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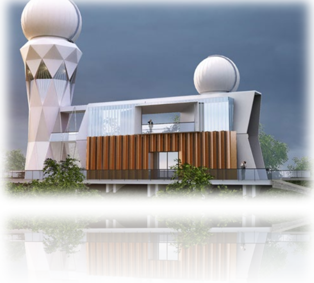
Department of Astronomy



Multi-wavelength Studies on TeV Gamma-ray Binaries

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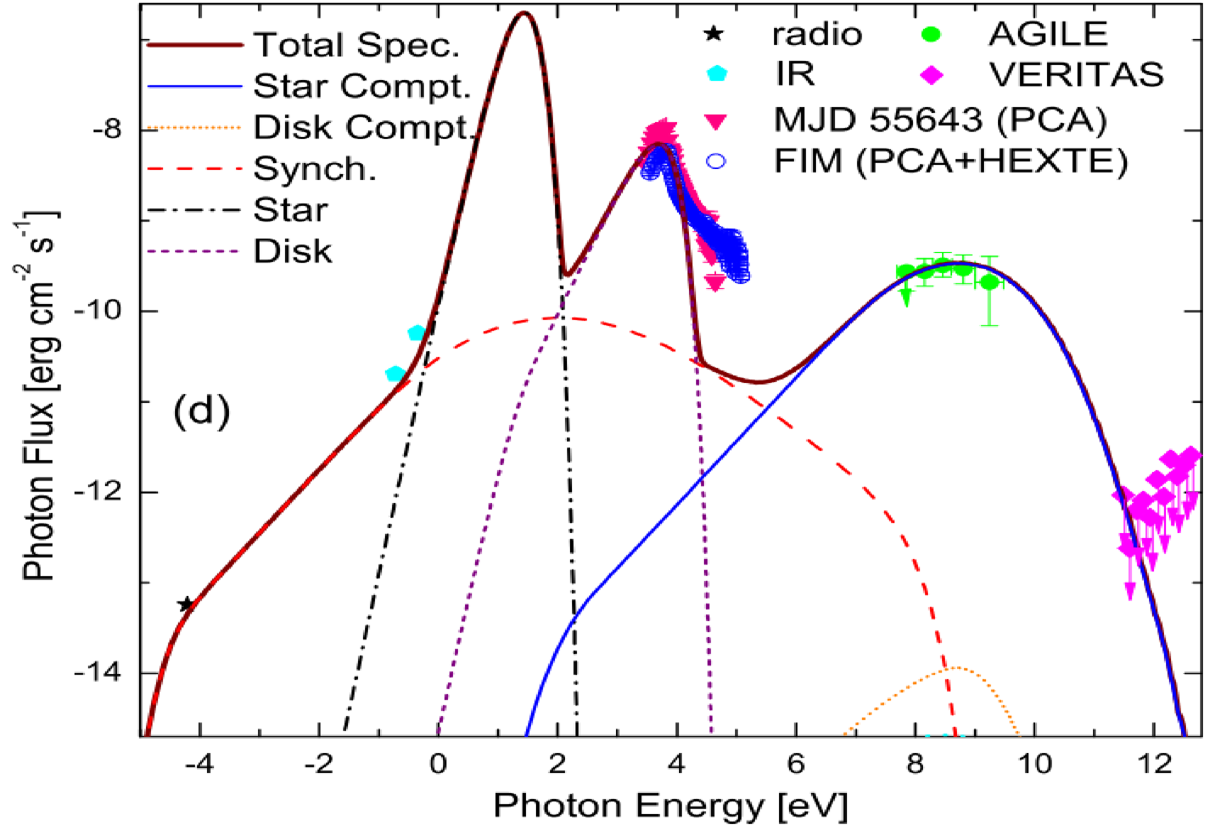
2021.10.26@TeVPA 2021·成都

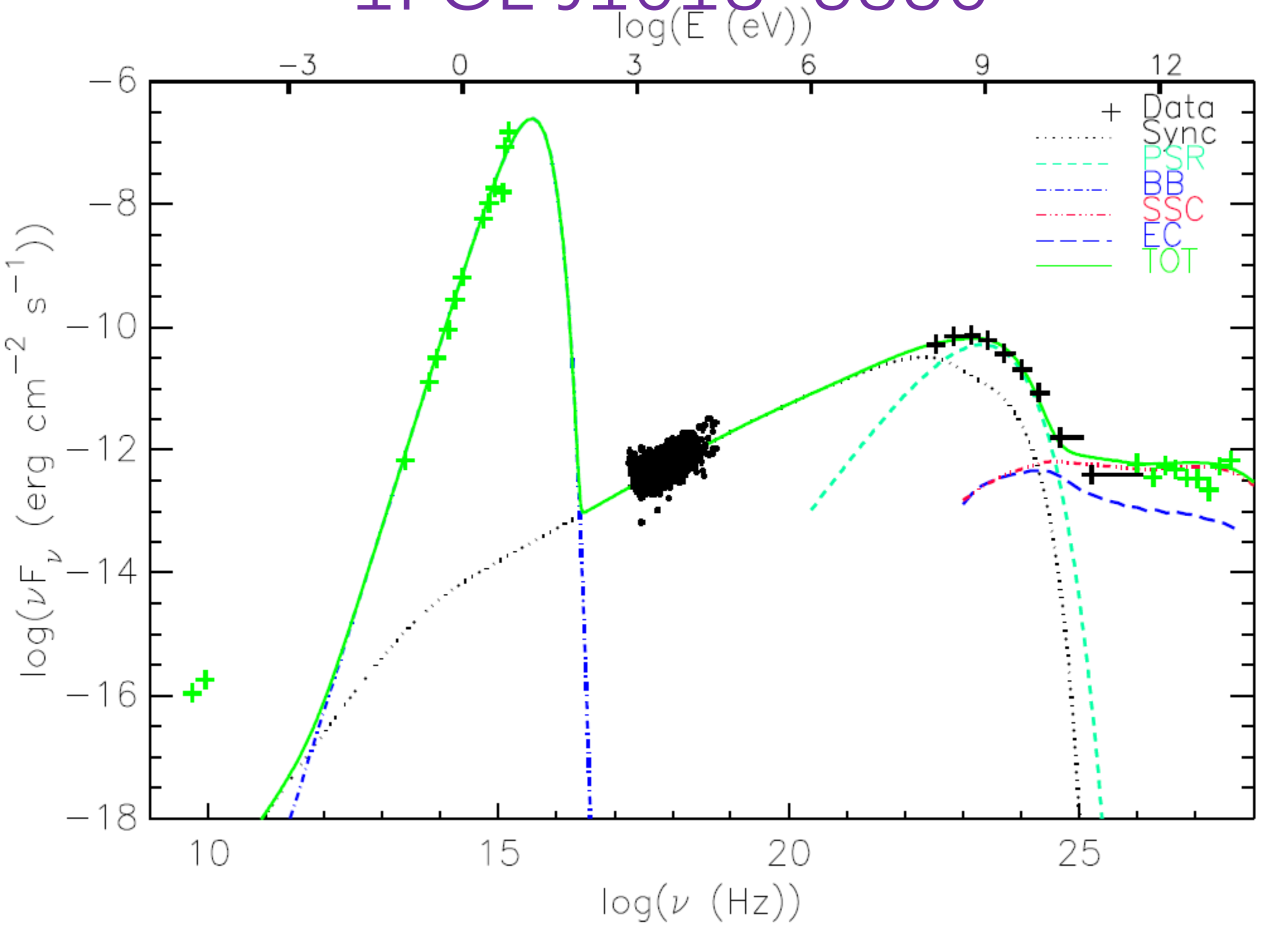
X-ray binaries V.S. γ-ray binaries

Cygnus X-3



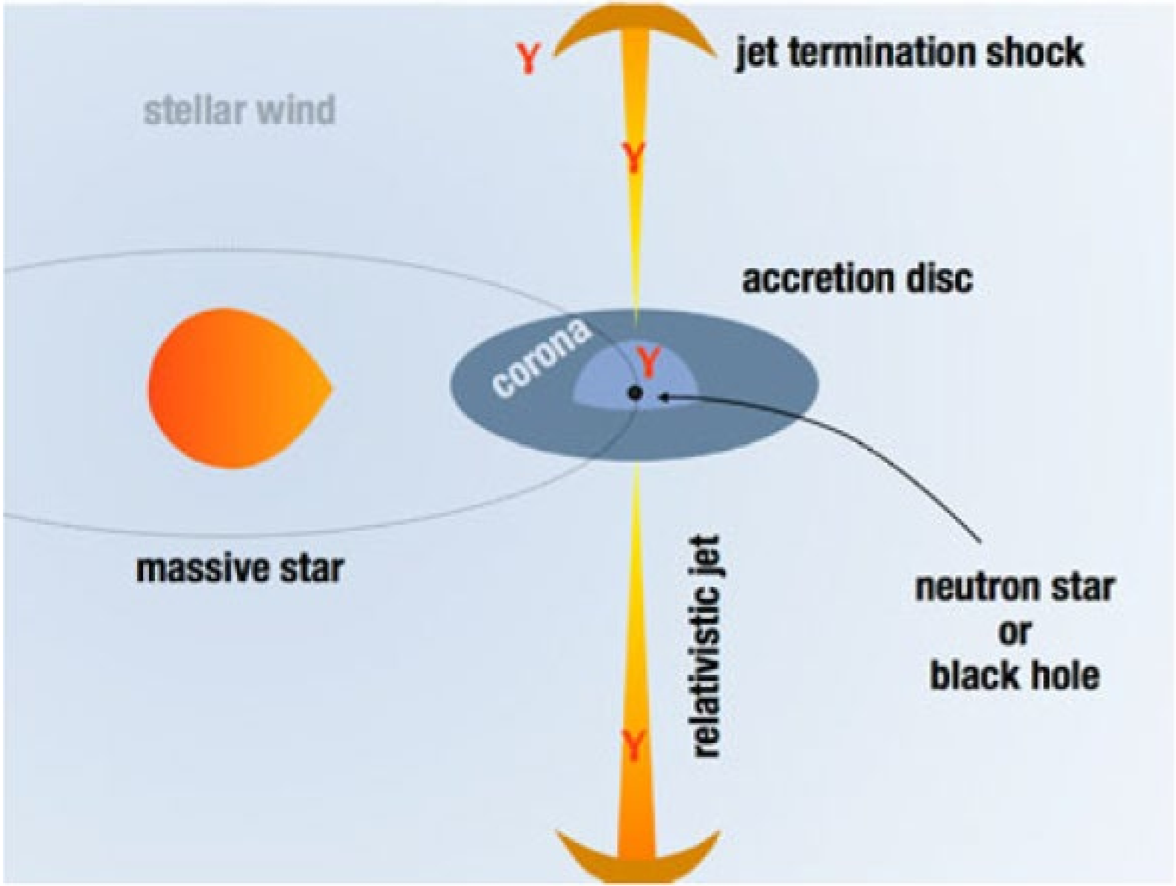
Zhang & Lu 2015

1FGL J1018-5856



An & Romani 2017

X-ray binaries V.S. γ-ray binaries



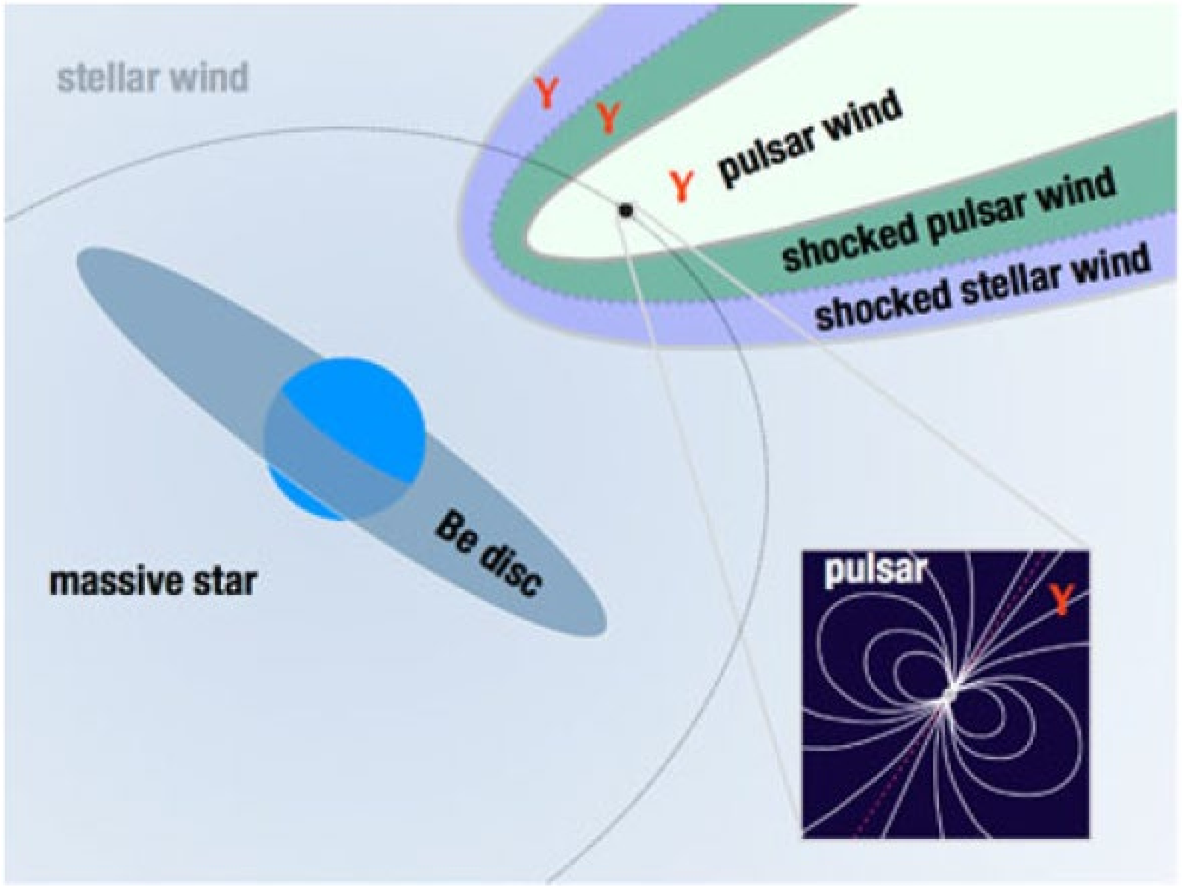


Figure: Dubus 2013, Astron Astrophys Rev

Basic properties of TeV gamma-ray binaries

- **a compact star + a massive star:**

a) Compact star: NS or BH

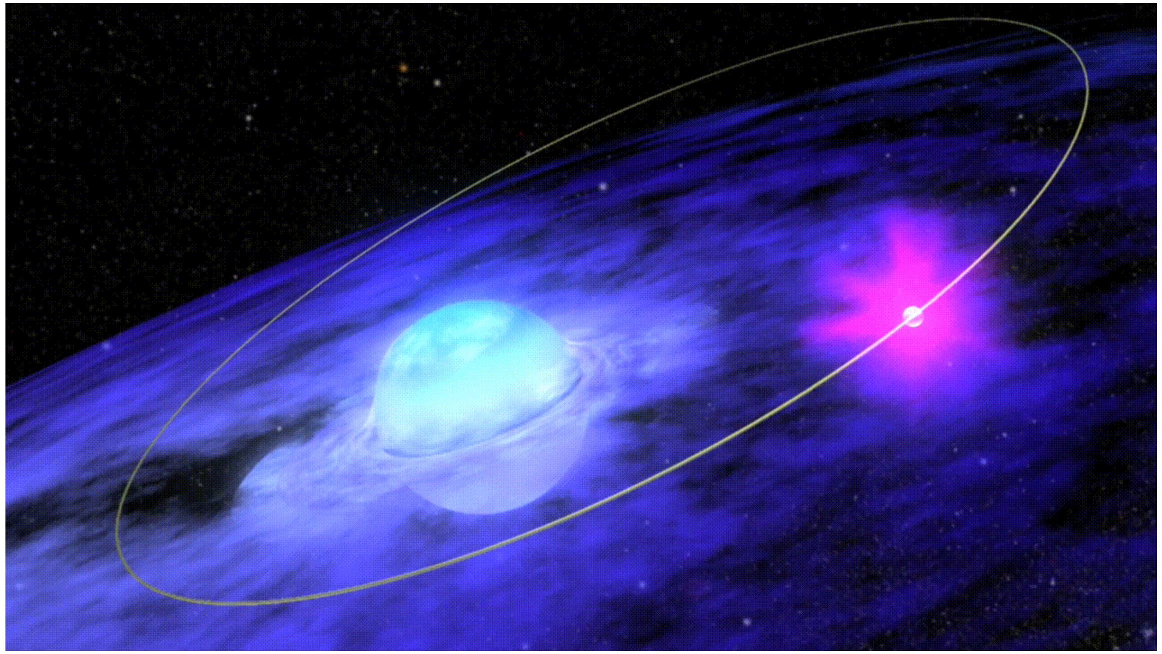
b) Massive star: O or Be star

- **multi-wavelength emissions:**

a) from radio to γ-rays (above TeV)

b) LC: orbital variations

c) SED: peak above 1 MeV

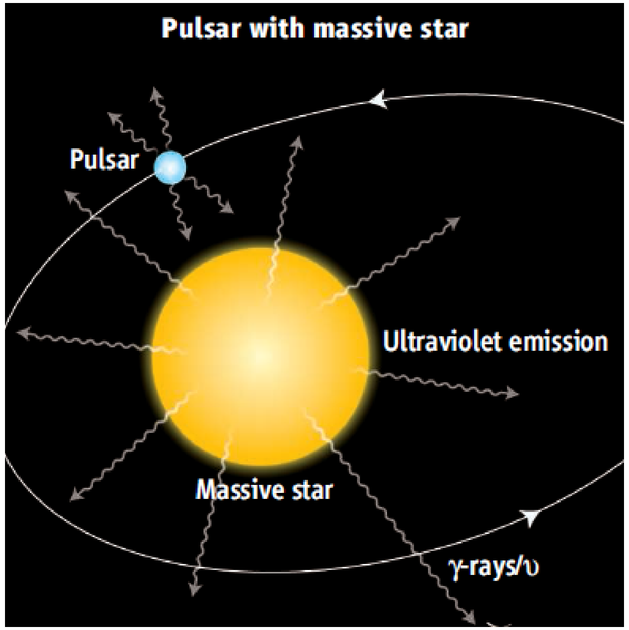


Movie: NASA/Goddard Space Flight Centre

All detected HMGBs:

