Binary stars observed in gamma-rays

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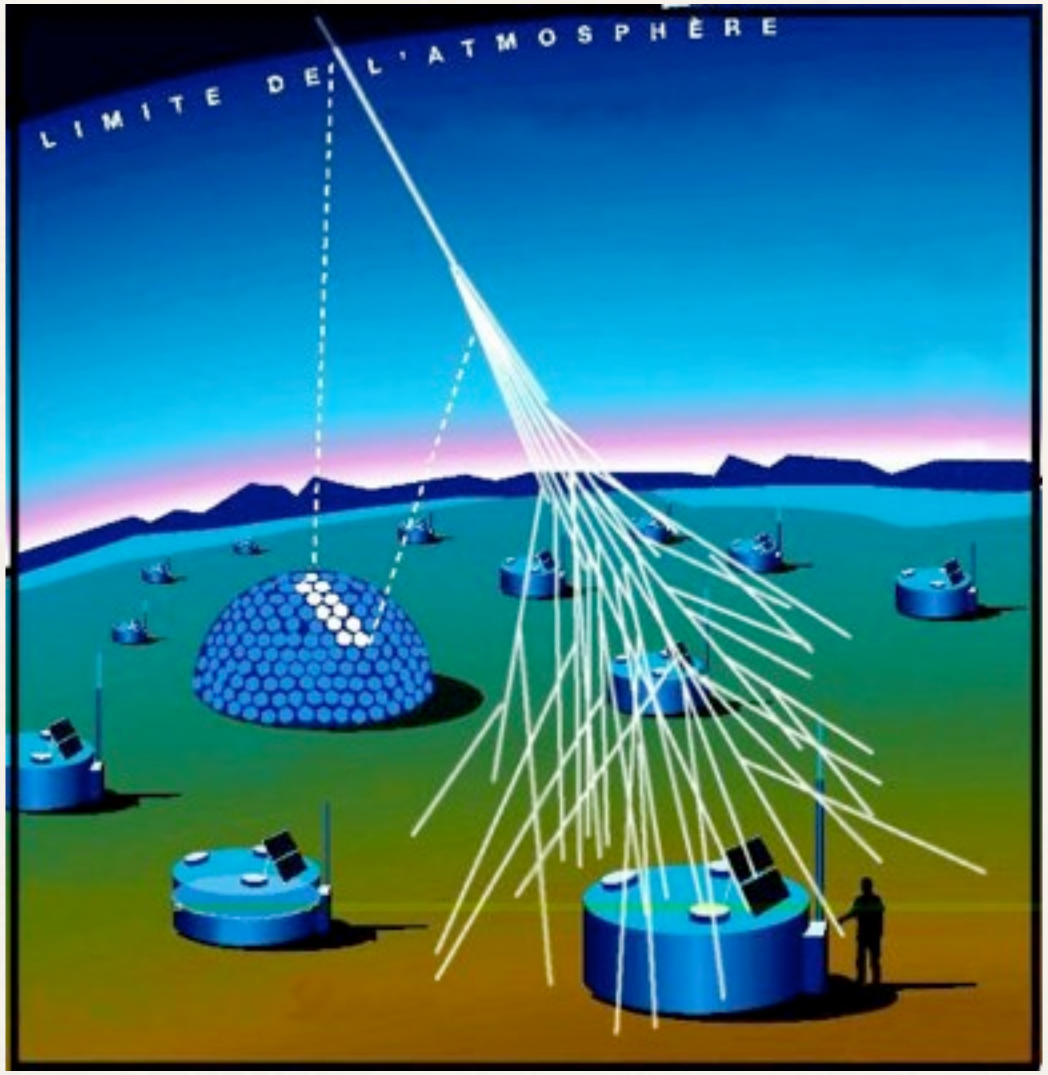
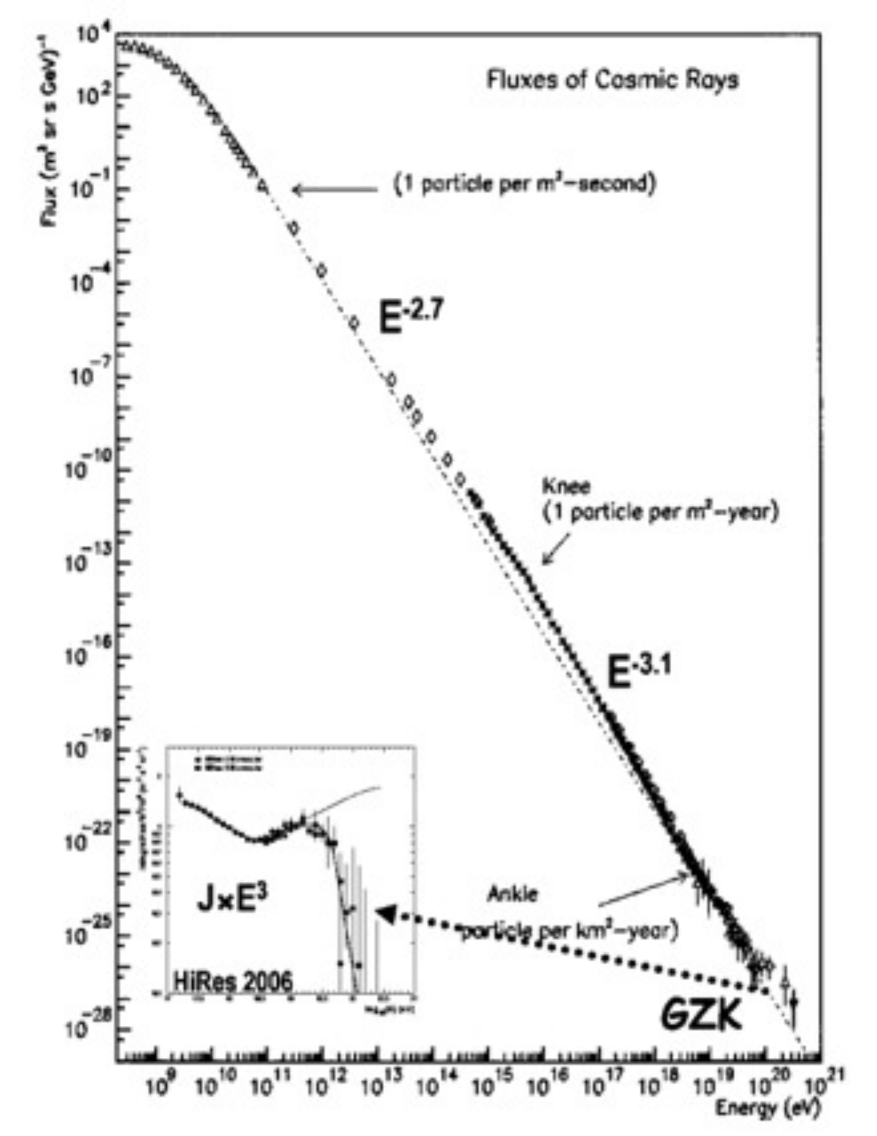
Astroparticle physics

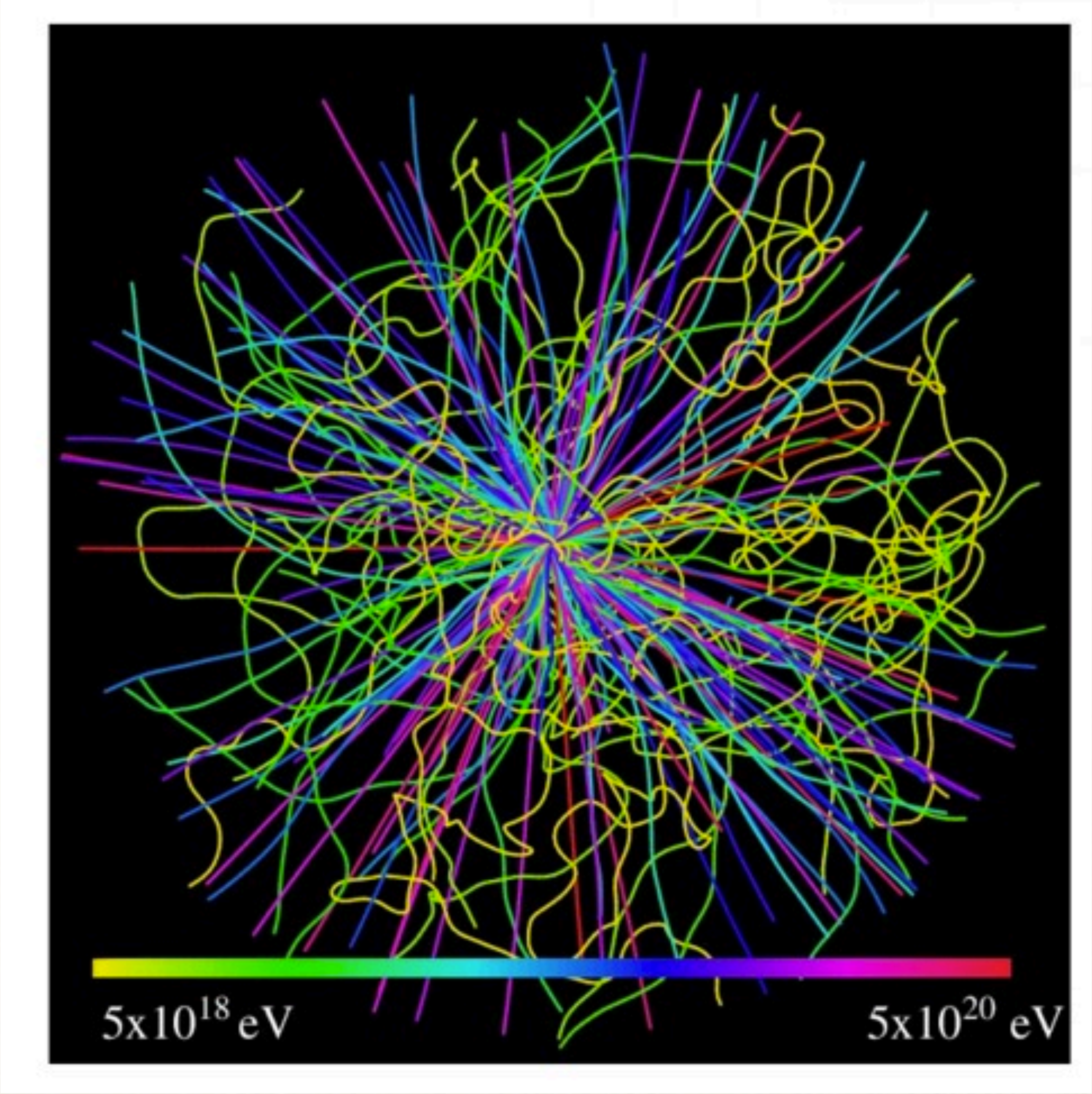
- Aims to understand the origin of cosmic rays and their role in the Universe
- The nature and variety of particle acceleration

Observations of particle showers created in Earth atmosphere





Only the ultra high energy CR (>10^{19} eV) keep their directional information



Credit: Los Alamos National Lab

Lower energy particles can be detected indirectly via their interactions with:

- Magnetic fields - synchrotron radiation
- Radiation - inverse Compton process
- Surrounding gas - hadronic processes

We can look for particles in the source of origin

Gamma-rays ➠ High energy particles

High energy particles ➠ Emission from radio to gamma-rays

What we want to learn from this

- Particle acceleration site
- Process of acceleration
- The energy spectrum of particles
- Escaping particles

Variable sources are important to understand it

- Internal and external environments of the particle accelerator change
- Change in the relative strength of spectra components
- Simultaneous multi-wavelength observations trace the correlations between different parts of the system providing diagnostics of the underlying engine
- Timescale of variability provides information about the size of emission region

Example variable, gamma-ray emitting particle accelerators

- Gamma-ray emitting binaries
- Blazars

There are currently 6 known gamma-ray emitting binaries

- **PSR B1259-63**
- **LS 5039**
- **LS I+61 303**
- **HESS J0632+057**
- **1FGL J1018.6-5856**
- **Cyg X-3**

All gamma-ray emitting binaries contain a massive star and a compact object

Massive star

>15 Msun

- O type
- Be type
- Wolf-Rayet
- Supergiant

+

Compact object

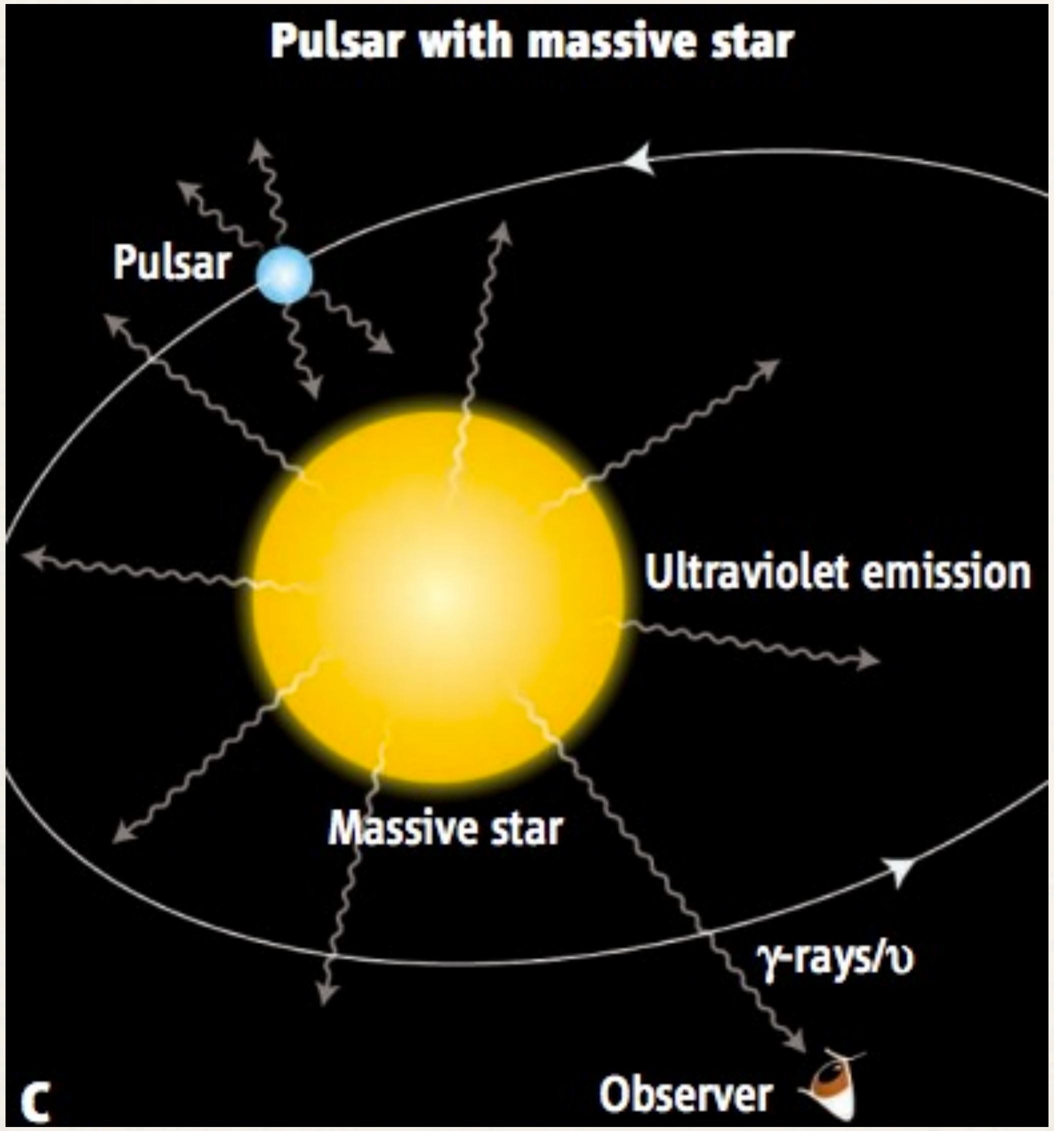
Final stages of stellar evolution

- Neutron star
- Black hole

How to produce gamma-rays in binaries?

- Pulsar wind scenario
  (e.g., Maraschi & Treves 1981, Dubus 2006)
- Microquasar jet
  (e.g. Romero et al. 2005)

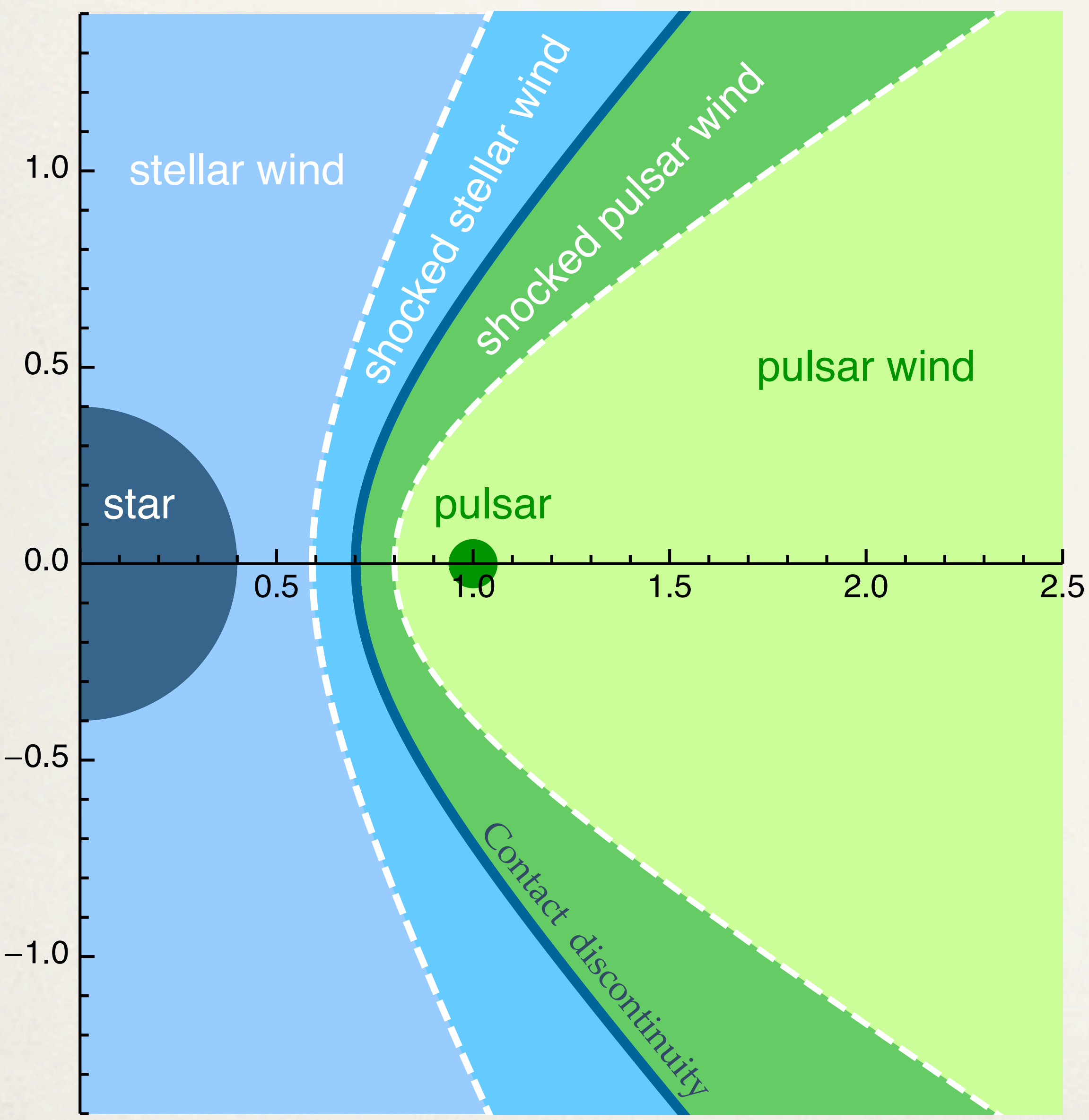
Main ingredients of the pulsar wind scenario



Credit: Mirabel Science, 2012, 335, 175

- Young millisecond pulsar with high spin down power
- Pulsar wind - a cold magnetized flow of relativistic electron-positron pairs
- Massive star
- UV photons from massive star
- Strong radiatively driven wind

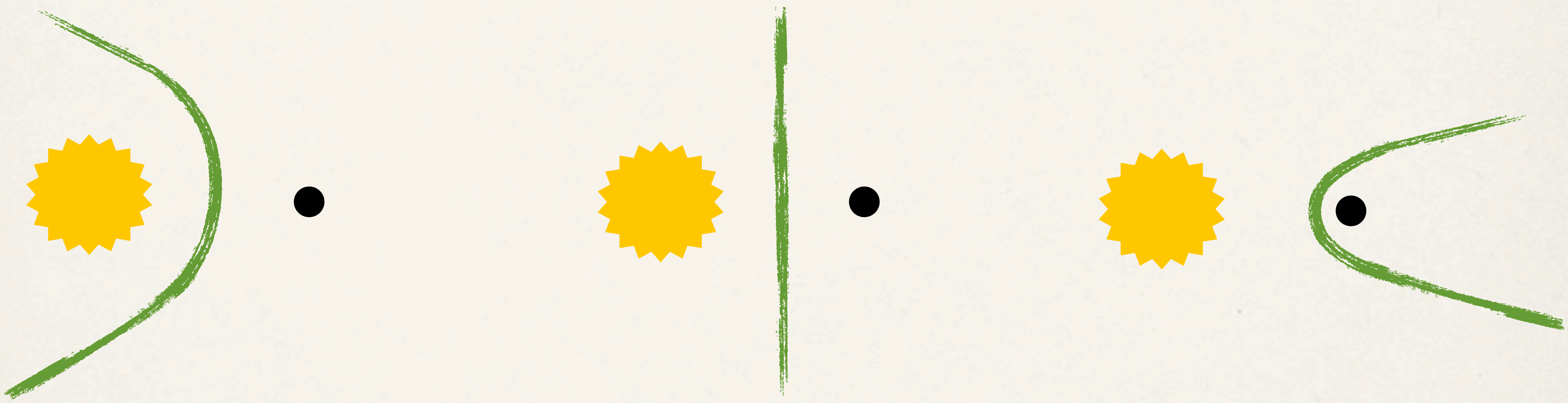
Where are the particles accelerated?



