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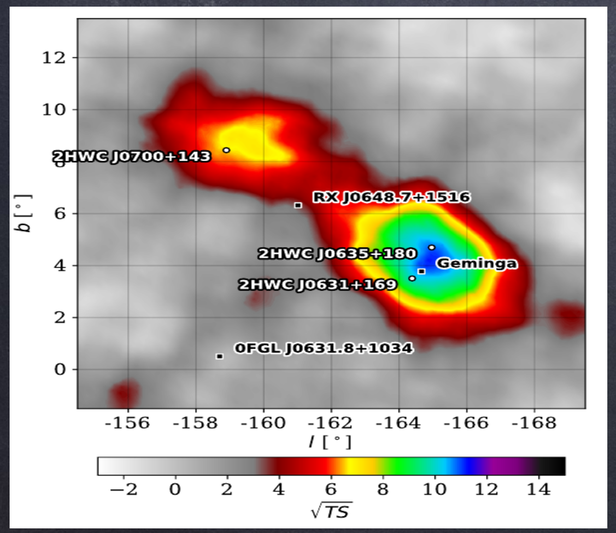
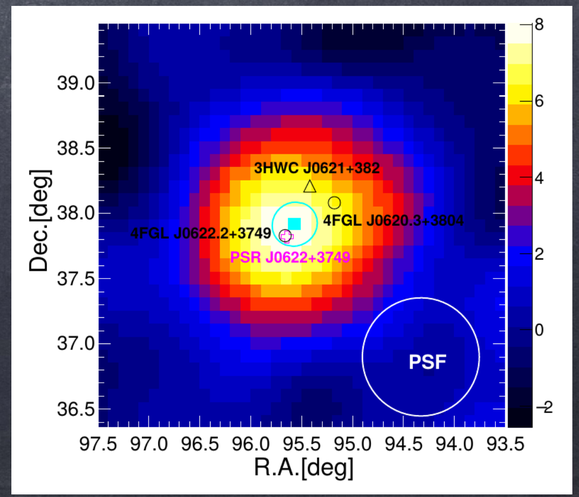
Cosmic ray propagation in the proximity of sources

TeV halos in the era of CTAO and ASTRI



Sarah Recchia

INAF Brera(Merate)



Summary

Amato & Recchia 2024 - review TeV halos

- TeV halos detected around middle-aged pulsars (HAWC, LHAASO)
- mot understood with current transport models
- new window on CR propagation at multi-TeV
- many open questions
- what ASTRI Mini-Array could do - superior angular resolution

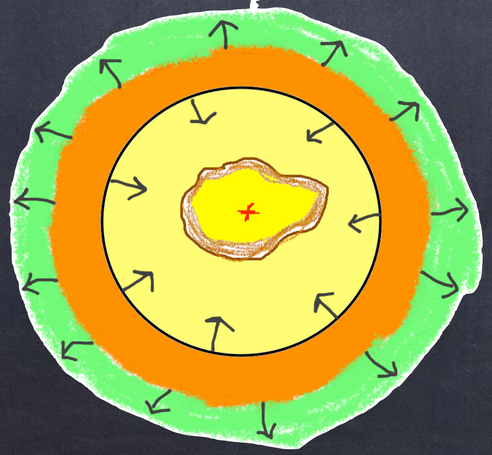
Pulsars and their nebulae

- fast rotating highly magnetized NS —> extracted e^-
- copious pair production in magnetosphere
- magnetized relativistic wind —> spin down $\dot{E}$
- outflow slow down due to ambient medium (SNR, ISM)
- termination shock —> bright non-thermal emission PWN
- TS powerful accelerator (high efficiency, close to $E_{\rm max}$)

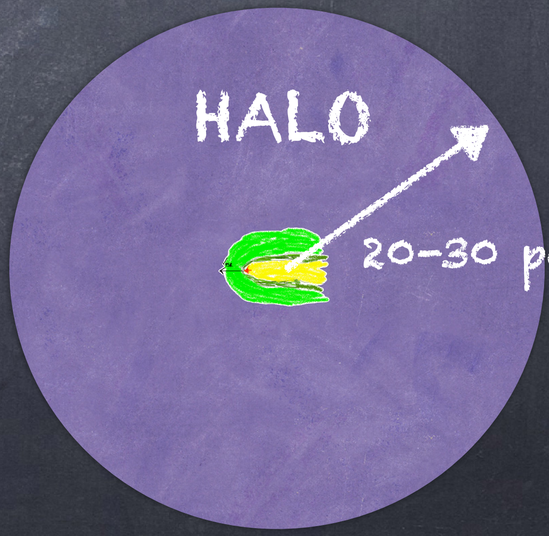
Pulsars and their nebulae

- $e^{\pm}$ pairs confined in PWNe before release in ISM
- Cannot leave system while pulsar is in SNR
- proper motion $v_{\rm psr} \sim 100s\,{\rm km/s}$ ⟶ out of SNR $\approx 10s\,{\rm kyr}$
- Bow shock ⟶ particle release in ISM

