gamma-ray halos around pulsars

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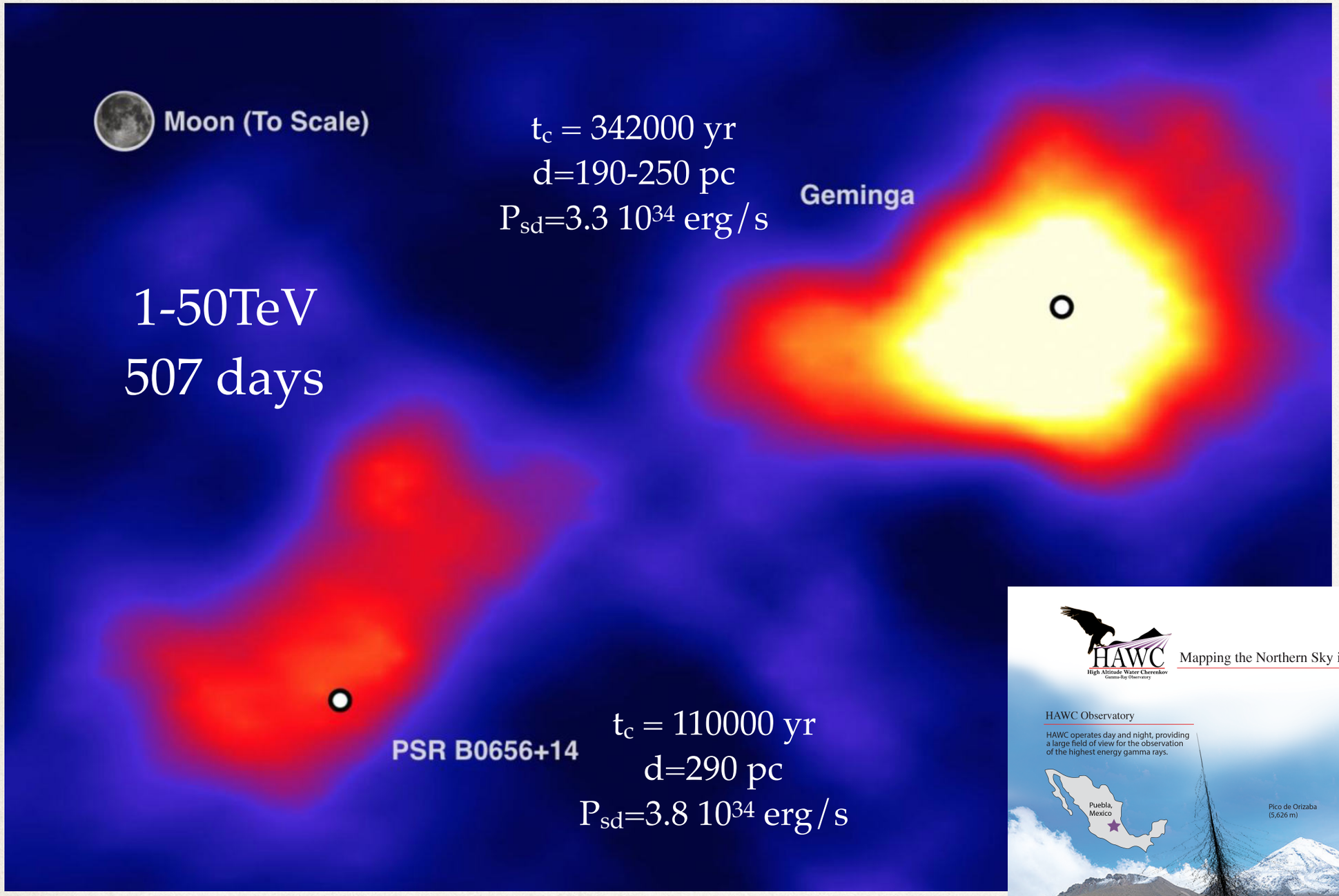
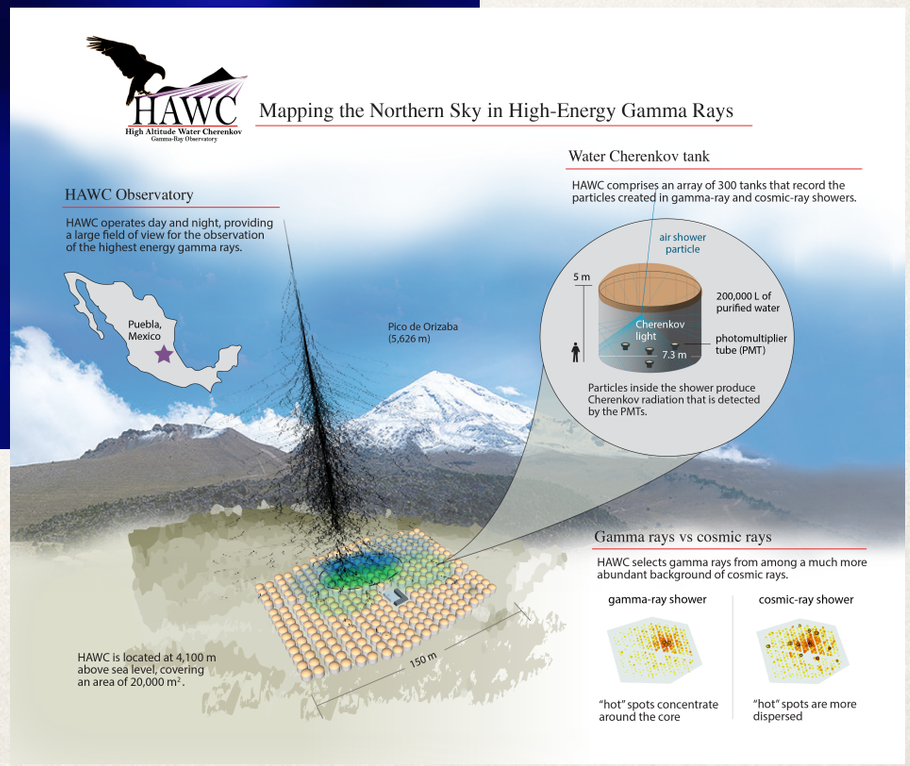
Talk fed by discussions with Alexandre Marcowith, Allard Jan van Marle, François Brun, Marianne Lemoine-Goumard, Fabio Acero, Carmelo Evoli

