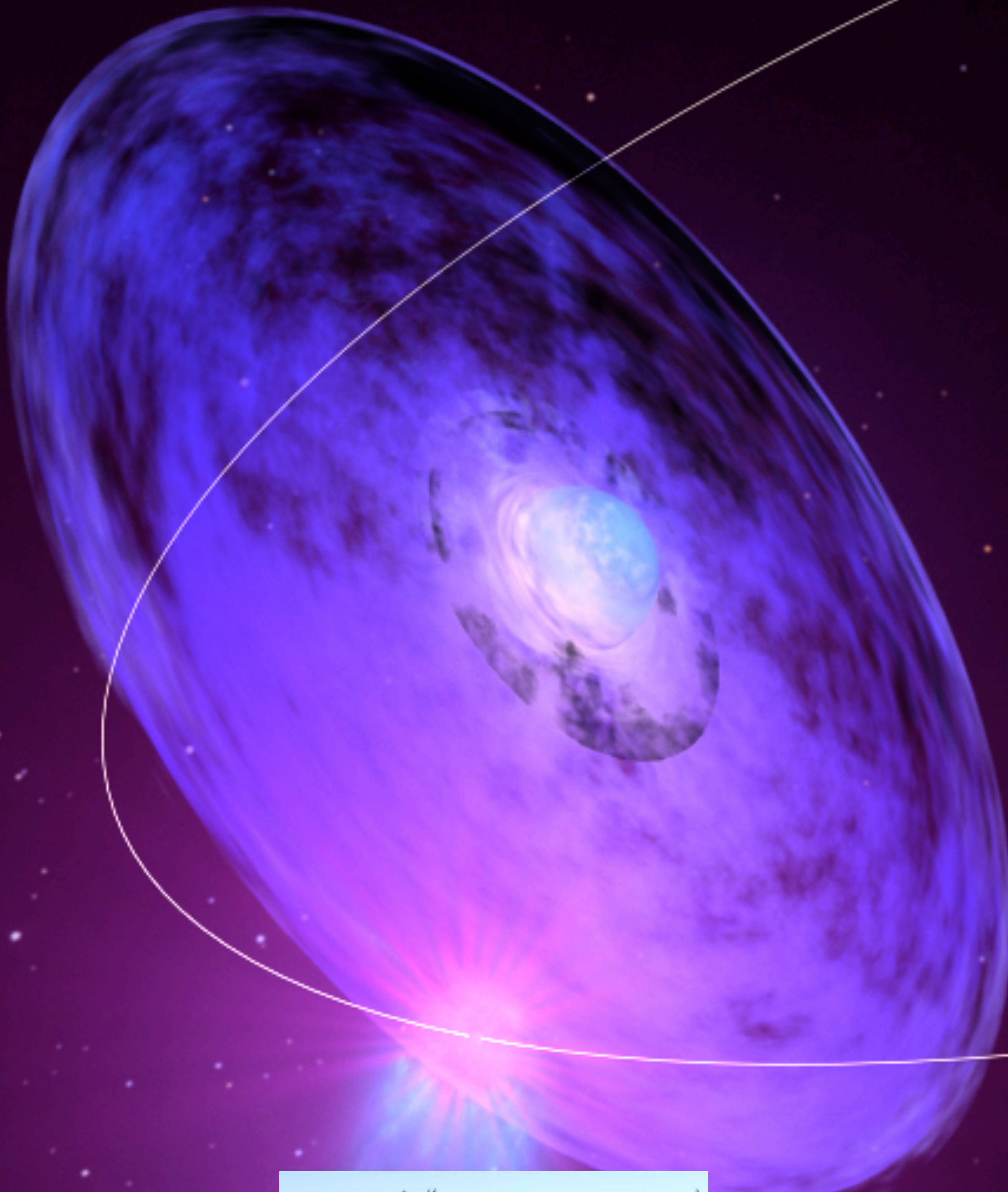
Gamma rays from binaries



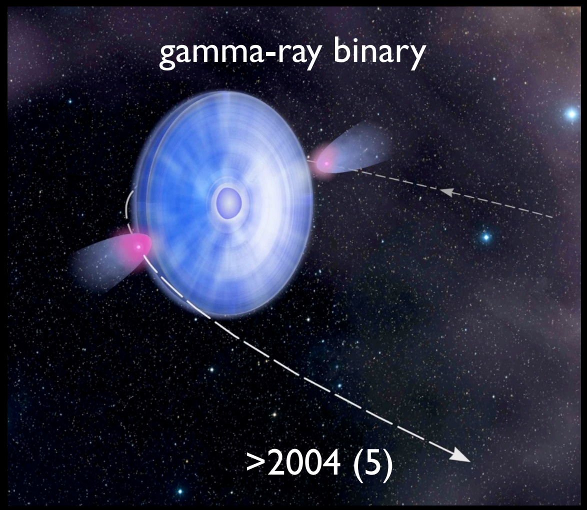
Credit: F. Reddy/NASA/GSFC

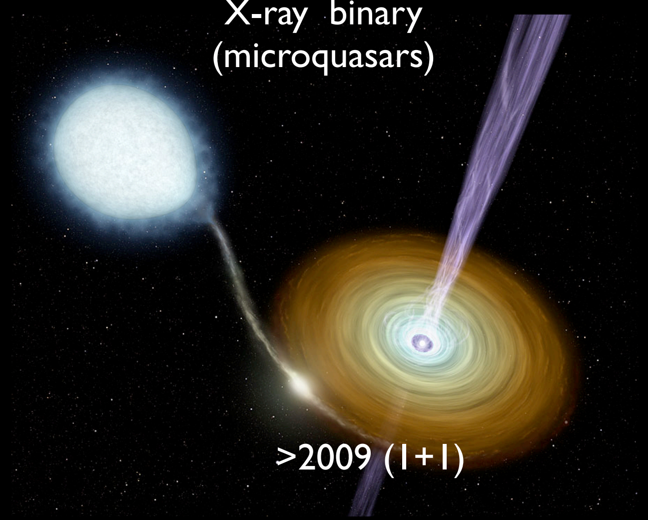
Guillaume Dubus

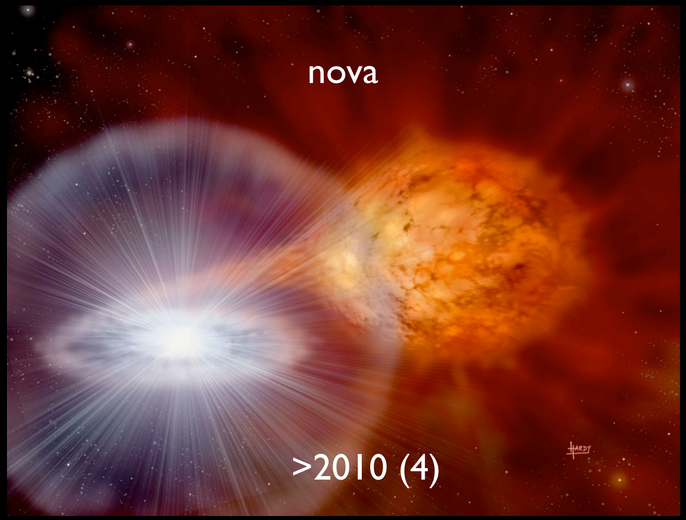
Fermi School 2014, Lewes DE

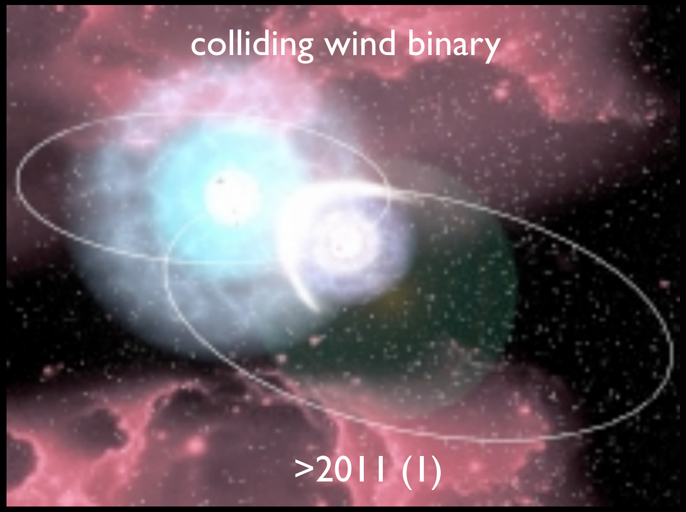
Institut de Planétologie et d'Astrophysique de Grenoble

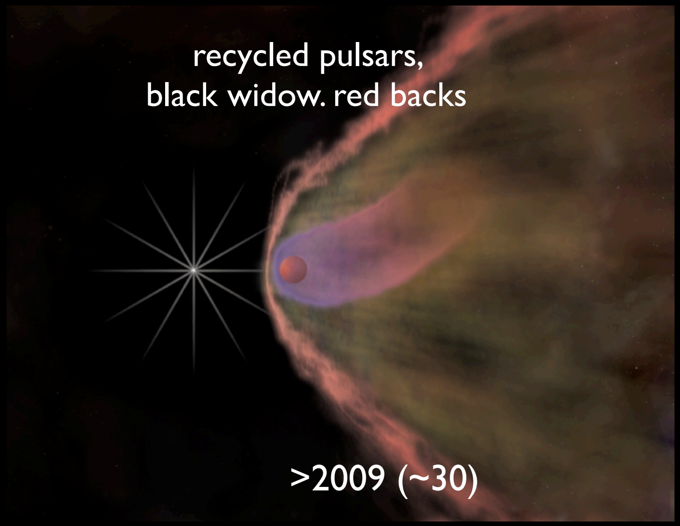
Binaries detected >100 MeV by Fermi, IACTs











see Dubus, 2013, Astron. Astrophys. Rev., 21, 64

A rare & diverse lot...

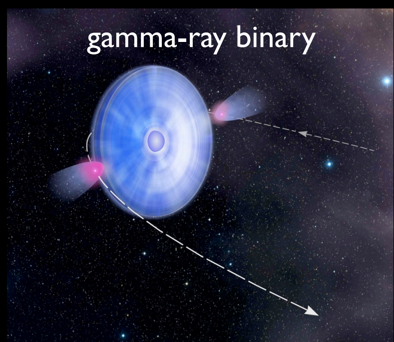
How special are they ?

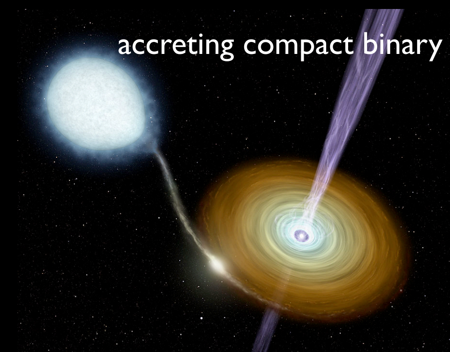
Do these systems have anything in common ?

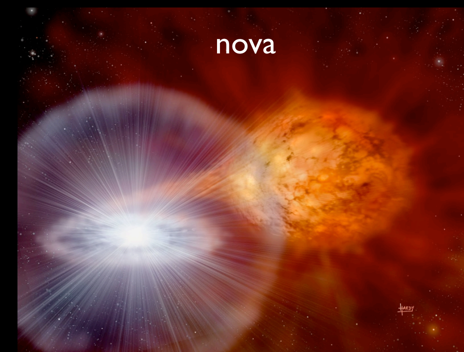
What's involved in producing gamma rays ?

How do they compare to other sources ?

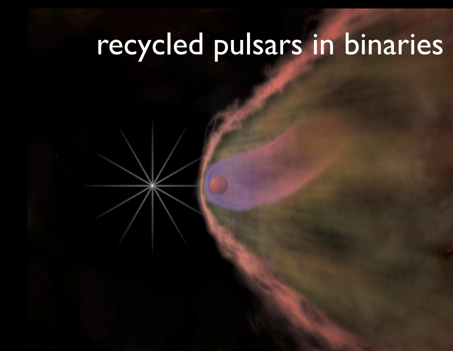
Motivation

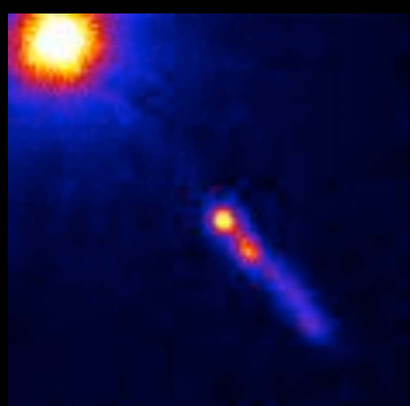

gamma-ray binary

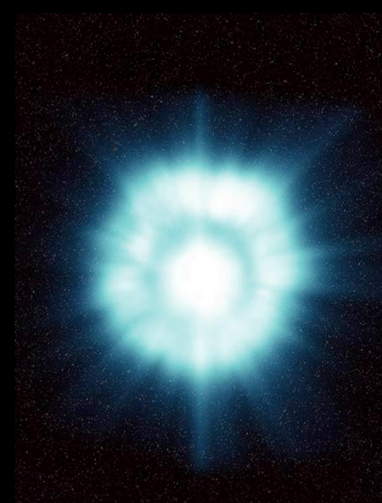

accreting compact binary

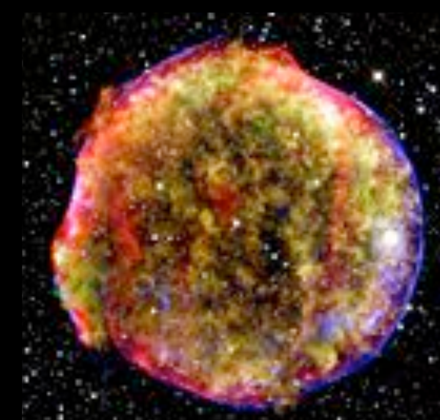

nova

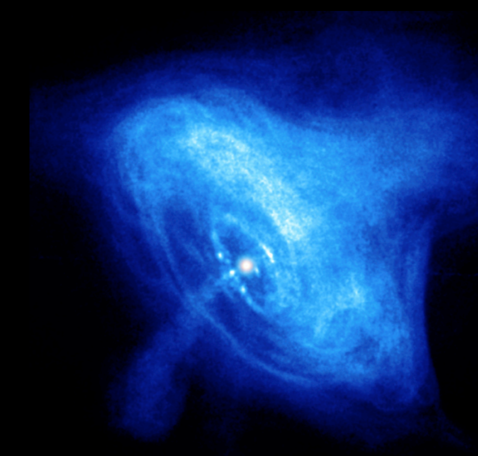

colliding wind binary


recycled pulsars in binaries


active galactic nuclei


γ-ray bursts


supernova remnants


pulsars & their nebula

use binaries to get a coherent picture across objects & scales of

- **magnetized relativistic outflows**
- **accretion - ejection phenomena**
- **particle acceleration**

geometry modulations

Overview

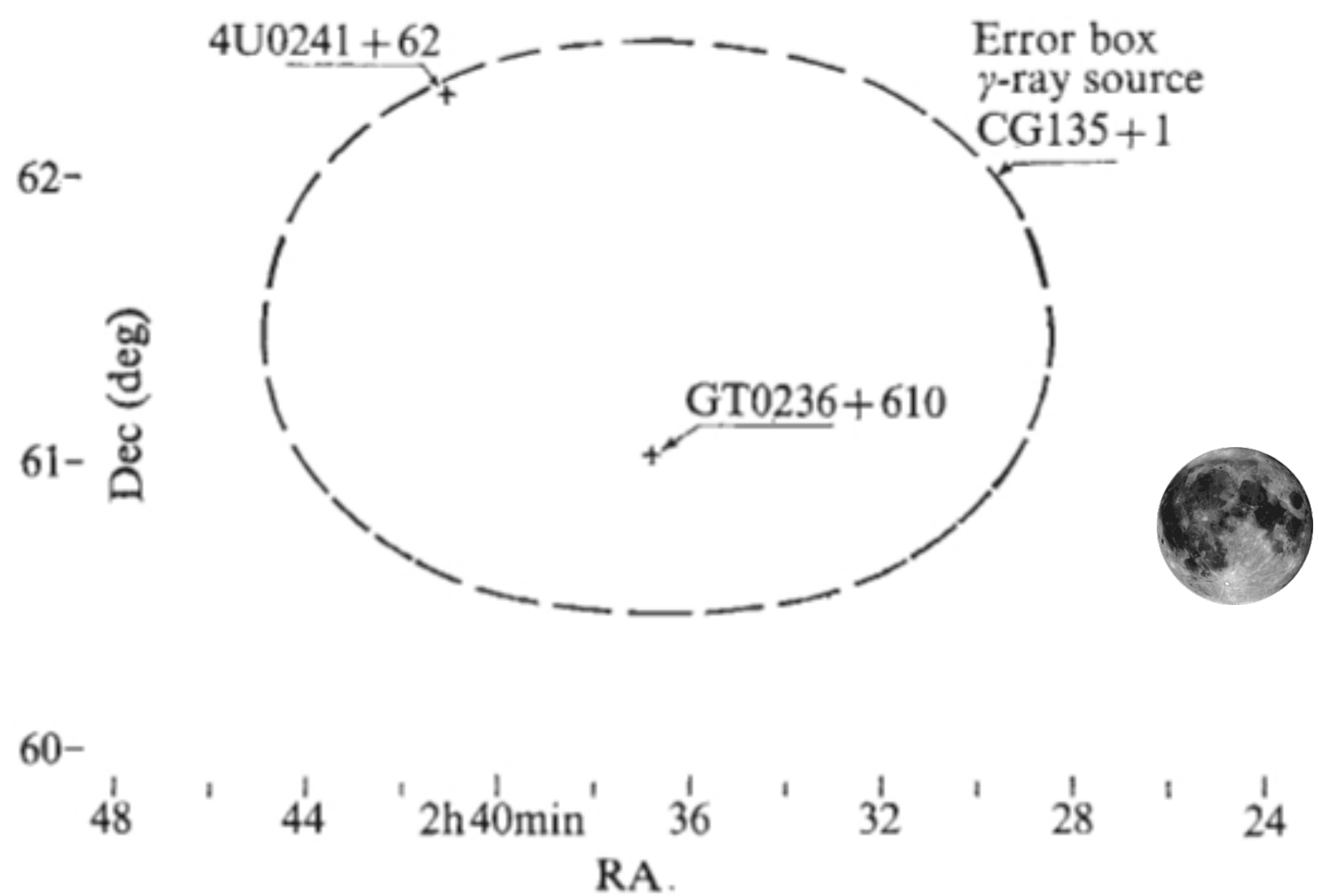
i. Some history
ii. Gamma-ray binaries: emergence of a new class
iii. What powers gamma-ray binaries ?
iv. Tools of the trade: HE radiation in the context of binaries
v. Current puzzles
vi. A microquasar in gamma rays: Cyg X-3
vii. A nova in gamma rays: V407 Cyg
viii. A colliding wind binary in gamma rays: Eta Car

binaries in gamma rays:
a checkered history...

2CG 135+01 = LS I+61º303?

- GeV source discovered in 1977 by Cos B.
- LSI +61º303 rare HMXB with periodic radio flares in error box

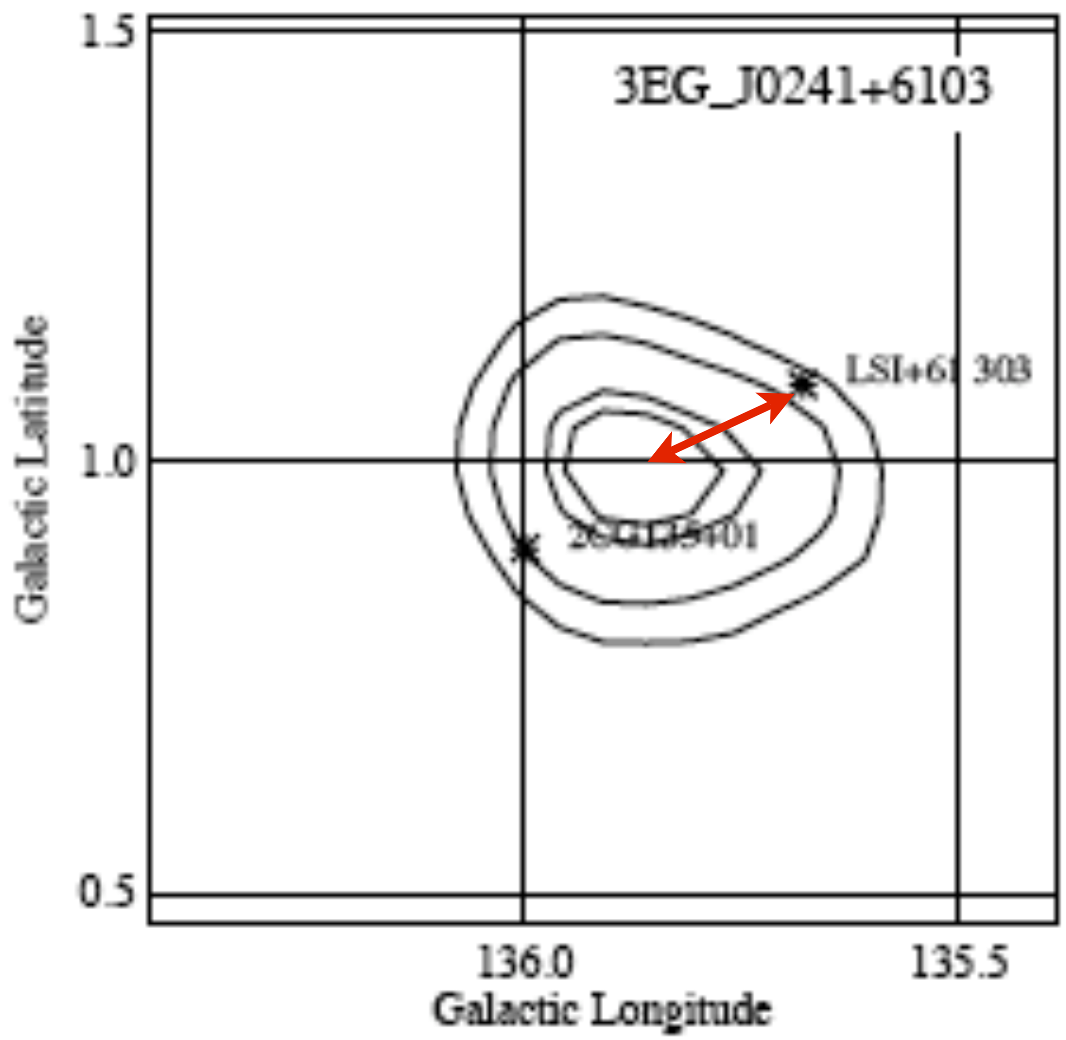
Gregory & Taylor 1978



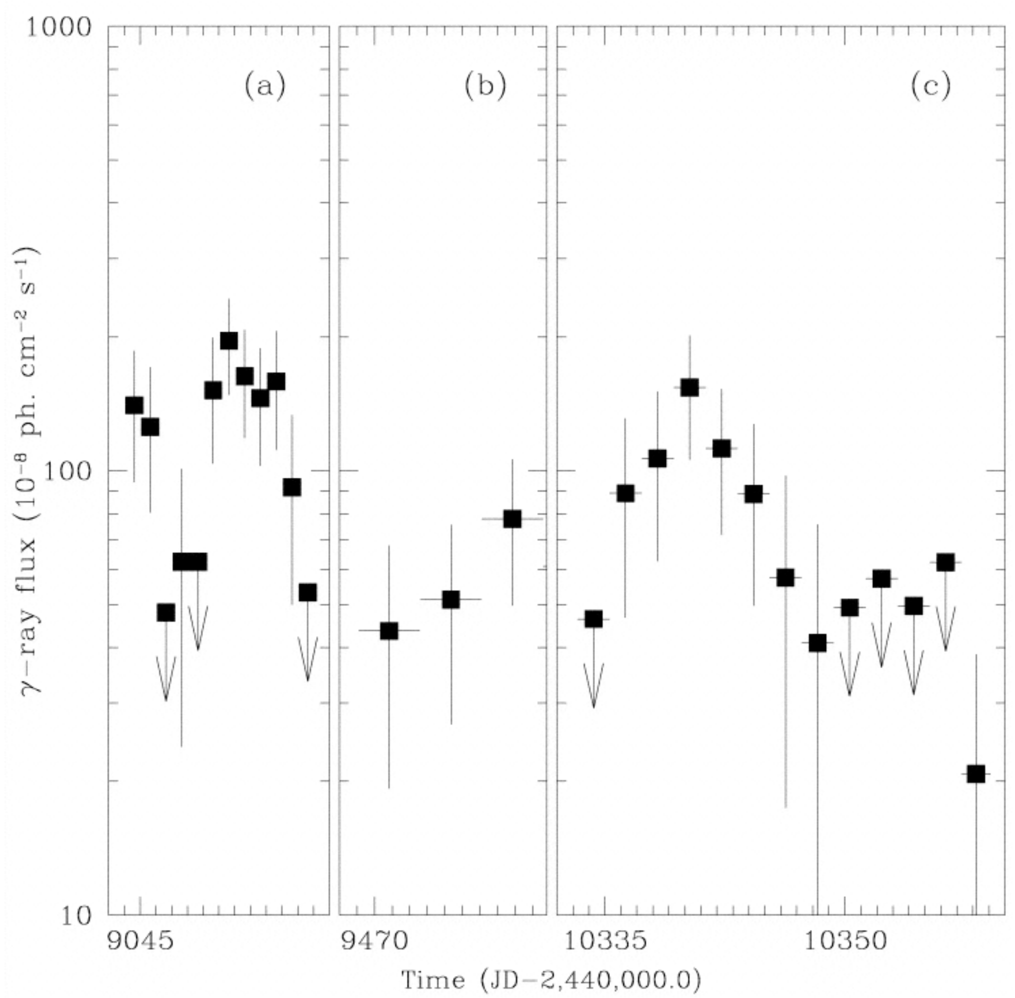
2CG 135+01 = LS I+61º303?

- GeV source discovered in 1977 by Cos B.
- LSI +61º303 rare HMXB with periodic radio flares in error box
- but source confusion, no tell tale variability.

Hartman et al. 1999 (3EG)

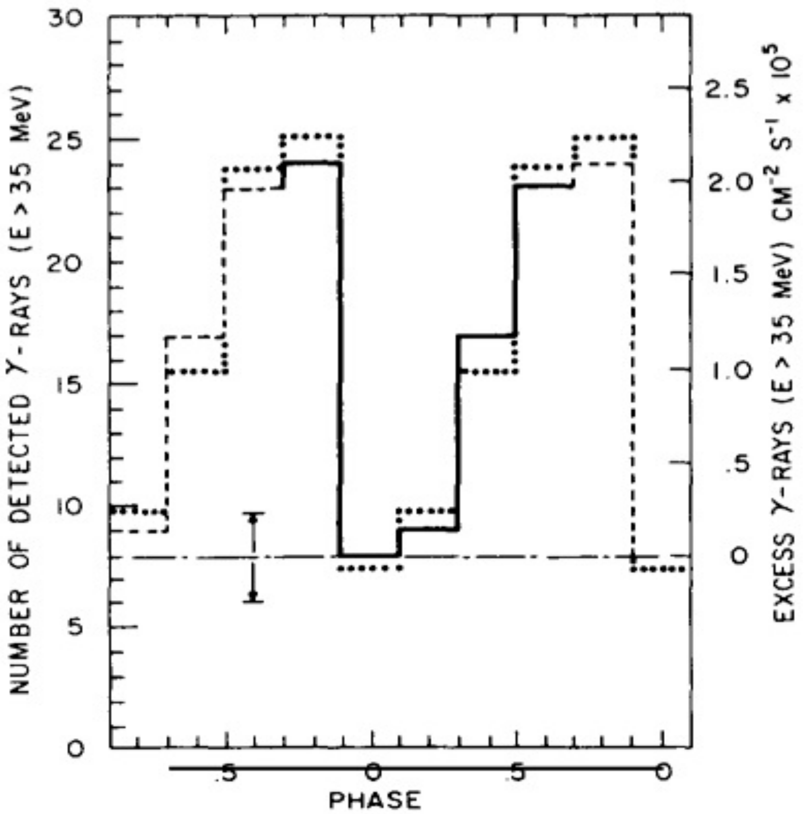


Tavani et al. 1998



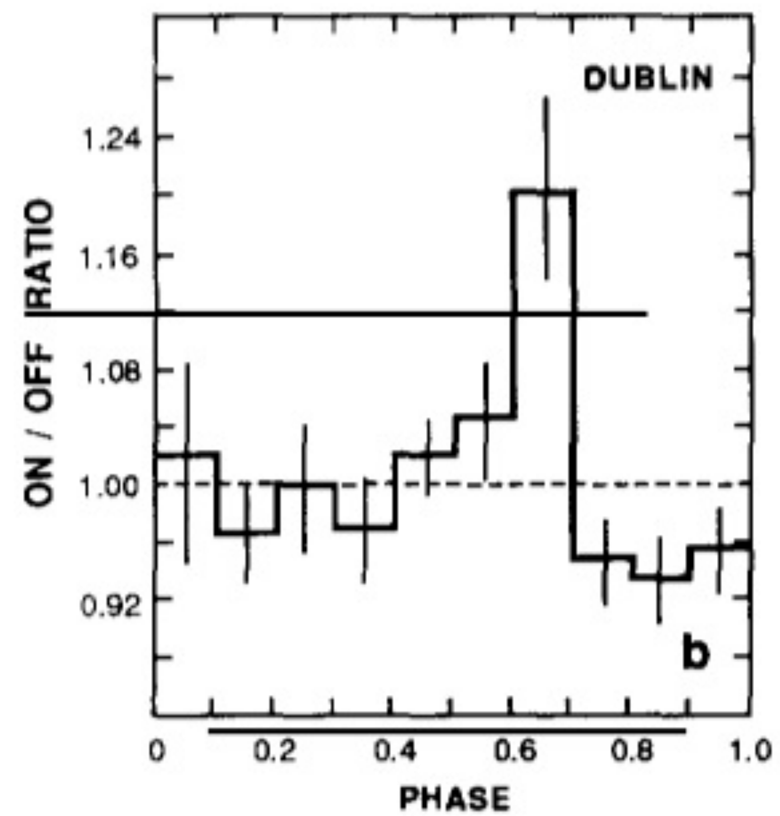
The notorious Cyg X-3

- X-ray binary discovered 1966, 4.8 hour orbit, large radio flares discovered 70s
- confused history in gamma rays... Chardin & Bonnet-Bideau 1988
- but triggered developments that led to today's gamma-ray astronomy



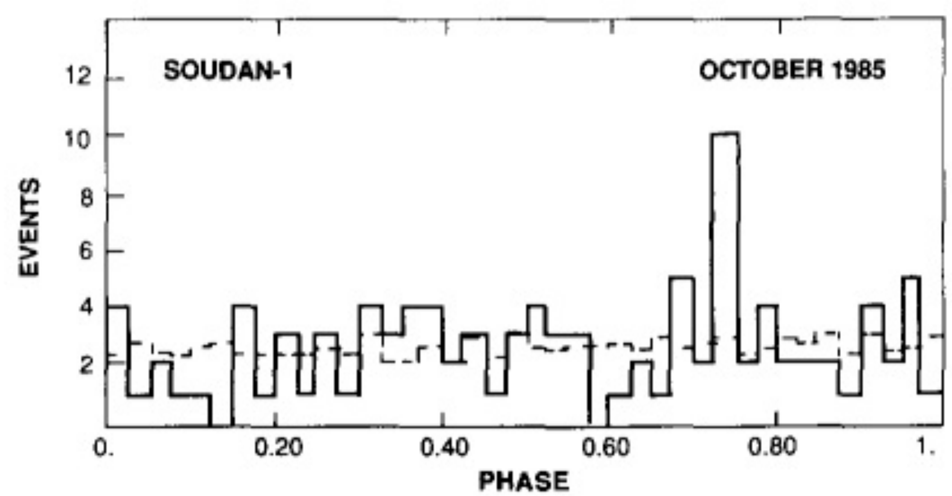
SAS-2 Parsignault et al. 1976

GeV



Weekes et al. 1981
12.8 ms pulsar: Chadwick et al. 1985

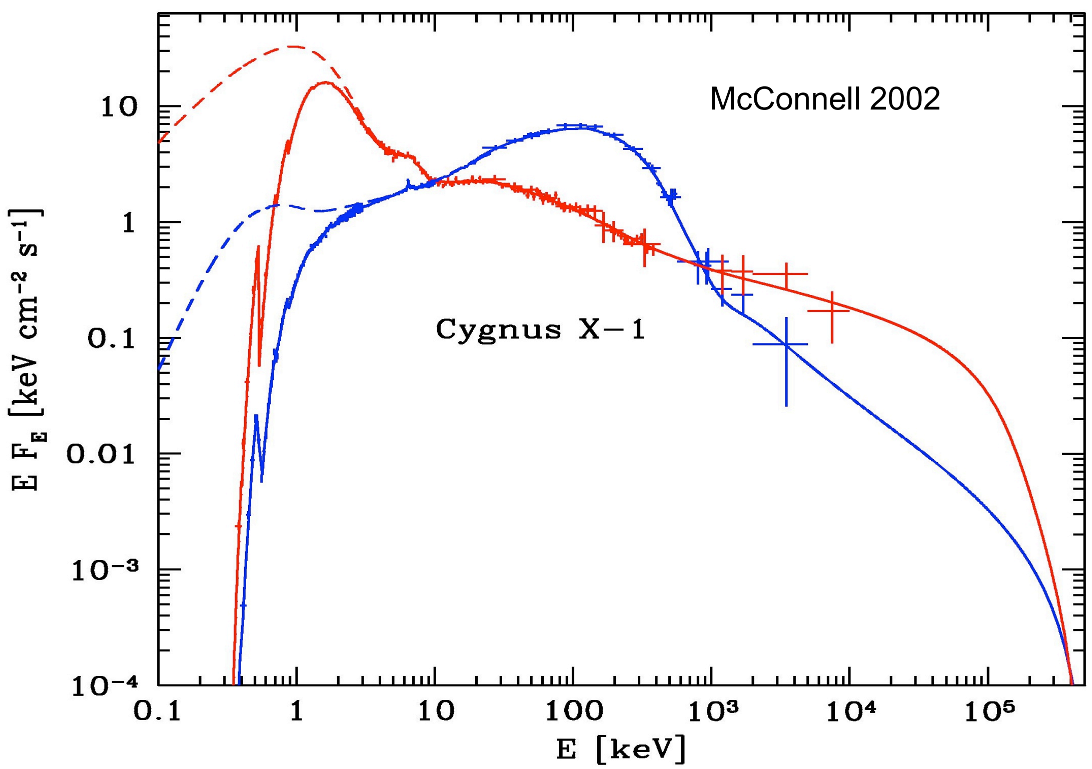
TeV

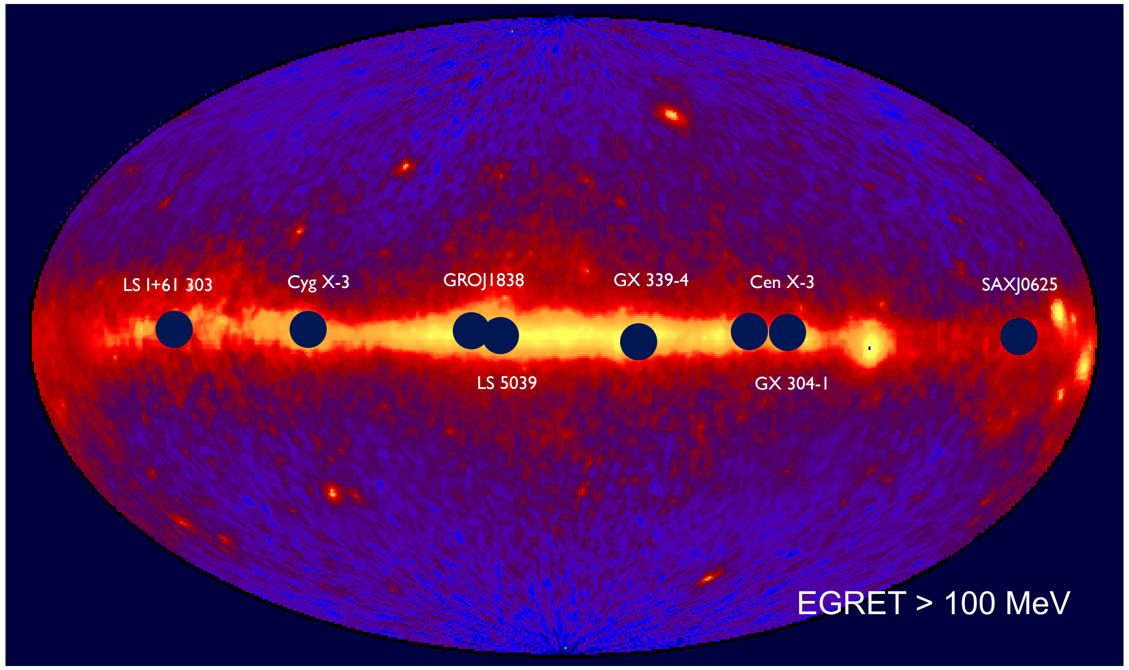


Sudan-I Marshak et al. 1986

muons

γ rays from compact binaries





pre-2004

- **> 1 MeV**
  non-thermal tails in a few binaries
- **> 100 MeV**
  tentative associations
- **> 100 GeV**
  confused situation since 1970s

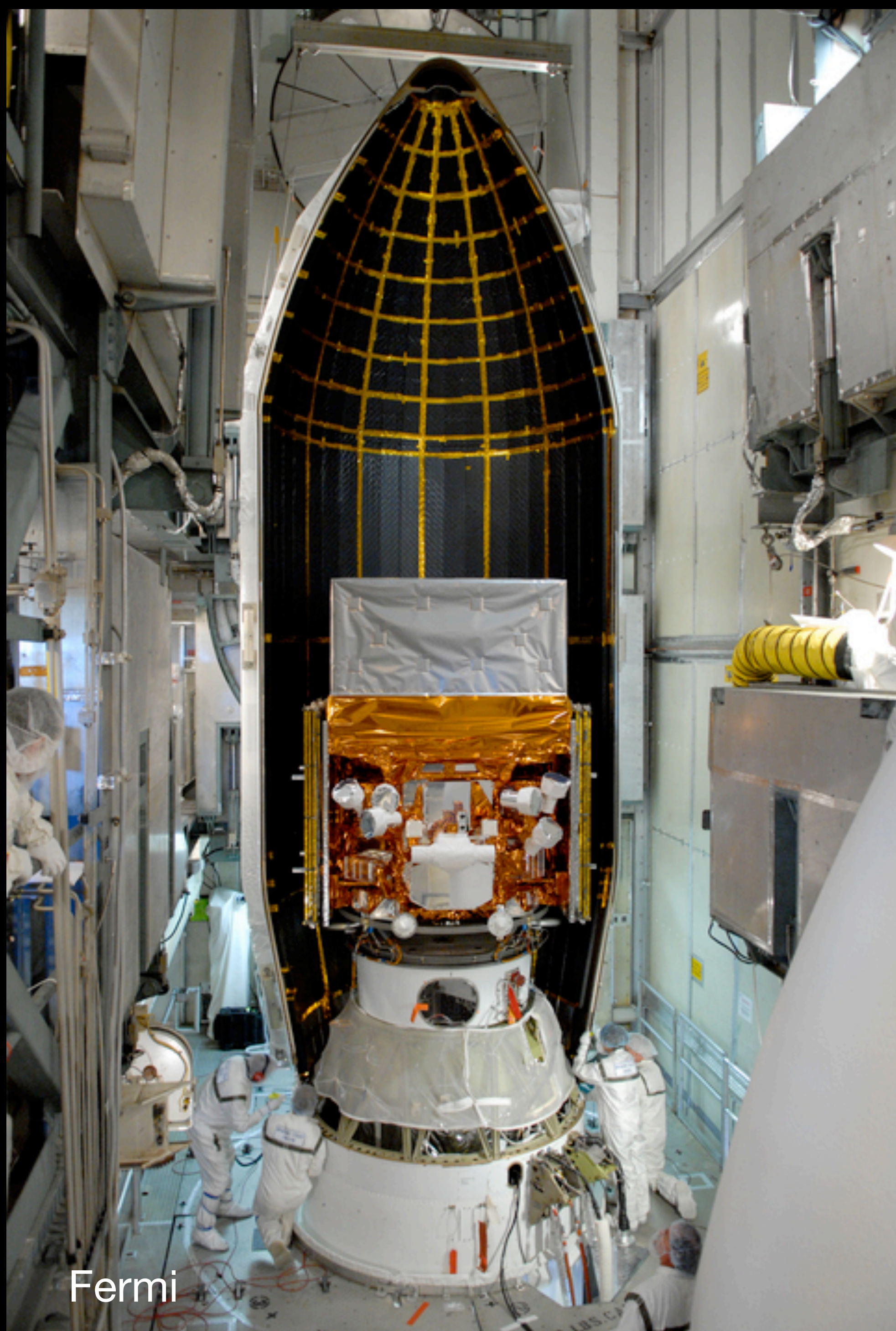
2004+ **breakthrough**

- new Cherenkov arrays detect VHE emission from several binaries

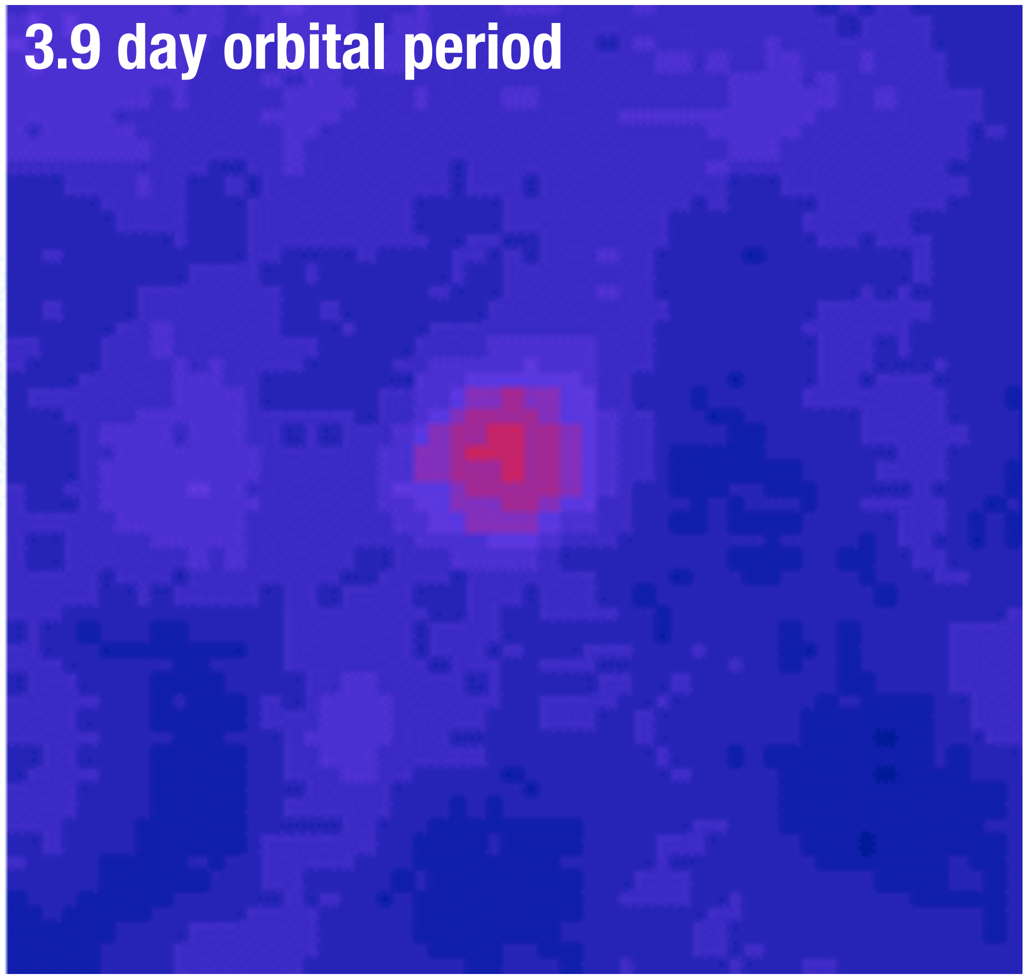
New generation of observatories

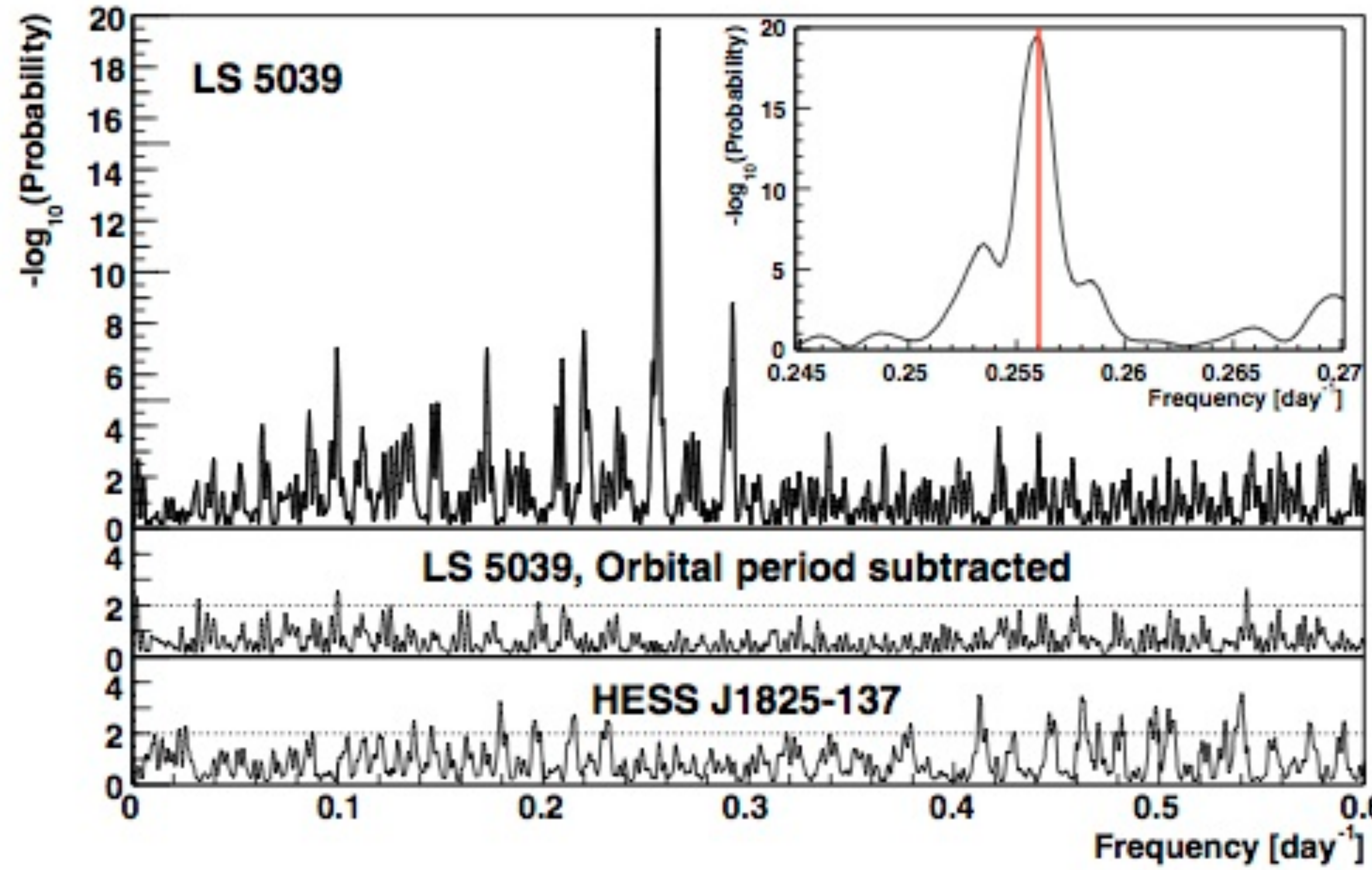
radio	mm	IR		UV	X-rays	γ	γ HE	γ VHE

γ HE	γ VHE
Fermi	HESS
Agile	MAGIC
	VERITAS



Identifying binaries: LS 5039

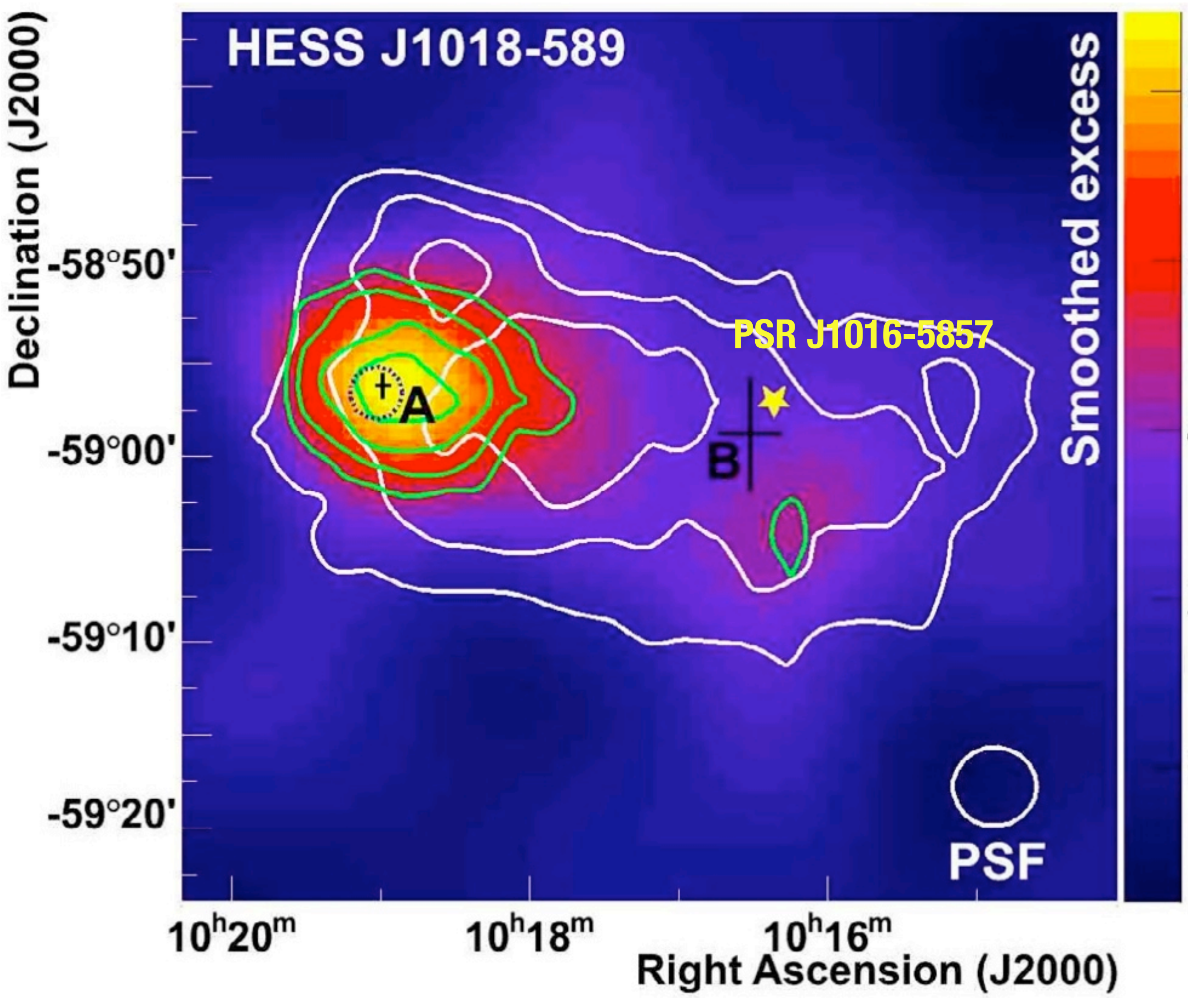


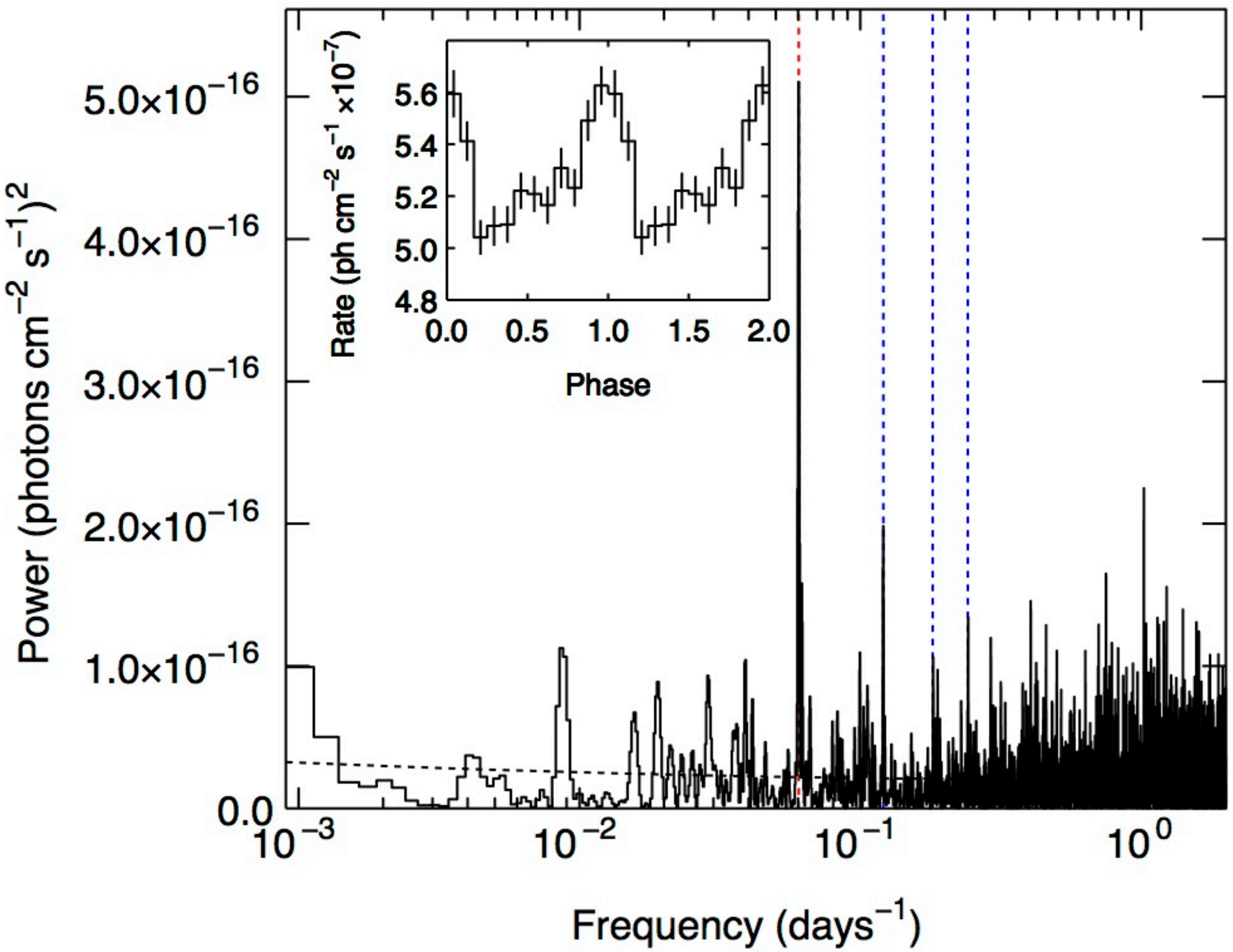


Aharonian et al. (HESS) 2006, A&A

Point source: position to within 30”
VHE orbital modulation fully confirms association.

