PeV particle acceleration in magnetospheres of millisecond pulsars

Z. Wadiasingh[ab], Z. Metzler[ab], M. Sim[c], H. An[c]

[a]NASA/GSFC, [b]University of Maryland College Park, [c]Department of Astronomy and Space Science, Chungbuk National University

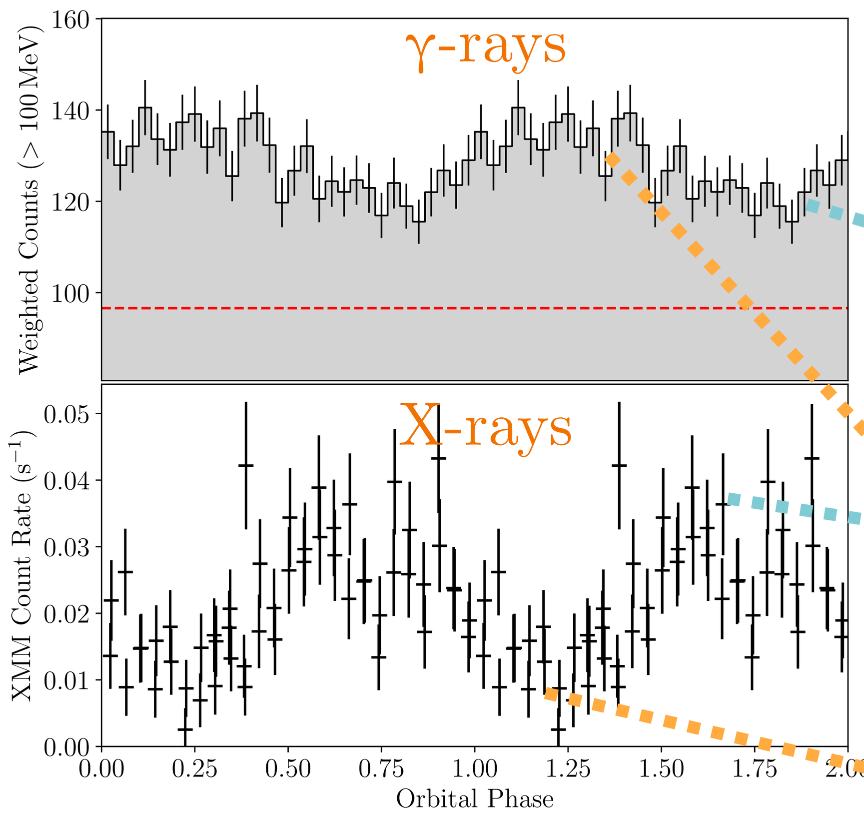
1) Recent detections by *Fermi*-LAT of orbitally modulated and **pulsed** gamma-ray emission in MSP pulsar binaries imply the presence of ~0.1 PeV leptons in phase with the regular pulsed GeV gamma-rays. This implies particle acceleration of PeV energies must take close where GeV gamma-rays are produced, likely near the light cylinder in the equatorial current sheet. These same electron/positrons likely produce the orbitally modulated GeV pulsed emission via radiation-reaction limited curvature radiation in the equatorial current sheet, implying low multiplicity are realized in real pulsars for the current sheet. These results also imply the shocks in millisecond pulsar binaries are the result of a strong companion magnetosphere.

2) New results (Metzler & Wadiasingh 2025) show that backsplash 511 keV emission exists in pulsar binaries, and it can also serve as a diagnostic for the particle content of pulsar winds.