21 October 2021

Discovery/confirmation of pulsar halos



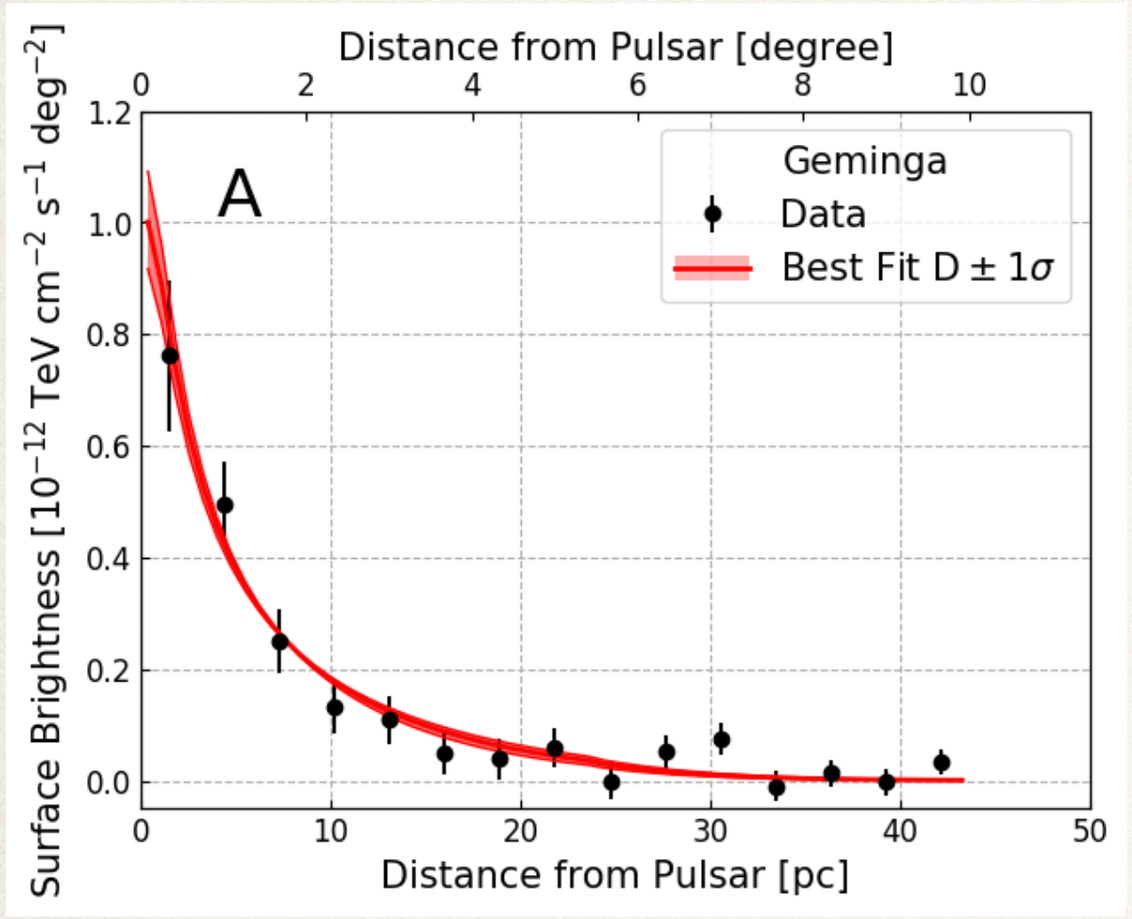


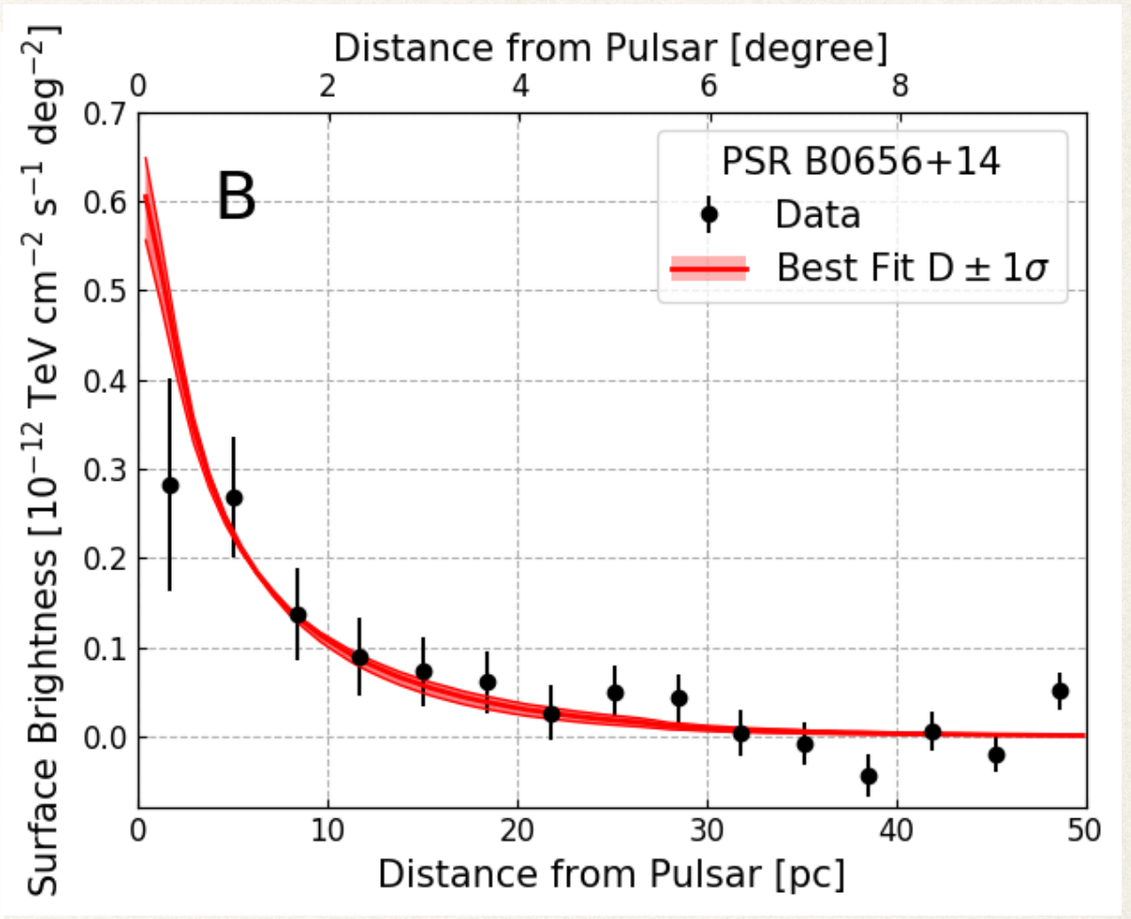
Abeysekara et al. 2017,Science, 358

First hints with MILAGRO: Abdo et al. 2007,ApJ,664

+70s/80s/90s papers

Discovery/confirmation of pulsar halos

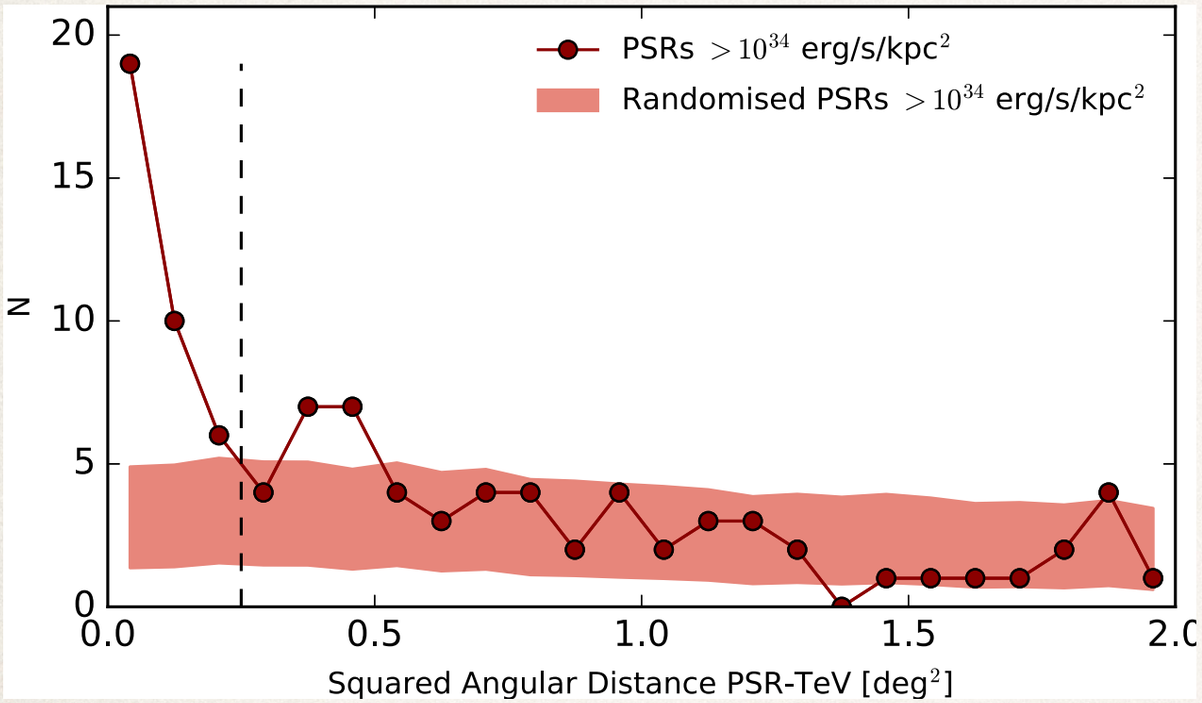


