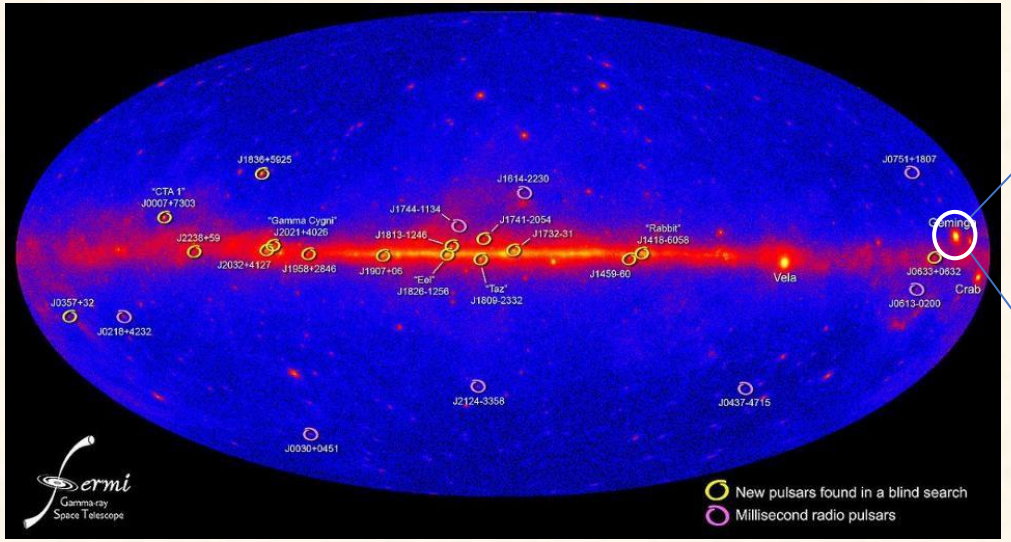
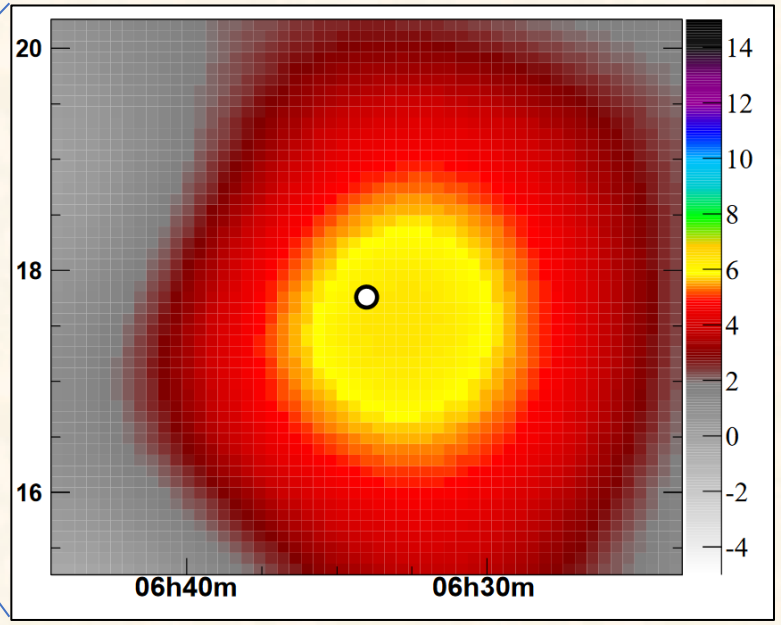
Based on ArXiv: 2205.08544

Anisotropic diffusion cannot explain TeV halo observations





Pedro de la Torre Luque OKC, Stockholm University pedro.delatorreluque@fysik.su.se

TeV halos – a few observations

Unexpected emission at high energies around PWNe :

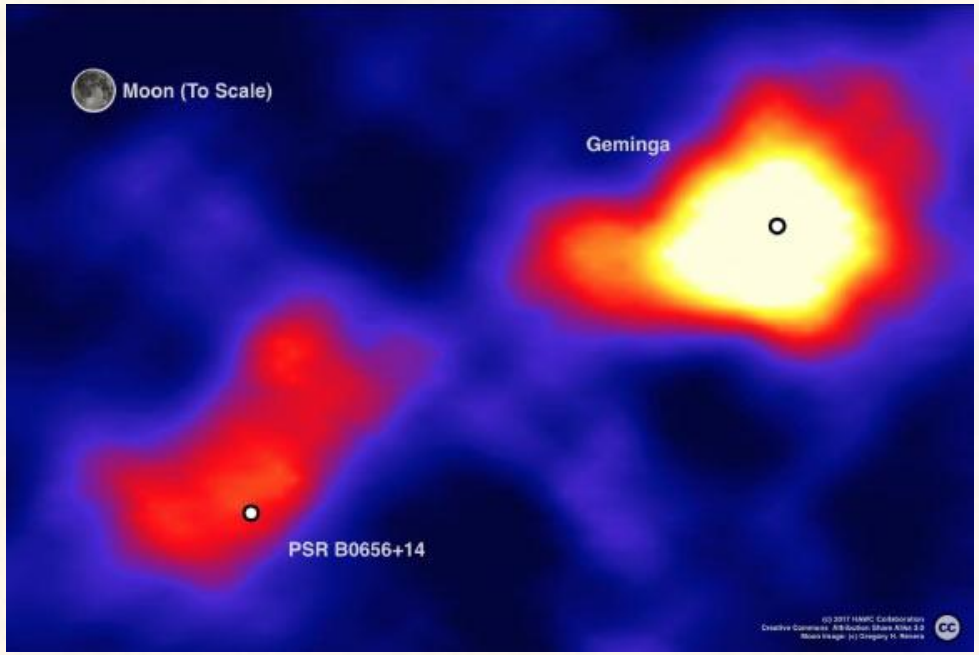
- PWN ~ 0.1 pc - few pc
- TeV halo Geminga 25 pc (2º)

Gamma-ray spectrum well compatible with **IC emission**

Emission profile ~1/r (**diffusive profile**)
Nevertheless, much less extended than expected assuming the typical **Diff. Coeff**. (**100 times smaller**)

A few TeV halos have been found - **all of them seem to be symmetric and explained by a similar Diff. Coeff.**

Abysekara et al. 2017



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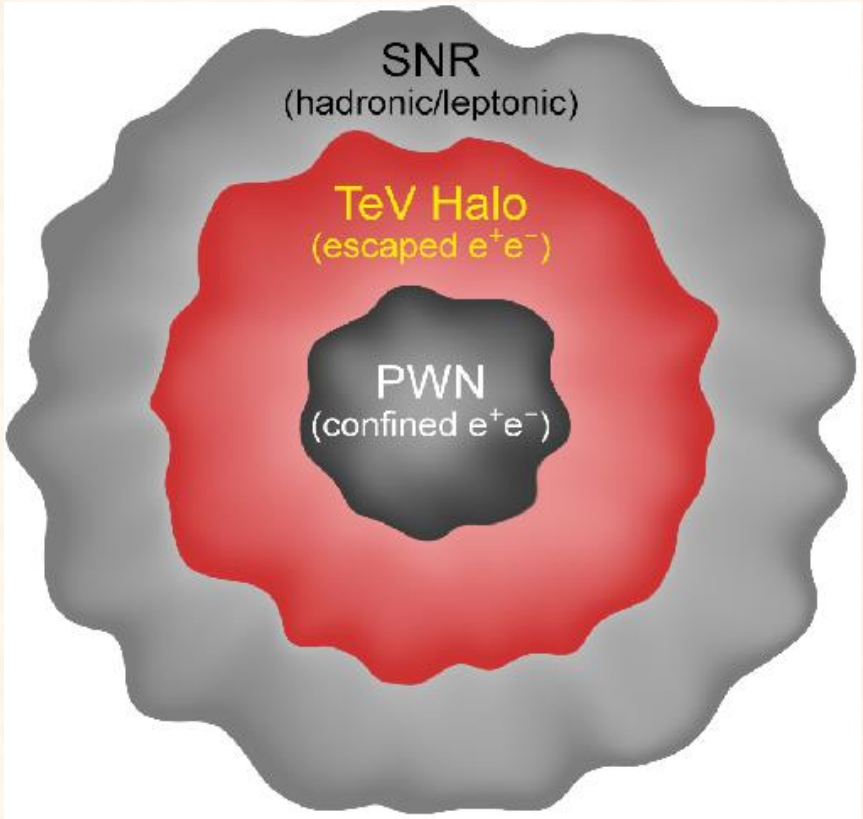

TeV halos – a few observations

Different theories try to explain the origin of these halos

- Ballistic propagation (Recchia et al. PRD 104, 123017, 2021)
- Self-generation of turbulence (Evoli et al. PRD 98, 063017, 2018)
- Anisotropic diffusion (Ruo-Yu Liu et al. PRL 123, 221103, 2019)

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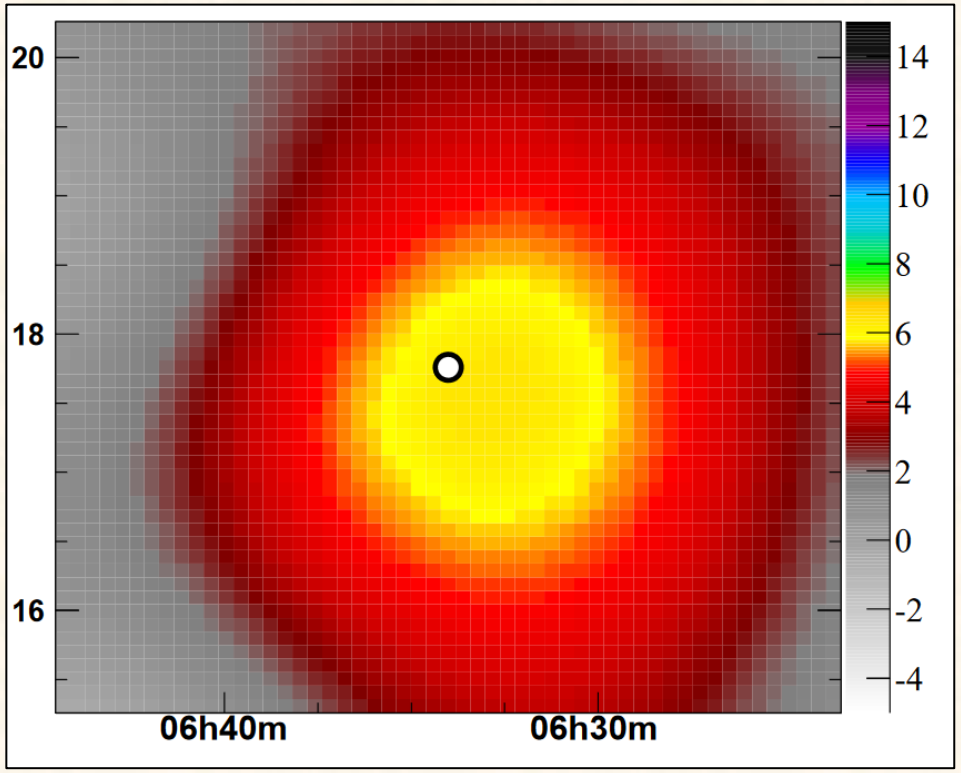

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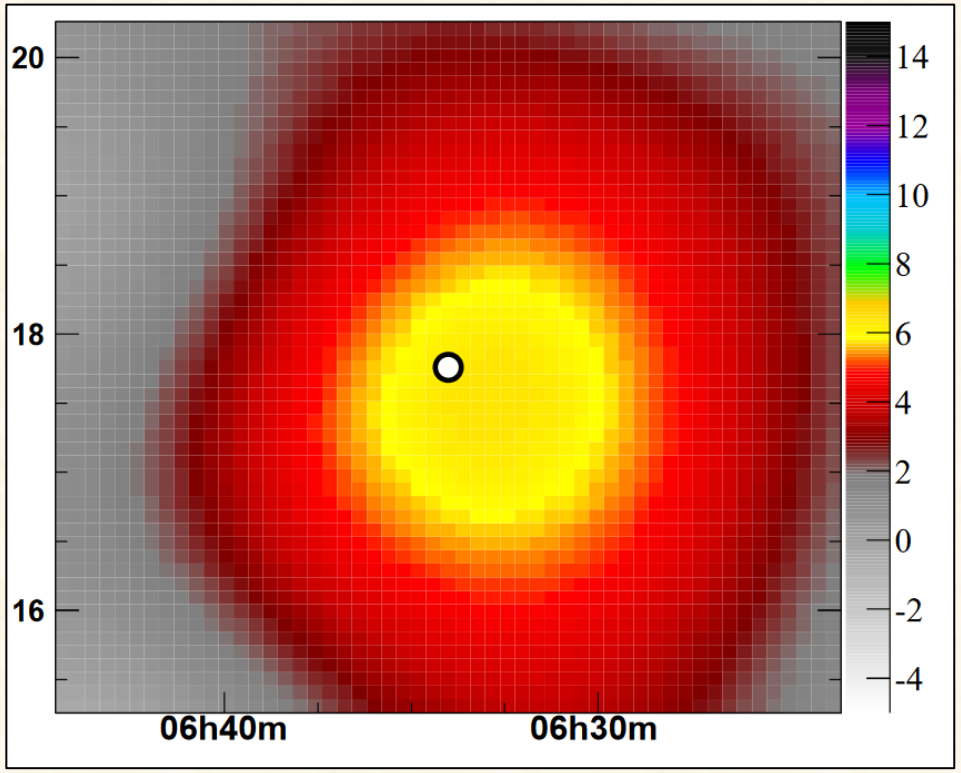

