Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

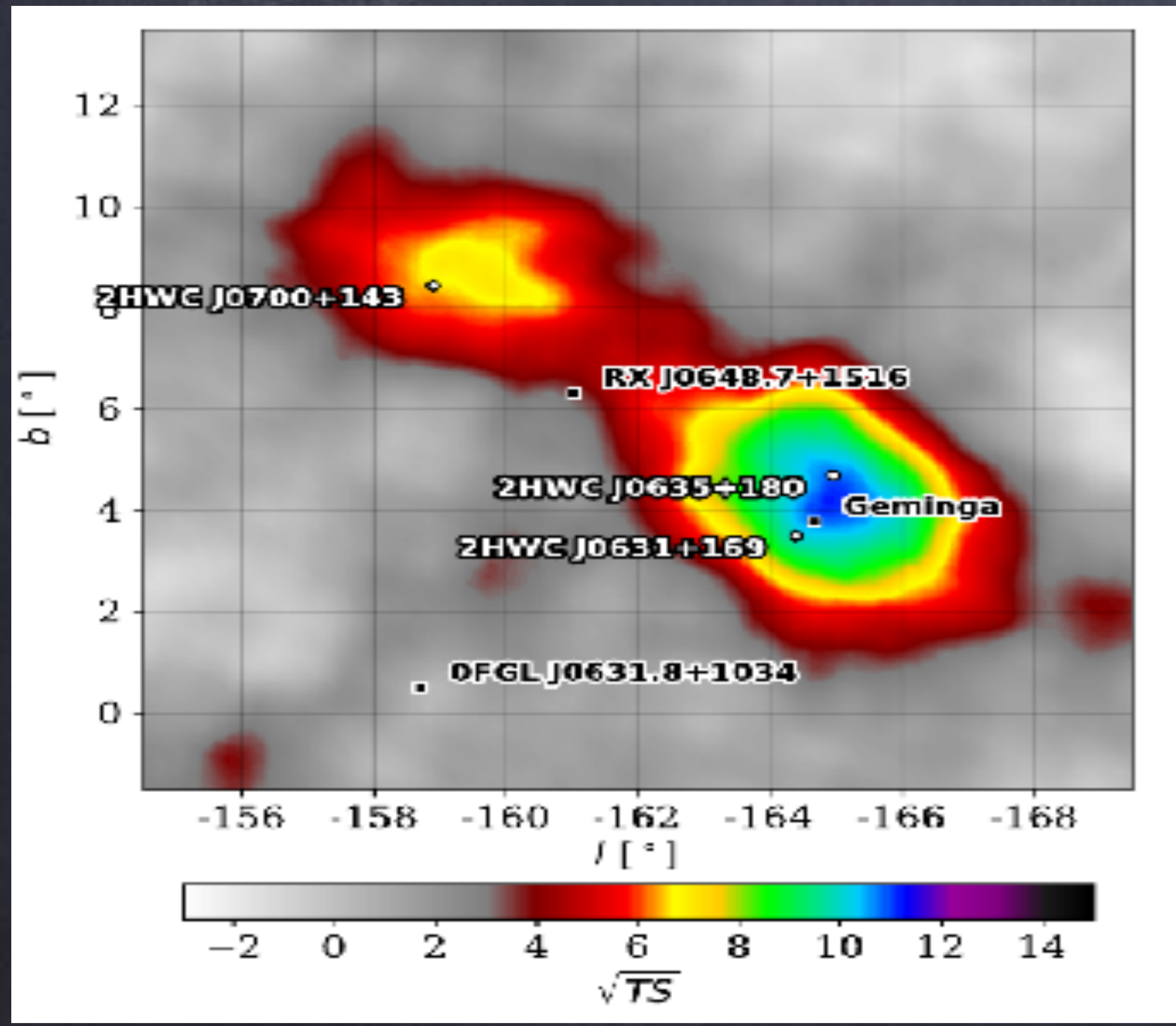
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

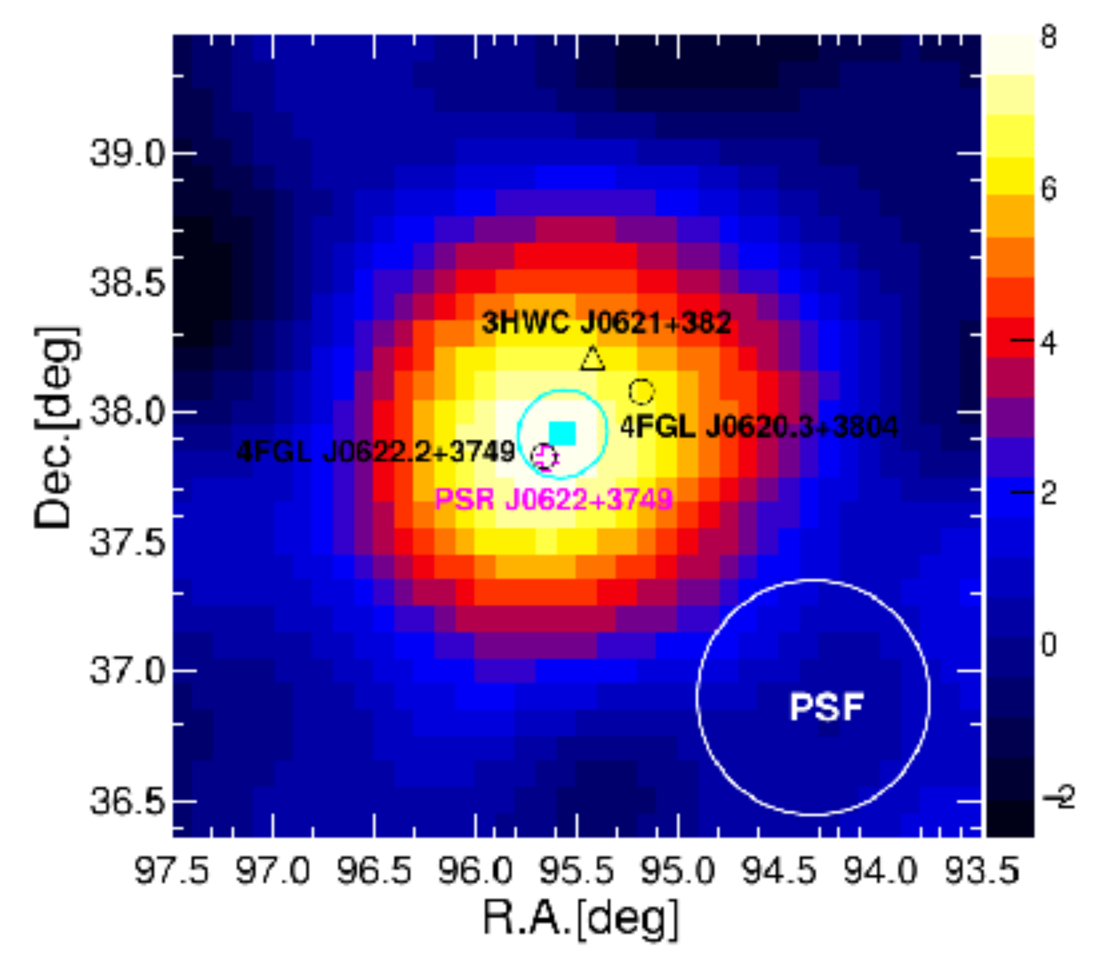
INAF

TeV gamma-ray halos

Sarah Recchia

INAF Arcetri (Firenze)





Summary

Amato & Recchia 2024 - review TeV halos

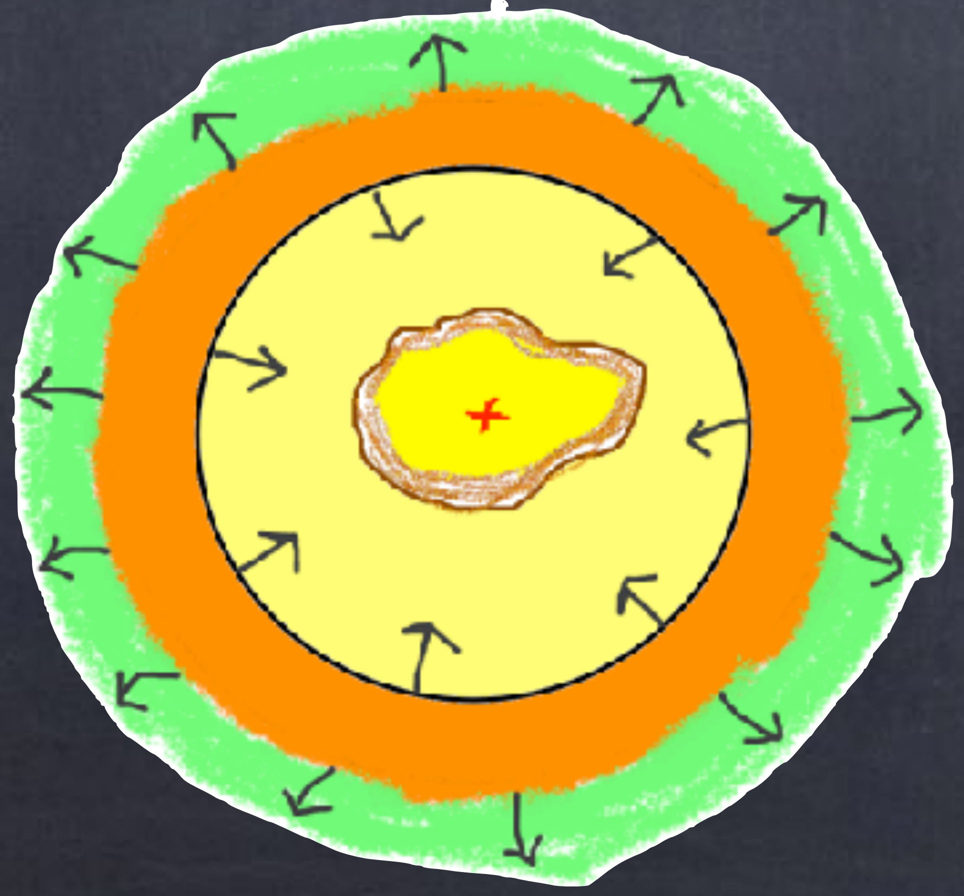
- TeV halos detected around middle-aged pulsars (HAWC, LHAASO)
- not understood with current transport models
- new window on CR propagation at multi-TeV
- many open questions
- what can be done with current and future instruments? LHAASO, ASTRI Mini-Array ... CTAO

Pulsars and their nebulae

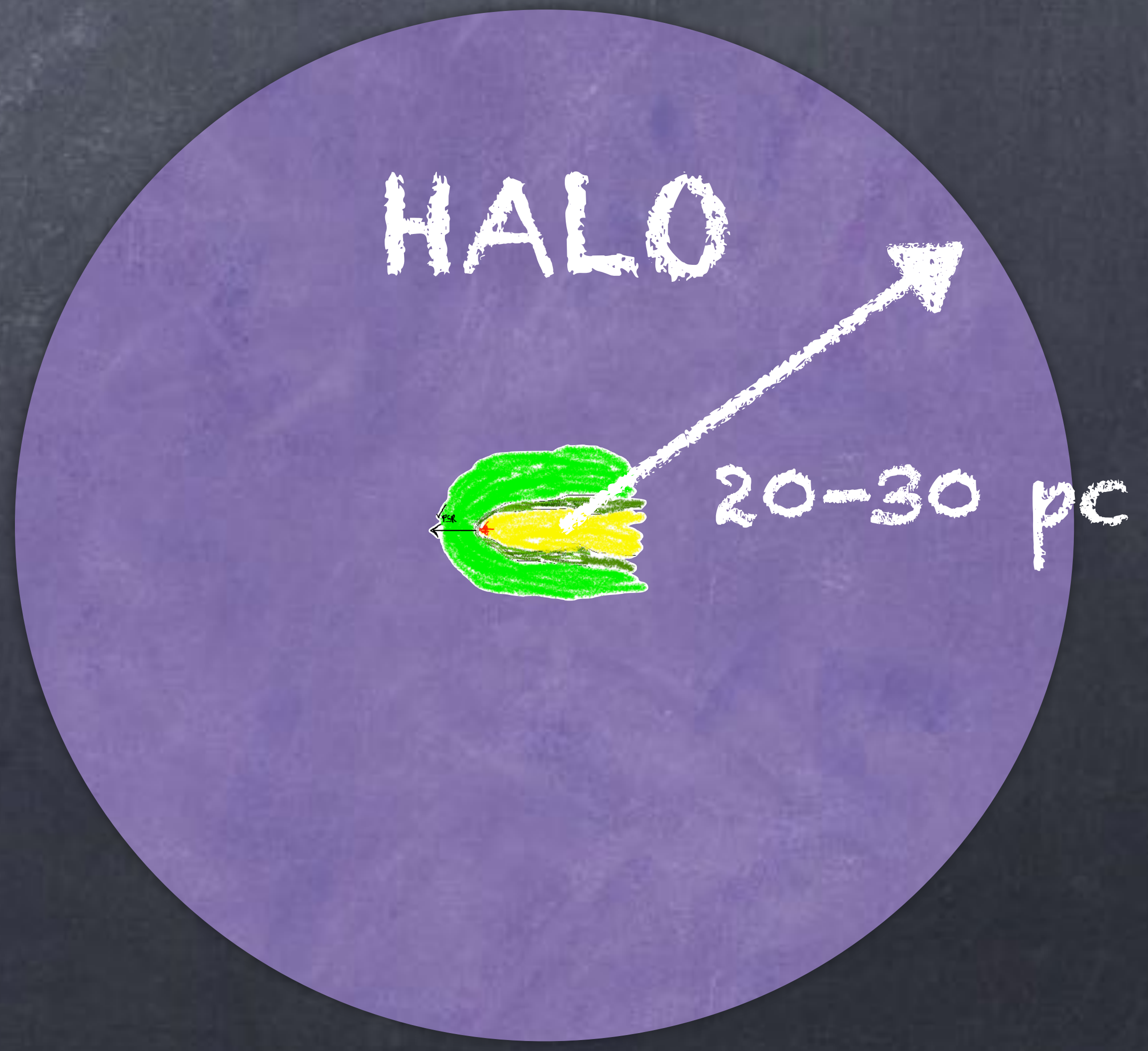
- $e^{\pm}$ pairs confined in PWNe before release in ISM
- Cannot leave system while pulsar is in SNR
- proper motion $v_{\rm psr} \sim 100s\,{\rm km/s}$ —> out of SNR $\approx 10s\,{\rm kyr}$
- Bow shock —> particle release in ISM