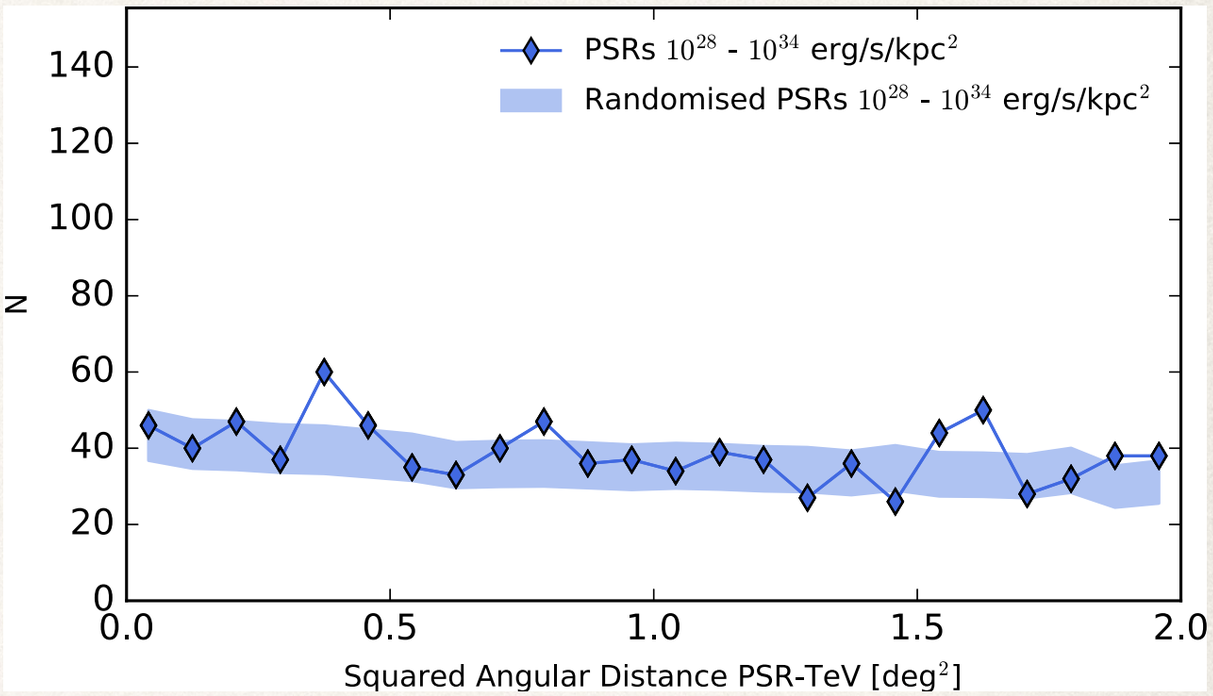


- Modeling the observed intensity profiles
  - **~10% of spin-down** power into >1GeV pairs
  - **continuous injection** spectrum with power-law index ~2.3 (above ~100GeV)
  - homogeneous **diffusion-loss** transport **in the ISM**
  - **suppressed diffusion** within at least 20-30pc, with $\mathbf{D_{HALO} \sim D_{ISM}/100}$
  - **inverse-Compton** scattering of ambient photons (CMB, IR)

At the crossroads of hot topics

- Pulsars = major players in the VHE/UHE sky





47/78 sources in **HGPS** coincident with energetic pulsars

14/20 new **3HWC** sources (with no previous TeV counterpart)