- Stellar wind and pulsar wind collide
- Contact discontinuity is formed bounded by two termination shocks
- Particles are accelerated to VHE in the shocked pulsar wind
- Particles are isotropised behind the shock

Shape of the contact discontinuity

- Depending on the ratio of pulsar wind ram pressure to that of stellar wind (denoted by η), the contact discontinuity will have different shape



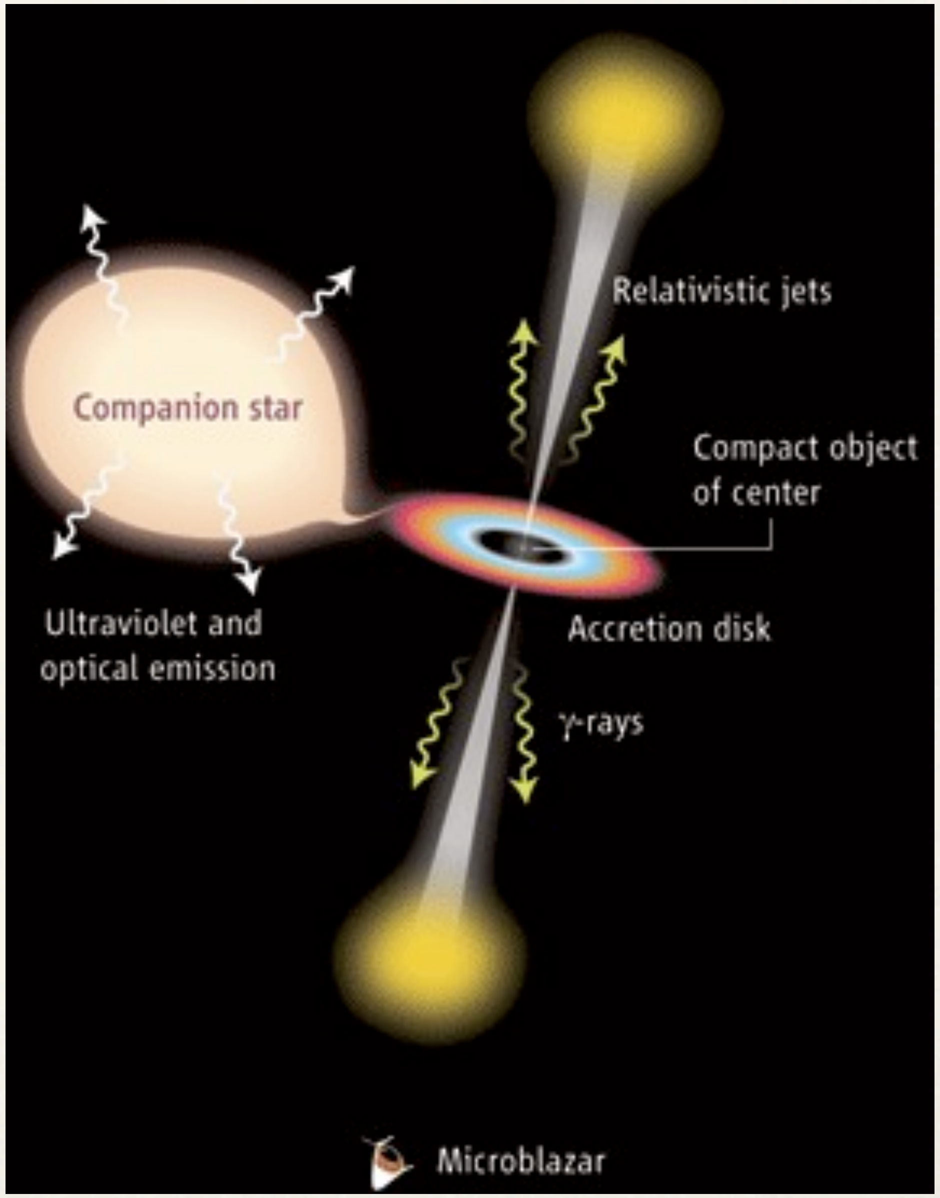
$\eta > 1$
Pulsar wind dominates

$\eta = 1$
Ram pressures equal

$\eta < 1$
Stelar wind dominates

Microquasar scenario

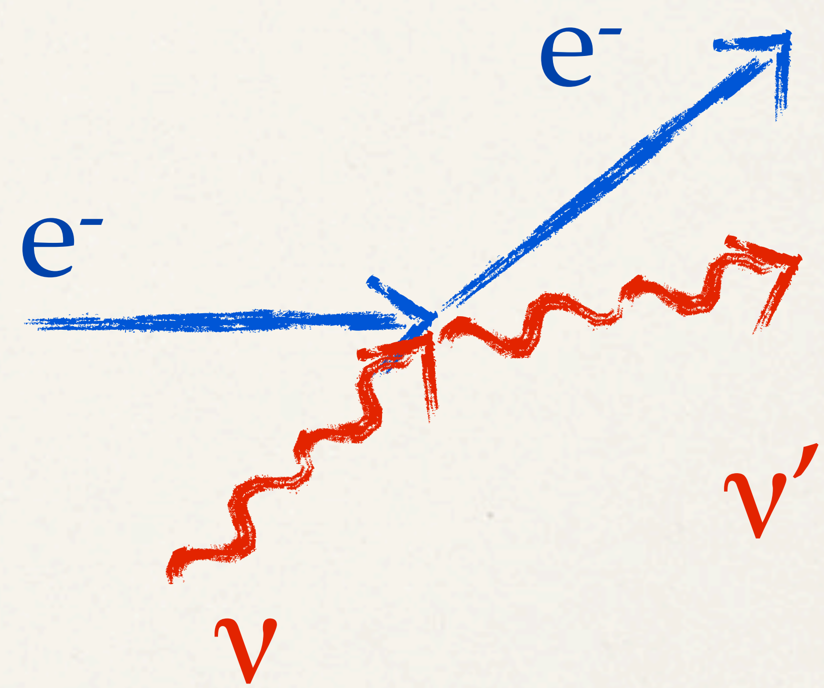
- Black hole or NS on an orbit around a normal star (can be massive or not)
- Matter from the star flows toward the compact object & creates accretion disk
- Relativistic jets are observed in radio with superluminal motion
- Particle acceleration takes place in the jet



Credit: Mirabel Science, 2012, 335, 175

Gamma-rays are produced via inverse Compton scattering

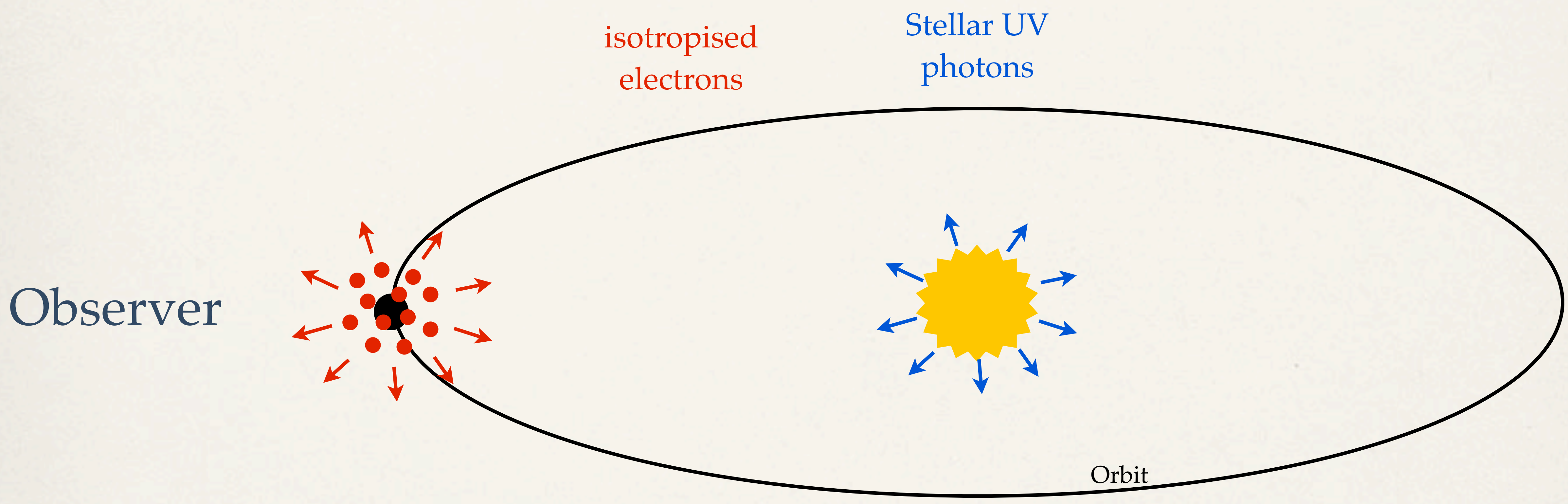
- In both scenarios
- In leptonic scenario, energetic particles in shocked pulsar wind region Compton (IC) upscatter stellar UV photons to VHE (REF)
- IC is a highly anisotropic process - depends on angles between electron and photon
- Photons are preferentially scattered in the direction of incoming electron
- Head on collisions have highest probabilities



$\nu' > \nu$

Photons are preferentially scattered

Inferior conjunction



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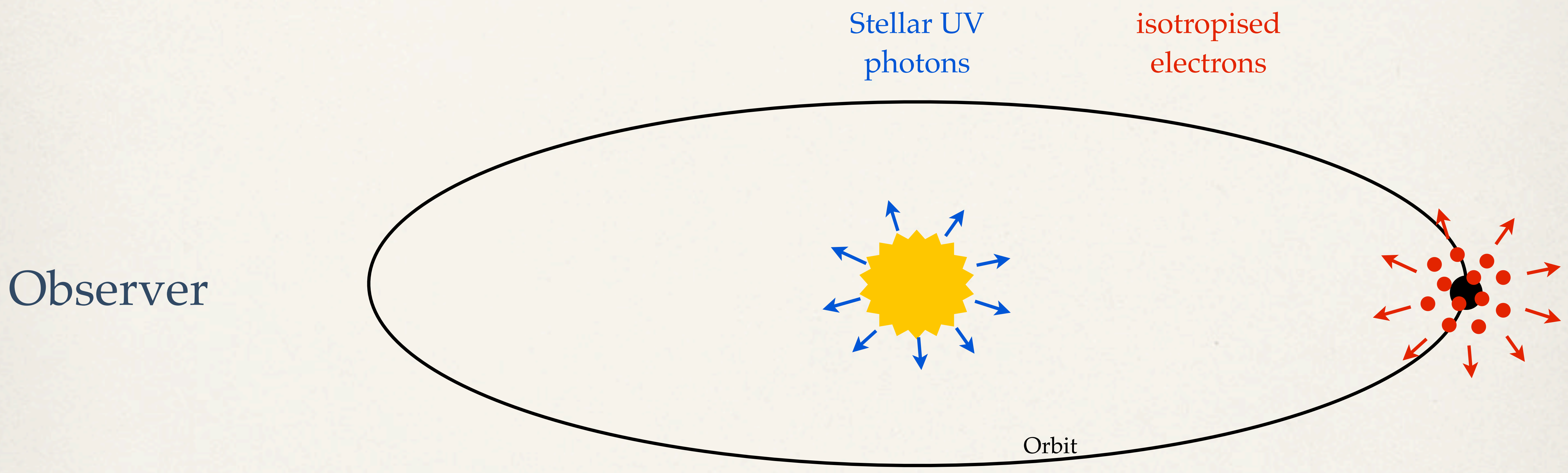

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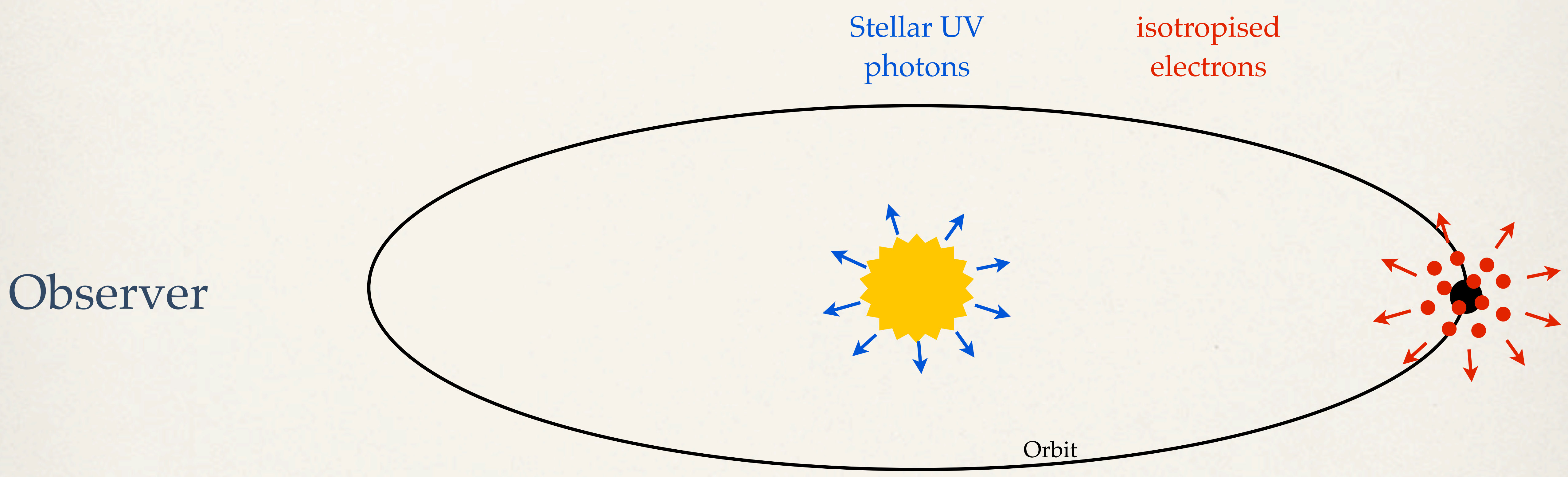
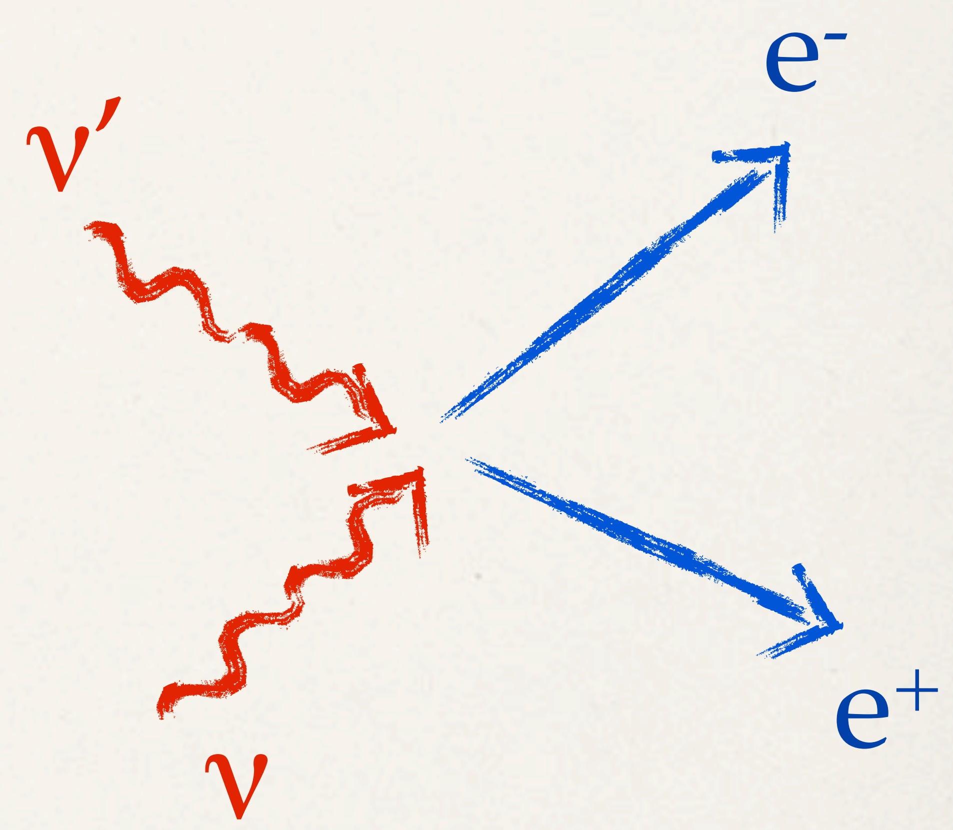


IC process produces:
maximum of gamma-rays during SUPC
minimum of gamma-rays in INFC

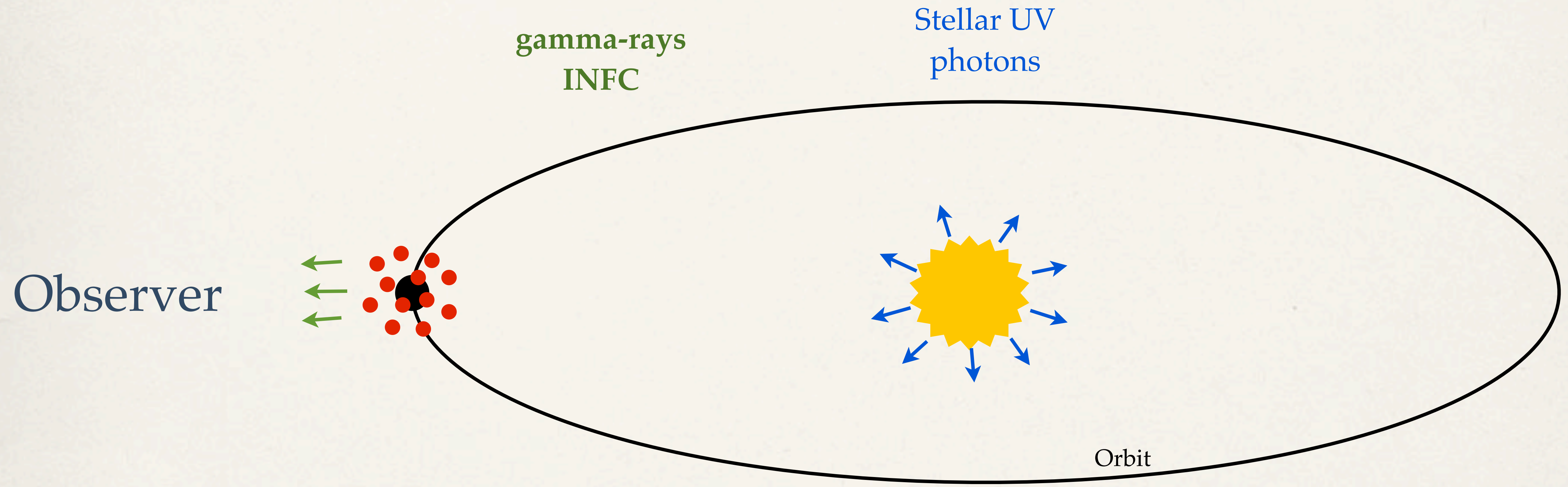
Gamma-rays are absorbed by stellar photons

- Gamma-ray photons create pairs with stellar UV photons
- Pair creation is also an anisotropic process
- Head on collisions of photons have higher probabilities



Highest gamma-ray absorption is in SUPC

Inferior conjunction



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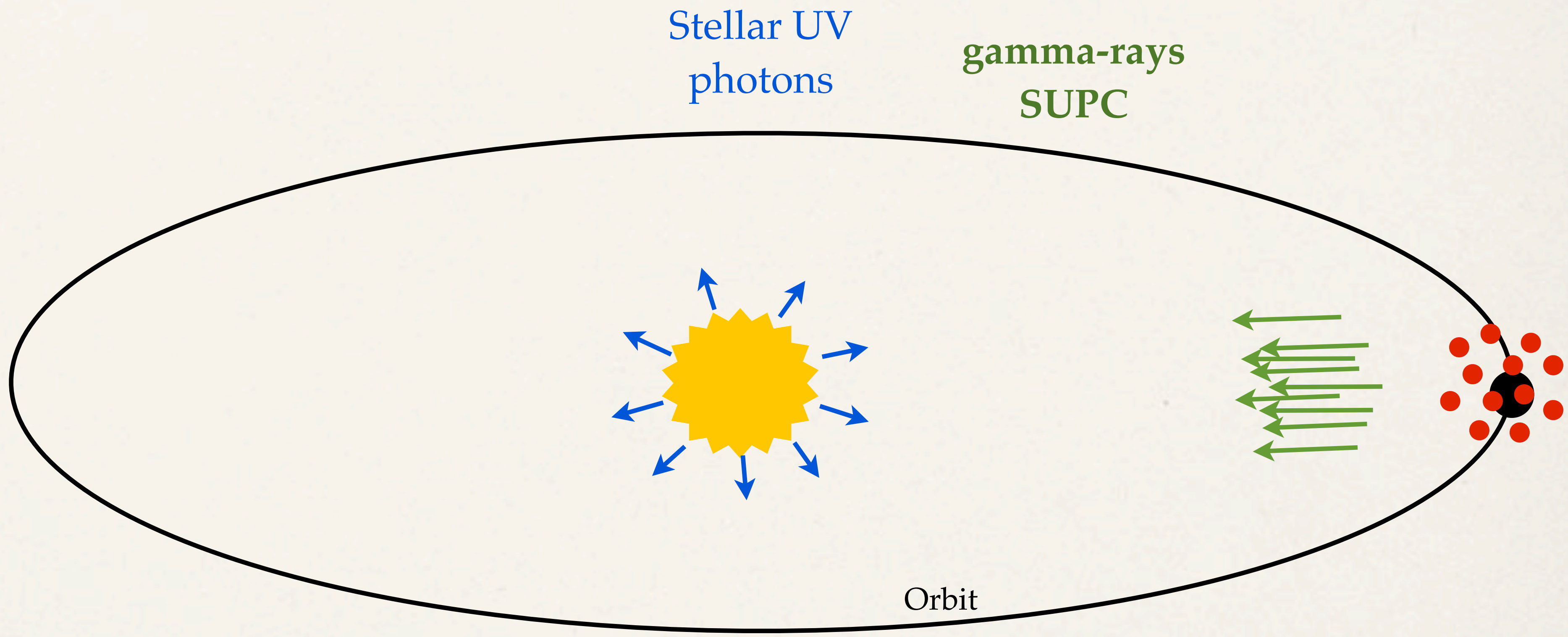
Observer



