
High-energy gamma-ray emission in compact binaries

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Outline

- 1. Binary systems** in the gamma-ray sky!
- 2. High-energy processes & anisotropies**
- 3. Gamma-ray** emission in gamma-ray binaries
- 4. Pair cascade** emission in gamma-ray binaries
- 5. Gamma-ray** emission from **relativistic outflow**
- 6. Conclusions & futures directions**

Binary systems in the gamma-ray sky!

Gamma rays

Electromagnetic spectrum:



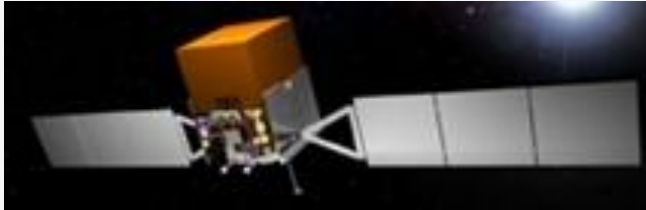
Gamma ray: photon $> 511 \text{ keV}$

- High-energy (**HE**): $\sim \text{GeV}$ (10^9 eV)
- Very-high energy (**VHE**): $\sim \text{TeV}$ (10^{12} eV)

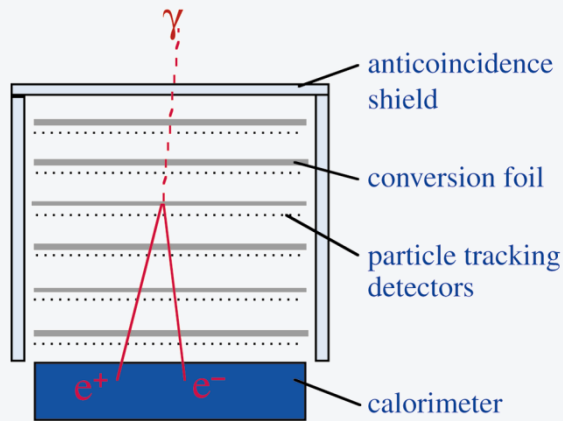
Gamma-ray Astronomy

Gamma-ray telescopes

From *space*: **GeV** domain



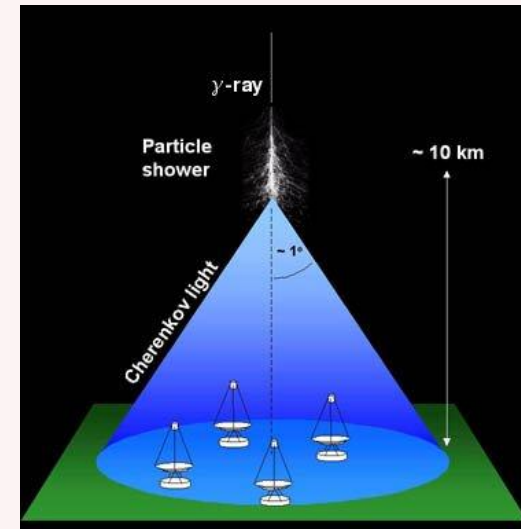
Fermi, AGILE



From the *ground*: **TeV** domain



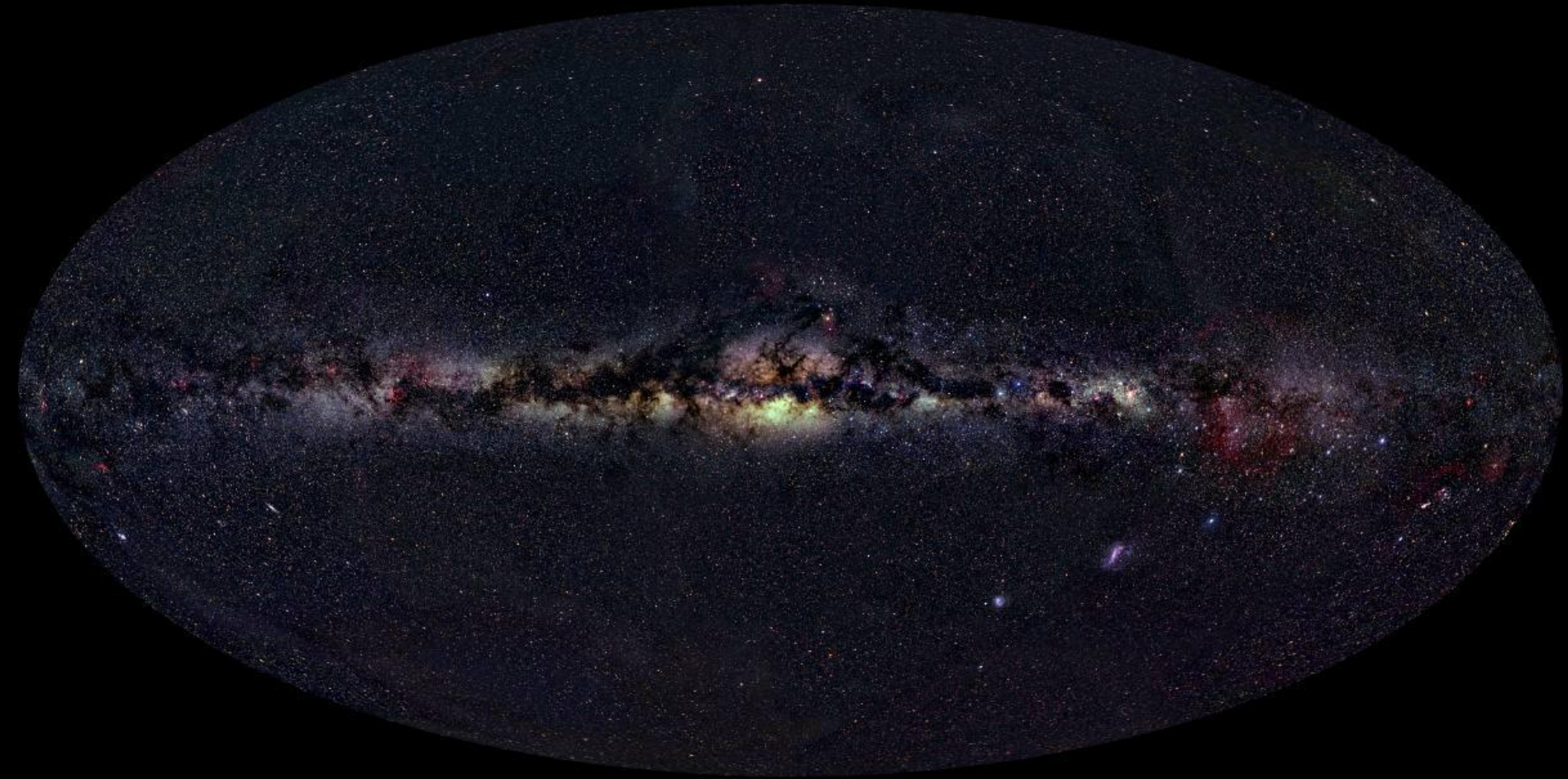
**HESS, MAGIC
& VERITAS**



- **Simultaneous** coverage of **HE** and **VHE** domains
- Unprecedented **sensitivity** and **angular resolution**

γ-ray astronomy!

The optical sky



© 2000, Axel Mellinger

The gamma-ray sky

1 year of exposure

Extra-Galactic γ -ray sources:

- Active Galactic Nuclei (AGN)
- Gamma-Ray Bursts (GRB)
- Starbursts Galaxies

Galactic γ -ray sources:

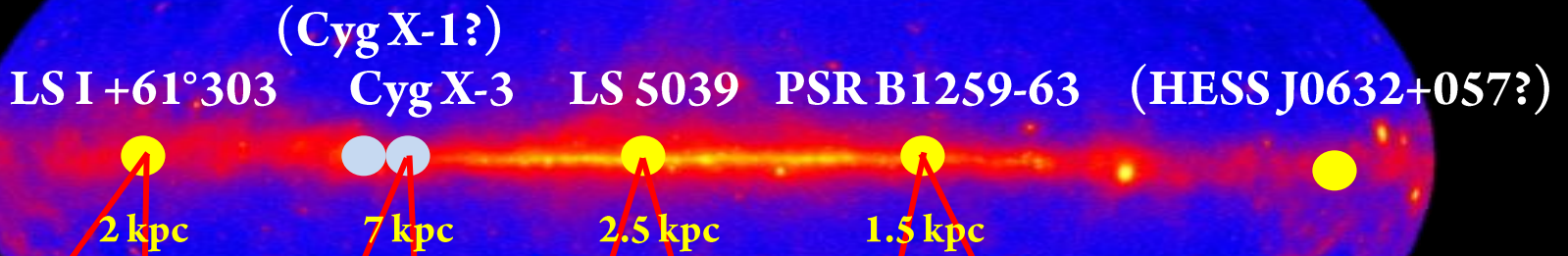
- Pulsars & Pulsar wind nebulae
- Supernovae remnants
- Many are unidentified
- **... and 4 binary systems!**



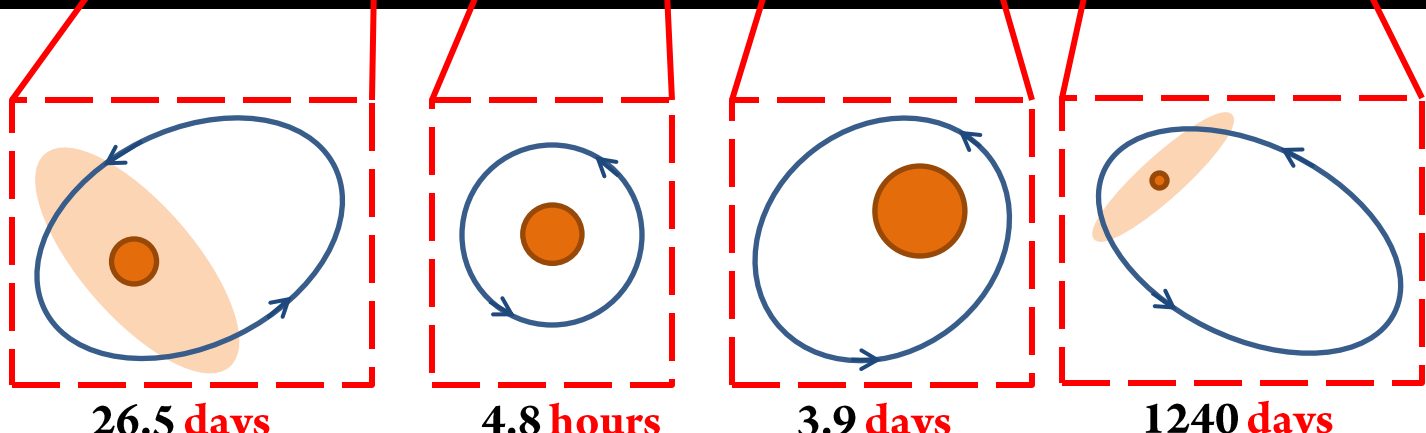
Gamma-ray emitting binaries

1 year of exposure

● γ -ray binary
● Microquasar



Credit: NASA/DOE/Fermi LAT Collaboration



Legend

- Massive star
- Compact object orbit

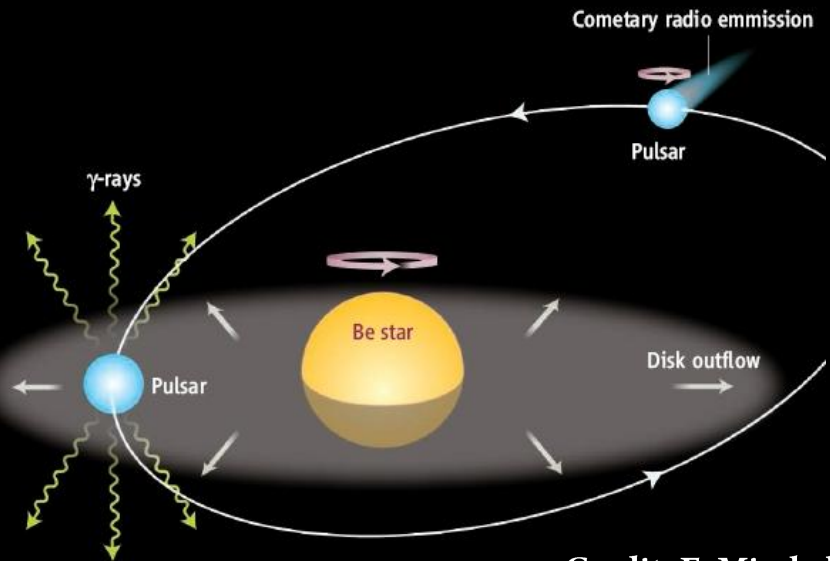
Two classes of binaries

GAMMA-RAY BINARIES

=

Massive star + young pulsar

[Maraschi & Treves 1980, Dubus 2006b]



Credit: F. Mirabel

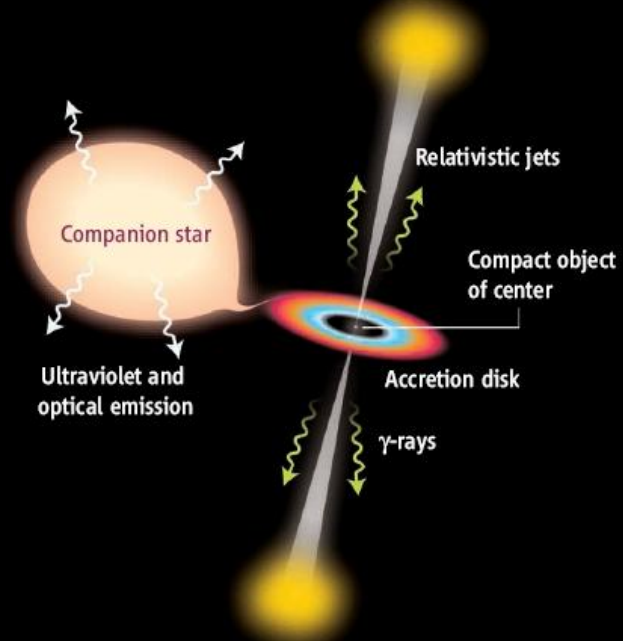
ROTATION-POWERED

LS I +61°303, LS 5039 & **PSR B1259-63**
(HESS J0632+057?)

MICROQUASAR

=

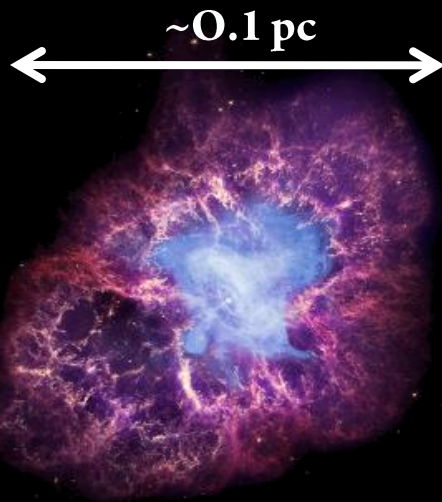
Massive star + accreting compact object
(neutron star or black hole)



ACCRETION-POWERED

Cyg X-3
(Cyg X-1?)

Why are these systems so interesting?