- **PSR? + O star:**
  - ➢LS 5039
  - ➢1FGL J1018.6-5856
  - ➢LMC P3
  - ➢4FGL J1405.1-6119
  - ➢HESS J1832-093

- **PSR + Be star:**
  - ➢PSR B1259-63/LS 2883
  - ➢PSR J2032+4127/MT91 213
  - ➢HESS J0632+057 ?
  - ➢LS I+61°303 ? ! **by Weng+2021 via FAST**



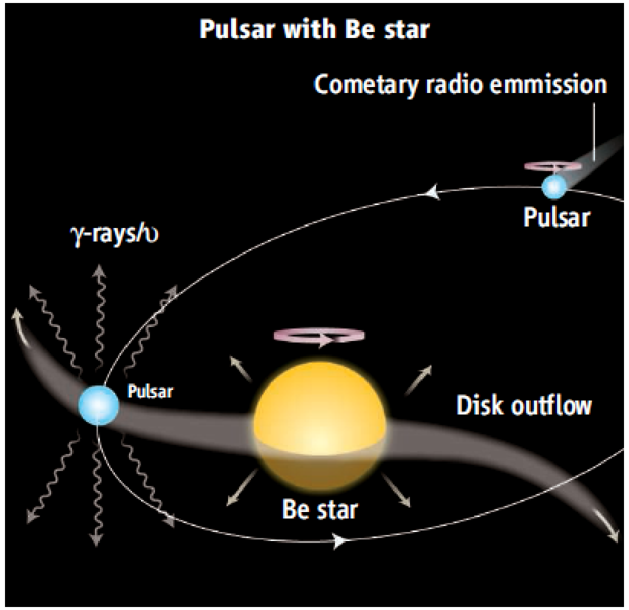


Figure: Mirabel 2006

Q1: Why only 2 HMGBs with radio pulsations being detected ?

- The radio beam is not pointing to us

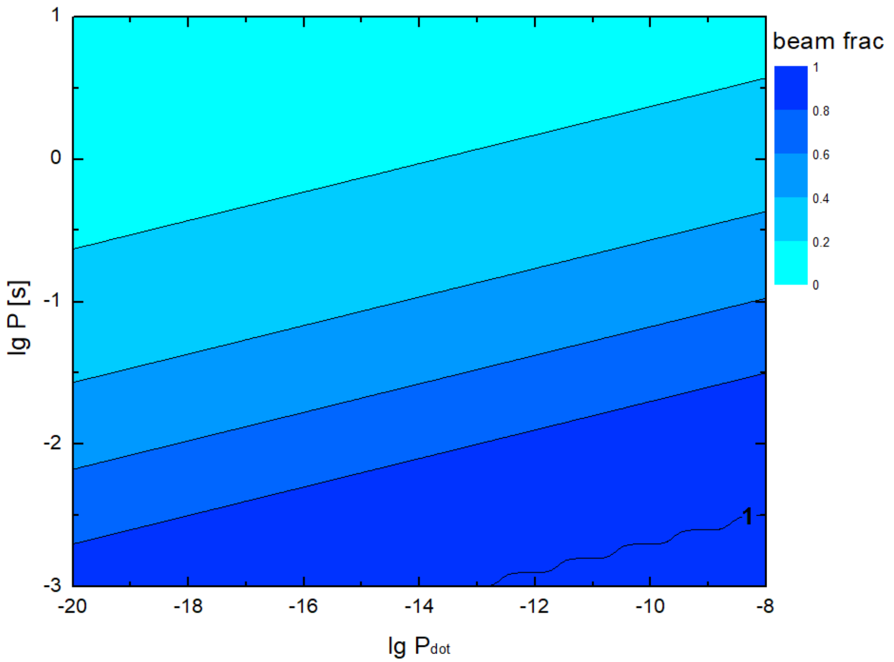
$$f(\chi) = (1-\cos\chi) + \left(\frac{\pi}{2} - \chi\right)\sin\chi,$$

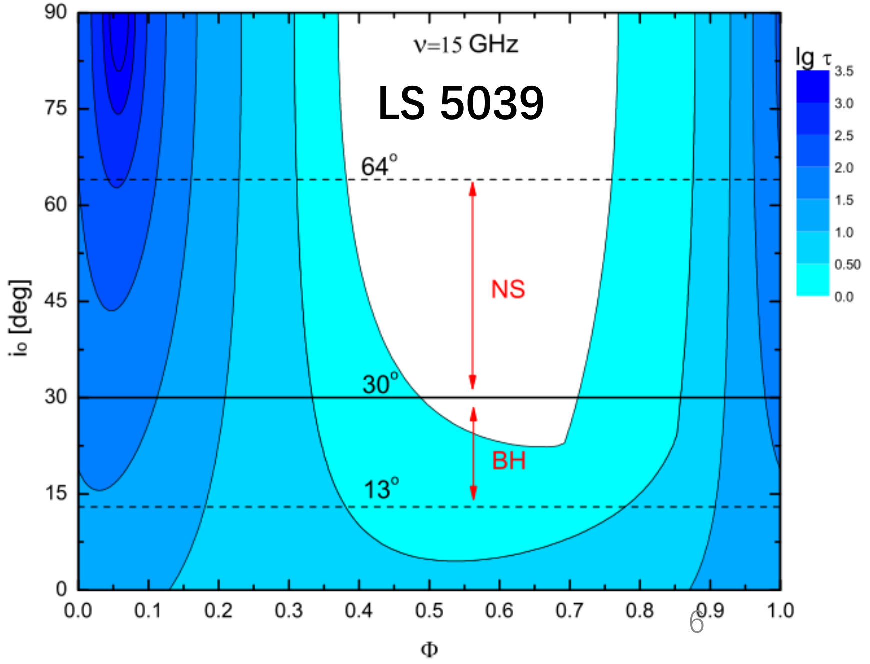
$$\chi \simeq 0.01265\nu_{\rm GHz}^{-0.13} P^{-0.35} \dot{P}_{-15}^{0.035} \ \ {\rm rad}$$

- Severe absorption and scattering by intense stellar outflows

$$DM = \int_{l_{\rm s,obs}}^{\infty} n_{\rm e} {\rm d}l,$$

$$\tau(\nu) = \int_{l_{\rm s,obs}}^{\infty} \alpha(\nu) {\rm d}l.$$





Chen et al. 2021a

Q2: Compared to 200+HMXBs, why only <10 HMGBs being detected so far ?

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

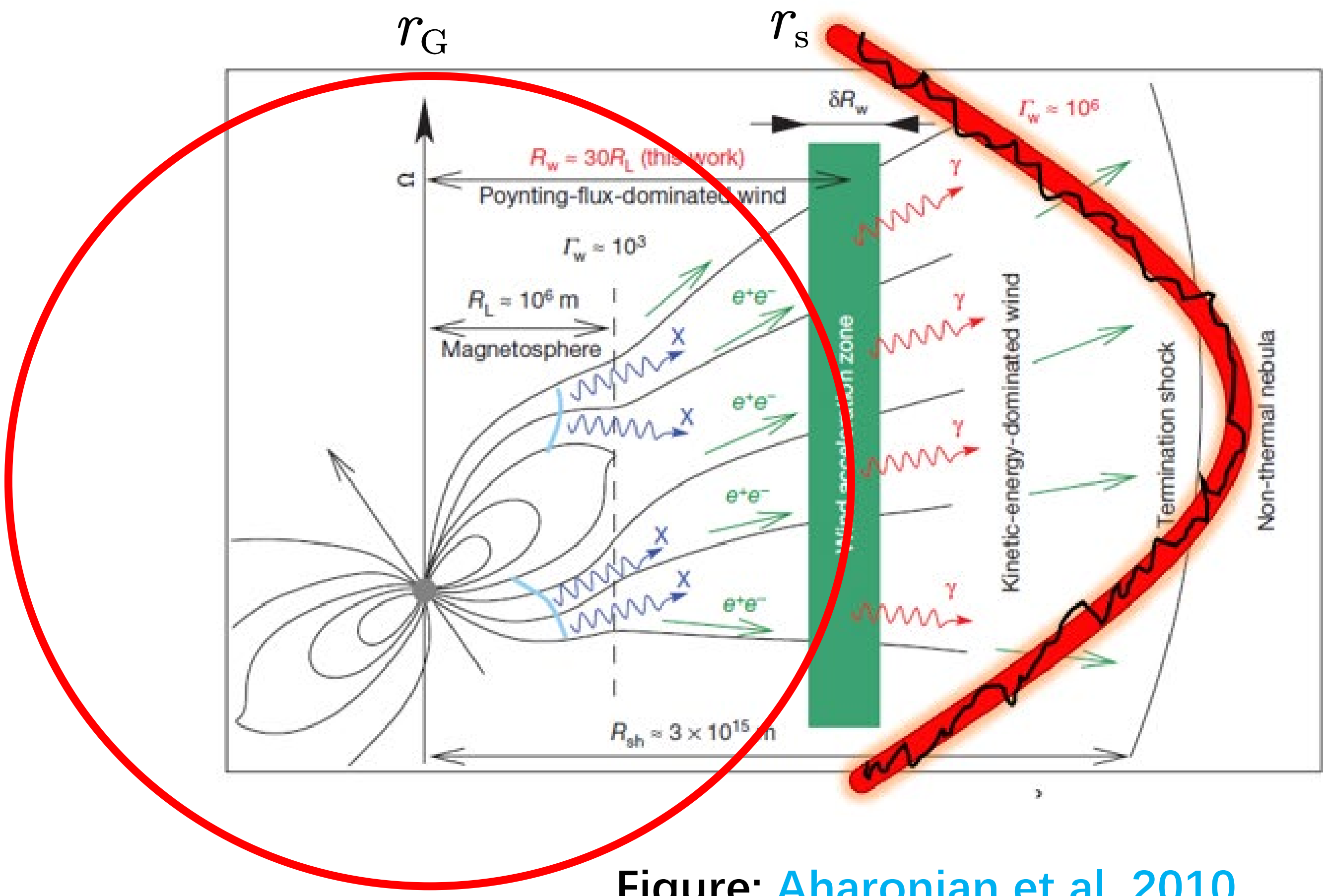


Figure: Aharonian et al. 2010

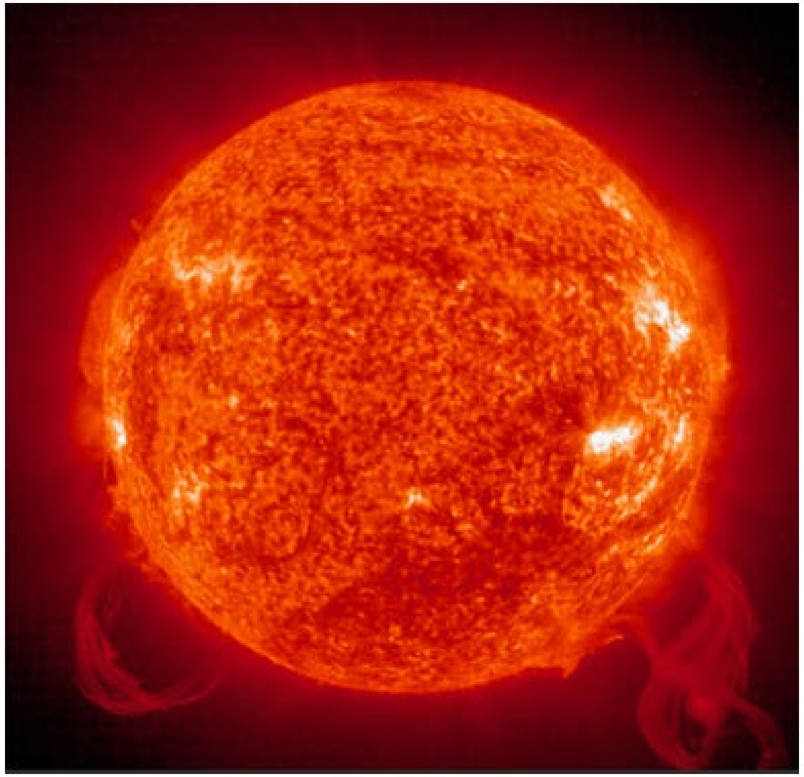


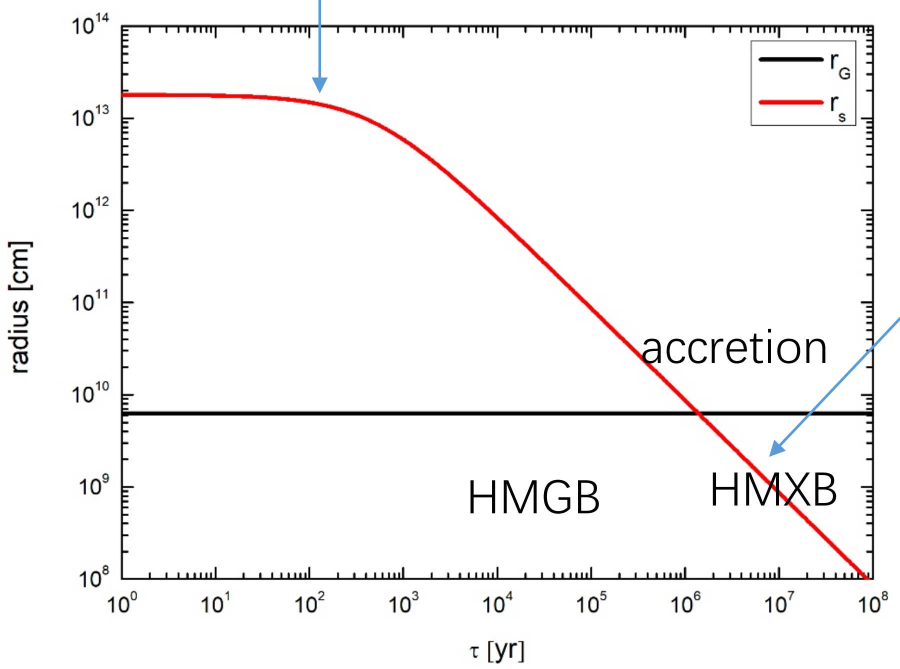
Figure: Wiki_Massive stars

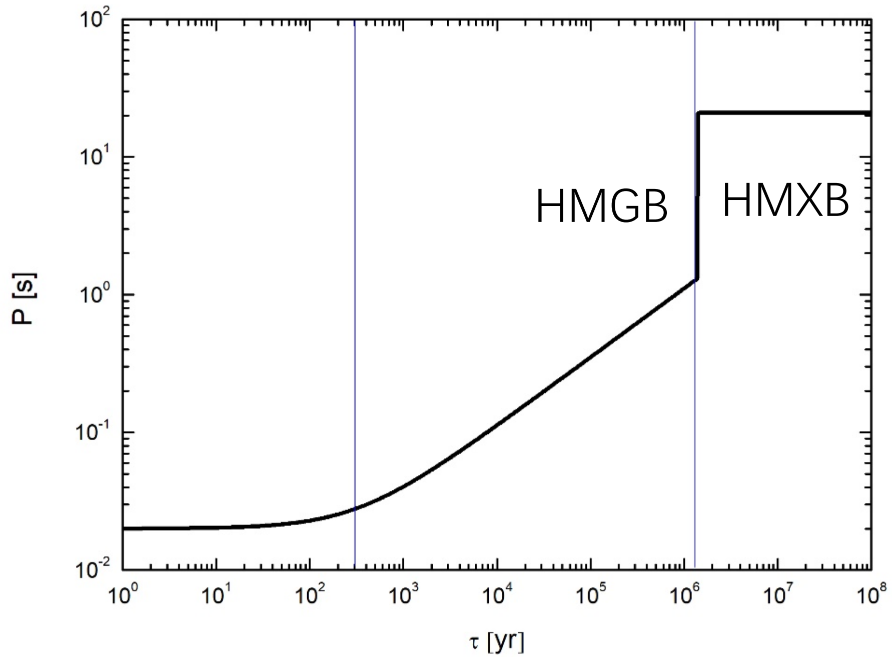
Q2: Compared to 200+HMXBs, why only <10 HMGBs being detected so far ?

