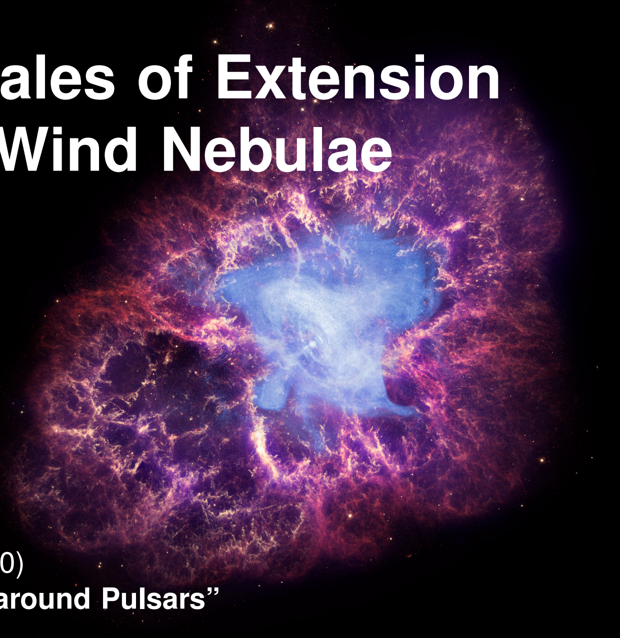
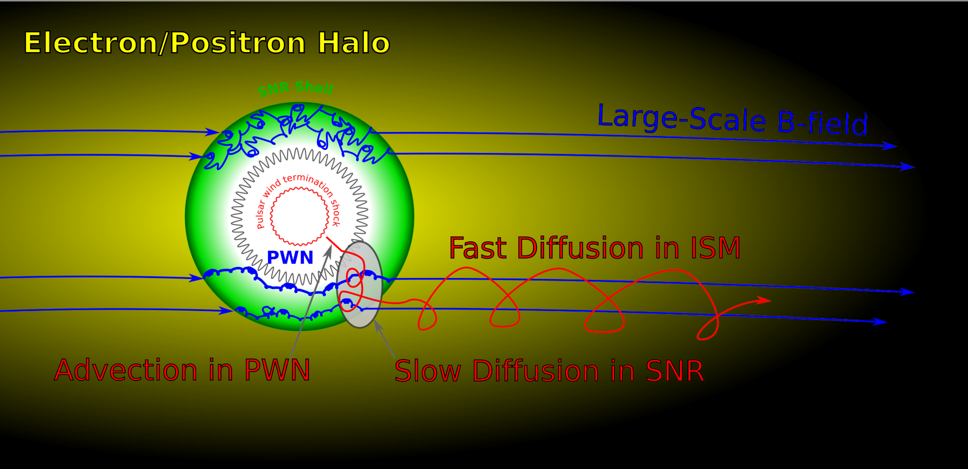
On the Scales of Extension of Pulsar Wind Nebulae



Dmitry Khangulyan
(Rikkyo University)

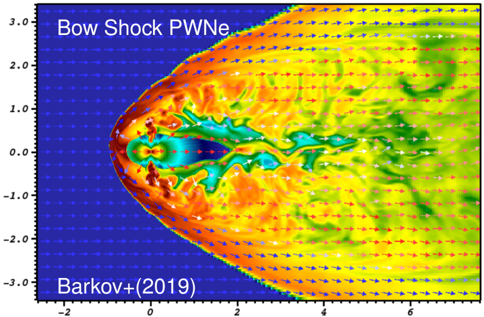
December 1st-3rd (2020)
“Gamma-Ray Halos around Pulsars”

Halo around a PWN



- ✔ If electrons escape from PWN/SNR, they can travel large distances in ISM
- ? How can we distinguish an extended PWN and a halo?
- ? How big can be PWNe? How far can NT particles reach?