Identifying binaries: 1FGL 1018





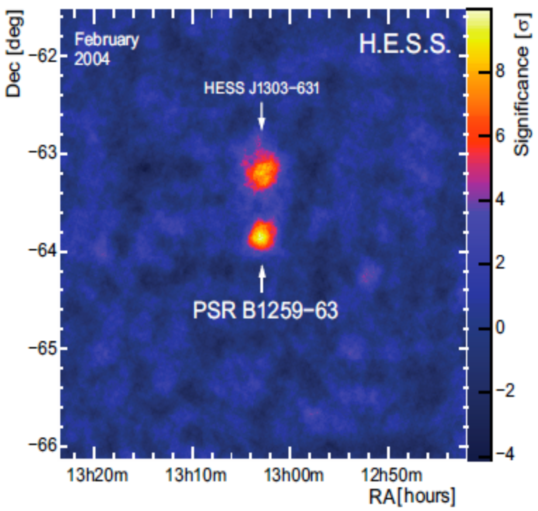
Abramowski et al. (HESS) 2012, A&A

Ackermann et al. (Fermi) 2012, Science

observations of gamma-ray binaries: emergence of a new class at TeV

Gamma-ray binaries discovery

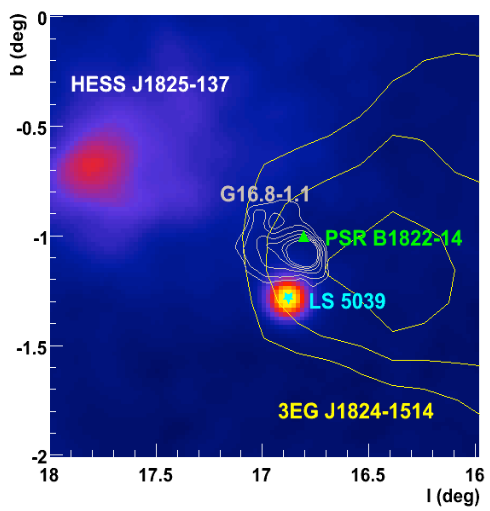
2004



PSR B1259-63

Johnston et al. 1992

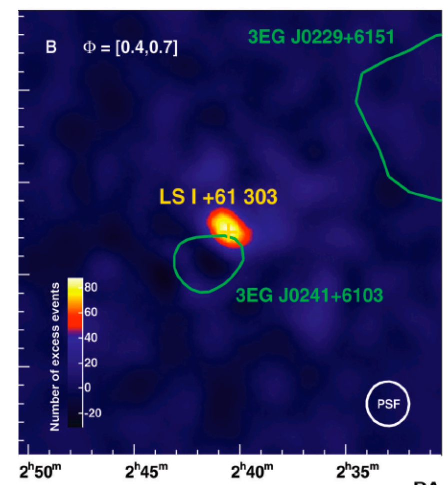
2005



LS 5039

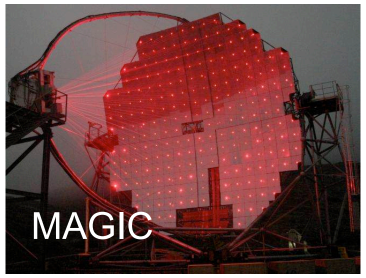
Motch et al. 1997

2006

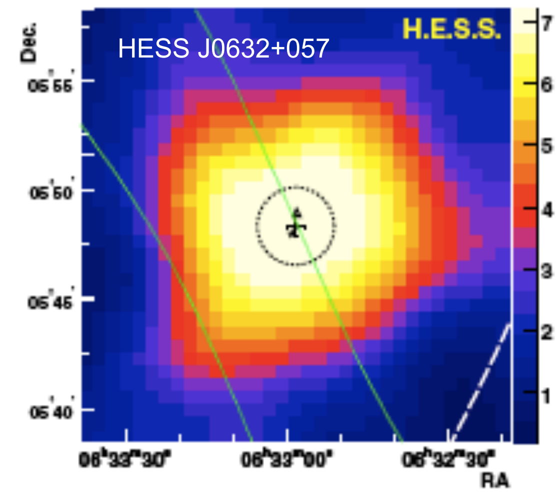


LS I+61 303

Hermsen et al. 1977

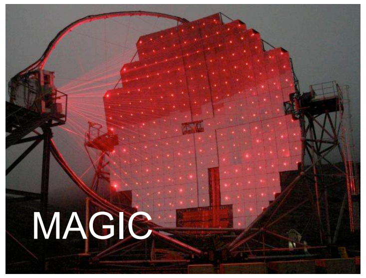


2008

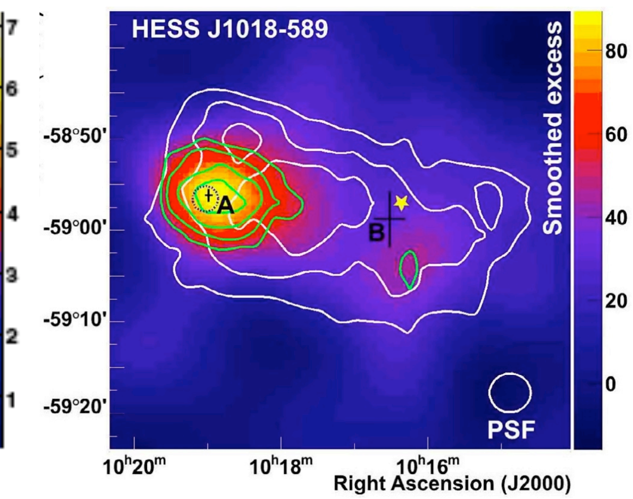


HESS J0632+057

Aharonian et al. 2008



2012

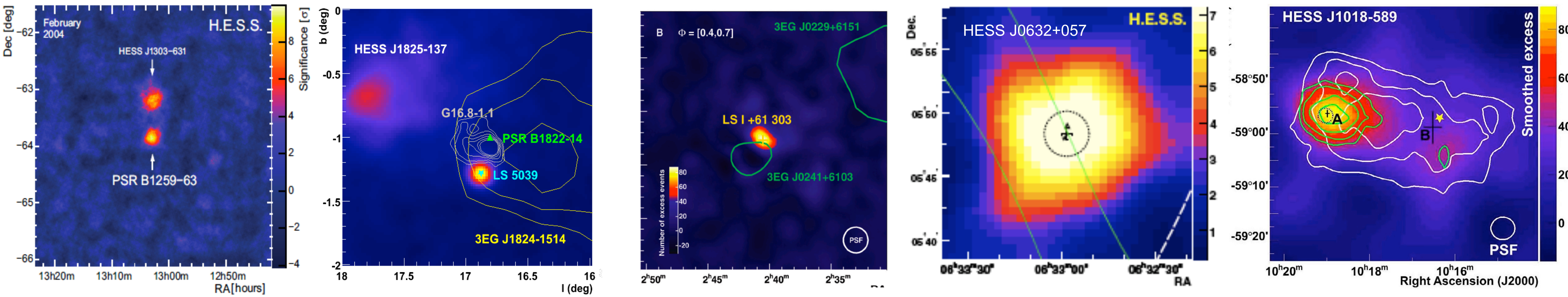


1FGL J1018.6-5856

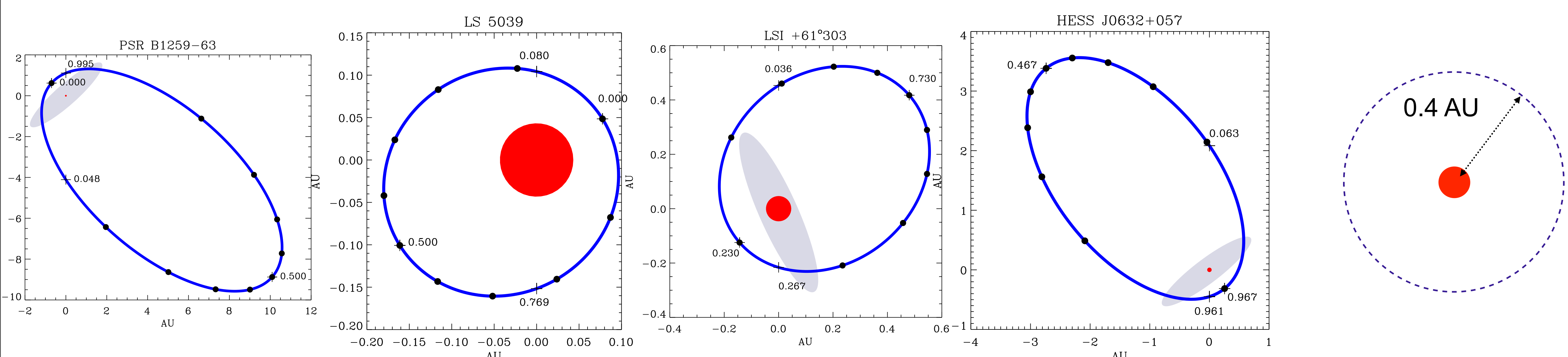
Abdo et al. 2012

Gamma-ray binaries optical

2004 2005 2006 2008 2012



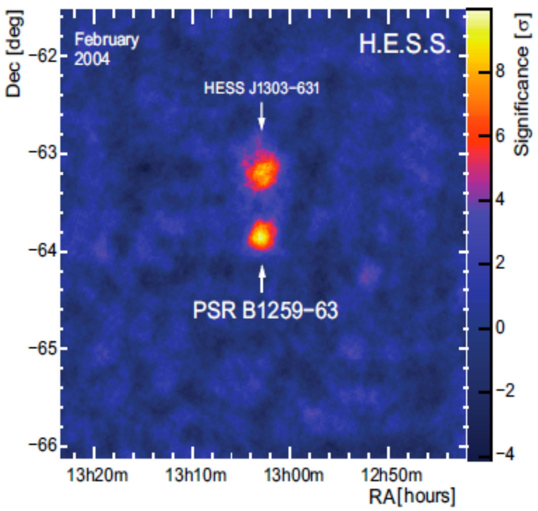
PSR B1259-63 LS 5039 LS I+61 303 HESS J0632+057 1FGL J1018.6-5856



Massive star (O,Be) in eccentric orbit around compact object (pulsar ?)

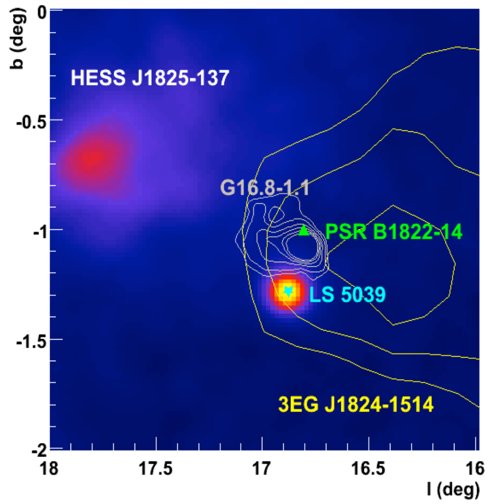
Gamma-ray binaries TeV

2004



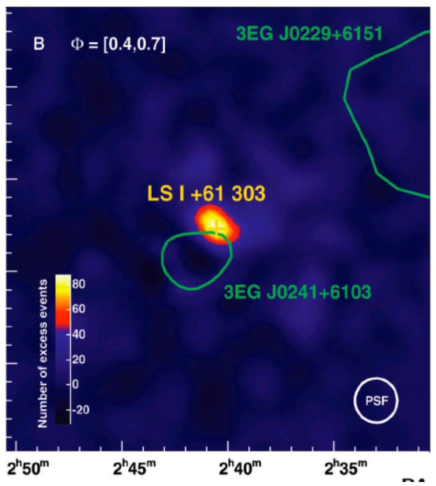
PSR B1259-63

2005



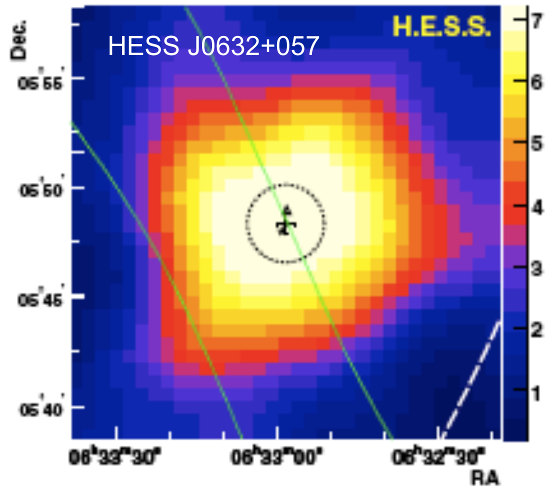
LS 5039

2006



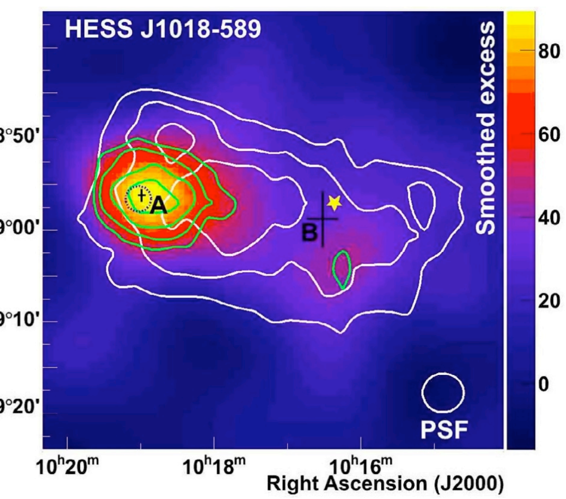
LS I+61 303

2008

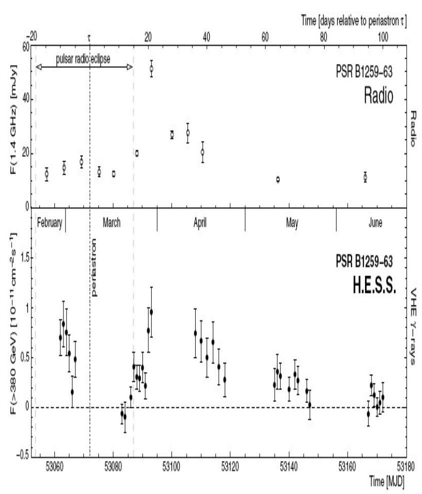


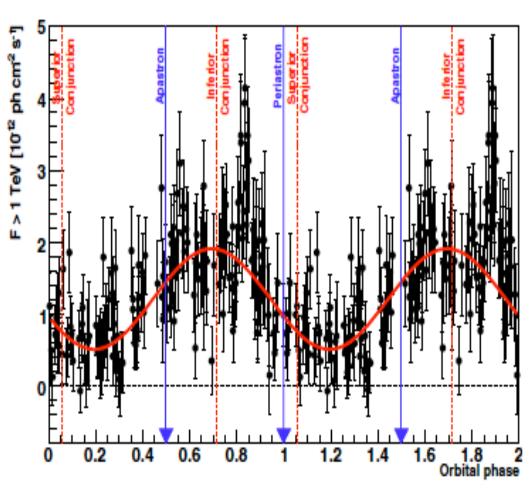
HESS J0632+057

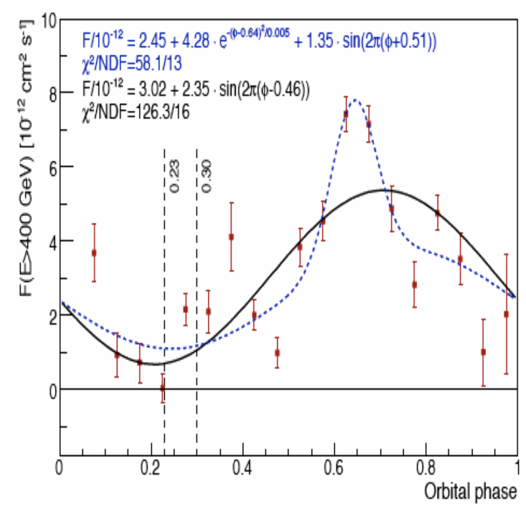
2012

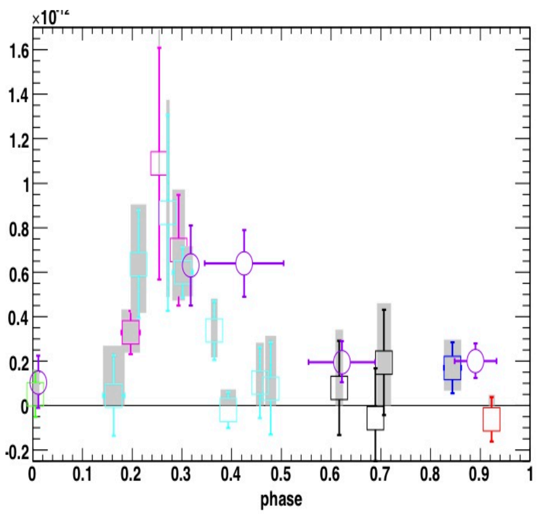


1FGL J1018.6-5856









NEW

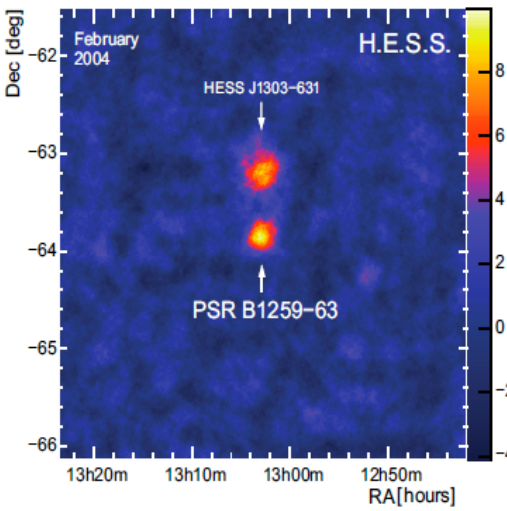
modulated @ TeV

All have TeV variability tied to orbital period

[Cyg X-1 in 2007]

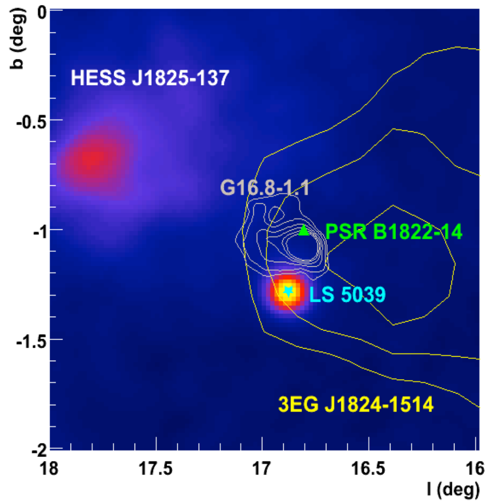
Gamma-ray binaries GeV

2004



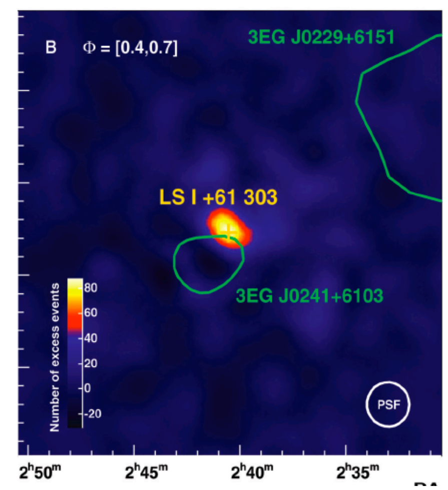
PSR B1259-63

2005



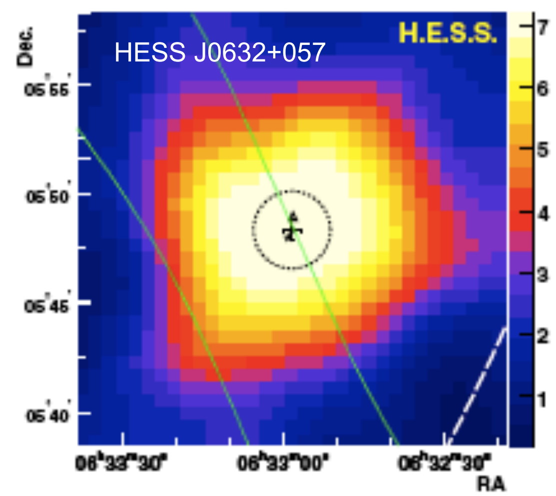
LS 5039

2006



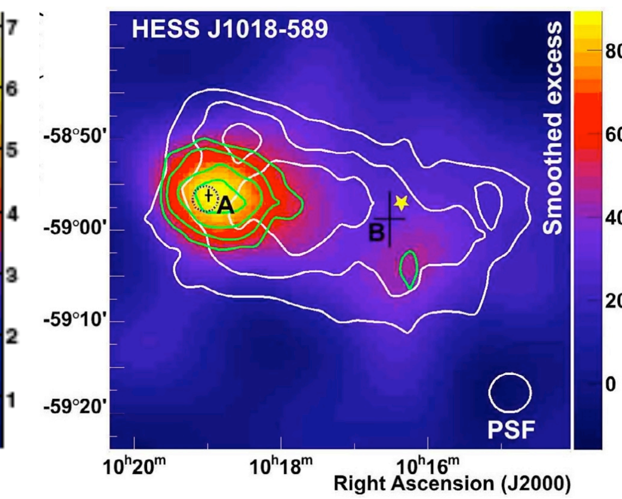
LS I+61 303

2008

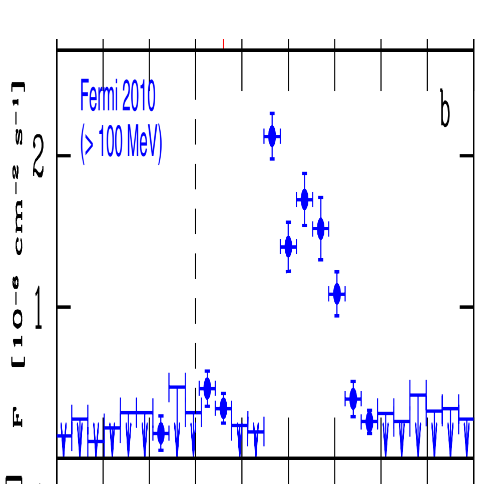


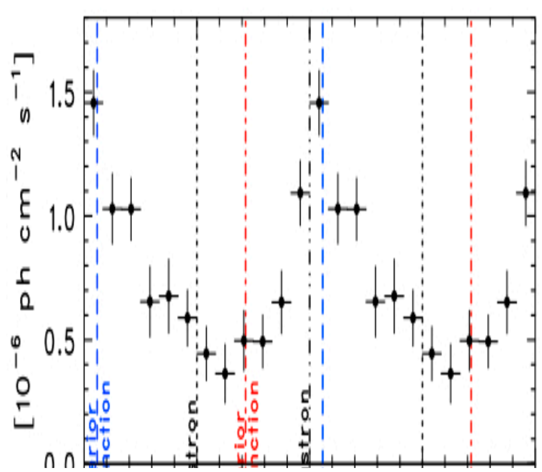
HESS J0632+057

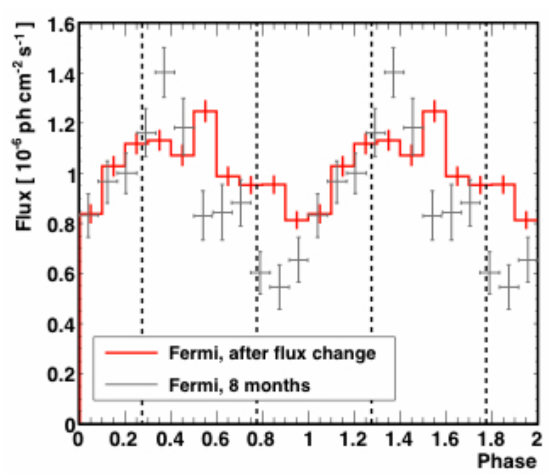
2012



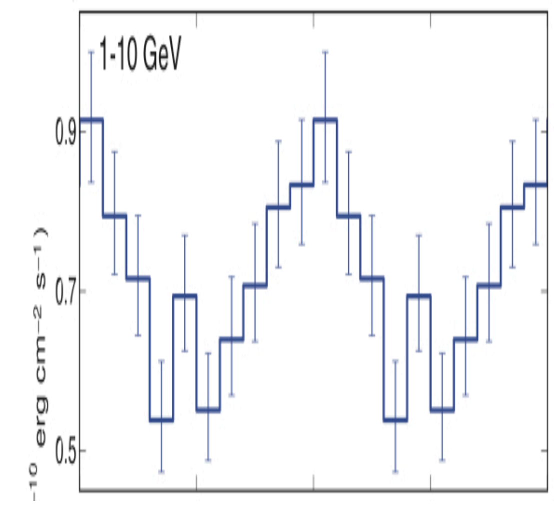
1FGL J1018.6-5856







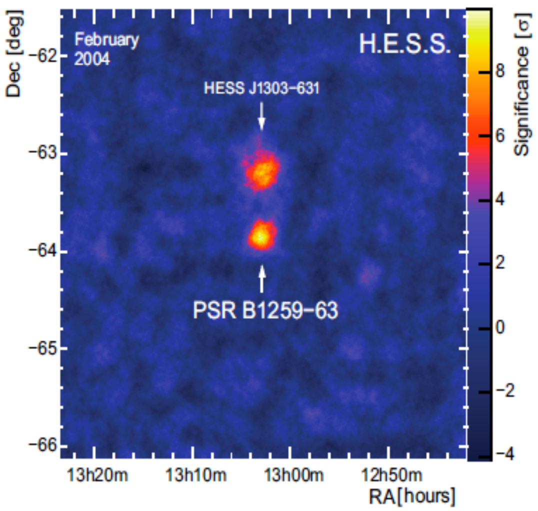
not detected



GeV variability tied to orbital period

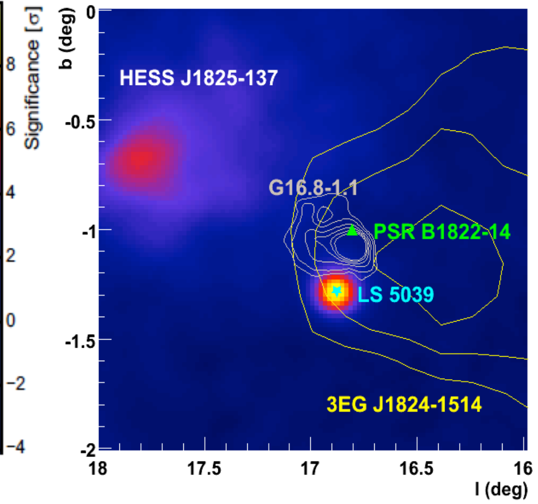
Gamma-ray binaries X-ray

2004



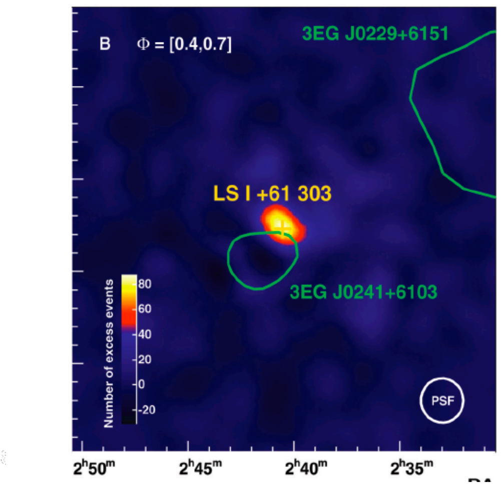
PSR B1259-63

2005



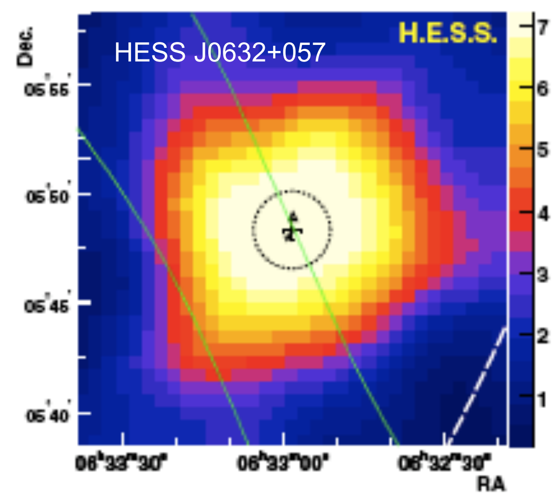
LS 5039

2006



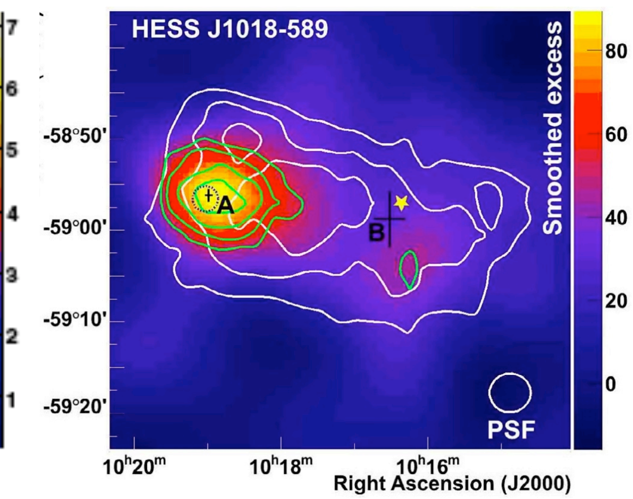
LS I+61 303

2008

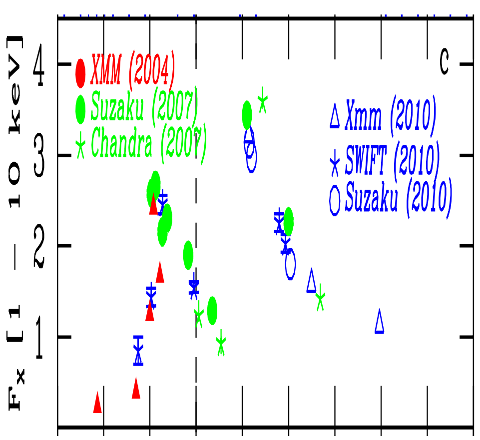


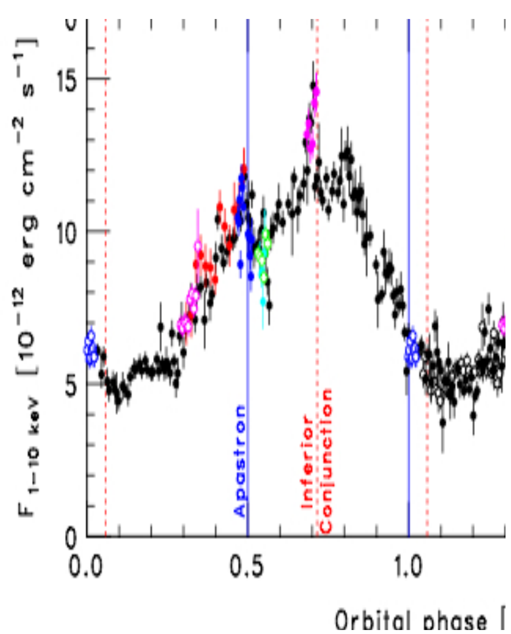
HESS J0632+057

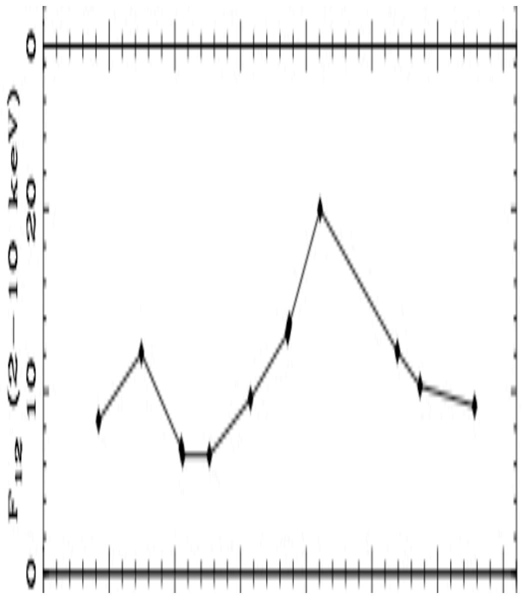
2012

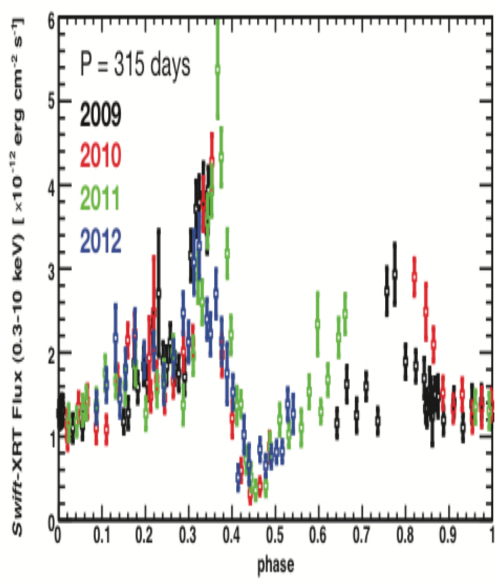


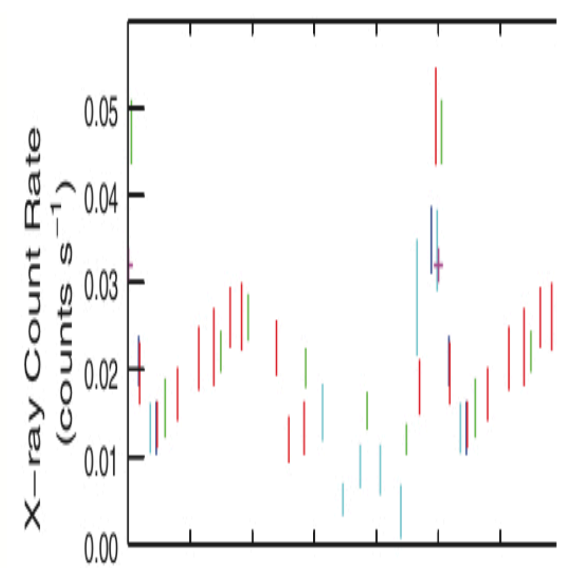
1FGL J1018.6-5856









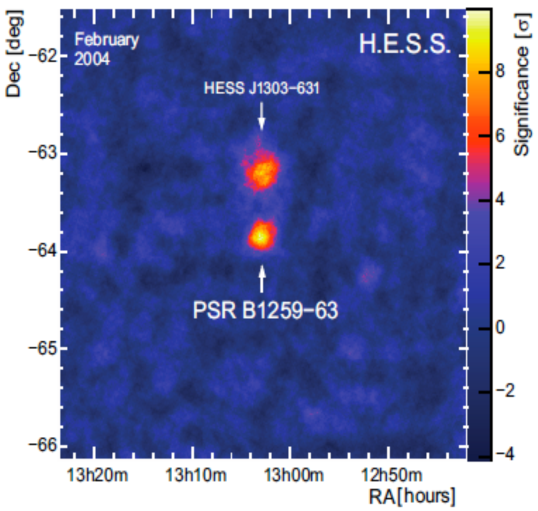


X-ray variability tied to orbital period (NEW **MeV also: LS 5039)**

Collmar et al. 2014

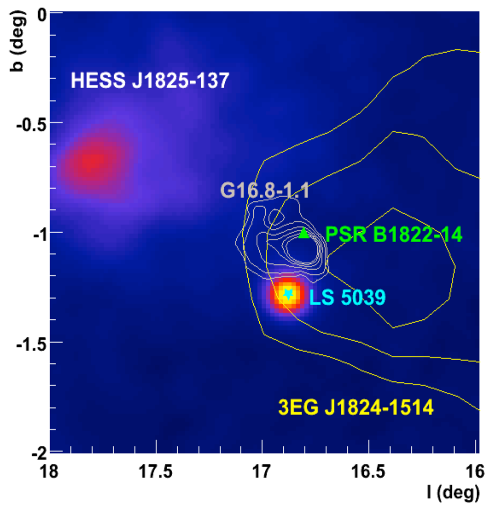
Gamma-ray binaries radio

2004



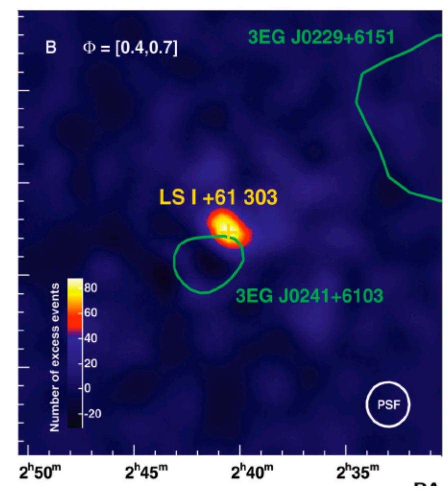
PSR B1259-63

2005



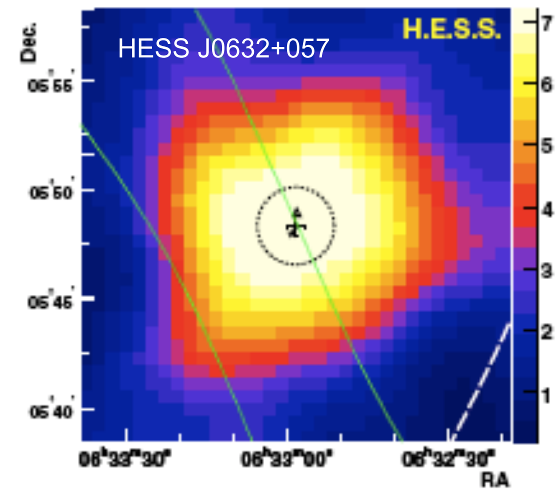
LS 5039

2006



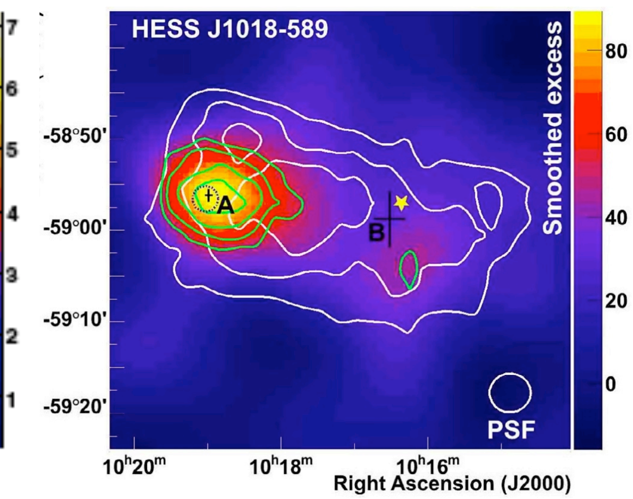
LS I+61 303

2008

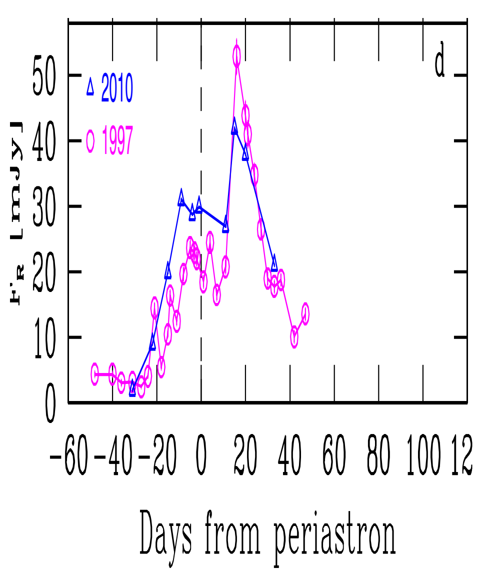


HESS J0632+057

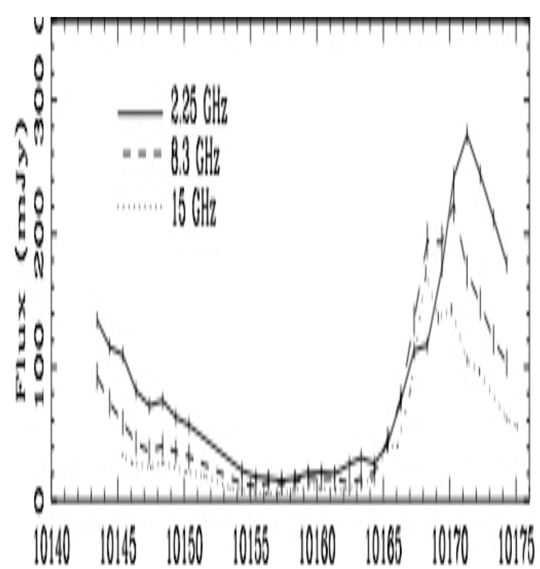
2012



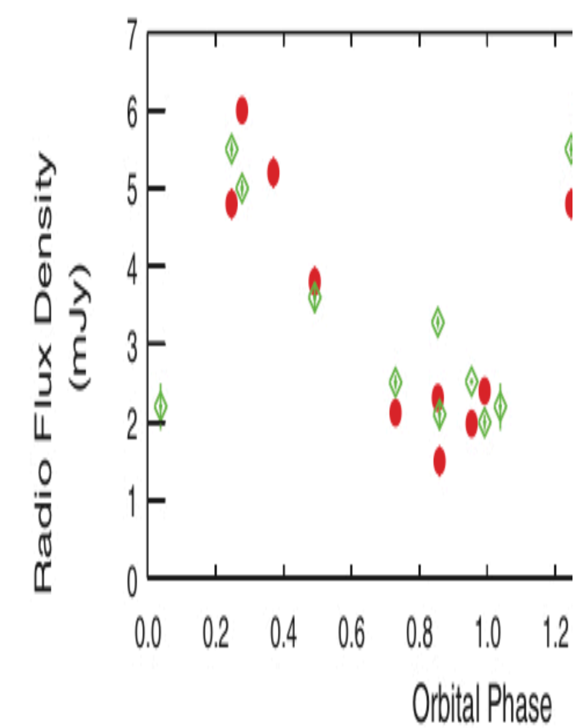
1FGL J1018.6-5856



~constant radio source



variable radio source



Also radio variability tied to orbital period

Gamma-ray binaries modulations

system			P_{orb}	radio	X-ray	GeV	TeV
PSR B1259-63	psr	Be	1237	90%	95%	100%	>75%
LS 5039	?	O	3.9	<30%	40%	60%	70%
LS I +61 303	?	Be	26.5	90%	70%	40%	>70%
HESS J0632+057	?	Be	320	<50%	85%		>50%
1FGL J1018.6-5856	?	O	16.6	60%	65%	20%	NEW

source detected

source detected + orbital variability

Gamma-ray binaries luminosities

	PSR B1259-63	LS 5039	LS I +61°303	HESS J0632+057	1FGL J1018.6-5856
norm @1 TeV (10^{-12} ph cm^{-2} s^{-1} TeV^{-1})	<0.4–2.9	0.5-3	<0.5–5	<0.3–1.2	0.1-0.9
Γ_{VHE}	2.7	1.8_{cut}–3.1	2.6	2.5	2.4
L_{VHE} (10^{35} erg s^{-1})	0.09	0.14	0.13	0.02	0.09
F_{HE}(> 0.1 GeV) (10^{-7} ph cm^{-2} s^{-1})	<0.09–35	4–15	6–14	<0.3	5.0-5.6
Γ_{HE}	1.4_{var}	2.1	2.1	(2.9)	1.9_{var}
E_{cut} (GeV)	0.3	2.2	3.9	-	2.5
L_{HE} (10^{35} erg s^{-1})	2.8	2.8	2.3	<0.03	9.7
F_X(1-10 keV) (10^{-12} erg s^{-1}cm^{-2})	1–37	5–12	5–30	0.3–4.1	0.5–5
Γ_X	1.2–2.0	1.4–1.6	1.5–1.9	1.2–1.7	1.3–1.7
L_X (10^{35} erg s^{-1})	0.23	0.12	0.14	0.01	0.17
F_{radio}(2 GHz) (mJy)	2–50	30	20–300	0.2–0.7	1.5–6
L_{radio} (10^{29} erg s^{-1})	6.3	6.0	28.7	0.04	4.2

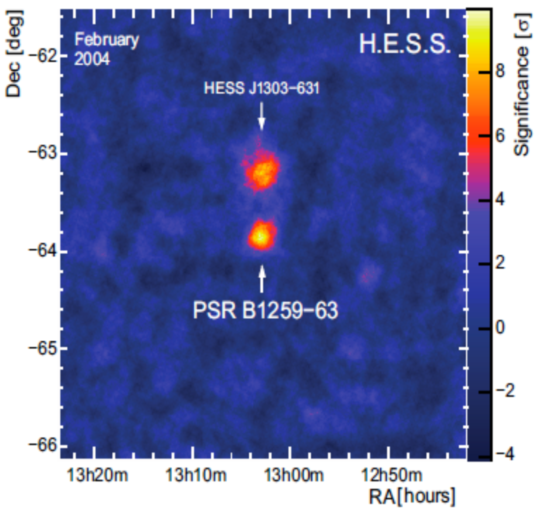
VHE luminosity above 100 GeV, HE luminosity from 0.1–10 GeV, derived from the values in the text & distances from Tab. 1
X-ray flux modulation and (peak) luminosity in the 1–10 keV range, radio flux and (peak) luminosity at ≈ 2 GHz.
The HE spectra marked $_{var}$ show more complex variability with orbital phase than is summarised here.