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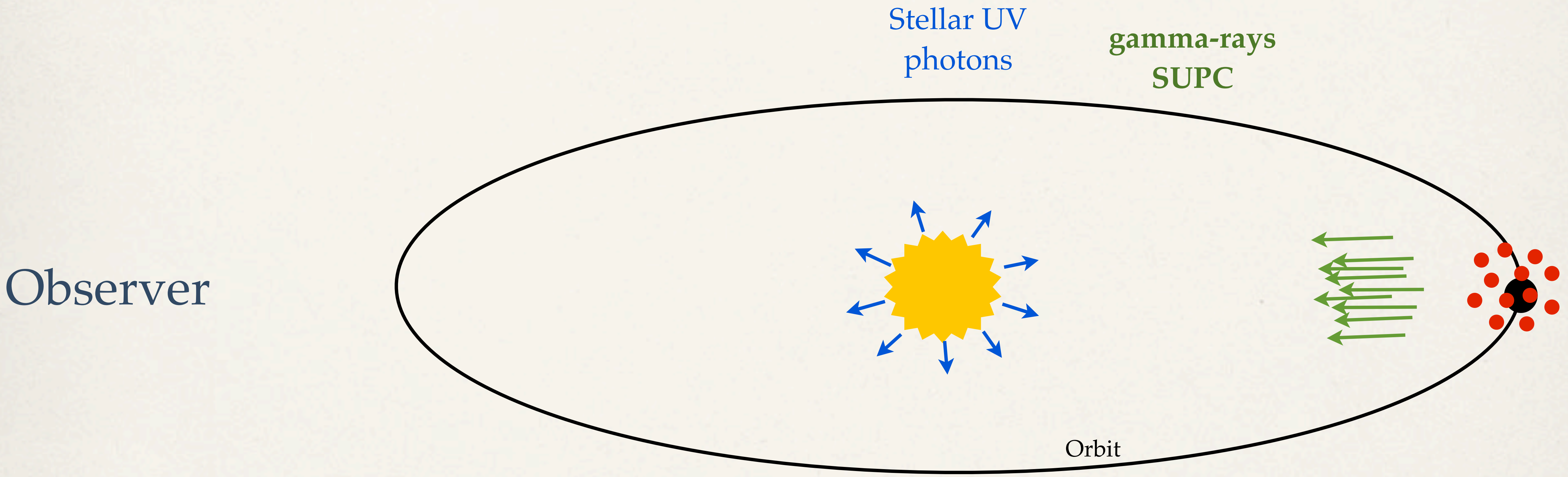


pair absorption process produces strongly reduces flux in SUPC

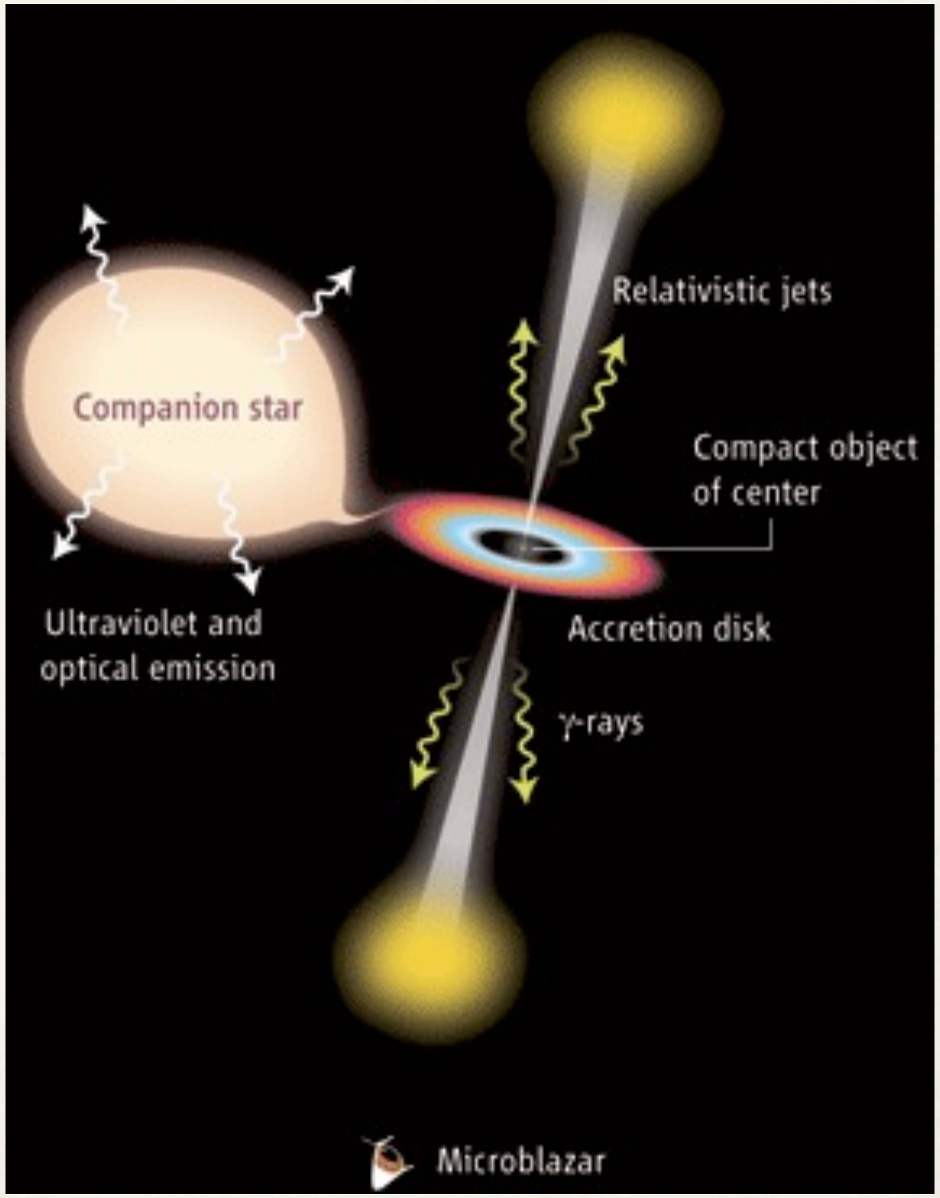
Which binaries contain pulsars?

- **PSR B1259-63**
- **LS 5039**
- **LS I+61 303**
- **HESS J0632+057**
- **1FGL J1018.6-5856**

- PSR B1259-63 is the **only** binary where we detect radio pulsations
- **most likely** contain pulsar, but pulsations were never detected there (REF). There is also no evidence for jet or accretion in these sources
- These binaries have a lot in common: are faint in X-rays and **emit most of their power above 100 MeV - def: Gamma-ray binaries**
- HESS J0632+057 only detected at VHE (TeV)
- 1FGL J1018.6-5856 is only detected in HE (GeV)

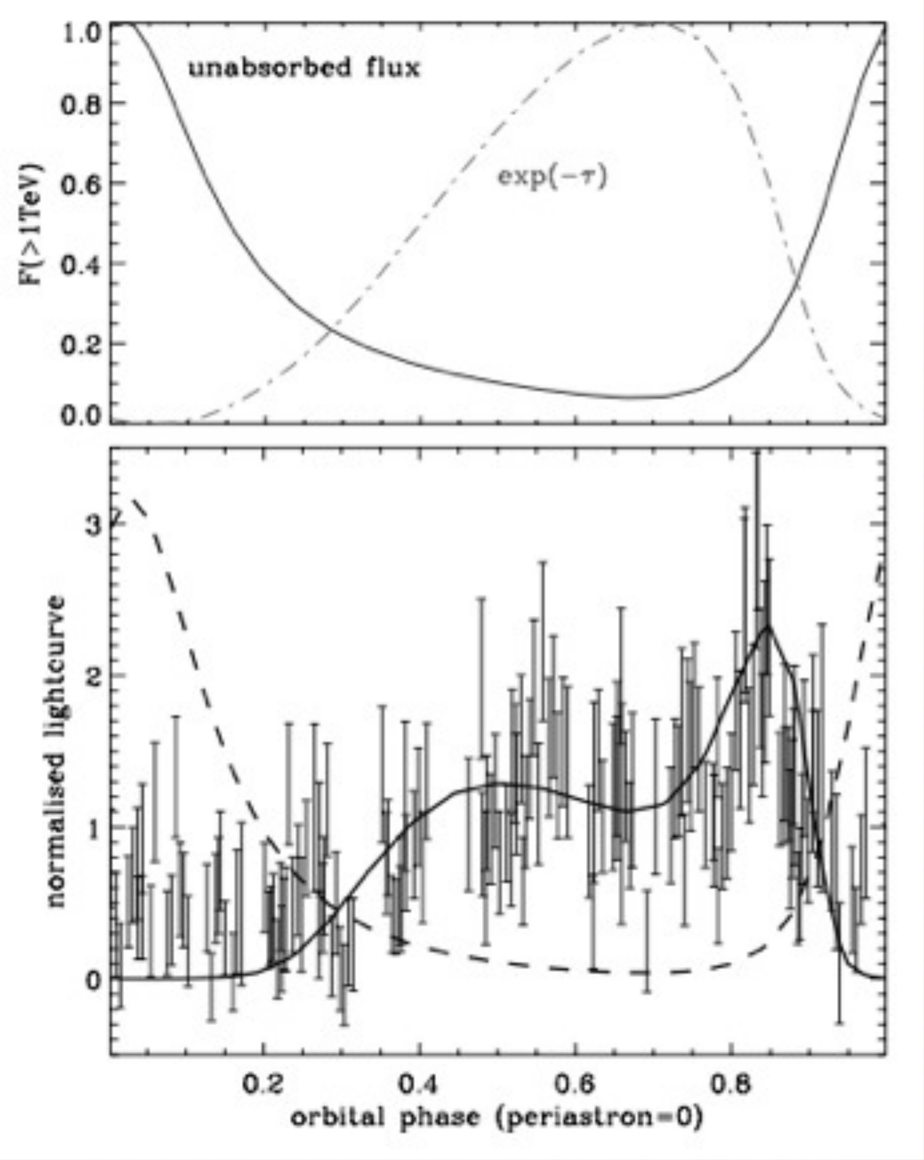
Cyg X-3 is a microquasar emitting in gamma-rays

- Cygnus X-3
- Relativistic jet
- Bright in X-rays & radio
- Never detected in VHE (Aleksic et al. 2012 - Magic Coll.)



LS 5039 is the most regular and well understood binary

- The VHE lightcurve well modeled by IC+pair absorption
- Except for minimum of modulation
- 3D cascades are necessary to explain this excess emission (REF)



Credit: Dubus et al. 2008

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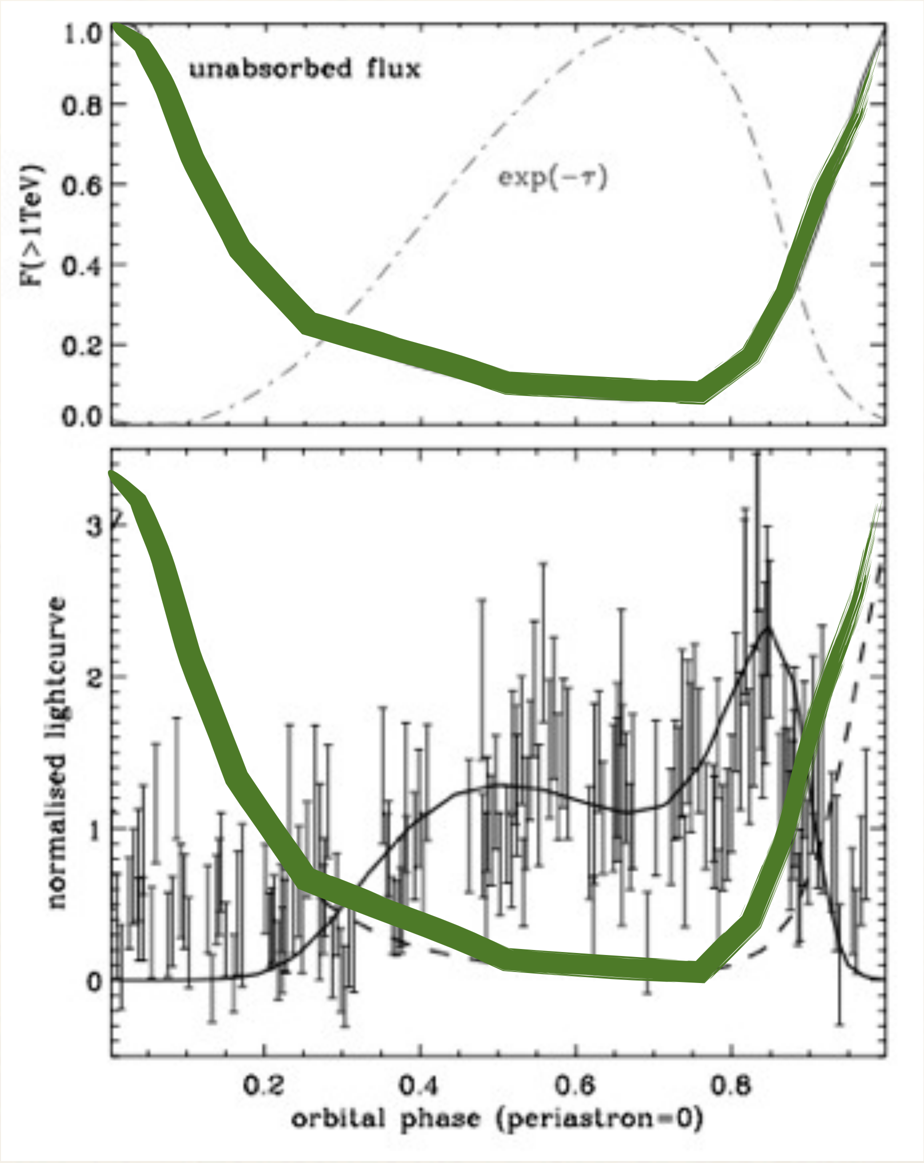

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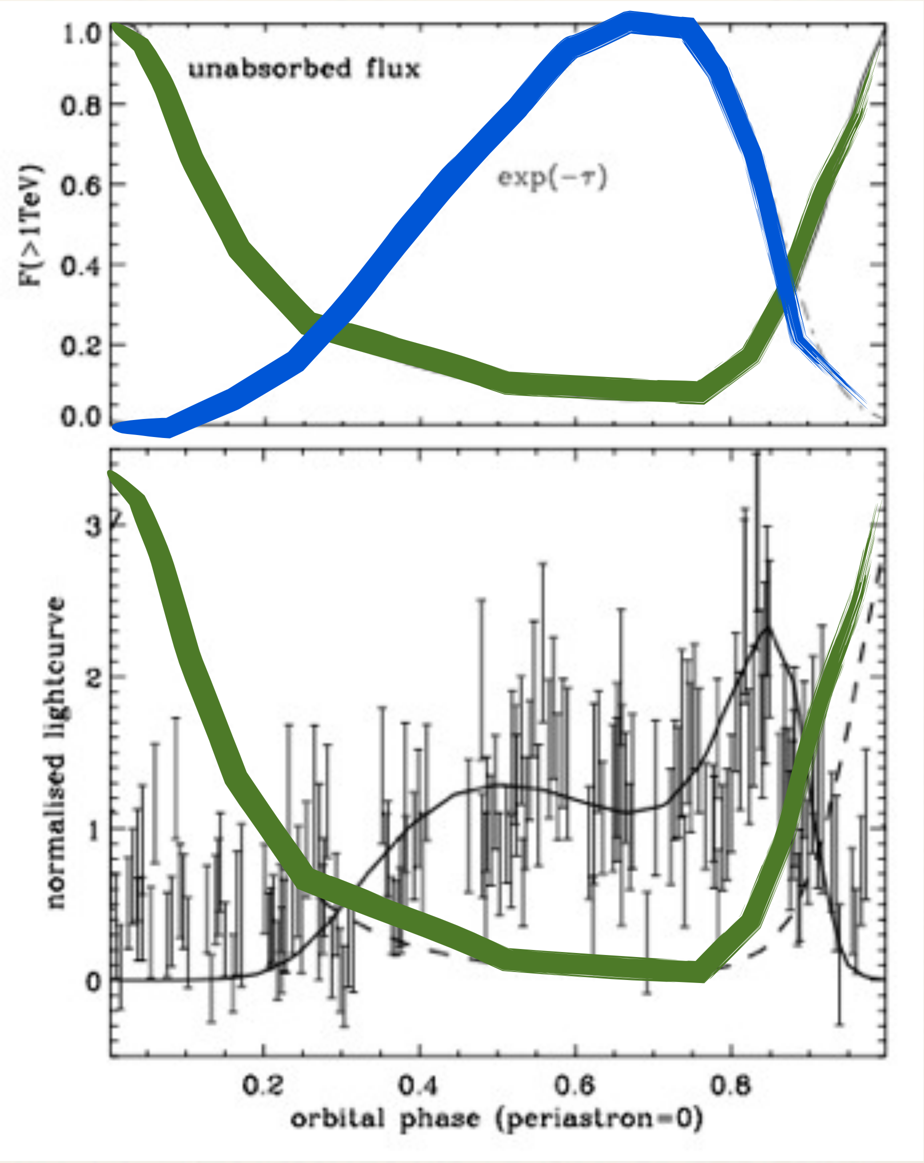

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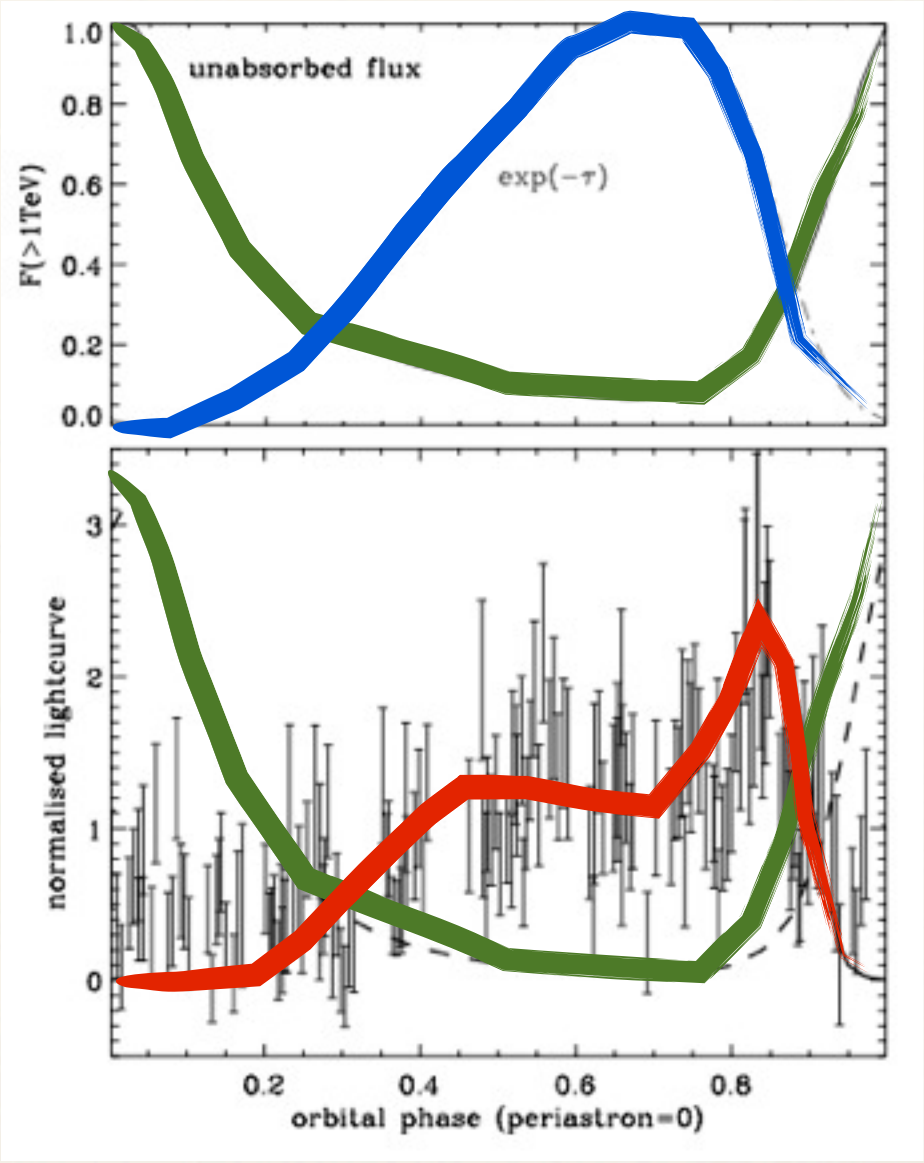