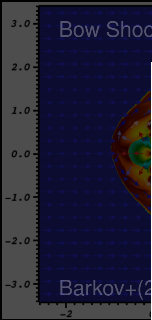
Escape of particles to ISM: Bow-Shock PWNe



- ✔ Formed when PSR gets a significant kick at birth
- ✔ PSR escapes SNR and interacts with ISM
- ✔ Bow-shaped structure of shocks is formed
- ✔ There are some examples in the sky

- ? How do such PWNe appear in the sky?
- ☞ As expected from 3D MHD simulations of anisotropic pulsar wind interaction (Non-thermal: Barkov+2019, Hα: Barkov+2020)
- ? Can we see some escaping particles?
- ☞ There are some extended structures that cannot have MHD origin (e.g., Bandiera+2008)

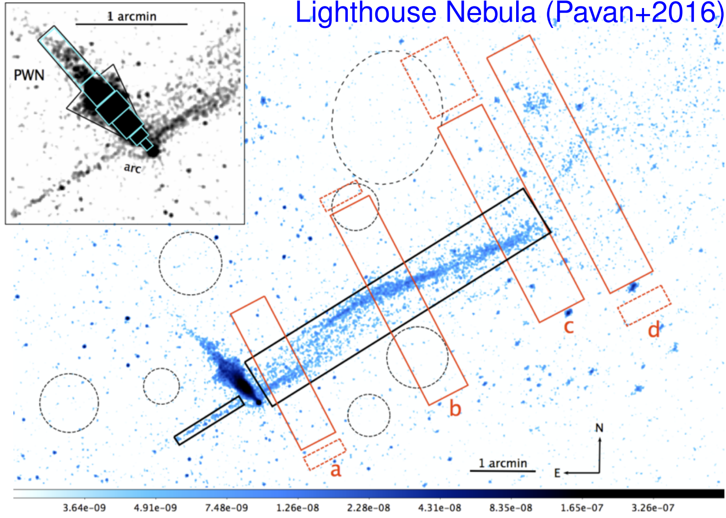
Escape of particles to ISM: Bow-Shock PWNe



Bow Shock PWNe

Barkov+(2

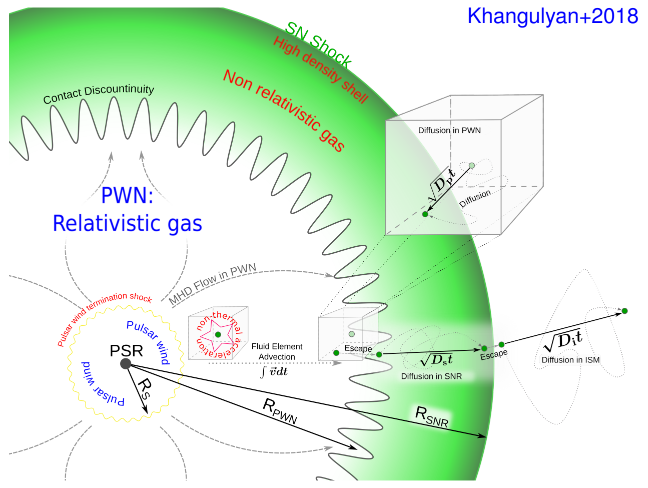
- ✔ Formed when PSR gets a significant kick at birth



Lighthouse Nebula (Pavan+2016)