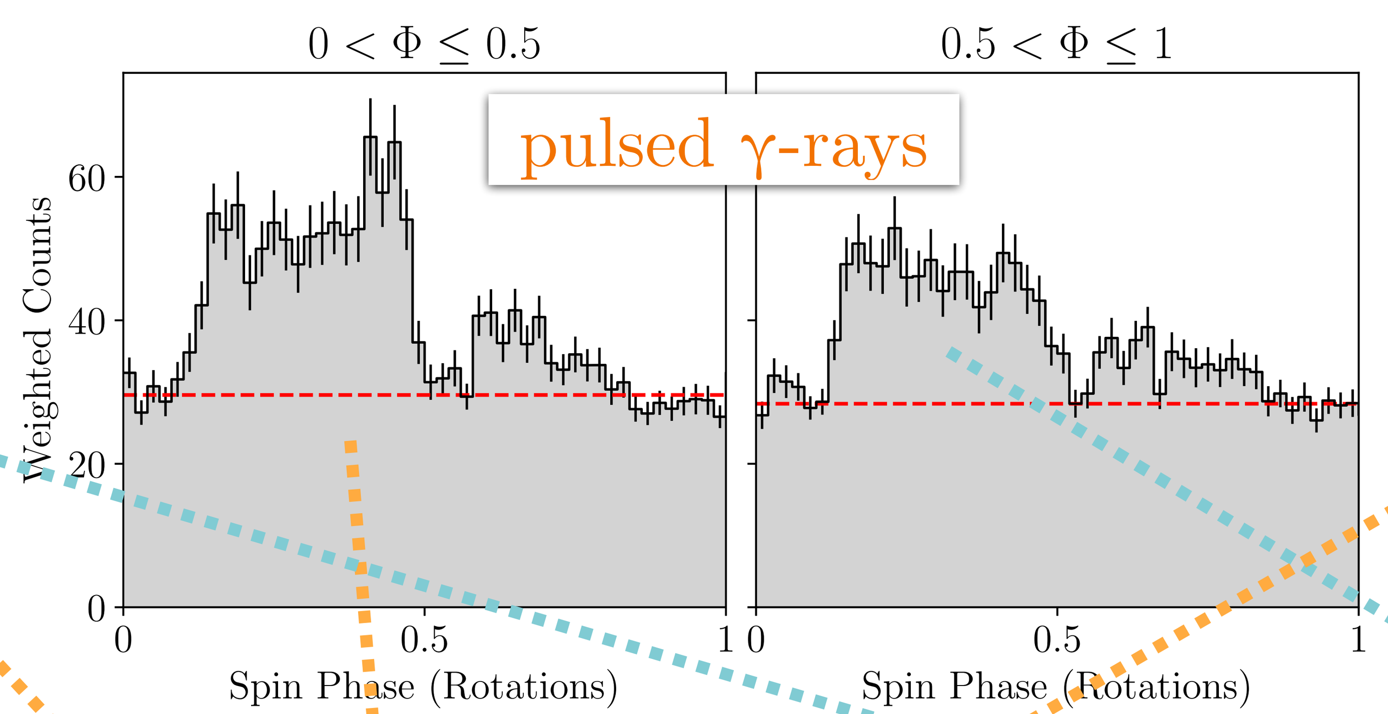
1. (Pulsed) Gamma-ray orbital modulation in MSPs

