Gamma-ray binaries at very-high-energies:

particle acceleration and non-thermal radiation

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Gamma-ray binaries:

1. Introduction:

➢TeV catalog → TeV Binaries

➢X-ray binaries → γ-ray binaries

2. Binary systems:

➢**O -type γBs:** PSR B1259-63, etc.

➢**Be-type γBs:** LS 5039, etc.

3. γBs with LHAASO & CTA:

➢Particle acceleration and radiation

➢TeV binaries → PeV binaries ?

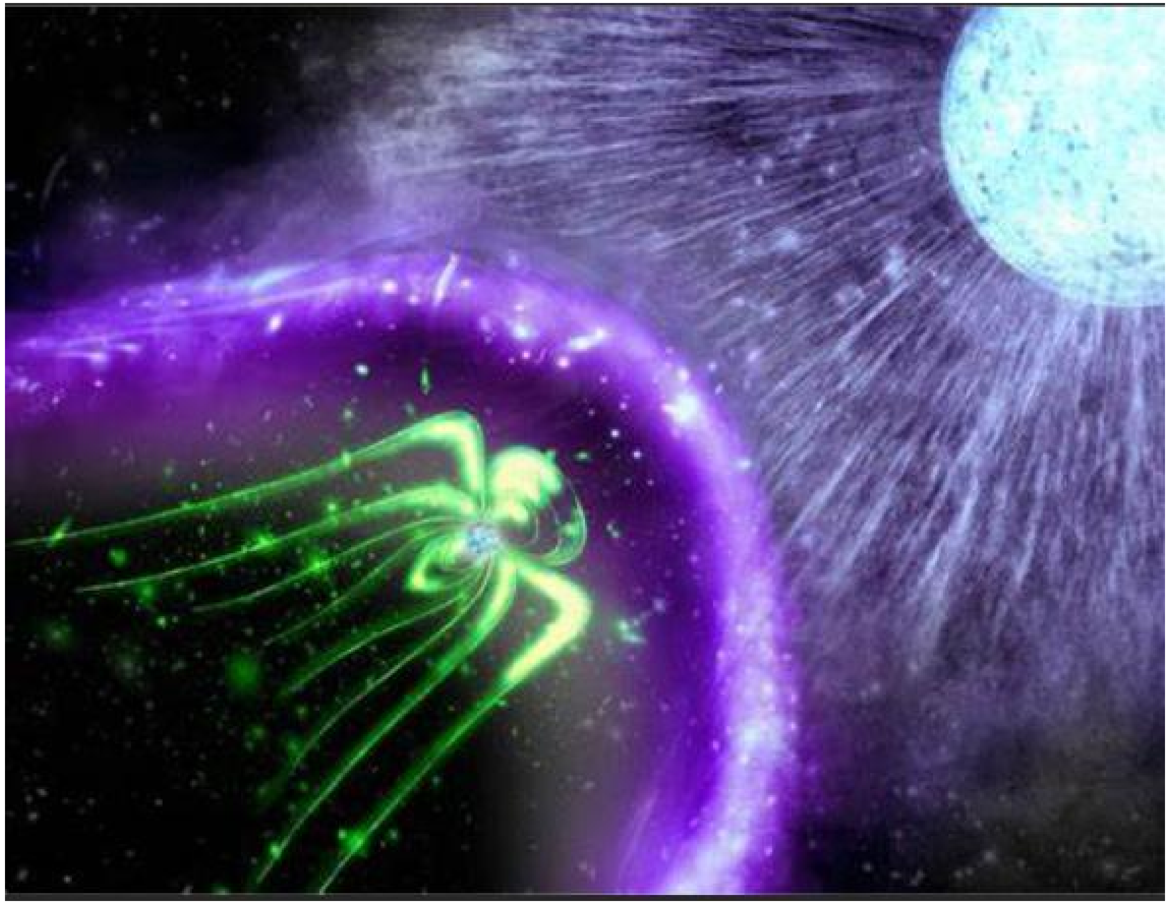


Figure: techexplorist

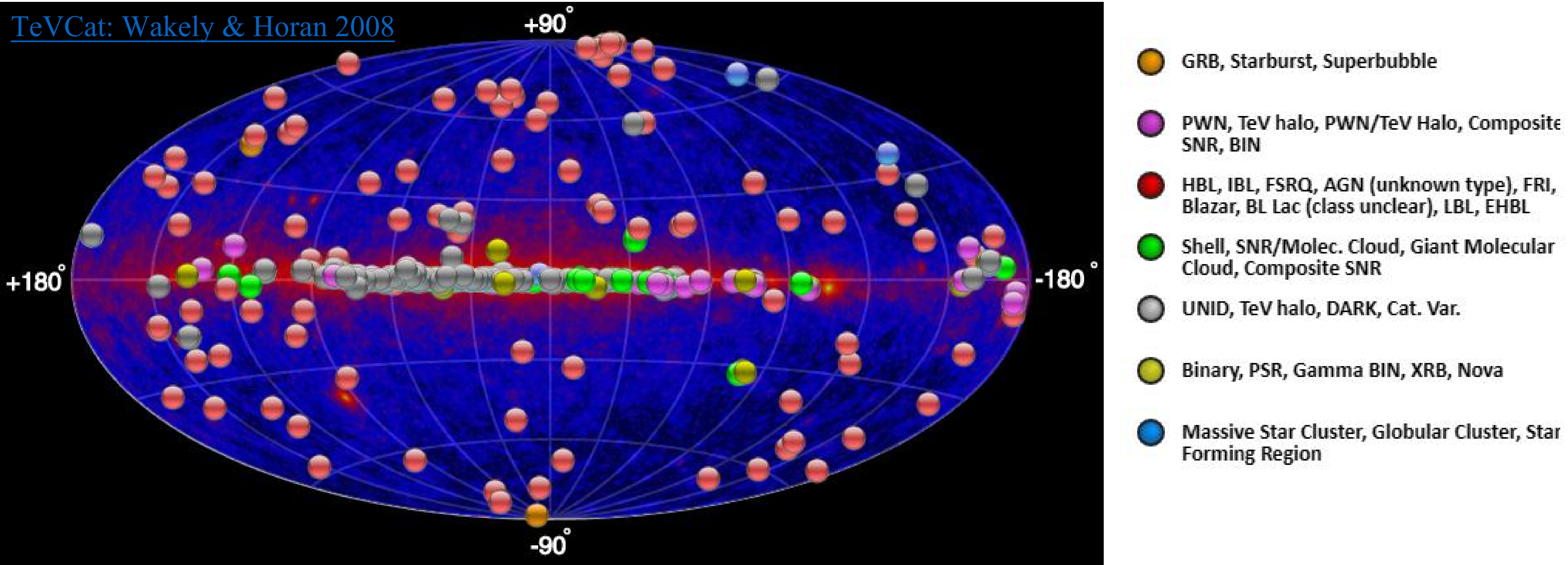
1.1 TeV Catalog:~300

a) Extra-Galactic: AGN, GRB, SBG, etc.

b) Galactic: PSR, PWN, SNR, Binary, etc.

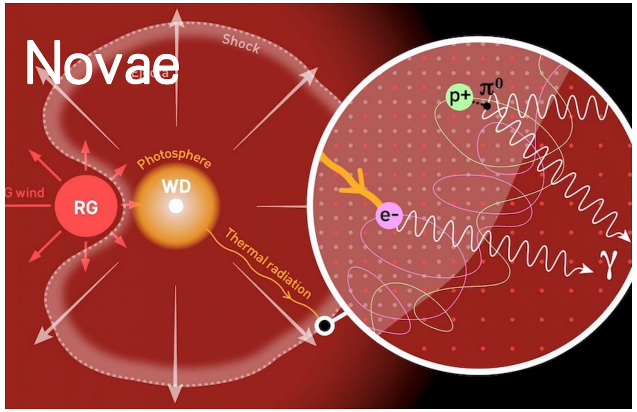
So far, more than 300 VHE (>0.1TeV) sources being discovered, with a few of them being detected at UHE (>0.1PeV) band.

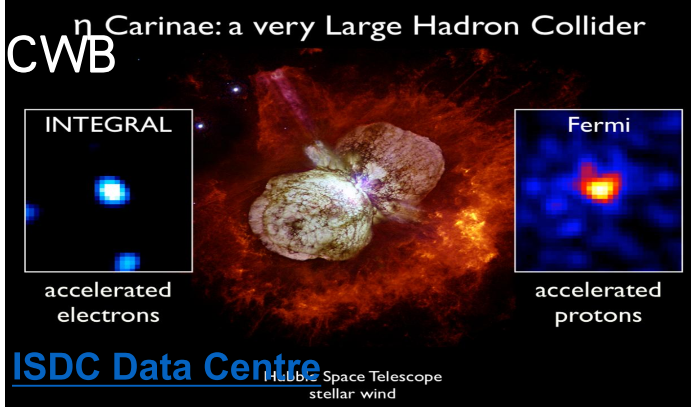
TeVCat: Wakely & Horan 2008



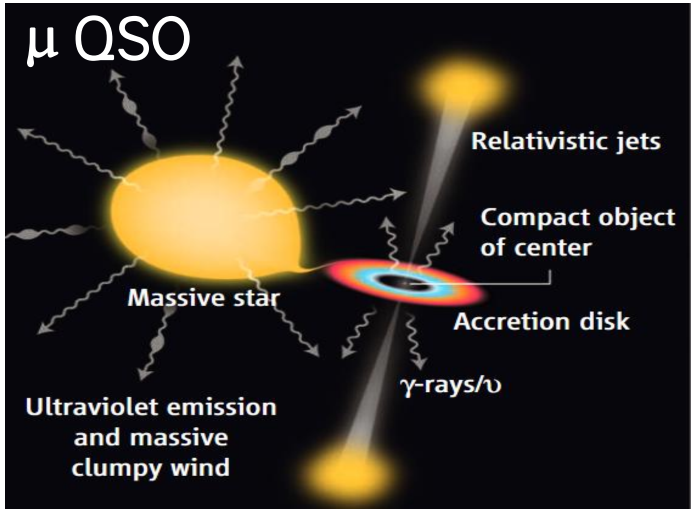
1.1 TeV Binaries:~12

a) Nova: only 1 (RS Ophiuchi)
b) Colliding wind binaries: only 1 (η-Car)
c) Micro-quasars: only 2 (SS 433, Cyg X-1)
d) Gamma-ray binaries: ~8 (PSR B1259-63, etc)

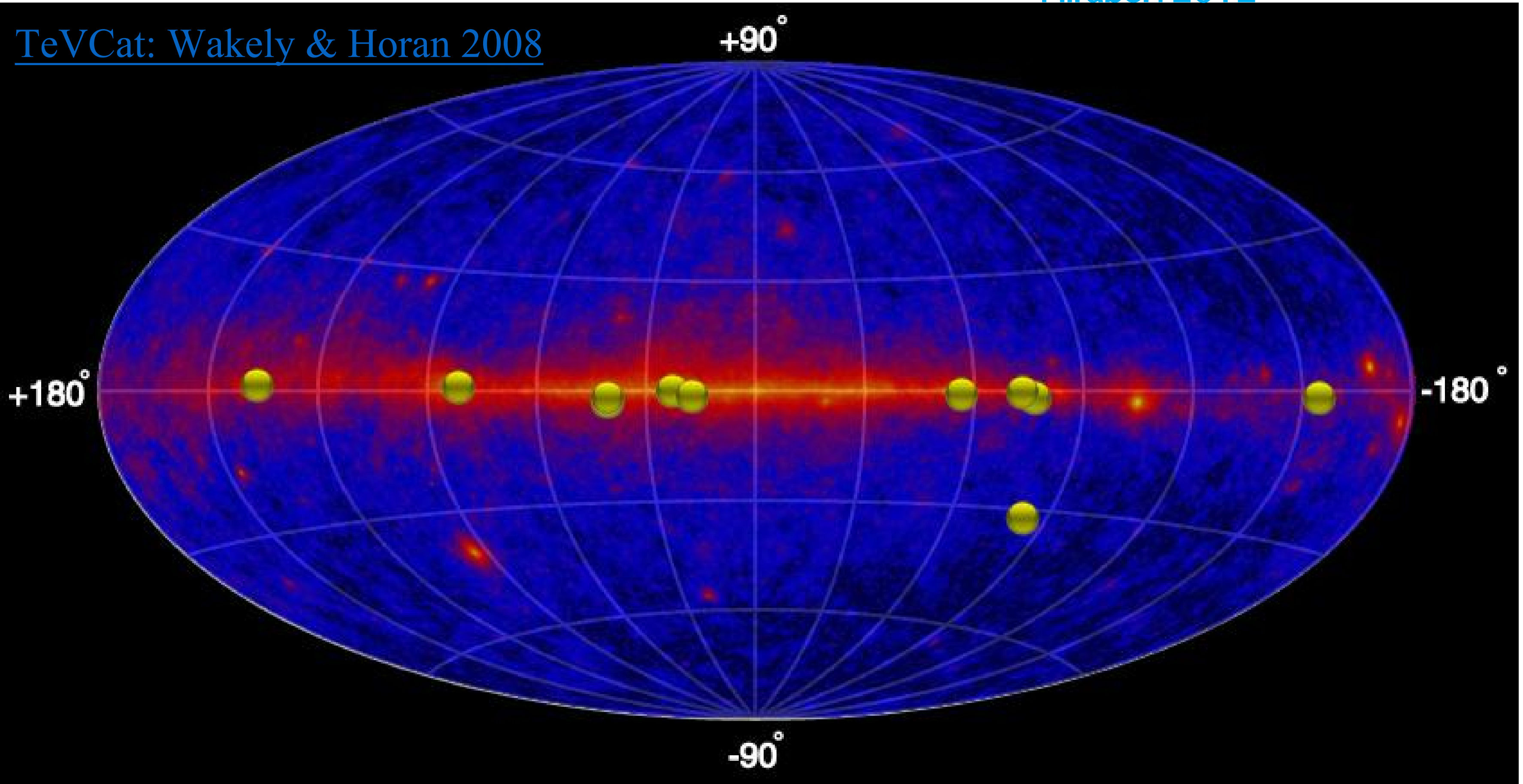


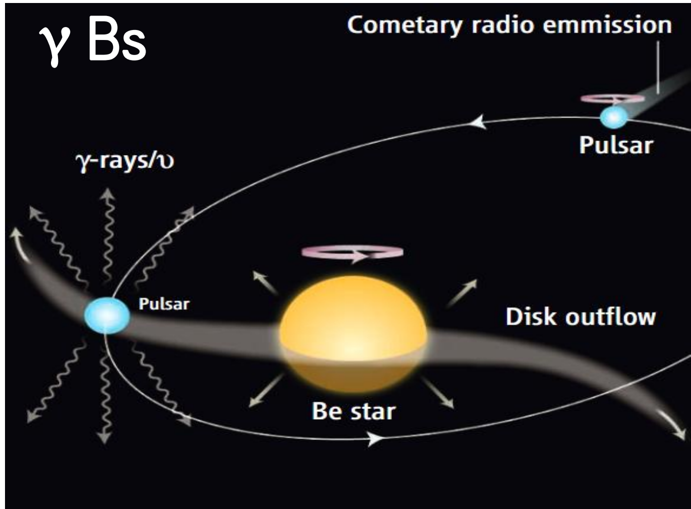


Credit: MAGIC+2022; ISDC; Mirabel+2012



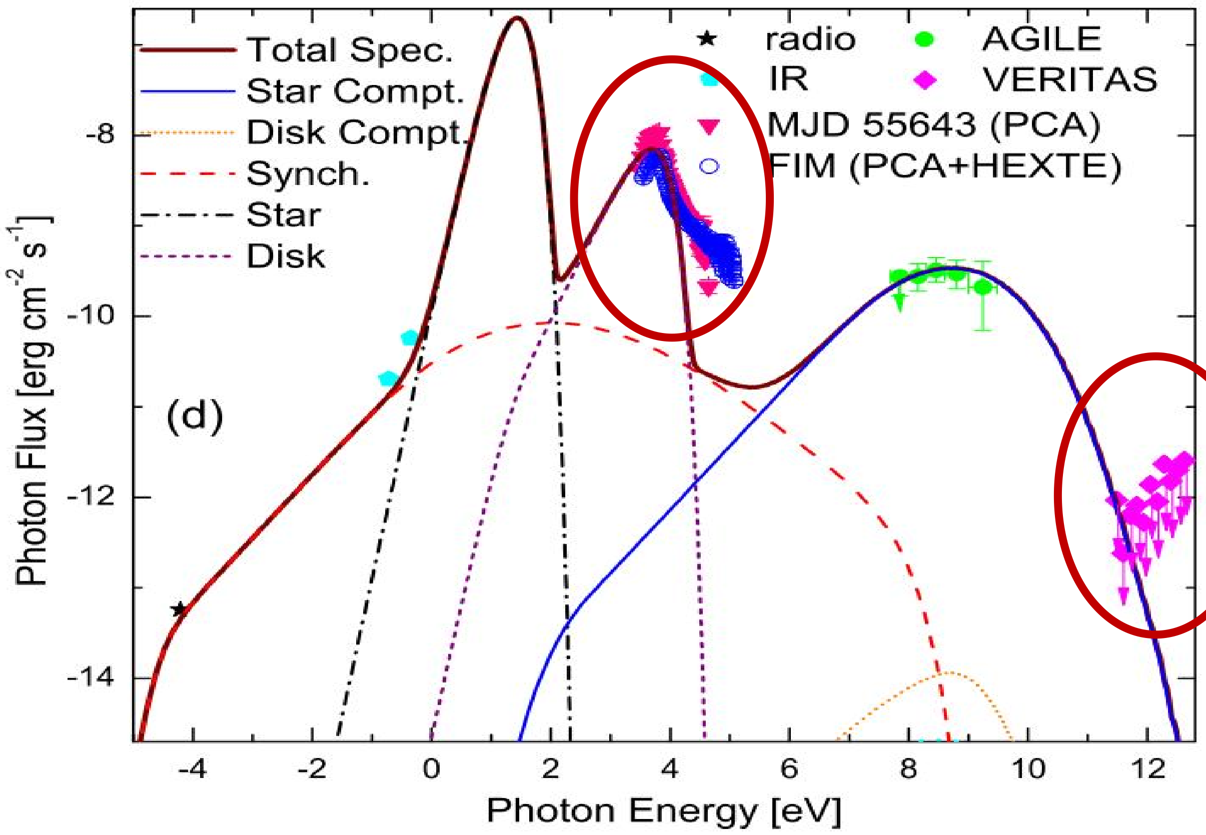
TeVCat: Wakely & Horan 2008





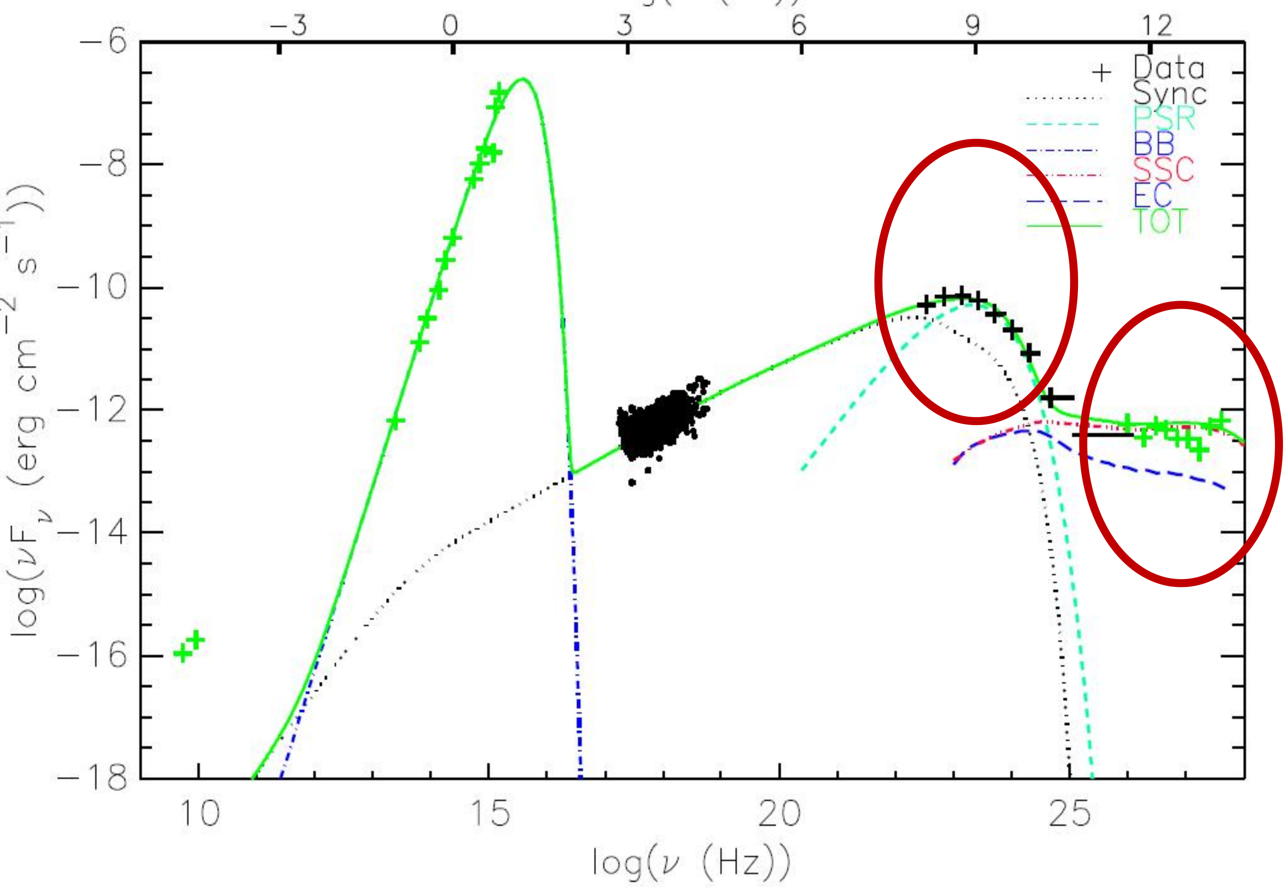
1.2 X-ray binaries V.S. γ-ray binaries

Cygnus X-3 $E_{\rm pk} \sim {\rm keV}$



Zhang & Lu 2015

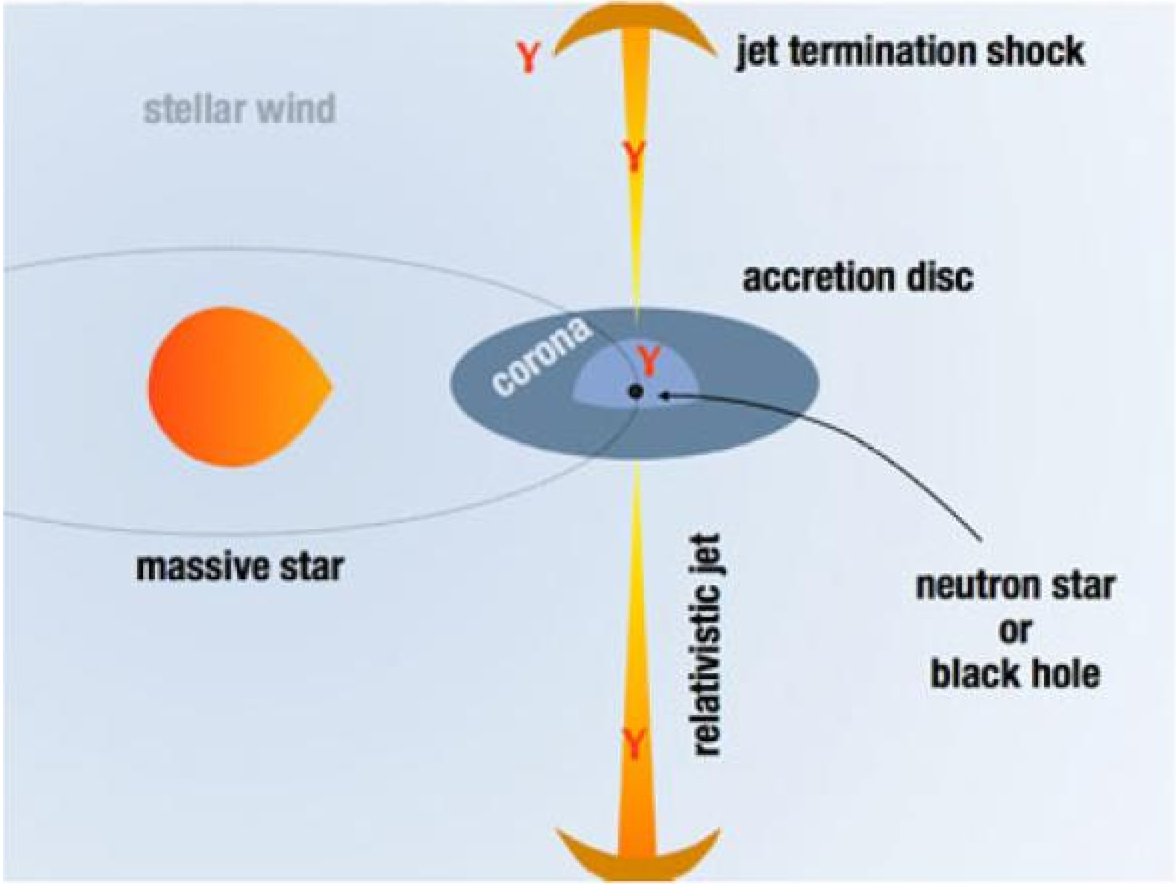
1FGL J1018-5856 $E_{\rm pk} \geq {\rm MeV}$