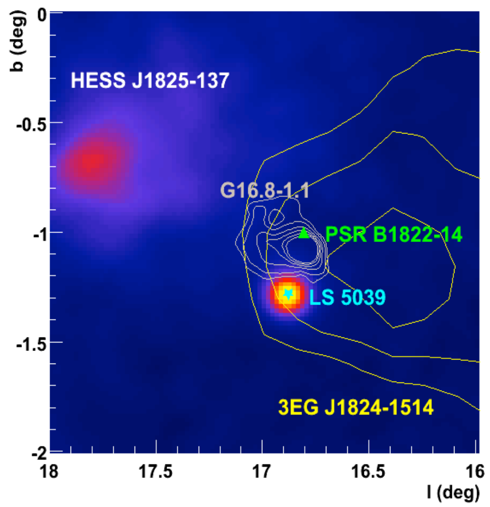
Dubus 2013 A&ARv

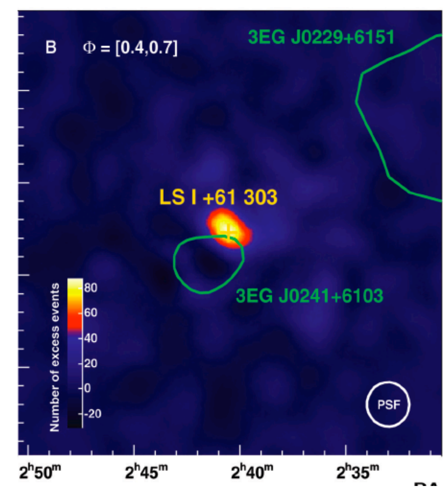
L_{HE}~10 L_{VHE} (except HESS J0632)
hard X-ray spectra with L_X~L_{VHE}

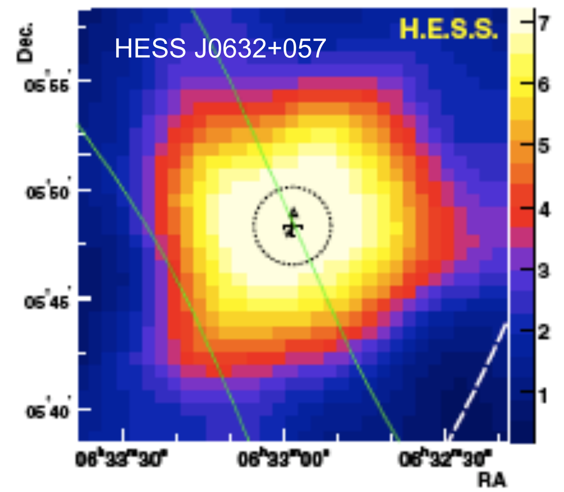
Gamma-ray binaries SED

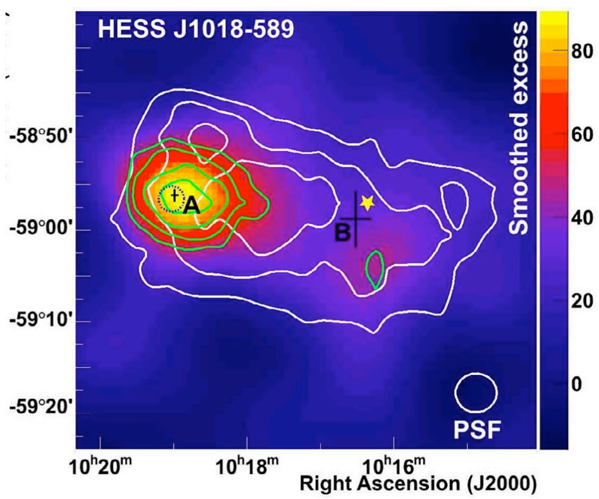
2004	2005	2006	2008	2012



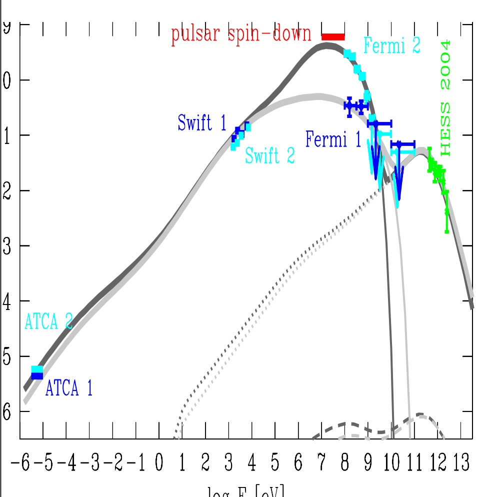


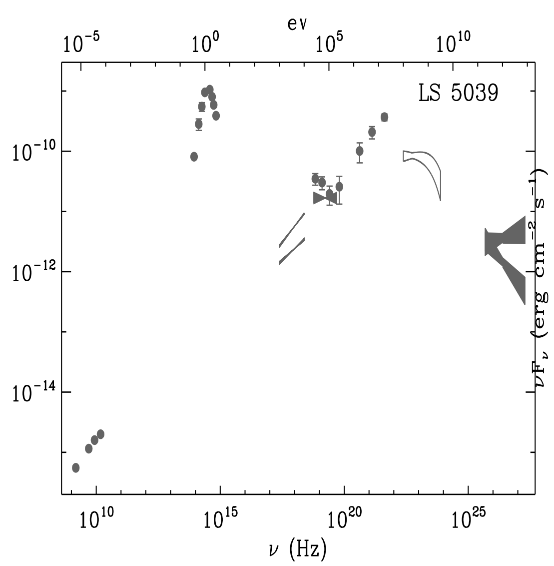


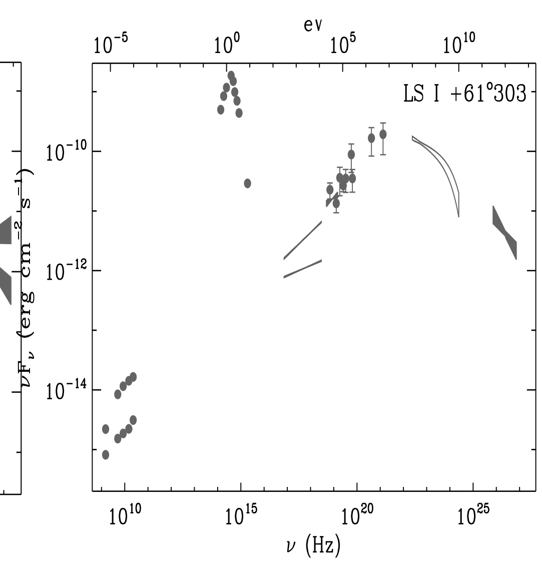


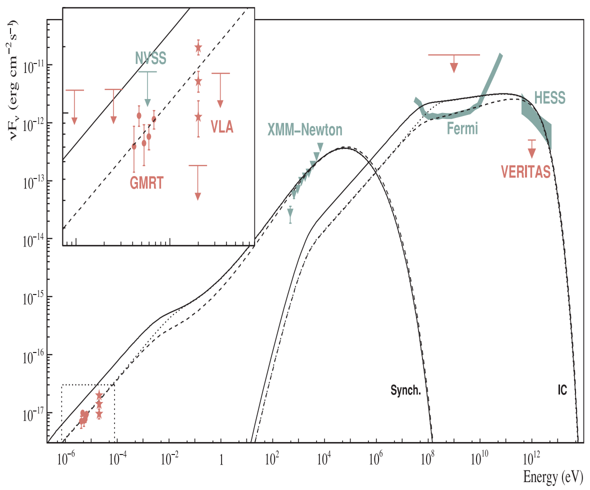


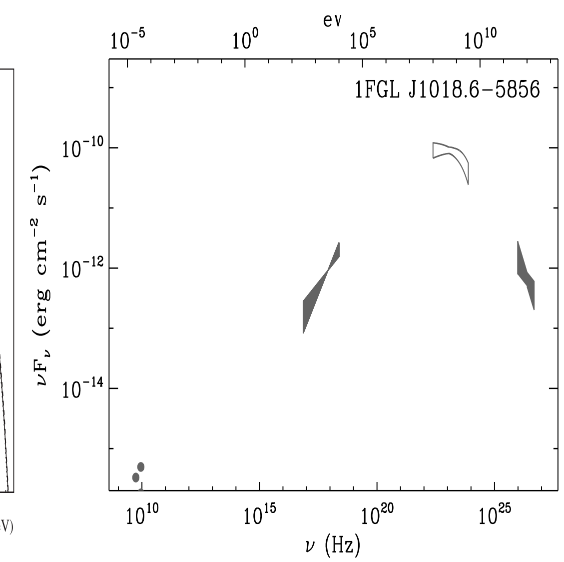
PSR B1259-63	LS 5039	LS I+61 303	HESS J0632+057	1FGL J1018.6-5856







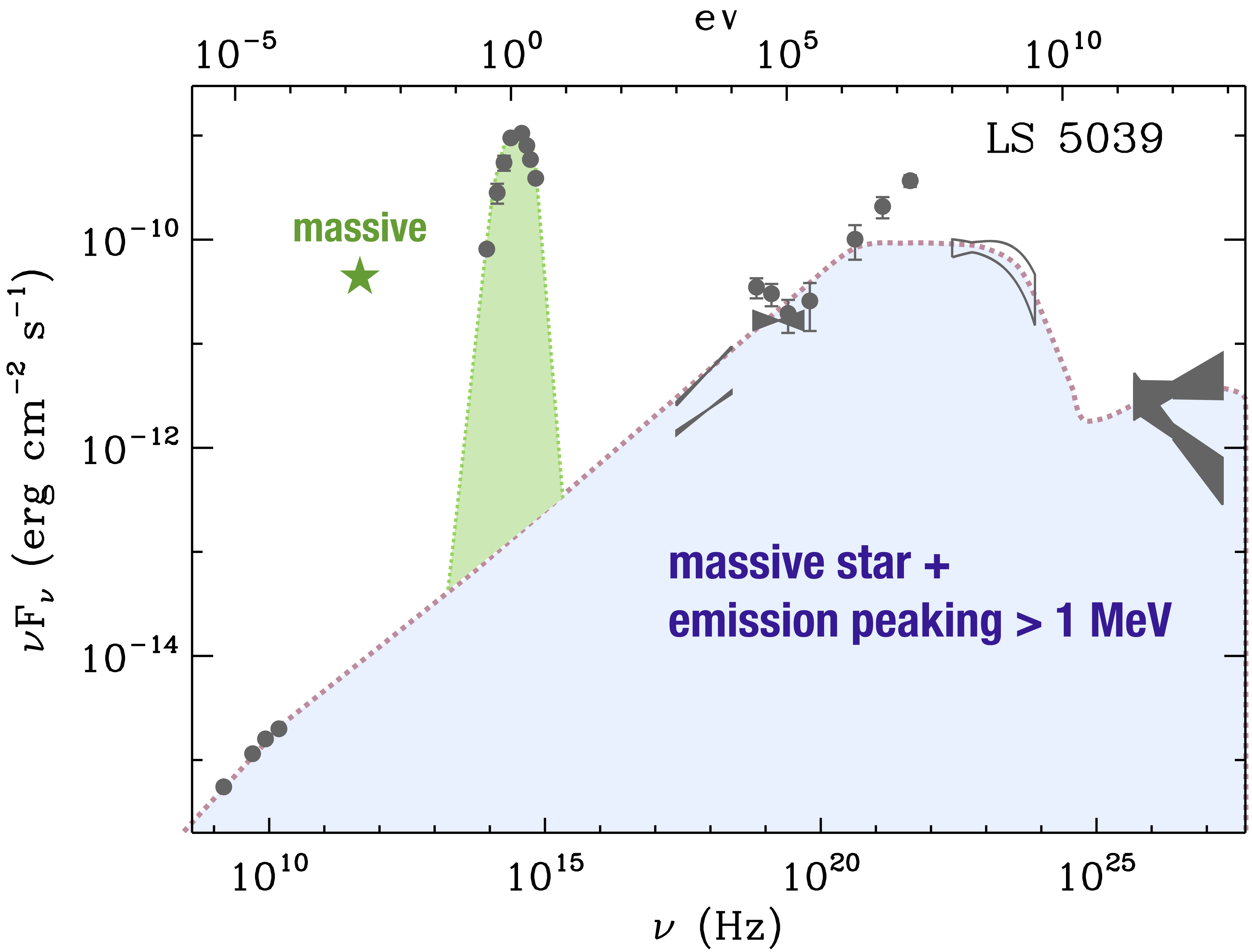




similar spectral energy distributions peaking > 1 MeV

Gamma-ray binaries definition

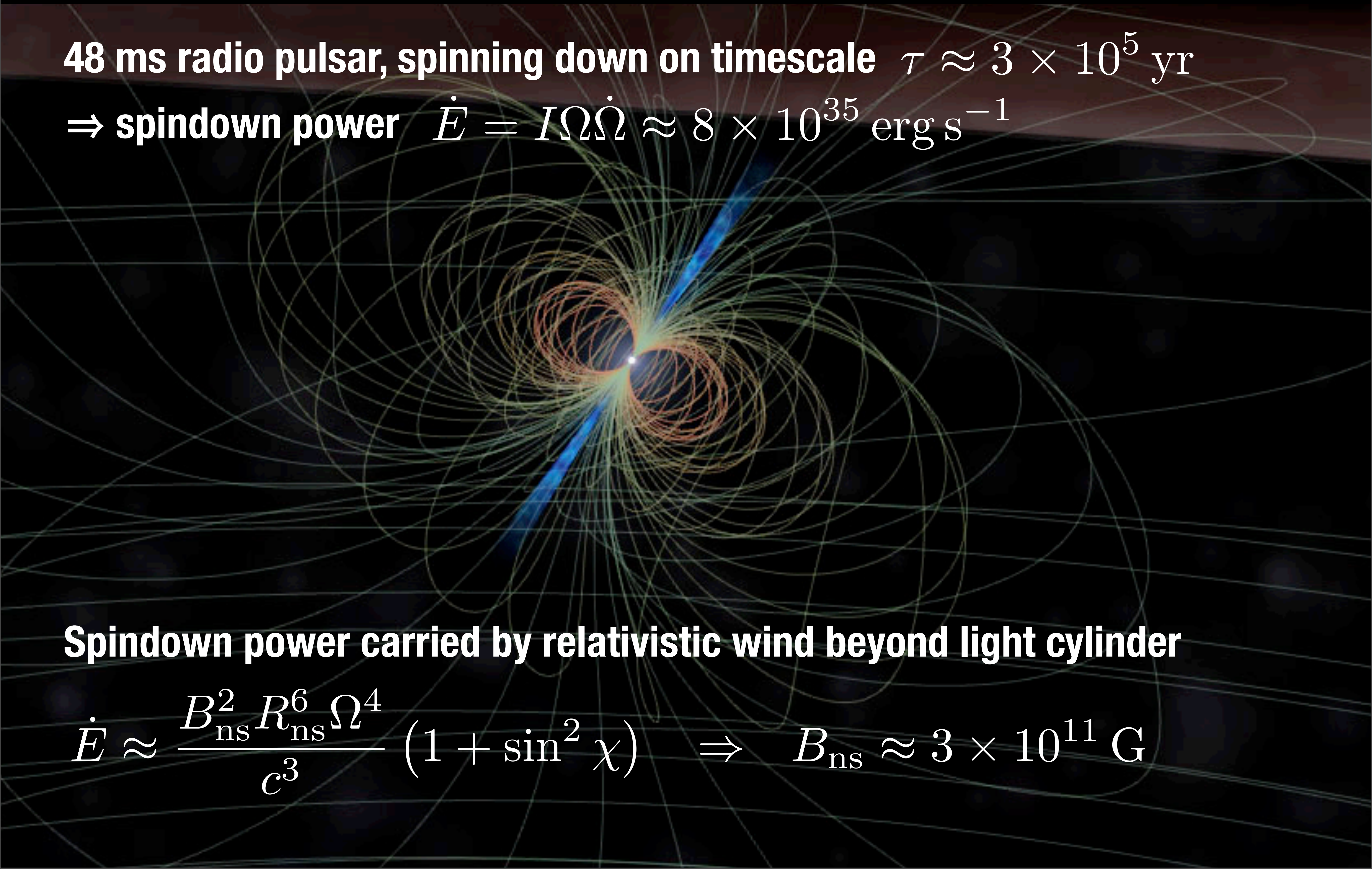
some confusion in the litterature



5 known systems incl. one with pulsar → a common scenario ?

What powers gamma-ray binaries ?

PSR B1259-63



48 ms radio pulsar, spinning down on timescale $\tau \approx 3 \times 10^5\,\mathrm{yr}$

⇒ spindown power $\dot{E} = I\Omega\dot{\Omega} \approx 8 \times 10^{35}\,\mathrm{erg\,s^{-1}}$

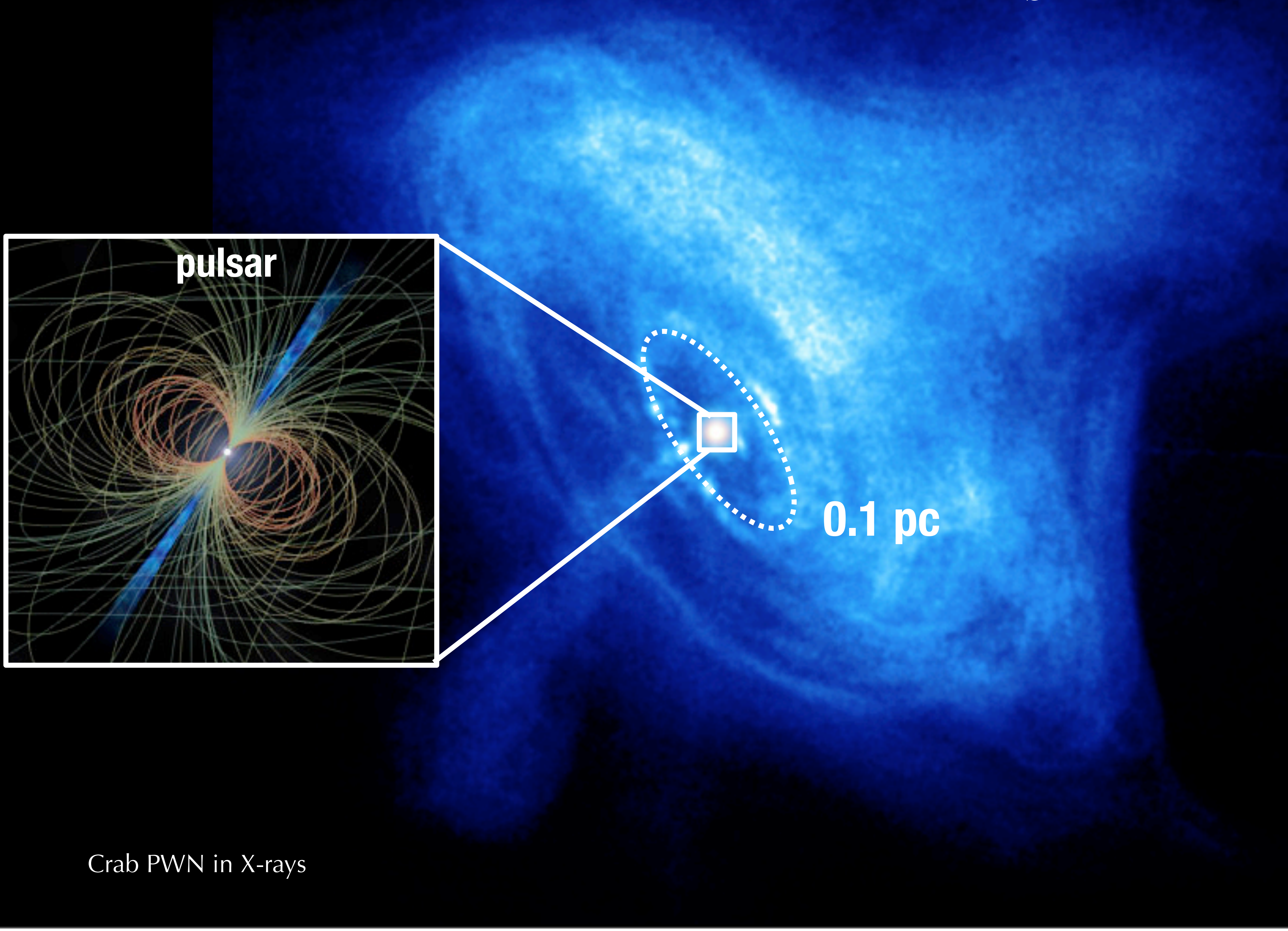
Spindown power carried by relativistic wind beyond light cylinder

$$\dot{E} \approx \frac{B_{\mathrm{ns}}^2 R_{\mathrm{ns}}^6 \Omega^4}{c^3}\left(1 + \sin^2\chi\right) \quad \Rightarrow \quad B_{\mathrm{ns}} \approx 3 \times 10^{11}\,\mathrm{G}$$

Pulsar Wind Nebula (PWN)

Pulsar wind termination shock

$$p_{\rm pw} = \frac{\dot{E}}{4\pi R_{\rm s}^2 c} = p_{\rm ext}$$

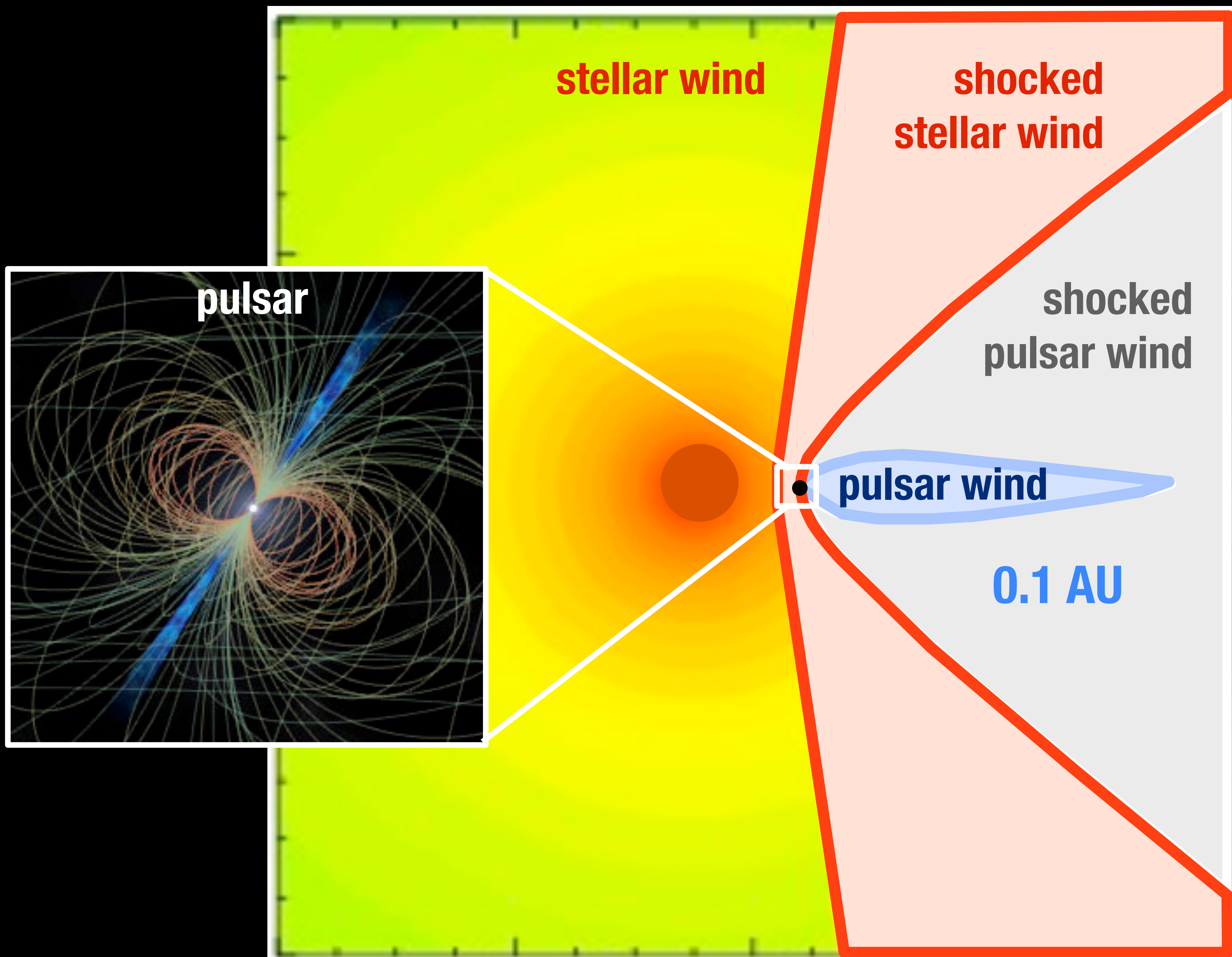


Crab PWN in X-rays

Pulsar wind in a binary

Pulsar wind termination shock

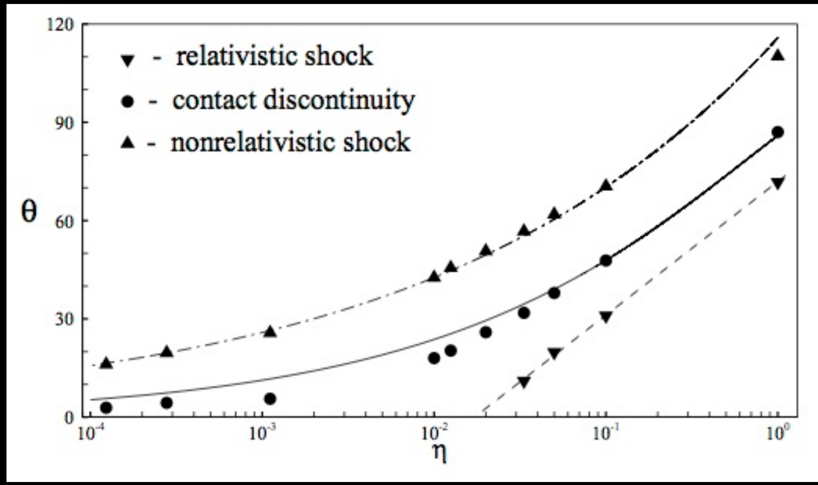
$$p_{\rm pw} = \frac{\dot{E}}{4\pi R_{\rm s}^2 c} = p_{\rm w} = \frac{\dot{M} v_{\rm w}}{4\pi (d - R_{\rm s})^2}$$



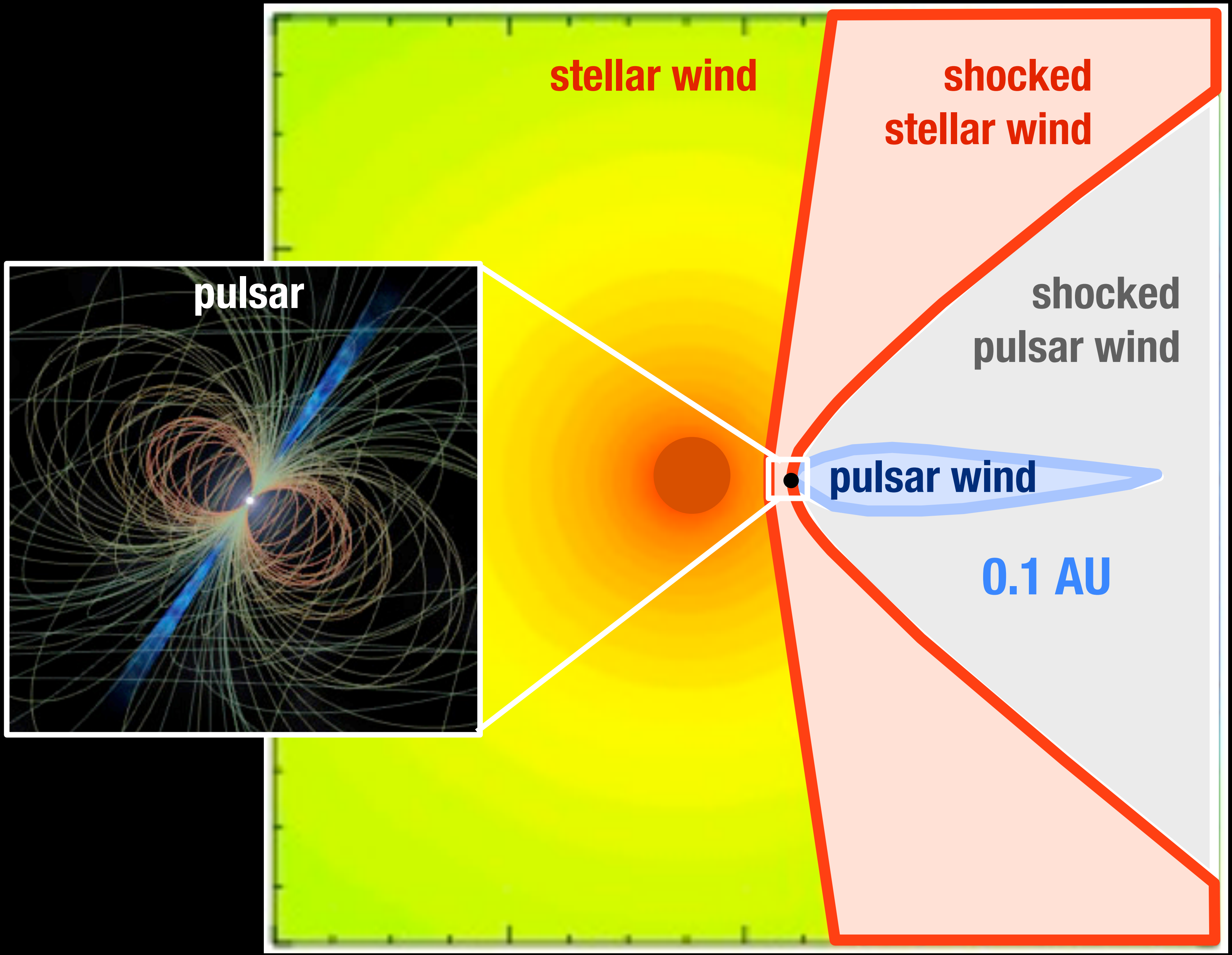
adapted from
Lamberts et al. 2013

Pulsar wind in a binary

Structure set by $$\eta = \frac{\dot{E}/c}{\dot{M} v_{\mathrm{w}}}$$



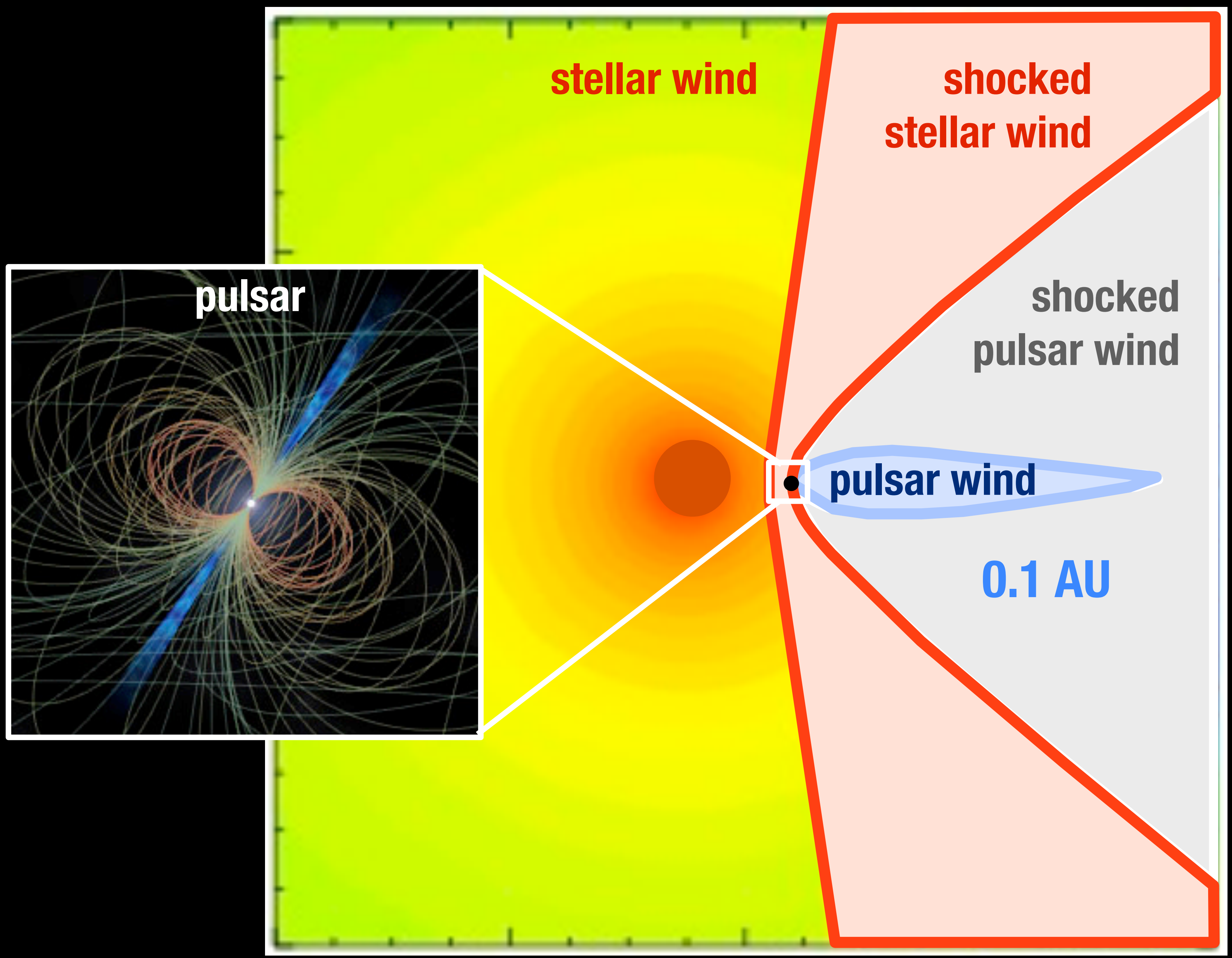
Bogovalov et al. 2008



adapted from Lamberts et al. 2013

Pulsar wind in a binary

Termination shock is much closer to pulsar: from 10^9 to 10^4 R_{LC}

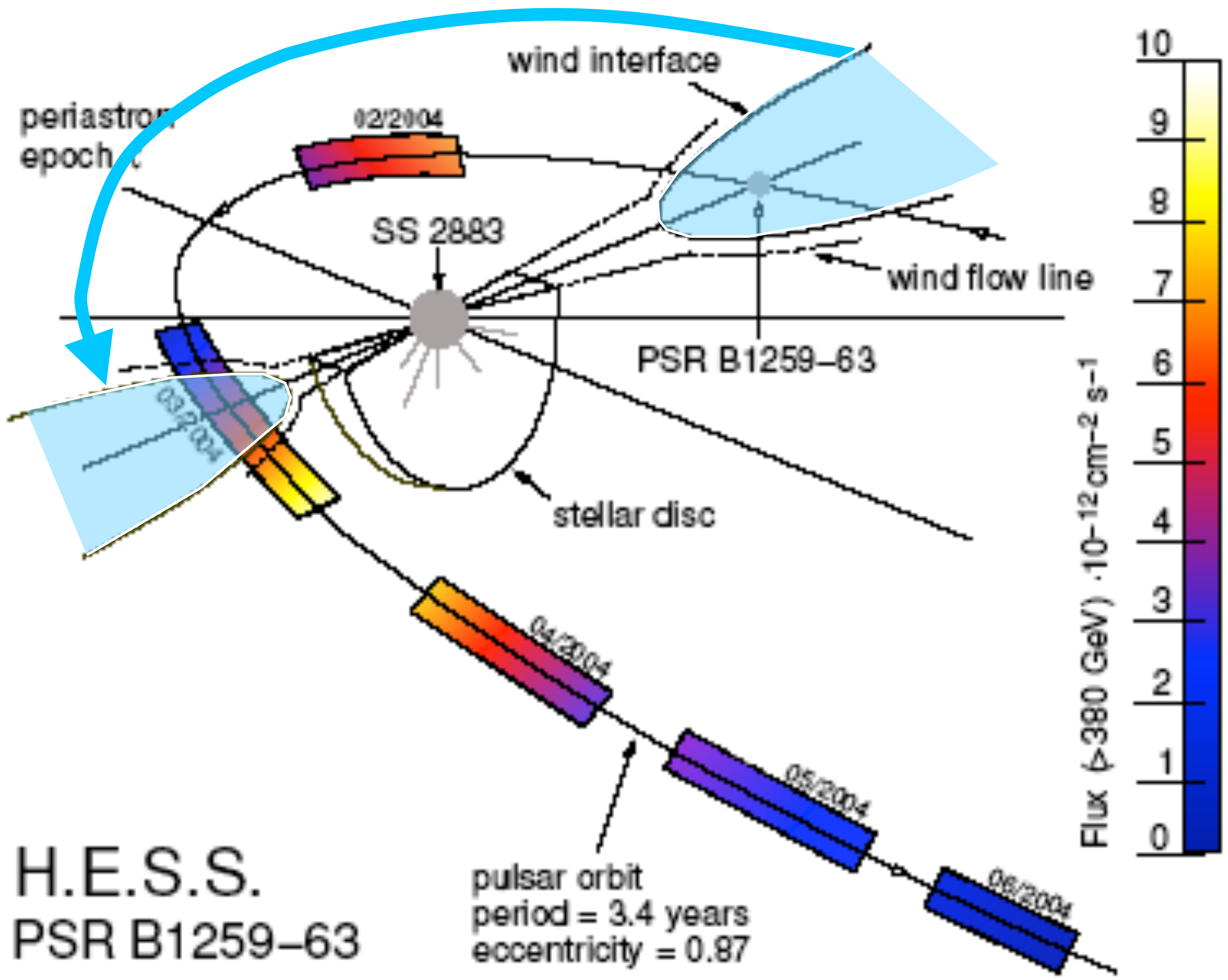


adapted from
Lamberts et al. 2013

PSR B1259-63

non-thermal emission at shock, powered by pulsar spindown

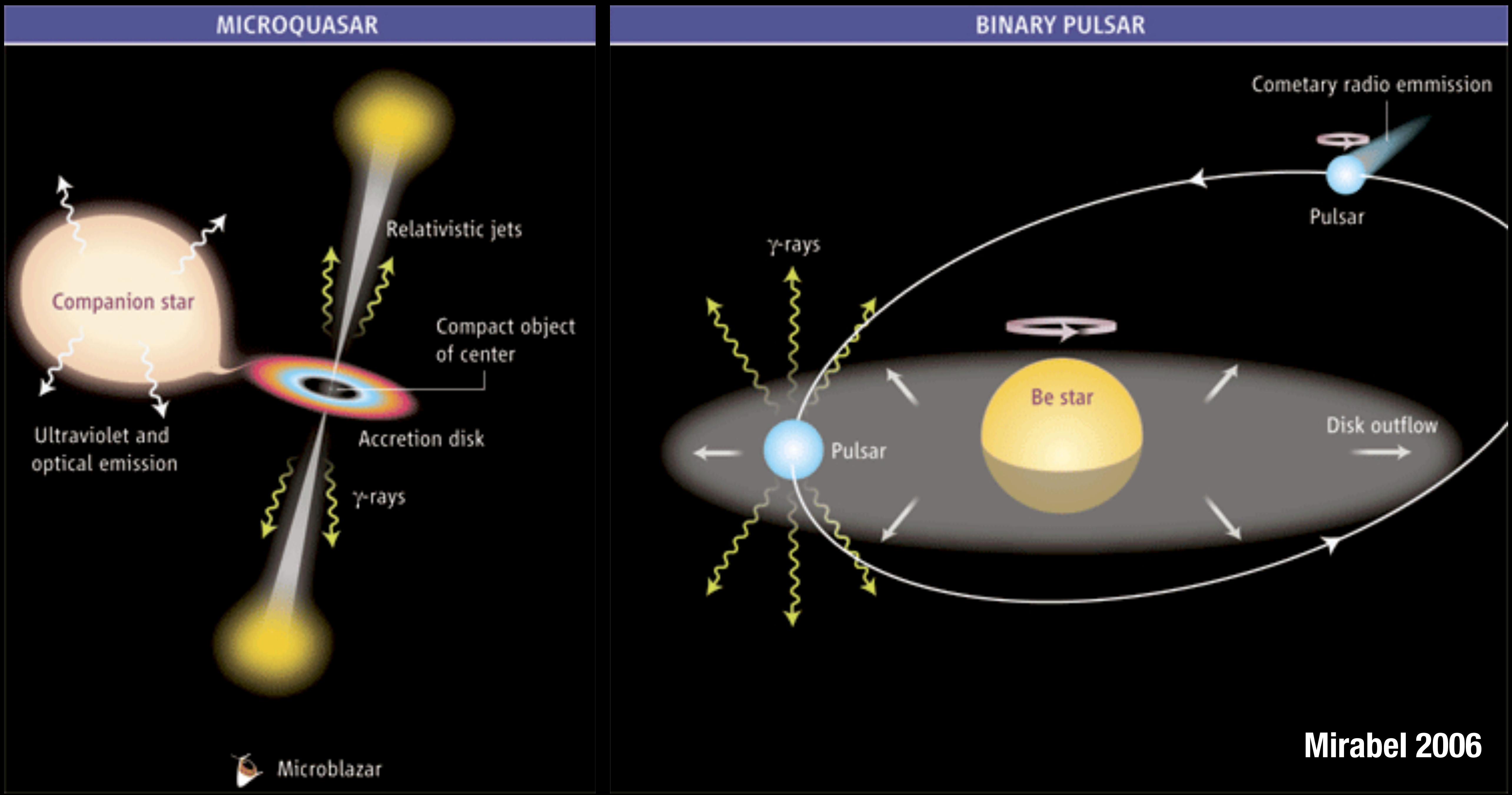
~1% of power emitted in VHE, as in pulsar wind nebulae



Tavani & Arons 1997
Kirk et al. 1999

- **Gamma-ray binaries: young pulsar + massive star like PSR B1259-63 ?**

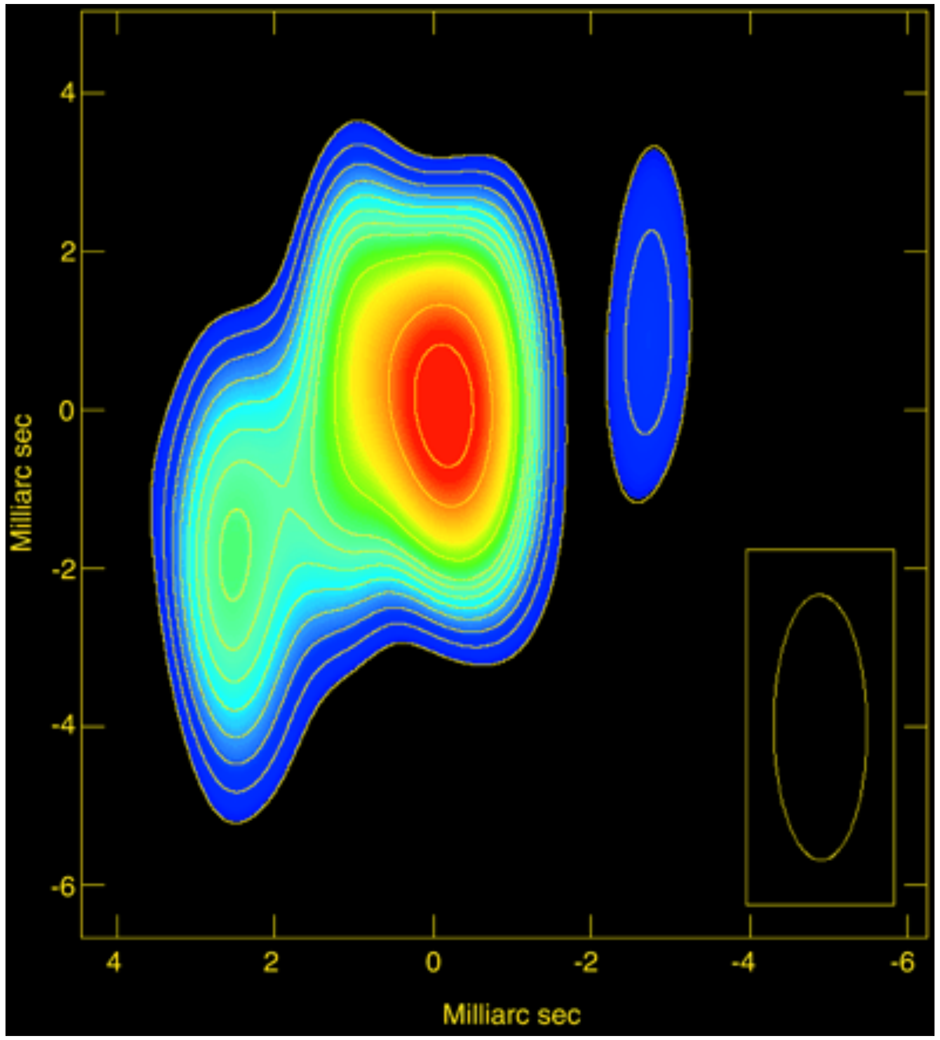
Controversy   microquasars or pulsars ?