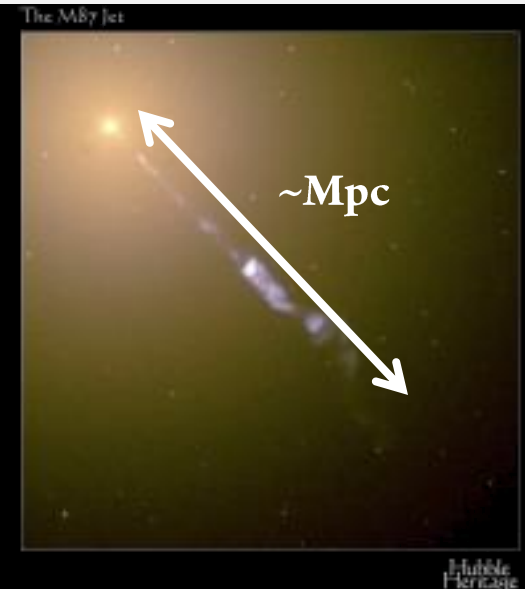
Gamma-ray binaries

- **Nearby** systems (kpc) and **well constrained physical** conditions (stellar radiation field, orbit)
- Probe **relativistic winds** at **small scale**: 0.1 AU !
- Exploration of **new class** of Galactic objects (population, evolution)
- Application to **pulsars** and **PWN**

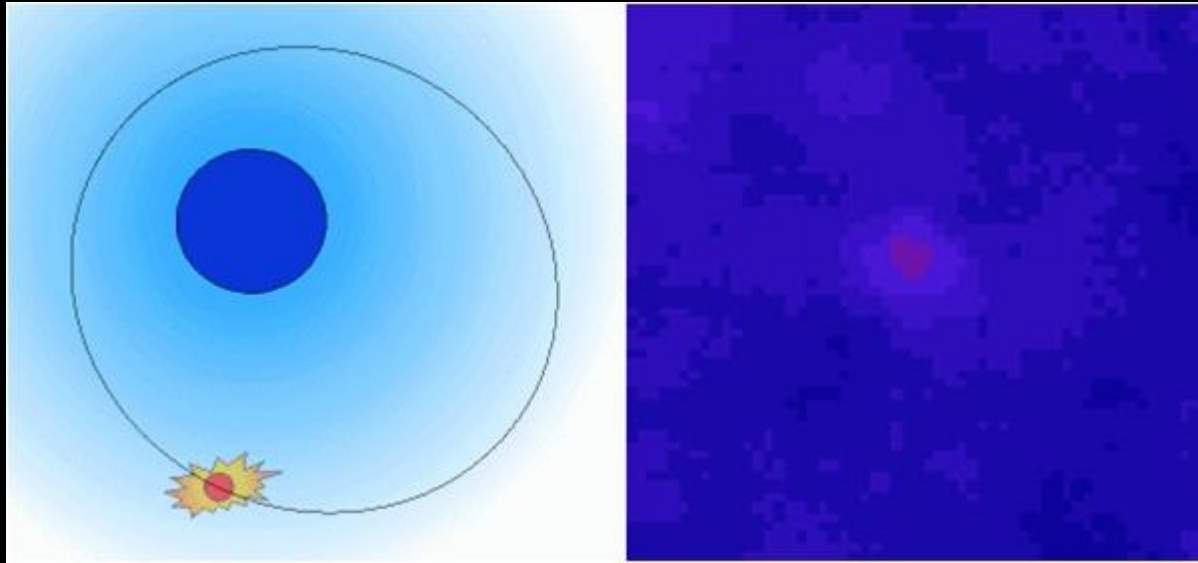
[Credit: F.Seward et al, J.Hester & A.Loll, R.Gehrz]

Microquasars

- **Nearby** systems (kpc) and **well constrained physical** conditions (stellar radiation field, orbit)
- Study the **physics of relativistic jets, accretion-ejection** mechanisms at small scales (AU-pc)
- Application to e.g. **AGN & GRBs**

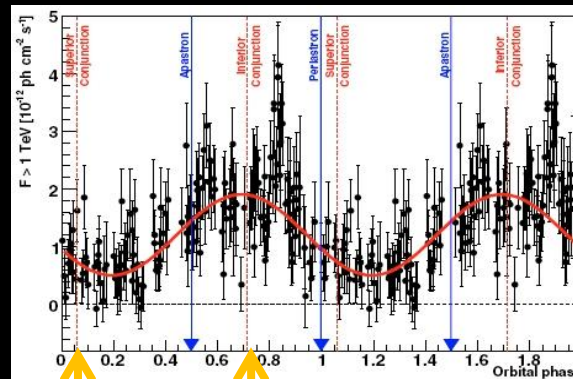


Gamma-ray beacons: the case of **LS 5039**

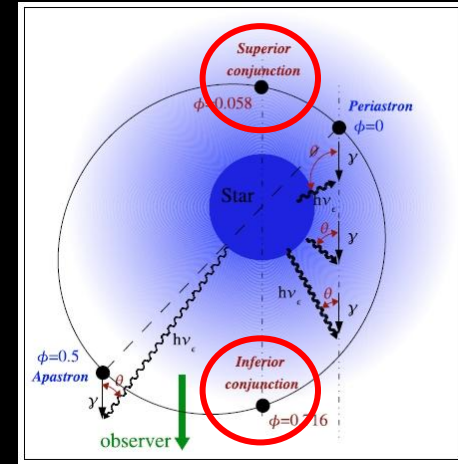


Credit: M. de Naurois

- **GeV/TeV** stable orbital modulation
- Min/Max at **conjunctions**
- ➔ **Geometrical effects !?**



Conj. Sup. Conj. Inf.



[Aharonian et al. 2006]

What we want to understand

GeV and/or TeV orbital modulation

GeV

- **LS I +61°303** [*Fermi LAT, 2009a*]
- **LS 5039** [*Fermi LAT, 2009b*]
- **Cygnus X-3** [*Fermi LAT, 2009c*]
- **(PSR B1259-63 ?)**

TeV

- **LS I +61°303** [*MAGIC coll., 2008*]
- **LS 5039** [*HESS coll., 2006*]
- **PSR B1259-63** [*HESS coll., 2005*]

Key questions

- **Where does the gamma-ray modulation come from?**
- **What are the relevant processes in binaries? Acceleration site?**
- **What can we learn on pulsar winds and relativistic jets?**

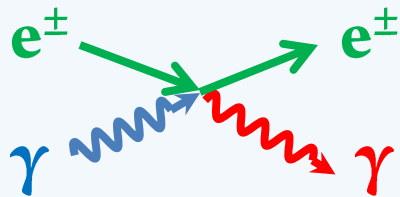
Goal thesis → Theoretical modeling of temporal & spectral γ -ray variability

High-energy processes & anisotropies

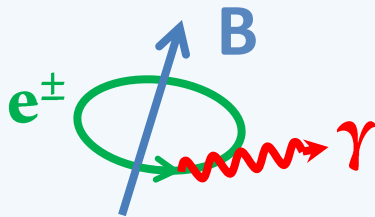
Relevant high-energy processes

Leptonic

- Inverse Compton scattering

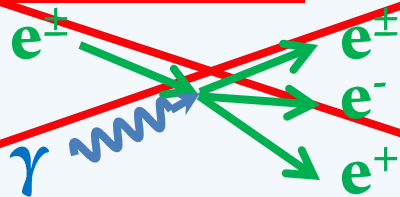


- Synchrotron radiation



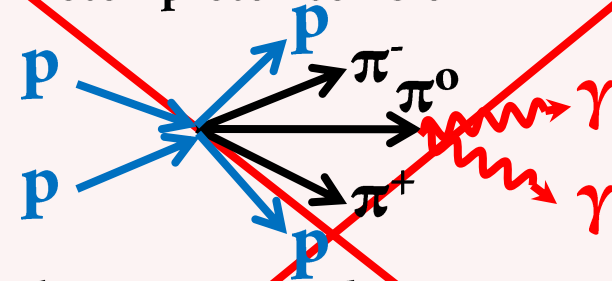
- Triplet Pair Production

Sarkis Rastikian work

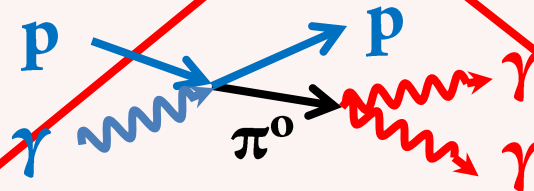


Hadronic

- Proton-proton collision

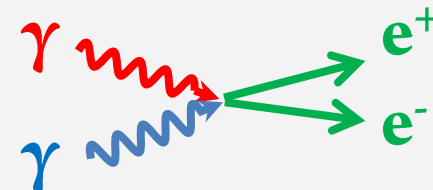


- Photomeson production

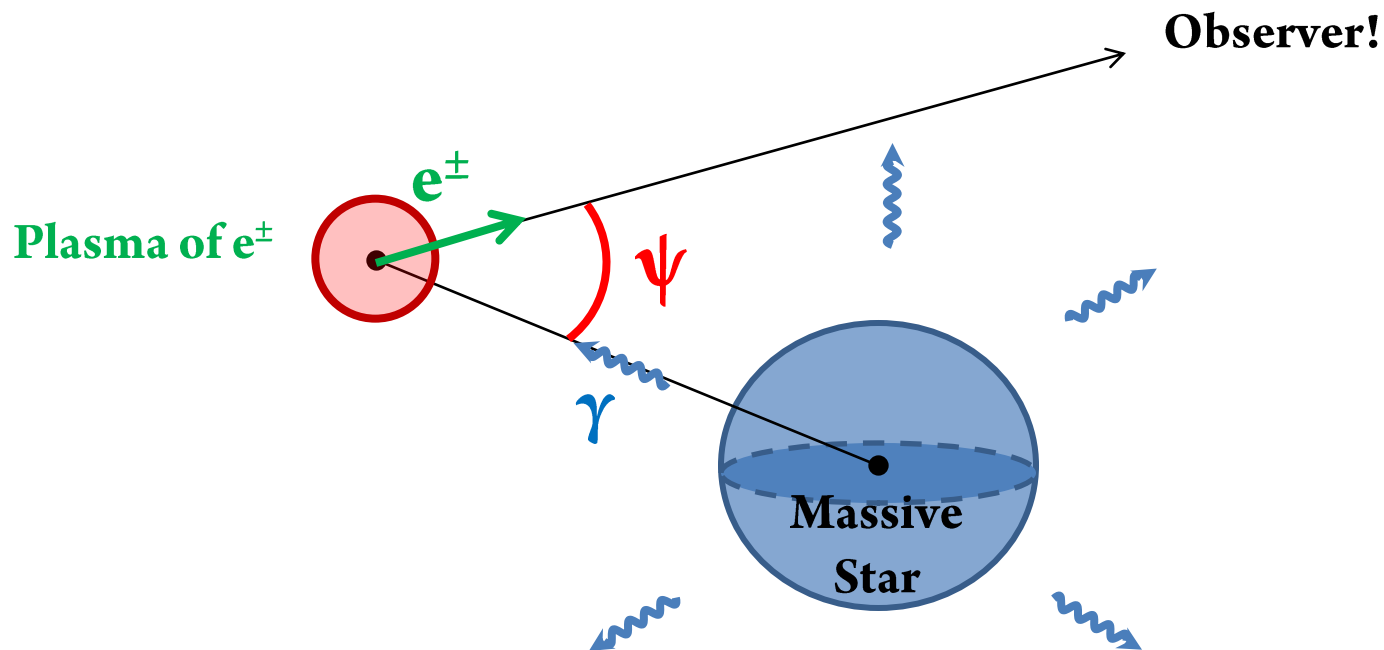


Absorption

- Pair production



Anisotropies

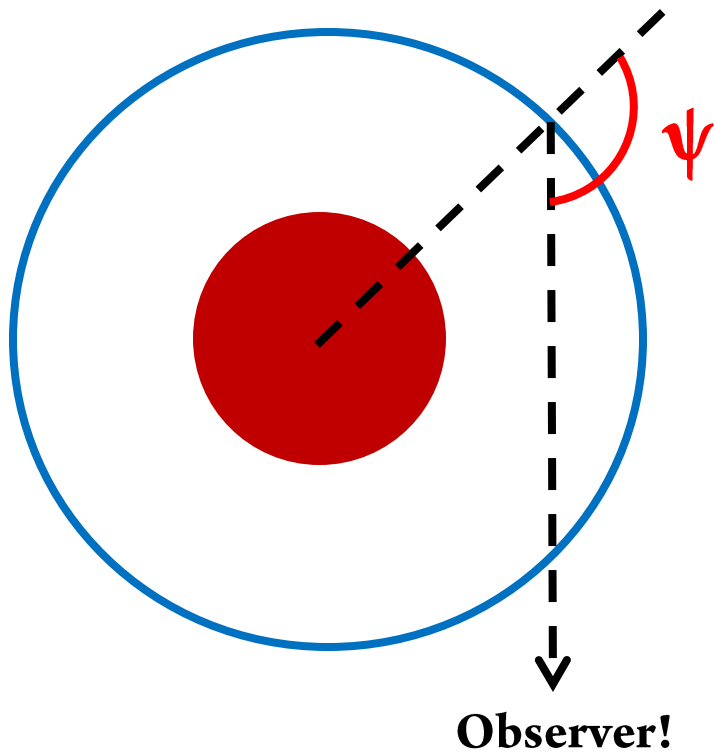


- High UV stellar photon density, **dominant source** ($n_{\text{ph}} \approx 10^{14} \text{ ph/cm}^3$ in **LS 5039!**)
- **Anisotropic** and **well constrained** radiation source
- ➔ **Angular dependence** on:
inverse Compton scattering (emission) & pair production (absorption)

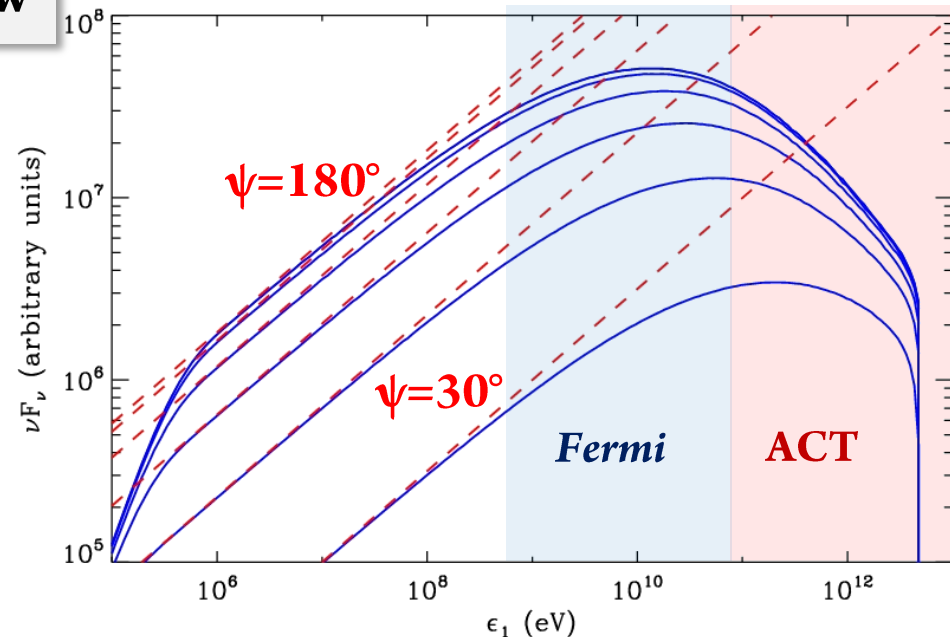
Anisotropic inverse Compton scattering

Derivation of **new analytical formulae** for anisotropic inverse Compton scattering