- **Pulsar wind shock radius** vs. **Gravitational capture radius**

$$r_{\rm s} \sim \sqrt{\frac{L_{\rm sd}/c}{4\pi\rho v^2}}$$

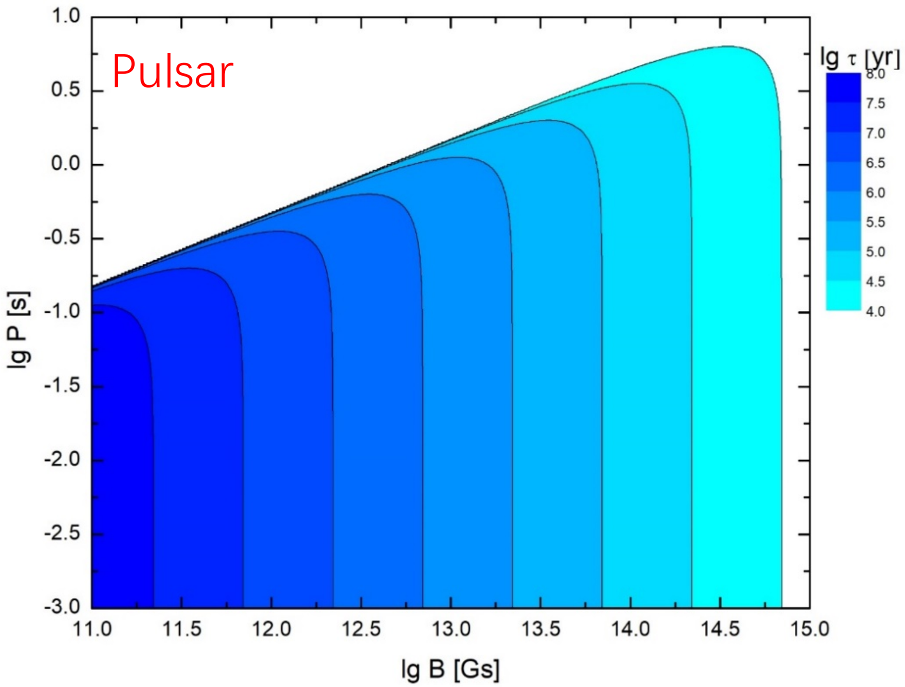
$$r_{\rm G} \sim \frac{2GM_{\rm p}}{v^2}$$



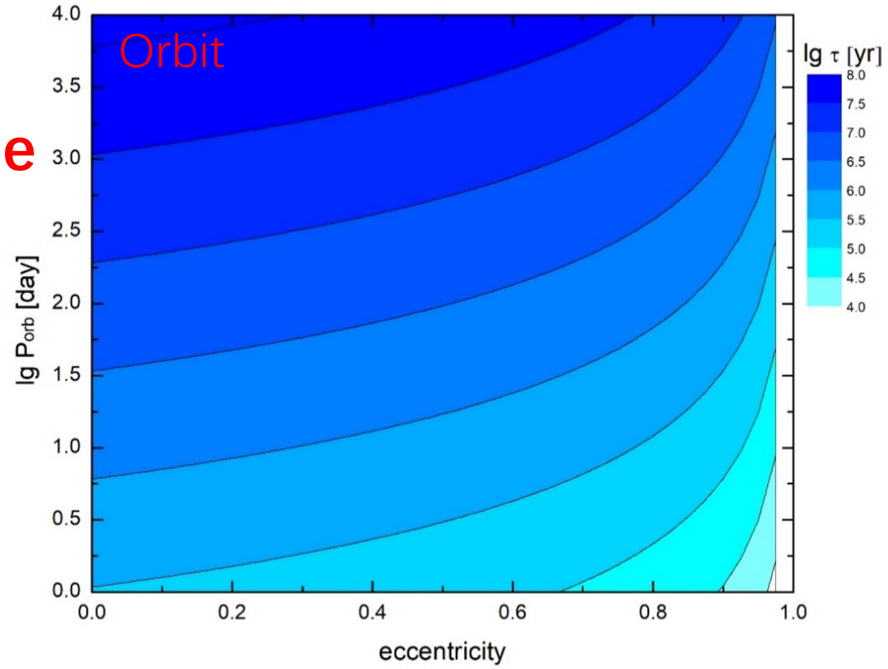


Q2: Compared to 200+HMXBs, why only <10 HMGBs being detected so far？

- **Pulsar:** Initial magnetic field and spin period;
- **Star:** Stellar mass and mass-loss rate;
- **Orbit:** orbital period and eccentricity.



The duration timescale



Q3: Where & how the VHE γ-ray being produced ?

- **Pulsar magnetosphere** (curvature radiation)
- **Pulsar wind** (anisotropic IC scattering)
- **Termination shock** (SYN & IC)

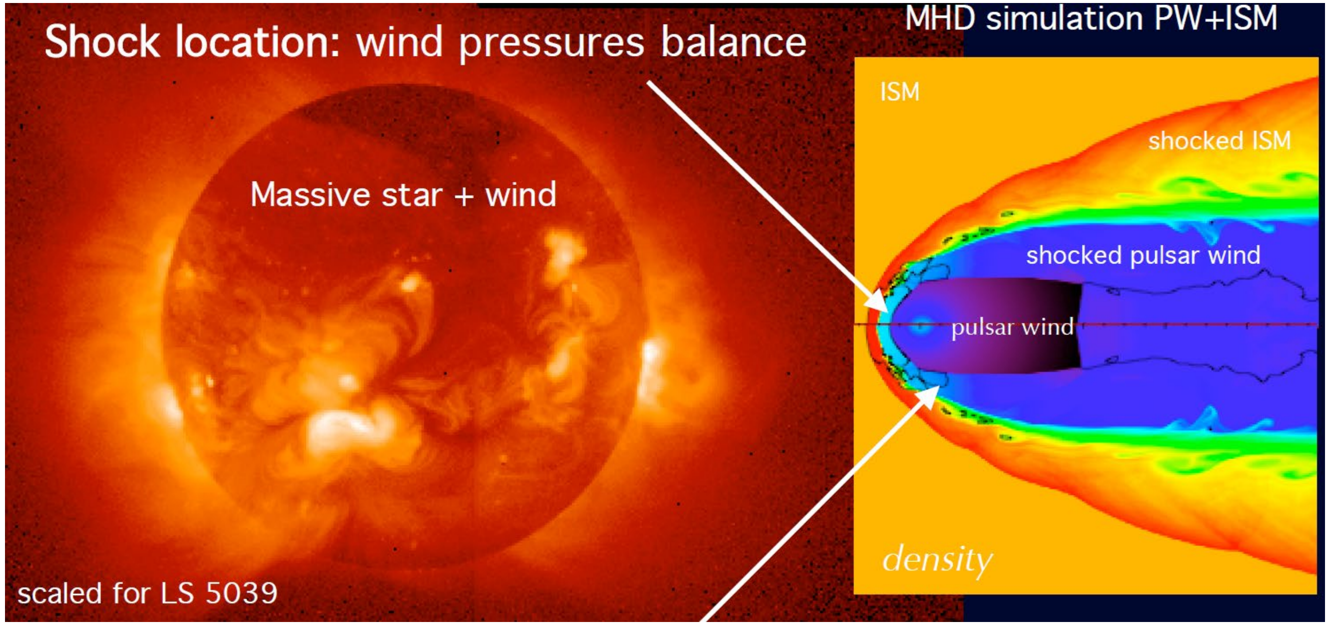
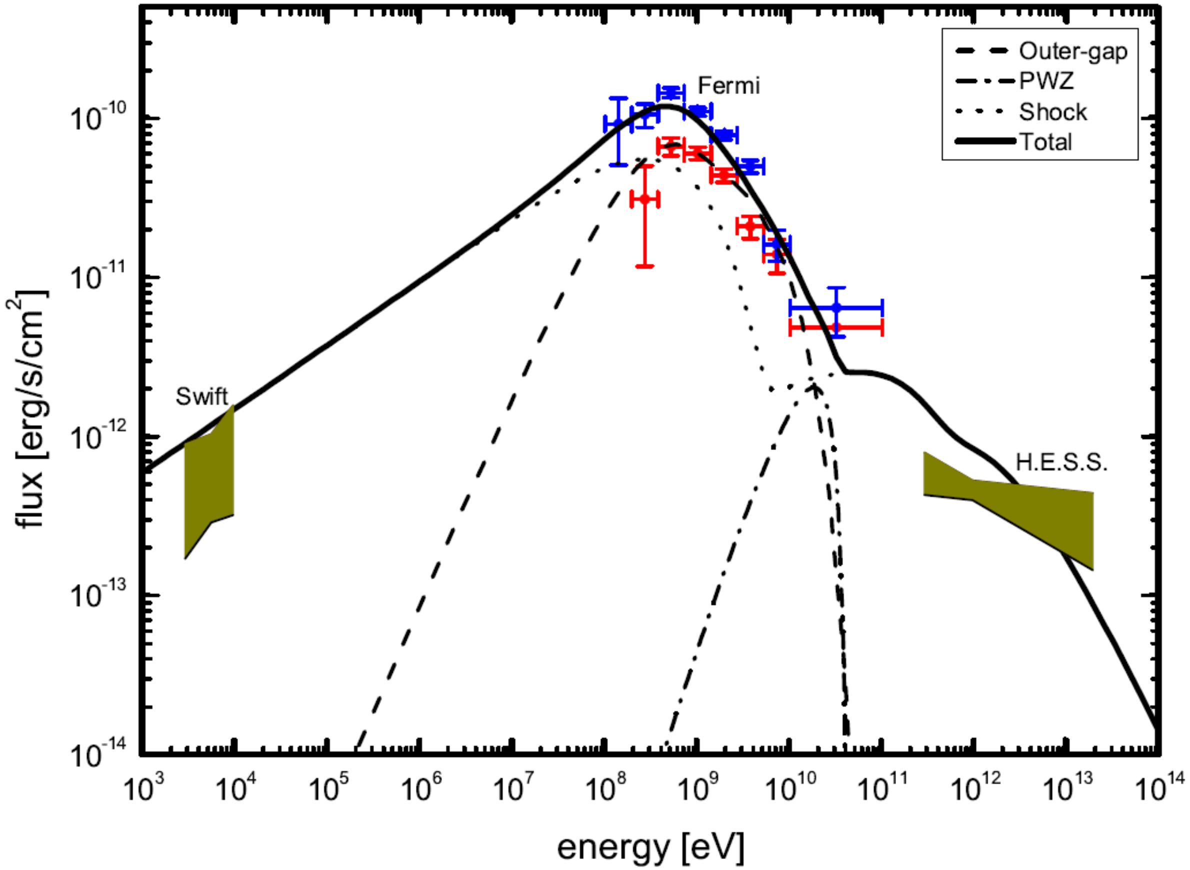


Figure: Dubus 2007



Chen et al. 2021b

表 1.2.1: 伽马射线双星系统的轨道参数

Parameters	PSR B1259-63	PSR J2032+4127	HESS J0632+057	LS I +61°303	LS 5039	1FGL J1018.6-5856	LMC P3
$P_{\rm orb}$(days)	1236.72432(2)	16000 - 17670	315(5)	26.496(3)	3.90603(8)	16.58(2)	10.301
e	0.8698872(9)	0.95–0.99	0.83(8)	0.54(3)	0.35(3)	0.31±0.16	0.40±0.07
a(AU)	7.17	∼18.12	2.375	0.415	0.14	0.41	-
$d_{\rm L}$(kpc)	2.3(4)	1.33±0.06	1.6(2)	2.0(2)	2.9(8)	5.4	∼ 50
$i(^\circ)$	19–31	∼ 60	47–80	10–60	13–64	26–50	∼ 50
$\omega(^\circ)$	138.6659(1)	∼40	129(17)	41(6)	212(5)	89±30	-
$d_{\rm peri}$(AU)	0.94	-	0.40	0.19	0.09	(0.41)	-
$d_{\rm apas}$(AU)	13.4	-	4.35	0.64	0.19	(0.41)	-
$\phi_{\rm peri}$	0	-	0.967	0.23	0	0	0.13
$\phi_{\rm supc}$	0.995	-	0.063	0.036	0.080	0.5	0.98
$\phi_{\rm infc}$	0.048	-	0.961	0.267	0.769	0	0.24
star	O9.5Ve	B0V	B0Vpe	B0Ve	O6.5V((f))	O6V((f))	OIII
disc	√	√	√	√	×	×	×
$M_\star(M_\odot)$	31	15 ± 2.8	16	12	23	31	∼ 33.5
$R_\star(R_\odot)$	9.2	10	8	10	9.3	10.1	∼ 14.5
$T_\star$(K)	33500	∼ 30000	∼ 30000	22500	39000	38900	36351

PSR B1259-63/LS 2883

- **Pulsar:**

$P = 47.76\,\mathrm{ms},\ \dot{P} \simeq 2.28\times10^{-15}\ \mathrm{s\cdot s^{-1}},\ \ L_{\rm sd} \simeq 8\times10^{35}\,\mathrm{erg/s}$