An & Romani 2017

1.2 X-ray binaries V.S. γ-ray binaries

Accretion-powered



Rotation-powered

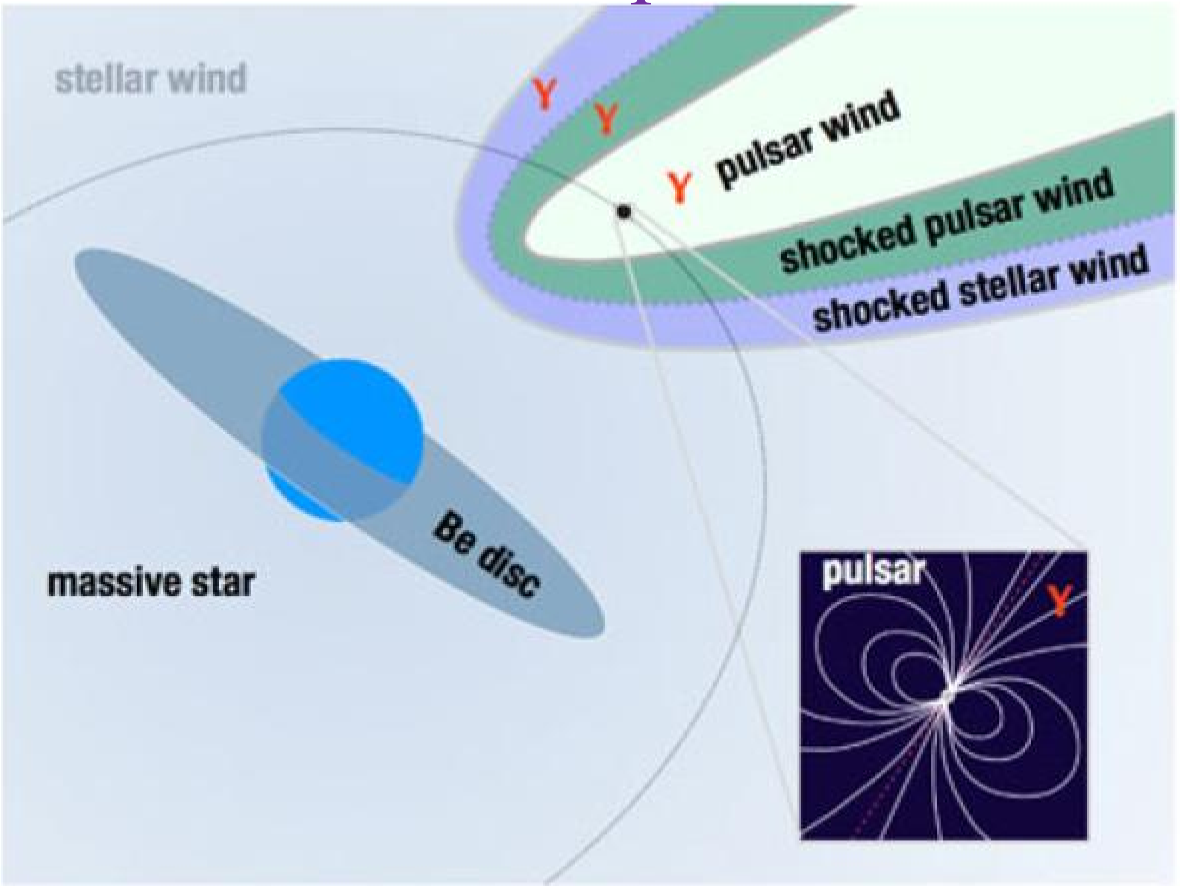


Figure: Dubus 2013, Astron Astrophys Rev

2. γ-ray binaries

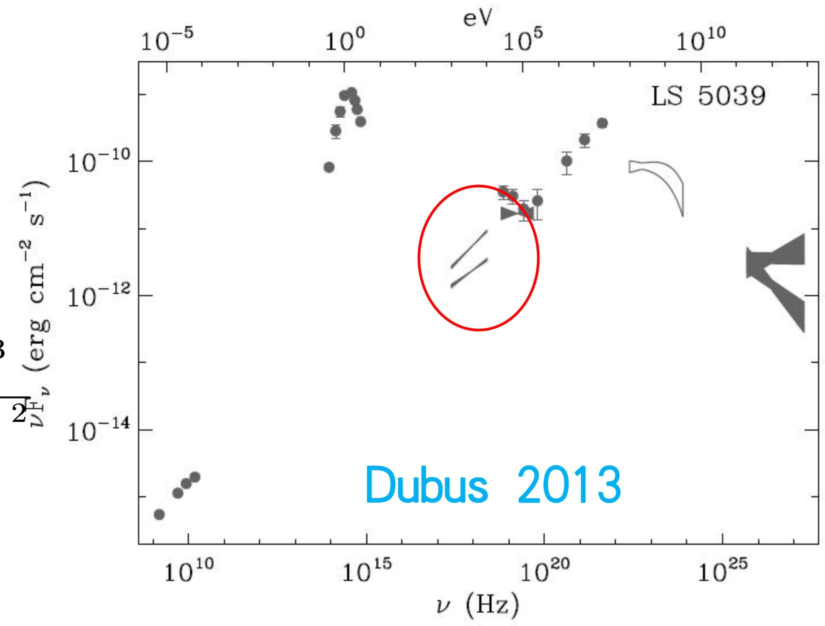
Be—type γ Bs　　O—type γ Bs

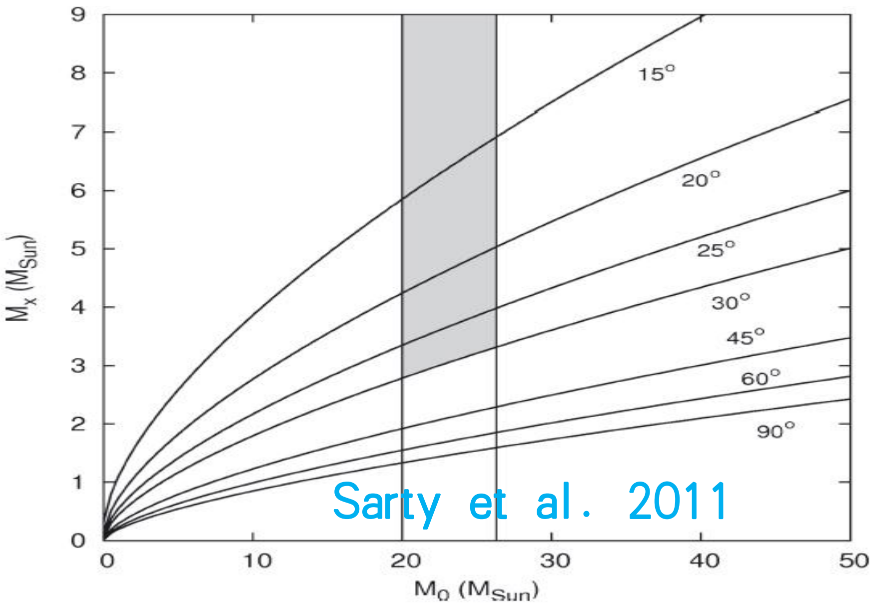
binaries	PSR B1259-63	PSR J2032+4127	HESS J0632+057	LS I +61 303	LS 5039	LMC P3	1FGL J1018.6-5856	HESS J1832-093
Compact object	Pulsar	Pulsar	?	Pulsar ?	Pulsar ?	?	?	?
Pulsation period	47.73 ms (Radio)	143 ms (Radio/γ-ray)	?	269 ms ? (Radio)	~9 s ? (X–ray)	?	?	?
Companion star	O9.5Ve	B0Ve	B0Vpe	B0Ve	O6.5V	O5III	O6V	O?
Stellar disk	√	√	√	√	×	×	×	×
Orbital eccentricity	0.87	0.96	0.64–0.83 ?	0.55–0.72 ?	0.35	0.40	0.31	?
Orbital period	1236.7d	~17000d	317.3d	26.496d	3.906d	10.314d	16.58d	~86d
Distance (kpc)	2.39	1.33	1.6	2.0	2.9	~50	5.4	4.4

COs in rest γBs are believed to be non—accreting NSs：

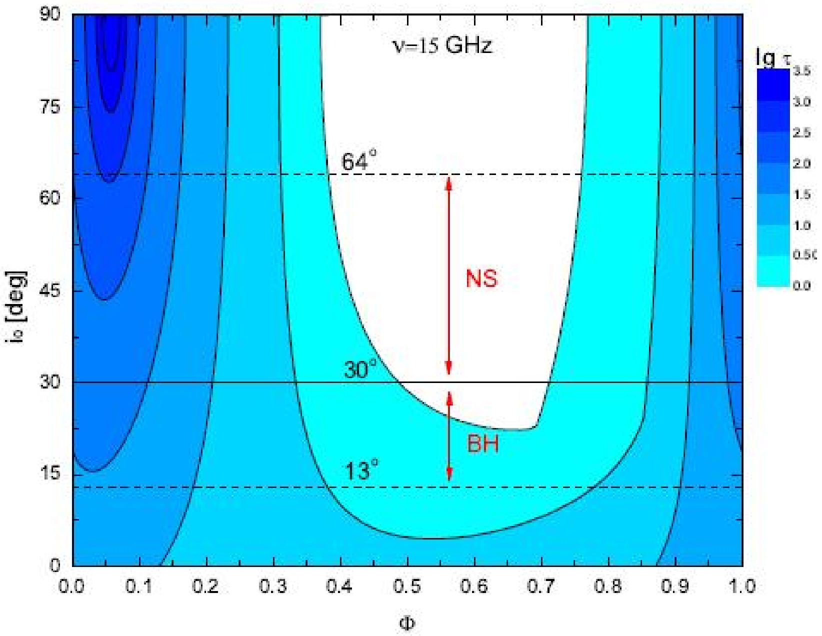
- Similar spectral characteristics
- Lack of accretion signal
- Binary mass functions

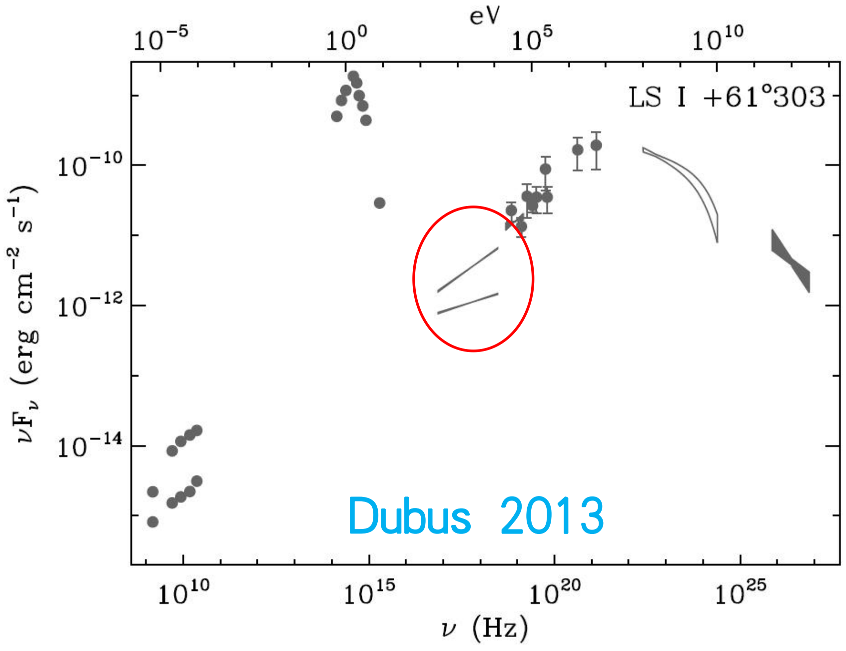
$$f(M_{\rm x}) = \frac{PK^3}{2\pi G}(1-e^2)^{3/2} = \frac{(M_{\rm x}\sin i)^3}{(M_{\rm x}+M_{\rm O})^2}$$

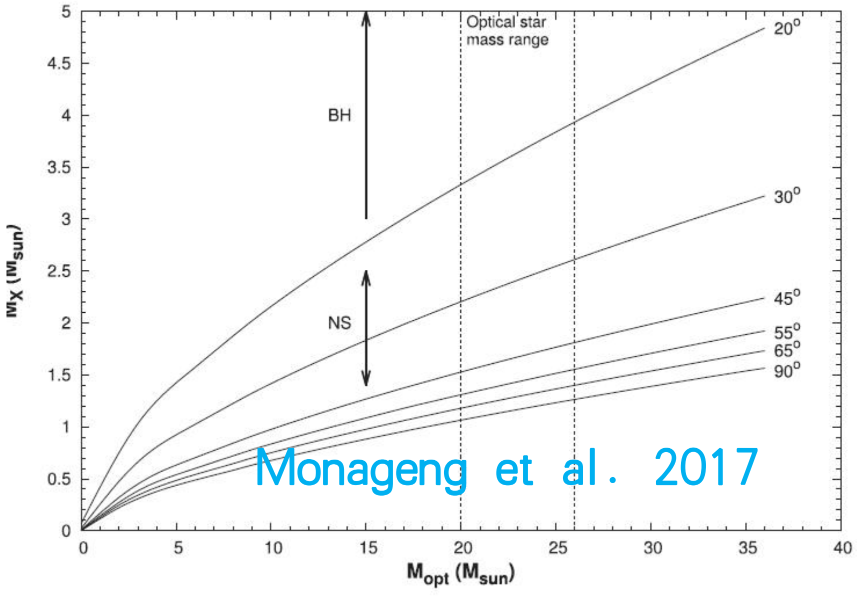




Chen et al. 2021a







Emission model:

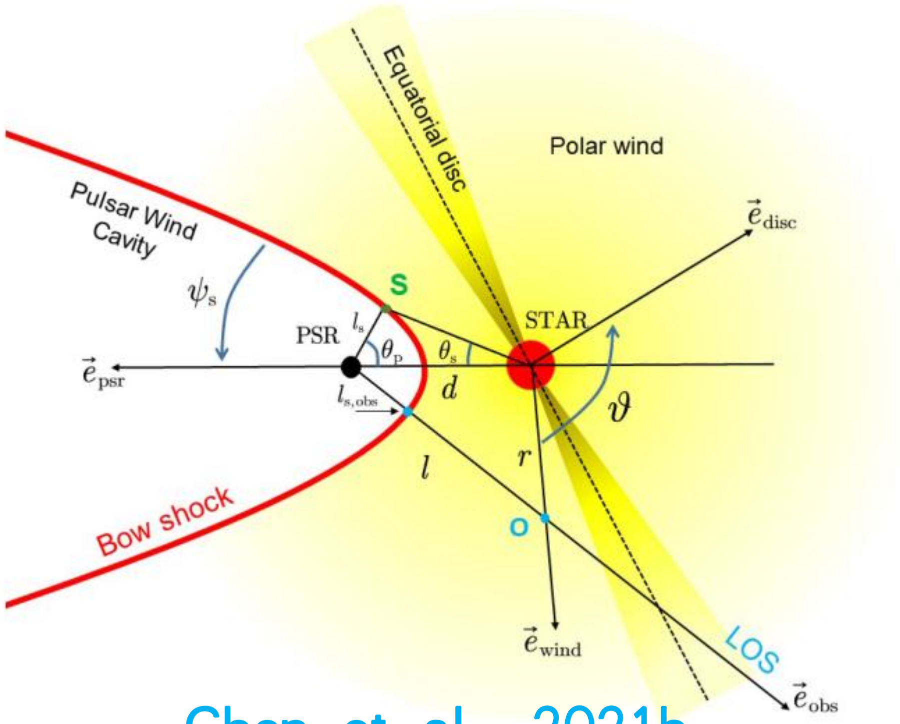
$$\eta = \frac{L_{\mathrm{sd}}/c}{\dot{M} v_{\mathrm{w}}}$$

$$\frac{L_{\mathrm{sd}}}{4\pi r_{\mathrm{s}}^2 c} = \rho_{\mathrm{w}}(R_{\mathrm{s}}) \left| \boldsymbol{v}_{\mathrm{w}}(R_{\mathrm{s}}) - \boldsymbol{v}_{\mathrm{p}} \right|^2$$

Shock position

$$l_{\mathrm{s}} = d \sin\theta_{\mathrm{s}} \csc(\theta_{\mathrm{s}} + \theta_{\mathrm{p}})$$

$$\theta_{\mathrm{s}} \cot\theta_{\mathrm{s}} = 1 + \eta(\theta_{\mathrm{p}} \cot\theta_{\mathrm{p}} - 1)$$



Chen et al. 2021b

Energy densities

$$B = \sqrt{\frac{L_{\mathrm{sd}}\sigma}{l_{\mathrm{s}}^2 c(1+\sigma)} \left(1 + \frac{1}{u^2}\right)}$$

$$u_B = \frac{B^2}{8\pi}, \quad u_{\mathrm{ph}} = u_{\mathrm{star}} + u_{\mathrm{disc}}$$

Radiation mechanisms

$$P_\nu^{\mathrm{syn}}(\gamma) = \frac{\sqrt{3} q_e^3 B}{m_e c^2} \frac{\nu}{\nu_0} \int_{\nu/\nu_0}^{\infty} K_{5/3}(k) dk,$$

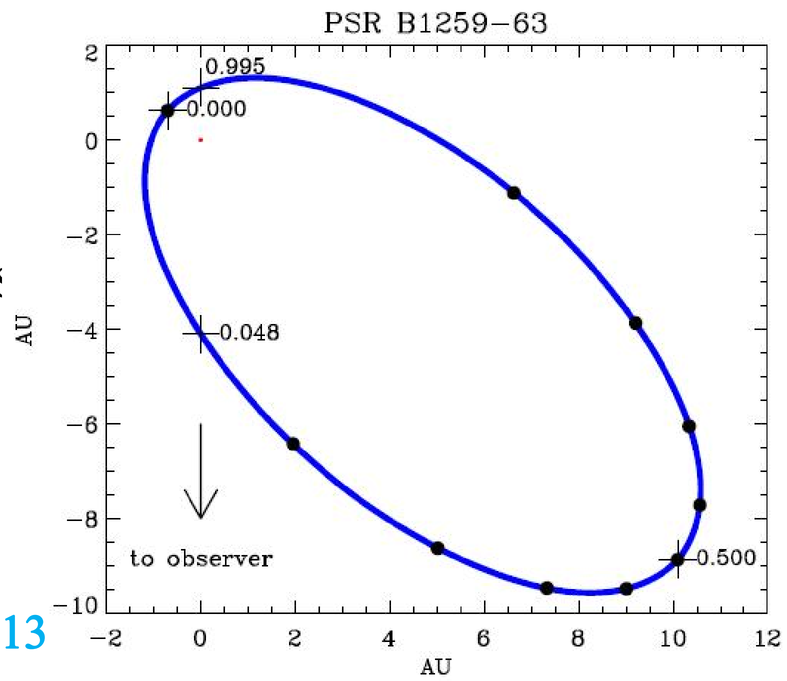
$$P_\nu^{\mathrm{IC}}(\gamma) = 3\sigma_T \int_{\nu_{s,\min}}^{\infty} \frac{\nu f_{\nu_s}}{4\gamma^2 \nu_s^2} h(\xi, b_\theta) d\nu_s.$$

$$j(\nu) = \int_\gamma n(\gamma) P_\nu(\gamma) d\gamma.$$

$$F(\nu) = \frac{1}{d_{\mathrm{L}}^2} \int_{\theta_{\mathrm{sh}}}^{\pi} \sin\theta \, \mathrm{d}\theta \int_0^{2\pi} \mathrm{d}\varphi \int_{l_{\mathrm{s}}}^{l_{\mathrm{s}}+\Delta_{\mathrm{s}}} r^2 \mathrm{d}r D^2 j(\nu/D) \exp(-\tau)$$

