

Study of maximum electron energy of sub-PeV PWN by MW Modelling

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India



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Dr. Luis Salvador Miranda (University of Hong Kong)
Prof. Soebur Razzaque (University of Johannesburg, South Africa)

Outline

Introduction

- Supernova and its pulsar wind nebula (PWN)
- Recent Observational Results

PWN Inside SNRs

- Restricted Expansion of the PWN/Collision with the SNR
 - Results using Modelling of UHE gamma-ray sources
-
- **Summary and Conclusion**

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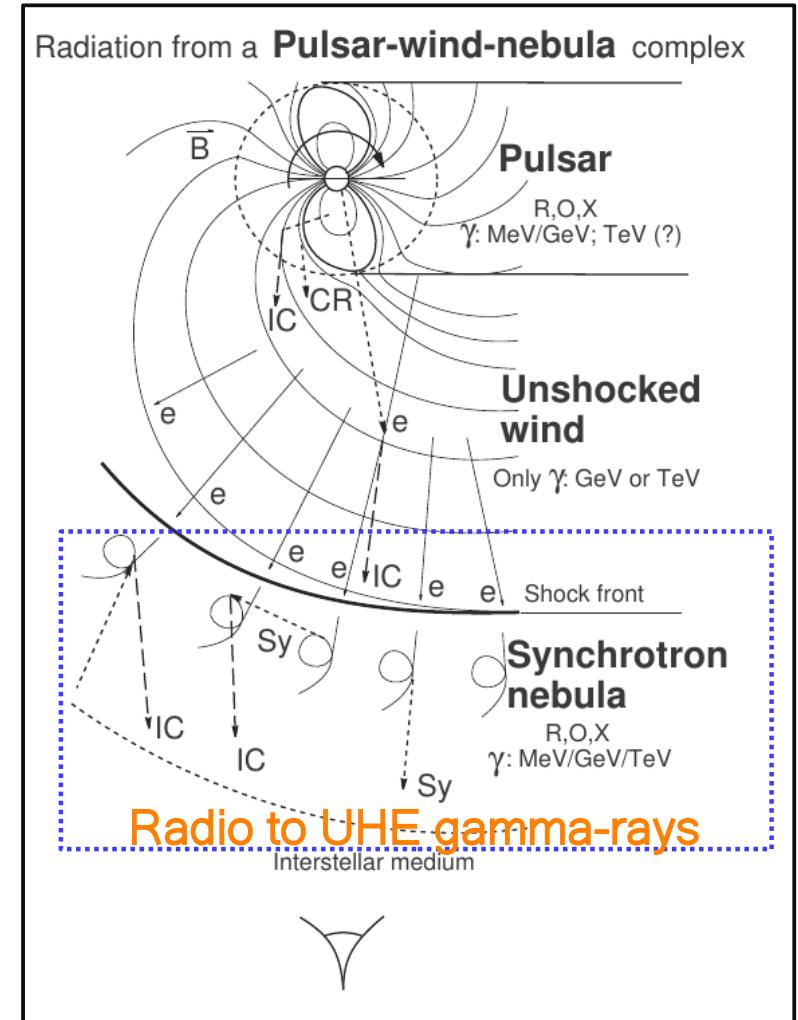
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Pulsar Wind Nebula

- PWNe are clouds of magnetised electron-positron plasma.
- Termination of ultrarelativistic wind by the outer nebula leads to particle acceleration.
- PWNe are associated with pulsars that are less than a few 100 kyr old.

pulsed Emission = [1-10%] L_0 (Mostly in radio)
pulsar wind ~ [90 %] L_0

Where L_0 is the initial luminosity of the pulsar.



Rotational Power: Pulsars

- Pulsars remain active for 10^5 - 10^6 years, but the outflow strength decreases with their age.

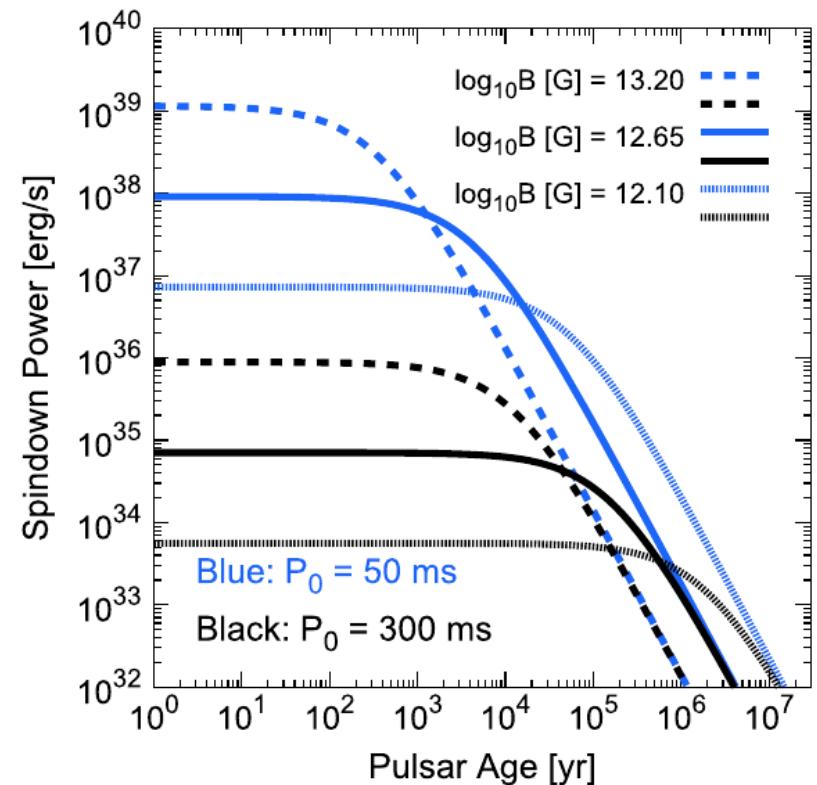
Power From Pulsar:

$$L(t) = L_0 \left(1 + \frac{t}{\tau_{\text{sd}}}\right)^{-2}; \quad L_0 = \frac{8\pi^4 B_s^2 R^6}{3c^3 P_0^4}$$

Age and spin-down timescales:

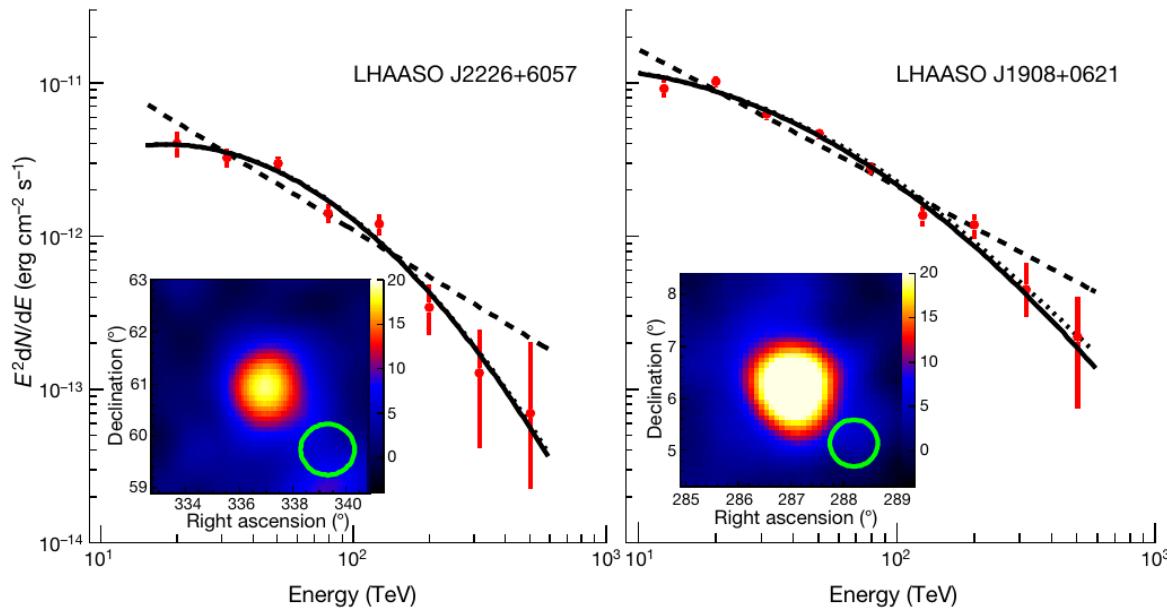
$$\frac{P}{2\dot{P}} = \frac{n-1}{2}(\tau_{\text{sd}} + t_{\text{age}})$$

Considering braking index $n=3$, a degeneracy exists in the age of the pulsar and its spin down timescale.



UHE Gamma-Ray Spectrum

- These UHE (> 100 TeV) gamma-ray spectrum are very useful to address the problem: ‘What are our galaxy’s most energetic and extreme particle accelerators?’



LHAASO	LHAASO
J2226+6057	J1908+0621
PSR J1907+0602	PSR J2229+6114
$L_0 \sim 5 \times 10^{37}$ erg/s	$L_0 \sim 2 \times 10^{38}$ erg/s

UHE gamma-ray Spectrum of the Galactic Sources

$$L_0[\text{Crab}] \sim 3 \times 10^{39} \text{ erg/s}$$

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Non-thermal Particles Inside PWN

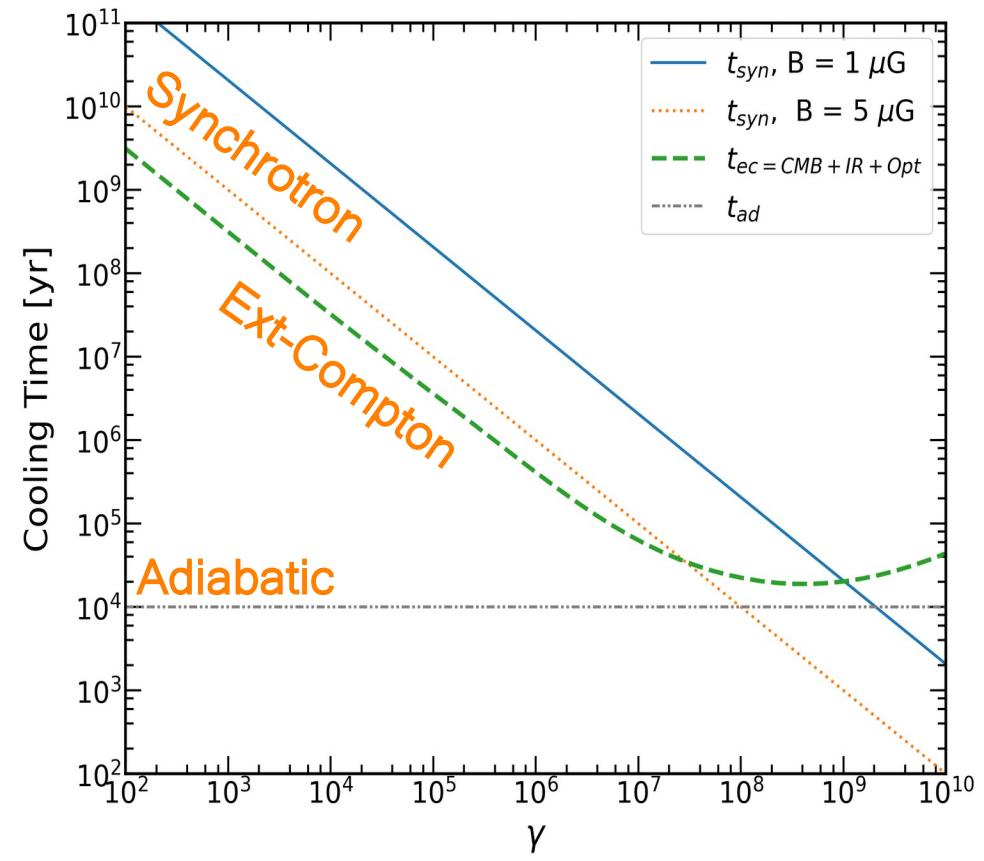
- We consider adiabatic and radiative losses to estimate particle population at a time t.