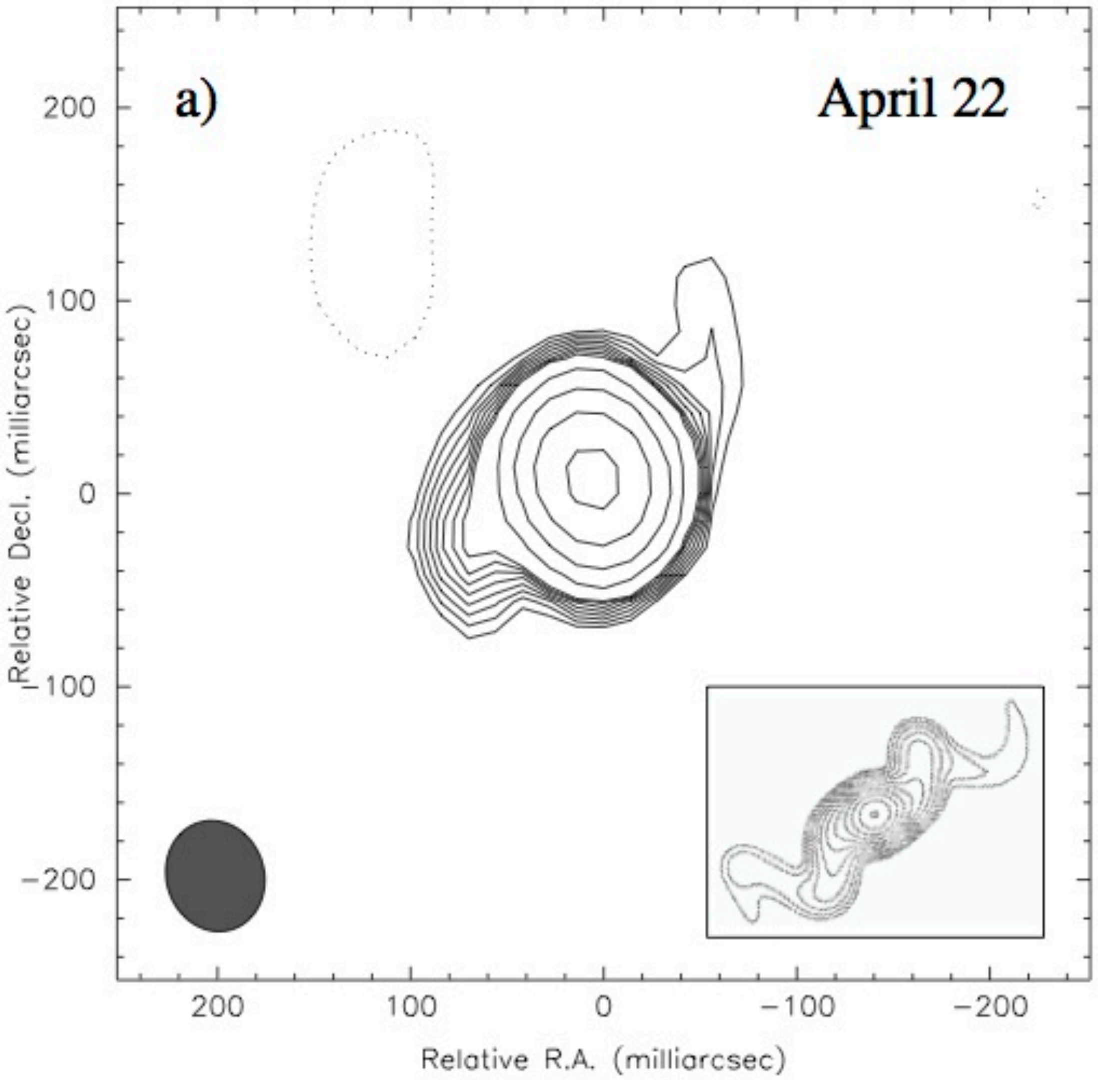
resolved radio emission on milliarcsec scale suggested microquasar jets

Compact radio jets ? (microquasars)

LS 5039



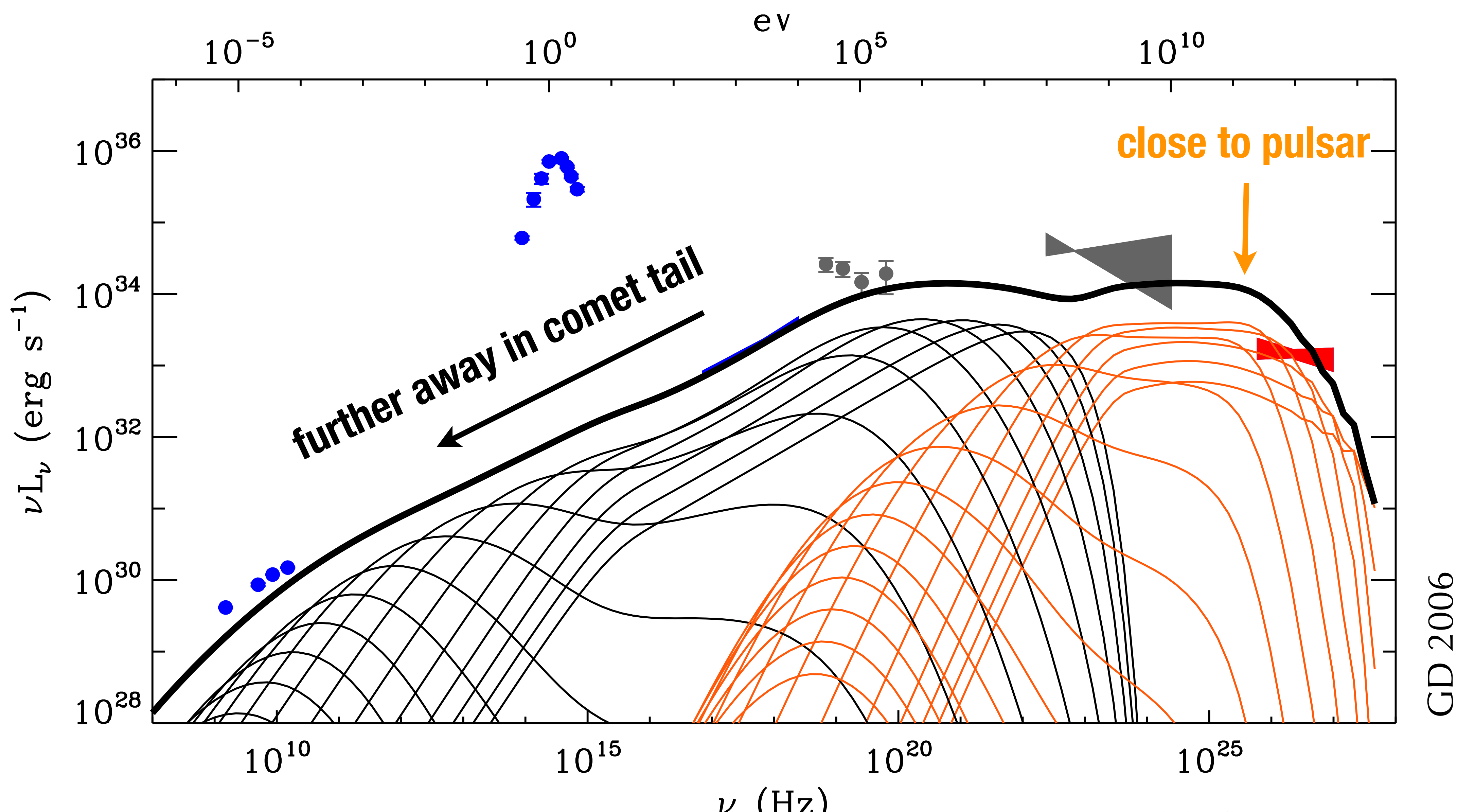
LS I +61º303

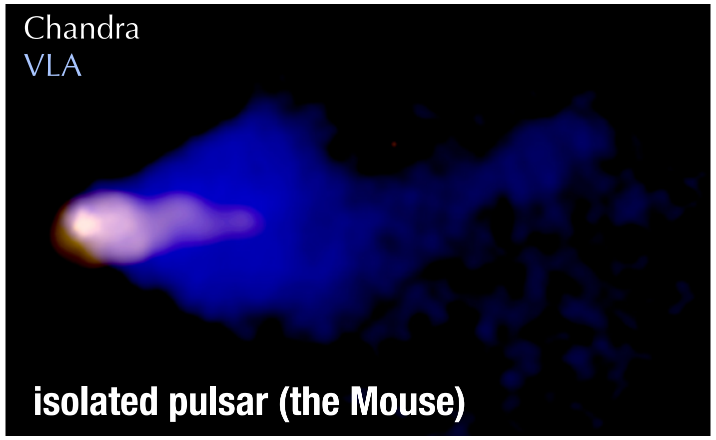


Paredes et al. 2000

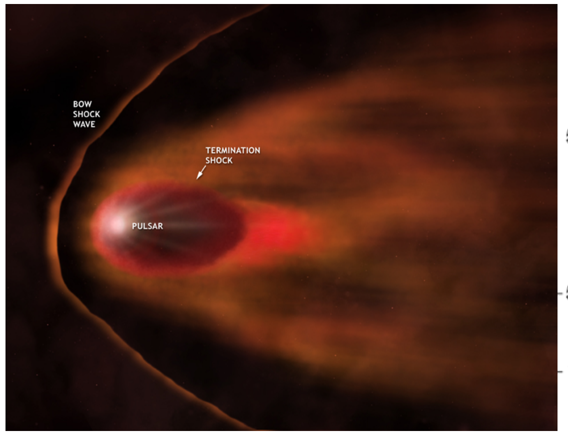
Massi et al. 2004

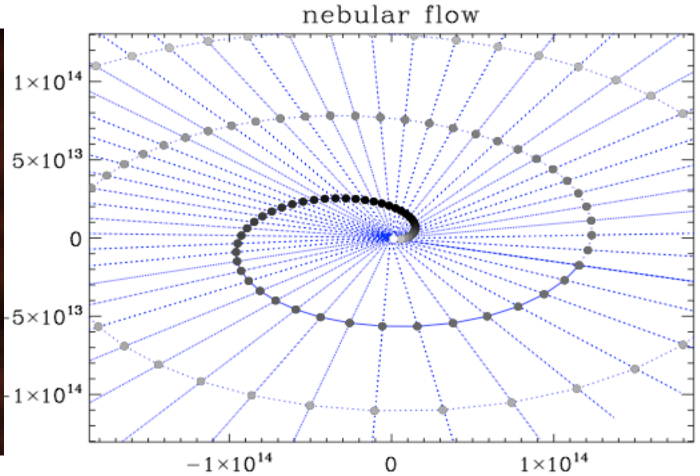
Gamma-ray binaries cometary nebula





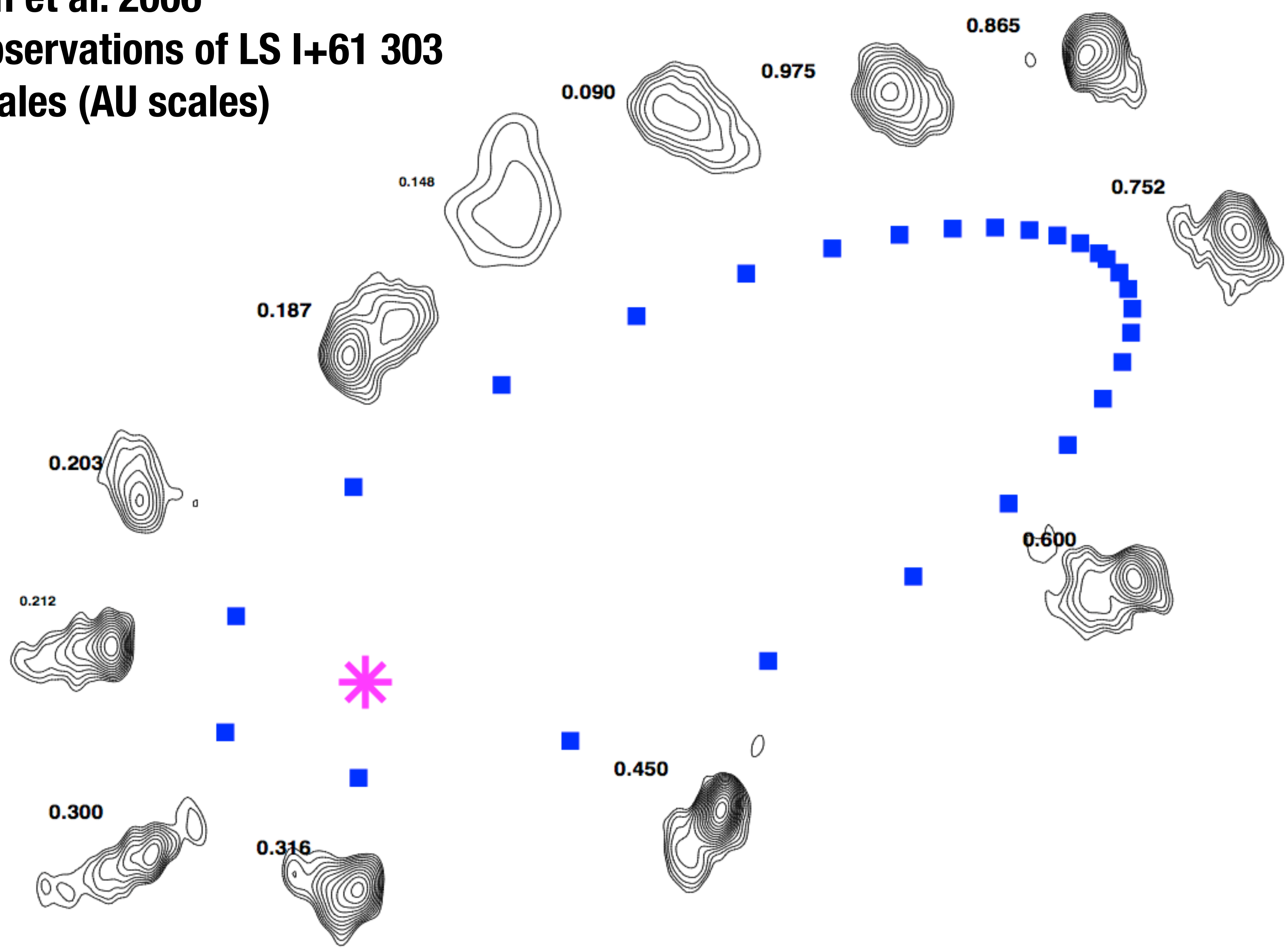
Gaensler et al. 2004





Pulsars, not microquasars

Dhawan et al. 2006
VLBI observations of LS I+61 303
mas scales (AU scales)



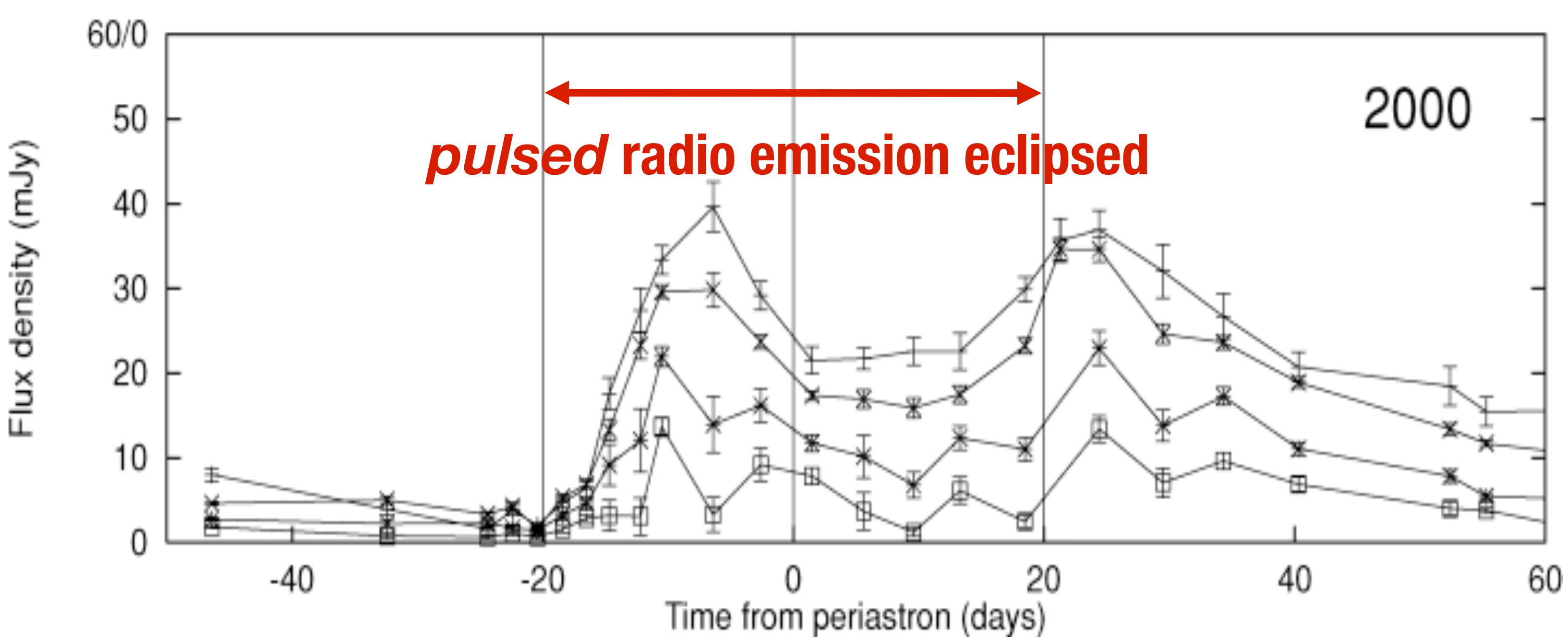
also LS 5039, HESS J0632, PSR B1259-63 (work by Moldón et al. 2011-3)

Where is the pulsar ?

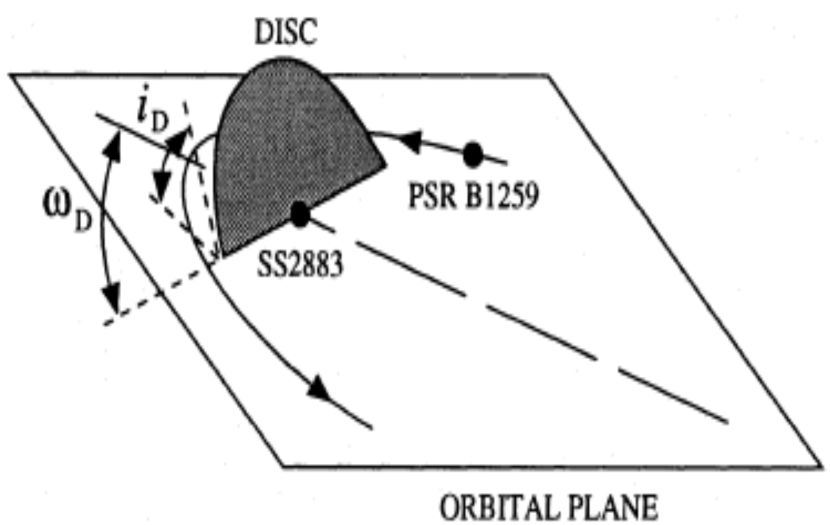
- **radio pulses strongly absorbed by stellar wind**

$$\tau_{\rm ff} \approx 14.7\, g_{\rm ff} \left(\frac{\nu}{10^9\,{\rm Hz}}\right)^{-2} \left(\frac{\dot{M}_{\rm w}}{10^{-7}\,{\rm M}_\odot\,{\rm yr}^{-1}}\right)^{2} \left(\frac{v_{\rm w}}{1000\,{\rm km\,s}^{-1}}\right)^{-2} \left(\frac{T_{\rm w}}{10\,000\,{\rm K}}\right)^{-3/2} \left(\frac{d}{1\,{\rm AU}}\right)^{-3}$$

- **detecting X-ray, γ-ray pulsations extremely difficult**



Connors et al. 2002



Melatos et al. 1995

PSR B1259-63

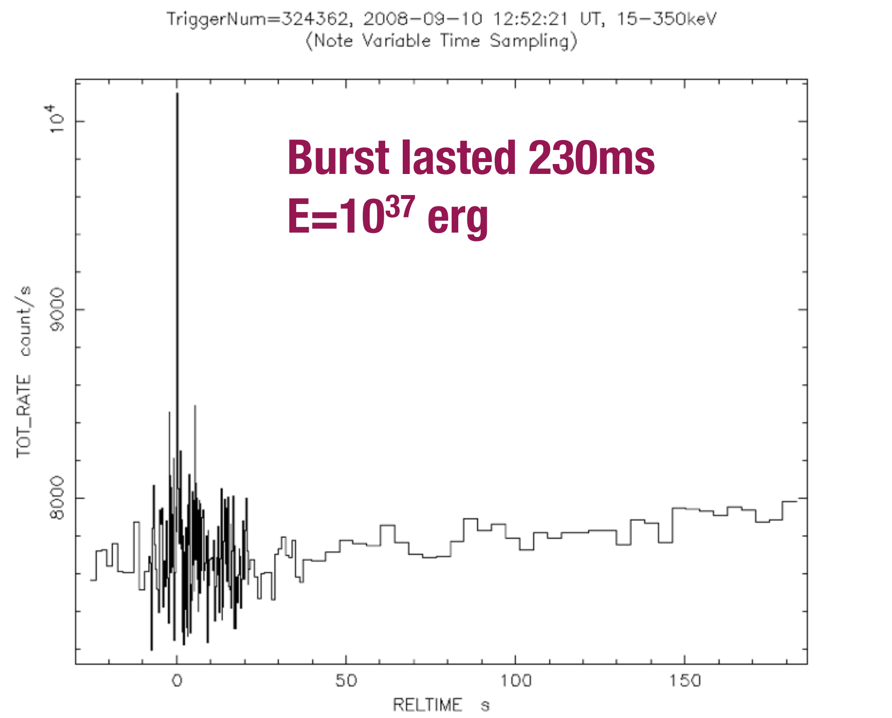
Where is the pulsar ?

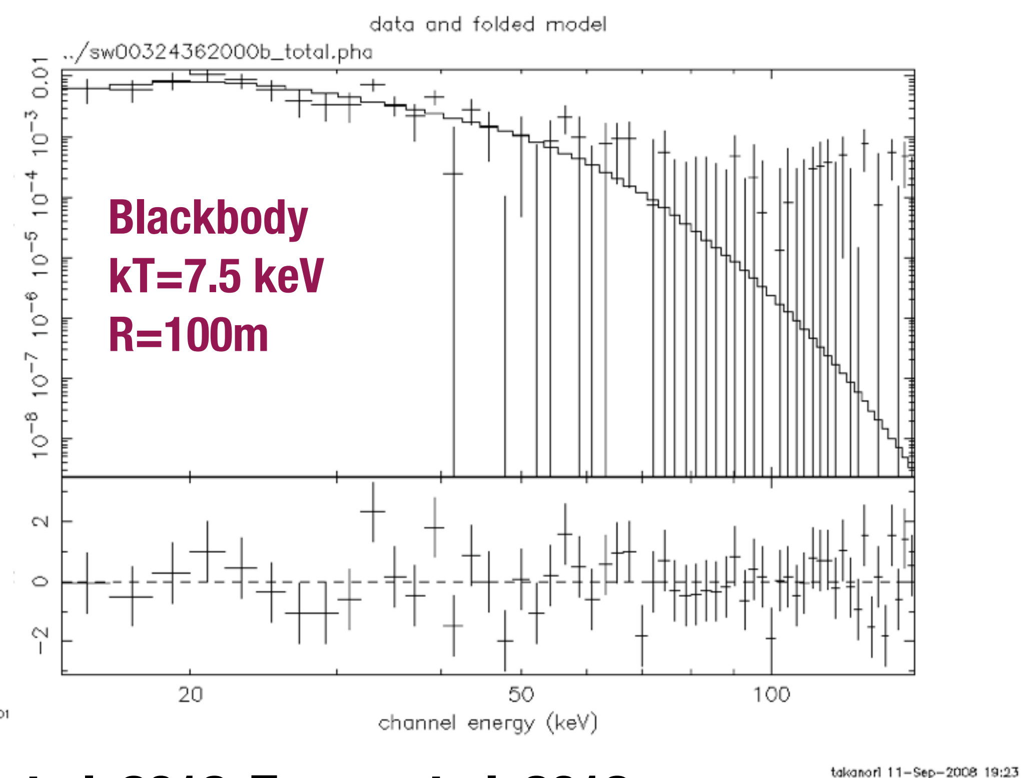
- radio pulses strongly absorbed by stellar wind

$$\tau_{\rm ff} \approx 14.7\, g_{\rm ff} \left(\frac{\nu}{10^9\,{\rm Hz}}\right)^{-2} \left(\frac{\dot{M}_{\rm w}}{10^{-7}\,{\rm M}_\odot\,{\rm yr}^{-1}}\right)^{2} \left(\frac{v_{\rm w}}{1000\,{\rm km\,s}^{-1}}\right)^{-2} \left(\frac{T_{\rm w}}{10\,000\,{\rm K}}\right)^{-3/2} \left(\frac{d}{1\,{\rm AU}}\right)^{-3}$$

- detecting X-ray, γ-ray pulsations extremely difficult

- 2 magnetar bursts seen by Swift/BAT < 2' of LSI +61º303 ⇒ young pulsar ?





Barthelmy et al. 2008, Burrows et al. 2012, Torres et al. 2012

Indirect evidence for pulsar

- only identified compact object in a gamma-ray binary is a pulsar (*)
- magnetar bursts detected from LS I+61 303
- similarities in timing/spectra
- periodic morphological changes in radio
- X-ray/GeV/TeV properties consistent with those of PWN
- lack of accretion signatures (spectral changes, outbursts...)
- expected progenitors of high-mass X-ray binaries & double NS

coherent interpretation

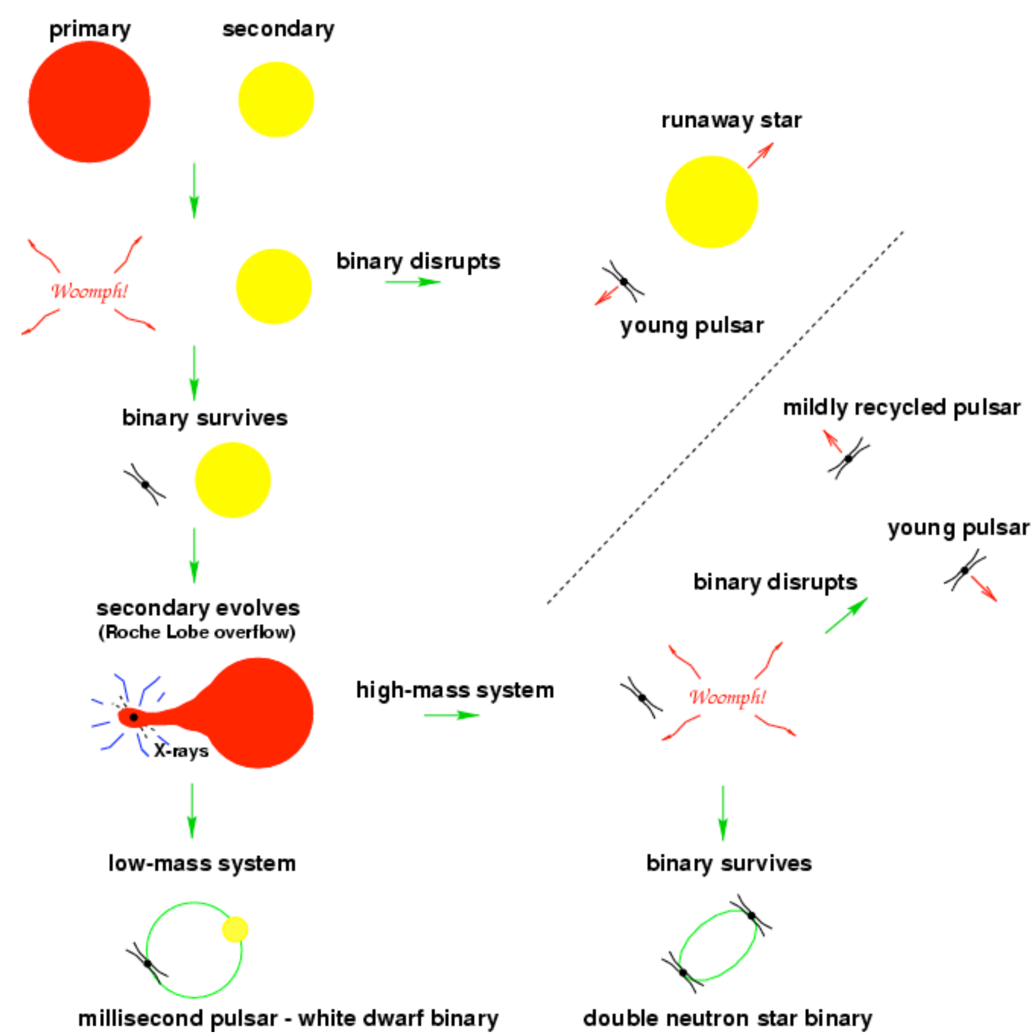
(*) + three other known pulsars with massive companion but far & low power so no gamma rays

Evolution

- **Accretion held off if $p_{pw}>p_{acc}$ at Bondi-Hoyle radius**

$$\dot{E} \approx 4 \times 10^{33} \left(\frac{\dot{M}_{\rm w}}{10^{-7}\,{\rm M_\odot\,yr^{-1}}}\right)\left(\frac{1000\,{\rm km\,s^{-1}}}{v_{\rm w}}\right)^3\left(\frac{0.1\,{\rm AU}}{d}\right)^2\,{\rm erg\,s^{-1}}$$

$L_\gamma>10^{34}$ erg/s so ok



Lorimer 2008

- **Pulsar spins down**

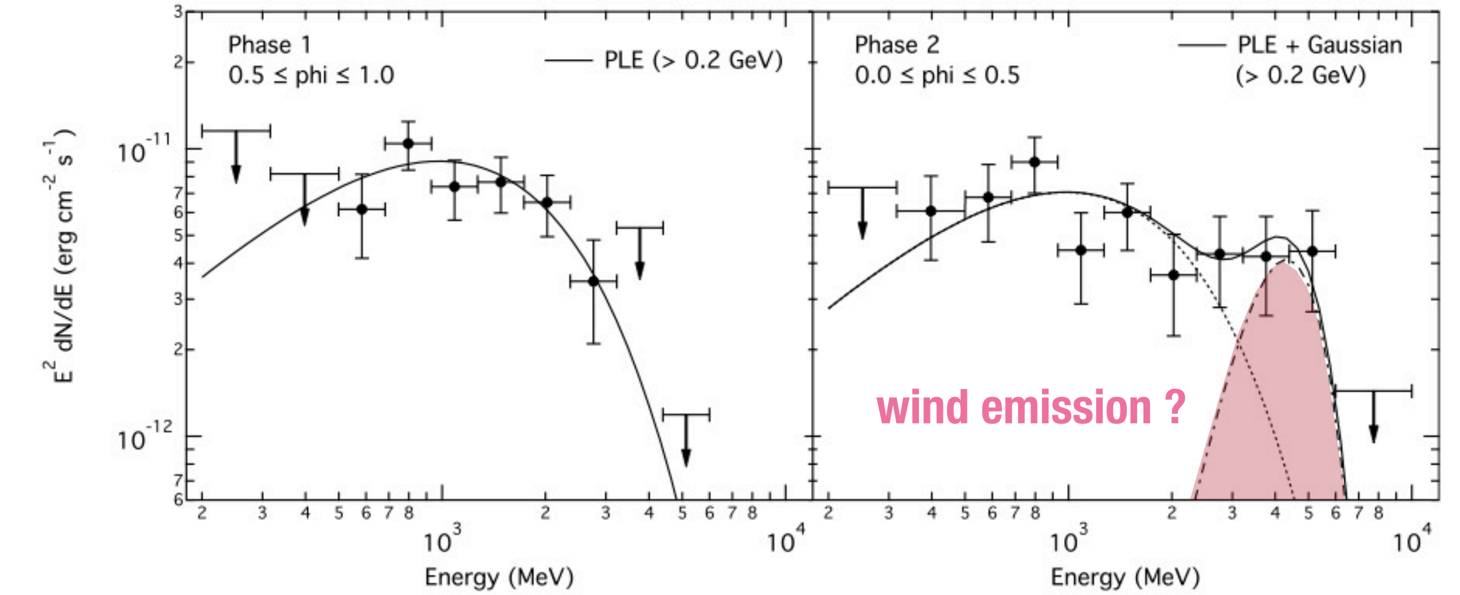
  → accretion eventually starts → HMXB

- **birthrate ~ 10^{-3} yr^{-1} x 10^5 yr lifetime ~ 100 gamma-ray binaries in Galaxy ?**

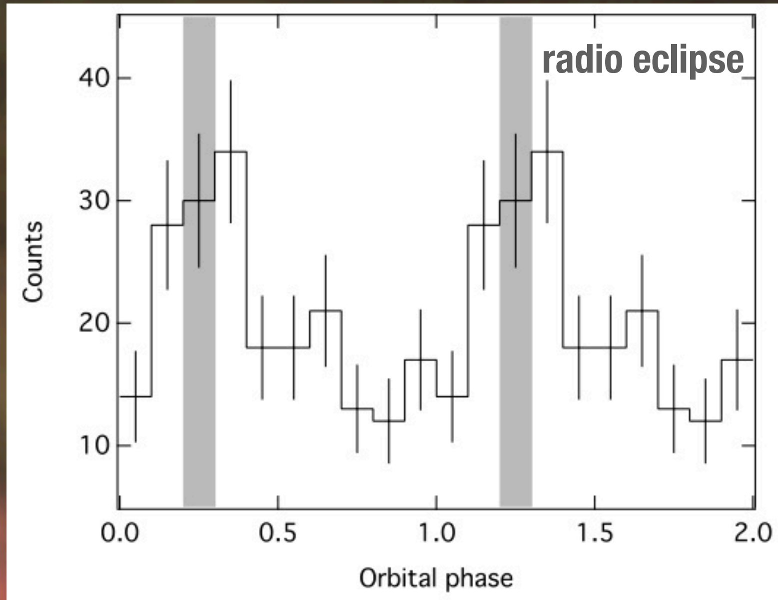
Low-mass gamma-ray binaries

- old pulsar spun-up by accretion in LMXB (recycled ms pulsar)
- pulsar pressure increases, ends up quenching accretion
- ~30 GeV pulsars in binaries
- modulated γ-ray emission in black widow pulsar (Wu et al. 2012)

"black widow" PSR B1957+20

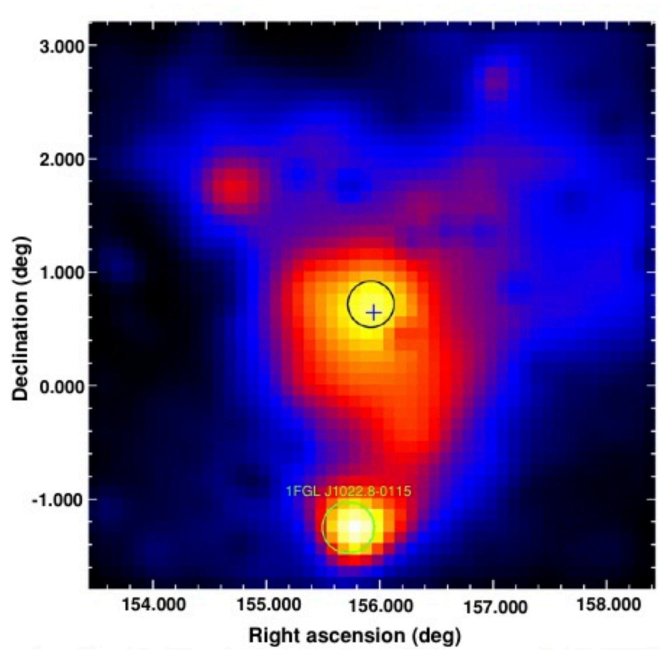


>2.7 GeV lightcurve

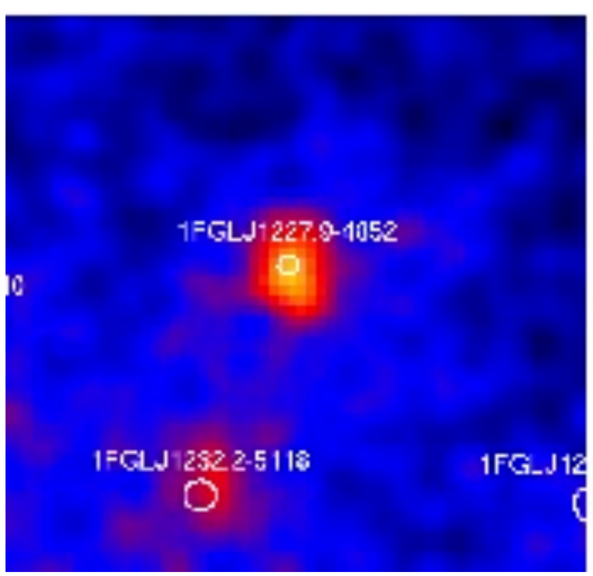


Low-mass gamma-ray binaries

Tam et al. 2010



Hill et al. 2011



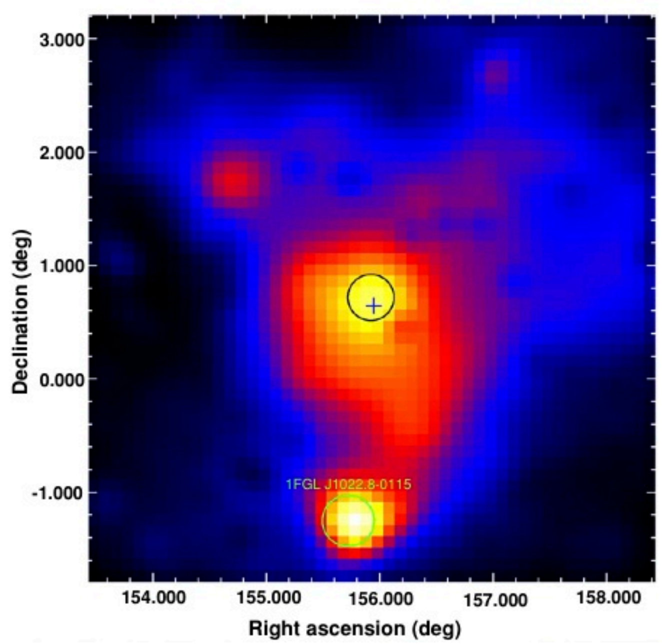
PSR J1023+0038
- 1.6-ms radio pulsar
- accretion disk disappears when radio pulsar on

both have
- 0.2d orbit, 0.2 $M_\odot$ star
- hard X-ray spectrum
- optical, X-ray variability
- pos. Fermi counterpart few 10^{33} erg/s

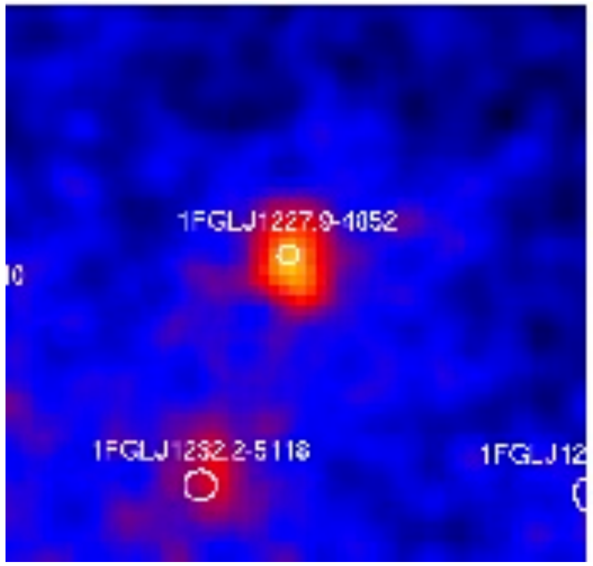
XSS J12270-4859
- unidentified compact object
- faint radio source

Low-mass gamma-ray binaries

Tam et al. 2010



Hill et al. 2011



PSR J1023+0038

1.6-ms radio pulsar

radio pulsar disappears as accretion back on

both have

0.2d orbit, 0.2 $M_\odot$ star

hard X-ray spectrum

optical, X-ray variability

GeV brighter when accretion on

XSS J12270-4859

~~unidentified compact object~~ 1.6 ms pulsar

switched to non-accreting state dec. 2012

Takata et al. 2014, Bassa et al. 2014...

tools of the trade:
high-energy radiative processes
in the context of binaries

Efficient particle acceleration

diffusive shock acceleration timescale

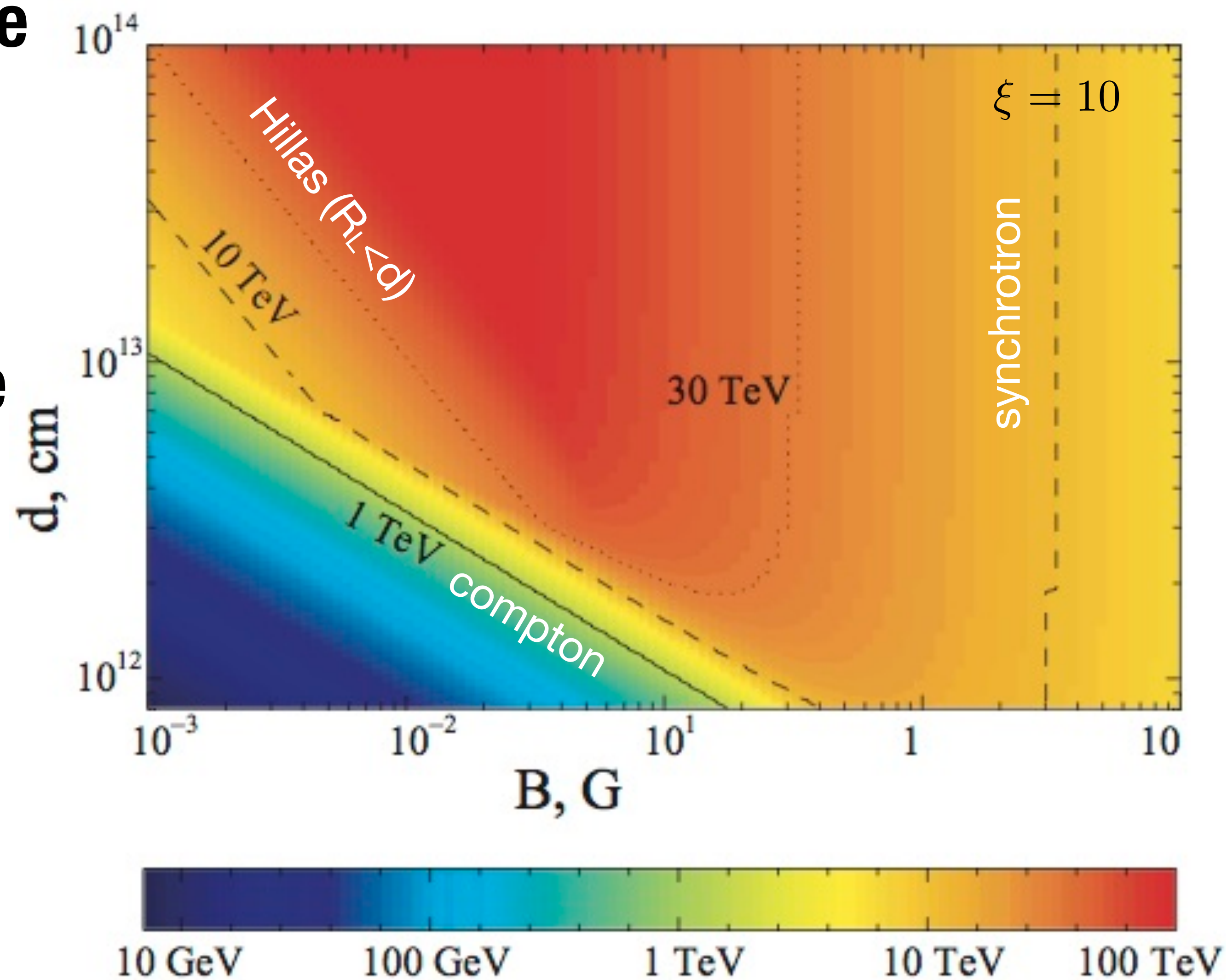
$$\tau_{\rm ac} \geq \xi \frac{R_L}{c} \approx 0.1\,\xi \left(\frac{E}{1\,\rm TeV}\right)\left(\frac{1\,\rm G}{B}\right)\ \rm s$$

must be < synchrotron loss timescale

$$\tau_{\rm sync} \approx 400 \left(\frac{1\,\rm TeV}{E}\right)\left(\frac{1\,\rm G}{B}\right)^2\ \rm s$$

maximum energy

$$\Rightarrow\quad E_{\rm max} \approx 60\,\xi^{-1/2} B^{-1/2}\,\rm TeV$$



Khangulyan et al. 2008

VHE photons > 20 TeV imply efficient acceleration (reconnection?)

Basics of spectrum formation

Assume steady **injection of pairs** with escape timescale ≫ radiative timescale

inverse Compton cooling on star photons

$$\tau_{\rm ic}=20\ \gamma_6 d_{0.1}^2/[\ln\gamma_6+1.3](T_{*,4}R_{*,10})\ \text{seconds}$$

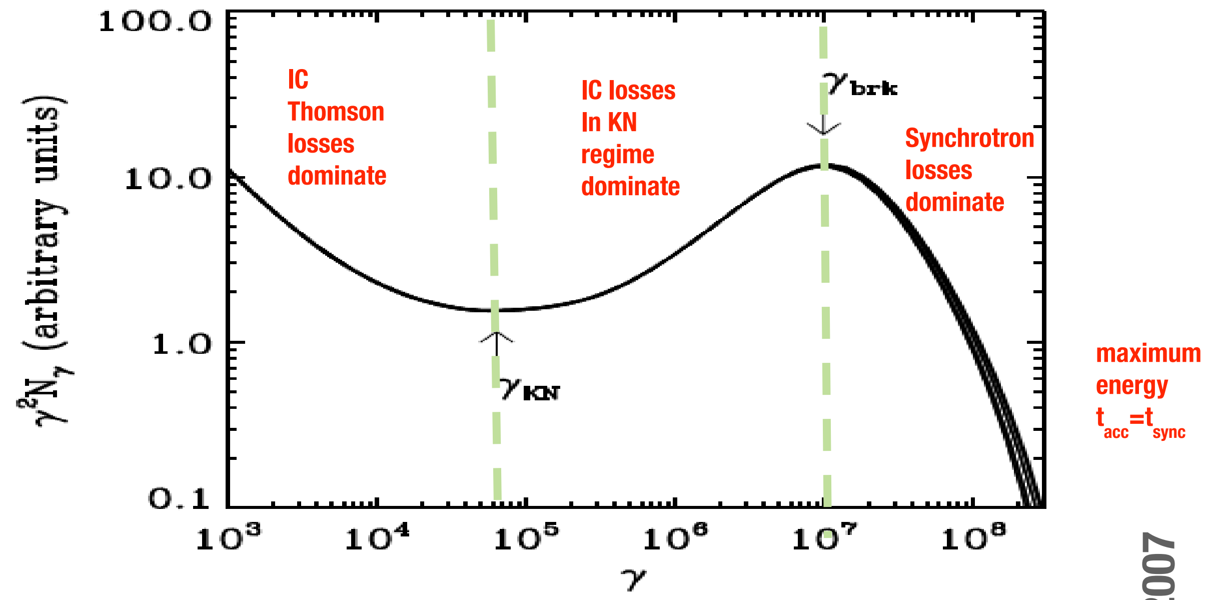
synchrotron cooling

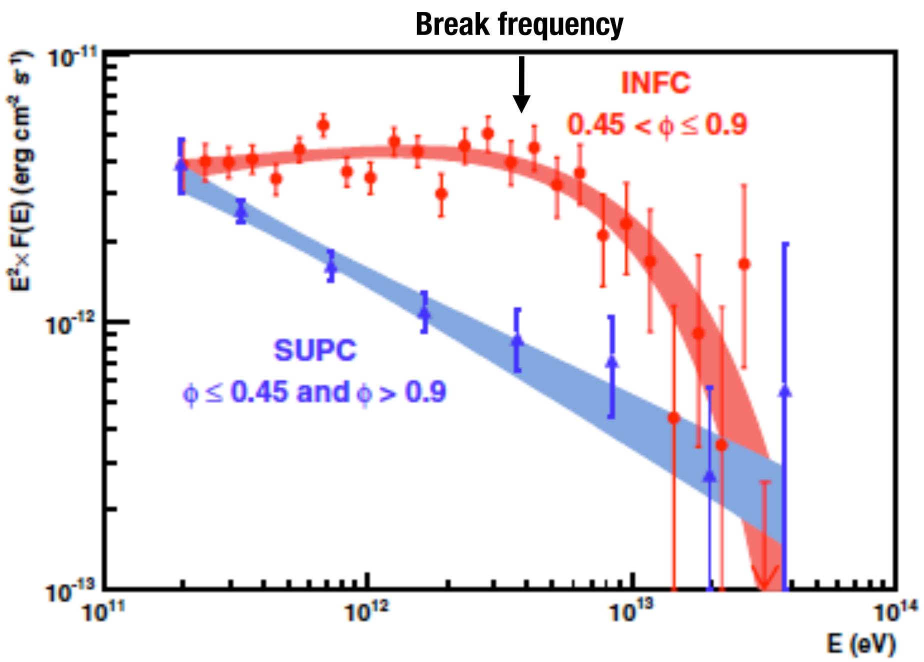
$$\tau_{\rm sync}=770\ \gamma_6^{-1}B_1^{-2}\ \text{seconds}$$

⇒ break frequencies

$$\epsilon_{\rm IC}=4\ (T_{*,4}R_{*,10}/d_{0.1})B_1^{-1}\ \text{TeV}$$

$$\epsilon_{\rm sync}=750\ (T_{*,4}R_{*,10}/d_{0.1})^2\ \text{keV}$$





Moderski et al. 2005, GD et al. 2007

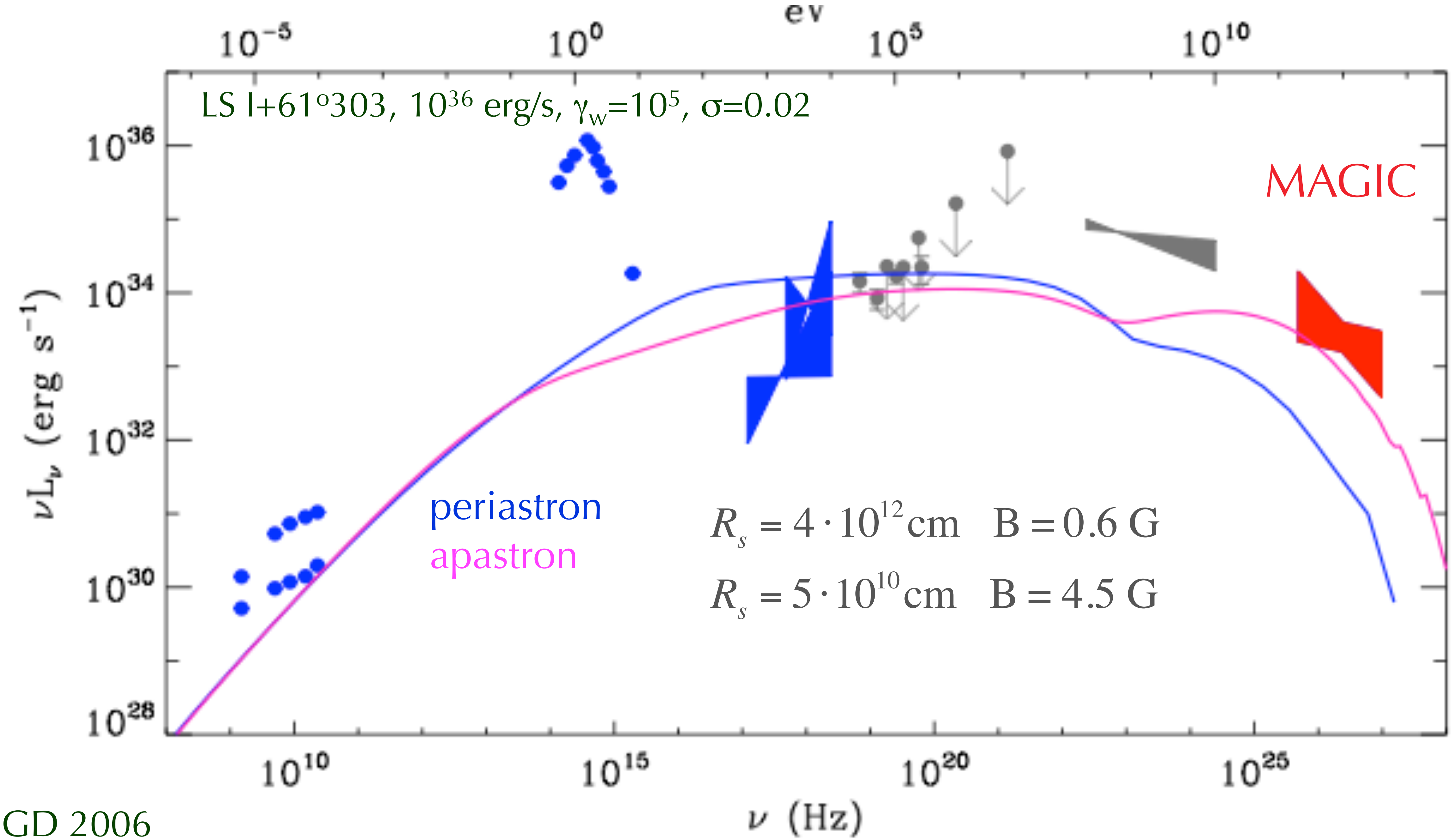
Massive star sets everything ⇒ B≃1G

caveat: adiabatic cooling

Intrinsic variations in R_s, σ, τ_{ad}...