Circular orbit with an inclination $i=90^\circ$
Massive star: **Black-body** spectrum
Relativistic electrons with a **-2 power-law**



Head-on: $e^\pm \longrightarrow \gamma$ **Max**
Rear-end: $e^\pm \longleftarrow \gamma$ **Min**



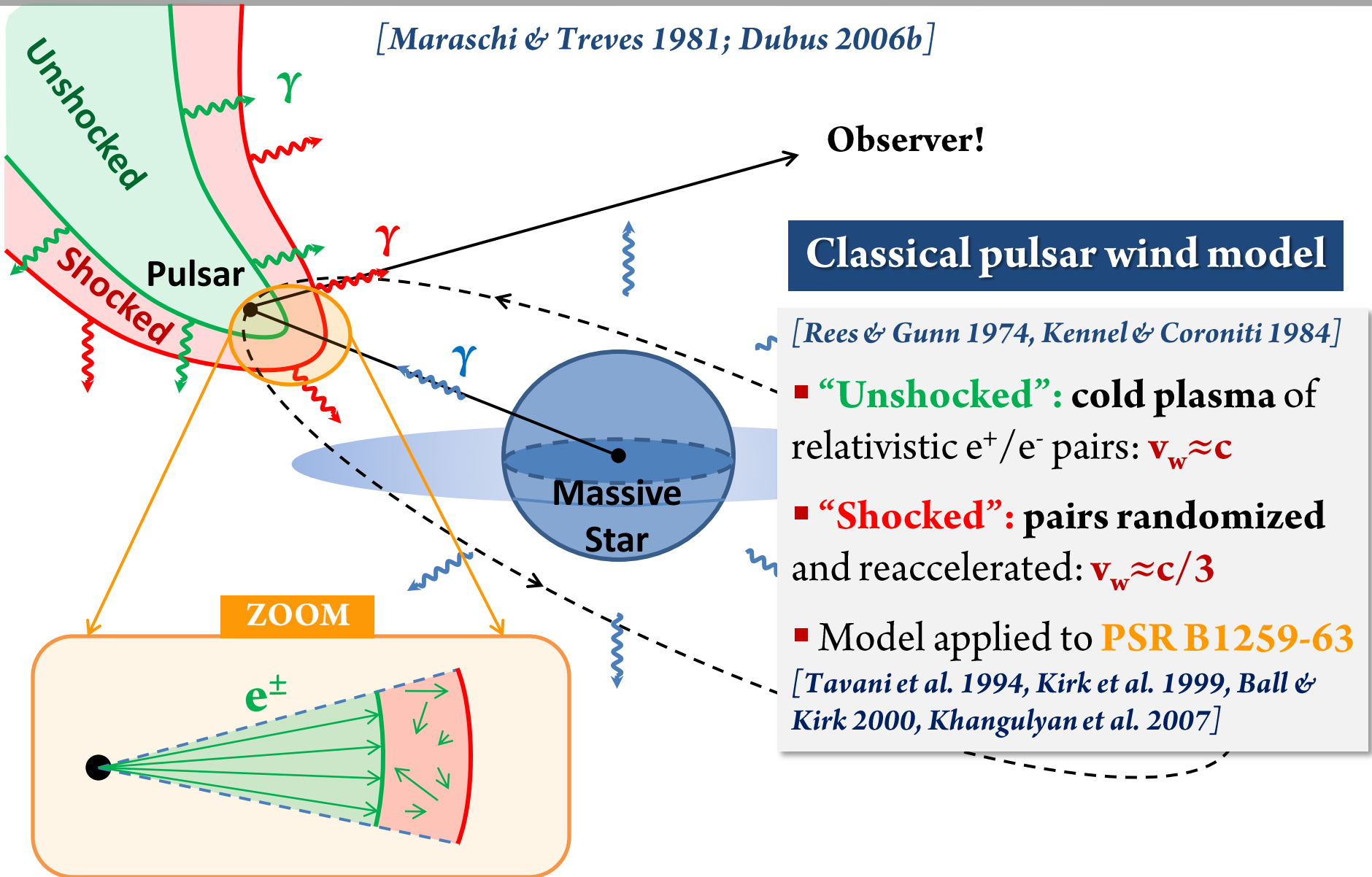
Strong angular dependence!

Similar dependence for **pair production**

Gamma-ray emission in γ -ray binaries

The scenario: the big picture!

[Maraschi & Treves 1981; Dubus 2006b]



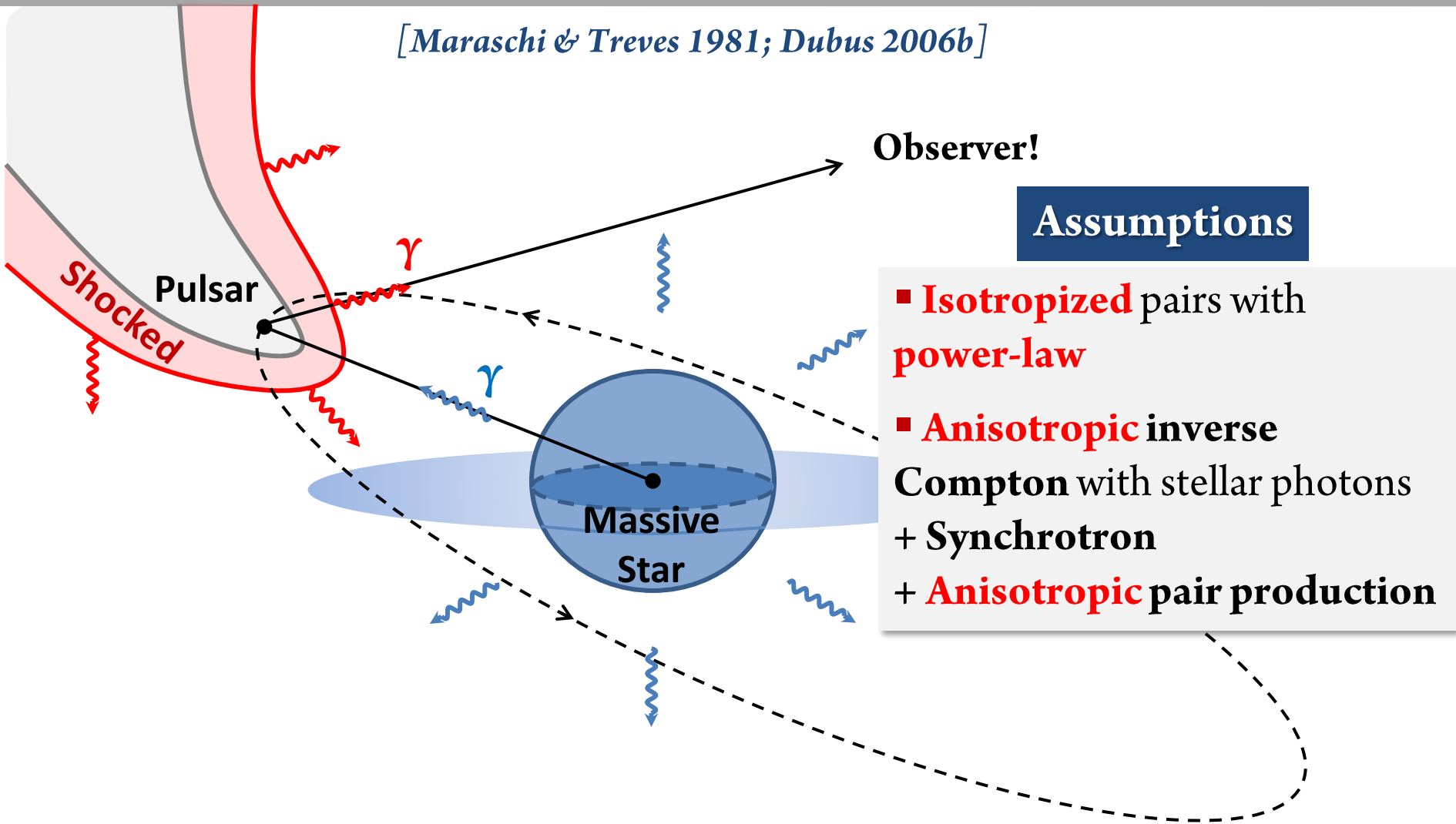
Classical pulsar wind model

[Rees & Gunn 1974, Kennel & Coroniti 1984]

- **“Unshocked”**: cold plasma of relativistic e^+/e^- pairs: $v_w \approx c$
- **“Shocked”**: pairs randomized and reaccelerated: $v_w \approx c/3$
- Model applied to **PSR B1259-63**
[Tavani et al. 1994, Kirk et al. 1999, Ball & Kirk 2000, Khangulyan et al. 2007]

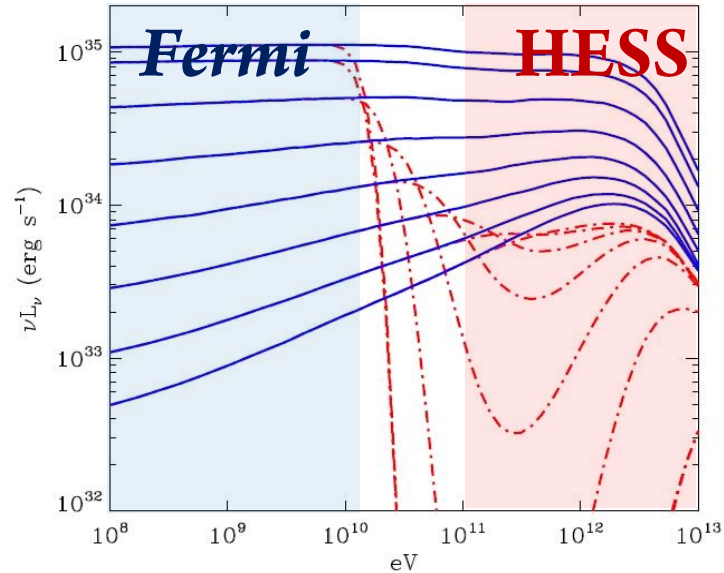
Emission from the “shocked” wind

[Maraschi & Treves 1981; Dubus 2006b]



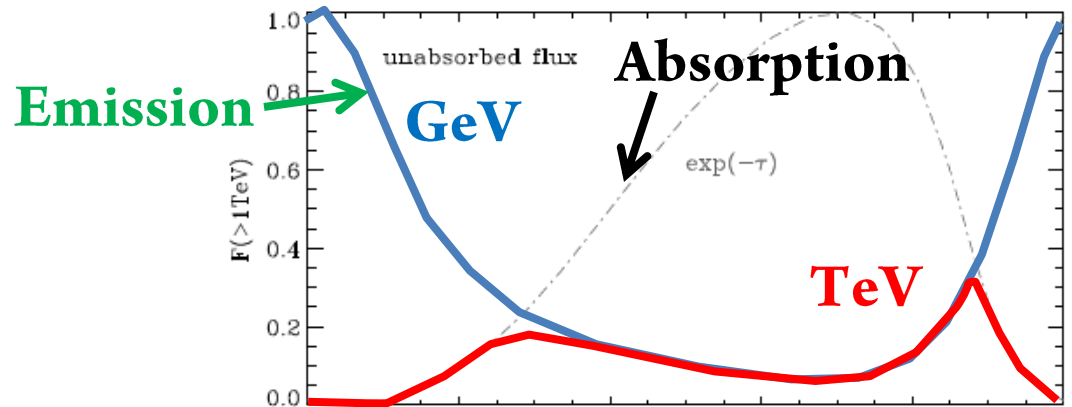
Application to **LS 5039**

Spectra

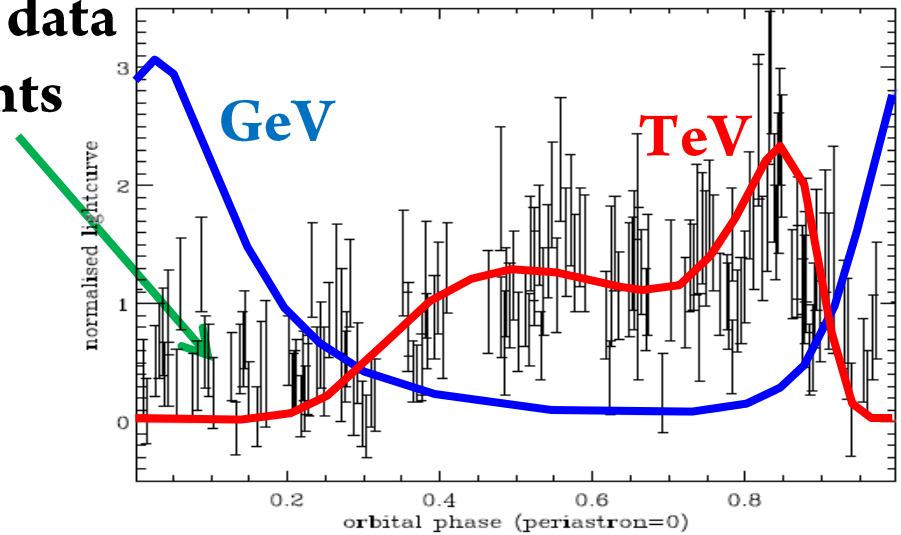


- **High inclination** favored
- ➔ compact object = **pulsar**
- **GeV/TeV anti-correlation predicted!** (due to absorption)
[see also *Bednarek 2006, Khangulyan et. al 2008*]