10/12 of **LHAASO** >100TeV sources

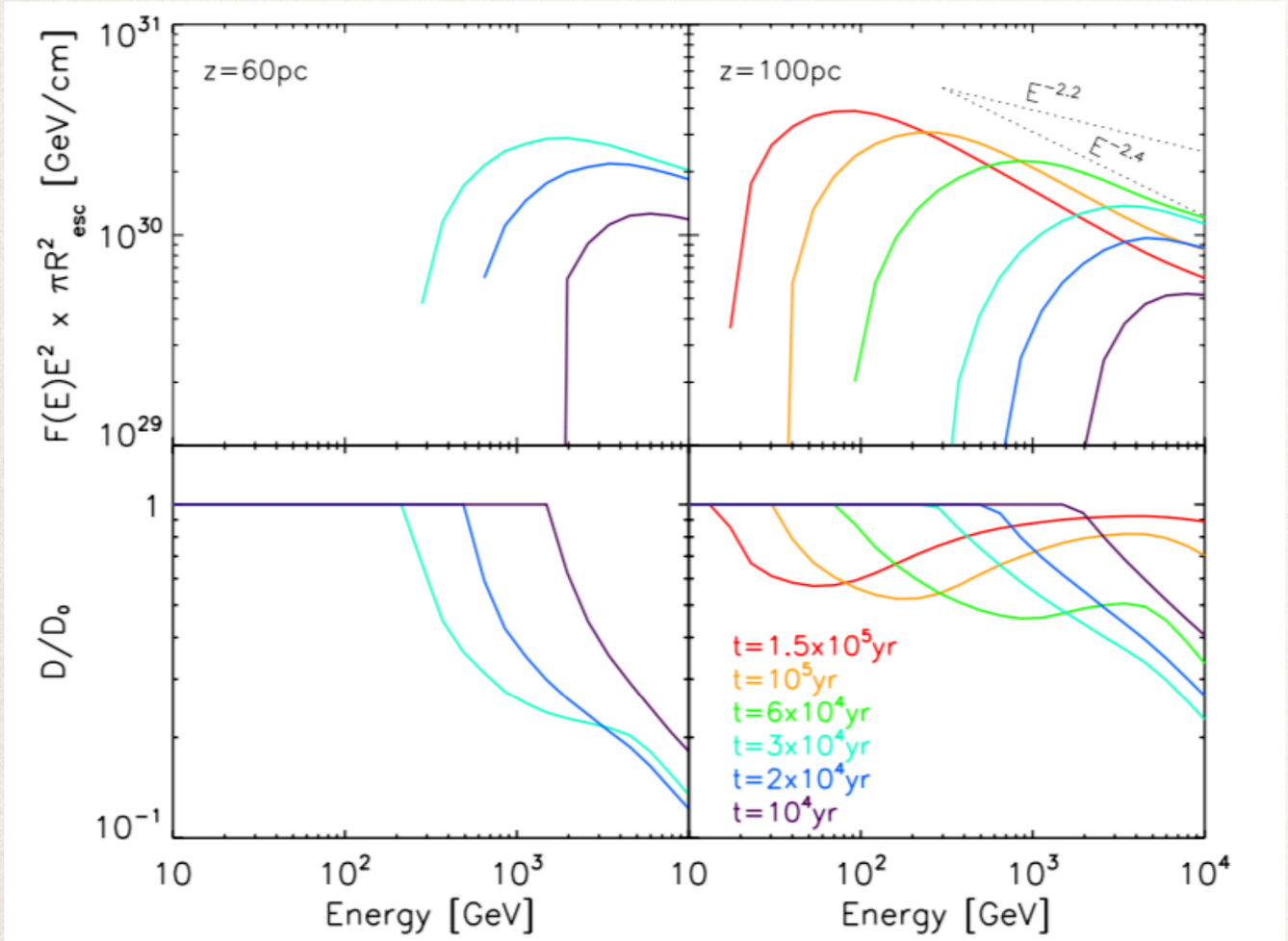
(3-4x more accounting for pulsars not beamed towards us)

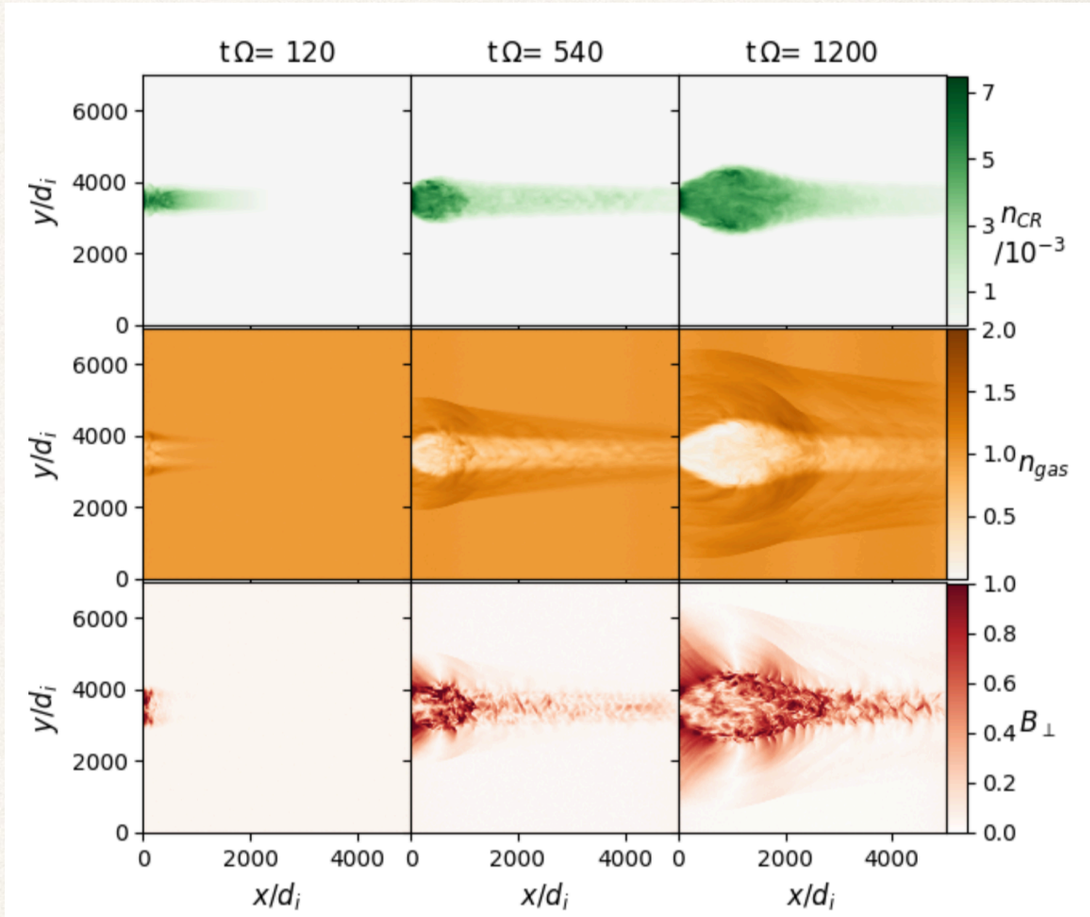
+ spectral and energetic arguments supporting IC from pulsars