Apastron: diffuse polar wind, large shock distance, **low B = VHE**

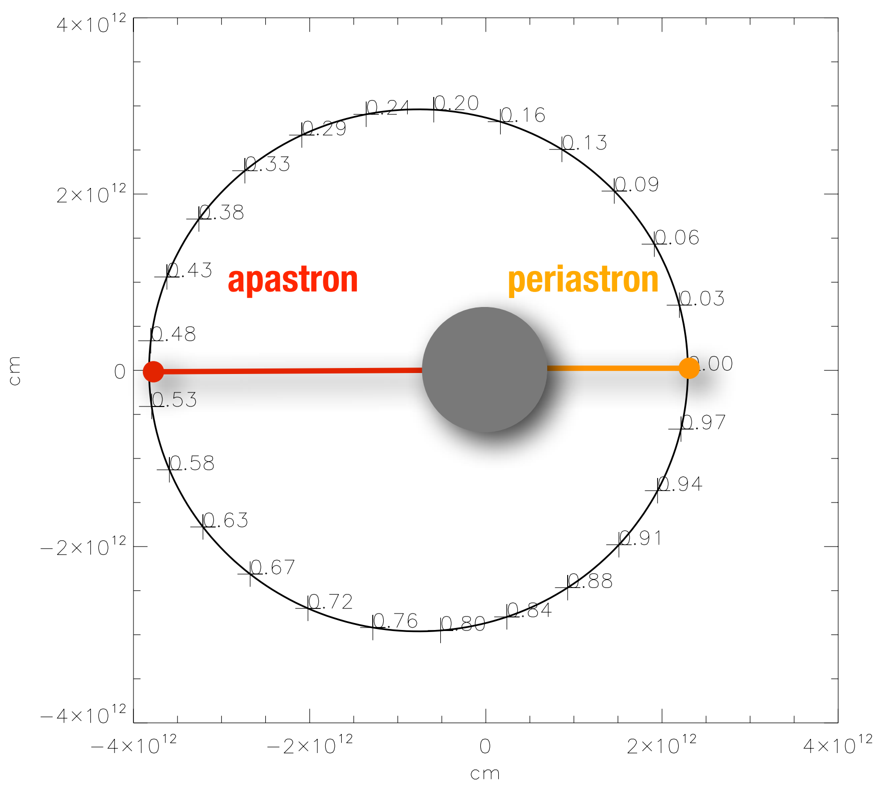
Periastron: dense equatorial wind, small shock distance, **high B =** *no* **VHE**



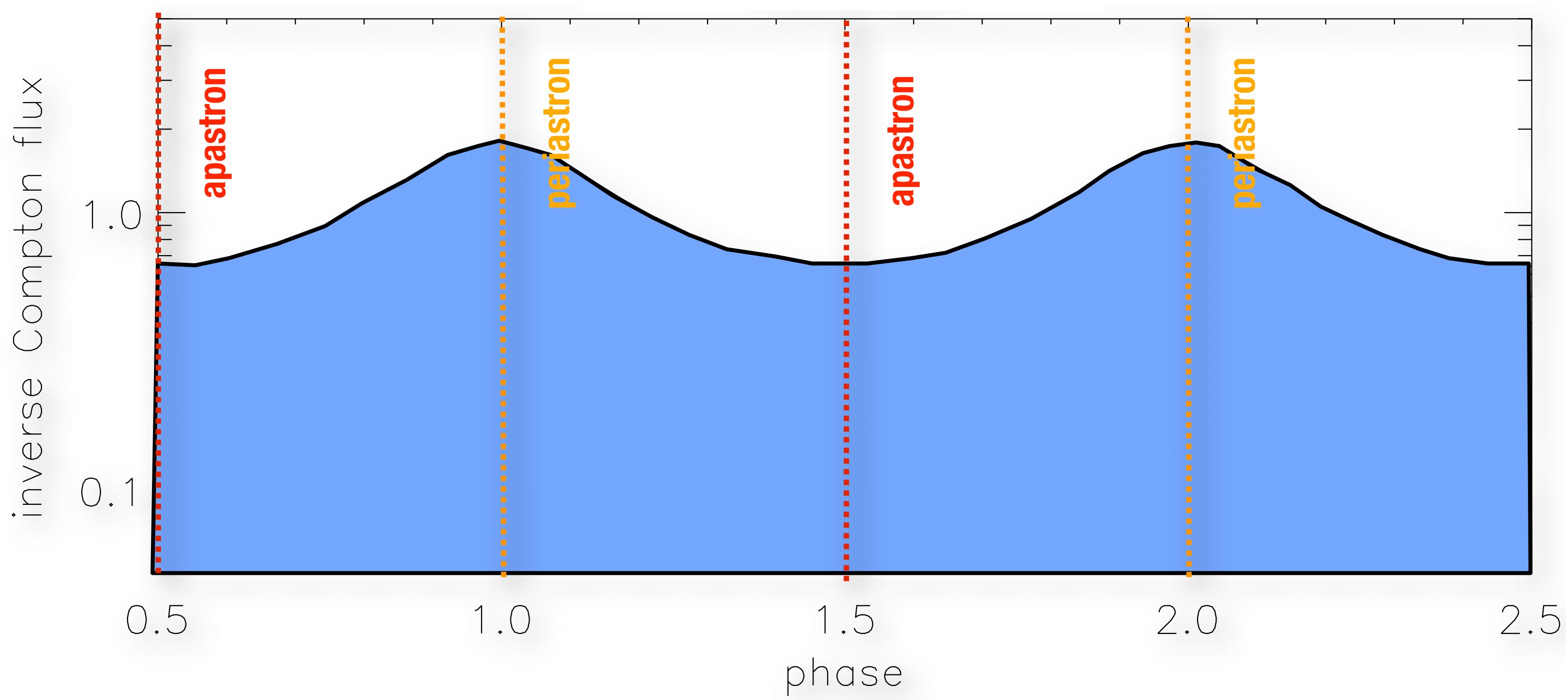
GD 2006

Geometrical γ-ray modulations

- **inverse Compton on star photons**



orbit seen face on

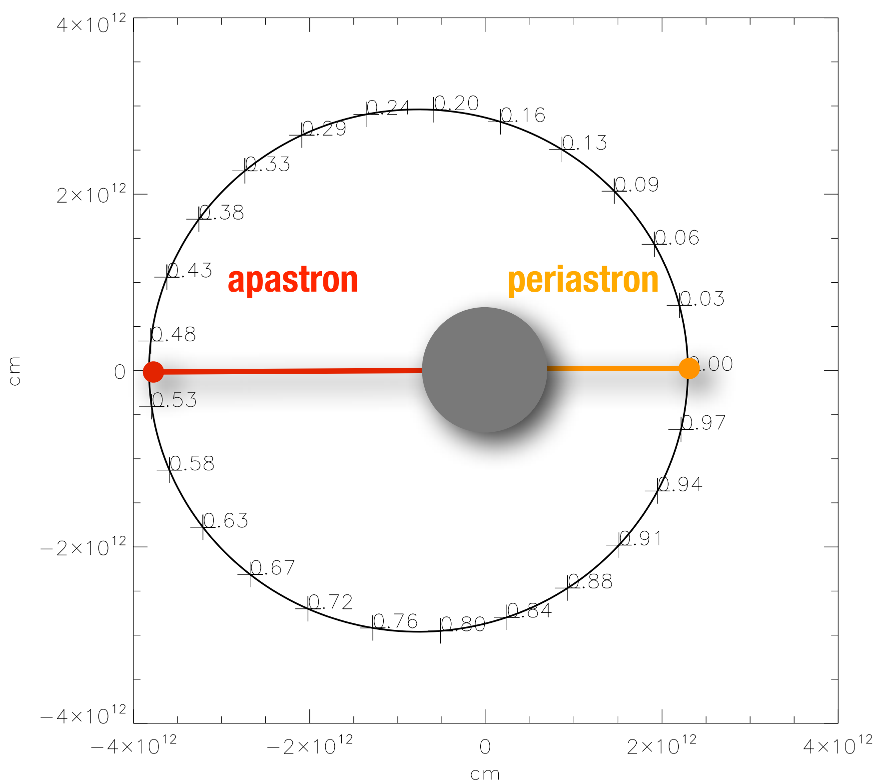


inverse Compton (GeV)

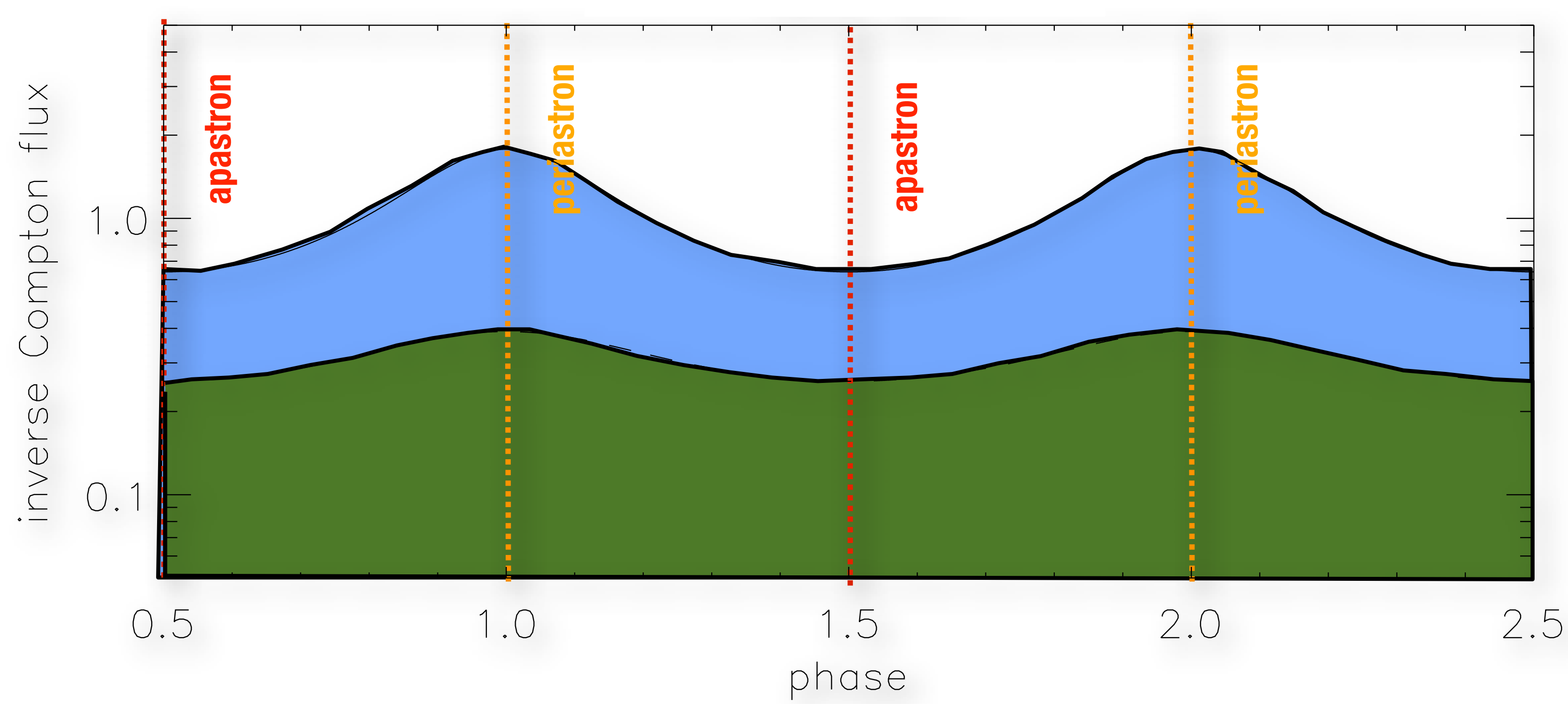
depends on photon density $U_\star = \frac{\sigma_{\rm SB} T_\star^4}{c}\left(\frac{R_\star}{d}\right)^2$ **so** $\propto d^{-2}$

Geometrical γ-ray modulations

- inverse Compton on star photons
- pair production on star photons (opacity) $\epsilon_{\rm min}\epsilon_\star \geq (511\,{\rm keV})^2$



orbit seen face on



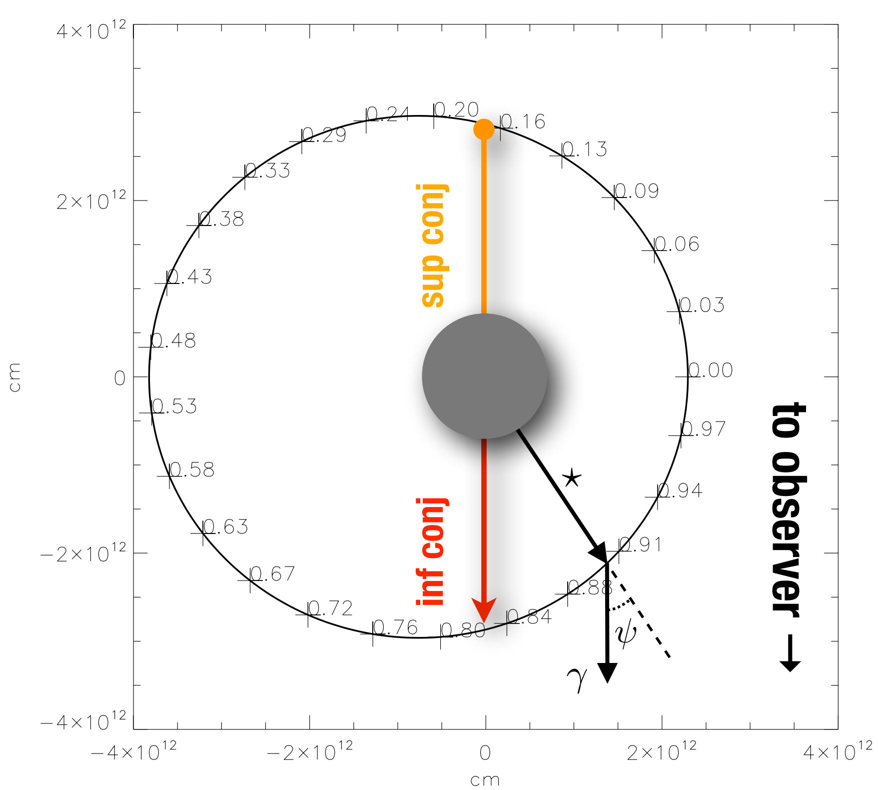
inverse Compton (GeV)

+ pair production above threshold (TeV)

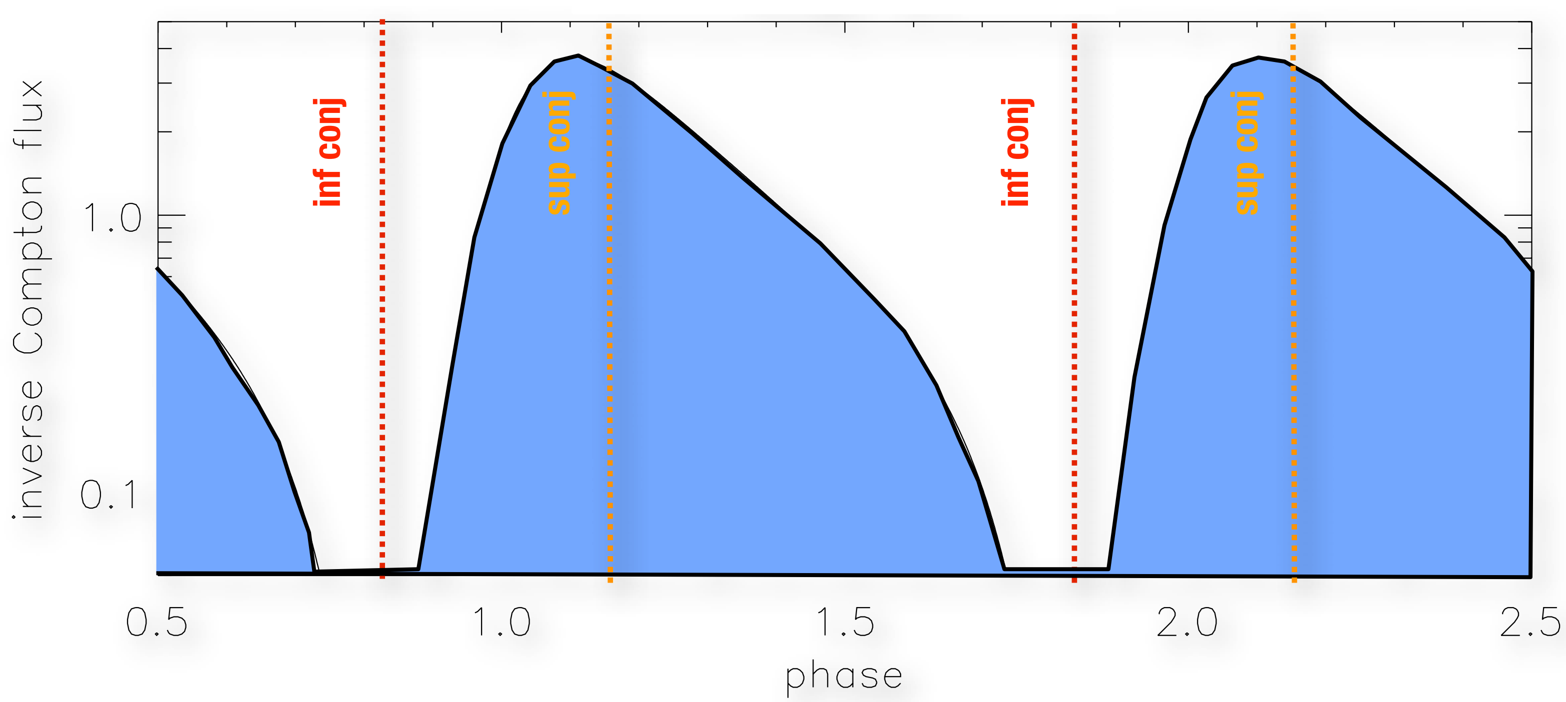
also depends on photon density so $\propto d^{-2}$

Geometrical γ-ray modulations

- inverse Compton on star photons: anisotropic
- pair production on star photons (opacity)



orbit seen edge on



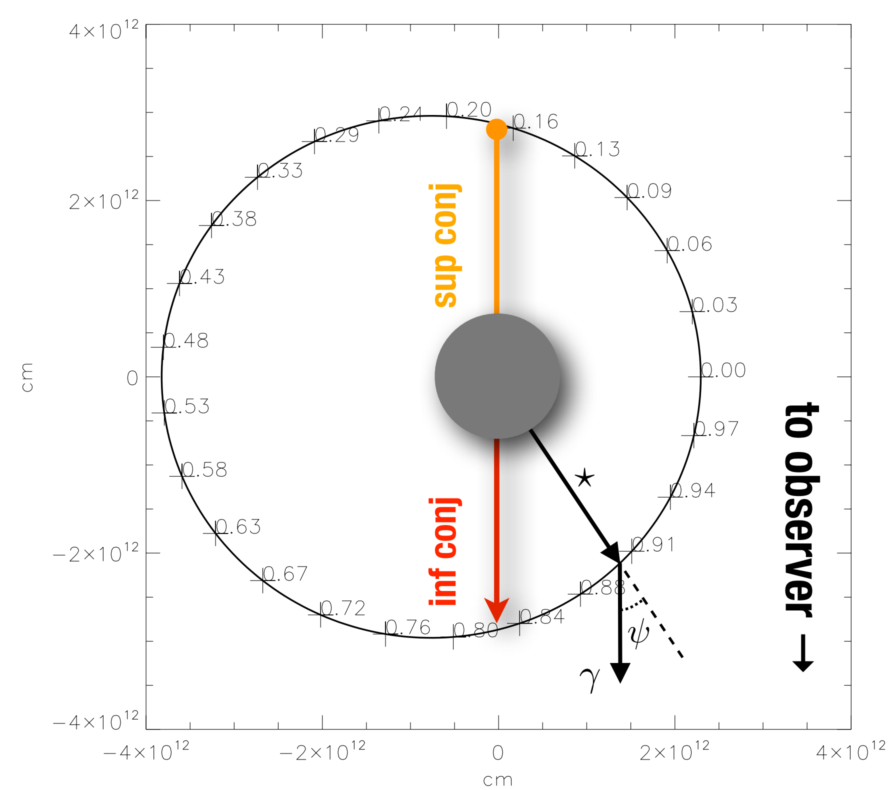
inverse Compton (GeV)

$$P_\star = \sigma_T c U_\star (1 - \beta \cos\psi) \left[(1 - \beta \cos\psi)\gamma^2 - 1 \right]$$

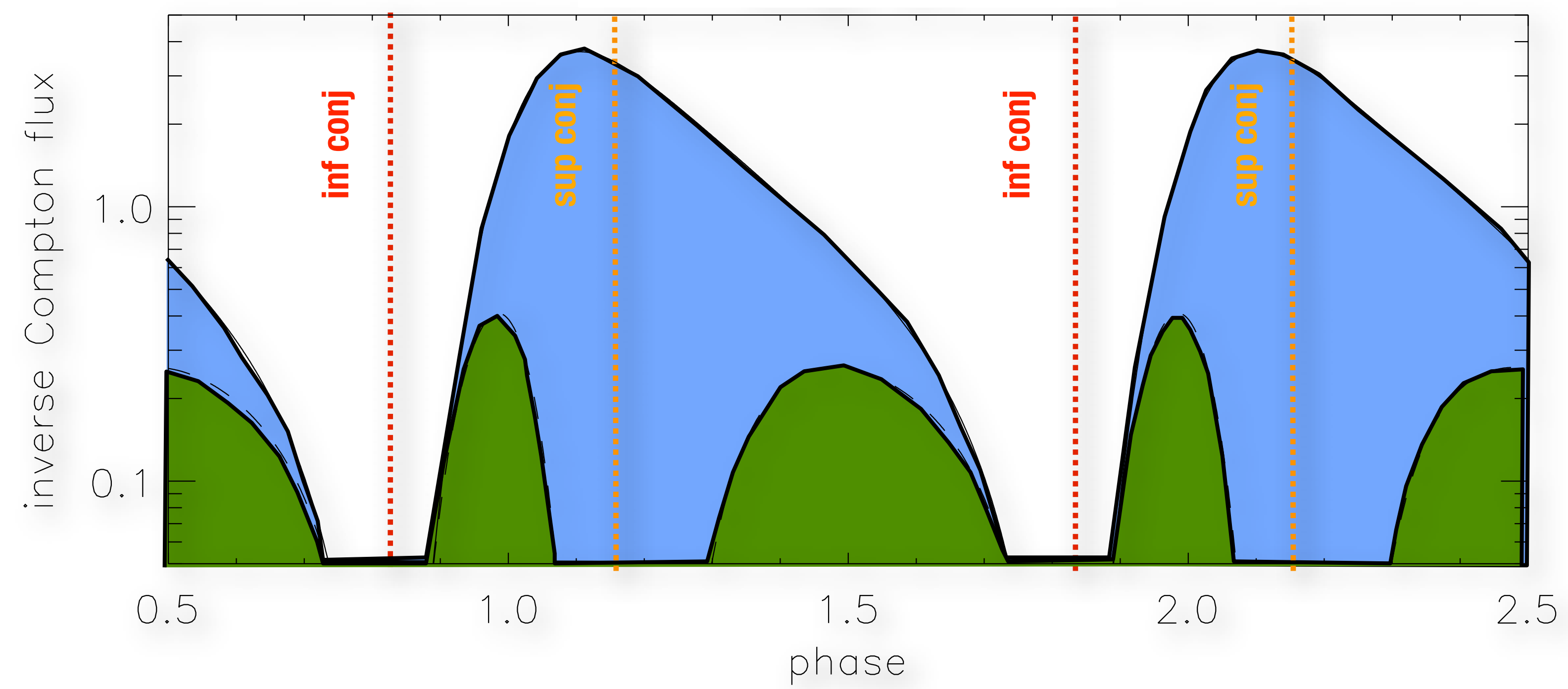
Thompson regime, electron Lorentz factor γ, ψ angle between incoming and outgoing photon

Geometrical γ-ray modulations

- inverse Compton on star photons: anisotropic
- pair production on star photons (opacity): anisotropic



orbit seen edge on

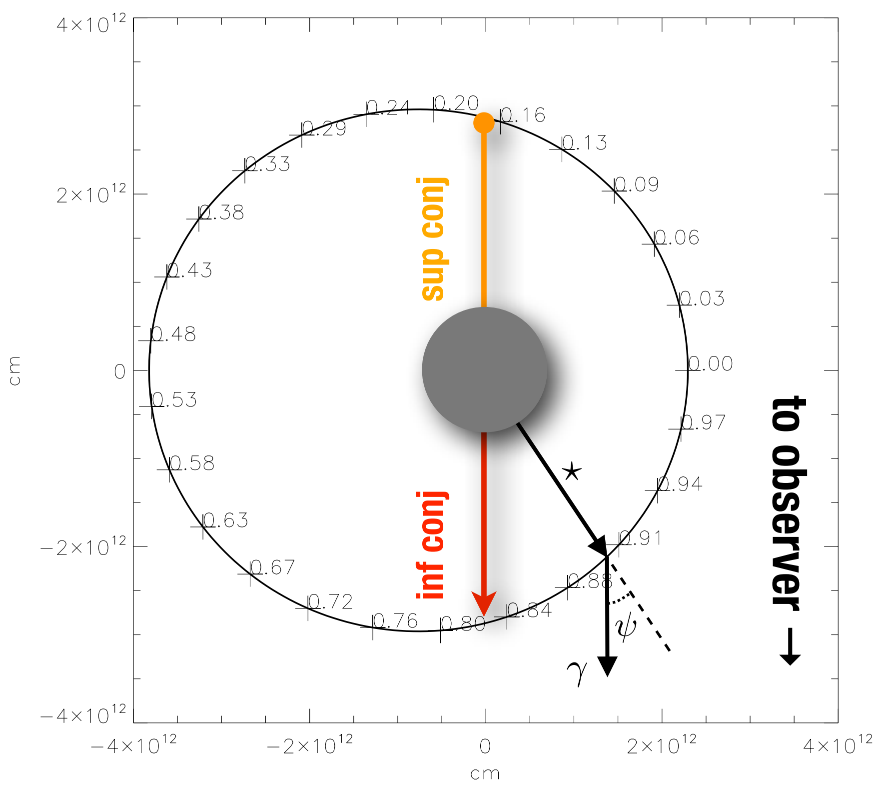


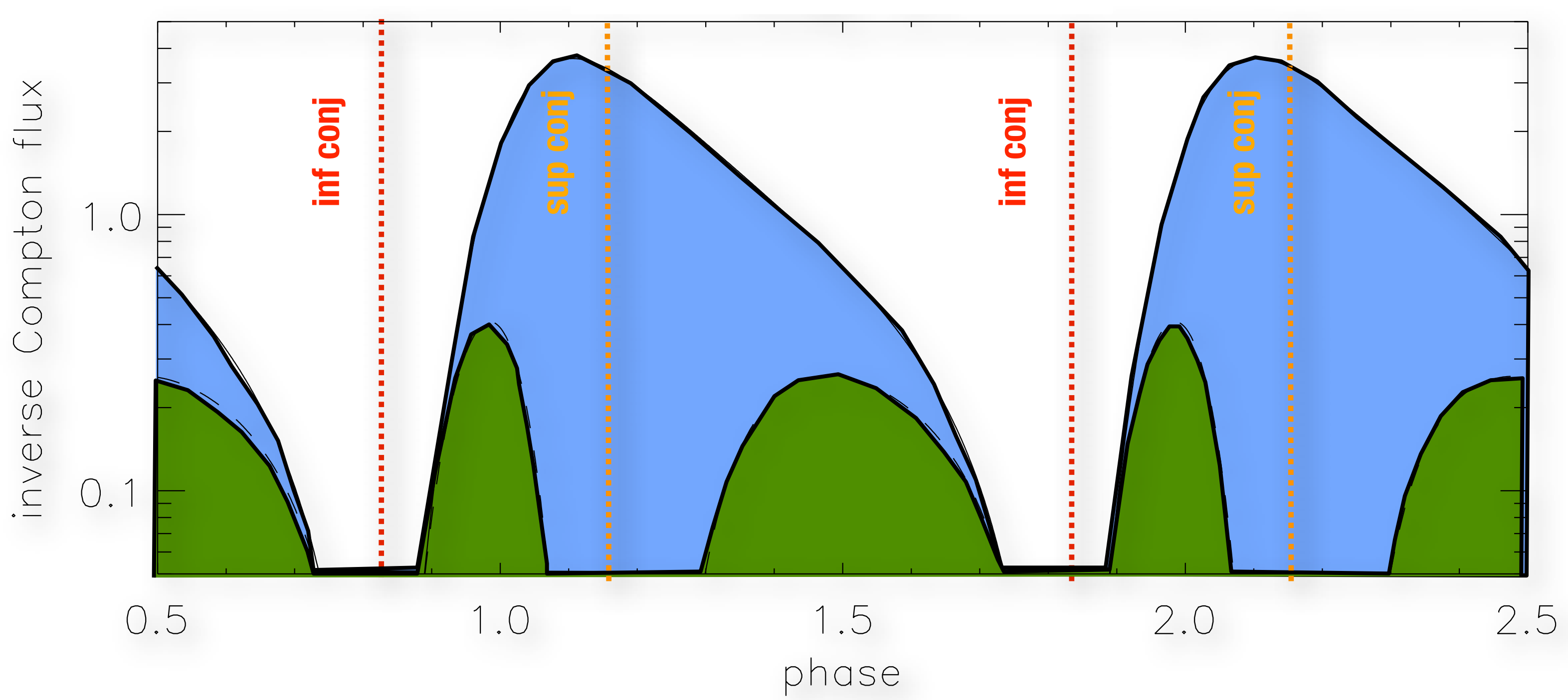
inverse Compton (GeV) + pair production above threshold (TeV)

$$\epsilon_\gamma \epsilon_\star (1-\cos\psi) \geq 2\left(m_e c^2\right)^2 \Rightarrow \epsilon_\gamma \geq 30 \left(\frac{10\,\mathrm{eV}}{kT_\star}\right) \mathrm{GeV}$$

Geometrical γ-ray modulations

- inverse Compton on star photons: anisotropic
- pair production on star photons (opacity): anisotropic



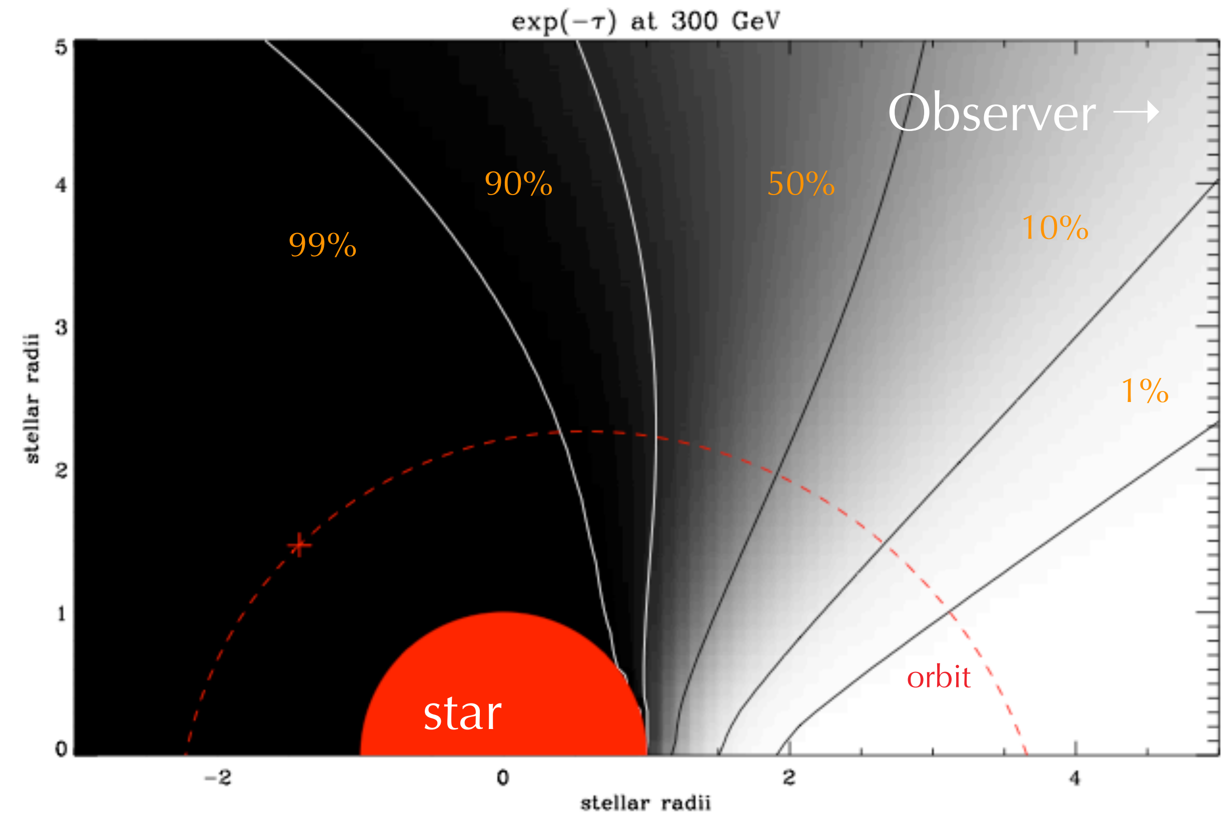


inverse Compton (GeV) + pair production above threshold (TeV)

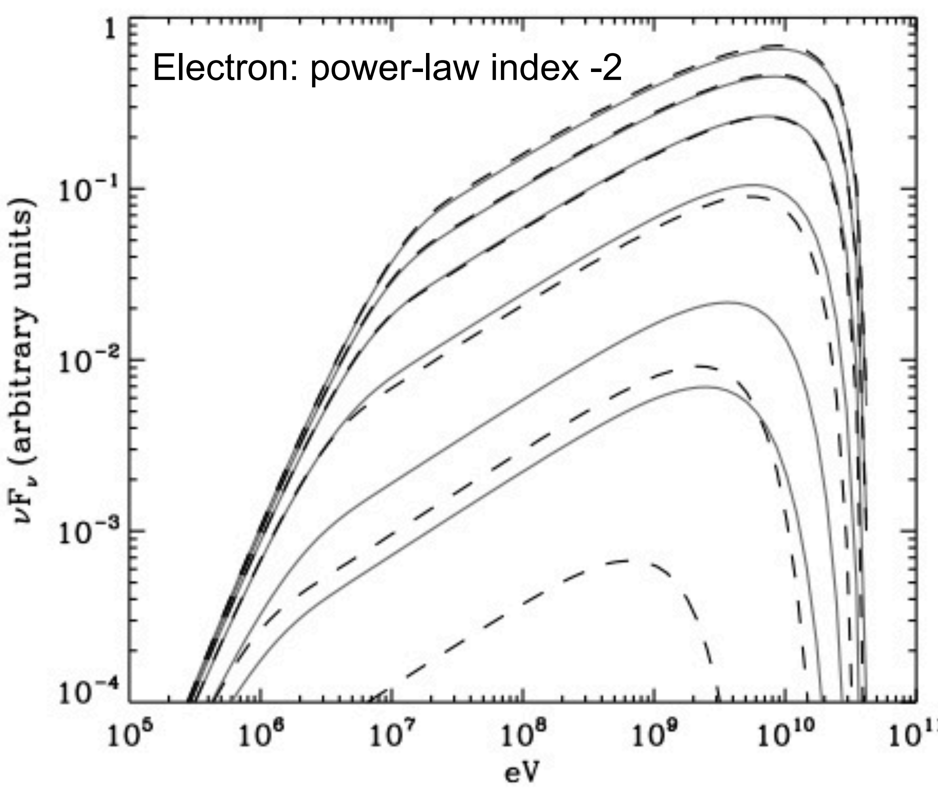
→ distinguish intrinsic variability from variability due to observer geometry

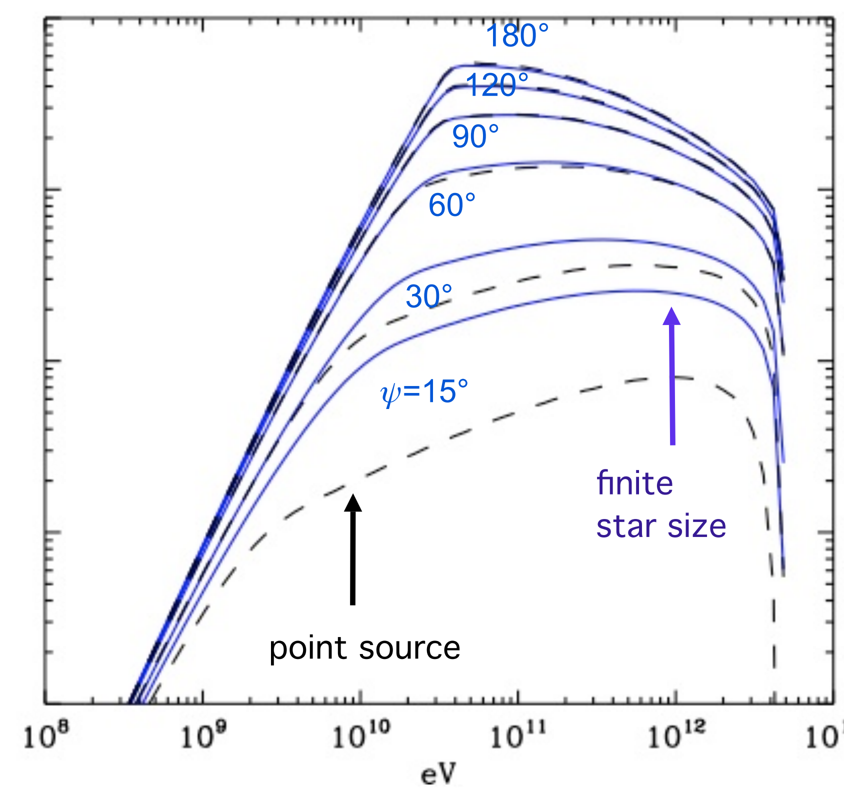
Anistropic IC and pair production

Protheroe & Stanev 1993
Moskalenko 1995
Dermer & Bottcher 2005
GD 2006



Thomson → Klein Nishina $\gamma(1-\beta\cos\psi)e_\star \geq m_e c^2$

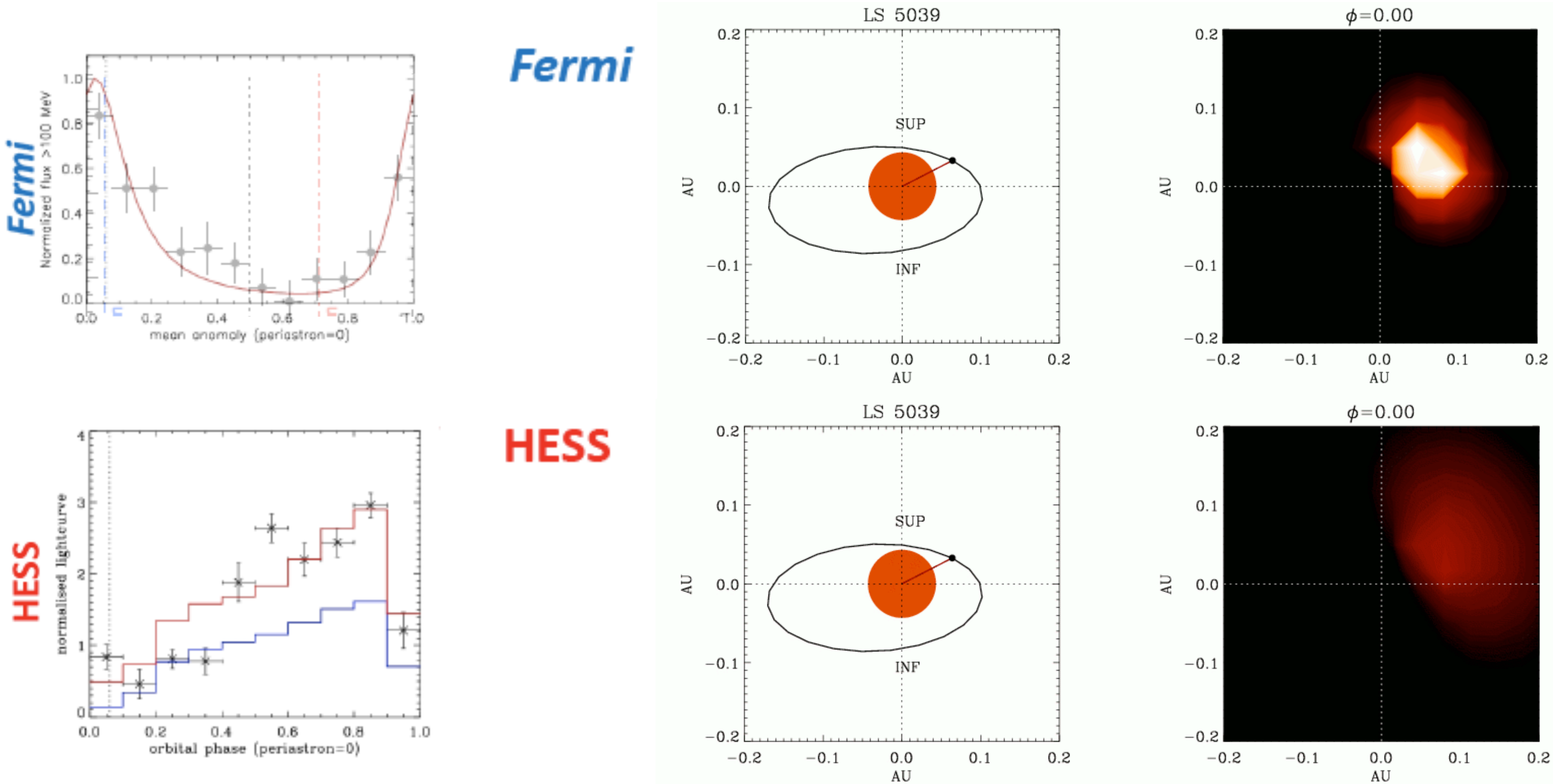




Jackson 1972
Bednarek 1997
Kirk et al. 1999
GD et al. 2008
Khangulyan et al. 2008