- ? How do
- ☞ As expe
  tion (Nor
- ? Can we
- ☞ There ar
  Bandiera

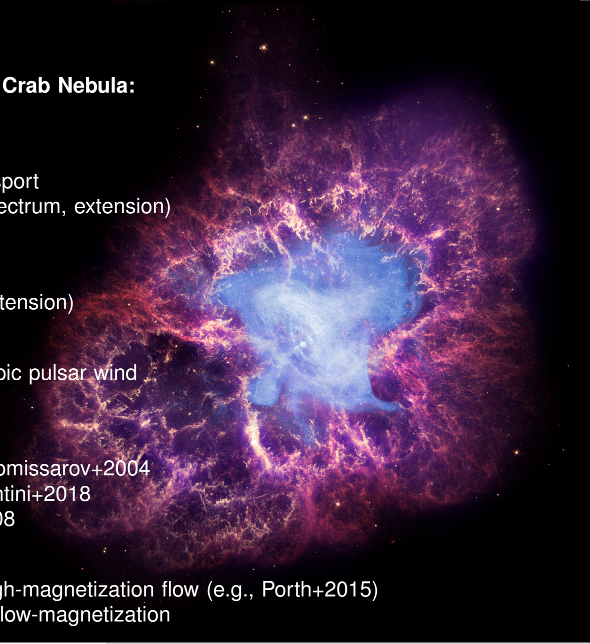
Particle Transport in PWNe



Khangulyan+2018

- ✔ Pulsar wind:
  - ☞ ultrarelativistic
  - ☞ no synchrotron cooling
  - ☞ no diffusion
- ✔ Shocked pulsar wind
  - ☞ relativistic
  - ☞ synchrotron cooling
  - ☞ advection
  - ☞ diffusion
- ✔ Escape to SNR/ISM
  - ☞ diffusion

Particle Transport in PWNe: Crab Nebula



Four-decades progress in studying Crab Nebula:

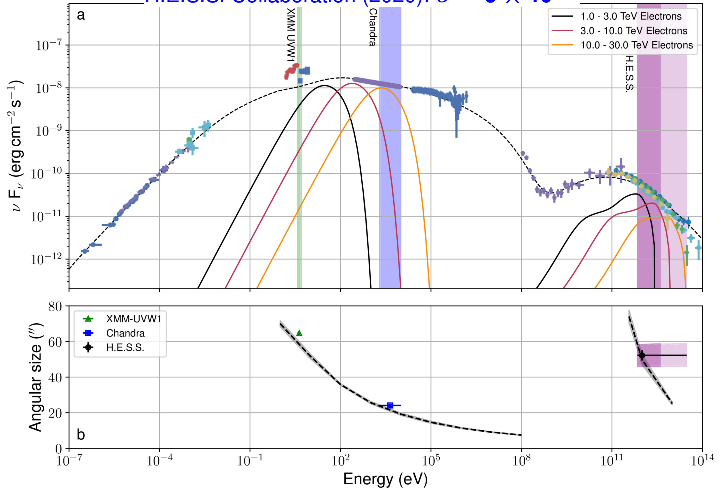
- ✓ Kennel&Coroniti (1984)
  - ☞ MHD model for PWN
  - ☞ Non-thermal particle transport
  - ☞ Synchrotron emission (spectrum, extension)
- ✓ Aharonian&Atoyan (1995)
  - ☞ Gamma-ray production
  - ☞ SSC model (spectrum, extension)
- ✓ Bogovalov&Khangulyan (2002)
  - ☞ MHD model with anisotropic pulsar wind
  - ☞ X-ray morphology
- ✓ Numerical MHD (2005-...)
  - ☞ X-ray morphology: e.g, Komissarov+2004
  - ☞ Polarization: e.g., Bucciantini+2018
  - ☞ IC morphology: Volpi+2008
- ? Is it all crystal-clear now?
  - ✗ MHD simulations favor high-magnetization flow (e.g., Porth+2015)
  - ✗ Gamma-ray observations low-magnetization

Particle Transport in PWNe: Crab Nebula

Four-decades pr

- ✔ Kennel&Co
  - ☞ MHD
  - ☞ Non-t
  - ☞ Synch
- ✔ Aharonian&
  - ☞ Gamm
  - ☞ SSC
- ✔ Bogovalov&
  - ☞ MHD
  - ☞ X-ray
- ✔ Numerical M
  - ☞ X-ray
  - ☞ Polari
  - ☞ IC mo
- ? I
  - ✗ Gamma-ray observations low-magnetization

H.E.S.S. Collaboration (2020): $\sigma = 5 \times 10^{-3}$



Extension of the gamma-ray emission is sensitive to the pulsar wind magnetization. Simple estimates favor weak magnetization.