- **Star:**

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

- **Orbit:**

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

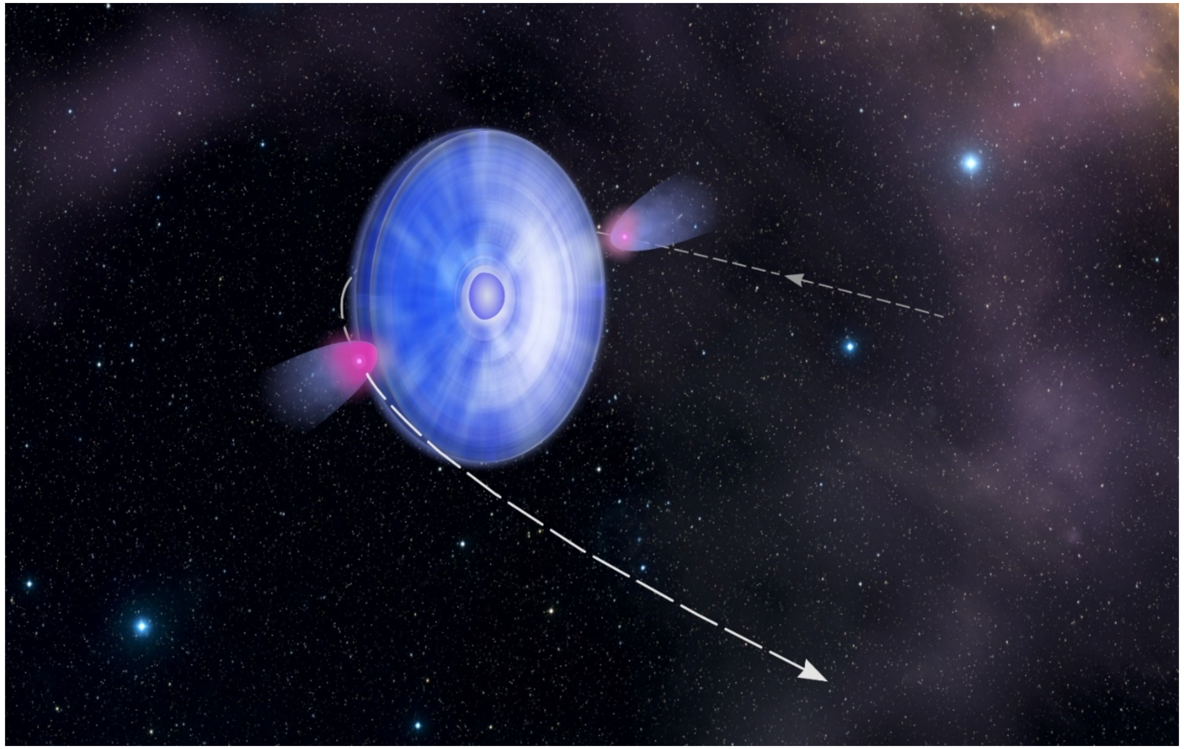
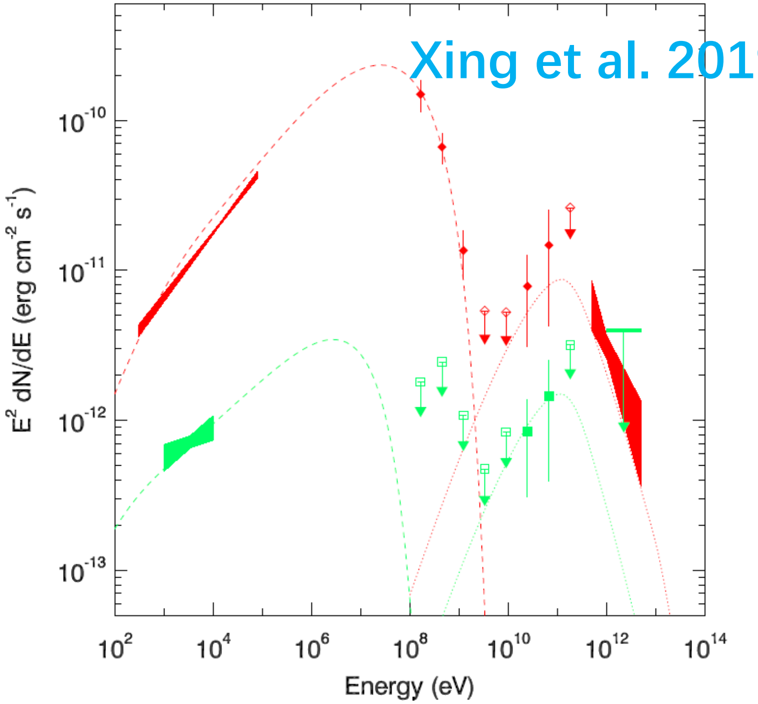
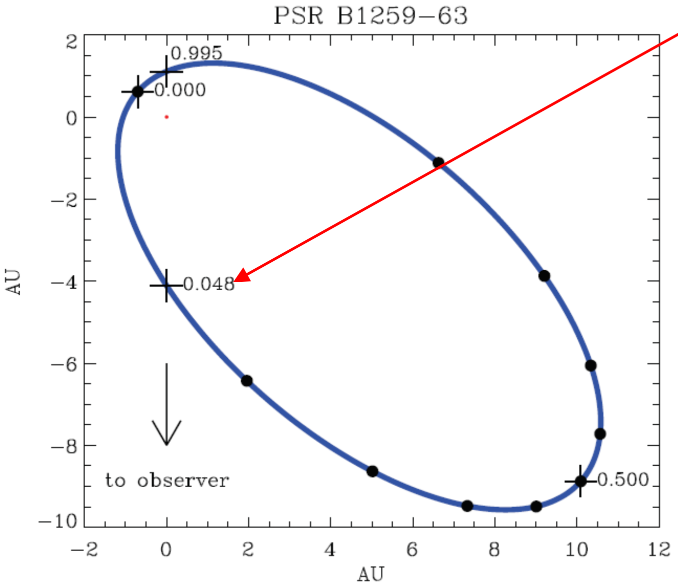


Figure: NASA/Goddard Space Flight Center

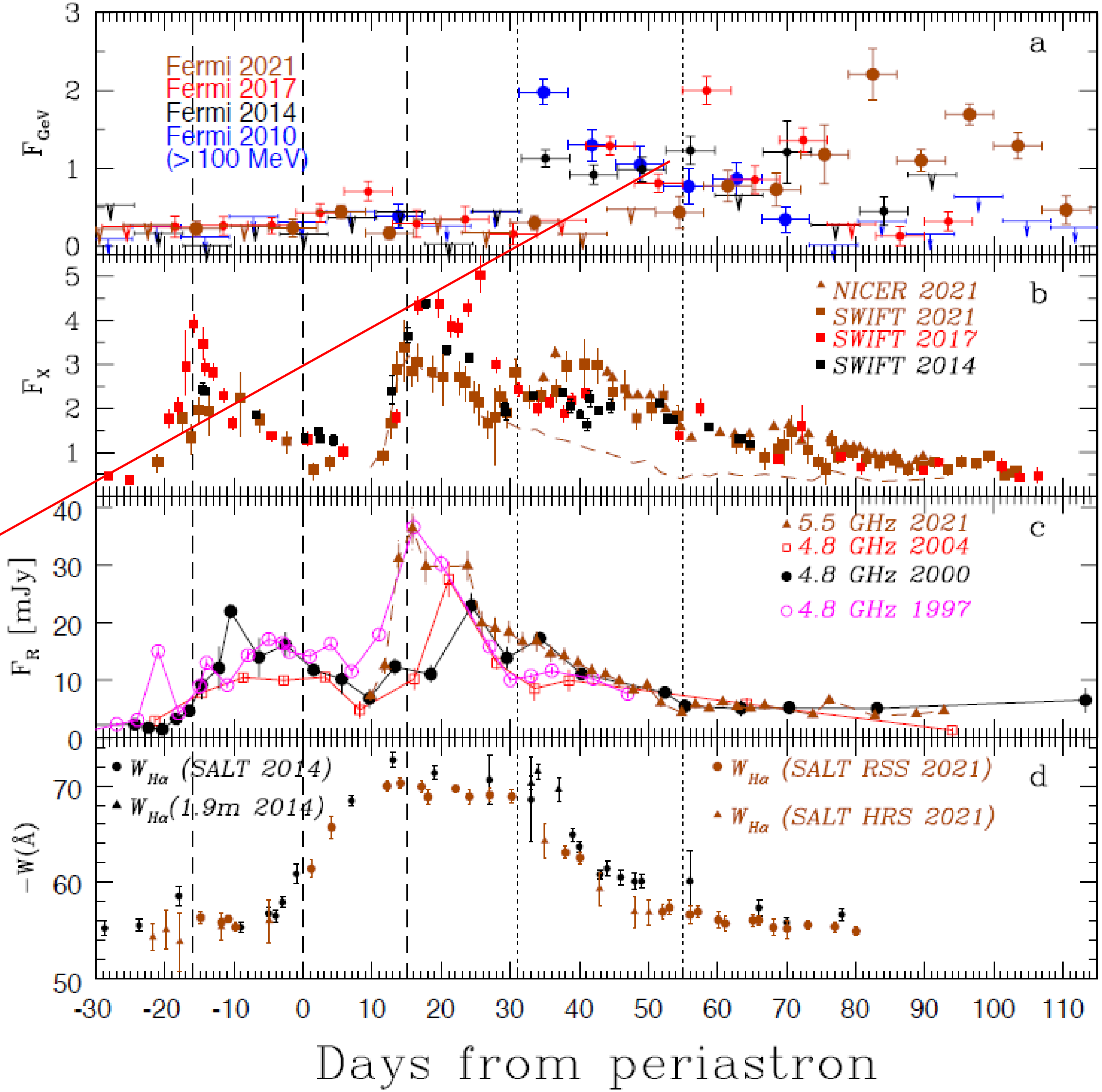
The companion star possesses an equatorial disc that is inclined to the orbital plane !