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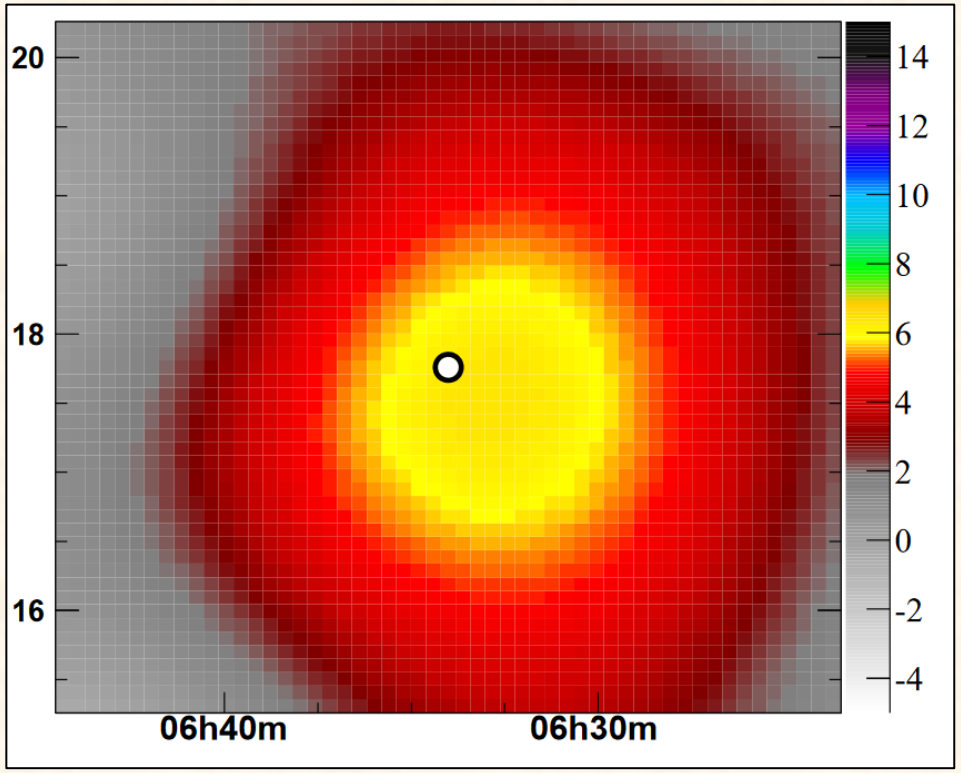

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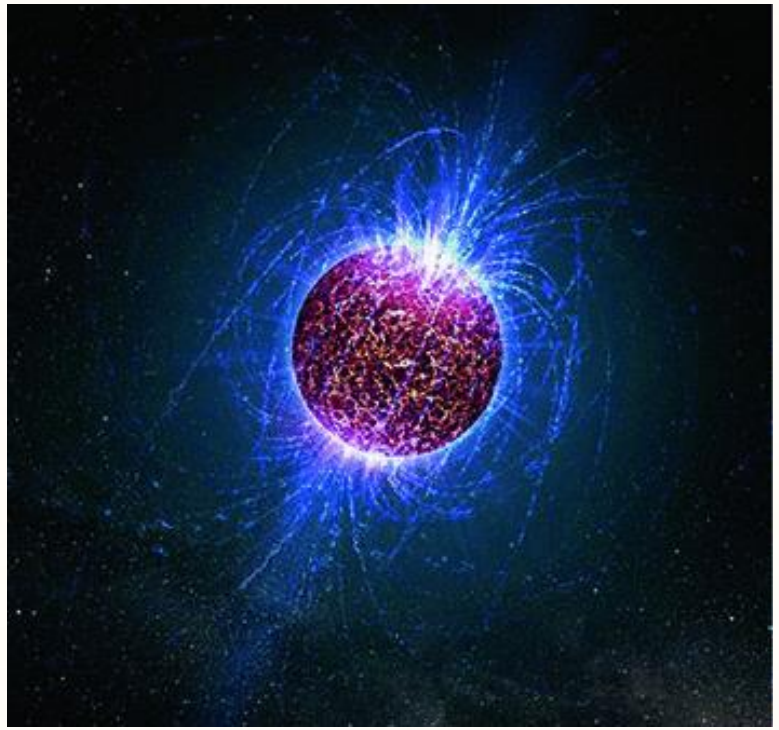

In the vicinity of the source, the **magnetic field** resembles a dipole, so that the magnetic lines follow the direction of the poles (**z axis**).

Propagation of particles along the lines (parallel to the **B** direction) is faster than in the **perpendicular direction** (**r axis**), creating a cylindrically symmetric diffusion around the PWN (around the z axis)

Yan et al. ApJ, 673:942-953, 2008

$$\boldsymbol{D_r} = X\,\boldsymbol{D_z} \;\; ; \;\; X = M_A^4$$

M_A → Alfvenic Mach number

$$M_A \sim \left.\frac{\delta B}{B_0}\right|_{L_{Inj}}$$

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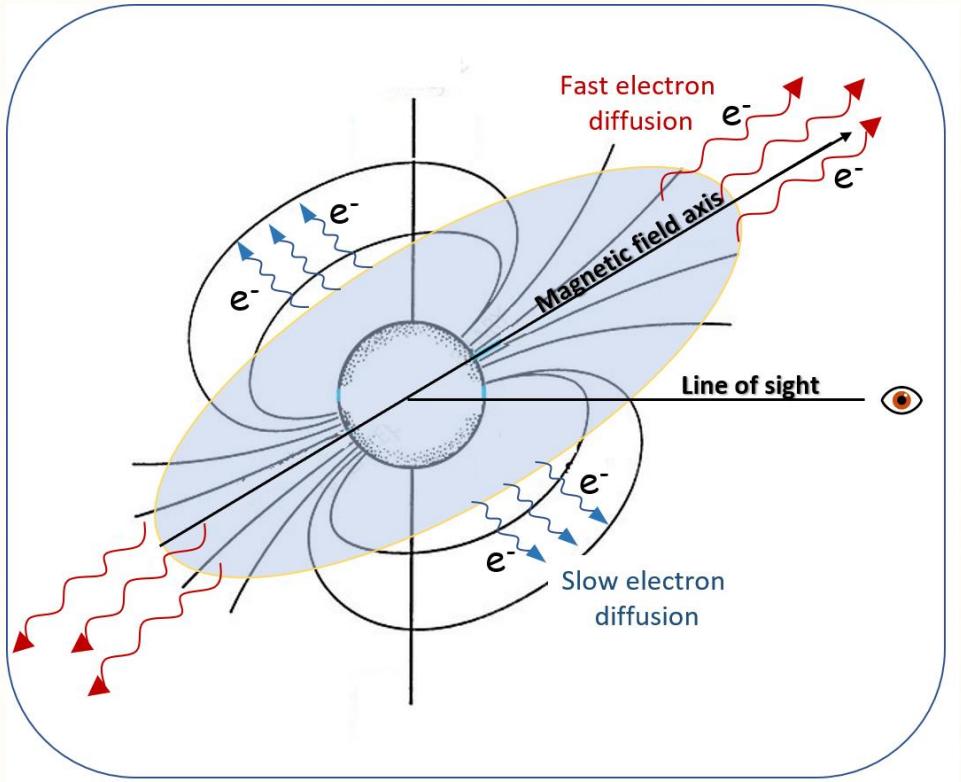

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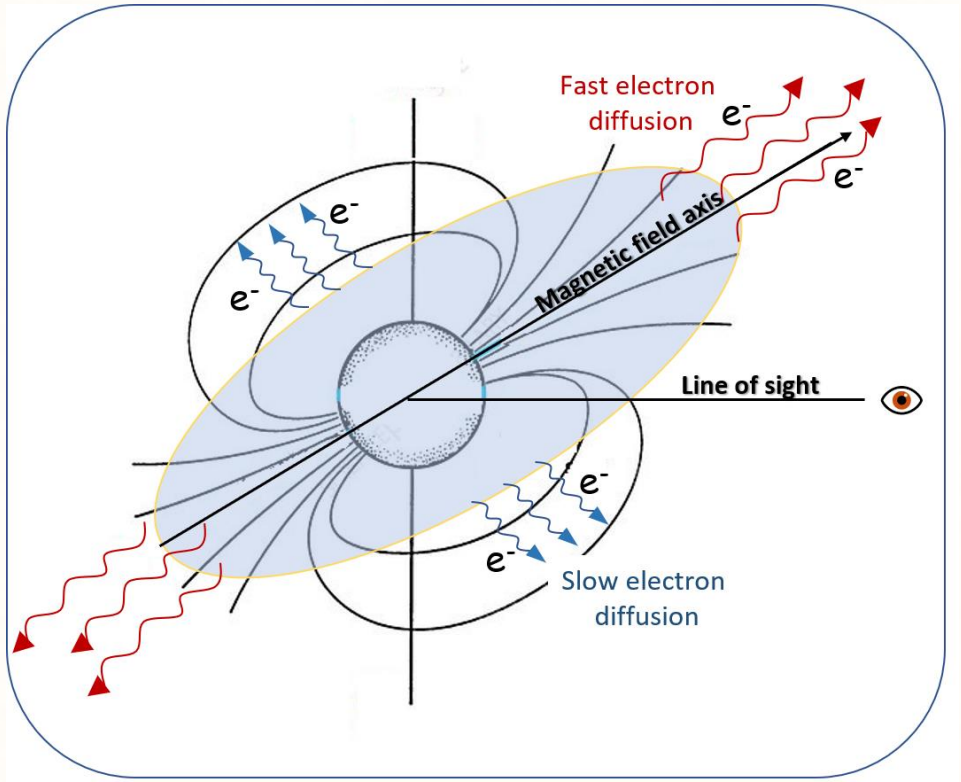

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Can it explain TeV halos for normal values of the diffusion coefficient?

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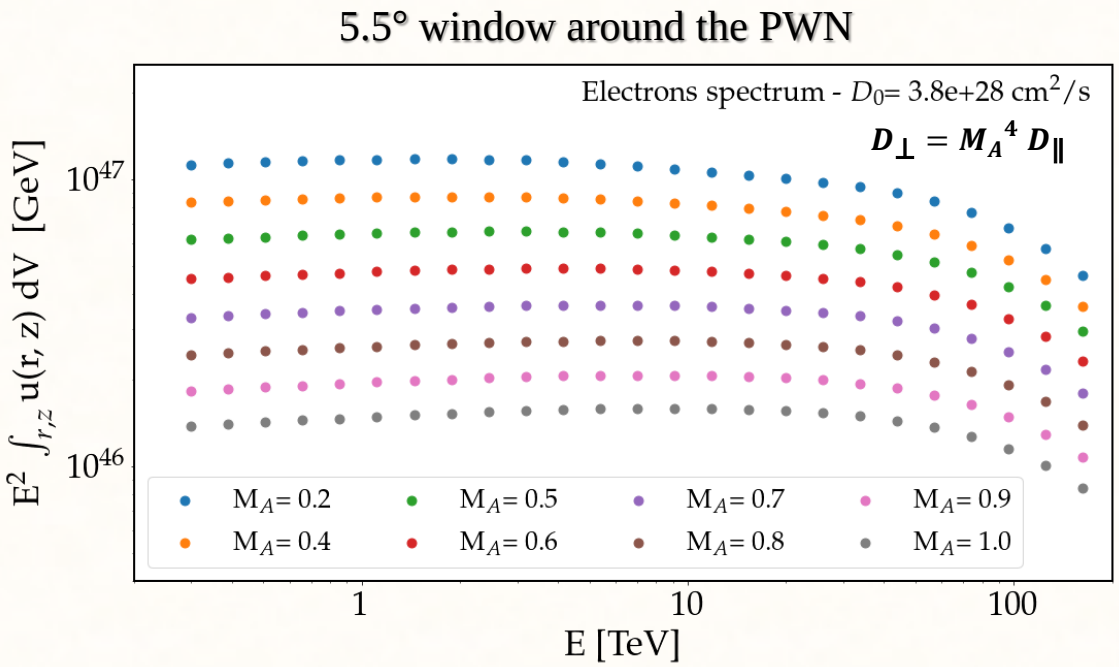

Leptons are injected with a source term following:

$$\mathcal{S}(r,z,t,E_e) = \mathcal{S}_0(1+t/\tau_0)^{-\frac{n+1}{n-1}}\left(E_e/\mathrm{GeV}\right)^{-\alpha} e^{-E_e/E_{\mathrm{cut}}}\,\delta(r,z)$$

Normalized by imposing $W_e = 1.1 \times 10^{49}\ erg$.