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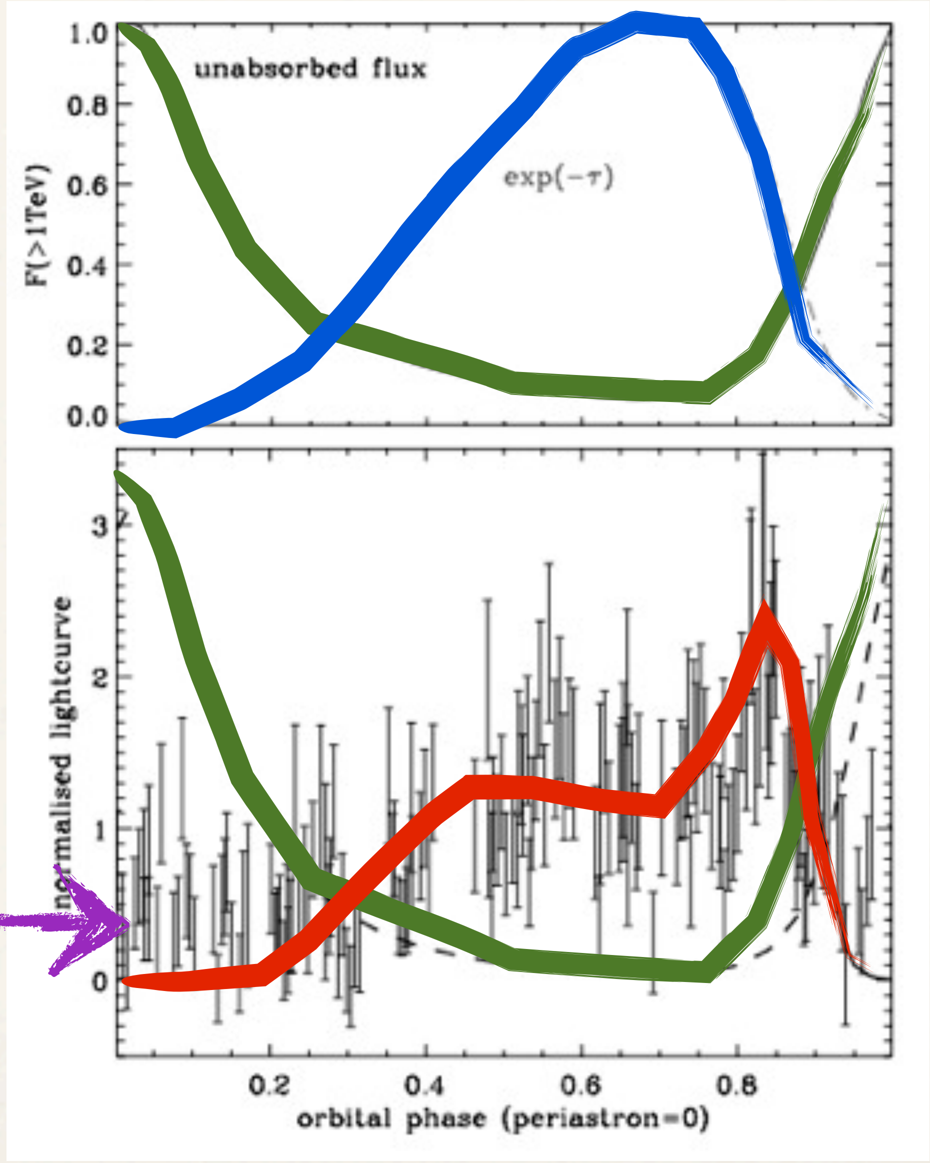
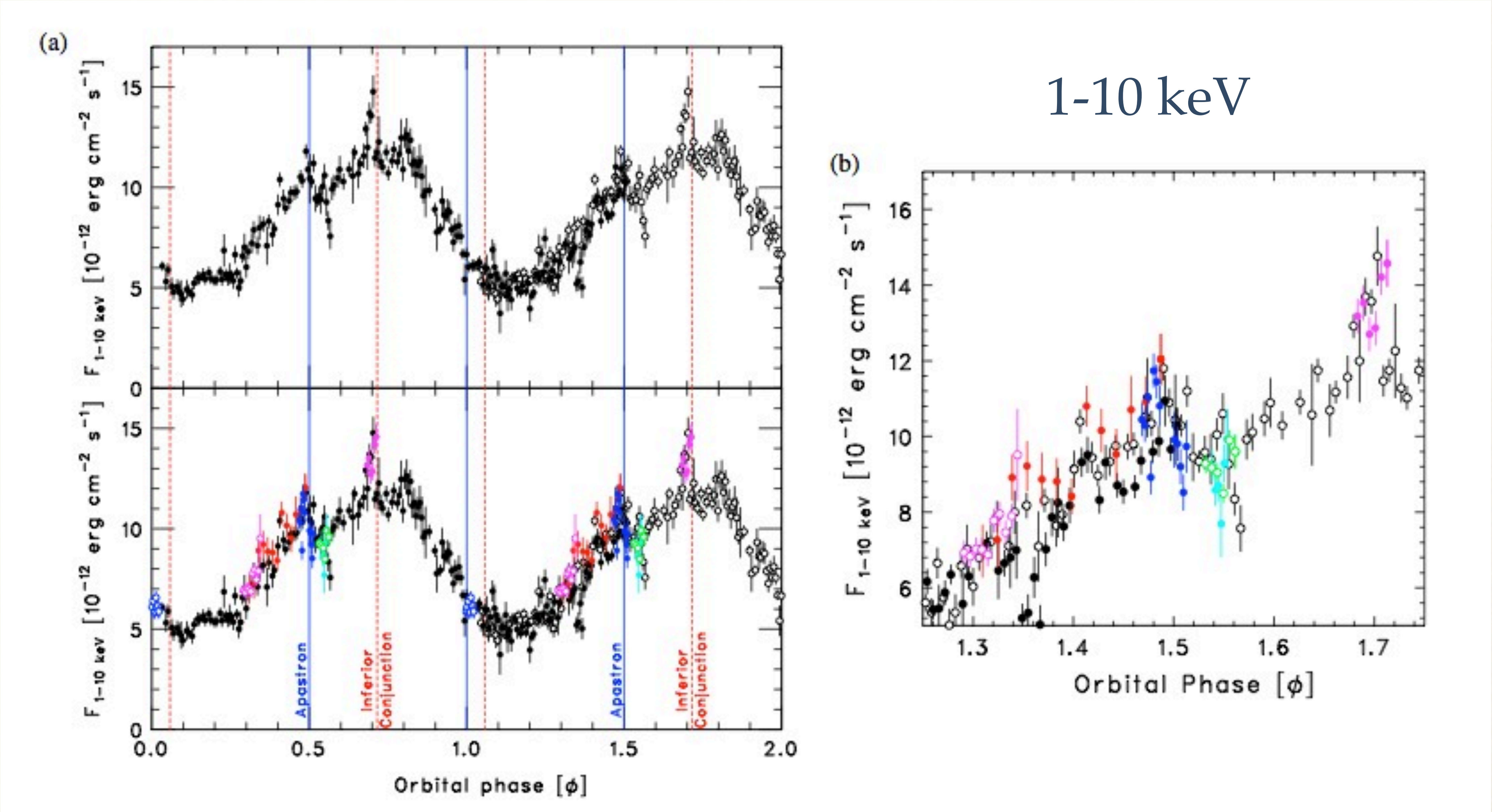


Credit: Dubus et al. 2008

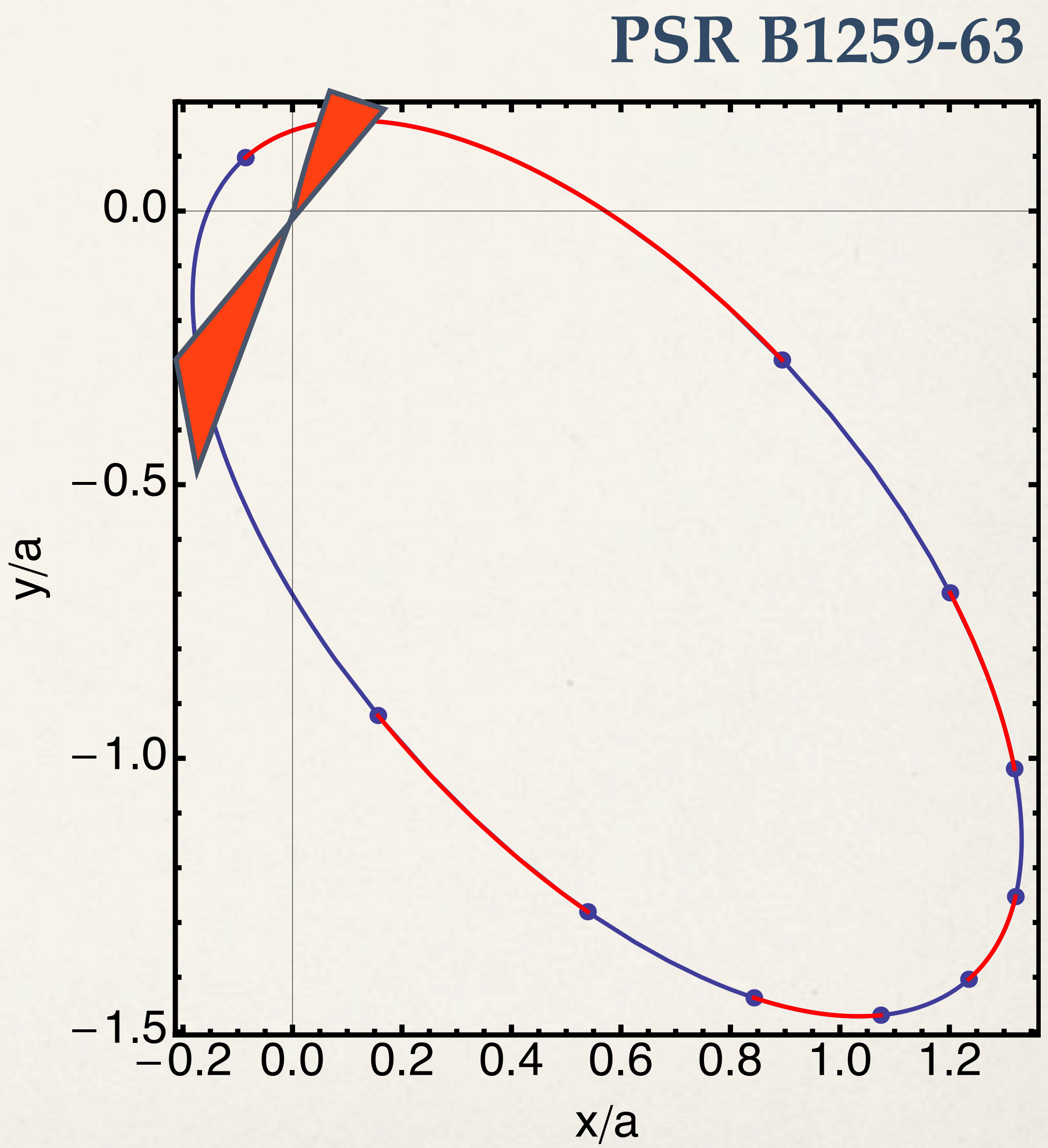
Remarkable stability of X-ray lightcurve of LS 5039



Credit: Kishishita et al. 2009

PSR B1259-63

- Longest orbital period 3.4 years, contains Be star
- The only one where we detect pulsations
- Gamma-rays only observed close to periastron passage
- Recently detected by Fermi - strange flare



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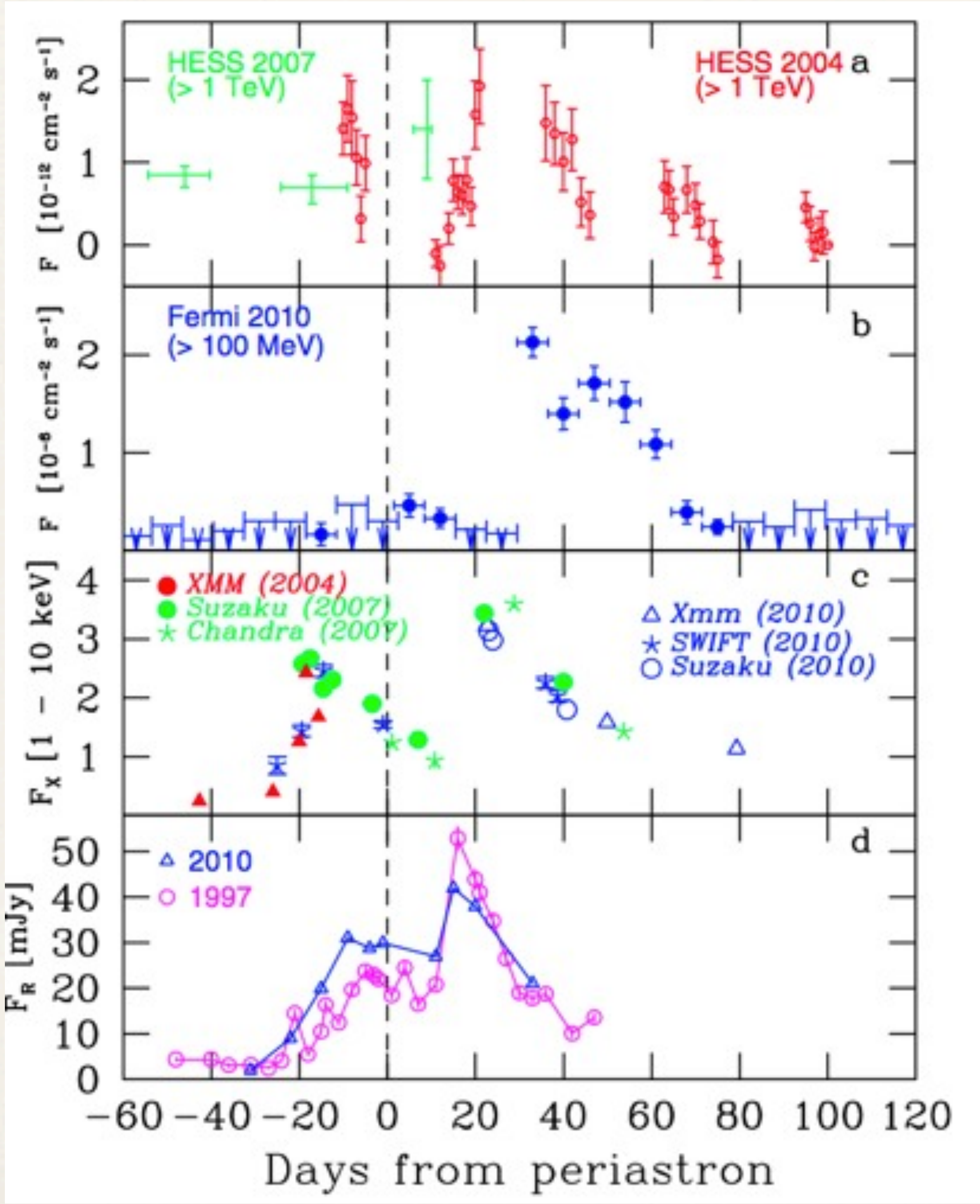
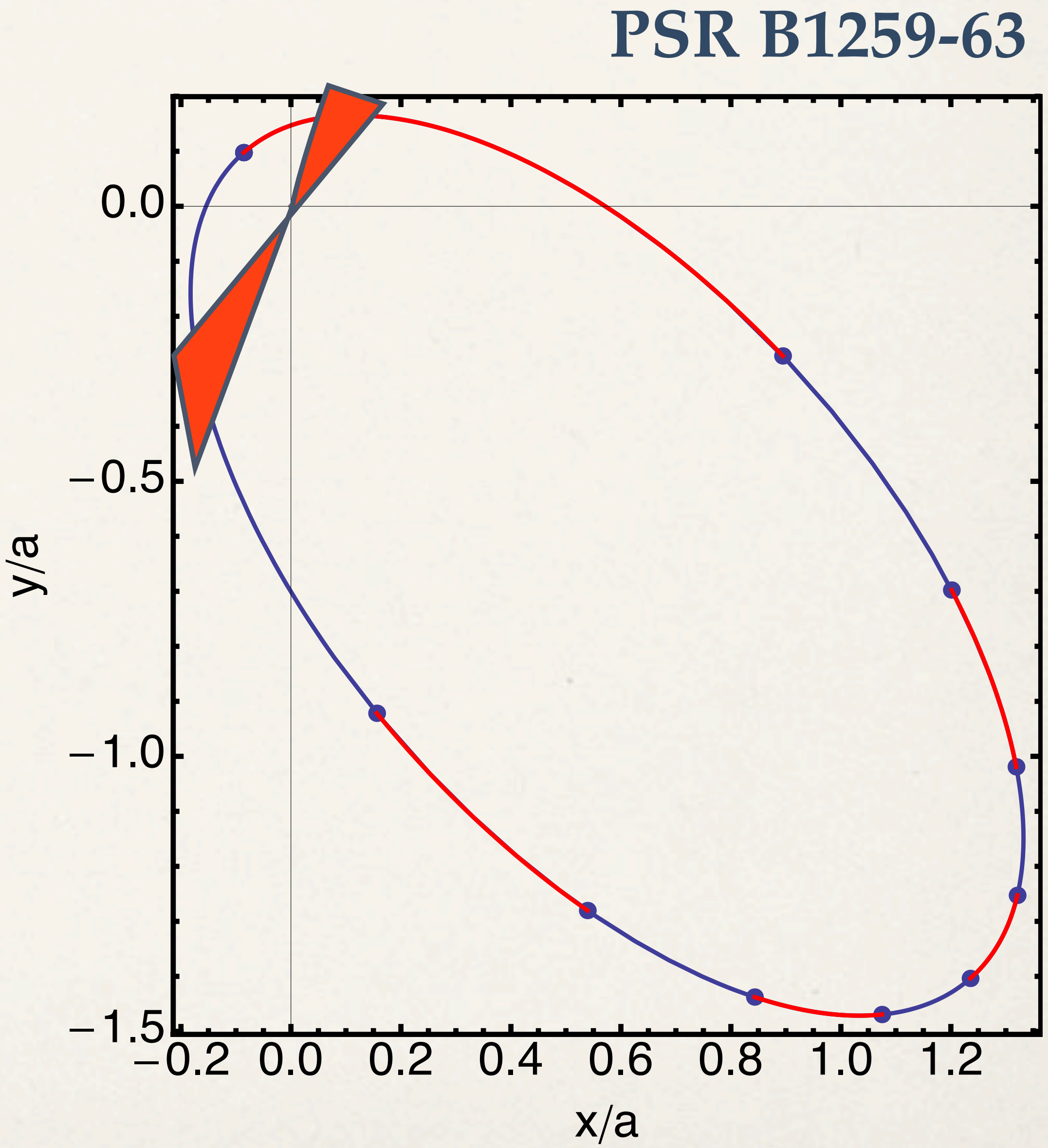
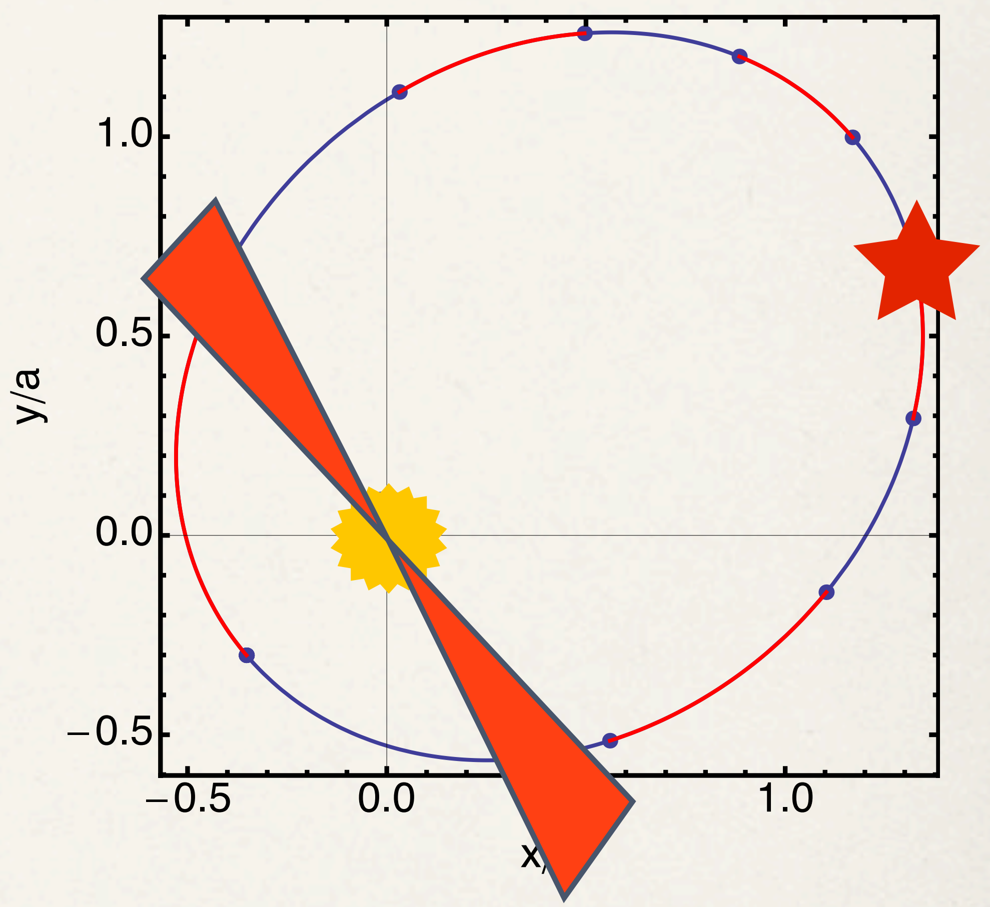