$$\frac{\partial N(\gamma, t)}{\partial t} + \frac{\partial}{\partial \gamma} [\dot{\gamma}(\gamma, t) N(\gamma, t)] = Q(\gamma, t),$$

Where, the source term is

$$Q(\gamma, t) = Q_{0,e} \begin{cases} \left(\frac{\gamma}{\gamma_b}\right)^{-p_1}; & \gamma_{\min} < \gamma \leq \gamma_b \\ \left(\frac{\gamma}{\gamma_b}\right)^{-p_2}, & \gamma_b < \gamma < \gamma_{\max} \end{cases}$$

$$Q_{0,e} = \frac{\eta_e L_0}{m_e c^2} \left(1 + \frac{t}{\tau_0}\right)^{-\frac{n+1}{n-1}} \left[\frac{\gamma_b^p \gamma_{\max}^{2-p}}{2-p} - \frac{\gamma_b^p \gamma_{\min}^{2-p}}{2-p} \right]^{-1}$$

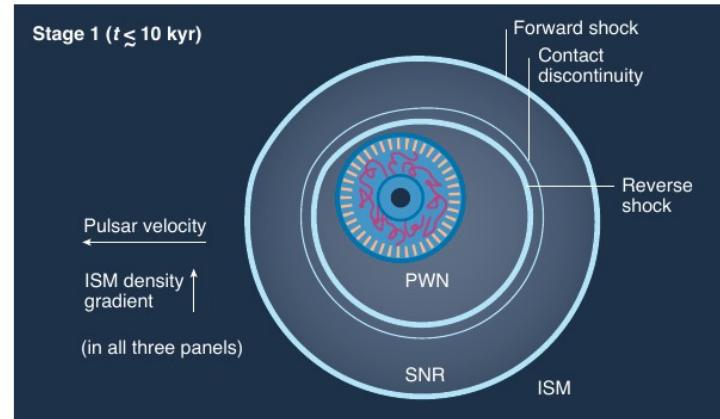


Cooling Timescales

Expansion of the Pulsar Wind

- The pulsar wind undergoes free expansion for the duration $\sim 1\text{-}10$ kyr.
- The collision time is determined using the condition:

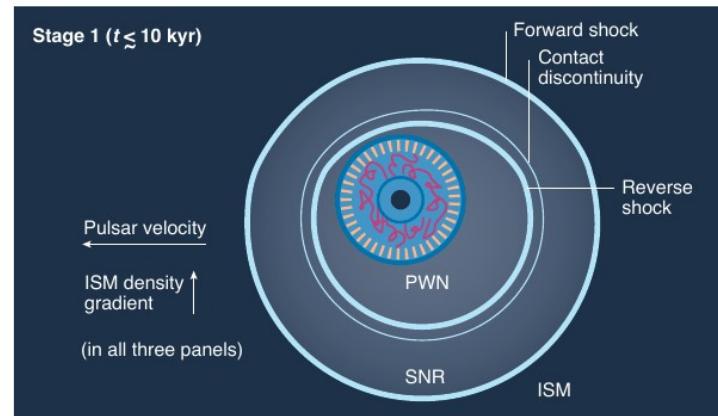
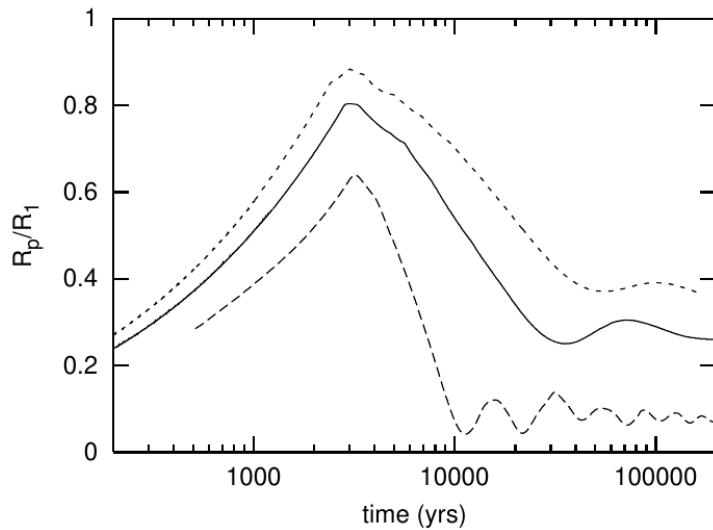
$$R_{\text{PWN}} = R_{\text{RS,SNR}}$$



Impact on PWN Radius

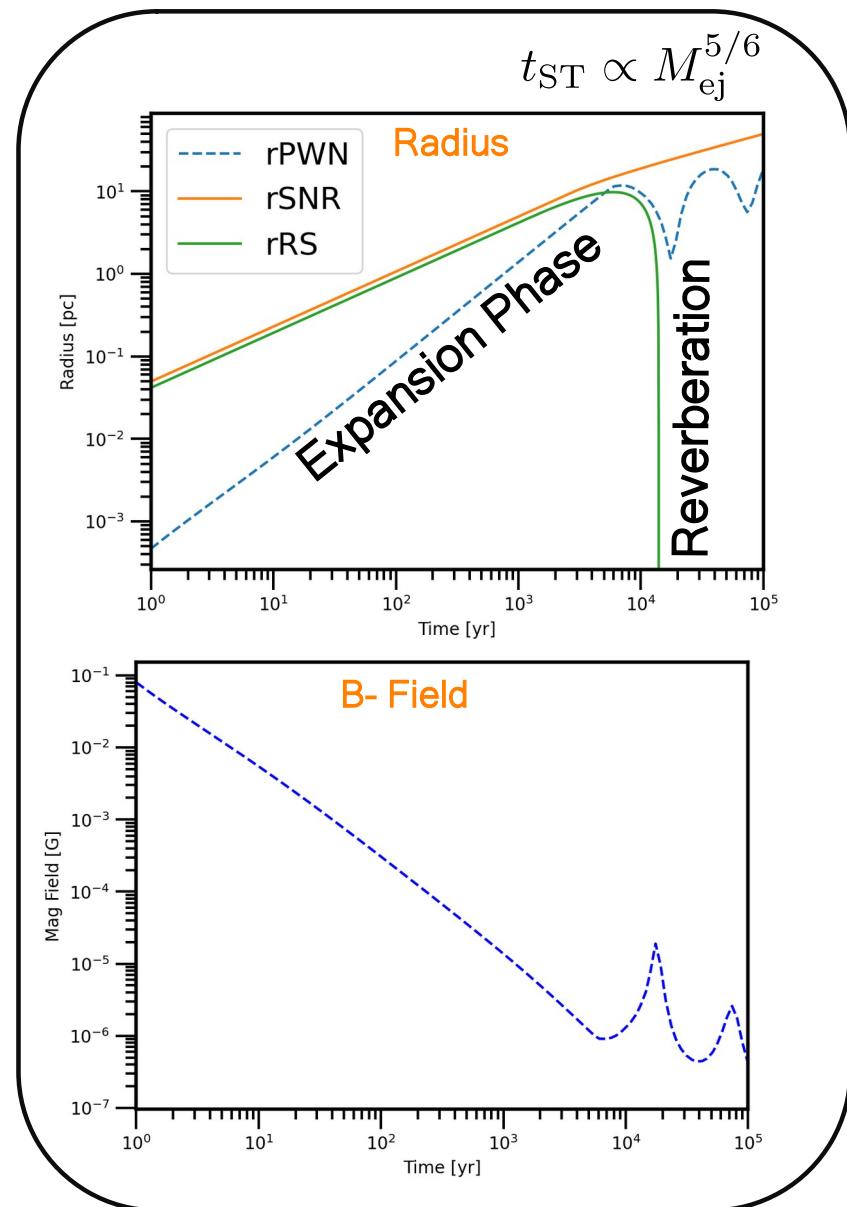
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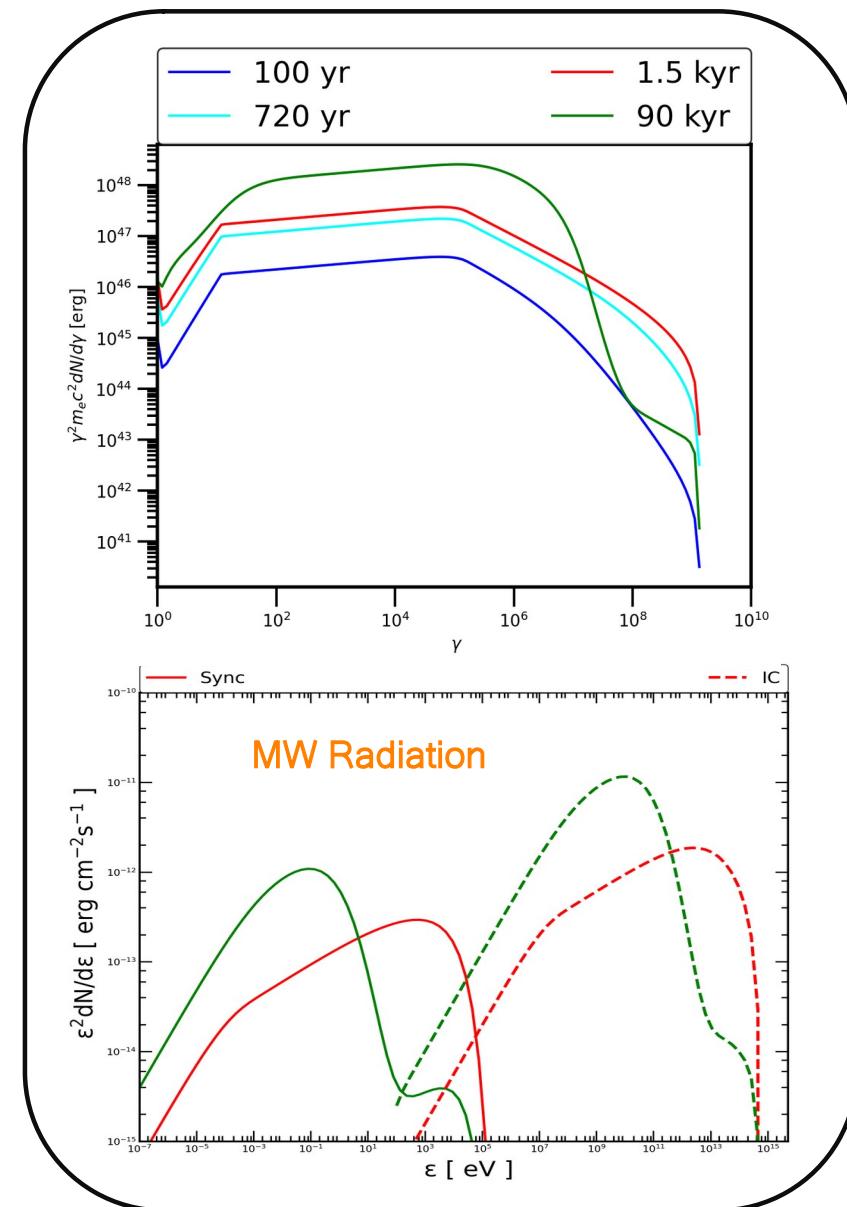
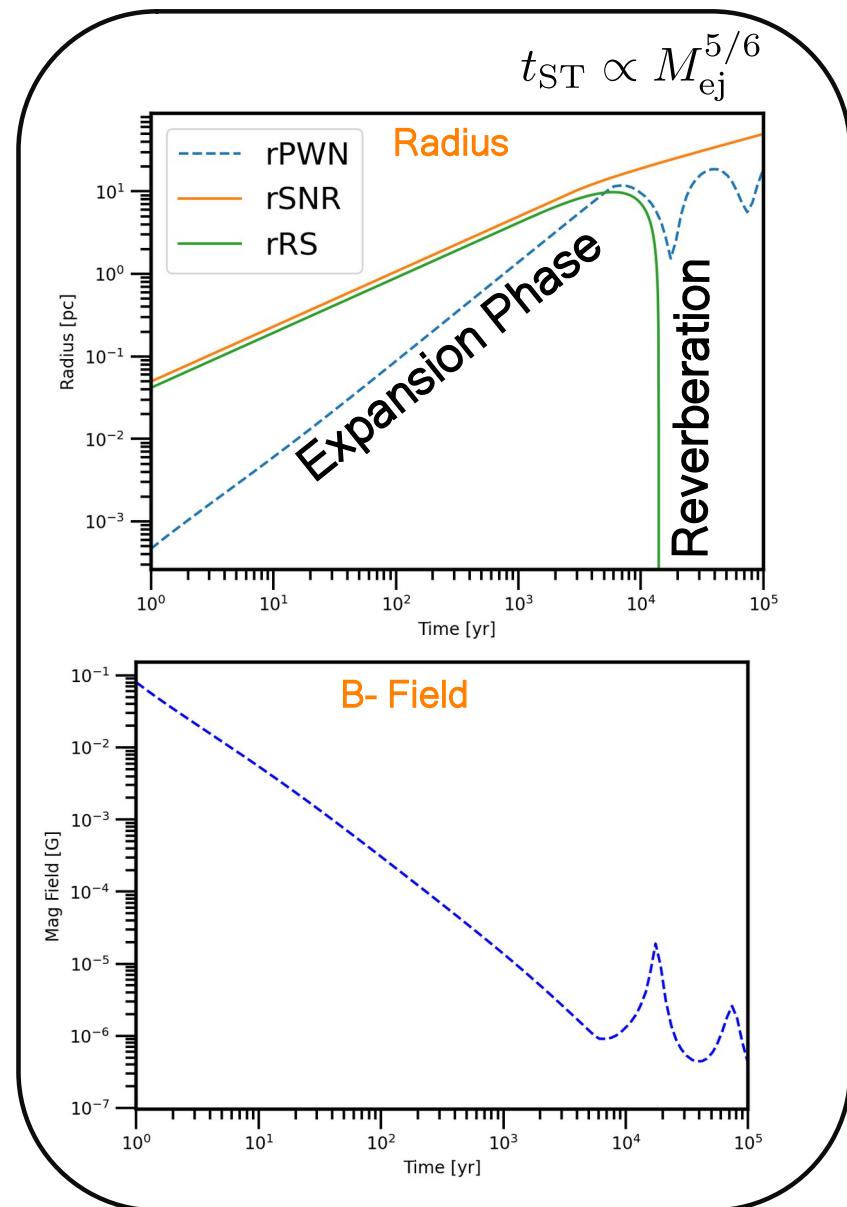


