Gamma-ray emission from Pulsar Wind Nebulae

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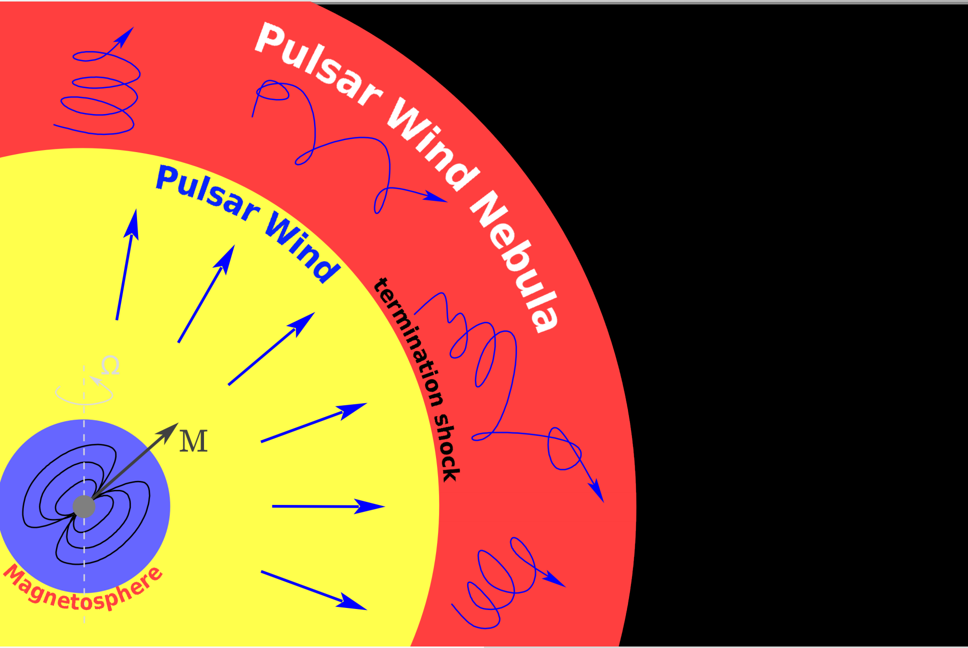
“Multimessenger High Energy Astrophysics in the Era of LHAASO” (July 7/28/2020)

Outline

- ✔ General introduction to Pulsar Wind Nebulae
- ✔ Pulsar Wind Nebulae as gamma-ray emitters
- ✔ What LHAASO can constrain in Crab Nebula?

Impact of the Pulsar Wind: PWN



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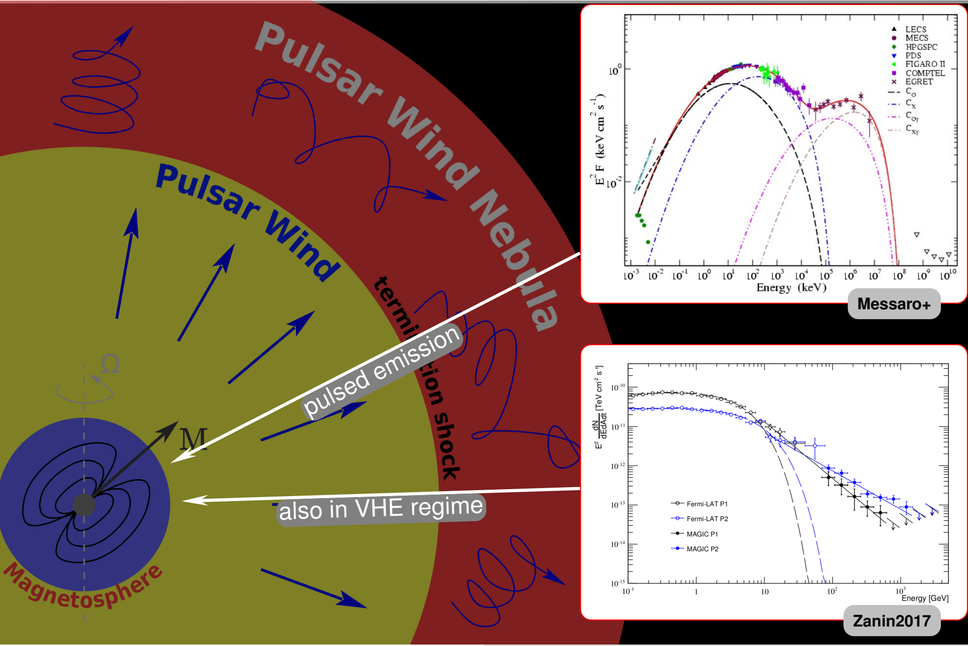