Abdo et al. 2011



LS I+61 303 is not regular

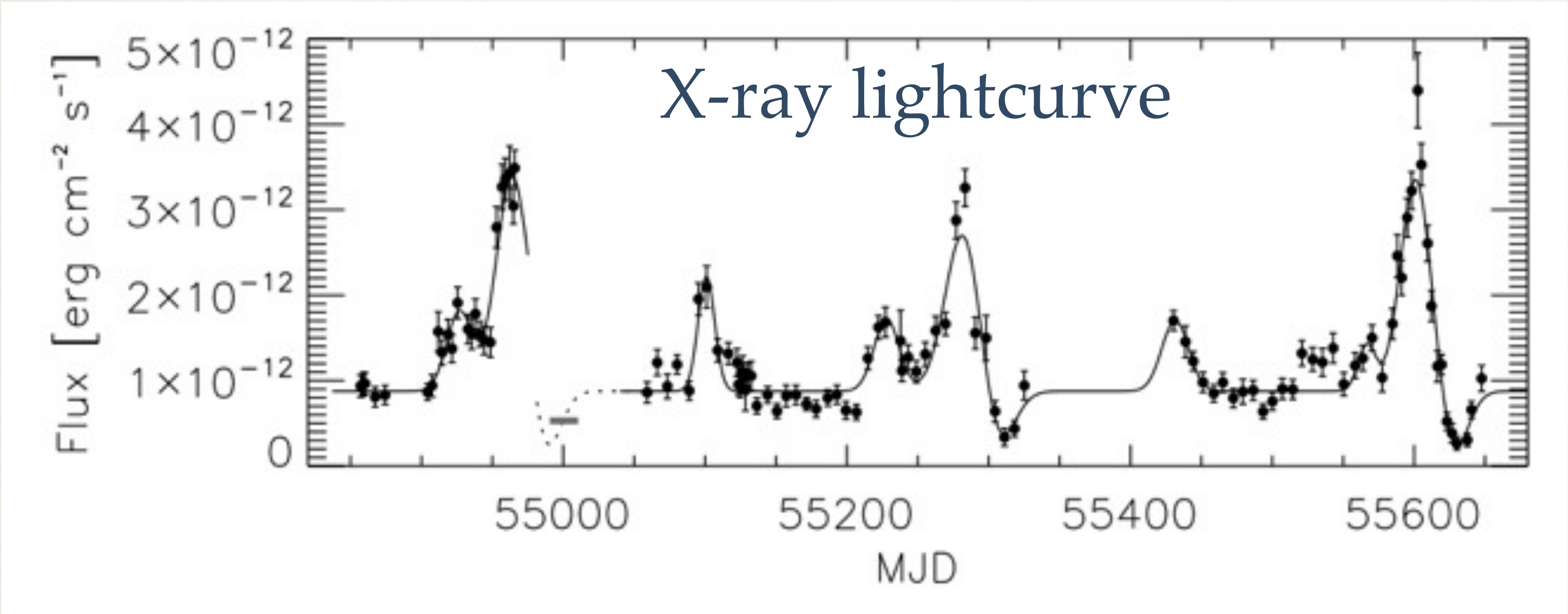
- The least understood binary, unstable lightcurve
- Be star, 26.5 days orbital period
- Highly variable, orbital modulation in different bands comes and goes, emission shows in different phases
- No good model on emission in X-rays or gamma-rays
- Radio outbursts in phase ~0.6. Maximum of flares modulated with period of ~1600 days (4.3 yr) (Gregory et al. 1989)
- X-rays, gamma-rays, Halpha are also modulated with superorbital period 4.3 yr (Li et al. 2011, Zamanov et al. 1999,)
- And recently this binary could be a magnetar (Torres 2011)



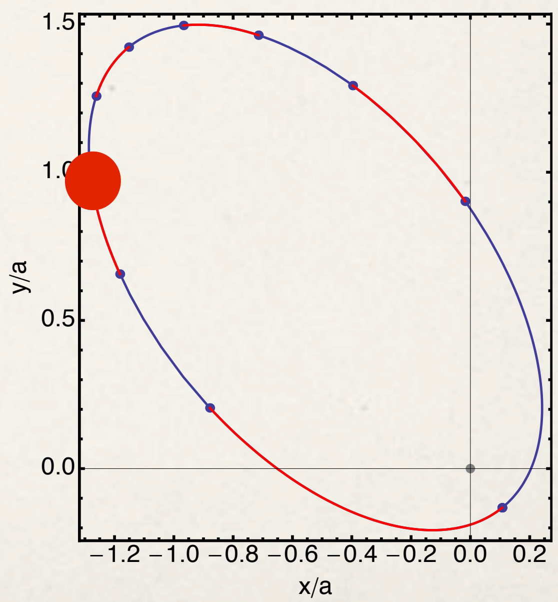
Shape and orientation of the Be disk is unknown

HESS J0632-057

- Discovered early in HESS history as point source (Aharonian et al. 2007)
- Be massive star as a counterpart of VHE source
- Source appeared and disappeared over time for HESS and VERITAS (Maier et al. 2009, Acciari et al. 2009)
- Orbital period of 320 days detected only recently (Bongiorno et al. 2009).



(Bongiorno et al. 2009)



Casares et al. 2012

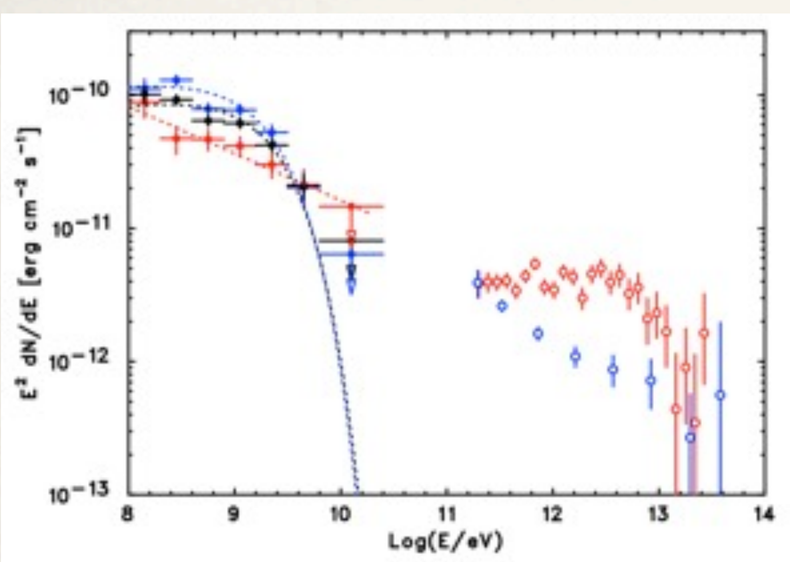
1 FGL J1018.6-5856

- Contains an O star
- 16 day orbital period
- HESS didn't yet publish its findings about this binary

GeV - TeV connection

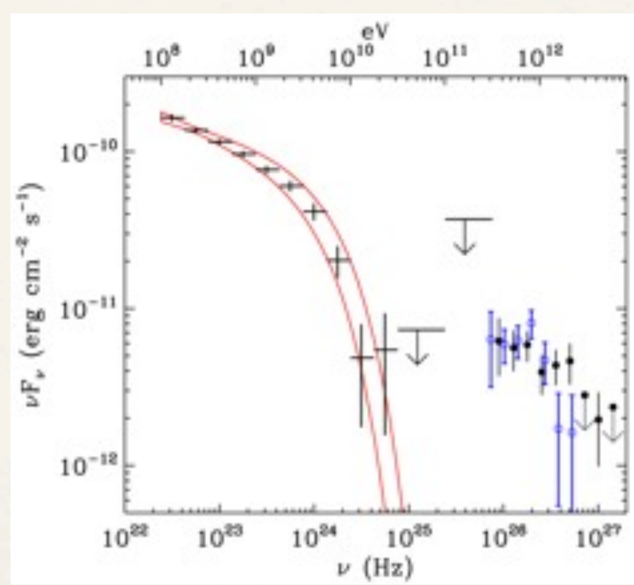
- Most likely two different emission components
- Possibly emission from pulsar (Petri & Dubus 2011) - spectrum resembles those of Fermi pulsars

LS 5039



Abdo et al. 2009

LS I+61 303



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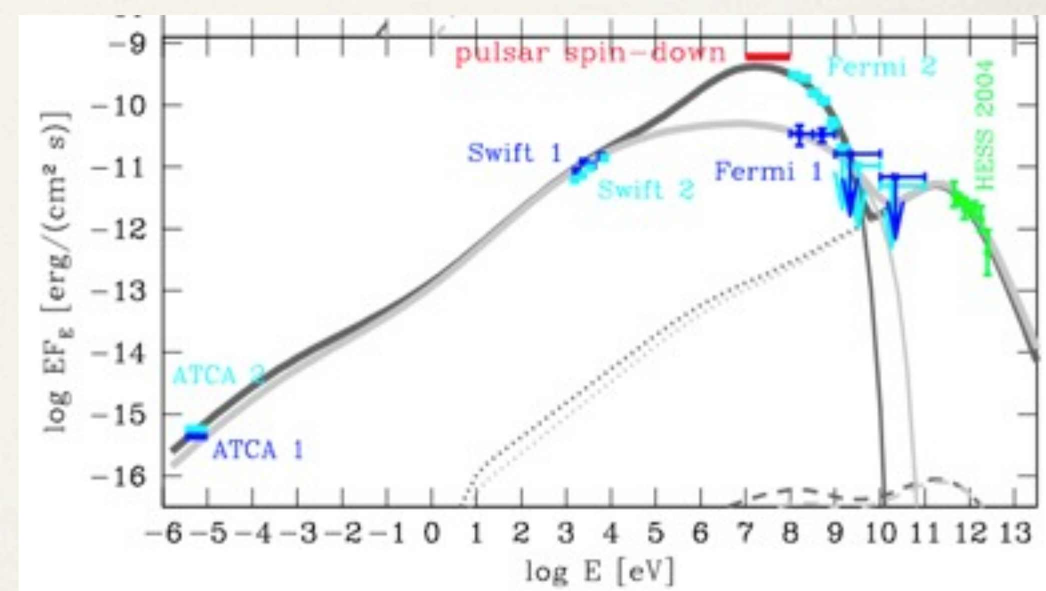


Abdo et al. 2011

The biggest questions for binaries

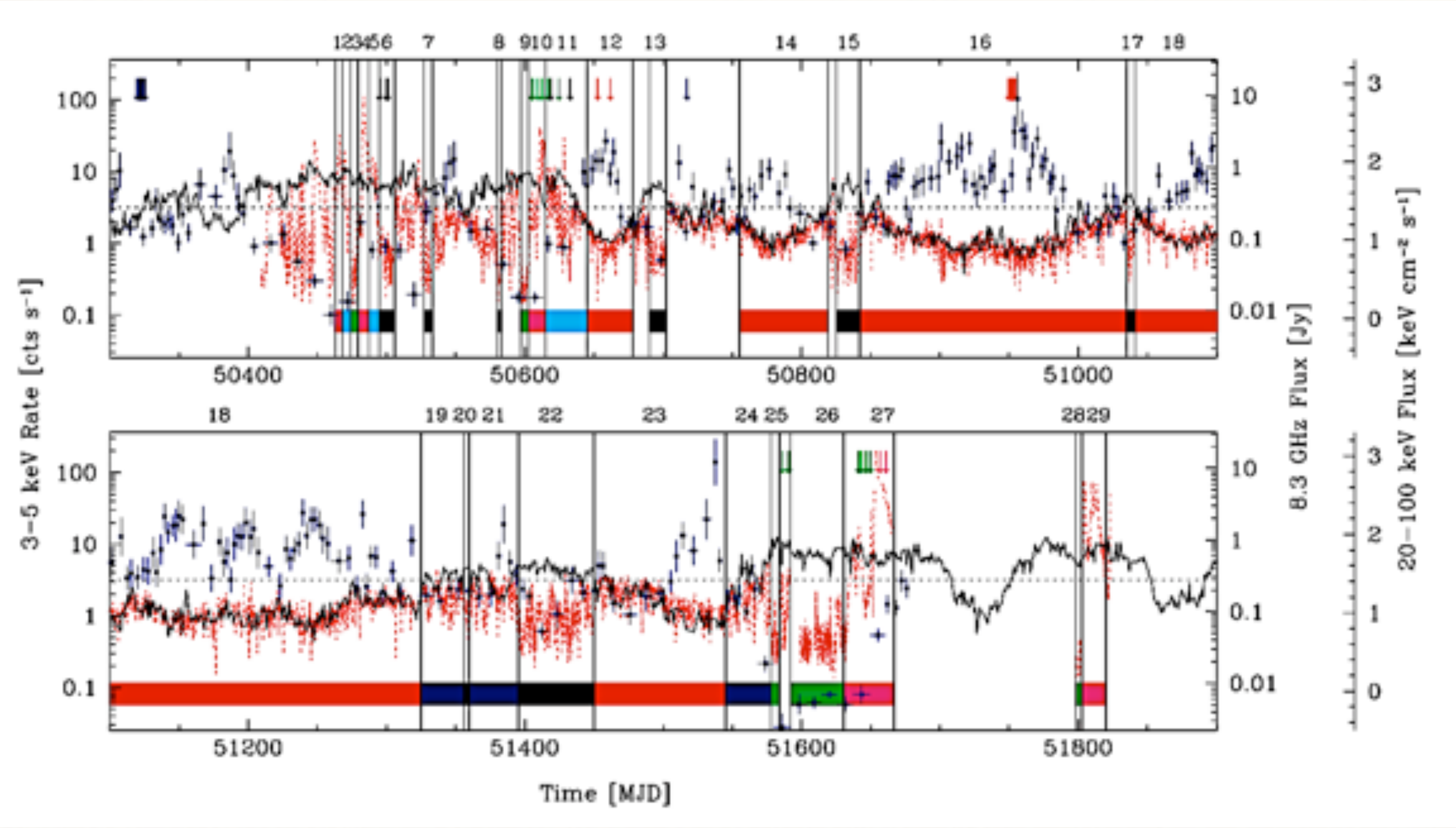
- Why only so few gamma-ray binaries?
- What is the acceleration mechanism
- What is the connection between GeV and TeV
- Lots of unknown related to individual binaries

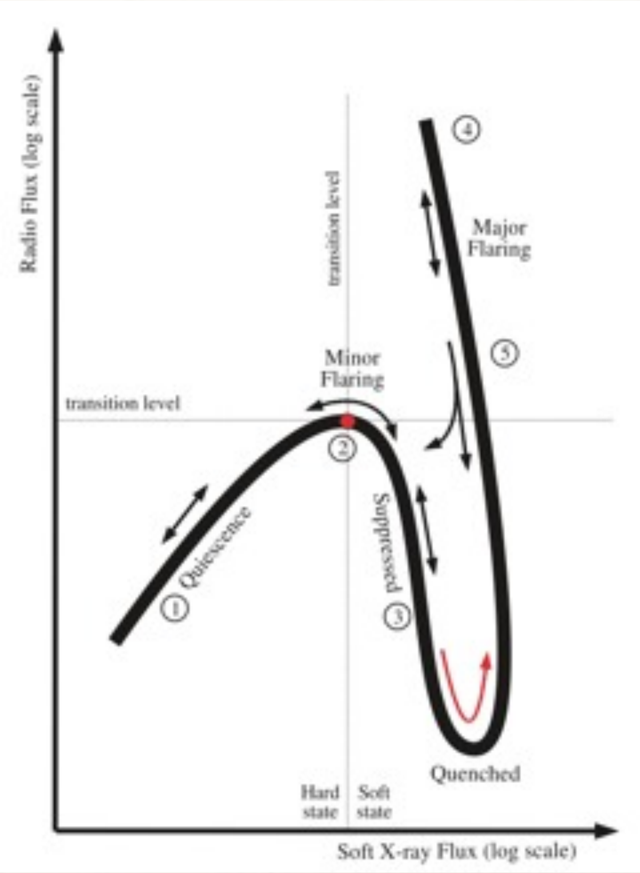
My projects

- Cyg X-3
- Search for new binaries
- P Cygni
- LS 5039 in minimum

Connection between jet and accretion

- Pattern of correlation between different energy bands changes with spectral state
- radio 8.3 GHz soft X-rays (3-5 keV) hard X-rays (20-100 keV)

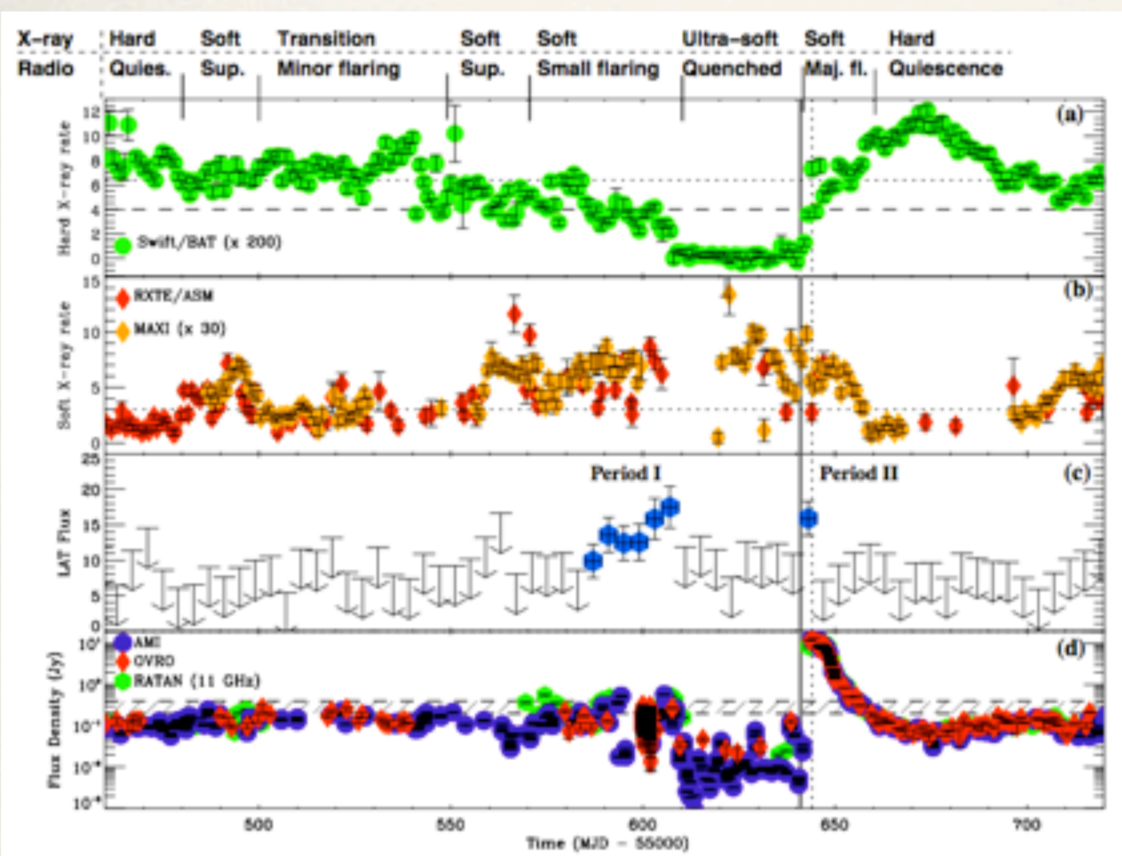


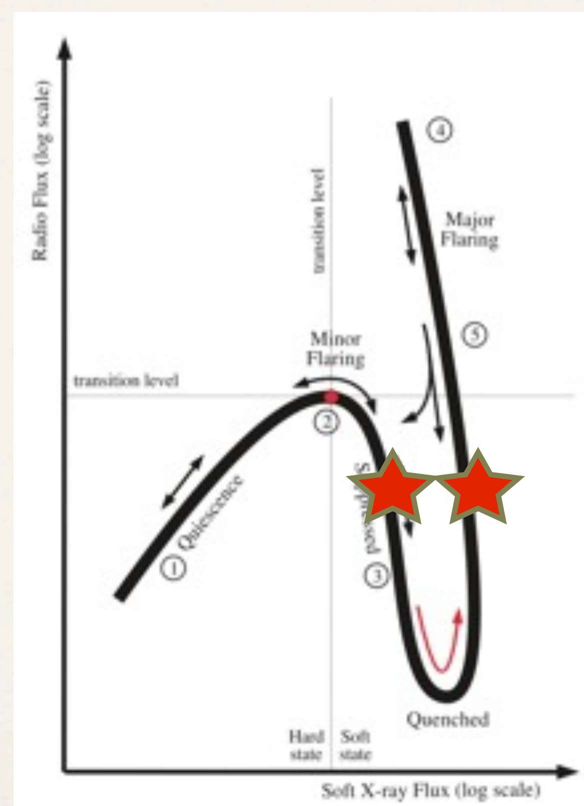


Szostek & Zdziarski 2008

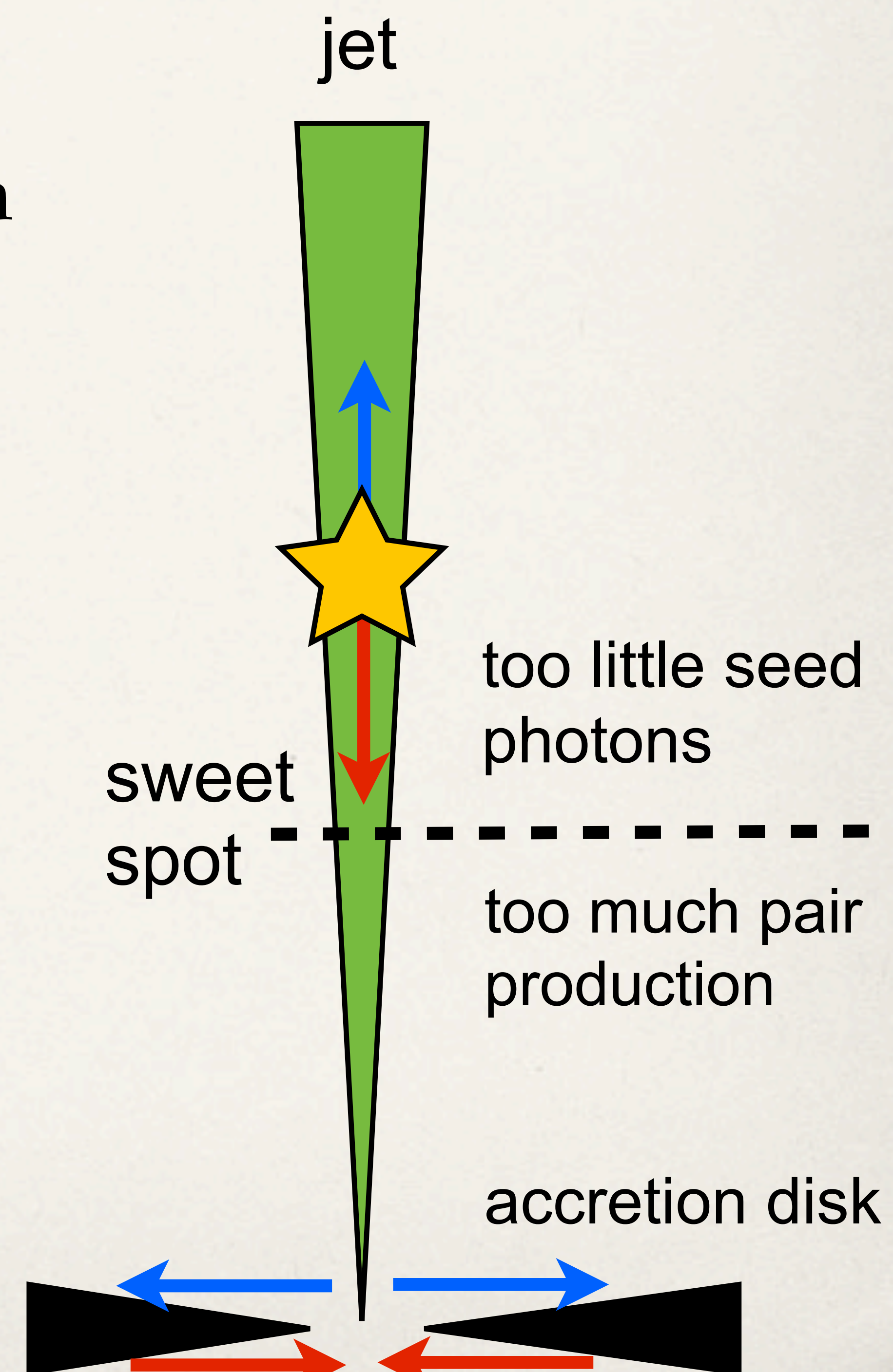
Accretion - jet connection extended to gamma-rays