big caveat …

in-SNR phase

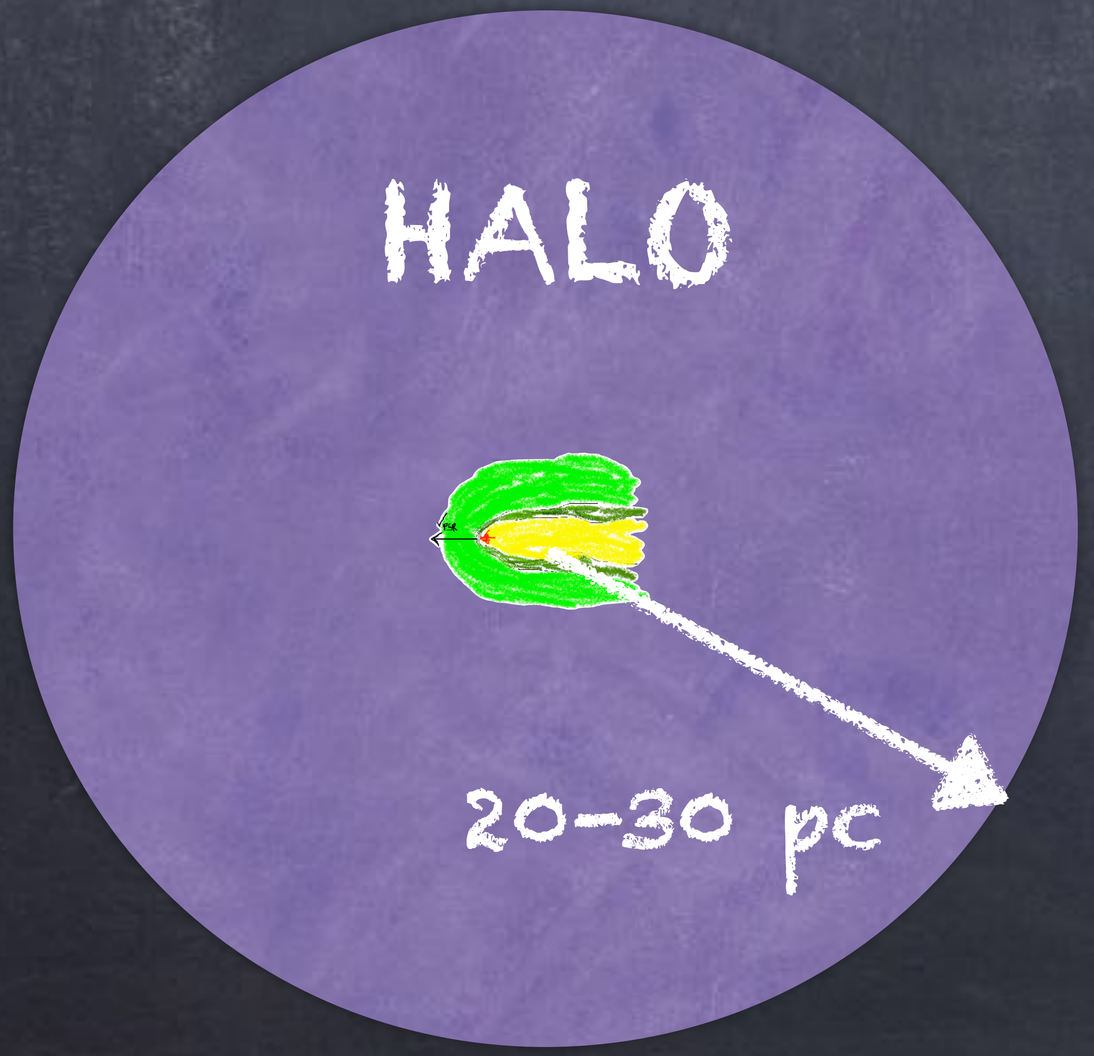


bow-shock phase

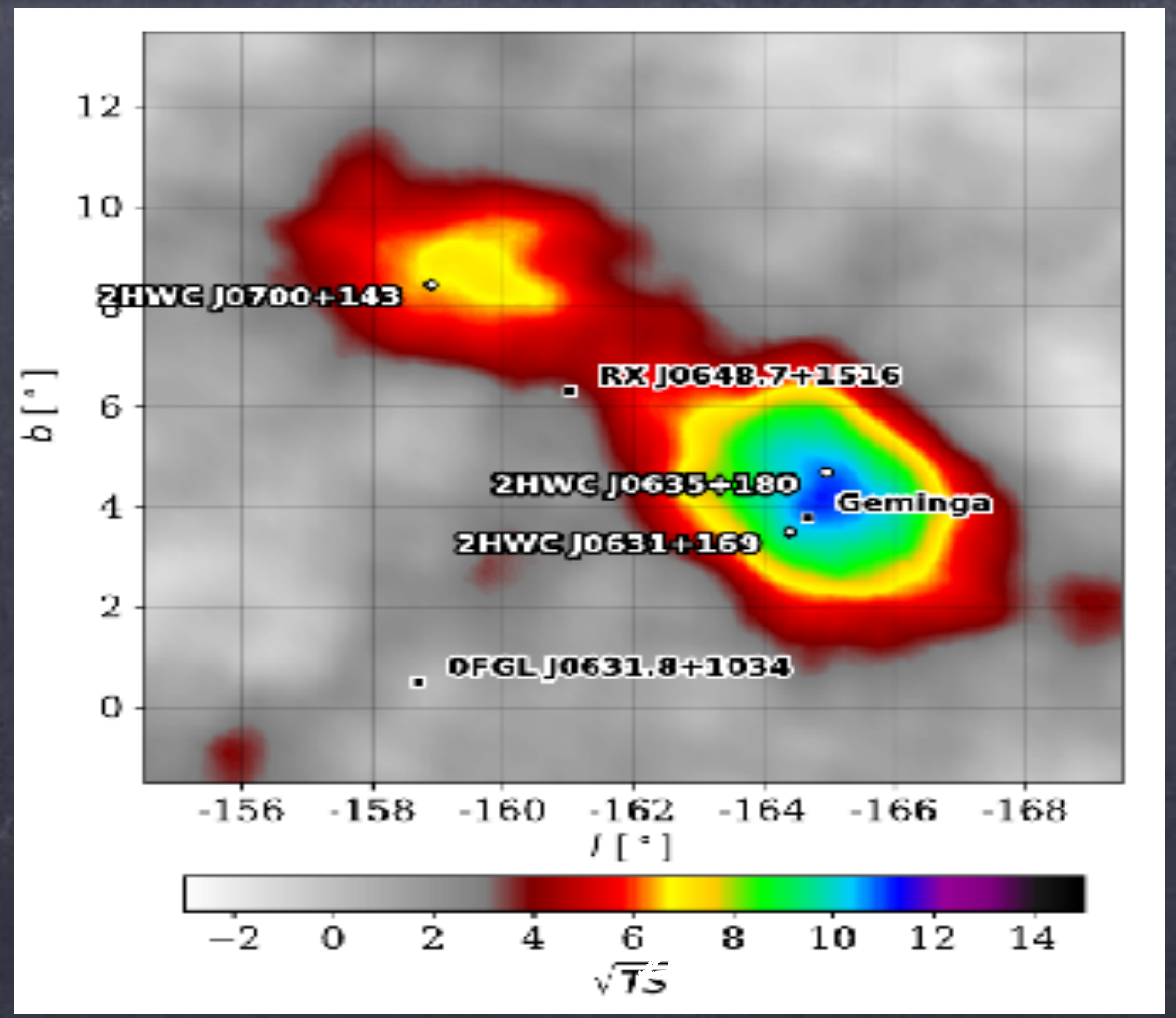


Bow-shock PWNe and TeV halos

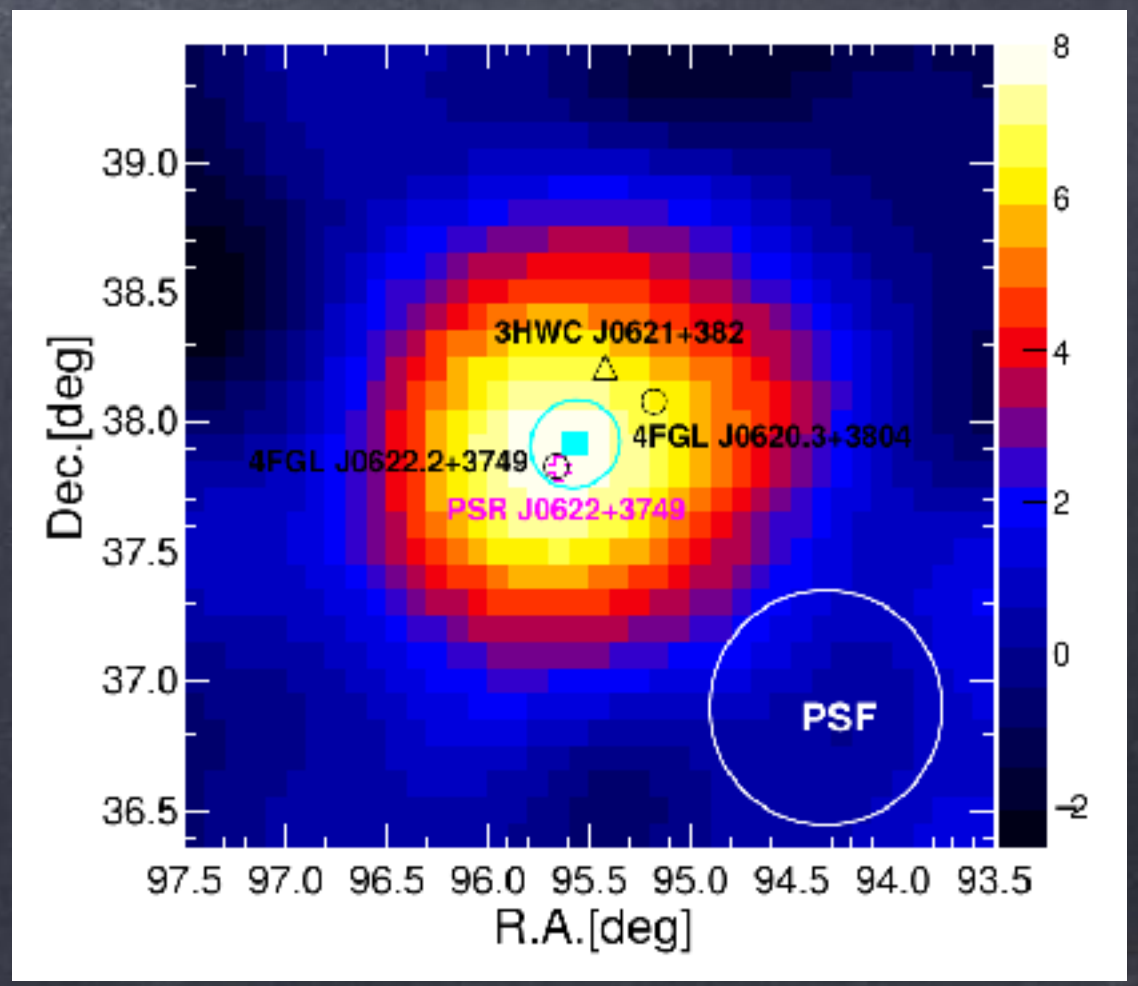
- Consider only middle-aged pulsars that are out of SNR
- diffuse in ISM to d >> PWNe (tens pc VS $\lesssim$ pc)
- ICS on CMB ——> TeV emission ($e^{\pm}$ of 10s-100s TeV)
- Clean probe of CR transport in multi-TeV particles



