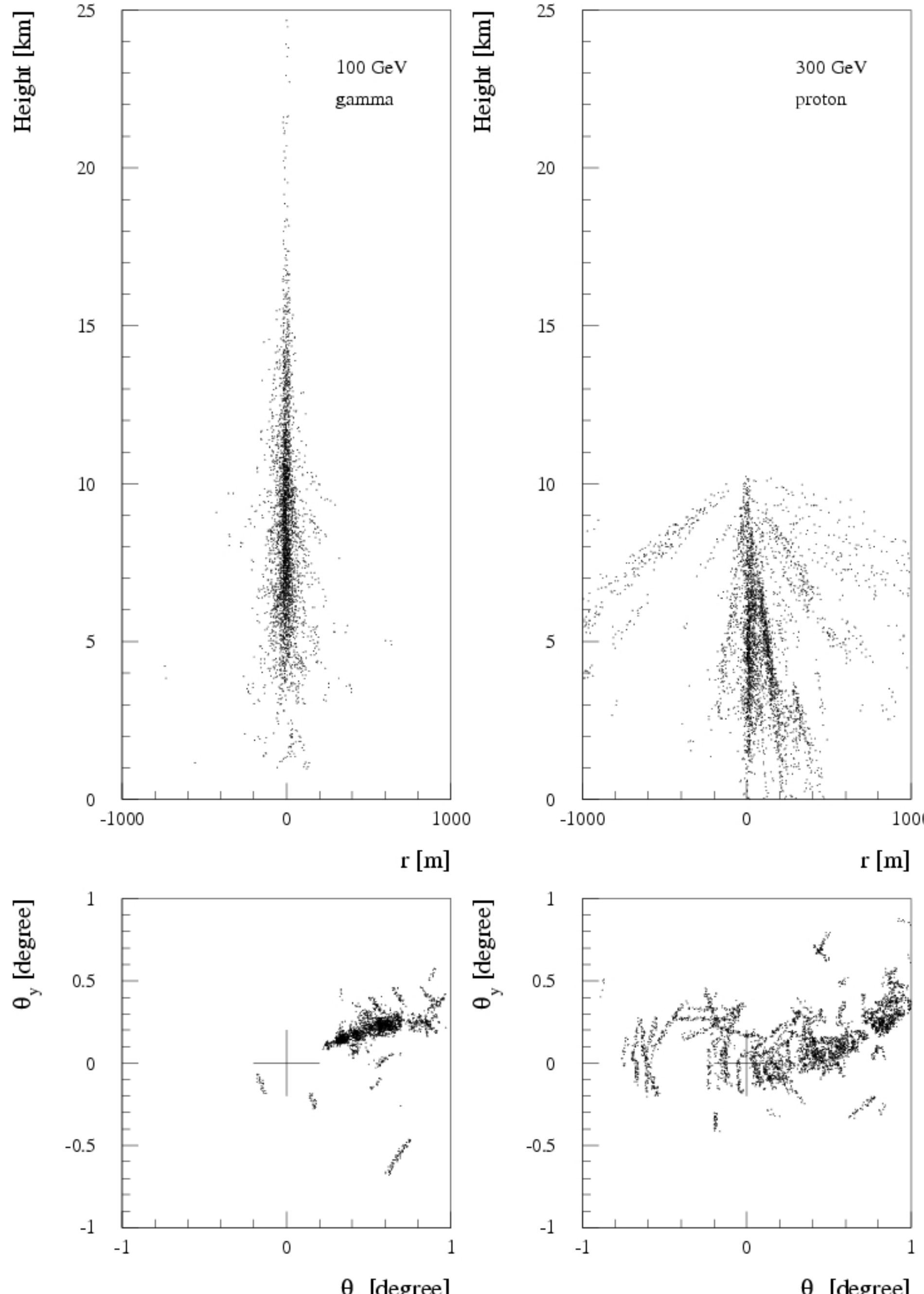


VHE - ground instruments

Imaging helps to discriminate between different cascades
(Hillas 1985)

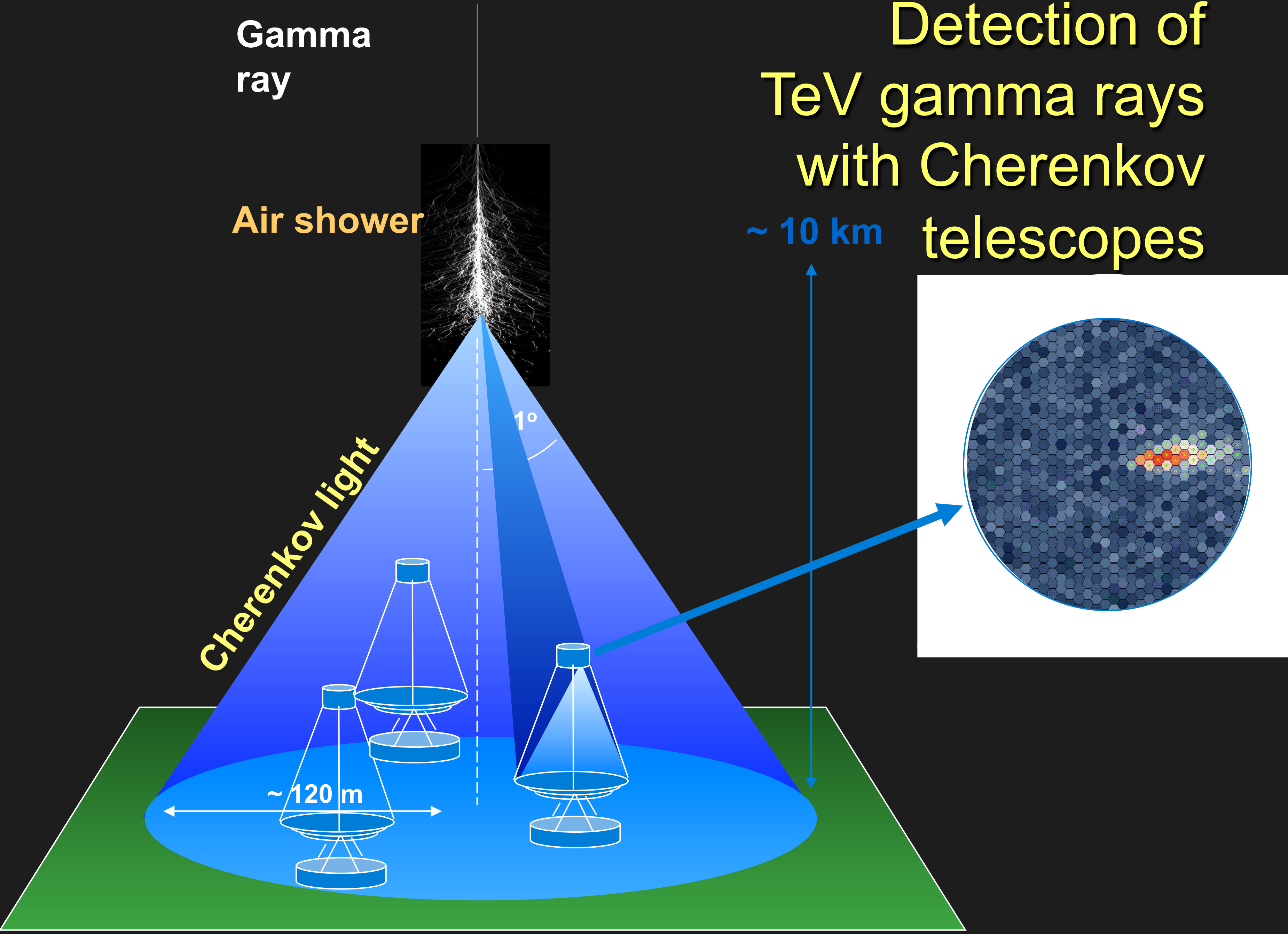
Imaging provides information on:

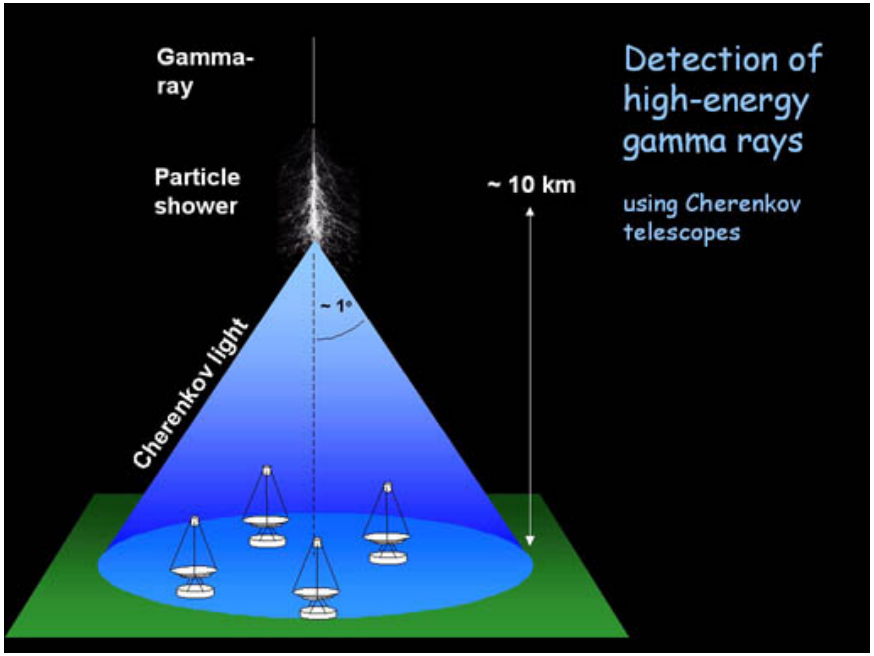
- Nature
- Energy
- Direction

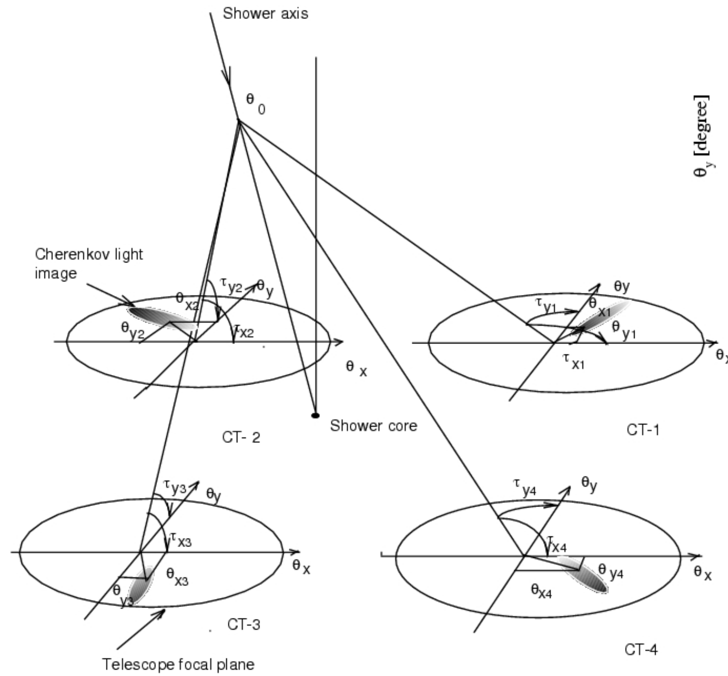


VHE - ground instruments

Detection of TeV gamma rays with Cherenkov telescopes

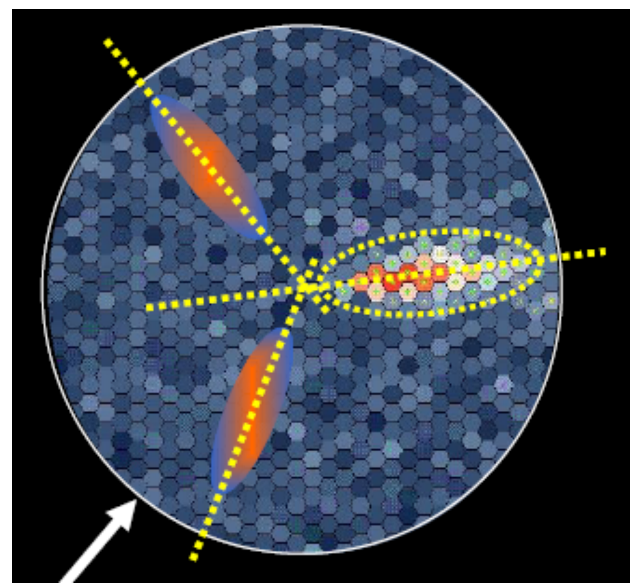






Stereoscopy provide better:

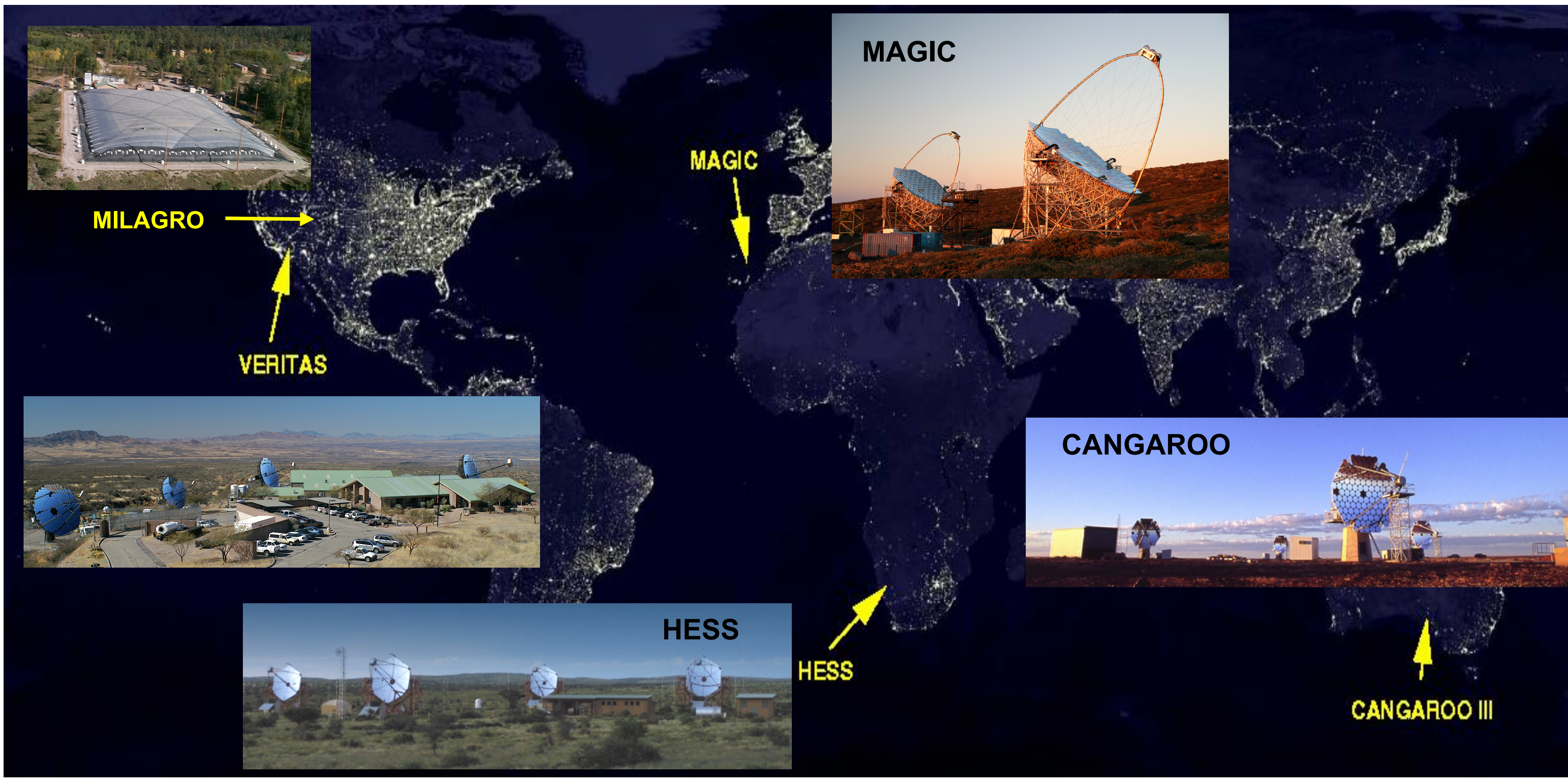
- Angular resolution
- Energy resolution
- Background rejection
- Sensitivity



VHE - ground instruments

Current TeV Instrumentation

Sensitivity ~1% of Crab Nebula flux, energy range ~0.1-50 TeV, energy resolution of ~10% ($\Delta E/E$ ~0.1), position accuracy of ~1’, wide FoV of 5º

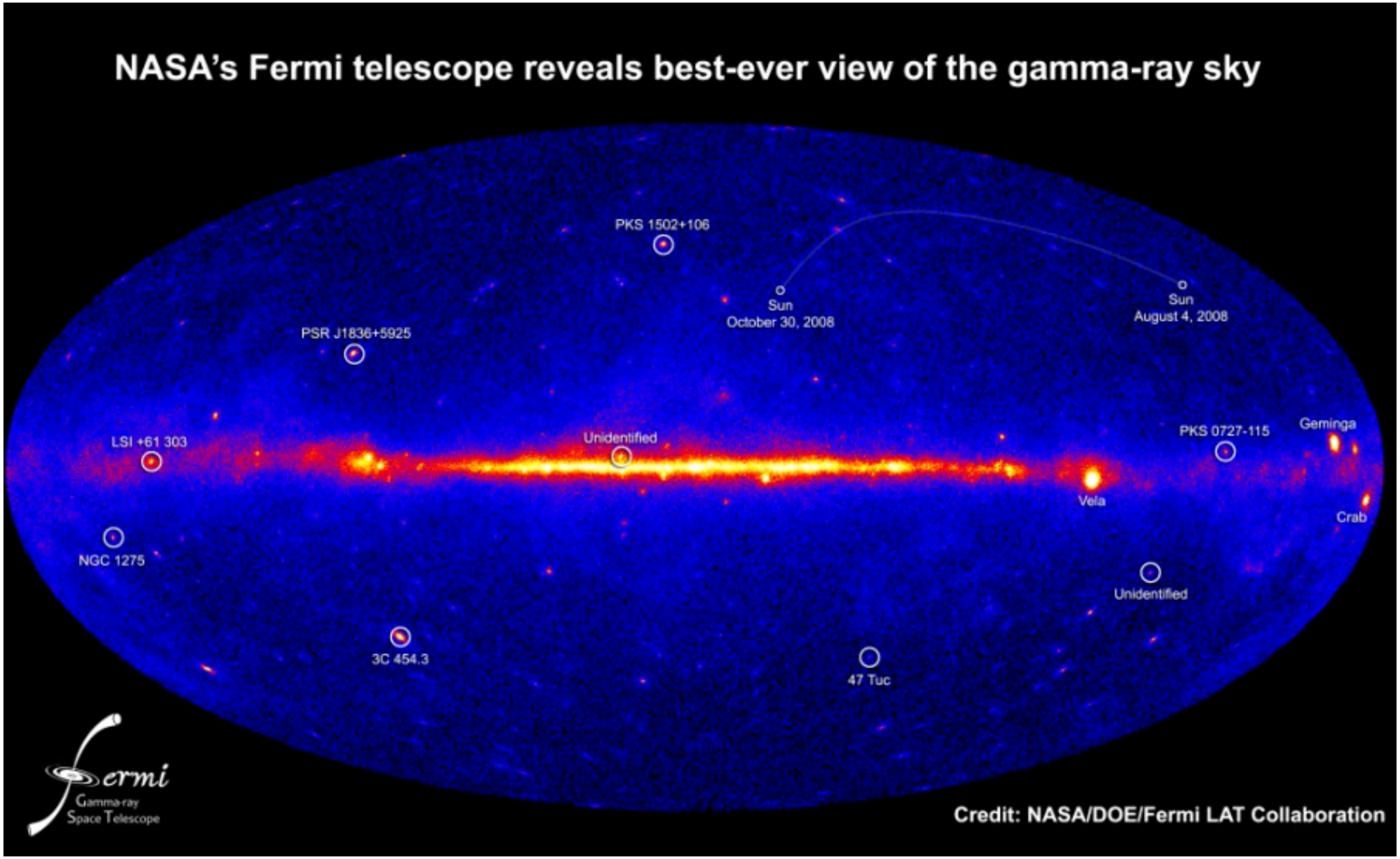


VHE - ground instruments

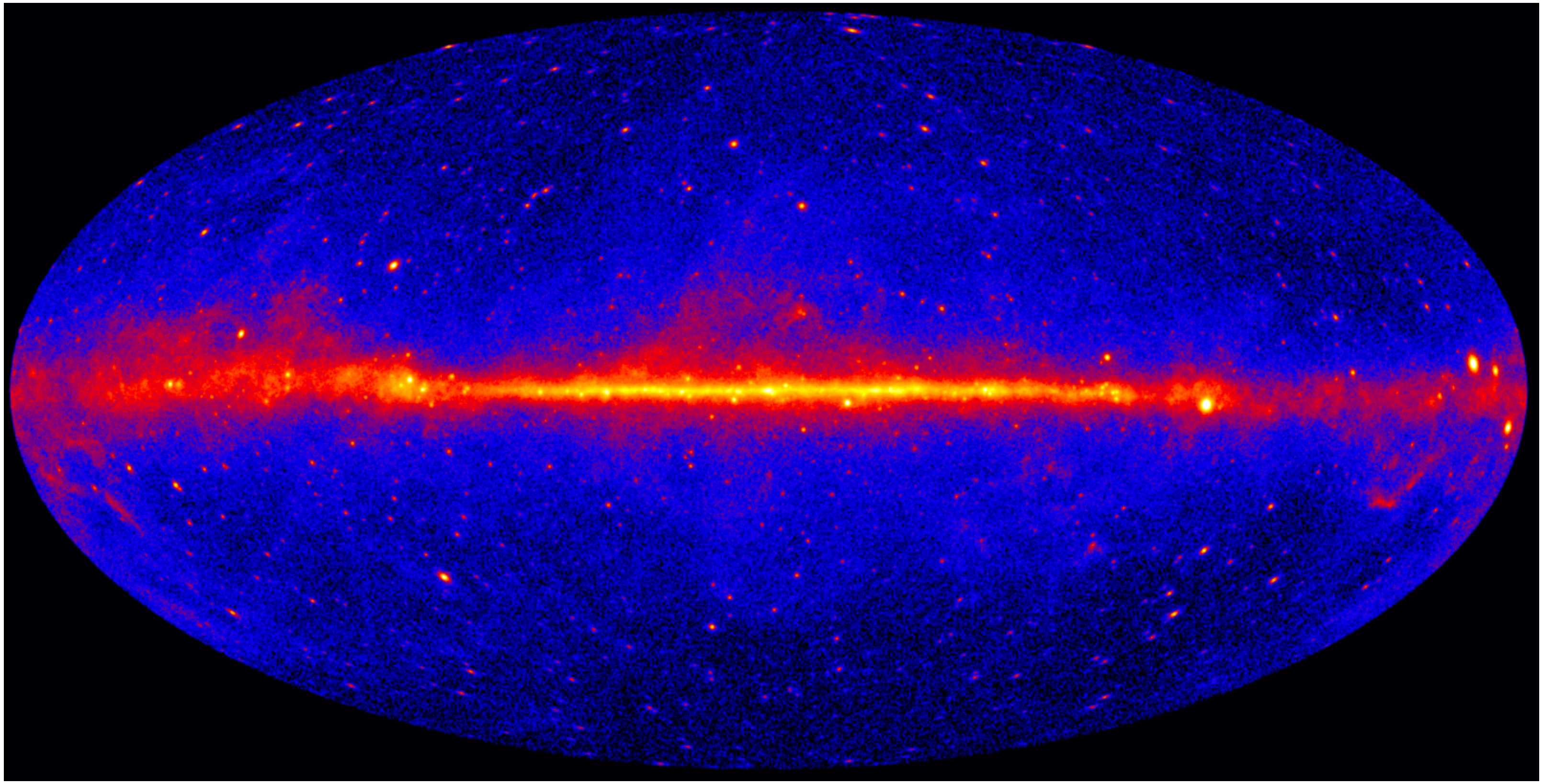
The gamma-ray sky

The HE gamma-ray Sky Map

First results of the *Fermi* satellite (Abdo et al. 2010, ApJS 188, 405)



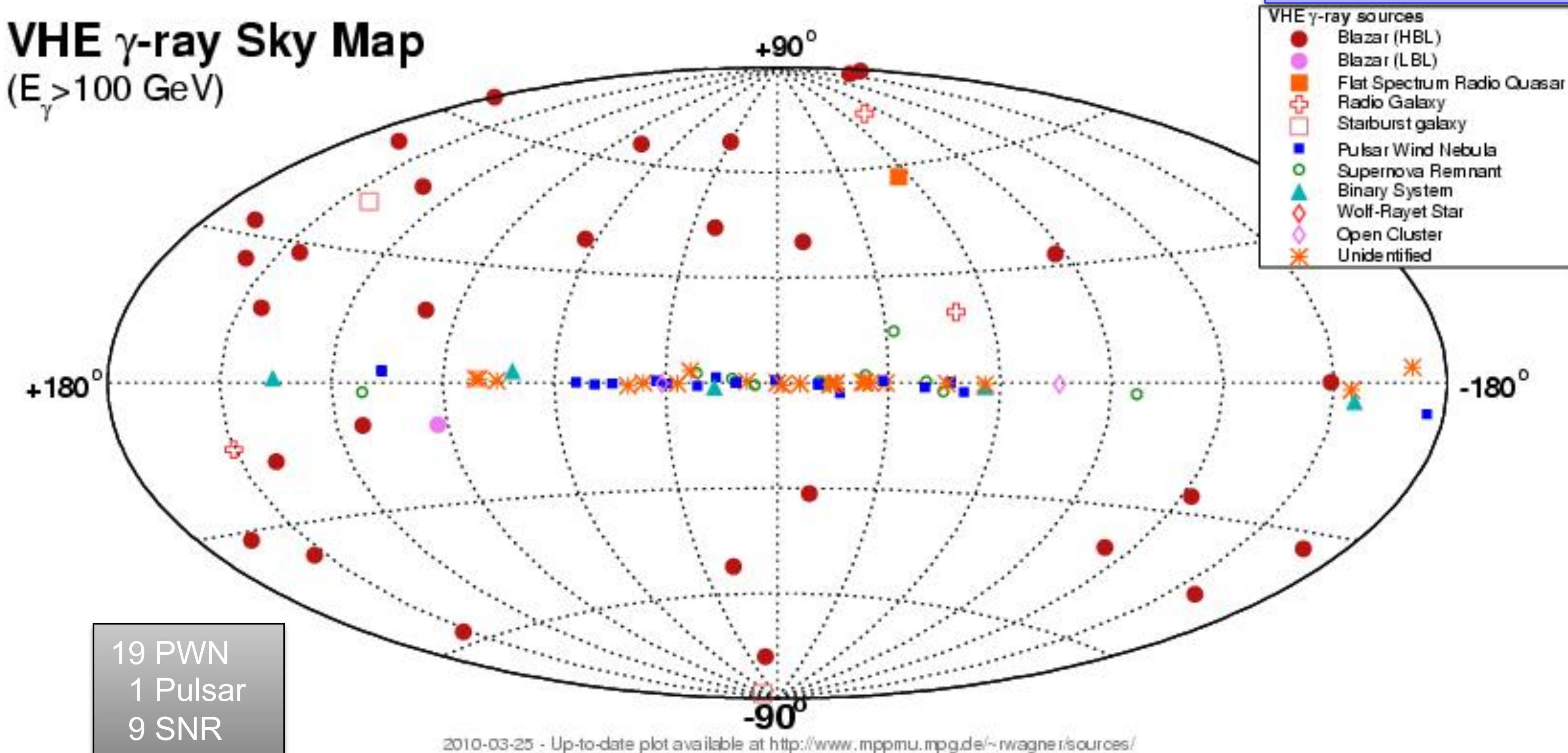
Two year of *Fermi* satellite data (Vandenbroucke et al. 2010)



The gamma-ray sky The VHE gamma-ray Sky Map

38 extragalactic

60 galactic



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

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

Binary systems

The most massive star in a binary system evolves faster than the other star.