γ-ray modulation of LS 5039

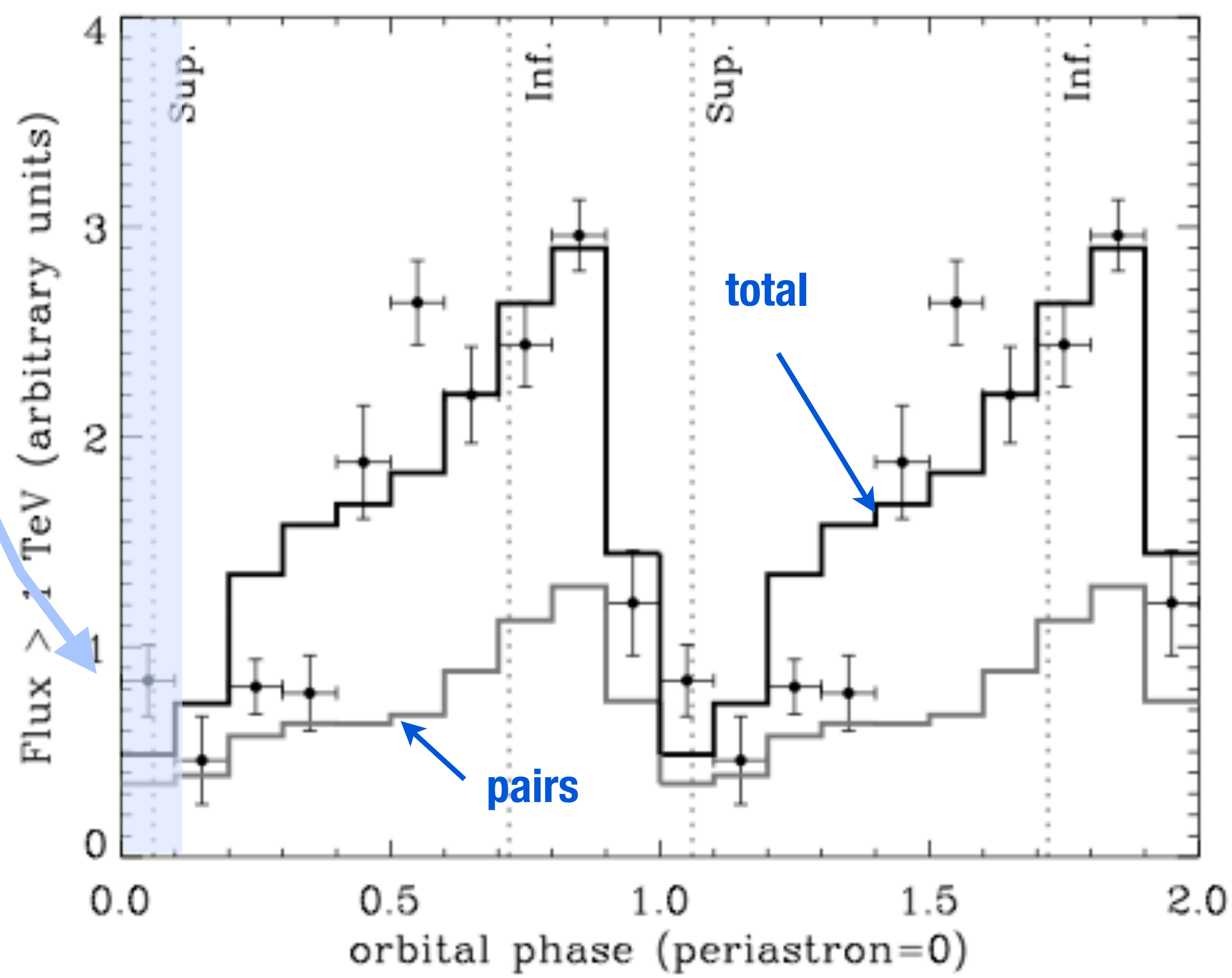
Cerutti et al. 2010

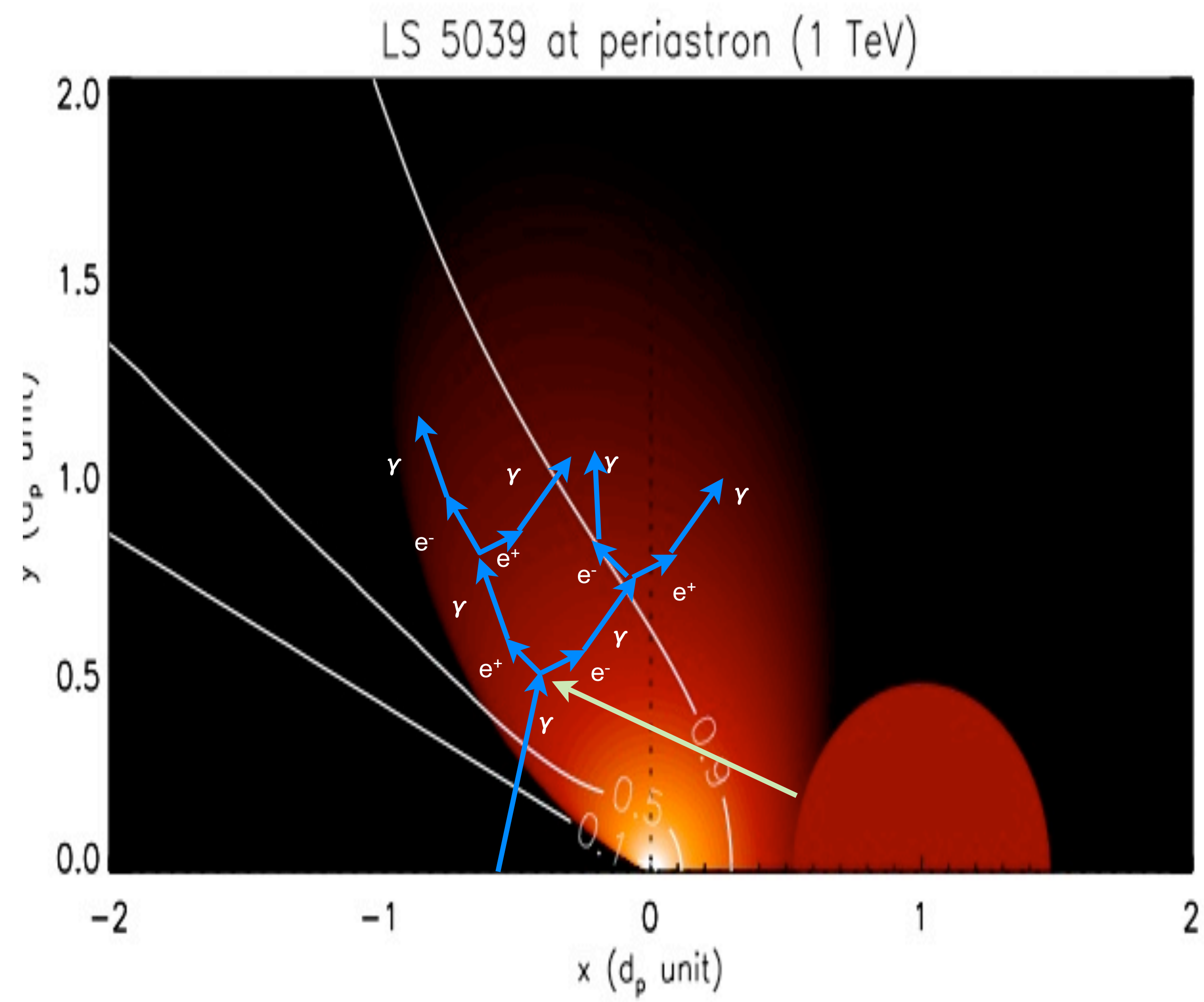


Led several groups to predict GeV modulation later seen by Fermi

Complications

- significant **pair cascade** emission at superior conjunction



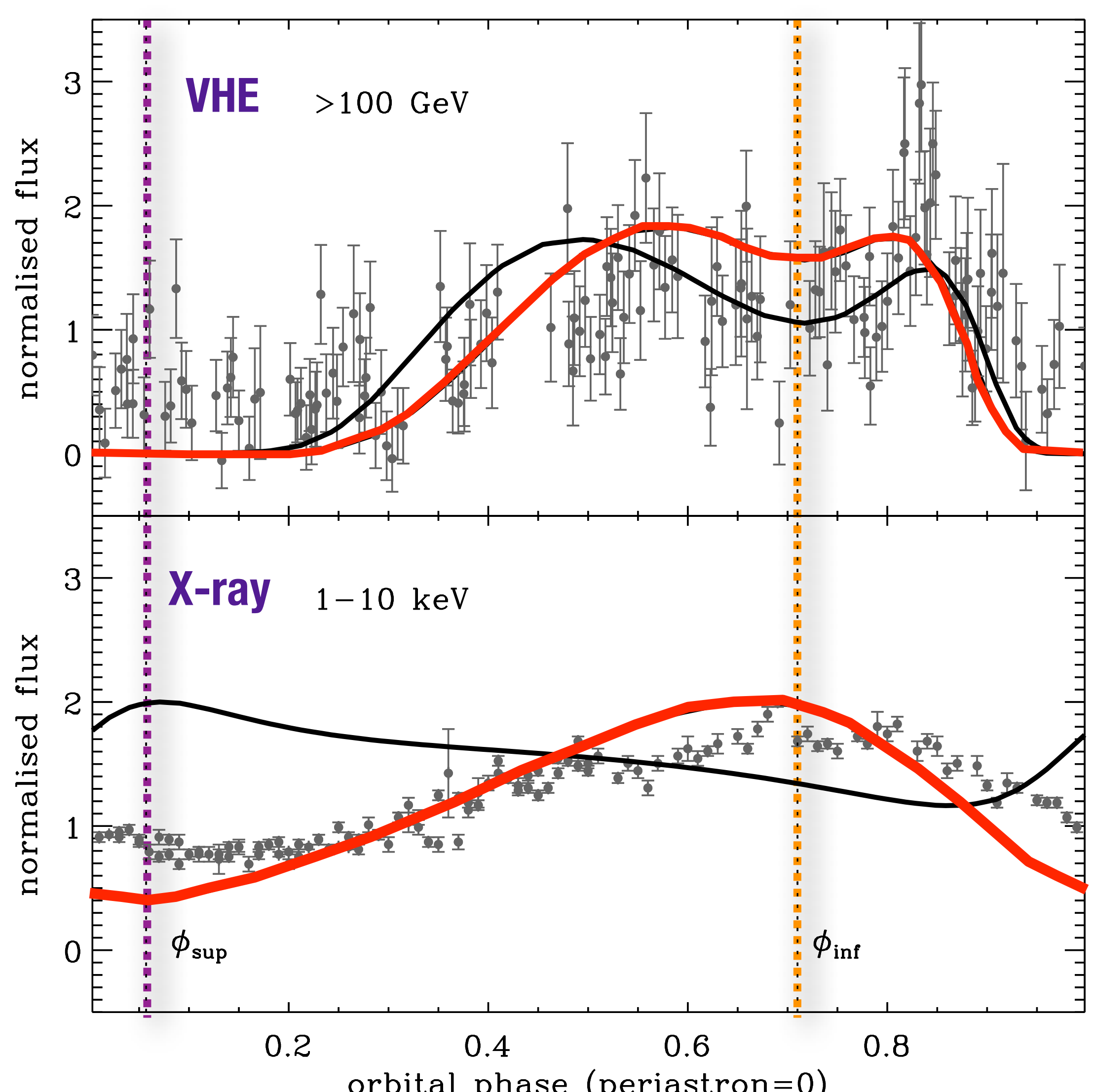


Cerutti et al. 2010

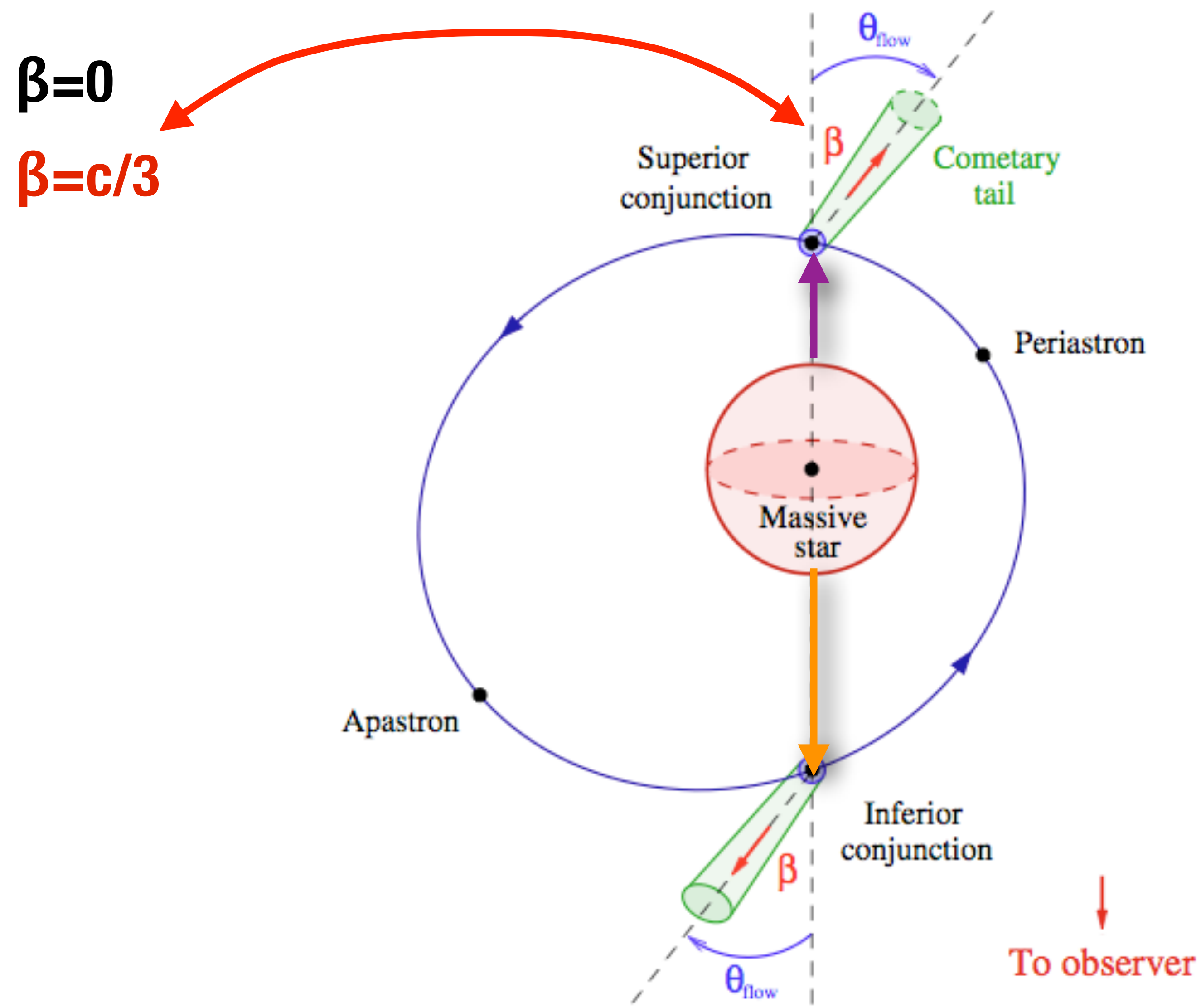
synchrotron emission from pairs in X-rays limit <B>~1 G

Complications

- significant **pair cascade** emission at superior conjunction
- bulk **doppler boost** in shocked wind modifies lightcurve



GD et al.2010



alternative: adiabatic timescale (Takahashi et al. 2009)

Radiative models: summary

Bednarek et al.; Kirk et al; Romero et al., Dermer & Bottcher, Khangulyan & Bosch-Ramon et al.; Neronov & Chernyakova; Dubus, Cerutti, Henri; Sierpowska-Bartosik & Torres; Takata & Taam; Yamaguchi & Takahara...

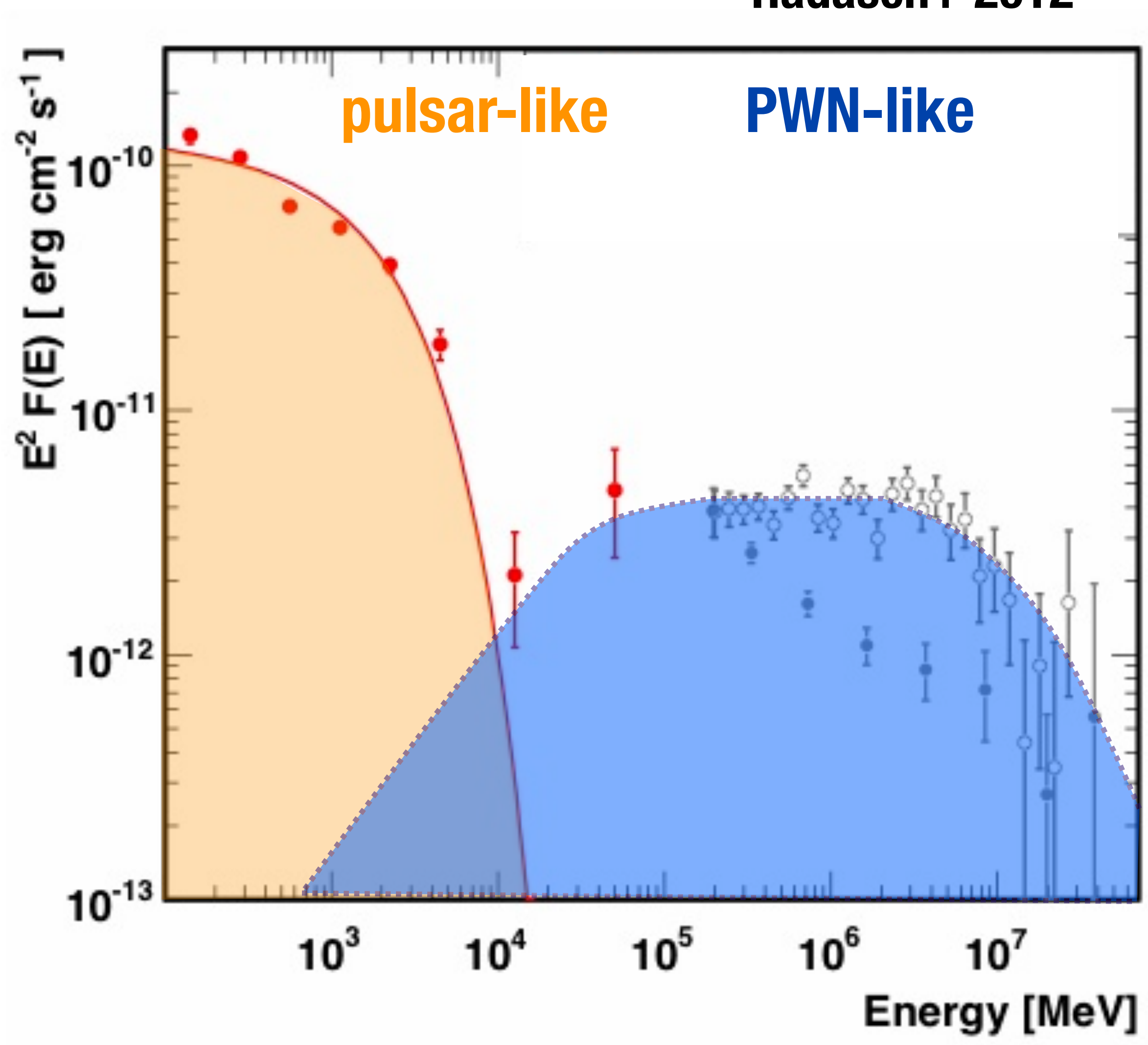
- Consensus
  - inv. Compton + synchrotron + pair production + cascade
  - anisotropic IC, $\gamma\gamma$ produce modulations without intrinsic variability
  - particle acceleration is efficient in these systems
- Differing options
  - size & location of emitter
  - impact of various processes (cascades, Doppler boosting)
  - intrinsic variability (shock location, adiabatic timescale)
  - no consensus yet...

current puzzles

Gamma-ray emission

two components : pulsar & pulsar wind nebula (PWN) ?

Hadasch+ 2012



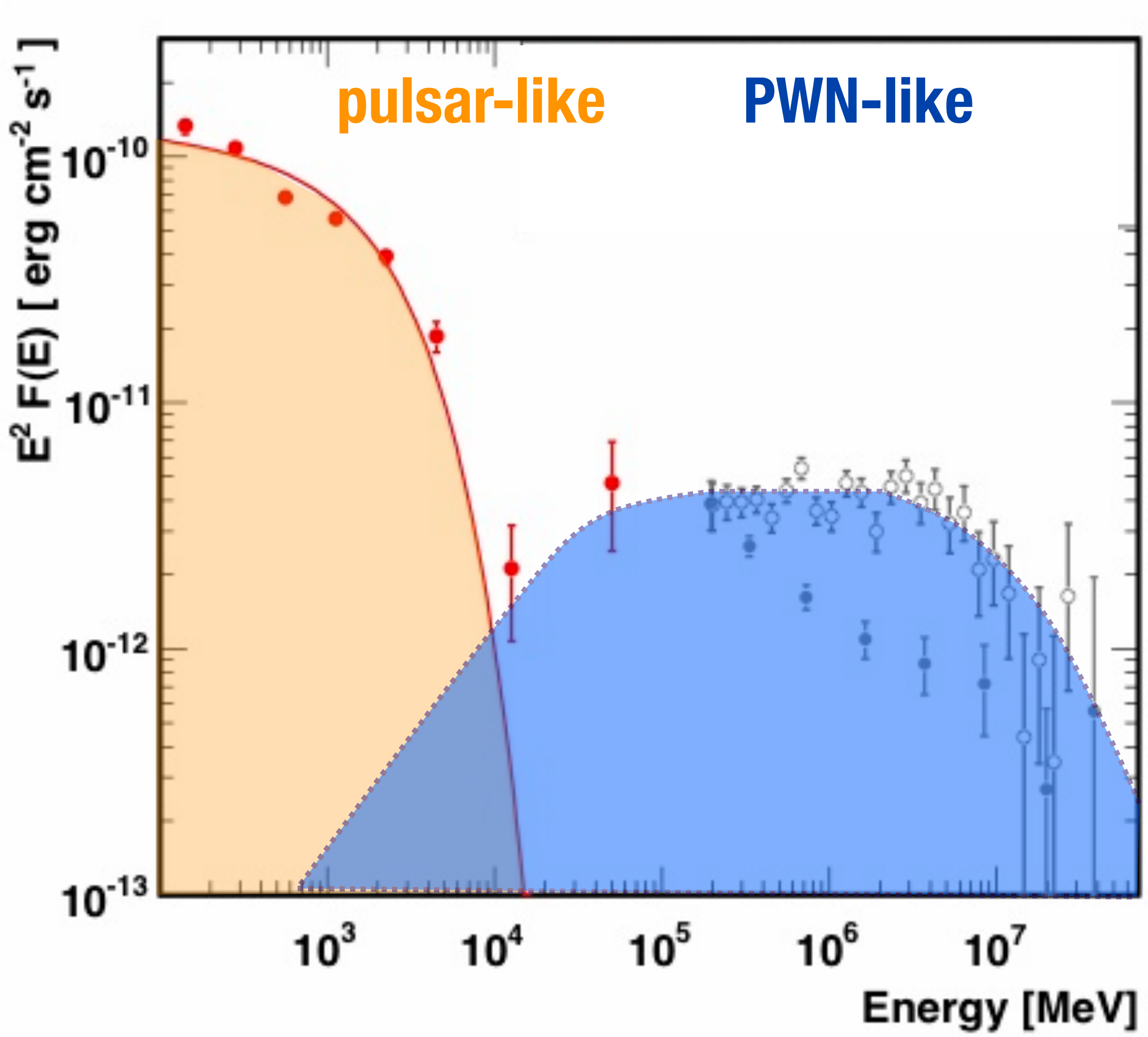
GeV spectra like that of the 100+ Fermi/LAT pulsars

TeV (X-ray) emission similar to pulsar wind nebulae

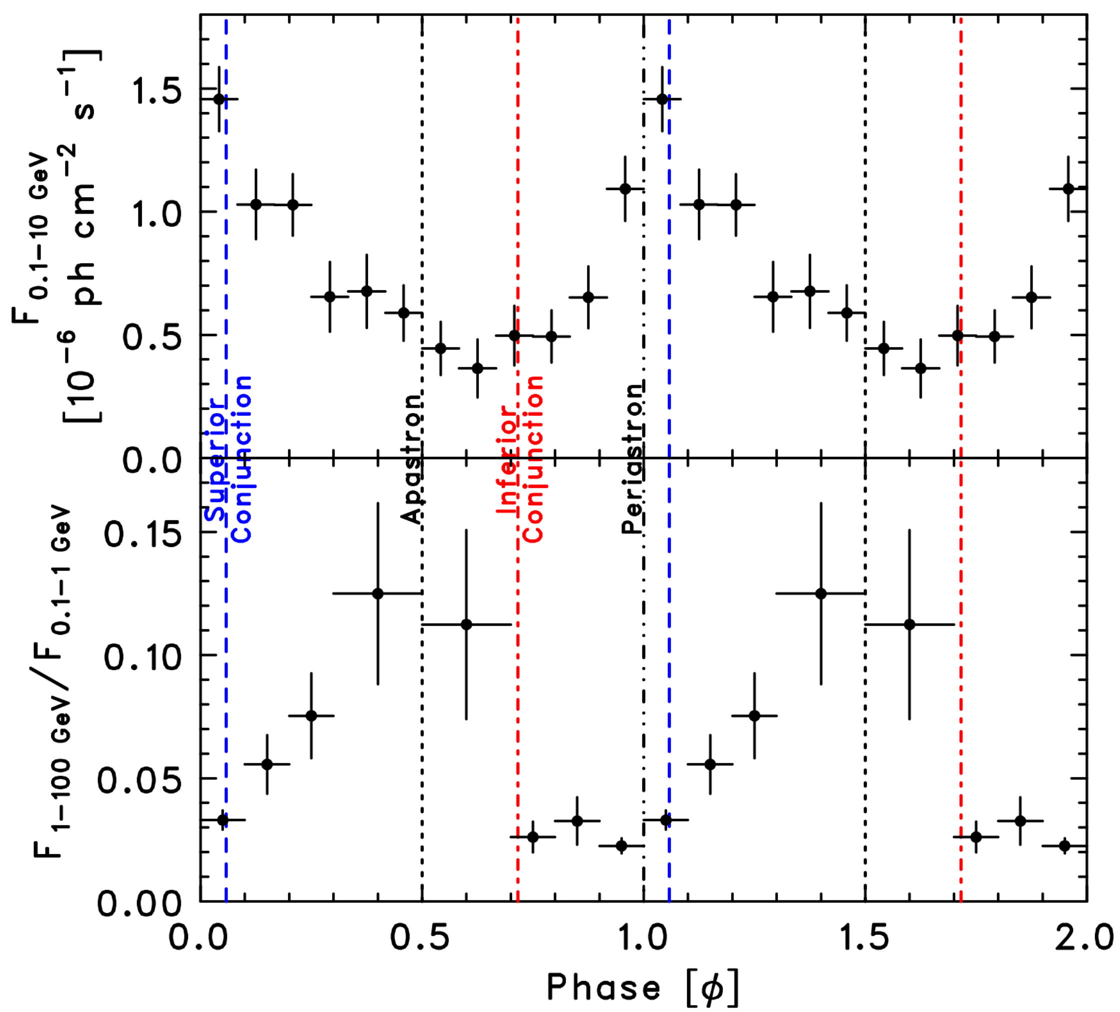
Puzzle: pulsar-like component

orbital modulation unexpected for pulsar emission within light cylinder

Hadasch+ 2012



Abdo+ 2009

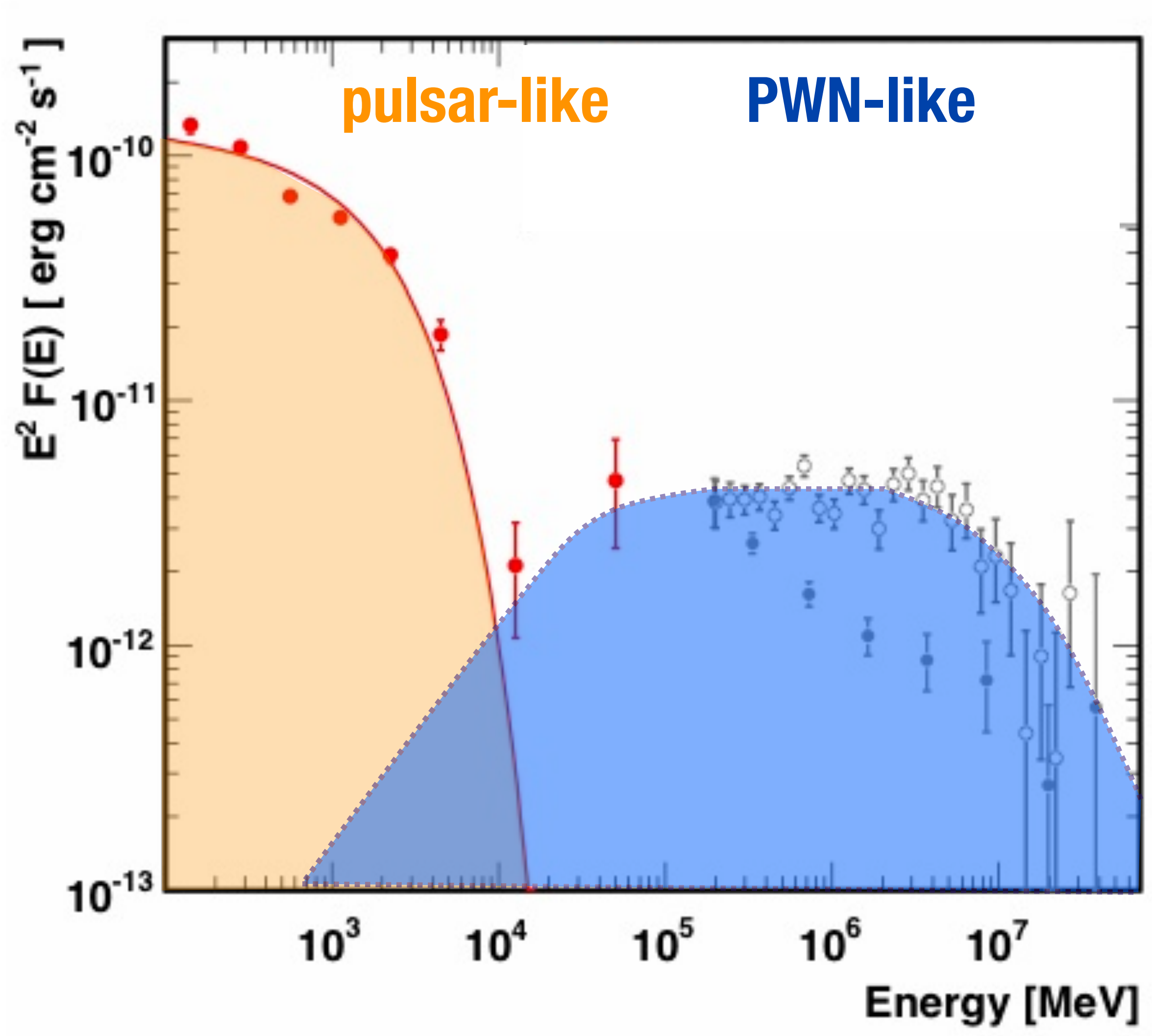


modulation best understood as inv. Compton on stellar light

Puzzle: pulsar-like component

orbital modulation unexpected for pulsar emission within light cylinder

Hadasch+ 2012



origin of pulsar-like component

- striped wind (Pétri & GD 2011)
- cold wind (à la Khangulyan+ 2012)
- thermalized particles at shock (Zabalza+ 2013, GD & Cerutti 2013)
- shocked stellar wind (Bednarek 2011)

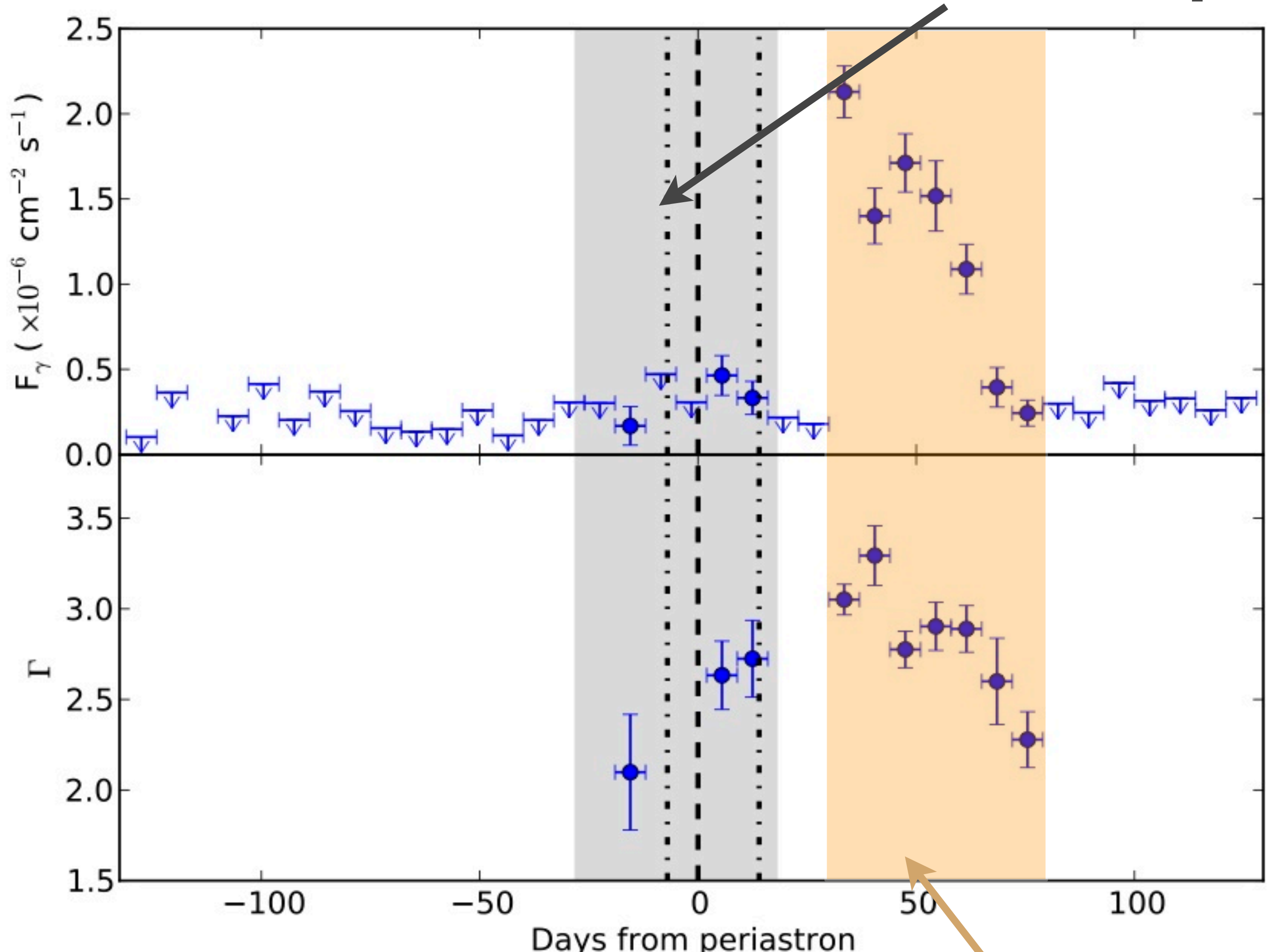
a clue to pulsar emission process ?

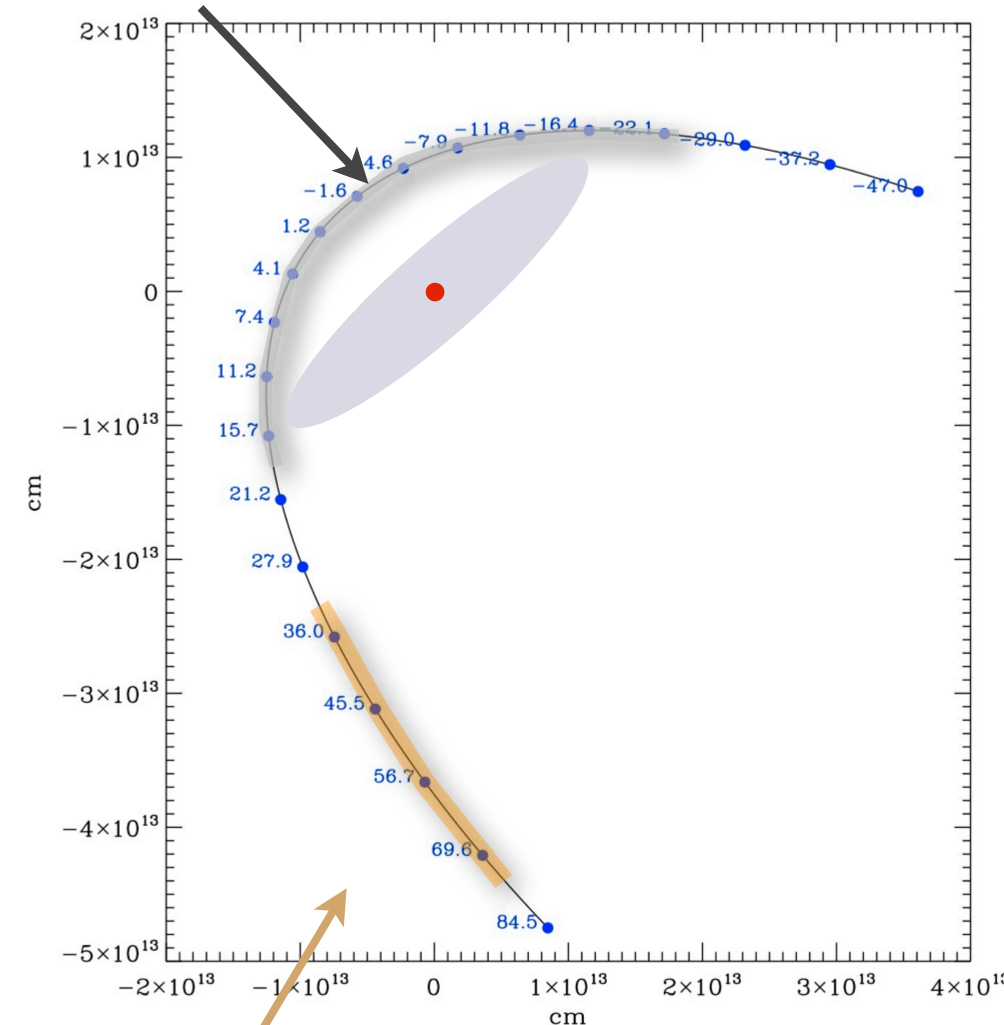
Puzzle: GeV flare of PSR B1259-63

Fermi/LAT lightcurve (Abdo et al. 2011)

max expected here

orbit close to periastron



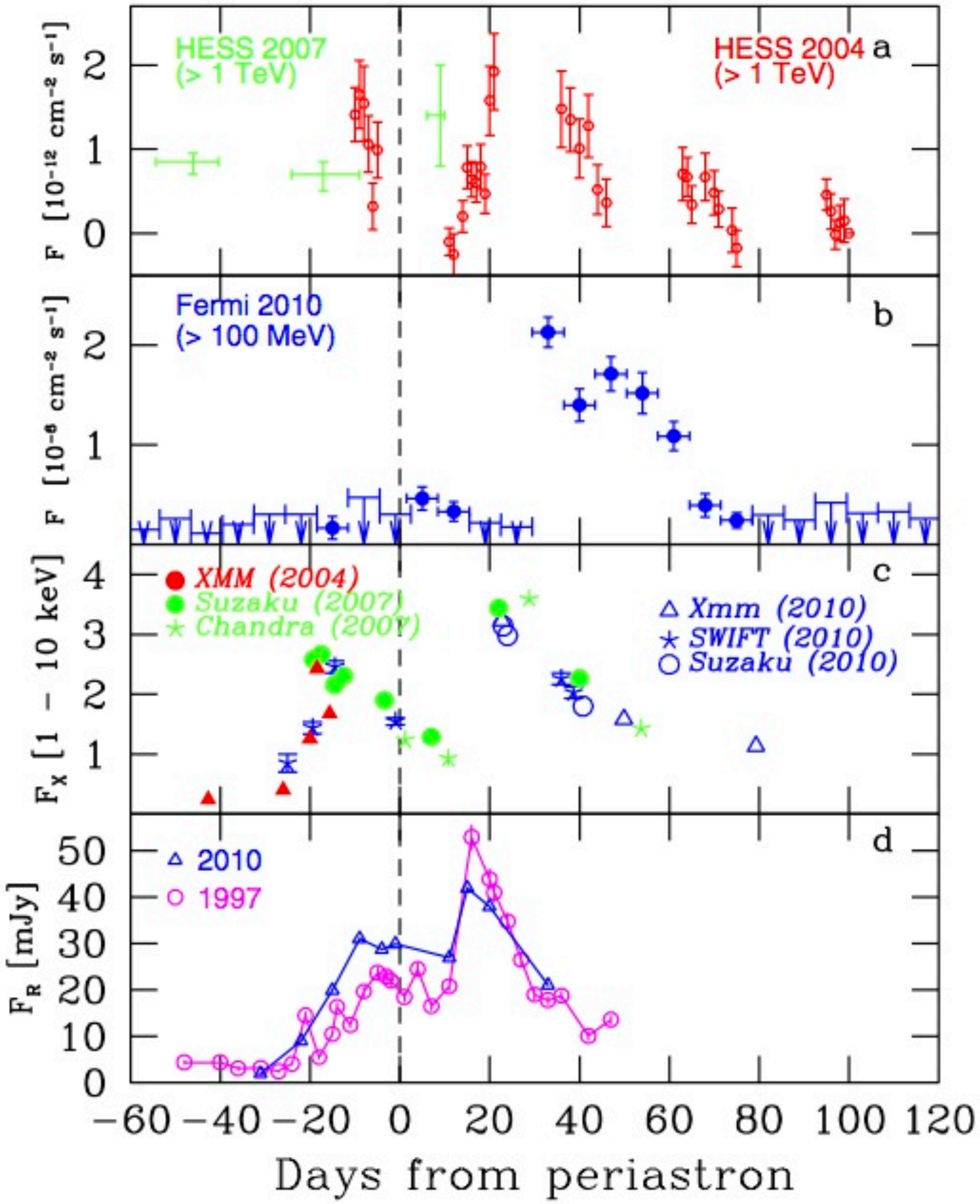


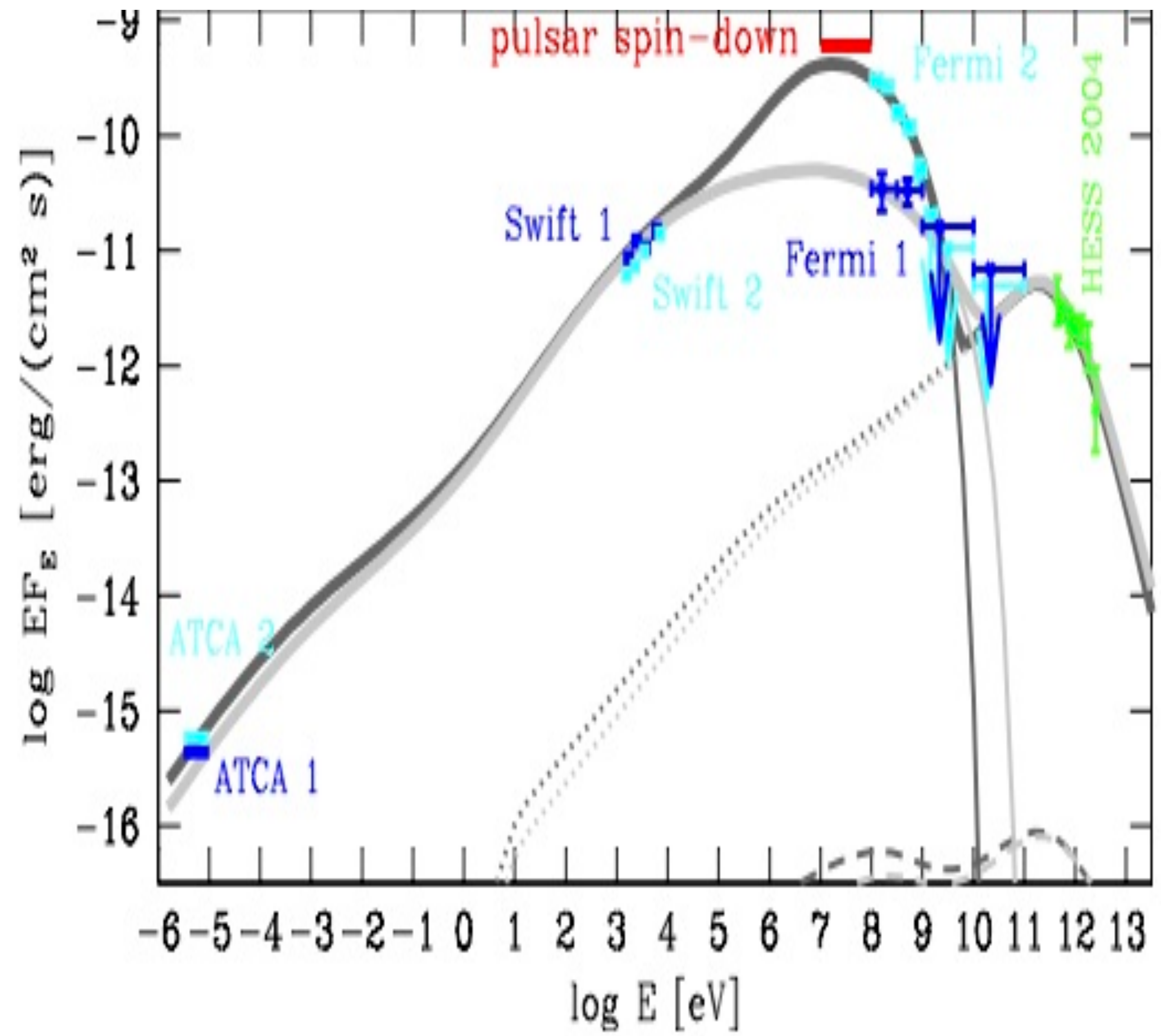
max occurred here

- **Fermi/LAT detection at periastron mid-December 2010 (next in 5/2014)**
- **orbital phasing unexpected for inverse Compton scattering of stellar photons**

Puzzle: GeV flare of PSR B1259-63

Fermi/LAT lightcurve (Abdo et al. 2011)





- **high L_γ → nearly all spindown power radiated away at peak**
- **GeV-only flare**

Puzzle: GeV flare of PSR B1259-63

Extremely efficient radiation with Lγ ~ spindown power !

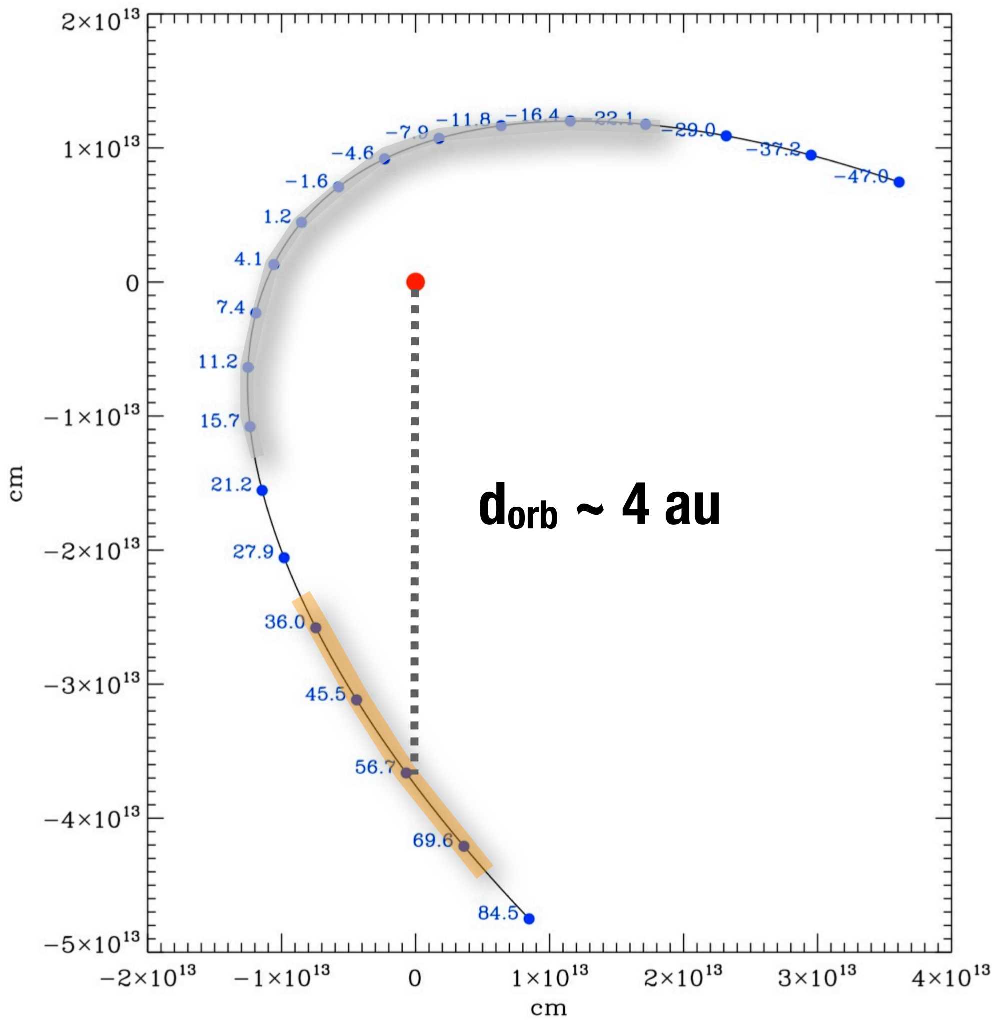
If inverse Compton, need very high radiation density to allow electrons to cool on a scale ~ d_{orb}

- Be disc photons ? (Khangulyan+ 2012)
- SSC on PWN emission ? (GD & Cerutti 2013)

Alternatives to IC

- Doppler boosting (Kong+ 2012)
- conversion to EM wave (Mochol & Kirk 2013)
- Crab-like reconnection unrelated to orbit ?

orbit close to periastron



periastron : May 2014

The puzzling γ-ray binaries

- Gamma-ray binaries powered by pulsar spindown, energy dissipated in shock with stellar wind → new probes of pulsar physics

- Puzzle: the GeV spectral component

  Is the similarity with emission from other pulsars telling us something about pulsar physics or ... a red herring ?

- Puzzle: the gamma-ray flare of PSR B1259-63

  Is it due to complex inverse Compton geometry (need simulations of interaction region) or is it evidence for alternate emission mechanisms ?