HAWC: Geminga-Monogem



LHAASO: PSR J0622+3749

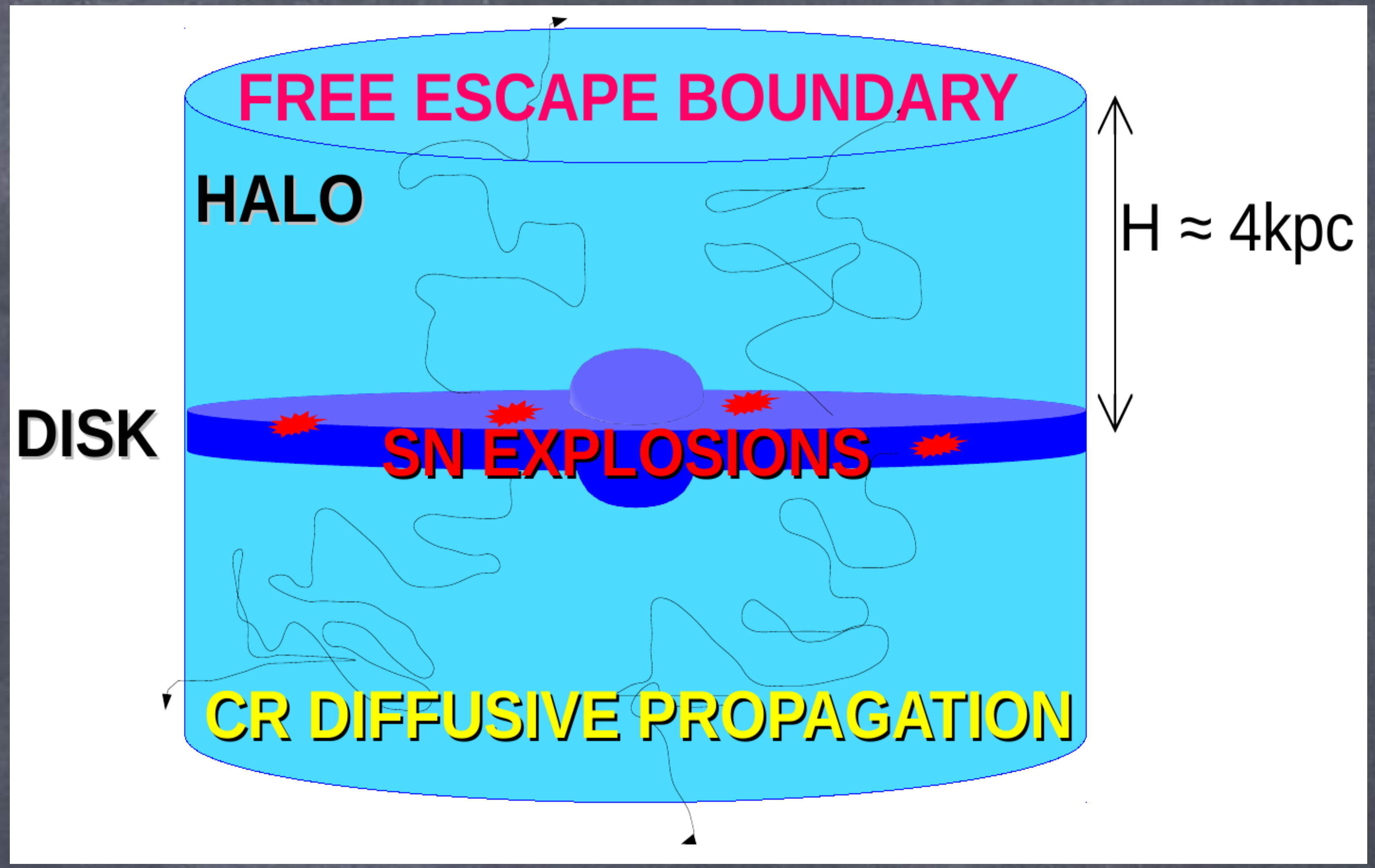


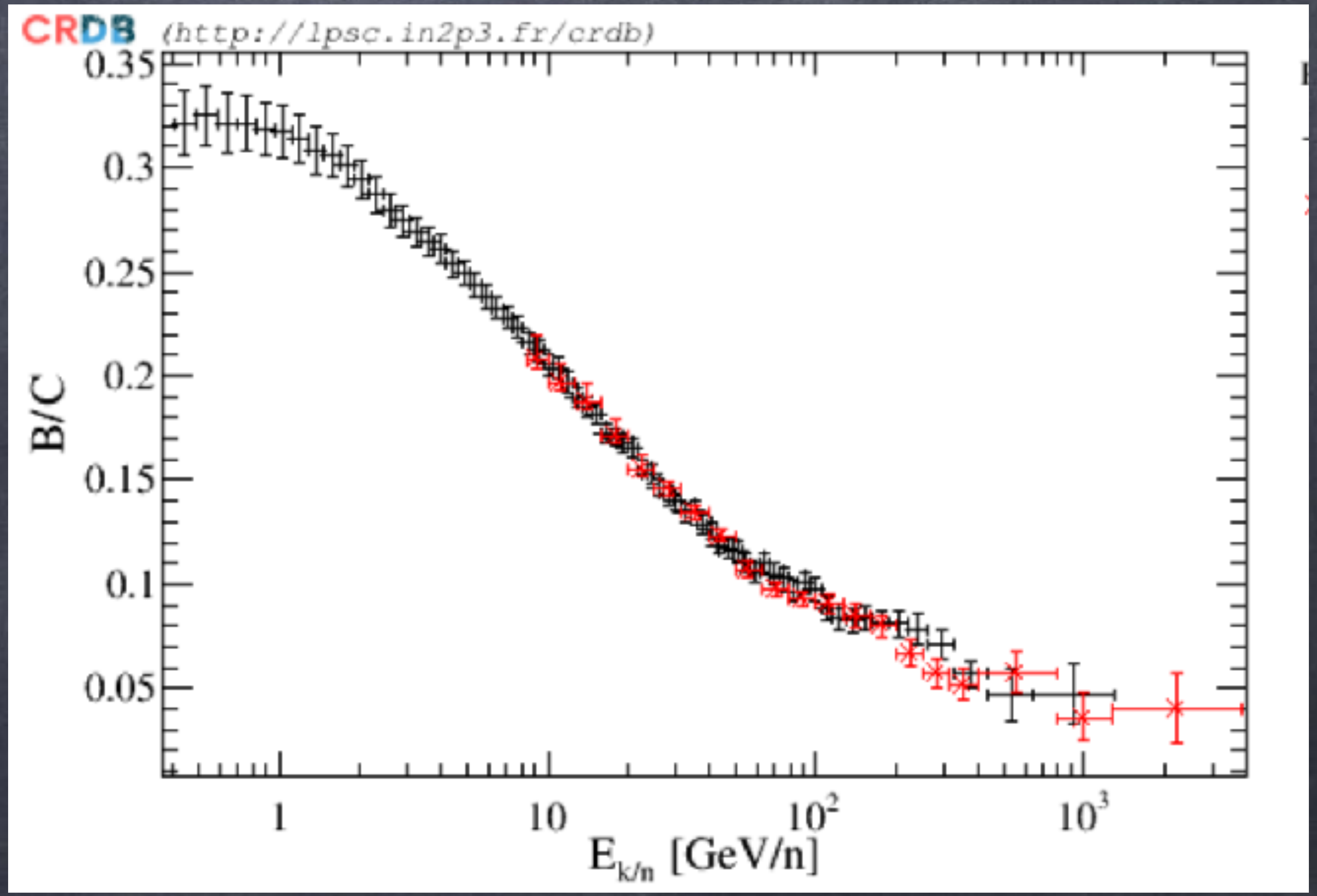
CR transport physics and data

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

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

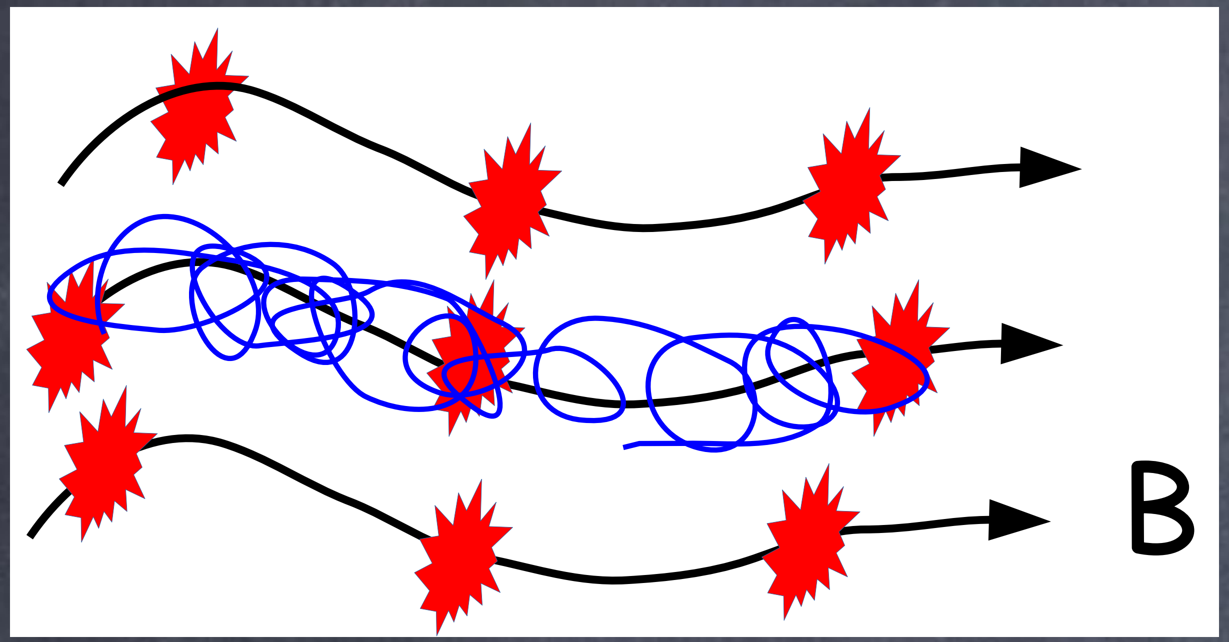
Gabici et al. 2019 - review CRs





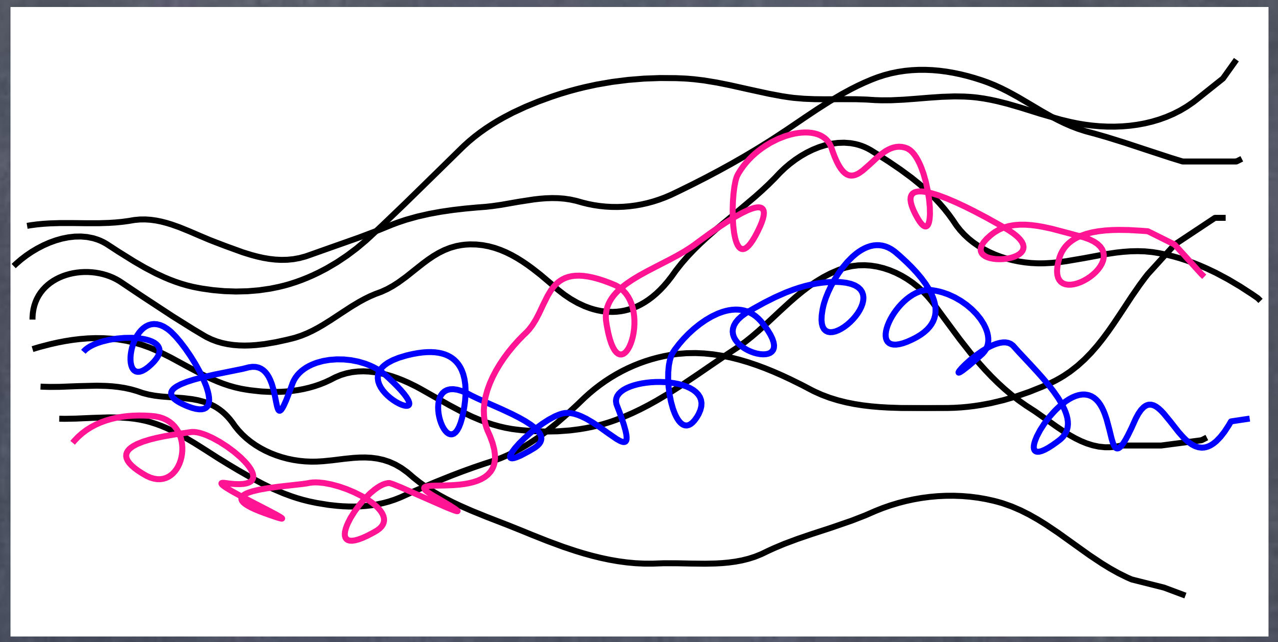
CR transport physics around sources

parallel diffusion



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

perp. transport



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

MHD turbulence

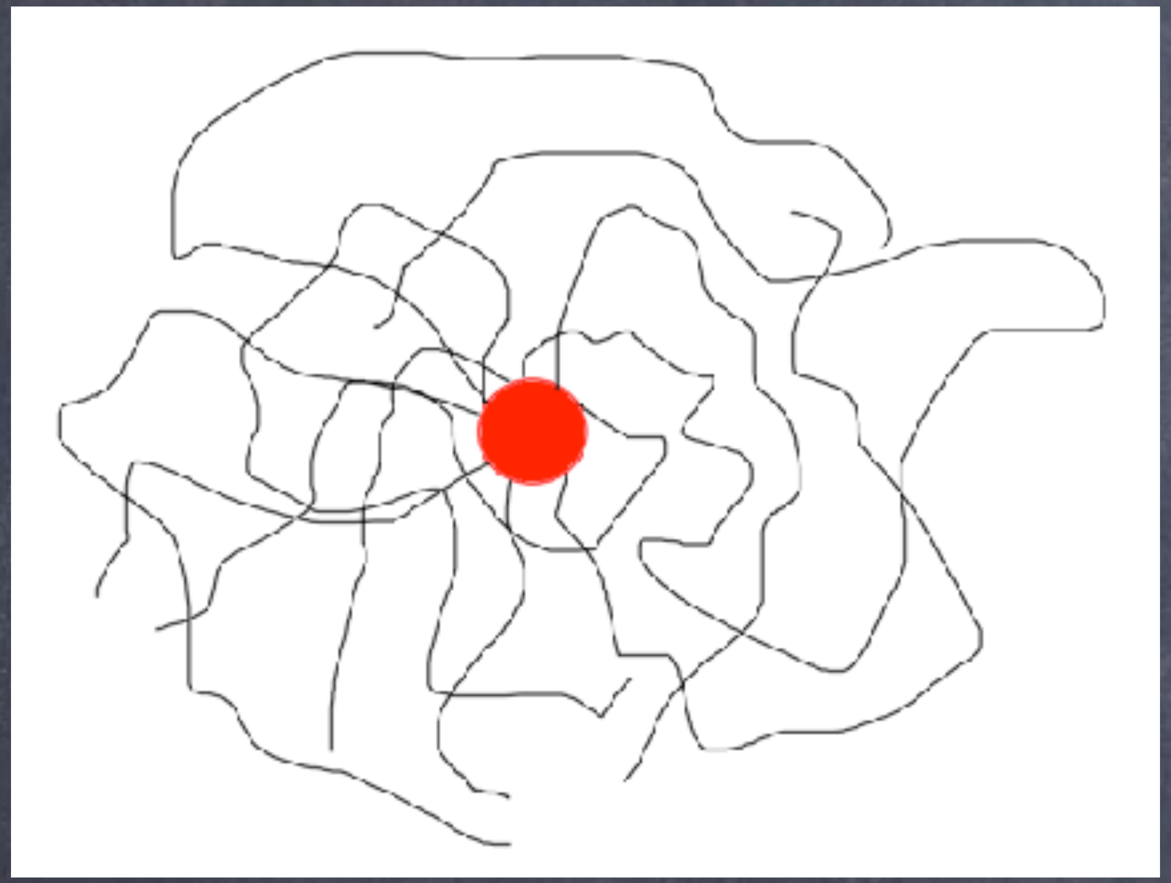
- source injection (10s pc)
- cascade to $k \sim 1/r_L$?
- damping?
- Produced by CRs ?

Mertsch 2020 - review turbulence & transport

Shalchi 2020 - review perp. Transport

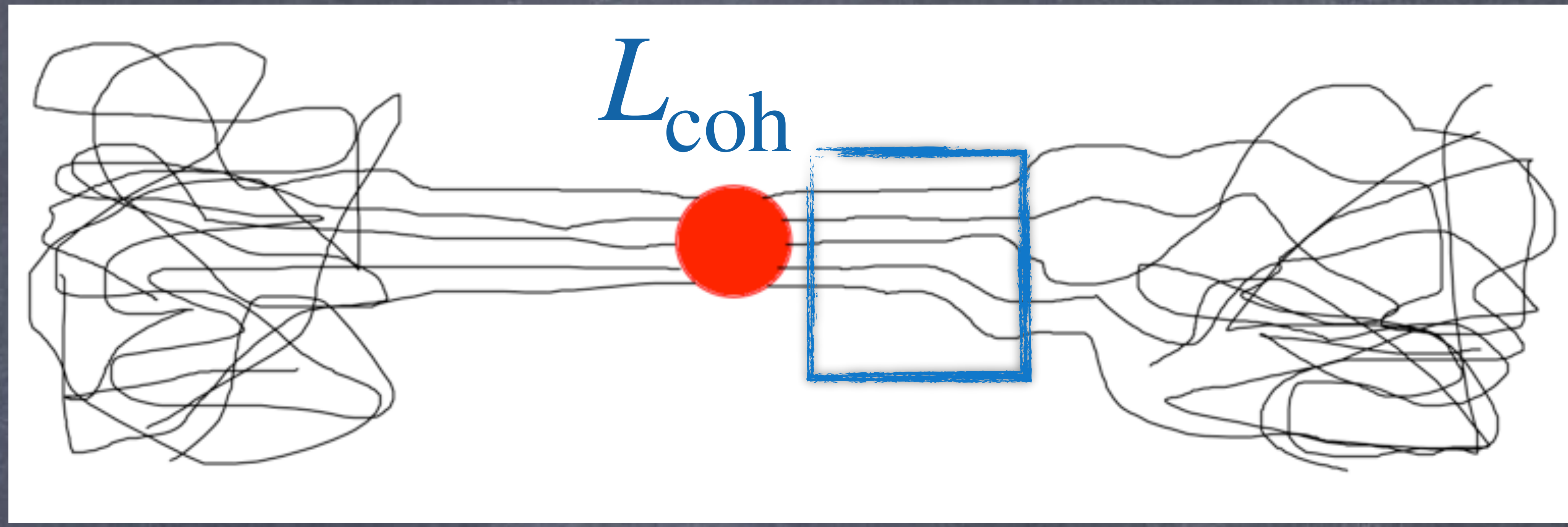
CR transport physics around sources

highly turbulent ISM



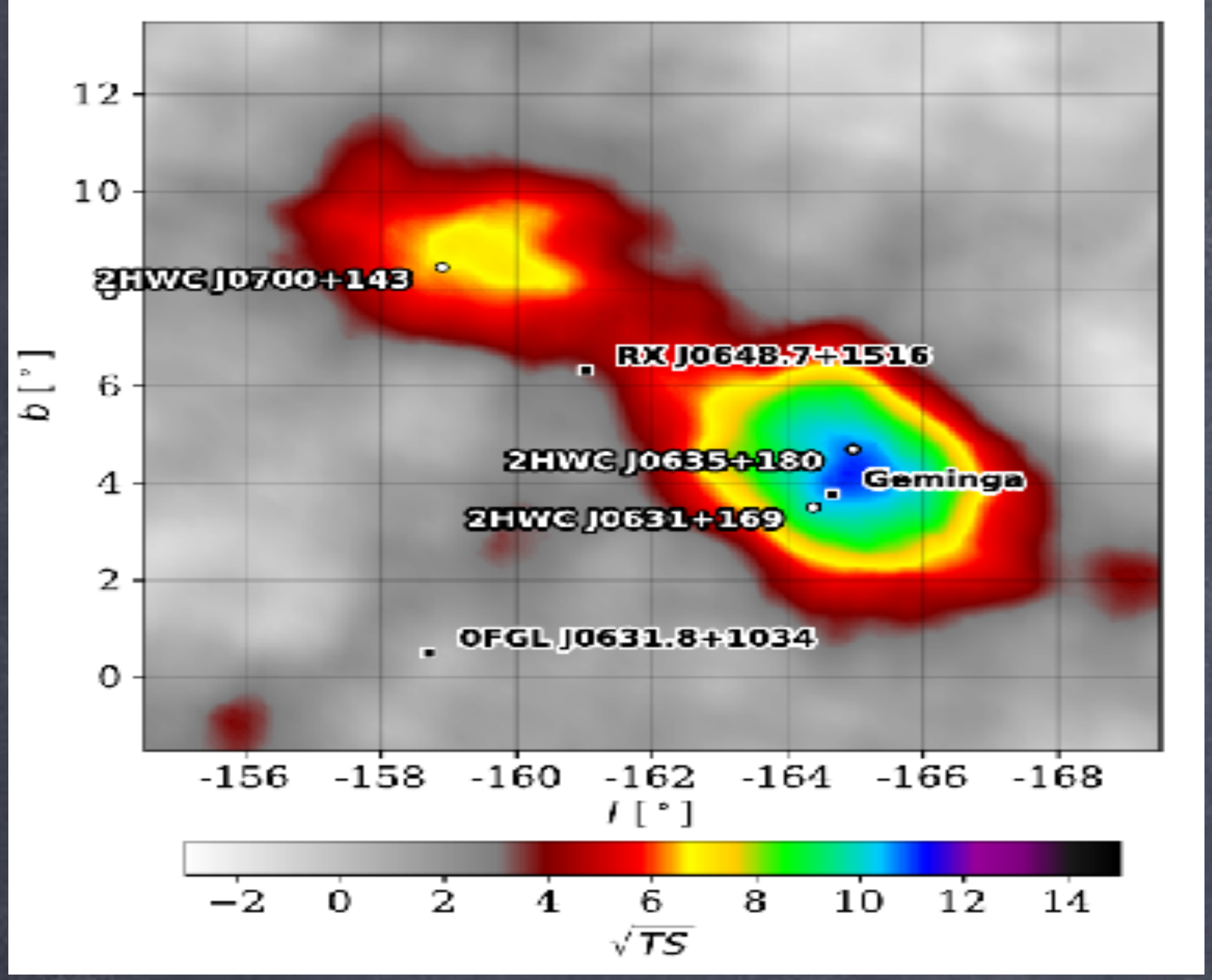
- small $L_{\rm coh}$ << size
- 3D isotropic diffusion
- Small D
- spherical morphology