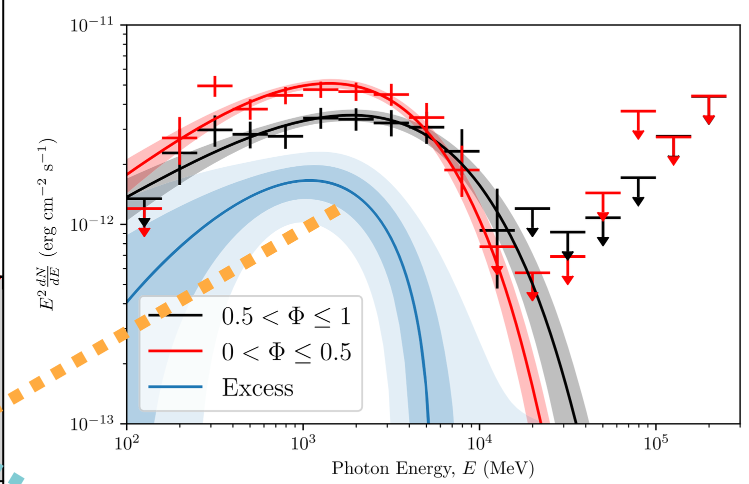
Redback PSR J2039-5617

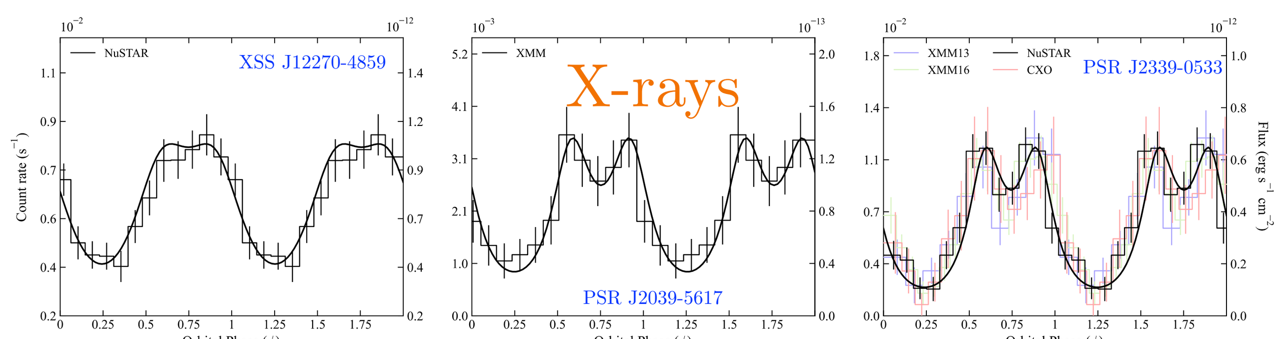
Clark C. J., Nieder L., Voisin G., et al., 2021, MNRAS, 502, 915