We assume $D_\parallel = D_Z = D_0(E/E_0)^\delta$, with $E_0 = 1$ GeV, $D_0 = 3.8 \times 10^{28}$ cm^2/s and $\delta = 0.33$ (Kolmogorov spectrum).

These leptons generate **γ-rays** via IC emission**,** which **follow the same spatial distribution as the lepton distribution** $\left(Rate\ of\ energy\ loss\text{:}\ \frac{\partial E_e}{\partial t} \propto E_e^2\right)$

PDTL, O. Fornieri, T. Linden (2022) ArXiv:2205.08544

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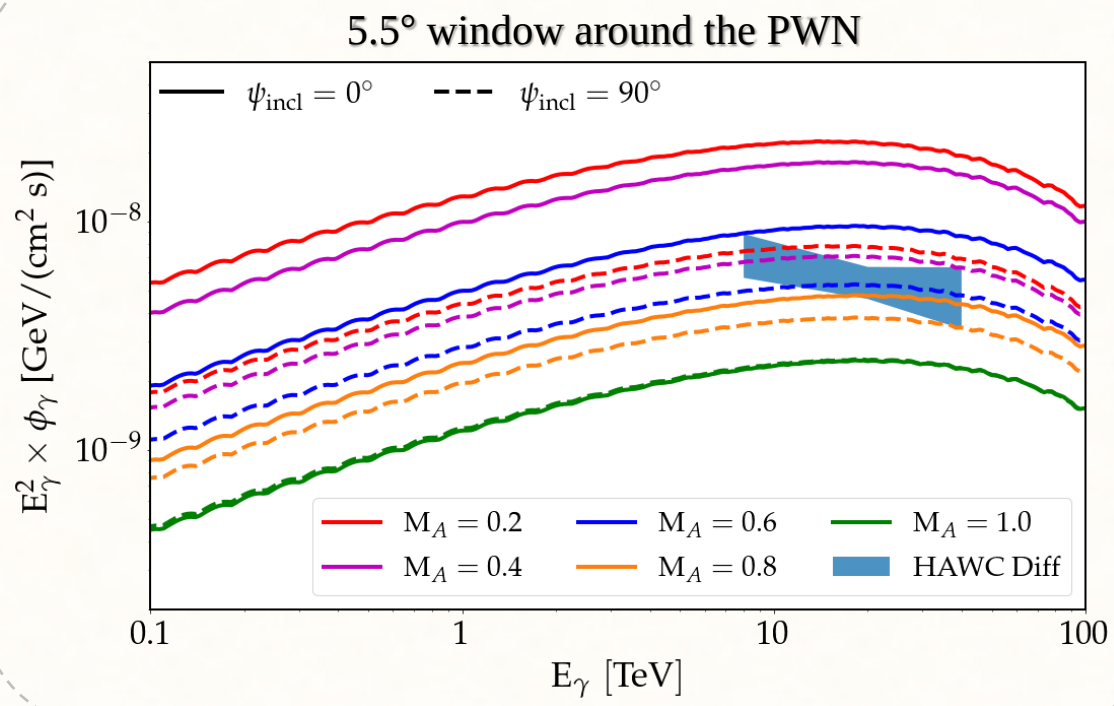

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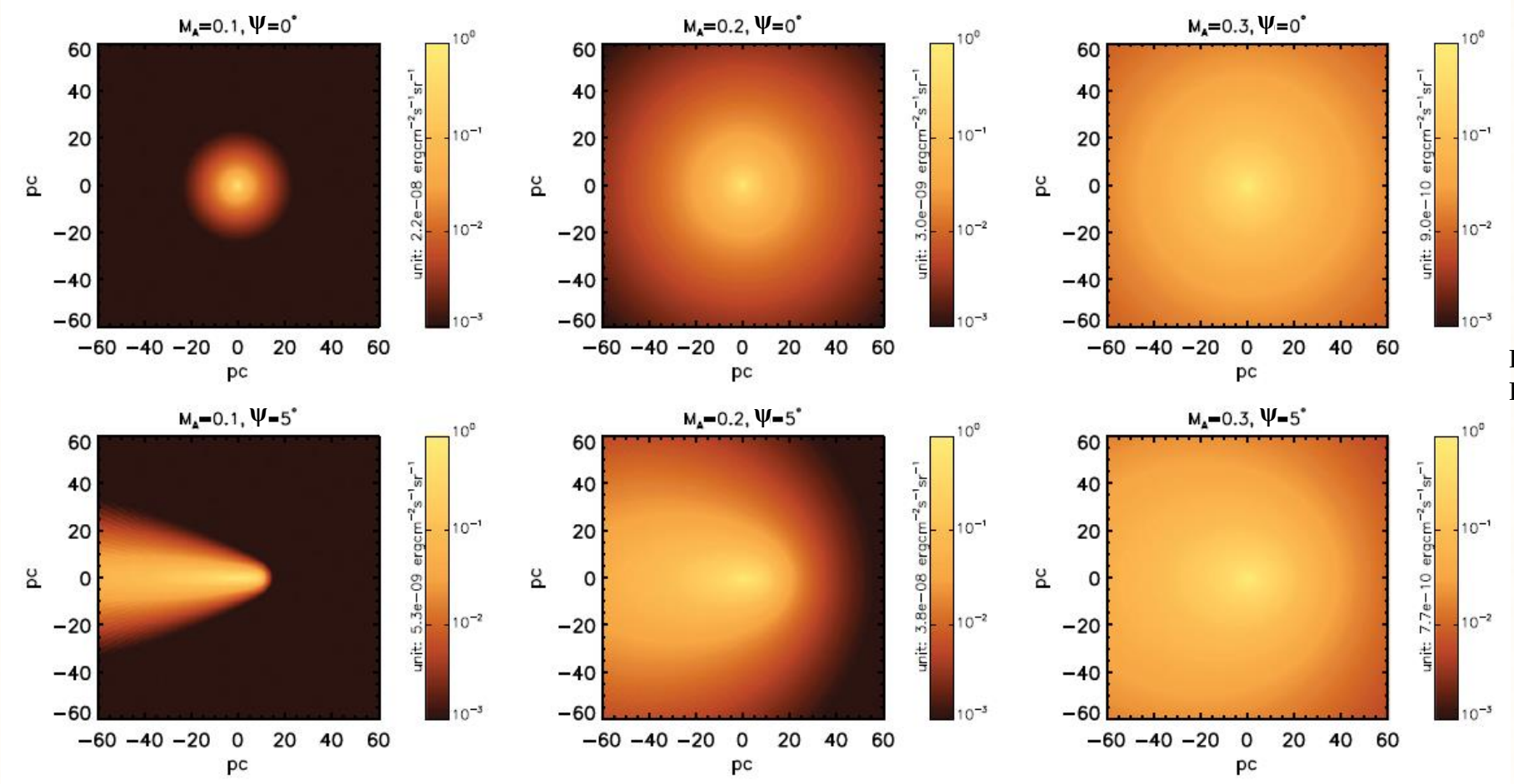
Anisotropic diffusion - Morphological consequences

A variety of shapes and sizes is expected for different objects and inclination angles!



Ruo-Yu Liu et al.
PRL 123, 221103 (2019)

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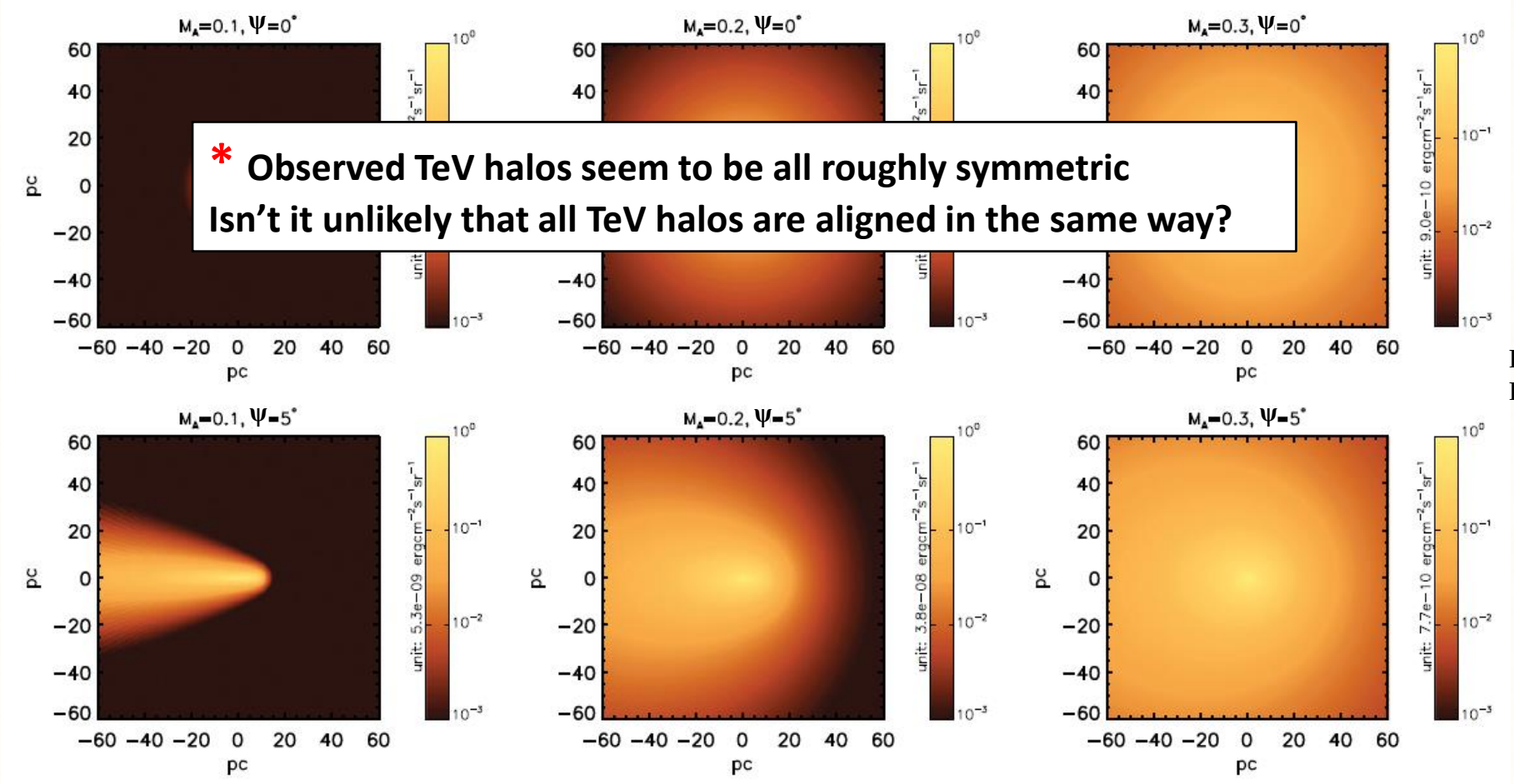


* **Observed TeV halos seem to be all roughly symmetric**
Isn't it unlikely that all TeV halos are aligned in the same way?

Ruo-Yu Liu et al.
PRL 123, 221103 (2019)

Parameter space allowed by TeV halo observations

We impose <u>two criteria</u> to determine the values of $\boldsymbol{\psi_{Incl}}$ and $\boldsymbol{M_A}$ that are **compatible with** the observations of a **few TeV halos observed** (5 out of the 11 brightest pulsars – Linden et al PRD 96, 103016, 2017) <u>based on the size of the halo along the parallel and perp. axes</u>

- ❖ How to estimate the "size" of a diffuse object?