Particle Transport in PWNe: Crab Nebula

Four-decades pr

- ✔ Kennel&Cor
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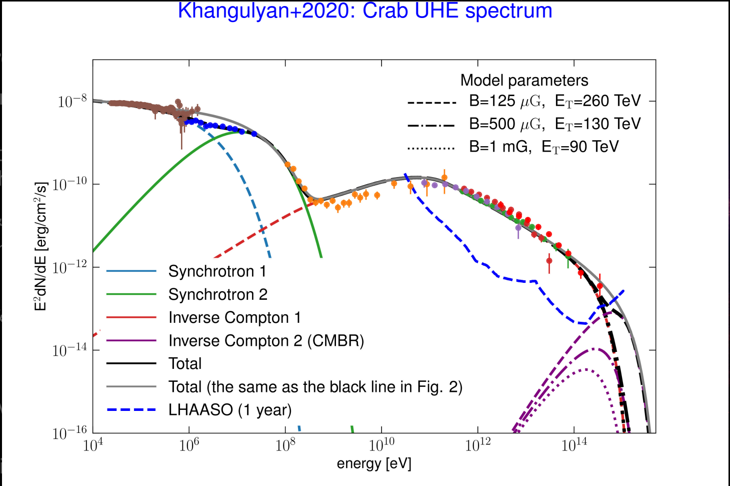


Khangulyan+2020: Crab UHE spectrum

PeV gamma-ray spectrum is a very sensitive probe for the magnetic field in the acceleration region. Tibet measurements favor weak magnetic field. LHAASO observations are essential for determining the magnetic field. (coming very soon?)

Gamma-ray observations low-magnetization

How big can be a PWN?

- ✔ Bow-shock PWN:

$$v_{\rm PWN}\tau_{\rm PWN} = \mathbf{30\,pc}\frac{v_{\rm PWN}}{\mathbf{300\,km\,s^{-1}}}\quad\frac{\tau_{\rm PWN}}{\mathbf{10^5\,yr}}$$

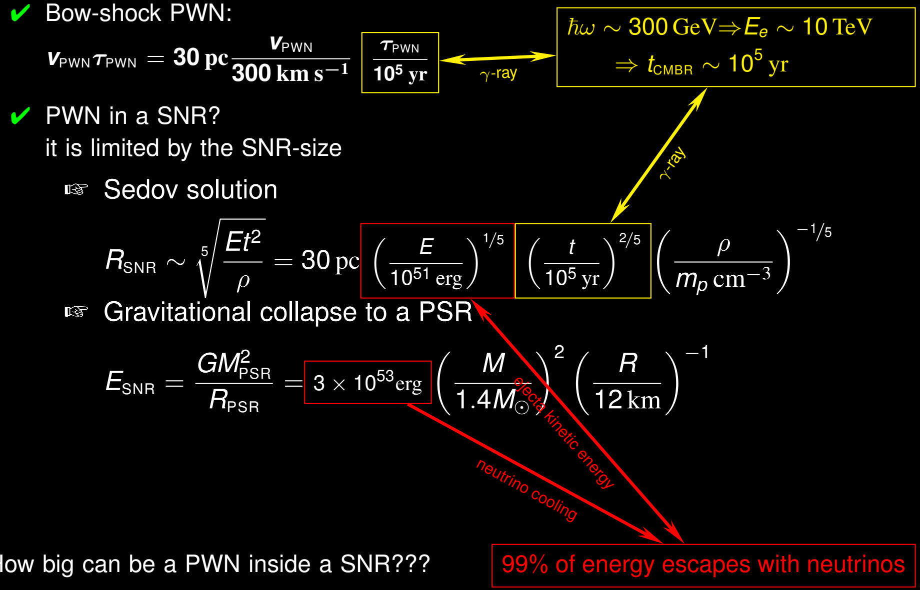
- ✔ PWN in a SNR?
  it is limited by the SNR-size
  - ☞ Sedov solution

$$R_{\rm SNR} \sim \sqrt[5]{\frac{Et^2}{\rho}} = 30\,{\rm pc}\left(\frac{E}{10^{51}\,{\rm erg}}\right)^{1/5}\quad\left(\frac{t}{10^5\,{\rm yr}}\right)^{2/5}\left(\frac{\rho}{m_p\,{\rm cm^{-3}}}\right)^{-1/5}$$

  - ☞ Gravitational collapse to a PSR

$$E_{\rm SNR} = \frac{GM_{\rm PSR}^2}{R_{\rm PSR}} = 3\times10^{53}{\rm erg}\left(\frac{M}{1.4M_\odot}\right)^2\left(\frac{R}{12\,{\rm km}}\right)^{-1}$$

How big can be a PWN?