We will discuss here a one zone model and the dynamics of the PWN radius is due to the particle pressure inside PWN and its compression due to the SN ejecta pressure.

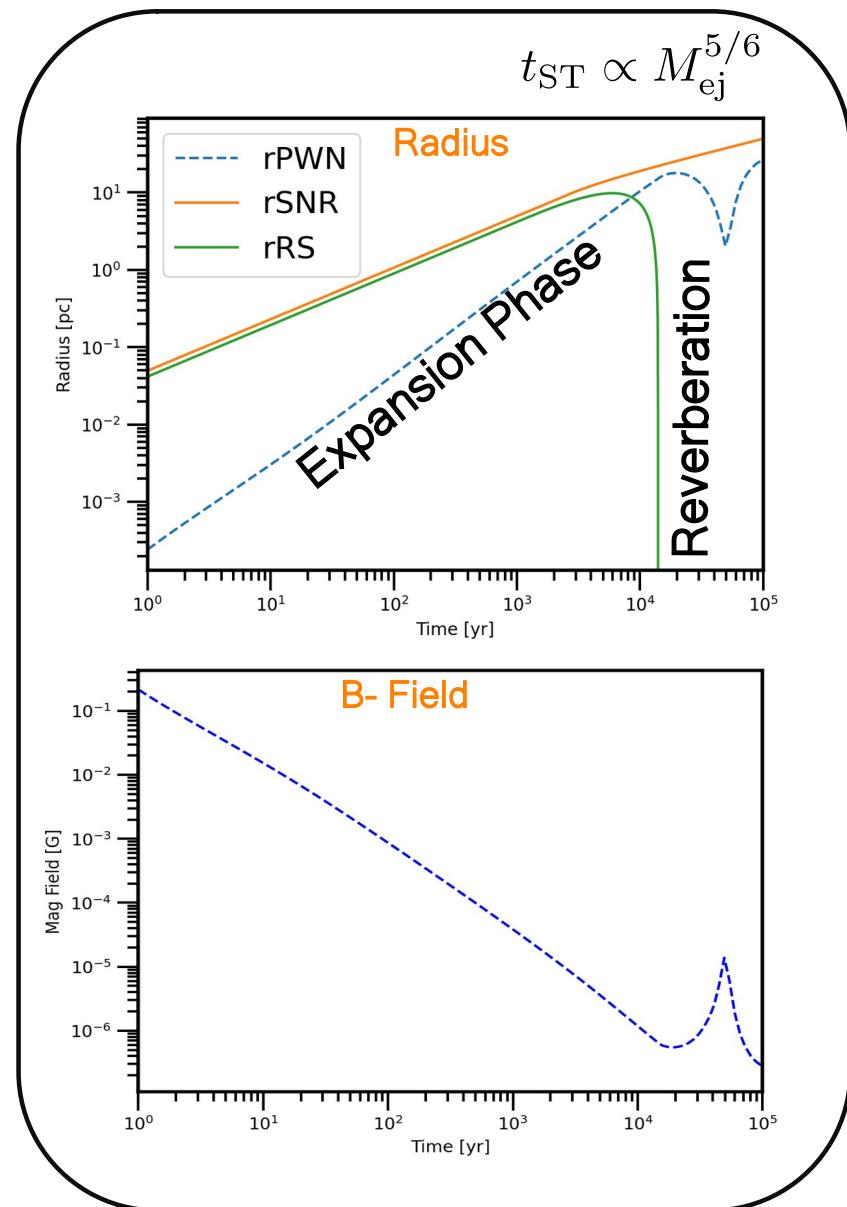
Ejecta Mass Impacts: 8 Ms



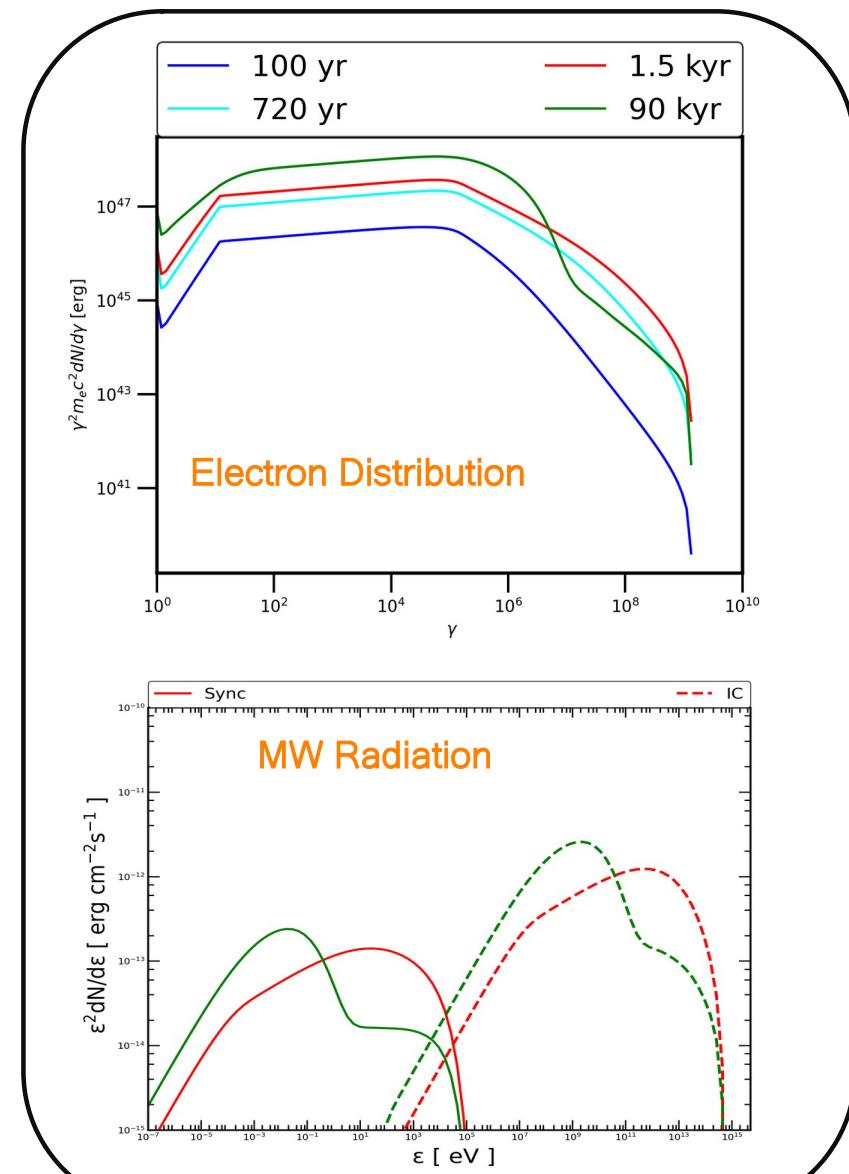
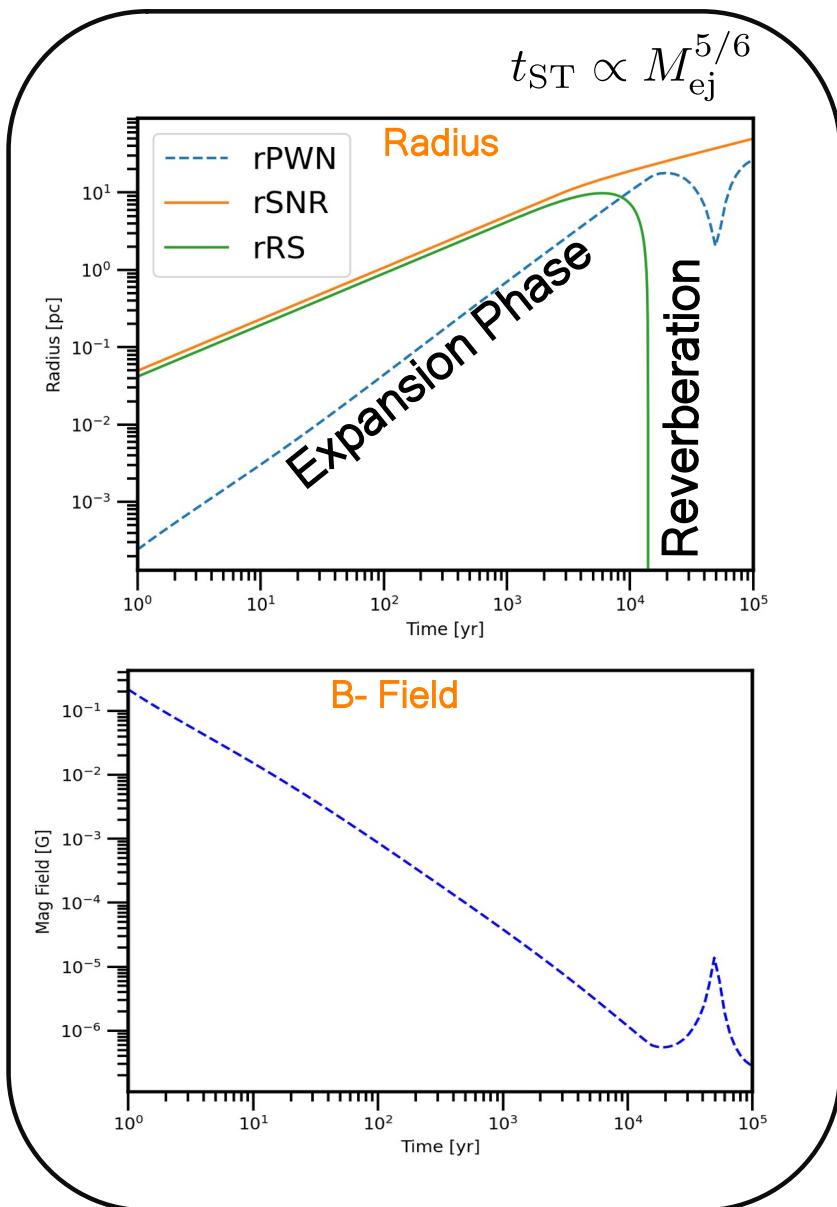
Ejecta Mass Impacts: 8 Ms