  Computing the percentage of particles that are contained within a given extension, so that we can quote the size of an object at a given containment (e.g. at 68% or 95% of particles contained)

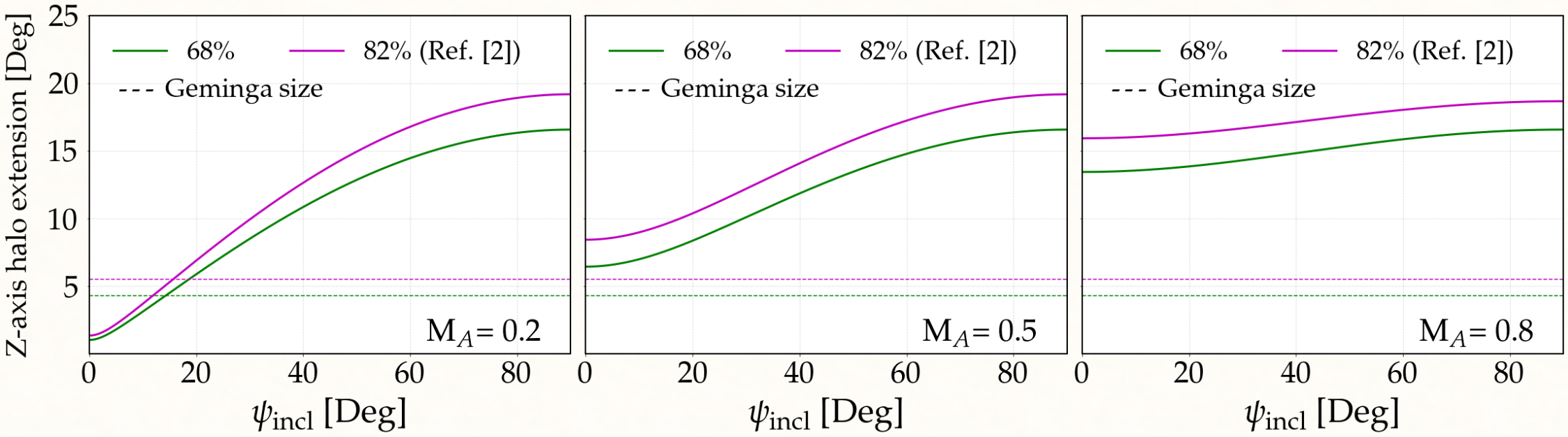
- ❖ How to estimate if an object is symmetric?

  Comparing the extension of an object in one axis with respect to the other axis

Parameter space allowed by TeV halo observations

- **Size condition**: The size of the halo must be smaller than the size of the Geminga - Abeysekara et al. Science 358 6365 (2017) - to be a valid candidate. Comparison with the size of the halos at equal containment. The size depends also on the value of D_0!

For details: https://github.com/tospines/Analyses-and-plotting-codes/blob/main/Anisotropic_TeV_Halos/Main_numbers-TeV_Halos.ipynb

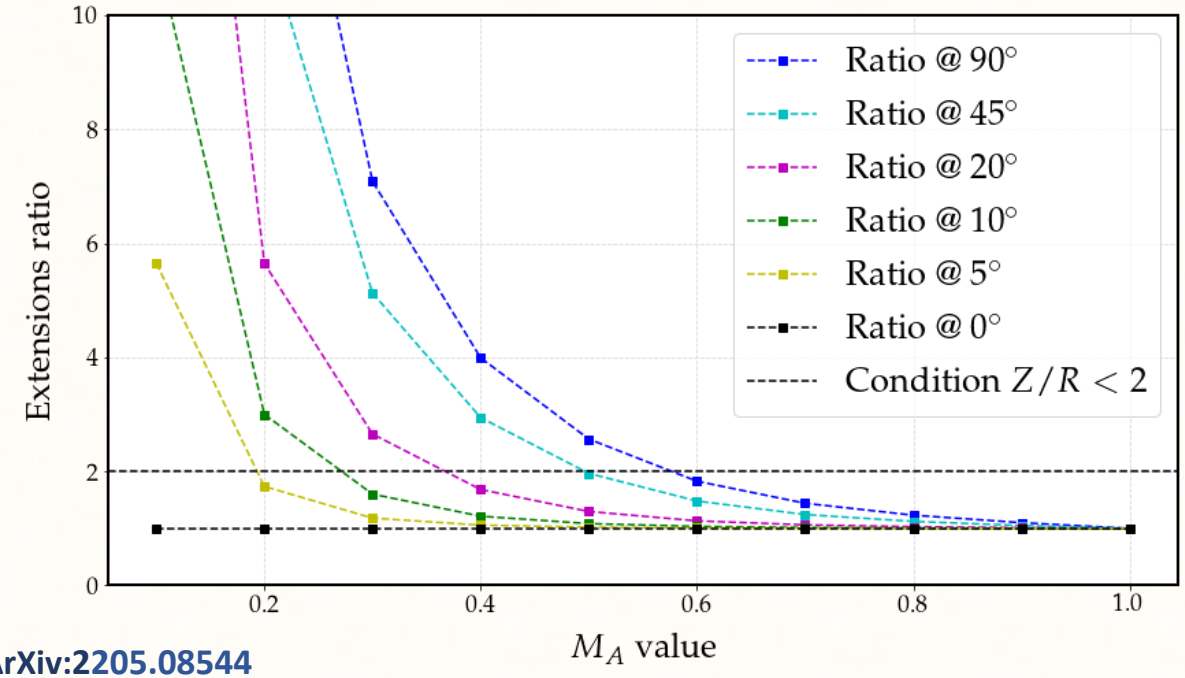


PDTL, O. Fornieri, T. Linden (2022) ArXiv:2205.08544

Parameter space allowed by TeV halo observations

- **Symmetry condition**: Given that all TeV halos seem to be compatible with roughly symmetric shape, the extension of halo along an axis can not be much different to the extension along the other axis. We impose that **Z/R < 2**.

The larger the level of anisotropy (smaller M_A) the more asymmetric the halo is



It is independent of the value of D_0!

PDTL, O. Fornieri, T. Linden (2022) ArXiv:2205.08544

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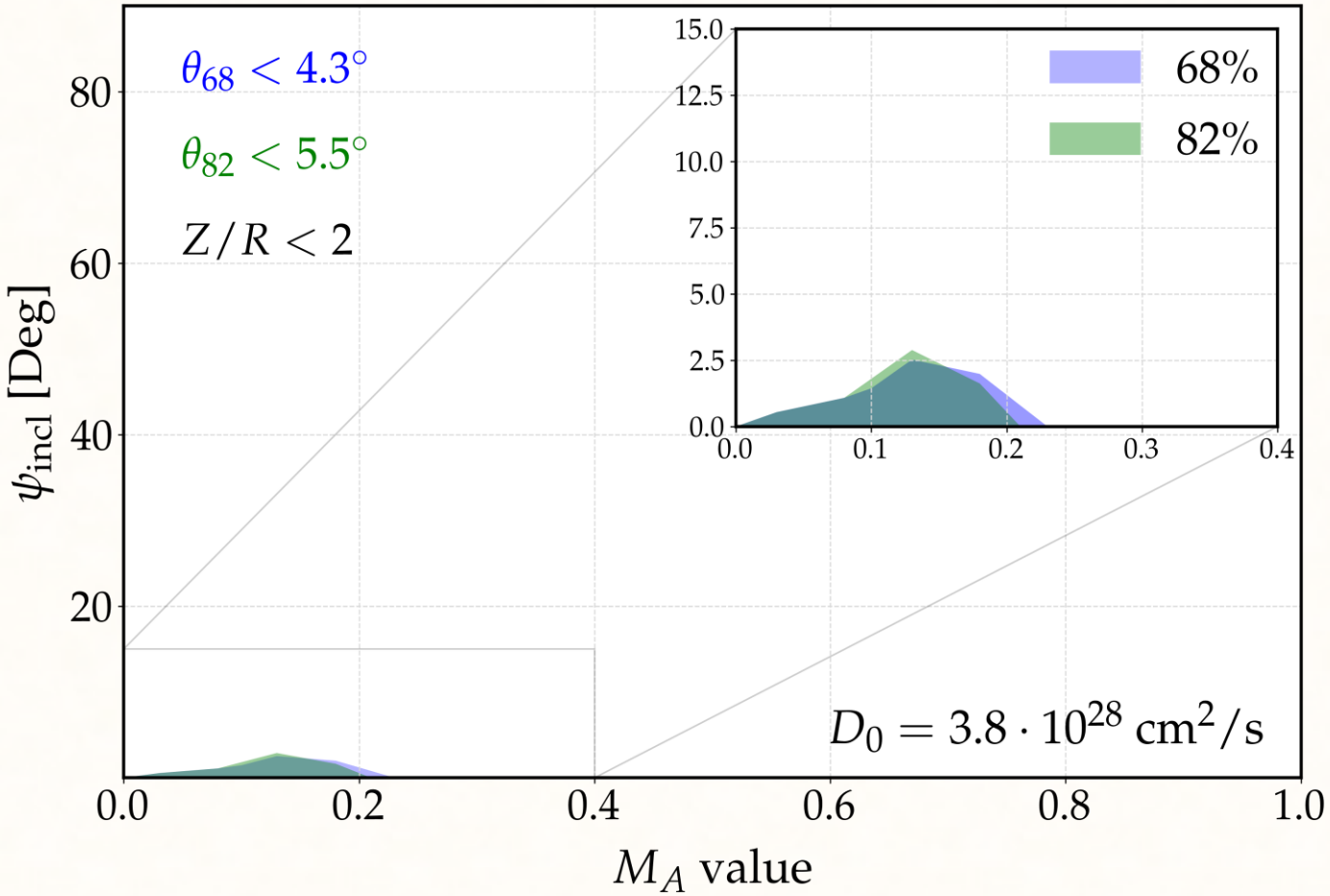


Symmetry condition: $Z/R < 2$
Size condition: $\theta_c <$ Geminga size

Only if the object is extremely well aligned with our line of sight (ψ_{Incl} < 5°), the halo will be compatible with the symmetry and size reported

$$P\binom{5}{11} \sim 3.6 \times 10^{-10}$$

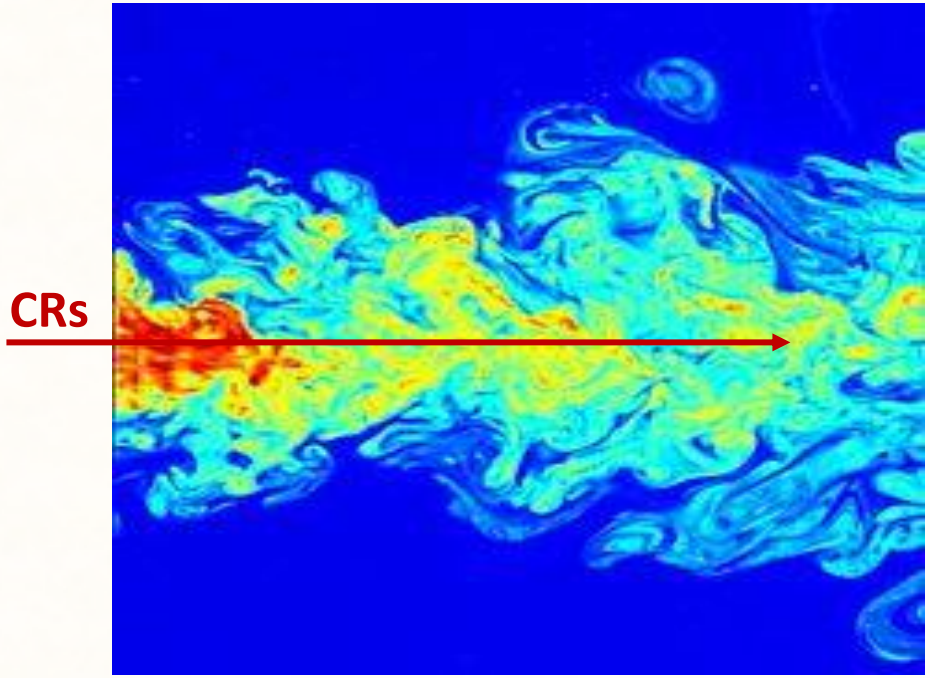
* **It is tremendously unlikely that all TeV halos are aligned in the same way!**

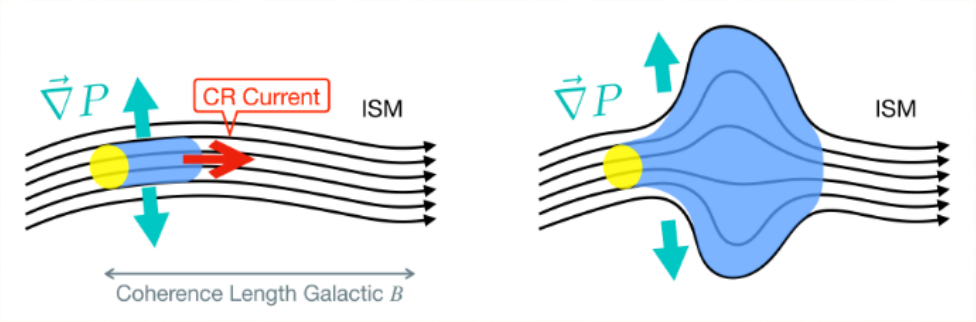
Why aren't there anisotropic features?