- ✔ Bow-shock PWN:

$$v_{\rm PWN}\tau_{\rm PWN} = 30\,{\rm pc}\,\frac{v_{\rm PWN}}{300\,{\rm km\,s^{-1}}}\boxed{\frac{\tau_{\rm PWN}}{10^5\,{\rm yr}}}$$

$$\boxed{\hbar\omega \sim 300\,{\rm GeV} \Rightarrow E_e \sim 10\,{\rm TeV} \Rightarrow t_{\rm CMBR} \sim 10^5\,{\rm yr}}$$

- ✔ PWN in a SNR?
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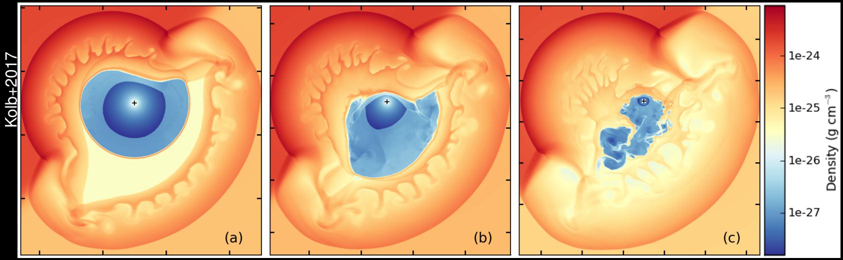
  - ☞ Gravitational collapse to a PSR

$$E_{\rm SNR} = \frac{GM_{\rm PSR}^2}{R_{\rm PSR}} = \boxed{3\times10^{53}{\rm erg}}\left(\frac{M}{1.4M_\odot}\right)^2\left(\frac{R}{12\,{\rm km}}\right)^{-1}$$

How big can be a PWN inside a SNR???

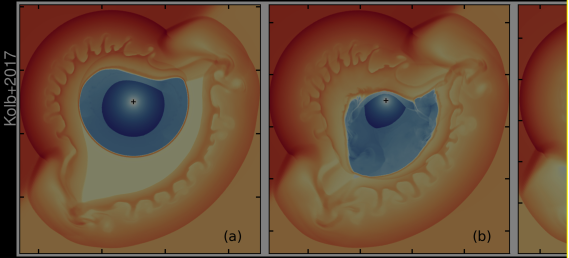
99% of energy escapes with neutrinos

PWNe in SNRs: the standard picture



PWN can extend to $\sim 10\,\mathrm{pc}$ inside the SNR. However after $\sim 5,000$ yr after the explosion, the nebula is hit by the reverse shock resulting in the nebula compression. In inhomogeneous media, the reverse shock is asymmetric, leading to the PWN displacement with formation of $\sim 10\,\mathrm{pc}$-structures.

PWNe in SNRs: the standard picture



Kolb+2017

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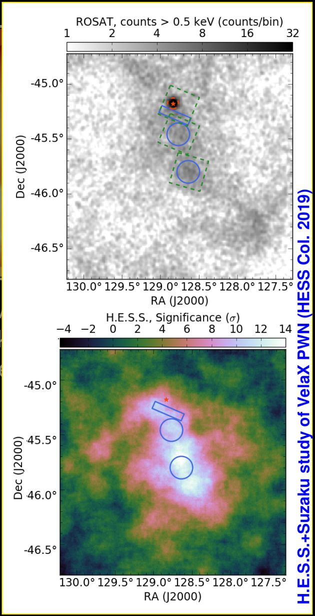

H.E.S.S.+Suzaku study of VelaX PWN (HESS Col. 2019)

- ☞ Crashed PWN is a feasible scenario for the formation of VelaX PWN, which is consistent with its X- and γ-ray properties.
- ☞ To overtake this limit one needs a configuration with an overpressured PWN, i.e., powered by a very powerful pulsar.