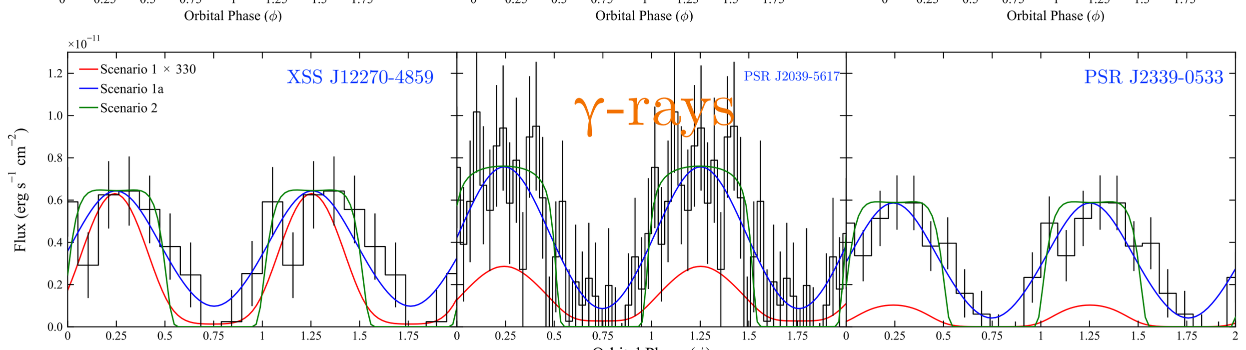


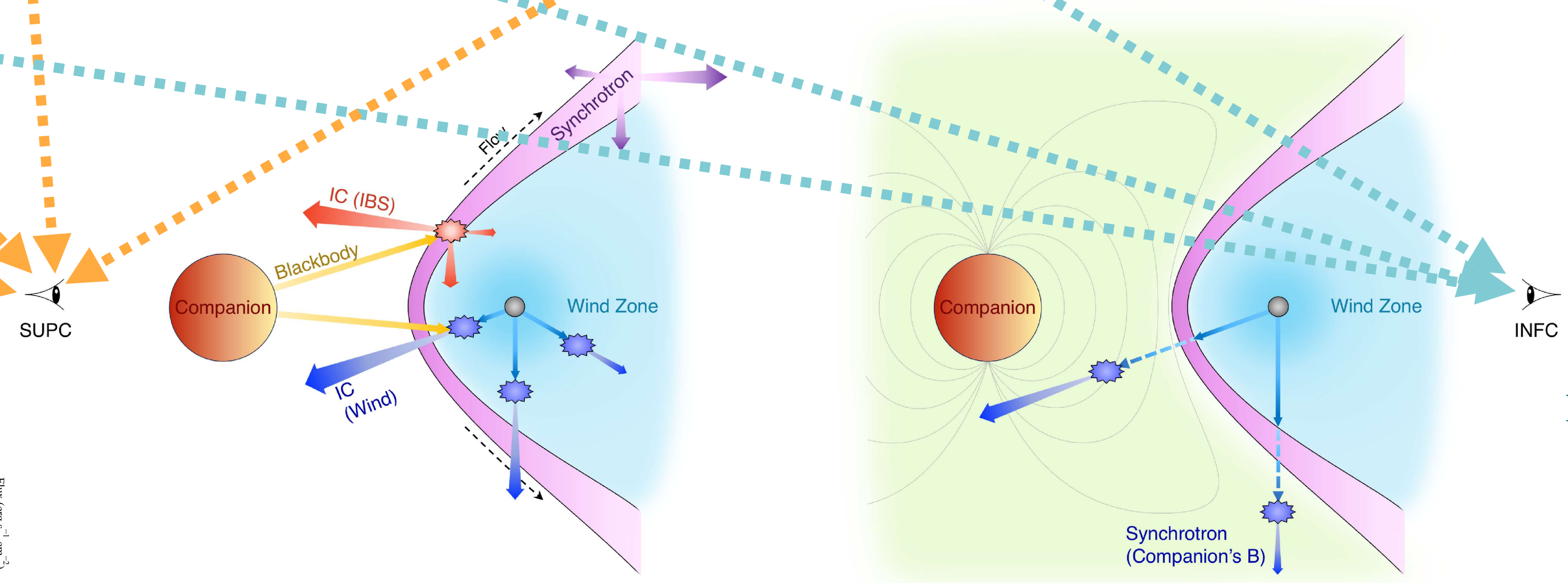
180° orbital phase difference between X-rays and γ-rays











Pulsed gamma-rays are enhanced at superior conjunction (orbital phase 0.75)

Shock X-ray emission peaks at inferior conjunction (orbital phase 0.25)

Sim M., An H., Wadiasingh Z., 2024, ApJ, 964, 109

Scenario I: Inverse Compton of companion photons on upstream pulsar wind particles is not tenable (too low flux) - the optical depth to scattering is not high enough for efficient production of MeV/GeV gamma-rays

$$F_{\rm IC,wind} = 4\sigma_{\rm T} c u_* \gamma_w^2 \frac{\eta_w E_{\rm SD}\tau_w}{4\pi d^2 \gamma_w m_e c^2} \approx 10^{-16}\frac{\eta_w \dot{E}_{\rm SD,35}\gamma_w}{d^2_{\rm kpc}}\left(\frac{u_*}{1\ {\rm erg\ cm^{-3}}}\right)\left(\frac{\tau_w}{1\ {\rm s}}\right)\ {\rm erg\ s^{-1}\ cm^{-2}},$$

Scenario II: 0.1 PeV electron/positrons catastrophically cooling in a kilogauss companion magnetosphere

$$F_{\rm SY} = \frac{c\sigma_{\rm T}\zeta \dot{N}_p t_{\rm cool}}{3\pi d^2}\gamma_p^2 U_B \approx 8\times10^{-10}\frac{\zeta\eta_p \dot{E}_{\rm SD,35}}{d^2_{\rm kpc}}\ {\rm erg\ s^{-1}\ cm^{-2}}$$