Abdalla et al. 2018a/b, Albert et al. 2020/2021, Cao et al. 2021, Linden et al. 2017
Sudoh et al. 2021, Breuhaus et al. 2021

At the crossroads of hot topics

- Behaviour of CRs in the vicinity of sources

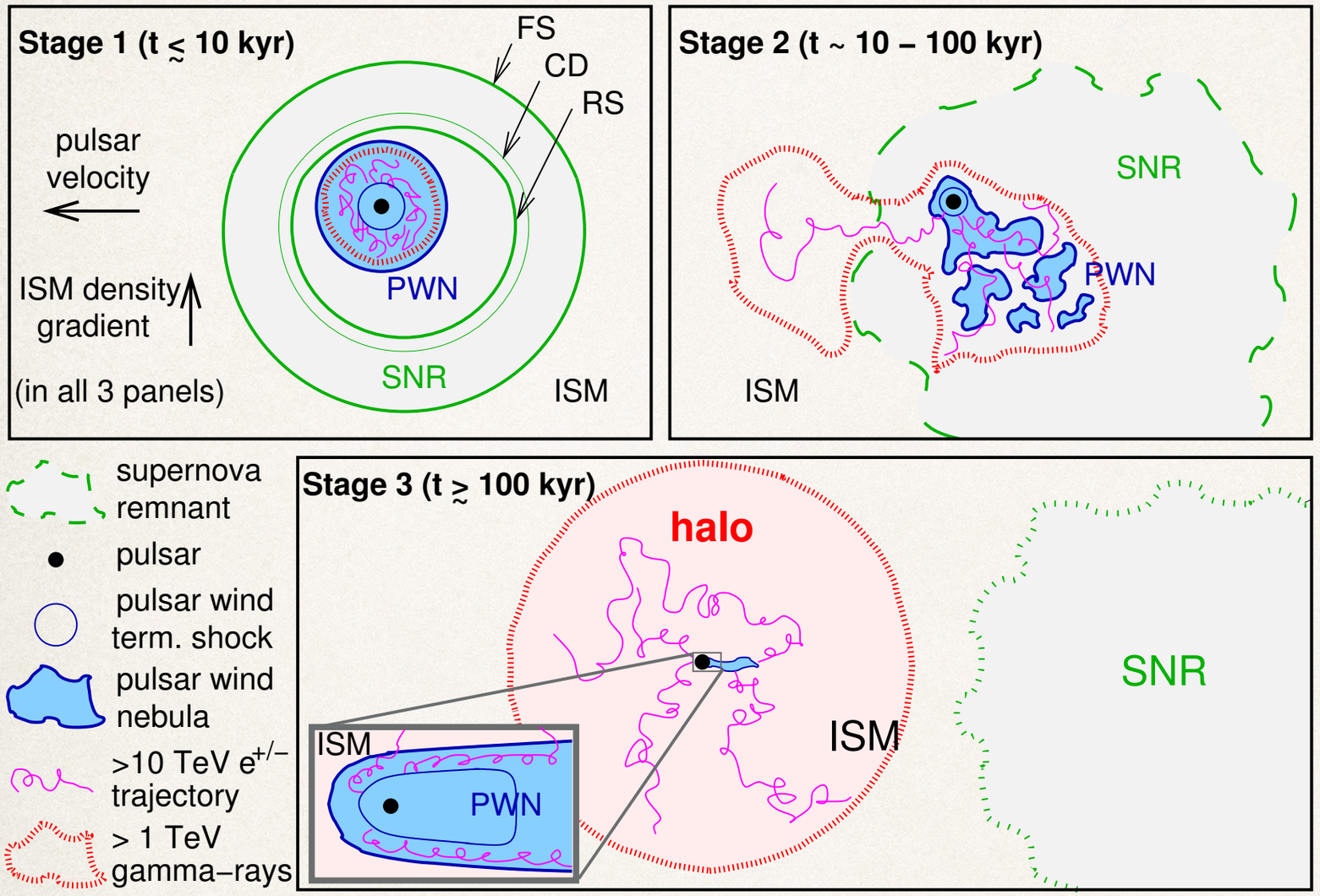




Freshly released CRs modifying their environment: time/energy-dependent **confinement**
Possible **impact** on certain **observables** (grammage, gamma-ray emission)
Opportunity to **probe earlier acceleration** stages ($E_{max}(t)$, PeVatron,…)

Nava et al. 2016/2019, D'Angelo et al. 2016a/b, Acciari et al. 2020, Schroer et al. 2020

