X-ray Emission as a Probe of Cosmic Ray Diffusion near Galactic Sources

Qi-Zuo Wu qzwu@smail.nju.edu.cn **Ruo-Yu Liu** ryliu@nju.edu.cn

The transport of VHE/UHE CRs around Galactic sources can become significantly intricate. We introduce our recent work on X-ray emission as a probe of cosmic ray diffusion near galactic sources. For instance, as a leptonic dominated source, the particle transport mechanism in the TeV halos is still in dispute. We calculate the expected X-ray emission from pulsar halos using three diffusion models. We show that the synchrotron radiation can produce a corresponding X-ray halo around the pulsar and that the expected surface brightness profiles (SBPs) are distinct in the three models. We suggest that sensitive X-ray detectors of a large field of view (such as eROSITA and the Einstein Probe) with a reasonably long exposure time are crucial to understanding the formation mechanism of pulsar halos. For hadronic scenario, we investigate the synchrotron radiation from secondary electrons produced in pp collision, assuming protons diffuse in a uniform medium. We find that secondary electrons behave unique spectral index distribution and produce distinctively flat X-ray surface brightness profile. Multi-band analyses, particularly X-ray morphology and spectra, can effectively discriminate between hadronic and leptonic scenarios in galactic sources with certain local environment.

§1: Leptonic Case: Application to Pulsar Halo

- Fitting parameter

Fit γ-ray data and satisfy the X-ray upper limit derived by Chandra, XMM-Newton and eROSITA

Source	Model	D(1 GeV) ($cm^2\ s^{-1}$)	B (μG)	η	Cutoff Energy (TeV)	χ^2
Monogem	ID	1×10^{25}	2	0.017	150	11.7
	B2D	3×10^{28}	1	0.76	100	25.8
	AD	1×10^{28}, $M_A=0.19$	5	0.033	150	11.1
PSR J0622+3749	ID	2×10^{25}	2.5	0.37	150	9.2
	B2D	3×10^{28}	2	12.97	70	18.5
	AD	1×10^{28}, $M_A=0.2$	3	0.17	250	9.5
Geminga	ID	1×10^{25}	0.8	0.04	100	7.0
	B2D	4×10^{28}	0.4	3.04	50	27.7
	AD	1×10^{28}, $M_A=0.19$	5	0.04	200	5.0

- Predicted SED and SBPs (Monogem)