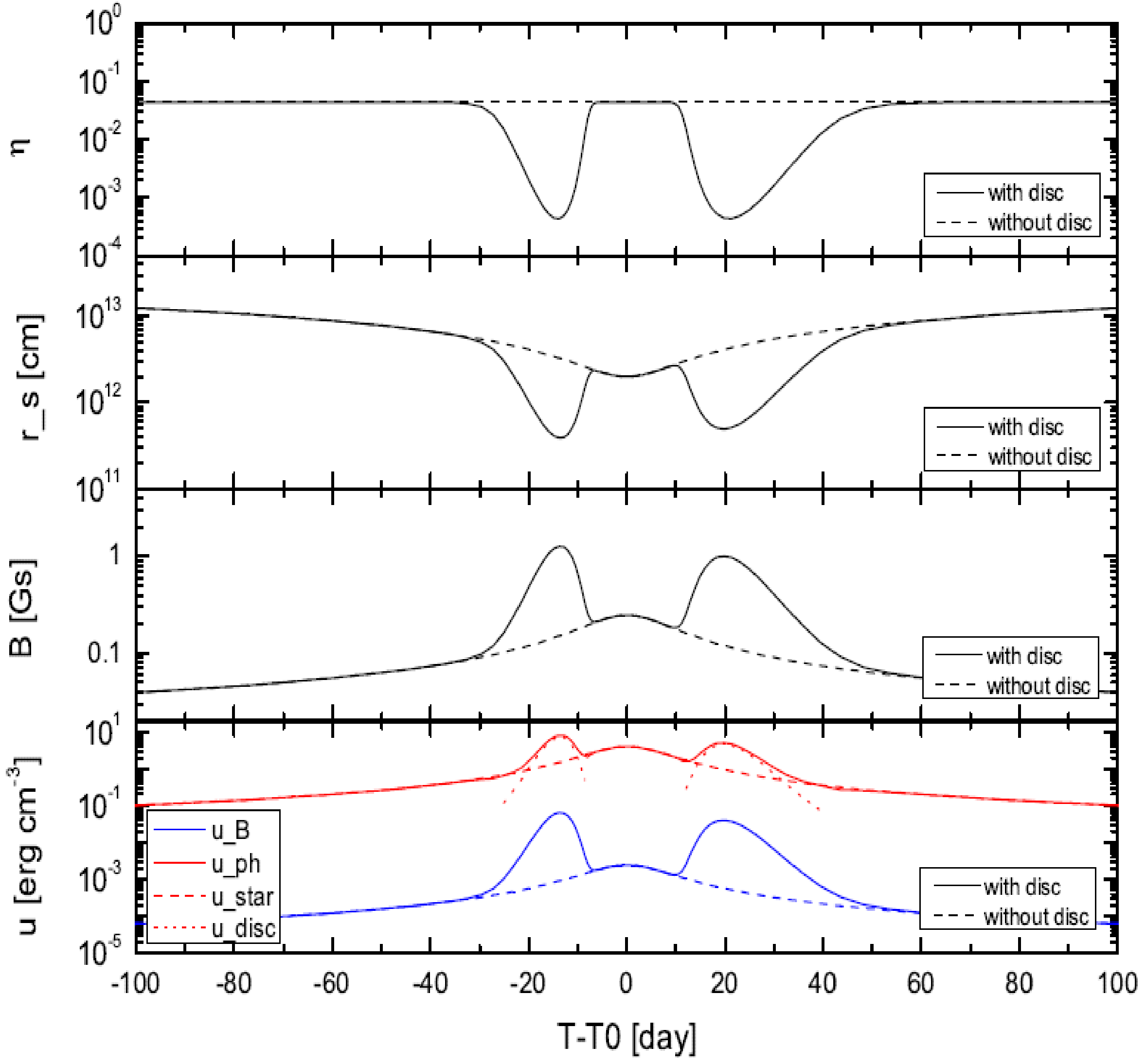
Xing et al. 2019

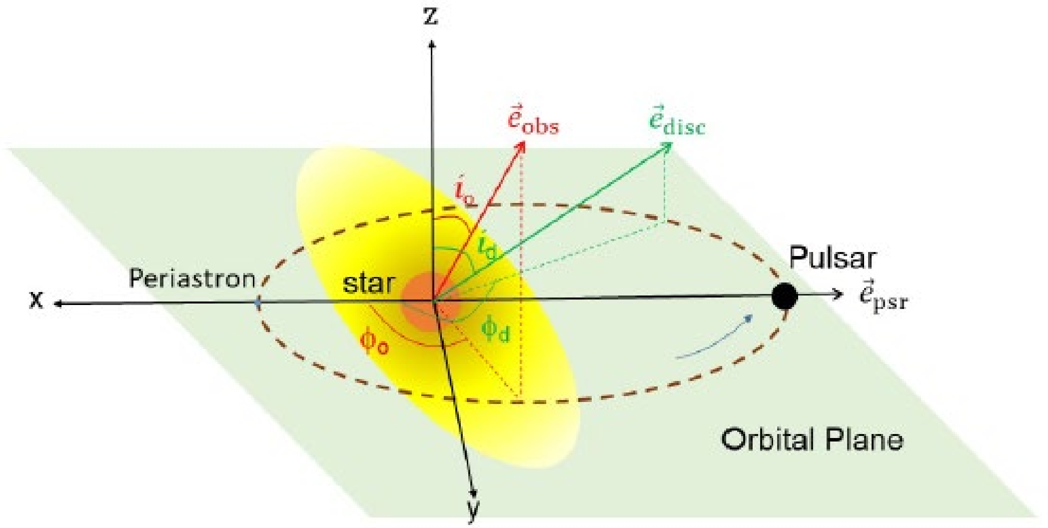


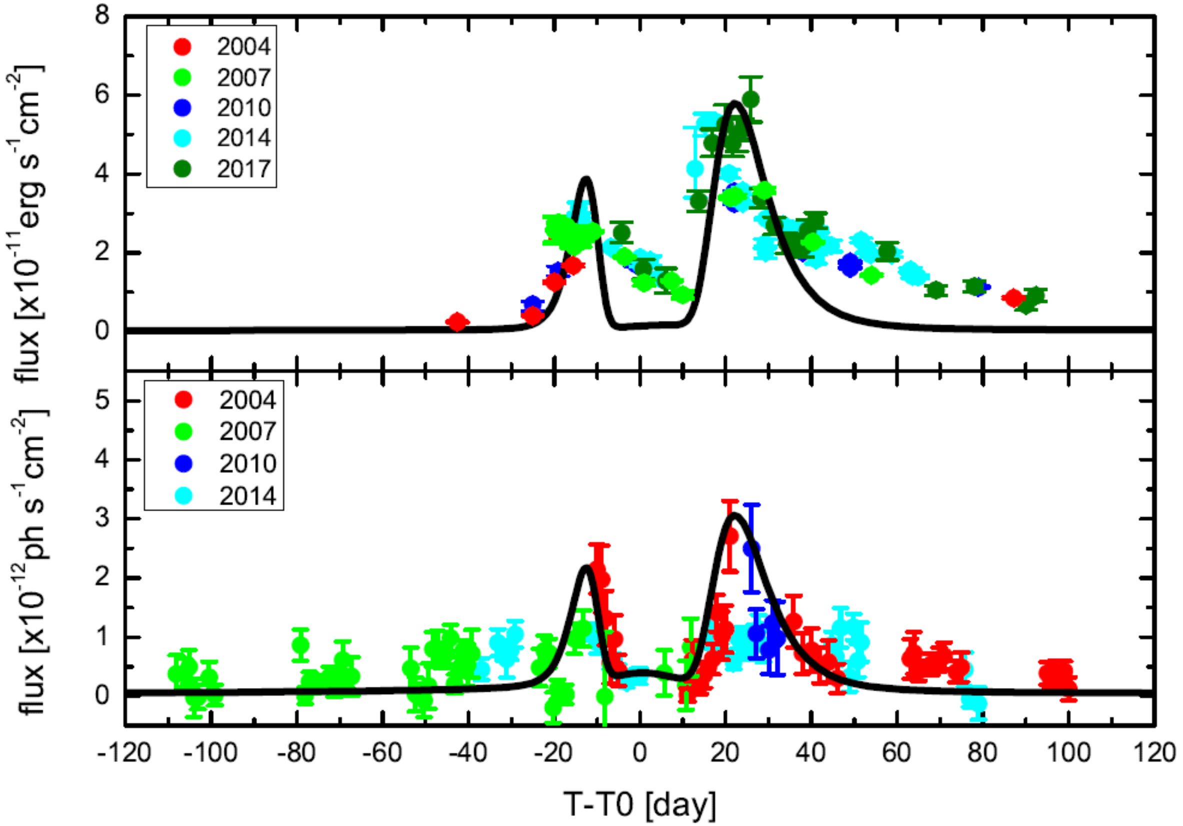
Dubus 2013



Chernyakova et al. 2021







Chen et al. 2019, 2021

PSR J2032+4127/MT91 213

- **Pulsar:**

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

- **Be star:**

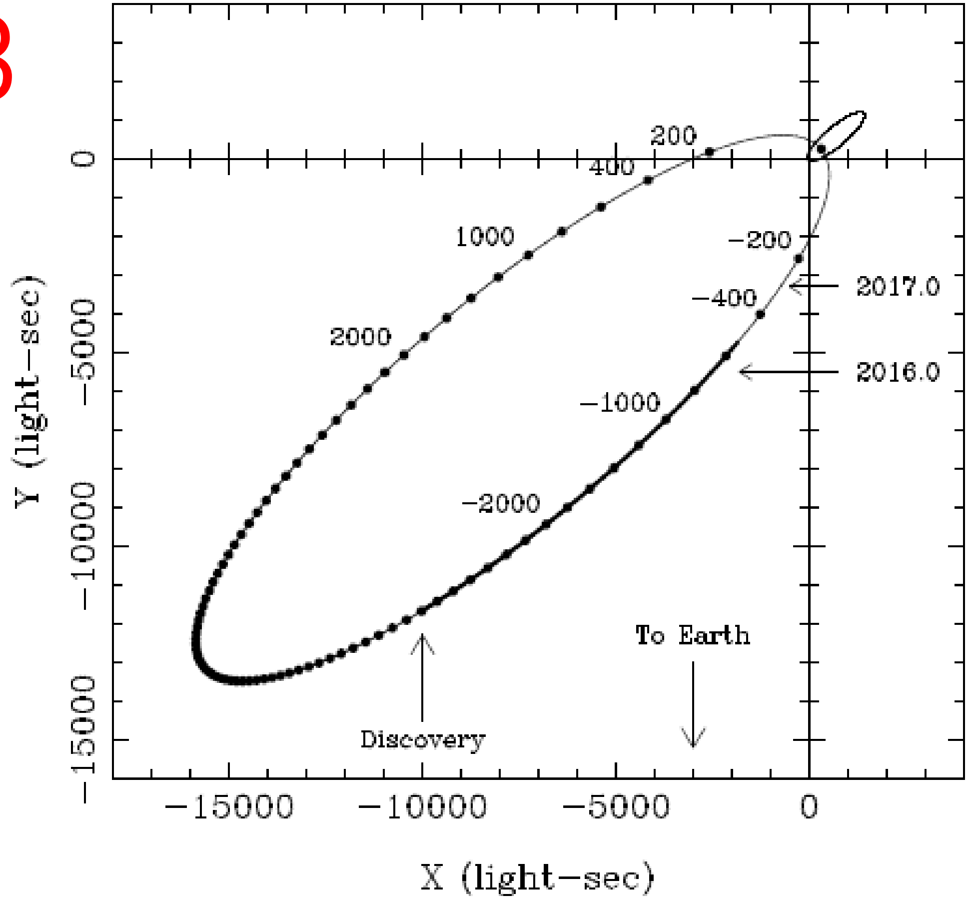
$\text{B0Ve} \;\; M_\star \simeq 25 \; M_\odot, \quad T_{\rm eff} \simeq 30000\,\text{K}$

- **Orbit:**

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

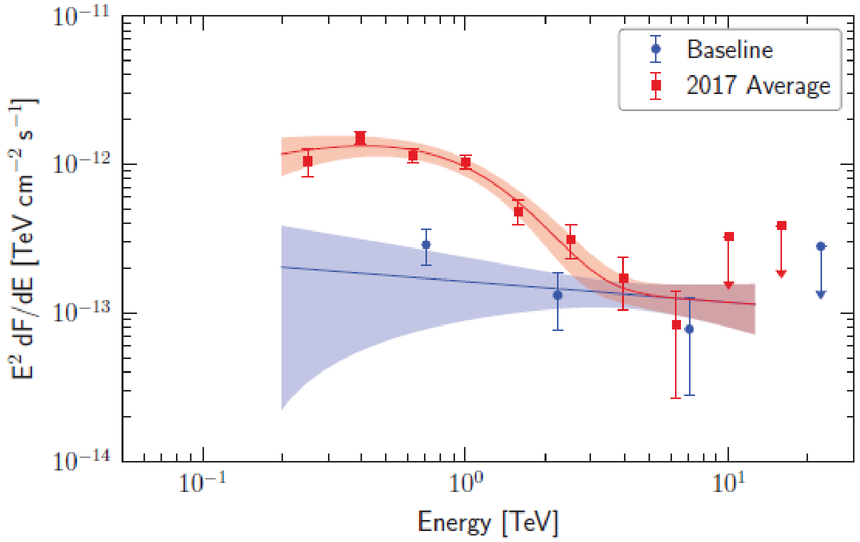
$e \simeq 0.93 - 0.99$

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

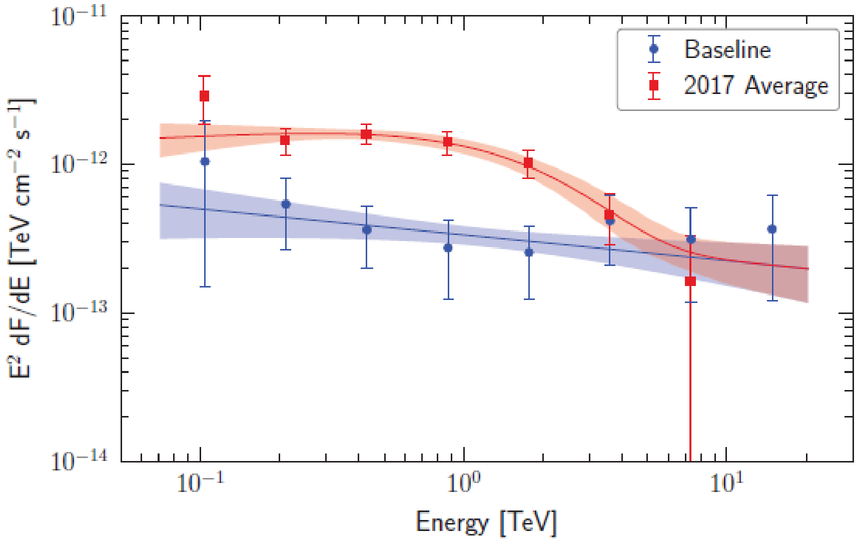


Ho et al. 2017

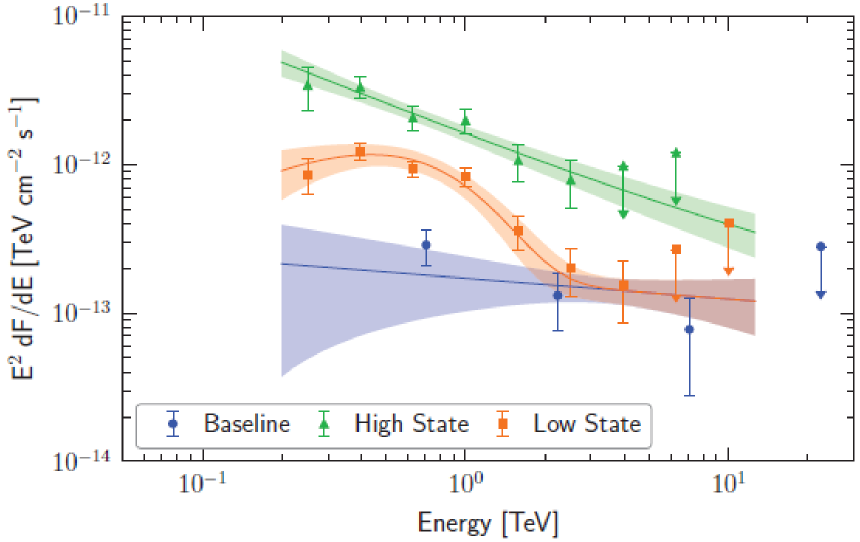
The recent periastron passage occurred in 2017 November, and next periastron phase would be around 2067.



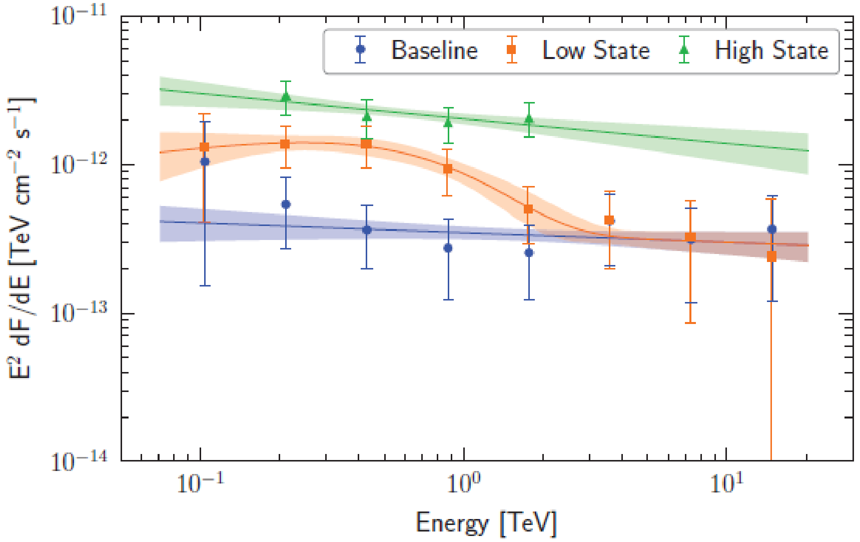
(a)VERITAS 2017 fall average



(b)MAGIC 2017 fall average



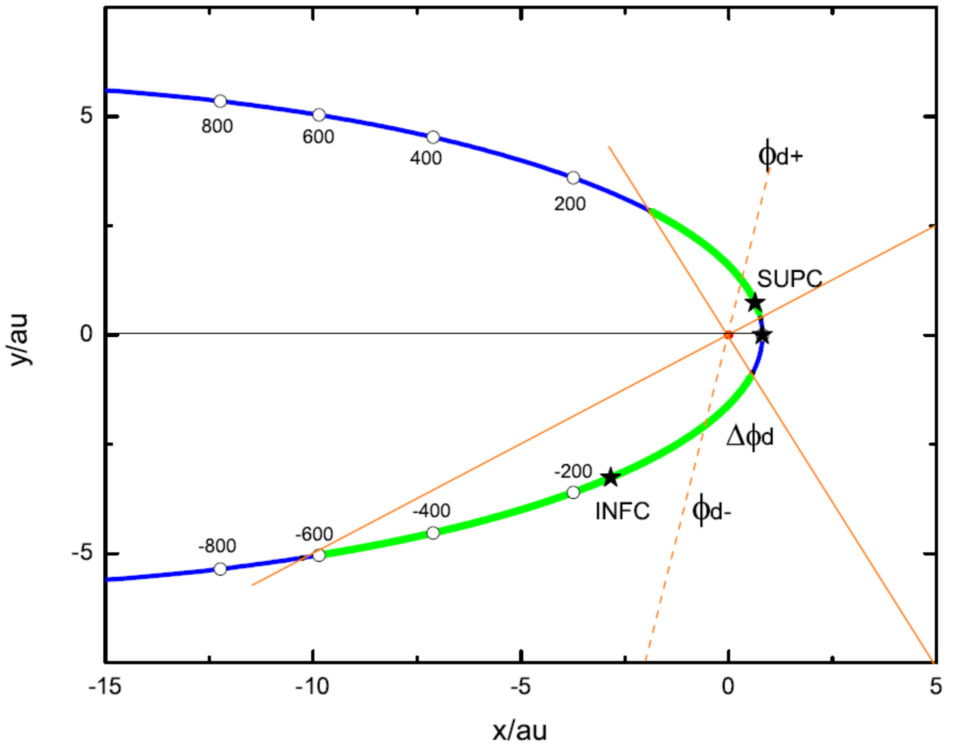
(c)VERITAS high & low states

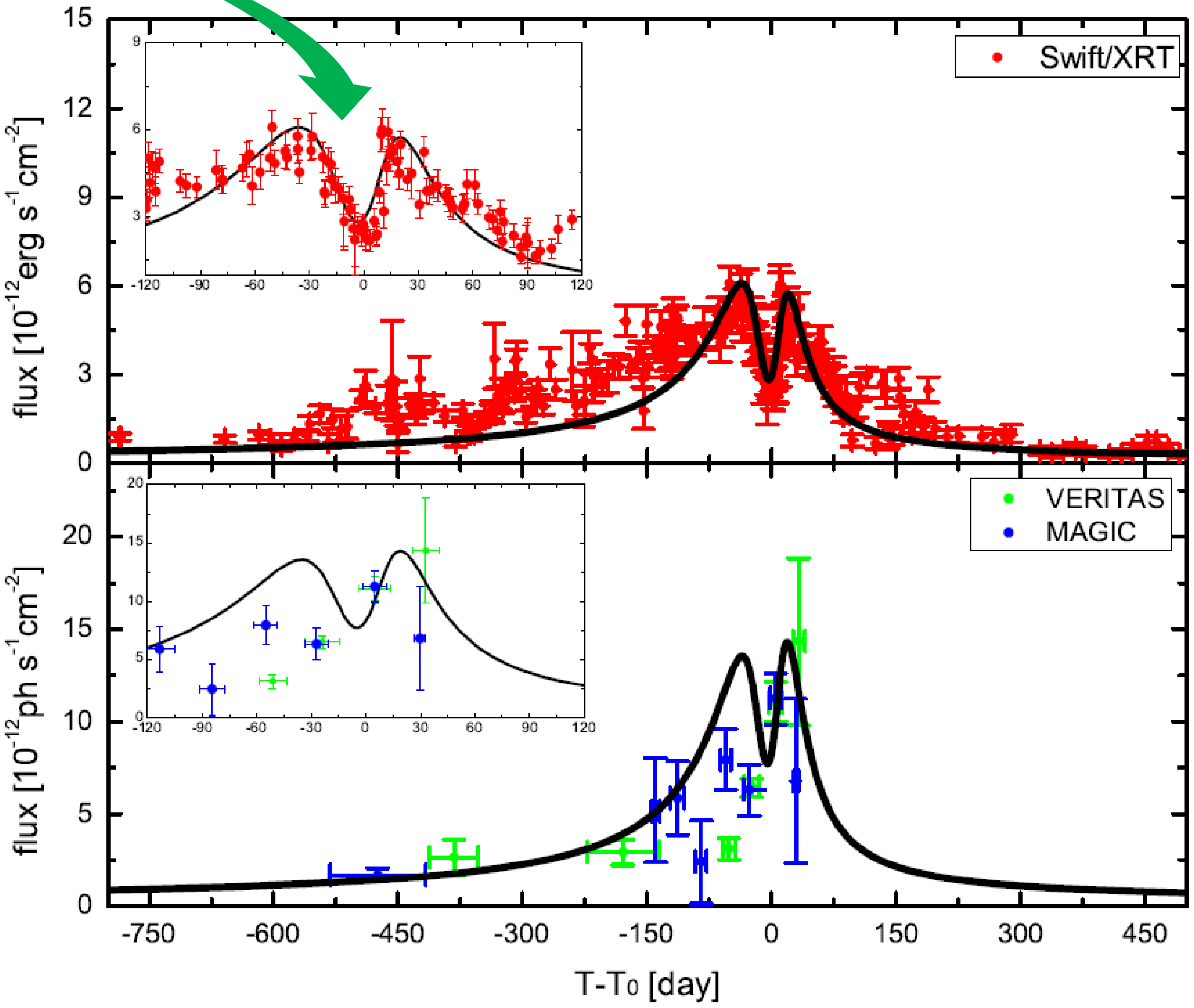


(d)MAGIC high & low states

VERITAS & MAGIC Collaboration 2018

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
$\omega_{\mathrm{p}}(^\circ)$	52	40	21
$a \sin i$ (lt-s)	7138	9022	16335





Chen et al. 2021, submitted

HESS J0632+057

- **Compact object:**

  NS or BH ?