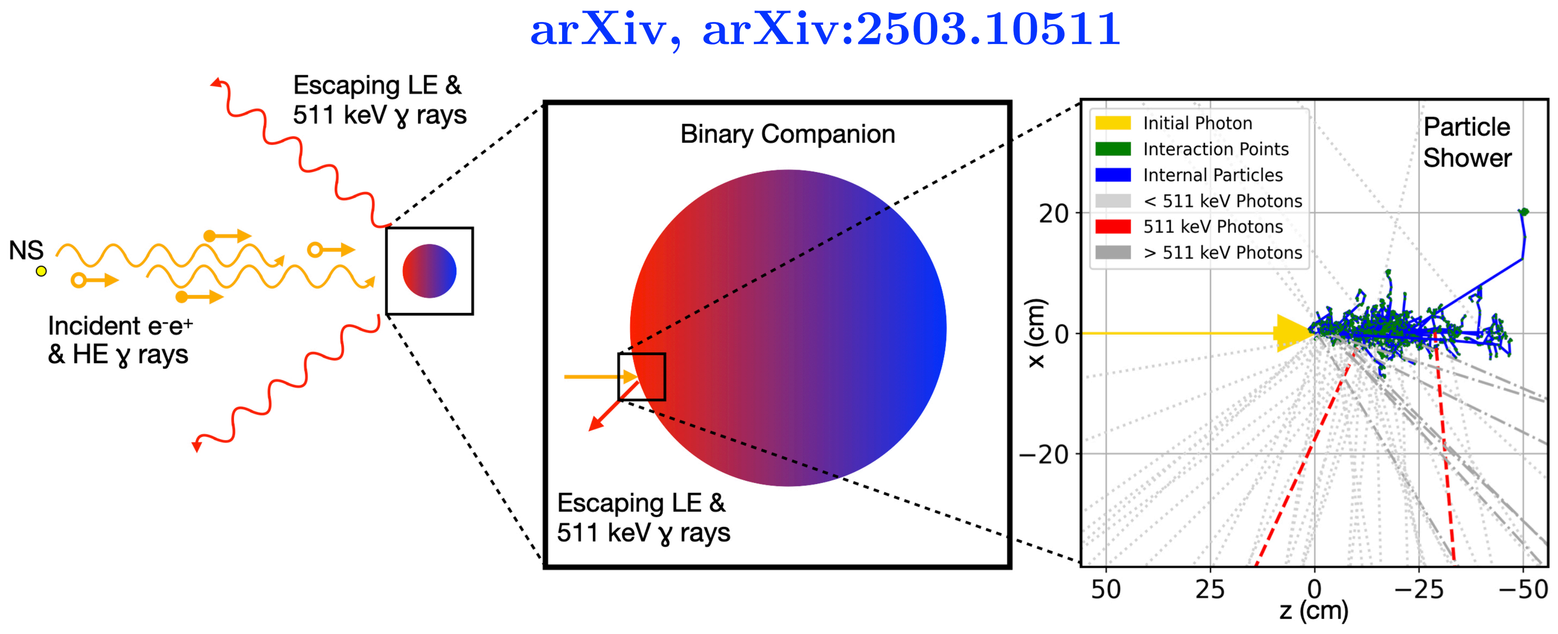
Phase coherence must be maintained and the same particles must produce the pulsed GeV emission

$$t_{\rm cool} \approx 8\times10^{-4}\left(\frac{\gamma_p}{10^8}\right)^{-1}\left(\frac{B}{0.1\ {\rm kG}}\right)^{-2}\ {\rm s}.$$

N.B. 10^7-10^8 Lorentz factors also required for pulsed GeV emission in the curvature radio scenario in the current sheet (e.g. Kalapotharakos et al. 2019, 2023) for millisecond pulsars, as corroborated by HESS for the Vela pulsar