Pulsar Rotation Energy

- ☞ Gravitational collapse to a PSR

$$E_{\rm EJ}=\kappa_{\rm nc}\frac{GM_{\rm PSR}^2}{R_{\rm PSR}}=3\times10^{51}{\rm erg}\,\frac{\kappa_{\rm nc}}{1\%}\left(\frac{M}{1.4M_\odot}\right)^2\left(\frac{R}{12\,{\rm km}}\right)^{-1}$$

- ☞ Rotation energy of a PSR

$$E_{\rm PSR}=\frac{I\Omega^2}{2},\text{ where } I\sim10^{45}{\rm g\,cm^2}\frac{M_{\rm PSR}}{1.4M_\odot}\left(\frac{R_{\rm PSR}}{12\,{\rm km}}\right)^2$$

$$\Omega<\Omega_{\rm BR}=\sqrt{\frac{GM_{\rm PSR}}{R_{\rm PSR}^3}}\sim10^4\,{\rm s^{-1}}\left(\frac{M_{\rm PSR}}{1.4M_\odot}\right)^{1/2}\left(\frac{R_{\rm PSR}}{12\,{\rm km}}\right)^{-3/2}$$

- ☞ Maximum rotation energy

$$E_{\rm PSR}^{\rm MAX}=10^{53}{\rm erg}\left(\frac{M}{1.4M_\odot}\right)^2\left(\frac{R}{12\,{\rm km}}\right)^{-1}$$

Pulsar Rotation Energy

- Gravitational collapse to a PSR

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- Maximum rotation energy

$$E_{\rm PSR}^{\rm MAX} = \boxed{10^{53}\,{\rm erg}}\left(\frac{M}{1.4M_\odot}\right)^2\left(\frac{R}{12\,{\rm km}}\right)^{-1}$$

$$\boxed{E_{\rm SNR}\sim3\times10^{53}\,{\rm erg}}$$

- Relation between characteristic energies

$$E_{\rm EJ} \ll E_{\rm PSR}^{\rm MAX} < E_{\rm SNR}$$

if a pulsar gets a very short birth rotation period, the PWN pressure not only can resist the reverse shock impact, but it can provide the dominant contributor for the SNR expansion.

PWN pressure-driven expansion

- ✓ the equation for the energy balance in the nebula:

$$3\frac{d\,PV_{\rm PWN}}{d\,t}+P\frac{d\,V_{\rm PWN}}{dt}=L_{\rm sd}(t)\,;$$

- ✓ the equation for the energy balance in the non-relativistic shell:

$$\frac{d}{d\,t}\left(\frac{Mu^2}{2}+\frac{3}{2}P(V_{\rm SNR}-V_{\rm PWN})\right)=P\frac{d\,V_{\rm PWN}}{d\,t}\,;$$

- ✓ the equation of motion:

$$\frac{d\,Mu}{d\,t}=4\pi R_{\rm SNR}^2P\,;$$

- ✓ pulsar spin-down losses

$$L_{\rm sd}(t)=\frac{L_p\left(\tilde\omega/\omega\right)^{(n+1)}}{\left(1+t/t_0\right)^{\frac{n+1}{n-1}}}\,,$$

where $t_0=\dfrac{2\tau}{(n-1)}\left(\dfrac{\omega}{\tilde\omega}\right)^{n-1}$ and $\tilde\omega$ is the initial angular velocity.

PWN pressure-driven expansion: Asymptotic

- ✔ The energy injection by the pulsar ceases with time, thus there is a characteristic energy E that determines the expansion
- ✔ Energy, density, time ⇒ Sedov solution? Almost, but there are several different distances
- ✔ There is a length-dimension constant that determines the size of the PWN as $PR_{\rm PWN}^4 = aE$
- ✔ This is sufficient to get the solution for $R_{\rm PWN} \gg a$ as

$$R_{\rm PWN} \propto a^{1/4}\left(\frac{Et^2}{\rho_{\rm ISM}}\right)^{3/20}$$

$$R_{\rm SNR} \propto \left(\frac{Et^2}{\rho_{\rm ISM}}\right)^{1/5}$$

$$R_{\rm TS} \propto \sqrt{\frac{L(t)}{P}} \propto t^{\frac{3}{5}-\frac{n+1}{2(n-1)}}$$