2.1: PSR B1259-63

PSRB1259−63 is the first variable galactic source of VHE γ-rays



Dubus 2013

- **Pulsar:**

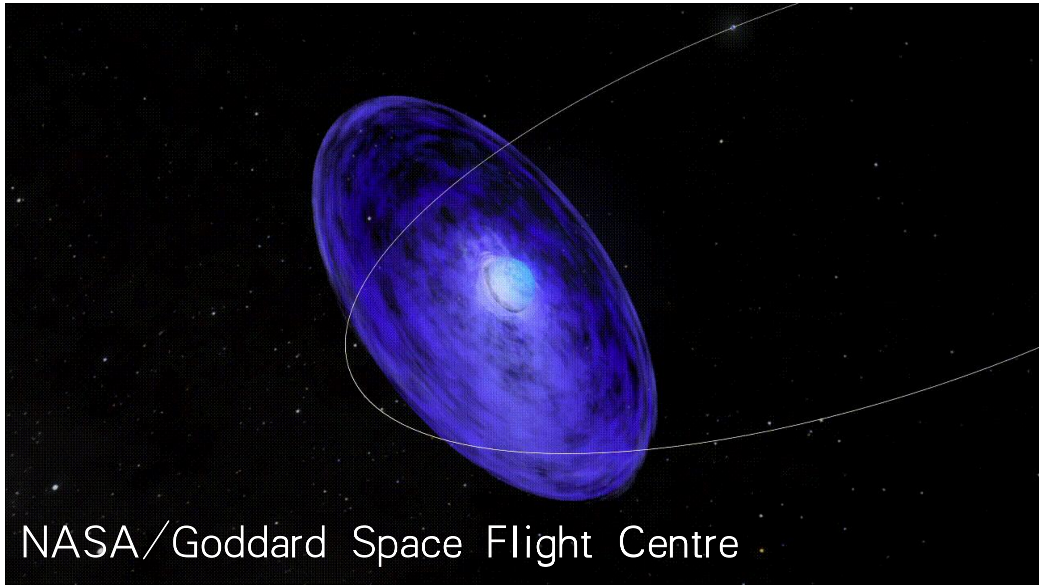
$P = 47.76\,\mathrm{ms},\ \dot{P} \simeq 2.28 \times 10^{-15}\ \mathrm{s \cdot s^{-1}},\ \ L_{\rm sd} \simeq 8 \times 10^{35}\,\mathrm{erg/s}$

- **Star:**

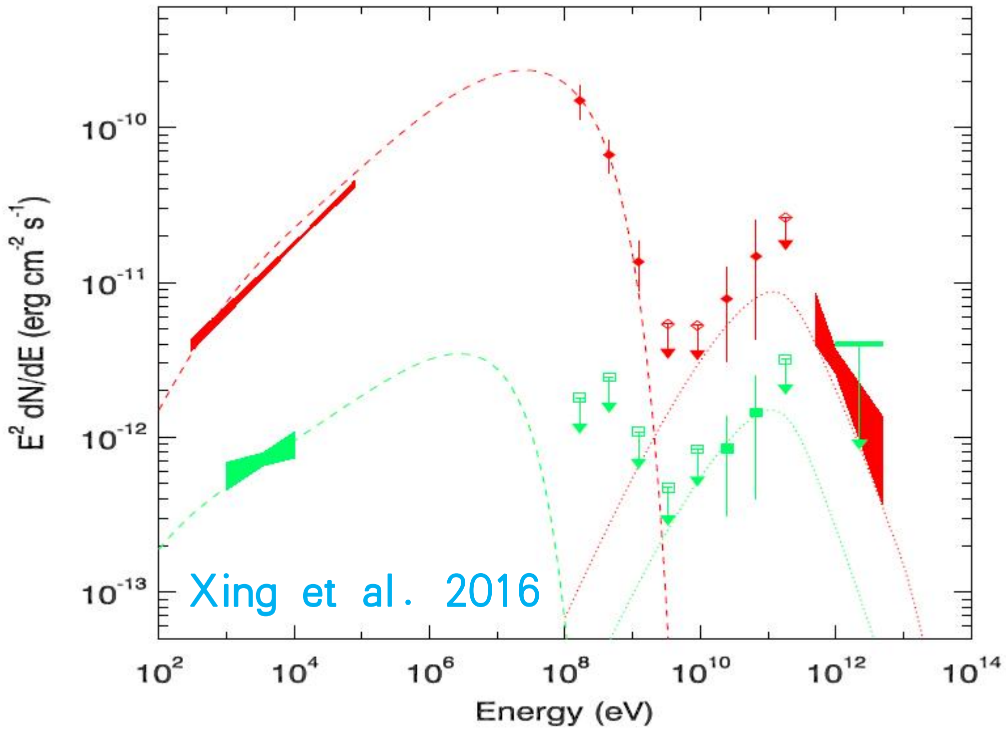
$\mathrm{O9.5Ve},\ \ M_\star \sim 30 M_\odot,\ \ R_\star \sim 9.5 R_\odot,\ \ T_{\rm eff} \simeq 33500\,\mathrm{K}$

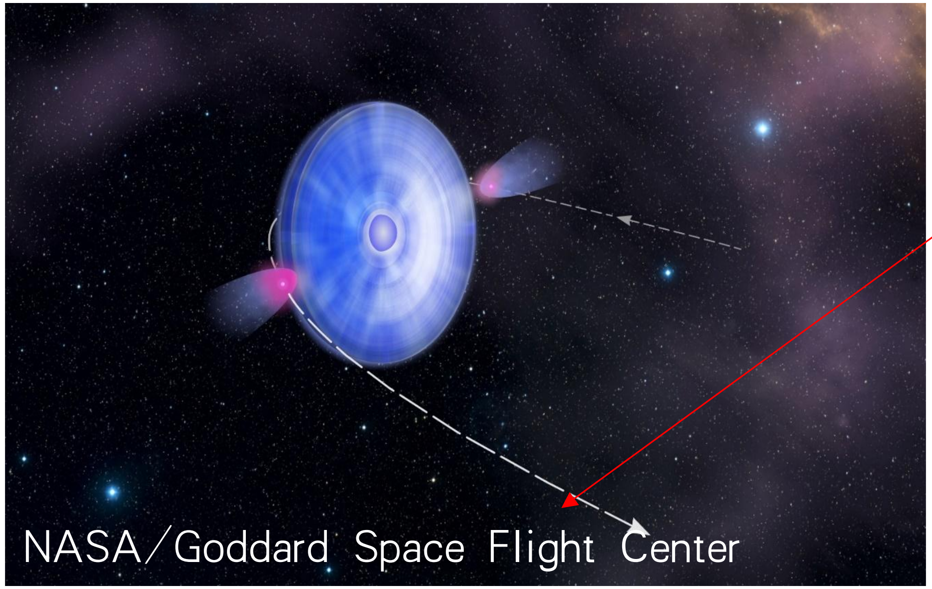
- **Orbit:**

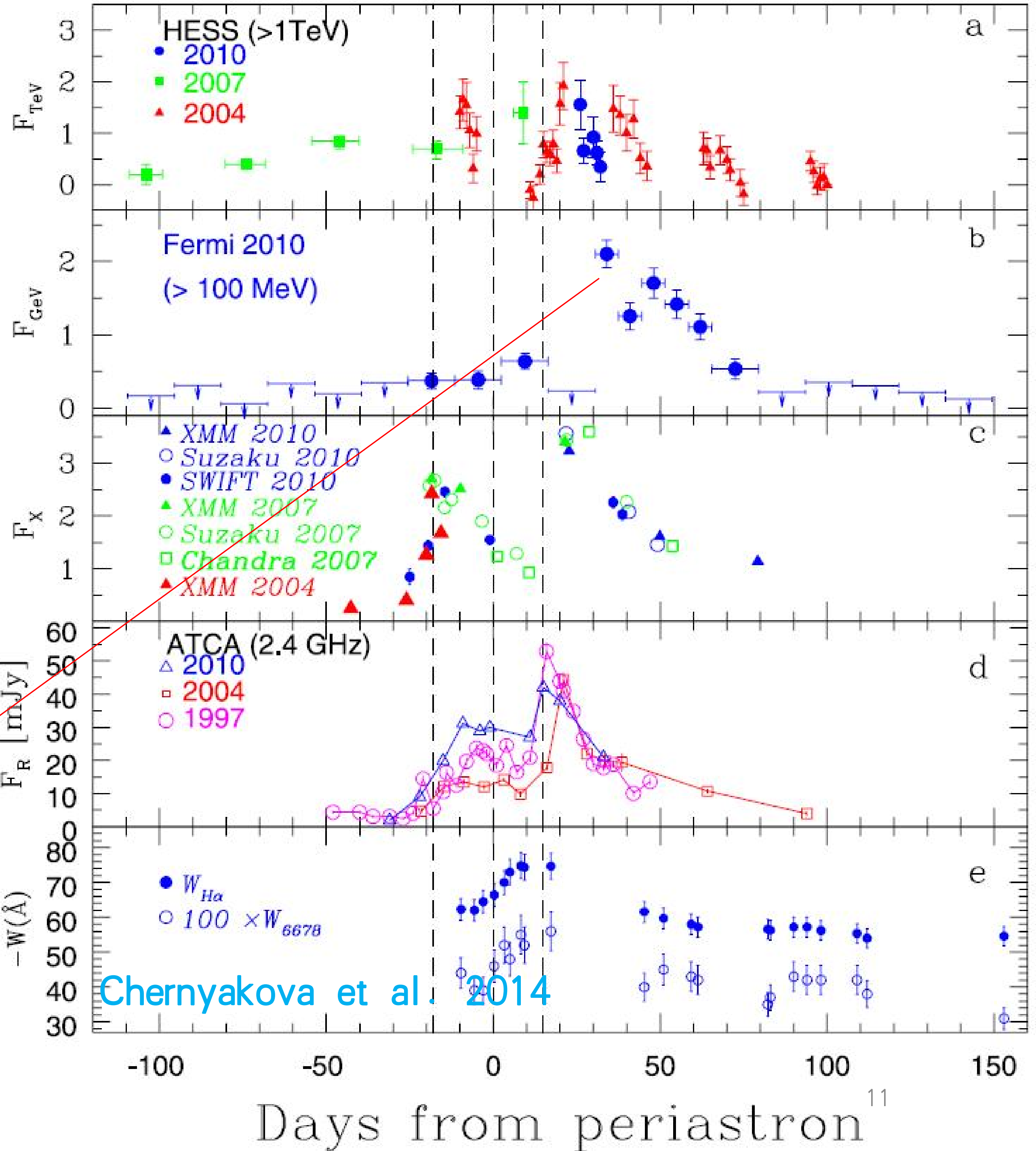
$e \simeq 0.87,\ \ a \sim 5\,\mathrm{AU},\ \ P_{\rm orb} \simeq 3.4\,\mathrm{yr},\ \ d_{\rm L} \sim 2.6\,\mathrm{kpc}$



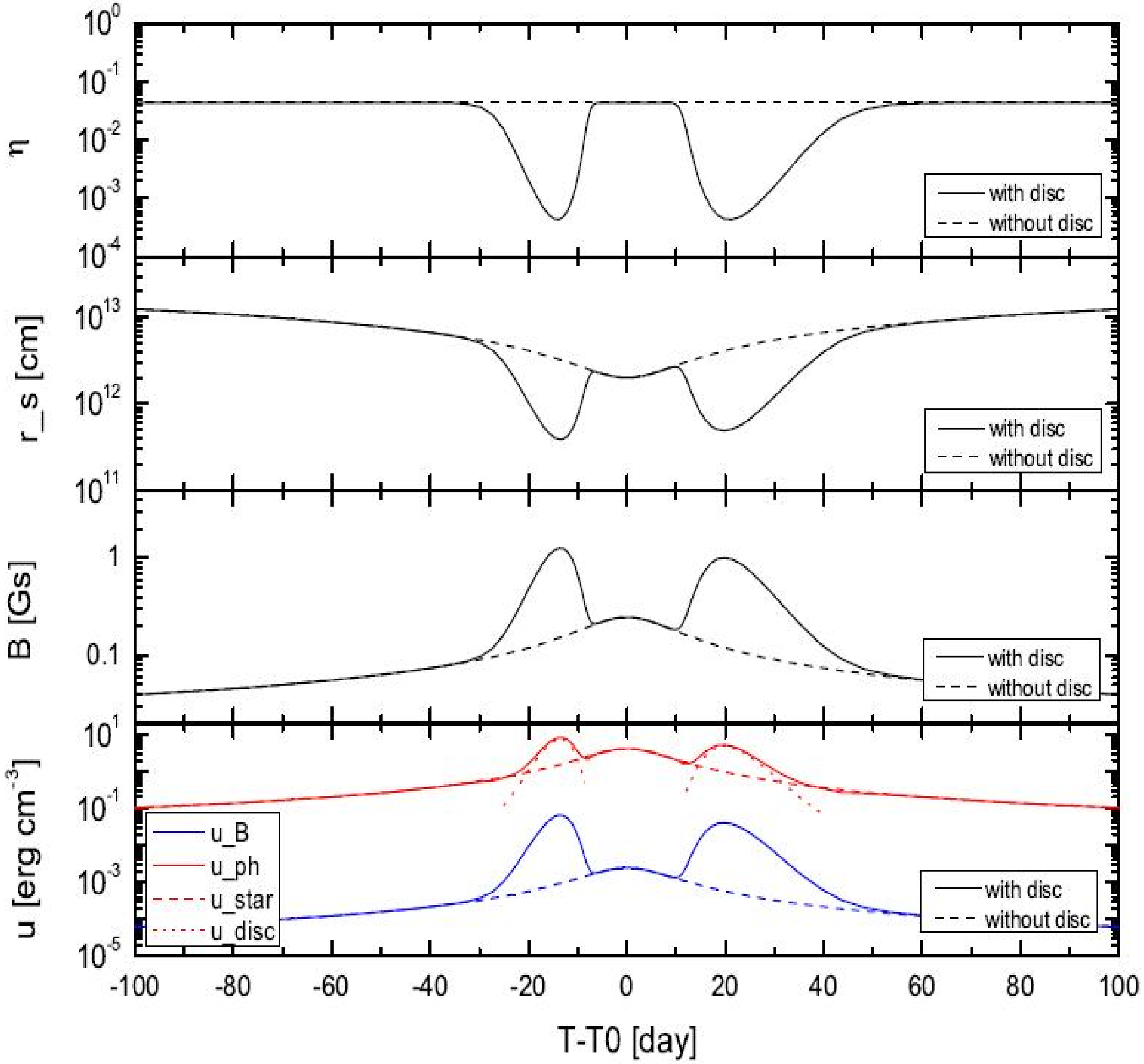
The companion star possesses an equatorial disc that is inclined to the orbital plane !

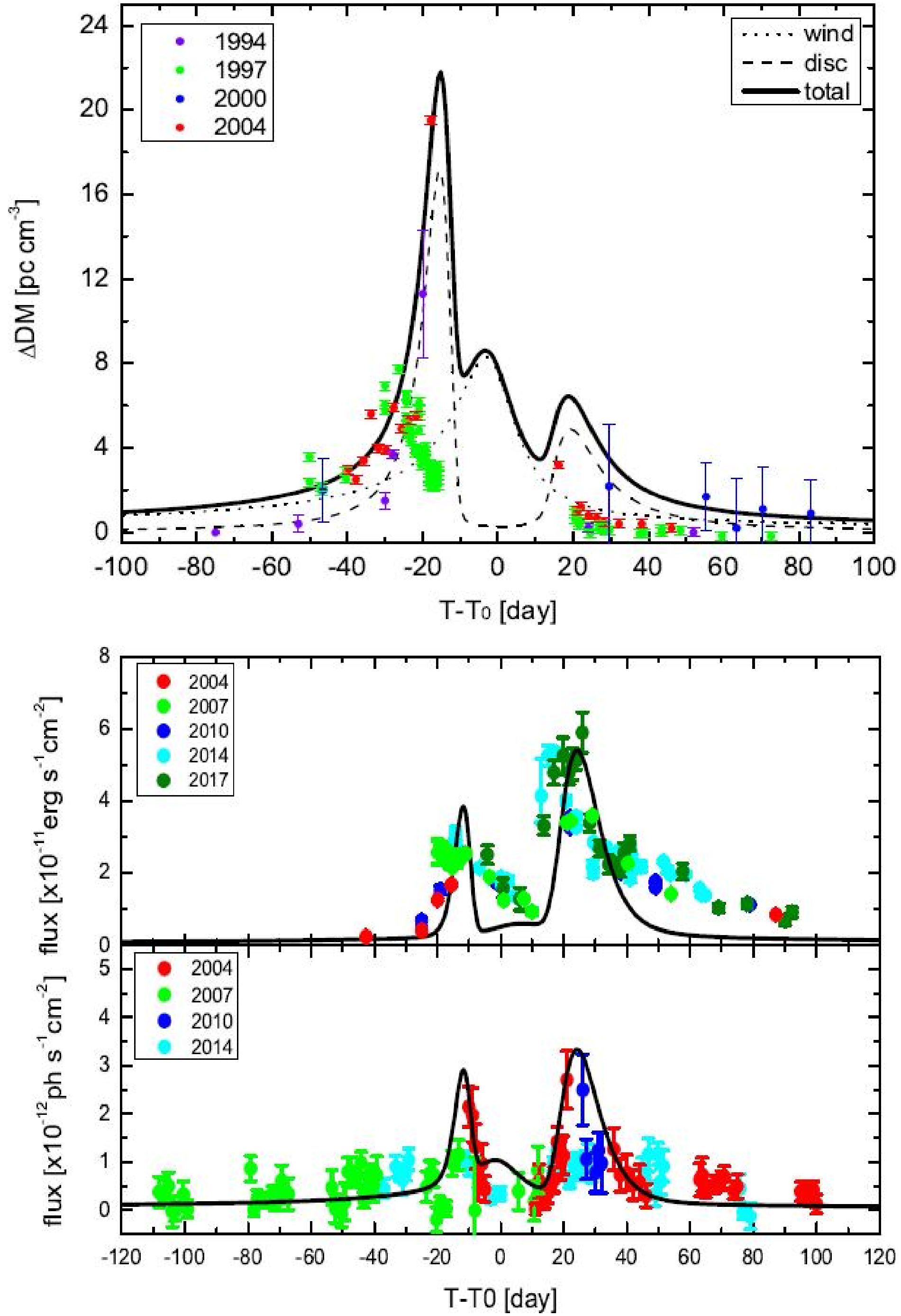

E^2 dN/dE (erg cm^{-2} s^{-1})
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
Energy (eV)
Xing et al. 2016


NASA/Goddard Space Flight Center


HESS (>1TeV)
2010
2007
2004
F_{TeV}
a
Fermi 2010
(> 100 MeV)
F_{GeV}
b
XMM 2010
Suzaku 2010
SWIFT 2010
XMM 2007
Suzaku 2007
Chandra 2007
XMM 2004
F_X
c
ATCA (2.4 GHz)
2010
2004
1997
F_R [mJy]
d
$W_{H\alpha}$
$100 \times W_{6678}$
$-W(\AA)$
e
Chernyakova et al. 2014
-100
-50
0
50
100
150
Days from periastron

$$\eta = \frac{L_{\rm sd}/c}{\dot{M} v_{\rm w}}$$





DM

keV

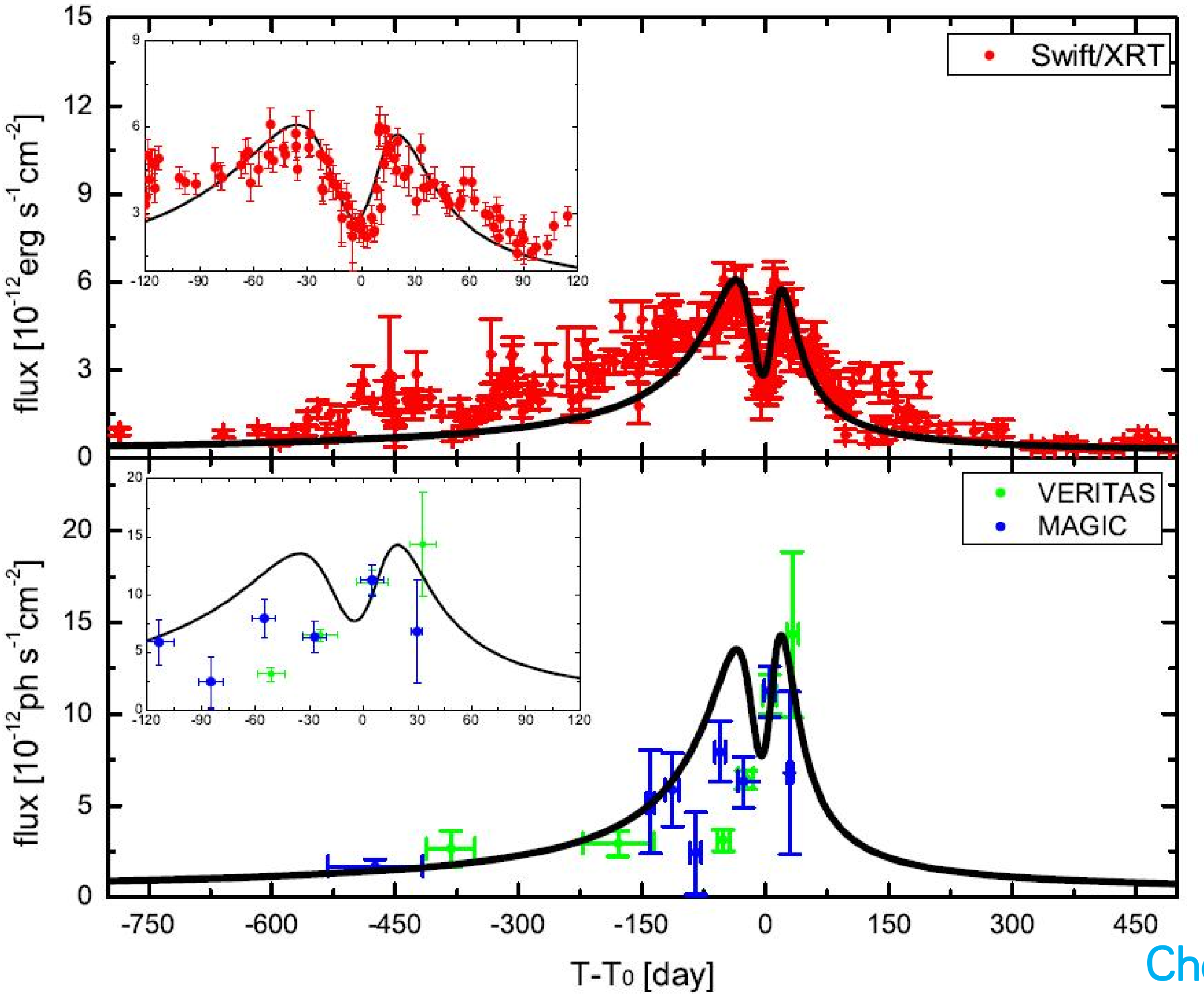
TeV

Chen et al. 2019, 2021a

2.2: PSR J2032+4127

$P_{\rm o} \sim 45 - 50$ yr !!!

