Nanjing University

Morphology of Gamma-Ray Halos around Middle-Aged Pulsars: Influence of the Pulsar Proper Motion

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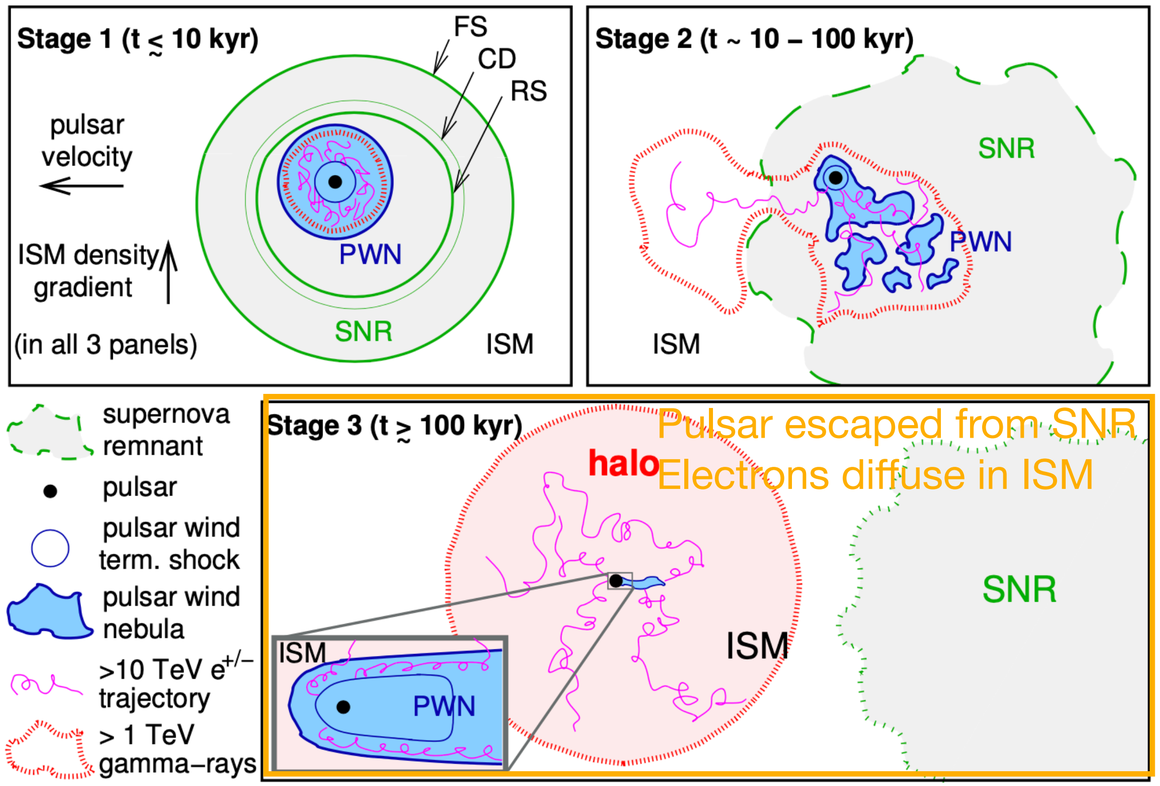
Pulsar Proper Motion - Pulsar Halo

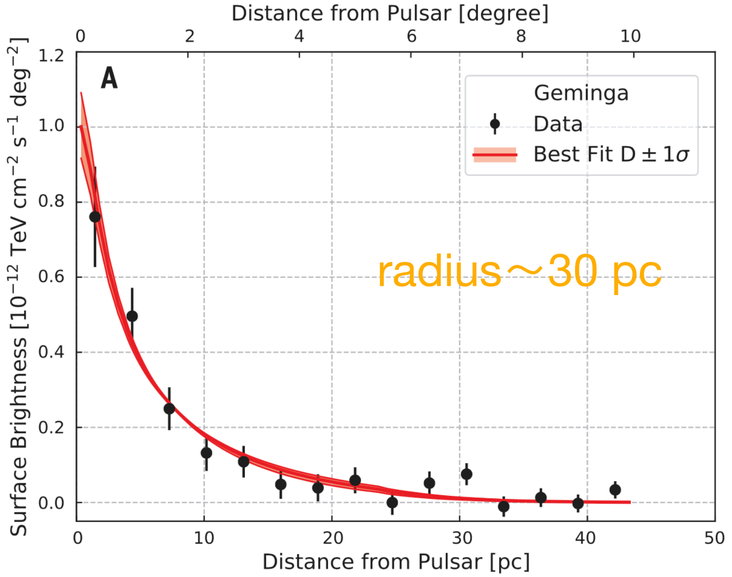
Evolution of pulsar halo:



Giacinti et al. 2019

Pulsar halo

HAWC Collaboration 2017

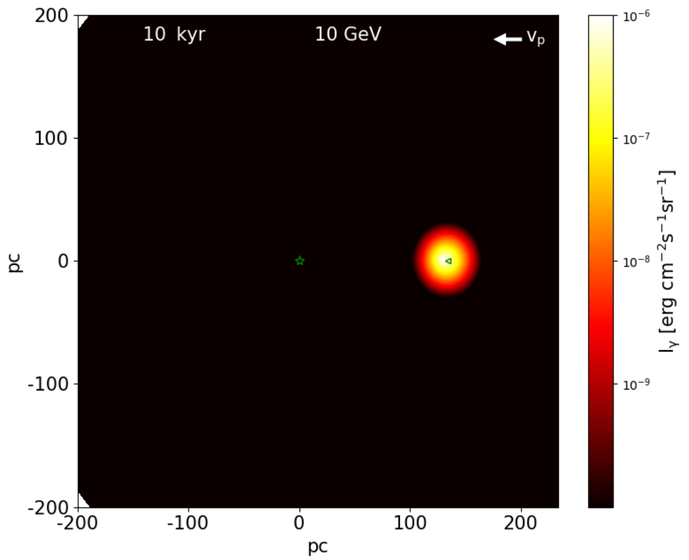


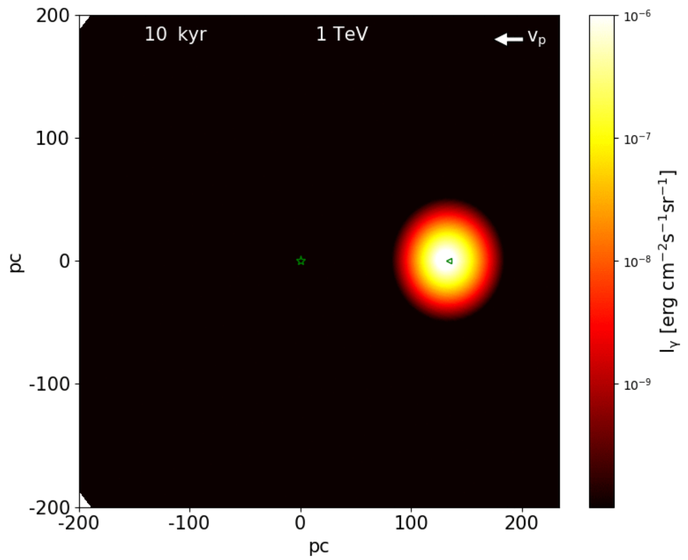
- Pulsar proper motion：300-500 km/s
- Pulsar Displacement: $80(v_{\rm p}/400\,{\rm km\ s^{-1}})(t_{\rm age}/200\,{\rm kyr})\,{\rm pc}$

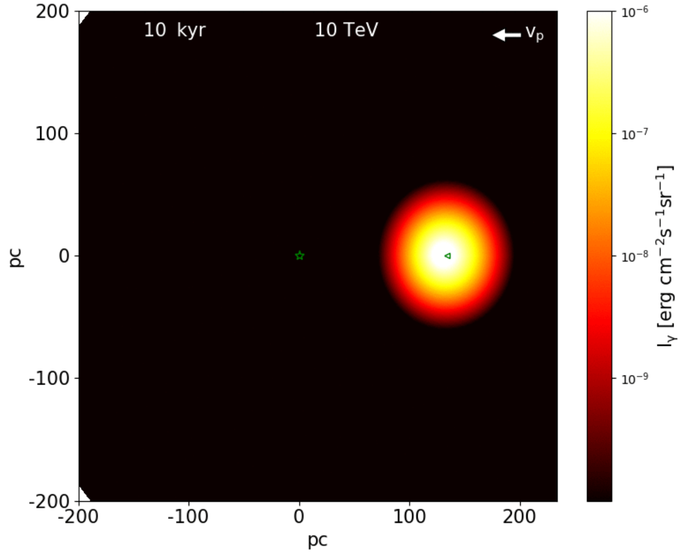
comparable scale of pulsar displacement and pulsar halo