anisotropic transport



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

TeV halos - Observations

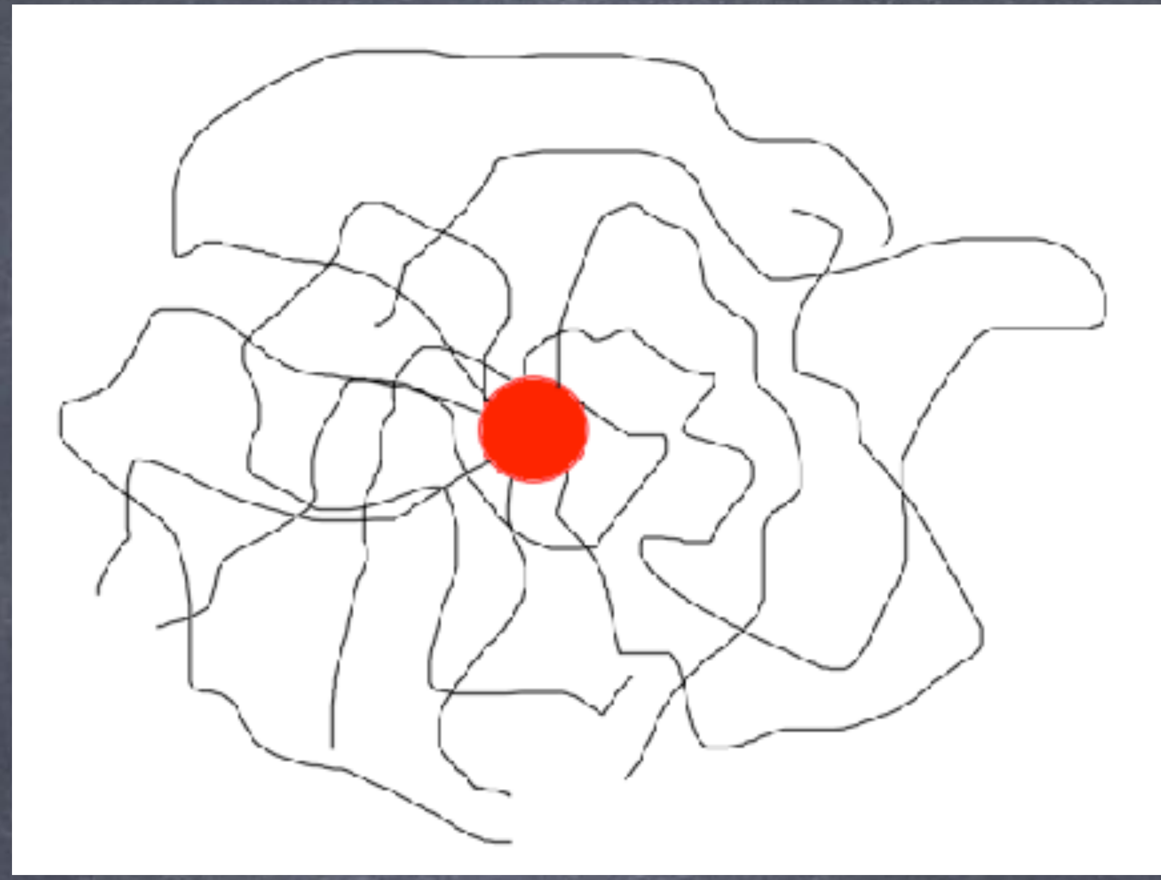


- 10-200 TeV $e^{\pm}$, ICS on CMB
- $E_e \sim 100\,\mathrm{TeV}, \quad E_\gamma \sim 20\,\mathrm{TeV}$
- age ~ 100s kyr
- distance ~ 300 pc
- 10s pc extension

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

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

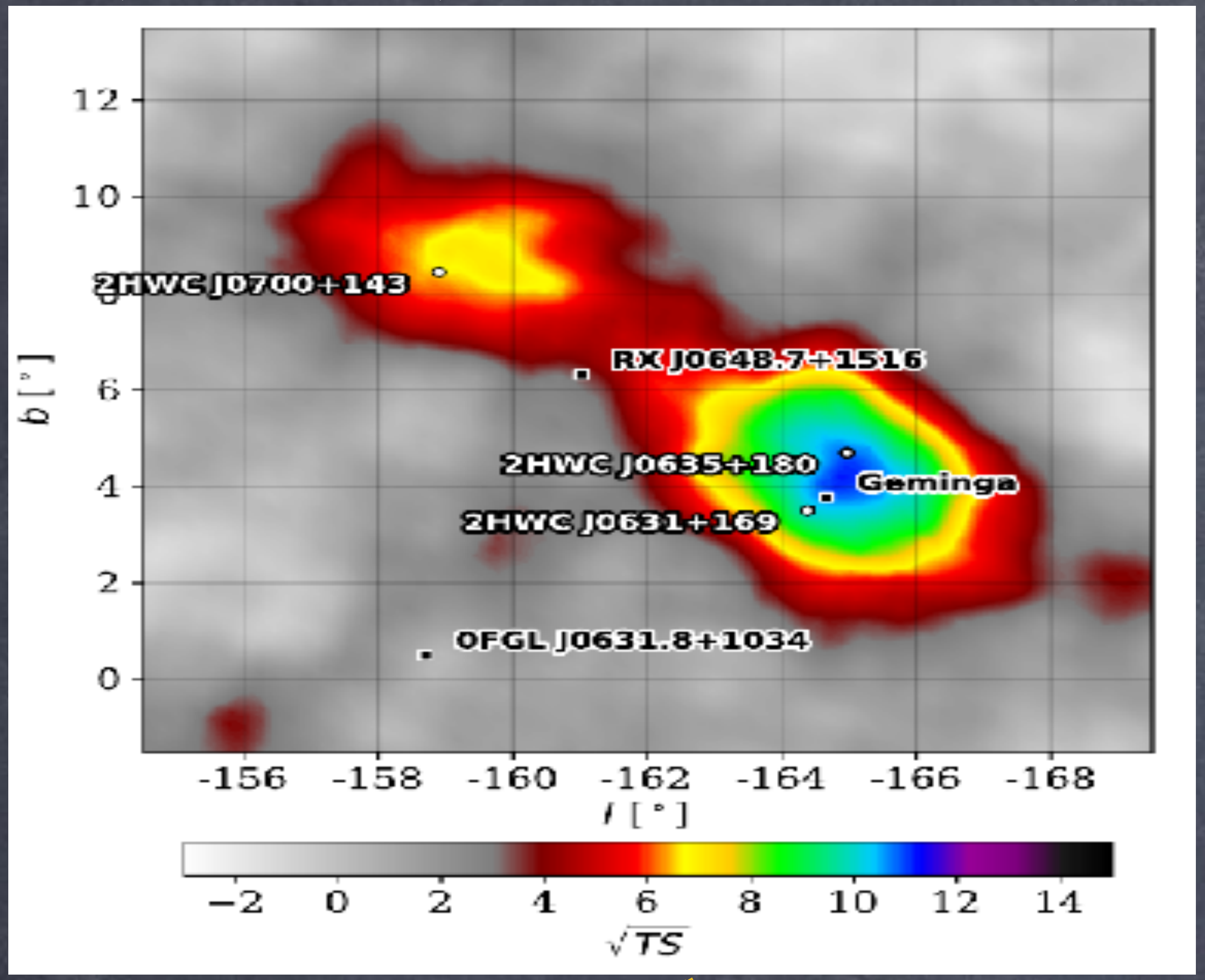
highly turbulent ISM



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

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

I - High turbulence from environment



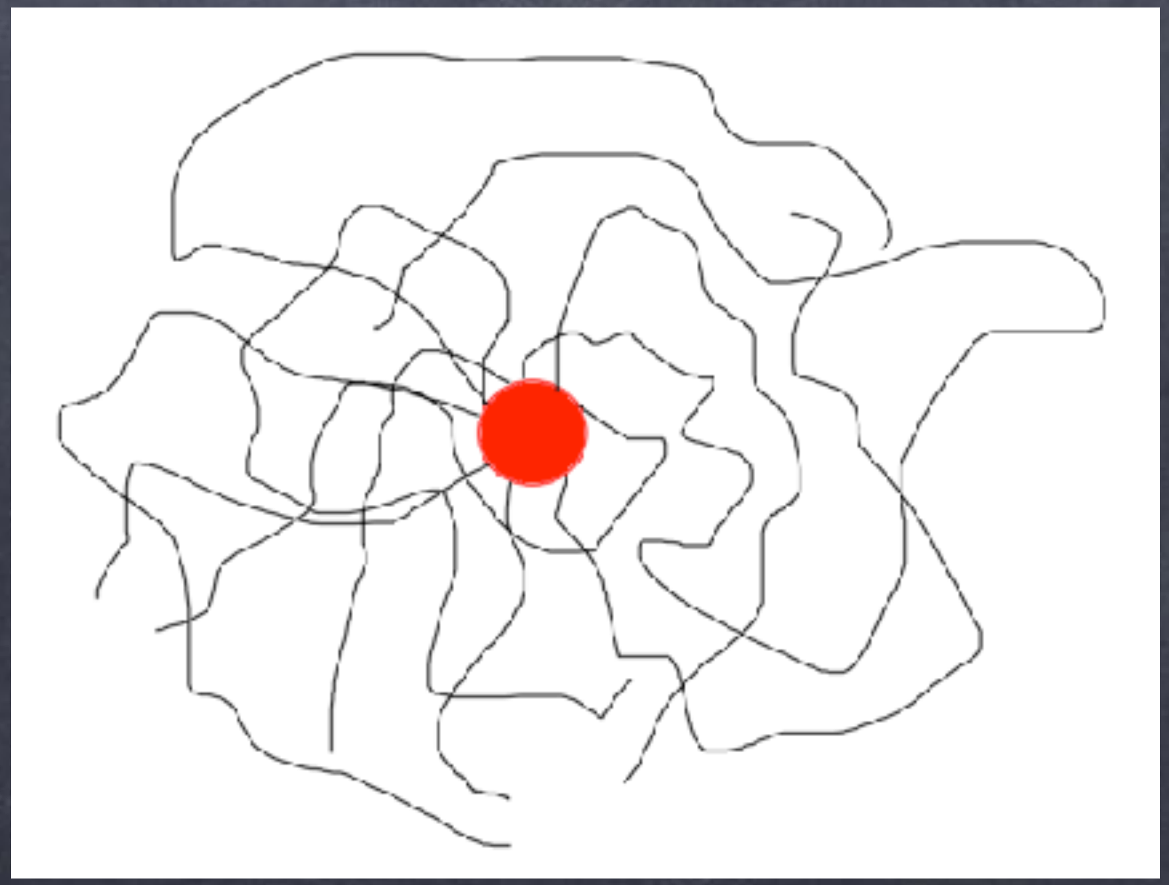
HIGHLY TURBULENT REGION

- filling factor?
- extension?
- how many halos?
- impact on positron fraction?

pulsar's environment ....

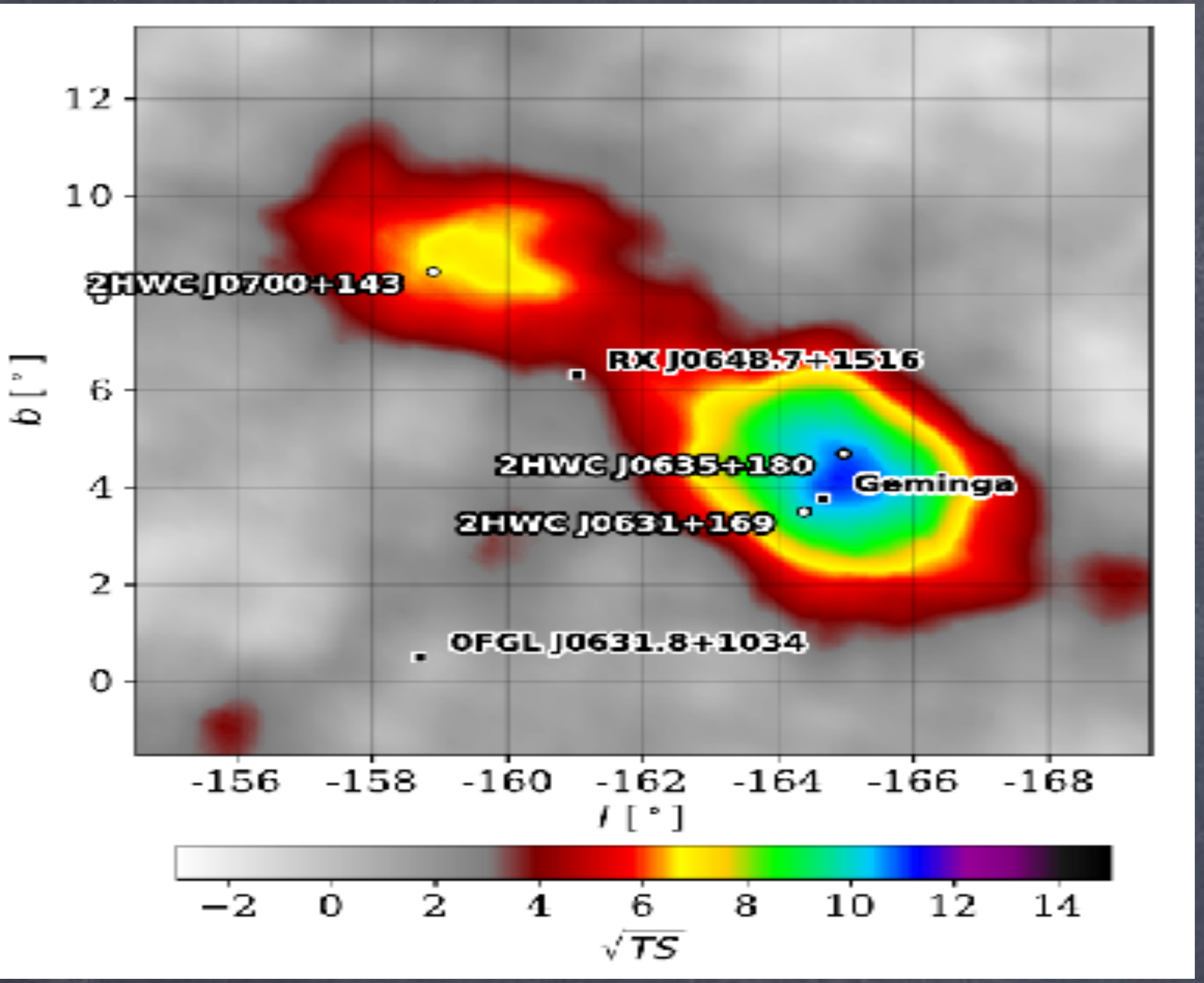
$D_{ISM}(100\text{TeV}) \approx 10^{30}\ \text{cm}^2/\text{s}$

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



Martin et al. 2022

II - Typical turbulence + anisotropy

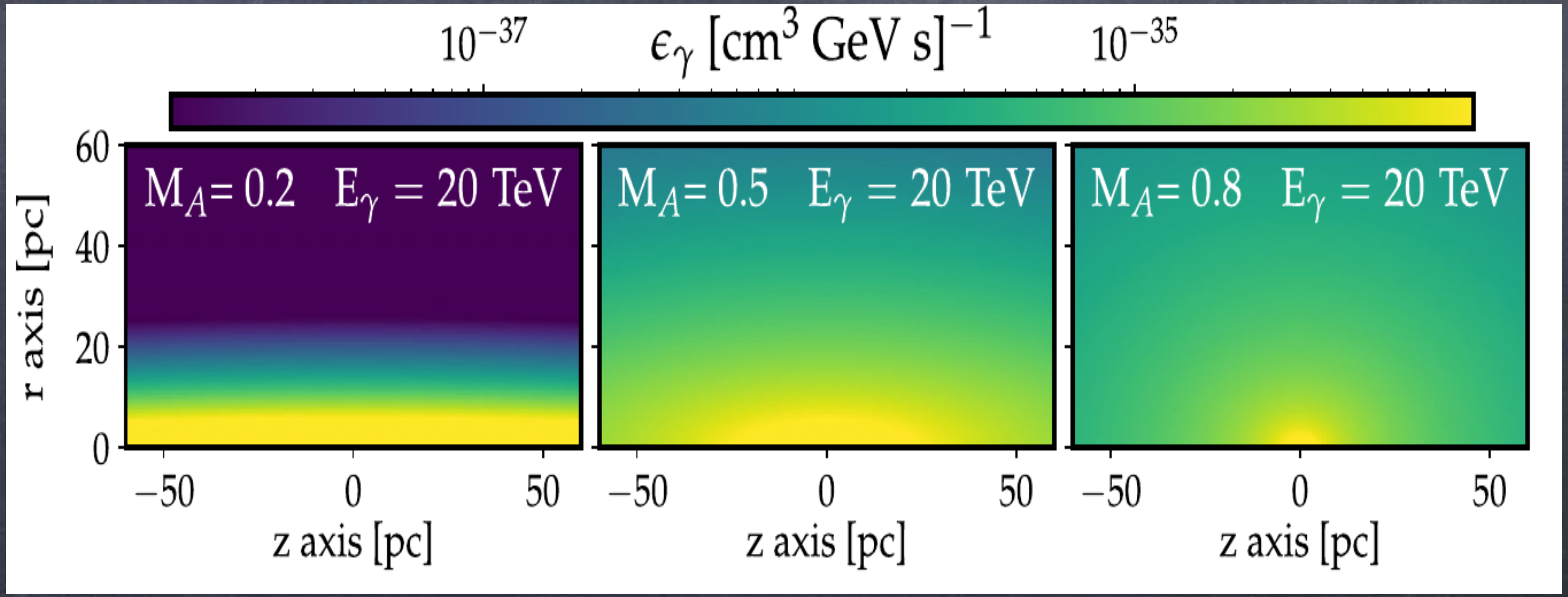


ANISOTROPIC DIFFUSION

- need small ψ_{incl} for spherical halo
- chance? morphology?
- look for features?