γ-ray flux: absorption & Compton

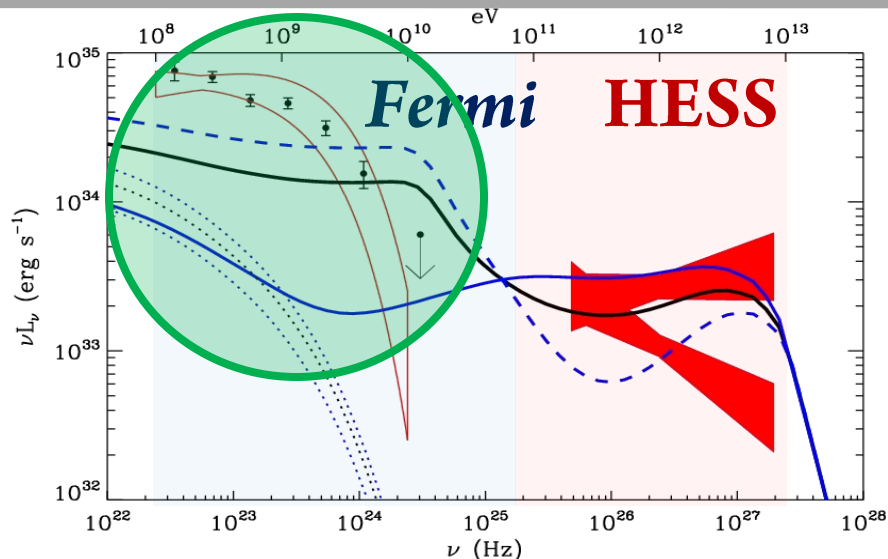
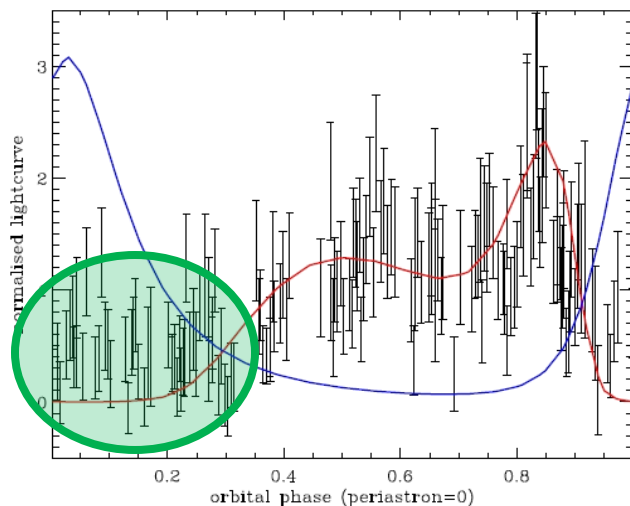


HESS data points



[*Dubus, Cerutti & Henri, A&A 2008*]

Strength & weakness



Strength

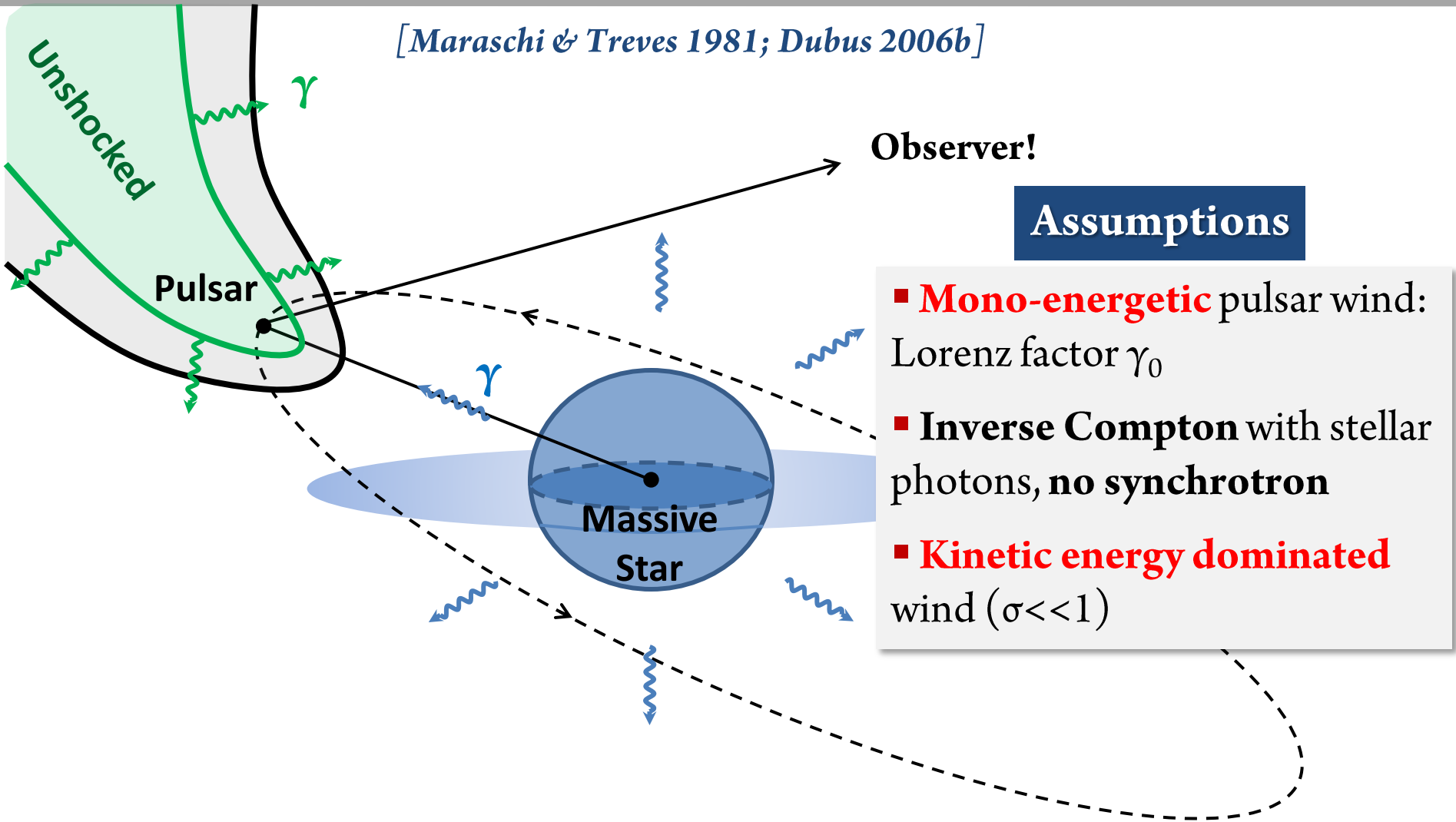
- **Simple** model
- Explains most of the **GeV** and **TeV** modulation in **LS 5039**.
- **Robust constraints** on physical parameters (B , p , L_p)

Weakness

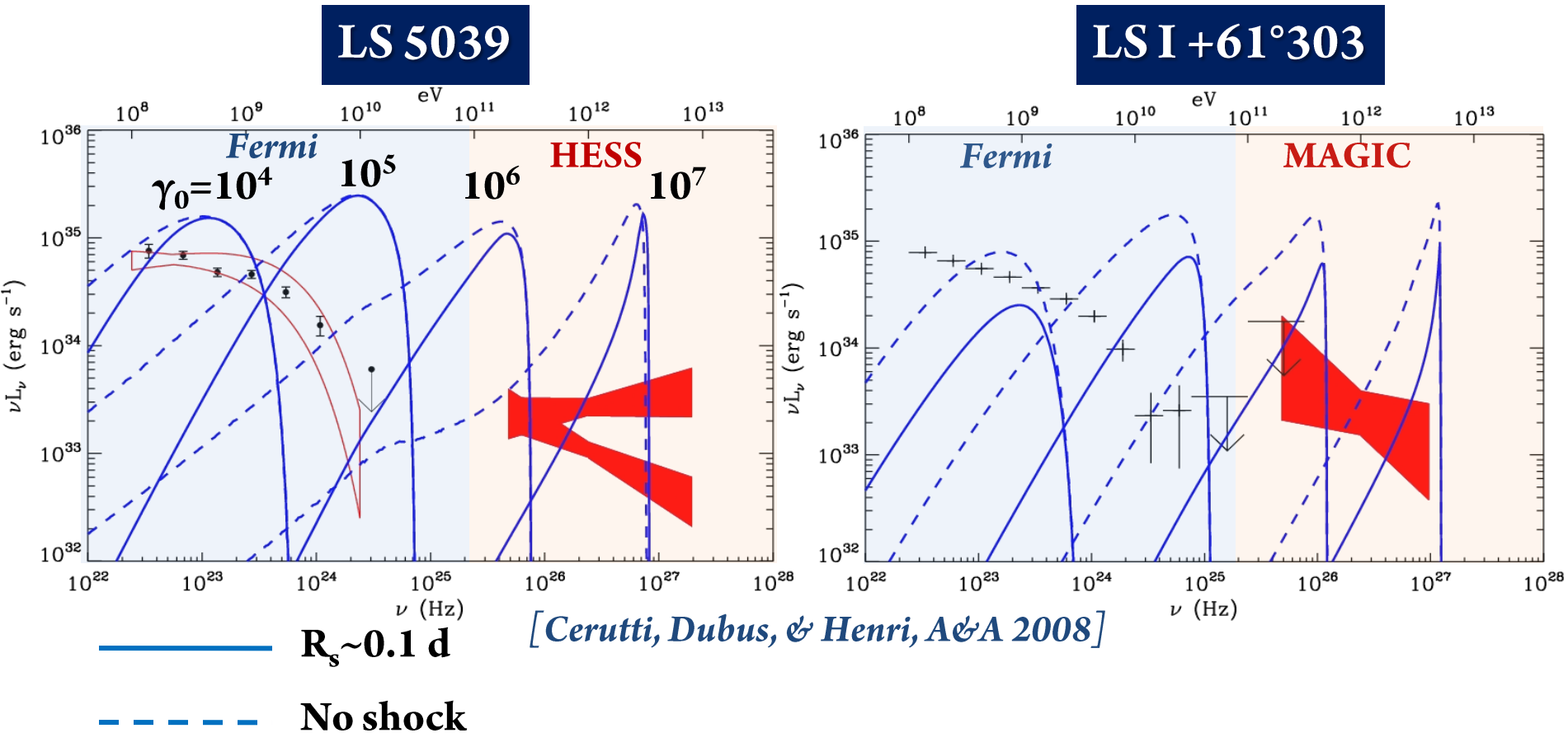
- **Fermi** observations **not explained!** Extra-component required.
- **HESS** flux @ **superior conjunction** not explained in **LS 5039** → **Pair Cascades?**
- Modulation in **LS I +61°303** and **PSR B1259-63** not explained

Emission from the “unshocked” pulsar wind

[Maraschi & Treves 1981; Dubus 2006b]



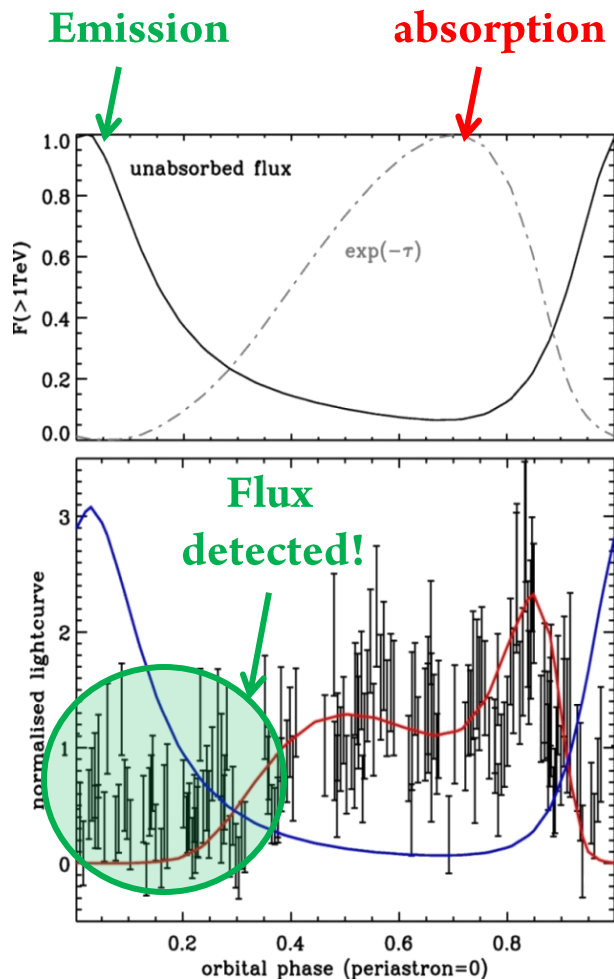
Application to γ -ray binaries



- **Strong** line-like spectra! → **Excluded** by *Fermi* and TeV observations
- **Not mono-energetic**, e.g. power-law? [Sierpowska-Bartosik & Torres 2008]
- Conversion Electromagnetic to kinetic energy **not completed**? **Striped wind**?

Pair cascade emission in γ -ray binaries

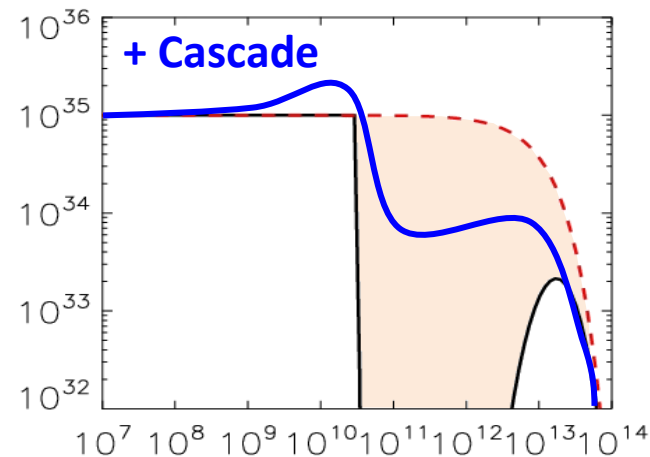
Motivations



[Dubus, Cerutti & Henri, A&A 2008]

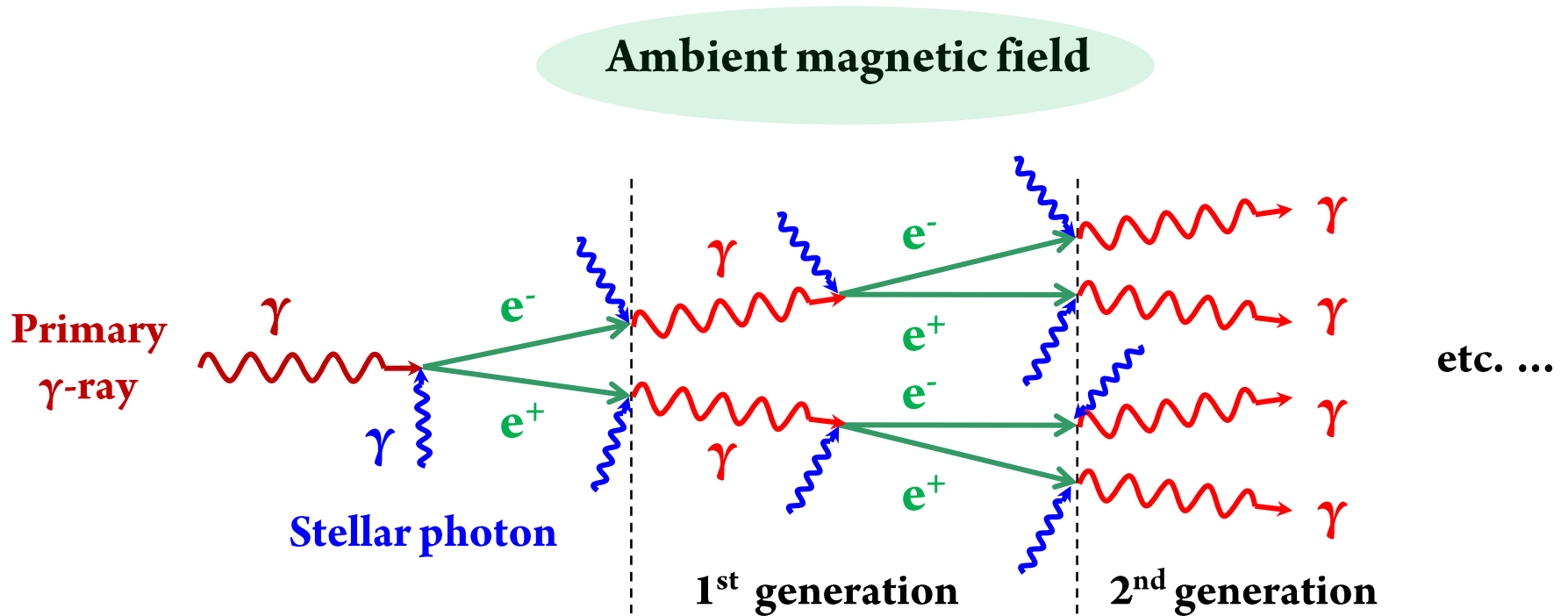
- **Model: Huge absorption** at superior conjunction \rightarrow no TeV flux...
- ... but, **excess** measured by HESS!