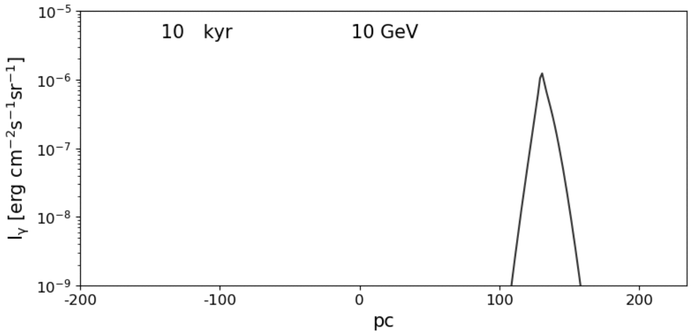
>> Pulsar proper motion influences the morphology of pulsar halo

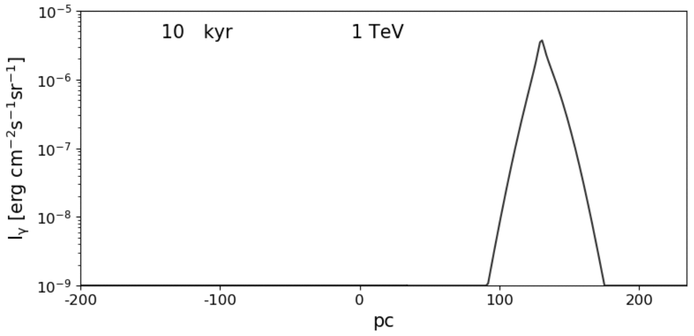
Evolution of pulsar halo morphology

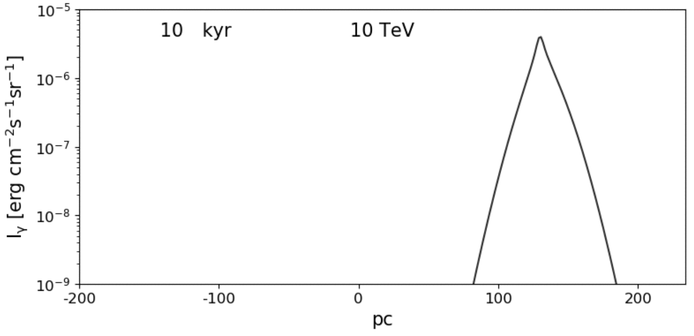












Evolution of pulsar halo morphology

Define two timescales:

Electron diffusion distance = pulsar displacement

$$t_{\rm pd} = 80(E_e/1\,{\rm TeV})^{1/3}(D_0/10^{26}{\rm cm^2 s^{-1}})(v_{\rm tr}/400\,{\rm km/s})^{-2}\,{\rm kyr}$$

Cooling timescale of electron from E_{max} to E_e $\tilde{t}_c(E_e)$

Three evolutionary phases :