The first star

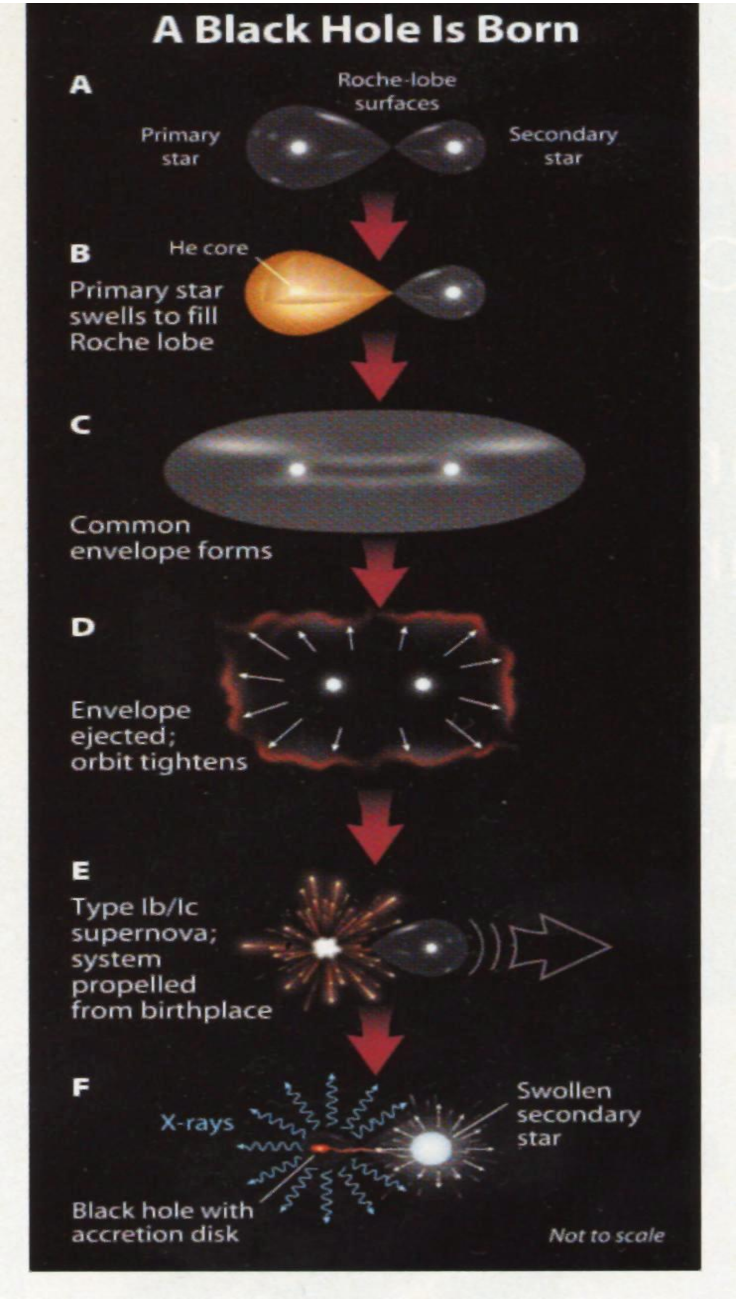
may evolve to a WD

or

explode (SN) and form a NS or BH

Compact objects (WD, NS, BH) can be found in **binary systems**

Opportunity to study the BH



1. Accreting binaries

- X-ray binaries
  - HMXRB
    - Be/X-ray transients
    - SG/obscure binaries
    - BH binaries
  - LMXRB
- Microquasars
  Relativistic jet
  - High-mass microquasars
  - Low-mass microquasars

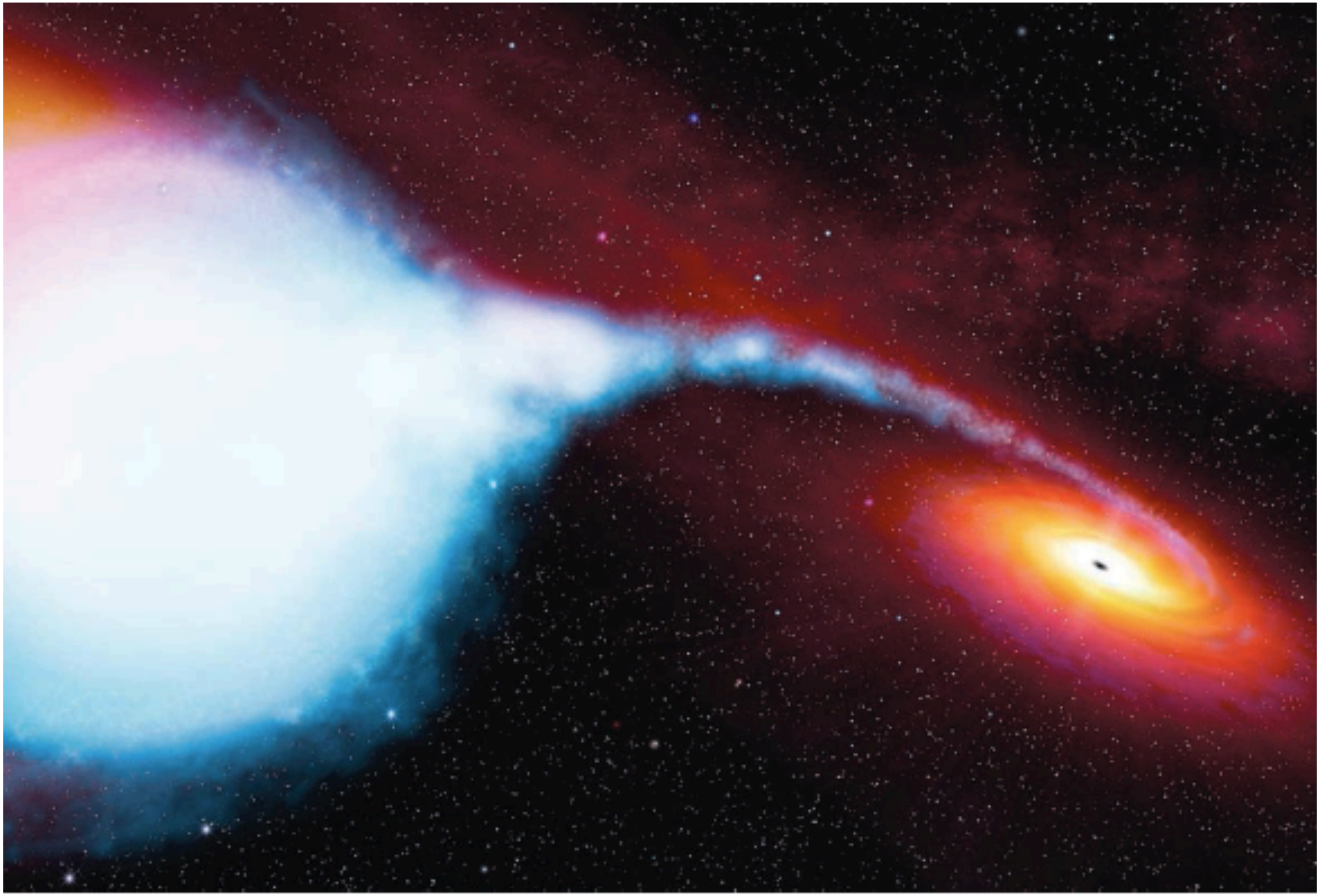
SED dominated by X-rays → X-ray binaries

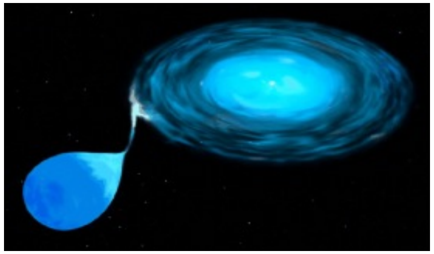
2. Non-accreting binaries

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

SED dominated by γ-rays → γ-ray binaries

X-ray binaries / Microquasars

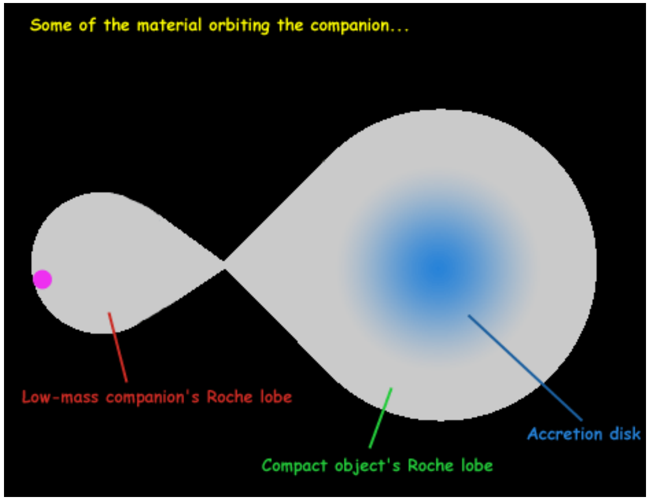




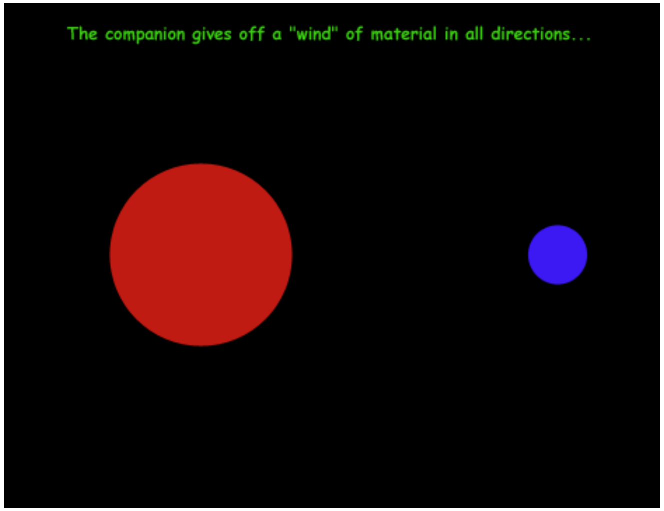
accretion disk

Mass transfer from the companion star to the compact star
(depend on separation and mass of the stars)

Filling the Roche lobe



Stellar wind



An accretion disk is formed around the compact object

As the matter in the accretion disk loses energy and spirals downward into the compact object it is heated to very high temperatures and emits

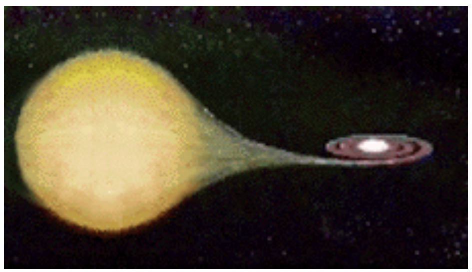
Optic & UV radiation if the compact object is WD (cataclysmic binaries)

and

X-ray if the compact object is NS or BH (X-ray binaries)

X-ray binaries

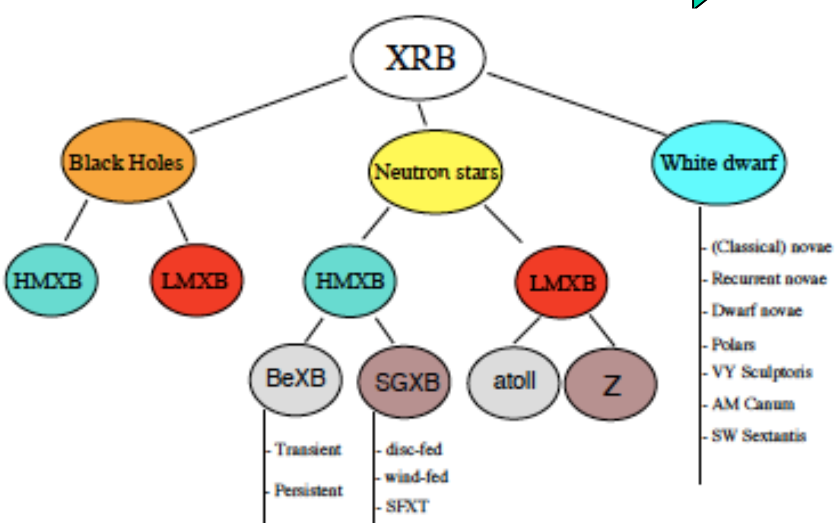
XB: A binary system containing a compact object (NS or a stellar-mass BH) accreting matter from the companion star. The accreted matter forms an accretion disc, responsible for the X-ray emission. A total of 299 XB in the Galaxy (HMXB, Liu et al. 2006, A&A 455,1165 and LMXB 2007, A&A 469, 807)

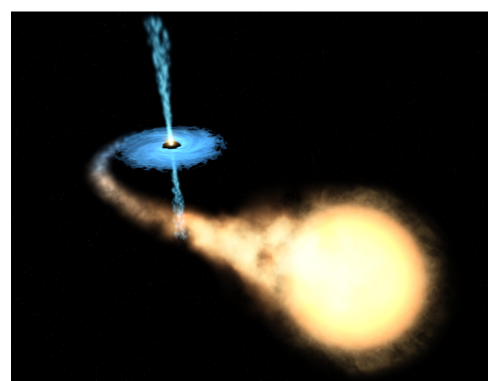


HMXBs: (114) Optical companion, O or B.
Mass transfer via decretion disc (Be stars) or via strong wind or Roche-lobe overflow

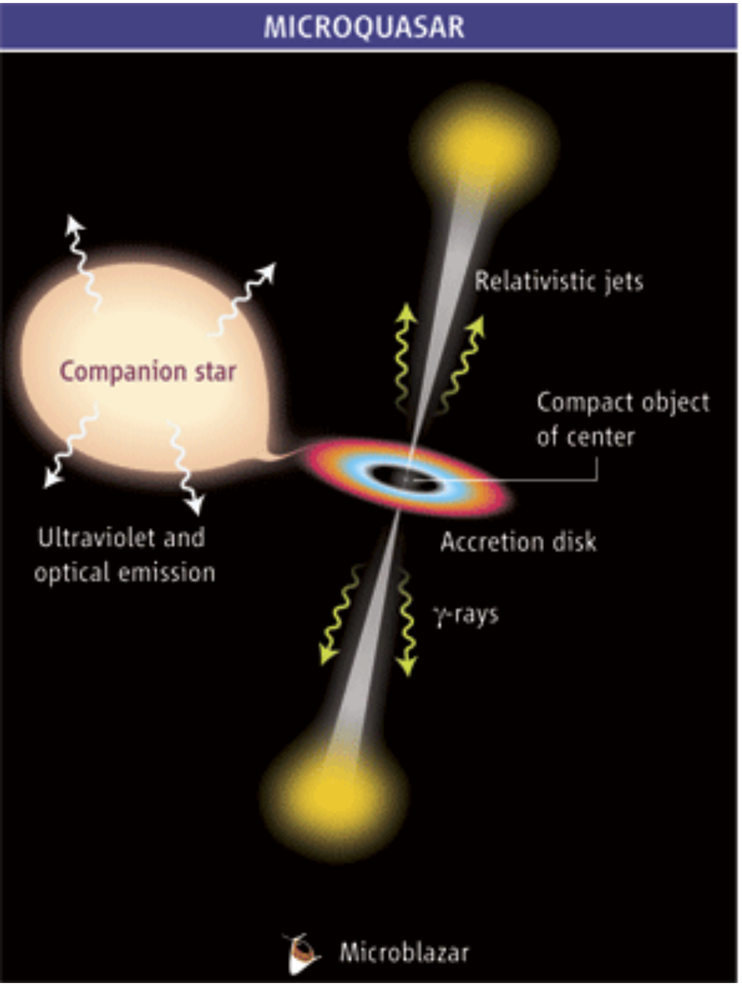
LMXBs: (185) Optical companion, spectral type later than B
Mass transfer via Roche-lobe overflow

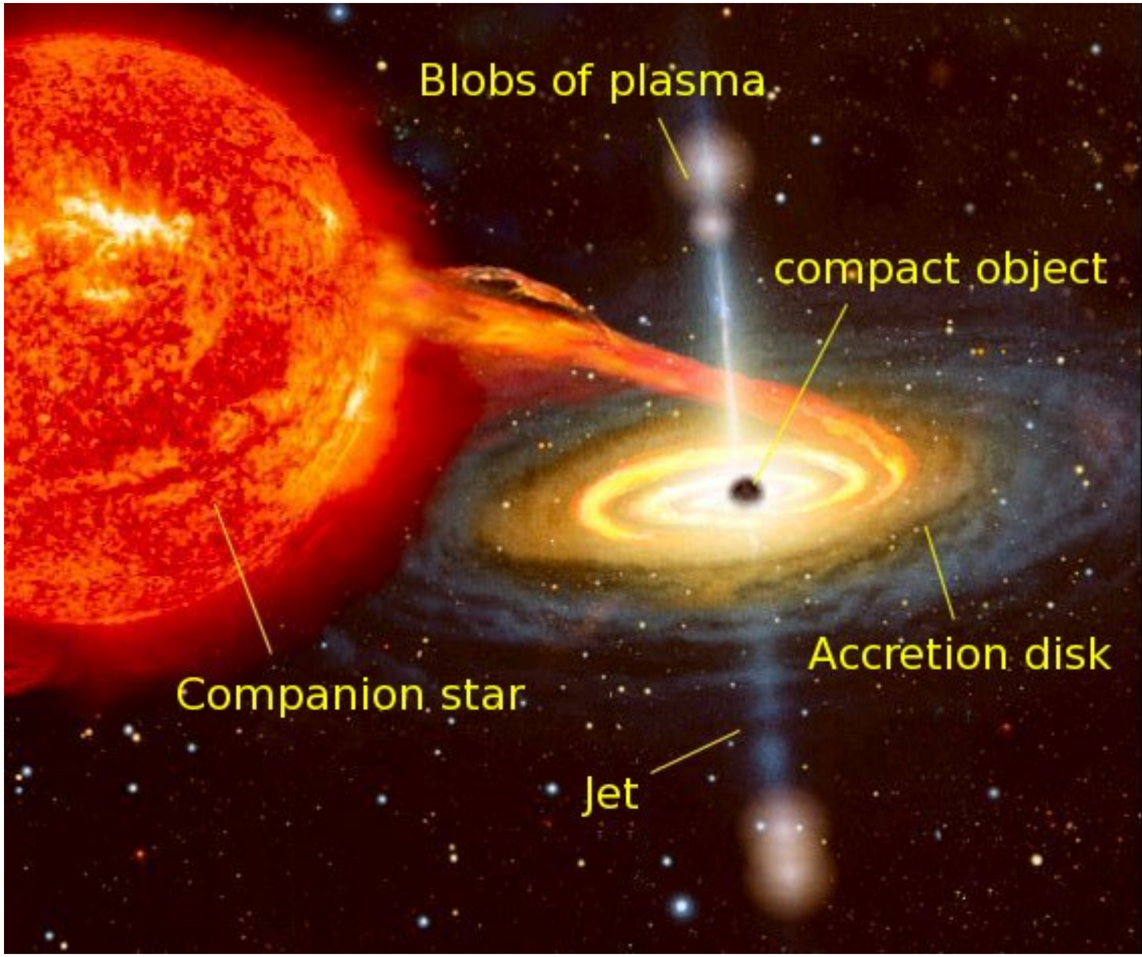
299 XB → 65 (22%) REXBs { 9 HMXBs, 56 LMXBs }





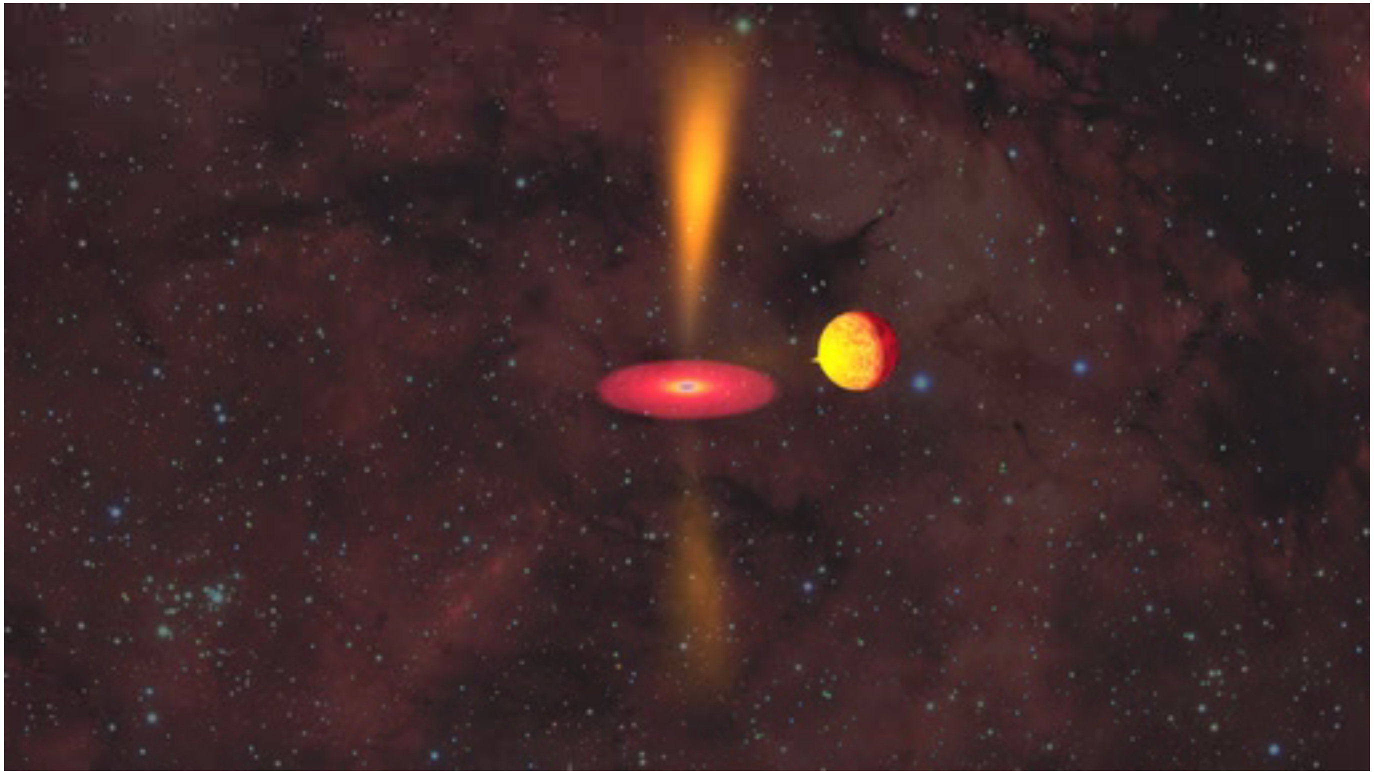
Microquasars:
(Accreting) X-ray binaries with relativistic jets





At least 15 microquasars

Maybe the majority of RXBs are MQs (Fender 2001)



Microquasars

REXBs displaying relativistic *radio* jets

Compact object may be a NS or a BH

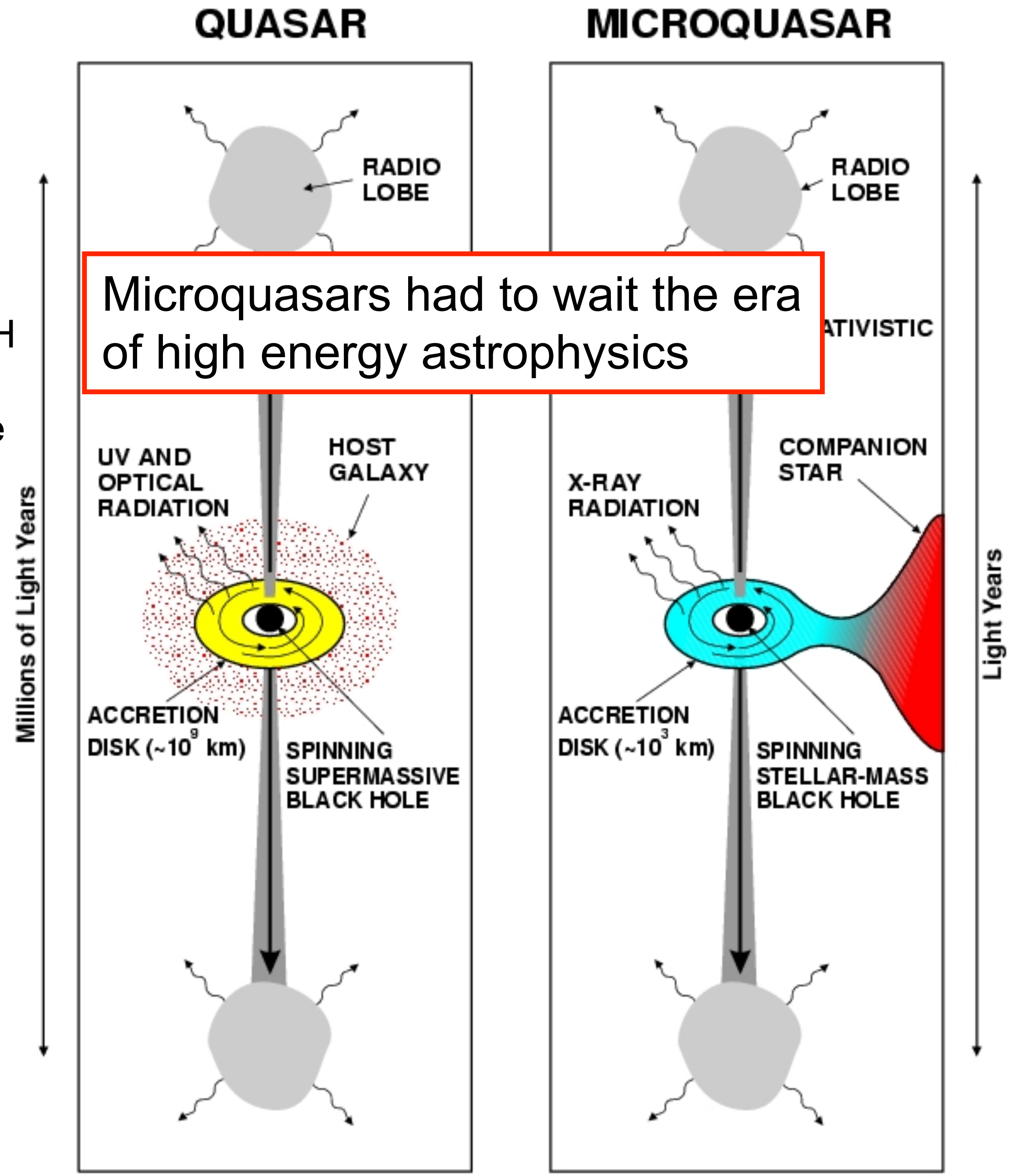
In BH, the length and time scales are proportional to M_{BH}:

$R_{Sh}=2GM_{BH}/c^2$, $\Delta t \propto M_{BH}$

The maximum color temperature of the accretion disk is

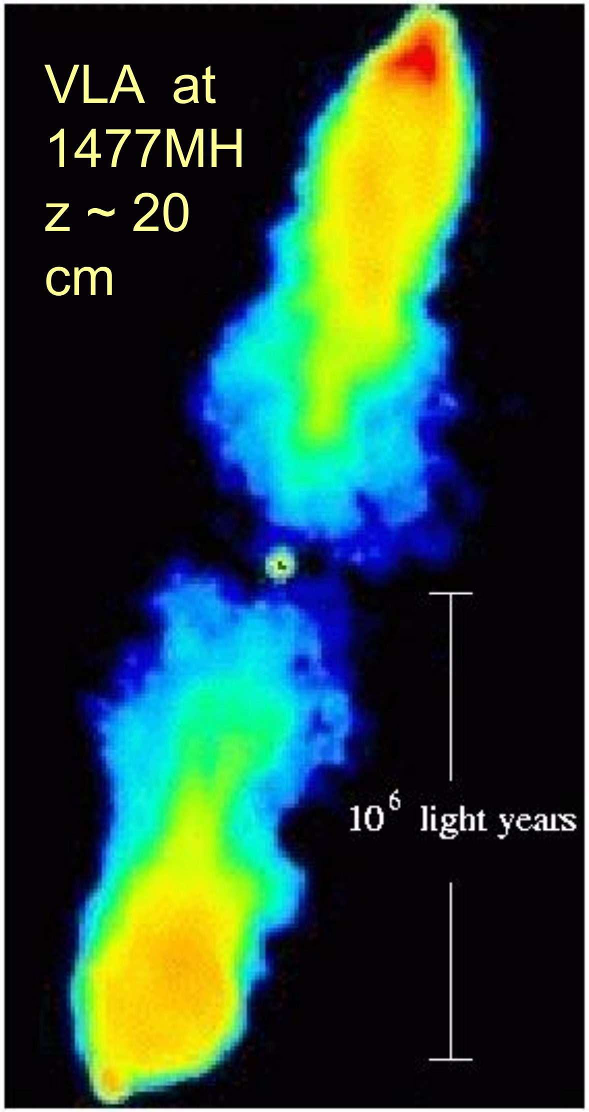
$T_{col} \approx 2\times10^7\, (M_{BH}/M_\odot)^{-1/4}$

(Mirabel & Rodríguez 1998)