in-SNR phase

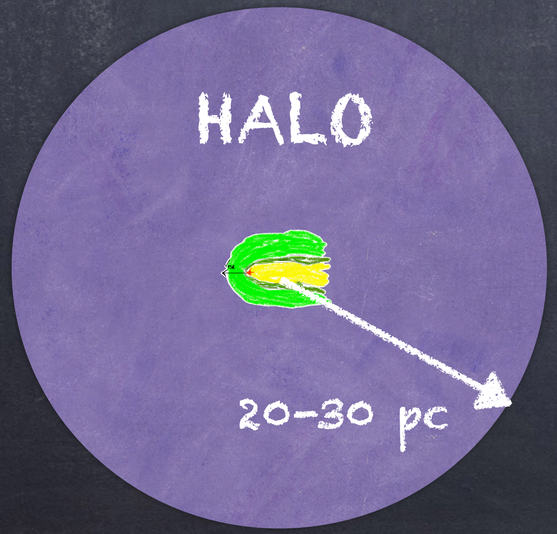


bow-shock phase

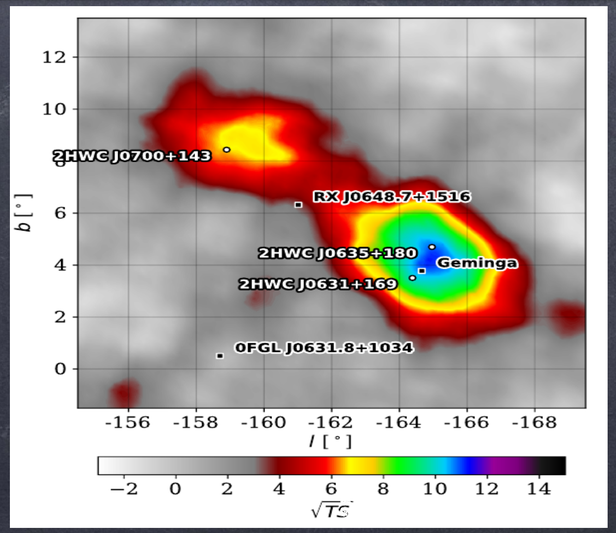


Bow-shock PWNe and TeV halos

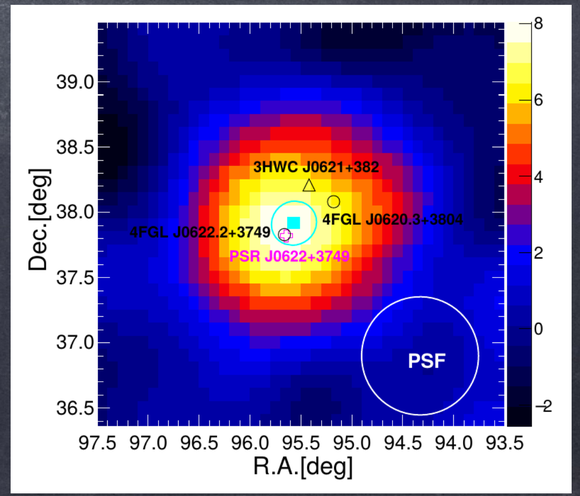
- Consider only middle-aged pulsars that are out of SNR
- diffuse in ISM to d >> PWNe (tens pc VS $\lesssim$ pc)
- ICS on CMB ——> TeV emission ($e^{\pm}$ of 10s-100s TeV)
- Clean probe of CR transport in multi-TeV particles