PHASE I: $t_{age}<t_{pd}$, $t_{age}<t_c$

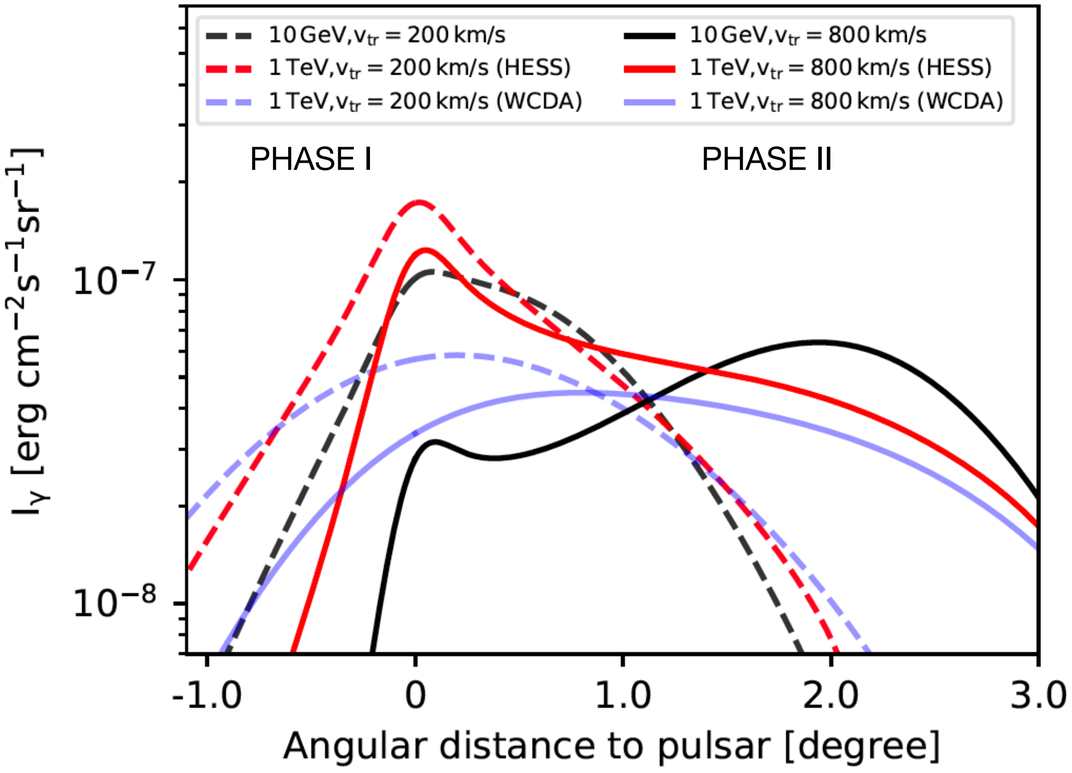
Single-peak

PHASE II: $t_{pd}<t_{age}<t_c$

Double-peak or single-peak with extension

PHASE III: $t_{age}>t_c$

Single-peak



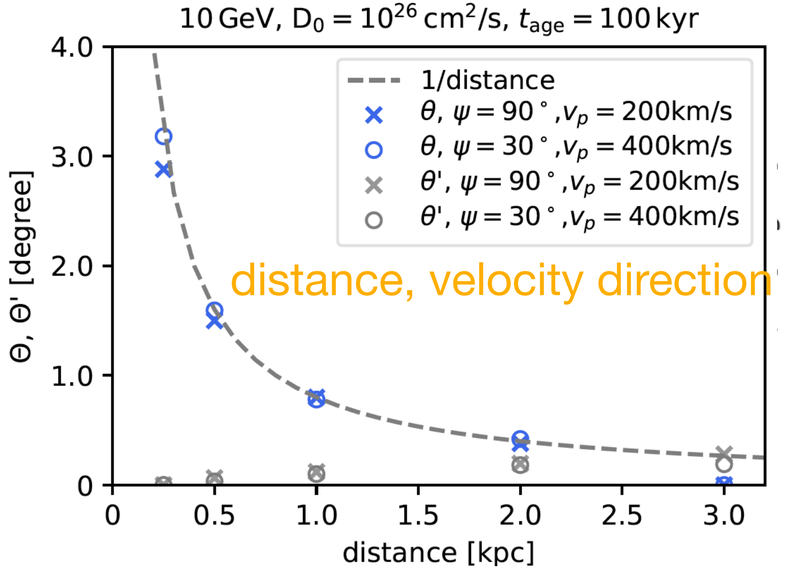
Separation angle

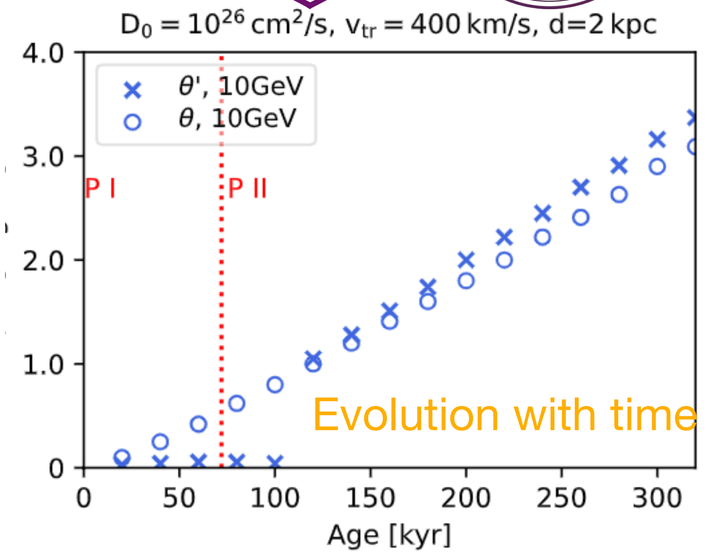
Define two separation angles:

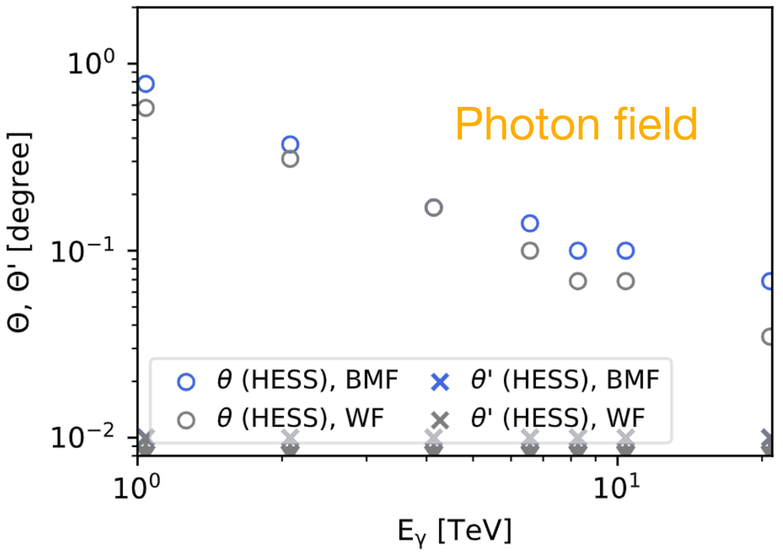
- θ'：between the brightest point of pulsar halo and pulsar
- θ：between the center of pulsar halo by fitting with Gaussian template and pulsar

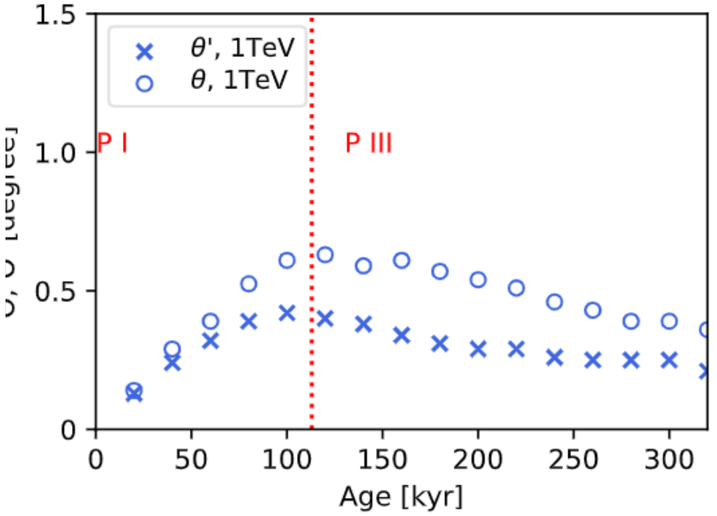
Dependence on:

- Energy
- Electron diffusion coefficient
- Electron injection history
- Electron injection spectra
- Pulsar distance
- Pulsar proper motion velocity
- Magnetic field
- Background photon field