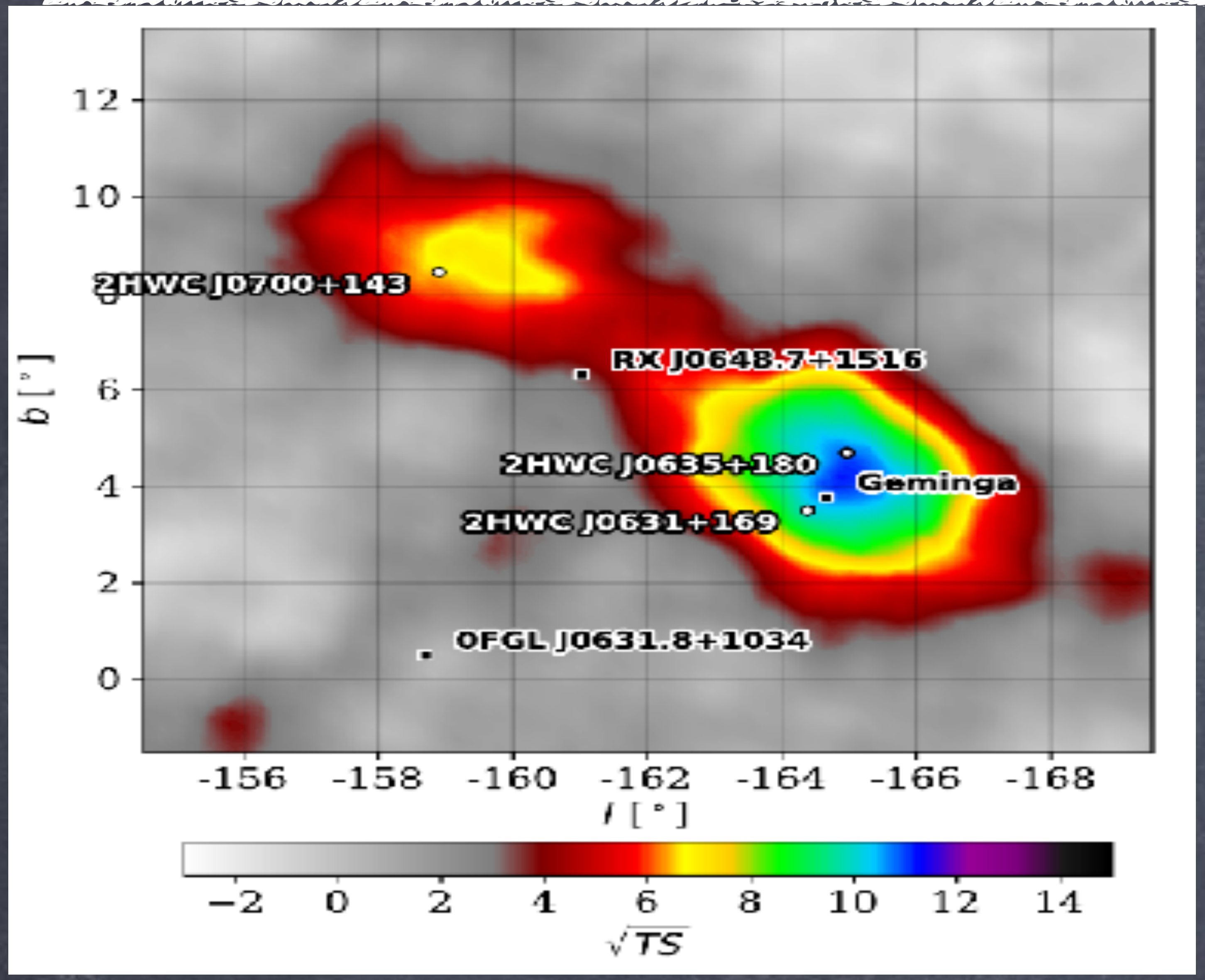
$D_{ISM}(100\text{TeV}) \approx 10^{30}\ \text{cm}^2/\text{s}$

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



De La Torre et al. 2022

III - High turbulence- self-gen.



SELF-GENERATED TURBULENCE

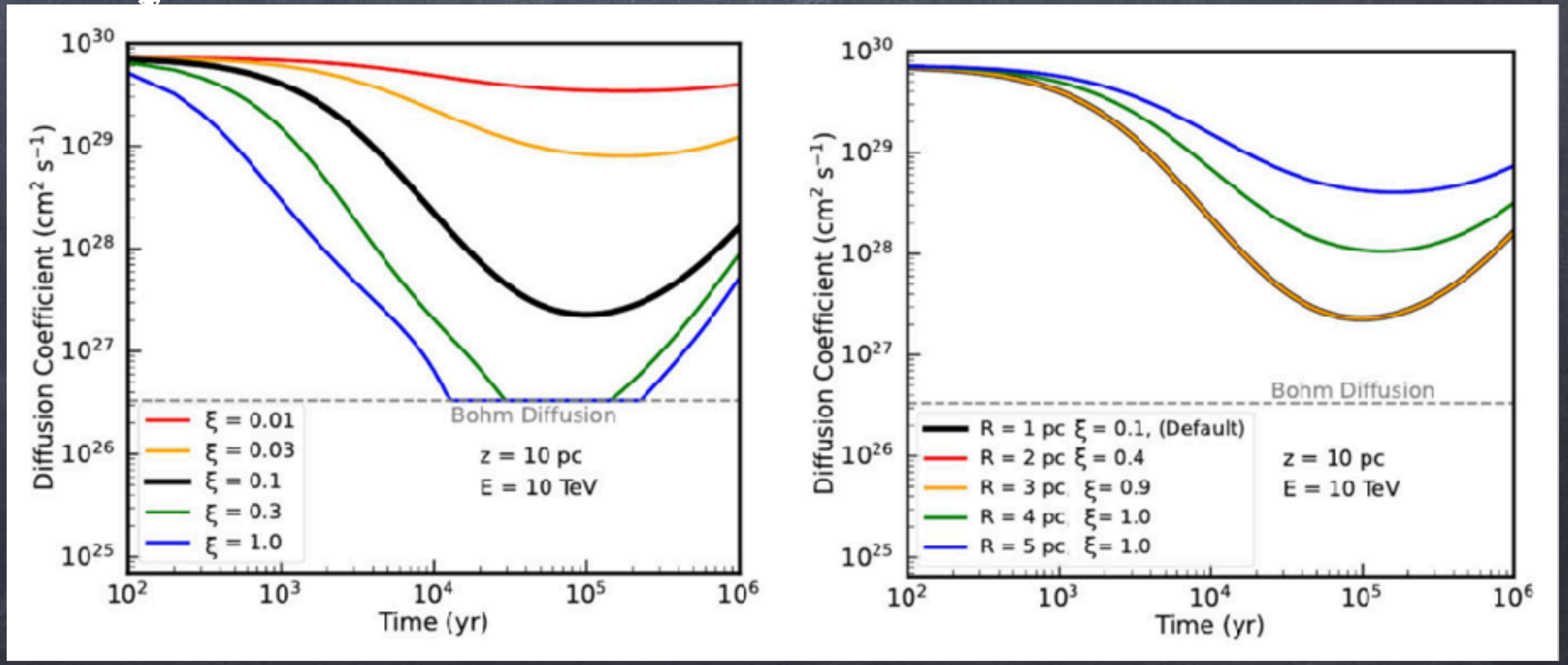
- several works shows that the effect can be there but...
- difficult even with flux-tube geometry and high efficiency
- same problems of anisotropic diffusion with morphology