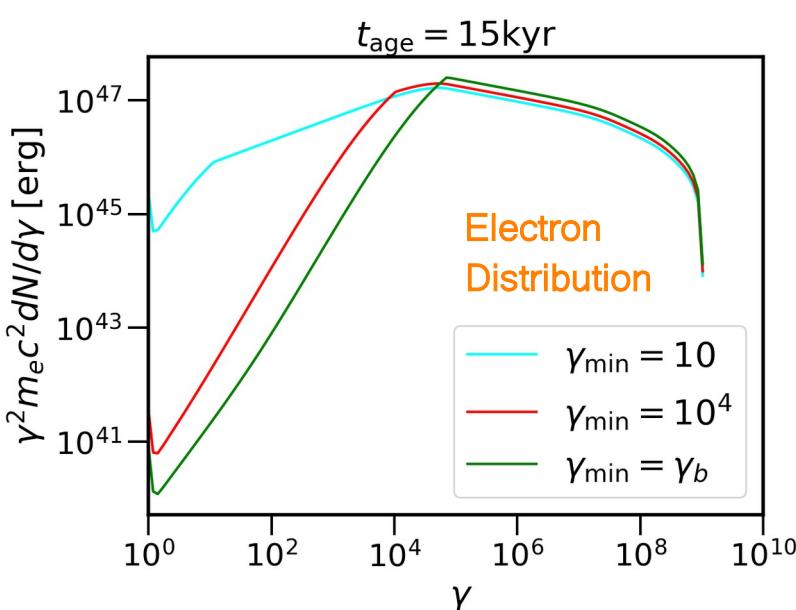
Ejecta Mass Impacts: 30 Ms



Ejecta Mass Impacts: 30 Ms

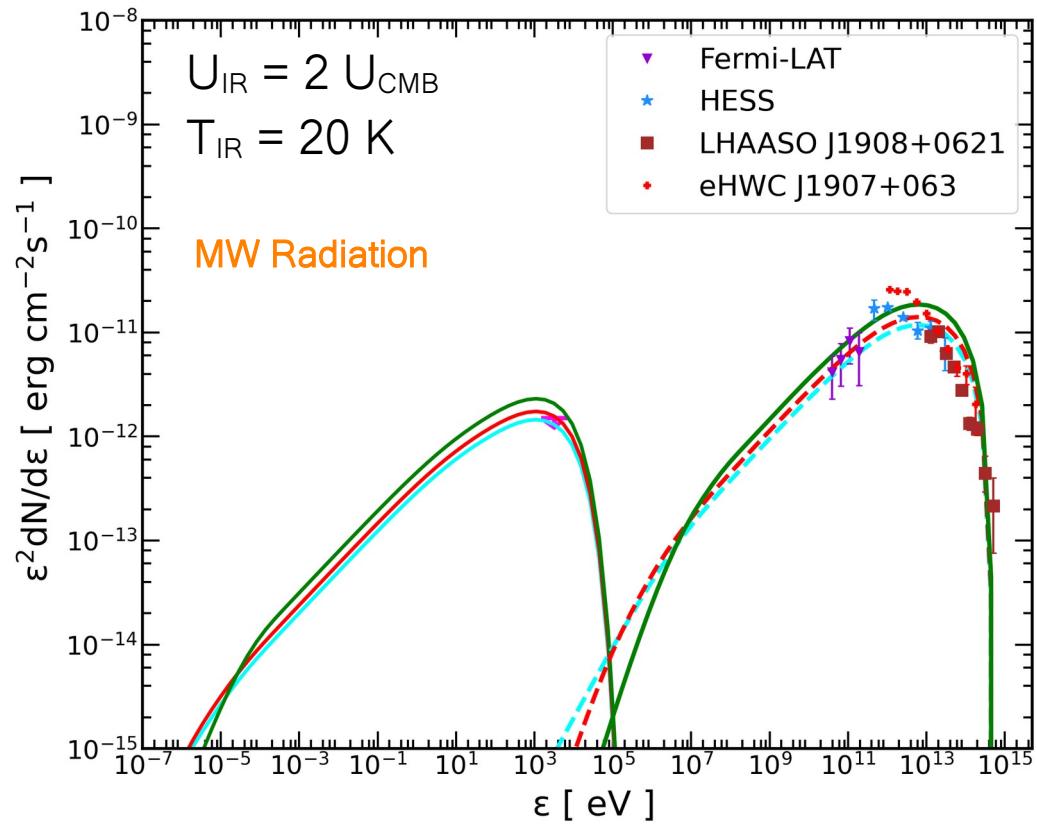


LHAASO J1908+0621: Expansion Phase



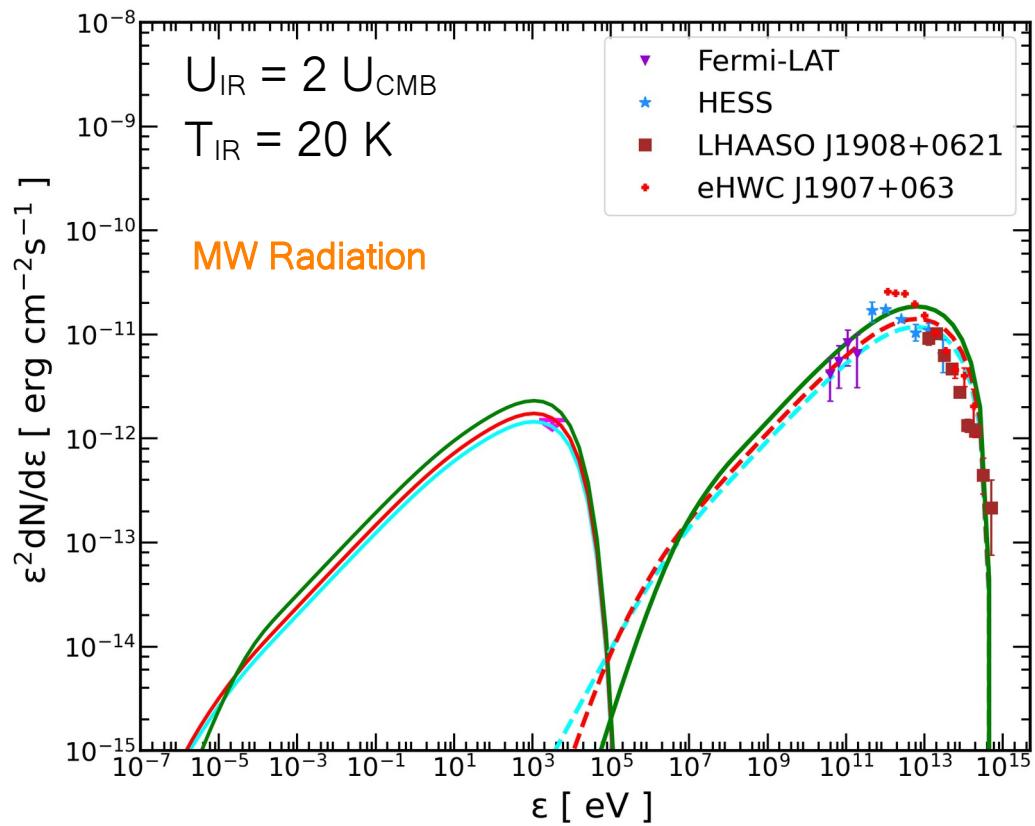
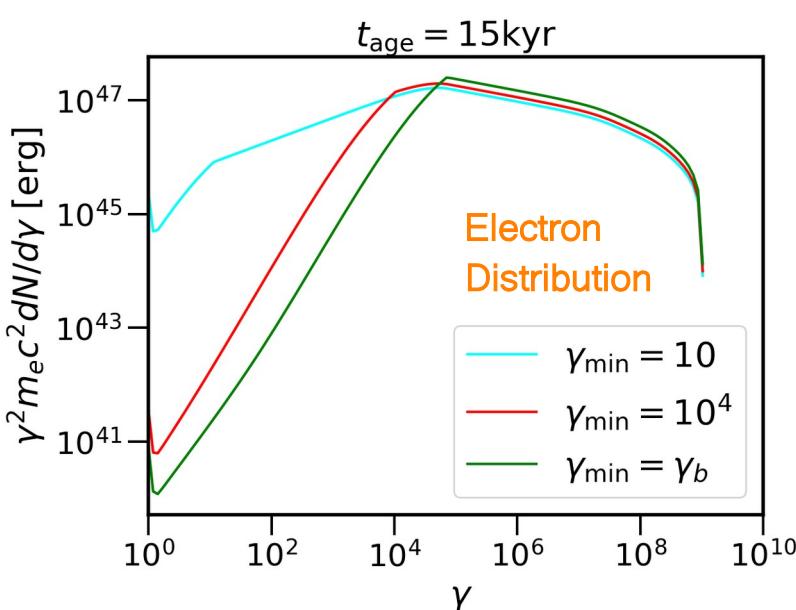
Max Energy of Electrons

$$E_{\max} = \gamma_{\max} m_e c^2 \simeq 1.1 \text{ PeV}$$



Parameters	B [G]	R _{pwn} [pc]	α ₁ , α ₂	γ _b , γ _{max}	p [ms], τ _{sd} [kyr], M _{ej} [Ms], n _{ISM} [pcc]
Values Used	10 ⁻⁶	7.5	1.6, 2.2	7×10^4 , 2.3×10^9	106.6, 4.4, 8, 0.1