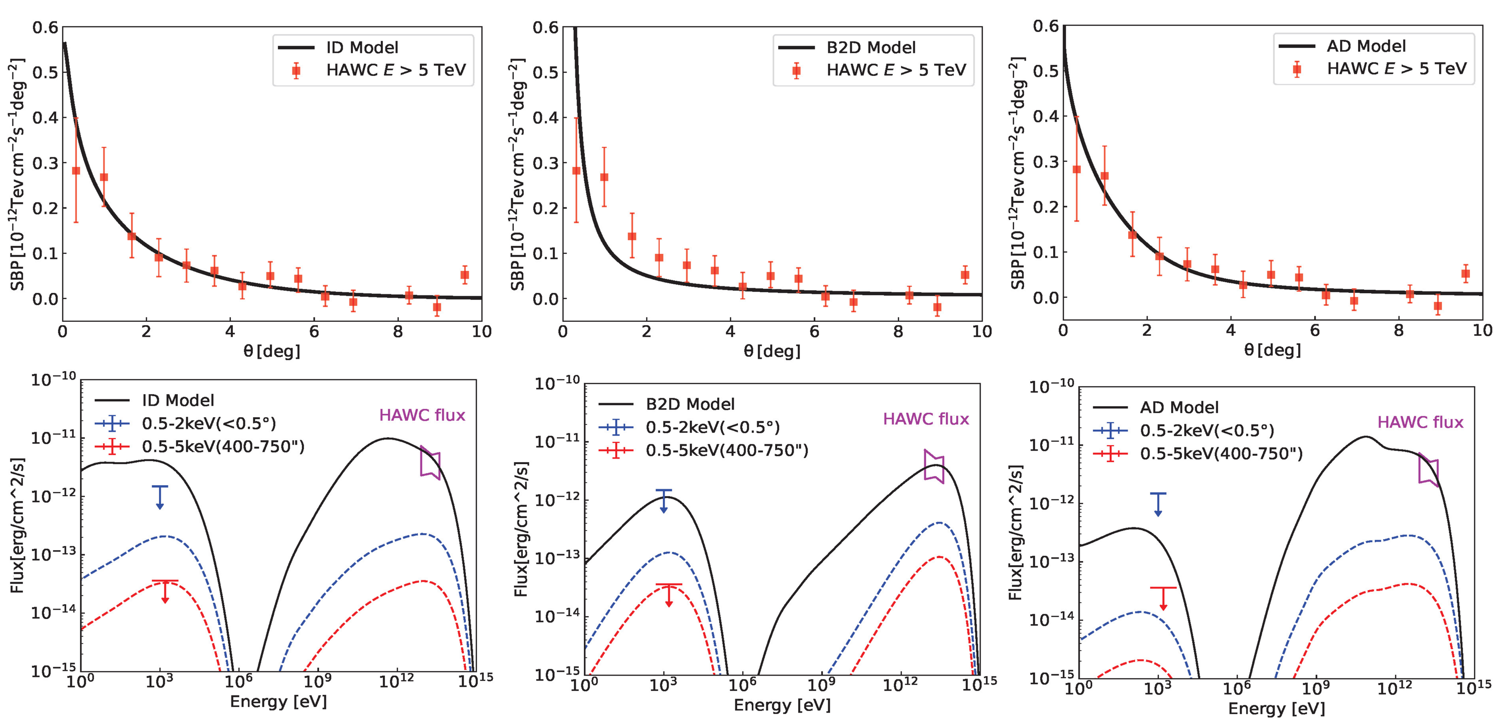


FIG.1.1 The expected SBP in TeV and the energy spectrum of Monogem with the ID model, B2D model, and AD model. Note that the red and blue dashed lines correspond to the flux within 600″ and within a 0°.5 region, respectively..

γ-ray observation is hard to distinguish these models either through the SBP or the energy spectrum.

➢Diffusion model

ID model: two-zone, isotropic diffusion

$$D(r,E)=\begin{cases} D_0\left(\frac{E}{1\mathrm{GeV}}\right)^{1/2}, 0<r<r_b,\\ D_{\mathrm{ISM}}, r\geqslant r_b\end{cases}$$

B2D model: considering the transition of particle transport from ballistic to diffusive regimes [1]

AD model: anisotropic diffusion [2] $D_{zz}=D_{\parallel}=D_{\mathrm{ISM}}$ $D_{rr}=D_{\perp}=D_{\mathrm{ISM}}M_A^4$

- Predicted X-ray SBP

The X-ray SBPs predicted by three models are different.

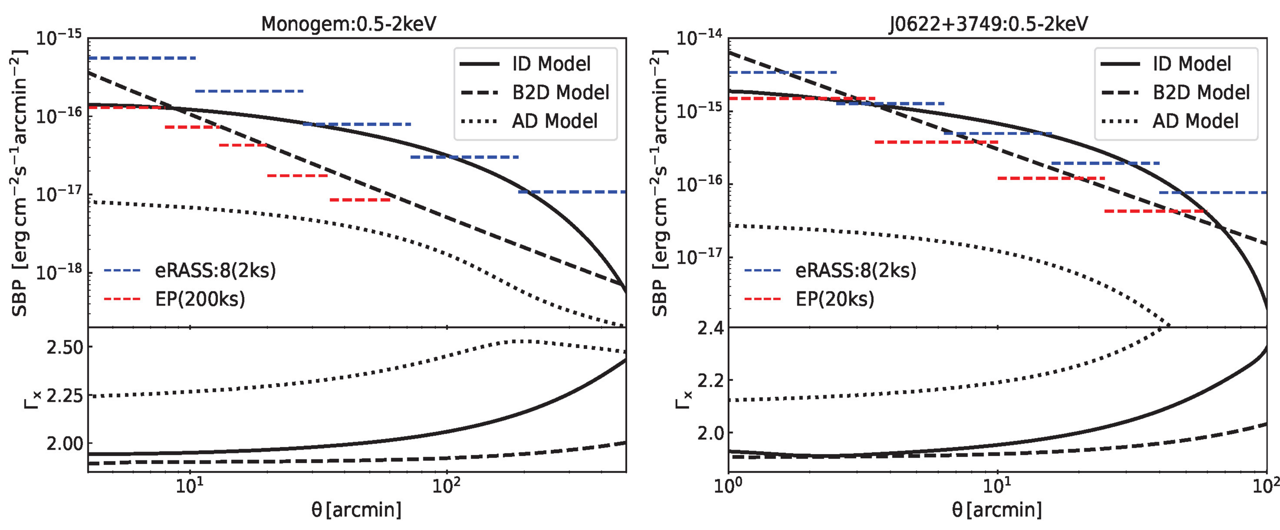
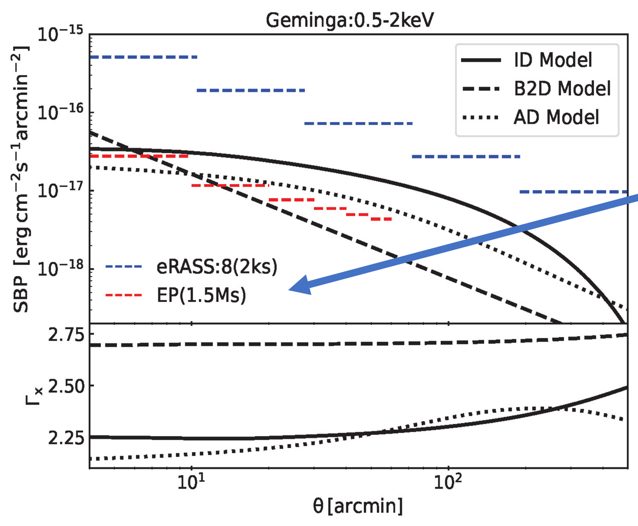


FIG.1.2 The predicted X-ray intensity and photon index with, different models. The blue line: the sensitivity of the eROSITA all-sky survey. The red line: the sensitivity of EP.