- ✔ Anything remarkable? **The size of the PWN keeps growing with time** $\propto t^{3/10}$

PWN pressure-driven expansion: Asymptotic

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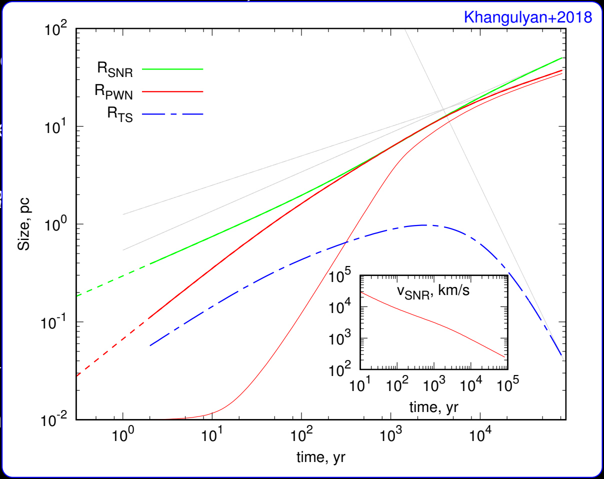
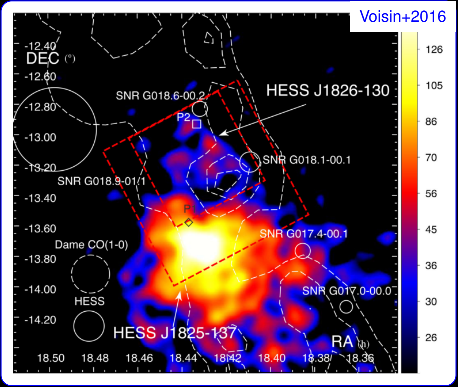

Khangulyan+2018

HESS J1825-137

- ✔ Very extended TeV emitter, $\sim 70\,\mathrm{pc}$
- ✔ Nearby molecular clouds$\Rightarrow$ high ISM density(?)
- ✔ Big SNR, $120\,\mathrm{pc}$
- ✔ X-ray observations suggest a TS at $0.03\,\mathrm{pc}$
- ✔ Pulsar characteristic age, $\tau = 2\times10^{4}\,\mathrm{yr}$ (i.e., $t < 10^{5}\,\mathrm{yr}$) and the “current” spin-down luminosity is $L = 3\times10^{36}\,\mathrm{erg/s}$


Voisin+2016

see in Clifton et al. (1992); HESS Col(2006,2019); Van Etten&Romani(2011); Voisin et al (2016)

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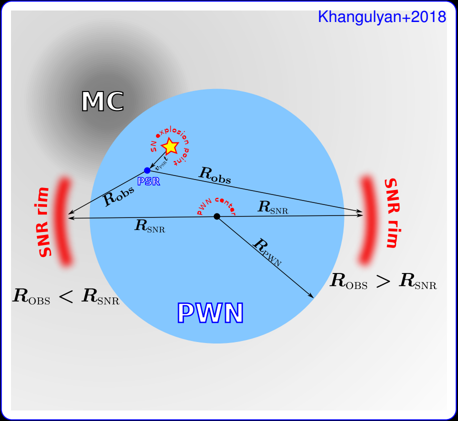
The question to answer: are there any reasonable ISM density, ρ, initial rotation energy $\tilde{\omega}$, and pulsar braking index that allow to get the PWN/SNR matching the observations?
What are the target values?