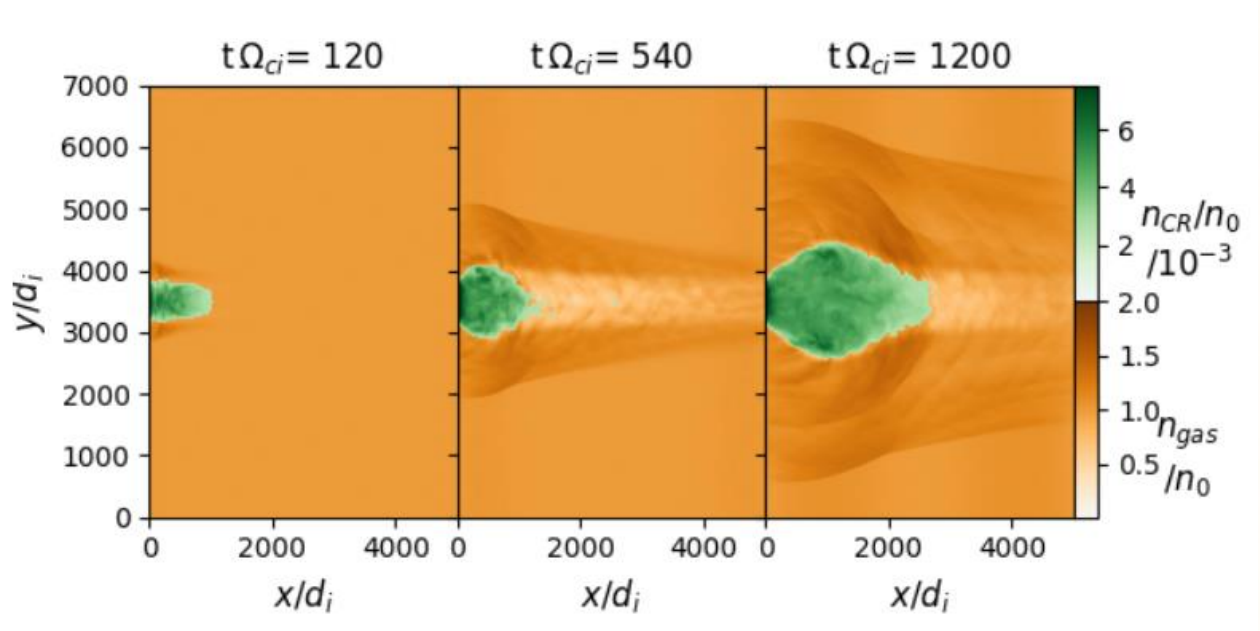
Schroer+ MNRAS 512, 1, (2022)

Self-generation of turbulence may explain the isotropization of the distribution of leptons.

Streaming instability seems insufficient







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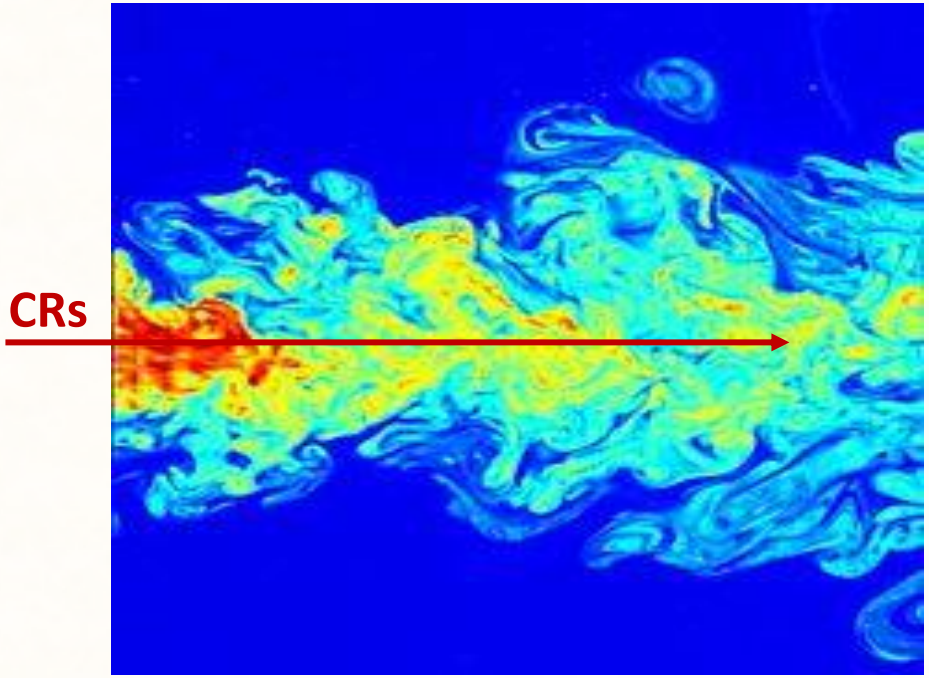
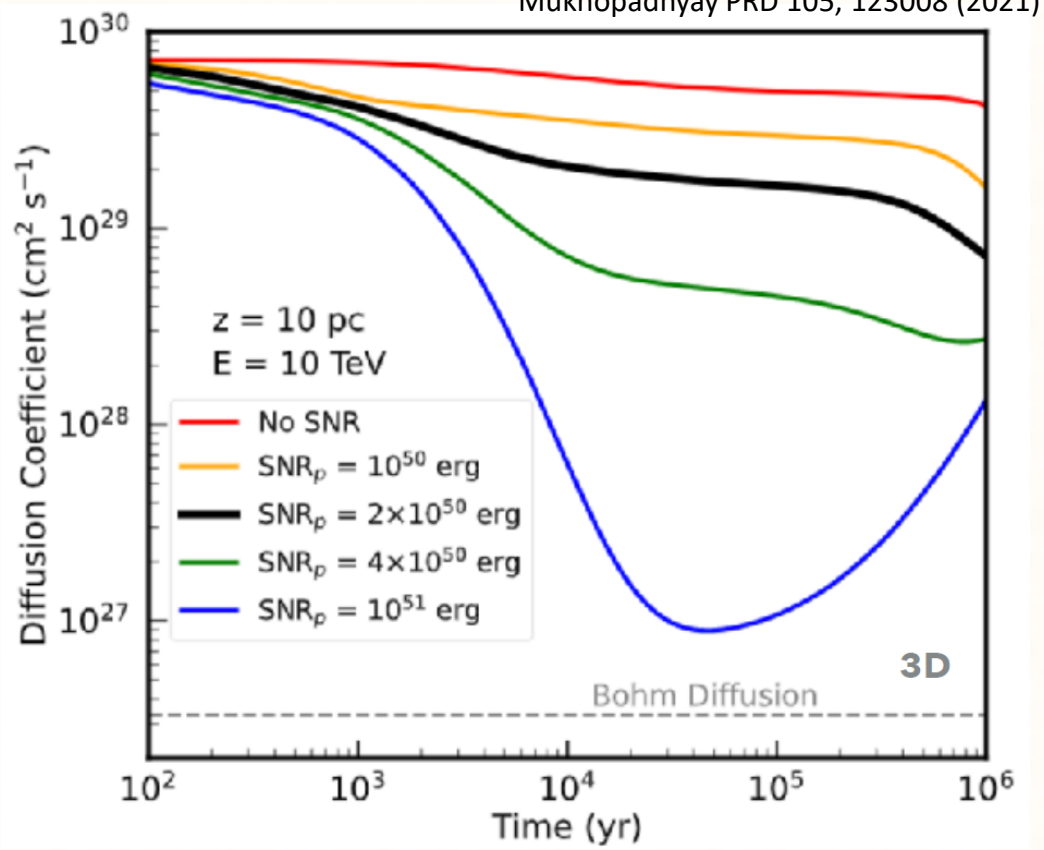
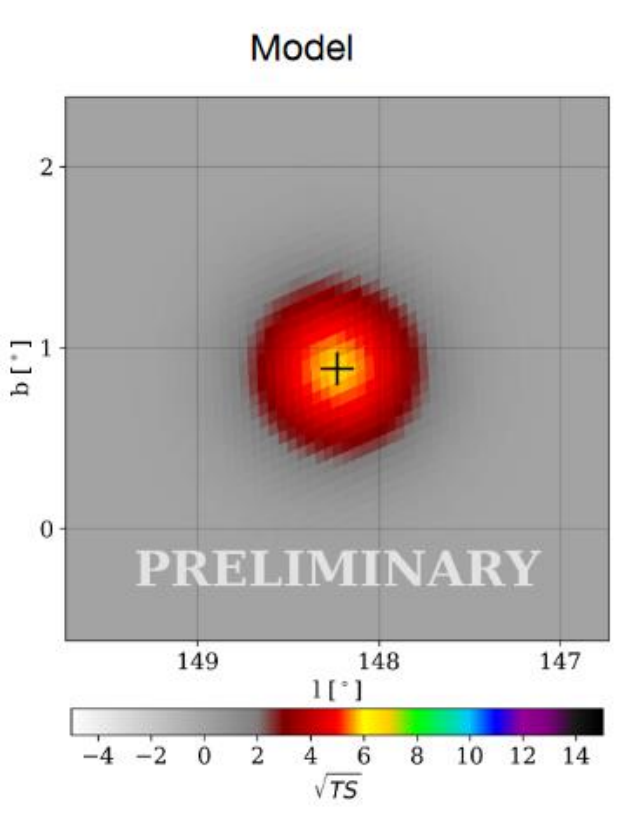


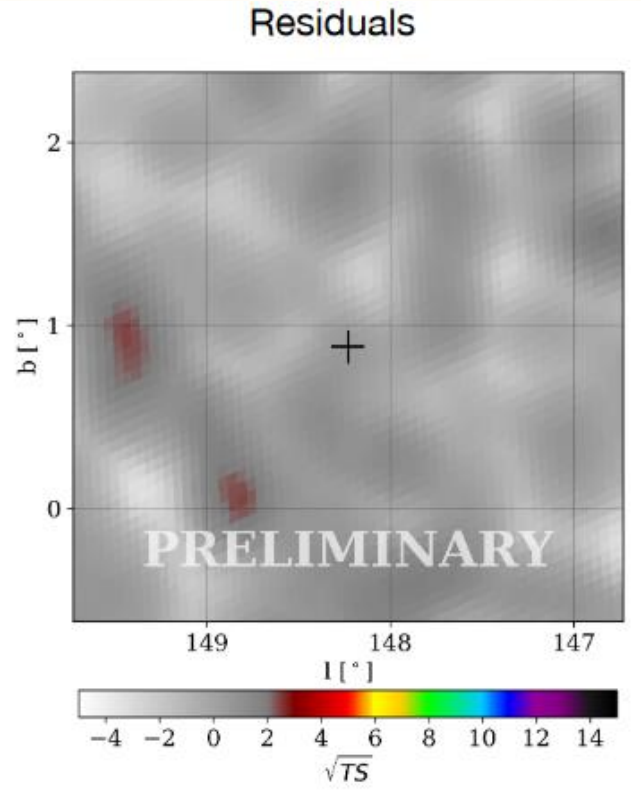
Mukhopadhyay PRD 105, 123008 (2021)



How to spot signatures anisotropic transport?