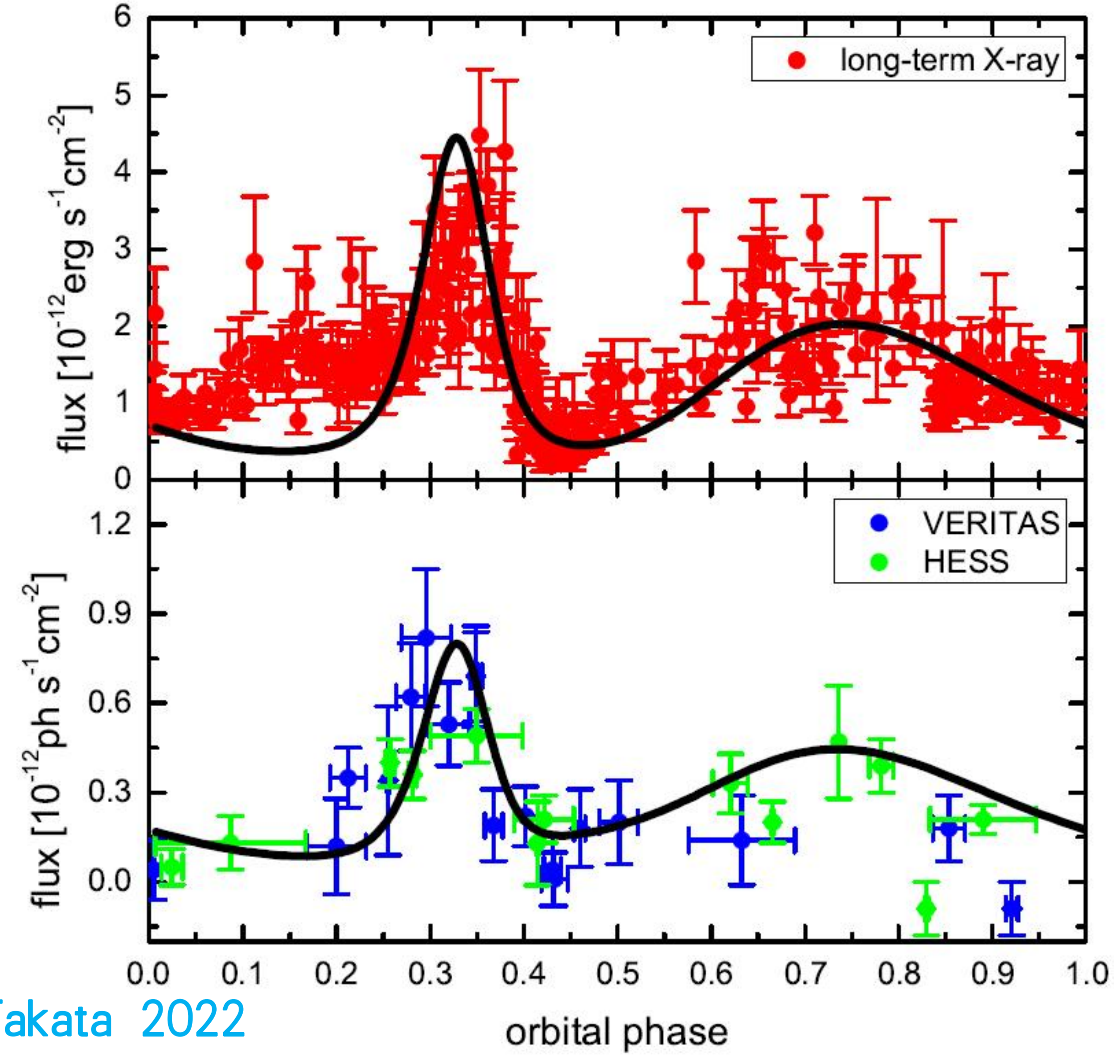
$e = 0.93 - 0.99$



2.3: HESS J0632+057

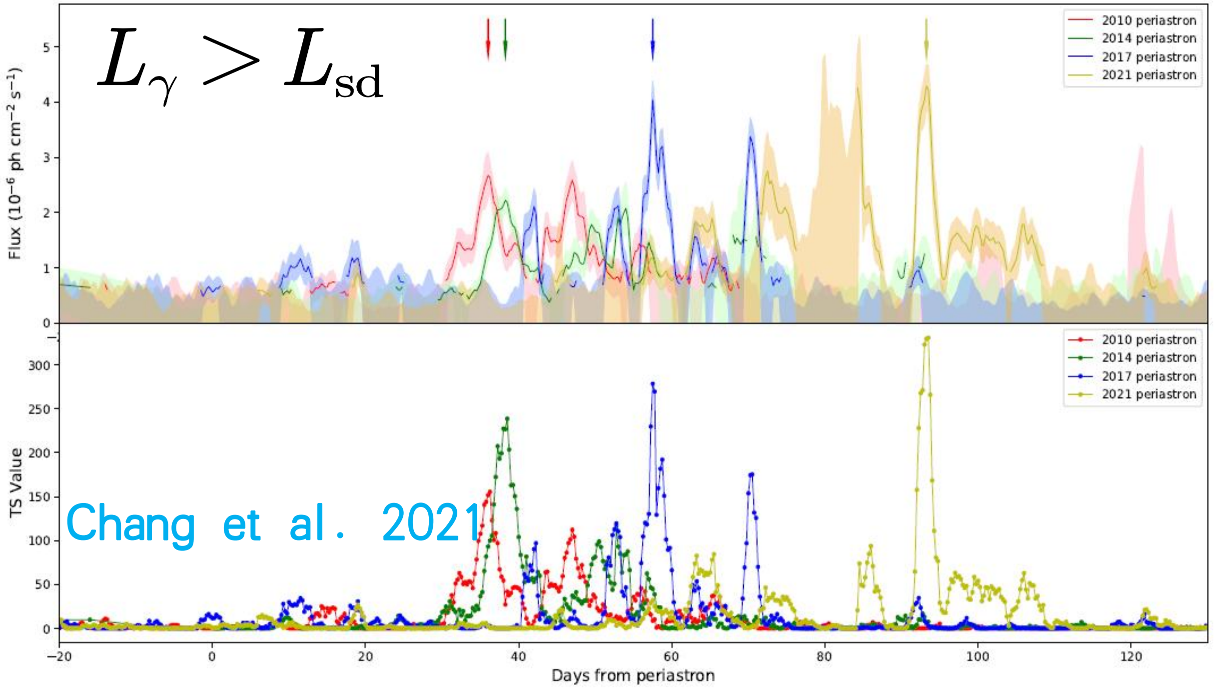
$P_{\rm o} \sim 308 - 321$ d

$e \sim 0.64 - 0.83$



Chen & Takata 2022

Mysterious GeV flares of PSR B1259-63 ?



No counterpart in other bands during GeV flares

Indicating distinctive emitting particles or regions?

IC in PWZ, with seed photons from:

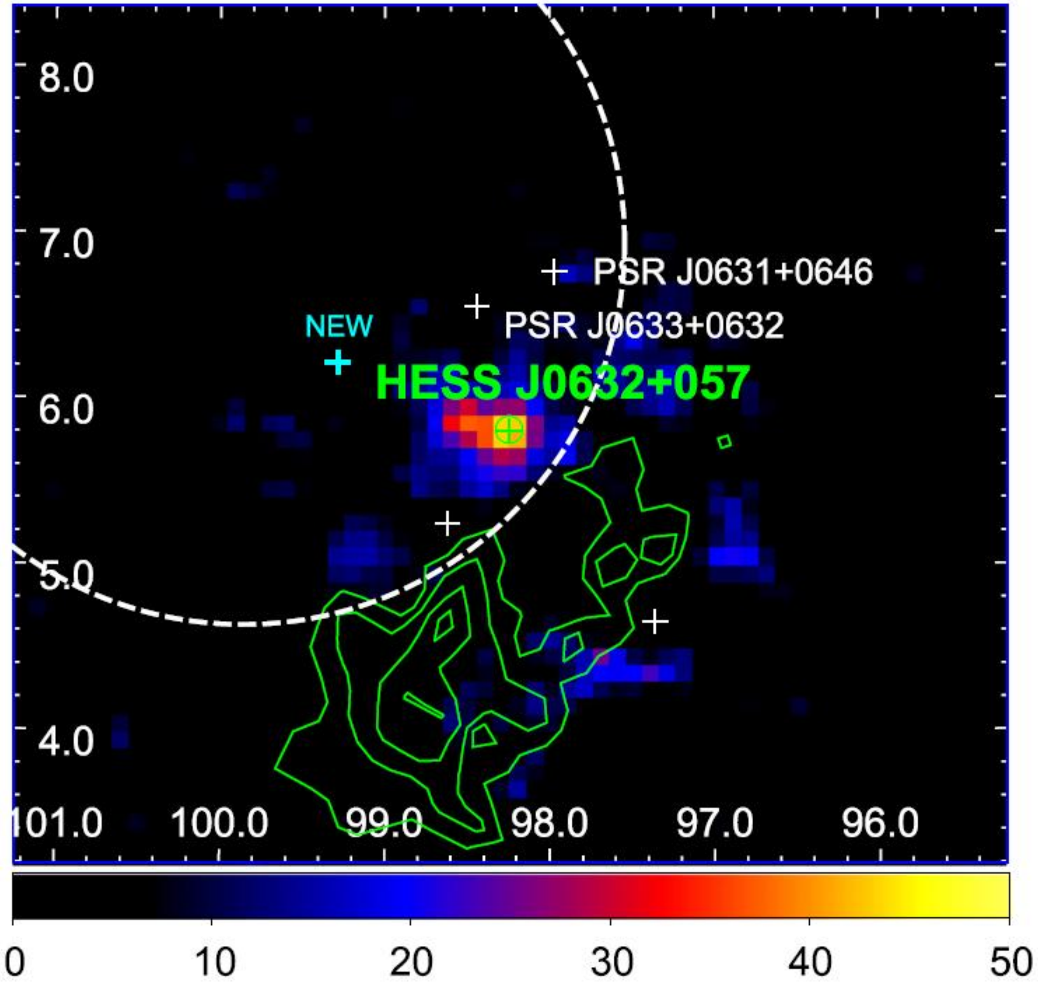
① The companion star (Kirk+2000): ×

② The stellar disc (van Soelen+2012) : ×

③ Synchrotron X-ray (Dubus+2010): ×

④ Transient accretion disc (Yi +2017,2018) : ×

Missing GeV emission from HESS J0632+057 ?



Li et al. 2017

Comparing to other very luminous γBs, why J0632's GeV emission is so weak?

2.4: LS 5039

- **Compact object:**

➢**BH or NS ?**

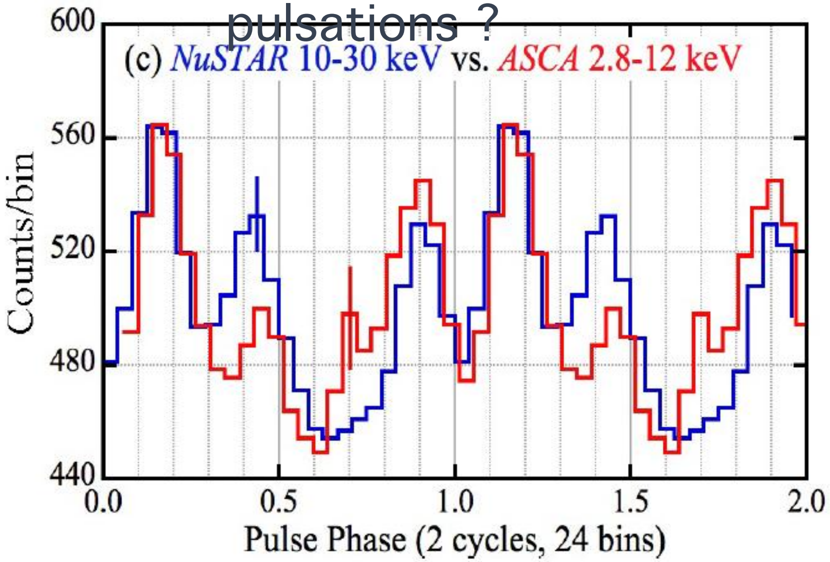
- **Companion star:**

O6.5V((f)) $T_{\rm eff} \simeq 39000\,{\rm K}$

- **Binary system:**

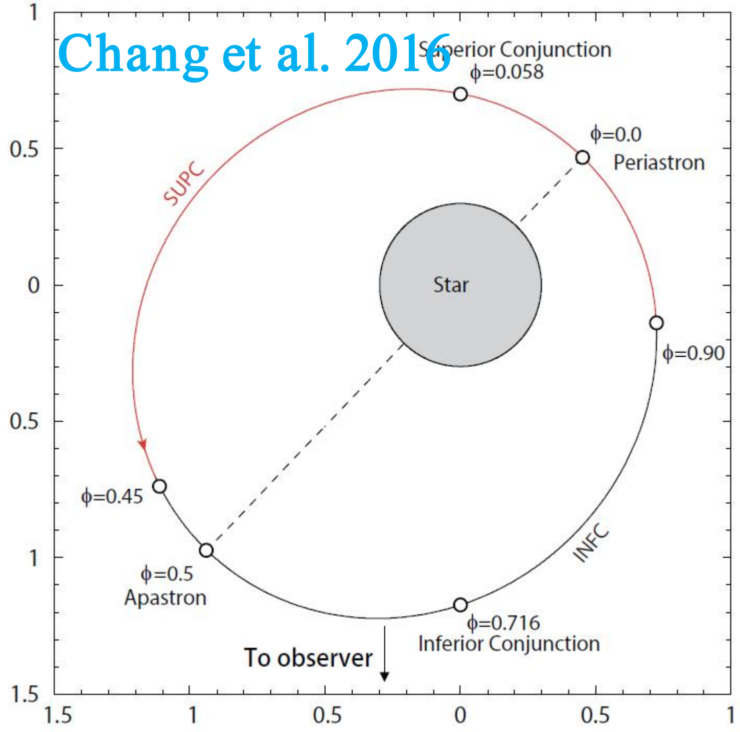
$P_{\rm orb} = 3.9{\rm d}, \quad e = 0.35, \quad d_{\rm L} \sim 2.9\,{\rm kpc}$

9-sec X-ray pulsations ?