HAWC: Geminga-Monogem



LHAASO: PSR J0622+3749

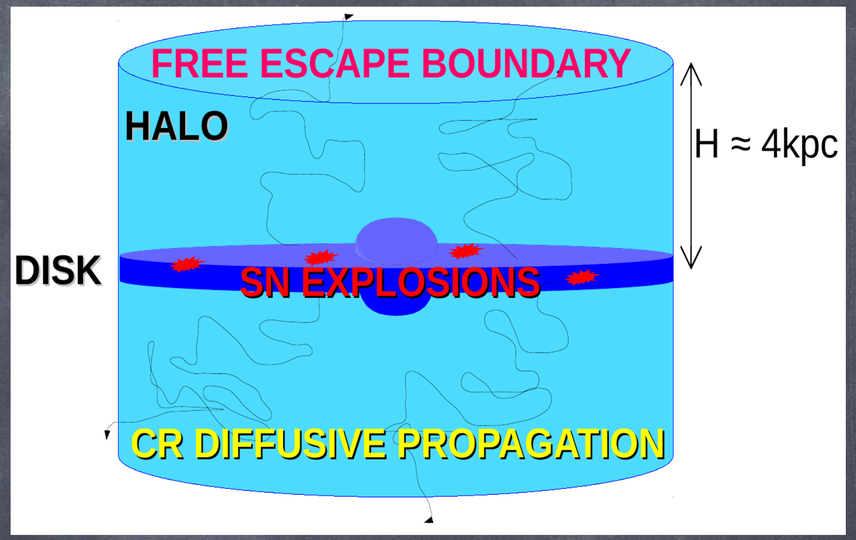


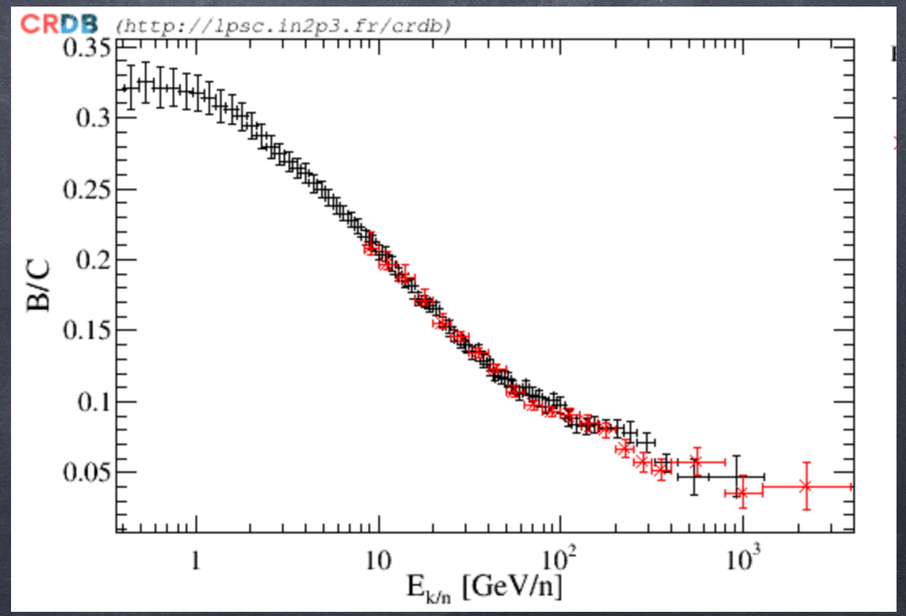
CR transport physics and data

- secondary /primary
- unstable isotopes
- diffusion in Galactic halo ~ few kpc
- high energy less confined
- $D(E) \propto E^{0.3...0.7}$
- magnetic confinement

$$r_L \approx 10^{-6}\,\mathrm{pc}\,\mathrm{E_{GeV}/B_{\mu G}}$$

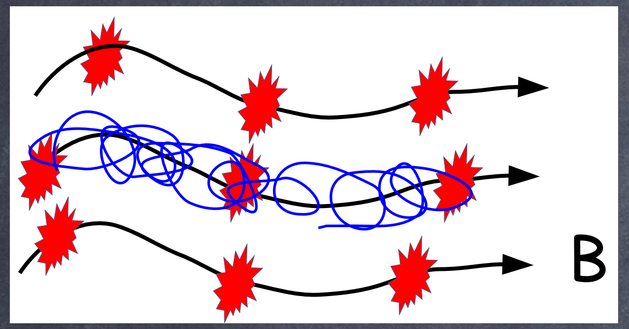
Gabici et al. 2019 - review CRs





CR transport physics and data

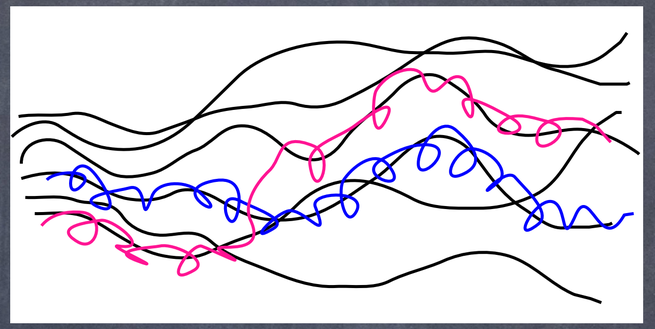
parallel diffusion



- CR gyromotion
- scattering off waves
- $k \sim 1/r_L$ (resonance)
- scattering mean free path $\lambda_{\rm mfp}$
- $D_{\parallel}(E) \propto \lambda_{\rm mfp}$

Mertsch 2020 - review turbulence & transport

perp. transport



- field line walk
- CR jump between lines
- large-scale perp diffusion
- $D_{\perp}(E) \lesssim D_{\parallel}(E)$

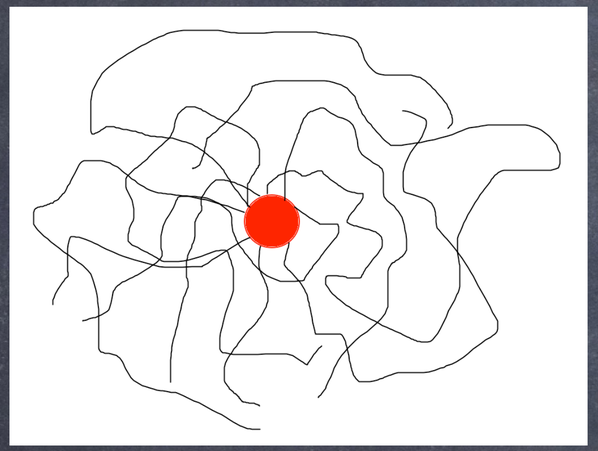
Schalchi 2020 - review perp. Transport

MHD turbulence

- source injection (10s pc)
- cascade to $k \sim 1/r_L$?
- damping?
- Produced by CRs ?