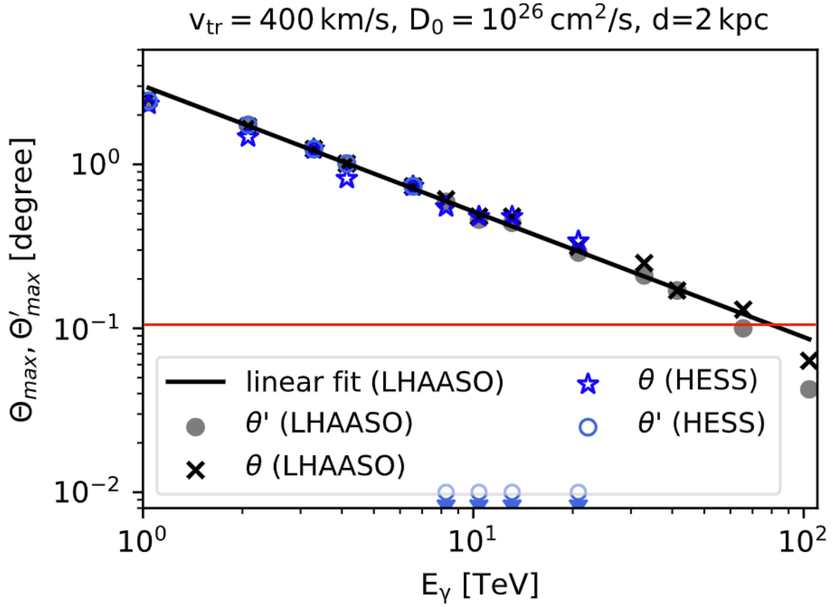




Discussion

Maximum separation angle:

$$\Theta_{\max} = 3^{\circ}\left(\frac{E_{\gamma}}{1\,\mathrm{TeV}}\right)^{-0.77}\left(\frac{v_{\mathrm{tr}}}{400\,\mathrm{km/s}}\right)\left(\frac{d}{2\,\mathrm{kpc}}\right)^{-1}$$



Constrain the origin of >10TeV pulsar halo

Is the association between extended source and pulsar possible?
If the offset can be explained by the pulsar proper motion?

Table 2. 3HWC and LHAASO sources with TeV halo candidate pulsars

3HWC	Pulsar	τ_c(kyr)	d (kpc)	v_{tr}(km/s)	θ_{obs}(°)	Comment
J0540+228	B0540+23	253	1.56	215	0.83	B< 1 μG or n < 2
J0543+231	B0540+23	253	1.56	215	0.36	Unaligned
J0631+169	J0633+1746	342	0.19	128	0.95	Possible
J0634+180	J0633+1746	342	0.19	128	0.38	Unaligned
J0659+147	B0656+14	111	0.29	60	0.51	Unaligned
J0702+147	B0656+14	111	0.29	60	0.77	Unaligned
J1739+099	J1740+1000	114	1.23	-	0.13	Unclear
J1831-095	J1831-0952	128	3.68	-	0.27	Unclear
J1912+103	J1913+1011	169	4.61	-	0.31	Unclear
J1923+169	J1925+1720	115	5.06	-	0.67	Unclear
J1928+178	J1925+1720	115	5.06	-	0.85	Unclear
J2031+415	J2032+4127	201	1.33	-	0.11	Unclear
LHAASO	Pulsar	τ_c(kyr)	d (kpc)	v_{tr}(km/s)	θ_{obs}(°)	Comment
J2032+4102	J2032+4127	201	1.4[a]	20.4[b]	0.42	Impossible
J1929+1745	J1928+1746	82.6	4.6	-	0.25	v_{tr} > 2700 km/s

Not associated or need other mechanisms

Morphology of Gamma-Ray Halos around Middle-Aged Pulsars: Influence of the Pulsar Proper Motion

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[2]Key laboratory of Modern Astronomy and Astrophysics (Nanjing University)
[3]Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, China
[4]TIANFU Cosmic Ray Research Center, China

Introduction:

- Many pulsar halos have been observed by HAWC, HESS and LHAASO.
- The gamma-ray radiation arises from relativistic electrons that escape the pulsar wind nebula and diffuse in the surrounding medium.
- Given a typical transverse velocity of 300–500 km/s for a pulsar, the displacement of the pulsars due to the proper motion could be important in shaping the morphology of the pulsar halos.

Model:

- Continuous injection of electrons
- One-zone diffusion of electrons in interstellar medium
- Synchrotron and IC cooling of electrons
- Convolving PSF of different detectors

Discuss morphology's dependence on parameters, like magnetic field, electron injection history, spectral index, et al.