- Interplay between IC on stellar photons and photon-photo pair production with accretion disk photons

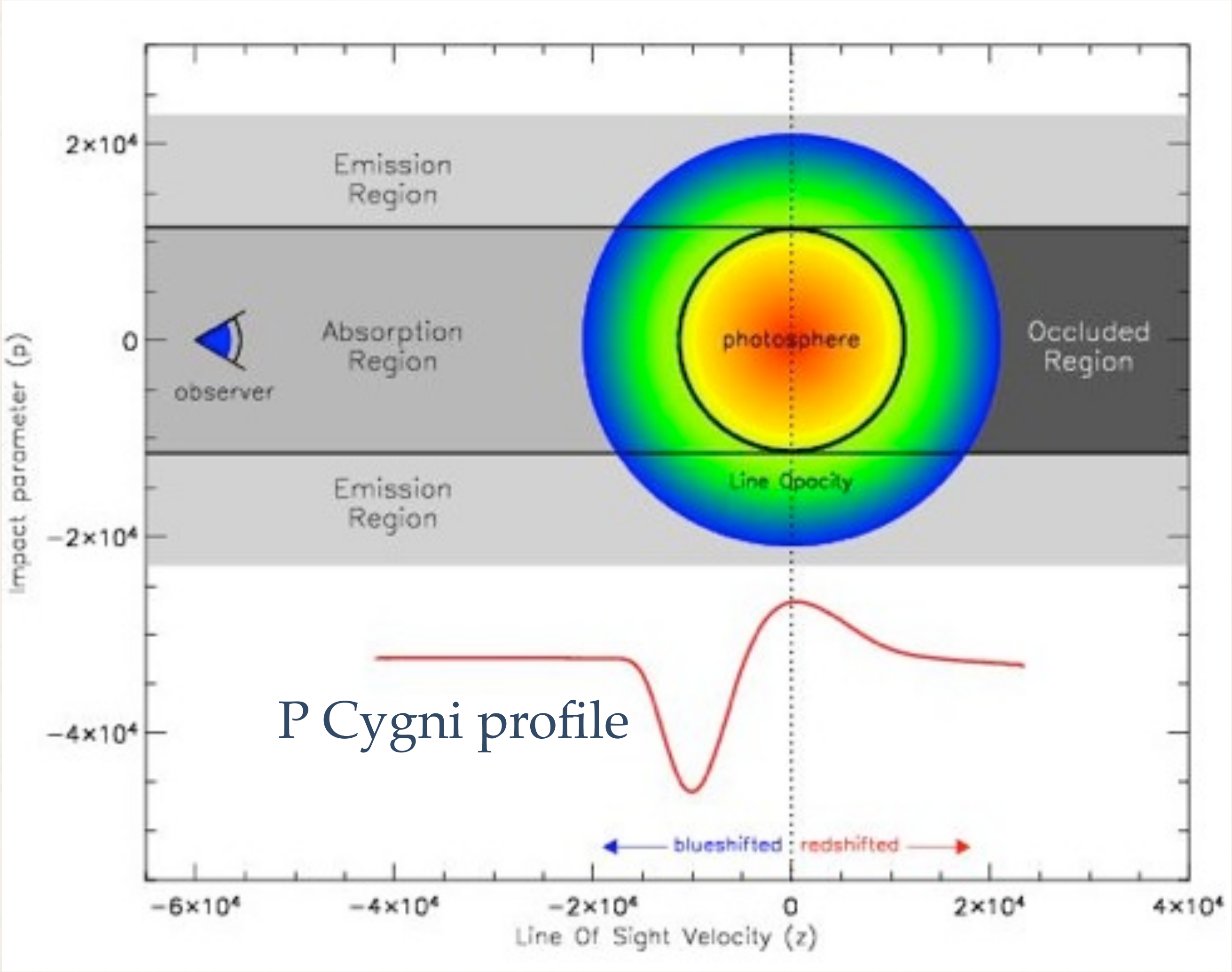




Corbel et al. 2012



UV emission lines can help us identify particle acceleration scenario



- The change in profile depends on cavity size, distance from the massive star and location with respect to the observer

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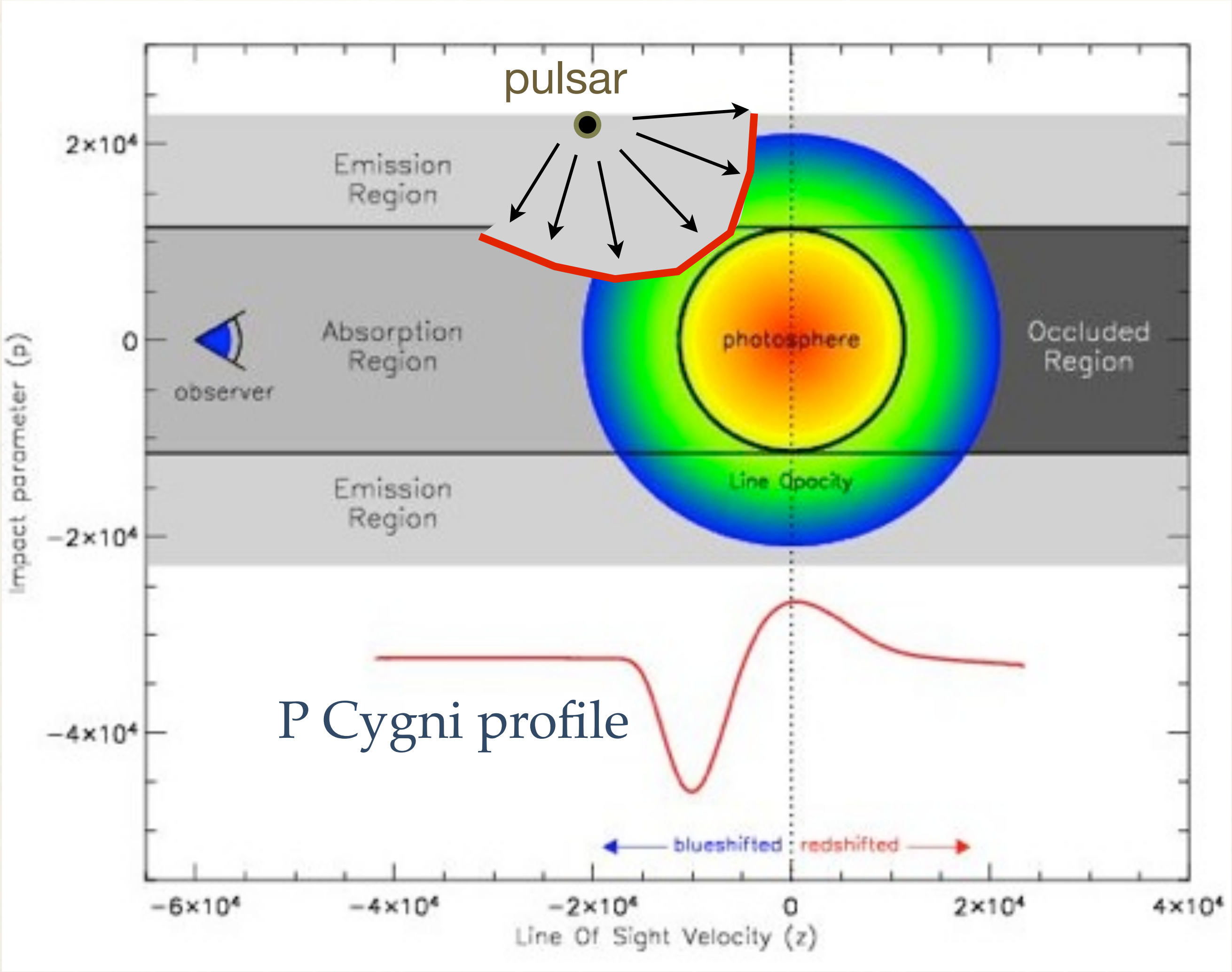
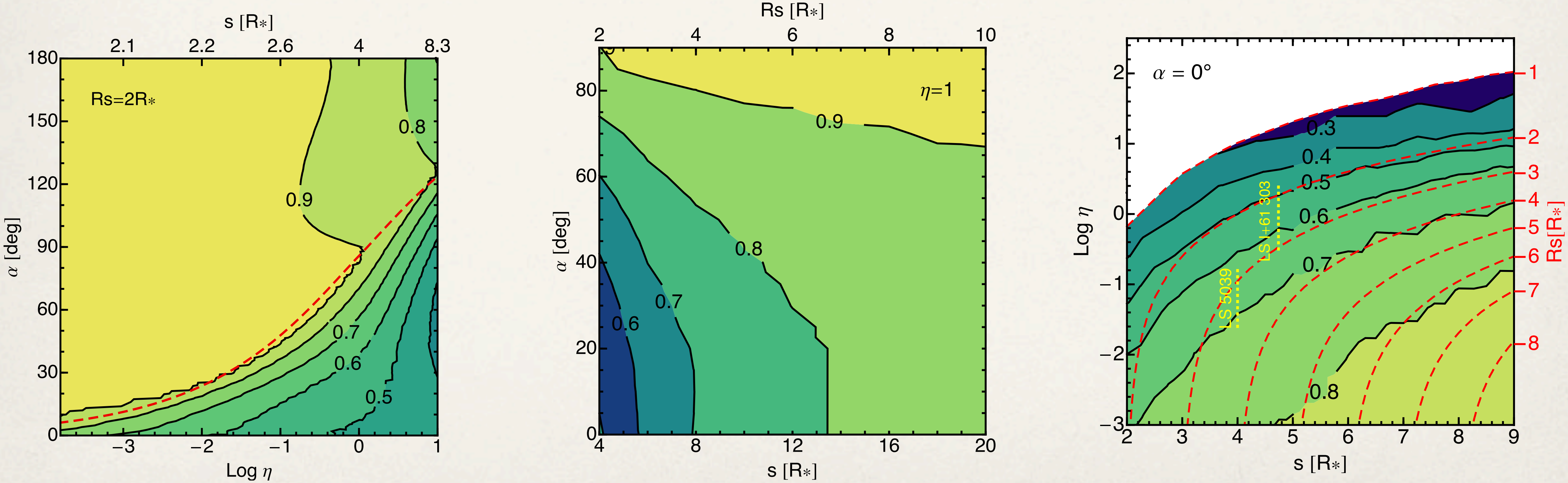


- The change in profile depends on cavity size, distance from the massive star and location with respect to the observer

The profiles differ most from that of a single star when:

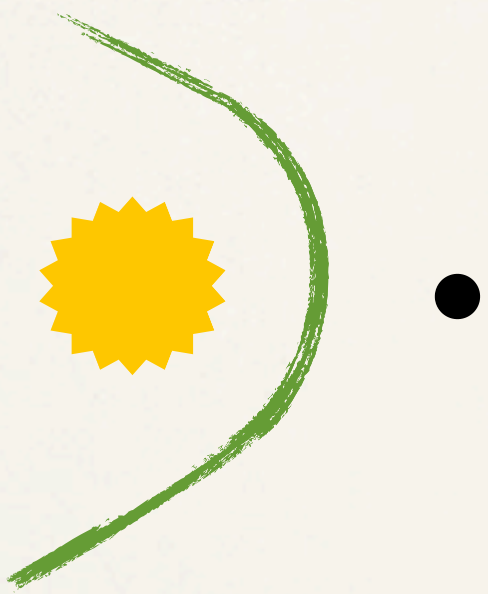
- Cavity is large - large opening angle - pulsar wind dominates over stellar wind

- Cavity is close to the line of sight



Szostek et al. 2012

LS I+61 303 is the only binary where the pulsar wind can dominate stellar



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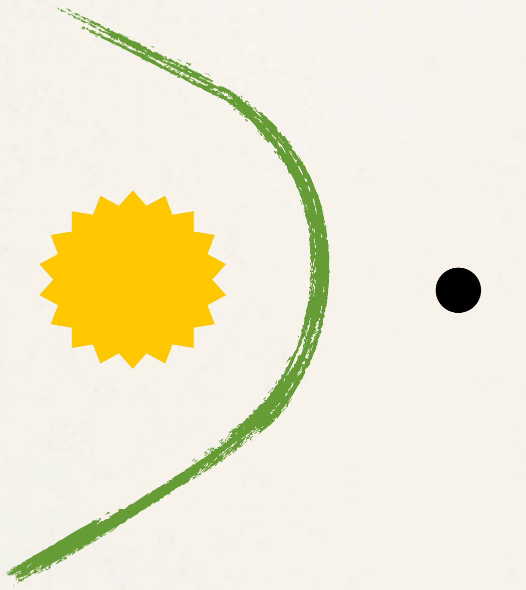

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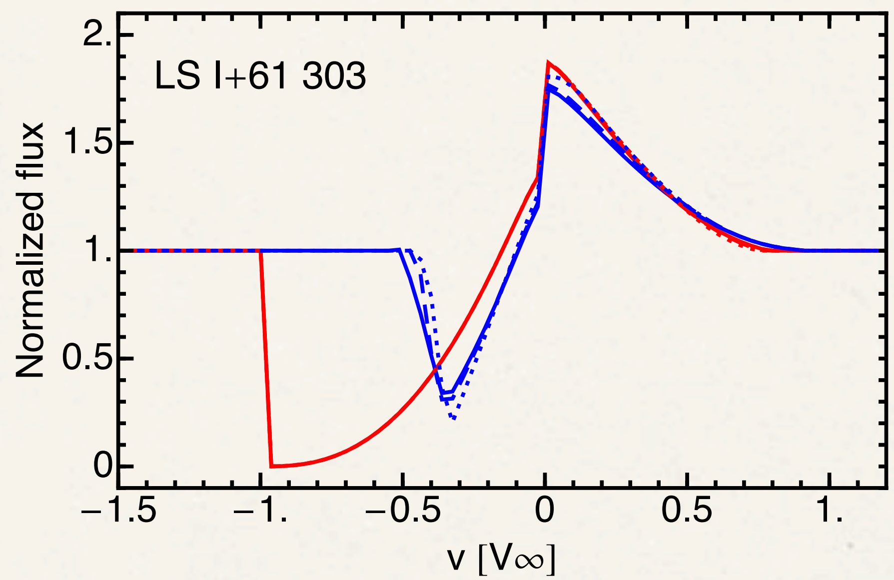
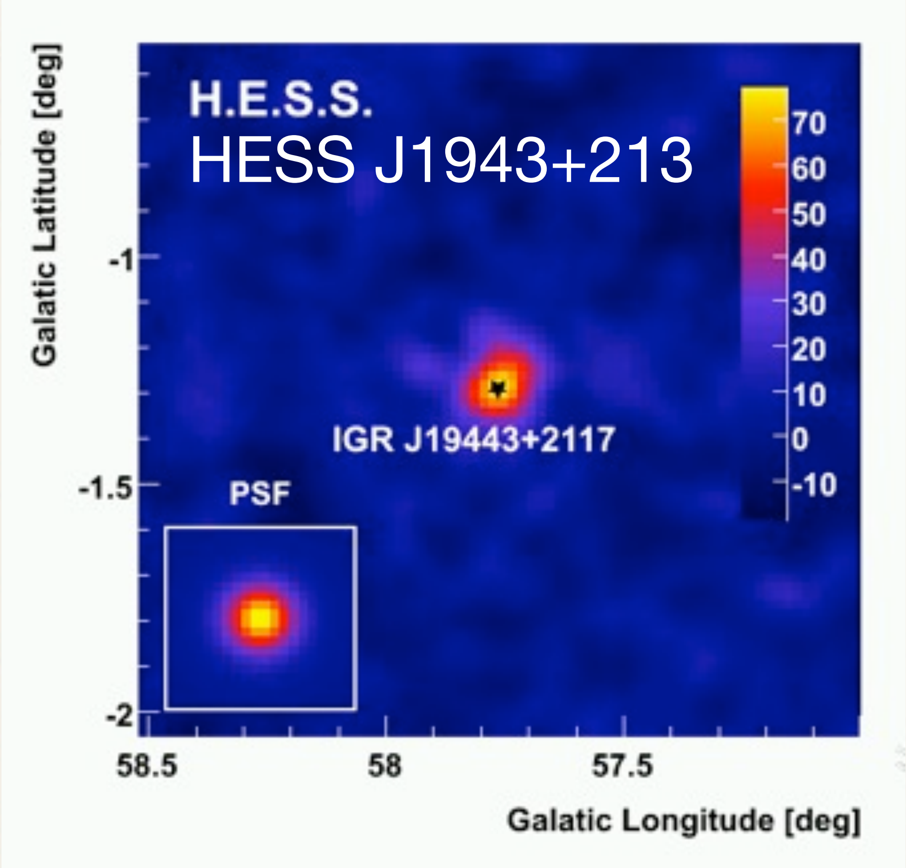


We predict the lines in LS I+61 303 will change significantly between conjunction

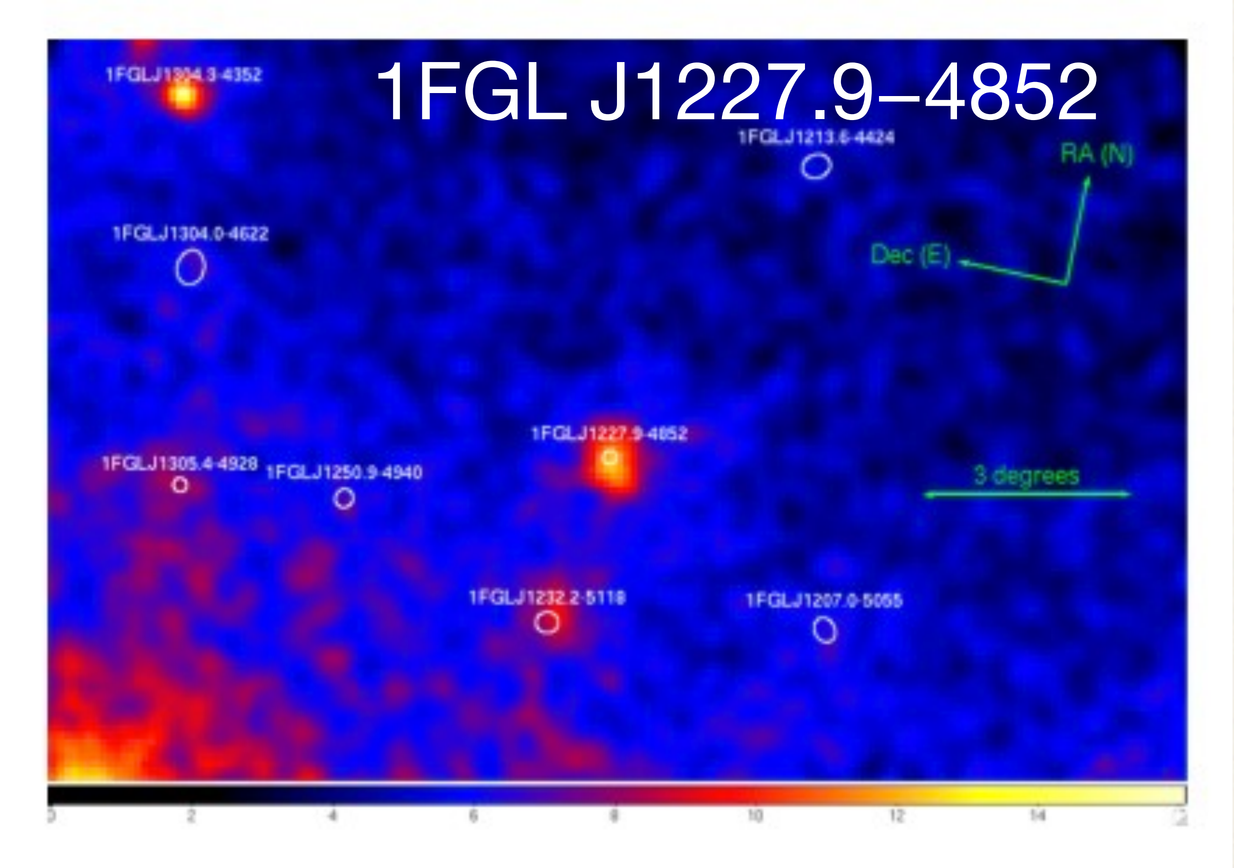
A. Szostek et al. 2012

Population studies predict there are 30 gamma-ray binaries in the Galaxy

- Search by cross correlation of gamma-ray and X-ray catalogs
- Search for point sources in HESS data