Solution: Pair cascade emission!



- Absorbed energy **recycled**
 \rightarrow Emission of new generations of pairs
- Increase the **transparency** of the source at superior conjunction.

The physics of pair cascading



Cascade regimes

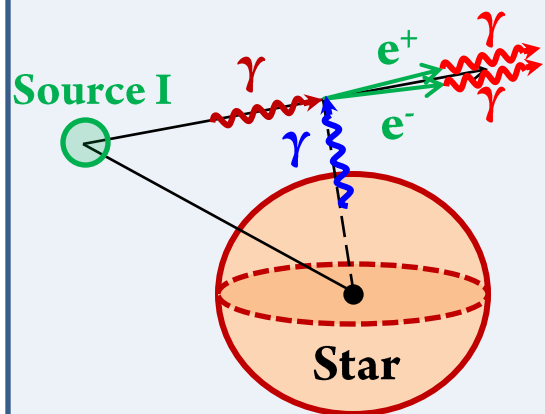
10^{-8} G

10^{-2} G

10 G

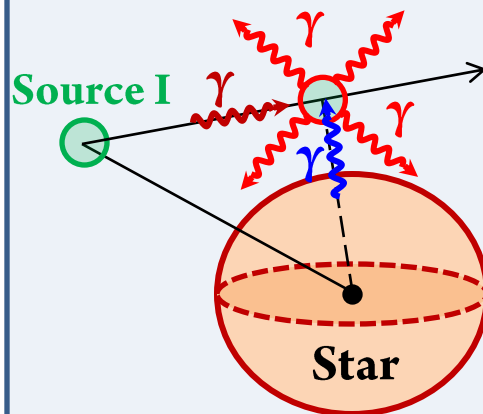
Magnetic field

1D Cascade



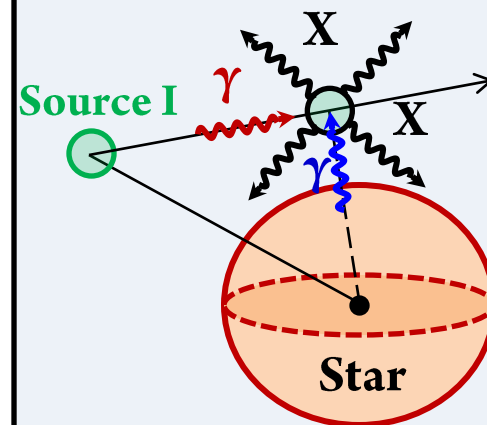
- Magnetic deviations **negligible** ($B < 10^{-8}$ G)
- Pairs and photons **boosted** in the direction of primary γ -rays

3D "isotropic" Cascade



- Pairs locally **isotropized** ($R_L < \lambda_{IC}$)
- **Extended** & **anisotropic** emission

Quenched 3D Cascade

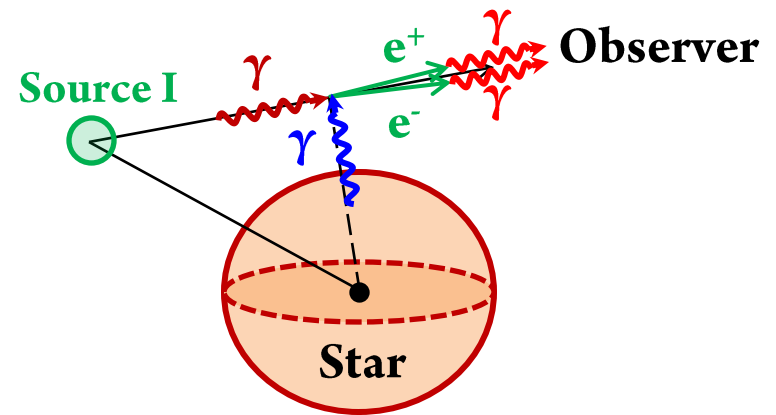
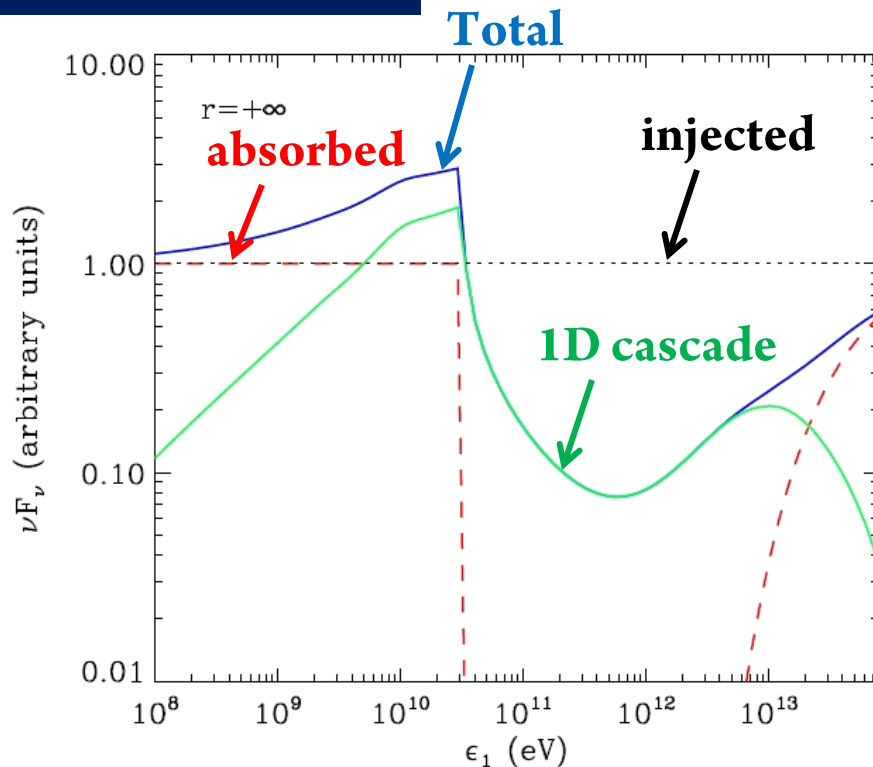


- Dominant **Synchrotron** cooling ($t_{syn} < t_{ic}$)
- X-ray emission, **γ -ray emission quenched**

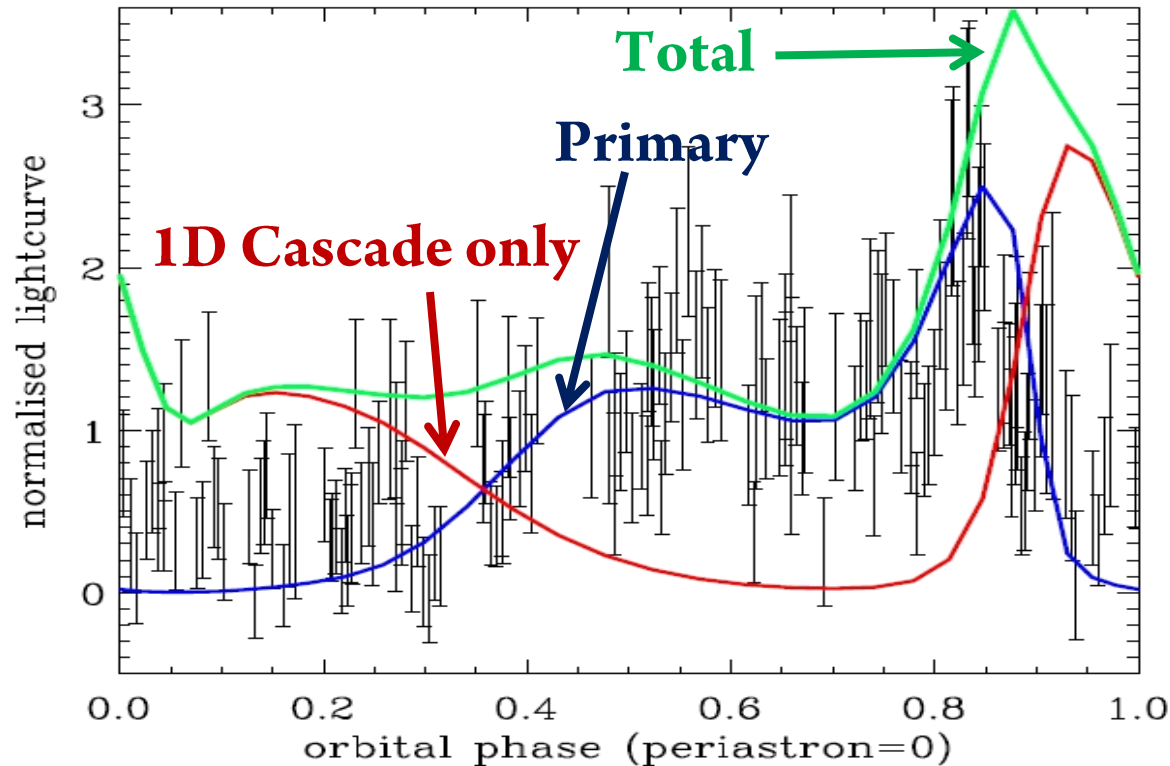
1D cascade

- **No magnetic field** (or $B < 10^{-8}$ Gauss)
- Cascade develops **along the line of sight** → **High anisotropy**
- **Complete** and **accurate** semi-analytical calculation possible (all generations)

Ex: LS 5039 at sup. conj.



Application to **LS 5039**



[Cerutti, Dubus & Henri, A&A 2009]

- Contribution too high from the cascade
→ **Cascade 1D excluded!**
- Upper limit for the cascade contribution @ superior conjunction
→ **Cascade 3D not excluded**

Cascade regimes

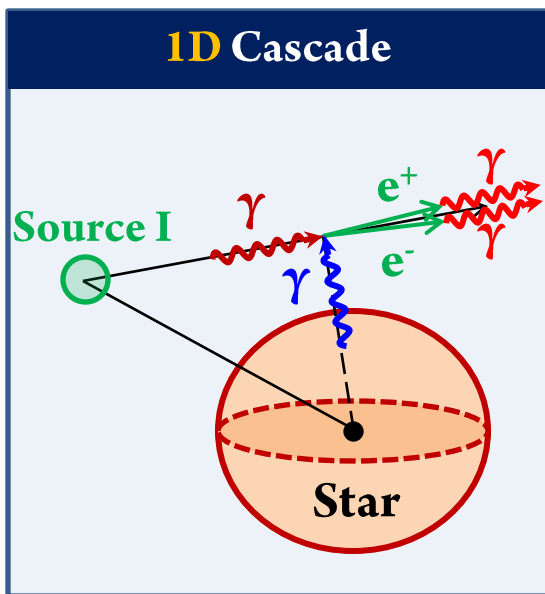
10^{-8} G

10^{-2} G

10 G

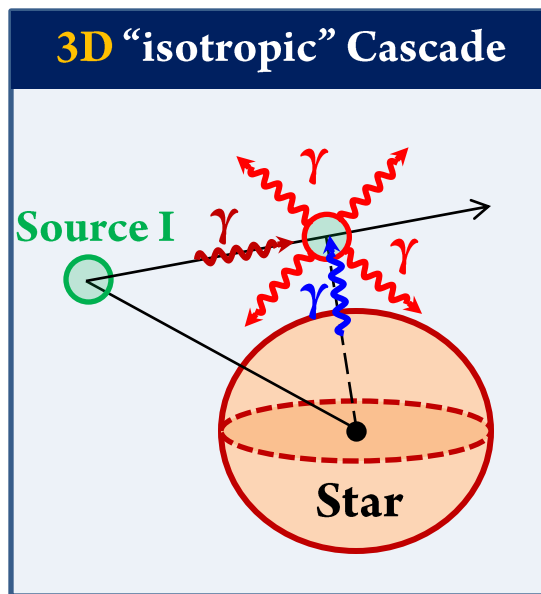
Magnetic field 

1D Cascade



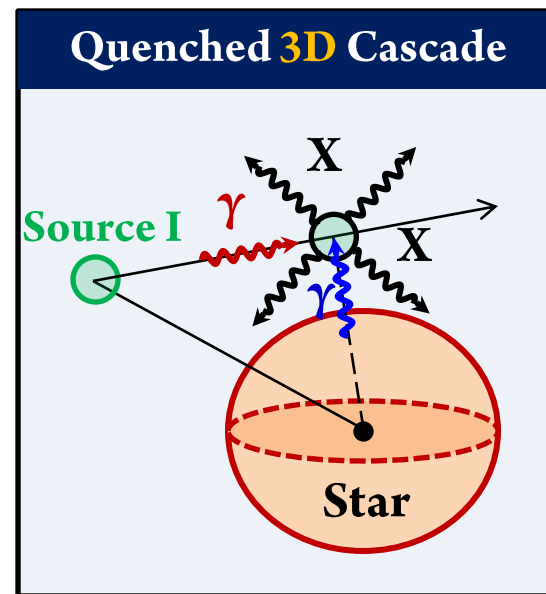
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3D "isotropic" Cascade



- Pairs locally **isotropized** ($R_L < \lambda_{IC}$)
- **Extended** & **anisotropic** emission

Quenched 3D Cascade



- Dominant **Synchrotron** cooling ($t_{syn} < t_{ic}$)
- X-ray emission, **γ -ray emission quenched**

3D cascades: assumptions

- Pairs **isotropized** at creation
- Compton & synchrotron **radiation** and **cooling**
- **No explicit** full analytical calculation possible