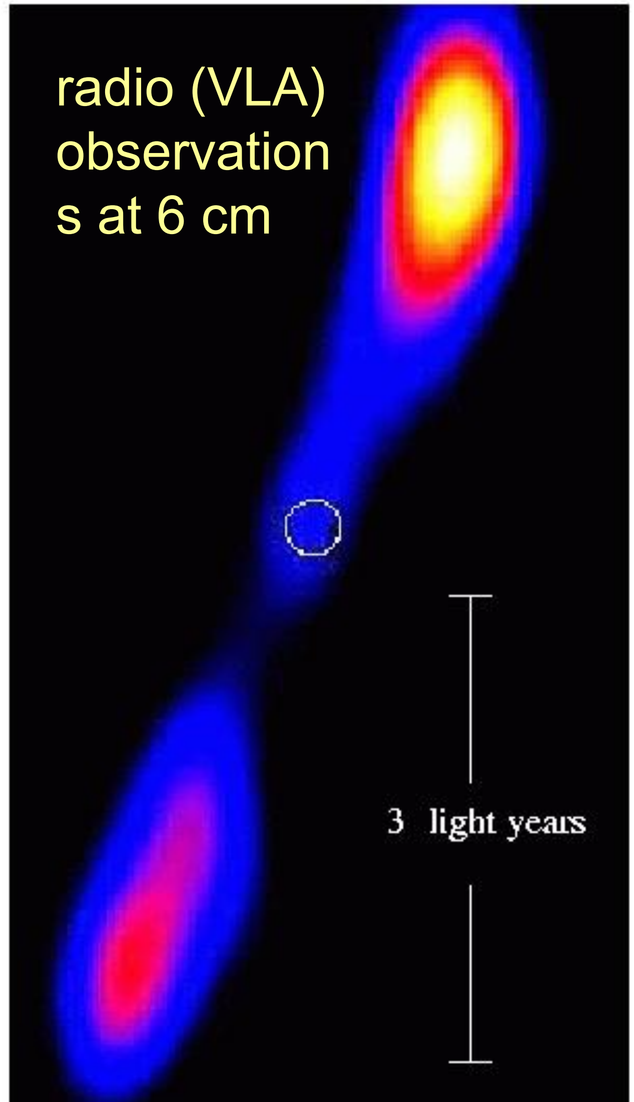


Microquasars had to wait the era of high energy astrophysics

Quasar 3C 223

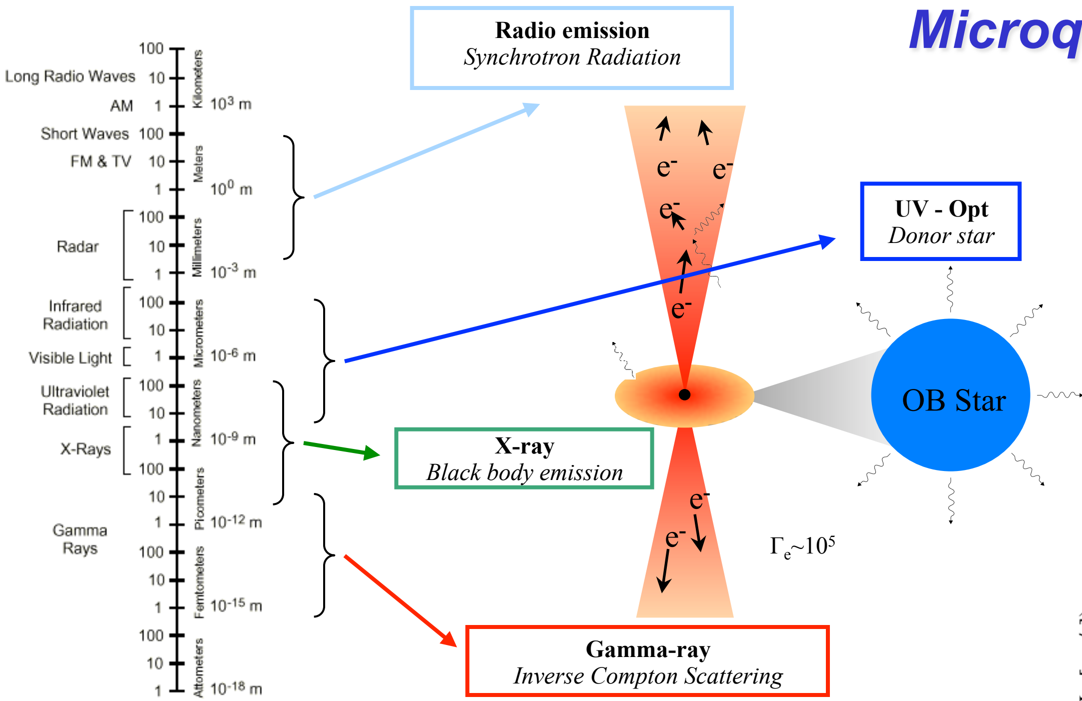


Microquasar 1E1740.7-2942

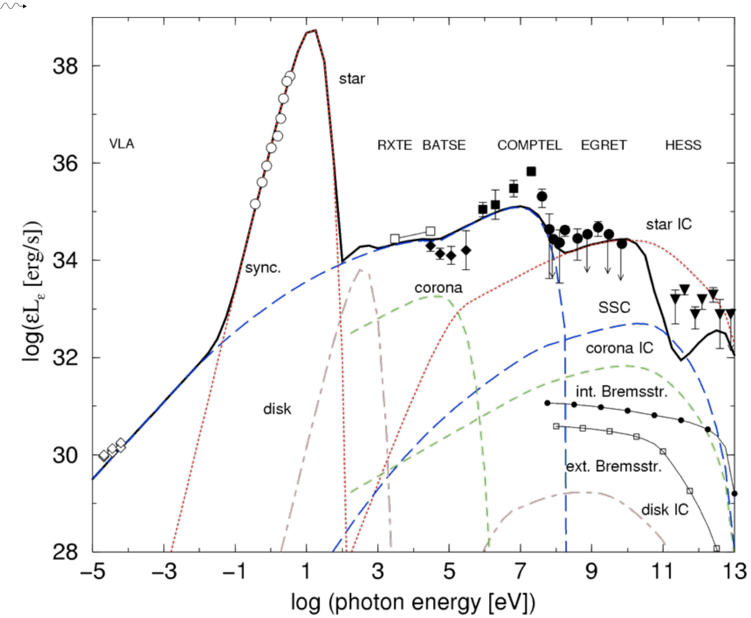


(Mirabel et al. 1992)

Microquasar scenario



Paredes et al. (2006)

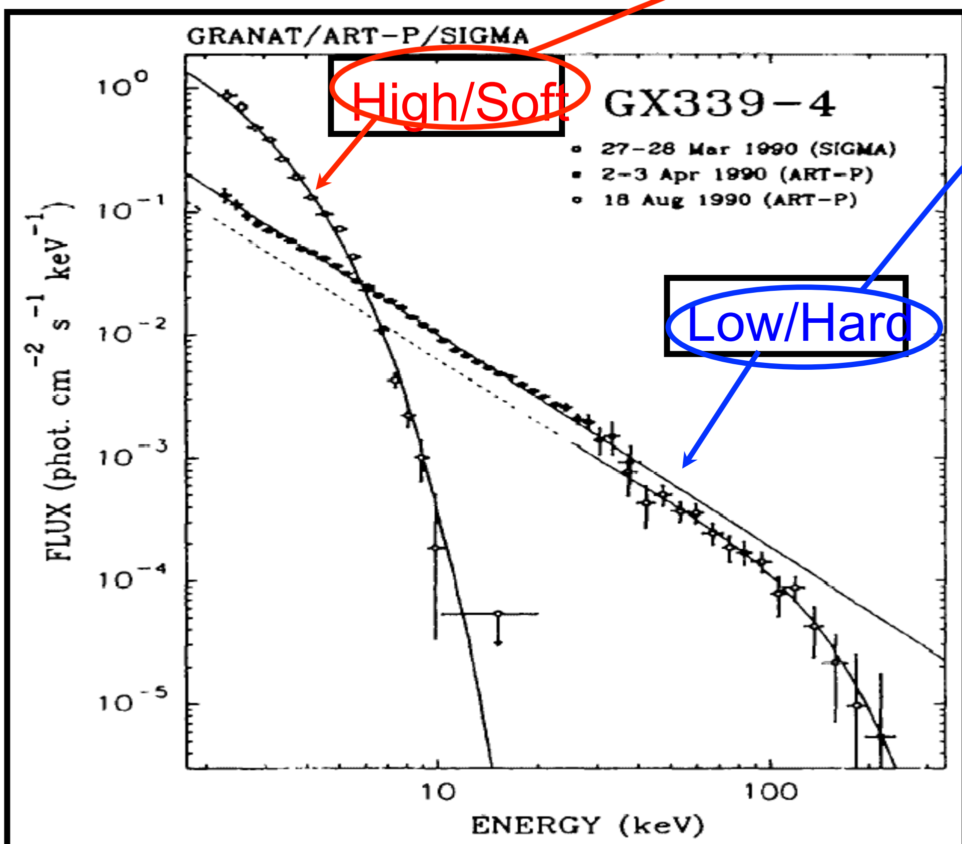


- An accretion disk is formed by the transfer of material
- Microquasars display bipolar jets of relativistic plasma
- The Jet electrons produce radiation by synchrotron emission when interacting with the magnetic field
- VHE emission is produced by inverse Compton scattering when the jet particles collide with stellar photons

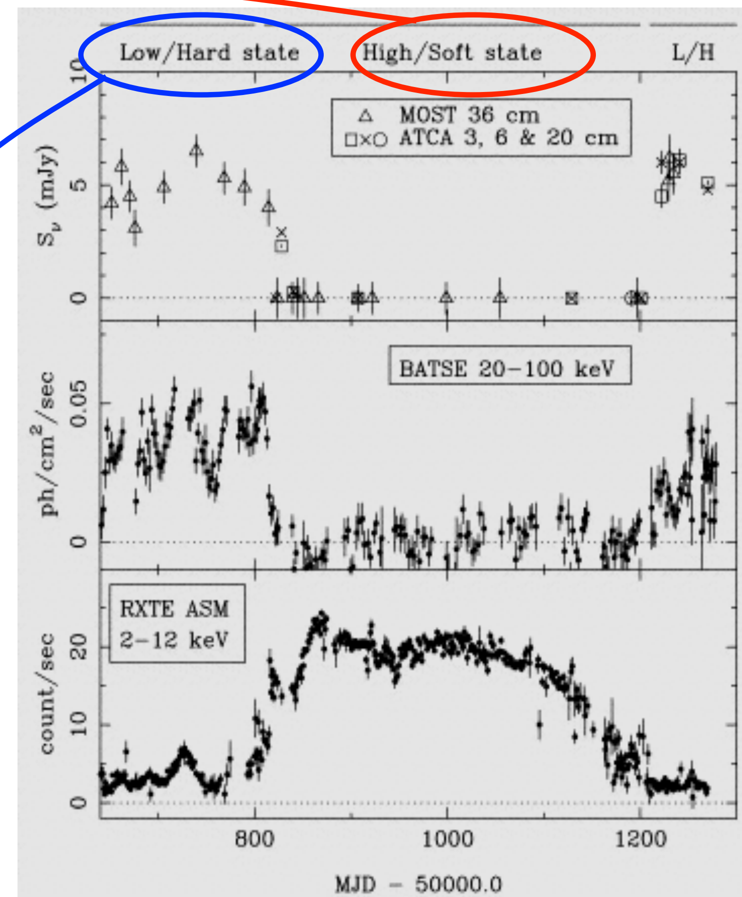
Black hole states

Black holes display different X-ray spectral states:

- Low/hard state (a.k.a. power-law state). Compact radio jet
- High/soft state (a.k.a. steep power-law state). No radio emission
- Intermediate and very high states → transitions. Transient radio emission

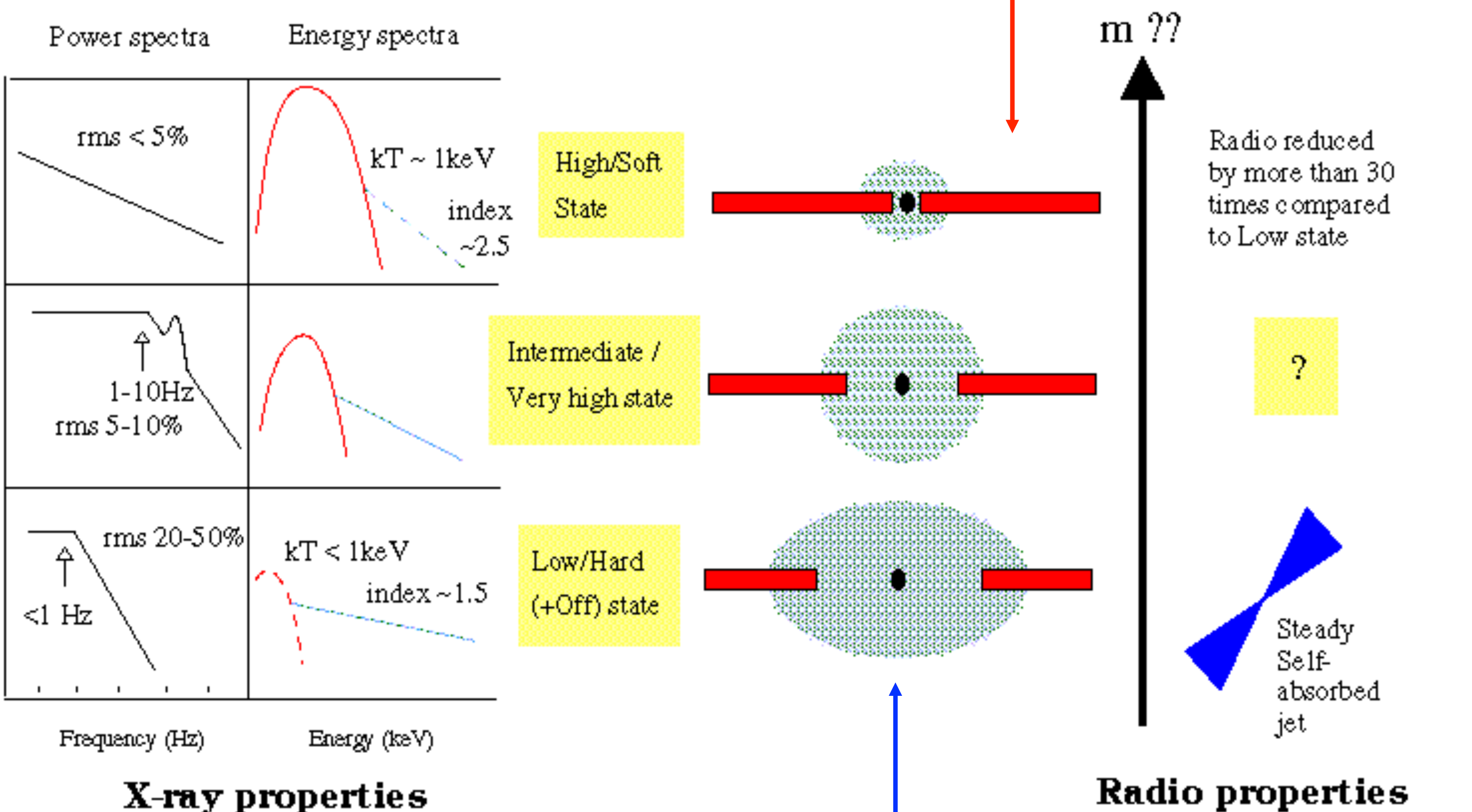


Grebenev et al. 1993, A&ASS 97, 281



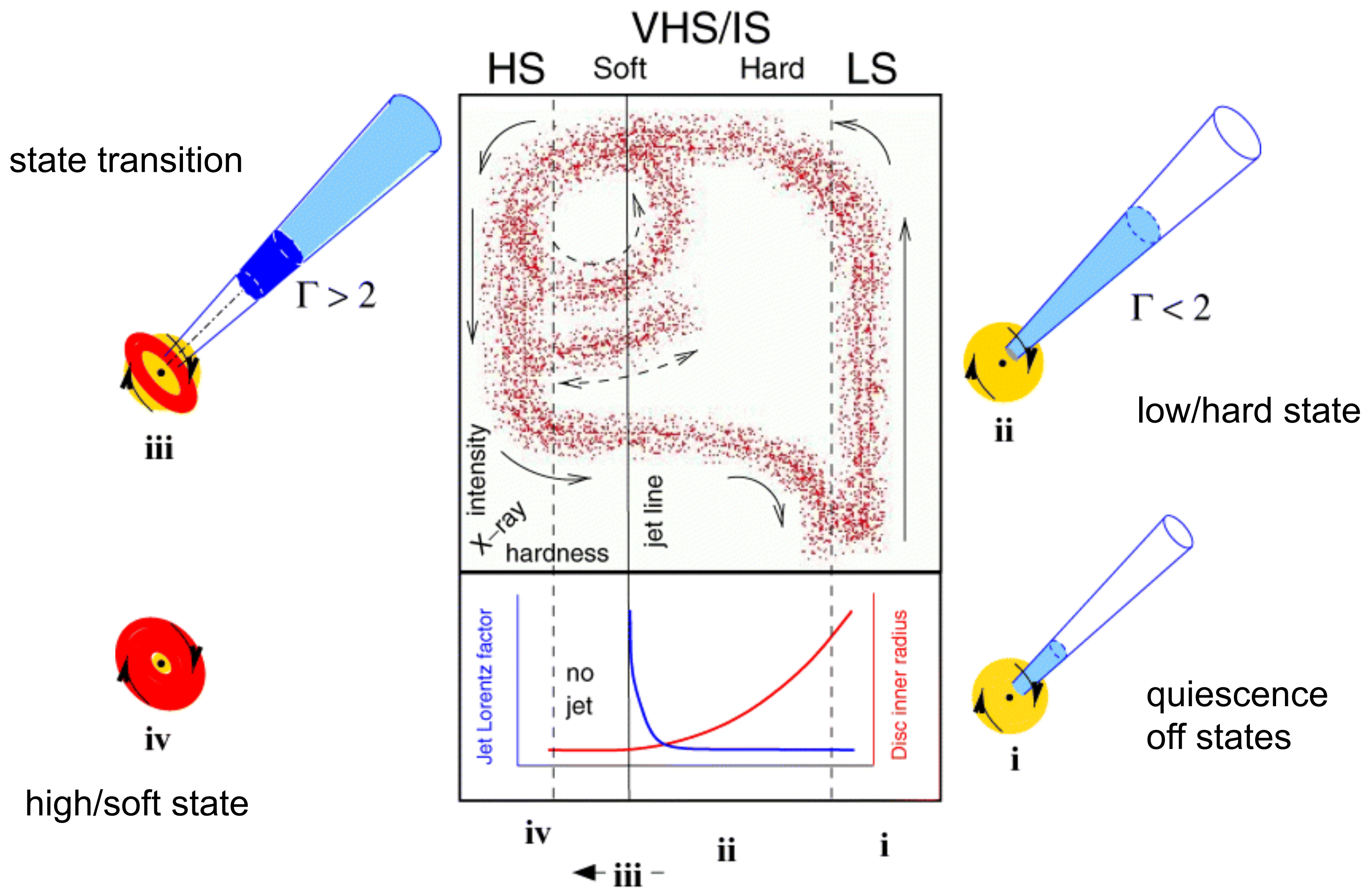
Corbel et al. 2000, A&A 359, 251

Black body from a geometrically thin optically thick accretion disk (Shakura & Sunyaev 1973).



Fender 2001, ApSSS 276, 69

Power-law from a geometrically thick optically thin plasma of electrons that comptonizes soft X-rays to higher energies: corona (Sunyaev & Titarchuck 1985, Titarchuk & Lyubarskij 1995)

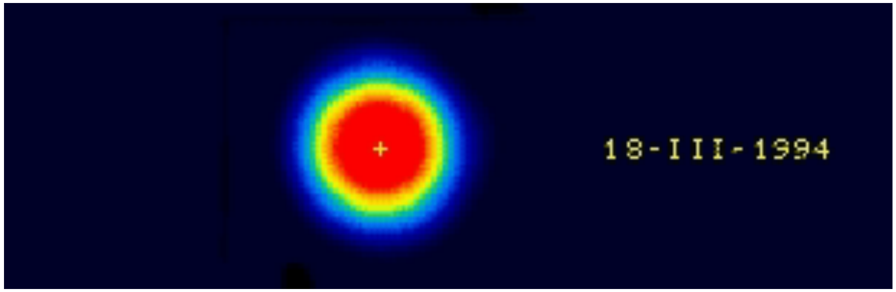


Fender et al. 2004

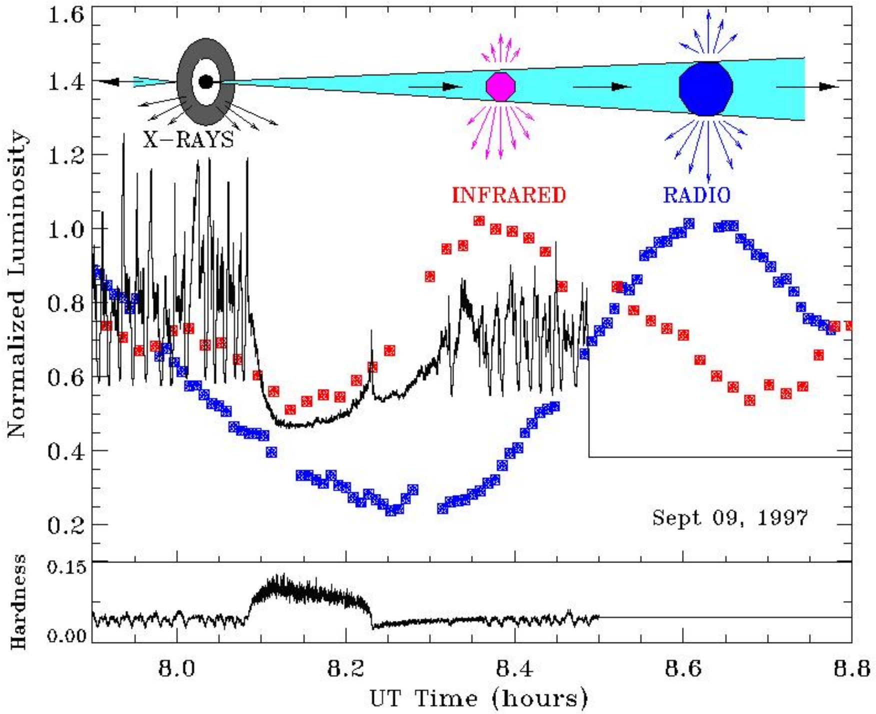
GRS 1915+105 First superluminal galactic source

- 1992: LMXB detected as very variable in X-rays
  Castro-Tirado et al. 1992

Mirabel & Rodríguez 1994, Nature 371, 46



accretion / ejection coupling



(Chaty 1998; Mirabel et al. 1998)

Cycles of 30 minutes in GRS 1915+105 :

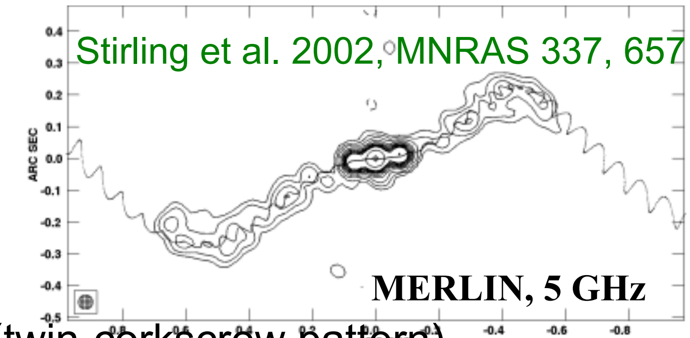
- ejections after an X-ray dip
- disappearance / refilling of the internal part of the disc ?
- transient ejections during changes of states

- same phenomenon in the quasar 3C 120 ? far slower !

SS 433 Precession of the jets

Moving lines in relativistic jets (0.26c) with precession movement. Jets precession observed in radio

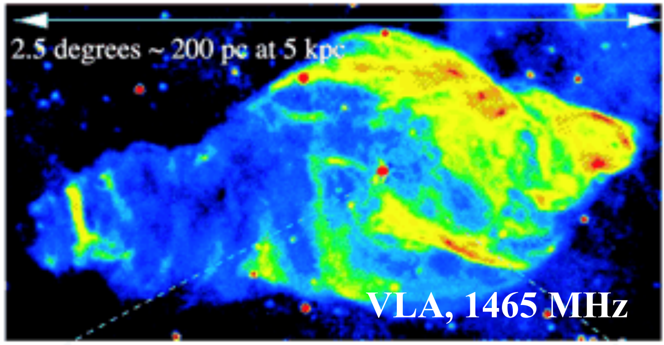
Stirling et al. 2002, MNRAS 337, 657



- Image of SS 433 and the predicted jet precession cycle (twin-corkscrew pattern)

- The surrounding W50 radio nebula. Clear traces of the interaction of the jets of SS 433 with the surrounding gas are shown

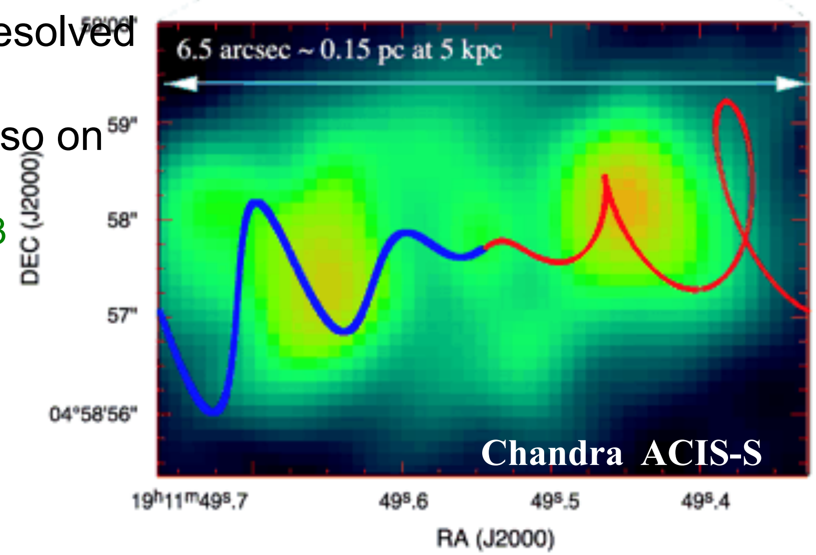
Dubner et al. 1998, AJ 116, 1842



X-ray image

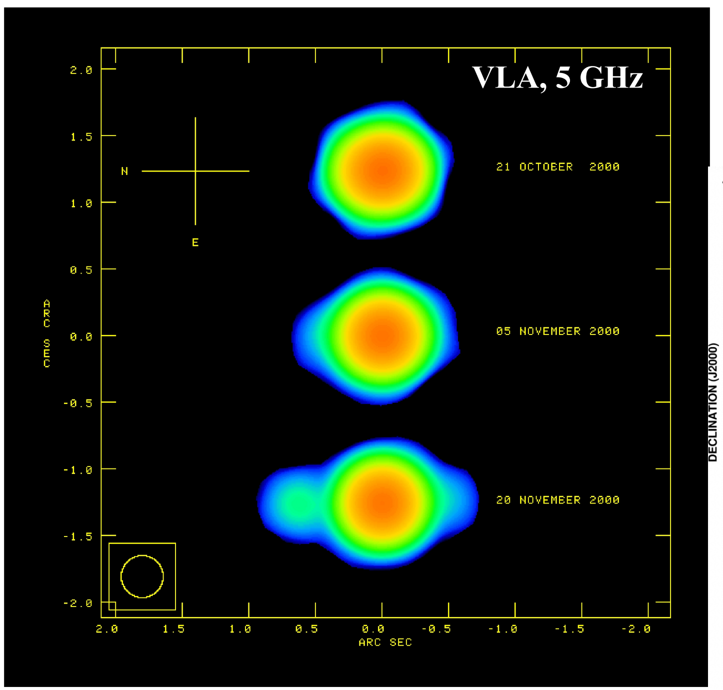
- Doppler-shifted iron emission lines from spatially resolved regions
- Particle re-acceleration in a relativistic jet can act also on atomic nuclei

Migliari et al. 2002, Science 297, 1673



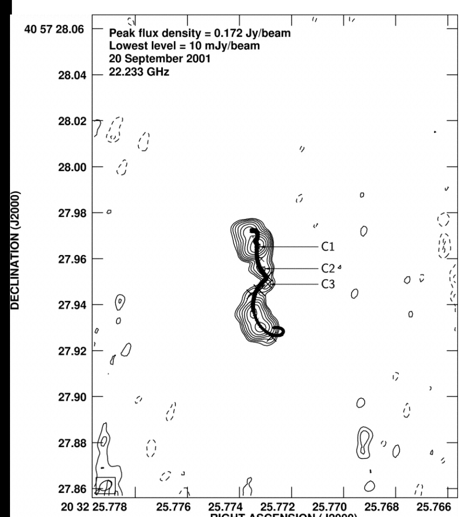
Cygnus X-3 Strong radio outbursts

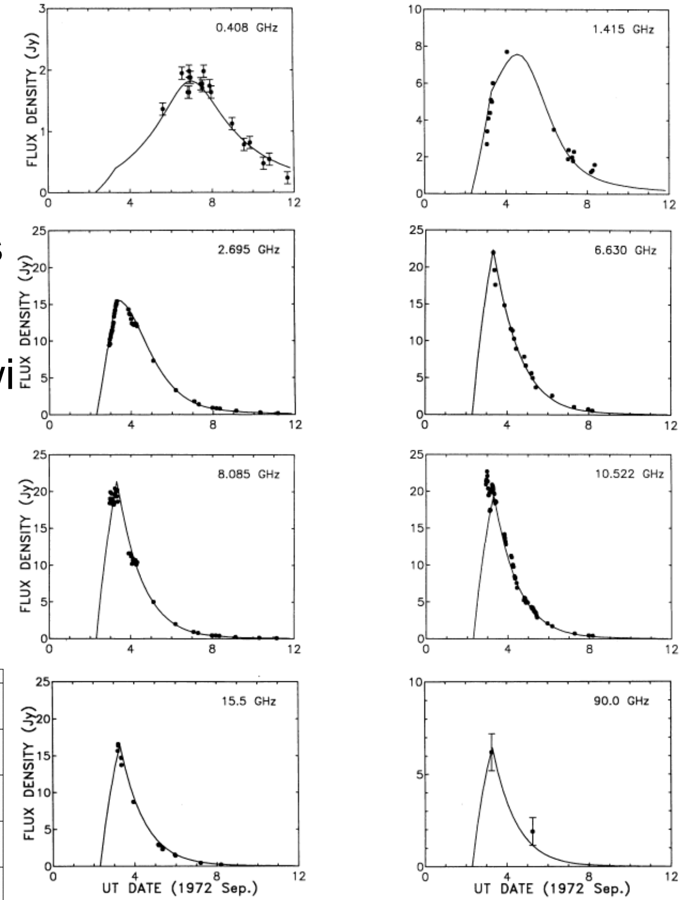
- Exhibits flaring to levels of 20 Jy or more
- In 1972 was first “caught” flaring above 20 Jy. These events are amongst the best-known examples of observed expanding synchrotron-emitting sources (21 papers Nature Phys. Sci. 239, No. 95 (1972))
- Modelling Cyg X-3 radio outbursts: particle injection into twin jets Martí et al. 1992, A&A 258, 309