LHAASO J1908+0621: Expansion Phase



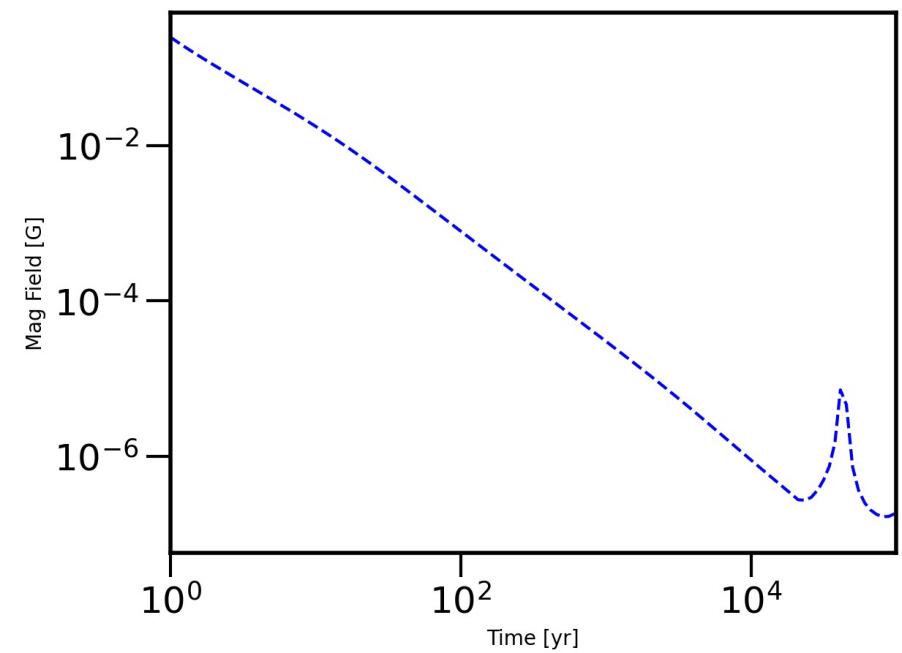
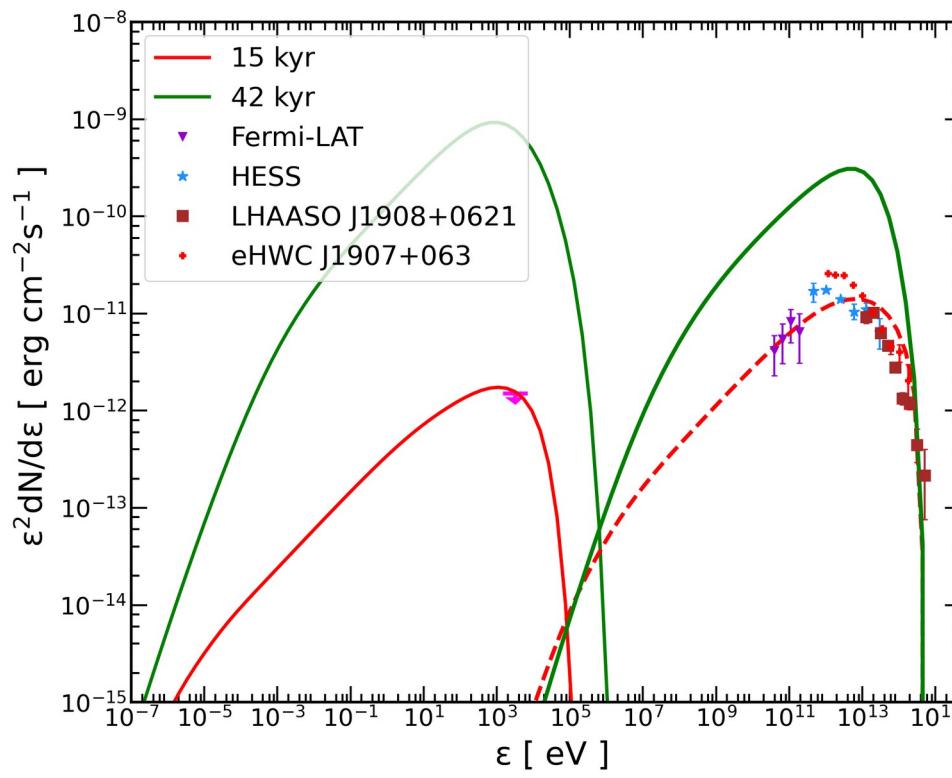
Pair production multiplicity:

$$\kappa \sim (L(t)/\gamma_b m_e c^2)(\gamma_b/\gamma_{\min})^{\alpha_1 - 1}/n_{\text{GJ}} \sim 10^5$$

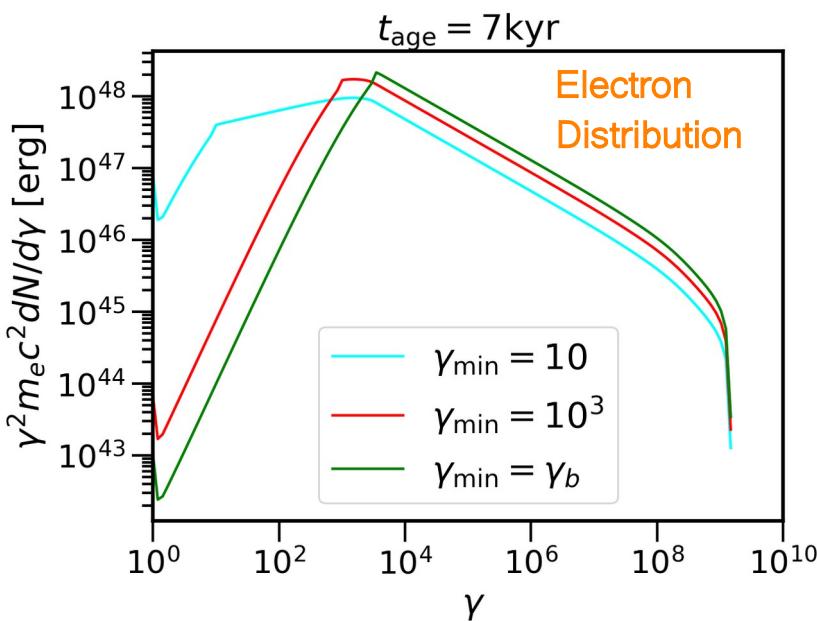
Parameters	B [G]	R _{pwn} [pc]	α_1, α_2	γ_b, γ_{\max}	L(t), p [ms], τ_{sd} [kyr], M _{ej} [Ms], n _{ISM} [pcc]
Values Used	10^{-6}	7.5	1.6, 2.2	$7 \times 10^4, 2.3 \times 10^9$	$3 \times 10^{36}, 106.6, 4.4, 8, 0.1$

LHAASO J1908+0621: Compression Phase

During the compression phase the magnetic field is enhanced at ~ 42 kyr for $M_{ej} = 8 M_s$ for our chosen model parameters .