Confusion in the definition of halos



Confusion about the definition and boundaries of the halo phenomenon

Obs: hard to differentiate from PWNe

Phy: uncertainty about the medium in which halos develop

Additional complications from likely existence of hybrid / transitional objects

Giacinti et al. 2020

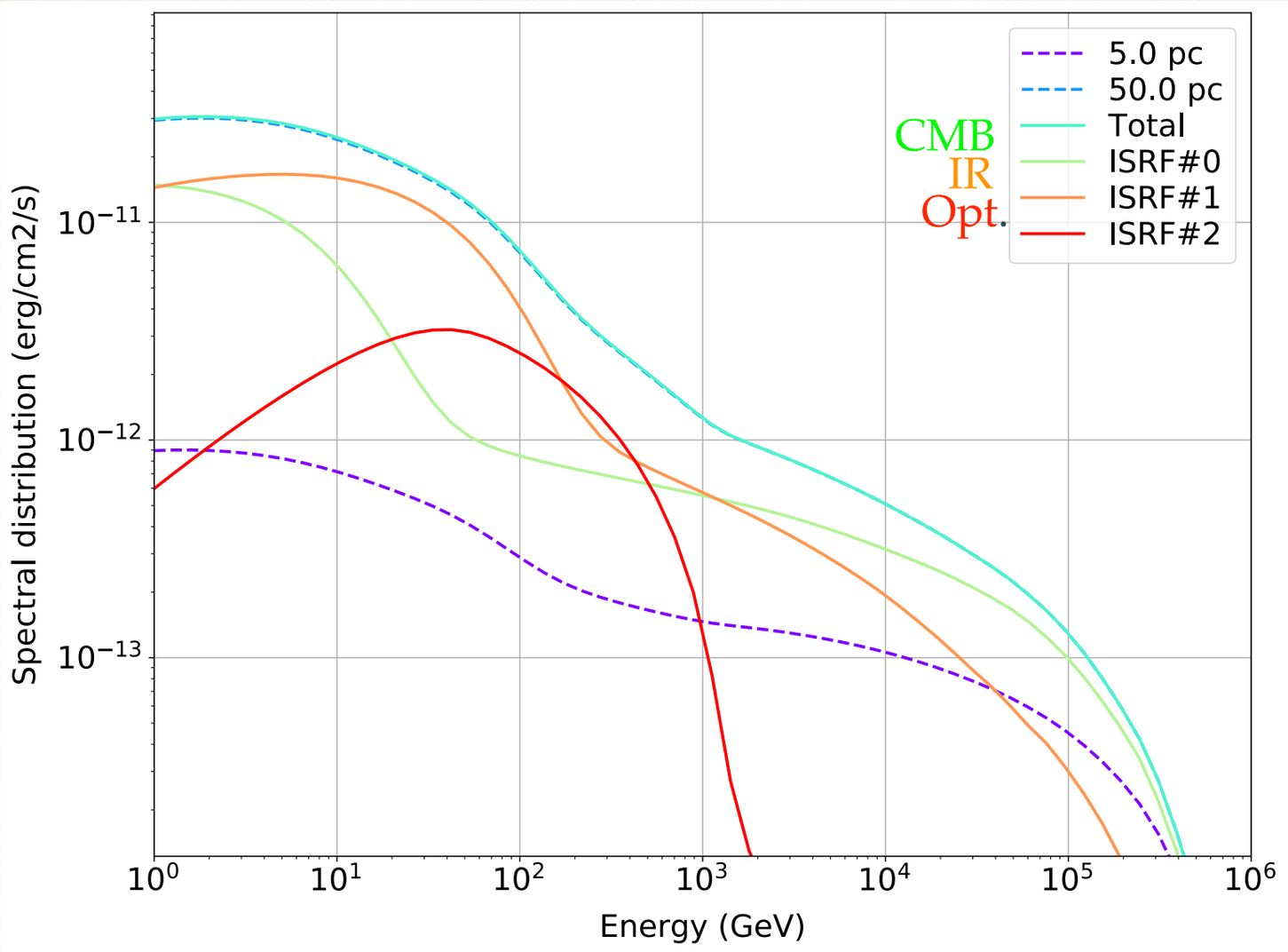
Sudoh et al. 2019/2021

Minimalist definition:

emission structure produced by pairs escaped from the shocked pulsar wind

(very inclusive but not very practical)