→ **Decomposition** into **discrete generations** of particles

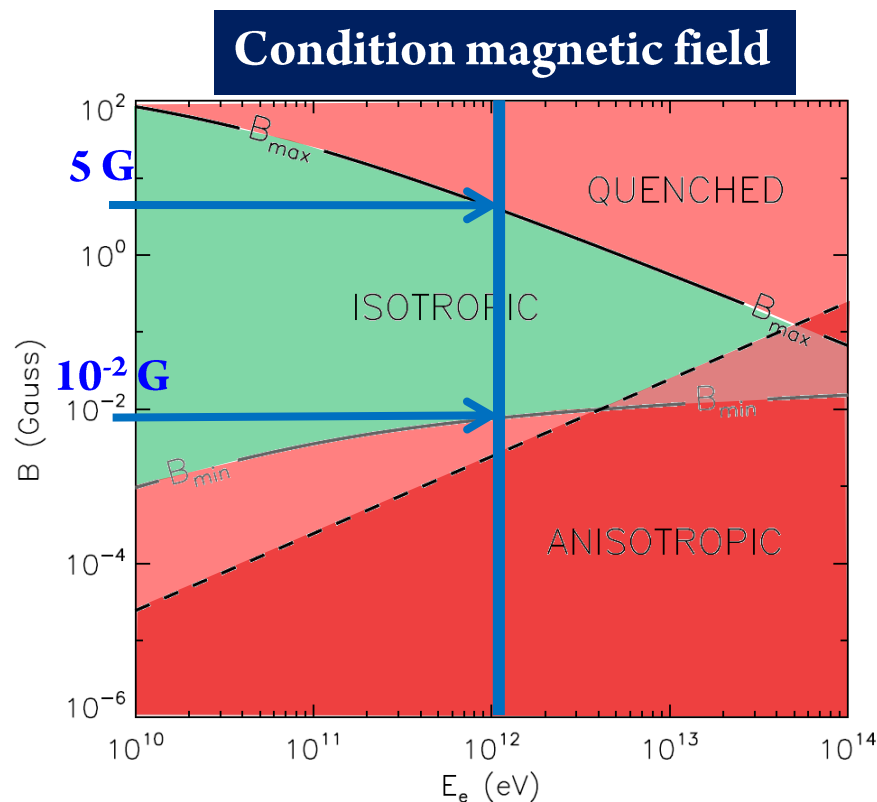
▪ Methods:

1. **Semi-analytical (1st generation)**
2. **Monte Carlo (all generations)**

→ **Collaboration with Julien Malzac**

Both methods **compatible**

Effect of **extra-generations** important

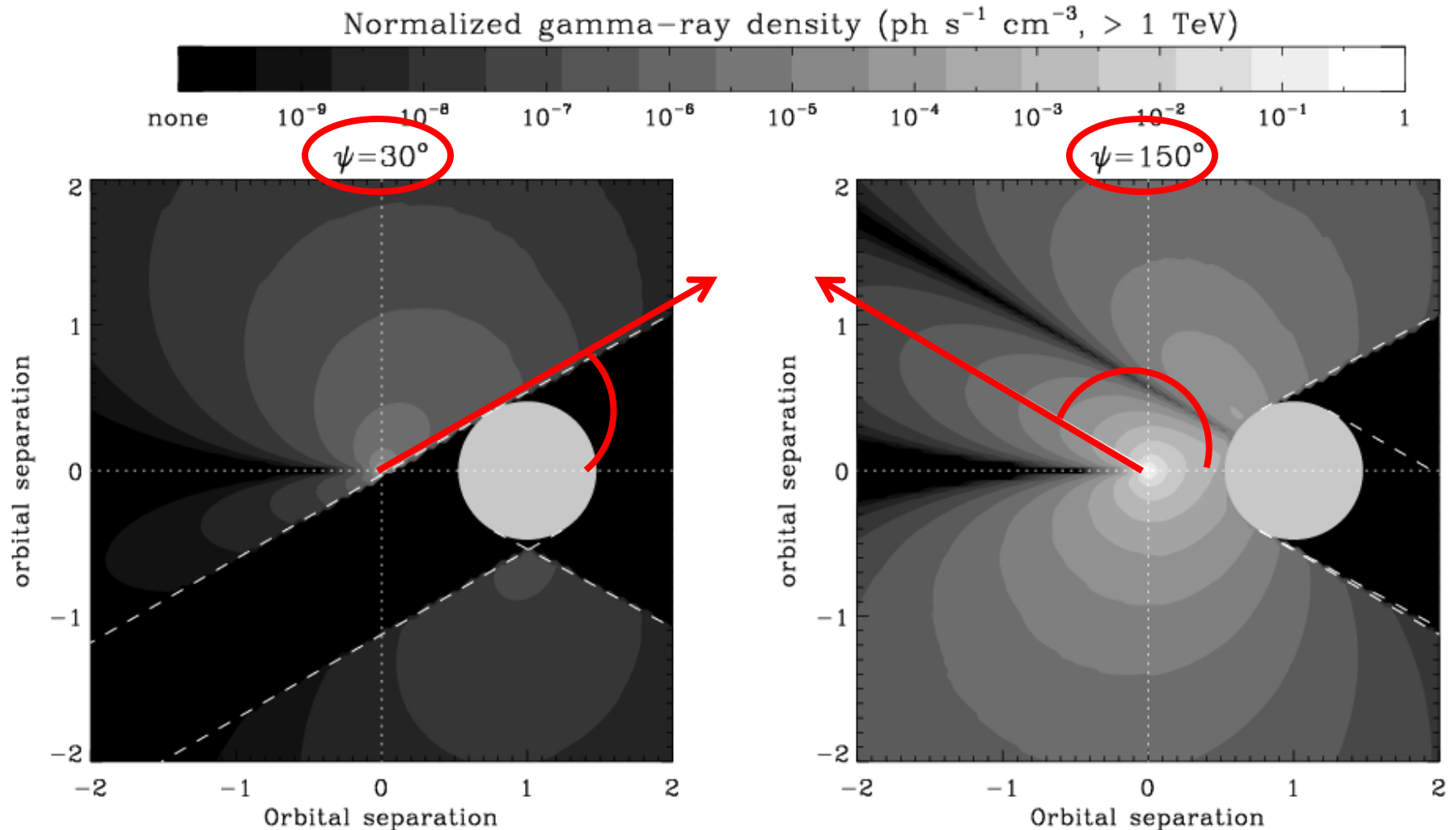


@ 1 TeV → 10^{-2} G < B < 5 G

[Cerutti, Malzac, Dubus, & Henri, A&A 2010, (accepted)]

Spatial distribution 1st generation γ rays

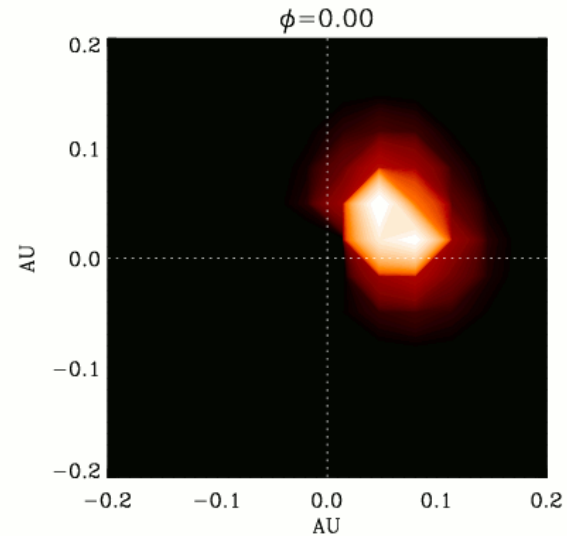
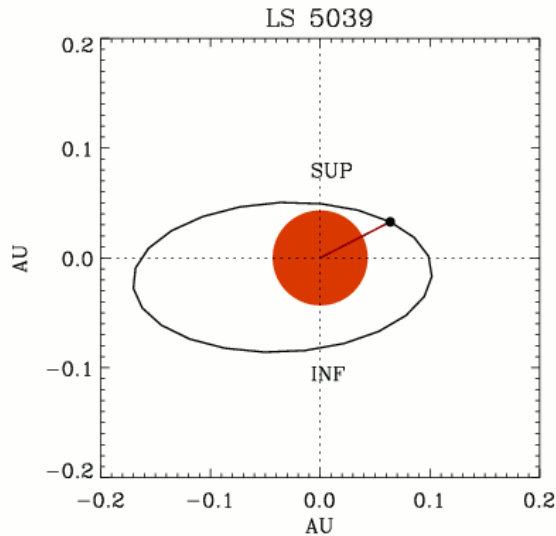
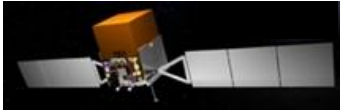
Application to LS 5039: Semi-analytical results



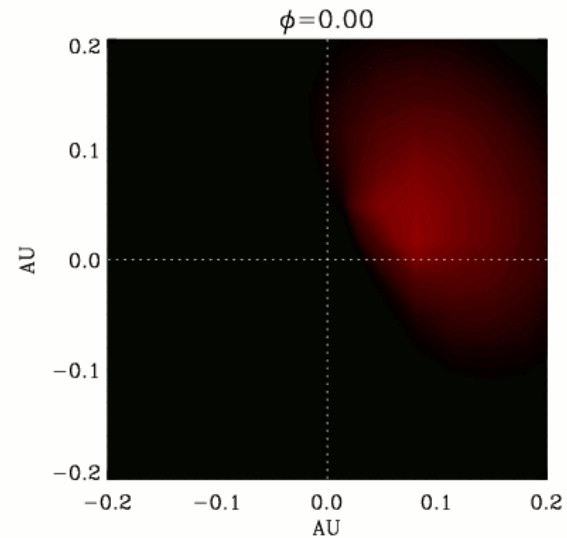
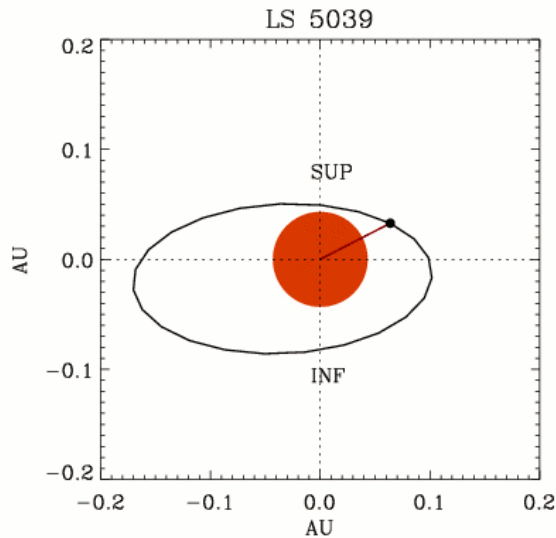
[Cerutti, Malzac, Dubus, & Henri, A&A 2010, (accepted)]

3D cascade modulation in LS 5039

Fermi

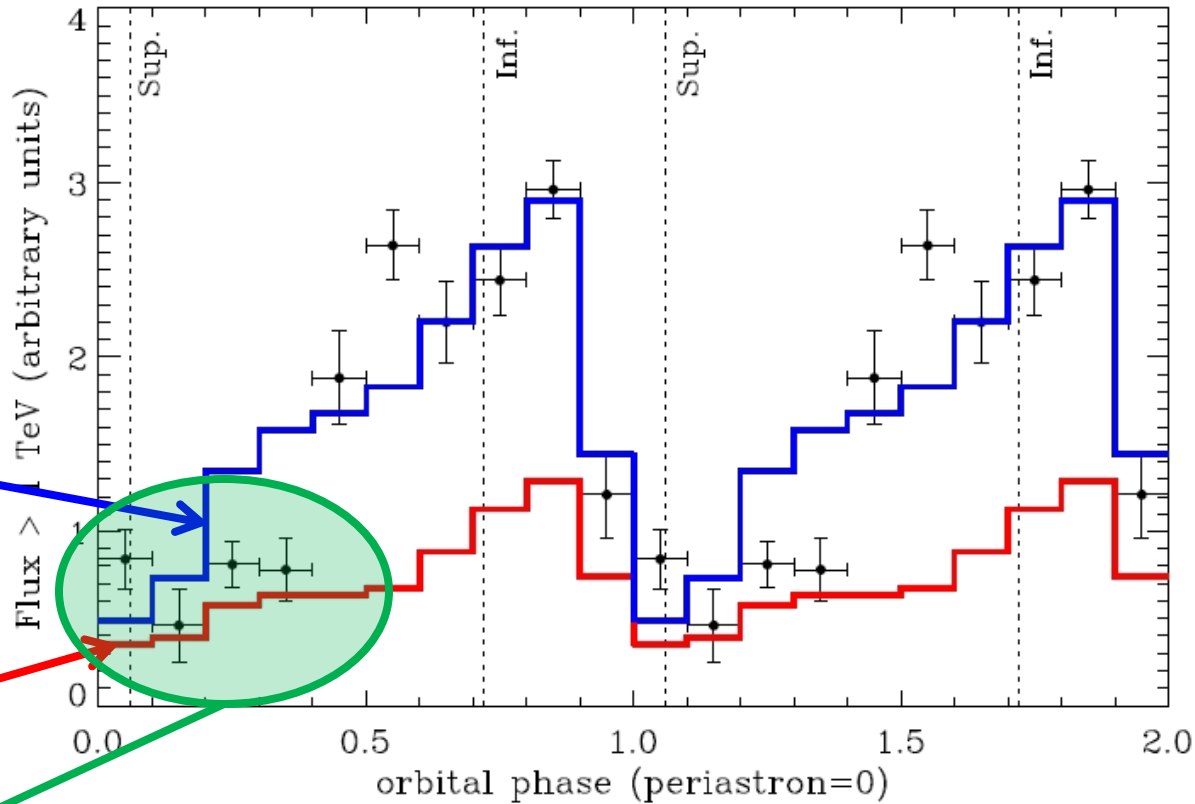


HESS



3D cascade modulation in LS 5039

$i=40^\circ$



[Cerutti, Malzac, Dubus, & Henri, *A&A* 2010, (accepted)]

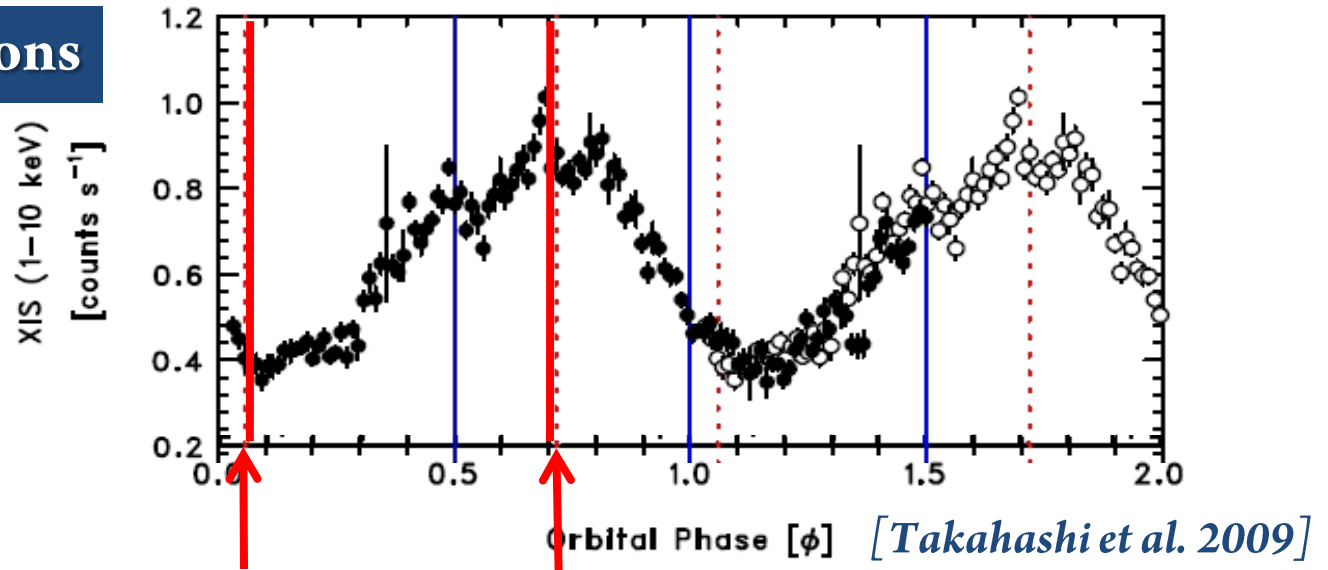
- **Rather low inclination:** $i \approx 40^\circ$
- **TeV** source should lie **close to the compact object**
- Ambient magnetic field **$B < 10$ G** (synchrotron radiation from pairs in the cascade)

γ -ray emission from relativistic outflow

The puzzling X-ray modulation in **LS 5039** !