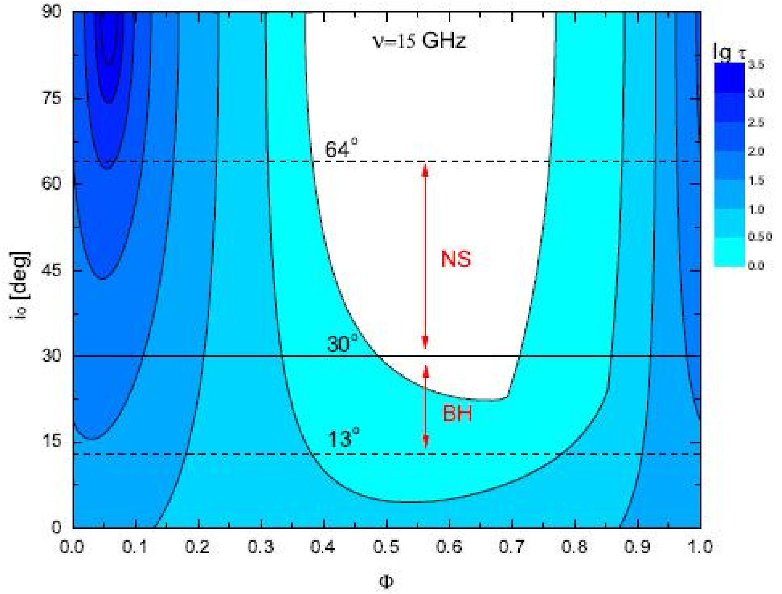


Makishima et al. 2023

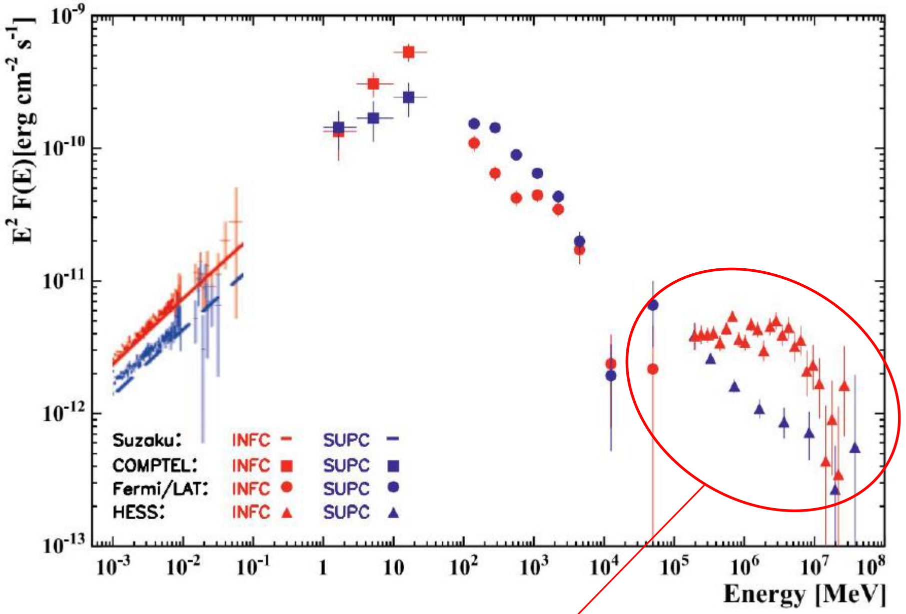
Chang et al. 2016



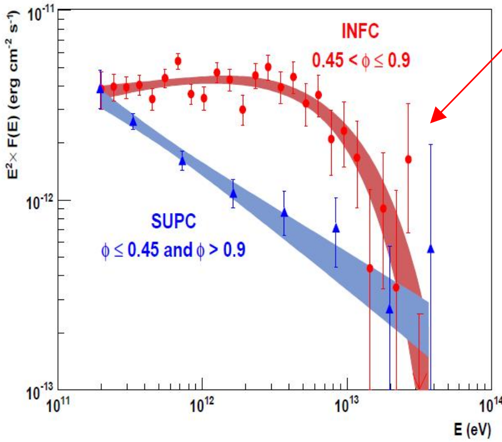
Chen et al. 2021a



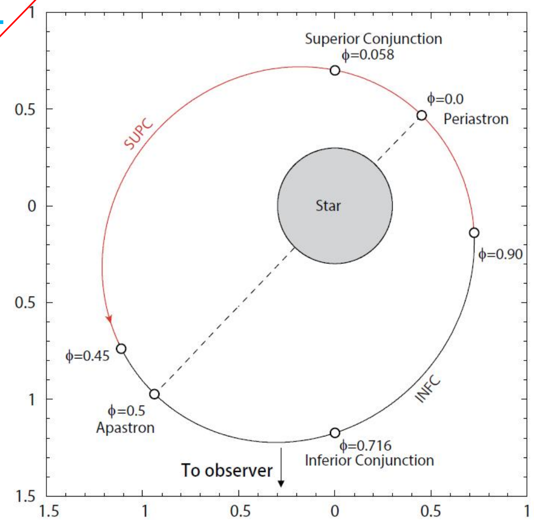
2.4: LS 5039



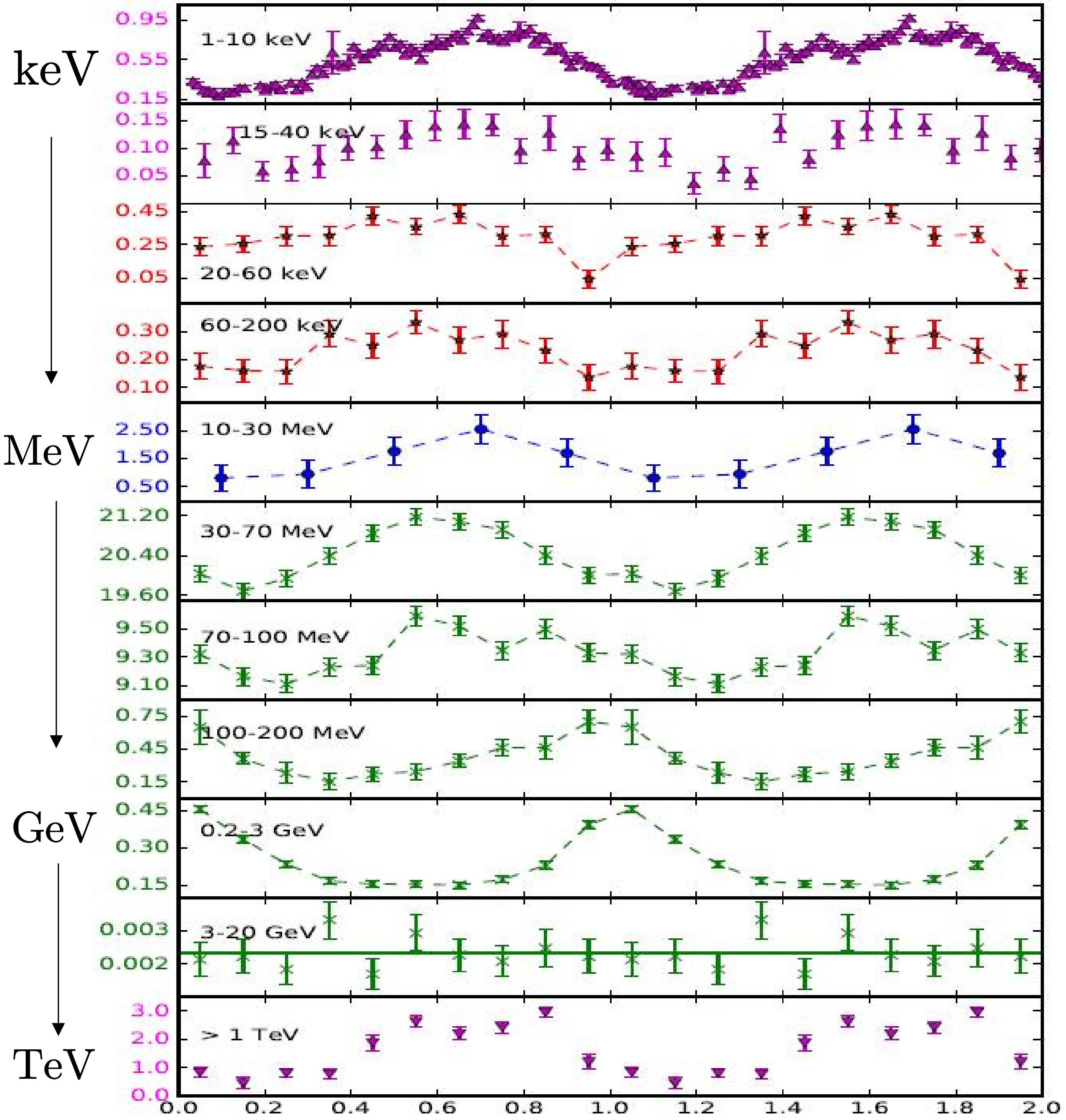
Collmar & Zhang 2014

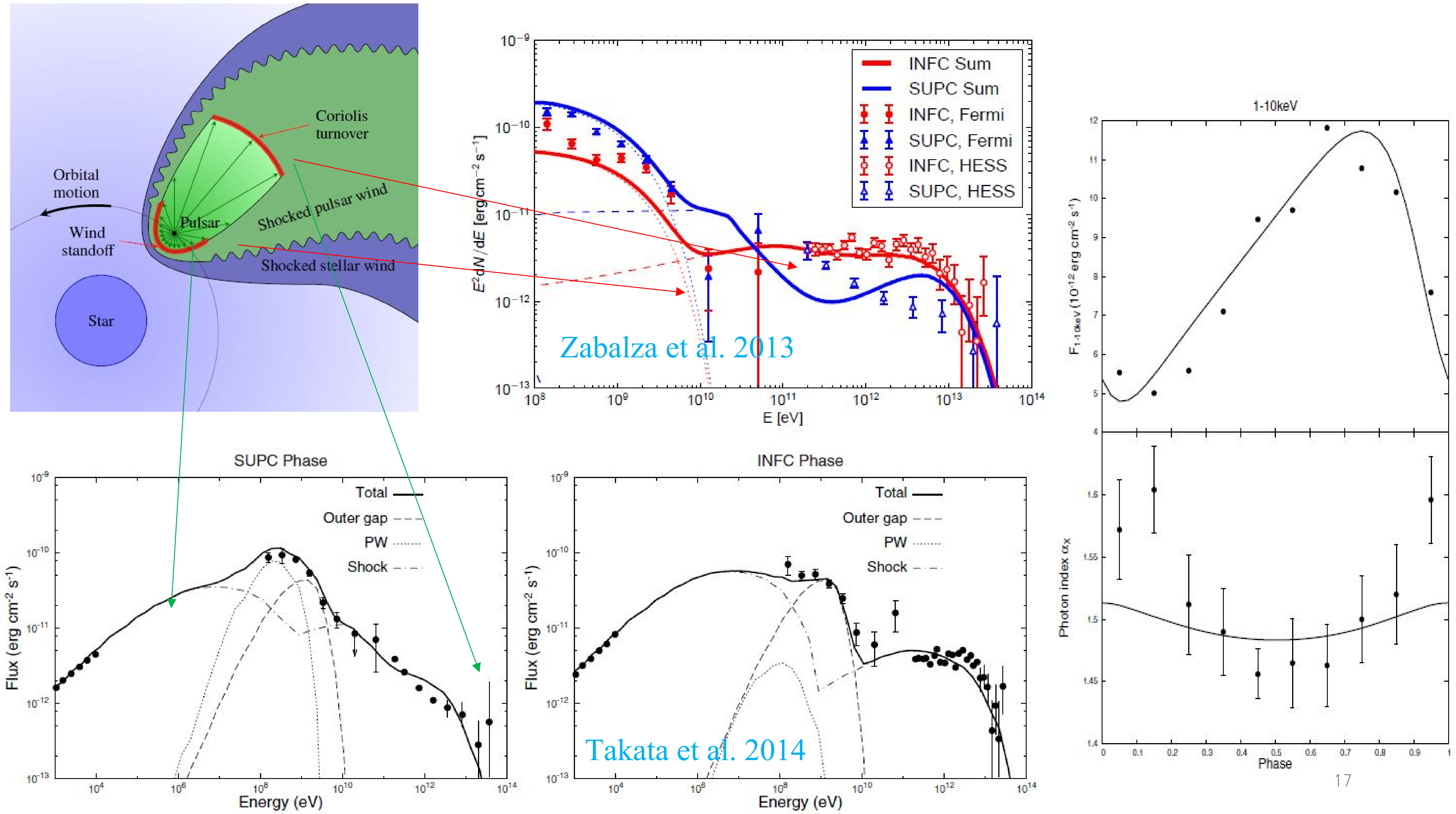


Aharonian et al. 2006

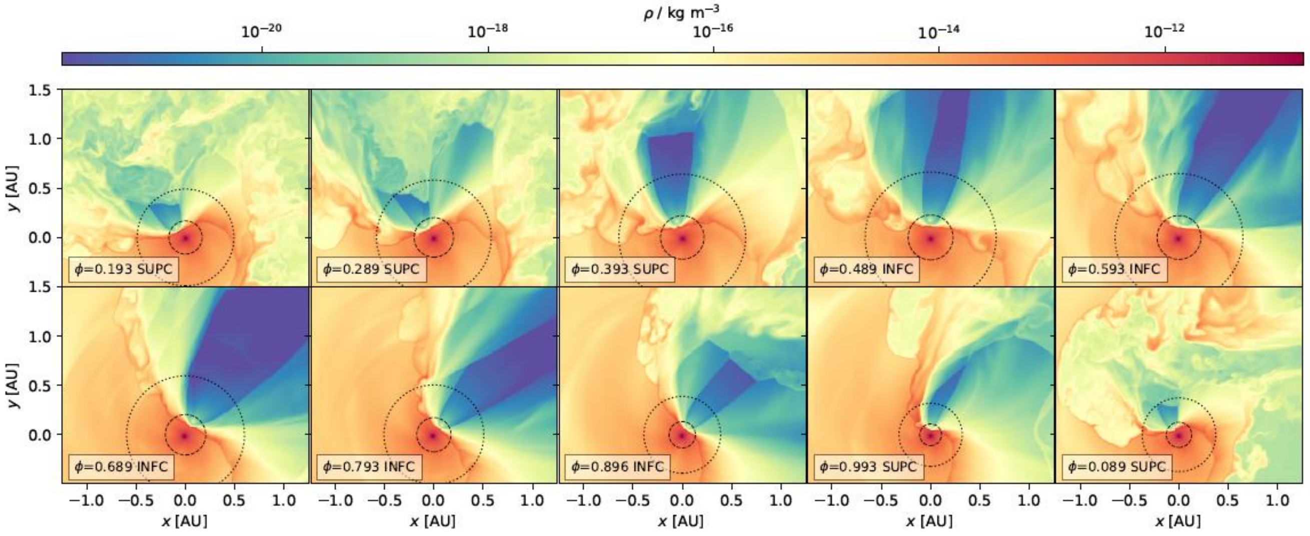


Chang et al. 2016

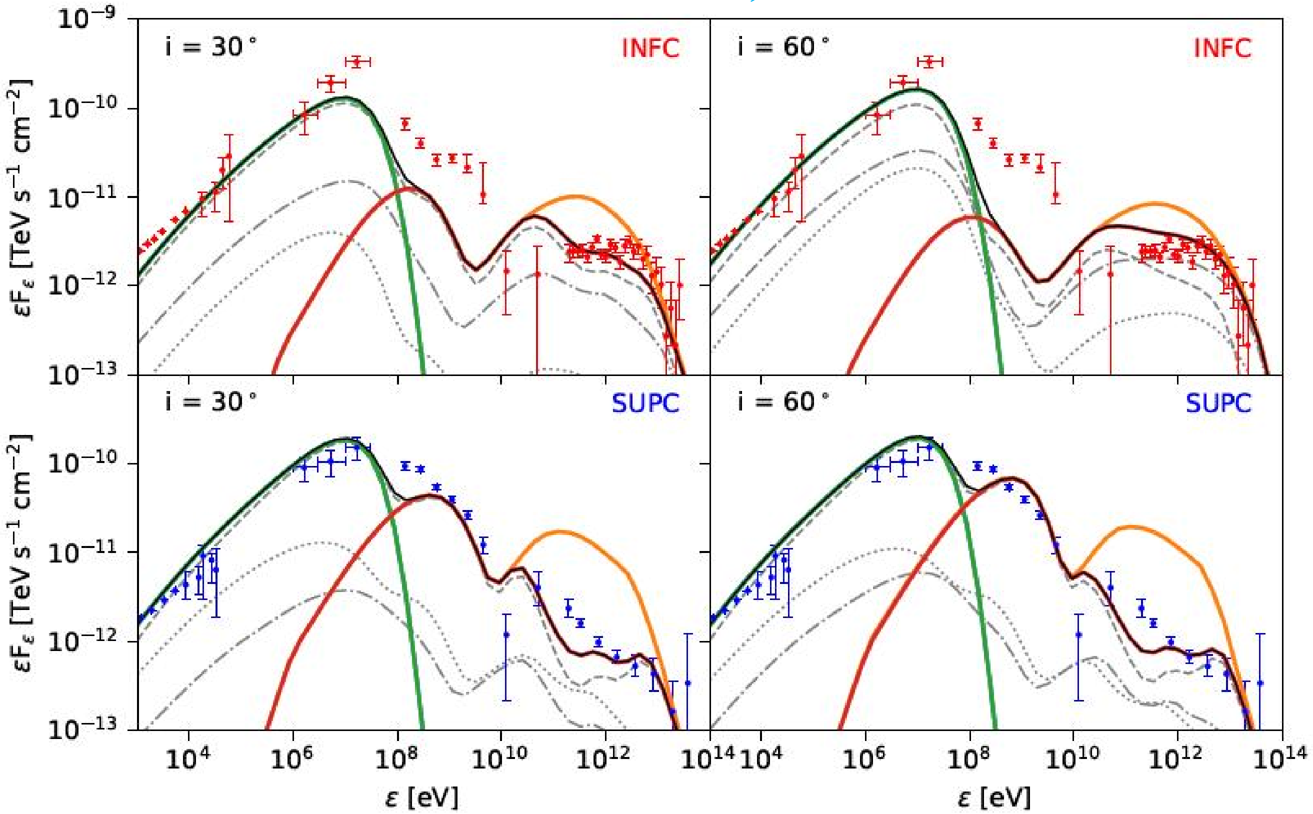


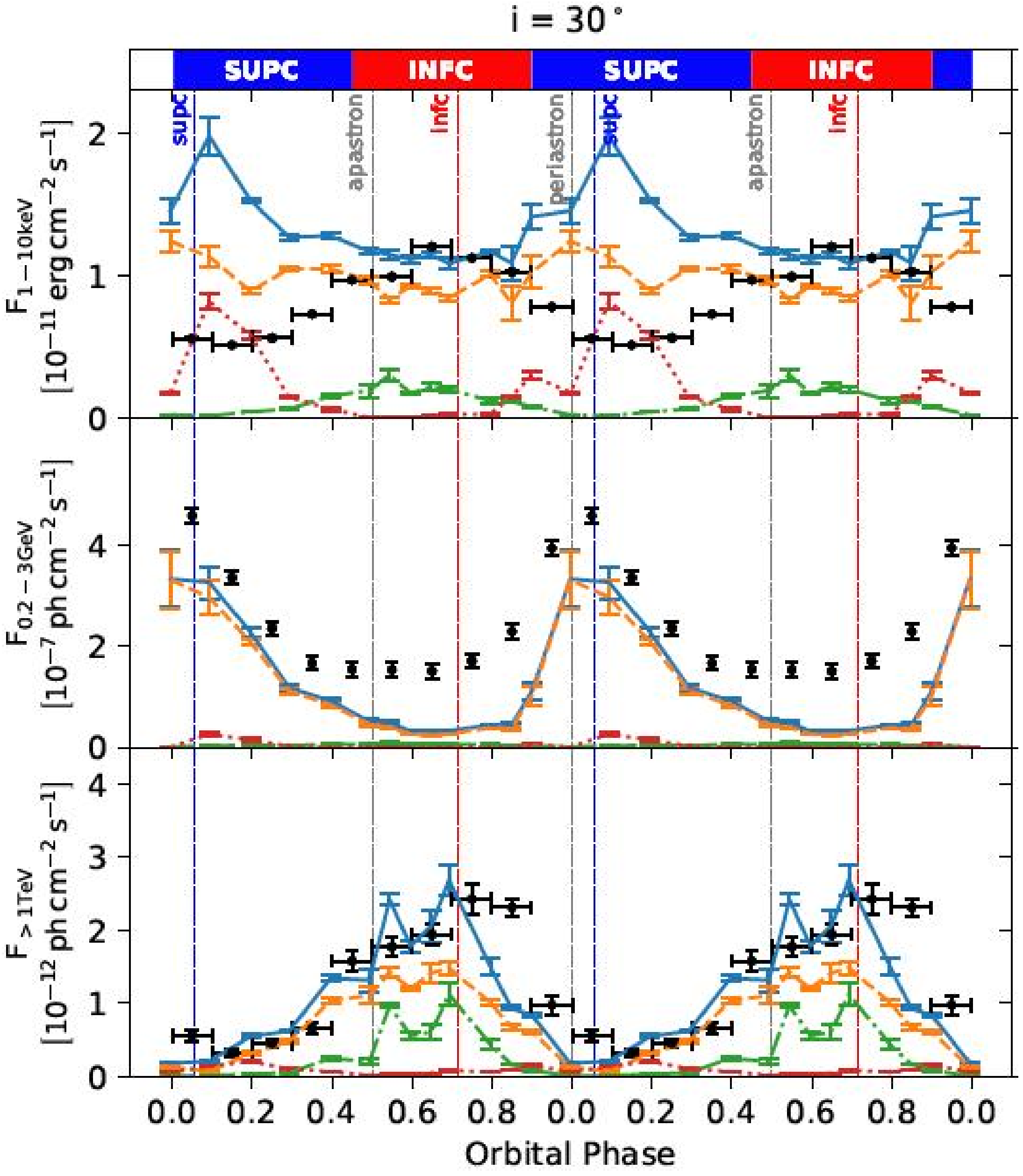


Coriolis turnover
Orbital motion
Pulsar
Shocked pulsar wind
Wind standoff
Shocked stellar wind
Star
INFC Sum
SUPC Sum
INFC, Fermi
SUPC, Fermi
INFC, HESS
SUPC, HESS
$E^2 dN/dE$ [erg cm^{-2} s^{-1}]
E [eV]
Zabalza et al. 2013
1-10keV
$F_{1\text{-}10keV}$ (10^{-12} erg cm^{-2} s^{-1})
Photon index α_X
Phase
SUPC Phase
Total
Outer gap
PW
Shock
Flux (erg cm^{-2} s^{-1})
Energy (eV)
INFC Phase
Total
Outer gap
PW
Shock
Flux (erg cm^{-2} s^{-1})
Energy (eV)
Takata et al. 2014



Huber et al. 2021a,b





Huber et al. 2021a,b

3. Can γBs be PeVatrons?

LHAASO coll. 2021, Nature

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2[d]	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3[e]	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3[f]	< 2[f]	—	HESS J1843-033, HESS J1844-030, 2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7[g]	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5[h]	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4[i]	$\sim 10 - 20$[j]	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8}_{-0.7}$[d]	$1.8 - 3.3$[k]	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2[d]	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7}_{-1.4}$[l]	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	3.3 ± 0.3[m]$/4.0 \pm 0.5$[n]	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08[o]	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08[o]	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8[p]	~ 10[p]	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8[p]	~ 10[p]	2.2×10^{37}	

3. Can γBs be PeVatrons?

(1) Leptonic processes: electrons

➢With the magnetic field: Synchrotron

$$e^{\pm} + B \rightarrow \gamma$$

➢With the photon field: IC scattering

$$e^{\pm} + \gamma \rightarrow \gamma'$$

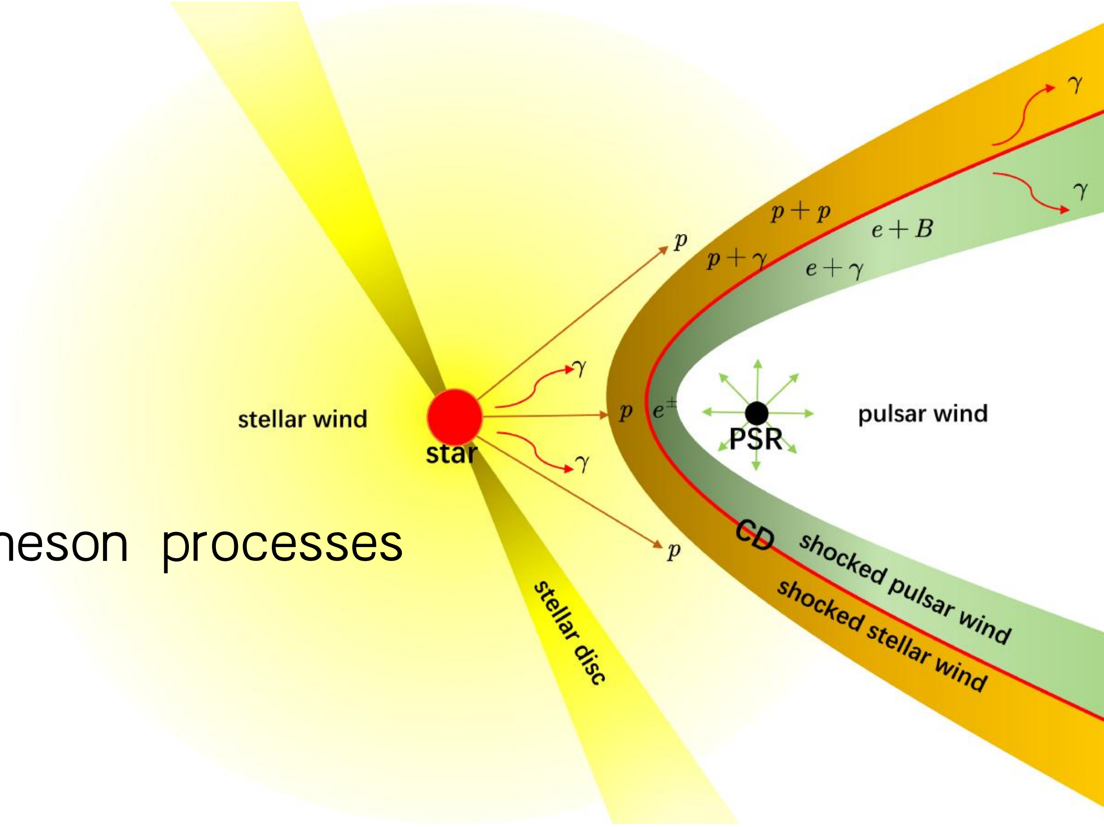
(2) Hadronic processes: protons

➢With photon field: p—IC, Bethe—Heitler & Photomeson processes

$$p + \gamma \rightarrow \begin{cases} p + \gamma' \\ p + e^{+} + e^{-} \\ p/n + n_0\pi^0 + n_+\pi^+ + n_-\pi^- \end{cases}$$

➢With stellar outflows: proton—proton interaction

$$p + p \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ \pi^+ \rightarrow \mu^+ + \nu_\mu, \ \mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu \\ \pi^- \rightarrow \mu^- + \overline{\nu}_\mu, \ \mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu \end{cases}$$



Chen et al. 2023, in preparation

3. Can γBs be PeVatrons?

(1) Leptonic processes: electrons $E_{e,\max}$?

➢Potential drop:

$$E_{e,\max}=q_e(L_{\rm sd}/c)^{1/2}\approx 2\times10^{15}L_{\rm sd,36}^{1/2}\ \rm eV$$

➢Hillas criterion:

$$E_{e,\max}=q_eBR\approx 3\times10^{14}B_1R_{11}\ \rm eV$$

➢Energy losses: Adiabatic or Radiative cooling

$$E_{e,\max}=3\eta_eq_eBR\approx 1\times10^{14}\eta_{-1}B_1R_{11}\ \rm eV$$

$$\boxed{E_{e,\max}=(6\pi\eta_eq_e/\sigma_TB)^{1/2}m_ec^2\approx 6\times10^{12}\eta_{-1}^{1/2}B_1^{-1/2}\ \rm eV}$$

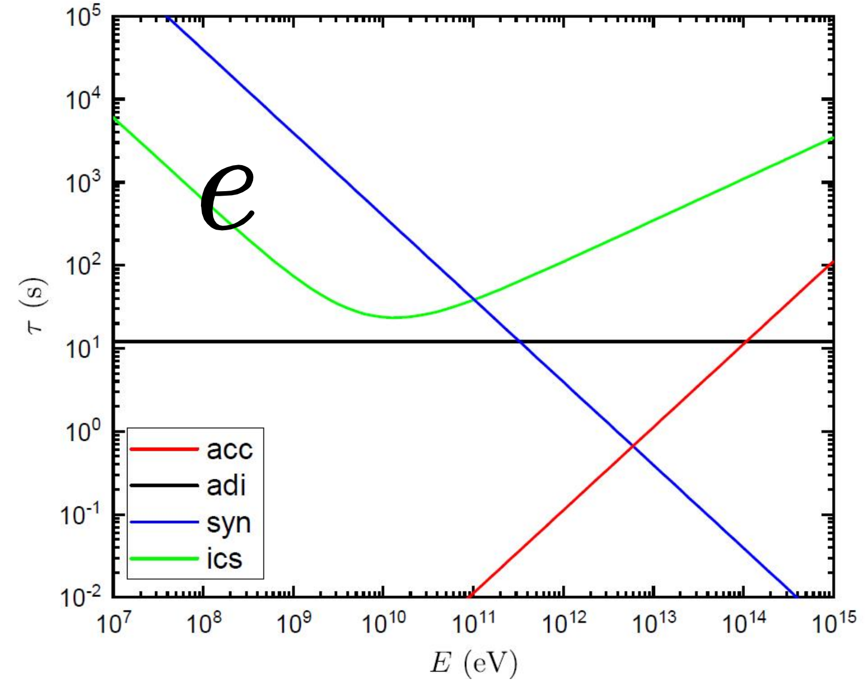
(2) Hadronic processes: protons $E_{p,\max}$?