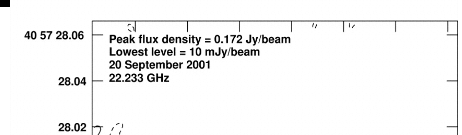


Development of arcsecond radio jets in CYGNUS X-3

Martí et al. 2001, A&A 375, 476



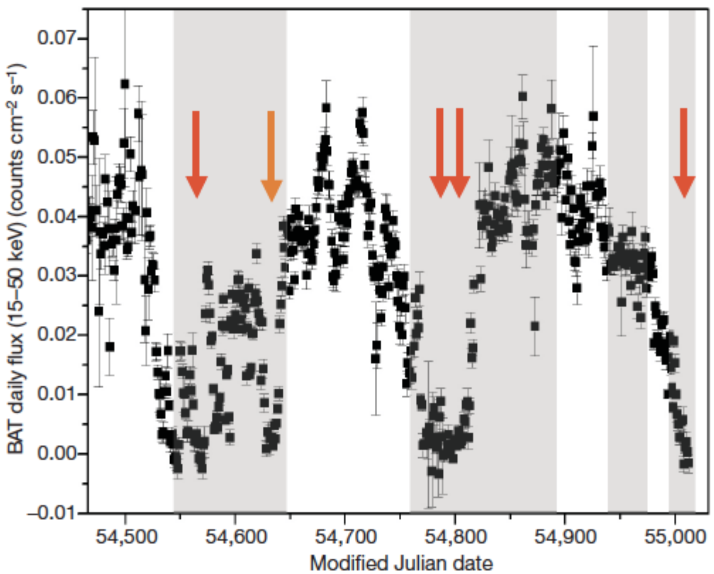


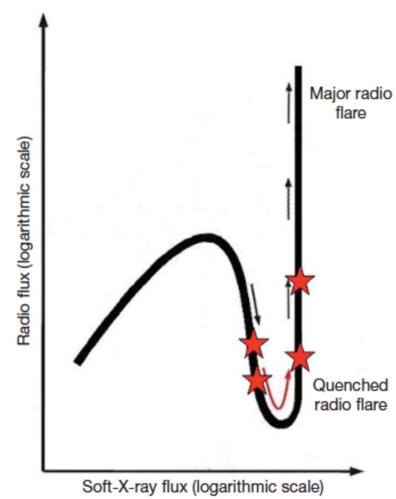


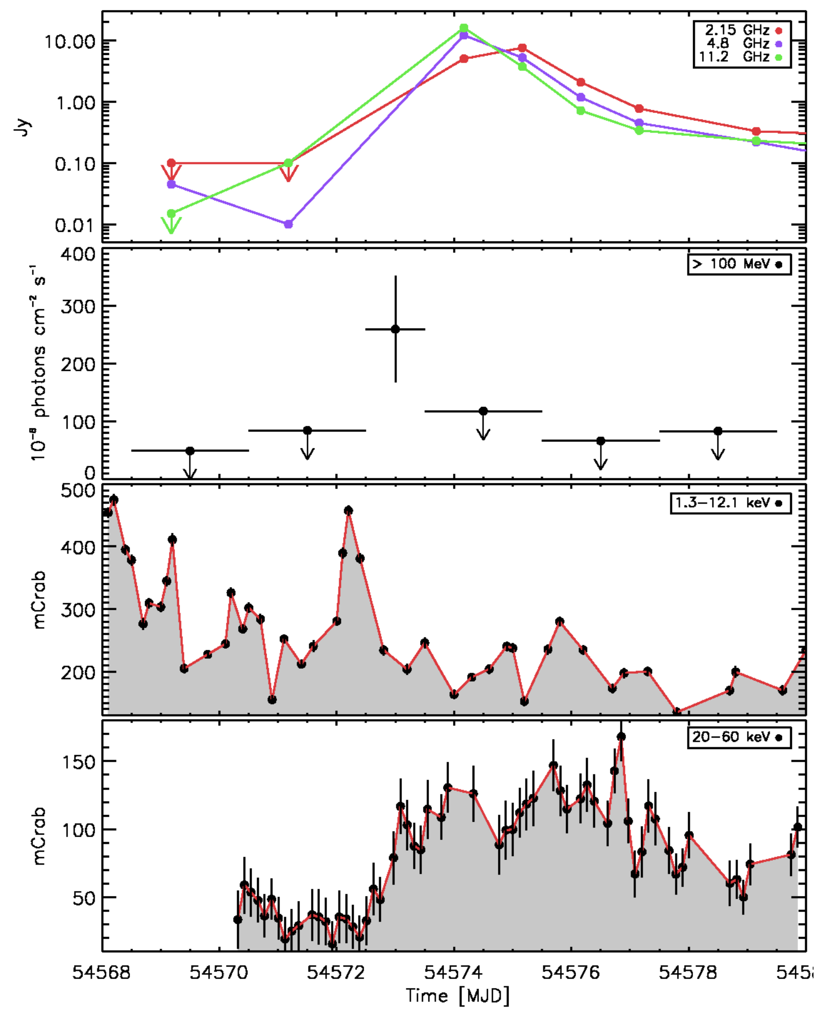
Miller-Jones et al. 2004, ApJ 600, 368

Cygnus X-3 Detection of HE Gamma-rays

AGILE



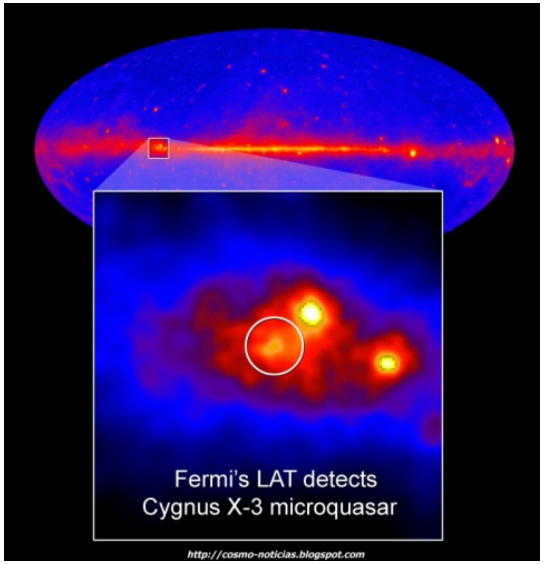


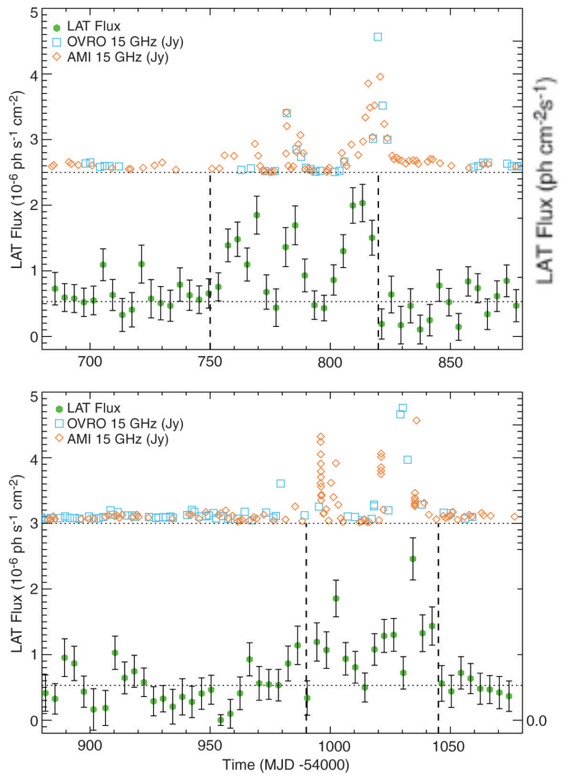


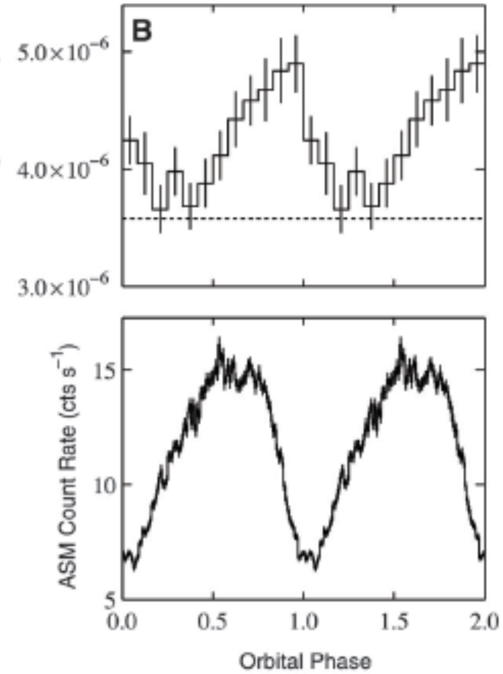
Tavani et al. 2009, Nature 462, 620

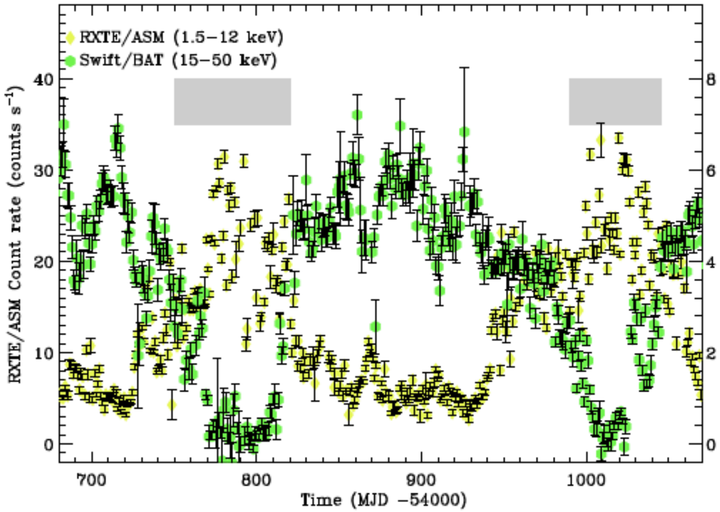
Gamma-ray flares occur then only during soft X-ray states or their transitions to or from quenched hard X-ray states

Cygnus X-3 Detection of HE Gamma-rays *Fermi*





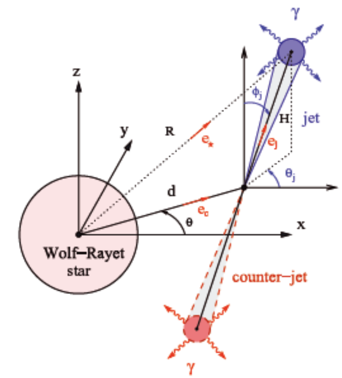




Abdo et al. 2009, Science 326, 1512

Jet IC emission
>100 MeV γ-ray modulation in Cyg X-3

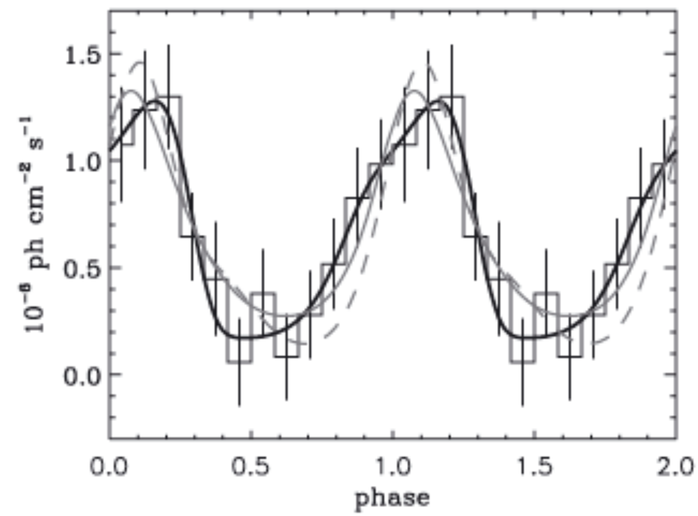
Anisotropic IC by jet relat. e^- with stellar photons along the orbit produces a modulation in the gamma-ray lightcurve (Khangulyan et al. 2008, MNRAS 383, 467)



Jet launched around a BH:

- moderate bulk relativistic speed
- oriented not too far from the light of sight
- HE e^- cannot be close to the compact object

Dubus et al. 2010, MNRAS 404, L55



- A shock occurs in the wind because (Perucho et al. 2010, A&A)
  - wind mass-loss rate is very large
  - orbit very tight

Most MQs jets will interact much further away when their pressure matches that of the ISM. Any HE particles will find a much weaker radiation environment and will be less likely to produce a (modulated) IC γ-ray

Anisotropic IC $e^{\pm}$ pair cascade model. The optical depths for γ-rays created inside the binary system are huge. Escape of γ-rays with energies above a few tens of GeV is not very likely.

Bednarek, 2010, MNRAS

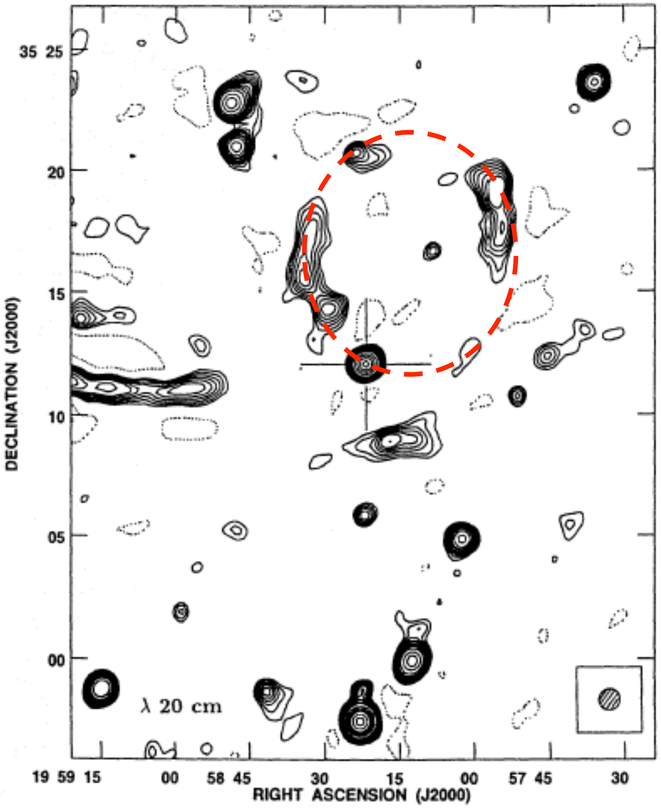
Cygnus X-1

Stellar Mass Black Hole

- HMXB, O9.71+BH

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

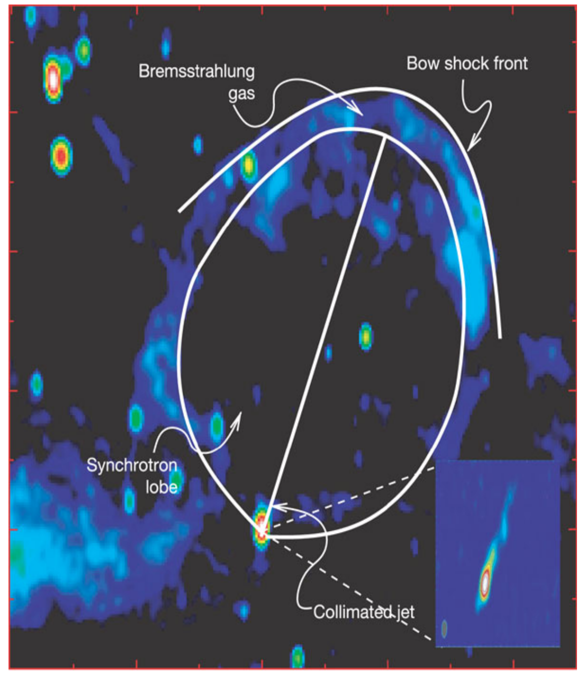
VLA



Cyg X-1. On the other hand, it is intringuing that Cyg X-1 does appear surrounded by several clumps of extended emission. All these clumps also appear in maps made from the individual visibility data sets. At a marginal level, their disposition reminds an elliptical ring-like shell with Cyg X-1 offset from the center by a few arcminutes.

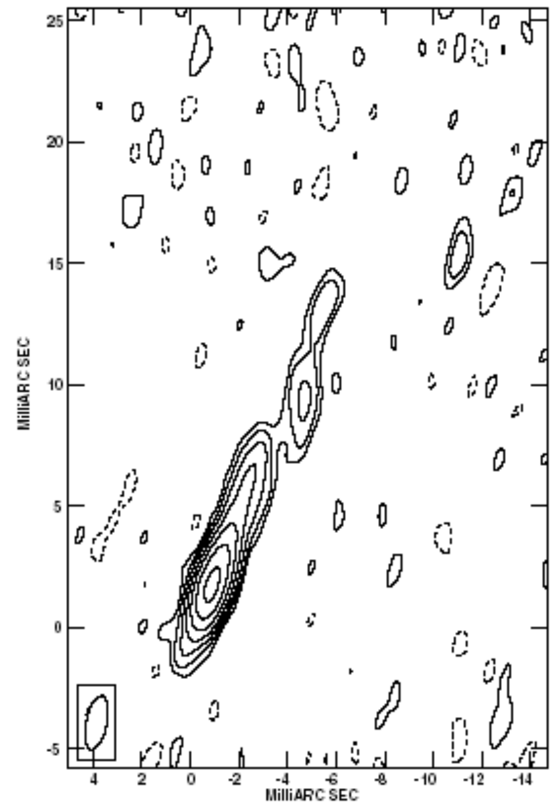
Martí et al. 1996, A&A 306, 449

WSRT



Gallo et al. 2005, Nature

VLBA+VLA



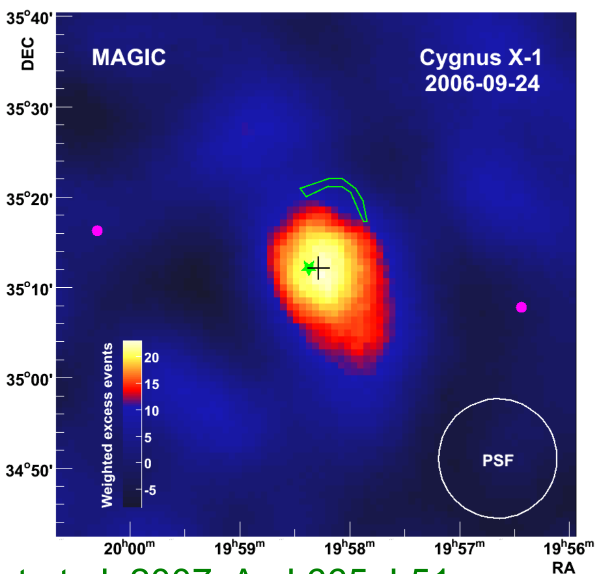
15 mas 30 AU

Stirling et al. 2001, MNRAS 327, 1273

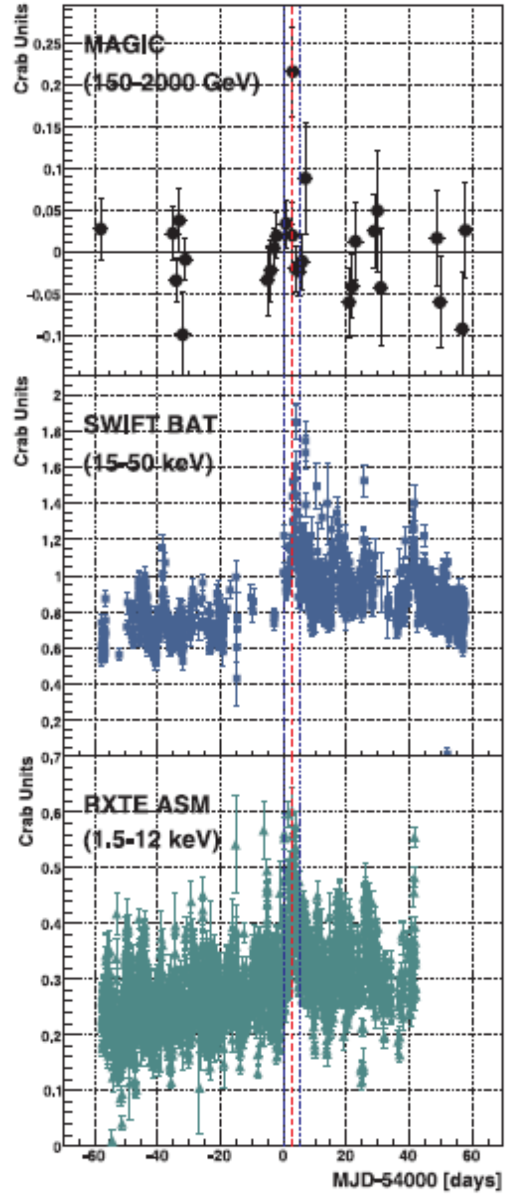
Cygnus X-1 Detection (?) of VHE Gamma-rays

TeV source

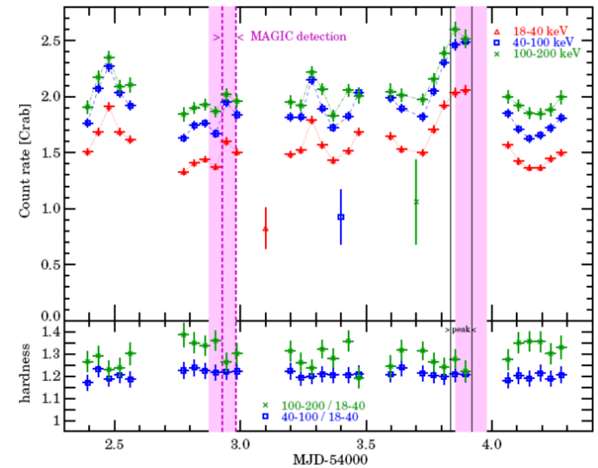
MAGIC



Albert et al. 2007, ApJ 665, L51



INTEGRAL



Malzac et al. 2008, A&A 492, 527

- Strong evidence (4.1s post trial significance) of intense short-lived flaring episode
- Orbital phase 0.9-1.0, when the black hole is behind the star and photon-photon absorption should be huge: flare in the jet?

Hard X-rays ==> base of the jet (non-thermal e in the hot comptonising medium, McConnell et al. 2002)

γ-rays ==> further away by interaction with stellar wind (shocks located in the region where the outflow originating close to the BH interacts with the wind of the star, Perucho & Bosch-Ramon 2008, A&A 482, 917)

Cygnus X-1

Detection (?) of HE Gamma-rays

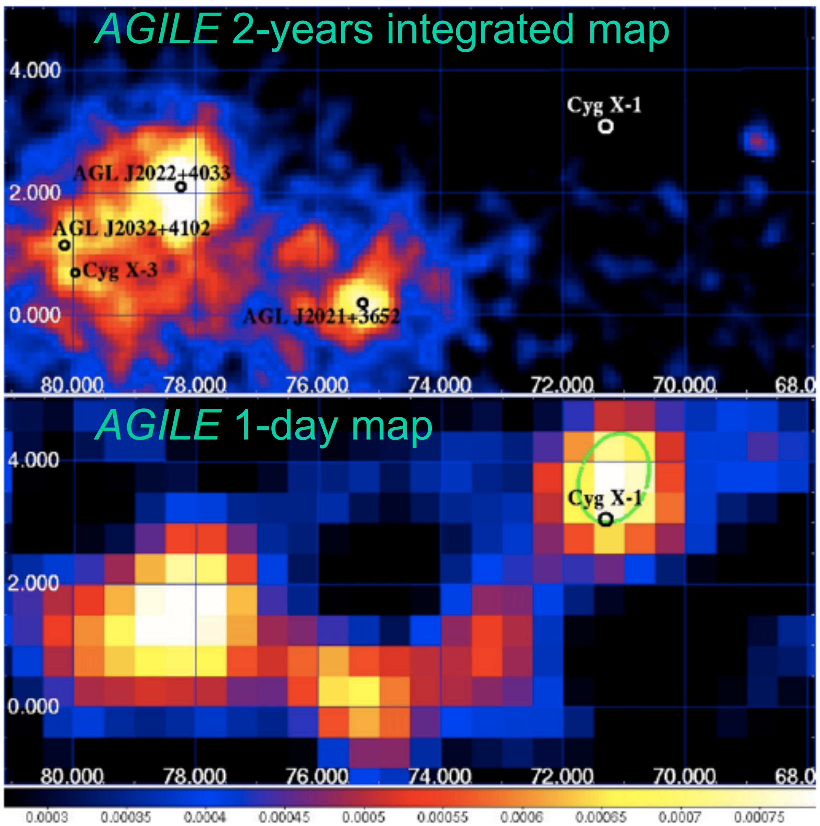
Detected (>100 MeV) by *AGILE* (Sabatini et al. 2010, ApJ 712, 10 and ATel ♯2715)

not by *Fermi*/LAT (Abdo et al. 2010, ATels and *Fermi*/LAT blog)

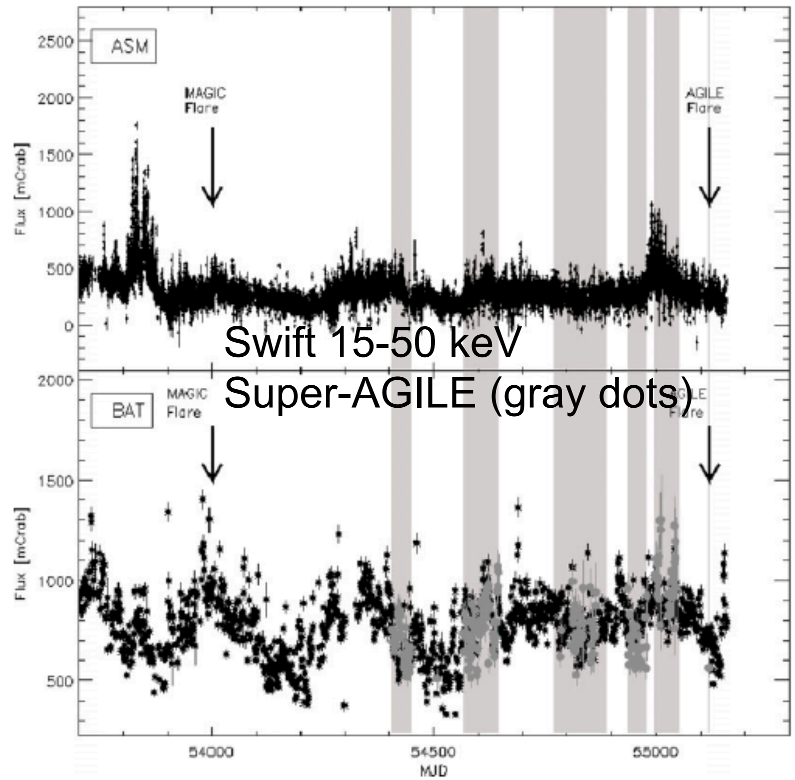
The detection

spans 1 d in about 2 years of observations

occurred during a low luminosity low/hard state



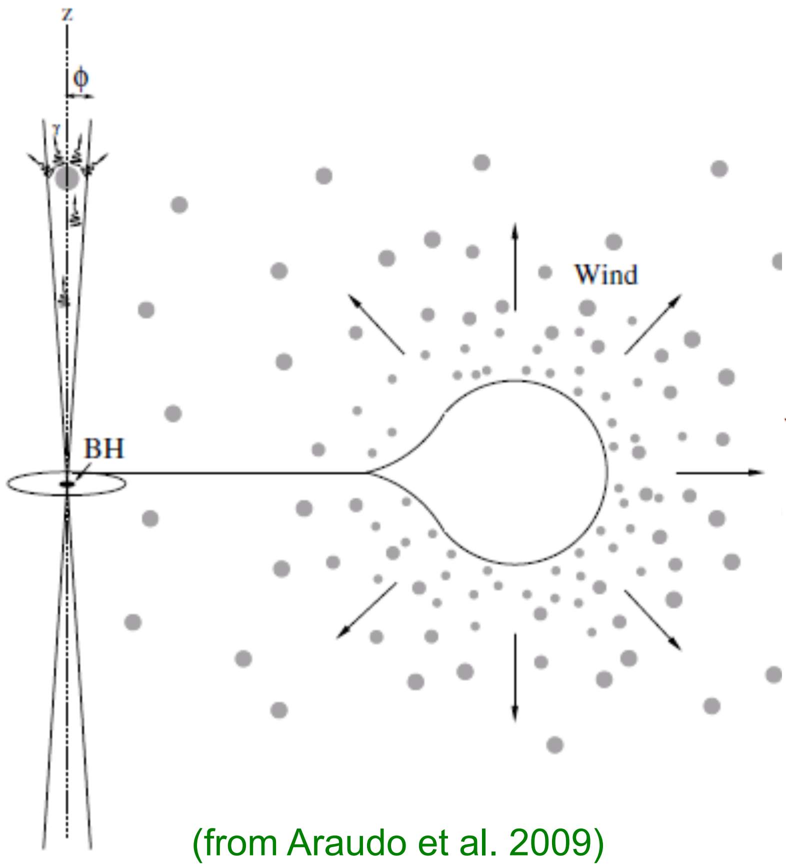
RXTE 2-10 keV



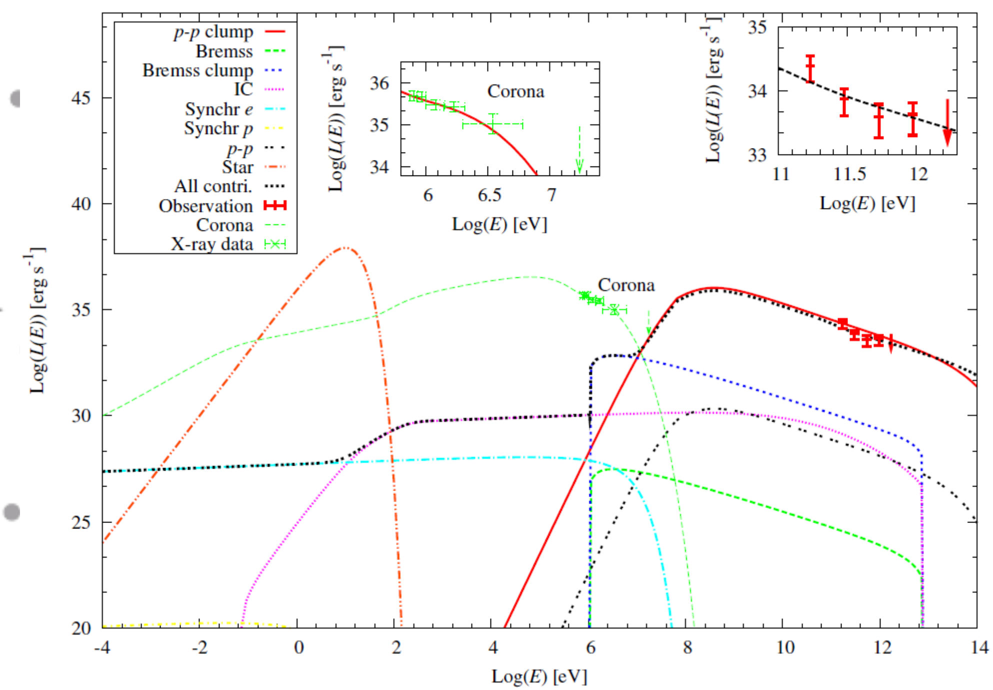
October 16, 2009

Black circle: optical position   Green contour: AGILE 2sig confidence level

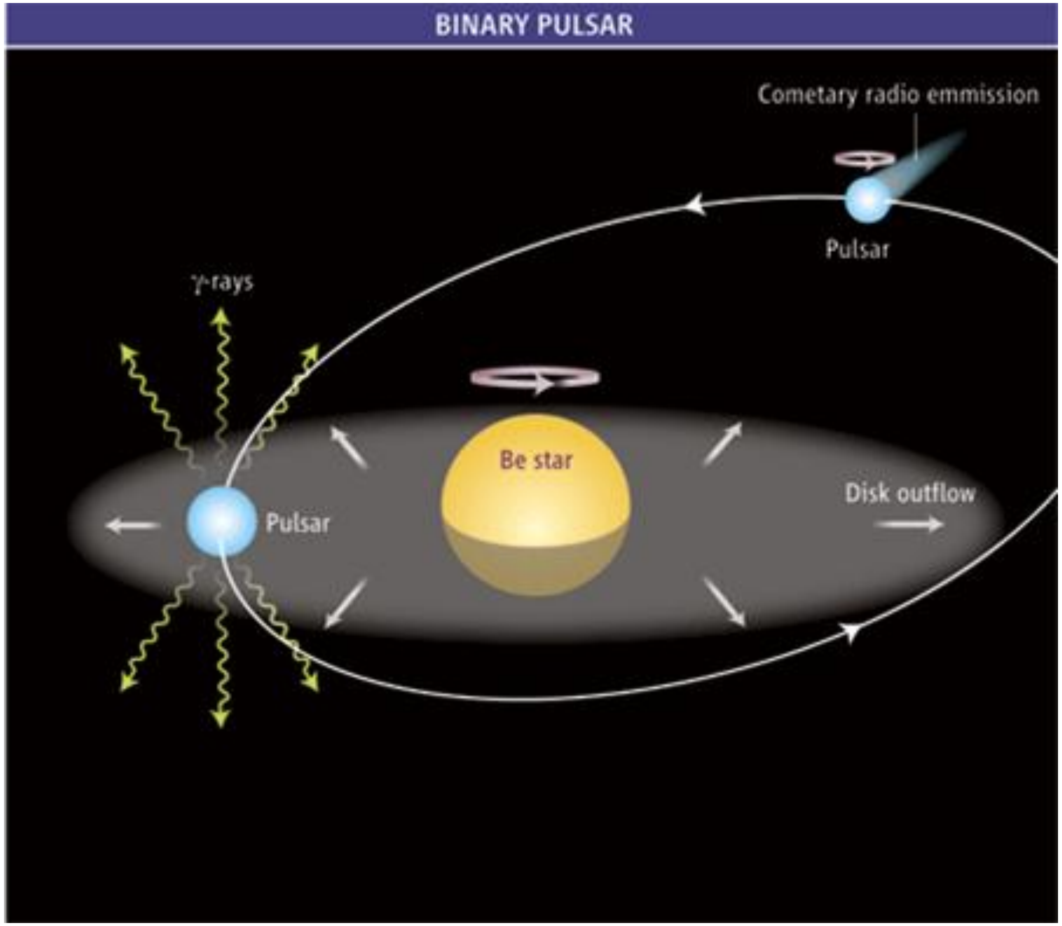
TeV flare seen by MAGIC interpreted as a jet-cloud interaction. Protons in the jet interact with ions in a cloud of a clumpy wind from the companion, producing inelastic p-p collisions and pion decay which produces a flare in TeV gamma rays (Romero et al. 2010, A&A 518, 12)



(from Araudo et al. 2009)



Gamma-ray binaries



Gamma-ray binary:

- A binary star system containing a non-accreting pulsar orbiting a massive luminous star
- SED peak at GeV (possibly dominating total flux)
- The gamma-ray emission is caused by an interaction between the two binary components

4 gamma-ray binaries have been detected at TeV energies:

- PSR B1259−63 by HESS (Aharonian et al. 2005, A&A, 442, 1)
- LS 5039 by HESS (Aharonian et al. 2005, Science, 309, 746)
- LS I +61 303 by MAGIC (Albert et al. 2006, Science, 312, 1771)
- HESS J0632+057 by HESS (Hinton et al. 2009, Skilton et al. 2009), MAGIC and VERITAS

Two gamma-ray binary candidates have been detected:

- AGL J2241+4454 (HD 215227?) by *AGILE*
- 1FGL J1018.6-5856 by *Fermi*

All of them are found in HMXBs, were:

- A huge UV photon field is available for inverse Compton scattering
- A decretion disk might exist, providing targets for *pp* collisions an p^0 decay

LMXBs are transient sources, and one has to observe at the right time!