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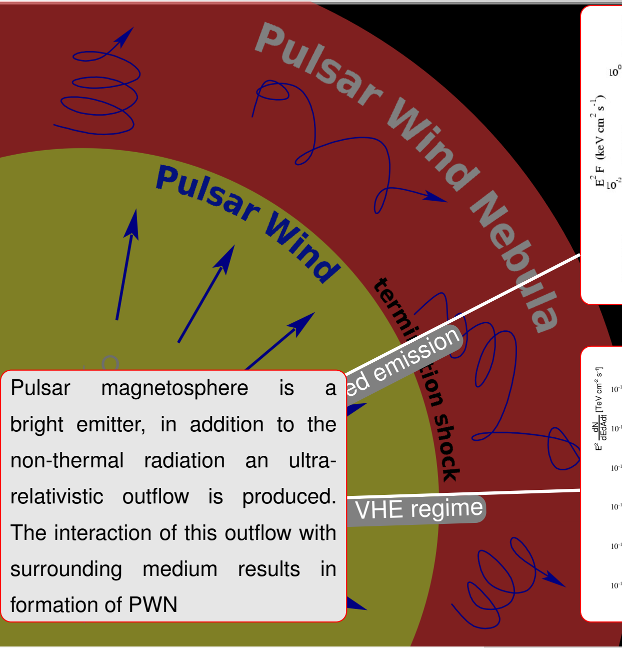
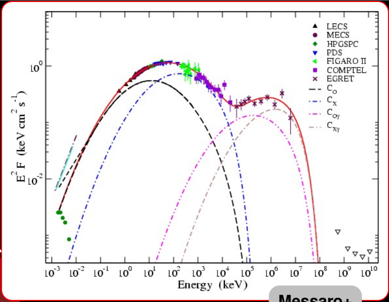
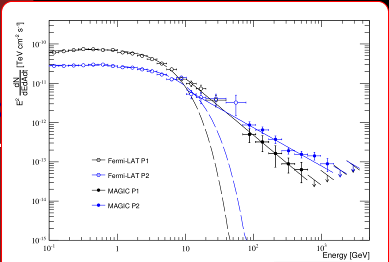


Pulsar magnetosphere is a bright emitter, in addition to the non-thermal radiation an ultra-relativistic outflow is produced. The interaction of this outflow with surrounding medium results in formation of PWN