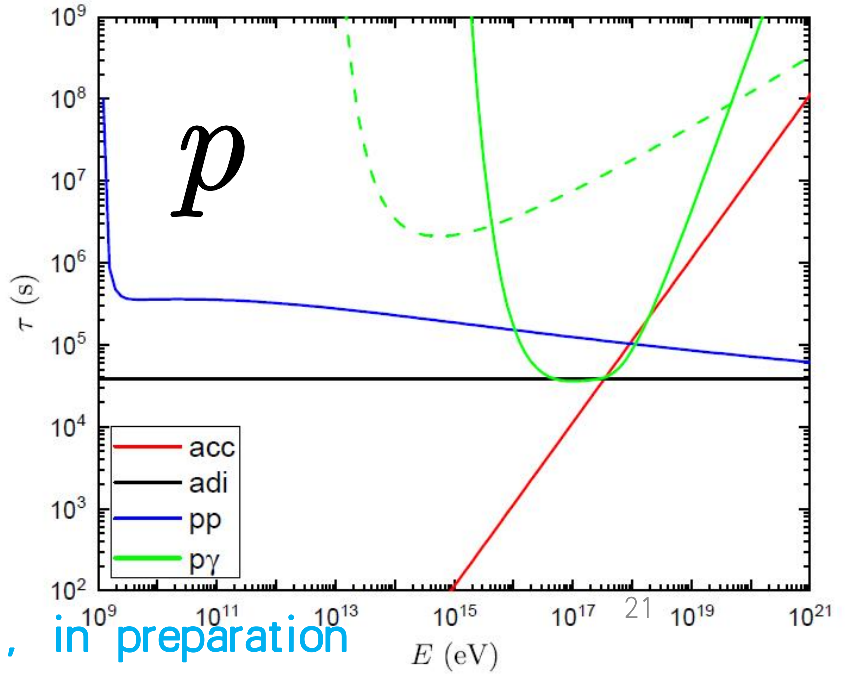
➢Hillas criterion:

$$\boxed{E_{p,\max}=q_eBL\approx 3\times10^{15}B_1L_{12}\ \rm eV}$$

➢Energy losses: Adiabatic cooling

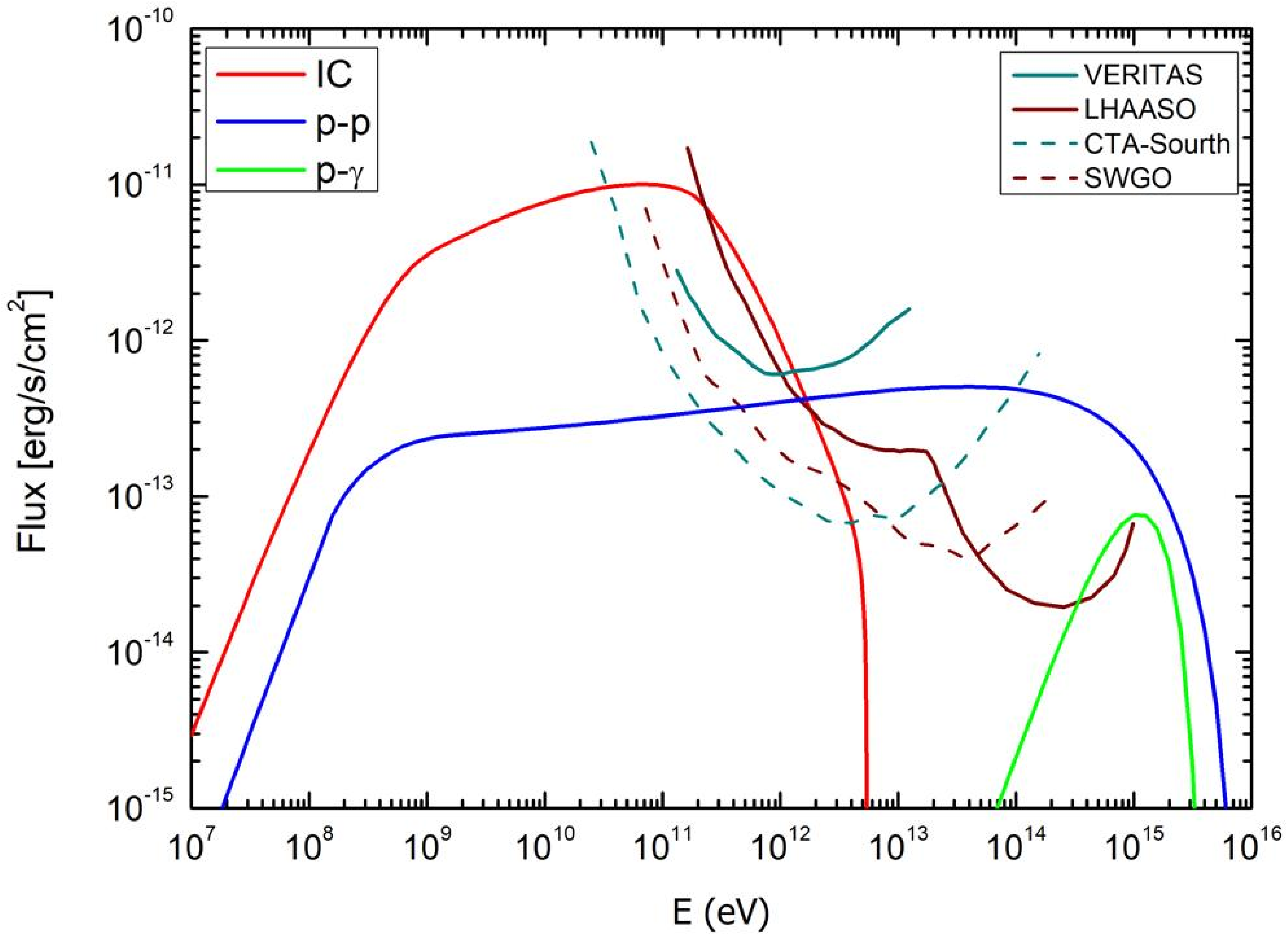
$$E_{p,\max}=4R_{\rm sh}\eta q_ecB/v_w\approx 3\times10^{17}B_1R_{12}\eta_{-1}v_{\rm w,8}\ \rm eV$$

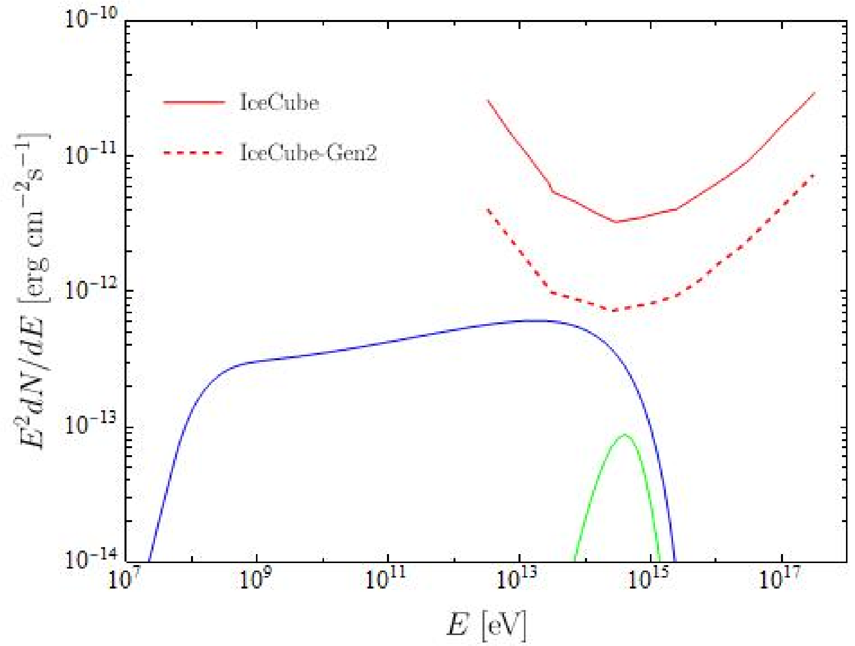


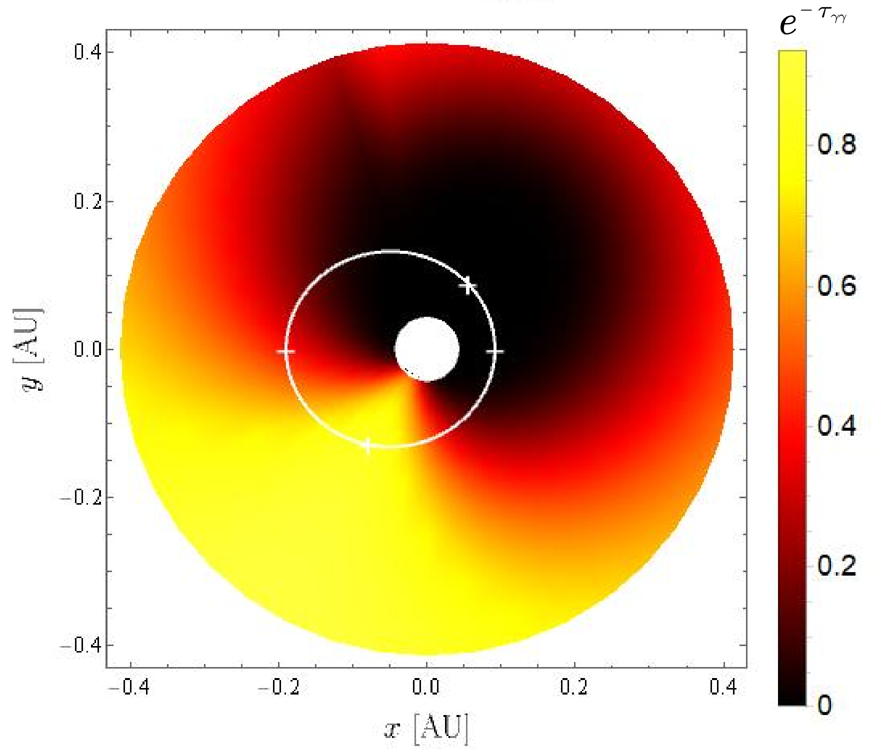


Chen et al. 2023, in preparation

3. Can γBs be PeVatrons?

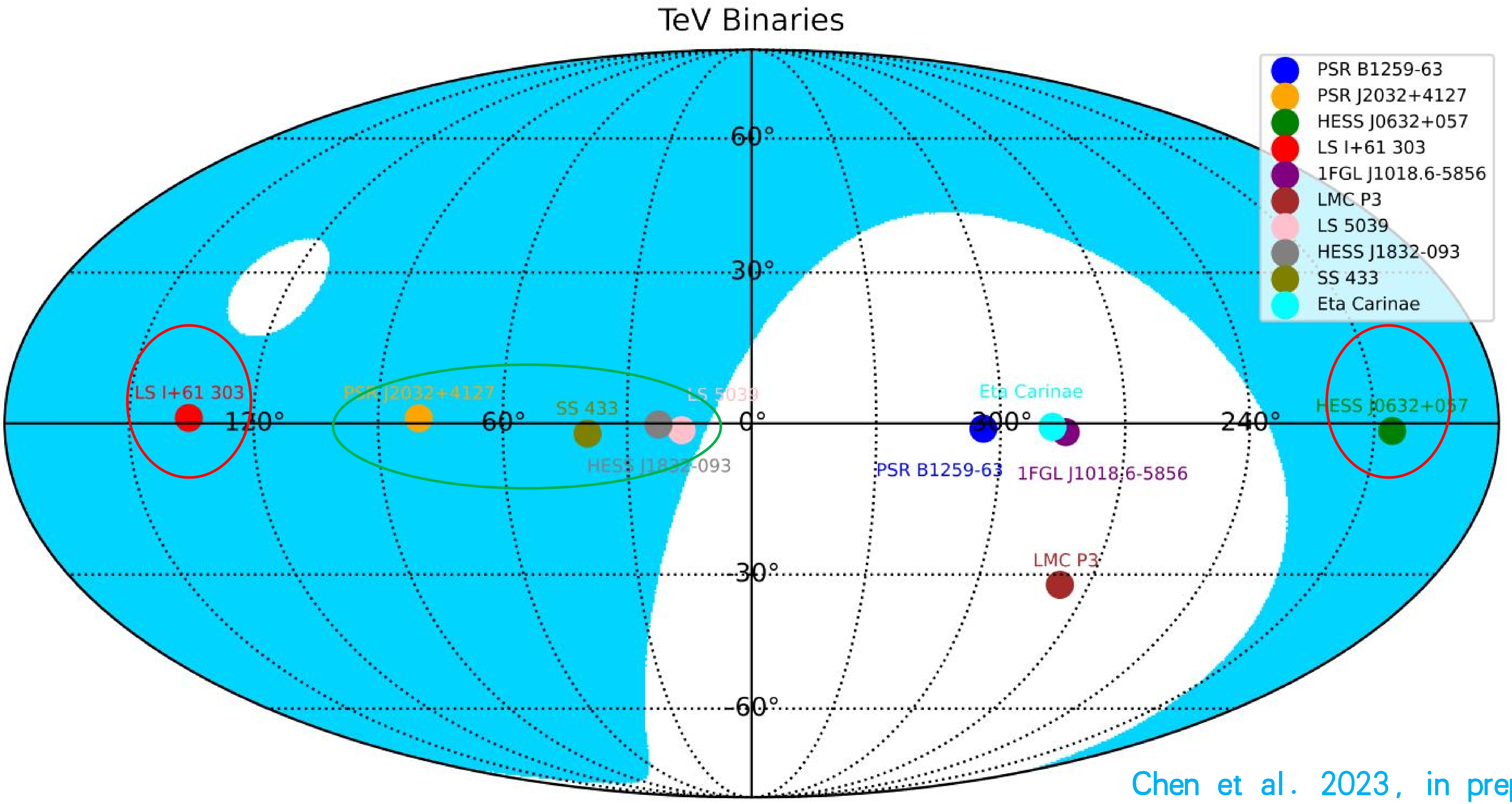




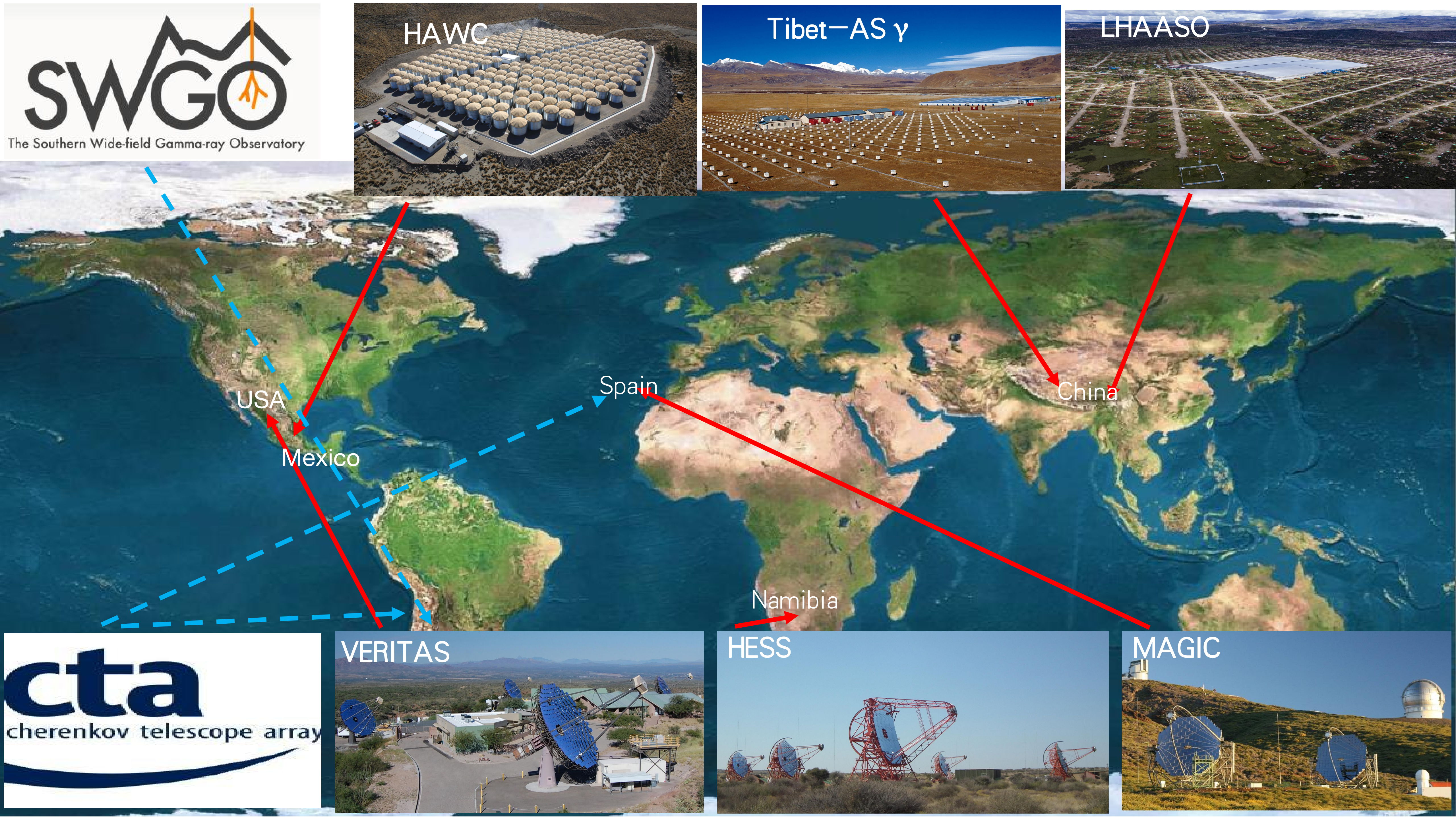


Chen et al. in preparation

γBs with LHAASO



Chen et al. 2023, in preparation


SWGO
The Southern Wide-field Gamma-ray Observatory
HAWC
Tibet—AS γ
LHAASO
USA
Mexico
Spain
China
Namibia
cta
cherenkov telescope array
VERITAS
HESS
MAGIC

- **VHE γ-ray sources**
  - Production: Leptonic or Hadronic
  - Annihilation: pair creation

- **Particle acceleration:**
  - Magnetic reconnection
  - Fermi 1th acceleration

What can we learn from HMGBs ?

$e^{\pm}$ pairs、$B-$field V.S. stellar outflows、photon field

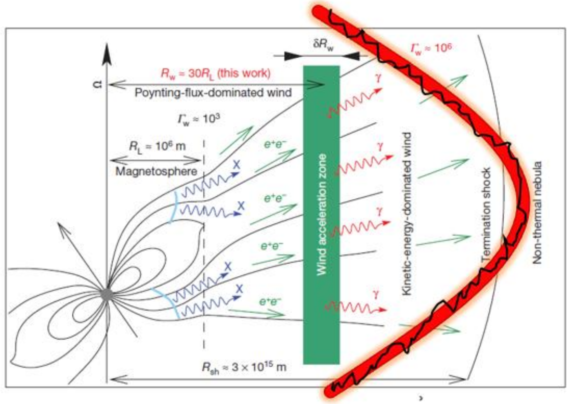


Figure: Aharonian et al. 2010

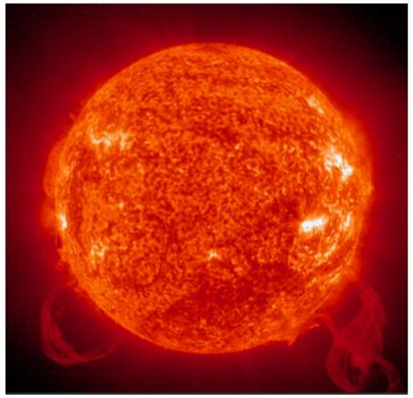


Figure: Wikipedia

- **Pulsar wind physics:**
  - σ-problem
  - B-field structure

- **Evolution of binary system:**
  - Pulsar spin-down
  - O/B star and its outflows

Thank you very much
for your attention.

Extra slides

Unsolved questions in gamma-ray binaries:

1. The unknown nature of compact objects in other binaries?

2. The origin of GeV flares from PSR B1259-63?

3. The missing GeV emission from HESS J0632+057?

4. The super-orbital modulations as seen in LS I+61 303?

5. The observed HMGBs are much less than predictions

Unsolved questions：

binaries	PSR B1259-63	PSR J2032+4127	HESS J0632+057	LS I +61 303	LS 5039	LMC P3	1FGL J1018.6-5856	HESS J1832-093
Compact object	Pulsar	Pulsar	?	Pulsar ?	Pulsar ?	?	?	?
Pulsation period	47.73 ms (Radio)	143 ms (Radio/γ–ray)	?	269 ms ? (Radio)	~9 s ? (X–ray)	?	?	?
Companion star	O9.5Ve	B0Ve	B0Vpe	B0Ve	O6.5V	O5III	O6V	O?
Stellar disk	√	√	√	√	×	×	×	×
Orbital eccentricity	0.87	0.96	0.64–0.83 ?	0.55–0.72 ?	0.35	0.40	0.31	?
Orbital period	1236.7d	~17000d	317.3d	26.496d	3.906d	10.314d	16.58d	~86d
Distance (kpc)	2.39	1.33	1.6	2.0	2.9	~50	5.4	4.4

2.2: PSR J2032+4127

PSR J2032+4127 is the longest-period gamma-ray binaries with largest orbital eccentricity.

- **Pulsar:**

  $P = 143\,\mathrm{ms}$, $L_{\rm sd} \simeq 1.7 \times 10^{35}\,\mathrm{erg/s}$, $\tau \sim 115.8\,\mathrm{kyr}$

- **Be star:**

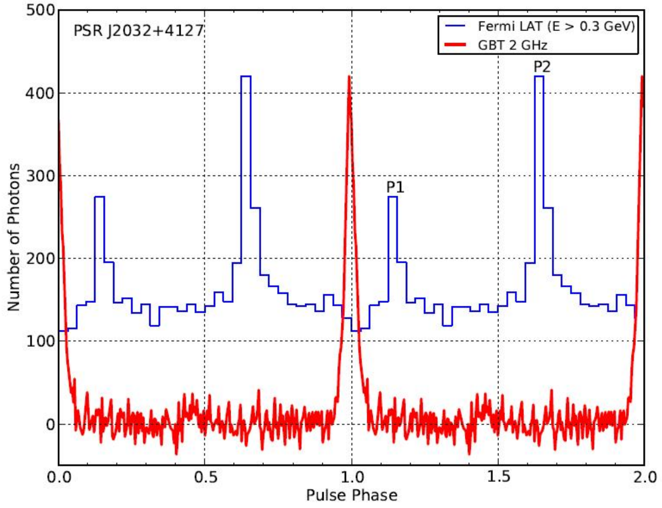
  B0Ve $T_{\rm eff} \simeq 30000\,\mathrm{K}$

- **Binary system:**

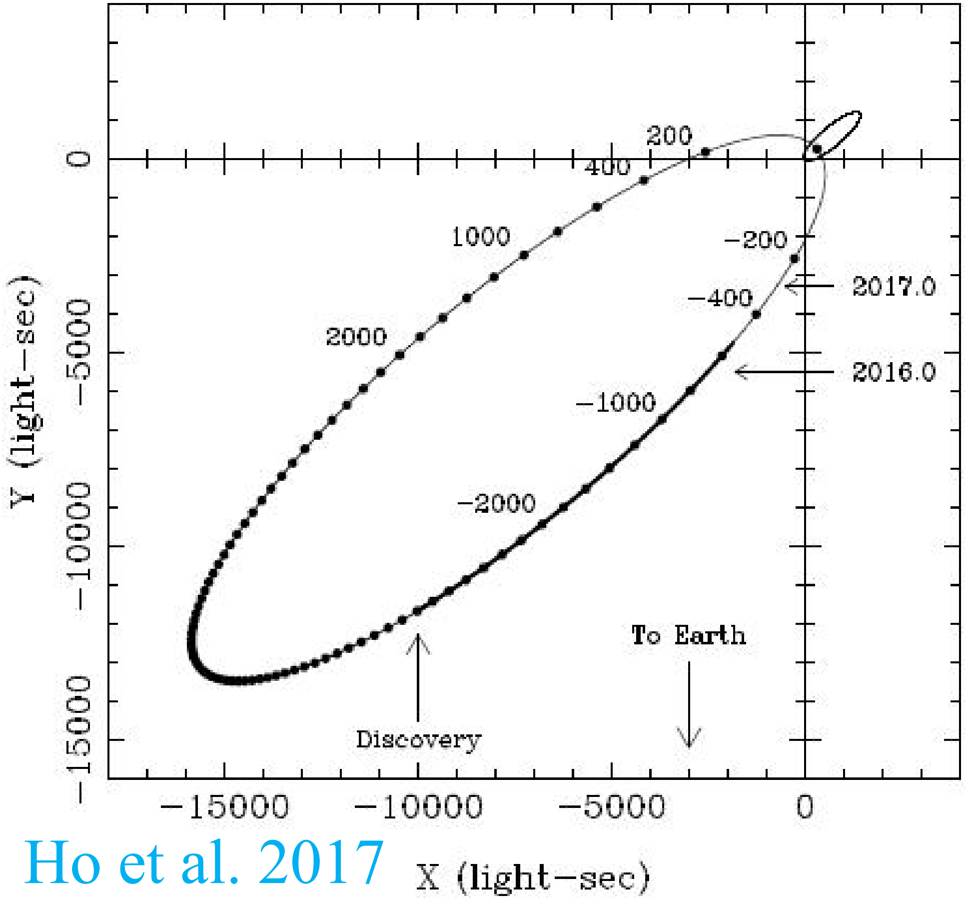
  $P_{\rm orb} \sim 45 - 50$ yr !!!