Suzaku observations

X-rays

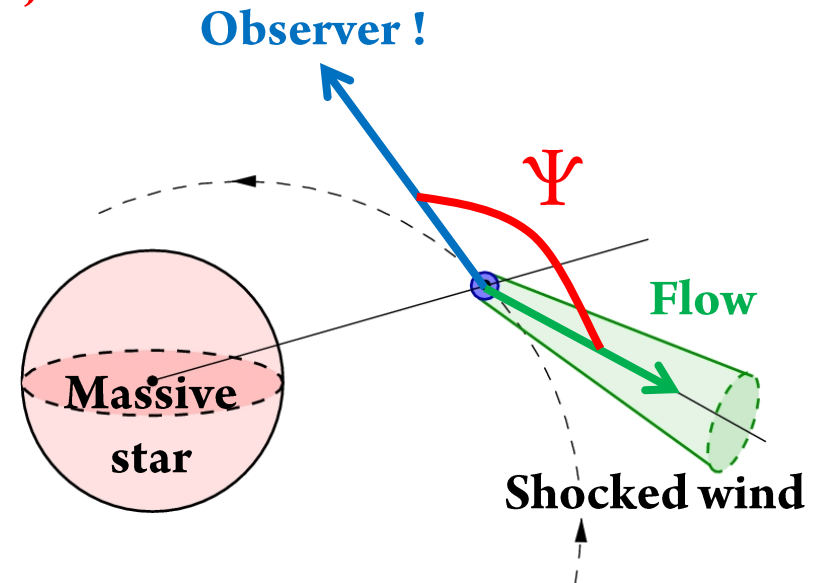


Sup. conjunction Inf. conjunction

X-ray lightcurve

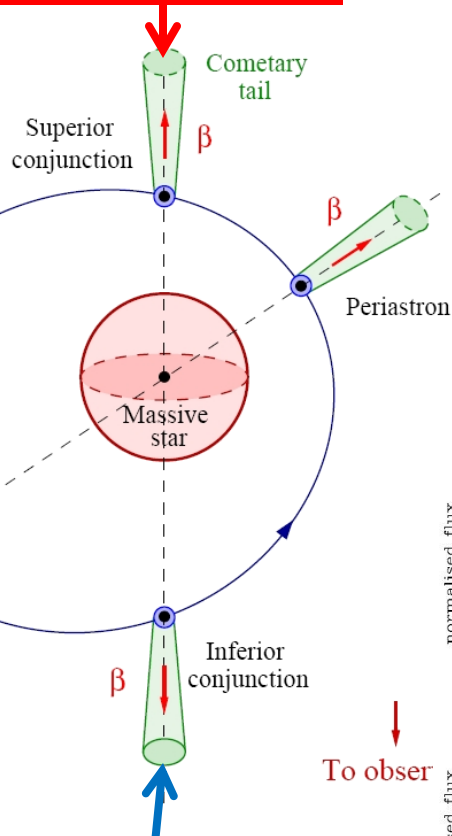
- **Orbital** modulation
- Min and Max at **conjunctions**:
 - ➔ **Intrinsic** variation **unlikely**
 - ➔ **Geometrical** explanation

Solution: Doppler Boost!



Boosted emission in LS 5039

Deboosted !



Boosted !

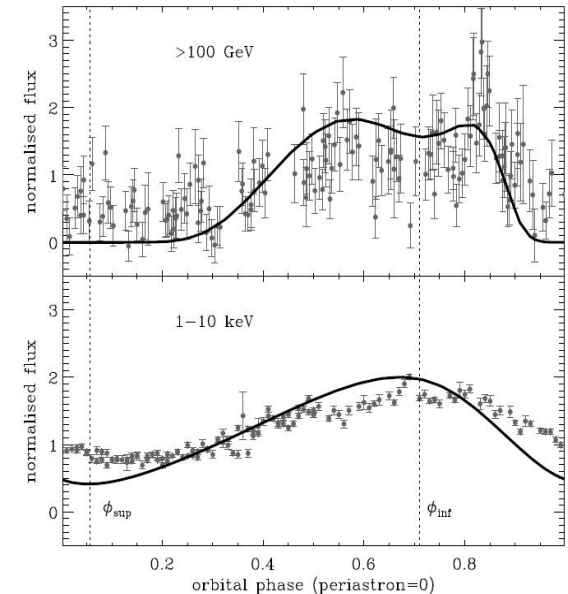
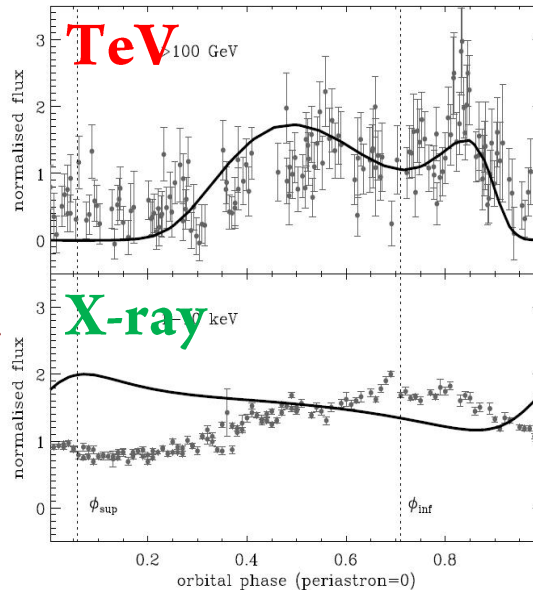
To obser

- Shocked pulsar wind \approx **radial**
(stellar wind speed \gg orbital motion pulsar)
- **Mildly** relativistic wind $\beta=1/3$ ($=v/c$)
 - **TeV** modulation \approx **unchanged**
 - **X-ray** modulation \approx **reproduced**

$\beta=0$

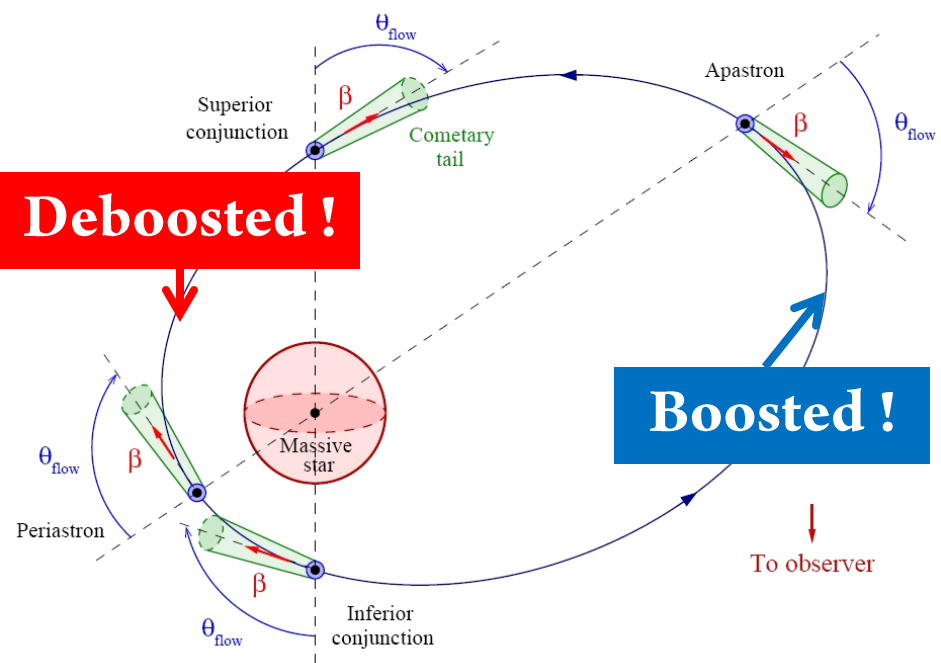
Boost

$\beta=1/3$



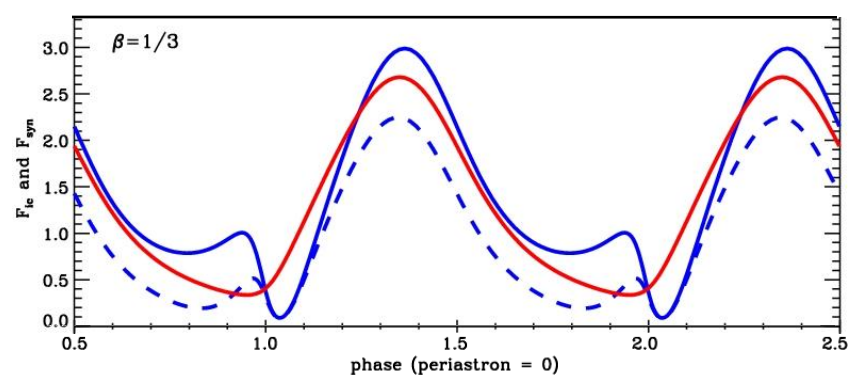
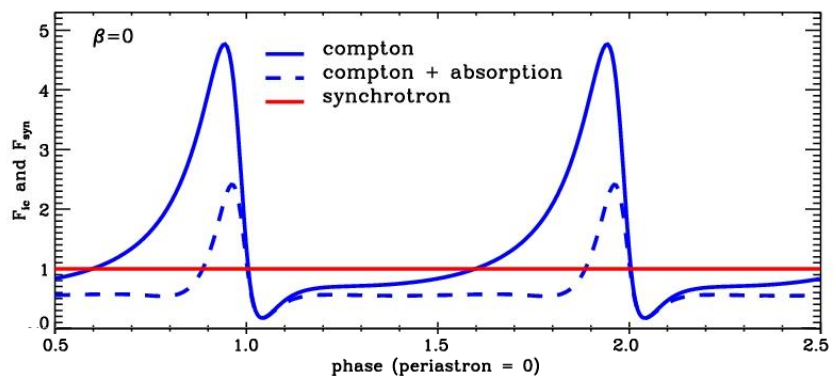
[Dubus, Cerutti, & Henri 2010b]

Boosted emission in **LS I +61°303** (1)



- **Model:** Pulsar wind **trailing** in the Be Keplerian disk
- **Mildly** relativistic wind $\beta=1/3$:
X-ray and **TeV** both **correlated** and **maximum** close to apastron

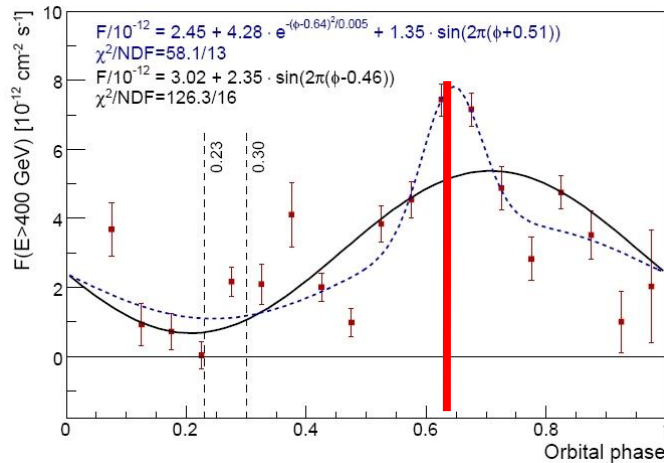
$\beta=0$ → Boost → $\beta=1/3$



[Dubus, Cerutti, & Henri 2010b]

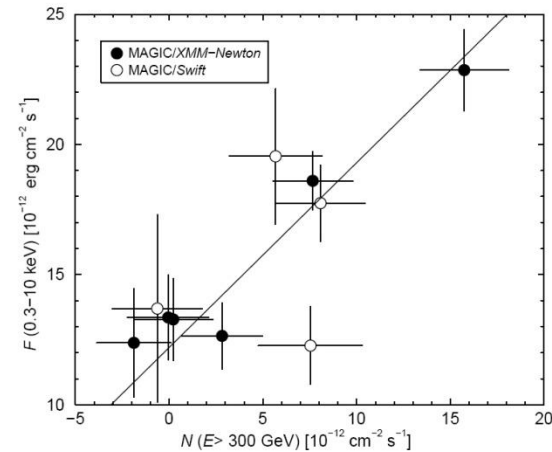
Boosted emission in **LS I +61°303** (2)

MAGIC lightcurve



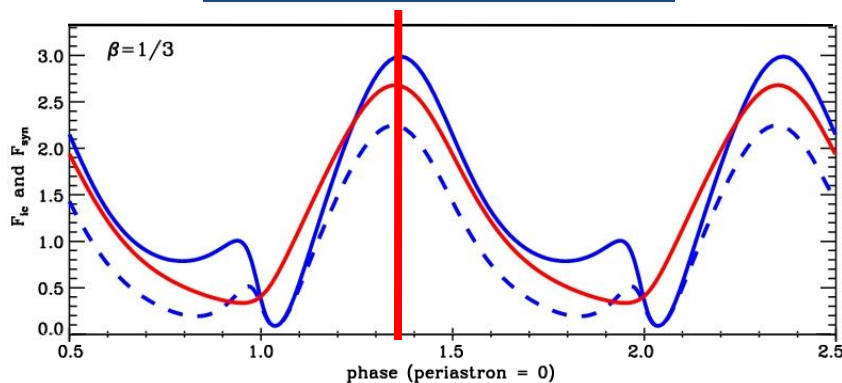
[Albert et al. 2009]

X- γ correlation



[Anderhub et al. 2009]

Model for $\beta=1/3$



[Dubus, Cerutti, & Henri 2010b]

- The Boost in **LS I +61°303** could explain **TeV** and **X-ray modulations !**
- Same model for **PSR B1259-63**
➔ **small impact**

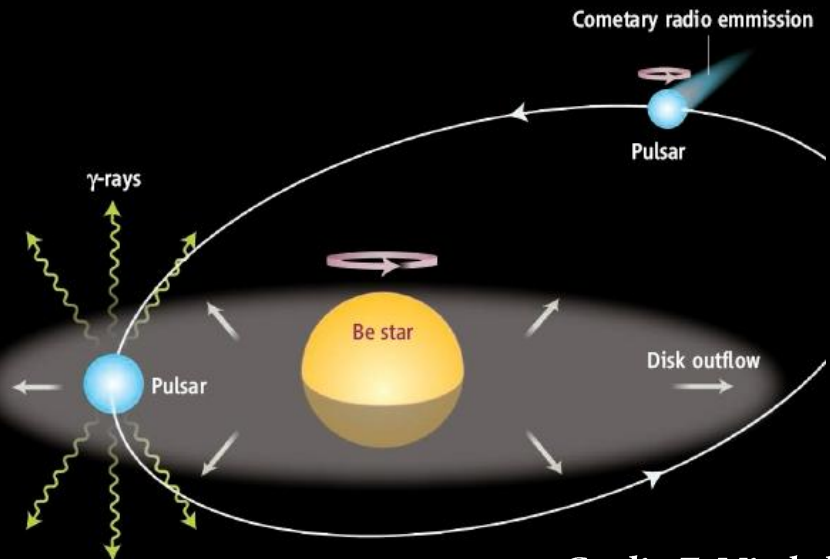
Two classes of binaries

GAMMA-RAY BINARIES

=

Massive star + young pulsar

[Maraschi & Treves 1980, Dubus 2006b]



Credit: F. Mirabel

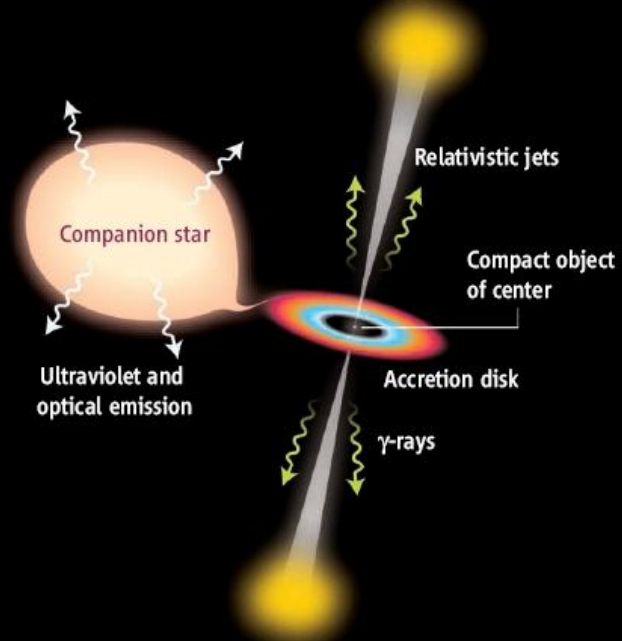
ROTATION-POWERED

LS I +61°303, LS 5039 & **PSR B1259-63**
(HESS J0632+057?)