In the most optimistic case, observations of EP could differentiate these models with a 200 ks exposure on Monogem and a 20 ks exposure on PSR J0622+3749



The X-ray emission of Geminga's halo is hard to detect given the current constraint on the magnetic field therein.

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§2: Hadronic Case: Propagation and Radiation of Secondary Electrons

➢Production and propagation of Secondary Electrons

We assume protons continuously injected from a point source and diffuse in uniform medium, then we can calculate the injection rate of secondary electrons using the parameterizations of energy spectra in [3]:

$$\frac{dN_e}{dE_e dV dt}=Q_e(E_e,r,t)=c\int_{100\mathrm{GeV}}^{E_p^{\max}} n_{\mathrm{gas}}(r)\sigma_{\mathrm{inel}}(E_p)\times n_p(E_p,r,t)F_e(E_e/E_p,E_p)\frac{dE_p}{E_p}$$

With this ~1/r injection, we can derive the final electrons distribution with diffusion equation:

$$\frac{\partial n_e}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D\frac{\partial n_e}{\partial r}\right)-\frac{\partial}{\partial E_e}(\dot{E}_e n_e)+Q_e(E_e,r,t)$$

Finally, we can obtain the corresponding Synchrotron and γ-ray emission from Pion-decay.

- Spectral index of secondary electrons

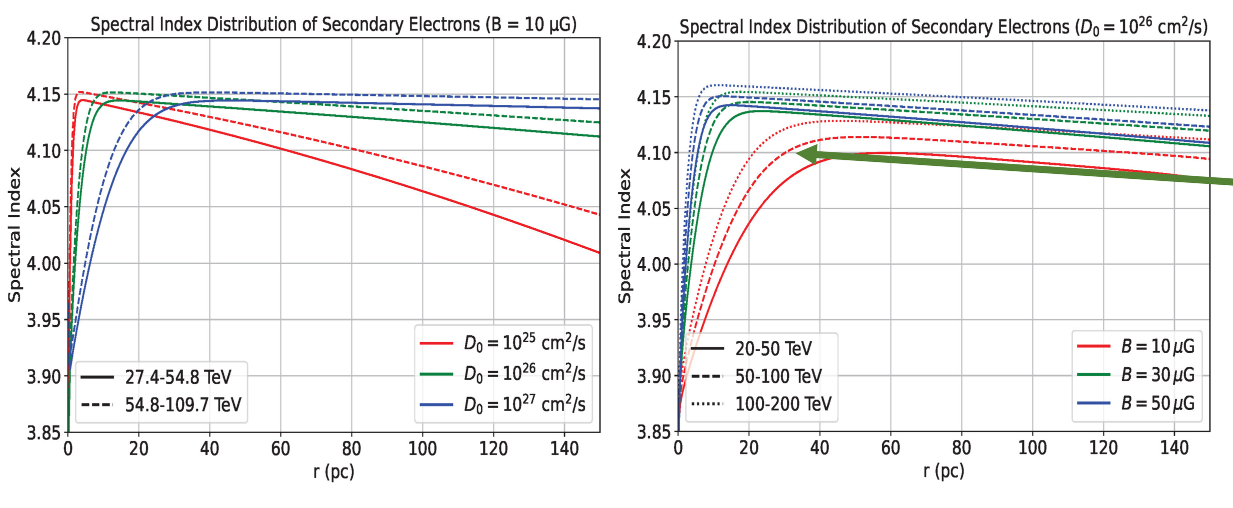

FIG.2.1 Spectral index distribution of secondary electrons. Left: case for different diffusion coefficient. Right: case for different magnetic field. The spectral index of electrons softens rapidly at first, then gradually hardens.

Rapidly soften: Dominated by electrons diffusing from the central dense region. **Cooling of electrons.**

Break point r_c : Positively correlated with the diffusion length R_{dif} of electrons

Gradually harden: Dominated by electrons locally injected. **Deviation of the injected electrons from the steady 1/r distribution (*erfc* term)**

- Identify X-ray/γ-ray origin via X-ray SBP

With appropriate parameters, the hadronic and leptonic models can have similar flux in X-ray and TeV band.