  $e = 0.93 - 0.99$

  $d_{\rm L} \sim 1.33\,\mathrm{kpc}$



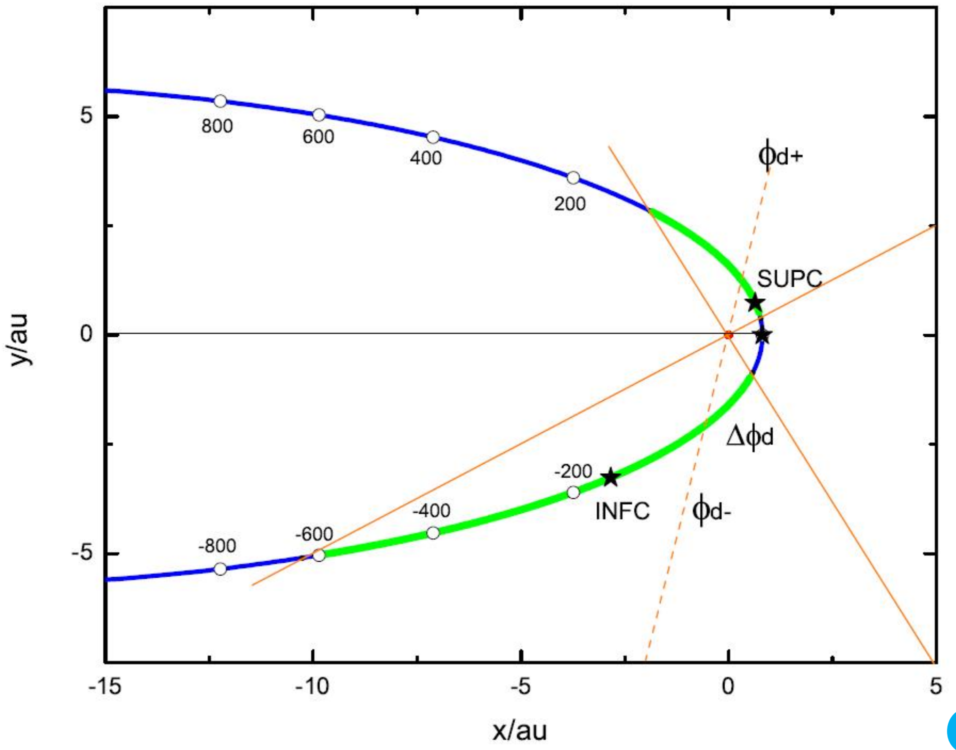
Camilo et al. 2009

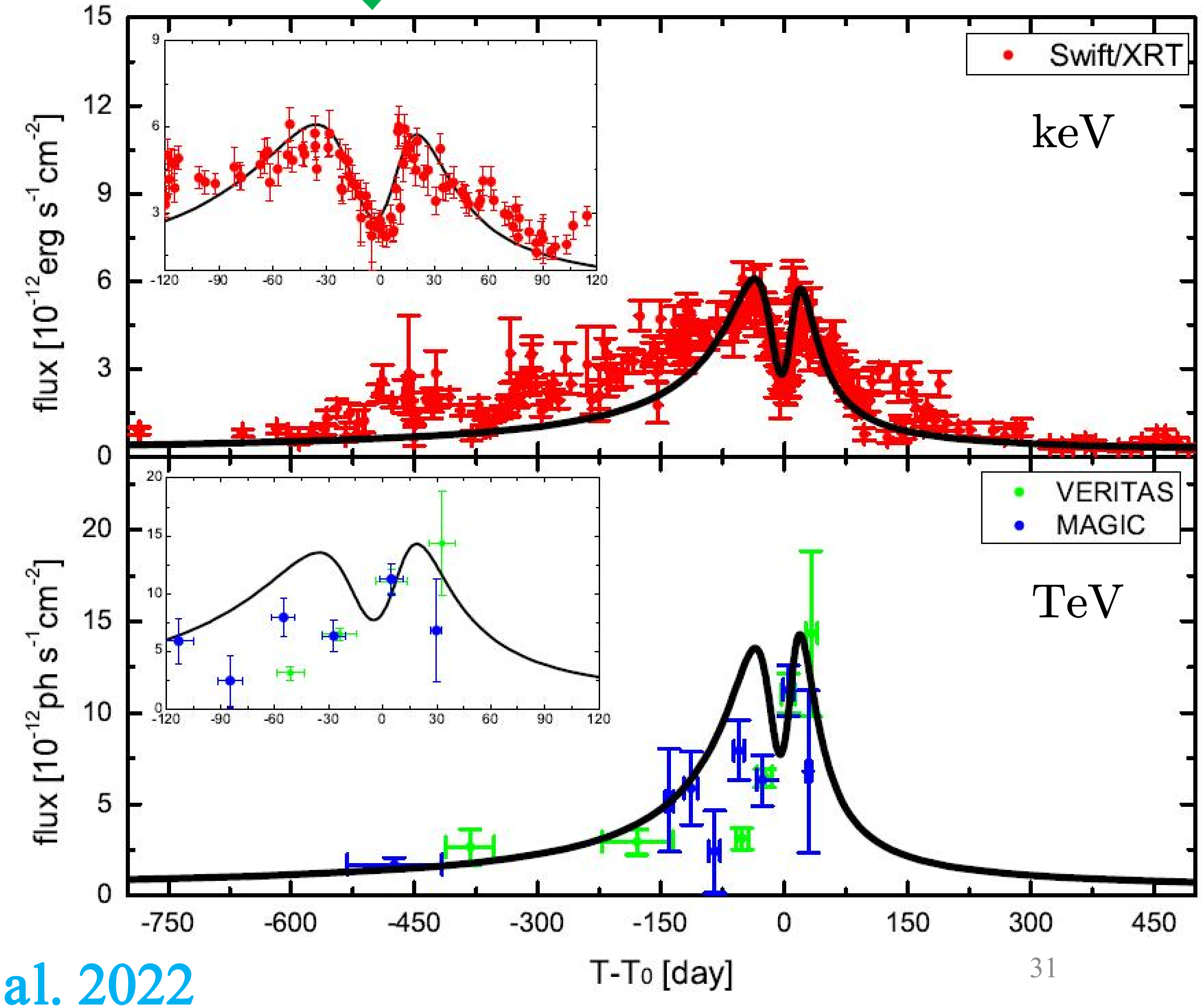


Ho et al. 2017

- The recent periastron passage occurred in 2017 November

Parameters	Model 1	Model 2	Model 3
e	0.936	0.961	0.989
P_o(d)	16000	17000	17670
T_0(MJD)	58053	58069	58068
ω_p(°)	52	40	21
$a \sin i$ (lt-s)	7138	9022	16335





Chen et al. 2022

2.3: HESS J0632+057

- Compact object：

  NS or BH ?

- Massive star：

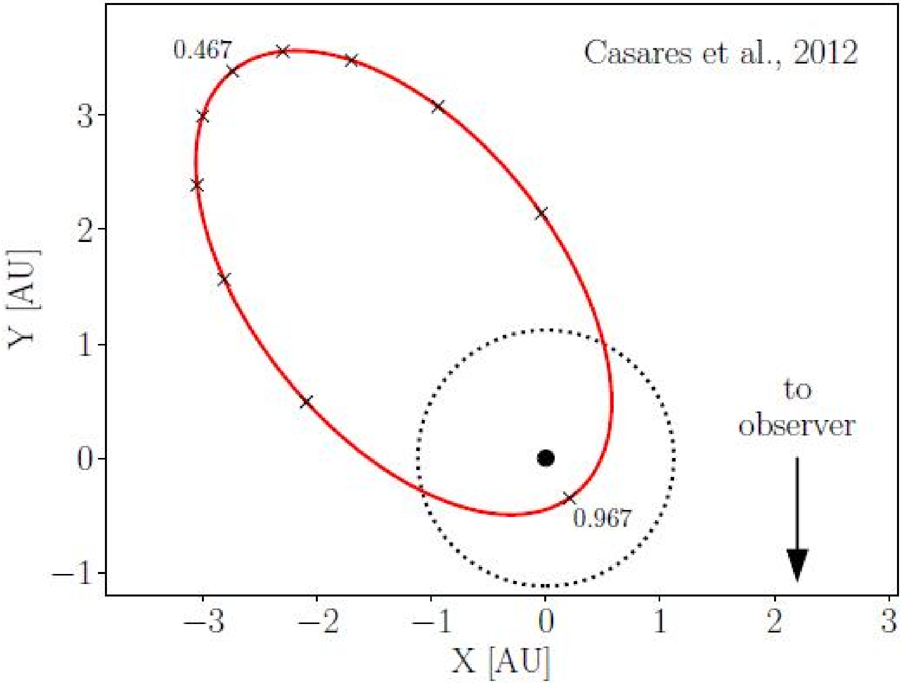
  MWC 148： B0Vpe

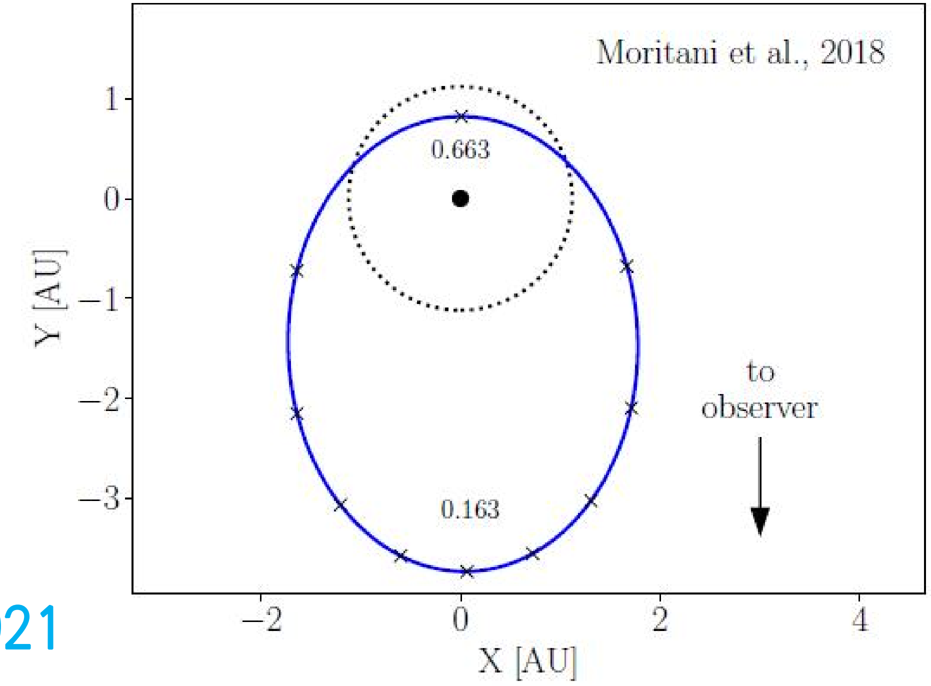
- Binary orbit：

  $e \sim 0.64 - 0.83$

  $P_{\mathrm{o}} \sim 308 - 321$ d

  $d_{\mathrm{L}} \sim 1.1 - 1.7$ kpc

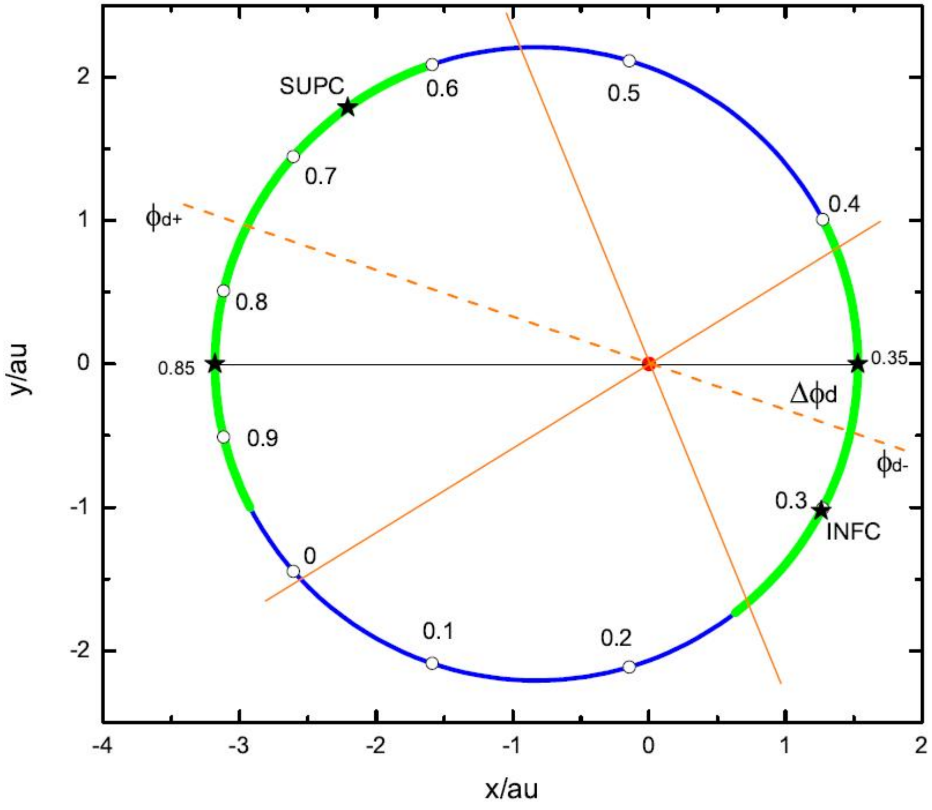


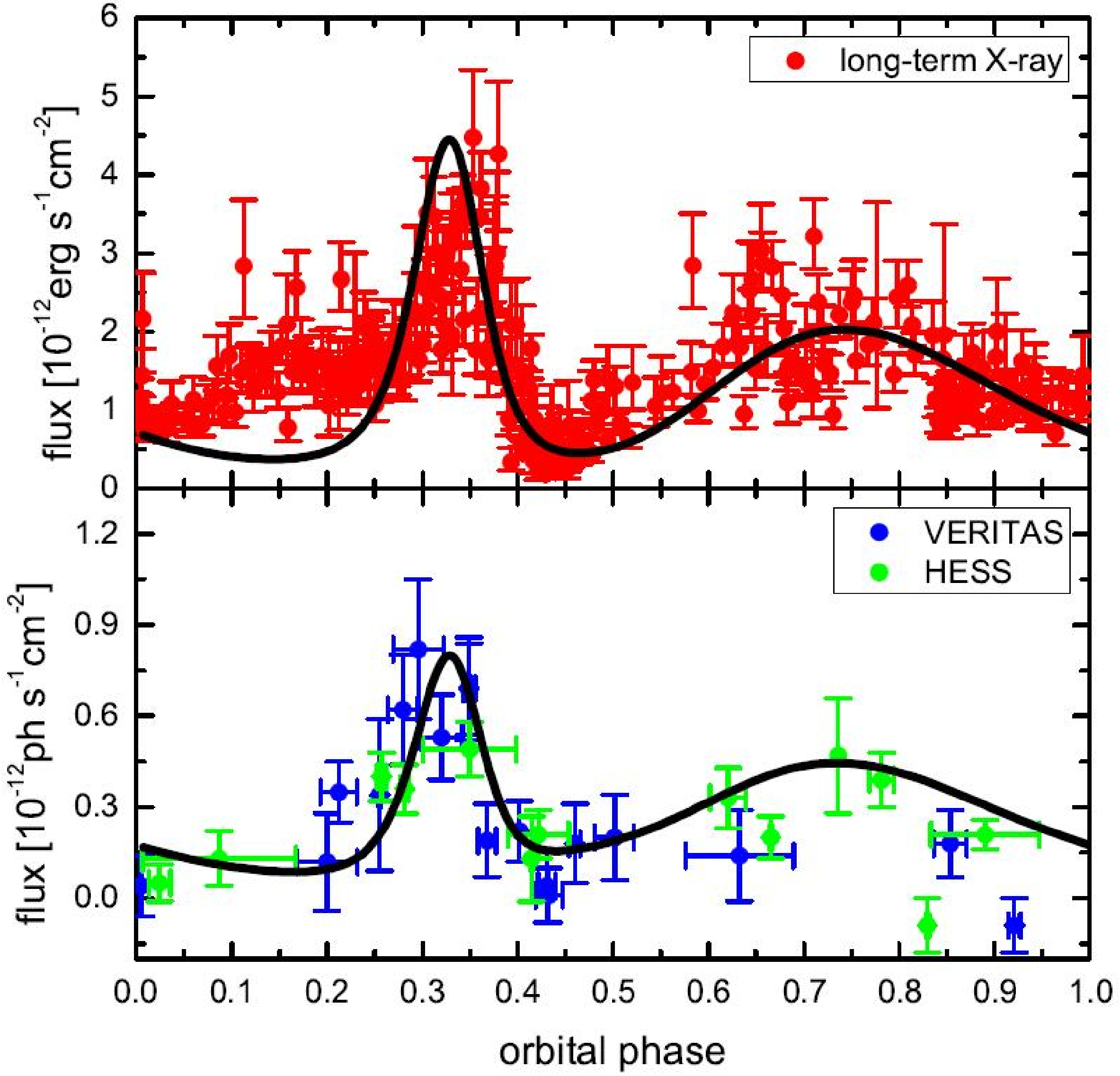


Adams et al. 2021

Parameters	Model 1†	Model 2‡	Model 3§
e	0.83 ± 0.08	0.643 ± 0.29	0.35
P_o(d)	321 ± 5	313^{+11}_{-8}	316.8
Φ_p	0.967 ± 0.008	0.663	0.35
$\omega_p(^\circ)$	129 ± 17	271 ± 29	129

† Casares et al. 2012;
‡ Moritani et al. 2018;
§ This work. The values adopted here are slightly different from that of Malyshev et al. 2019 (i.e., $e \sim 0.5$, $\Phi_p \sim 0.4$).