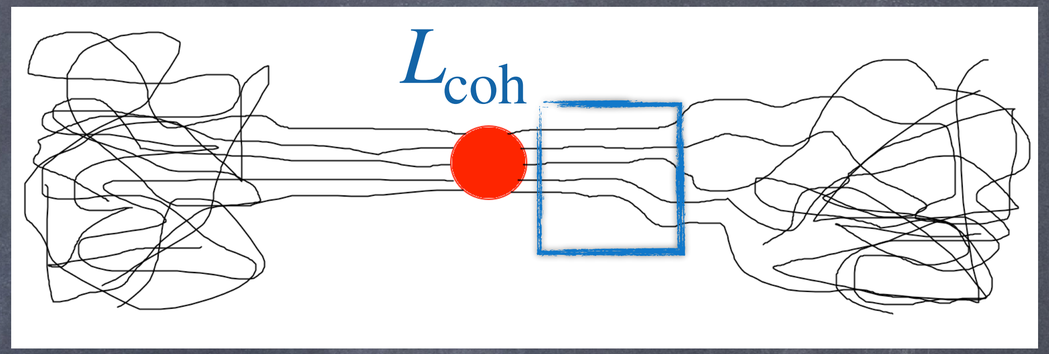
CR transport around sources

highly turbulent ISM



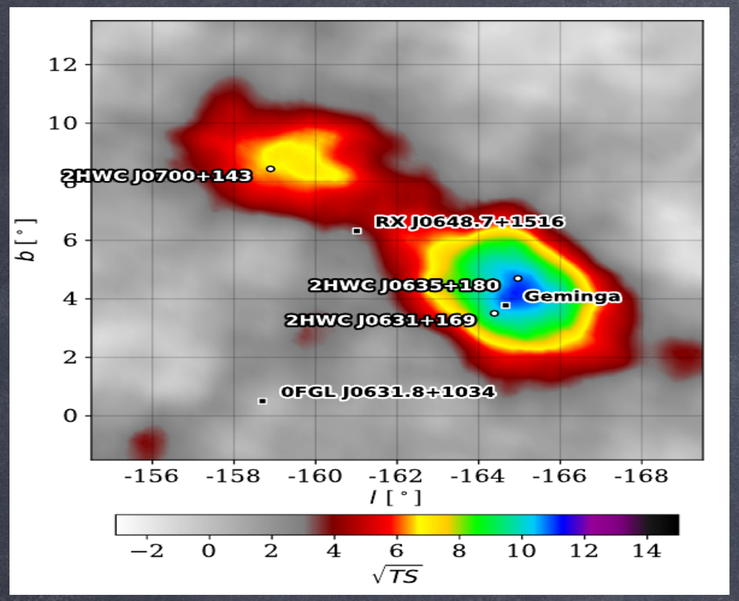
- small $L_{\rm coh}$ << size
- 3D isotropic diffusion
- Small D
- spherical morphology

anisotropic transport



- $L_{\rm coh} \gtrsim$ size
- typical $D_{\parallel}$, $D_{\perp} \ll D_{\parallel}$
- emission morphology depends on flux-tube orientation
- elongated structures

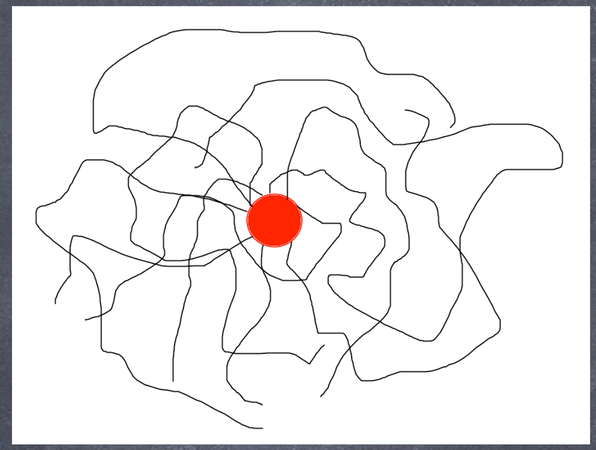
CR transport - TeV halos



- 10-200 TeV $e^{\pm}$, ICS on CMB
- $E_e \sim 100\,\mathrm{TeV}$, $E_\gamma \sim 20\,\mathrm{TeV}$
- age ~ 100s kyr
- distance ~ 300 pc
- 10s pc extension

