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

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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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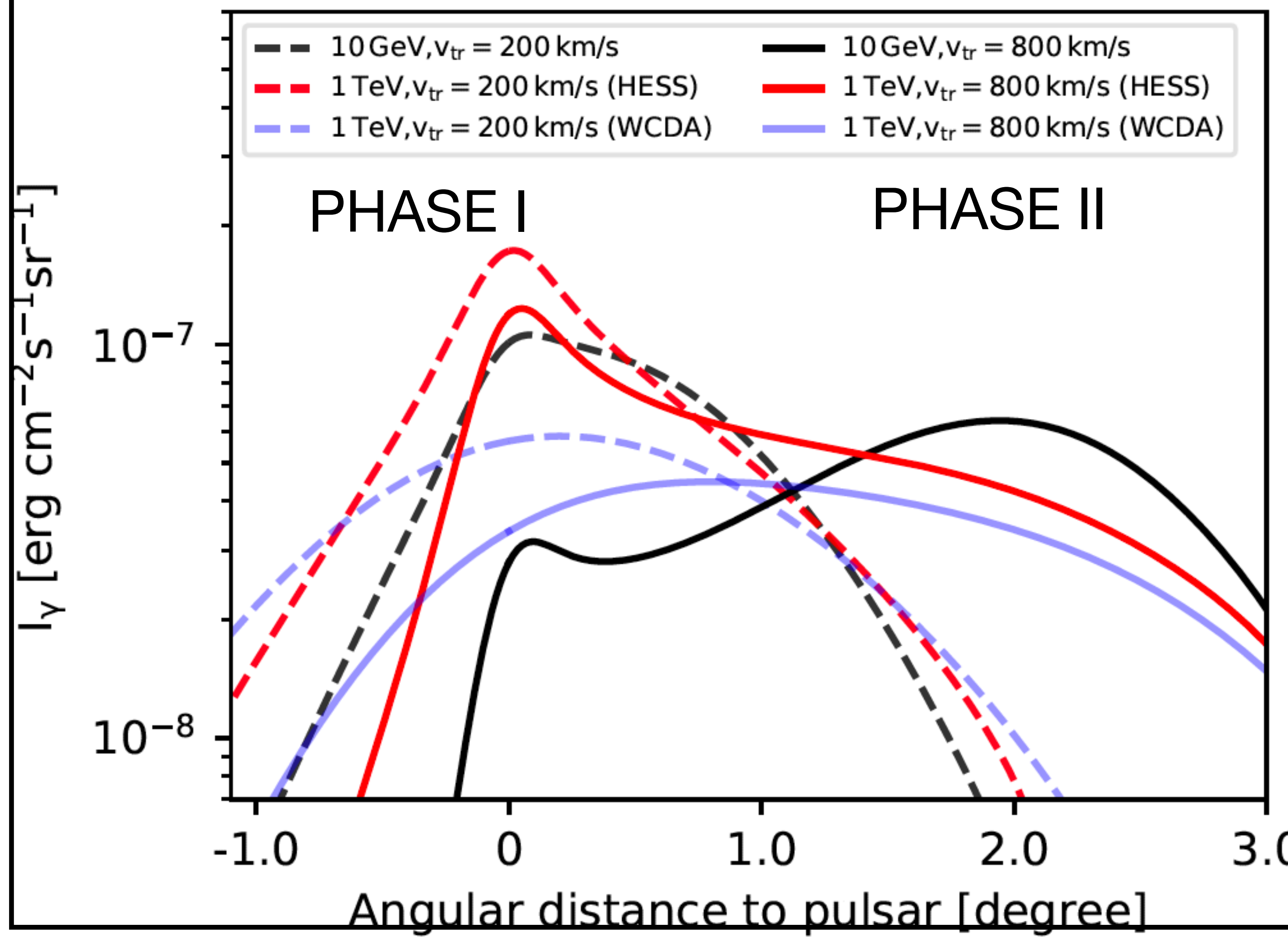
Results:

- Define three evolutionary phases of pulsar halo morphology

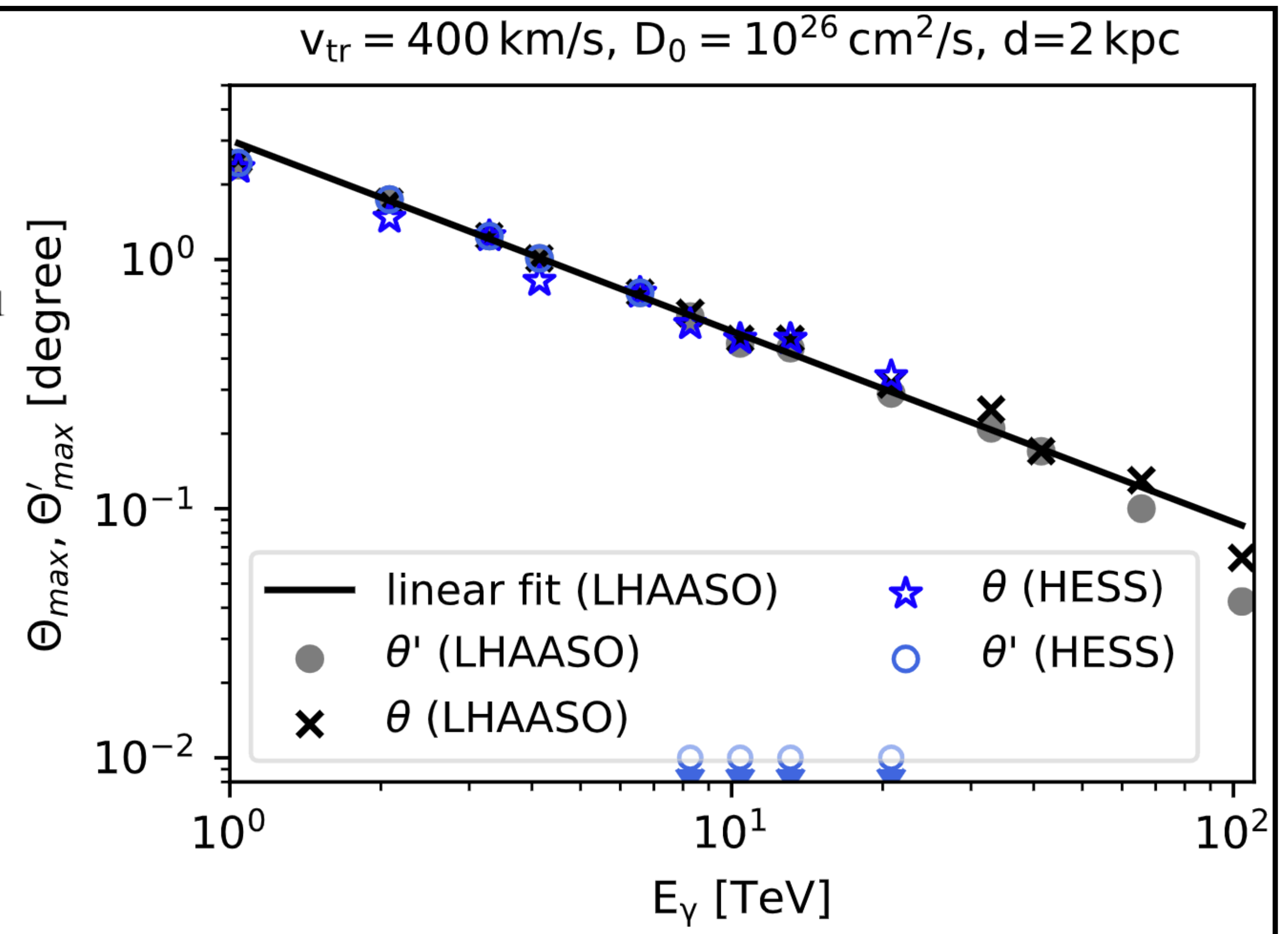
PHASE I : $t_{age}<t_{pd}$, $t_{age}<t_c$, single-peak
PHASE II : $t_{pd}<t_{age}<t_c$, double-peak or single-peak with extension
PHASE III : $t_{age}>t_c$, single-peak

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



- Maximum separation angle

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



- Application to observation

Is the association between extended source and pulsar possible?

3HWC[1]	Pulsar	τ_c(kyr)	d (kpc)	v_{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
LHAASO[2]	**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

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.