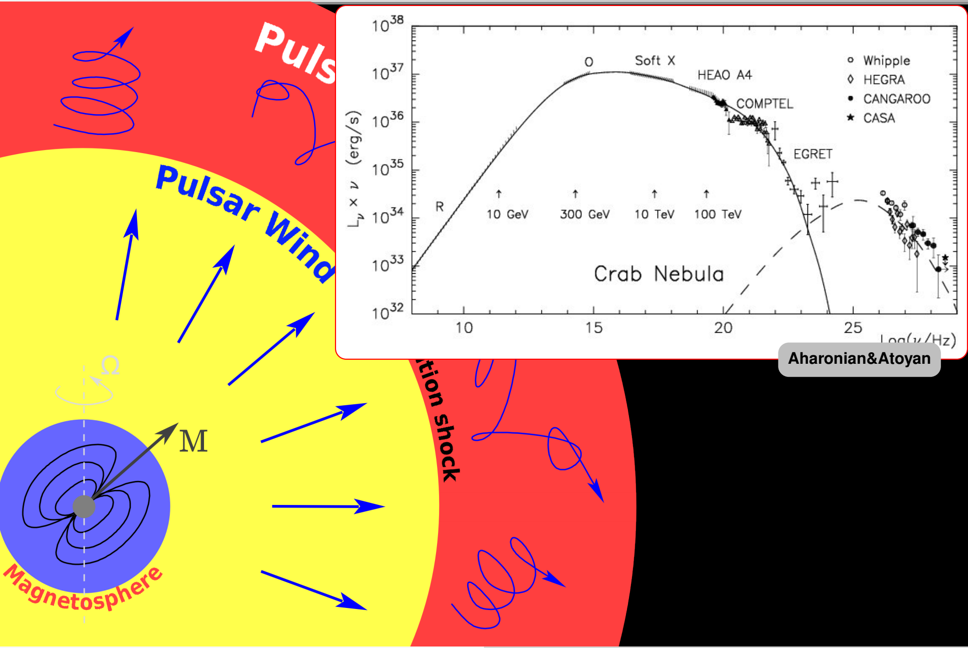


Messaro+



Zanin2017

Impact of the Pulsar Wind: PWN



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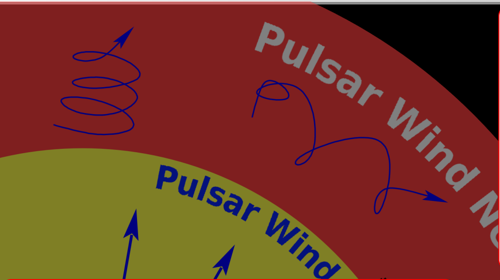
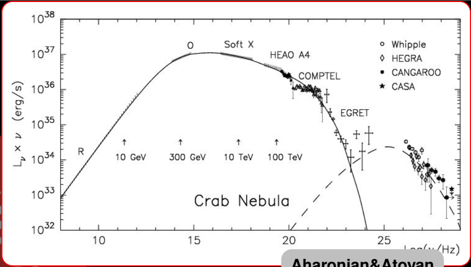
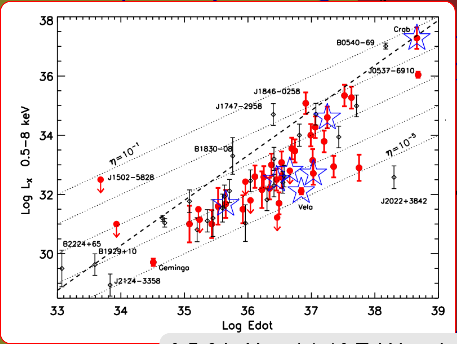
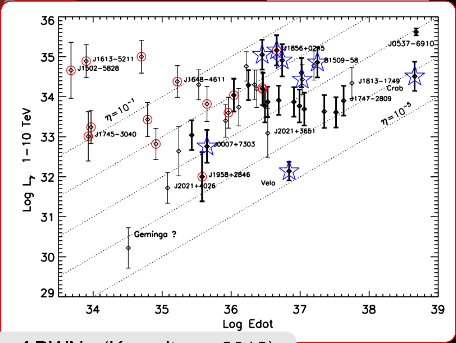




Aharonian&Atoyan





0.5-8 keV and 1-10 TeV Luminosities of PWNe (Kargaltsev+2013)

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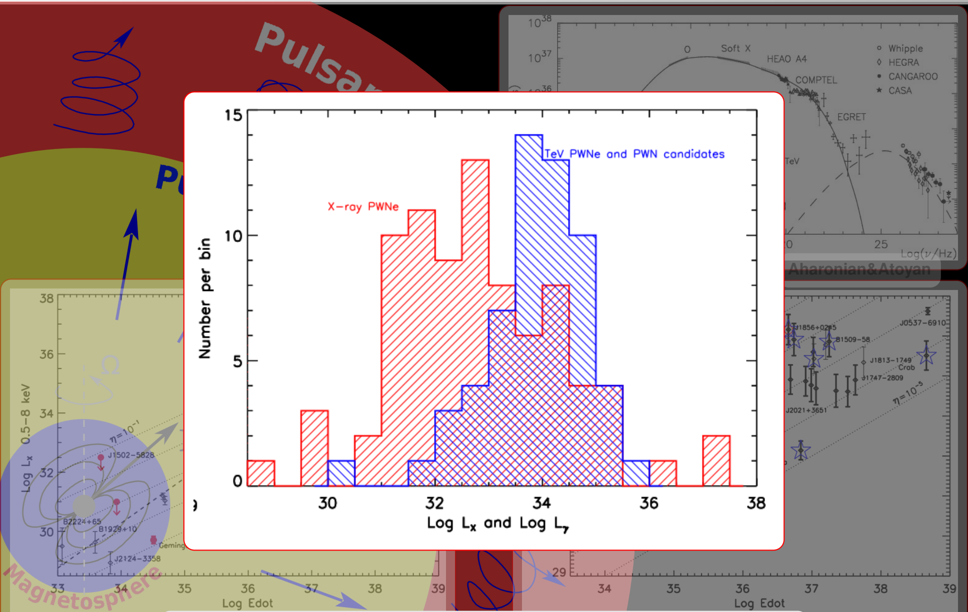


0.5-8 keV and 1-10 TeV Luminosities of PWNe (Kargaltsev+2013)

Key aspects of PWNe

- ✔ Pulsar spindown losses:

$$L_{\rm SD} \sim 10^{30} - 10^{38}\,\rm erg\,s^{-1}$$

- ✔ Lifetime:

$$\tau \sim \frac{2\pi^2 I}{P^2 L_{\rm SD}} \sim 10^6 \left(\frac{P}{100\,\rm ms}\right)^{-2} \left(\frac{L_{\rm SD}}{10^{35}\,\rm erg\,s^{-1}}\right)^{-1}\,\rm yr$$

- ✔ Size:

$$R_{\rm SNR} \sim \left(\frac{E_{\rm EJ} t^2}{\rho}\right)^{1/5} \rm (Sedov's\ solution)$$

$$\sim 10 \left(\frac{E_{\rm EJ}}{10^{51}\,\rm erg\,s^{-1}}\right)^{1/5} \left(\frac{t}{10\,\rm kyr}\right)^{2/5} \left(\frac{\rho}{m_p\,\rm cm^{-3}}\right)^{-1/5}\,\rm pc$$

$$R_{\rm SNR} \gtrsim R_{\rm PWN} \sim \rm pc$$

Physical conditions in PWNe

- ✔ Pressure ($PV \sim L_{\rm SD} t/2$):

$$P \sim \frac{L_{\rm SD} t}{8\pi/3 R_{\rm PWN}^3}$$

$$\sim 80 \left(\frac{L_{\rm SD}}{10^{35}\,{\rm erg\,s^{-1}}}\right)\left(\frac{R_{\rm PWN}}{1\,{\rm pc}}\right)^{-3}\left(\frac{t}{10\,{\rm kyr}}\right)\,{\rm eV\,cm^{-3}}$$