$D_{\mathrm{ISM}}(100\mathrm{TeV}) \approx 10^{30}\ \mathrm{cm}^2/\mathrm{s}$

highly turbulent ISM

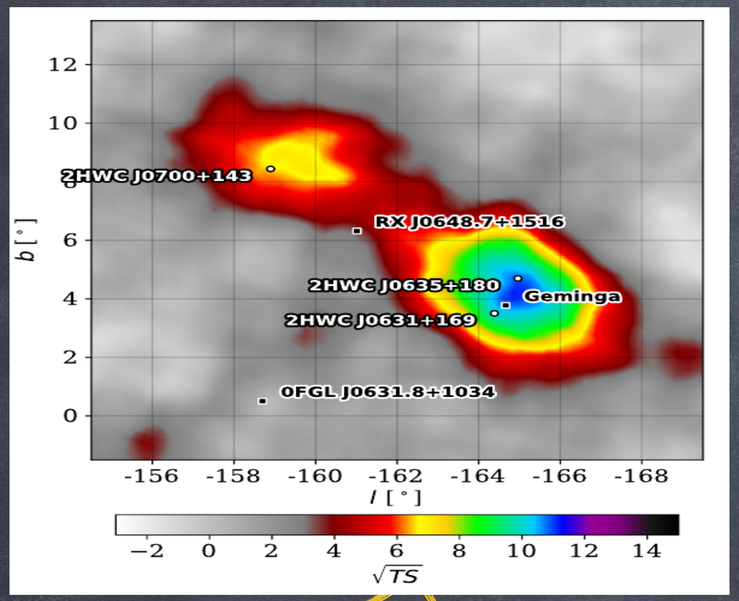


$D_{\mathrm{halo}}(100\mathrm{TeV}) \approx 10^{27}\ \mathrm{cm}^2/\mathrm{s}$

- small L_{coh} << size ⟶ small λ_{mfp}
- 3D isotropic diffusion & small D
- energy losses CMB/B $\tau_{\mathrm{CMB}} \approx 10\,\mathrm{kyr}$

$$R_{\mathrm{halo}} \sim \sqrt{4D\tau_{\mathrm{CMB}}} \sim 30\mathrm{pc}\sqrt{D_{27}\tau_4}$$

CR transport - TeV halos



$D_{ISM}(100TeV) \approx 10^{30}\ cm^2/s$

$D_{halo}(100TeV) \approx 10^{27}\ cm^2/s$

- highly turbulent region around some PSR
  - filling factor? extension?
  - how many halos?
- anisotropic diffusion
  - need small ψ_{incl} for spherical halo
  - chance? morphology?
  - look for features?
- self-generated turbulence
  - Difficult even with flux-tube and high efficiency
  - problems with morphology