Very flat SBP: selecting a background near the source may subtract a significant portion of the source's contribution. **Also help to identify the X-ray origin.**

If future wide-field X-ray telescopes confirm the hadronic origin of X-ray, it could imply that the gamma radiation also has a hadronic origin.

This manuscript is to be submitted. Feedback and comments are welcome.

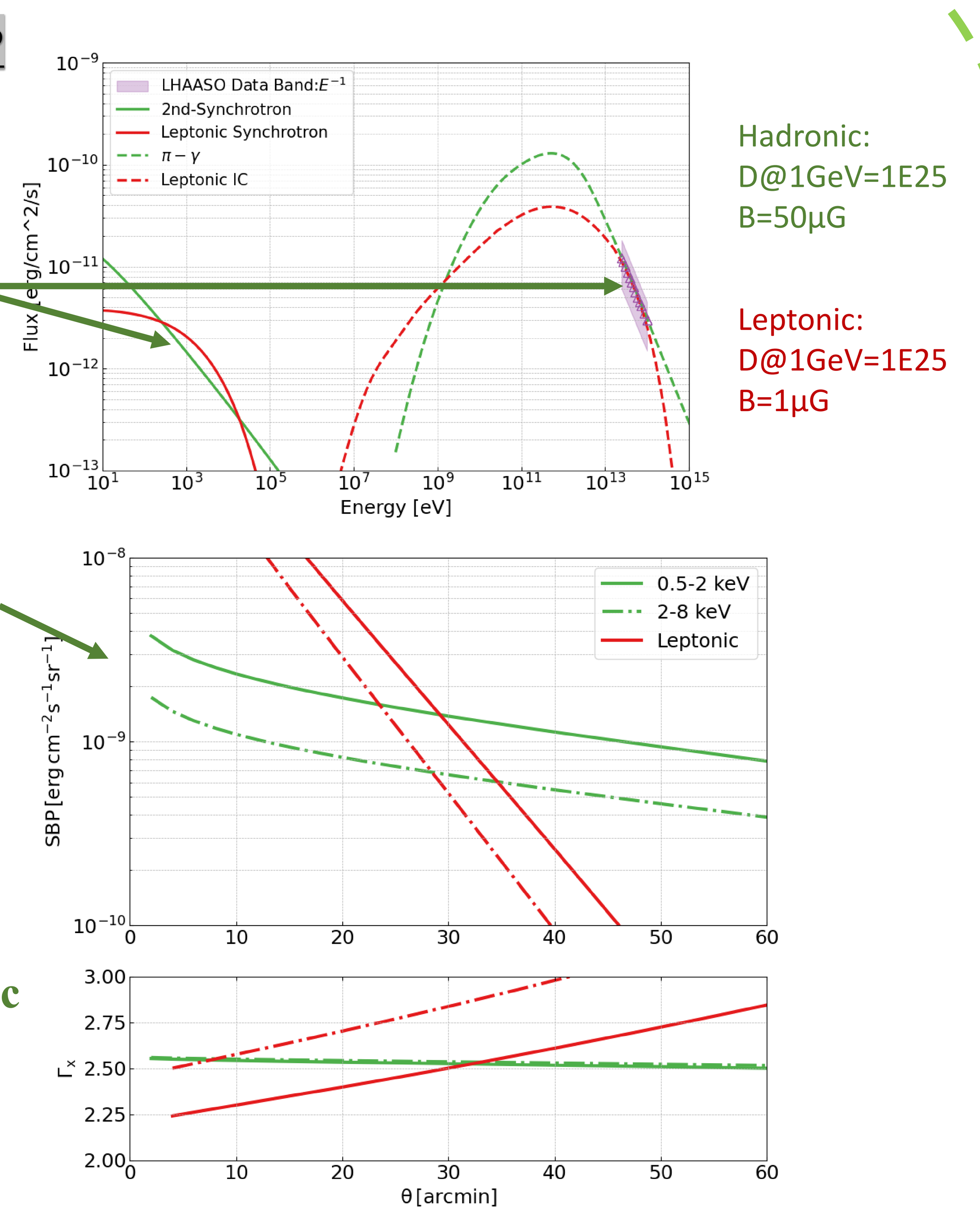

FIG.2.2 Spectrum and X-ray SBP for hadronic and leptonic scenario. Adjust the parameters so that the 25-100 TeV energy spectrum follows E^{-1} (similar to LHAASO observation), and ensure that the X-ray flux is similar in both scenarios.

➢**Conclusion**

(1) For leptonic case, X-ray observation could be helpful to distinguish the transport mechanism in TeV halos between different models.

(2) For hadronic case, secondary electrons behave unique spectral index distribution and produce flat X-ray surface brightness profile. The features of the profile could be used to identify the origin of X-ray and γ-ray emission of galactic sources.

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