- ✔ Magnetic field:

$$B_{\rm eq} \sim \sqrt{4\pi P}$$

$$\sim 40 \left(\frac{L_{\rm SD}}{10^{35}\,{\rm erg\,s^{-1}}}\right)^{1/2}\left(\frac{R_{\rm PWN}}{1\,{\rm pc}}\right)^{-3/2}\left(\frac{t}{10\,{\rm kyr}}\right)^{1/2}\,\mu{\rm G}$$

- ✔ Photon fields: CMBR, FIR, NIR, and synchrotron photons (SSC)

$$w_{\rm SYN} \simeq \frac{L_X}{4\pi R_{\rm PWN}^2 c}$$

$$\sim 2\times 10^{-2}\left(\frac{L_X}{L_{\rm SD}}\right)\left(\frac{L_{\rm SD}}{10^{35}\,{\rm erg\,s^{-1}}}\right)\left(\frac{R_{\rm PWN}}{1\,{\rm pc}}\right)^{-2}\,{\rm eV\,cm^{-3}}$$

What is the most important photon field in PWNe?

- ✔ Energy density

$$\frac{dE_e}{dt} \propto w_{\rm ph} E_e^2 \quad \text{(Thomson regime)}$$

- ✔ Klein-Nishina Effect: suppression of IC scattering for

$$\hbar\omega E_e \geq m_e^2 c^4 \Rightarrow T < 10^3 \left(\frac{E_e}{1\ \text{Tev}}\right)^{-1}\ \text{K}$$

- ✔ For a PL electron distribution (slope α), the gamma-ray emissivity is (Aharonian,Atoyan&Kifune 1997)

$$q(E_\gamma) \propto w_{\rm ph} T_{\rm ph}^{(\alpha-3)/2} E_\gamma^{-(\alpha+1)/2}$$

What is the most important photon field in PWNe?

Three photon fields considered

- CMB:

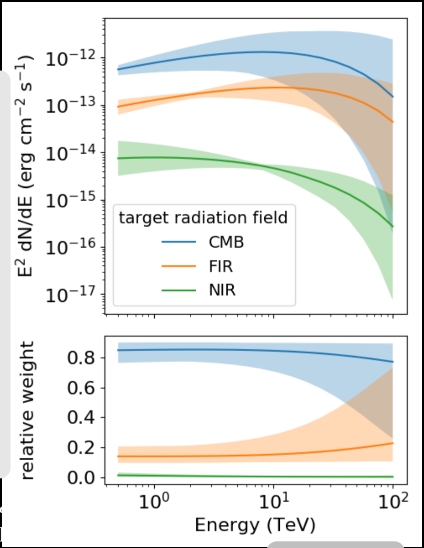
  $T = 2.7\,\mathrm{K}$ and $w = 0.25\mathrm{eV\,cm^{-3}}$
- FIR:

  $T = 30\,\mathrm{K}$ and $w = 0.2\mathrm{eV\,cm^{-3}}$
- NIR:

  $T = 3000\,\mathrm{K}$ and $w = 1\mathrm{eV\,cm^{-3}}$

for a PL exponential cutoff electron spectrum ($\alpha = 1.75$ and $E_{\mathrm{cut}} = 70\,\mathrm{TeV}$)

$$q(E_\gamma) \propto w_{\mathrm{ph}}\, T_{\mathrm{ph}}^{(\ldots}$$



HESS Col. 2019

PWNe as TeV gamma-ray sources: X-ray counterpart

✔ Radio–to–X-ray emission (synchrotron radiation) requires acceleration of TeV electrons in PWNe

$$E_e \simeq 100 \left(\frac{B}{10\,\mu\mathrm{G}}\right)^{-1/2} \left(\frac{\varepsilon}{1\,\mathrm{keV}}\right)^{1/2} \mathrm{TeV}$$

☞ Potential VHE source (Aharonian, Atoyan, Kifune 1997):

$$\frac{f_{\rm IC}(E_\gamma)}{f_{\rm SYN}(\varepsilon)} \simeq \frac{w_{\rm ph}}{w_B}$$

here $\frac{\varepsilon}{100\,\mathrm{eV}} = \left(\frac{E_\gamma}{2\,\mathrm{TeV}}\right)\left(\frac{B}{10\,\mu\mathrm{G}}\right)\left(\frac{T}{2.7\,\mathrm{K}}\right)^{-1}$

synchrotron

IC

same electrons radiate soft X-ray and TeV gamma rays if $B \sim 10^{-5} - 10^{-4}\,\mathrm{G}$