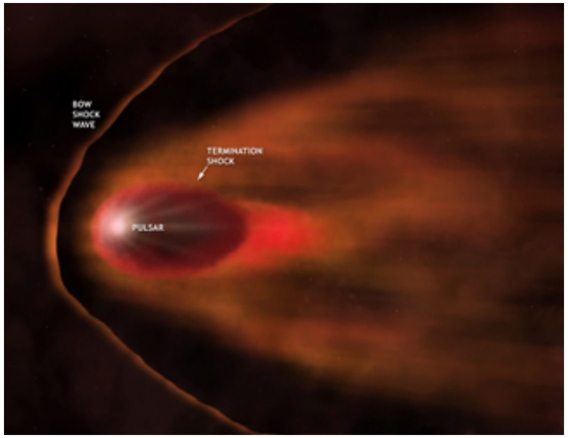
Non-accreting young pulsar scenario

• The relativistic wind of a young (ms) pulsar is contained by the stellar wind.

• Particle acceleration at the termination shock leads to synchrotron emission and inverse Compton emission

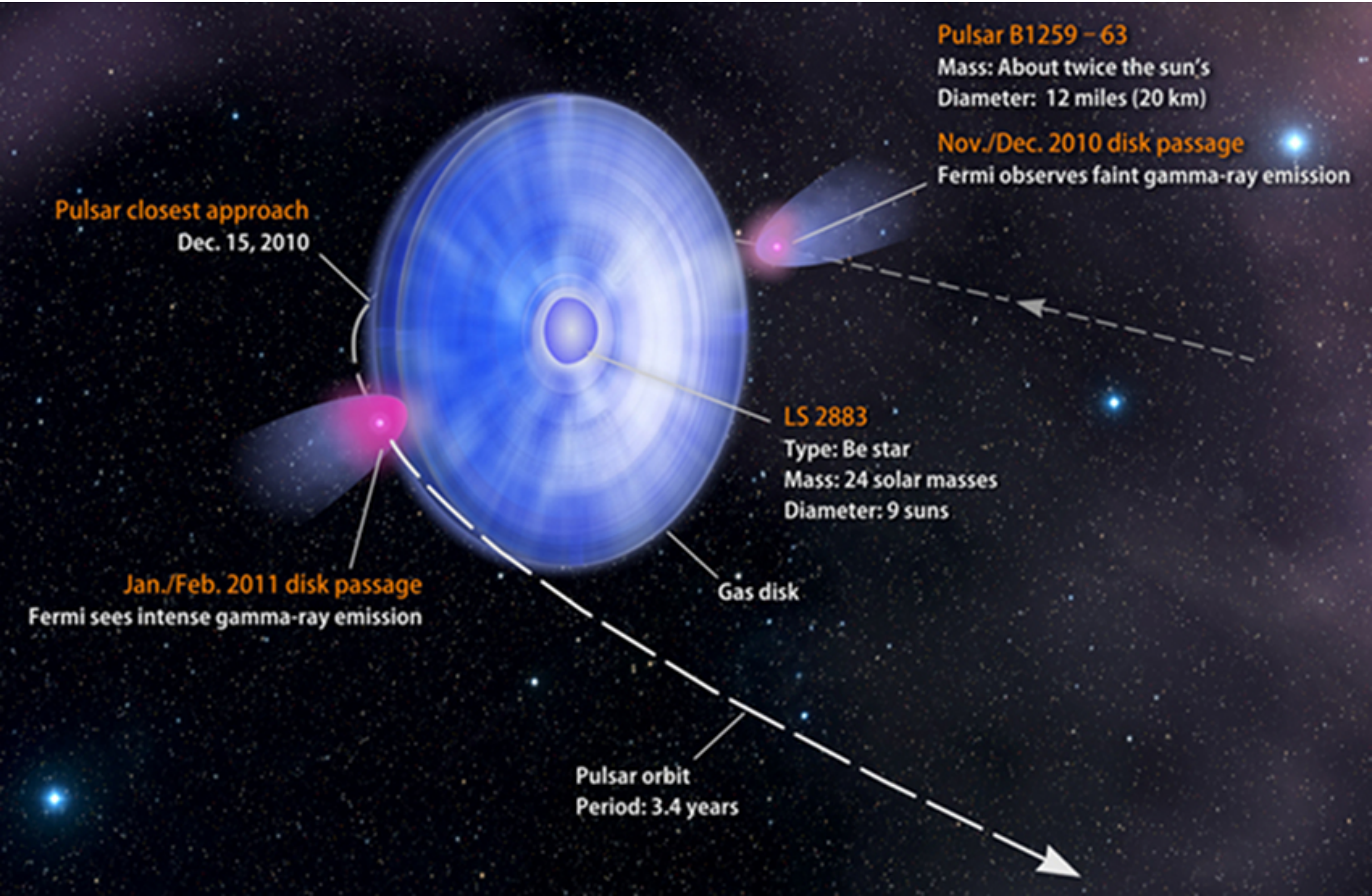
• After the termination shock, a nebula of accelerated particles forms behind the pulsar

• The cometary nebula is similar to the case of isolated pulsars moving through the ISM

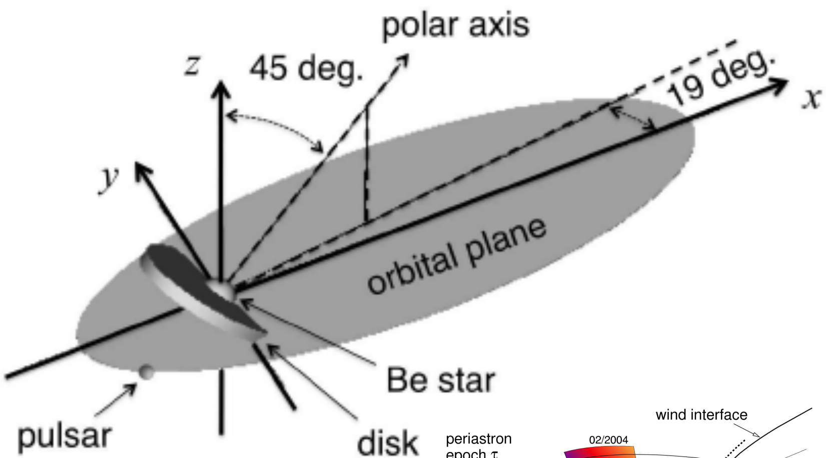


PSR B1259-63 *Young pulsar wind interacting with the companion star*

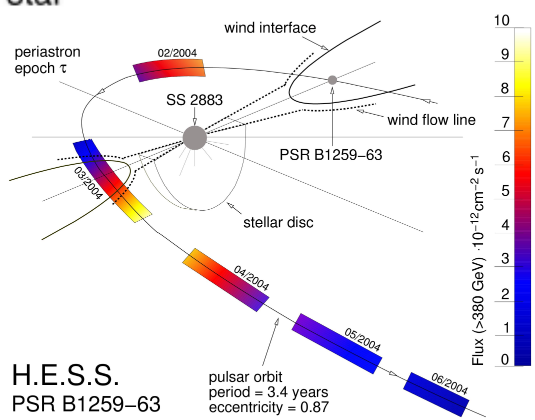
The first variable galactic source of VHE



- PSR B1259-63 / LS 2883: O8.5-9 Ve (Negueruela et al. 2010)
- Dense equatorial circumstellar disk) + 47.7 ms radio pulsar, *P*= 3.4 yr, *e*=0.87
- The elliptic orbit with long (3.4-yr) period offers a unique experimental field of wind interaction with varying distance between the pulsar and the Be star (Kawachi et al. 2004, Okazaki et al. 2011)
- No radio pulses are observed when the NS is behind the circumstellar disk (free-free absorption)
- The observed **X-ray/soft gamma-ray** emission was consistent with the shock-powered high-energy emission produced by the pulsar/outflow interaction



Tavani & Arons 1997, ApJ 477, 439 studied the radiation mechanisms and interaction geometry in a pulsar/Be star system



VHE gamma-rays are detected when the NS is close to periastron or crosses the disk (Aharonian et al. 2005, A&A 442, 1)

- significant variability

-power-law spectrum (Γ=2.7) explained by IC scattering processes

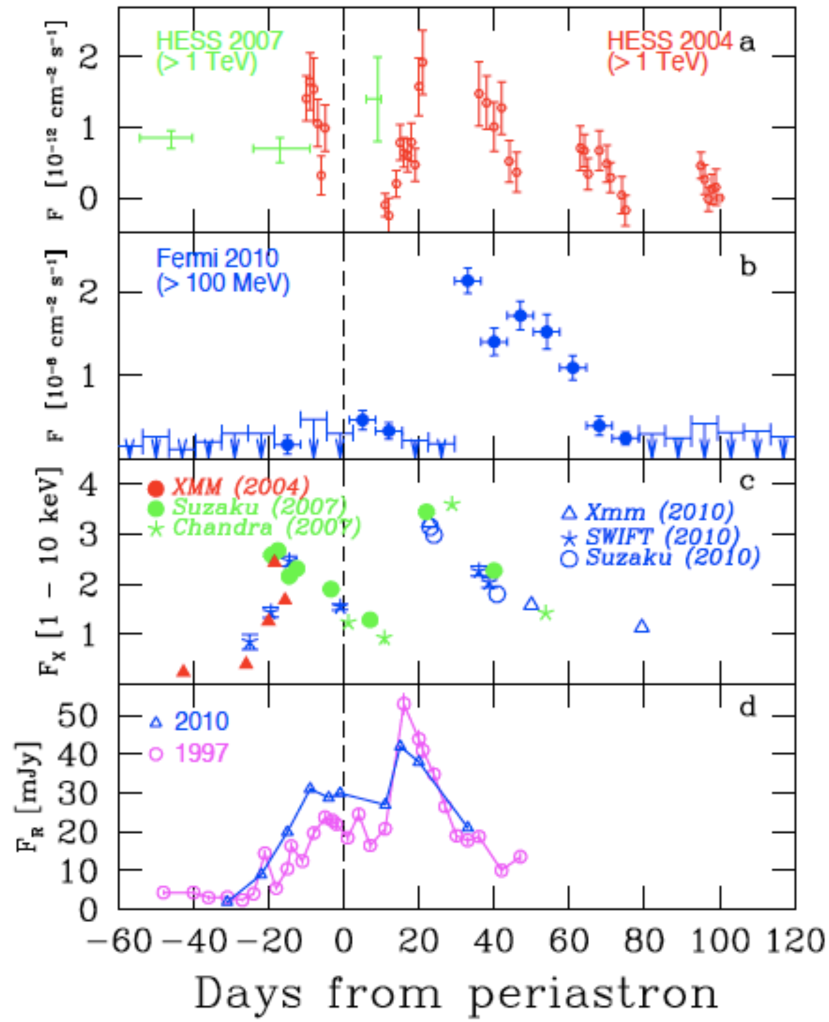
The firm detection of VHE photons emitted ~50 days prior to the periastron passage, disfavors the stellar disk target scenario as a primary emission mechanism

Aharonian et al. 2009, A&A 507, 389

Abdo et al. 2011, arXiv 1103.4108

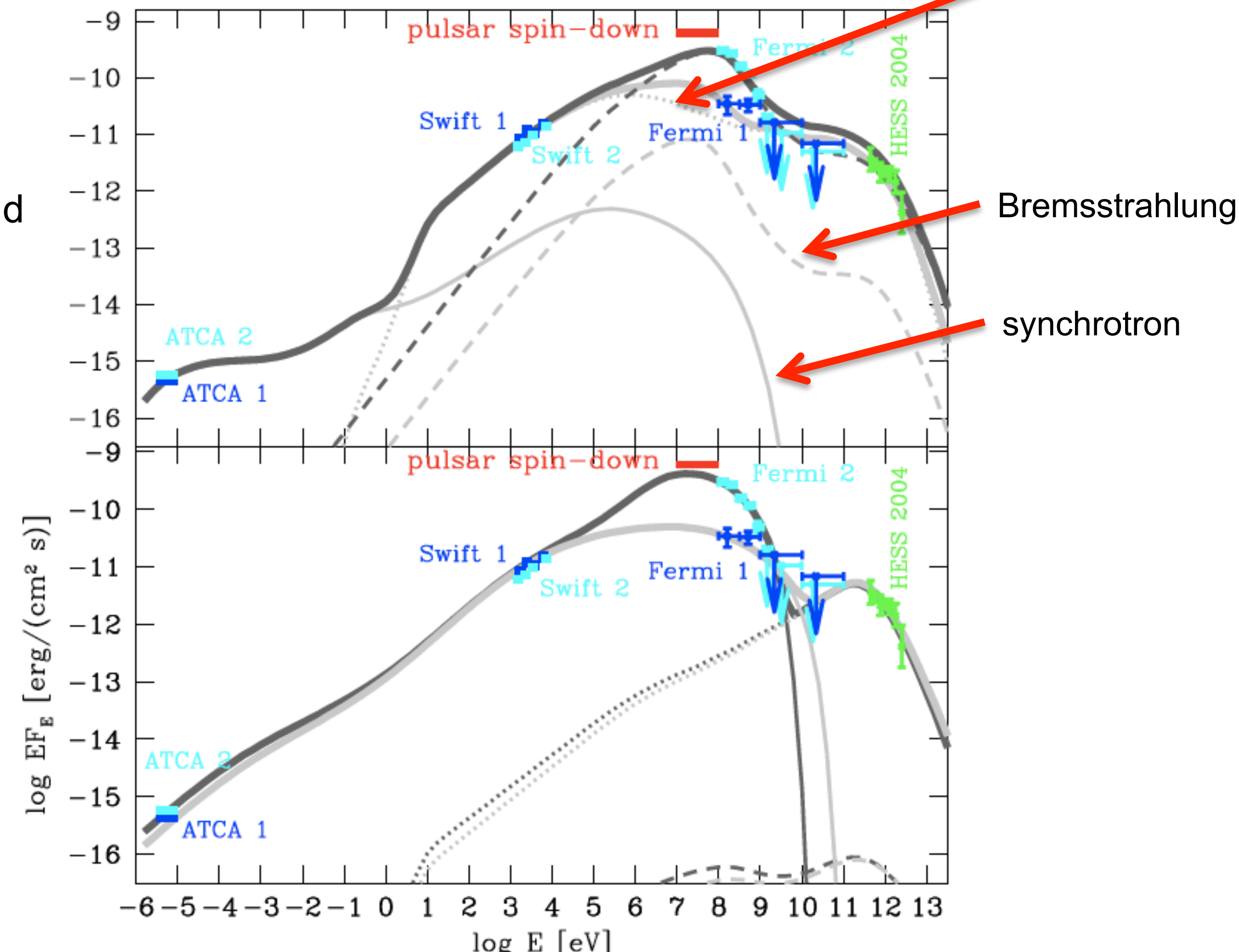
Chernyakova et al. 2006, MNRAS 367, 1201

Johnston et al. 1999



3D simulations: the pulsar wind strips off an outer part of the Be disk on the side of the pulsar, truncating the disk at a radius significantly smaller than the pulsar orbit. These results rule out the idea that the pulsar passes through the Be disk around periastron, which has been assumed in the previous studies Okazaki et al. 2011, astro-ph 1105.1481.

The high-energy particles are assumed to escape from the system with the speed of the stellar wind c/3

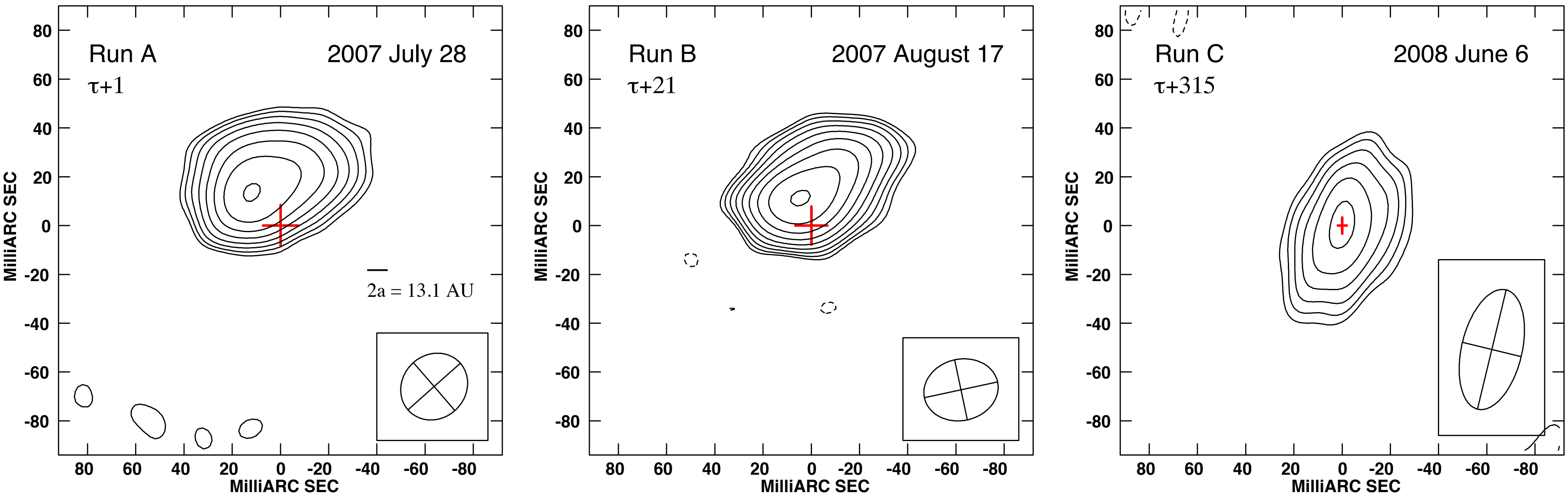


Abdo et al. 2011, arXiv 1103.4108

Australian Long Baseline Array (LBA)
2.3 GHz

New

Moldón et al. 2010, 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

This is the first observational evidence that non-accreting pulsars orbiting massive stars can produce variable extended radio emission at AU scales

Run	S_{total} (mJy)	S_{peak} (mJy beam^{-1})	Size (mas)	Size (AU)	P.A. (°)	$\Delta\alpha$ (mas)	$\Delta\delta$ (mas)	Separation (mas)	Separation (AU)
A	19.9±1.4	10.4±0.2	50	120±20	−67	11.3±0.4	14.0±0.5	(14–22)±1	(31–51)±3
B	46.7±1.0	32.7±0.4	55	132±22	−50	4.2±0.1	11.3±0.1	(9–16)±1.3	(20–36)±3
C	3.0±0.4	2.8±0.4	<2.8	<6.7±1.1	…	0.0±0.6	0.0±1.1	…	…

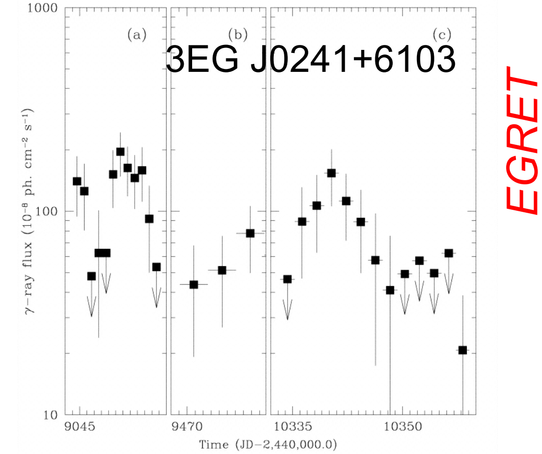
LS I +61 303

- HMXB, B0Ve+NS?

  COS-B γ-ray source CG/2CG 135+01

  Hermsen et al. 1977, Nature 269, 494

Tavani et al. 1998, ApJ 497, L89

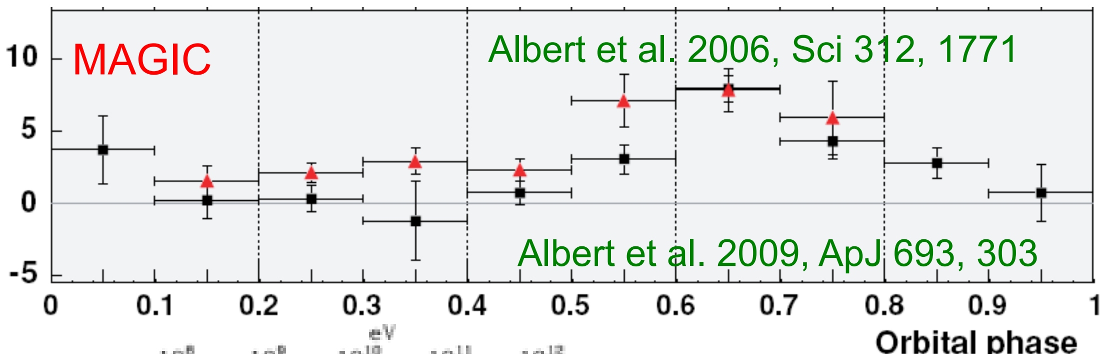


periodicity

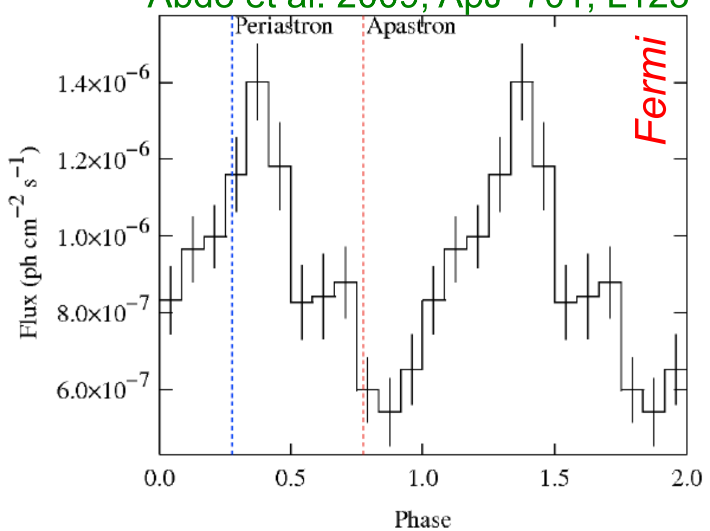
Radio (P=26.496 d) Taylor & Gregory 1982, ApJ 255, 210

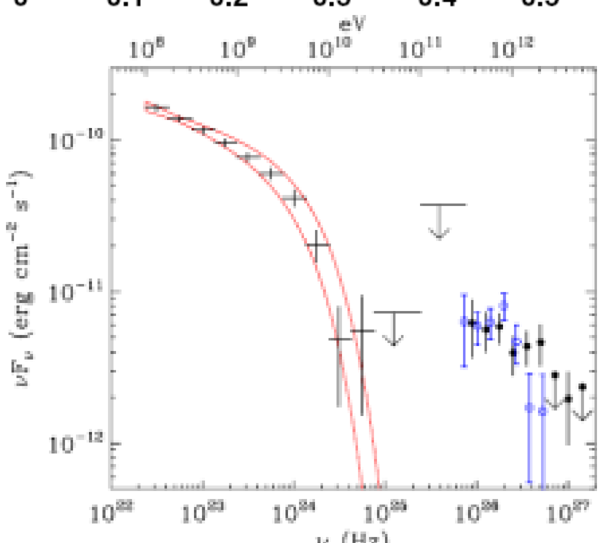
Optical and IR Mendelson & Mazeh 1989, MNRAS 239, 733; Paredes et al. 1994 A&A 288, 519

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



Abdo et al. 2009, ApJ 701, L123



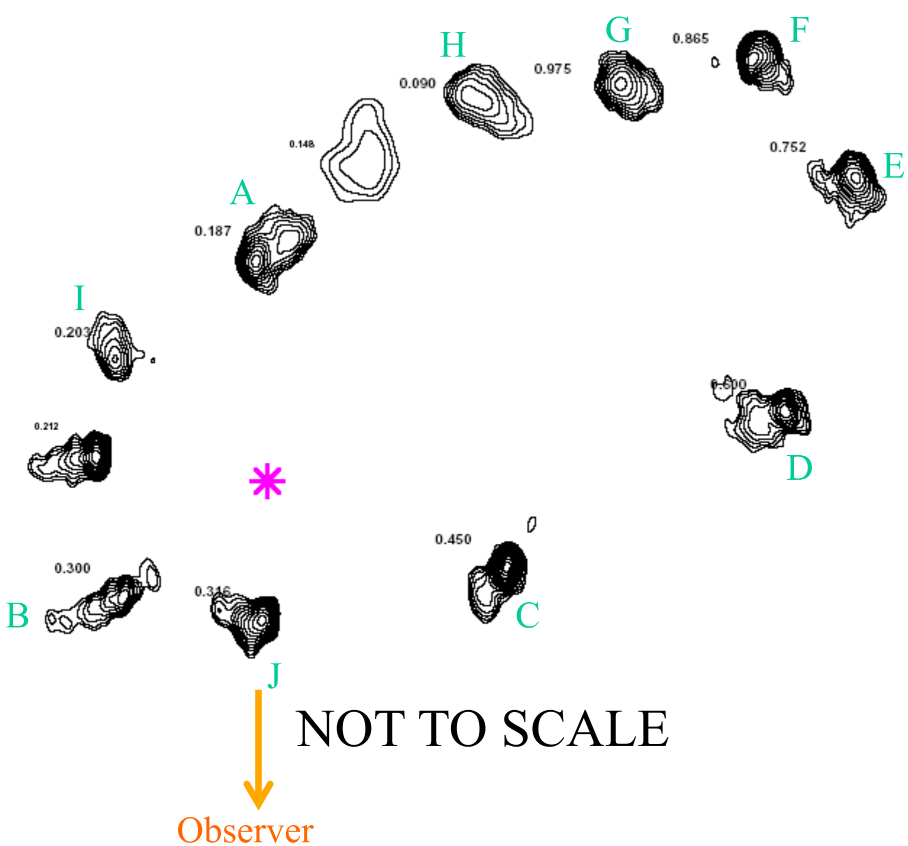


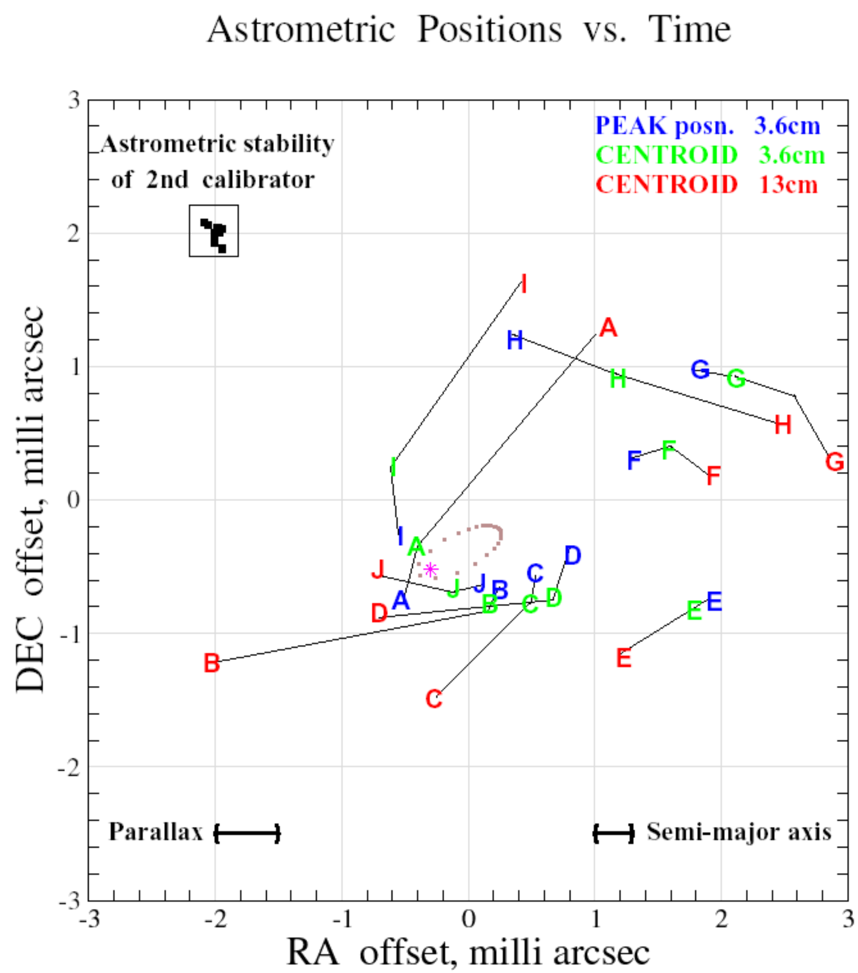
Fermi
MAGIC blue, 0.5-0.7
VERITAS black, 0.5-0.8