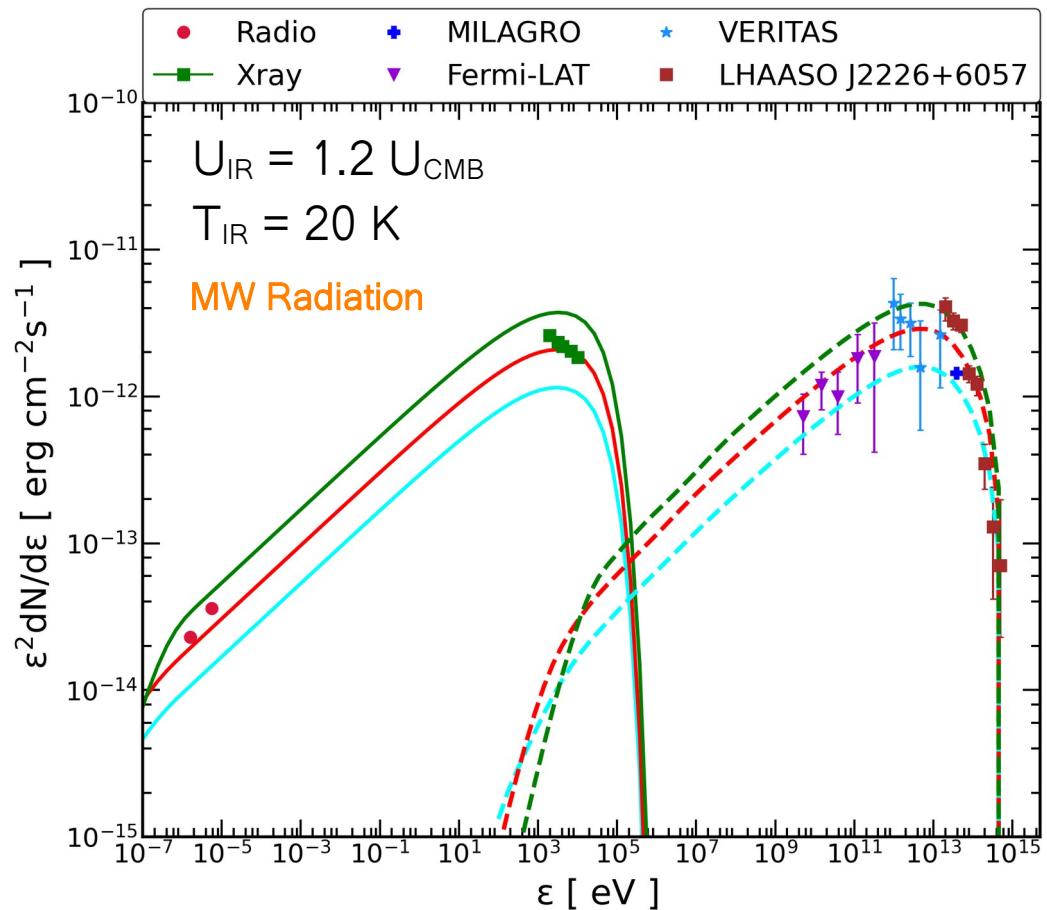


LHAASO J2226+6057: Expansion Phase



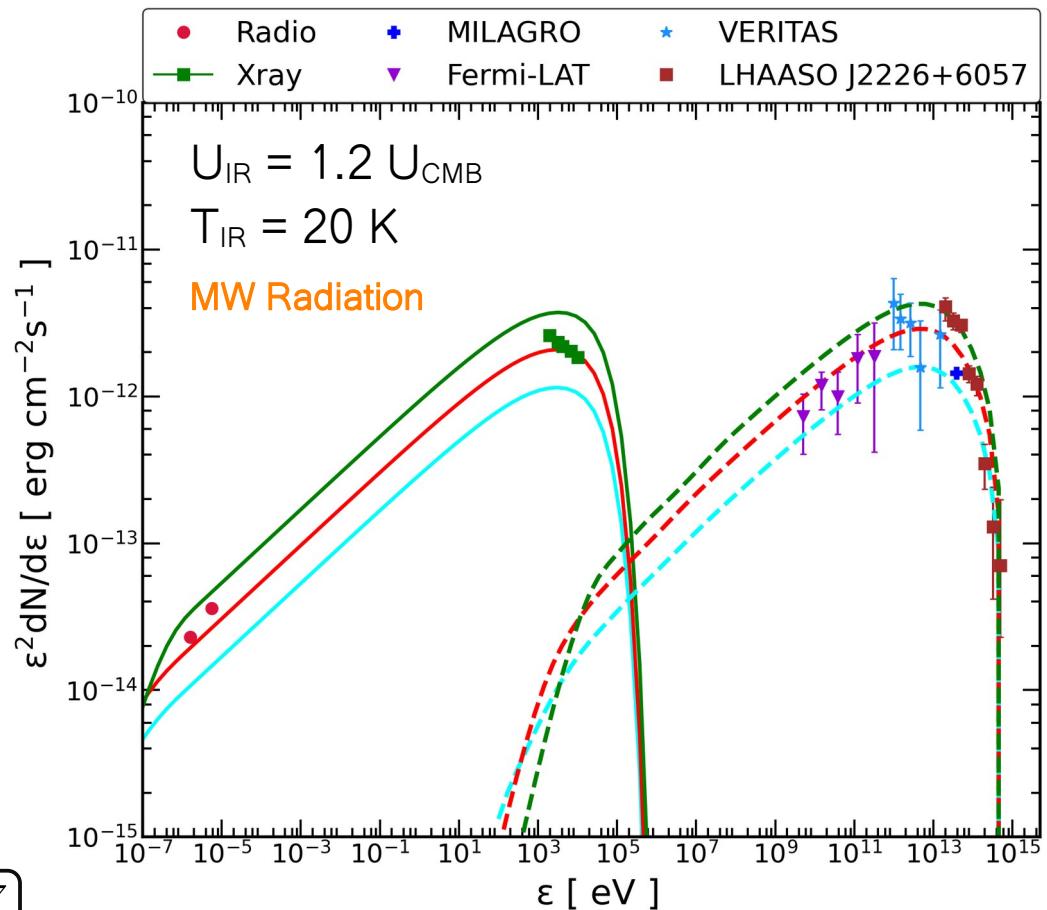
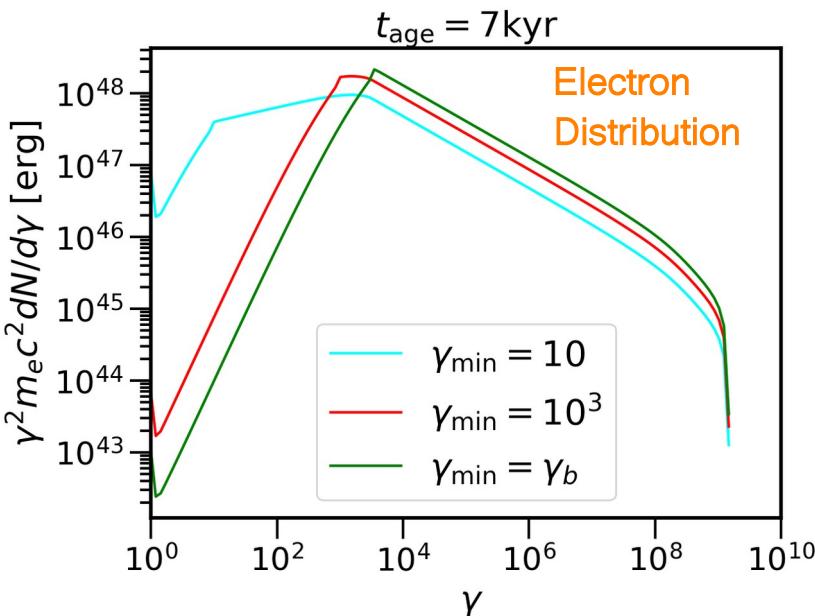
Max Energy of Electrons

$$E_{\max} = \gamma_{\max} m_e c^2 \simeq \text{PeV}$$



Parameters	B [G]	R _{pwn} [pc]	α_1, α_2	γ_b, γ_{\max}	$\rho [\text{ms}], \tau_{\text{sd}} [\text{kyr}], M_{\text{ej}} [\text{Ms}], n_{\text{ISM}} [\text{pcc}]$
Values Used	2.1×10^{-6}	11	1.8, 2.5	$3 \times 10^3, 2 \times 10^9$	51.6, 3.5, 8, 0.1

LHAASO J2226+6057: Expansion Phase



Pair production multiplicity:

$$\kappa \sim (L(t)/\gamma_b m_e c^2)(\gamma_b/\gamma_{\min})^{\alpha_1 - 1}/n_{\text{GJ}} \sim 10^7$$

Parameters	B [G]	R _{pwn} [pc]	α_1, α_2	γ_b, γ_{\max}	L(t), p [ms], τ_{sd} [kyr], M _{ej} [Ms], n _{ISM} [pcc]
Values Used	2.1×10^{-6}	11	1.8, 2.5	$3 \times 10^3, 2 \times 10^9$	$2.3 \times 10^{37}, 51.6, 3.5, 8, 0.1$

Maximum Energy of Electrons

- The maximum energy required to interpret the multi-wavelength emission of these objects is consistent with the polar cap (PC) potential injected maximum energy of the particles:

$$E_{\max, \text{PC}} \approx 6 \times 10^{12} \text{ eV} \left(\frac{B_p}{10^{12} \text{ G}} \right) \left(\frac{R_{\text{NS}}}{10 \text{ km}} \right)^3 \left(\frac{P}{1 \text{ s}} \right)^{-2}$$

- For LHAASO J1908+0621, maximum polar cap potential value is 1.6 PeV and for LHAASO J2226+6057 it is 4.5 PeV.

Summary and Conclusion

- PWN scenario can also explain the observed UHE emission from LHAASO J1908+0621 and LHAASO J2226+6057.
- The impacts of the reverse shock on the PWN radius affects the model parameters in the one zone model.
- The maximum energy of the electrons based on the MW modelling is in the PeV range. Further, we also estimate the upper limits of the minimum electron Lorentz factor using MW modelling and its useful to constrain the minimum value of the pair-production multiplicity.

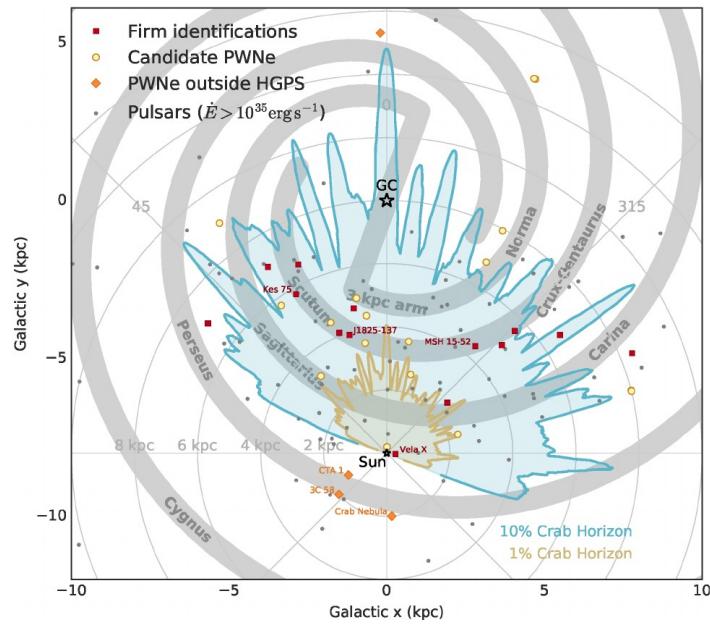
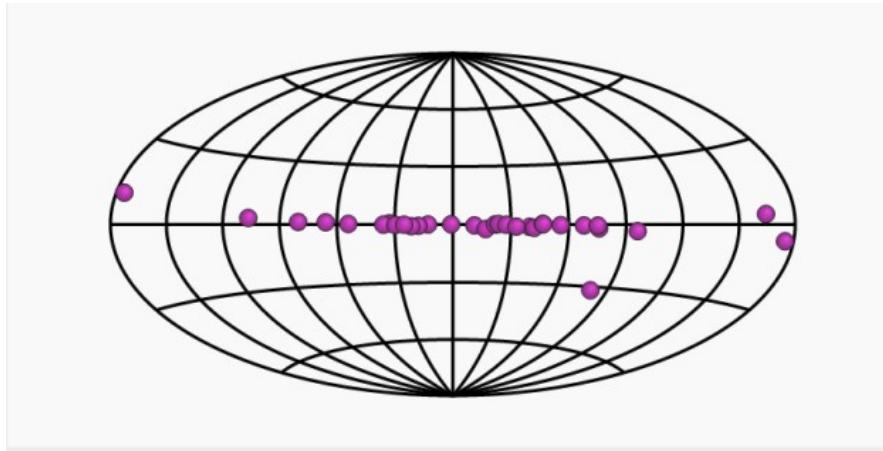
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Thank You for your Attention!!

Galactic VHE and UHE PWN Sources

Out of 31, 26 are VHE and remaining are VHE + UHE, PWN sources.