PWNe as TeV gamma-ray sources: steady and bright

✔ Gamma-ray flux critically depends on the strength of the magnetic field:

$$L_\gamma = \boxed{\frac{1}{1+\frac{w_B}{w_{\rm ph}}}}\, L_{\rm SD}$$

synchrotron target

IC target

☞ Magnetic field energy density:

$$w_B = \frac{B^2}{8\pi}$$

$$\boxed{w_B = 2.5\left(\frac{B}{10\ \mu{\rm G}}\right)^2 {\rm eV\ cm^{-3}}}$$

☞ Photon target:

$$w_{\rm ph} = {\rm CMBR + FIR + NIR + SYN}$$

$$\boxed{w_{\rm ph} = 0.25 + 1 + 2\ {\rm eV\ cm^{-3}} + w_{\rm SYN}}$$

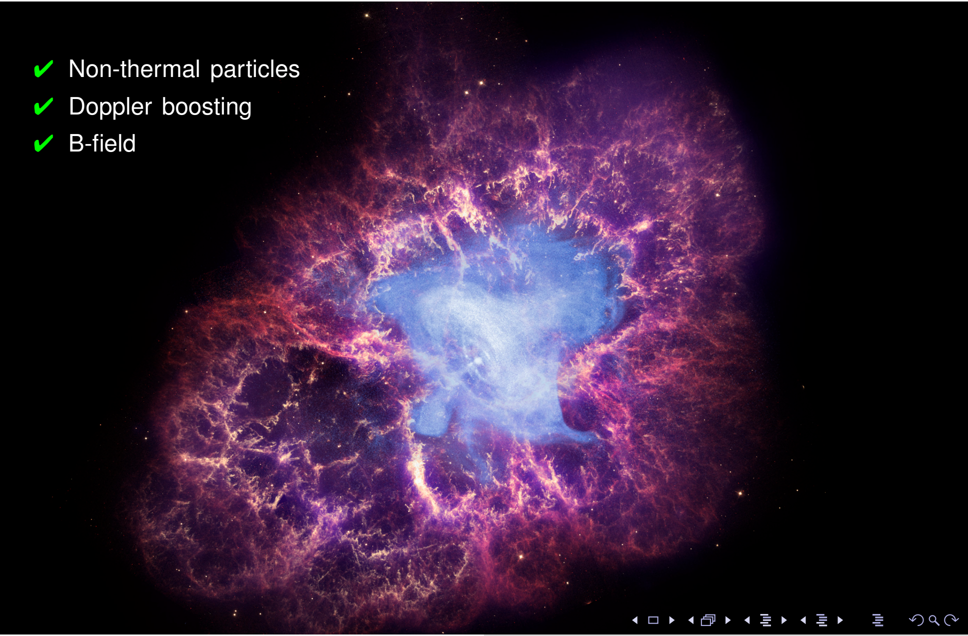
$$w_{\rm SYN} \sim \frac{L_{\rm SYN}}{4\pi R_{\rm PWN}^2 c}$$

✔ Radiative cooling time:

$$t_{\rm rad} = 10^5 \boxed{\frac{1}{1+\frac{w_{\rm ph}}{w_B}}} \left(\frac{E_e}{1\ {\rm TeV}}\right)^{-1} \left(\frac{B}{10\ \mu{\rm G}}\right)^{-2} {\rm yr}$$

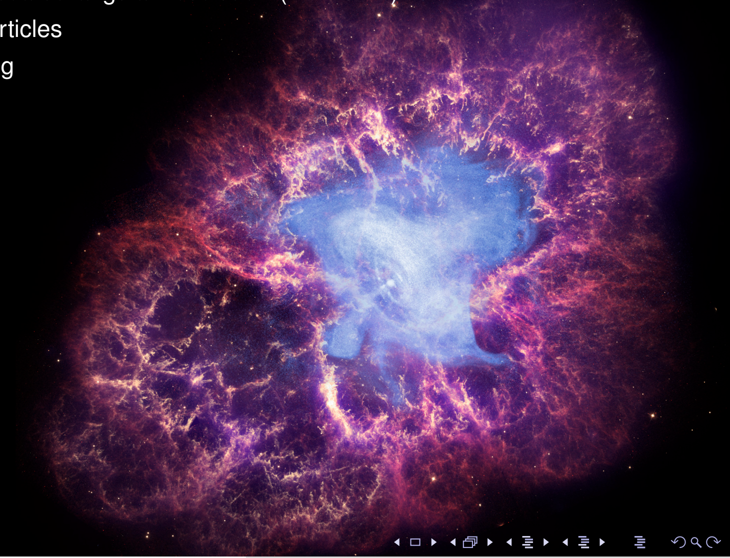
PWNe: What do we see in X-rays?

- ✔ Non-thermal particles
- ✔ Doppler boosting
- ✔ B-field



PWNe: What do we see in gamma rays?