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

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

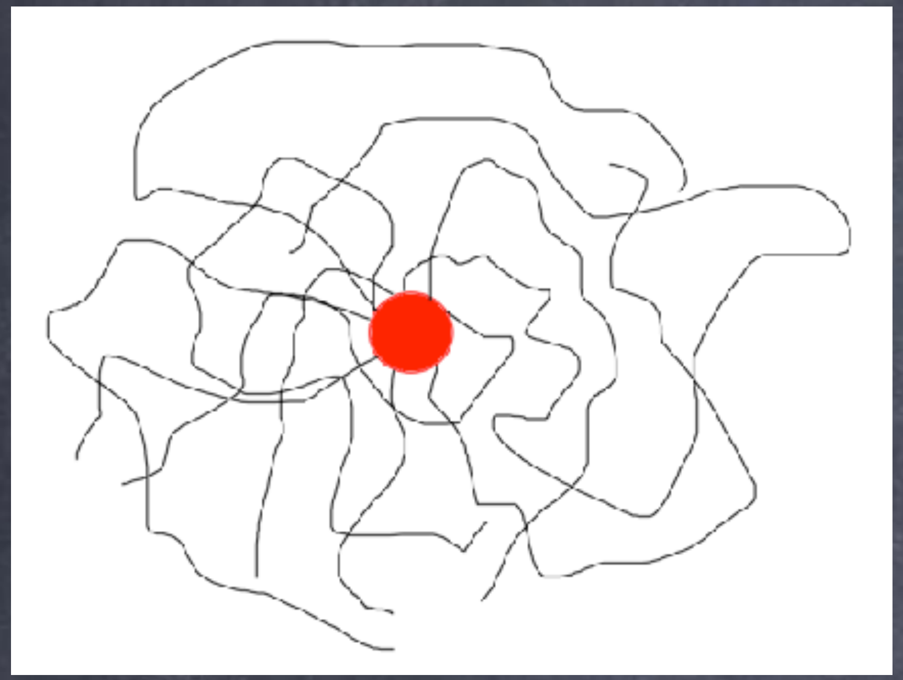
Evoli et al. 2018

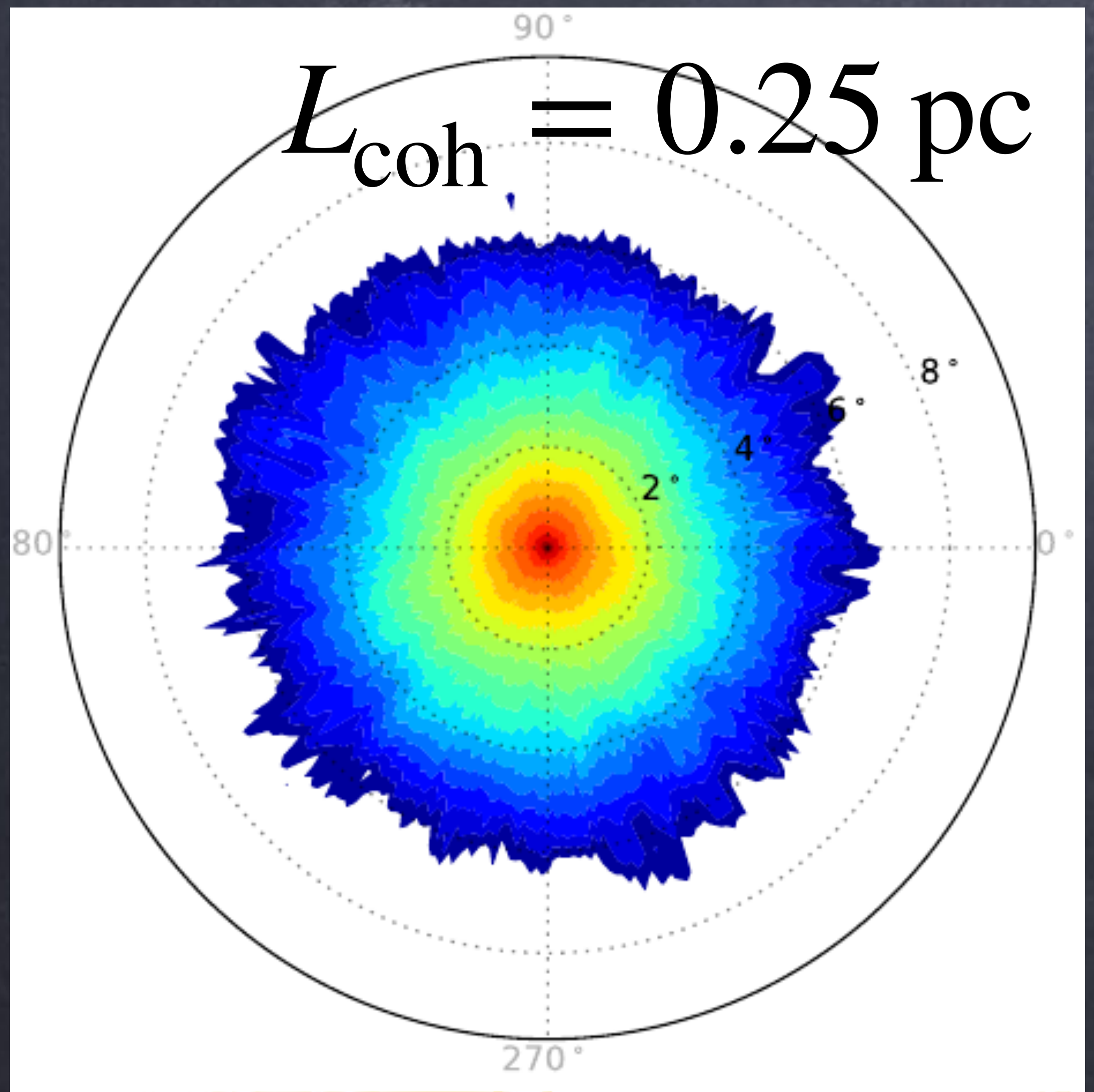
Mukhopadhyay & Linden 2022



TeV halos interpretations in a nutshlell

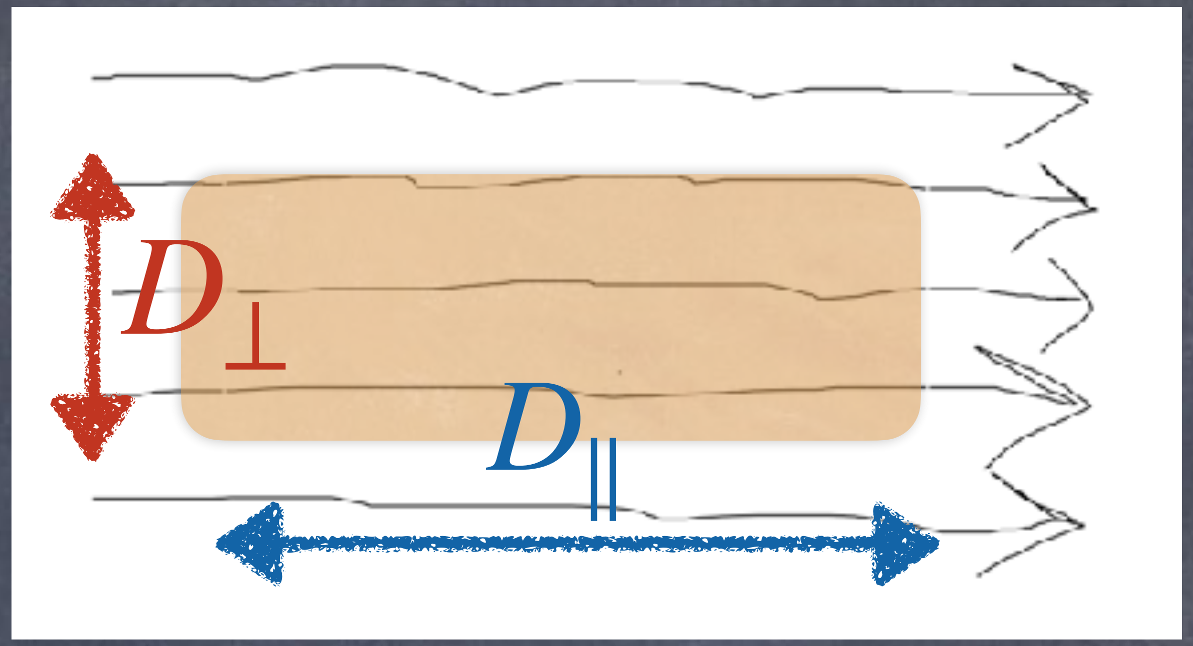
3D isotropic diffusion

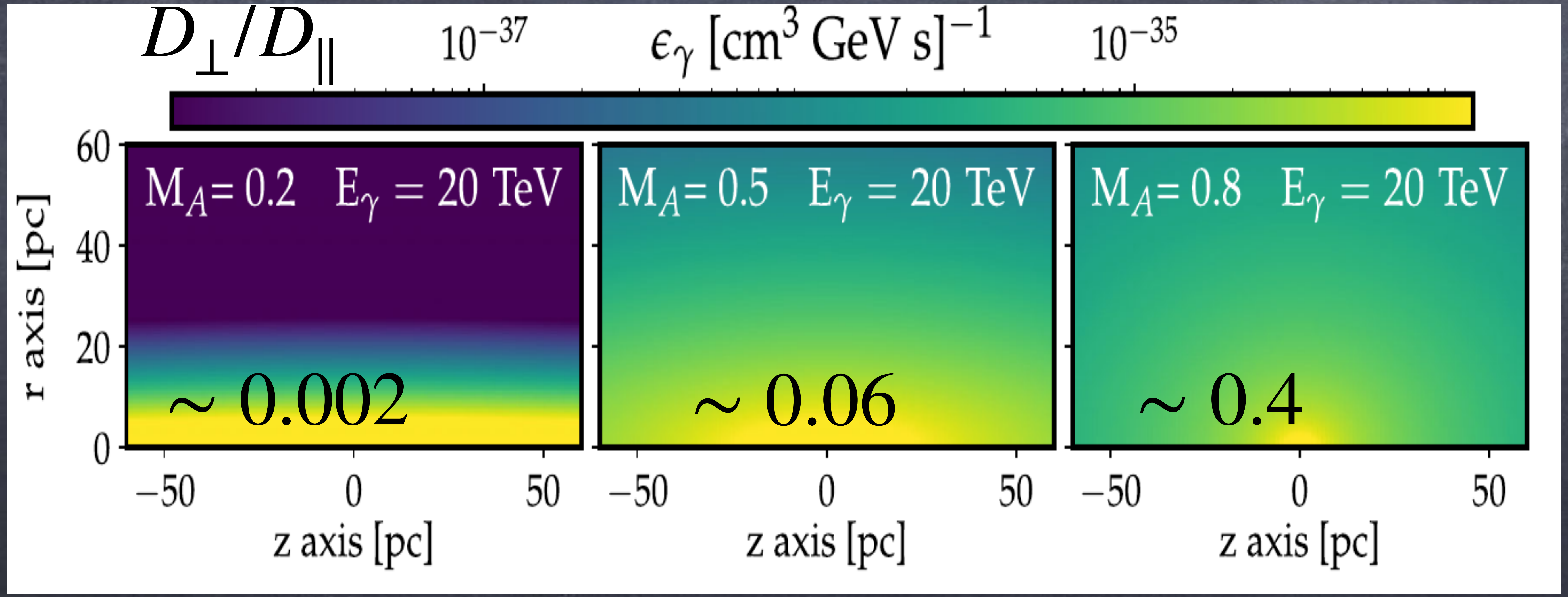




Lopez-Coto & Giacinti 2018

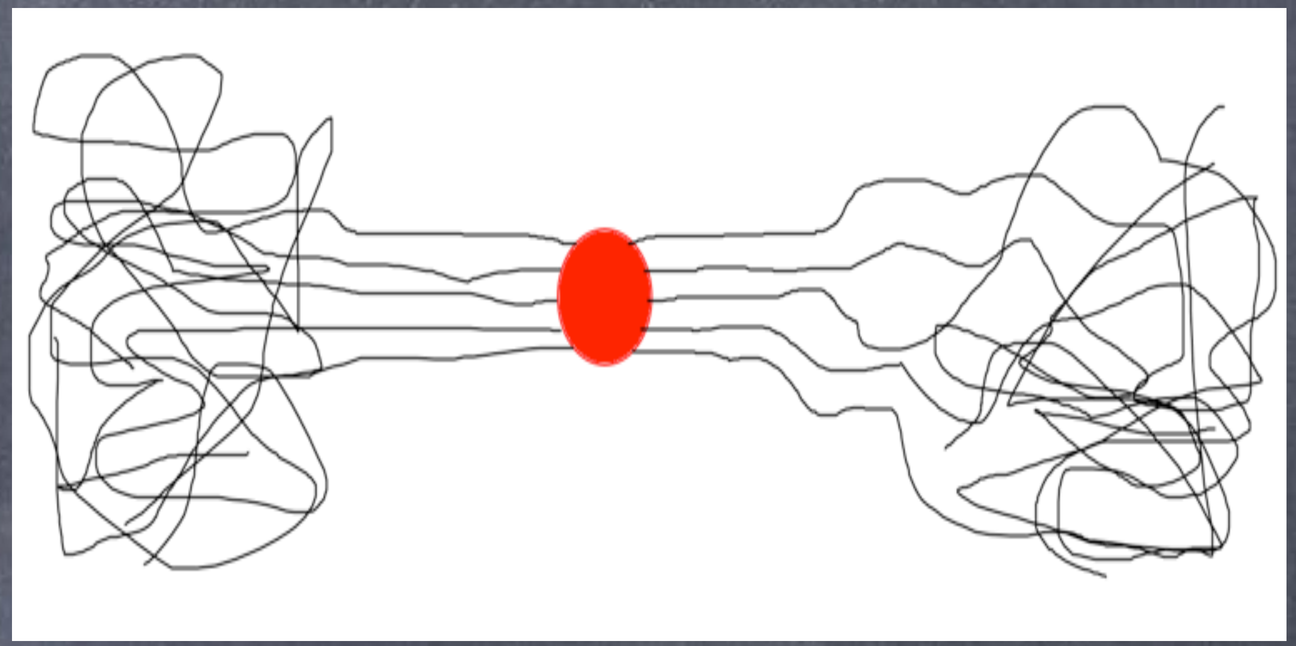
anisotropic diffusion

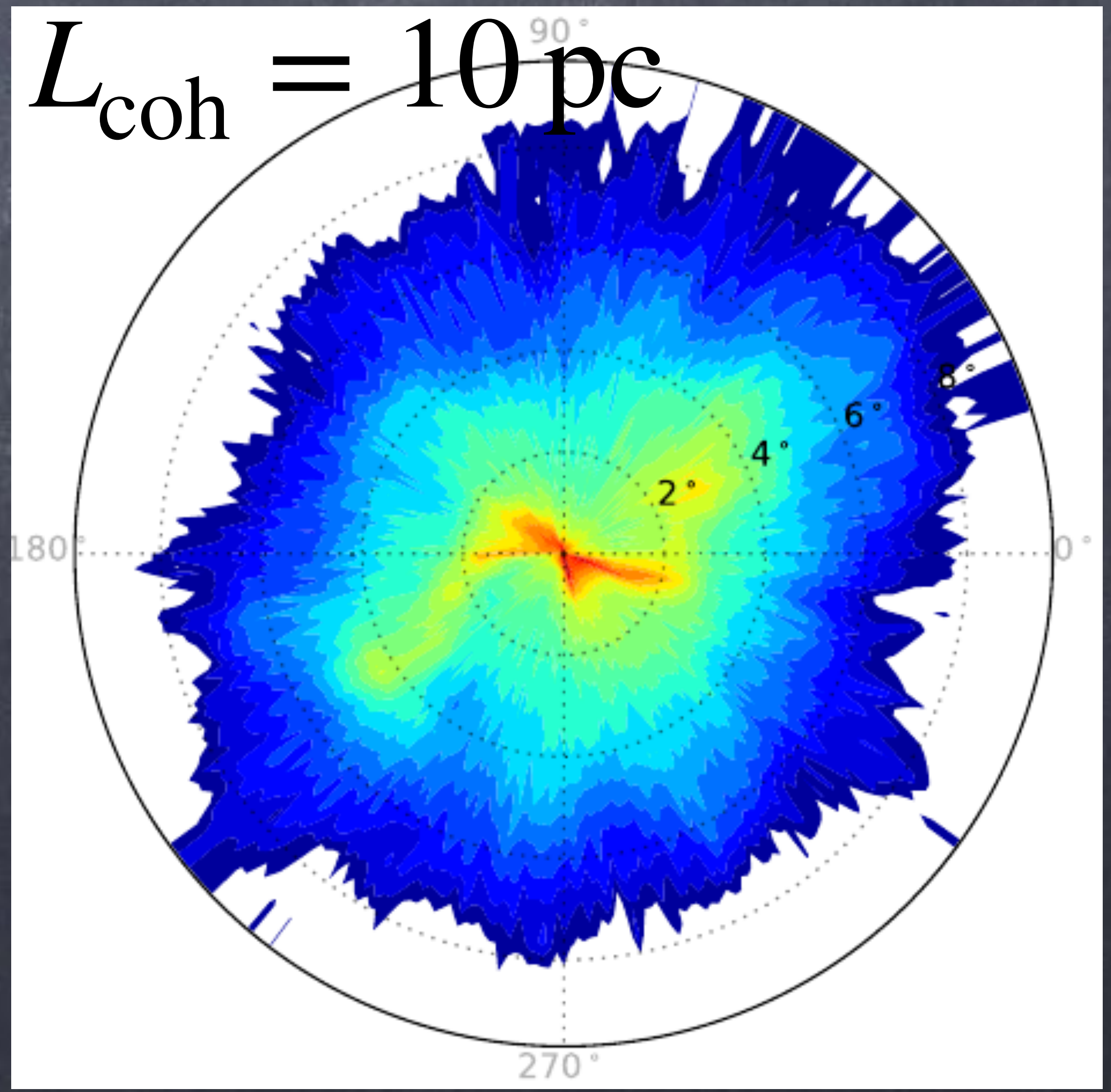




De La Torre et al. 2022

more realistic setup?





What more? - Dedicated Surveys

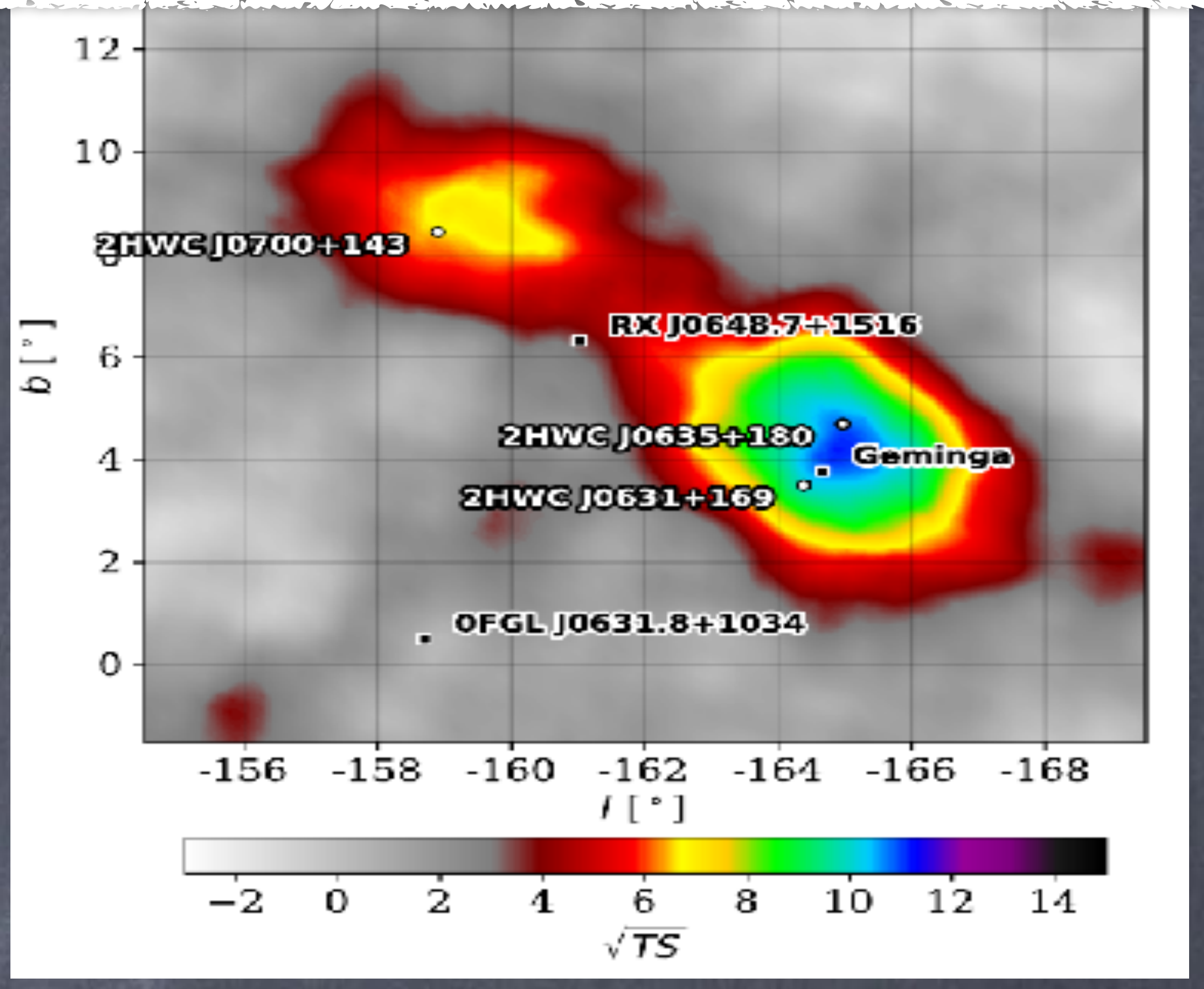
So far "only" 3 clear observations of TeV halos

… we mean sources old enough to be in ISM …

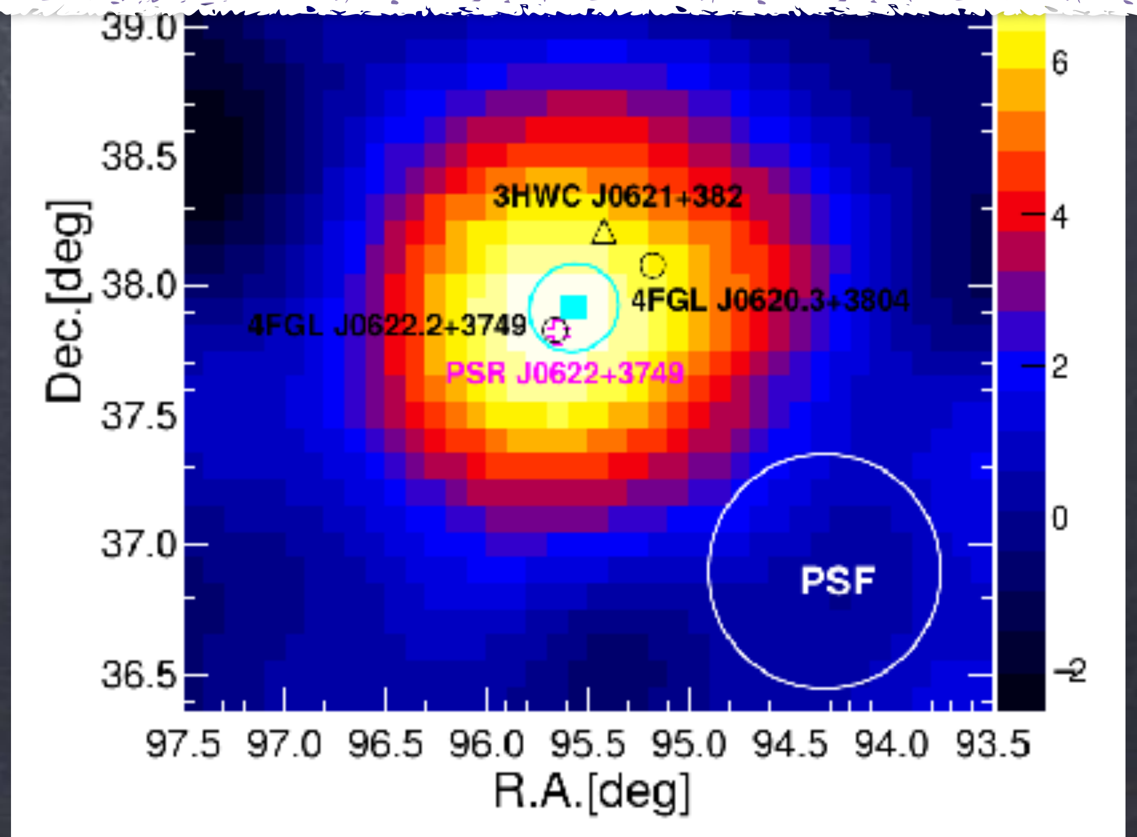
- Why only 3?
- are TeV halos rare?
- dedicated surveys that target nearby known middle-aged pulsars
- … LHAASO: high sensitivity, 2sr FoV
- nearby = could be seen as an extended source (~ 2-3 PSF)