- Use ellipsoid/oval templates instead of gaussians to search for TeV sources

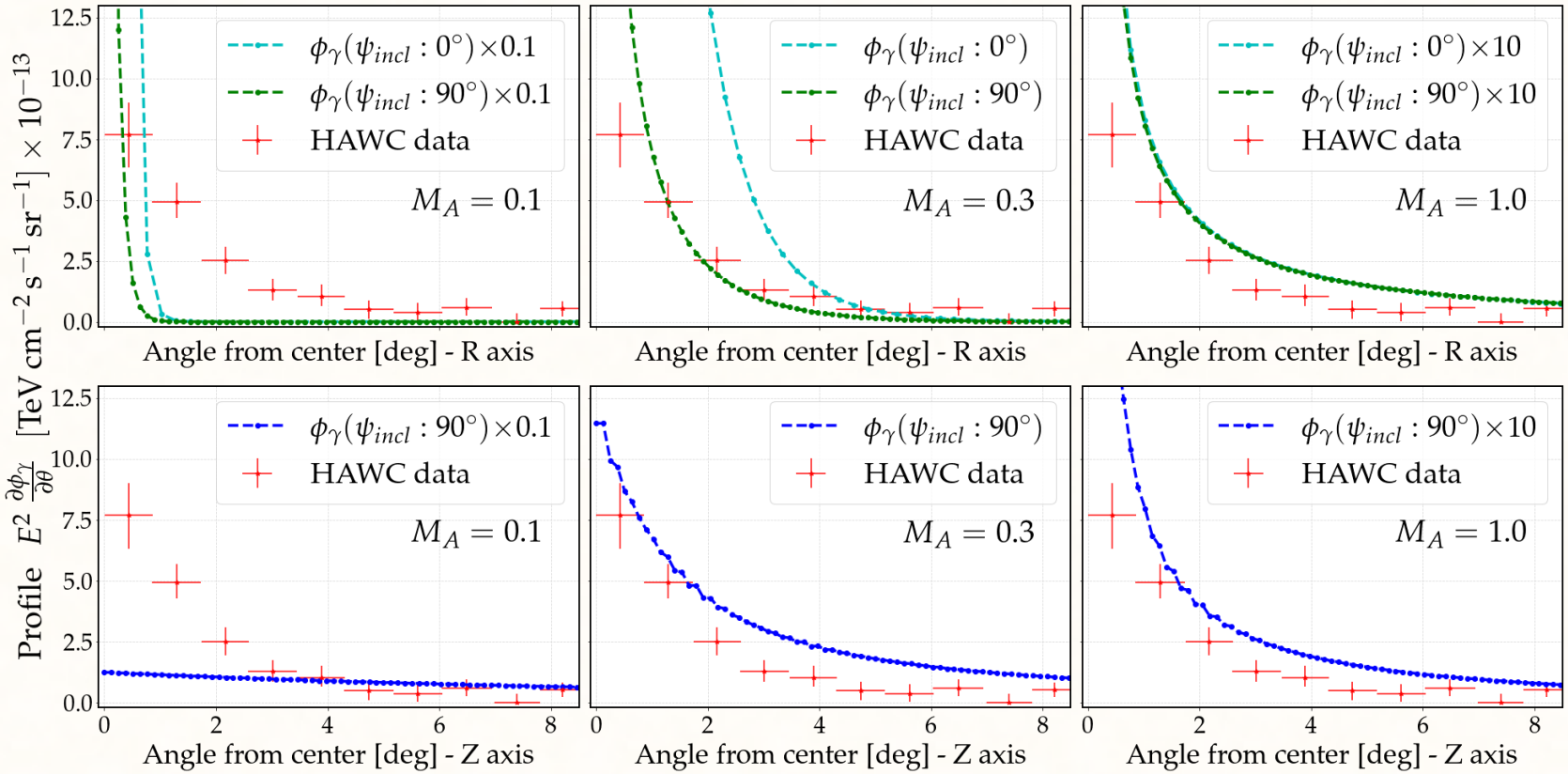




Sara Coutiño de León
$\gamma - 2022, Barcelona$

How to spot signatures anisotropic transport?

- Surface brightness assumes symmetry! → Report the profile along different directions



PDTL, O. Fornieri, T. Linden (2022) ArXiv:2205.08544

ArXiv: 2205.08544

Conclusions

- **TeV halos** are newly discovered sources that allow us to improve our understanding on the interactions of particles with plasma turbulence

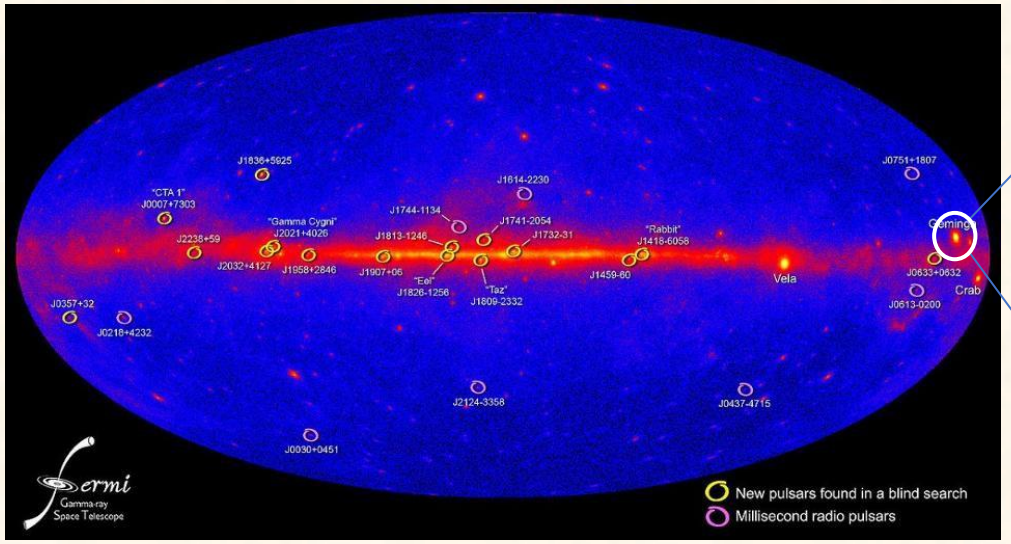
- **Need of more observations** to stablish the nature and "commonness" of TeV halos. The emission from these objects can have important implications in the measurements of leptons at Earth and the diffuse gamma-ray emission

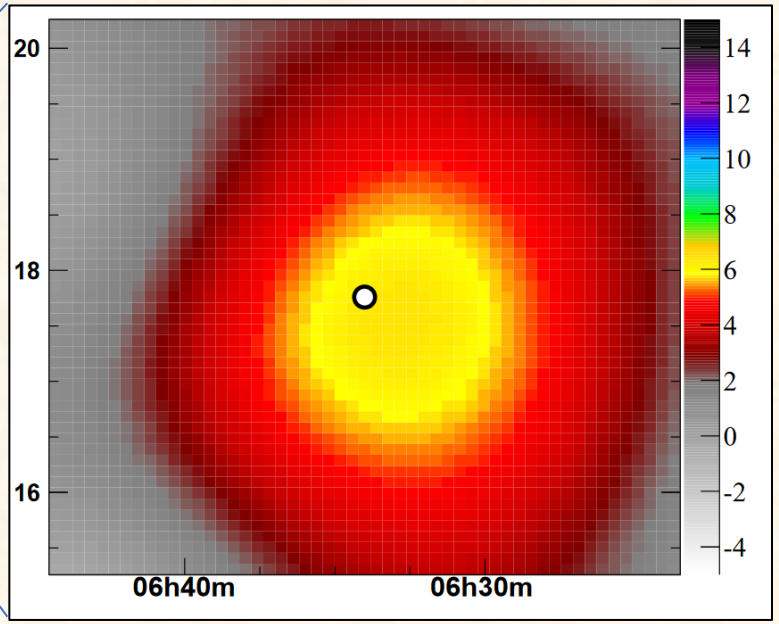
- **Anisotropic diffusion as the production mechanism** of TeV halos seems to be **tremendously unlikely**, although dedicated searches for anisotropic features are need!

- Self-generation of turbulence could explain why we do not observe anisotropic signatures of diffusion but the knowledge on the instabilities triggered by cosmic rays is very limited yet… **Stay tuned!**

Pedro de la Torre Luque Stockholm University pedro.delatorreluque@fysik.su.se

BACK-UP slides





Anisotropic diffusion cannot explain TeV halo observations

P. De la Torre Luque (OKC, Stockholm), O. Fornieri (GSSI, Italy), T. Linden (OKC, Stockholm)

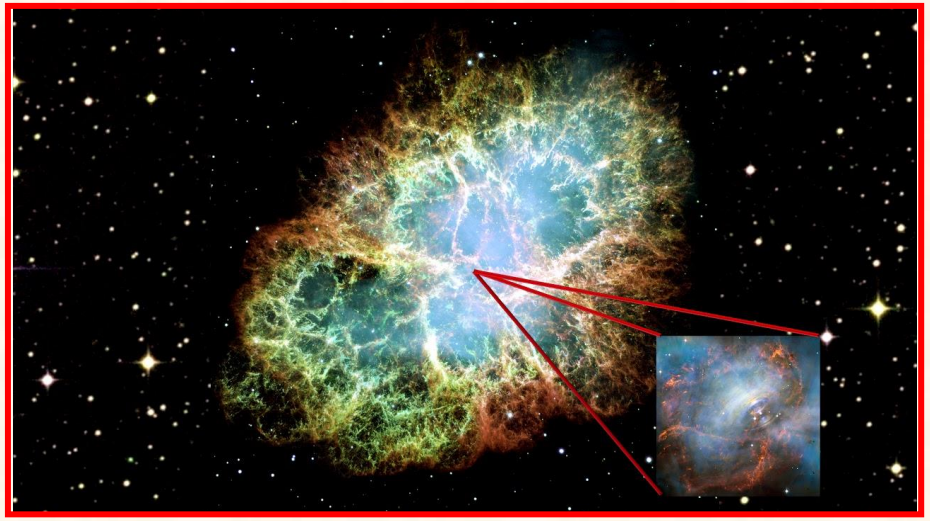
ArXiv: 2205.08544

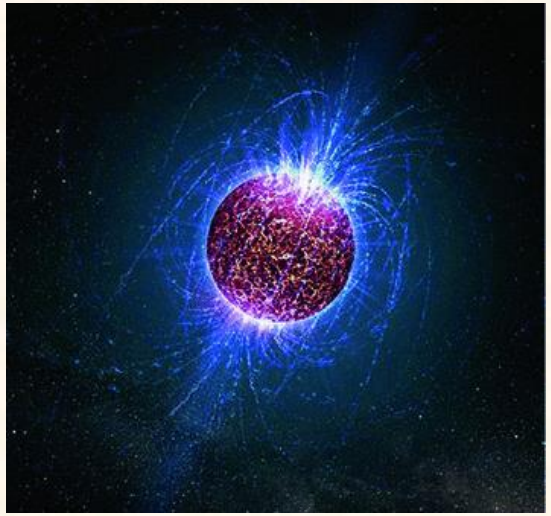
Why to study TeV halos?

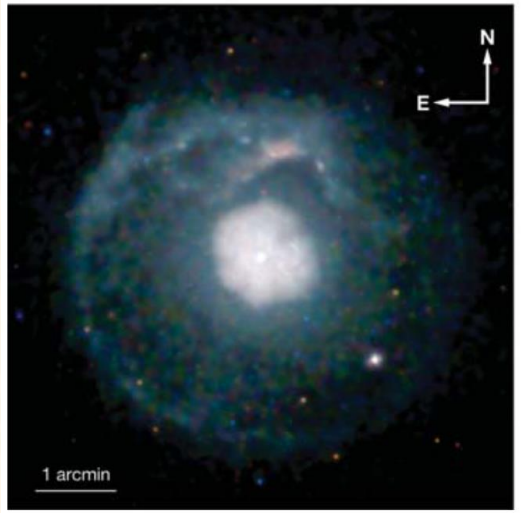
- Injection mechanism of PWNe (PeVatrons?)
- Environments of PWNe and SNRs as well as the mechanism of gamma-ray emission, pulsar evolution, …
- Background diffuse gamma-ray spectrum in the Galaxy (Astrophysical plasmas, magnetic fields, ionization rates in MCs)
- Galaxy formation See Semenov et al (2021) 2012.01427
- CR lepton spectrum (DM hints?)

A few basics

- Charged particles are accelerated at shocks! Both in SNRs and in PWN
- These sources are bright in gamma rays due to hadronic and leptonic emission processes
- Diffusion occurs because of scattering of charged particles with MHD waves







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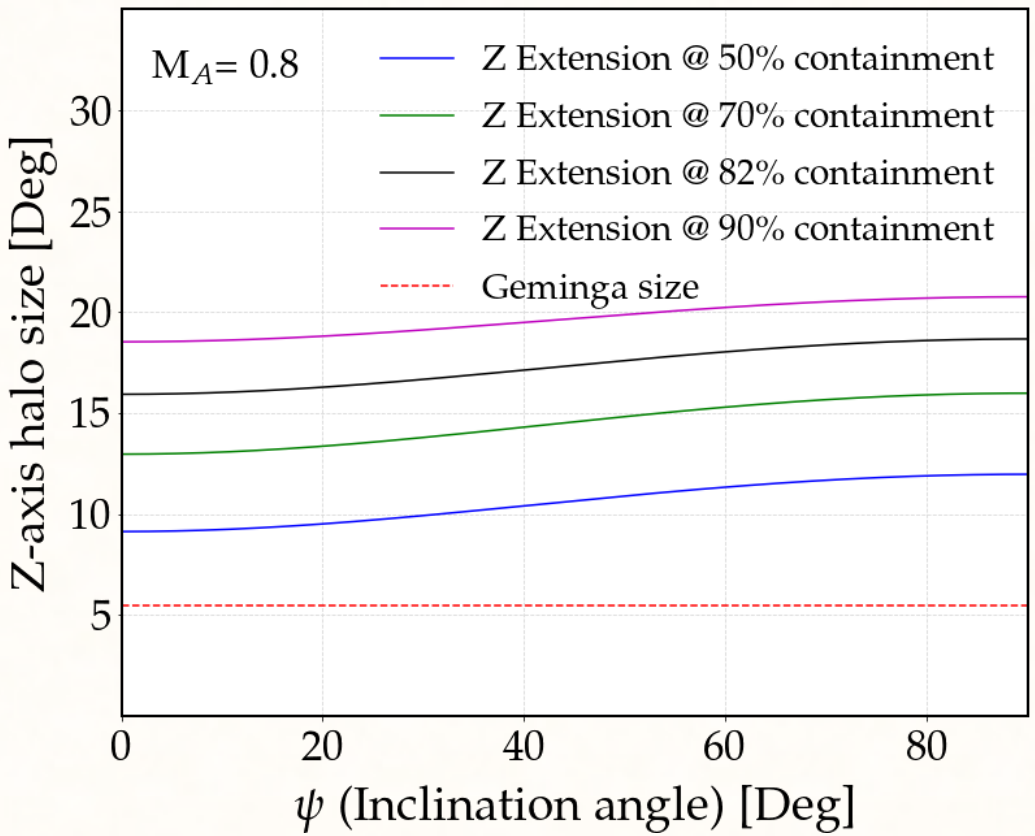
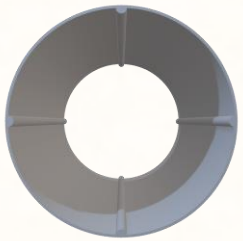


The size of the object depends on the angle at which we observe it!