Link between HE and VHE γ-rays is nontrivial

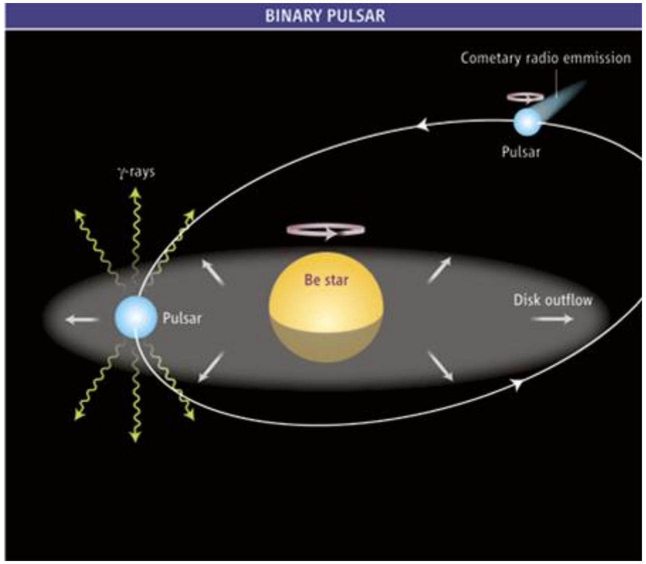
VLBA

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)



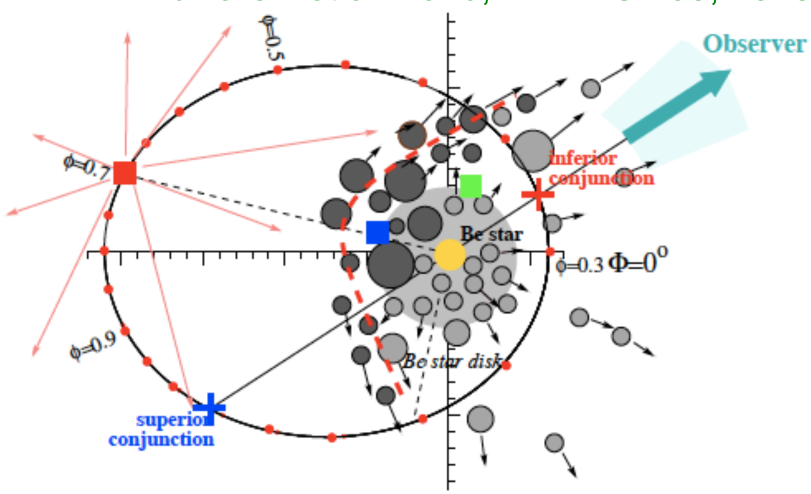


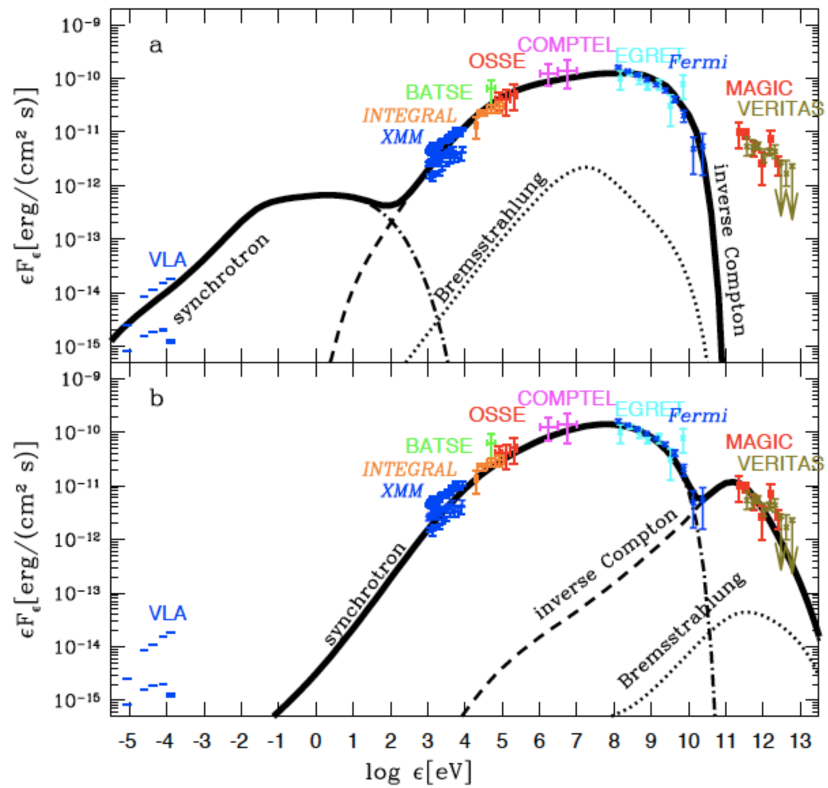
3.6cm images, ~3d apart, beam 1.5x1.1mas or 3x2.2 AU.
Semi-major axis: 0.5 AU



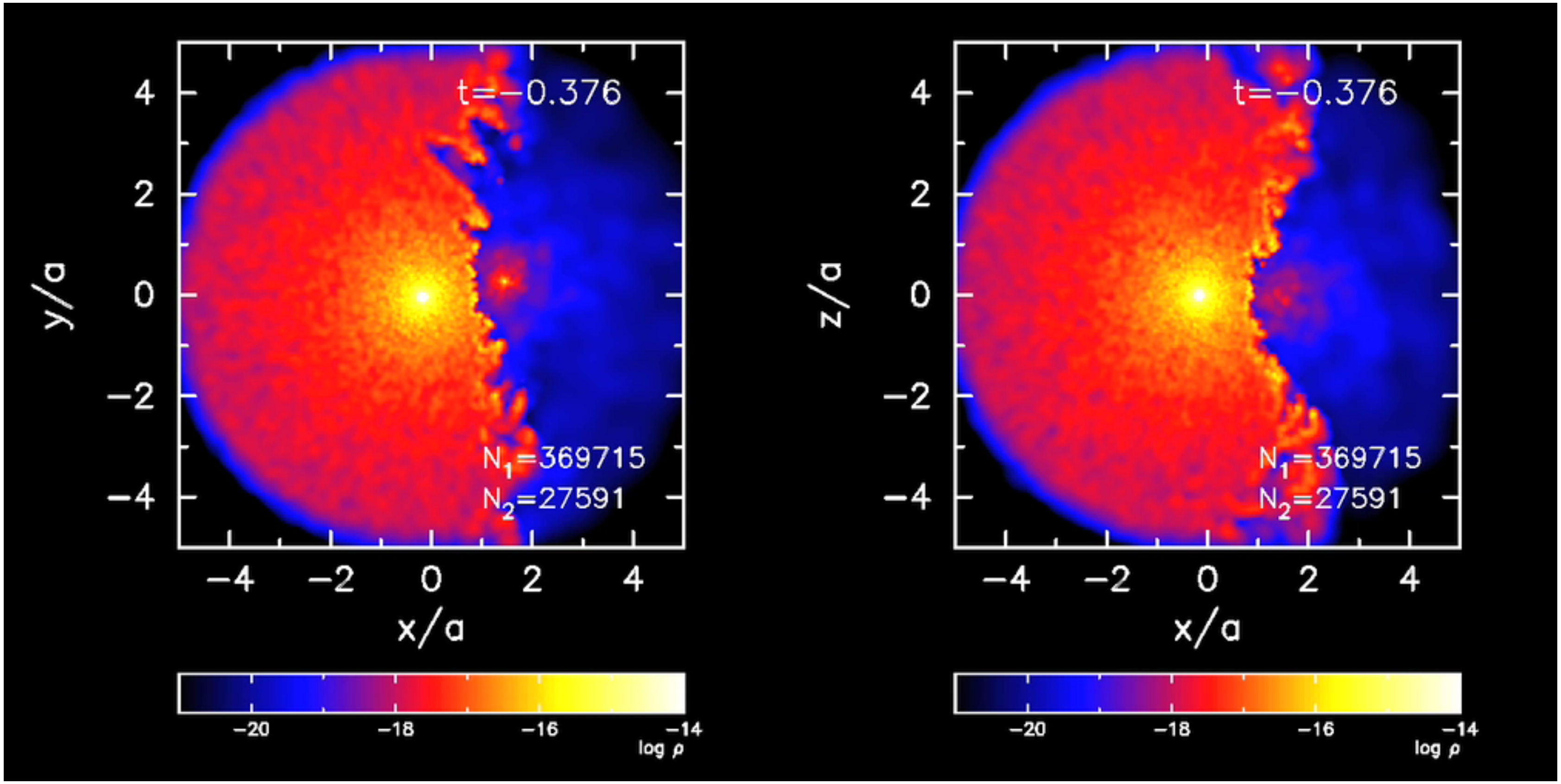
Pulsar scenario: Interaction of the relativistic wind from a young pulsar with the wind from its stellar companion. A comet-shape tail of radio emitting particles is formed rotating with the orbital period. We see this nebula projected (Dubus 2006, A&A 456, 801). UV photons from the companion star suffer 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)



Romero, Okazaki et al. (2007, A&A 474, 15)

"Smoothed Particle Hydrodynamics" (SPH) code in 3D

orbital effects

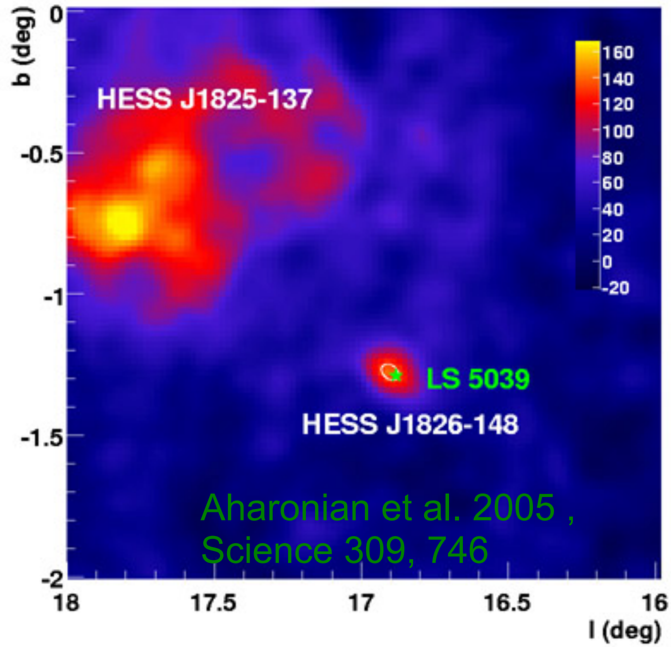
most favourable assumptions toward a large Be/pulsar wind momentum ratio

do not produce the simple elongated shape inferred in the VLBI radio image

LS 5039

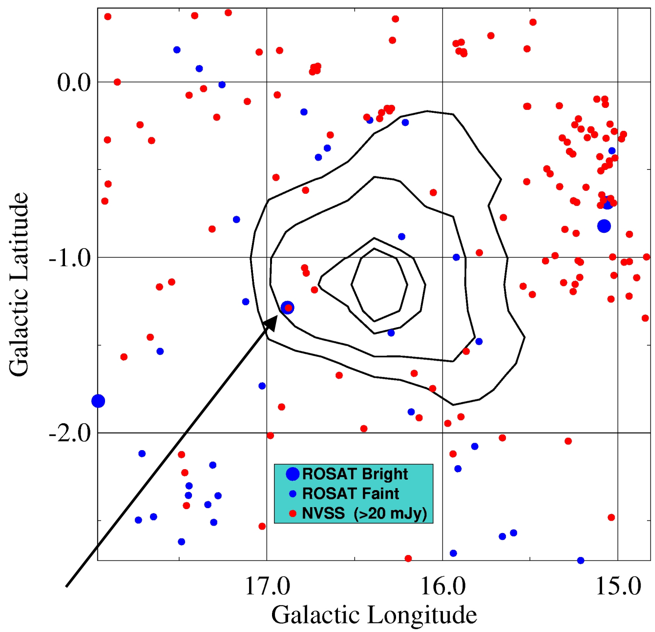
- HMXB, O6.5V+NS?

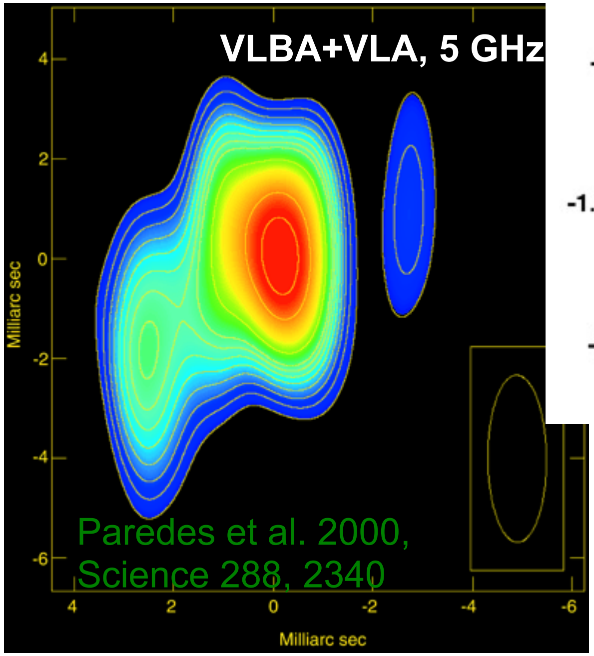
HESS



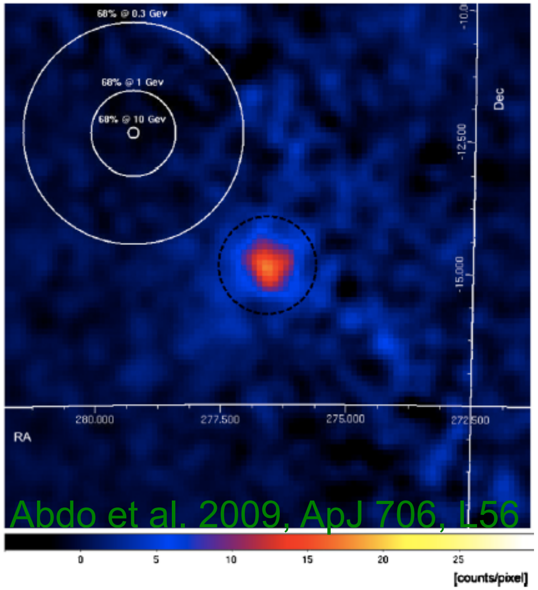
EGRET

3EG J1824-1514



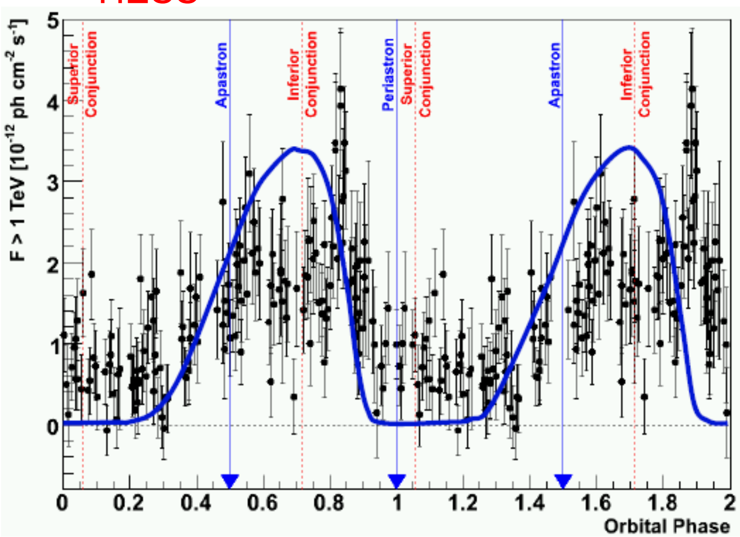


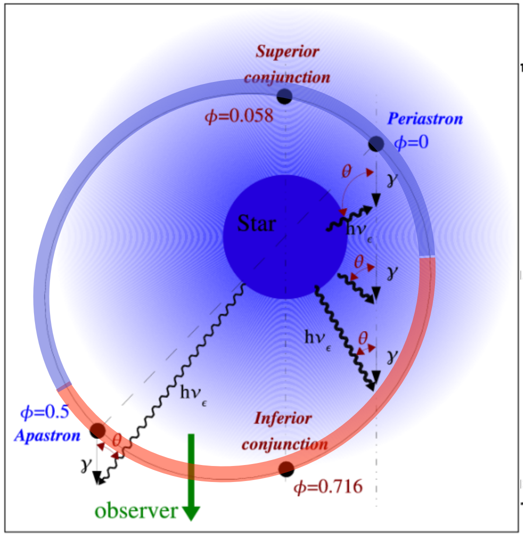
Fermi

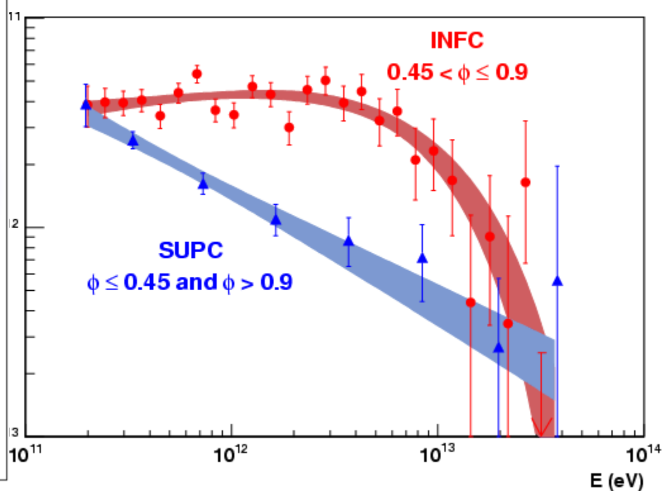


Variable TeV emission with the orbital period of the binary system. Flux maximum at inferior conjunction of the compact object (Aharonian et al. 2006).
This suggests that γ-γ absorption (e^+-e^- pair production on stellar UV photons), which has an angle dependent cross-section plays a major role but…

HESS





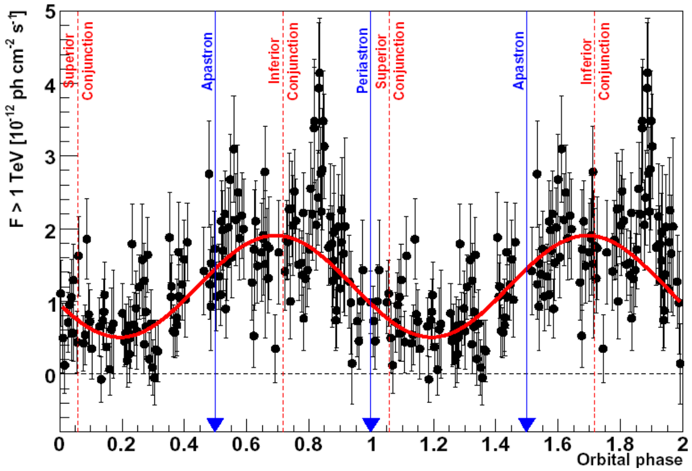


… the flux should be 0 at periastron and superior conjunction, and is not!
… the spectrum shows strong variability, but not at 200 GeV as predicted by absorption models! (Dubus 2006, Böttcher 2007)

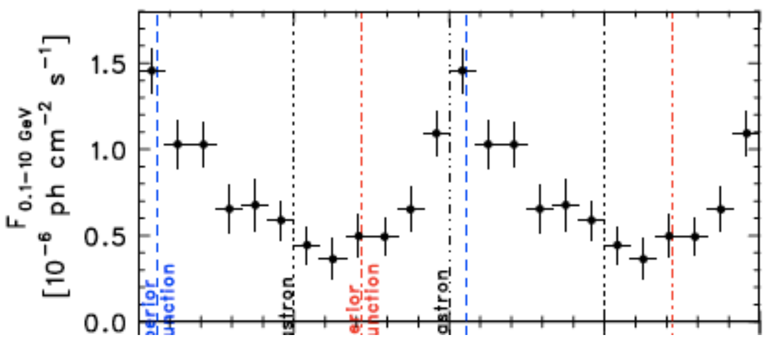
- Cascading has to be modeled in detail (Cerutti et al. 2010).
- Phase-dependent electron acceleration? Accretion or wind interaction?
- The TeV emission could be produced away from the compact object. Maybe in jets… if there are jets!

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

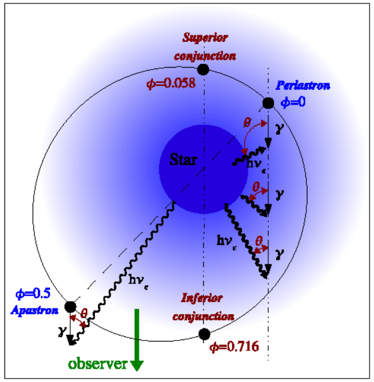
HESS



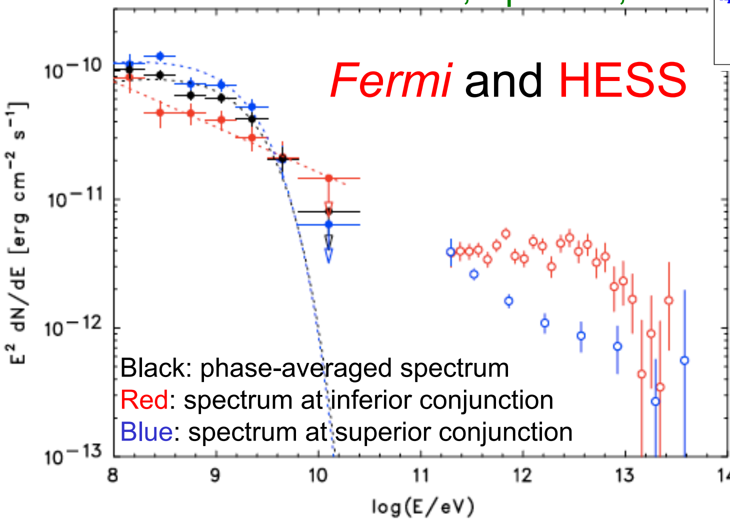
Fermi



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



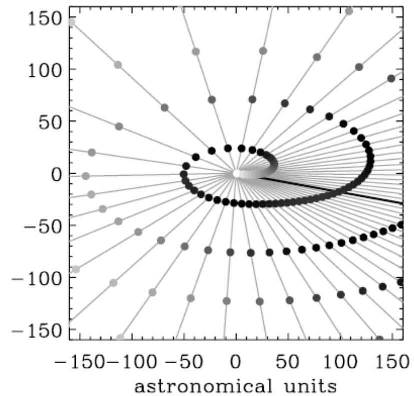
Abdo et al. 2009, ApJ 706, L56

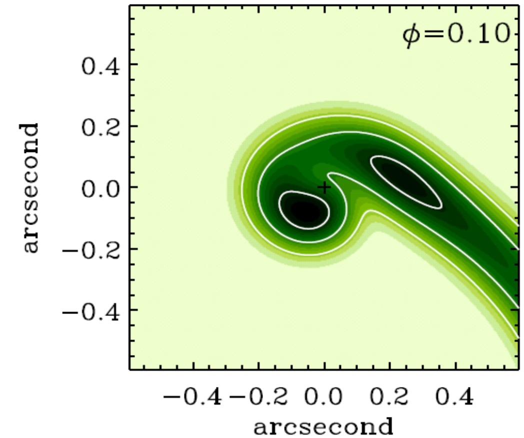


- IC scattering will vary with radiation density
- The flux will also depend on the geometry seen by the observer because the source of seed photons is anisotropic (Khangulyan et al. 2008; Sierpowska-Bartosik&Torres 2008b)
- The emission is enhanced (reduced) when the highly relativistic electrons seen by the observer encounter the seed photons head-on (rear-on), i.e., at superior (inferior) conjunction

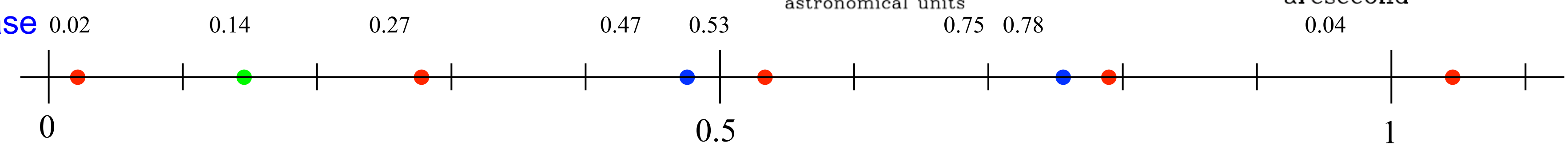
Radio

Particles move downstream away from the pulsar at a speed *v* (initially ≈*c*/3). A cometary nebula of radio emitting particles is formed. It rotates with the orbital period of the binary system. We see this nebula projected (Dubus 2006)

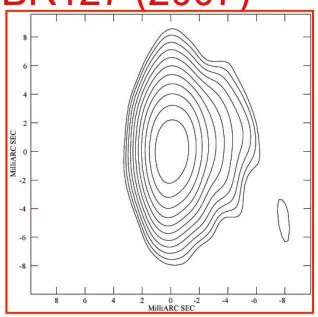


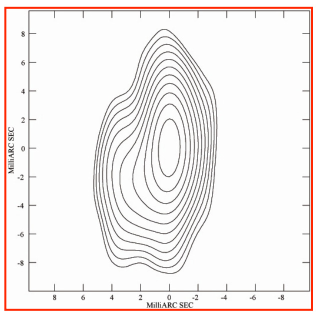


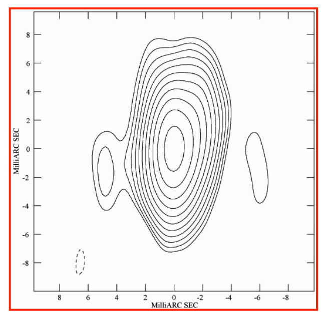
Phase

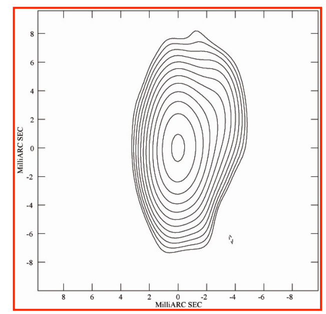


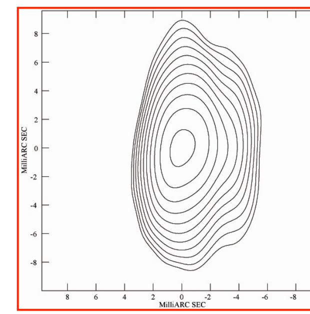
BR127 (2007)



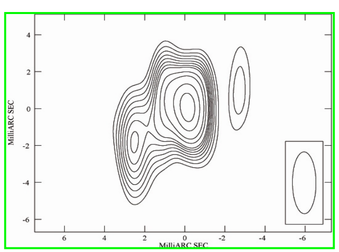


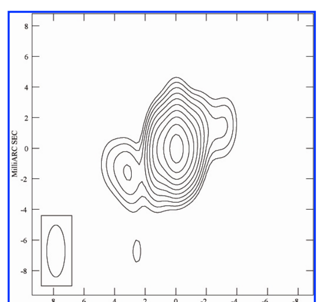


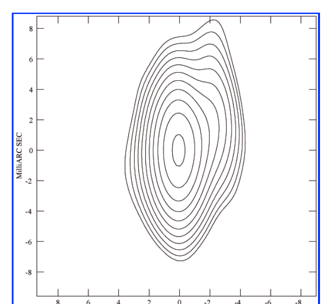




BP051 (1999)







GR021 (2000)

Preliminary!