- ✔ At much more coarse angular resolution ($10'$ vs $1''$)
- ✔ Non-thermal particles
- ✔ Doppler boosting
- ✔ Target photons



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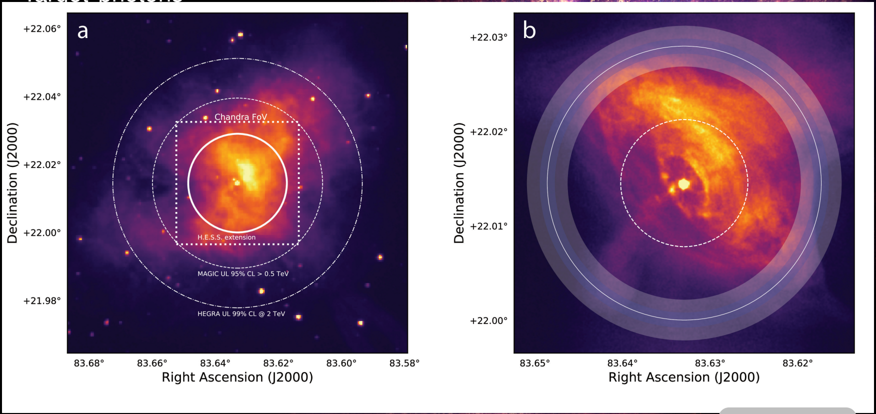

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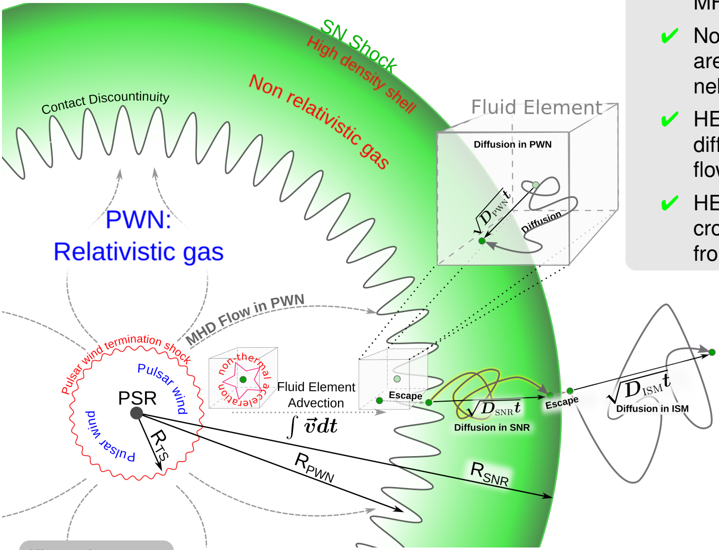
What is a PWN seen in gama rays?



- ✔ PWNe are formed by MHD process
- ✔ Non-thermal particles are advected through the nebula
- ✔ HE particles can also diffuse across the MHD flow
- ✔ HE particles can freely cross CD and shock fronts

Khangulyan+2018

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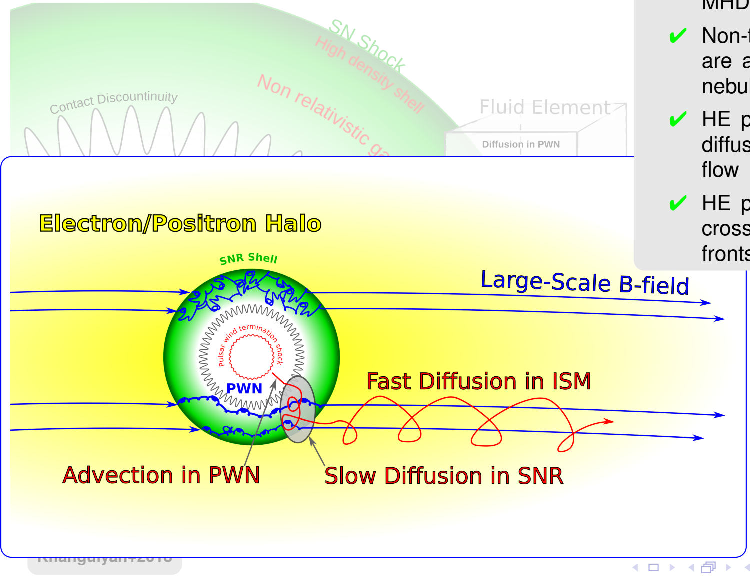
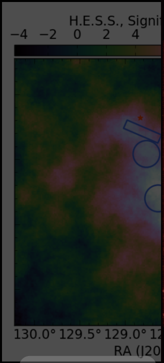