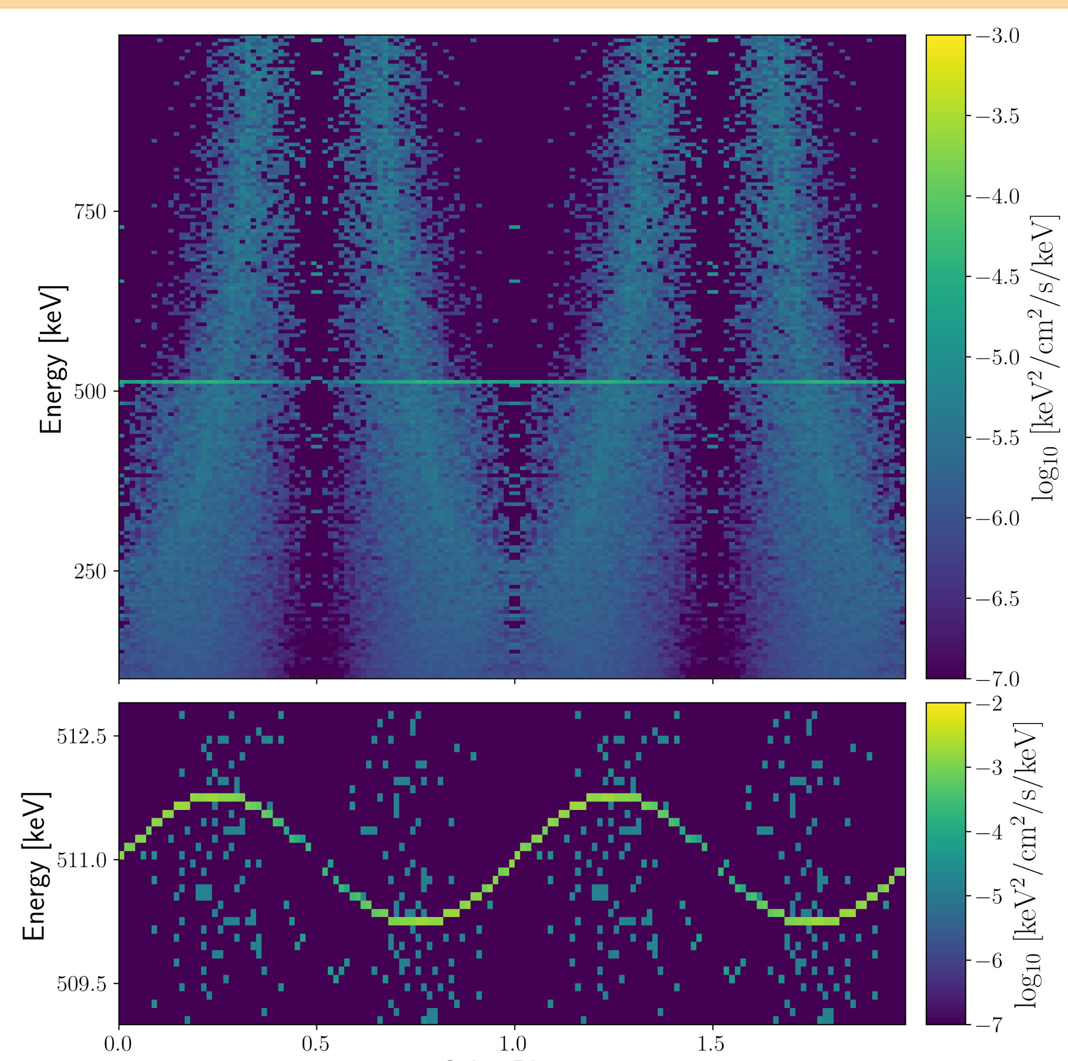
2. Pulsar binary backsplash 511 keV positron annihilation line emission