- ☞ $R_{\rm PWN} = 35\,\mathrm{pc}$
- ☞ $R_{\rm SNR} = 60\,\mathrm{pc}$ & $R_{\rm TS} = 0.03\,\mathrm{pc}$


Khangulyan+2018

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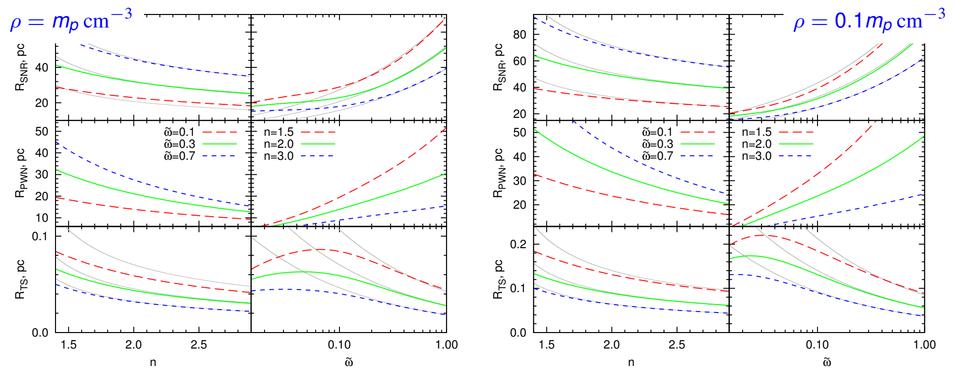
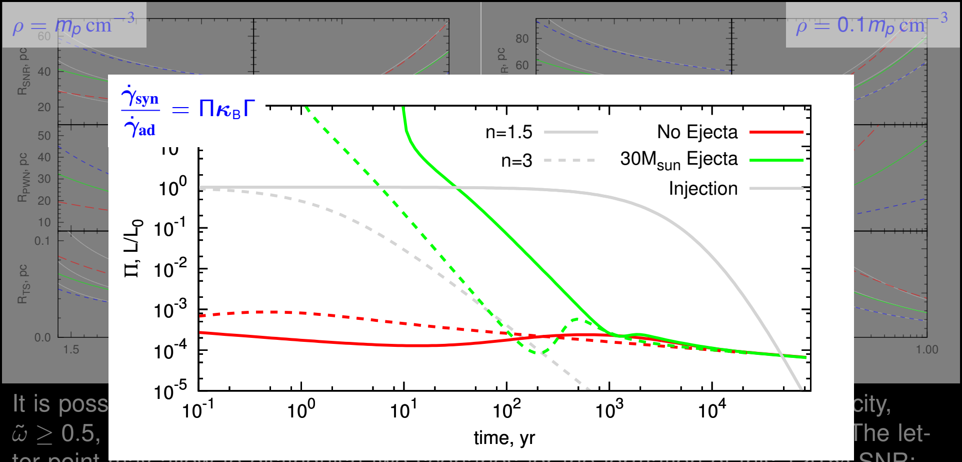
HESS J1825-137: Results



It is possible to achieve the target values if we adopt a high initial angular velocity, $\tilde{\omega} \geq 0.5$, small braking index, $n \leq 2$, and dense ISM medium $\rho_{\text{ISM}} \geq m_p\,\mathrm{cm}^{-3}$. The letter point may allow to distinguish two scenarios for the formation of this 120 pc SNR: Sedov solution requires a quite diluted environment, $\rho_{\text{ISM}} \ll m_p\,\mathrm{cm}^{-3}$.

Important caveat: In these simulations we ignored radiation cooling, which might be critically important at the initial stage of PWN expansion (e.g., Pacini&Salvati1973). To avoid too strong cooling one may need $n \sim 1.5$ and/or small ejecta mass.

HESS J1825-137: Results



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Summary

- ✔ Gamma-ray data from the Crab Nebula suggest that multi-TeV electrons are accelerated in regions of weak magnetic field, therefore UHE can escape the acceleration sites and potentially travel for large distances
- ✔ Electrons can propagate through the nebula with MHD flow (advection) and/or diffuse/drift in PWN, SNR, ISM. This creates uncertainties for the interpretation of extended gamma-ray emission around pulsars: “do we see CRs or these particles are still confined inside some source?”
- ✔ It is relatively easy to create a PWN of $< 10\,\mathrm{pc}$ size: bow-shock PWNe, composite PWNe inside extended SNRs.
- ✔ If one needs to go beyond $10\,\mathrm{pc}$ then a PWN created by initially rapidly rotating PSR has significant advantages
- ✔ Even in the case of HESS J1825-137, we can reproduce the extension of this nebula