- **Massive star:**

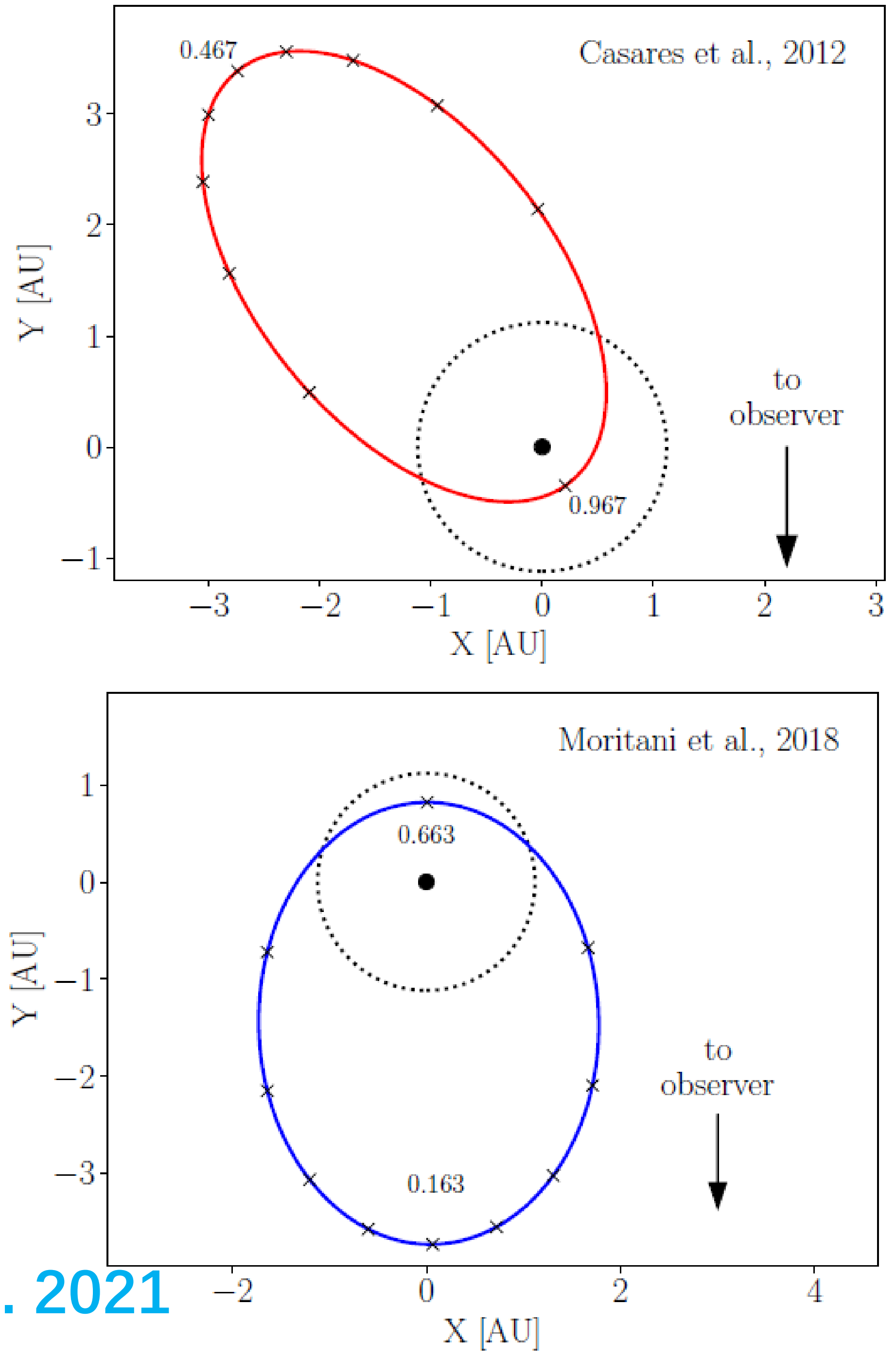
  MWC 148: B0Vpe

- **Binary orbit:**

  $e \sim 0.64 - 0.83$

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

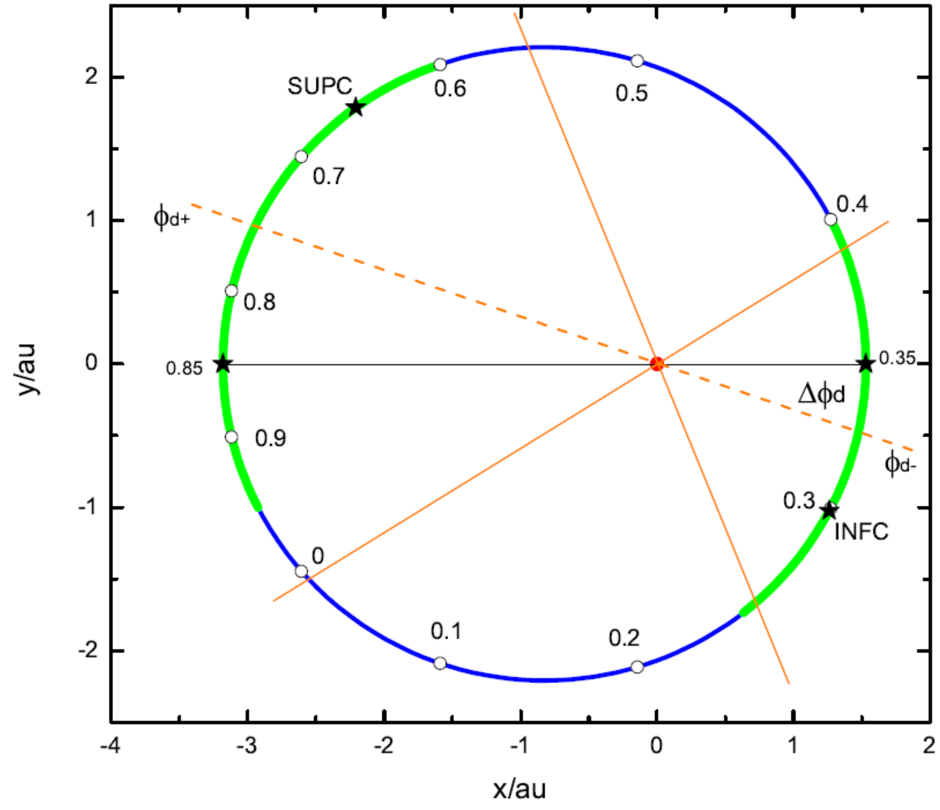
  $d_{\rm L} \sim 1.1 - 1.7\ \rm kpc$

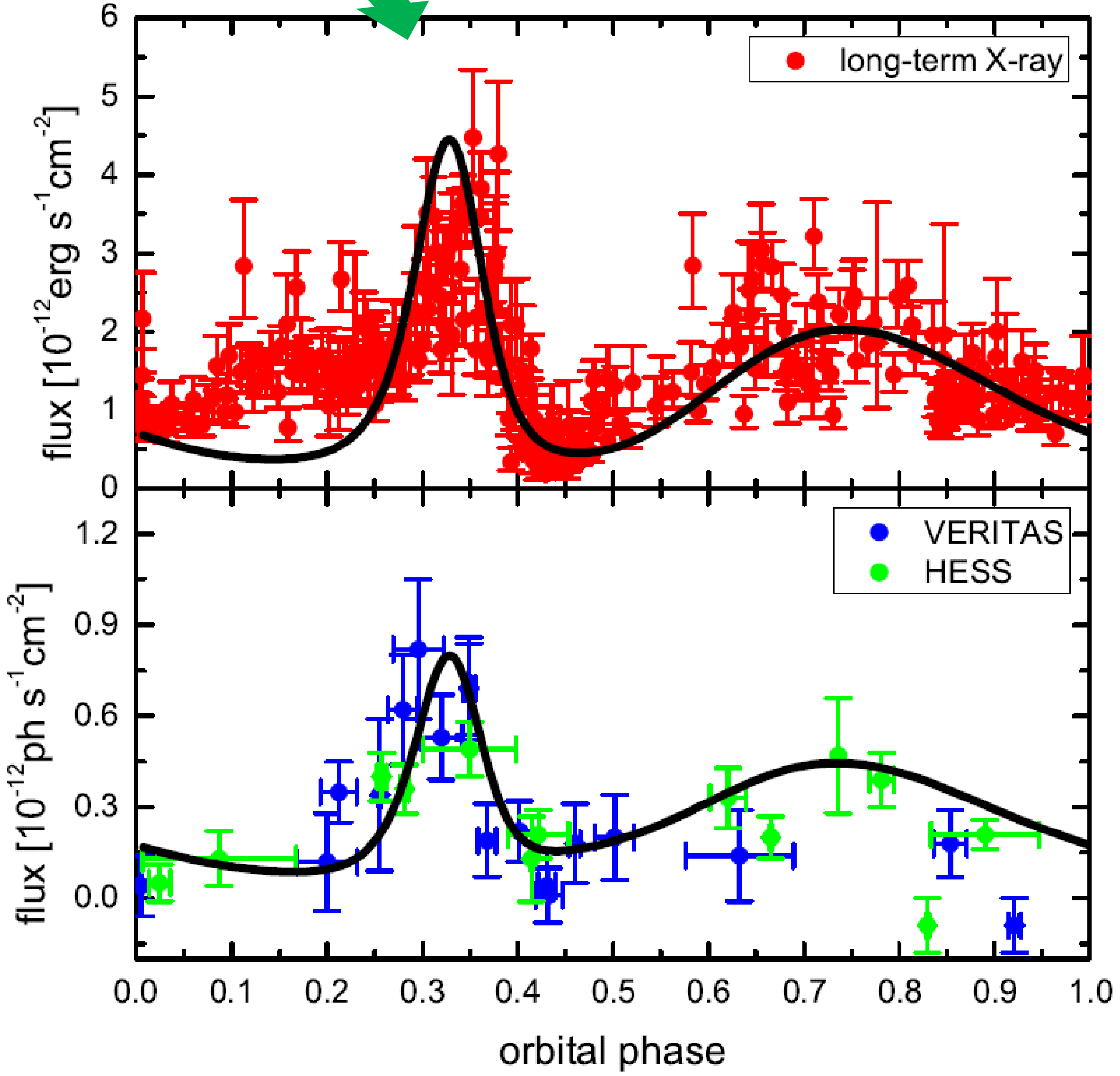


Adams et al. 2021

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., $e \sim 0.5$, $\Phi_p \sim 0.4$).