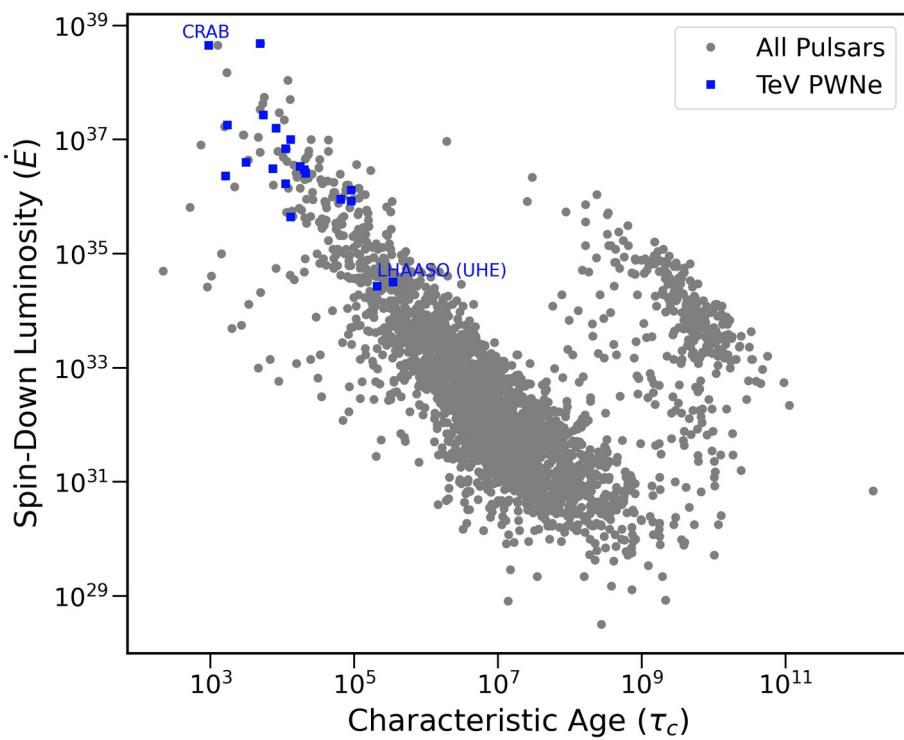
Name	RA	Dec	Type Tags	Distance	Catalog
Crab	05 34 30.9	+22 00 44.5	Gal,SNR,PWN,PeV...	2.0 kpc	Default Catalog
LHA 120-N 157B	05 37 44	-69 09 57	Gal,SNR,PWN	50.0 kpc	Default Catalog
LHAASO J0621+3755	06 21 52.8	+37 55 12	Gal,PWN,TeVHalo	$z=0$	Default Catalog
Geminga	06 32 28	+17 22 00	Gal,SNR,PWN,TeV...	0.25 kpc	Default Catalog
Vela X	08 35 00	-45 36 00	Gal,SNR,PWN,TeV...	0.29 kpc	Default Catalog
HESS J1018-589 B	10 16 31	-58 58 48	Gal,PWN	$z=0$	Default Catalog
HESS J1026-582	10 26 38.4	-58 12 00	Gal,SNR,PWN	2.3 kpc	Default Catalog
SNR G292.2-00.5	11 19 00	-61 24 00	Gal,SNR,PWN	8.4 kpc	Default Catalog
HESS J1303-631	13 02 48.0	-63 10 39	Gal,SNR,PWN	6.6 kpc	Default Catalog
Kookaburra (Rabbit)	14 18 04	-60 58 31	Gal,SNR,PWN	5.6 kpc	Default Catalog
Kookaburra (PWN)	14 20 09	-60 45 36	Gal,SNR,PWN	5.6 kpc	Default Catalog
HESS J1458-608	14 59 39	-60 46 49	Gal,SNR,PWN	0.0 kpc	Default Catalog
MSH 15-52	15 14 07	-59 09 27	Gal,SNR,PWN	5.2 kpc	Default Catalog
SNR G327.1-01.1	15 54 37	-55 05 27	Gal,SNR,PWN	9.0 kpc	Default Catalog
HESS J1616-508	16 16 24.0	-50 53 60	Gal,SNR,PWN	6.5 kpc	Default Catalog
HESS J1632-478	16 32 09.6	-47 49 12	Gal,SNR,PWN	0.0 kpc	Default Catalog
HESS J1640-465	16 40 38	-46 34 23	Gal,SNR,PWN	8.6 kpc	Default Catalog
HESS J1708-443	17 08 11	-44 20 00	Gal,SNR,PWN	2.3 kpc	Default Catalog
HESS J1718-385	17 18 07	-38 33 00	Gal,SNR,PWN	4.2 kpc	Default Catalog
SNR G000.9+00.1	17 47 23.2	-28 09 06	Gal,SNR,PWN	8.5 kpc	Default Catalog
HESS J1813-178	18 13 36.0	-17 50 24	Gal,SNR,PWN	4.7 kpc	Default Catalog
HESS J1825-137	18 25 49	-13 46 35	Gal,SNR,PWN,TeV...	3.9 kpc	Default Catalog
HESS J1833-105	18 33 35	-10 34 18	Gal,SNR,PWN	4.8 kpc	Default Catalog

Sources Listed: 31

UHE (100 TeV - 10 PeV)
VHE (100 GeV - 100 TeV)

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Out of 31, 26 are VHE and remaining are VHE + UHE, PWN sources.



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LHAASO J0621+3755	06 21 52.8	+37 55 12	Gal,PWN,TeVHalo	$z=0.0$	Default Catalog
Geminga	06 32 28	+17 22 00	Gal,SNR,PWN,TeV...	0.25 kpc	Default Catalog
Vela X	08 35 00	-45 36 00	Gal,SNR,PWN,TeV...	0.29 kpc	Default Catalog
HESS J1018-589 B	10 16 31	-58 58 48	Gal,PWN	$z=0.0$	Default Catalog
HESS J1026-582	10 26 38.4	-58 12 00	Gal,SNR,PWN	2.3 kpc	Default Catalog
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MSH 15-52	15 14 07	-59 09 27	Gal,SNR,PWN	5.2 kpc	Default Catalog
SNR G327.1-01.1	15 54 37	-55 05 27	Gal,SNR,PWN	9.0 kpc	Default Catalog
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HESS J1640-465	16 40 38	-46 34 23	Gal,SNR,PWN	8.6 kpc	Default Catalog
HESS J1708-443	17 08 11	-44 20 00	Gal,SNR,PWN	2.3 kpc	Default Catalog
HESS J1718-385	17 18 07	-38 33 00	Gal,SNR,PWN	4.2 kpc	Default Catalog
SNR G000.9+00.1	17 47 23.2	-28 09 06	Gal,SNR,PWN	8.5 kpc	Default Catalog
HESS J1813-178	18 13 36.0	-17 50 24	Gal,SNR,PWN	4.7 kpc	Default Catalog
HESS J1825-137	18 25 49	-13 46 35	Gal,SNR,PWN,TeV...	3.9 kpc	Default Catalog
HESS J1833-105	18 33 35	-10 34 18	Gal,SNR,PWN	4.8 kpc	Default Catalog

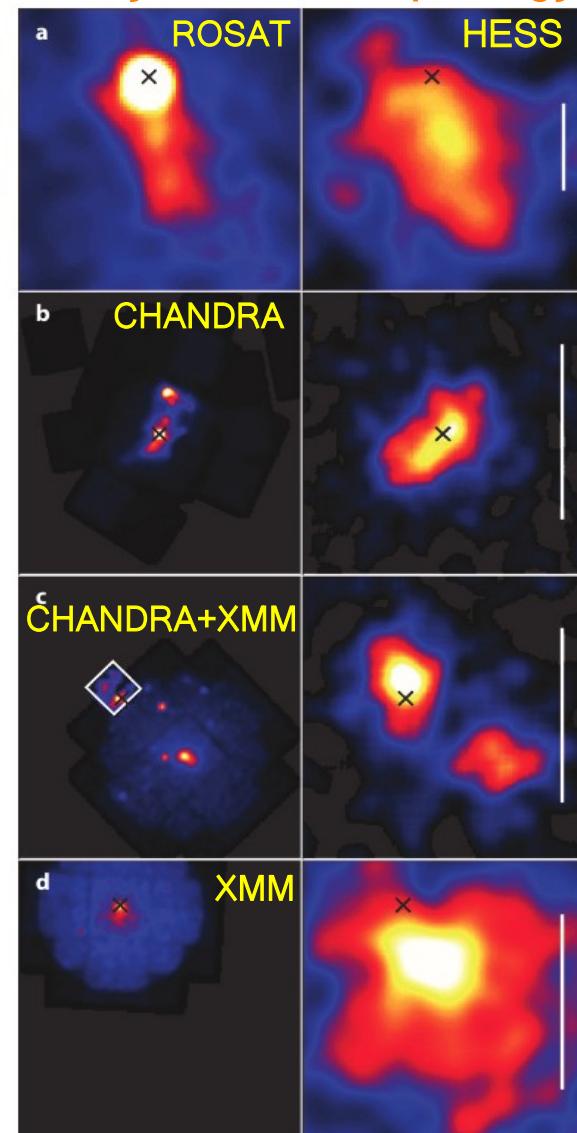
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UHE (100 TeV - 10 PeV)
VHE (100 GeV - 100 TeV)

X-Ray vs TeV Emission

- TeV emission in PWNe is more extended than x-ray emission. Hence TeV morphology provides a more accurate and complete picture of the electron population than the synchrotron photons.

X-Ray vs TeV morphology



Free Expansion of the PWN

$$R_{\text{PWN,ej}} \simeq 3.5 \text{ pc} \left(\frac{E_{\text{SN}}}{10^{51}} \right)^{3/10} \left(\frac{M_{\text{ej}}}{M_{\odot}} \right)^{-1/2} \left(\frac{L_0}{10^{38} \text{ erg/s}} \right)^{1/5} \left(\frac{t}{\text{kyr}} \right)^{6/5}$$

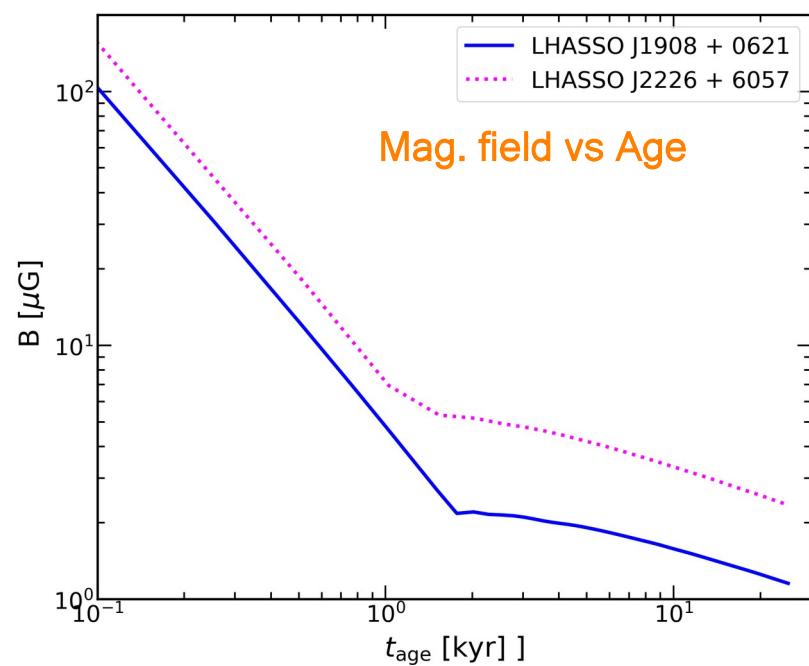
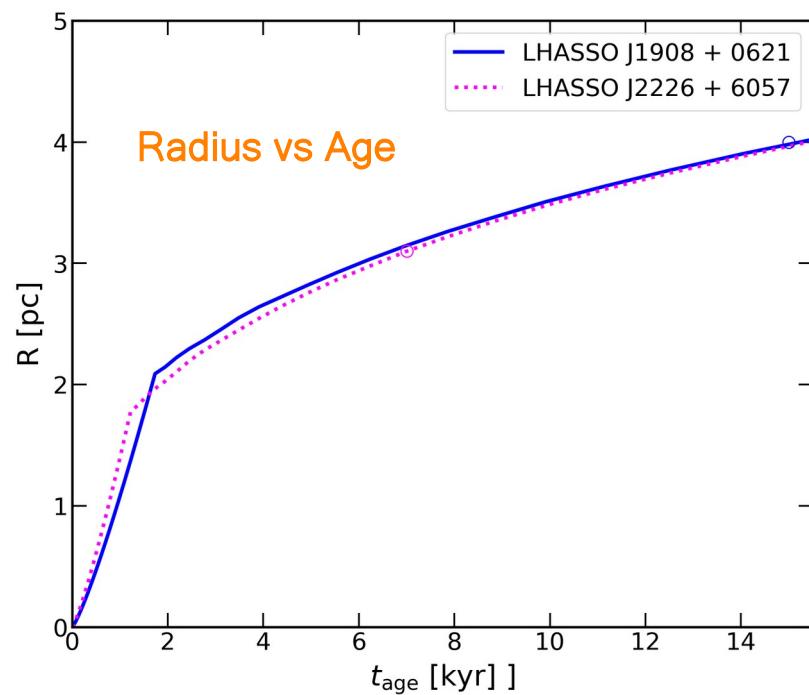
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$M_{\text{ej}} > \frac{4\pi}{3} R_{\text{SN}}^3 n_{\text{ISM}}$
Ejecta Phase

$$\frac{dR_{\text{PWN}}}{dt} = \frac{1}{5P_i} \left[\frac{L(t)}{2\pi R_{\text{PWN}}^2} - R_{\text{PWN}} \frac{dP_i}{dt} \right], \quad P_i \simeq 0.074 \left(\frac{E_{\text{SN}}}{R_{\text{SN}}^3} \right)$$