$R_{\text{HALO}} \approx 10 - 20\,\text{pc}$ $\theta_{\text{PSF}} \approx 0.3^{\circ}$ → $D \approx 1 - 2\,\text{kpc}$

HAWC: Geminga-Monogem

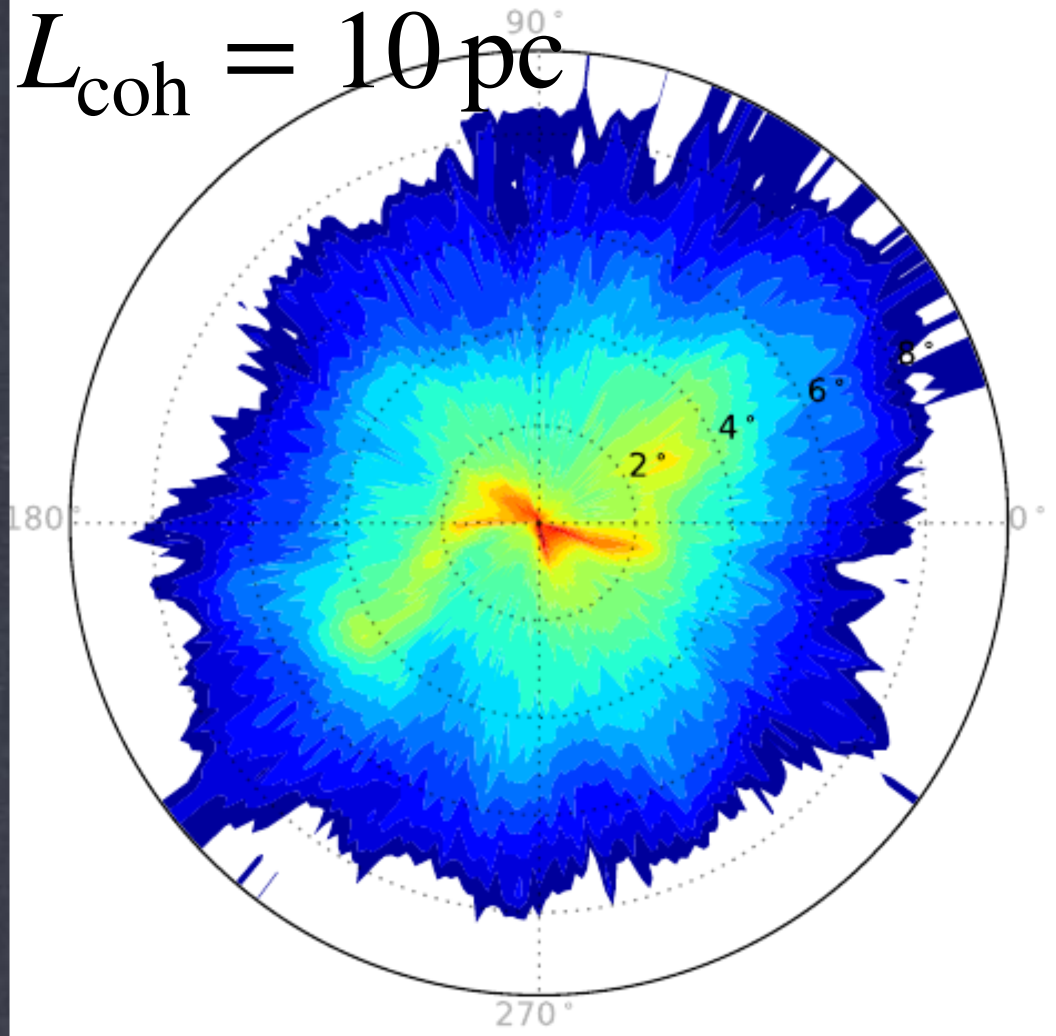


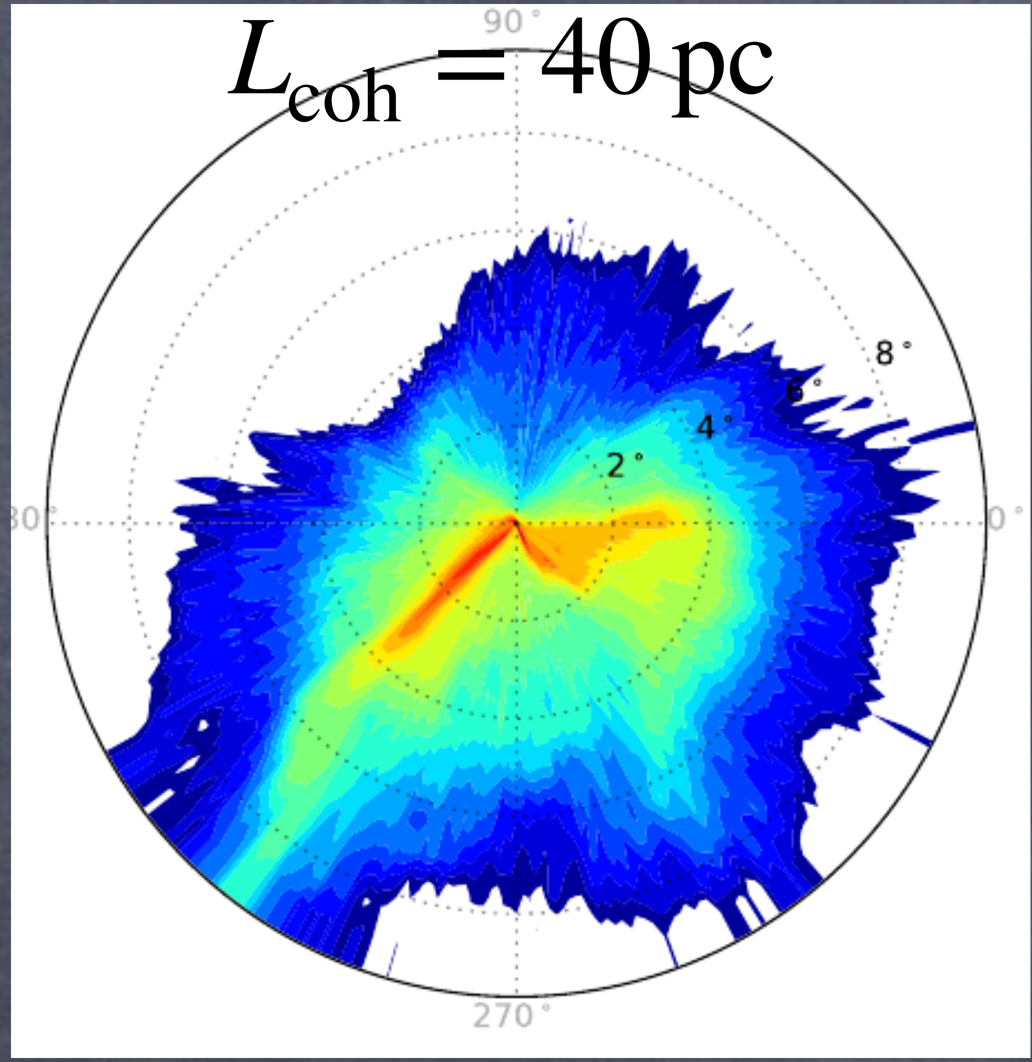
LHAASO: PSR J0622+3749



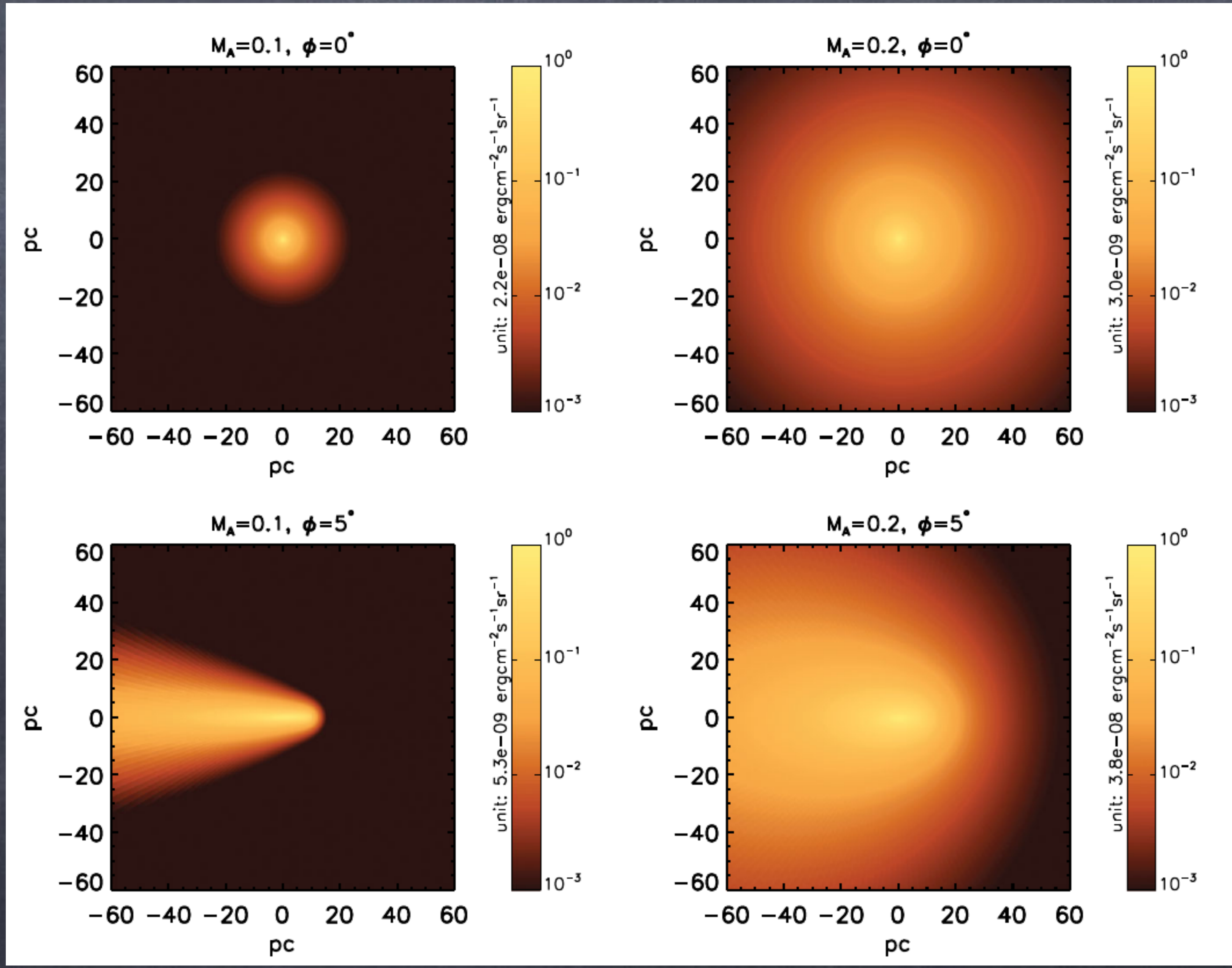
What more? - Features

FEATURES OF ANISOTROPIC DIFFUSION





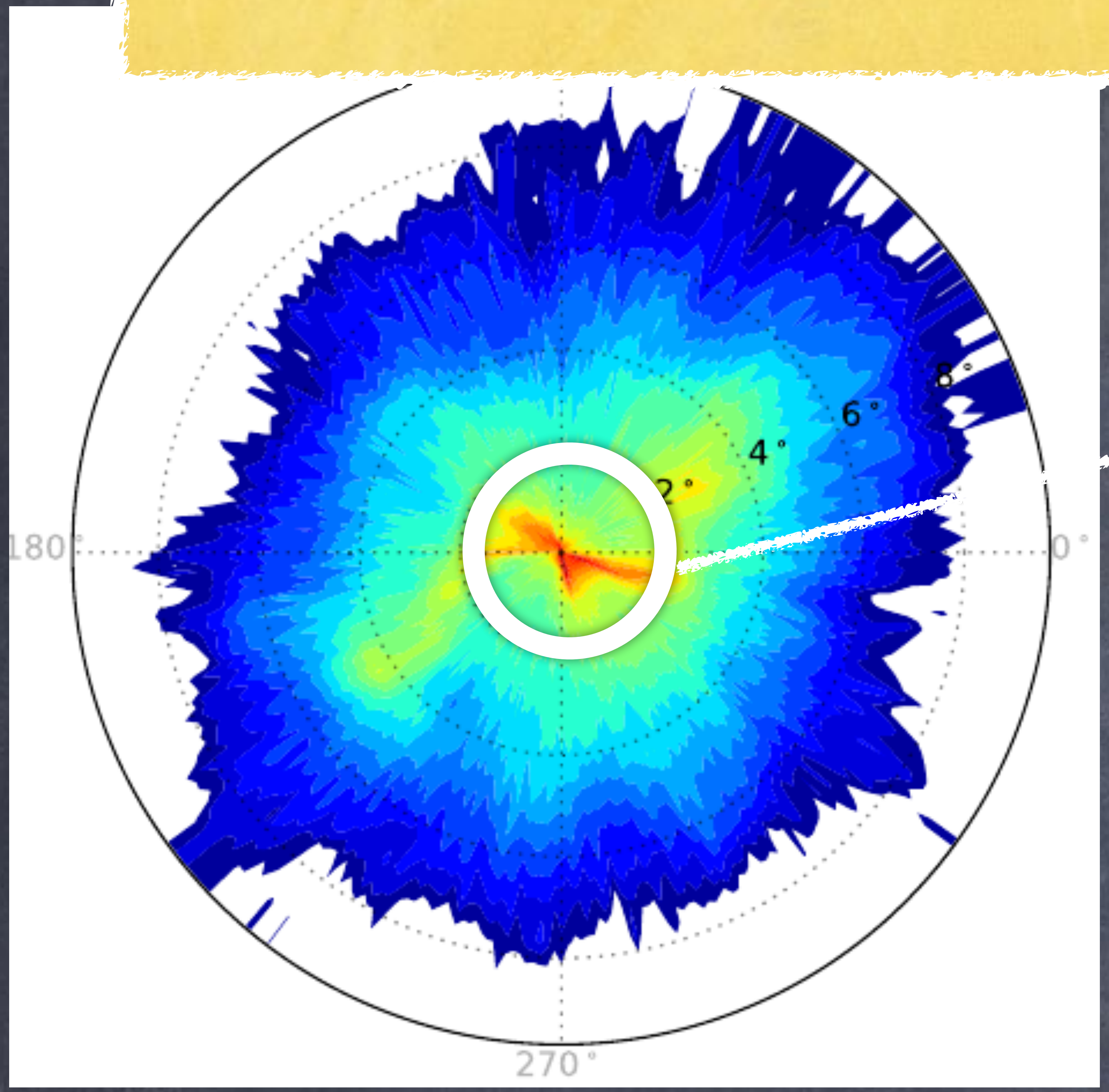
Liu et al. 2019



- non-spherical emission $\propto \sqrt{D_{\parallel}/D_{\perp}}$
- orientation of B field
- separation γ−ray source - pulsar
- filamentary structures

What more? - Features

COMPLEMENTARITY WITH IACTS



2°

	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

- need for targeted analyses on Geminga-like pulsars
- high sensitivity, large FoV —> LHAASO ...
- high sensitivity, angular resolution —> IACTS
- probe different energy ranges

- bias on spherical shape?
- go beyond analyses that assume spherical symmetry
- discriminating morphological features
  - filamentary structures
  - separation pulsar - TeV source
  - asymmetry in halo shape

Pulsar's Environment ???