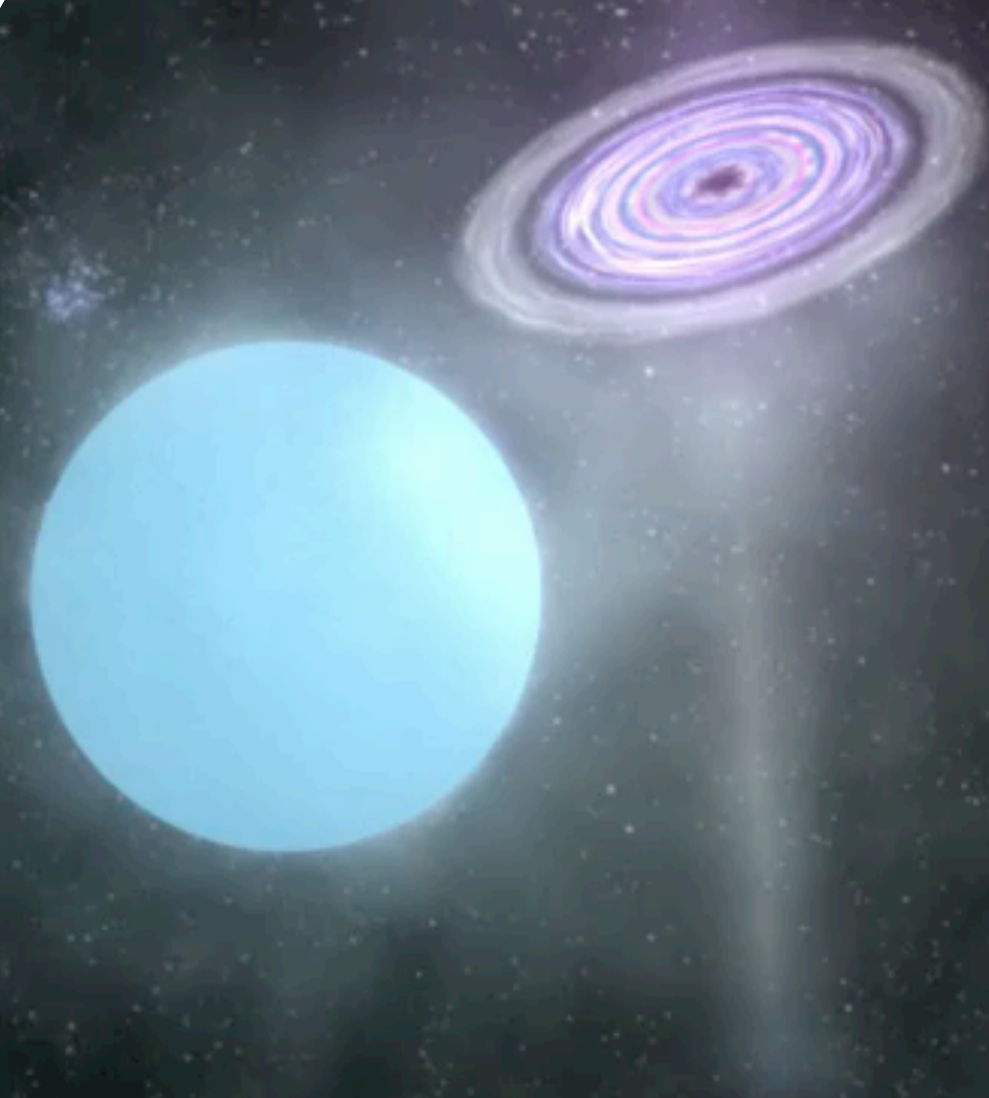
A microquasar in gamma rays: Cygnus X-3

Cygnus X-3

only confirmed γ-ray microquasar (good evidence also for Cyg X-1)

Tavani et al. 2009 (AGILE) Abdo et al. 2009 (Fermi)

4.8hr orbital modulation (X, γ)

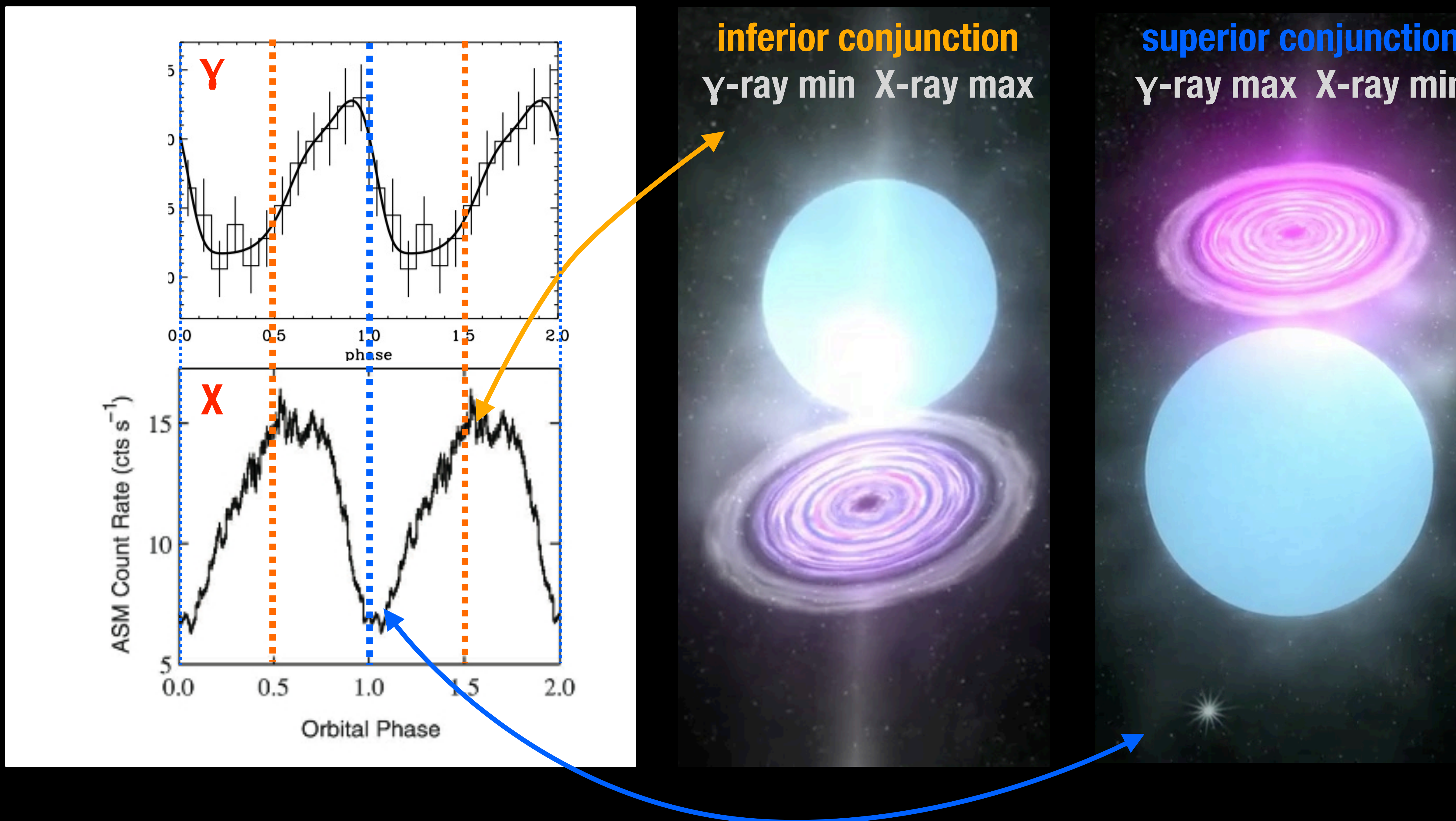


Wolf-Rayet + black hole (?)

Credit: W. Feimer/NASA/GSFC

γ-ray & X-ray modulation

inverse Compton on ★ photons

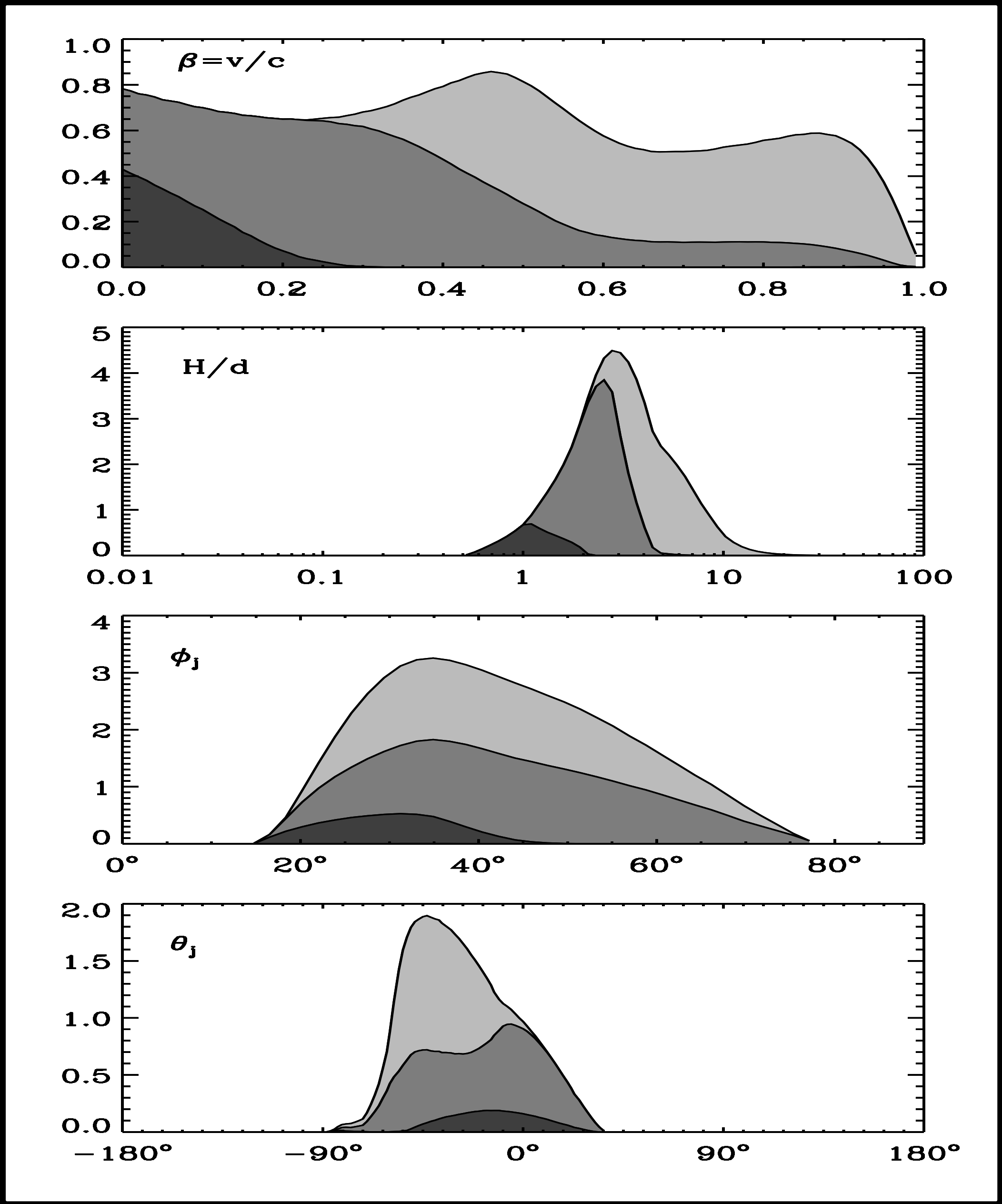


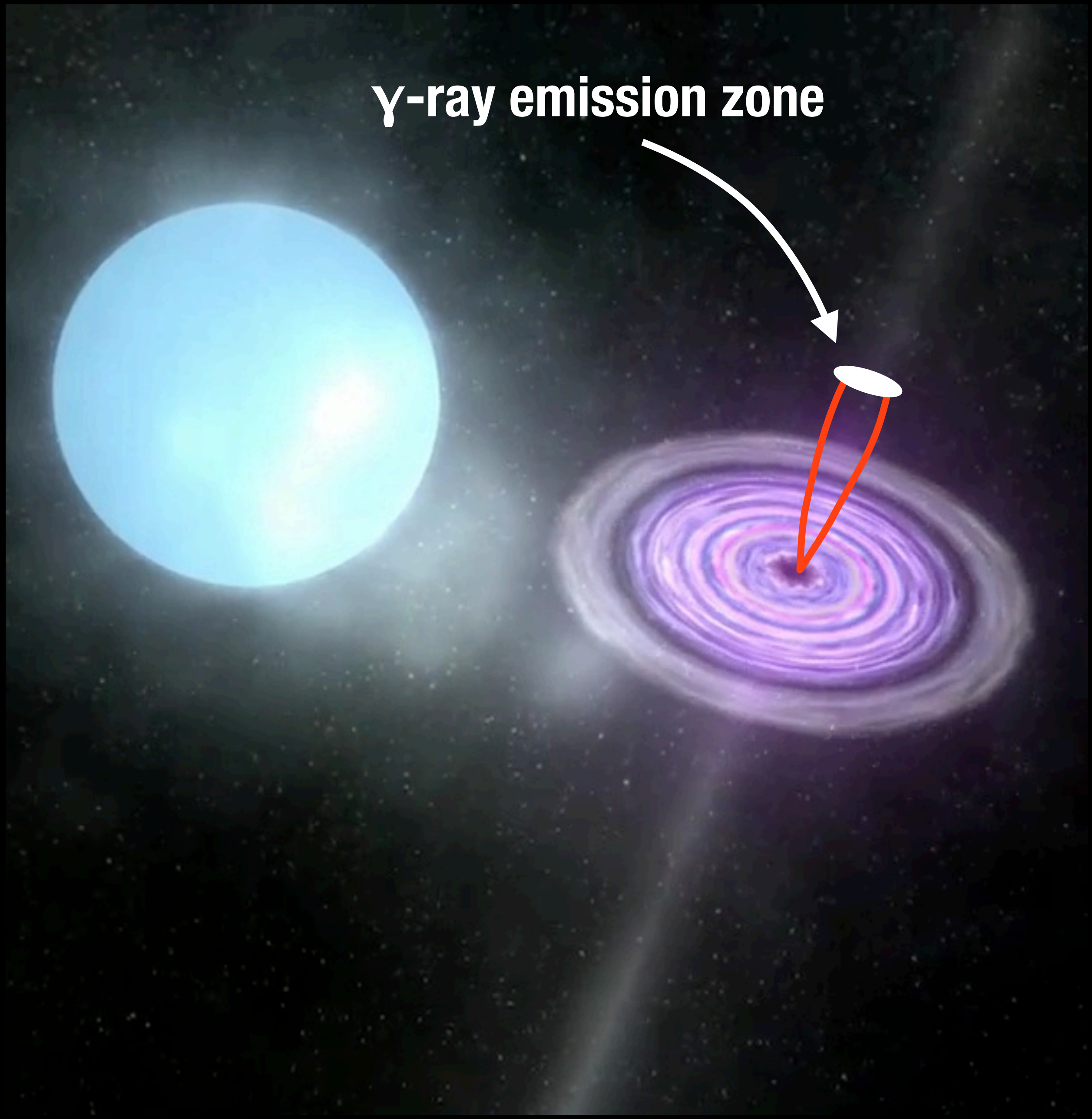
Abdo+ (Fermi/LAT coll.) 2009

γ-ray & X-ray modulation

inverse Compton on ★ photons ⇒ γ-ray emission zone far out

GD+ 2010



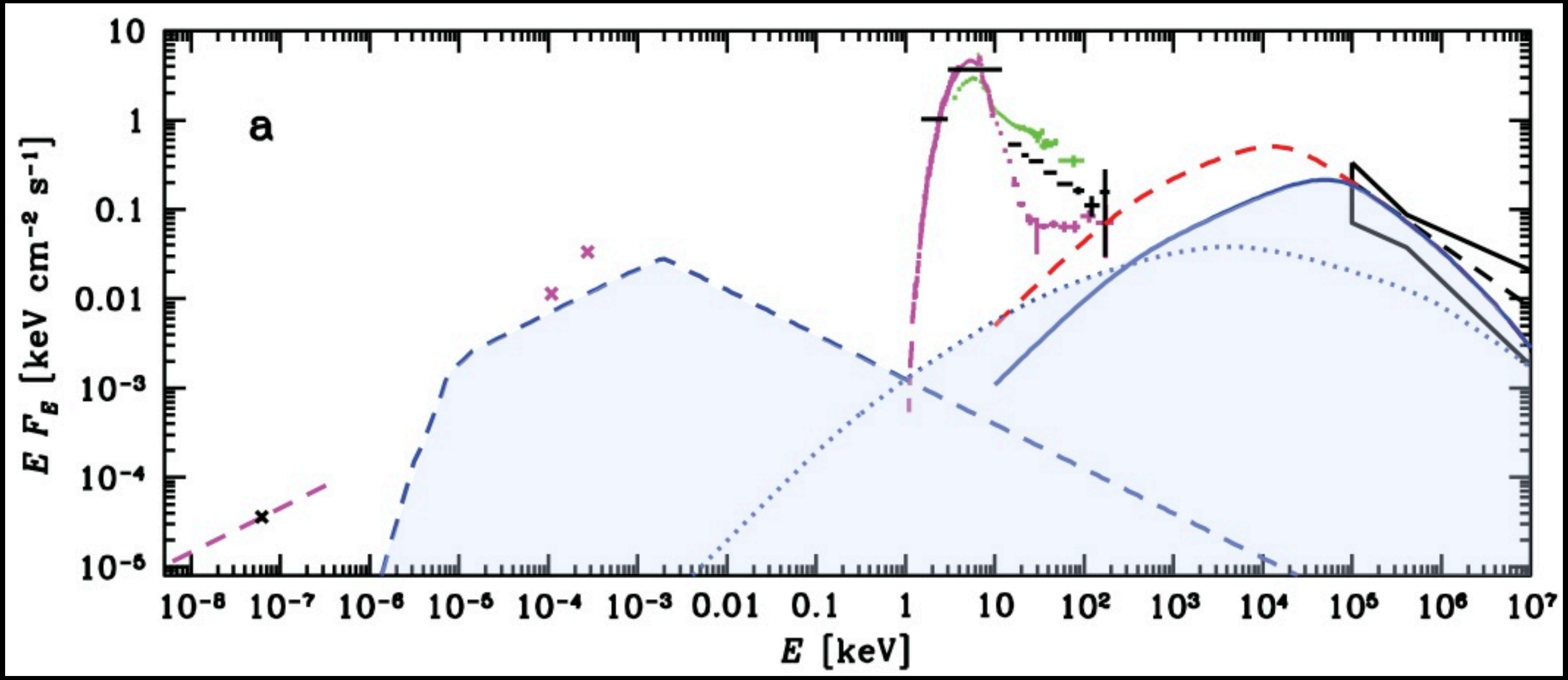


γ-ray & X-ray modulation

different origin for hard X-rays and γ-rays

- accretion disk corona excluded (γγ + modulations)
- injection energy $\gamma_{inj} \approx 1000$
- magnetic field B<100 G
- $L_{jet} \approx 10^{38}$ erg/s

Cerutti et al. 2011, Zdziarski et al. 2012a, b

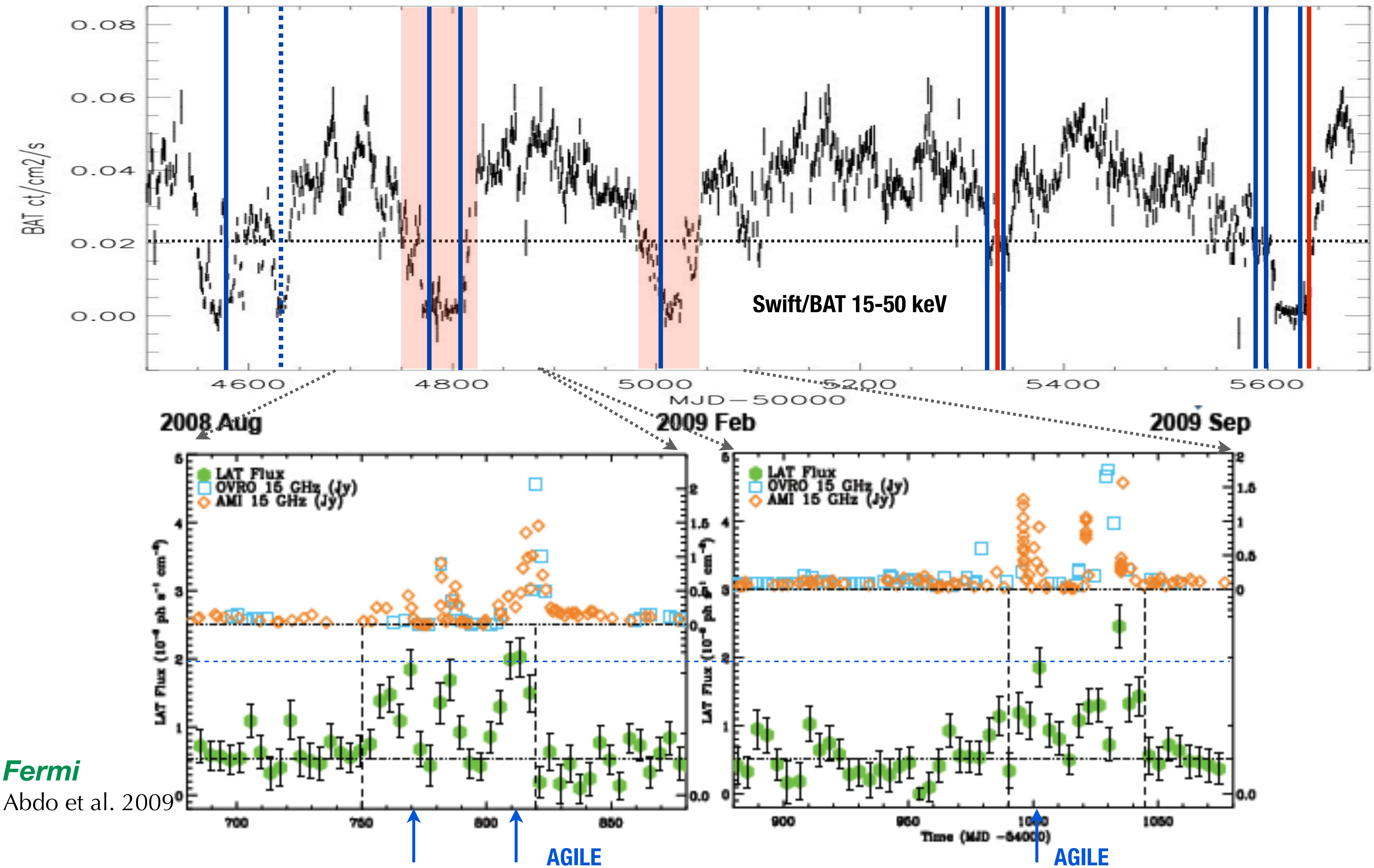


γ-rays <10% X-rays

Cygnus X-3 flares

AGILE & Fermi/LAT detections

Tavani et al. 2009, Abdo et al. 2009, Williams et al. 2011, + ATels

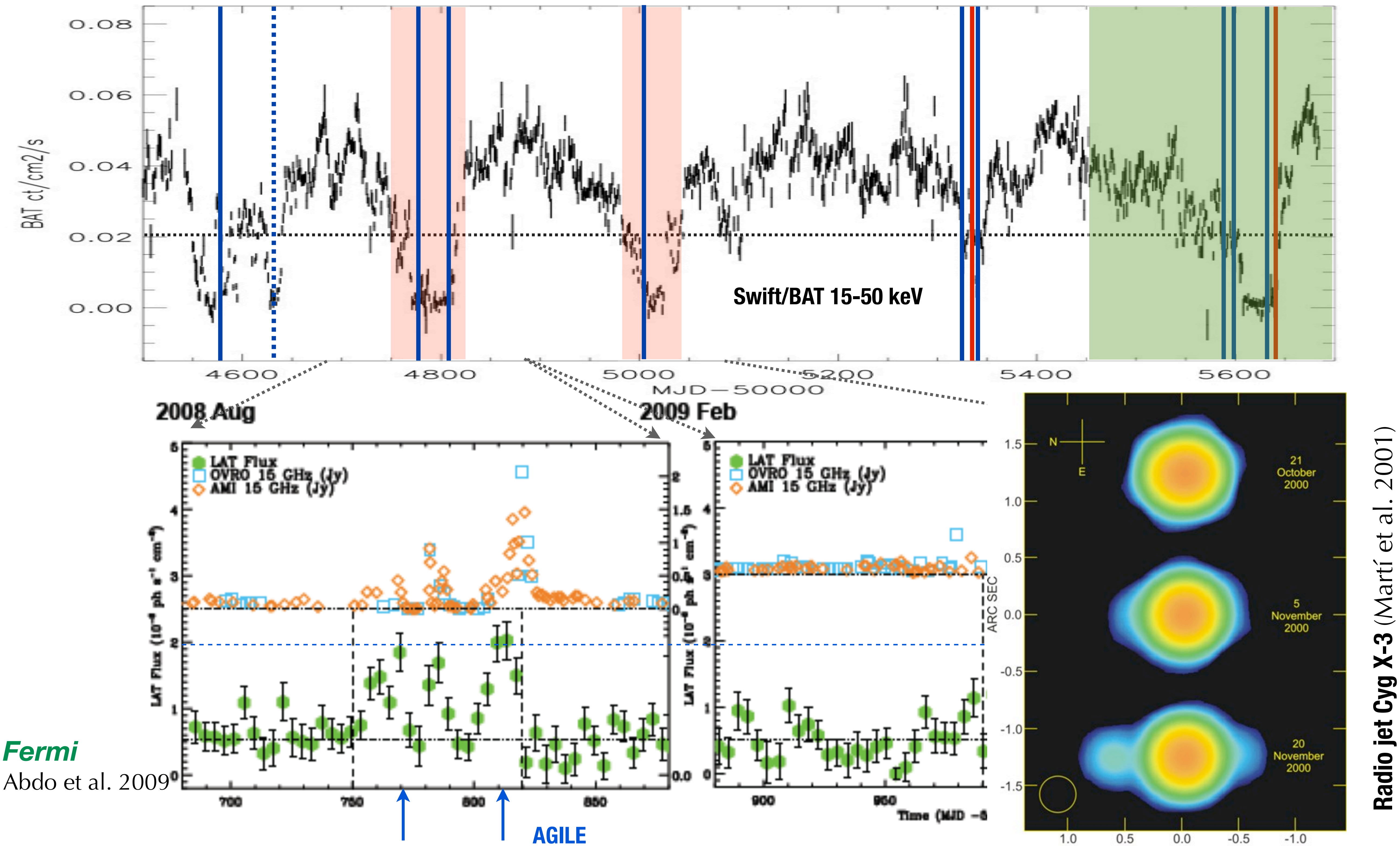


Fermi
Abdo et al. 2009

Cygnus X-3 flares

AGILE & Fermi/LAT detections

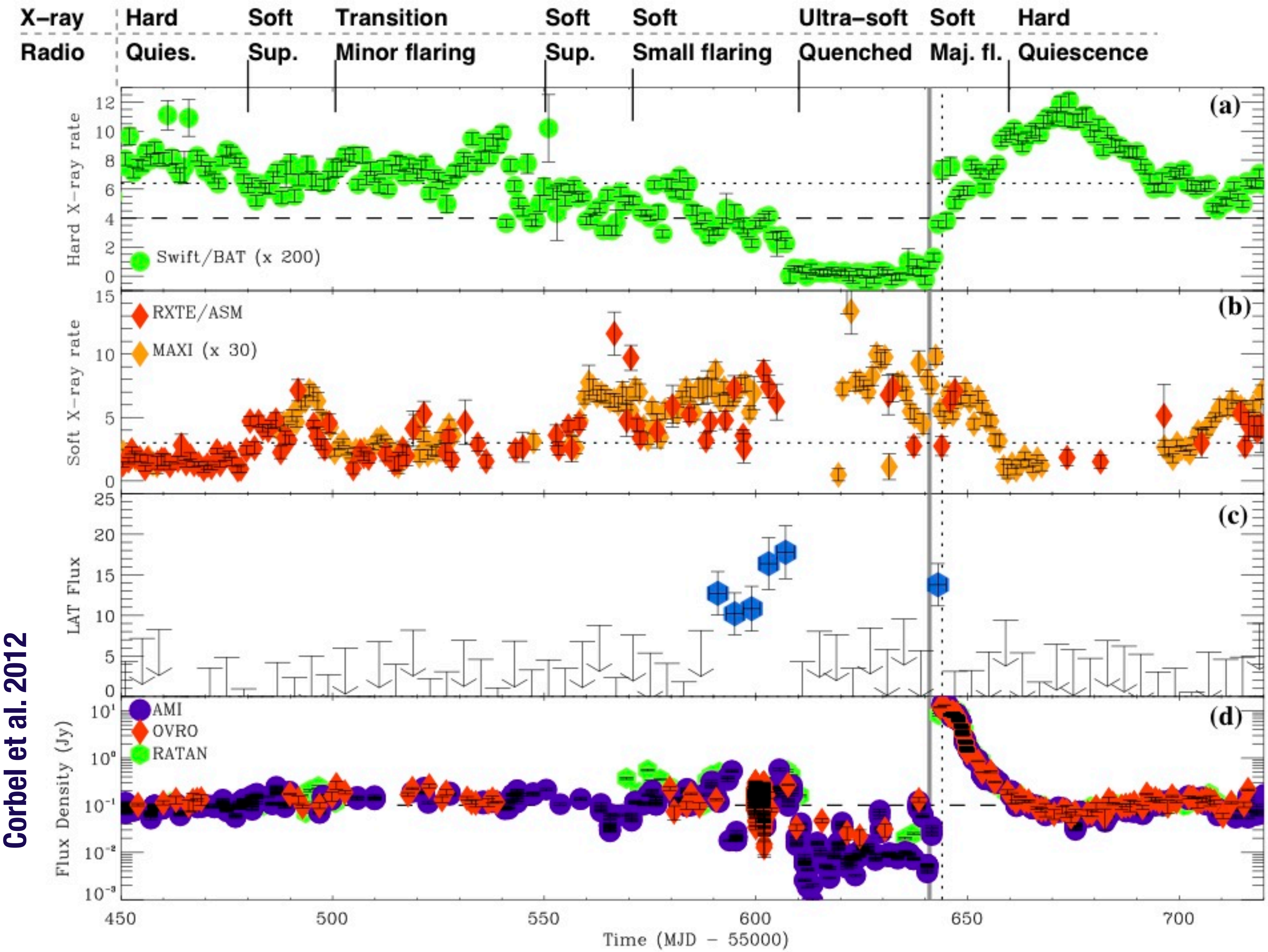
Tavani et al. 2009, Abdo et al. 2009, Williams et al. 2011, + ATels



Fermi
Abdo et al. 2009

Radio jet Cyg X-3 (Martí et al. 2001)

γ-ray & X-ray emission are linked



Corbel et al. 2012

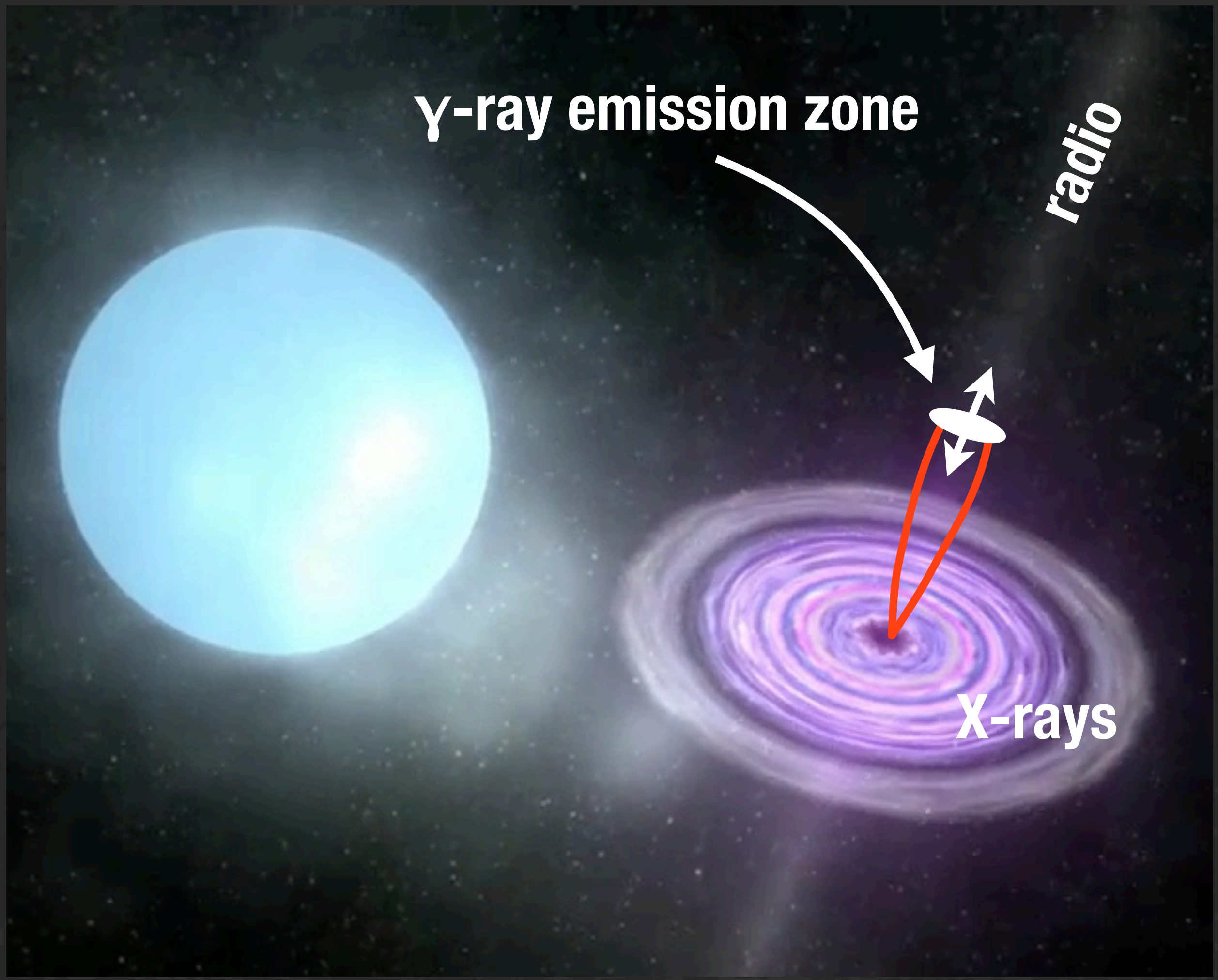
Accretion

non-thermal / thermal

Ejection

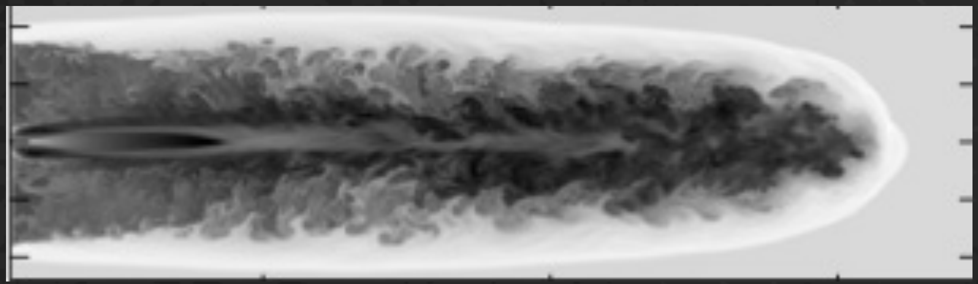
A window into accretion-ejection

- How are γ-rays, X-rays and radio connected ?



- How unique is Cyg X-3 ?

- Are γ-rays produced at a recollimation shock ?

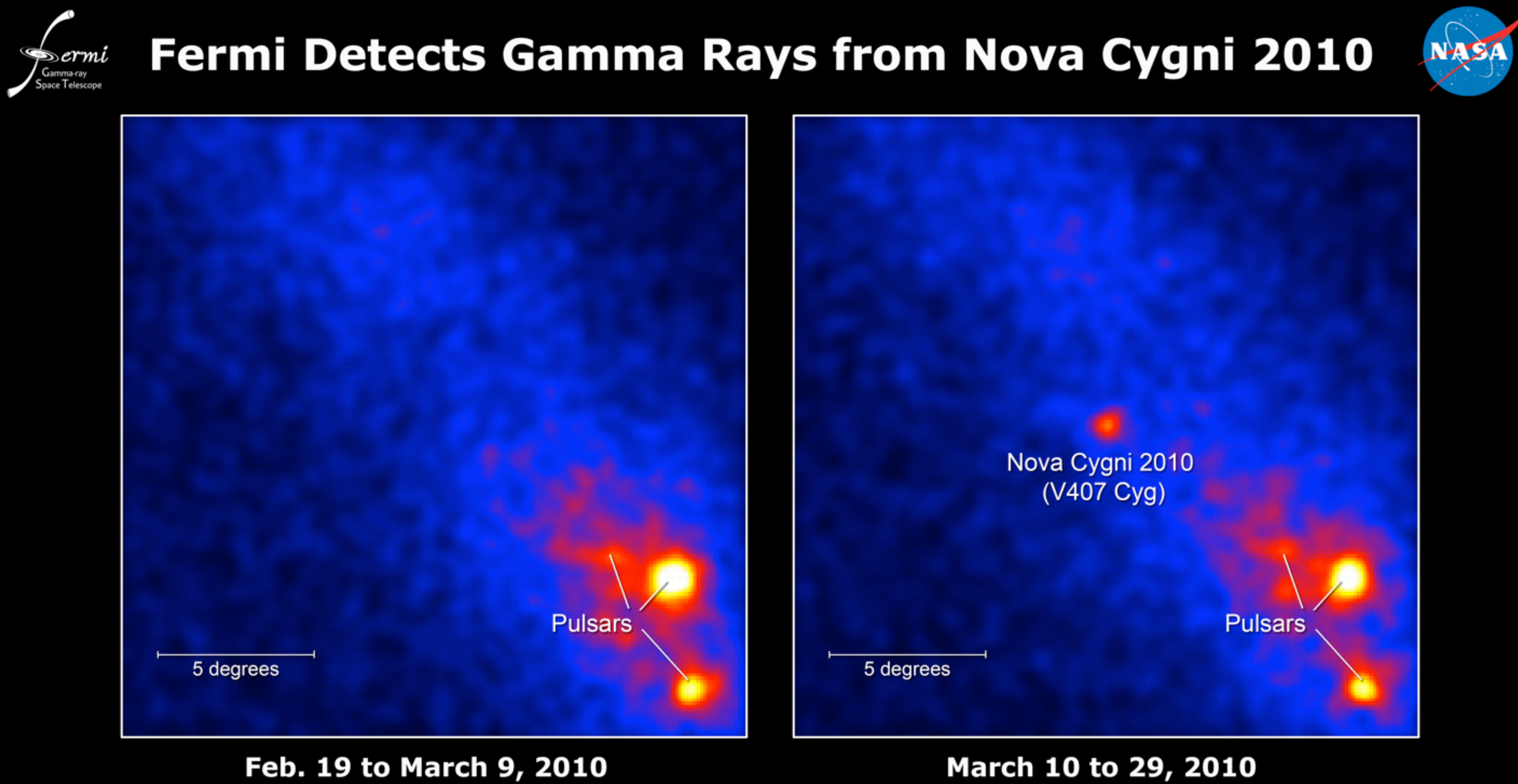


Perucho et al. 2010

- How is its formation related to the conditions in the corona, radio jet?

A nova in gamma rays:
V407 Cyg

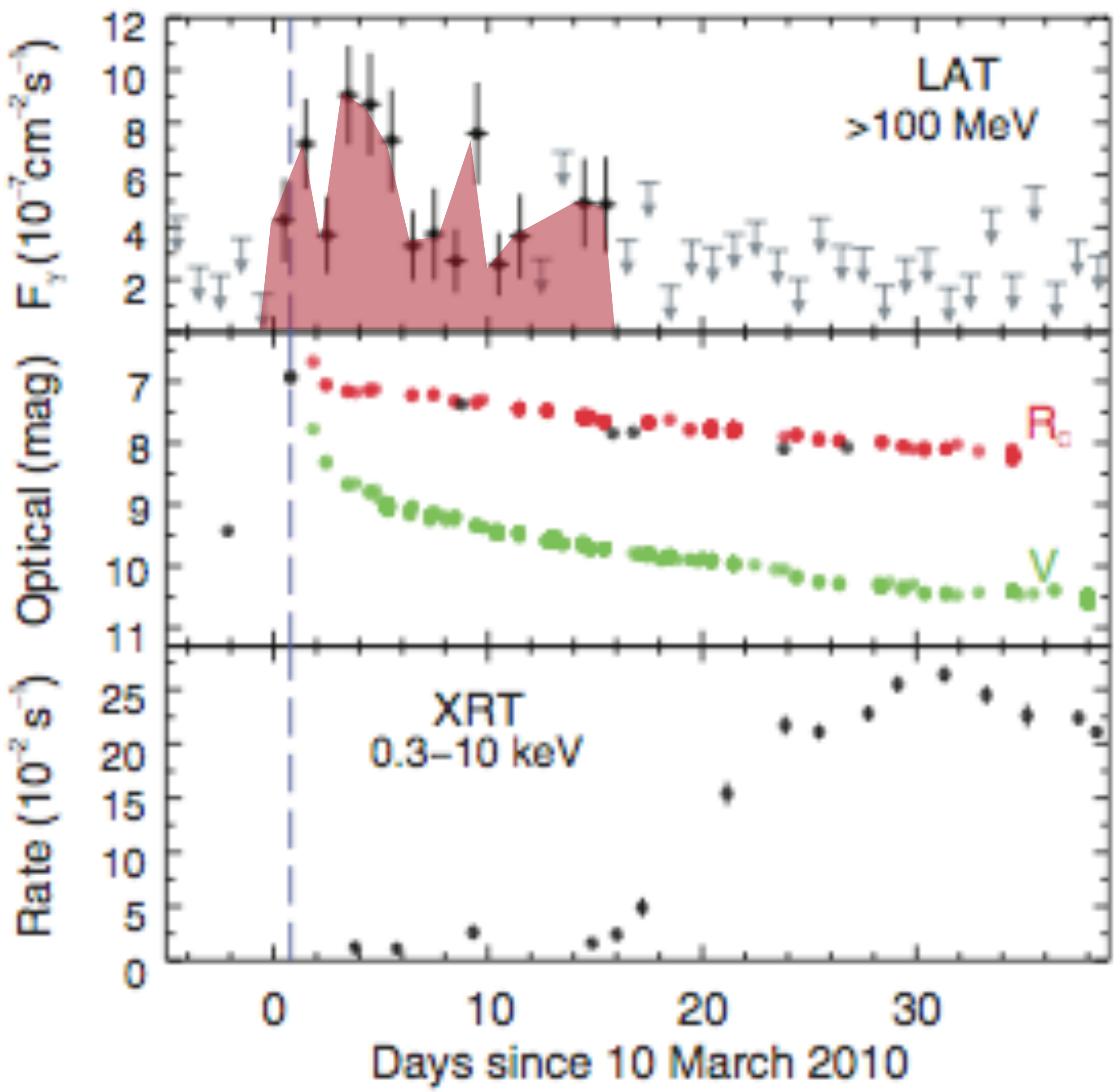
A surprising transient



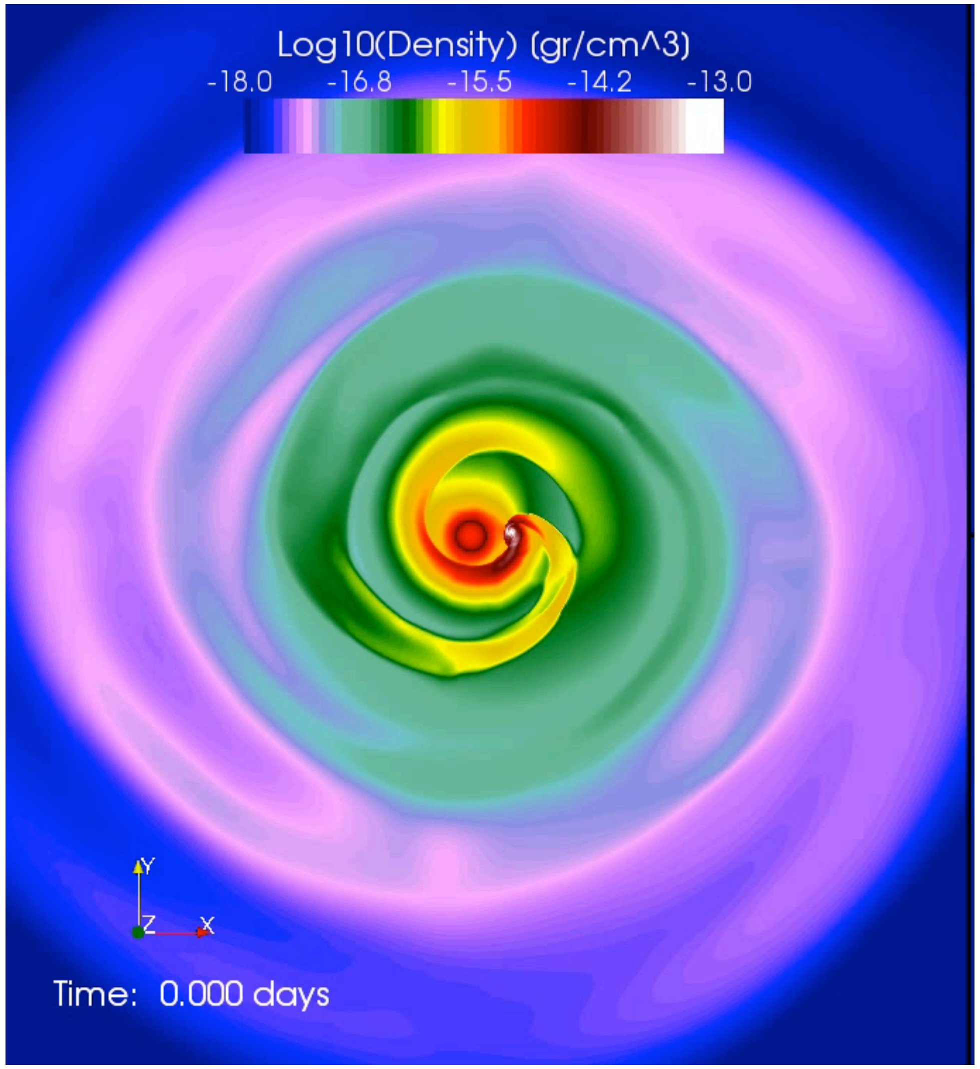
Gamma-rays from V407 Cyg

- symbiotic system: red giant wind & radiation
- thermonuclear runaway WD ejects 10^{-6} $M_\odot$ at ~ 3000 km/s

Abdo et al. (Fermi) 2010



Walder, Folini & Shore 2008

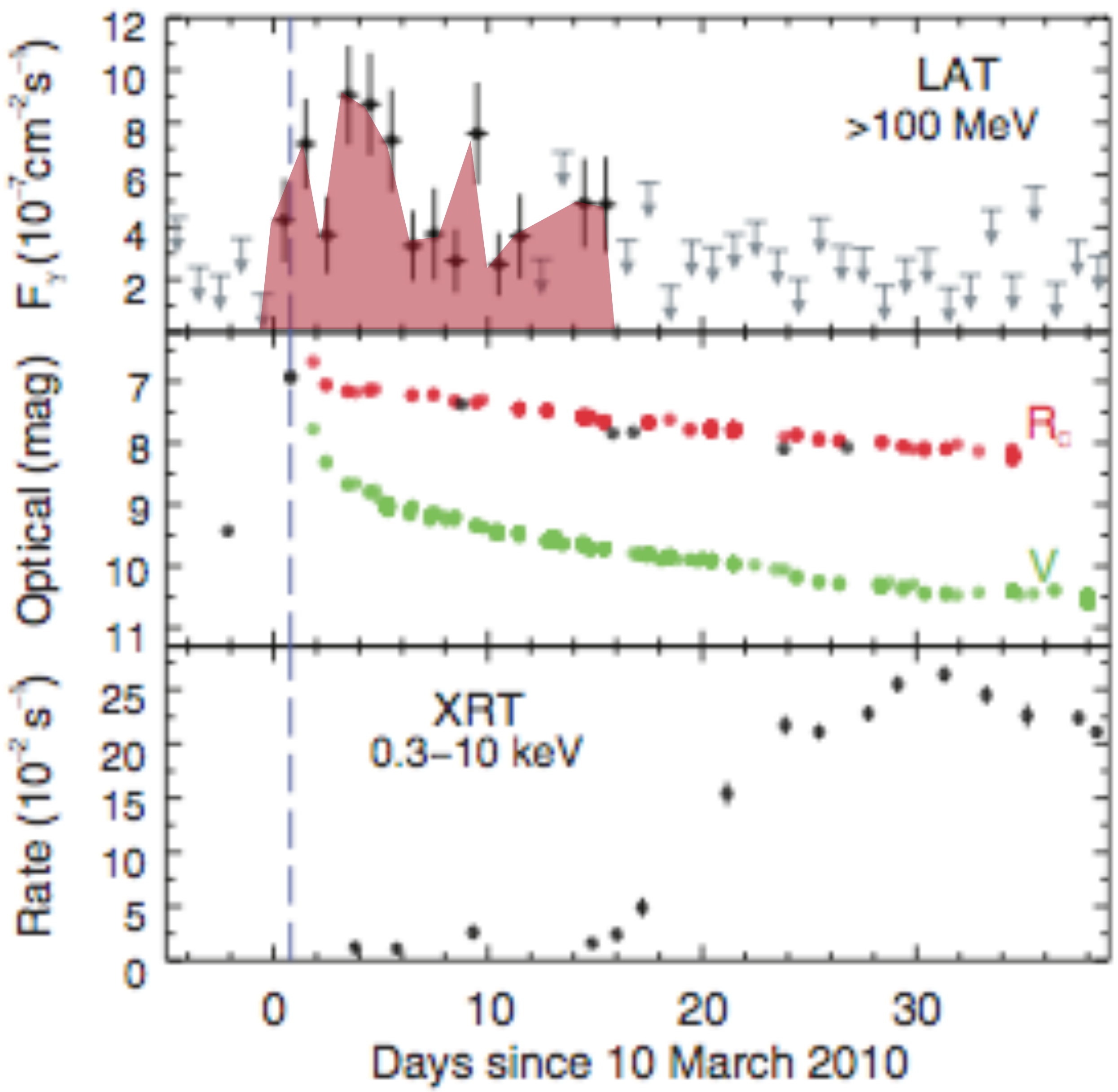


Gamma-rays from V407 Cyg

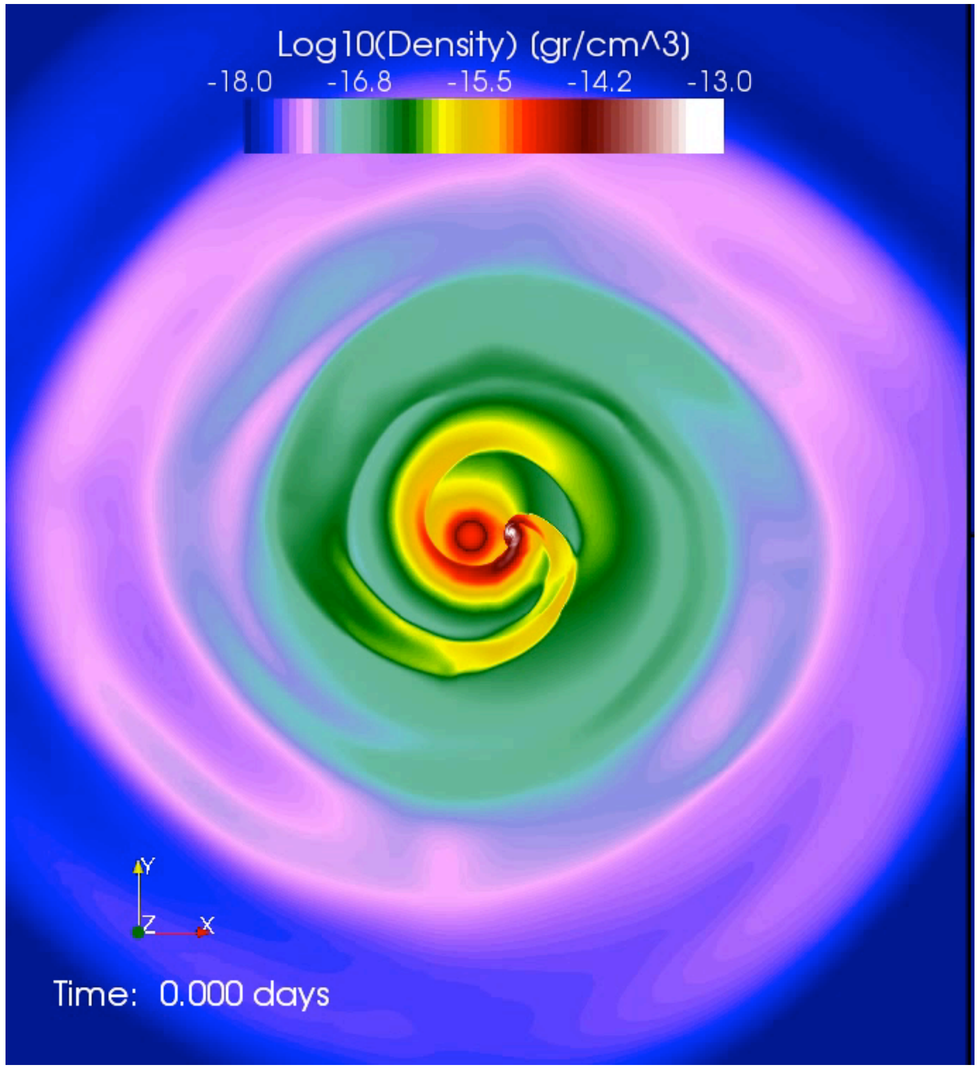
- Mini-supernova, 10^{44} erg, developping in “real time”
- γ-rays: π_0 & IC on e^-, thermal X-rays from shocked material