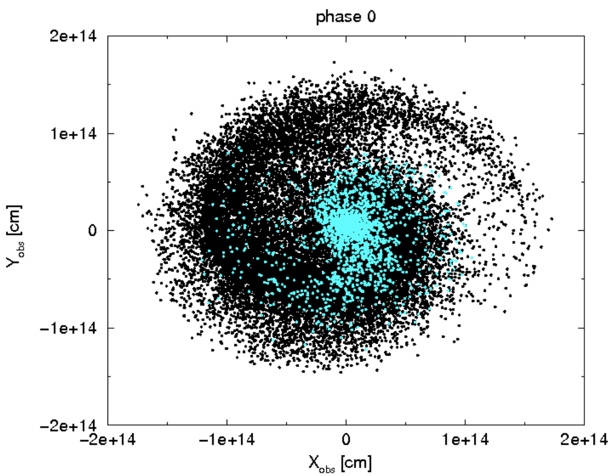
[Moldón et al., in preparation]

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.)

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

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

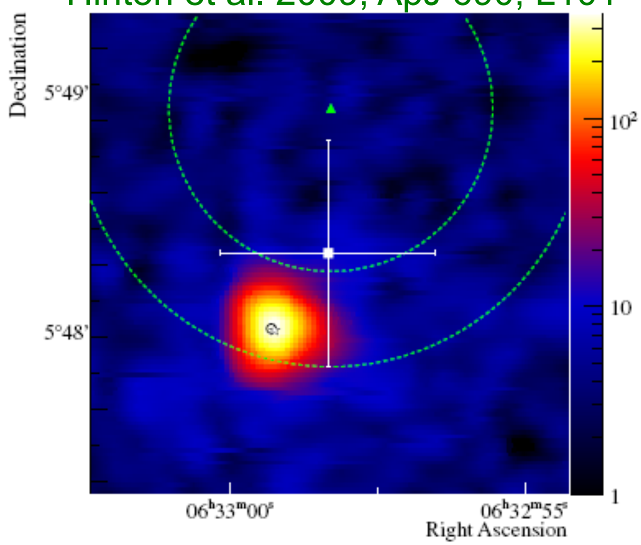
- In gamma-ray binaries in general, the pairs created due to photon-photon interactions can contribute significantly to the core, and generate an extended structure (Bosch-Ramon & Khangulyan 2011, astro-ph 1105.2172)

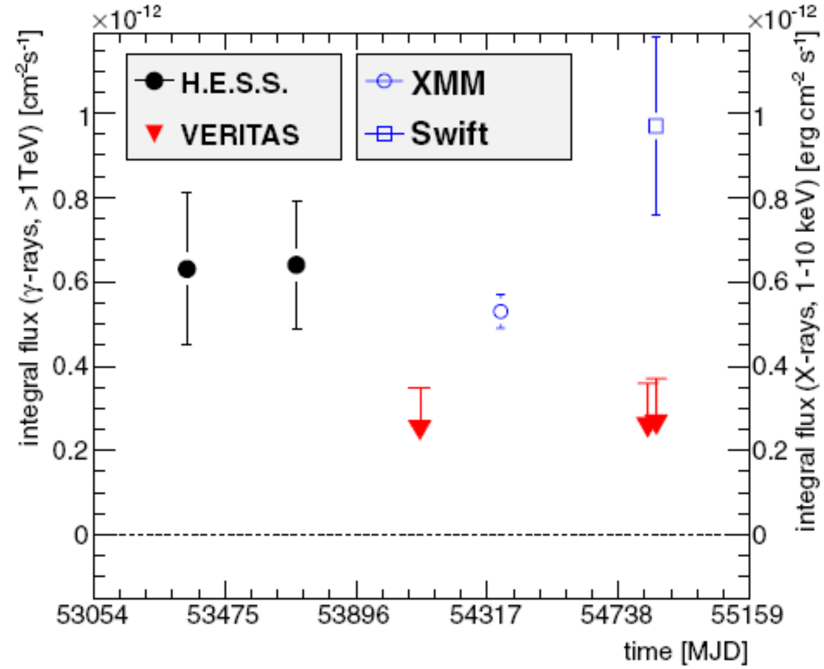


Computed spatial distribution of the secondary pairs, projected in the observer plane ($i = 45^{\circ}$), for phase 0.0. About 10^5 particles have been injected (black spots), among which about 10^4 particles have GHz synchrotron emitting energies (light blue spots)

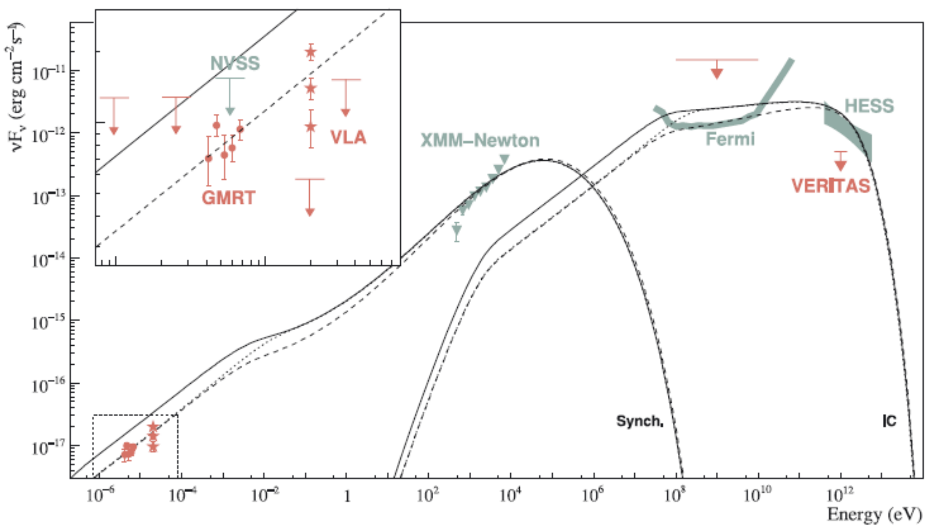
HESS J0632+057

Hinton et al. 2009, ApJ 690, L101





Acciari et al. 2009, ApJ 698, L133



Skilton et al. 2009, MNRAS 399, 317

Binary system?

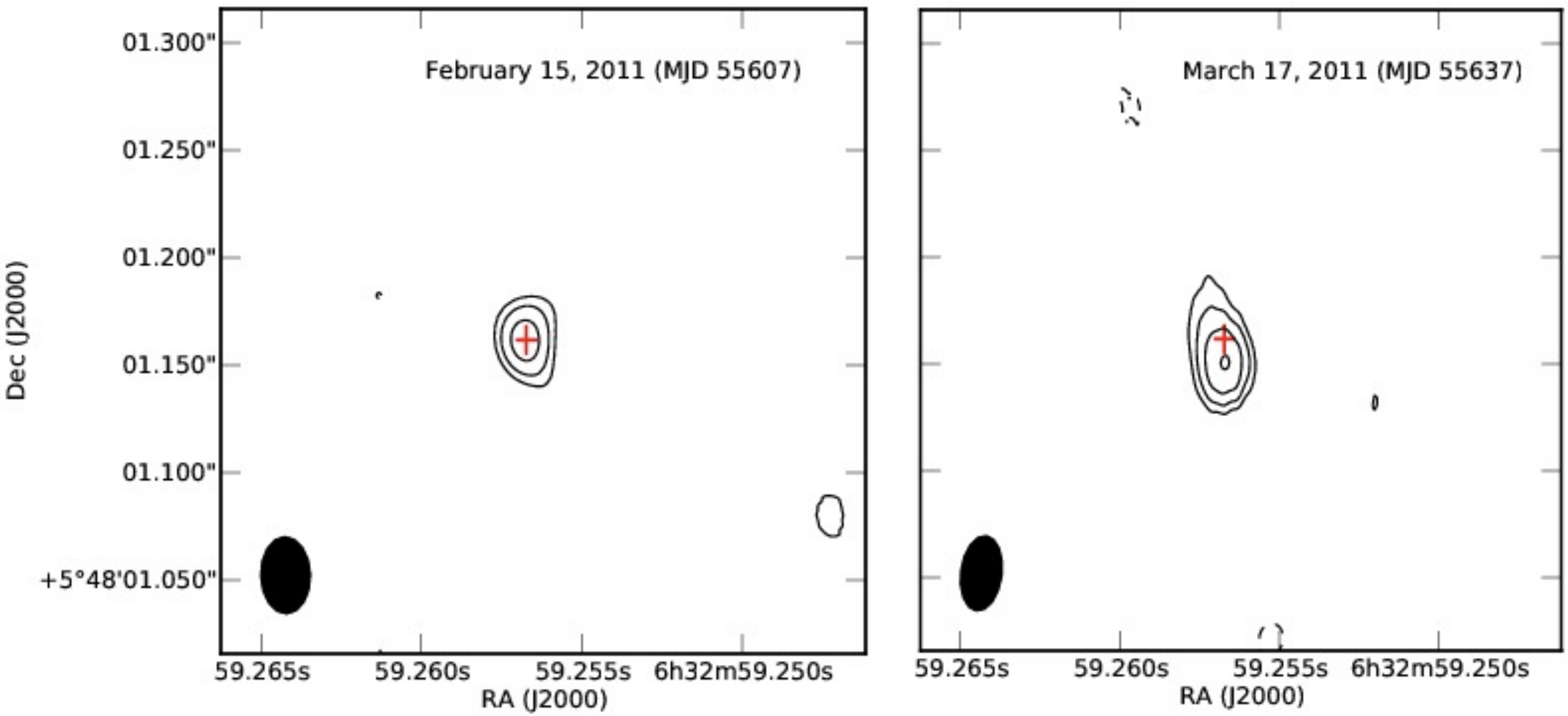
-Coincident with Be star MWC 148

-Variable X-ray and radio emission

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

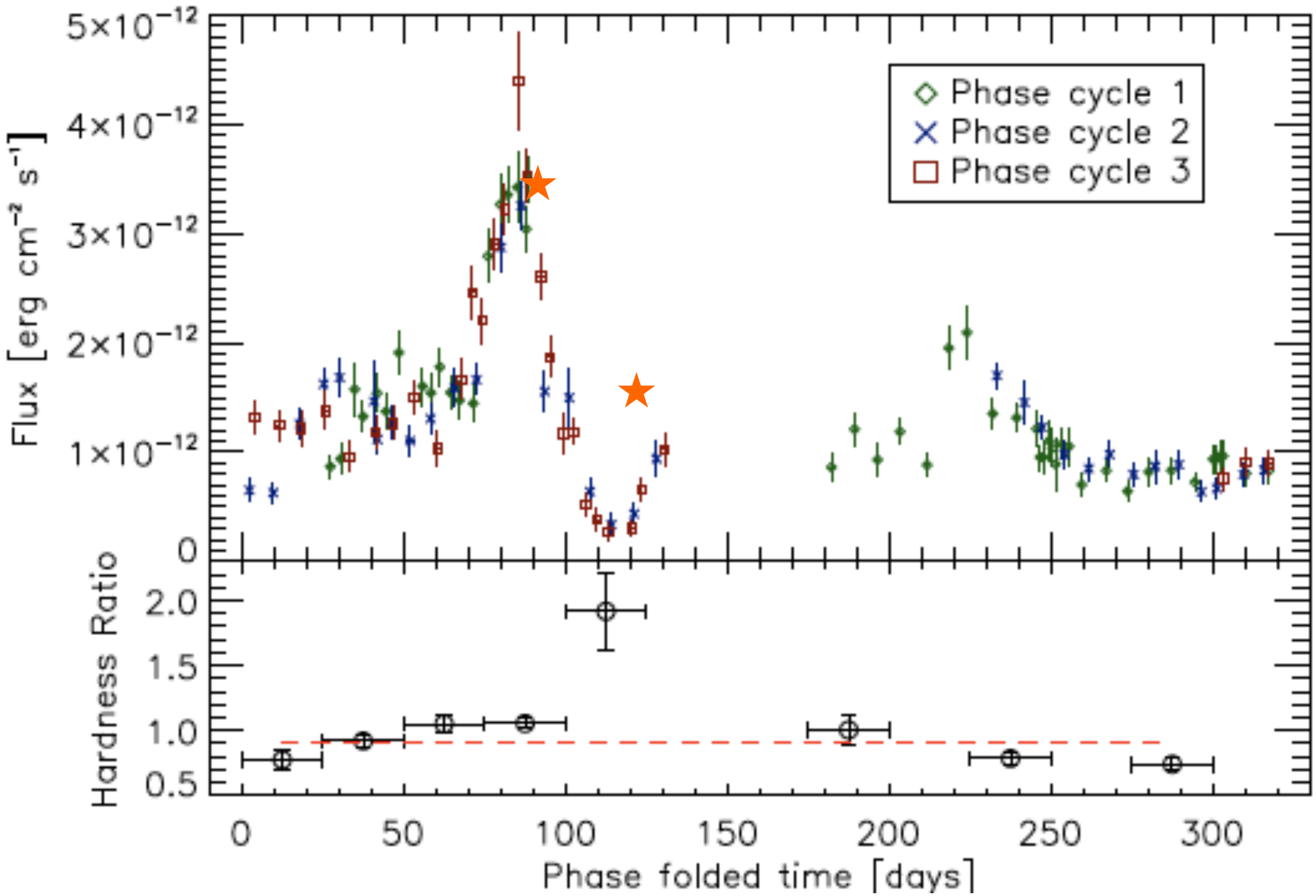
VERITAS and MAGIC detected elevated TeV gamma-ray emission (Ong et al. 2011, Atel # 3153; Mariotti et al. 2011, Atel # 3161)

VLBI counterpart (Moldón et al. 2011, Atel # 3180)



Discovery of the orbital period
Swift, P=320 ± 5 days

Bongiorno et al., 2011, arXiv 1104.4519



X-ray / radio correlation ?

Candidate gamma-ray binary (I)

AGL J2241+4454

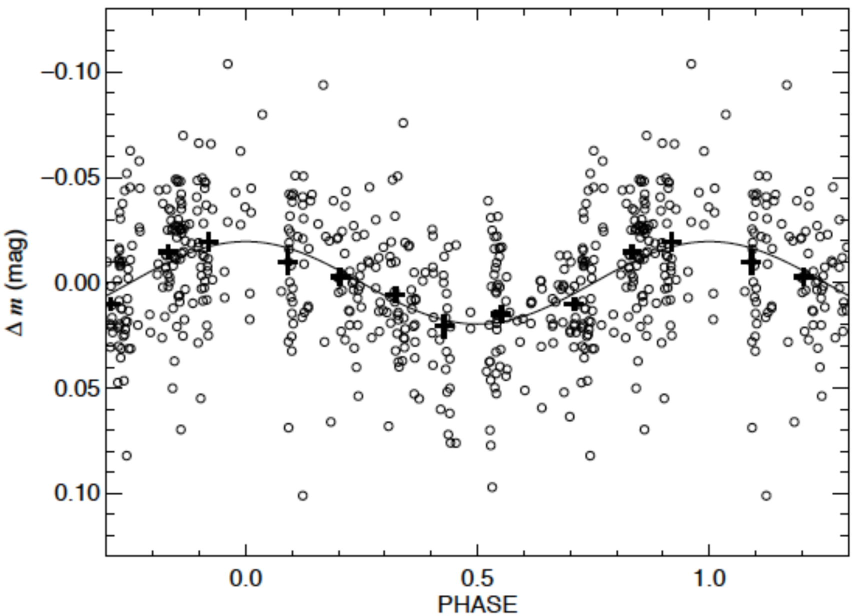
(l, b) = (100.0°, -12.2°) ± 0.6°

Lucarelli et al. 2010, Atel 2761

Be star HD 215227

Table 1. Stellar Properties

Parameter	Value
$T_{\rm eff}$ (kK)	19 ± 3
$\log g$ (cm s^{-2})	3.7 ± 0.2
$V \sin i$ (km s^{-1})	300 ± 50
V_r(HJD 2,455,405.9461) (km s^{-1})	0.2 ± 1.9
V_r(HJD 2,455,406.9124) (km s^{-1})	2.0 ± 2.4
$F_d/F_\star$	0.5 ± 0.3
$E(B-V)$ (mag)	0.02 ± 0.06
θ_{LD} (10^{-6} arcsec)	24 ± 5
$M_\star$ ($M_\odot$)	7.8 ± 2.0
$R_\star$ ($R_\odot$)	6.6 ± 1.9
d (kpc)	2.6 ± 1.0
z (kpc)	-0.56 ± 0.20
V_{Tp} (km s^{-1})	19 ± 17
V_{Rp} (km s^{-1})	21 ± 17
V_{Sp} (km s^{-1})	28 ± 24



b = −12° ➔ the star is quite far from the GP, and hence it may be a runaway star formed by a SN explosion in a binary system

P= 60.37 ± 0.04 d

Optical counterpart of AGL J2241+4454 ?

Williams et al. 2010, astro-ph 1009.4947

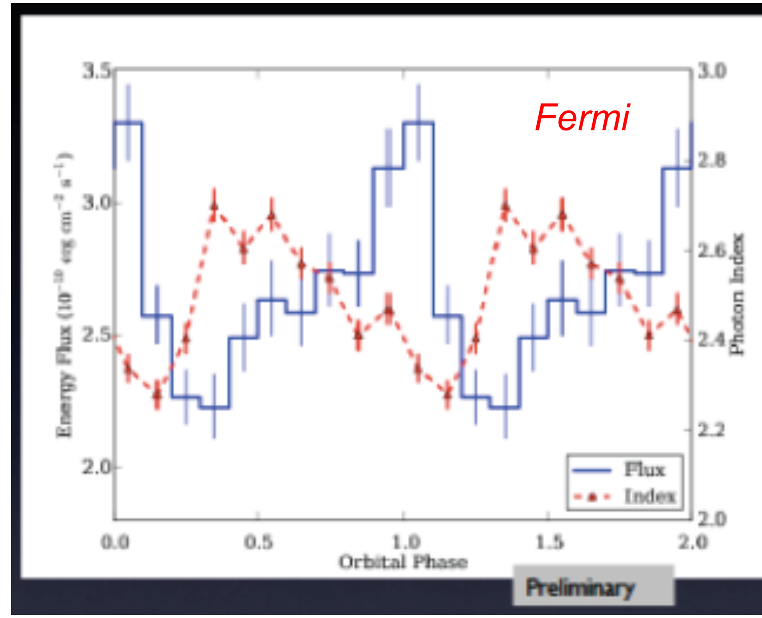
Candidate gamma-ray binary (II)

1FGL J1018.6-5856

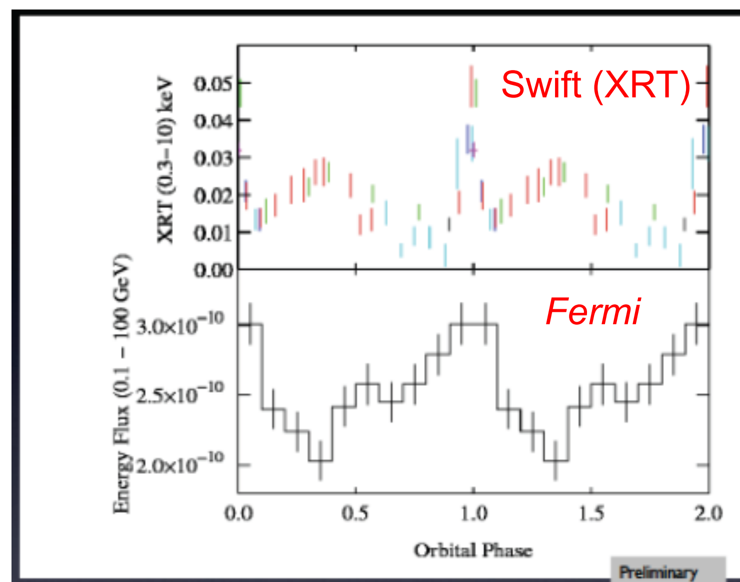
- 1FGL J1018.6-5856 is one of the brighter Fermi sources
- LAT spectrum similar to a pulsar - but no pulsations seen
- Optical counterpart ~O6V((f)), just like LS 5039

Corbet et al. 2011, Fermi Symposium

- Flux and gamma-ray spectrum modulated with a 16.6 d period

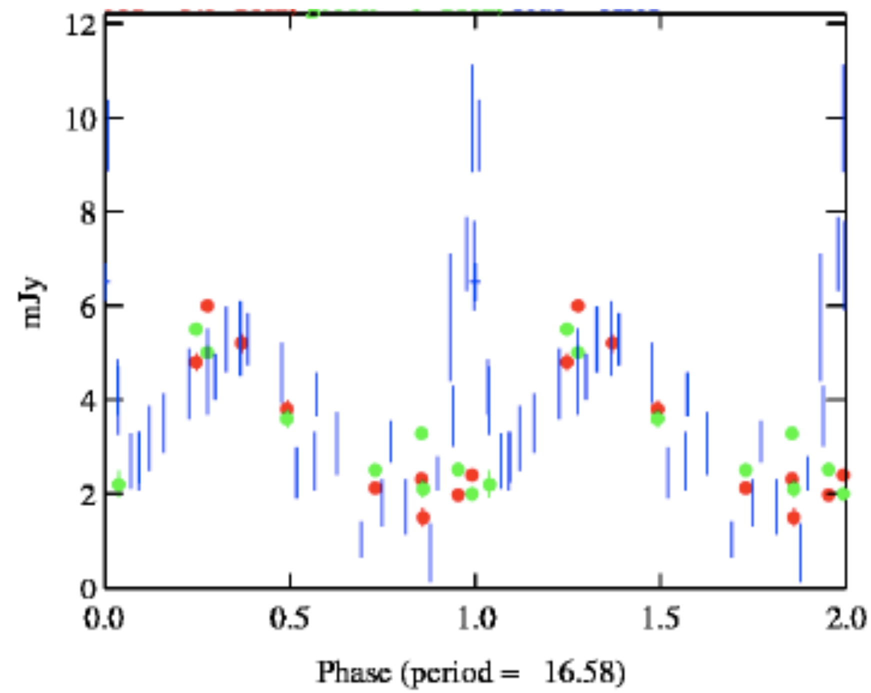


- Large X-ray variability
- Flare-like behaviour near phase 0, coinciding with gamma-ray maximum
- X-ray modulation also has a quasi-sinusoidal component with peak at phase ~ 0.4

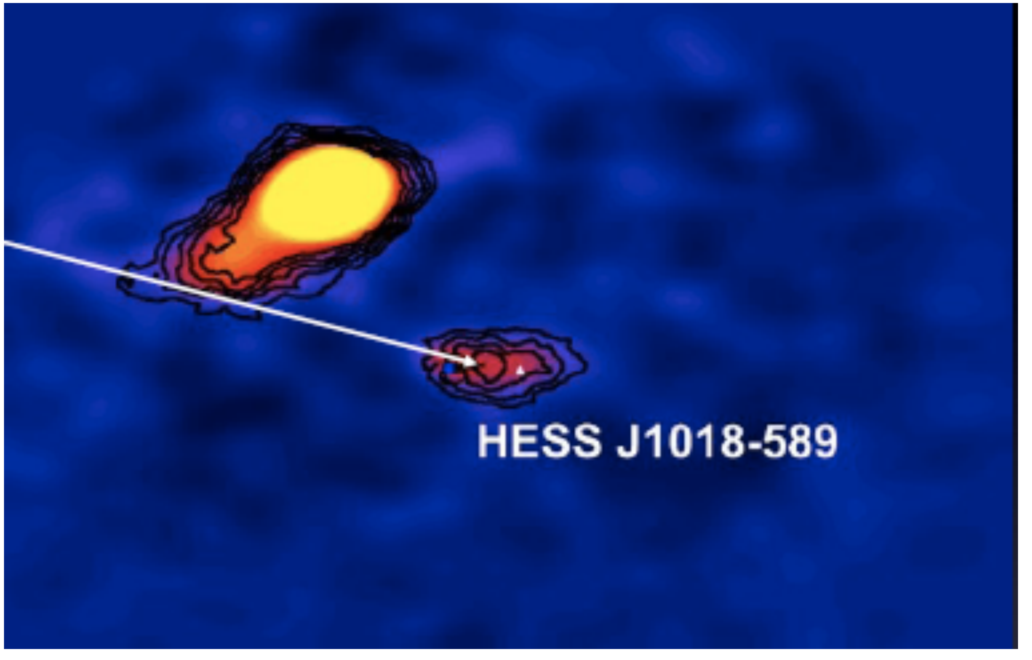


- An spatially coincident variable radio source
- The radio flux appears to be modulated on the orbital period
- But, no increase at phase 0
- Radio flux may be following sine wave component of X-ray flux

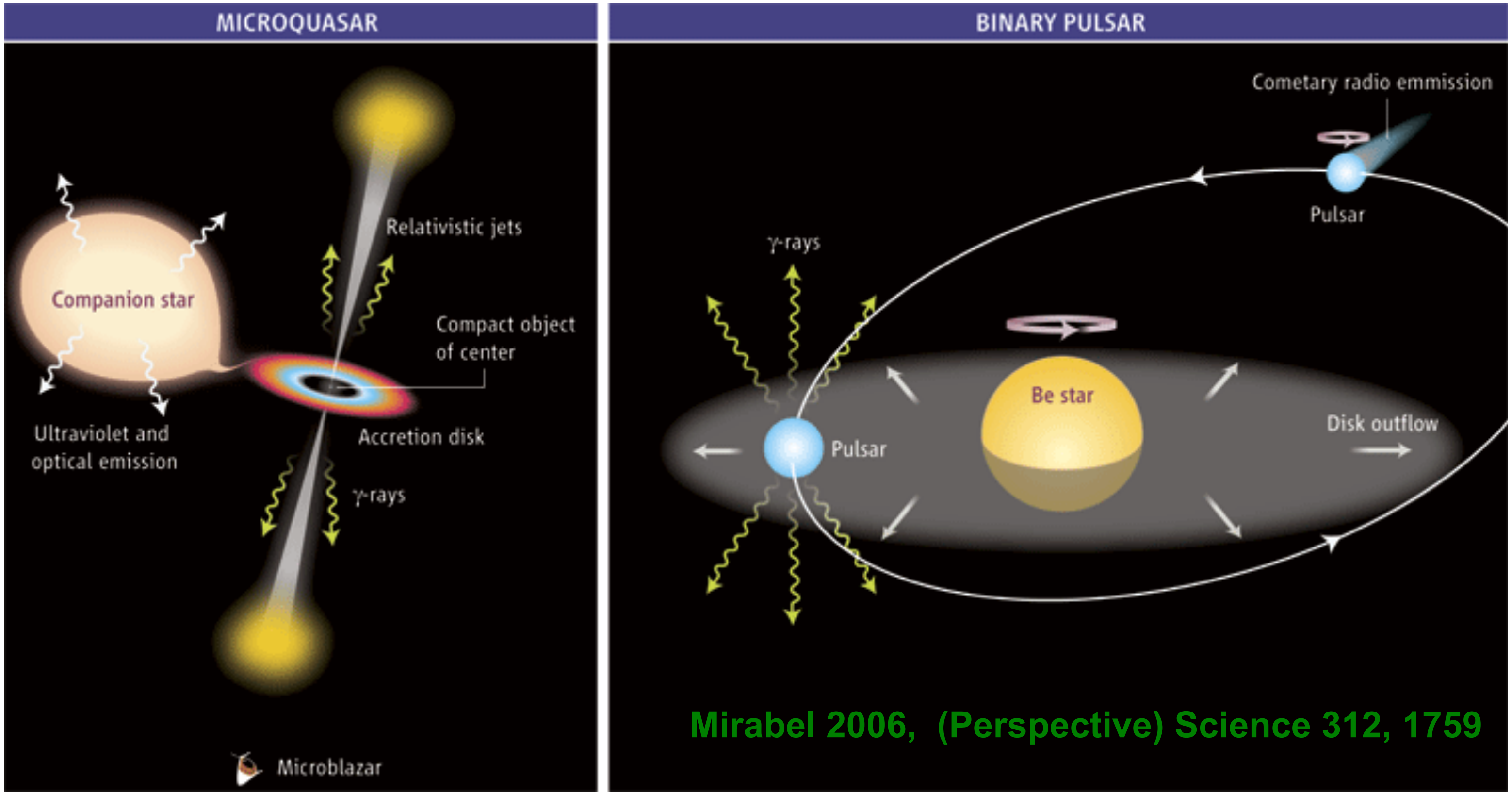
ATCA: 5.5 GHz, 9 GHz; Swift-XRT



- HESS (de Ona Wilhelmi et al., 2010) reported a TeV source in this region
- The positions are consistent, but it's not certain the HESS source is associated with 1FGL J1018.6-5856
- Is this the TeV counterpart of 1FGL J1018.6??