MICROQUASAR

=

Massive star + accreting compact object
(neutron star or black hole)

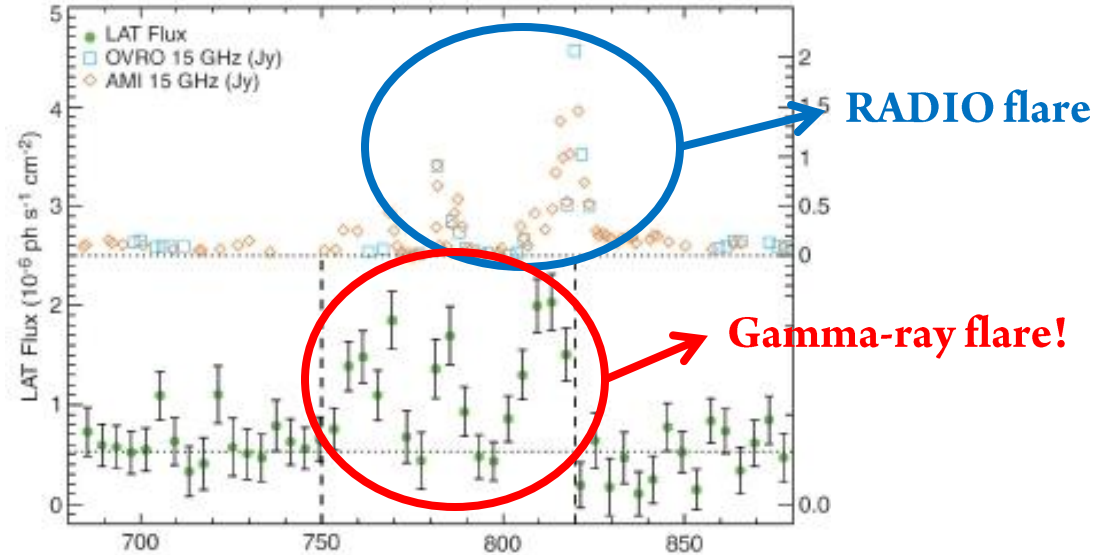
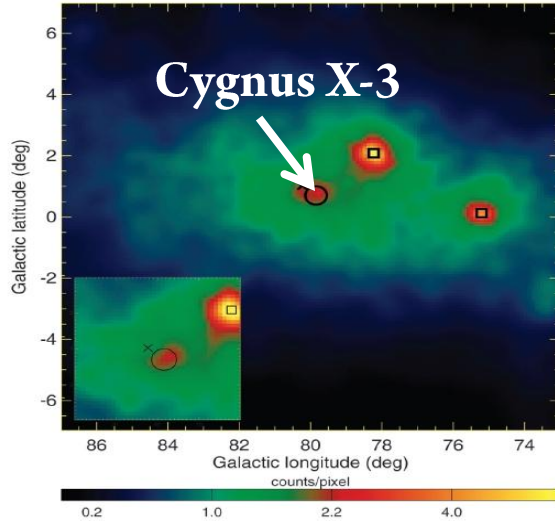


ACCRETION-POWERED

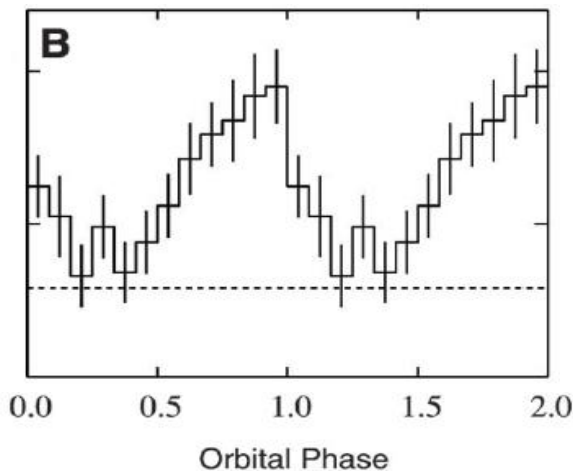
Cyg X-3
(Cyg X-1?)

Cygnus X-3: The first GeV microquasar!

[Fermi LAT coll., 2009c]

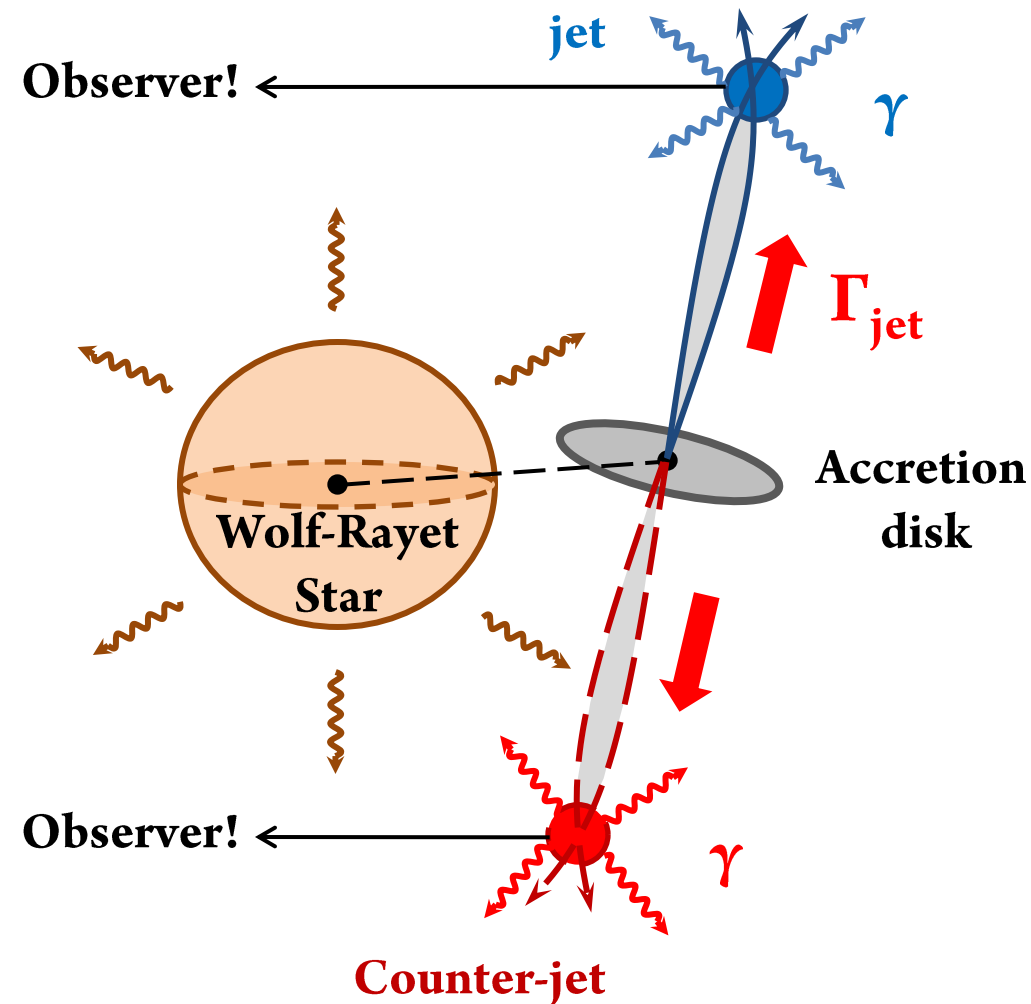


GeV light curve



- **First firm detection** of a microquasar at **GeV** by **AGILE & Fermi** [Tavani et al. 2009, Fermi LAT coll. 2009c]
- γ -ray flares **correlated** with radio flares
➔ γ -ray emission related to the **jet**
- γ -ray flux **modulated** at the **orbital period** (4.8 h)

Relativistic Doppler emission in **Cygnus X-3**



Assumptions

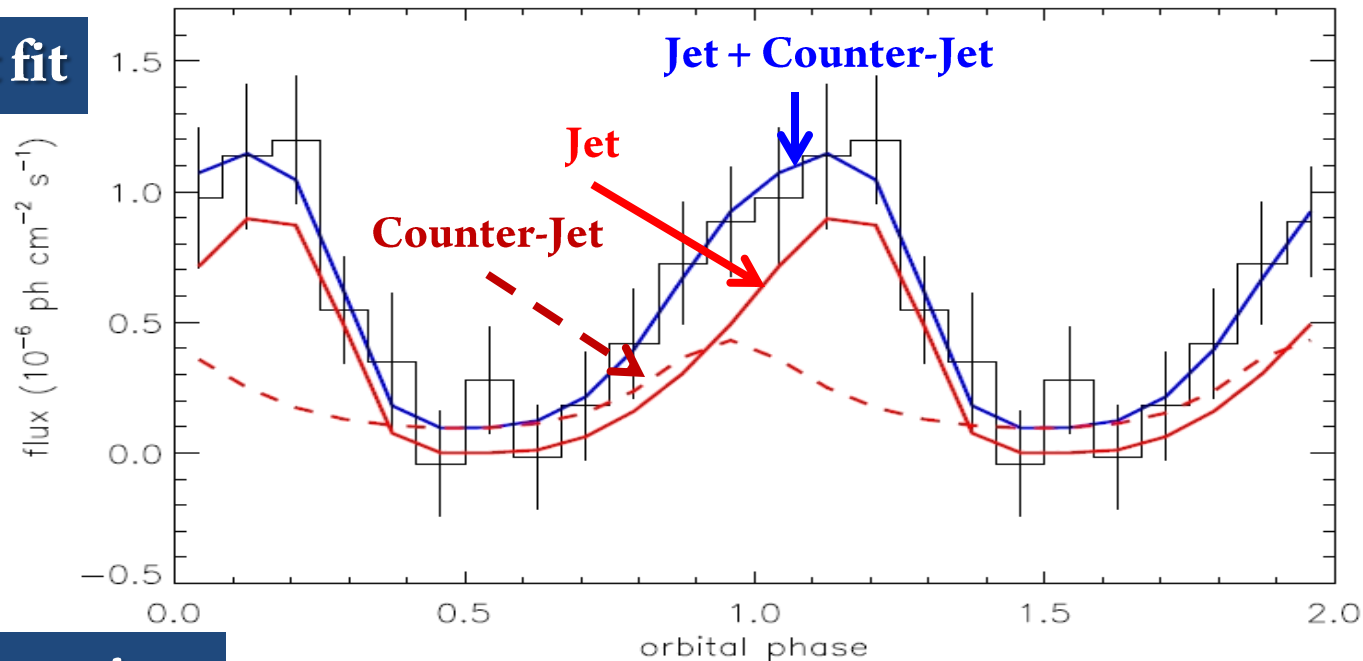
- **Boosted** Inverse Compton stellar photons – pairs in the jet
- The jet is **inclined & relativistic**
- Energetic electrons **located @ specific locations**

Parameters

- **5 free** parameters
- **Exhaustive exploration** of parameter space $\rightarrow \min \chi^2$

Best fit solution

Best fit



Constraints

[*Dubus, Cerutti, & Henri, MNRAS 2010a*]

- e^\pm **not located** within the system
- Jet **inclined close to the line of sight** (μ -blazar!)
- Jet **mildly relativistic** ($\beta < 0.9$)
- Black-hole **avored**
- **Precession of the jet: strong impact** on the modulation

Conclusions & futures directions

Summary

Pulsar wind emission

- **Shocked: Anisotropic IC + absorption: TeV modulation OK in LS 5039.**
- **Unshocked: Strong emission excluded: wind highly magnetized?**

Publications: [Dubus, Cerutti, & Henri, 2008]; [Cerutti, Dubus, & Henri 2008]

Cascades

- **1D cascade: provides an upper limit, excluded in LS 5039**
- **3D cascades: Viable solution for TeV flux @ sup. conj. in LS 5039**

Publications: [Cerutti, Dubus, & Henri, 2009]; [Cerutti, Malzac, Dubus, & Henri, 2010]

Boosted emission

- **γ -ray binaries: changes significantly high-energy modulation (X, γ)**
- **Cygnus X-3: Boosted Compton scattering \rightarrow GeV modulation OK**

Publications: [Dubus, Cerutti, & Henri, 2010a]; [Dubus, Cerutti, & Henri, 2010b]

Open questions and looking forward

Open questions

- What is the origin of the **GeV** component? -> **Striped** pulsar wind in binaries?
- What is the origin of the γ -ray modulation in **LS I +61°303** and **PSR B1259-63**?
- Particle **acceleration** in **microquasar jet**?

Looking forward

- **Present** and **future** observational backdrop favorable (Fermi, CTA, ...)
➔ **Discovery of new systems!**
- Exciting **new modeling challenges** with **GeV** observations!
(pulsar emission, model for microquasars ...)
- **Theoretical expertise** in **high-energy processes** in astrophysics
➔ Application to many other objects *e.g.*:
 - **AGN** and **GRBs**
 - **Pulsars, PWN... and magnetars!**

Future directions

Post-doc

- **Research associate** position with Pr. **Dmitri Uzdensky** in Theoretical plasma astrophysics @ **University of Colorado, Boulder, USA**.
- Magnetic reconnection in **High-energy-density astrophysical environment** (e.g. *magnetars & GRBs*)



University of Colorado

The end