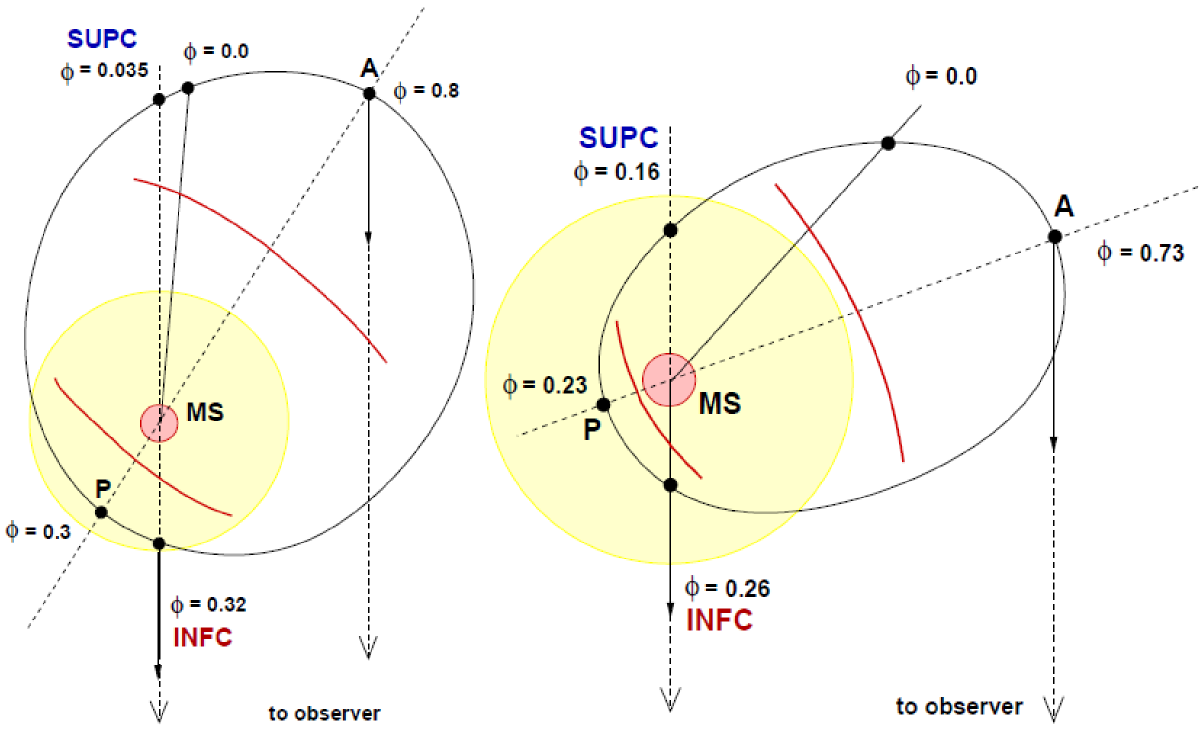




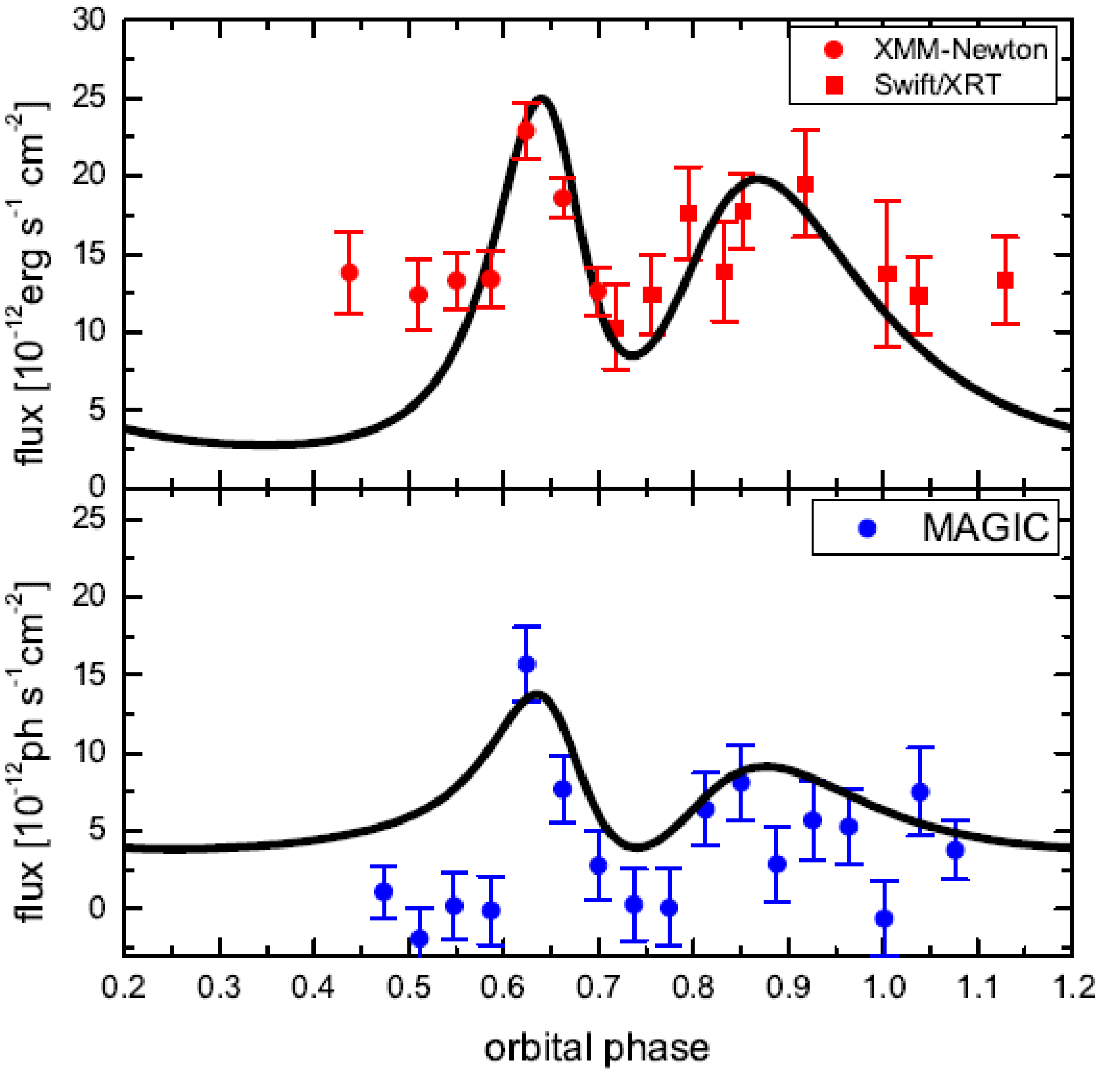
Chen et al. 2021, submitted

LS I+61°303

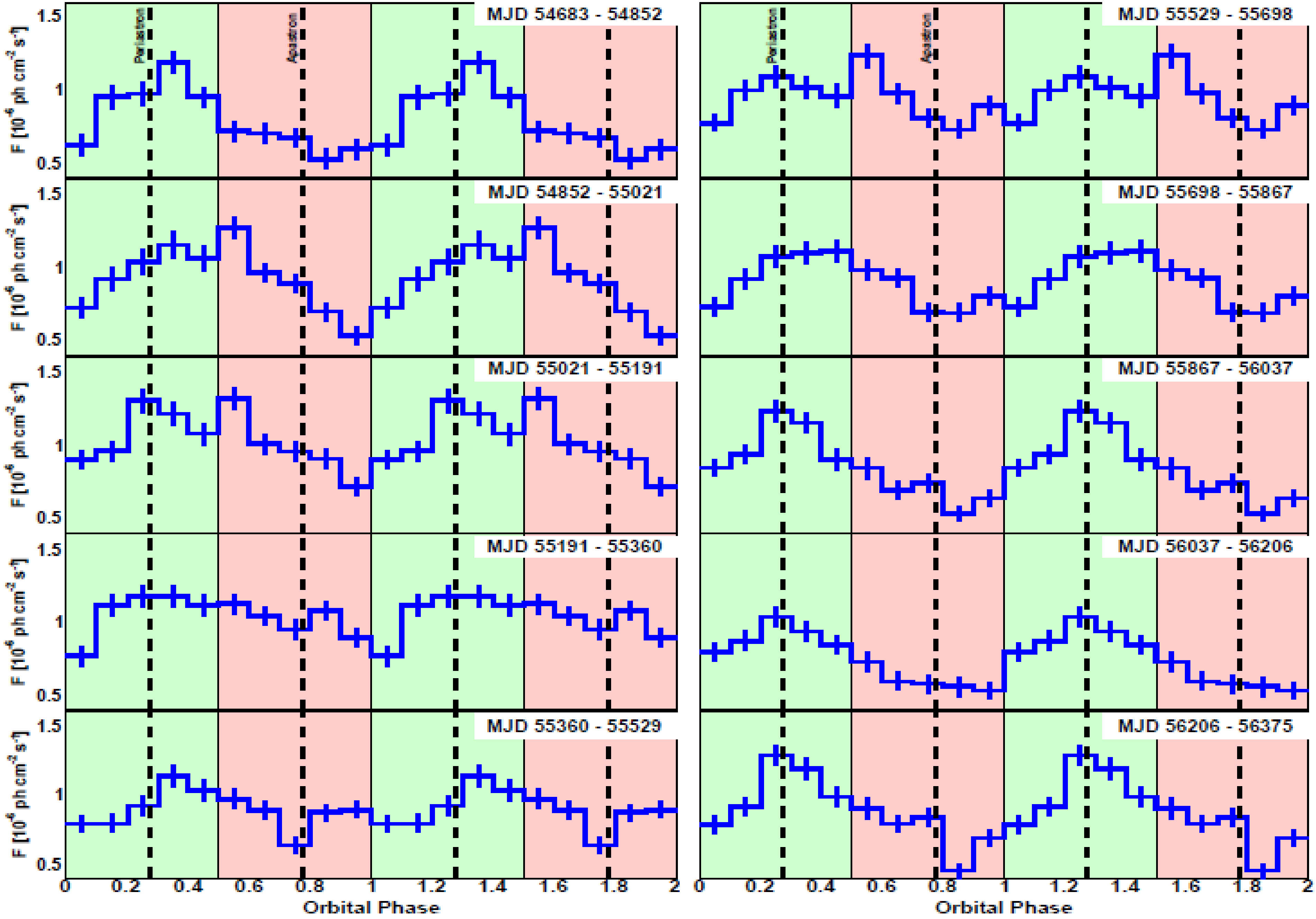
Grundstrom+2007；　　Casares+2005；



Sierpowska-Bartosik & Torres 2009

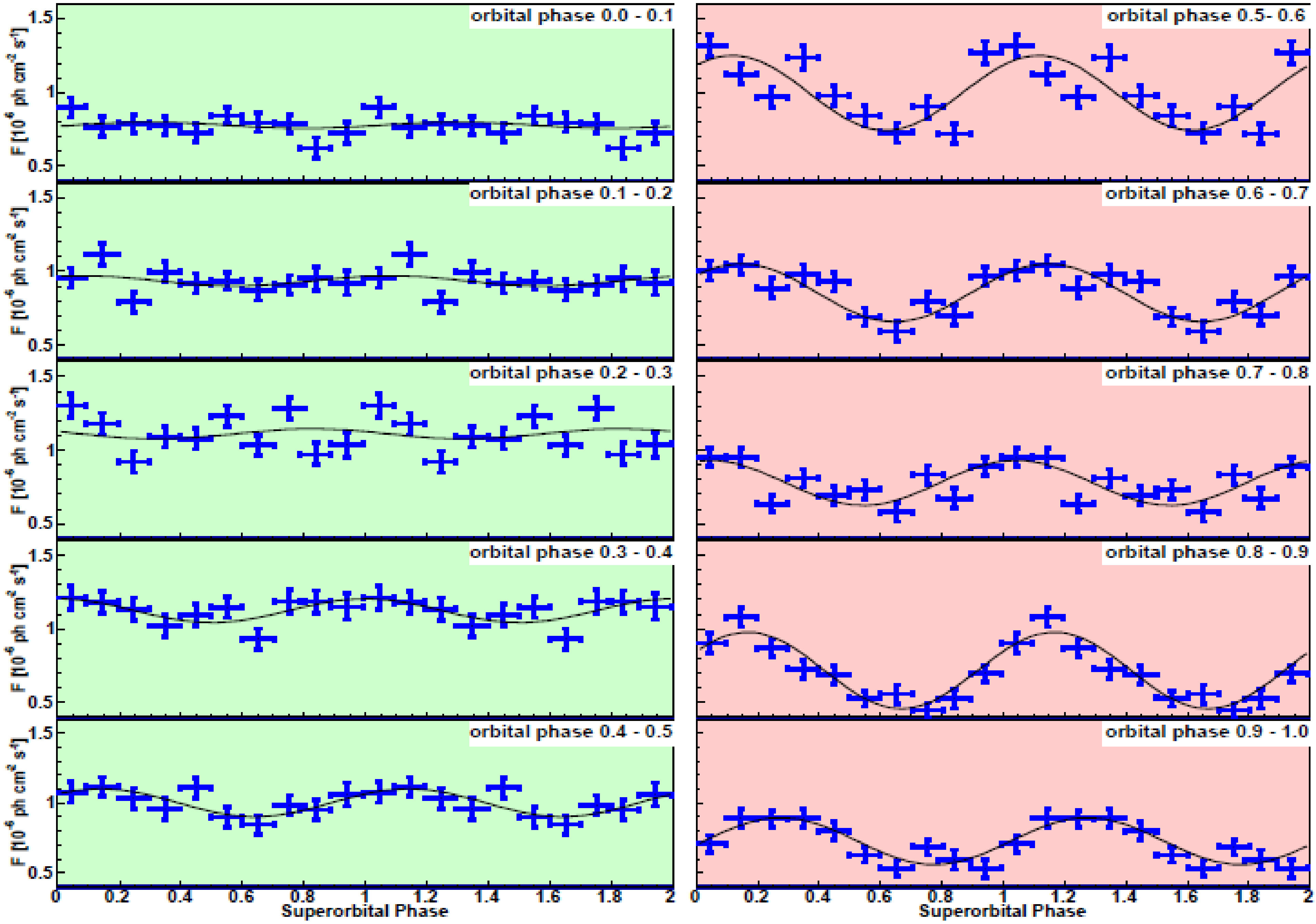


Chen et al. 2021, submitted



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

Ackermann+2013

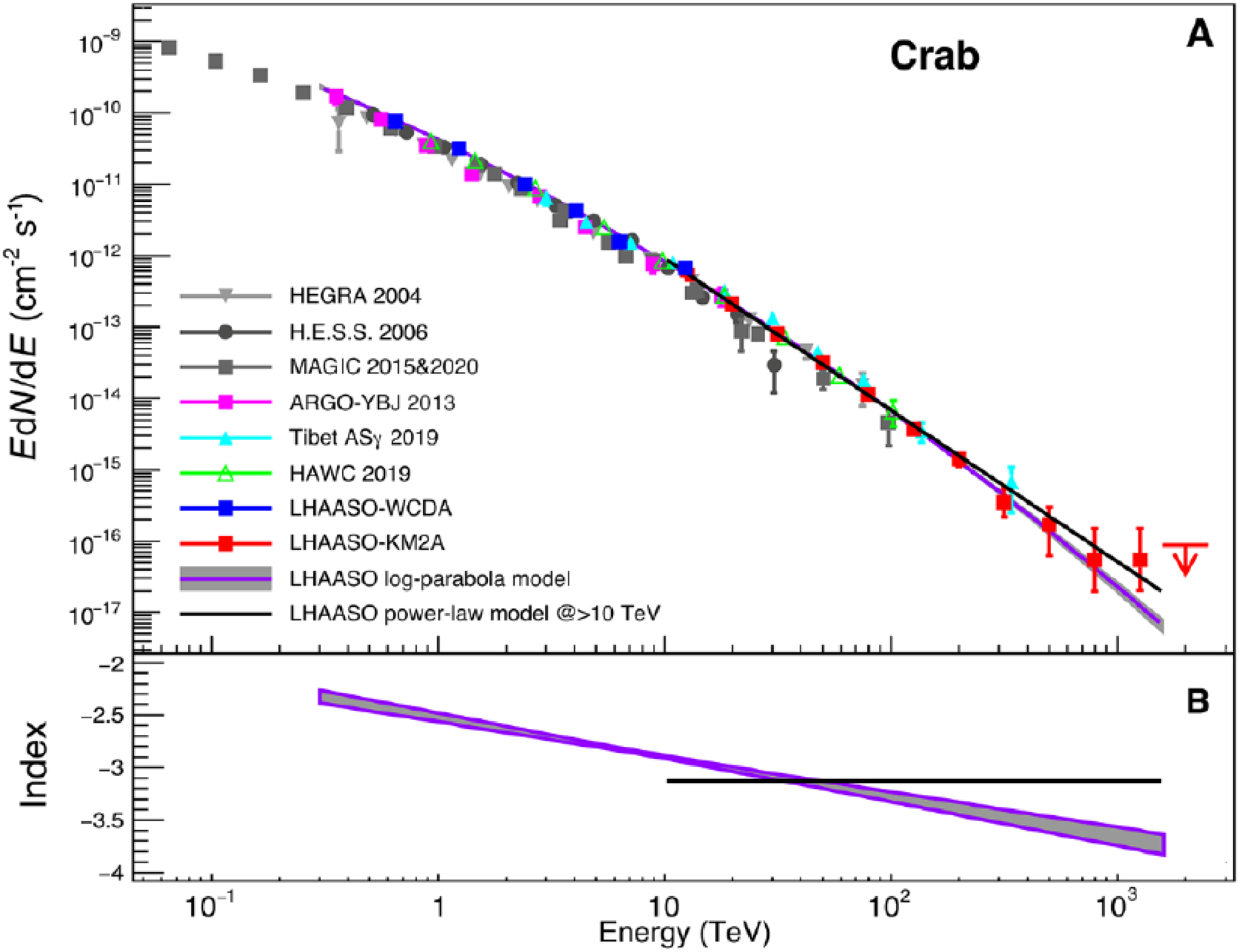


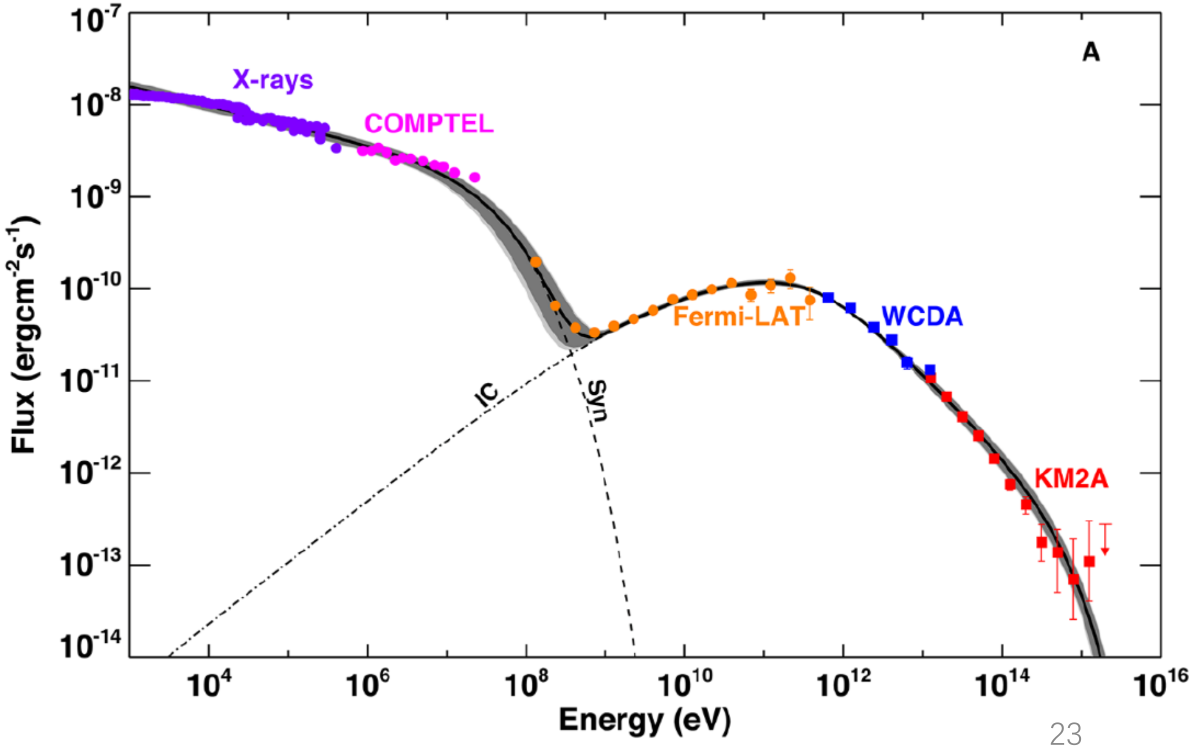
$$P_{\rm sup} \simeq 1667 \text{ days}$$

Ackermann+2013

Q4: Can HMGBs produce PeV γ-rays?

LHAASO 2021a, Science




Science
RESEARCH ARTICLES

Cite as: The LHAASO Collaboration, *Science* 10.1126/science.abg5137 (2021).

PeV gamma-ray emission from the Crab Nebula

The LHAASO Collaboration*†

Cao et al. 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	$6.3^{+0.8\ d}_{-0.7}$	$1.8 - 3.3^k$	—	
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	$1.8^{+1.7\ l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	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	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

Radiation mechanism for PeV γ-rays ?

(1) Leptonic processes: electrons

➢With the magnetic field:

- Curvature radiation
- Synchrotron radiation

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

➢With the photon field:

- IC scattering

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

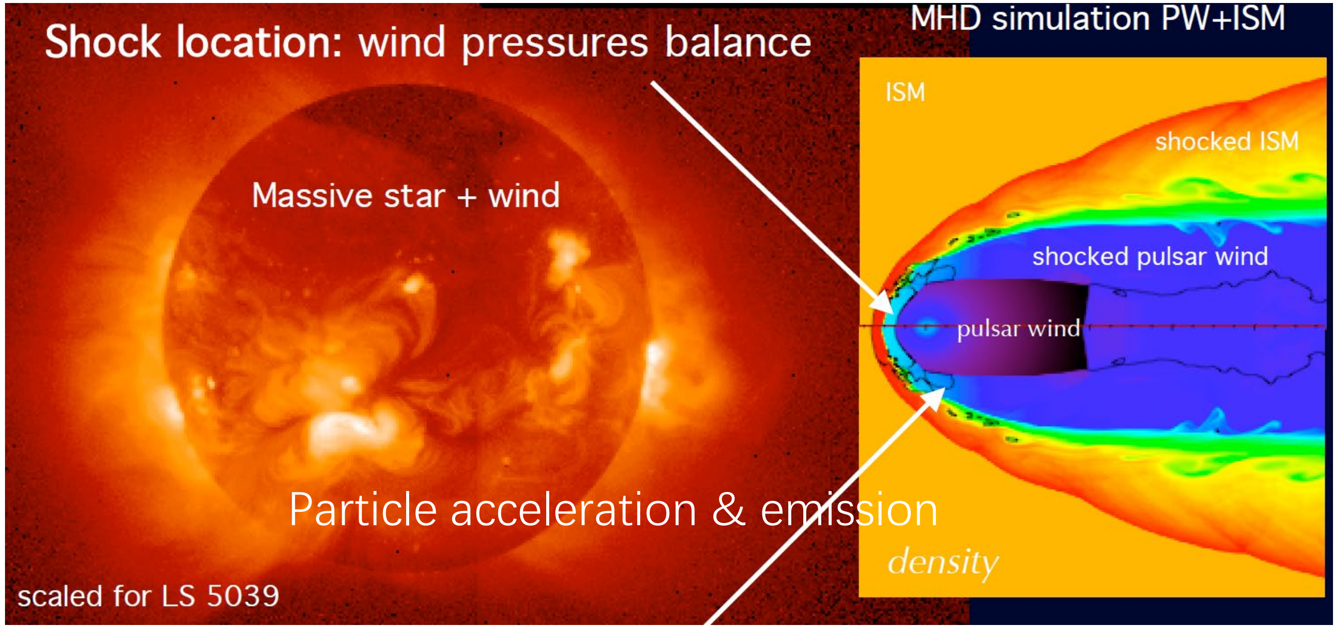


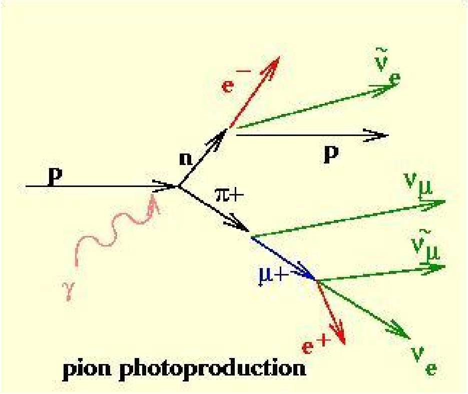
Figure: Bucciantini+2005; Dubus+2007

Radiation mechanism for PeV γ-rays ?