Microquasars and gamma-ray binaries



Cygnus X-1, Cygnus X-3

PSR B1259-63

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

New microquasars can be detected while flaring

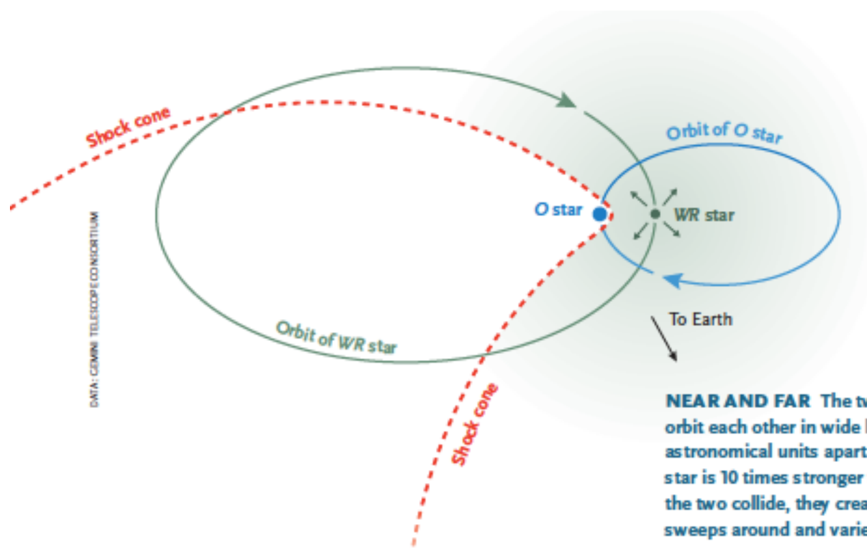
New VLBI observations and detailed wind-interaction simulations can unveil the real nature of LS 5039 and LS I +61 303

Colliding wind binaries

Colliding Winds in massive binary systems

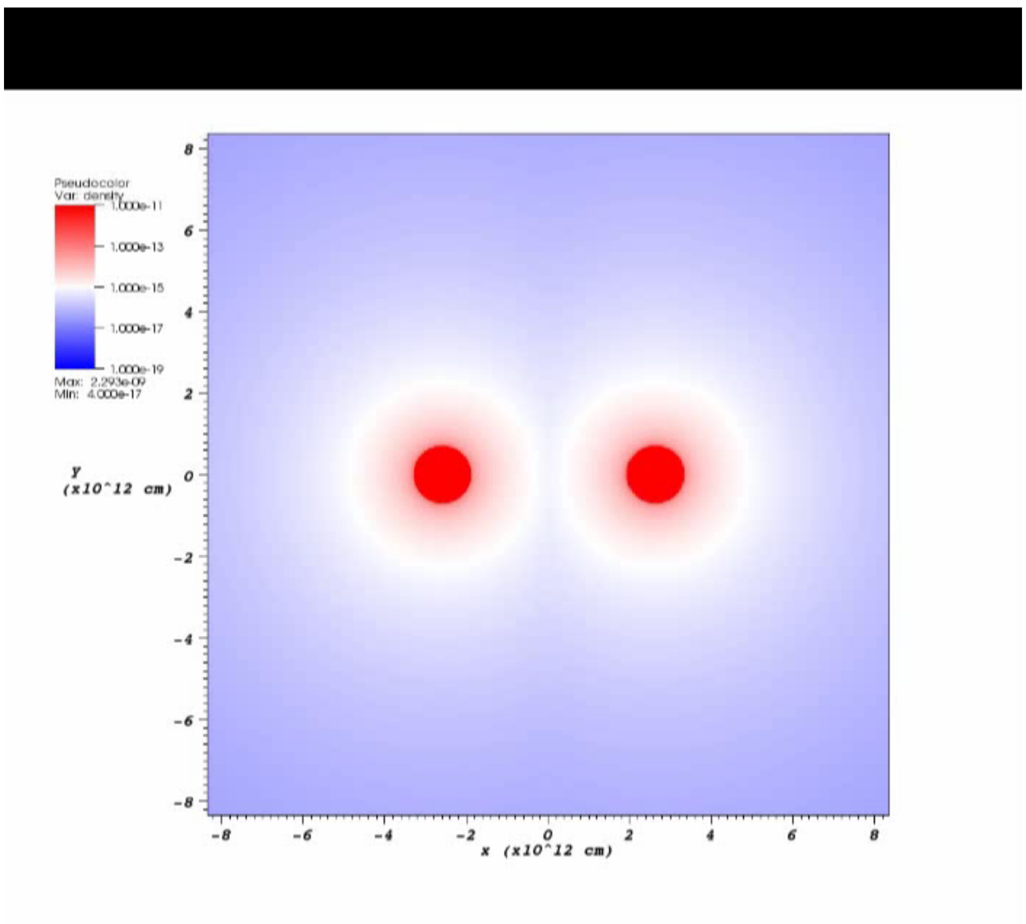
Collision of supersonic winds in massive star binaries (WR have very strong winds, v_∞ up to 5000 km s^{-1})

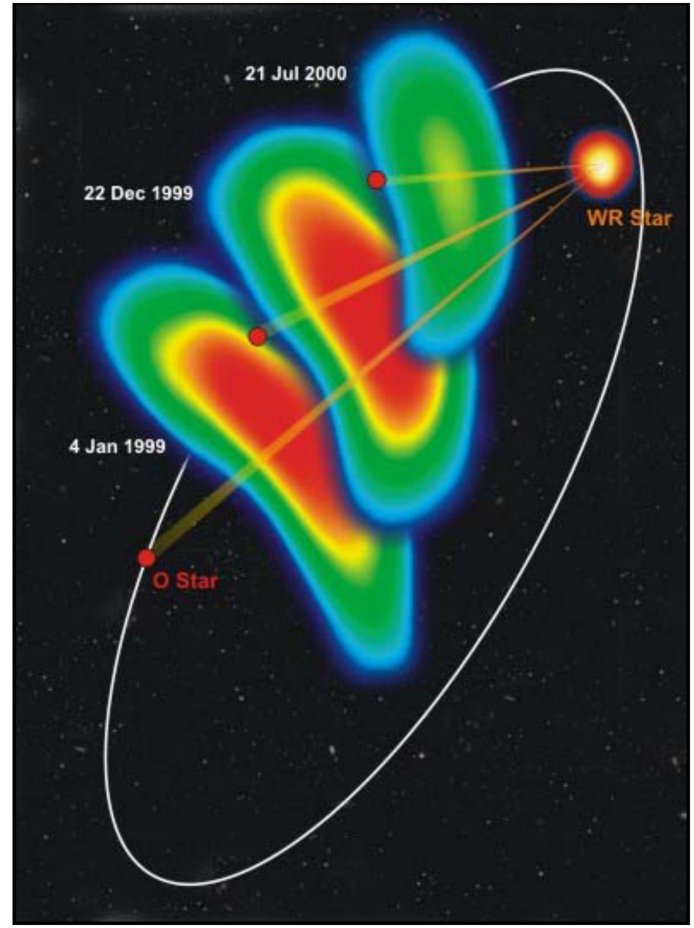
→ strong shocks where both e^- and p can be efficiently accelerated up to relativistic energies through first-order Fermi mechanism (Eichler& Usov 1993)



NEAR AND FAR The two brilliant, massive stars of WR 140 orbit each other in wide loops, dipping from about 30 to 2 astronomical units apart. The stellar wind from the type-*WR* star is 10 times stronger than the wind from the *O* star. Where the two collide, they create an X-ray-bright shock cone that sweeps around and varies in intensity as the stars orbit.

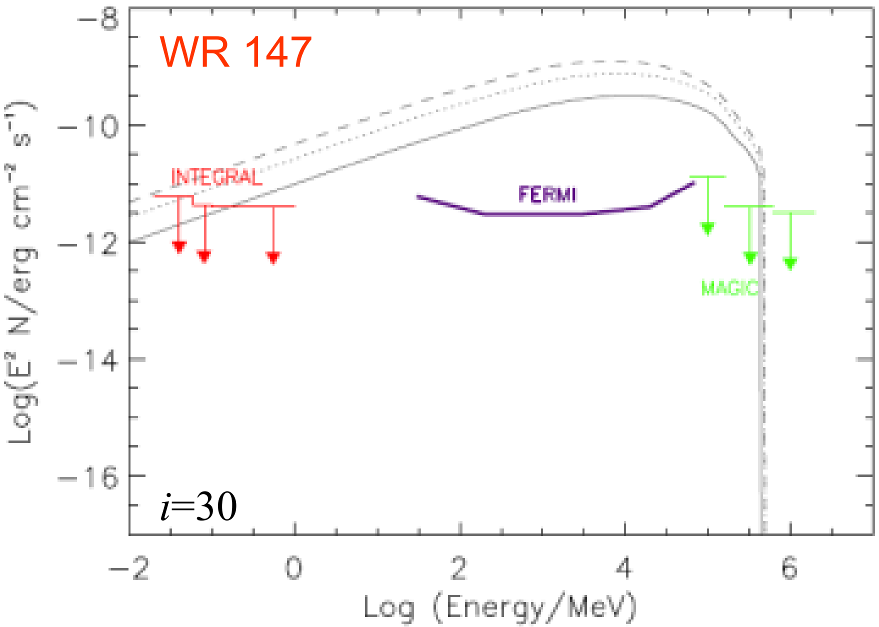
Strong synchrotron and IC losses are expected for relativistic e^- in this scenario
(Eichler & Usov 1993, Benaglia et al. 2001)



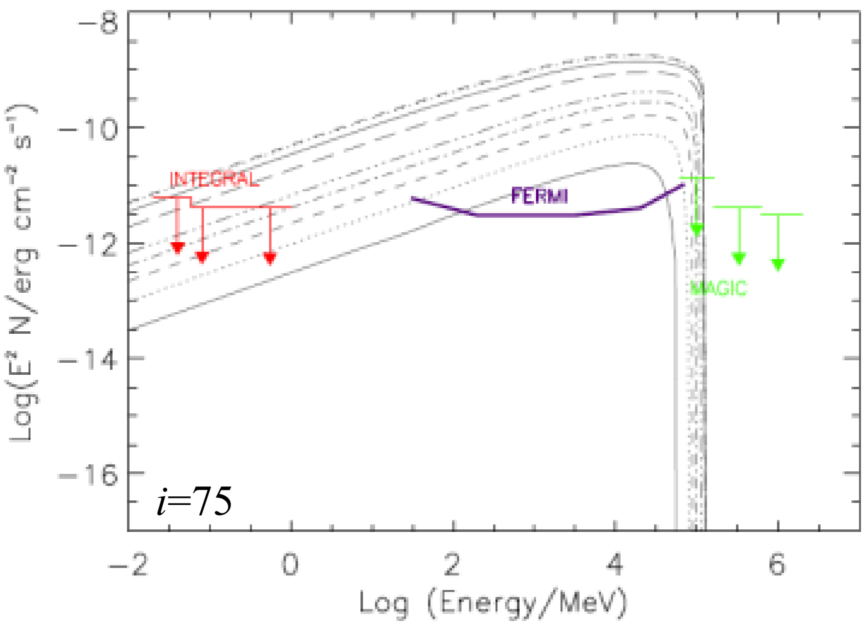


Dougherty & Pittard 2006, Proceedings of Science

MAGIC



WR146 and WR147, both containing WR+O stars have been observed with MAGIC
(Aliu et al. 2008, ApJ, 685, L71)



anisotropic IC scattering reacts sensitively on the line-of-sight angle with respect to the orbital plane

→

deduction of system parameters

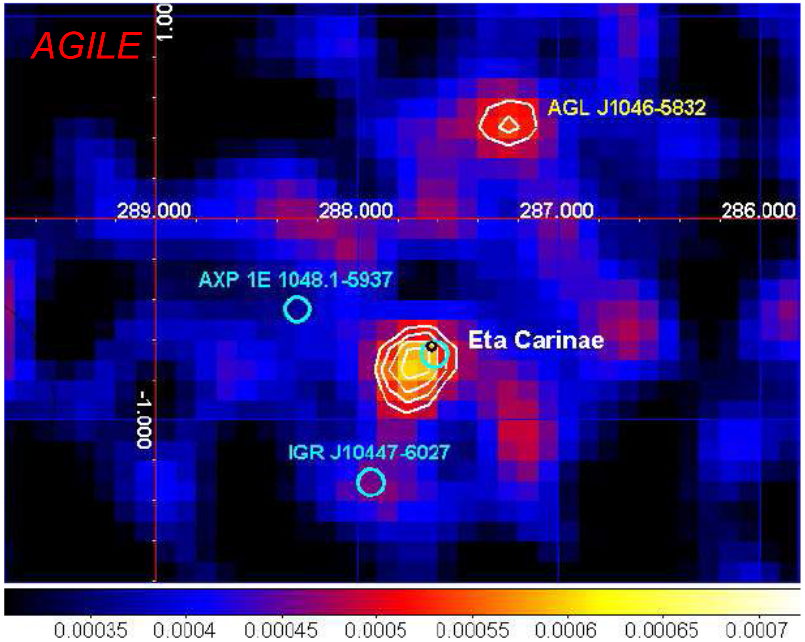
From MAGIC data the inclination should be high (Reimer et al. 2009, ApJ, 694, 1139)

Eta Carinae

- Is the CWB with the largest mass loss rate in our Galaxy and

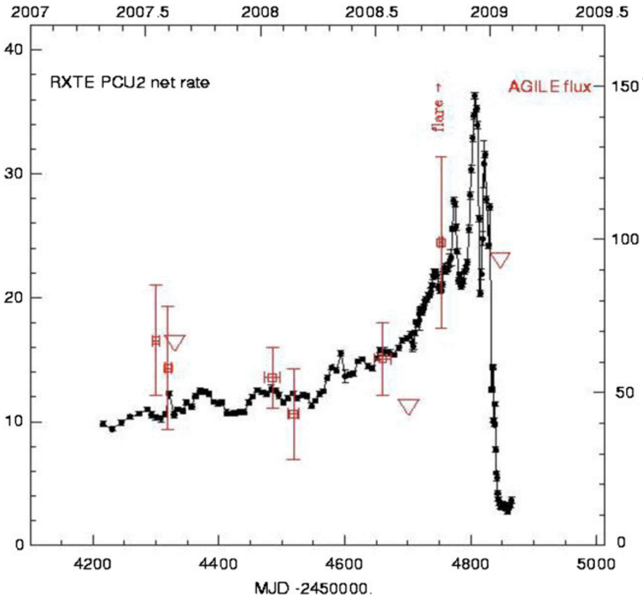
optical position: small black circle
INTEGRAL sources: cyan circles

Tavani et al. 2009, ApJ 698, L142



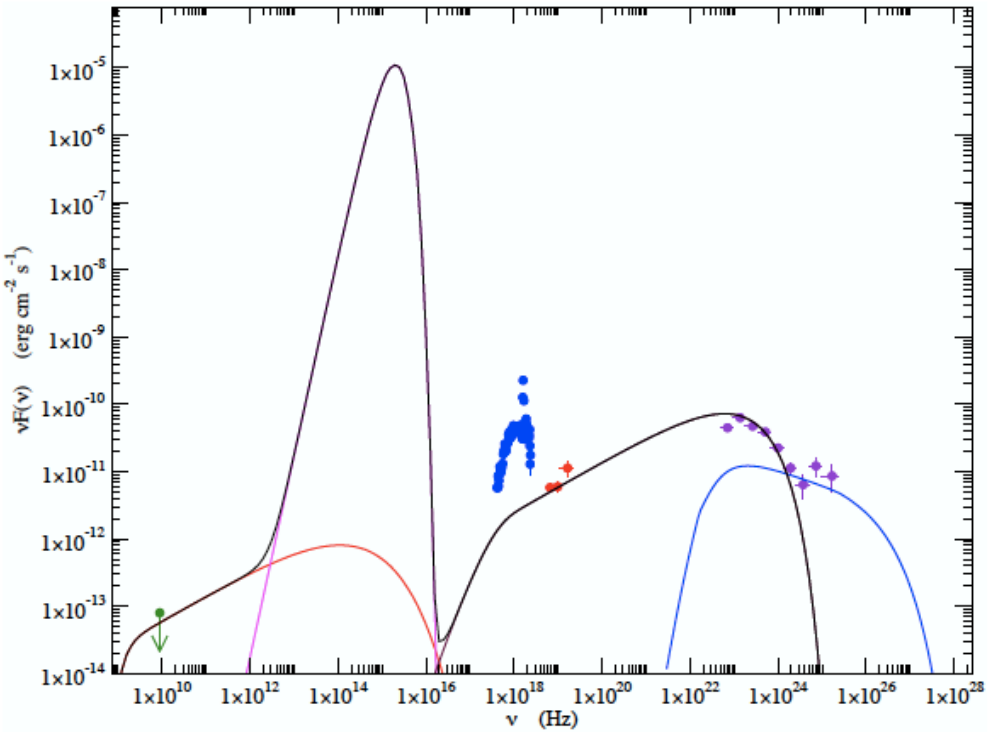
- Significant variability on a few day time-scale
- The gamma-ray emission can be associated with intermittent strong shock acceleration episodes and/or magnetic field enhancements to be expected for a very variable and inhomogeneous mass outflow from the stars of the Eta Carinae system

(Tavani et al. 2009, ApJ 698, L142)



10^{-8}ph cm^{-2} s^{-1}

Triangles: 2σ upper limits



Spectral energy distribution of η Carinae including *BeppoSAX*/MECS, *INTEGRAL*/ ISGRI and *Fermi*/LAT data, and a radio upper limit to the synchrotron emission

From low to high energies are shown the synchrotron, stellar emission, inverse Compton and π^0-decay spectral components.

Walter et al. 2010, PoS 164

The average broad-band gamma-ray spectrum determined by AGILE is in qualitative agreement with expectations of CWB spectra as calculated for dominant IC and neutral pion decay processes (Benaglia & Romero 2003, A&A 399, 1121; Reimer et al. 2006, ApJ 644, 1118)

Eta Car ⟷ 1AGL J1043-5931 ?
FGL J1045.0-5942 ?

If YES, → the first remarkable detection of a colliding wind system at hundreds of MeV energies, confirming the efficient particle acceleration and the highly non-thermal nature of the strong shock in a CWB

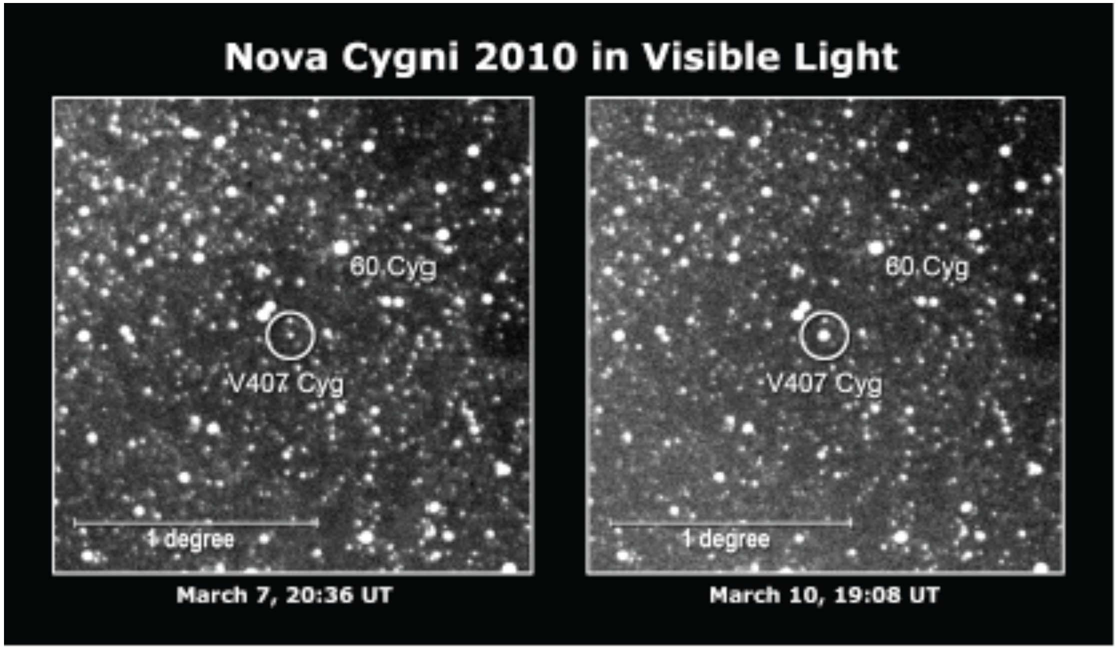
Symbiotic binaries

Novae are thermonuclear explosions on a white dwarf surface fueled by mass accreted from a companion star.

Current physical models posit that shocked expanding gas from the nova shell can produce X-ray emission but emission at higher energies has not been widely expected

Symbiotic binary V407 Cyg:

small white dwarf (WD) and large red giant (RG) orbiting each other closely

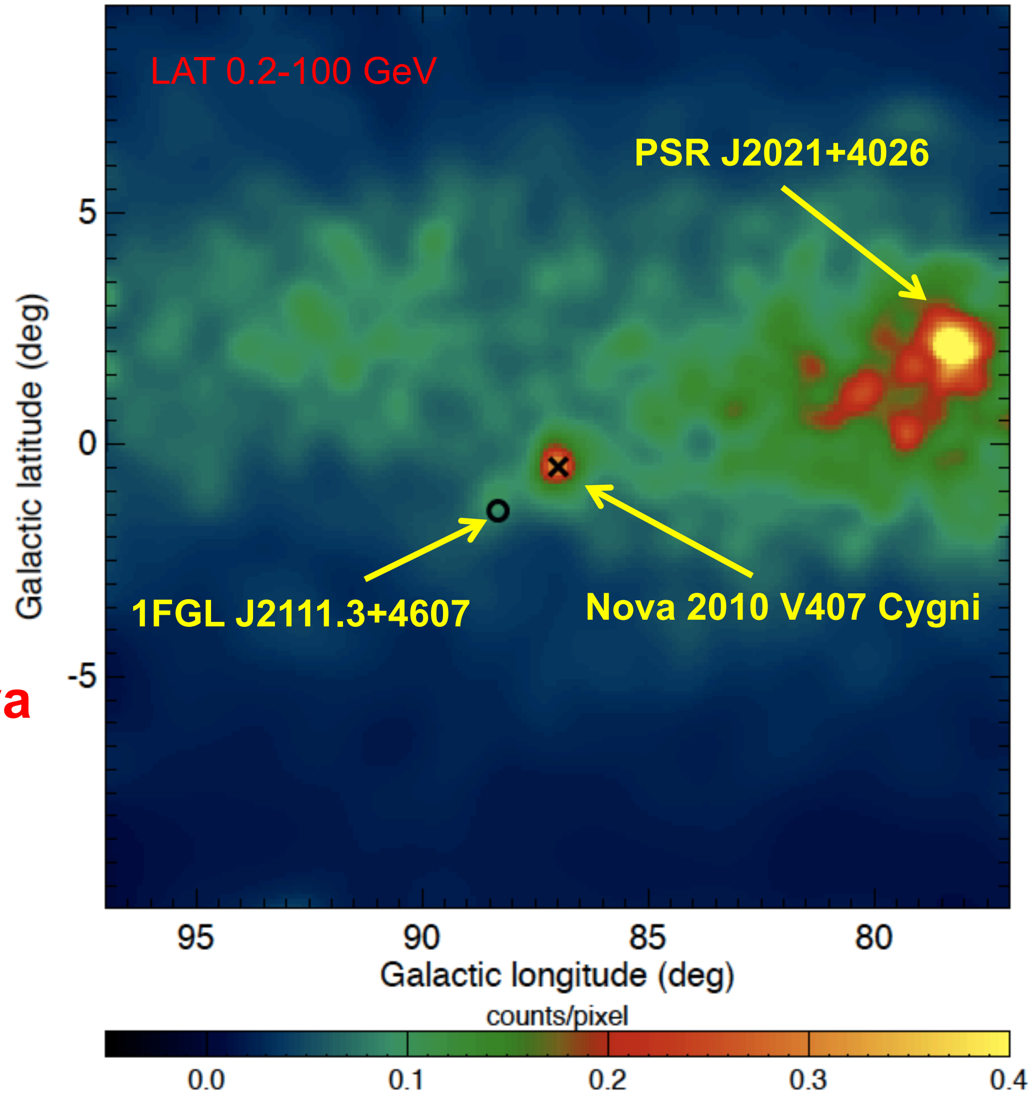


Nova discovery by Nishiyama & Kabashima IAUC 2199 (2010); H. Maehara (Kyoto)

Gamma-ray Emission Concurrent with the Nova in the Symbiotic Binary V407 Cygni

New LAT source detected (6-8σ, > 100 MeV) initially on March 13-14 (Cheung et al. 2010, Atel #2487)

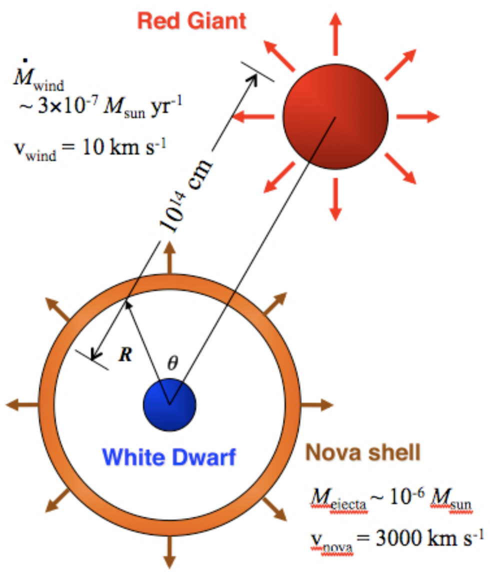
V407 Cyg nova detected on March 10, subsequent analysis found first LAT detection same day



First γ-ray detection of a nova

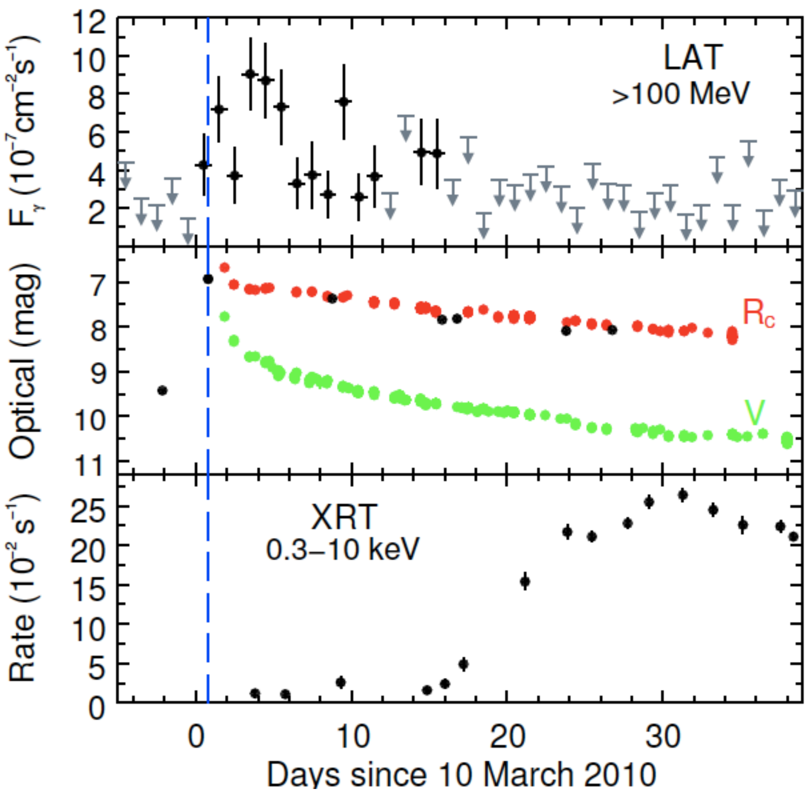
WD in binary system

Abdo et al. 2010, Science 329, 817



✧ Fermi acceleration in nova shell; interaction with massive red giant wind plays important role

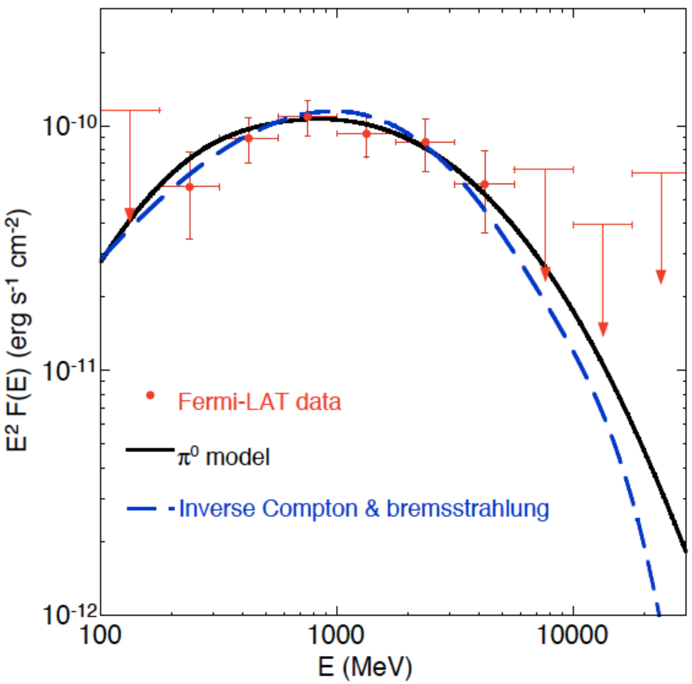
✧ Shell evolution recapitulates SNR evolution in miniature, and scaled down in timescale



✧ Nova shell initially freely expands into asymmetric dense medium

✧ Shell toward RG slows down quickly, Sedov condition reached in few days
Gamma rays peak early when efficiency for pion and IC processes is favorable

✧ Shell decelerates slowly away from RG
X-rays peak later, flux increasing with volume of shock-heated gas



✧ **Pion**: accelerated p's collide with ambient material producing π^0 with prompt decay

✧ **Inverse Compton**: accelerated e^- up-scattering infrared photons from the red giant

- Kinetic energy of shell: ~10^{44} erg
- Total energy in γ-rays: ~ 4 × 10^{41} erg
- Total energy of p (e^-) gone into producing in γ-rays ~ 9% (~0.4%) of kinetic energy

Gamma-ray nova V407 Cyg 2010 not necessarily unique; symbiotic binaries relatively common, novae are numerous

Summary

Microquasars & γ-ray binaries

Instrument	PSR B1259-63	LS I +61 303	LS 5039	Cygnus X-1	Cygnus X-3	HESS J0632+057
EGRET >100 MeV	—	3EG J0241+6103	3EG J1824-1514	—	—	—
AGILE 30 MeV-50 GeV	—	yes	—	yes	yes	—
FERMI 30 MeV-300 GeV	yes	yes Periodic	yes Periodic	—	yes Periodic	—
HESS >100 GeV	yes	not visible	yes Periodic	—	—	yes
MAGIC >60 GeV	not visible	yes Periodic	—	yes	—	yes
VERITAS >100 GeV	not visible	yes	—	—	—	yes

All of them are HMXBs

- All of them are radio emitters
- All of them have a bright companion (O or B star) → source of seed photons for the IC emission and target nuclei for hadronic interactions

- NS and BH are among these detected XRBs
- HESS J0632+057: New gamma-ray binary?

LMXBs are transient sources, and one has to observe at the right time!

CWB & Symbiotic

- New types of stellar gamma-ray sources:
  - Confirmed: Colliding Wind Binaries (Eta Carina)
  - Confirmed: Symbiotic binaries (Nova V 407 Cyg)

  although

  - No TeV detections yet

Raibh maith agat !!

Thanks !!