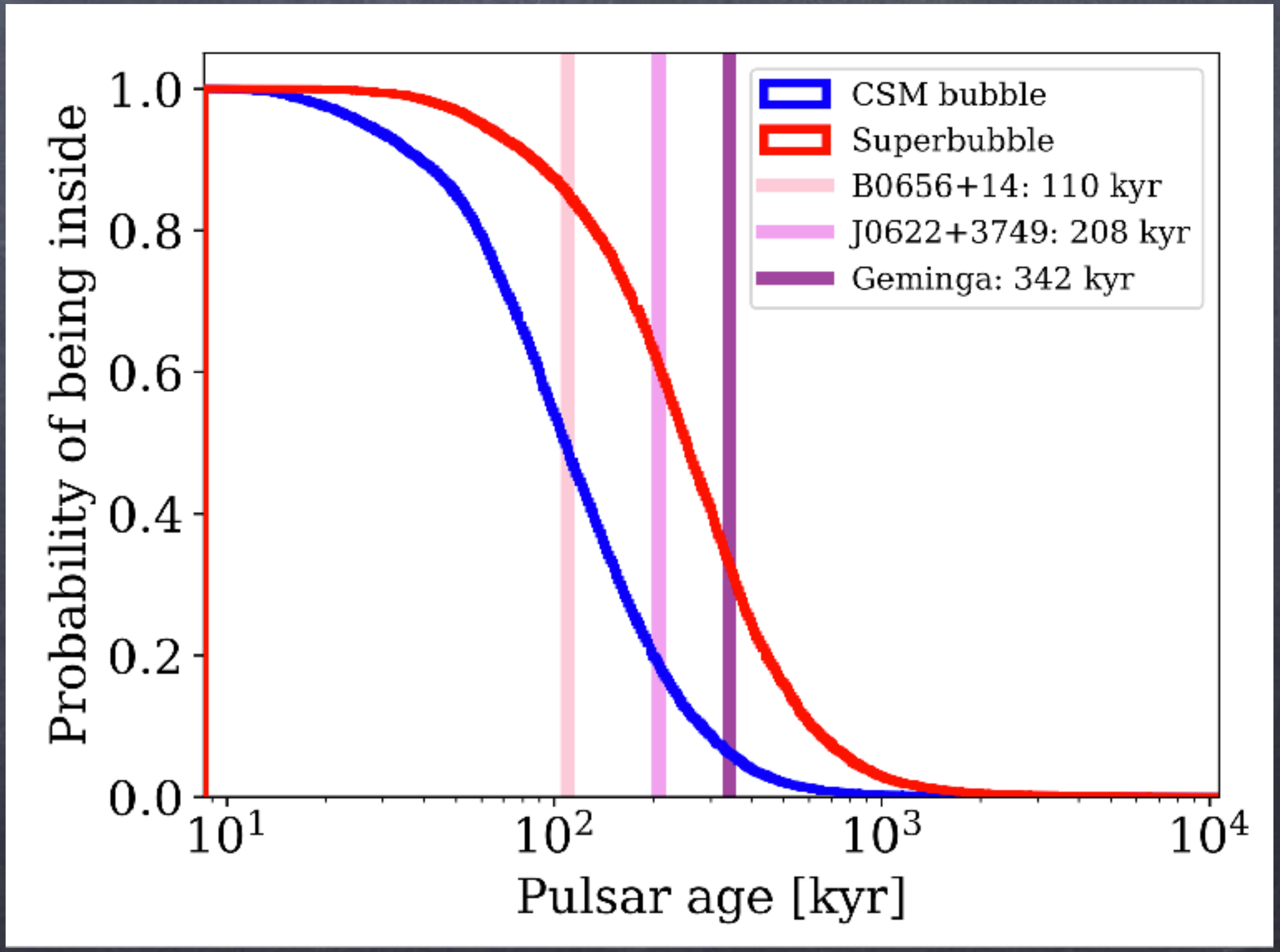
- proper motion $v_{psr} \sim 100s$ km/s ⟶ out of SNR $\approx 10s$ kyr
- Bow shock ⟶ particle release in ISM

big caveat ...

For how long a pulsar stays in a given environment?

Bourguinat + paper in preparation 2024-2025

Pulsar	Age [kyr]	Inside (CSM, 4%[1])	Inside (SB, 96%[1])
B0656+14	110	49%	85%
J0622+3749	208	19%	61%
Geminga	342	6%	33%



Relevant probability for middle-aged pulsar to in hot ionized medium ... ALSO HIGH TURBULENCE?

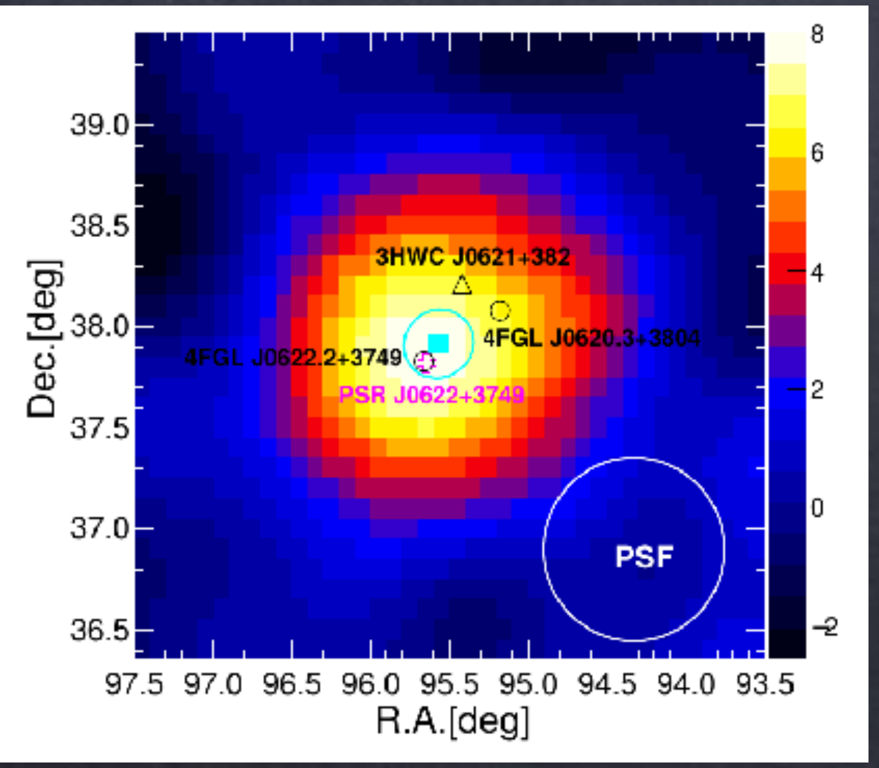
ARE TeV HALOS A ENVIRONMENT-DEPENDENT SOURCE?

Pulsar's Environment & TeV sources

Could we envisage the following situation?

pulsar in hot/turbulent ISM

- TeV halo
- spherical emission

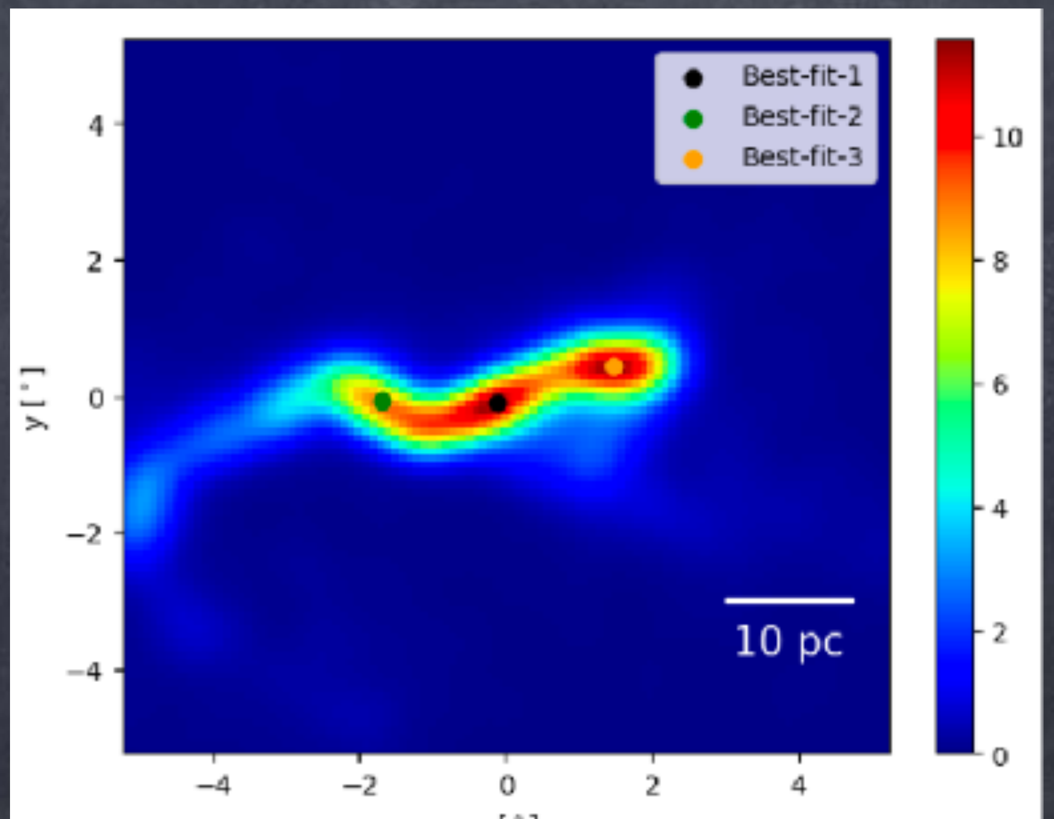


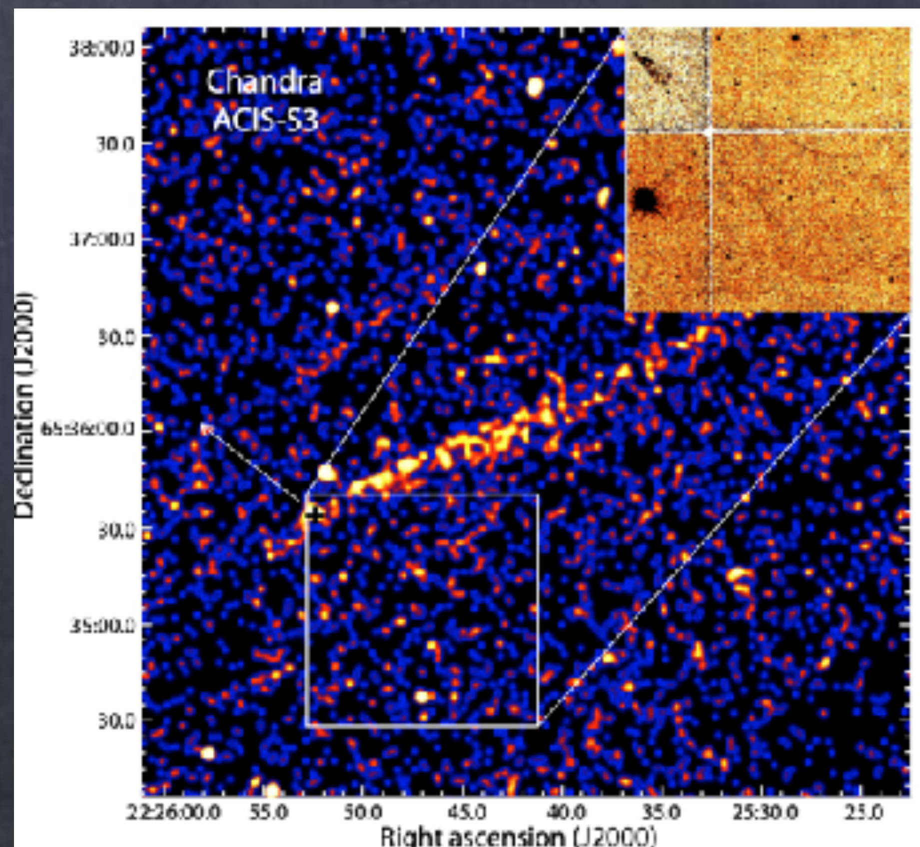
Olmi et al. 2024

Bao et al. 2024

pulsar in cold/warm & "quiet" ISM

- No halo? Features?
- X-ray filaments?
- multiple (mirage) sources





Summary

- TeV halos detected around middle-aged pulsars (HAWC, LHAASO)
- not understood with current transport models
- new window on CR propagation at multi-TeV
- surveys with high-sensitivi & large FoV —> LHAASO ...
- high sensitivity & good angular resolution —> IACTS
- energy dependent analysis —> complementarity
- look at the pulsars environment ...

Thank you - references

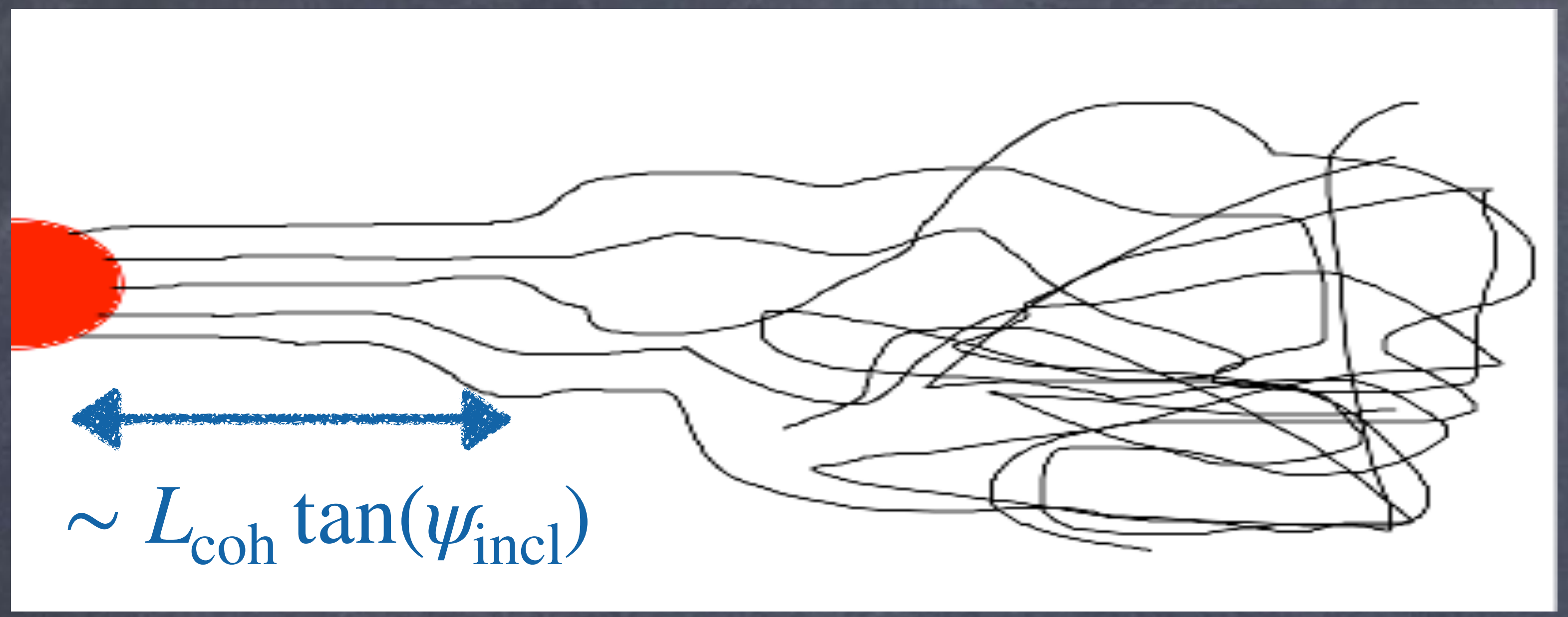
1. HAWC paper (2017) https://doi.org/10.1126/science.aan4880
2. LHAASO paper (2021) https://doi.org/10.1103/PhysRevLett.126.241103
3. Gabici et al. (2019) https://doi.org/10.1142/S0218271819300222
4. Mertsch (2020) https://doi.org/10.1007/s10509-020-03832-3
5. Shalchi (2020) https://doi.org/10.1007/s11214-020-0644-4
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
13. Olmi at al. (2024) https://ui.adsabs.harvard.edu/abs/2024A%26A...684L...10/abstract
14. Bao et al. (2024) https://arxiv.org/abs/2407.02829

What more? - Features

COMPLEMENTARITY WITH IACTS

ASTRI science paper 2022

$\sim \sigma_{PWN}$



	ASTRI Mini-Array	HAWC	LHAASO
Location	28° 18′ 04″ N	18° 59′ 41″ N	29° 21′ 31″ N
	16° 30′ 38″ W	97° 18′ 27″ W	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

$\sigma_{PWN} \lesssim 1$ pc

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

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

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

halo asymmetry

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