(2) Hadronic processes: protons

- **With photon field:** proton IC, Bethe-Heitler or 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

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

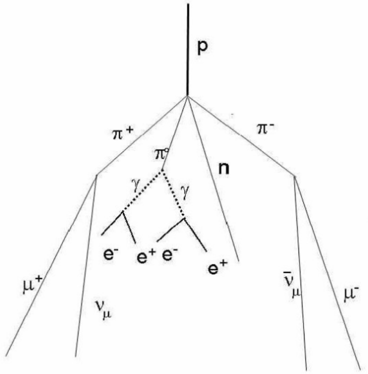


Figure: wiki

Summary

- HMGBs are kind of like enhanced versions of PWN with much more complicated environments !
- LHAASO are likely to detect the PeV photons from binaries in the future (or already have, e.g., LHAASO J2032+4107 ?)

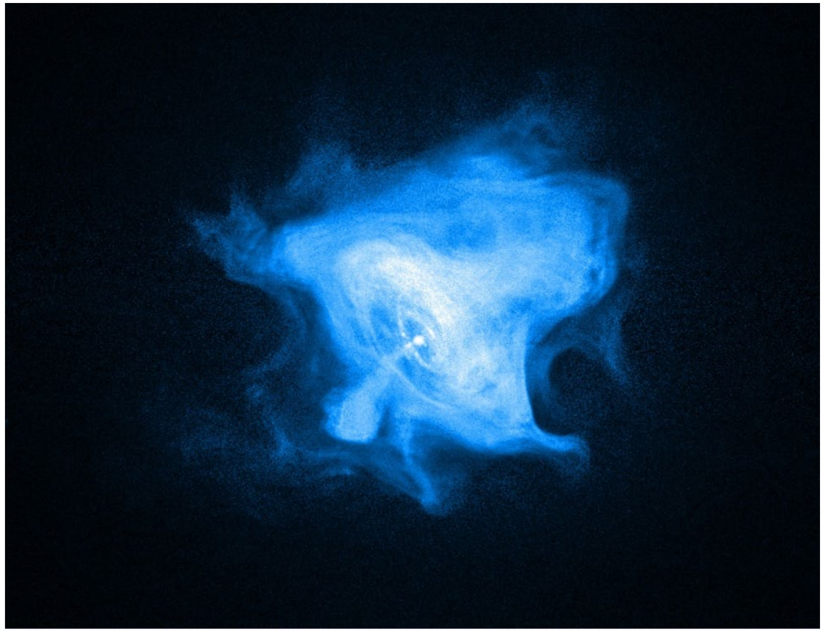


Figure: NASA / CXC / SAO / Seward, Tucker, Fesen

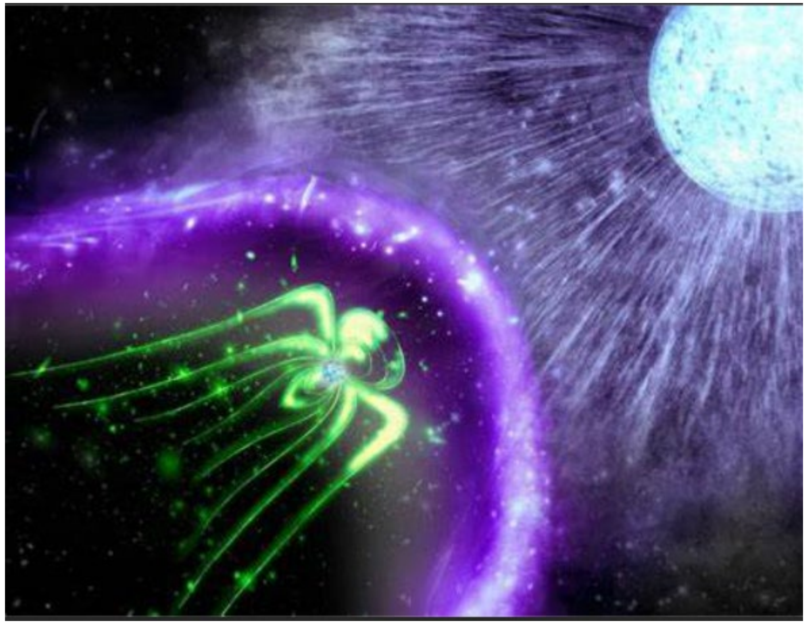


Figure: techexplorist

- **VHE γ-rays:**
  - ➢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

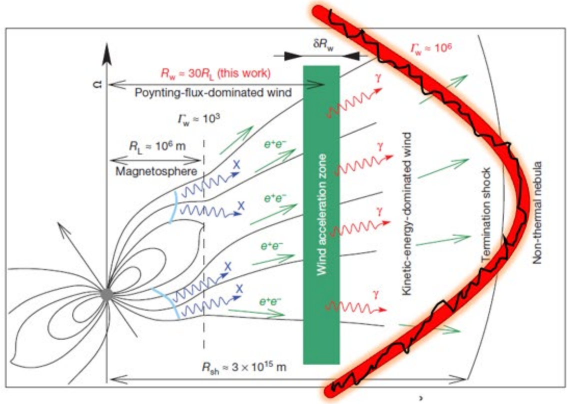


Figure: Aharonian et al. 2010

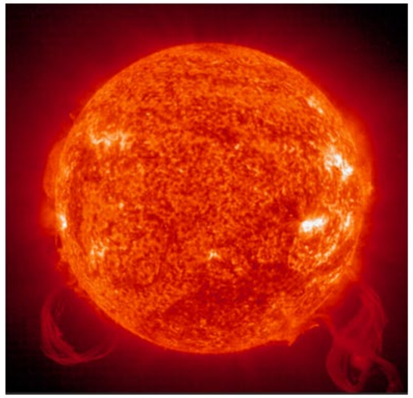


Figure: Wikipedia

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

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

Backup slides

Terminal shock

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

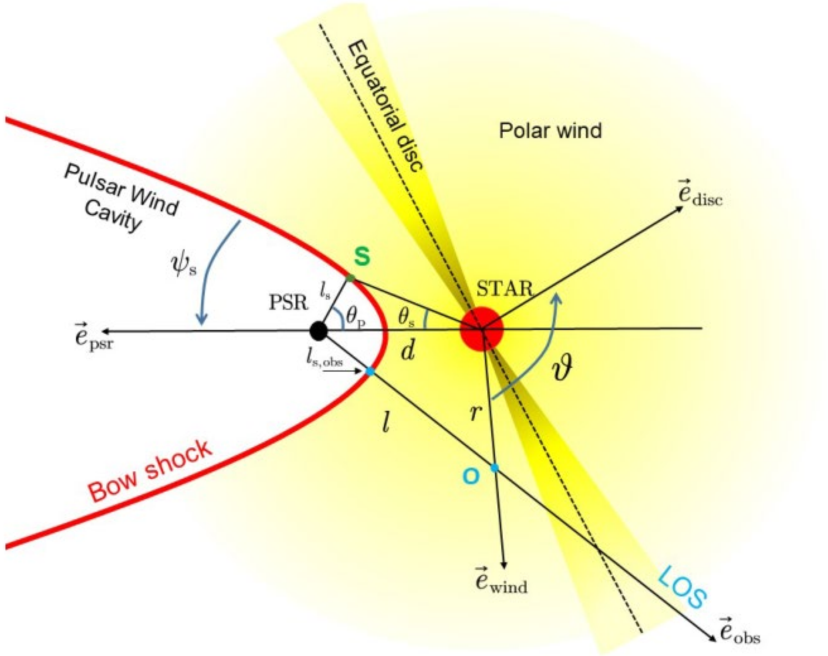
$$l_{\rm s} = d\sin\theta_{\rm s}\csc(\theta_{\rm s}+\theta_{\rm p})$$

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

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

$$L_{\rm star} = 4\pi R_{\rm star}^2 \cdot \sigma_{\rm SB} T_{\rm star}^4$$

$$u_B = \frac{B^2}{8\pi}, \qquad u_{\rm star} = \frac{L_{\rm star}}{4\pi R_{\rm s}^2 c}$$



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

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

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

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

Chen et al. 2021b

Energy distribution

$$\frac{\partial n(\gamma,t)}{\partial t} + \frac{\partial \dot{\gamma} n(\gamma,t)}{\partial \gamma} = \dot{Q}(\gamma,t)$$

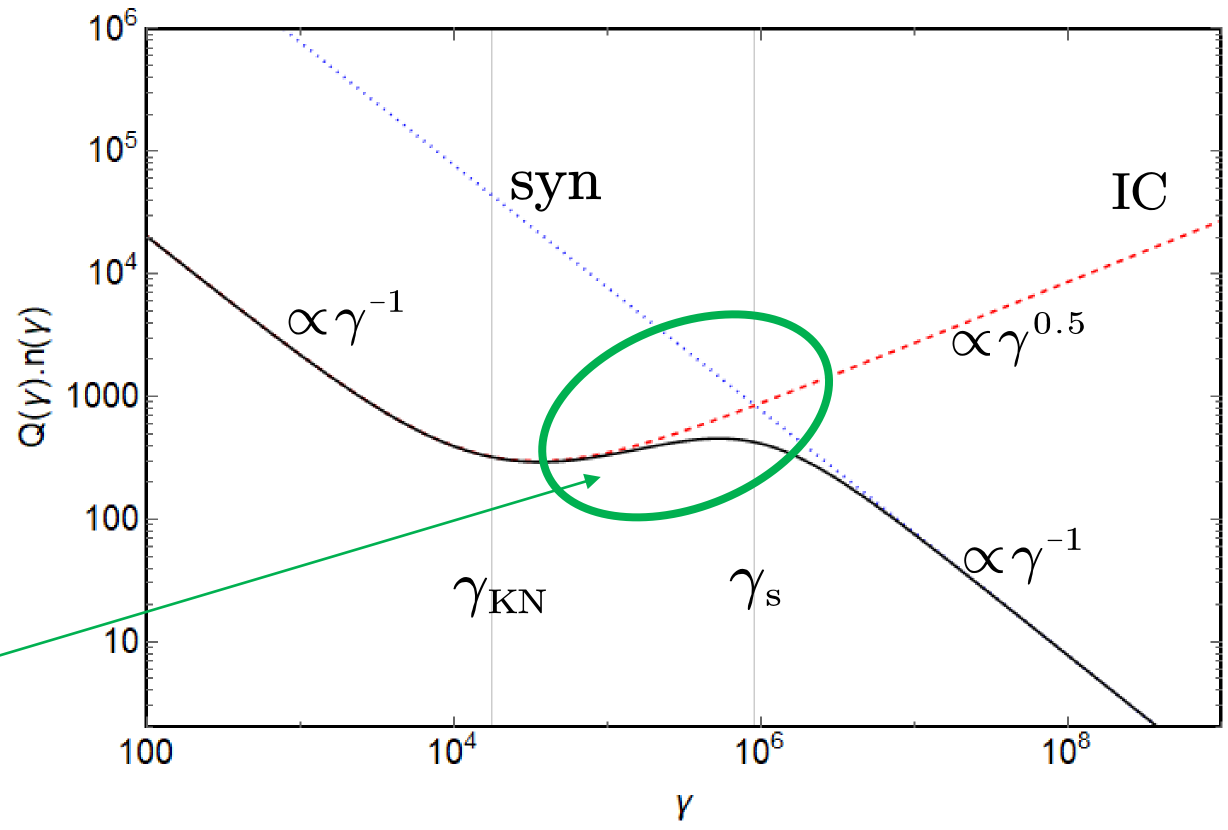
$$\partial n(\gamma,t)/\partial t = 0$$

$$n(\gamma) = \frac{1}{|\dot{\gamma}|}\int_{\gamma} \dot{Q}(\gamma')d\gamma'$$

$$\dot{\gamma}_{\rm rad} = \dot{\gamma}_{\rm syn} + \dot{\gamma}_{\rm ics}$$

$$\dot{\gamma}_{\rm syn} = \frac{4c\sigma_T}{3m_{\rm e}c^2}u_B\gamma^2$$

$$\dot{\gamma}_{\rm ics} = \frac{4c\sigma_T}{3m_{\rm e}c^2}u_{\rm ph}\gamma^2 F_{\rm KN}(\gamma)$$



Chen et al. 2021b

Pair production

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

$$d\tau_{\gamma\gamma} = (1-\mu) n_\epsilon \sigma_{\gamma\gamma} d\epsilon d\Omega dl$$

$$1-\mu = 1 + \cos\psi \cos\theta + \sin\psi \cos\phi \sin\theta,$$

$$n_\epsilon = \frac{2}{h^3 c^3} \frac{1}{\exp(\epsilon/kT) - 1} \text{ ph cm}^{-3}\text{erg}^{-1}\text{sr}^{-1}.$$

$$\sigma_{\gamma\gamma} = \frac{\pi r_e^2}{2}(1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right]$$

$$\Downarrow$$

$$\tau_{\gamma\gamma} = \int_0^\infty dl \int_{c_{\min}}^1 d\cos\theta \int_0^{2\pi} d\phi \int_{\epsilon_{\min}}^\infty d\epsilon \frac{d\tau_{\gamma\gamma}}{d\epsilon d\Omega dl}.$$

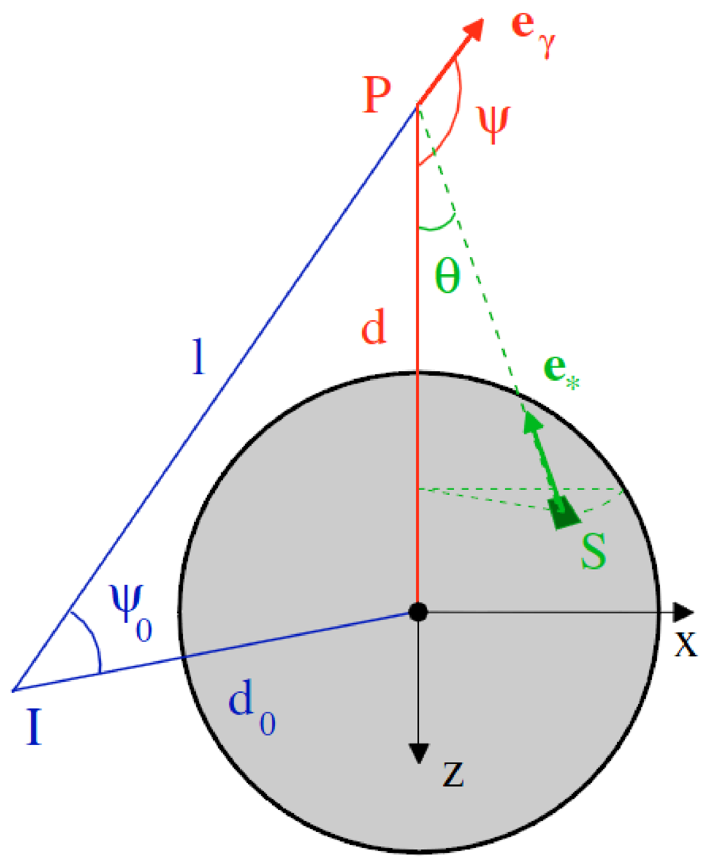


Figure: Dubus 2006