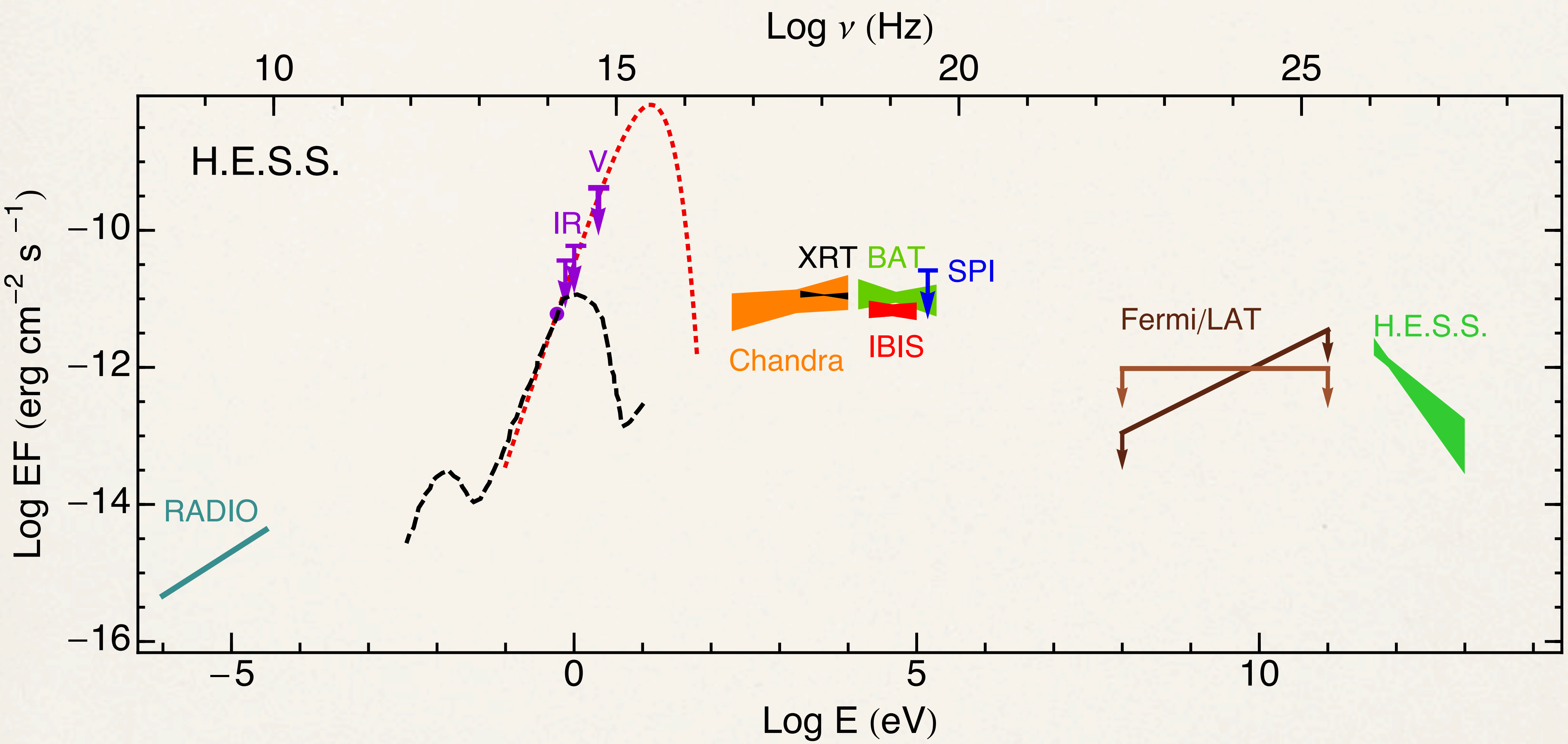


A. Szostek on behalf of HESS Collaboration, Abramowski et al. 2011



A. Hill, A. Szostek et al. 2011

HESS J1943+213 - extreme blazar



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Collaboration, Abramowski et al. 2011

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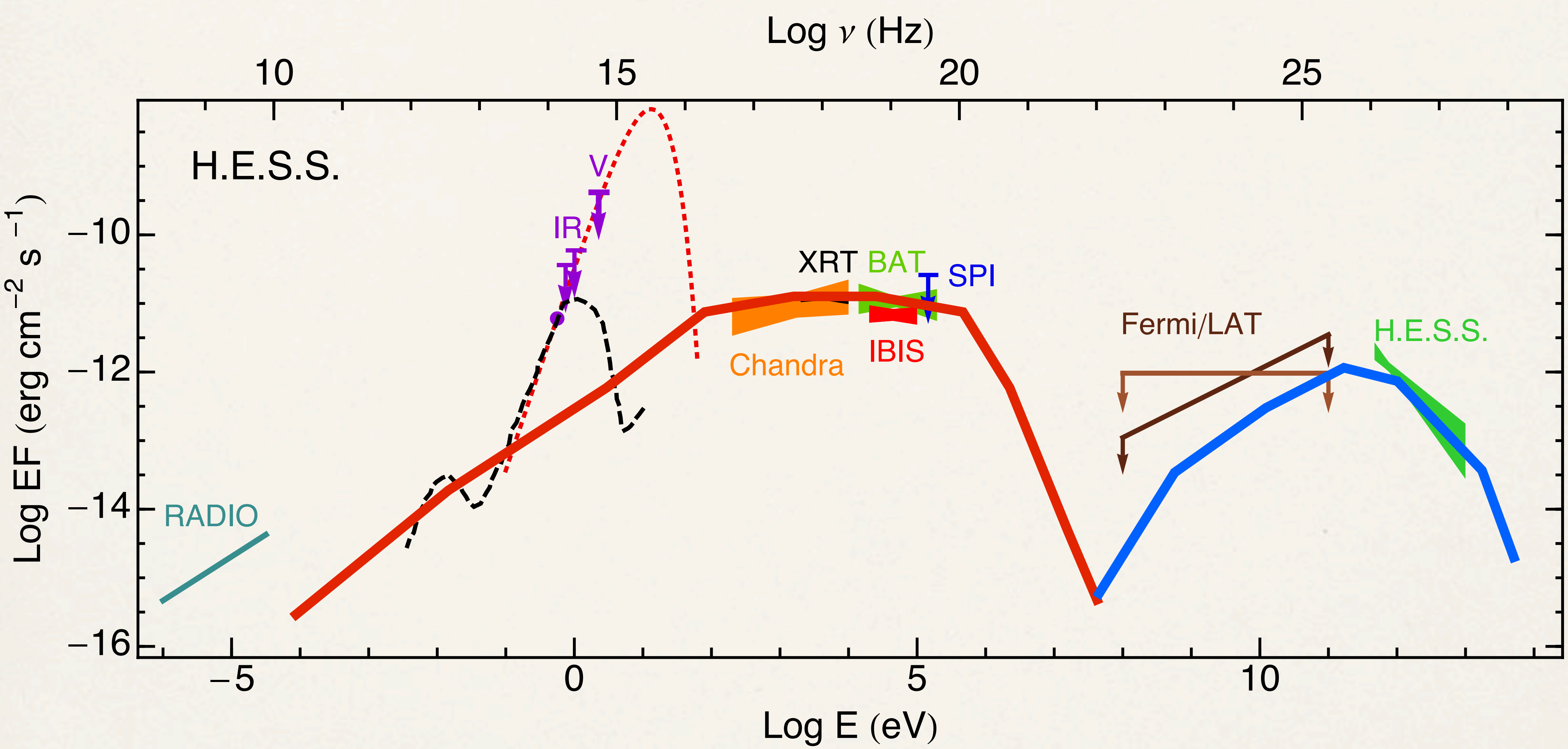

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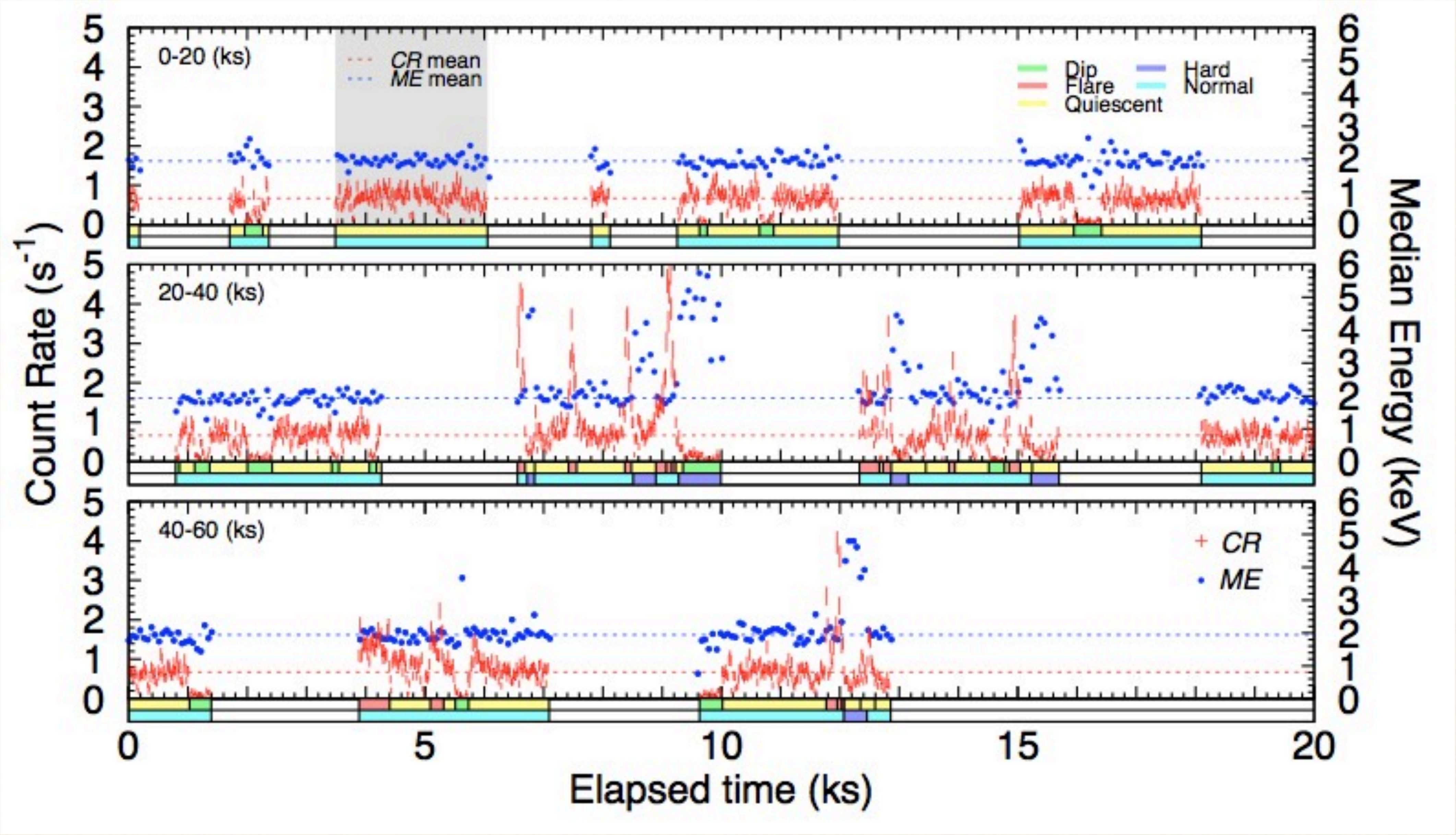
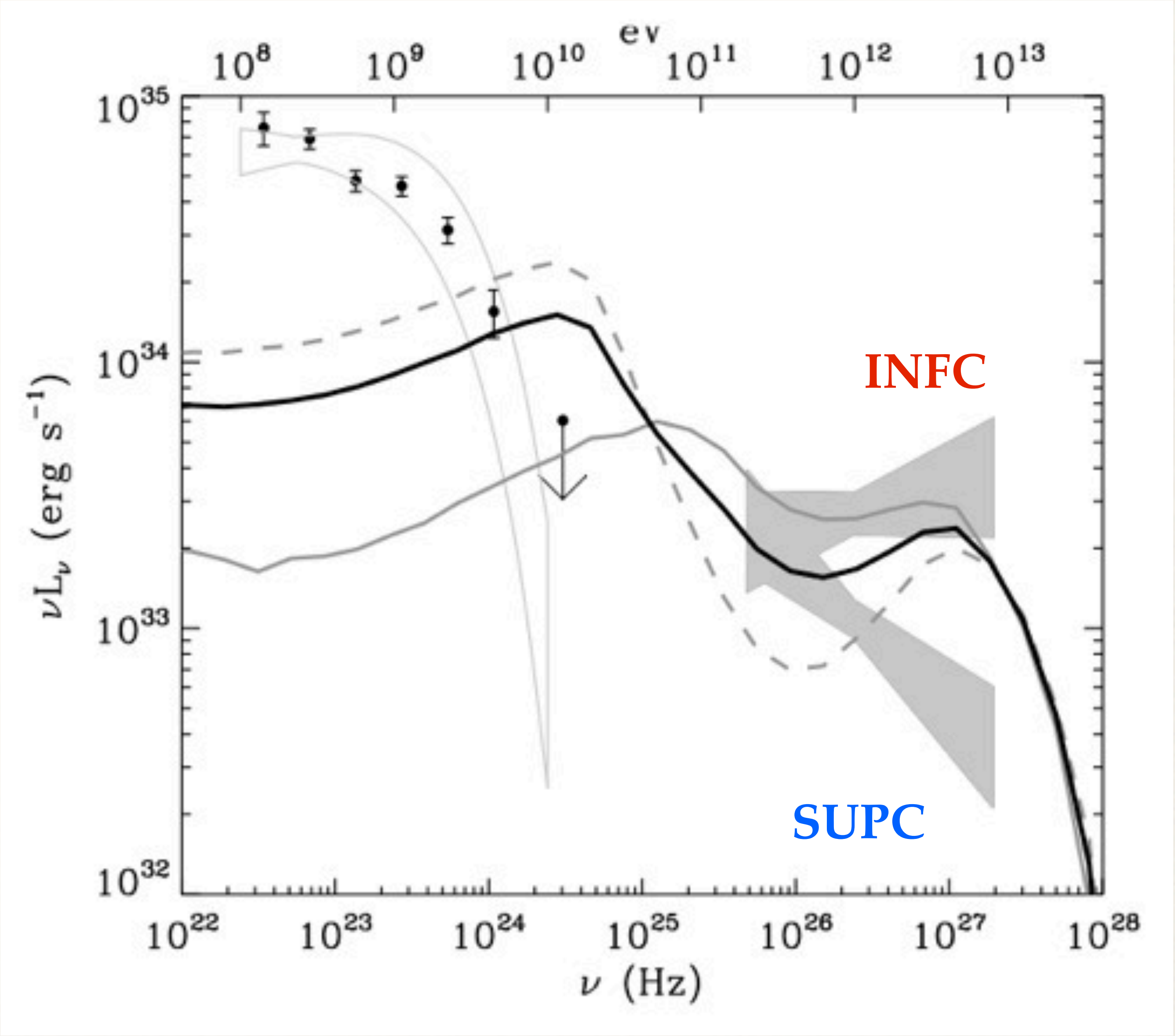
Peculiar low-mass X-ray binary 1FGL J1227.9–4852



Saitou et al. 2009

Emission in minimum of VHE modulation in LS 5039

- Models can't predict shape of spectrum in SUPC
- There are no signatures of pair absorption in spectrum
- HESS-II can tell us if there are any below 0.1 TeV



Credit: Cerutti et al. 2010

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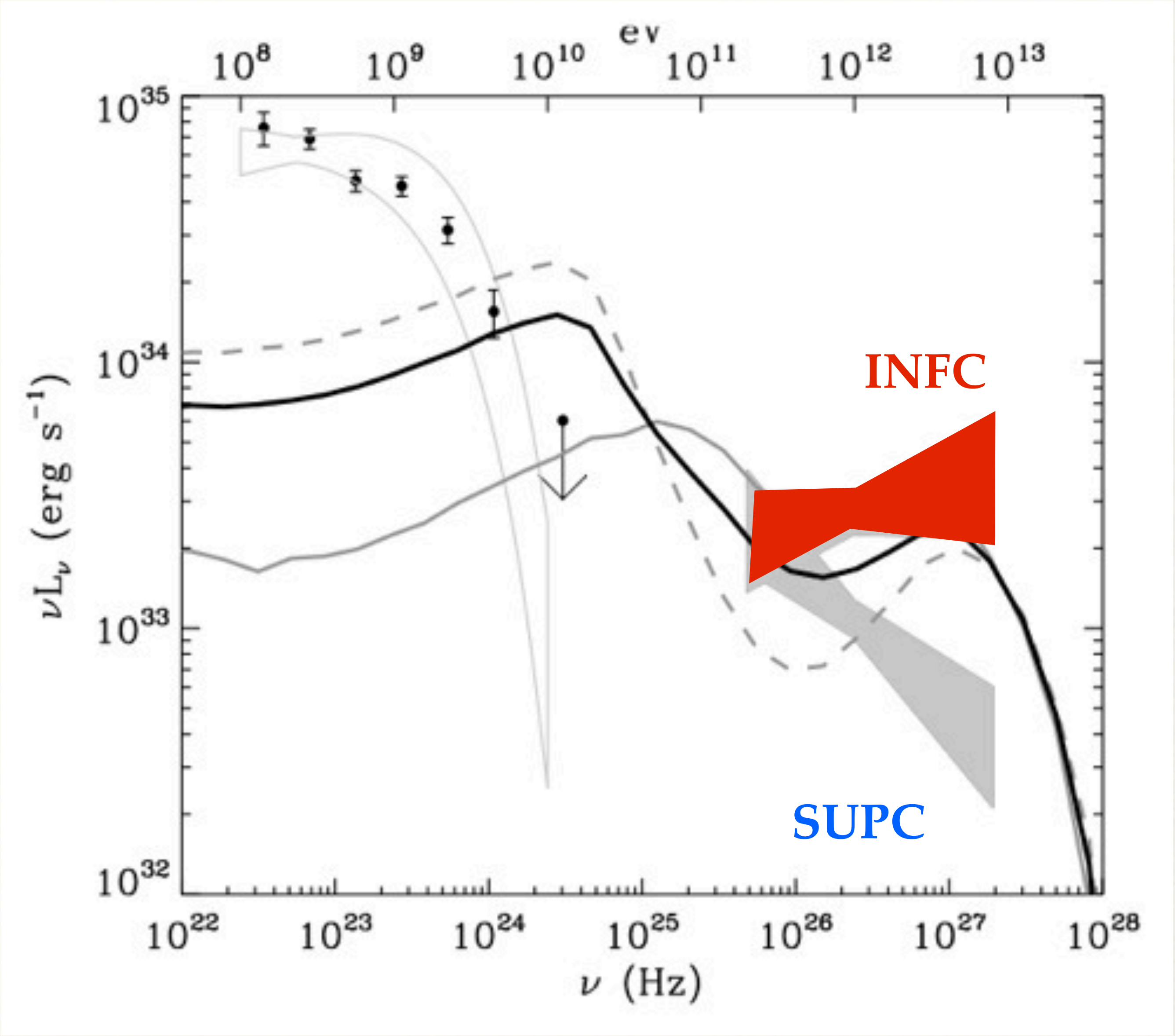