Vela X PWN: correlated extended X- and gamma-ray emission



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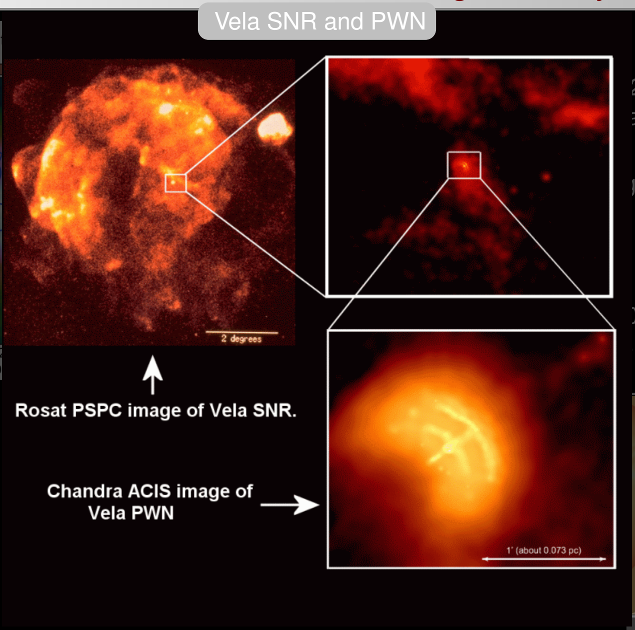
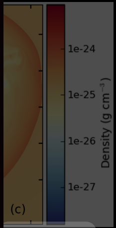


regime
25-137, dif-
ation of VHE

gamma-ray

interpretation

) TeV, but
the cutoff of



Kolb+2017

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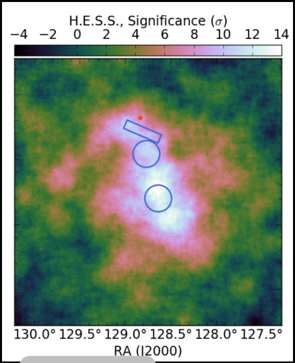
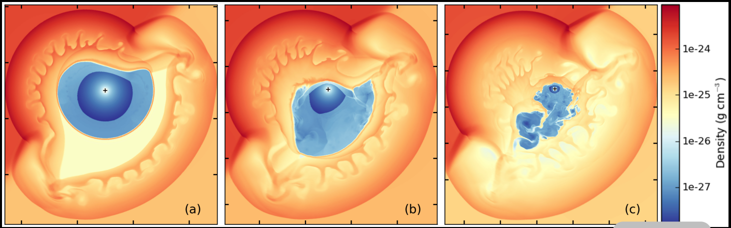


HESS Coll.2018

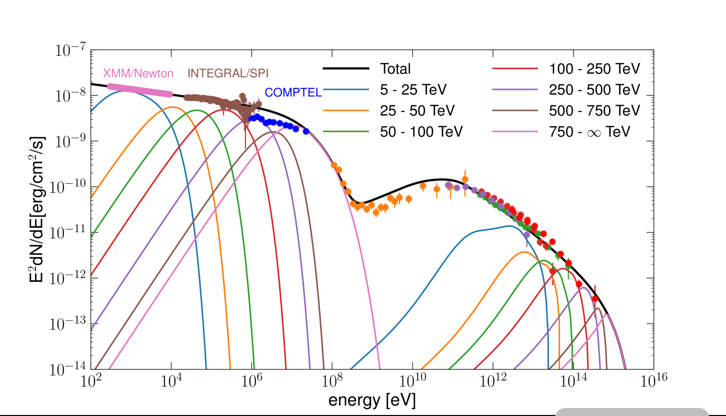
- ✔ Many PWNe are resolved in the VHE regime
- ✔ In some other cases, e.g., HESS J1825-137, diffusion might be essential for interpretation of VHE observations
- ✔ In some cases, e.g., Vela X, X- and gamma-ray emission is well correlated
- ✔ MHD processes may provide a viable interpretation for the morphology
- ✔ The electron spectrum cutoff is at 100 TeV, but these are dislocated particles, what is the cutoff of the acceleration spectrum?



Kolb+2017

What is the maximum energy of electrons in PWN?

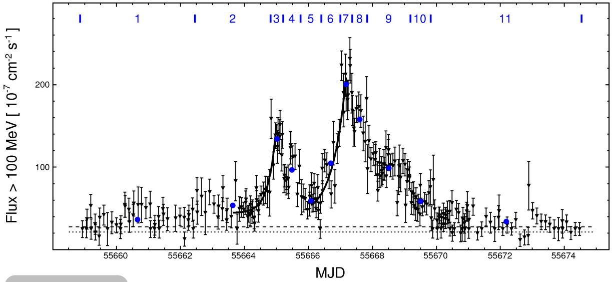
Majority of models for Crab Nebula adopt either a fixed magnetic field of $\sim 100\,\mu\mathrm{G}$ or implement simple (1D analytic or 2D numerical) prescription for particle and magnetic field distribution. In this case current (pre-LHAASO) data constrain the IC component for electrons with energy up to $500\,\mathrm{TeV}$. The synchrotron component suggests the presence of multi-PeV electrons.



Khangulyan+2020

100 μG: Is that a good magnetic field?