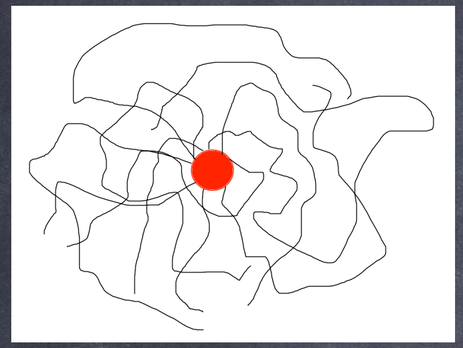
Martin et al. 2022

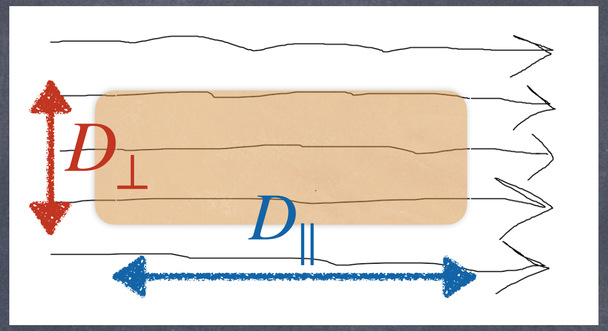
CR transport - TeV halos

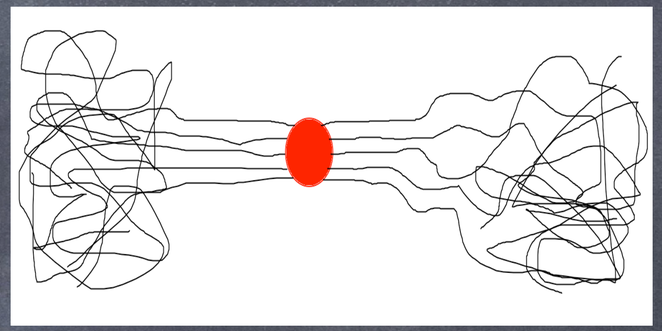
3D isotropic diffusion

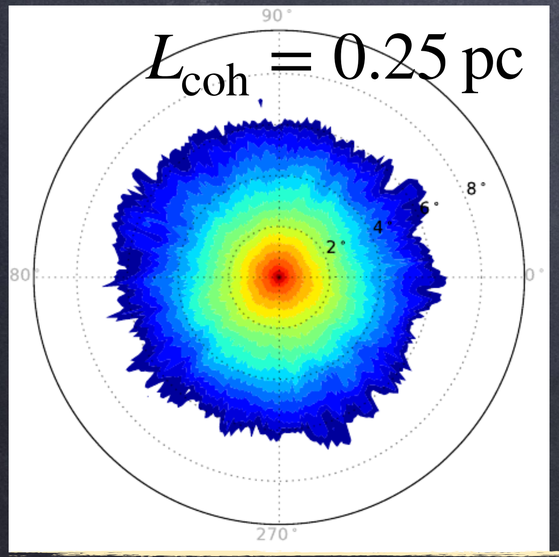
anisotropic diffusion

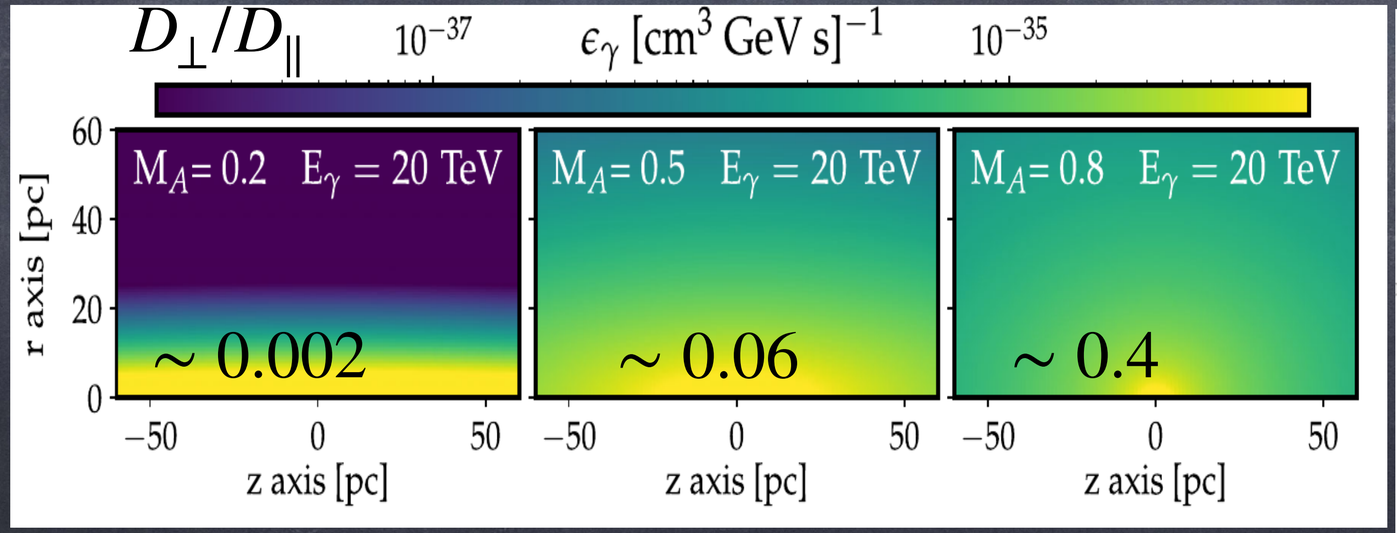
more realistic setup?