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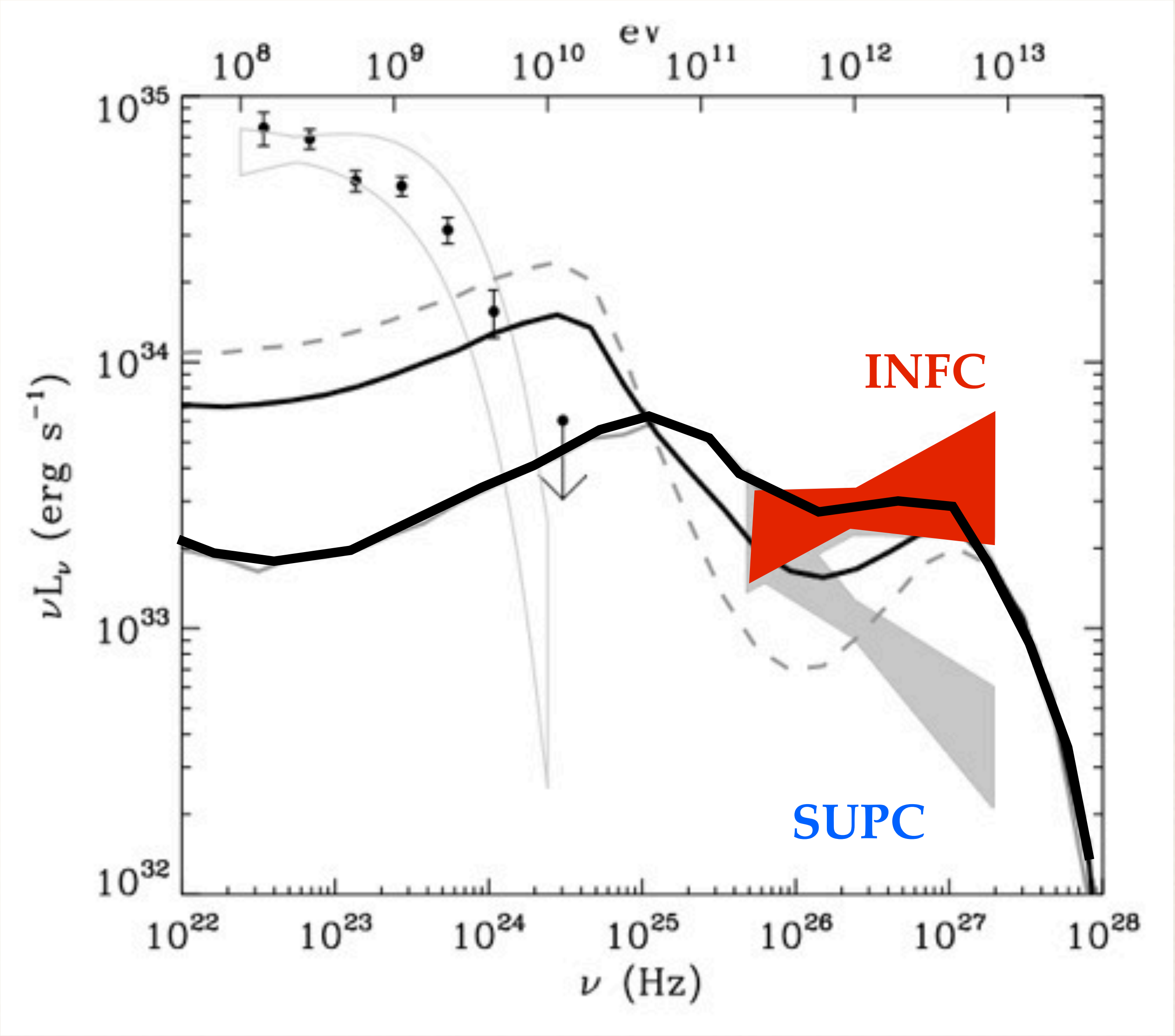
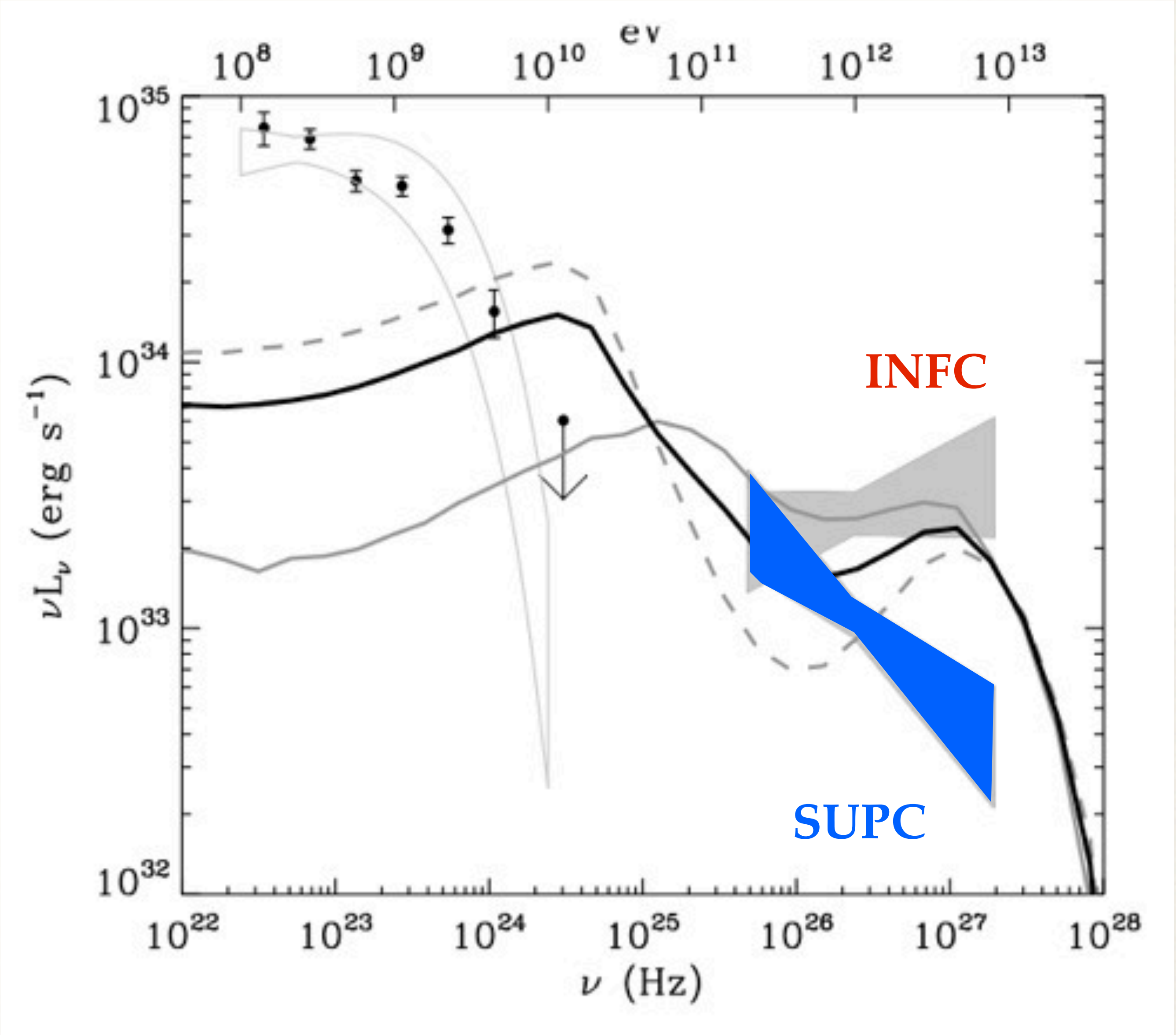


Credit: Cerutti et al. 2010

Emission in minimum of VHE modulation in LS 5039

- Models can't predict shape of spectrum in SUPC
- There are no signatures of pair absorption in spectrum
- HESS-II can tell us if there are any below 0.1 TeV



Credit: Cerutti et al. 2010

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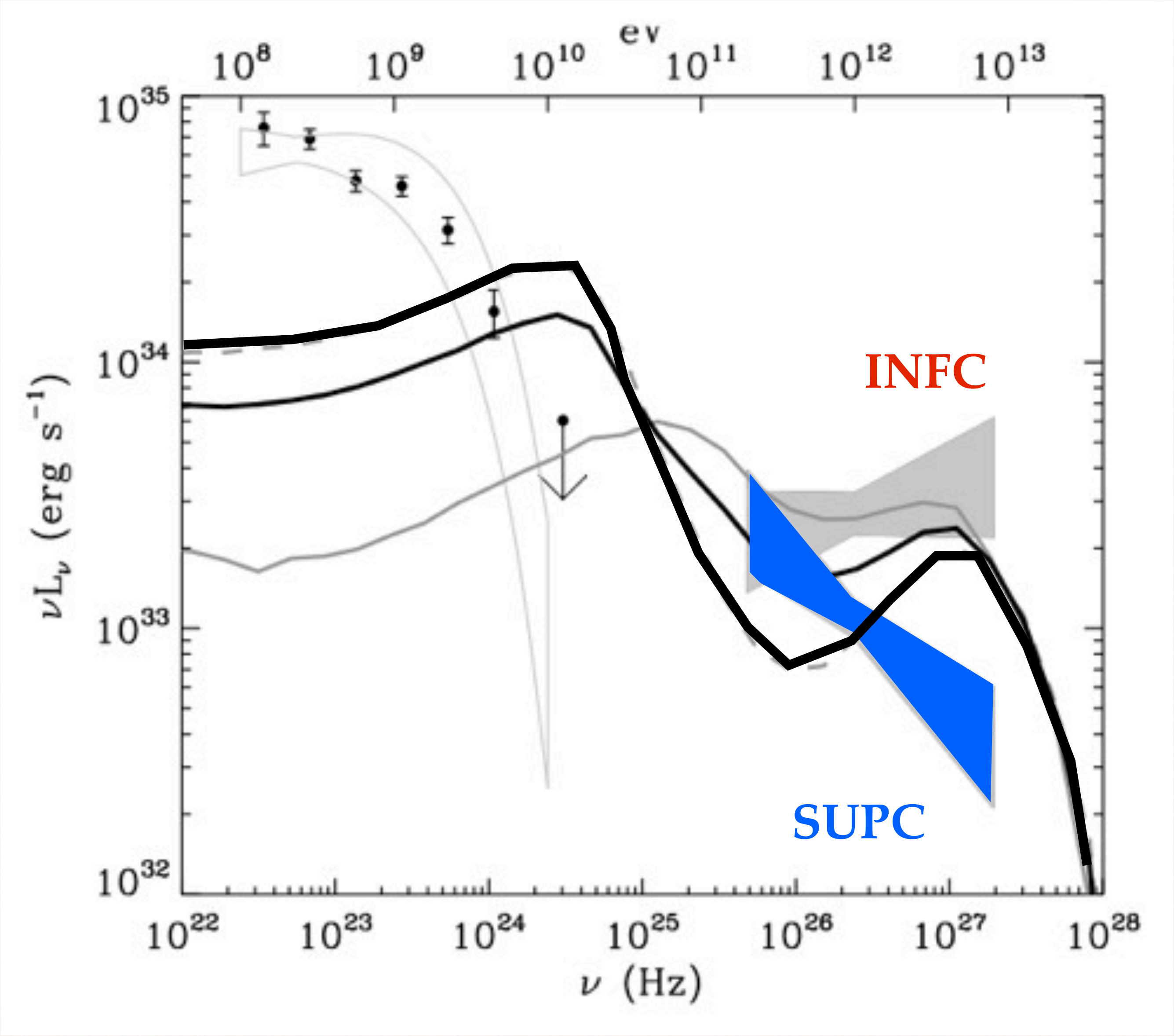
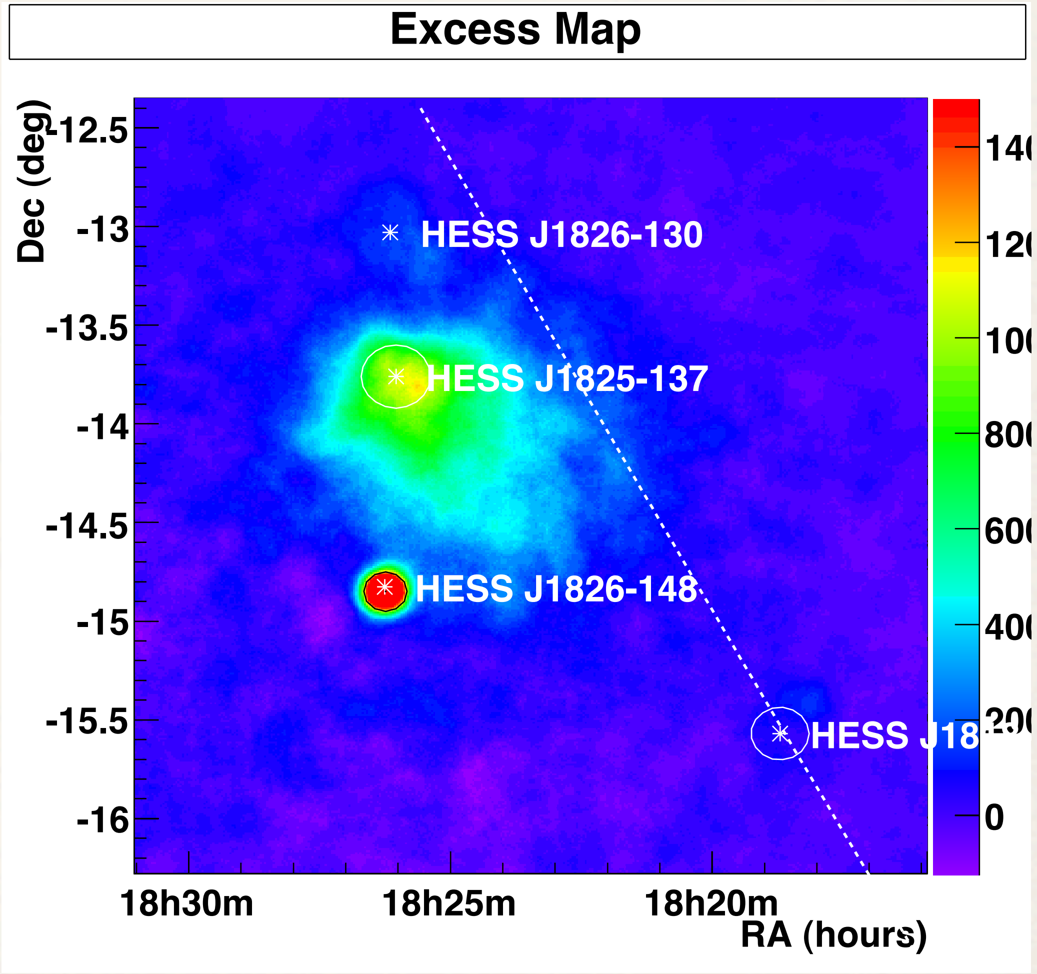


Credit: Cerutti et al. 2010

Emission in minimum of VHE modulation in LS 5039

- Could be contamination from PWN HESS J1825-137
- I hope to find out with new HESS data



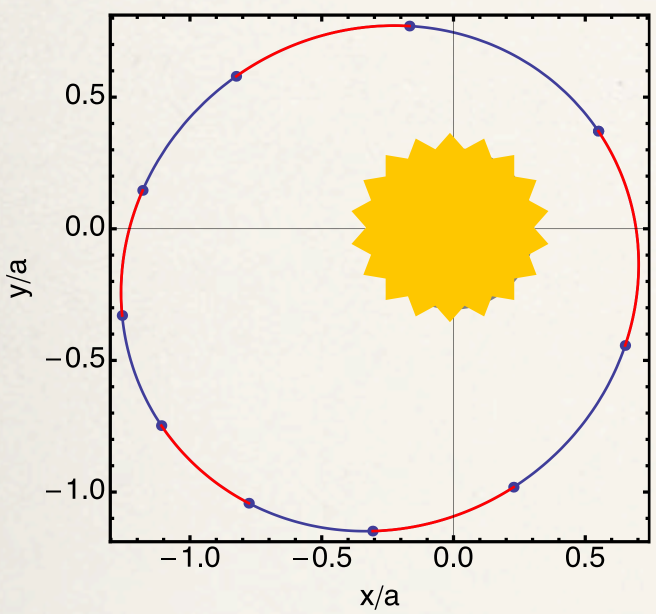
Conclusions

- Gamma-ray emitting binaries are an important class of variable particle accelerators
- Our knowledge of this class is very limited
- Rather inhomogeneous group of sources
- There is a lot of science that is to be uncovered

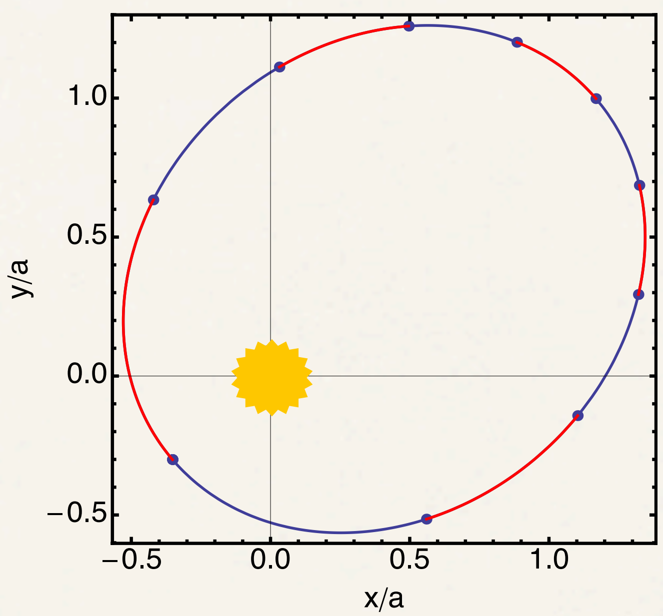
Supplementary slides

Gamma-ray binaries

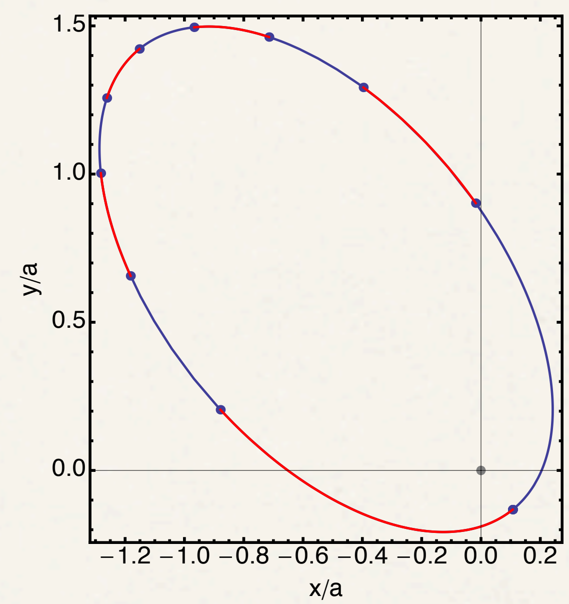
LS 5039



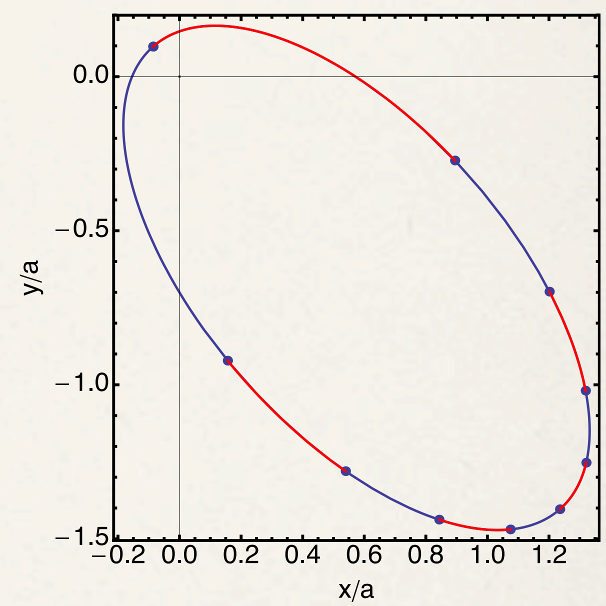
LS I+61 303



HESS J0632-057



PSR B1259-63

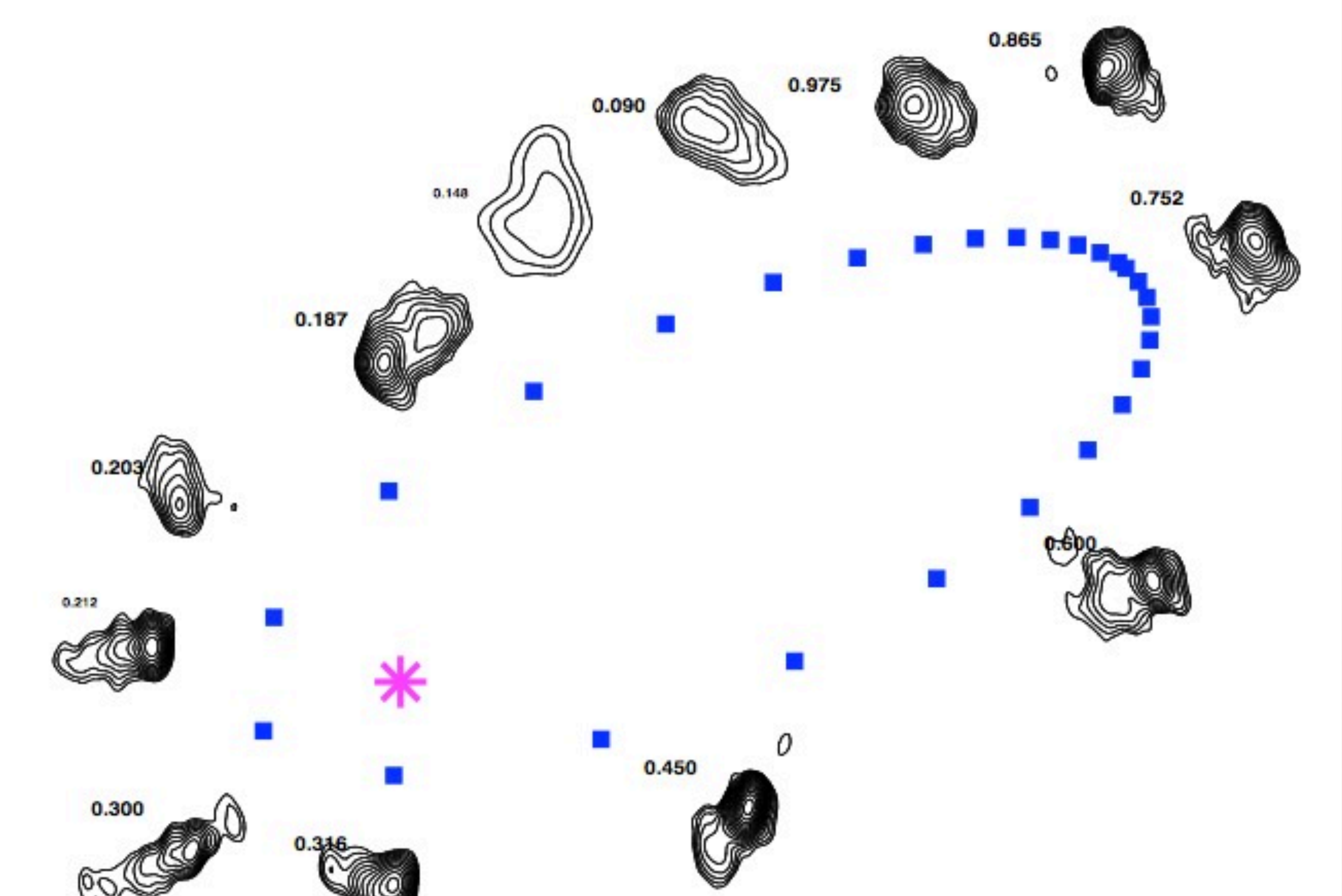


Name	γ-ray activity	Spectral type	M_{opt} ($M_\odot$)	R_{opt} ($R_\odot$)	i (°)	P_{orb} (d)	e	$a(1-e)$ (au)	$a(1+e)$ (au)	EW (Å)	d (kpc)	Reference[a]
LS 5039	HE, VHE	O6.5 V((f))	20–26	9–10	13–64	3.91	0.35	0.09	0.19	−2.8	2.5	(1)
1FGL J1018.6−5856	HE	O6 V((f))	~37	~10	–	16.58	–	–	–	–	~5.4	(2), (3)
LS I +61 303	HE, VHE	B0 Ve	10–15	~7	10–60	26.50	0.54	0.19	0.64	8–19	1.9	(4), (5), (6), (7)
~~MWC 656~~	~~HE~~	~~B3 IVne+sh~~	~~6–10~~	~~5–9~~	~~67–80~~	~~60.37~~	~~0.40~~	~~0.38~~	~~0.89~~	~~19–25~~	~~~2.6~~	~~(8), this paper~~
HESS J0632-057	VHE	B0 Vpe	13–19	6–10	47–80	321	0.83	0.40	4.35	48–56	~1.4	(9), this paper
PSR B1259−63	HE, VHE	O9.5 Ve	31	9	19–31	1236.79	0.87	0.93	13.44	40–80	2.3	(10), (11), (12)

[a](1) Casares et al. (2005b). (2) Corbet et al. (2011). (3) Napoli et al. (2011). (4) Aragona et al. (2009). (5) Zamanov et al. (1999). (6) Casares et al. (2005a). (7) McSwain et al. (2010). (8) Williams et al. (2010). (9) Aragona et al. (2010). (10) Negueruela et al. (2011). (11) Johnston et al. (1994). (12) Grundstrom et al. (private communication).

Credit: Casares et al. 2012

Gamma-ray binaries in radio and X-rays



Dhavan et al. 2006