→

$M_{\text{ej}} < \frac{4\pi}{3} R_{\text{SN}}^3 n_{\text{ISM}}$
Sedov-Taylor Phase



LHAASO UHE Gamma-Ray Sources

LHAASO Source	Possible Origin	Type
LHAASO J0534+2202	PSR J0534+2200	PSR
LHAASO J1825-1326	PSR J1826-1334	PSR
	PSR J1826-1256	PSR
LHAASO J1839-0545	PSR J1837-0604	PSR
	PSR J1838-0537	PSR
LHAASO J1843-0338	SNR G28.6-0.1	SNR
LHAASO J1849-0003	PSR J1849-0001	PSR
	W43	YMC
LHAASO J1908+0621	SNR G40.5-0.5	SNR
	PSR 1907+0602	PSR
	PSR 1907+0631	PSR
LHAASO J1929+1745	PSR J1928+1746	PSR
	PSR J1930+1852	PSR
	SNR G54.1+0.3	SNR
LHAASO J1956+2845	PSR J1958+2846	PSR
	SNR G66.0-0.0	SNR
LHAASO J2018+3651	PSR J2021+3651	PSR
	Sh 2-104	H II/YMC
LHAASO J2032+4102	Cygnus OB2	YMC
	PSR 2032+4127	PSR
	SNR G79.8+1.2	SNR candidate
LHAASO J2108+5157	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR
	PSR J2229+6114	PSR

Large High Altitude Air Shower Observatory (LHAASO)



More than 6,300 detectors, an array of 12 Cherenkov telescopes and three water ponds containing 3,000 detecting units. At an altitude of 4,410 metres located in Sichuan, China.

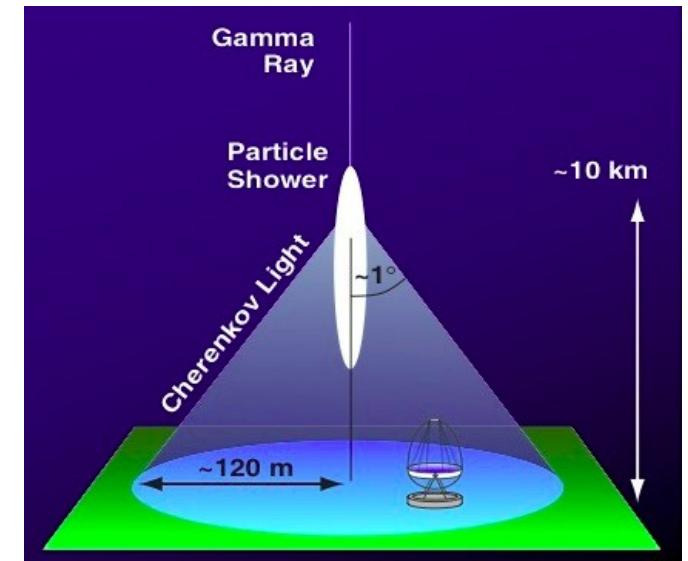
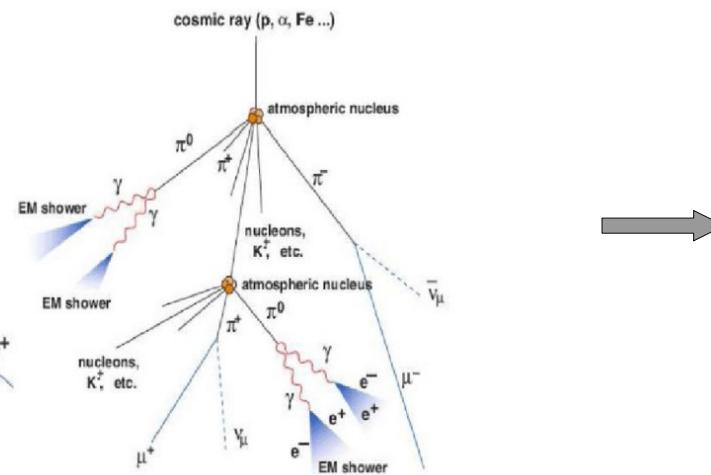
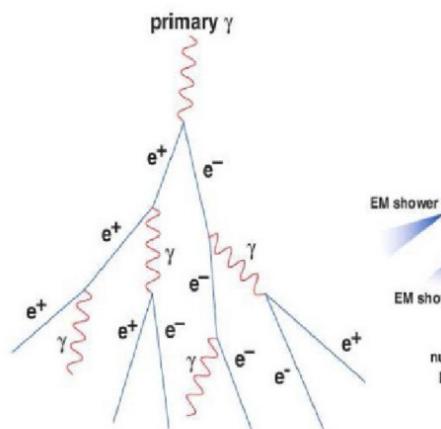
LHAASO UHE Gamma-Ray Sources

LHAASO Source	Possible Origin	Type
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LHAASO J1825-1326	PSR J1826-1334	PSR
	PSR J1826-1256	PSR
LHAASO J1839-0545	PSR J1837-0604	PSR
	PSR J1838-0537	PSR
LHAASO J1843-0338	SNR G28.6-0.1	SNR
LHAASO J1849-0003	PSR J1849-0001	PSR
	W43	YMC
LHAASO J1908+0621	SNR G40.5-0.5	SNR
	PSR 1907+0602	PSR
	PSR 1907+0631	PSR
LHAASO J1929+1745	PSR J1928+1746	PSR
	PSR J1930+1852	PSR
	SNR G54.1+0.3	SNR
LHAASO J1956+2845	PSR J1958+2846	PSR
	SNR G66.0-0.0	SNR
LHAASO J2018+3651	PSR J2021+3651	PSR
	Sh 2-104	H II/YMC
LHAASO J2032+4102	Cygnus OB2	YMC
	PSR 2032+4127	PSR
	SNR G79.8+1.2	SNR candidate
LHAASO J2108+5157	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR
	PSR J2229+6114	PSR

For LHAASO J 1908+062 there are two associated pulsars. However, the current spin-down luminosity of PSR 1907+0602 is 5 times brighter than PSR 1907+0631.

Gamma-Ray and CR Detection

Cascade Emission



- Nitrogen molecule emits fluorescence light!!
- Relativistic particles emit Cherenkov light which can be detected.

VHE gamma-rays

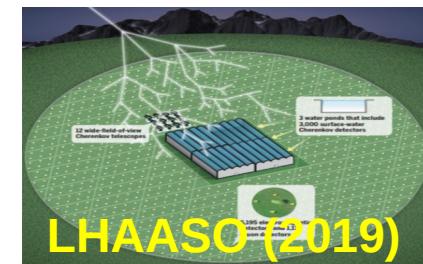


HESS (2003)

UHE gamma-rays

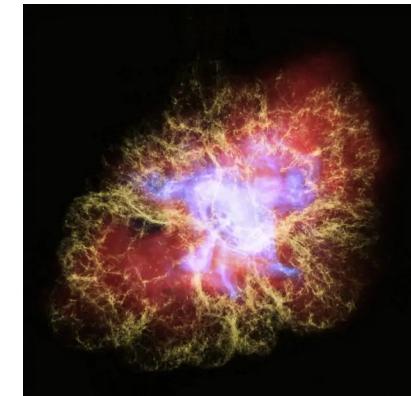
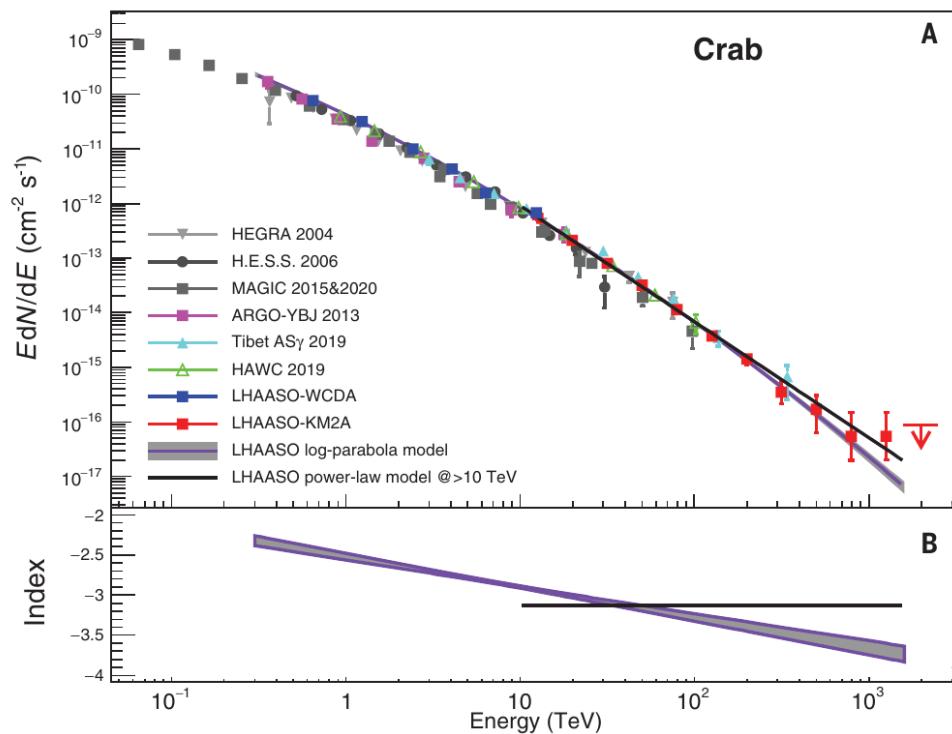


HAWC (2015)



LHAASO (2019)

First Confirmed Leptonic Pevatron



Max photon Energy
 (1.12 ± 0.09) PeV

The production of UHE photons requires electrons of energy ~ 2.3 PeV.