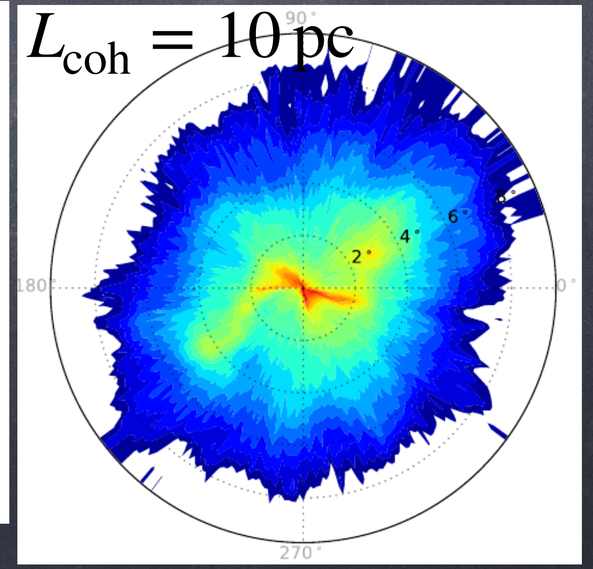










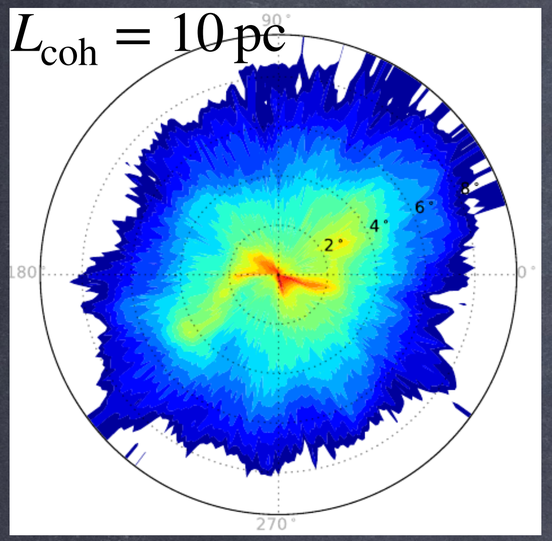


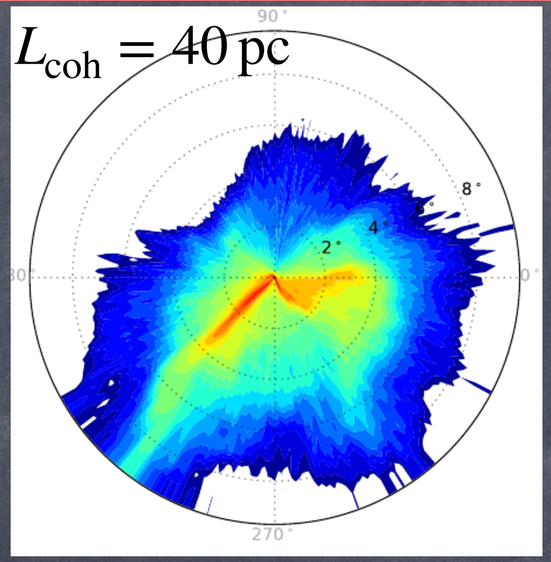
Lopez-Coto & Giacinti 2018

De La Torre et al. 2022

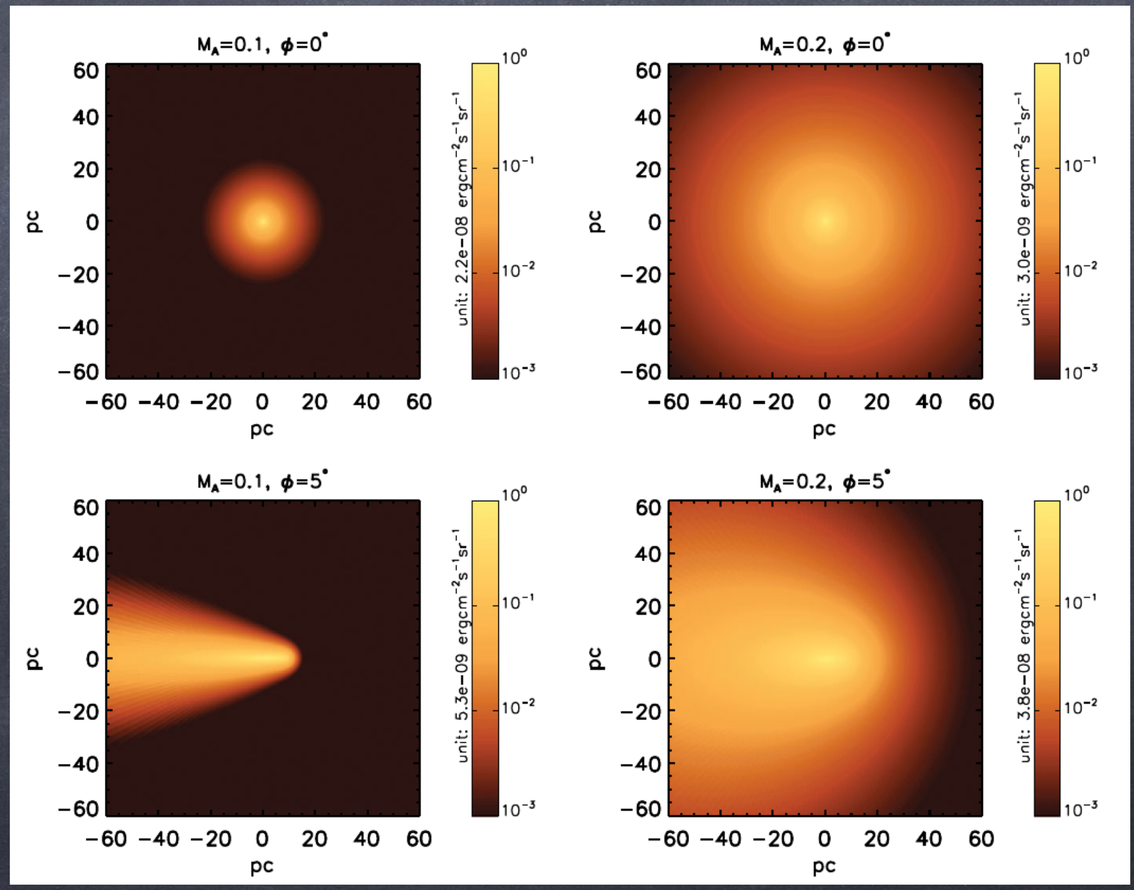
CR transport - TeV halos

FEATURES OF ANISOTROPIC DIFFUSION



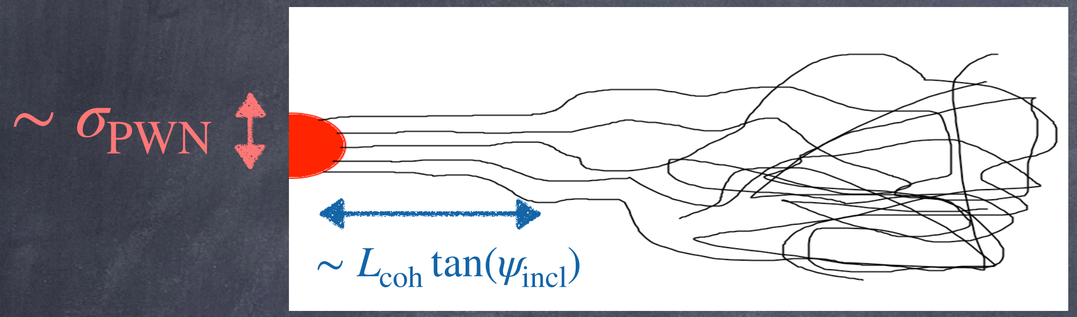


Liu et al. 2019



- non-spherical emission
- orientation of B field
- separation γ-ray source - pulsar
- filamentary structures