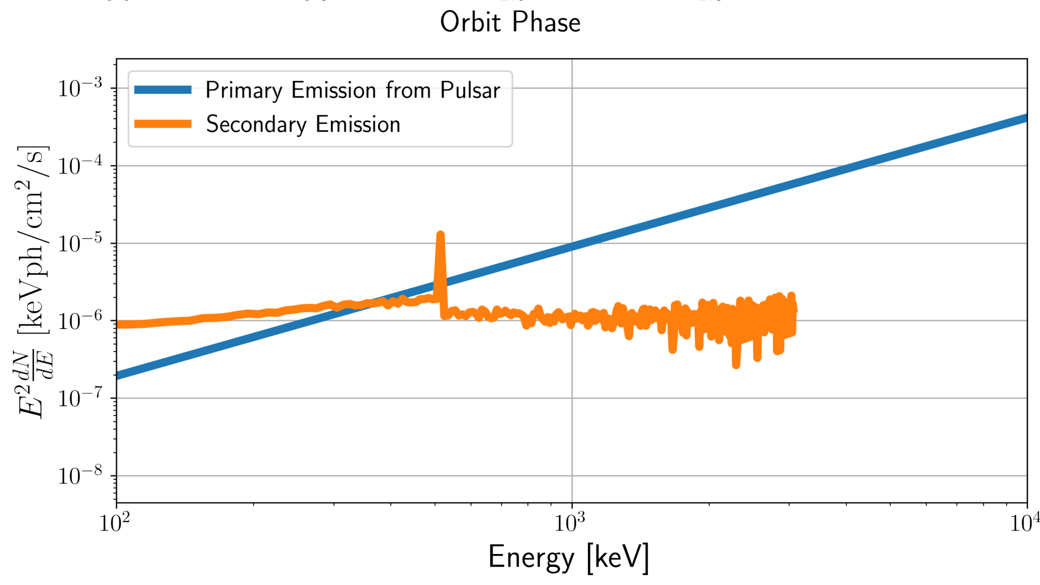
Metzler Z., Wadiasingh Z., 2025, arXiv, arXiv:2503.10511



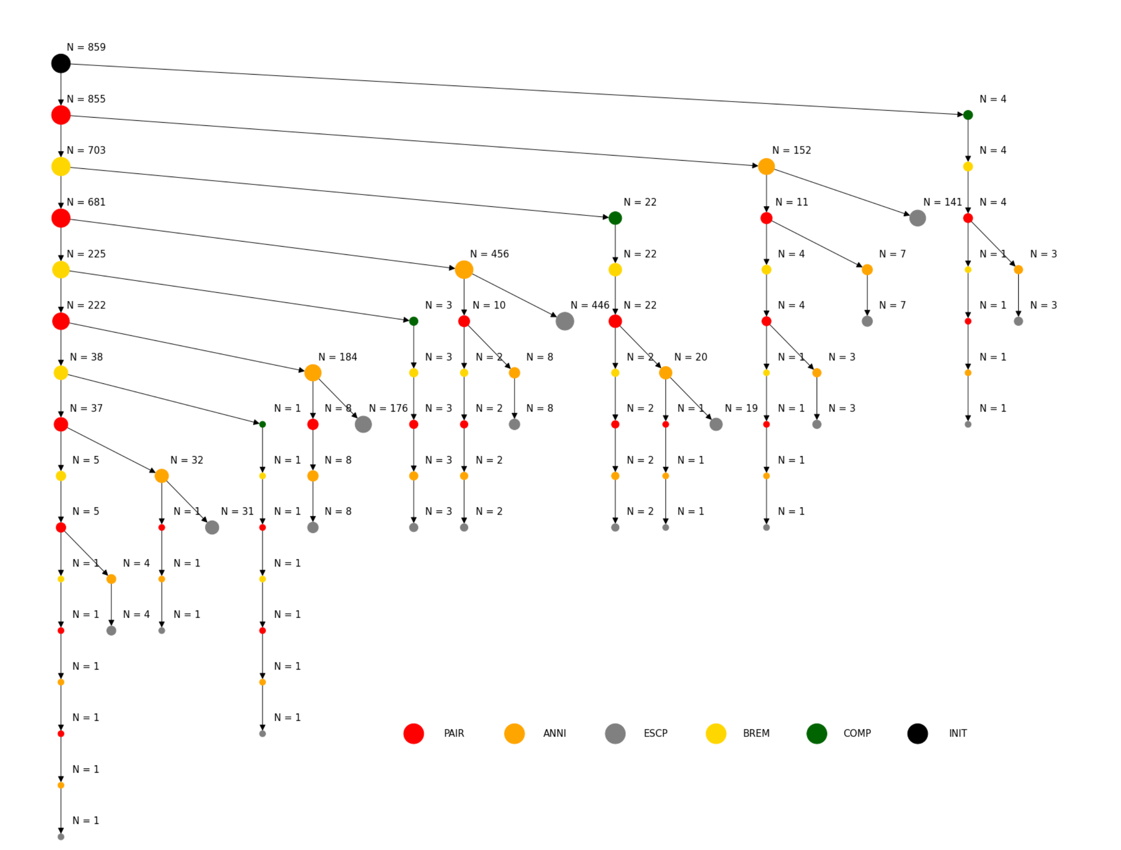
Cosima (MEGALib + GEANT4) simulations of showers by gamma-ray and particle irradiation of a companion