Tatischeff & Hernanz 2007

Abdo et al. (Fermi) 2010

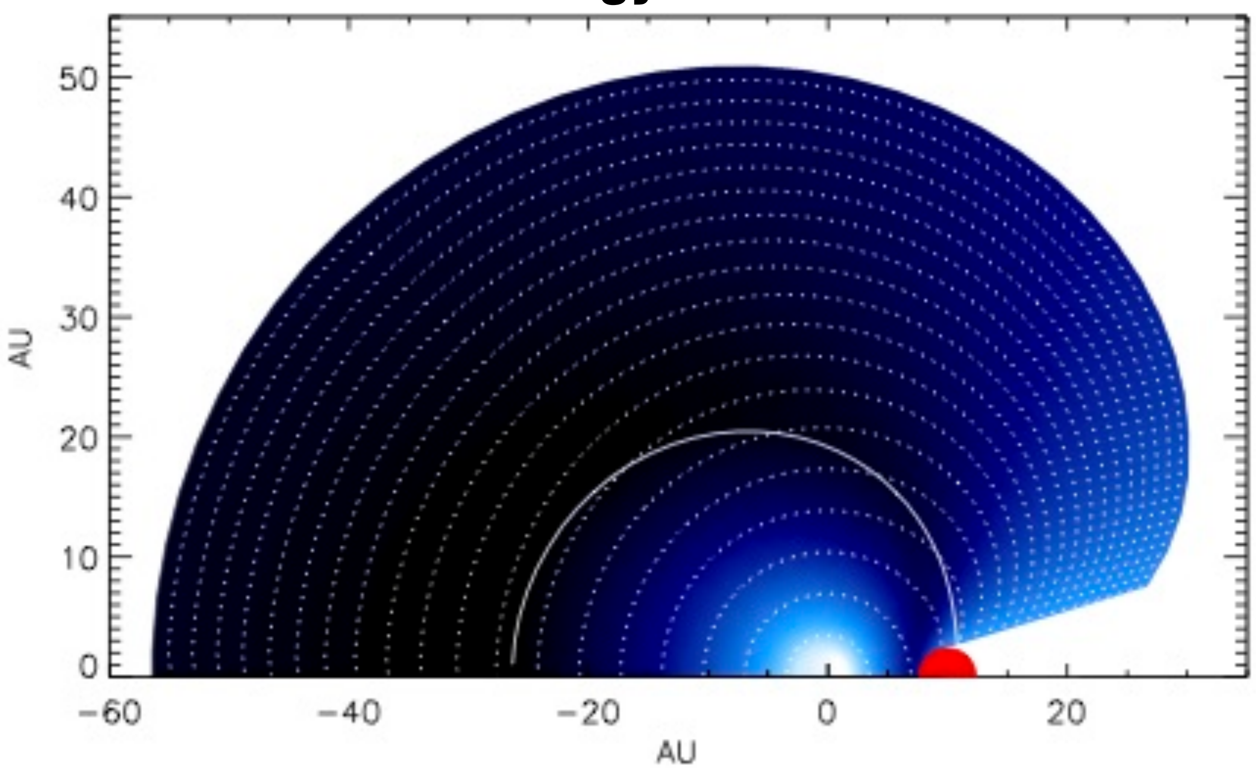


Walder, Folini & Shore 2008

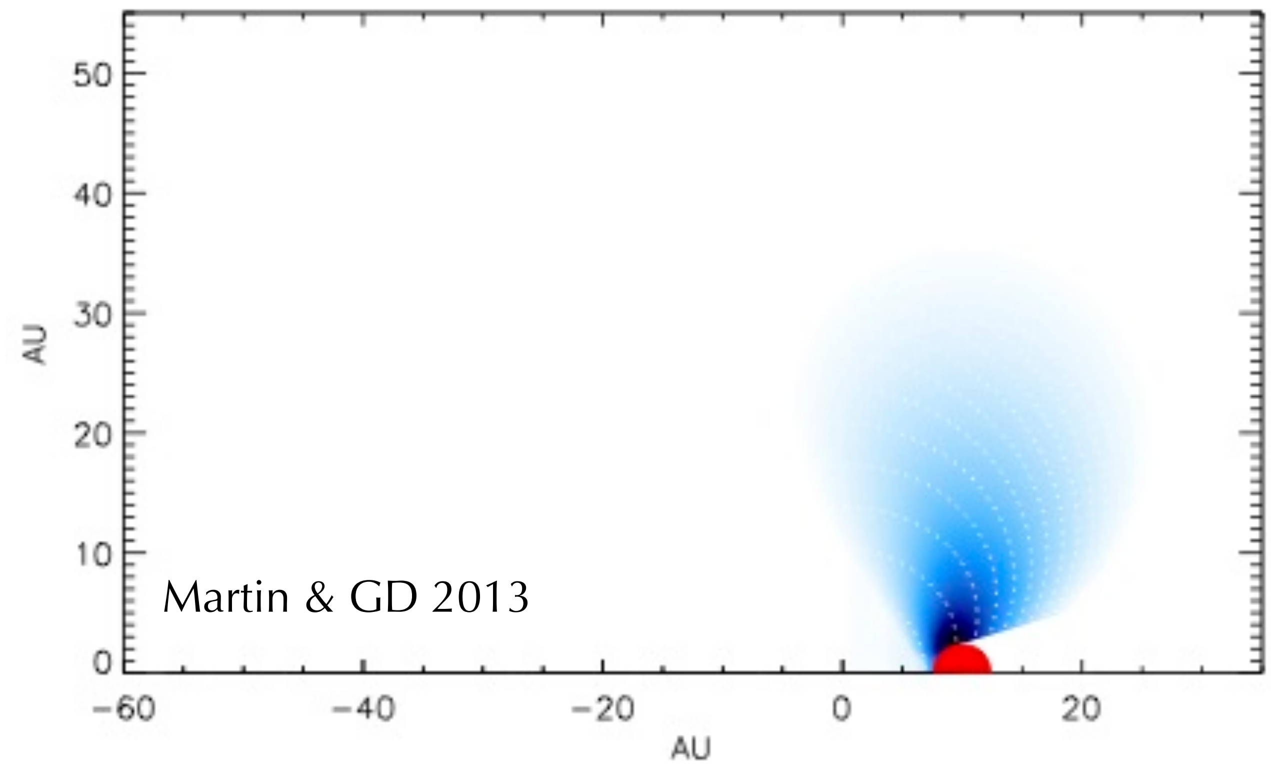


SNR evolution in ‘real’ time

max electron energy



IC emission

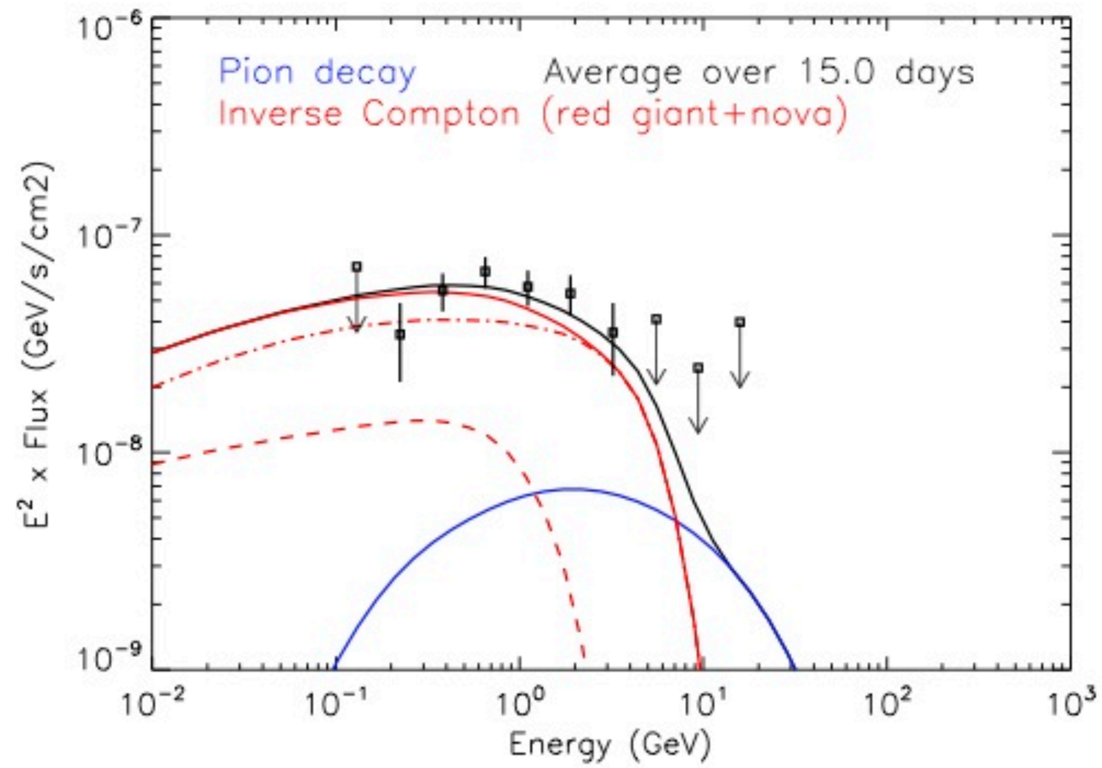


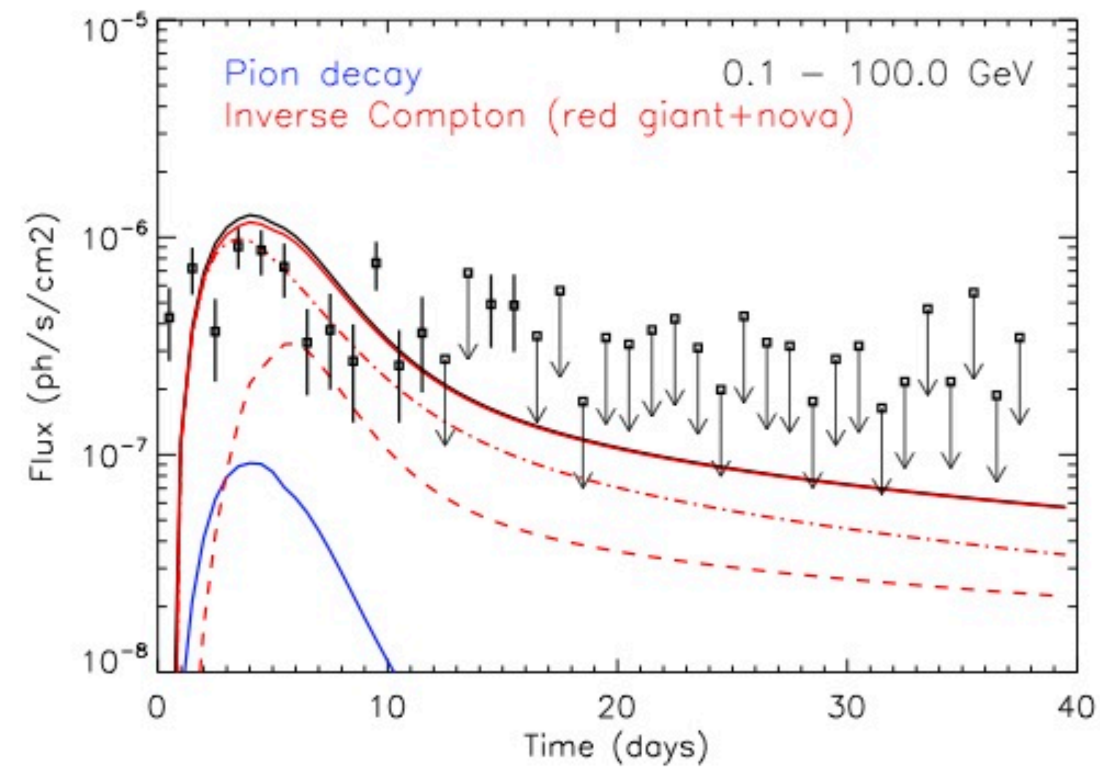
γ-ray Razzaque+ 2010, Sitarek+Bednarek 2012 **X-ray** Nelson+, Orlando+ 2012 **radio** Chomiuk+ 2013

time & location-dependent γ-ray, X-ray, radio emission depends on

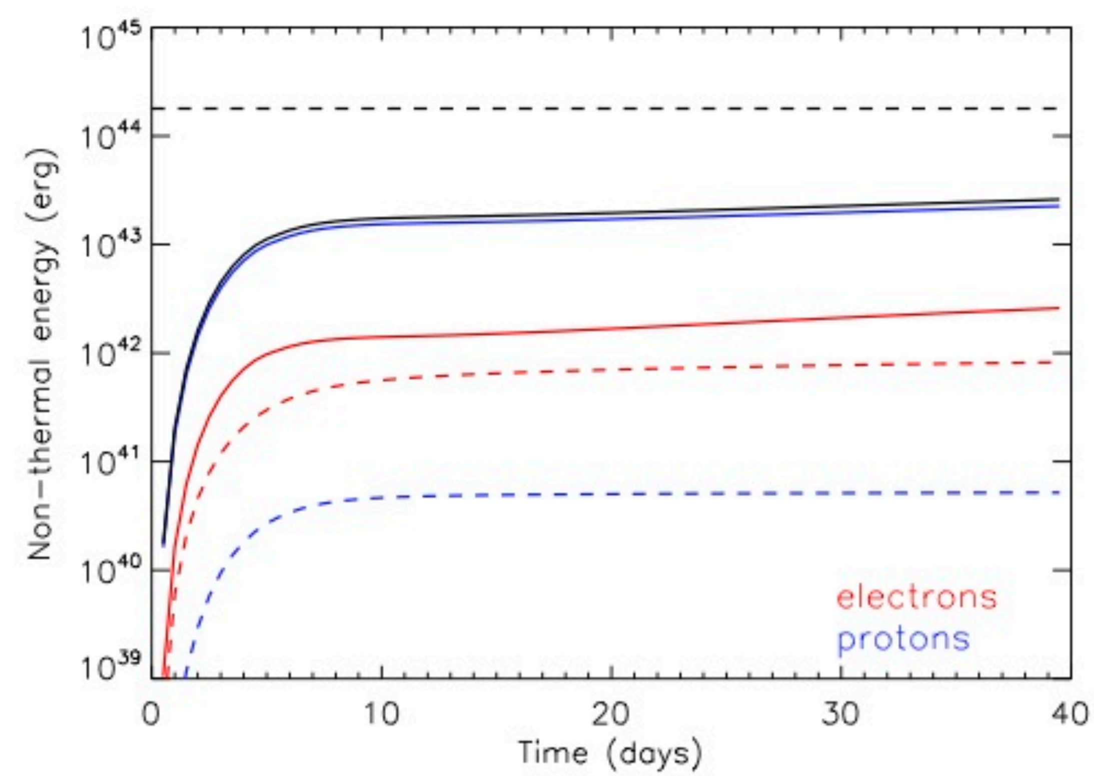
- **ejecta parameters (~10^{-6} $M_\odot$ at 3000 km/s)**
- **system parameters (stellar wind, radiation, separation, circumstellar material)**
- **acceleration parameters (test particle, diffusion eff., B field, e-/p inj. fraction)**

SNR evolution in ‘real’ time





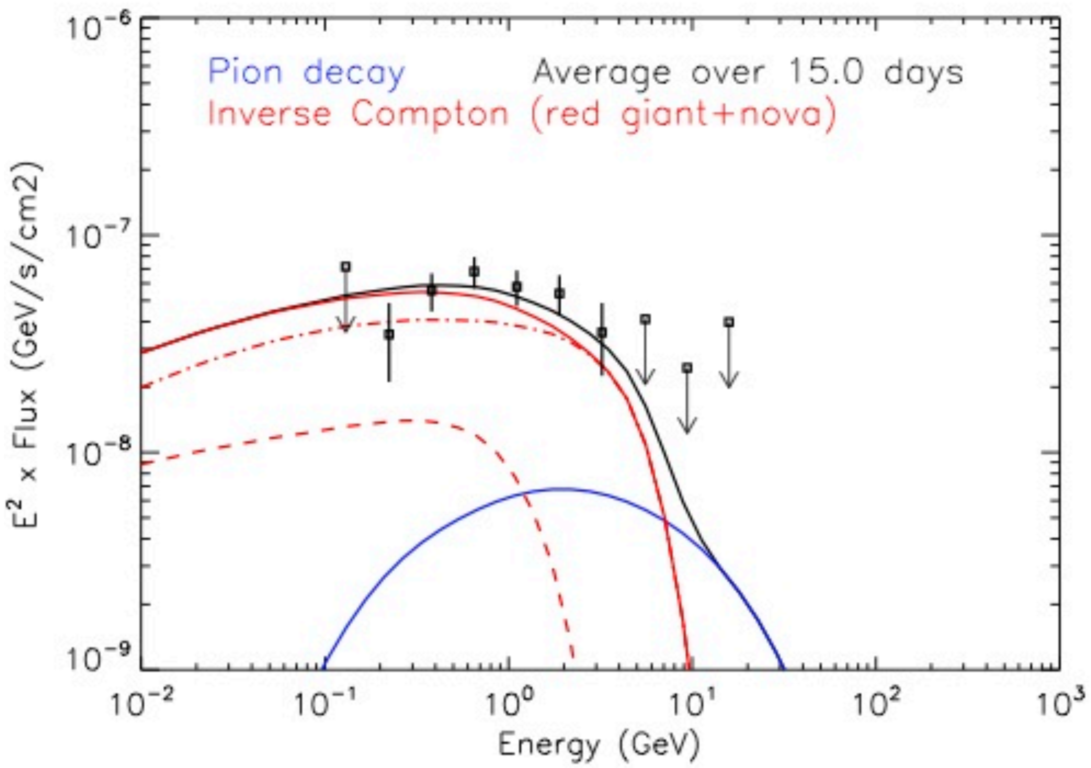
Martin & GD 2013

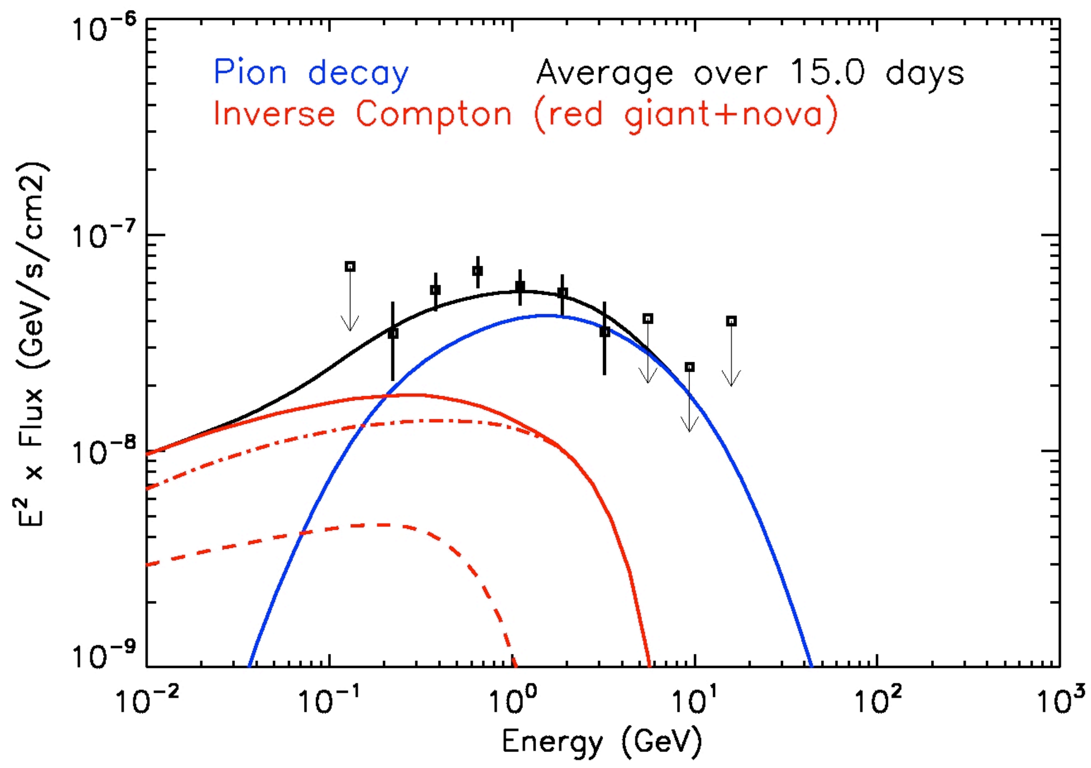


Inverse Compton model

- nova light dominates
- need density enhancement
- 10% energy in acc. particles
- e~0.03%, p~0.5%

SNR evolution in ‘real’ time





Martin & GD 2013

Inverse Compton model

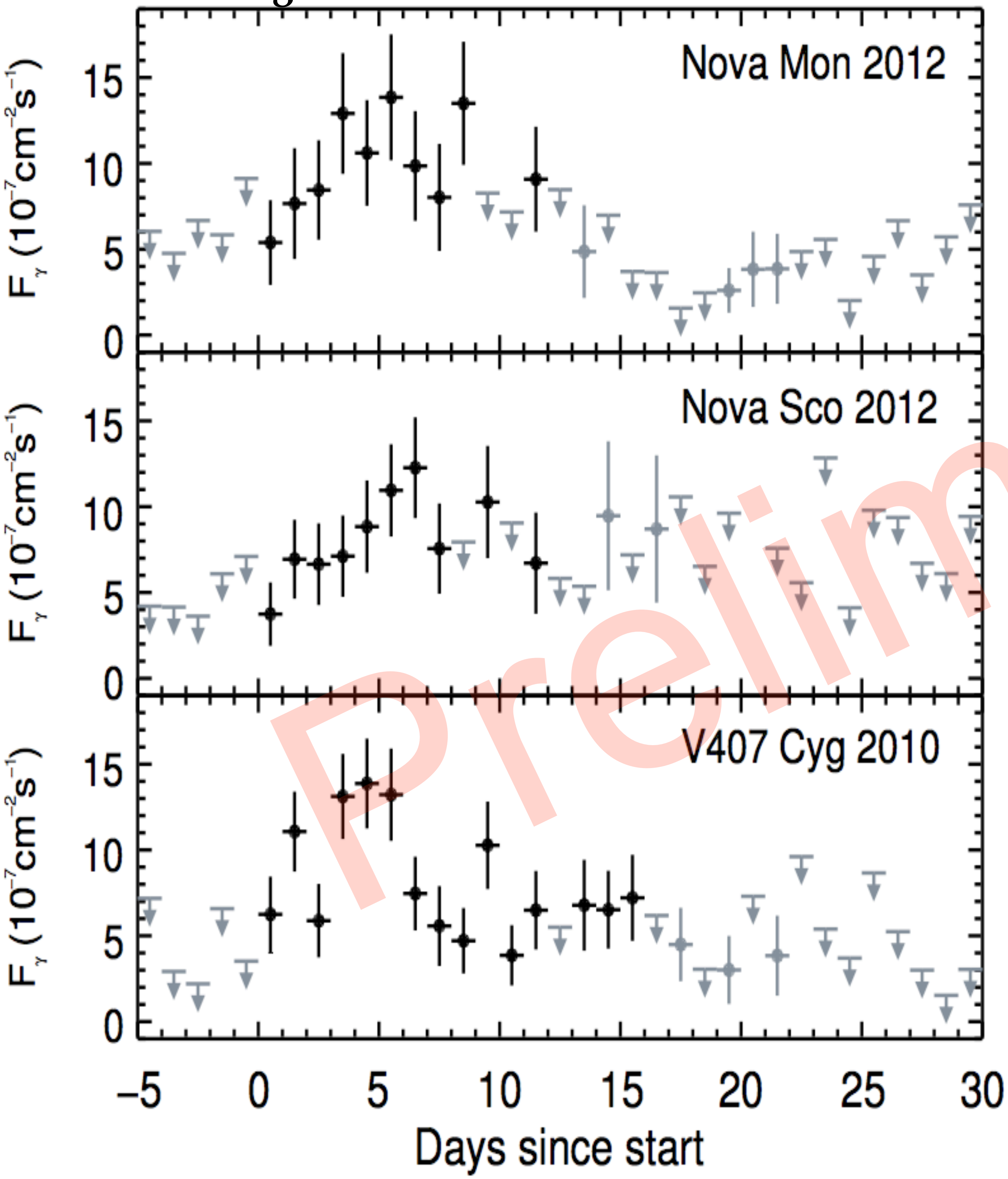
- nova light dominates
- need density enhancement
- 10% energy in acc. particles
- e~0.03%, p~0.5%

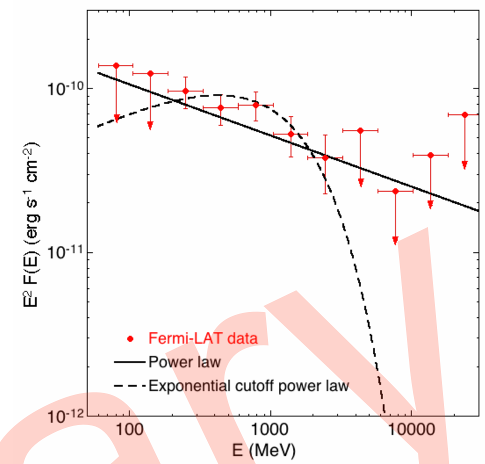
π_0 model

- helps with low γ points
- X-ray thermal important
- 100% energy in acc. particles
- acceleration: non-linear regime !

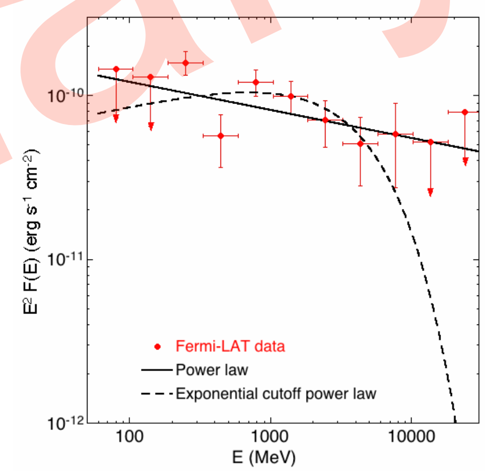
New novae

Cheung 2013 Hill 2013 + Nova Del 2013

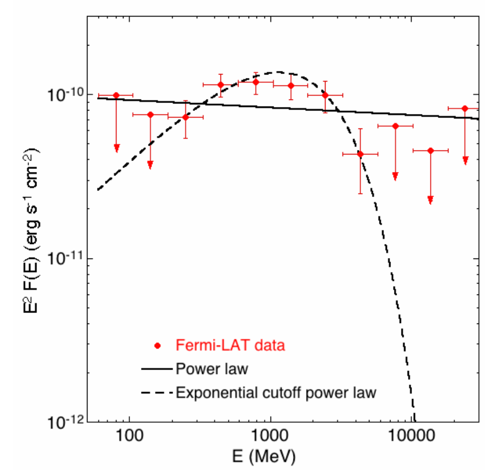




Nova Mon



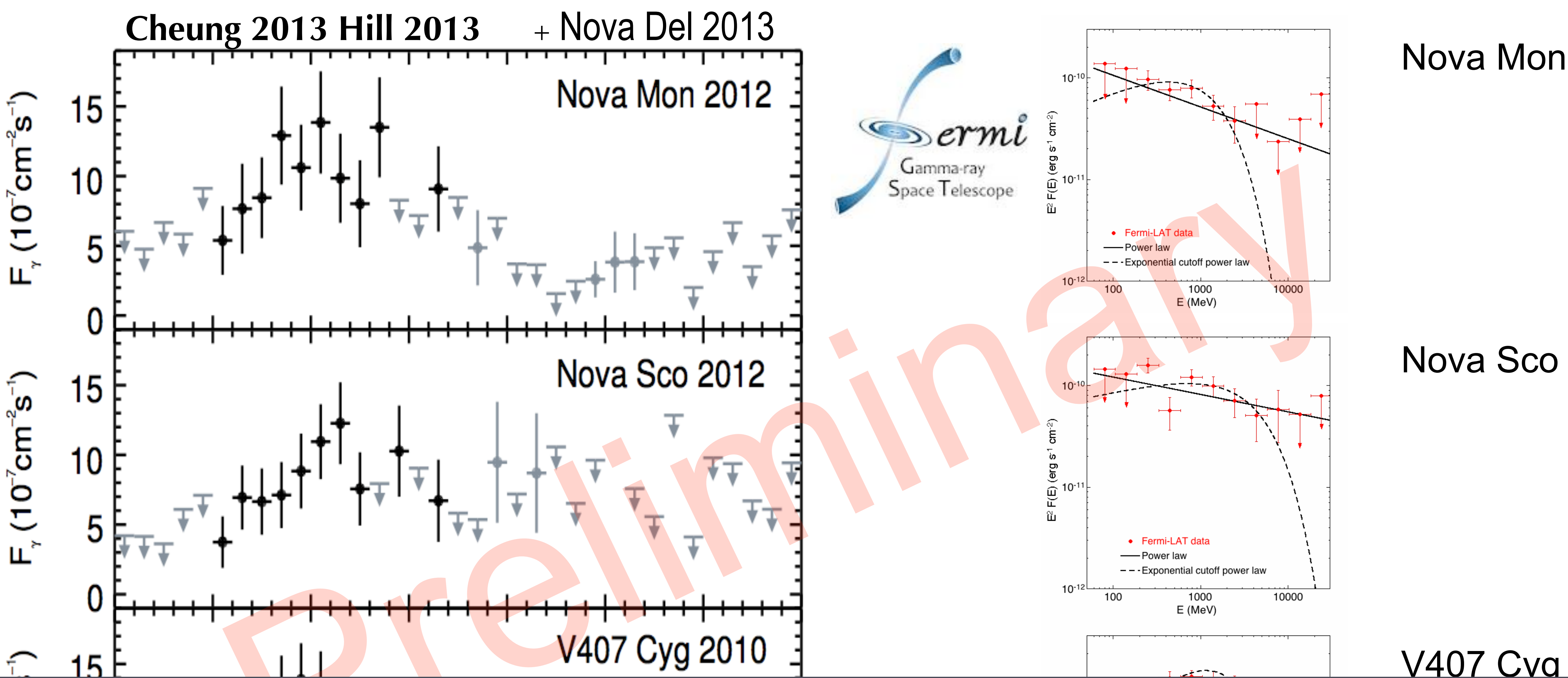
Nova Sco



V407 Cyg

Courtesy: Teddy Cheung, Pierre Jean for the Fermi/LAT collaboration

New novae



- **Problem**: not symbiotics so no dense stellar wind, small system
  - Nova Mon 2012: KV star, Porb=7.1 hour
  - Nova Sco 2012: -

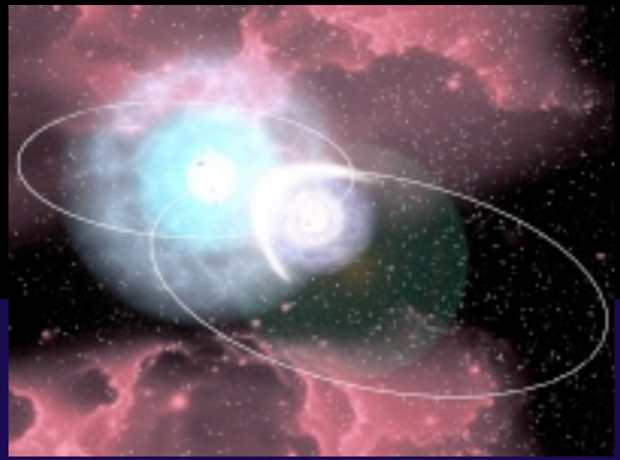
all fast novae ?

Shore et al. 2013ab

- **What's accelerated and where ?!** need to revisit nova physics ?

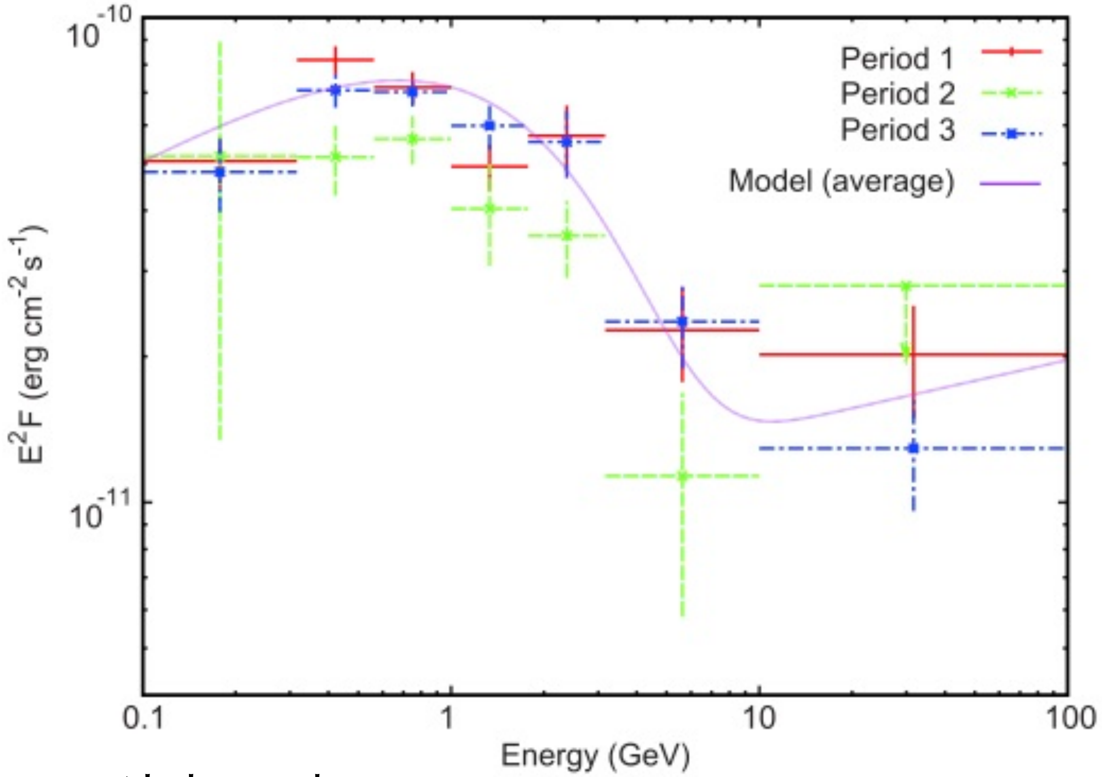
A colliding wind binary in gamma rays: Eta Carina

Eta Carina and CWB

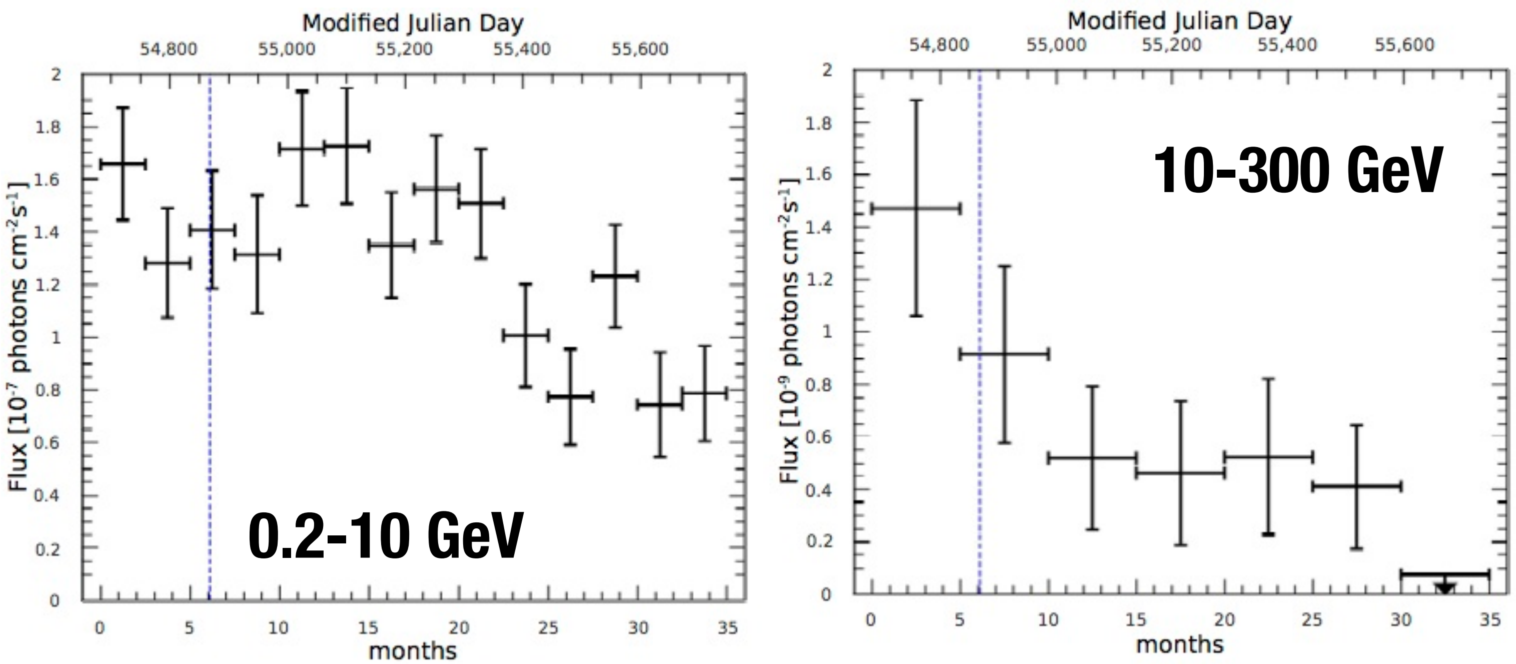


- η Carinae, ~100 $M_\odot$ star + comp., 5.5 yr orbit
- kinetic power of stellar winds L_{kin} ~6 x 10^{37} erg/s
- variable γ-ray emission (~0.1% L_{kin})

Walter & Farnier 2011, Reitberger et al. 2012



Abdo et al. 2010



Reitberger et al. 2012

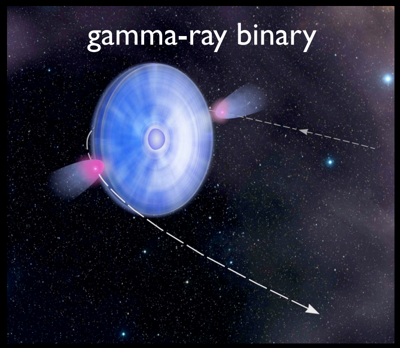
HESS-2 obs. planned for periastron passage this year

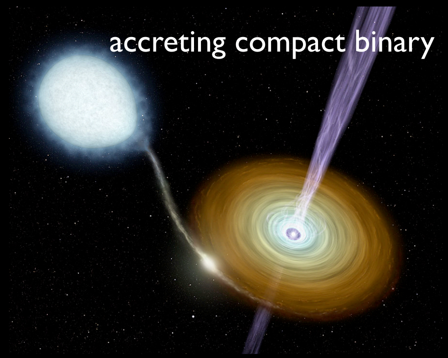
- No γ-rays from other colliding wind binaries: why ?

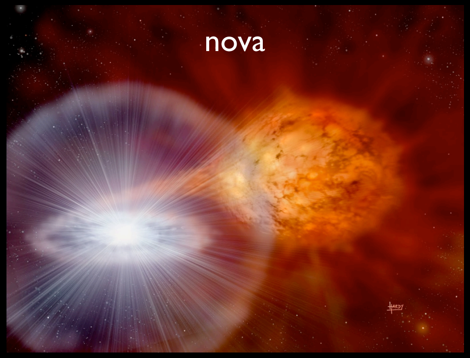
Werner et al. 2013

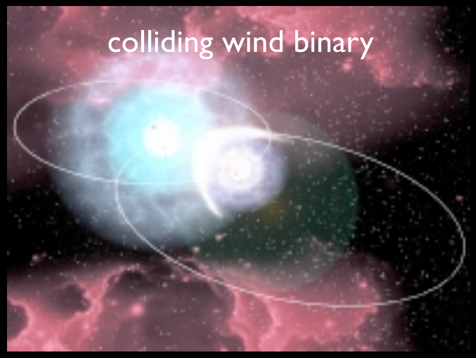
Summary

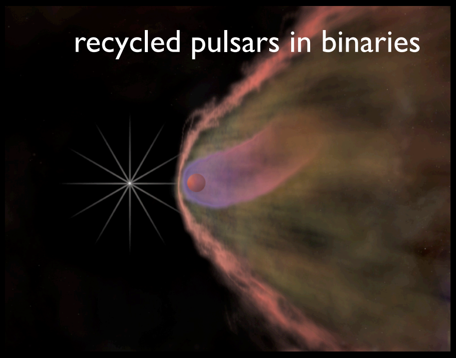
Binaries > 100 MeV







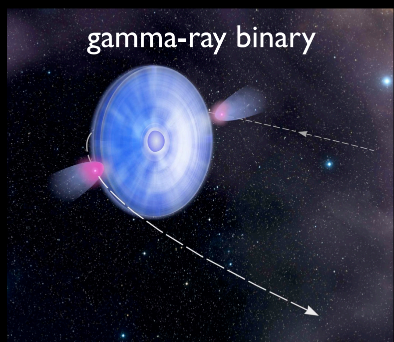


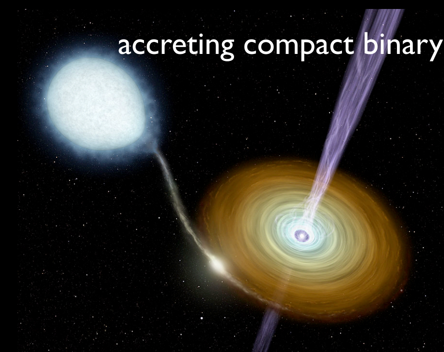


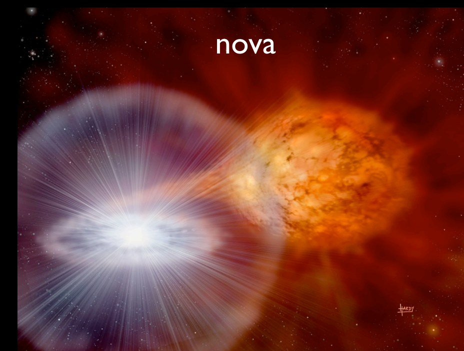
Rich variety of binaries observed

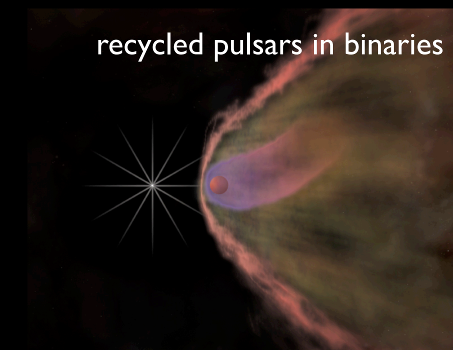
- a new field with a history...
- γ-rays reveal a new class: gamma-ray binaries
- twists to radiative processes in context of binaries → modulations
- binary-fixed radiation field & geometry constrain physics

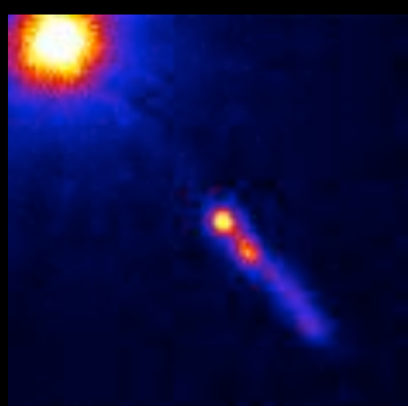
Binaries > 100 MeV

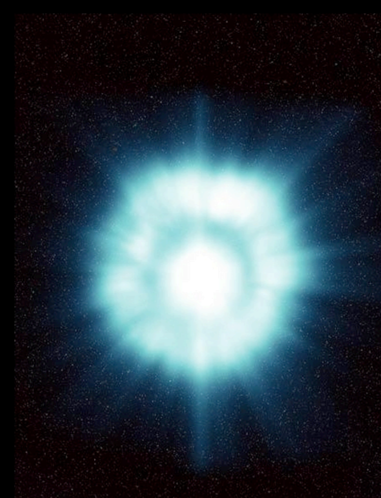


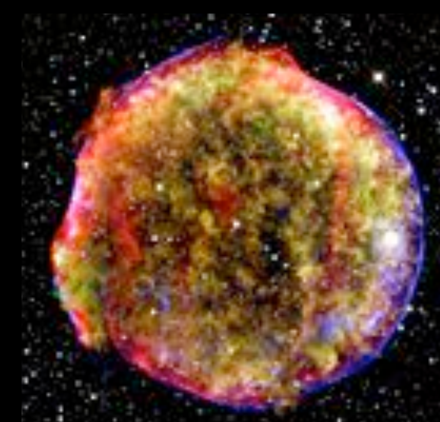


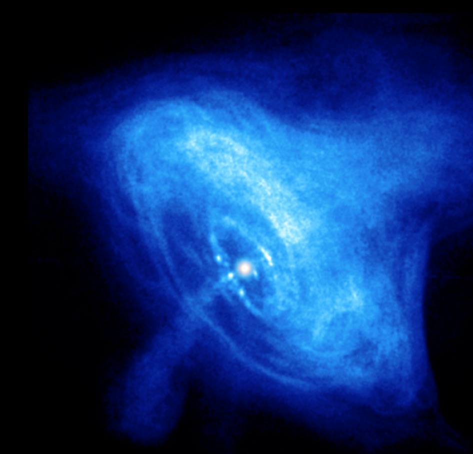





active galactic nuclei


γ-ray bursts


supernova remnants


pulsars & their nebula

Use γ rays from binaries to build a consistent picture across objects & scales of

- **accretion - ejection**
- **relativistic, magnetized outflows**
- **particle acceleration**