Possibilities with ASTRI Mini-Array



ASTRI science paper 2022

	ASTRI Mini-Array	HAWC	LHAASO
Location	28° 18′ 04″ N 16° 30′ 38″ W	18° 59′ 41″ N 97° 18′ 27″ W	29° 21′ 31″ N 100° 08′ 15″ E
Altitude [m]	2,390	4,100	4,410
FoV	~ 10°	2 sr	2 sr
Angular Res.	0.05° (30 TeV)	0.15°[a] (10 TeV)	(0.24–0.32)°[b] (100 TeV)
Energy Res.	12% (10 TeV)	30% (10 TeV)	(13–36)% (100 TeV)[b]
Energy Range	(0.3-200) TeV	(0.1-1000) TeV	(0.1-1000) TeV

$\sigma_{\rm PWN} \lesssim 1$ pc

- $\theta \lesssim 0.2^\circ$ (d = 300 pc)
- $\theta \lesssim 0.02^\circ$ (d = 3 kpc)

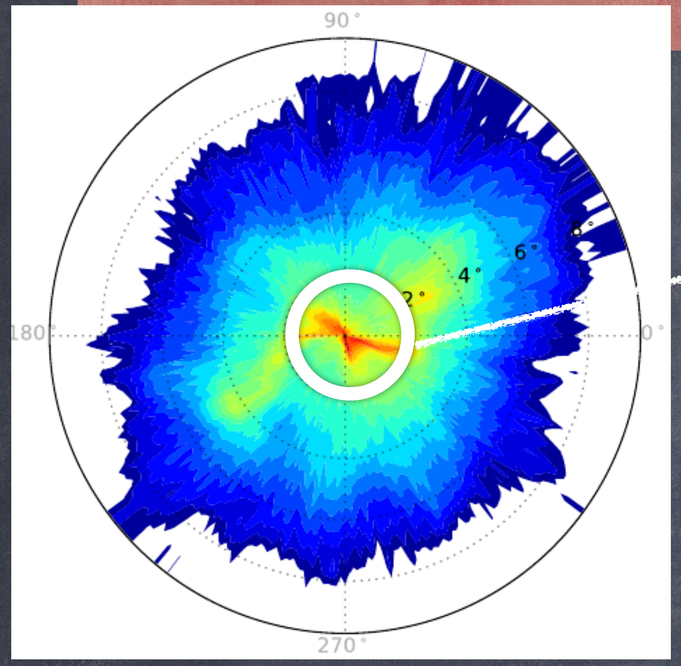
$L_{\rm coh} \approx 10 - 20$ pc

- $\theta \lesssim 2 - 4^\circ$ (d = 300 pc)
- $\theta \lesssim 0.2 - 0.4^\circ$ (d = 3 kpc)

halo asymmetry

- $\propto \sqrt{D_\parallel / D_\perp}$
- L/H $\approx 3 - 10$

Possibilities with ASTRI Mini-Array



2°

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Energy Range	(0.3-200) TeV	(0.1-1000) TeV	(0.1-1000) TeV

- superior angular resolution
- discriminating morphological features
  - filamentary structures
  - separation pulsar - TeV source
  - asymmetry in halo shape

- need for targeted analyses on Geminga-like pulsars
- bias on spherical shape?
- go beyond analyses that assume spherical symmetry

Thank you - references

1. HAWC paper (2017) https://doi.org/10.1126/science.aan4880
2. LHAASO paper (2021) https://doi.org/10.1103/PhysRevLett.126.241103
3. Gabici et al. (2019) https://doi.org/10.1142/S0218271819300222
4. Mertsch (2020) https://doi.org/10.1007/s10509-020-03832-3
5. Shalchi (2020) https://doi.org/10.1007/s11214-020-0644-4
6. Lopez-Coto & Giacinti (2018) https://doi.org/10.1093/mnras/sty1821
7. Liu et al. (2019) https://doi.org/10.1103/PhysRevLett.123.221103
8. De la Torre et al. (2022) https: //doi.org/10.1103/PhysRevD.106.123033
9. Evoli et al. (2018) https://doi.org/10.1103/PhysRevD.98.063017
10. Mukhopadhyay & Linden (2022) https: //doi.org/10.1103PhysRevD.105.123008
11. Martin et al. (2022) https://doi.org/10.1051/0004-6361/202243481
12. ASTRI science paper (2022) https://doi.org/10.1016/j.jheap.2022.05.005