Model	a_{10}	$P_{\rm orb}$	$R_{\rm comp}$	ϵ (%)	Peak $\dot{n}_{511}$	$\dot{N}_{511}$
Units	–	10^4s	10^8cm	%	ph/cm^2/s	ph/s
He planet	8.8	1.1	6	2	$10^{-12.0}$	$10^{29.8}$
C planet	8.8	1.1	6	10	$10^{-11.4}$	$10^{30.5}$
Si planet	8.8	1.1	6	42	$10^{-10.8}$	$10^{31.2}$
S planet	8.8	1.1	6	54	$10^{-10.6}$	$10^{31.3}$
Fe planet	8.8	1.1	6	126	$10^{-10.3}$	$10^{31.6}$
He WD	9.7	1.2	200	2	$10^{-9.1}$	$10^{32.8}$
C WD	2.3	0.12	7	10	$10^{-10.1}$	$10^{31.8}$
0.01 $M_\odot$ BD	8.0	0.94	69	1	$10^{-10.0}$	$10^{31.8}$
0.03 $M_\odot$ MS	4.9	0.45	60	1	$10^{-9.7}$	$10^{32.2}$
0.1 $M_\odot$ MS	4.7	0.41	83	1	$10^{-9.5}$	$10^{32.4}$
0.3 $M_\odot$ MS	8.2	0.90	200	1	$10^{-9.2}$	$10^{32.8}$
0.9 $M_\odot$ MS	17	2.4	550	1	$10^{-8.9}$	$10^{33.0}$





Channel	L_{511}[erg/s]
Primary GeV γ-rays, $L_{511,i}$	$10^{25.5}L_{\rm MSP,34}$
*Primary e$^-$e$^+$Pairs, $L_{511,ii}$	$10^{23.4}L_{\rm ee,34}$
Mono. 1 GeV e$^+$e$^-$Pairs	$10^{22.5}L_{34}$
Mono. 10 GeV e$^+$e$^-$Pairs	$10^{23.2}L_{34}$
Mono. 100 GeV e$^+$e$^-$Pairs	$10^{23.9}L_{34}$
Mono. 1 TeV e$^+$e$^-$Pairs (proj.)	$10^{24.6}L_{34}$
Mono. 10 TeV e$^+$e$^-$Pairs (proj.), $L_{511,iii}$	$10^{25.3}L_{34}$
**Shock MeV γ-rays, $L_{511,v}$	$10^{25.7}L_{\rm Shock,32}$



Genealogy of backsplash 511 keV photons