Z-R plane

Z-axis at 90° angle with respect our line of sight

X-Y plane



Z-axis parallel to our l.o.s.

* **It is tremendously unlikely that all TeV halos are aligned in the same way**

PWN around the pulsar (lepton emission)

$Q(E) \sim Q_0\, E^{-\gamma}$ with γ=1.6

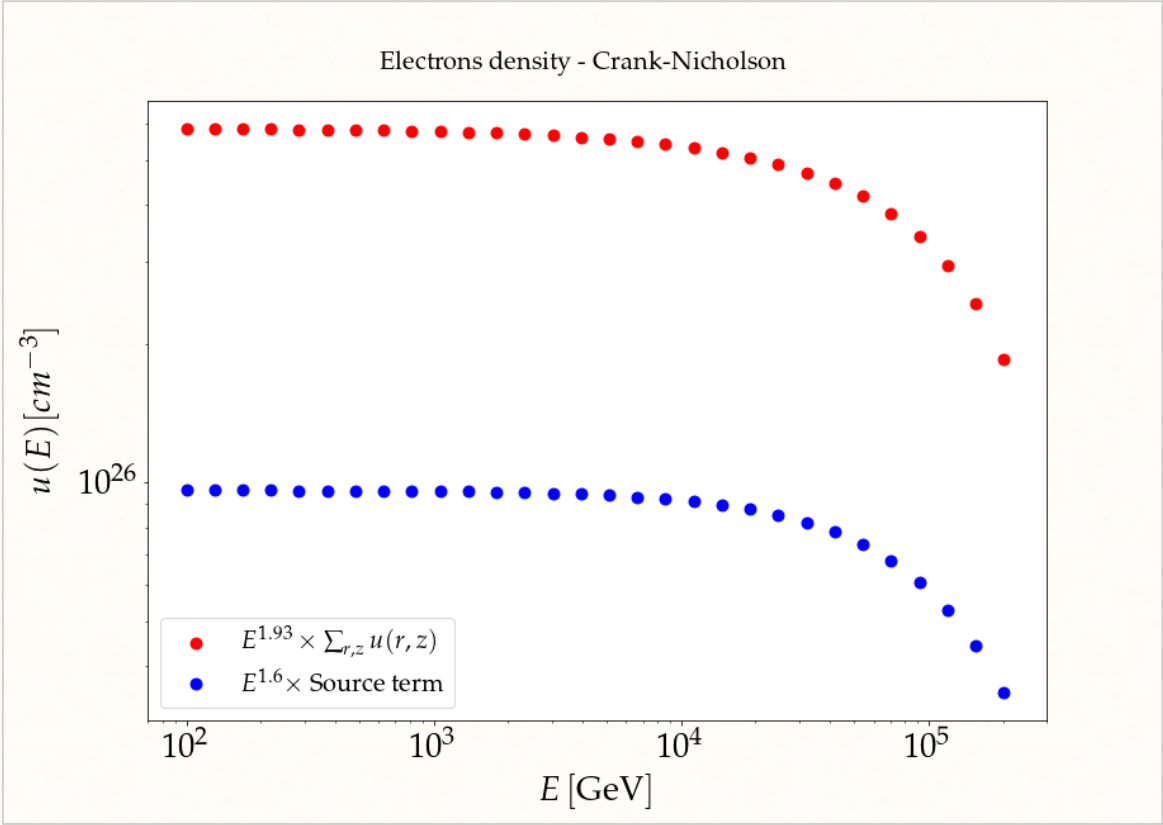
Diffusion coefficient

$D \sim D_0 \frac{E^{\delta}}{1\mathrm{GeV}}$ with $\delta = 1/3$

$\lambda_c \approx 0.3\, D_{0,28} \frac{E^{\delta}}{1\mathrm{GeV}}$ pc with $D_{0,28} = 3.8$

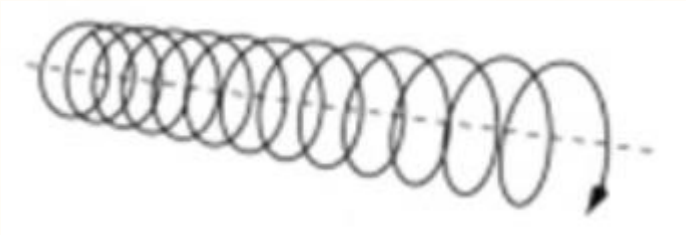
Inhomogeneous diffusion (w.r.t. the pulsar **B**)

$D_{\perp} = M_A{}^4\, D_{\parallel}$



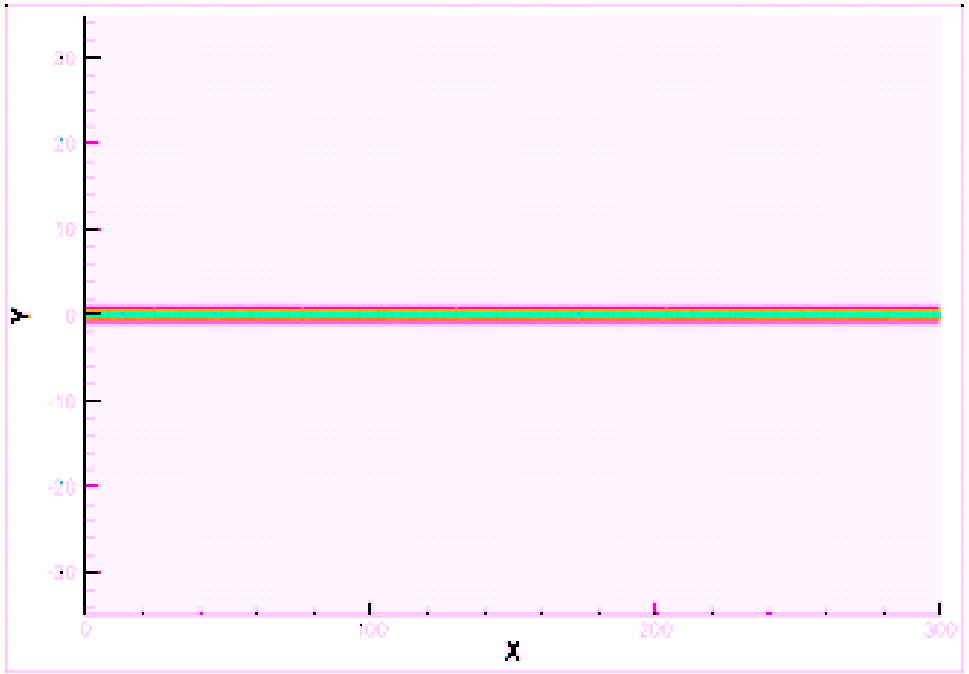
$$\frac{\partial u}{\partial t}(r,z,t,E_e) = \frac{1}{r}\frac{\partial}{\partial r}\left(rD_r\frac{\partial u}{\partial r}(r,z,t,E_e)\right) + \frac{\partial}{\partial z}\left(D_z\frac{\partial u}{\partial z}(r,z,t,E_e)\right) + \\ +\mathcal{S}(r,z,t,E_e) + \frac{\partial}{\partial E_e}\left(\frac{\partial E_e}{\partial t}u(r,z,t,E_e)\right)$$

The **Milky Way** *is a magnetised plasma medium following the Magnetohydrodynamic equations*



$$B = B_0 + \delta B \rightarrow \langle B \rangle = B_0$$

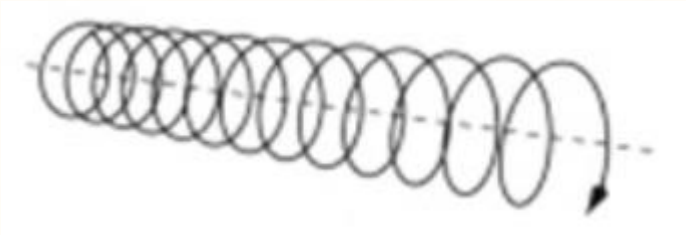
$$E = 0 + \delta E \rightarrow \langle E \rangle = 0$$



The generation of waves in the interstellar plasma makes things a lot more complex!

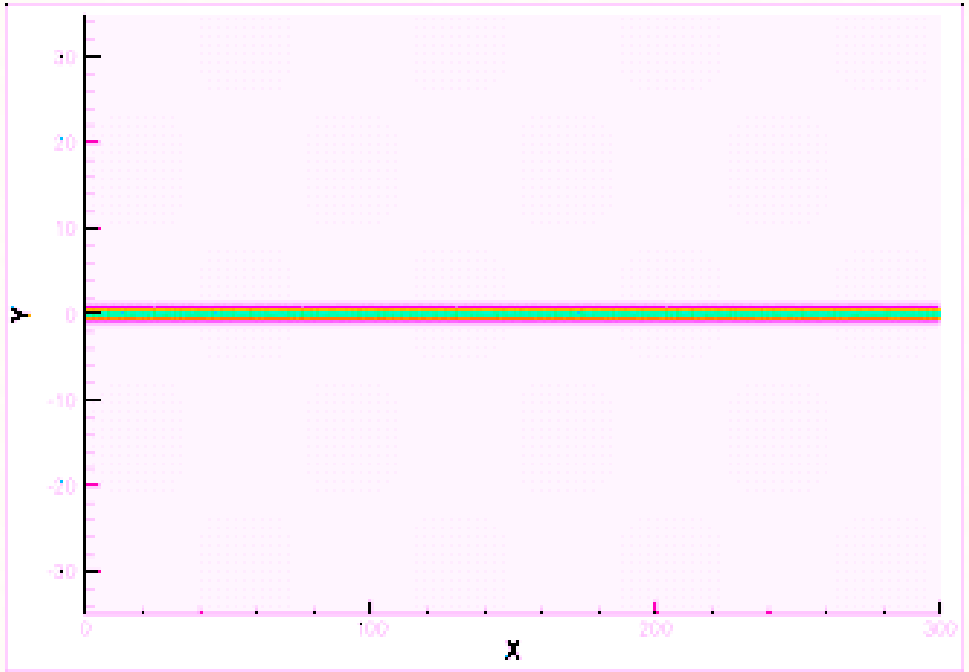
Plasma waves are generated from <u>instabilities</u> in the chill plasma medium. This creates <u>turbulence</u> that cascade from higher to smaller scales propagating <u>waves</u> that exchange energy and momentum with cosmic rays and the plasma itself

The **Milky Way** *is a magnetised plasma medium following the Magnetohydrodynamic equations*

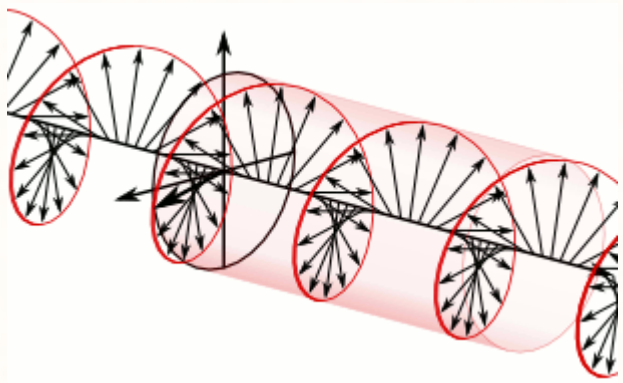


$$\mathbf{B} = \mathbf{B}_0 + \delta\mathbf{B} \rightarrow \langle \mathbf{B} \rangle = \mathbf{B}_0$$