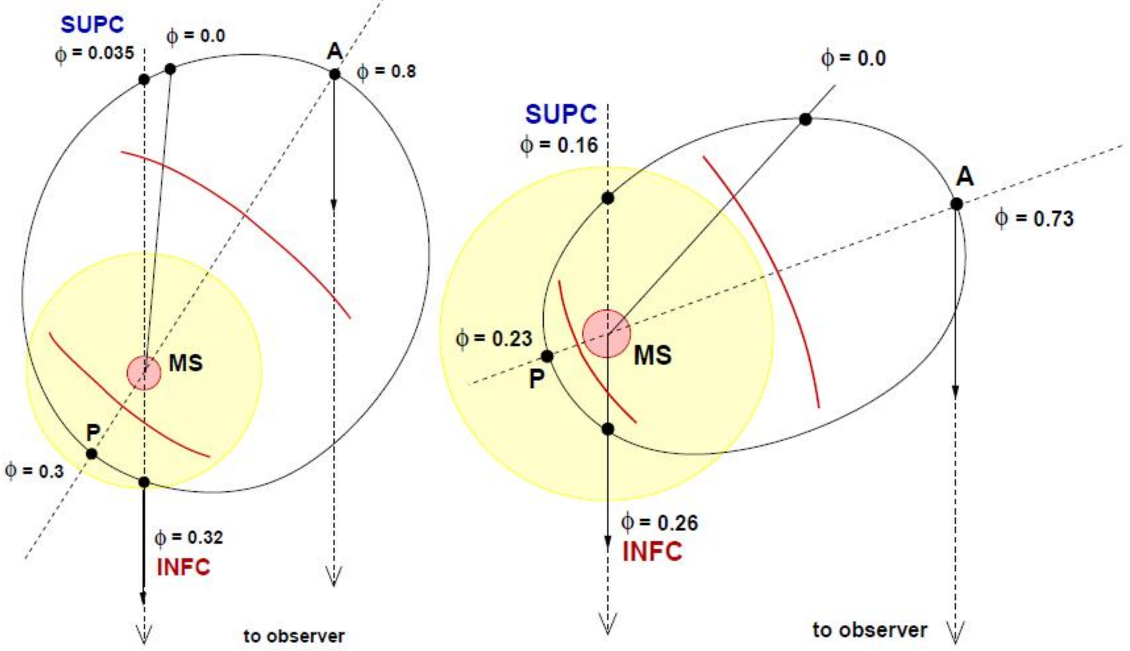




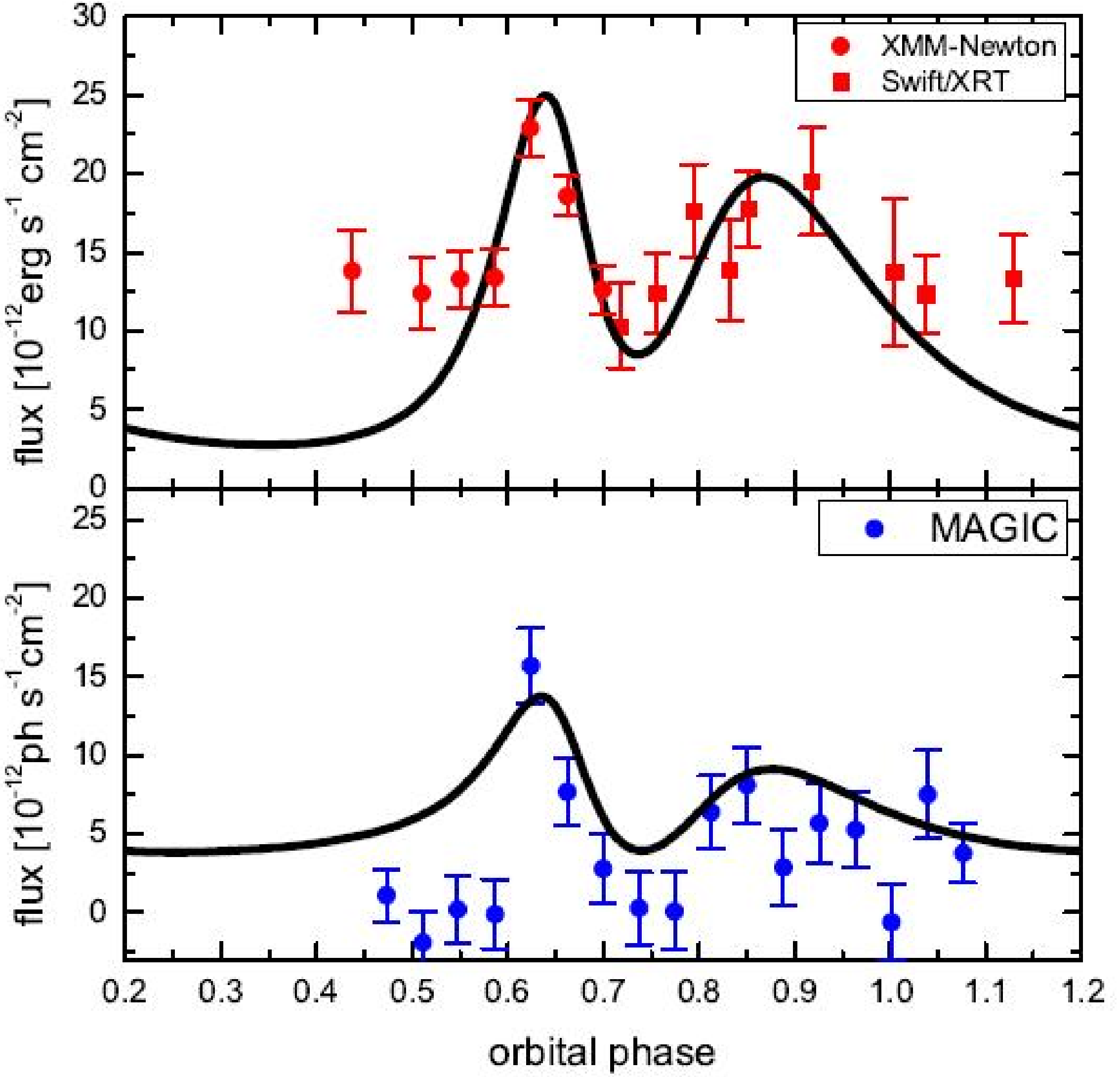
Chen & Takata 2022

2.4: LS I+61° 303

Grundstrom+2007;
Casares+2005;



Sierpowska-Bartosik & Torres 2009

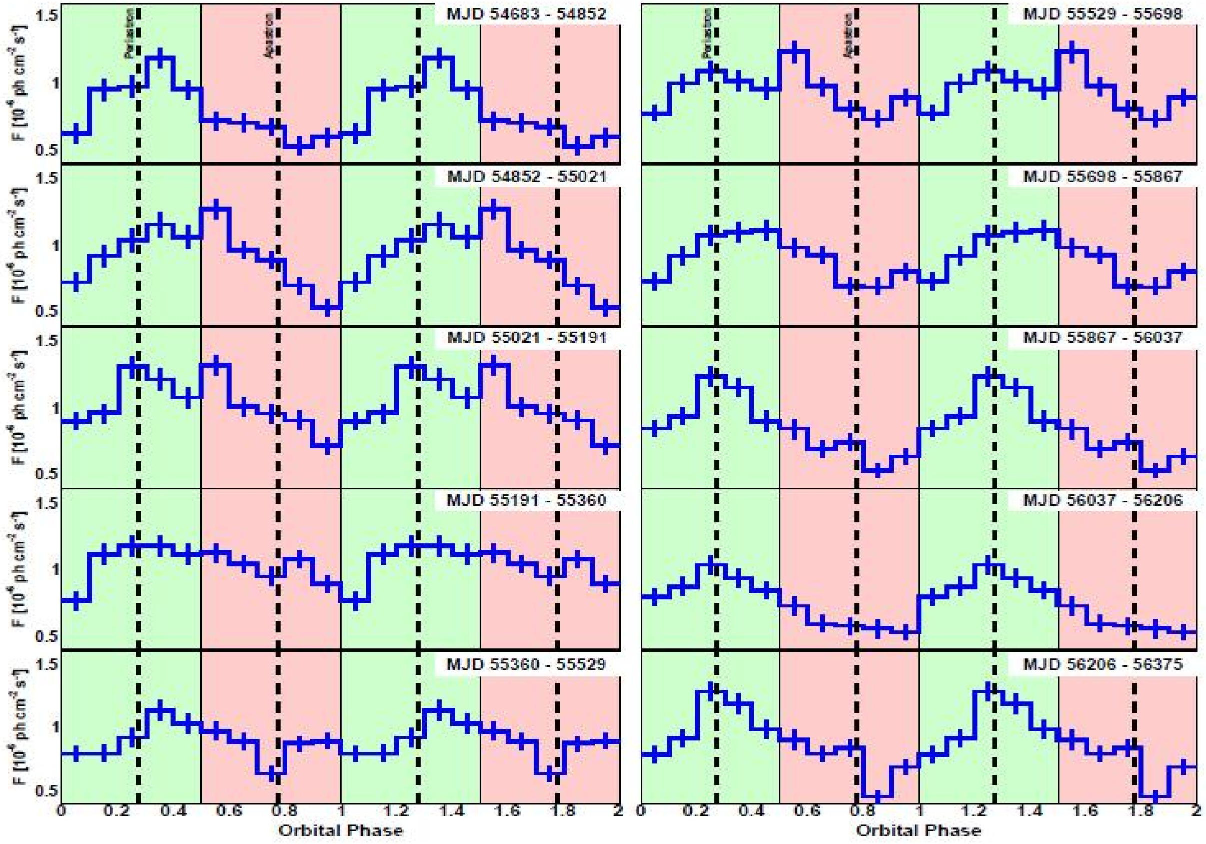


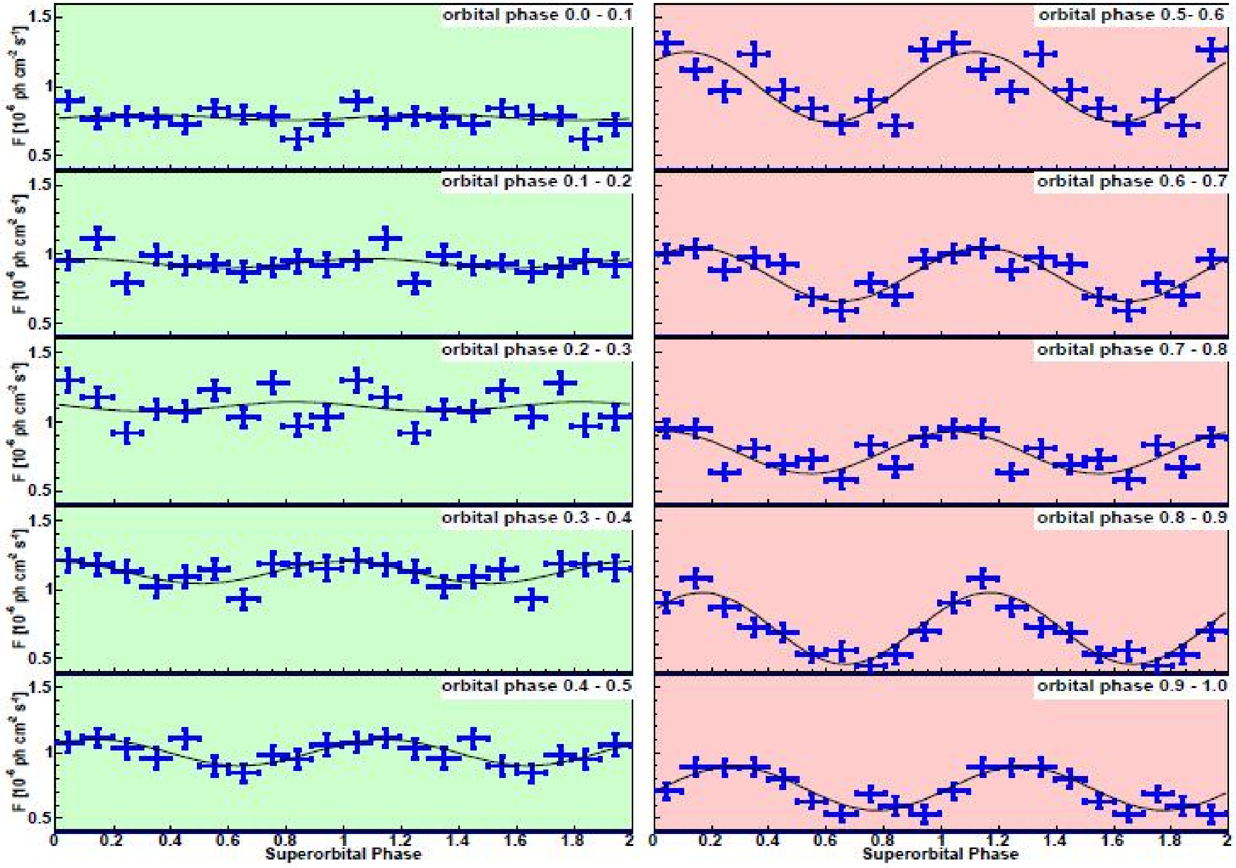
Chen & Takata 2022

Precession of the stellar disc?

$P_{\rm orb} \simeq 26.5$ days

$P_{\rm sup} \simeq 1667$ days



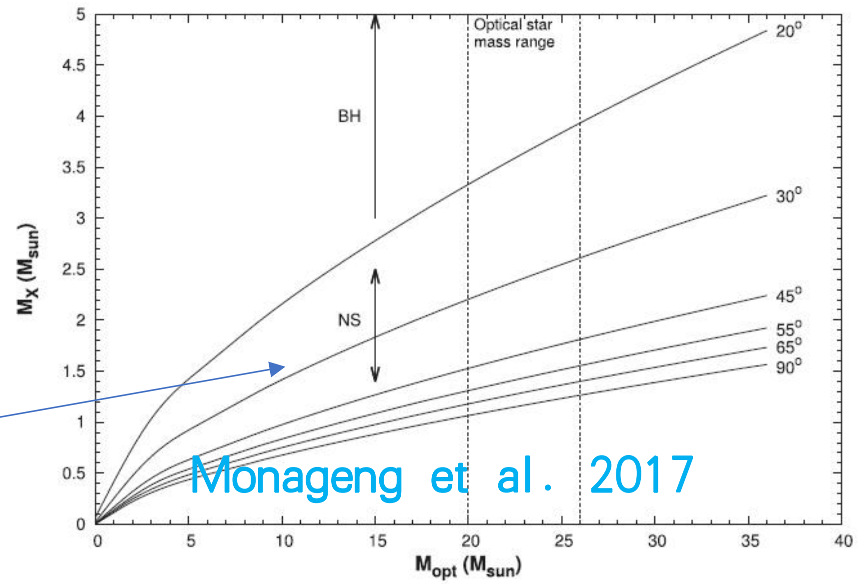


Ackermann et al. 2013

2.6: 1FGL J1018.6-5856

- **Compact object:** unknown yet， however

$$f(M_x) = \frac{PK^3}{2\pi G}(1-e^2)^{3/2} = \frac{(M_x \sin i)^3}{(M_x + M_O)^2}$$



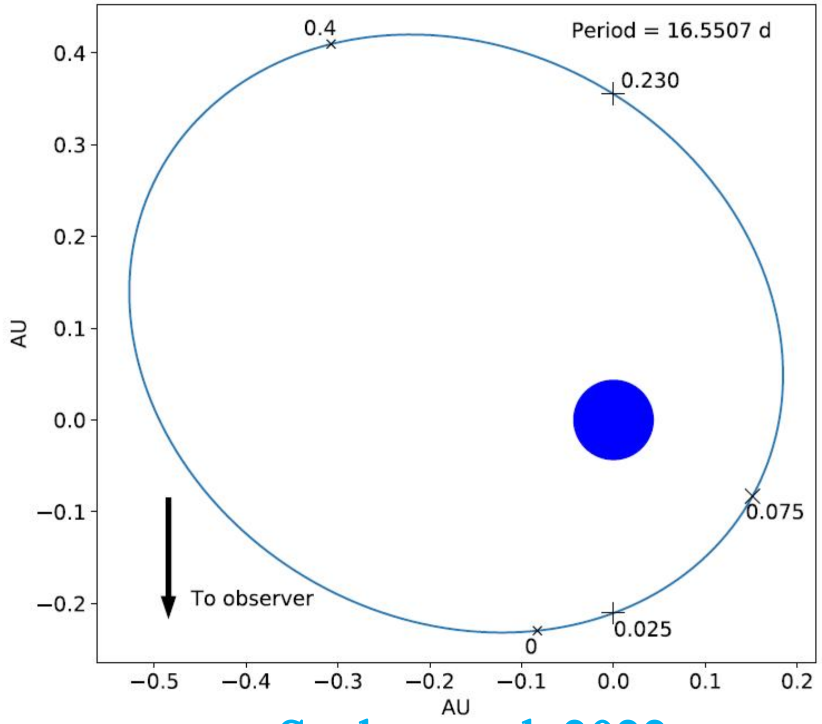
Monageng et al. 2017

- **Companion star:**

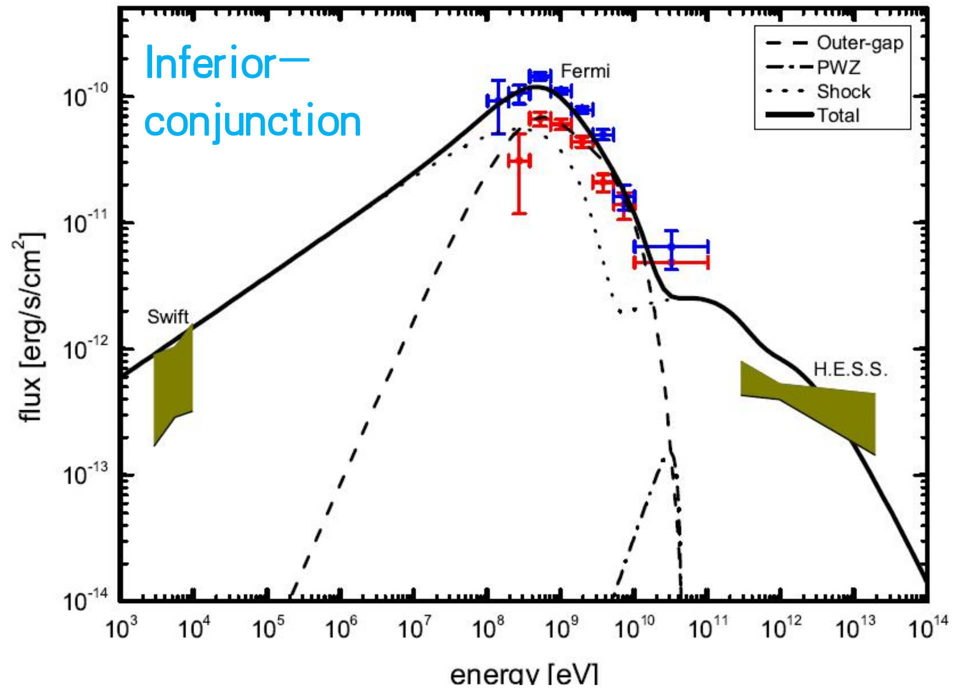
$$\mathrm{O6V((f))} \quad T_{\mathrm{eff}} \simeq 38900\,\mathrm{K}$$

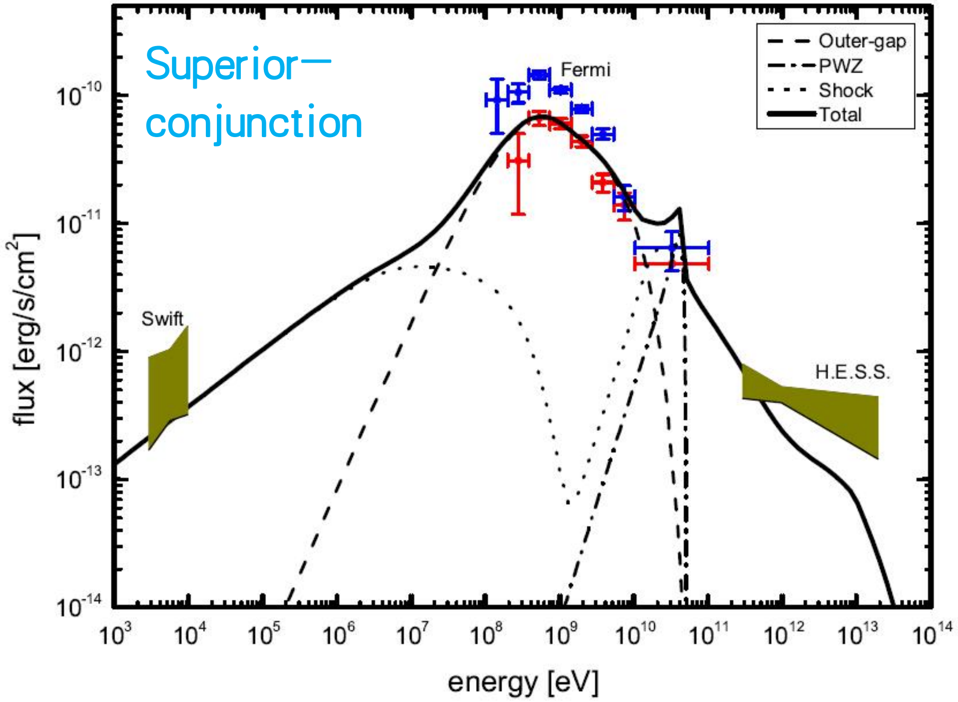
- **Binary system:**

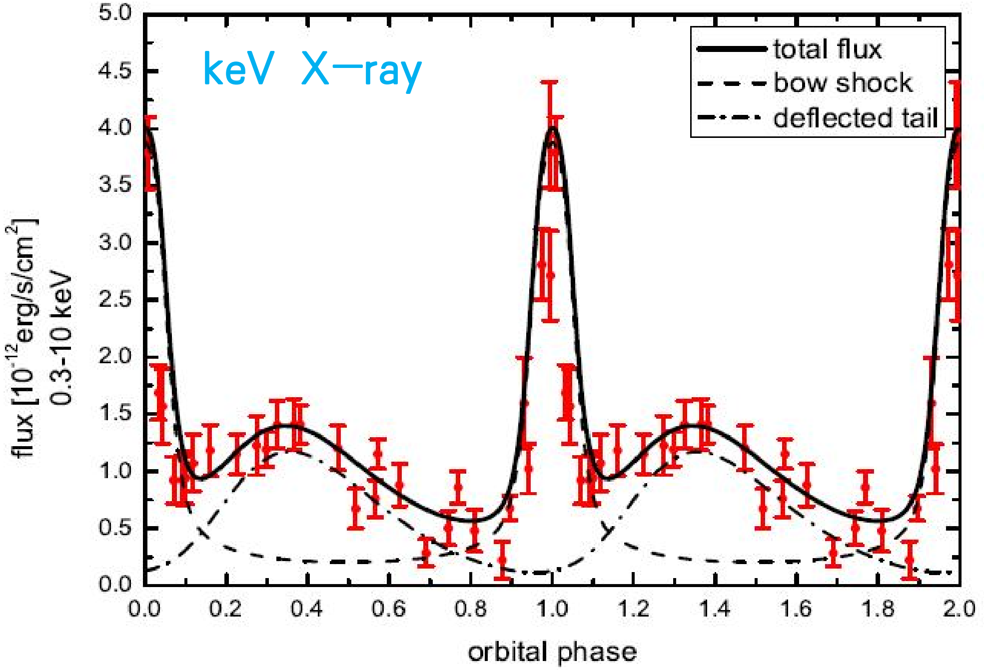
$$P_{\mathrm{orb}} = 16.5507\,\mathrm{d}, \quad e = 0.531, \quad d_{\mathrm{L}} \sim 4.4\,\mathrm{kpc}$$

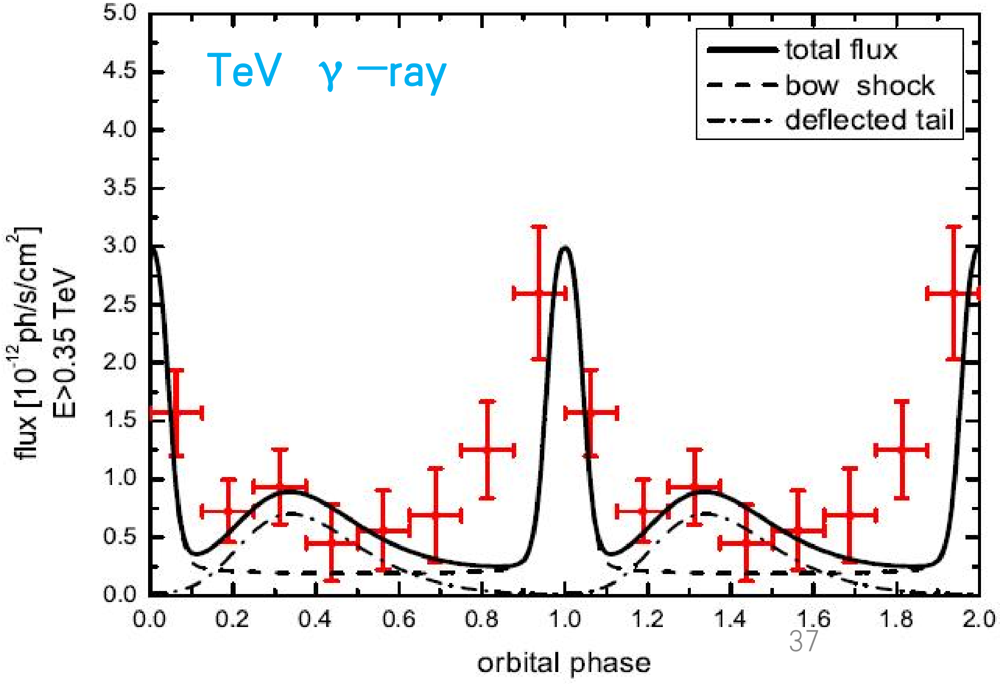


van Soelen et al. 2022









Chen et al. 2021b