References:

[1] Albert et al. 2020
[2] LHAASO Collaboration, 2021

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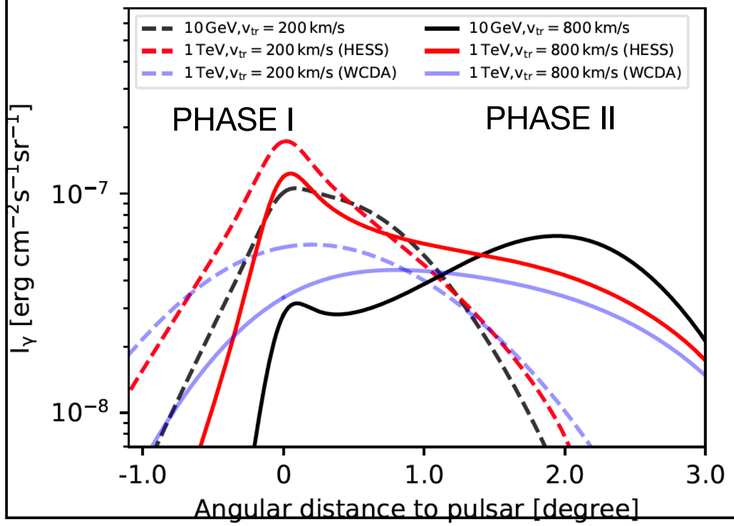
Results:

- Define three evolutionary phases of pulsar halo morphology

PHASE I : $t_{age}<t_{pd}$, $t_{age}<t_c$, single-peak
PHASE II : $t_{pd}<t_{age}<t_c$, double-peak or single-peak with extension
PHASE III : $t_{age}>t_c$, single-peak

t_{pd} : electron's diffusion distance = pulsar displacement
t_c : electron's cooling timescale

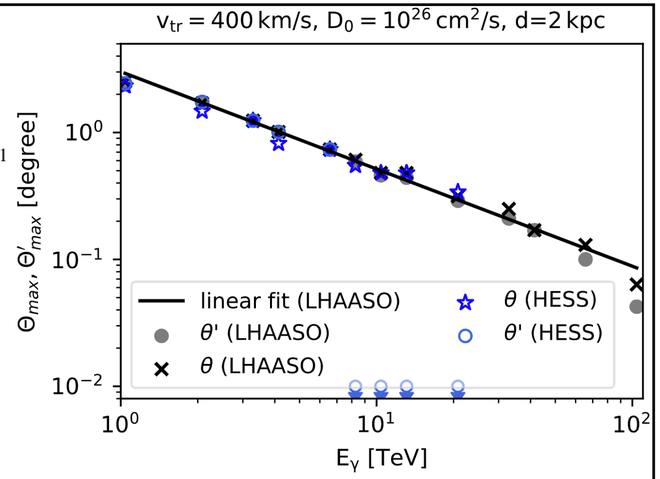


- Maximum separation angle

$$\Theta_{\max} = 3^\circ \left(\frac{E_\gamma}{1\,\mathrm{TeV}}\right)^{-0.77} \left(\frac{v_{\rm tr}}{400\,\mathrm{km/s}}\right) \left(\frac{d}{2\,\mathrm{kpc}}\right)^{-1}$$

- Application to observation

Is the association between extended source and pulsar possible?



3HWC[1]	Pulsar	τ_c(kyr)	d (kpc)	$v_{\rm tr}$(km/s)	$\theta_{\rm obs}$(°)	Comment
J0540+228	B0540+23	253	1.56	215	0.83	B< 1 μG or n < 2
J0543+231	B0540+23	253	1.56	215	0.36	Unaligned
J0631+169	J0633+1746	342	0.19	128	0.95	Possible
J0634+180	J0633+1746	342	0.19	128	0.38	Unaligned
J0659+147	B0656+14	111	0.29	60	0.51	Unaligned
J0702+147	B0656+14	111	0.29	60	0.77	Unaligned
LHAASO[2]	Pulsar	τ_c(kyr)	d (kpc)	$v_{\rm tr}$(km/s)	$\theta_{\rm obs}$(°)	Comment
J2032+4102	J2032+4127	201	1.4[a]	20.4[b]	0.42	Impossible
J1929+1745	J1928+1746	82.6	4.6	-	0.25	$v_{\rm tr}$ > 2700 km/s

Conclusion:

- The morphology of pulsar halos below 10 TeV show double-peak or single-peak with an extended tail, which depends on the electron injection history.
- Due to the short cooling timescale (<50 kyr) of tens TeV electrons, the morphology of pulsar halos above 10 TeV is nearly spherical.
- We do not expect to observe the separation between distant pulsar and halo above 10 TeV with LHAASO or HAWC.