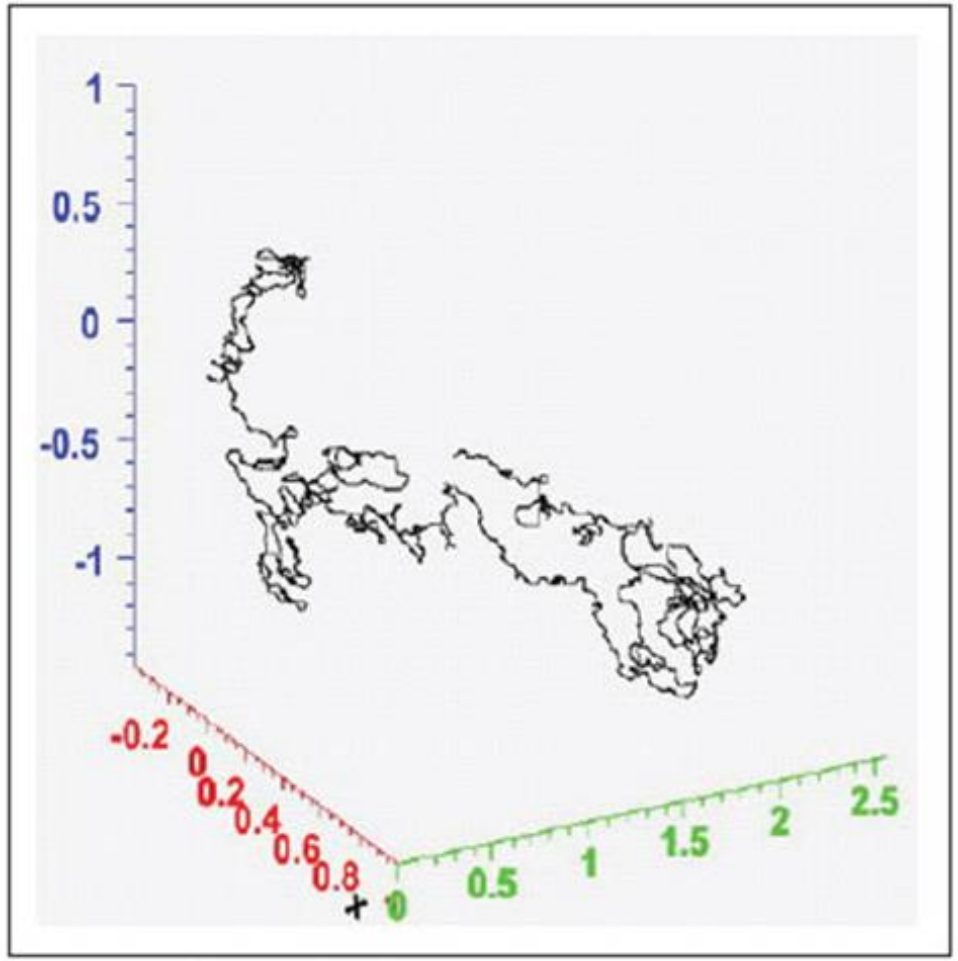
$$\mathbf{E} = 0 + \delta\mathbf{E} \rightarrow \langle \mathbf{E} \rangle = 0$$

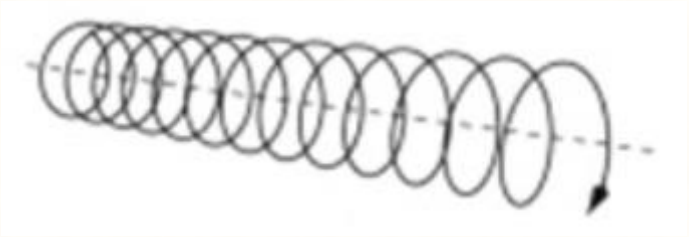


Alfven waves are circularly polarized whose resonant interaction governs the CR scattering

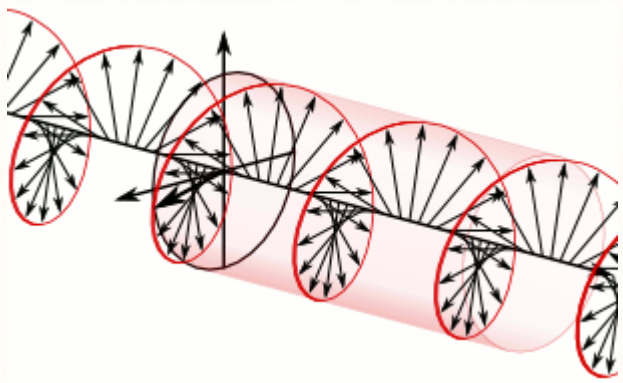


The **Milky Way** *is a magnetised plasma medium following the Magnetohydrodynamic equations*





Alfven waves are circularly polarized whose resonant interaction governs the CR scattering



TeV halo candidate list from the Third HAWC Catalog (3HWC, Albert et al. 2020) for a 1523-day data set (November 2014, June 2019)

HAWC	l (°)	b (°)	Pulsar	Age (kyr)	$\dot{E}$ (erg s^{-1})	Distance (kpc)	Separation (°)	TeVCat
3HWC J0540+228	184.58	−4.13	B0540+23	253.0	4.09e+34	1.56	0.83	HAWC J0543+233
3HWC J0543+231	184.67	−3.52	B0540+23	253.0	4.09e+34	1.56	0.36	HAWC J0543+233
3HWC J0631+169	195.63	3.45	J0633+1746	342.0	3.25e+34	0.19	0.95	Geminga
3HWC J0634+180	195.00	4.62	J0633+1746	342.0	3.25e+34	0.19	0.38	Geminga Pulsar
3HWC J0659+147	200.60	8.40	B0656+14	111.0	3.8e+34	0.29	0.51	2HWC J0700+143
3HWC J0702+147	200.91	9.01	B0656+14	111.0	3.8e+34	0.29	0.77	2HWC J0700+143
3HWC J1739+099	33.89	20.34	J1740+1000	114.0	2.32e+35	1.23	0.13	...
3HWC J1831-095	22.13	0.02	J1831−0952	128.0	1.08e+36	3.68	0.27	HESS J1831-098
3HWC J1912+103	44.50	0.15	J1913+1011	169.0	2.87e+36	4.61	0.31	HESS J1912+101
3HWC J1923+169	51.58	0.89	J1925+1720	115.0	9.54e+35	5.06	0.67	...
3HWC J1928+178	52.93	0.20	J1925+1720	115.0	9.54e+35	5.06	0.85	2HWC J1928+177
3HWC J2031+415	80.21	1.14	J2032+4127	201.0	1.52e+35	1.33	0.11	TeV J2032+4130

Note. The age of the pulsar in kyr and the spin-down luminosity, $\dot{E}$, in erg s^{-1} are also given. The Separation column indicates the angular distance between the HAWC source and the ATNF pulsar (Manchester et al. 2005). The TeVCat column lists the previously detected TeV counterpart of each source.

Abeysekara et al 2017

Dependence of the flux with the size of the object

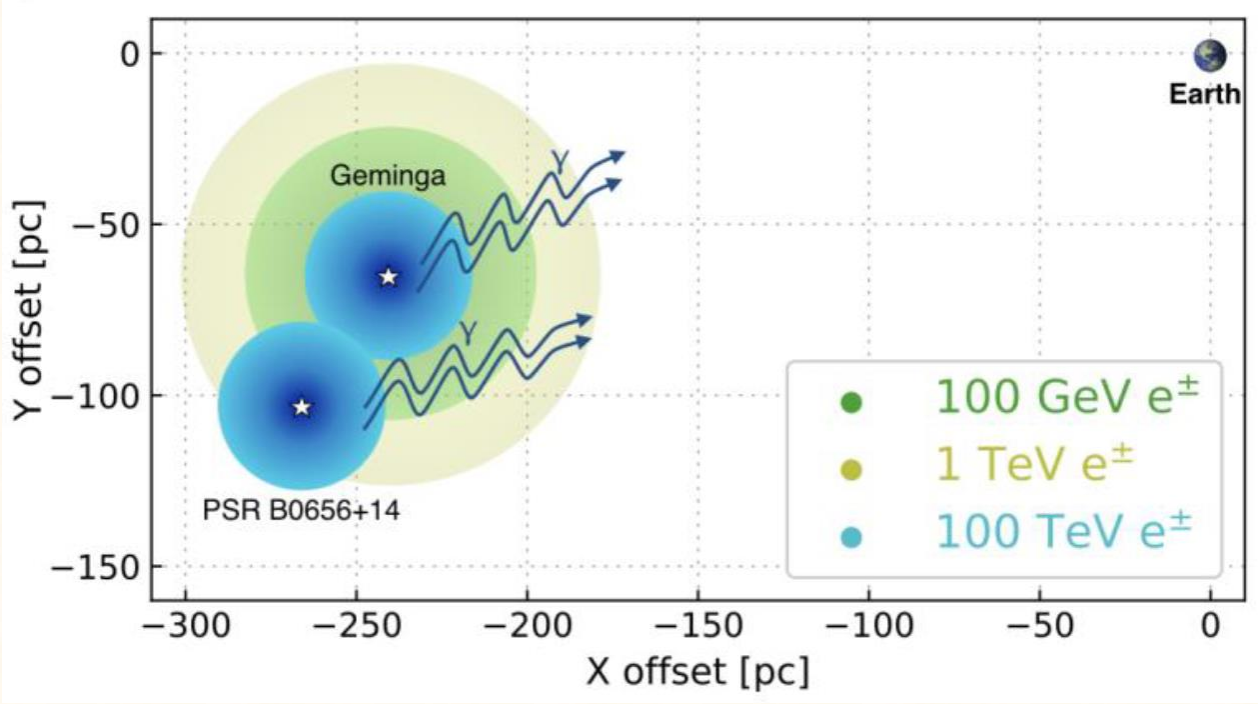
$$\frac{dN}{d\Omega} = \frac{1.22}{\pi^{3/2}\theta_{\mathrm{d}}(E)(\theta + 0.06\theta_{\mathrm{d}}(E))} \times \exp\left[-\frac{\theta^2}{\theta_{\mathrm{d}}(E)^2}\right]$$

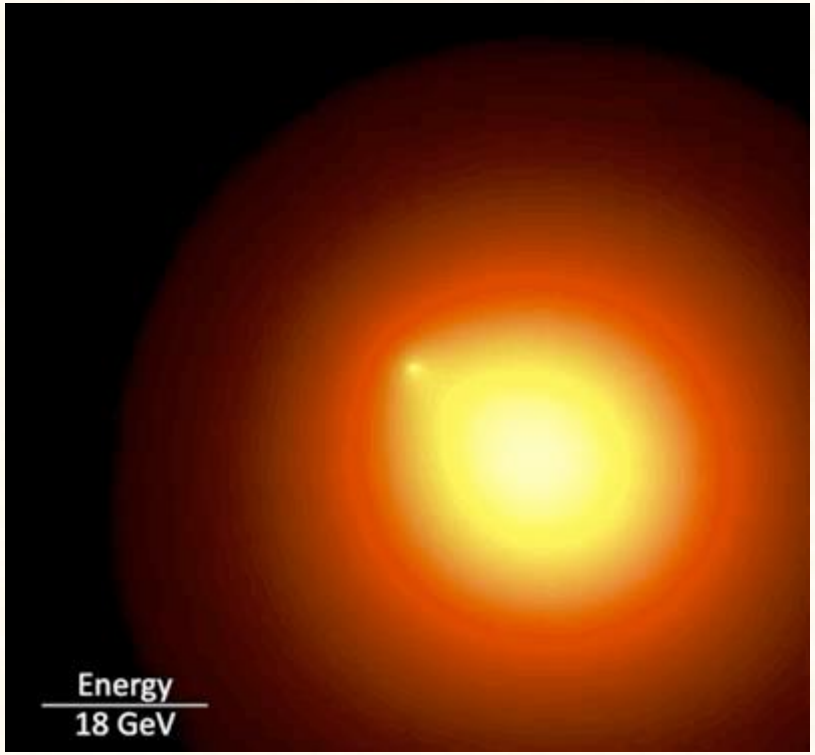
$$\theta_{\mathrm{d}} = \frac{180}{\pi}\frac{R_{\mathrm{diff}}}{d_{\mathrm{src}}}$$

$$R_{\mathrm{diff}} = 2\sqrt{D(E_{\mathrm{e}})t_{\mathrm{e}}}$$

t_e is the cooling time.

At E ≤ ~100 GeV the object seems asymmetric because of its movement and the fact that at these energies π^0 decay is the main source of gamma rays





NASA's Goddard Space Flight Center/M. Di Mauro

Ballistic propagation preceding diffusive propagation

S. Recchia+ (2021)