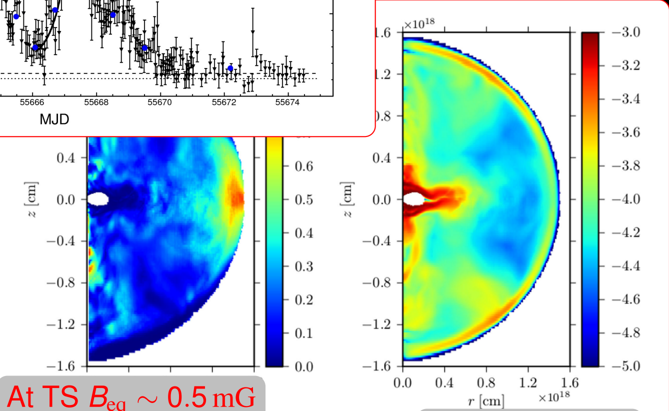
$t_{\rm var} \sim 12\,{\rm h} \to {\rm B} > 2\,{\rm mG}$



Buehler+2012

Fermi flares require strong magnetic field

3D MHD simulation suggest that regions close to TS features strong magnetic field $\sim 1\,{\rm mG}$

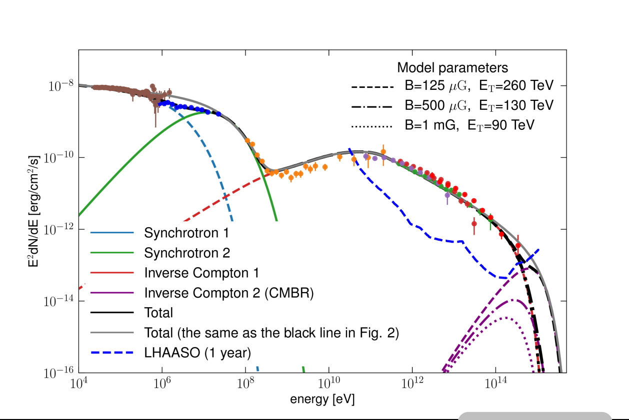


At TS $B_{\rm eq} \sim 0.5\,{\rm mG}$

Magnetic field (Porth+2014)

Two zone model? Ruled out by LHAASO?

X-ray and gamma-ray (pre-LHAASO) data are consistent with two zone model for Crab Nebula (Aharonian&Atoyan 1998). This allows a natural interpretation for the Comptel spectral feature; particle acceleration in regions with strong magnetic field (Crab Flares sites?). This scenario implies a sharp cutoff between 500 TeV and 1 PeV, which seems to be inconsistent with preliminary LHAASO results.



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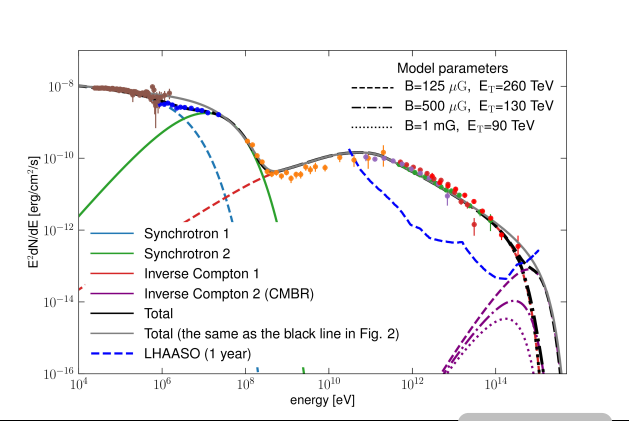
Detection of a PL spectrum up to 1 PeV implies:

- ☞ Acceleration of multi PeV electrons
- ☞ Acceleration in a region of 100 μG magnetic field



Khangulyan+2020

Summary

- ✔ PWNe are perfect gamma-ray sources: in the majority of PWNe, the magnetic field strength should be relatively weak, $B < 10^{-4}\,\mathrm{G}$, making IC very effective process
- ✔ Typical size of PWNe is not sufficient for resolving these source with gamma-ray instruments (but many resolved!)
- ✔ Gamma-ray emission morphology is less sensitive to the internal structure of the PWN (as compared to the X-ray band), which hardens interpretation of gamma-ray data from very extended PWNe
- ✔ Pre-LHAASO gamma-ray data constrain the electron spectrum up to $500\,\mathrm{TeV}$
- ✔ Pre-LHAASO gamma-ray data constrain the magnetic field in the region of $\sim 100\,\mathrm{TeV}$ electrons' acceleration, $B \simeq 100\,\mu\mathrm{G}$
- ✔ Emission of hypothetical PeV electron in Crab Nebula is constrained only by their synchrotron emission (and now by LHAASO?), so there is (was?) a degeneracy related to the strength of the magnetic field (leaving a possibility of particle acceleration in regions with strong magnetic field, $B \sim 1\,\mathrm{mG}$, making a possible connection to Crab Flares)
- ✔ Extension of power-law spectrum up to $1\,\mathrm{PeV}$ implies acceleration of multi PeV electrons in regions of weak magnetic field, $B \simeq 100\,\mu\mathrm{G}$