Halo spectrum



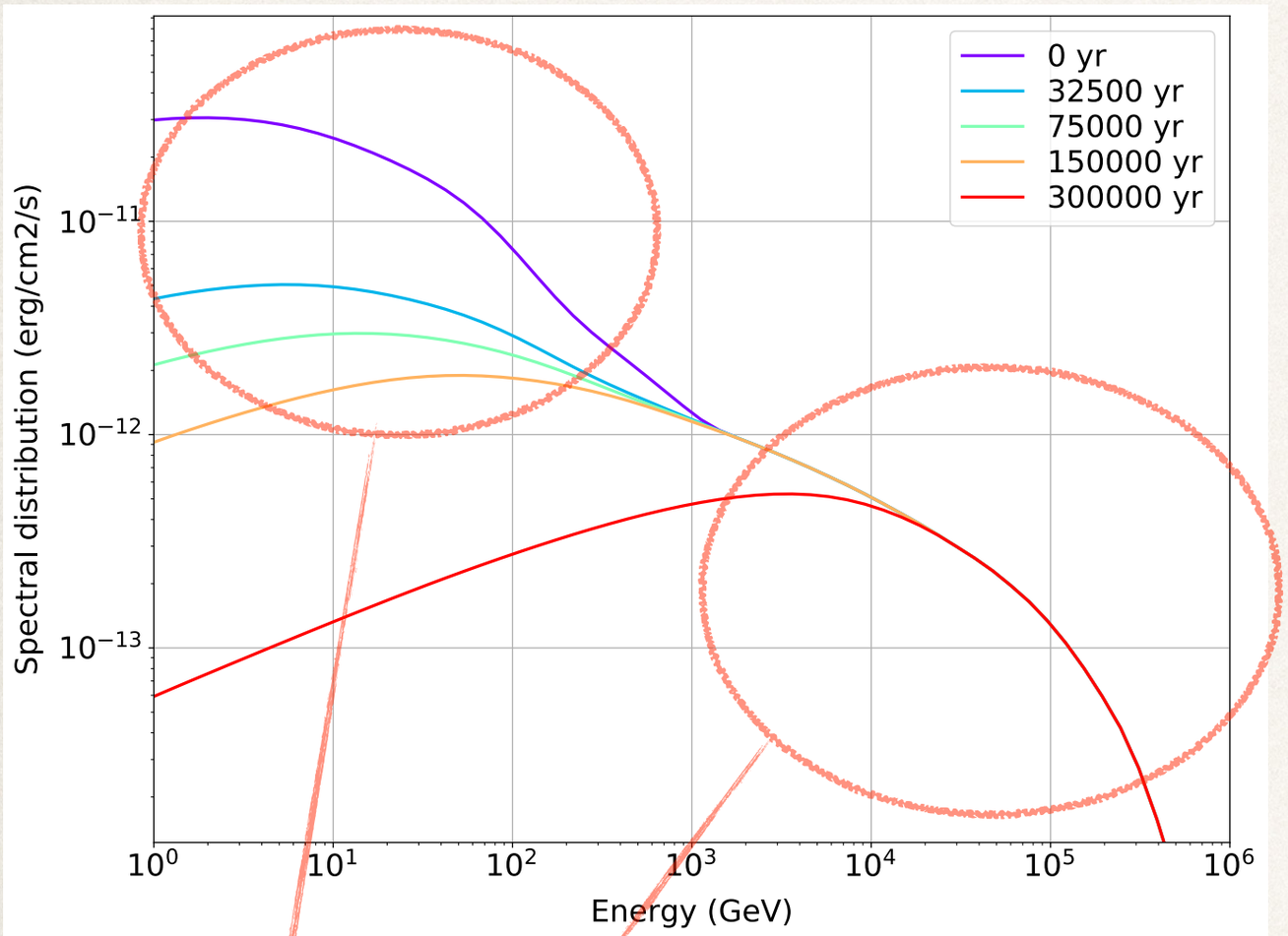
Geminga-like halo model
injection-diffusion-loss

$3x10^{34}$ erg/s @ 320 kyr
spin-down time scale 3kyr
1kpc distance

30% acceleration efficiency
BPL injection spectrum
index 1.5/2.3 E_{br}=0.1TeV

two-zone diffusion
$D_{HALO}=D_{ISM}/300$ within 50pc
B = 3μG
ISRF ~0.3eV/cm^3 in CMB,IR,O

Halo spectrum



> 1-10TeV: loss-limited regime

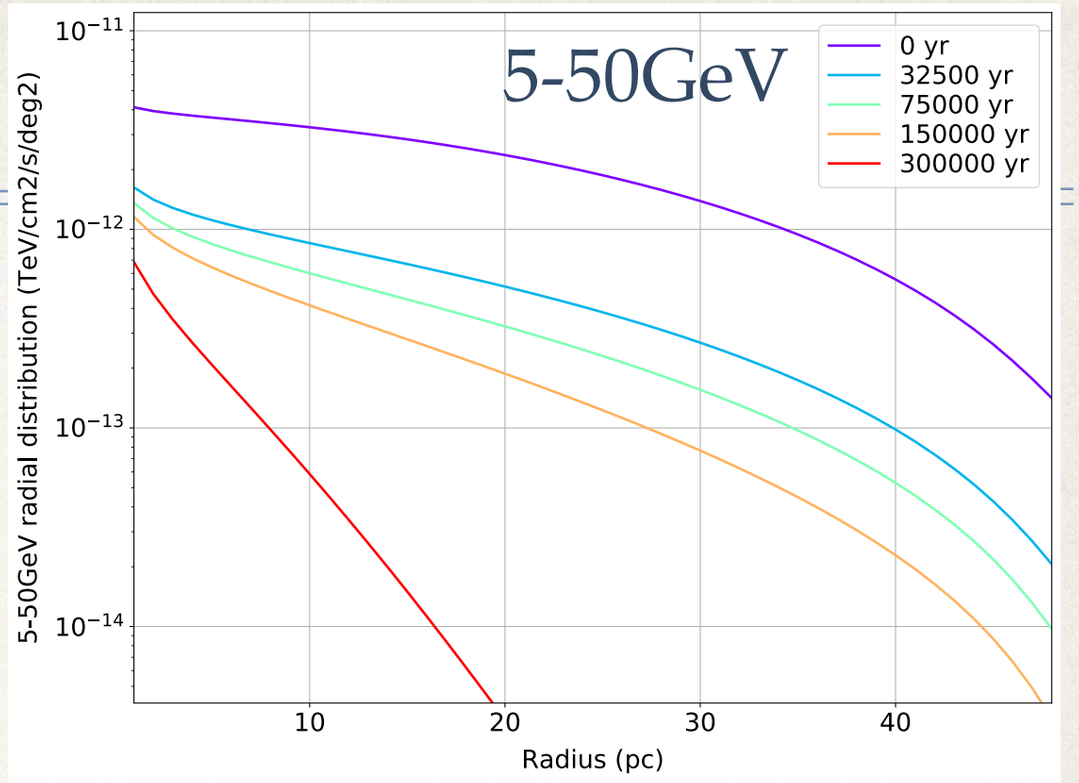
current spin-down power

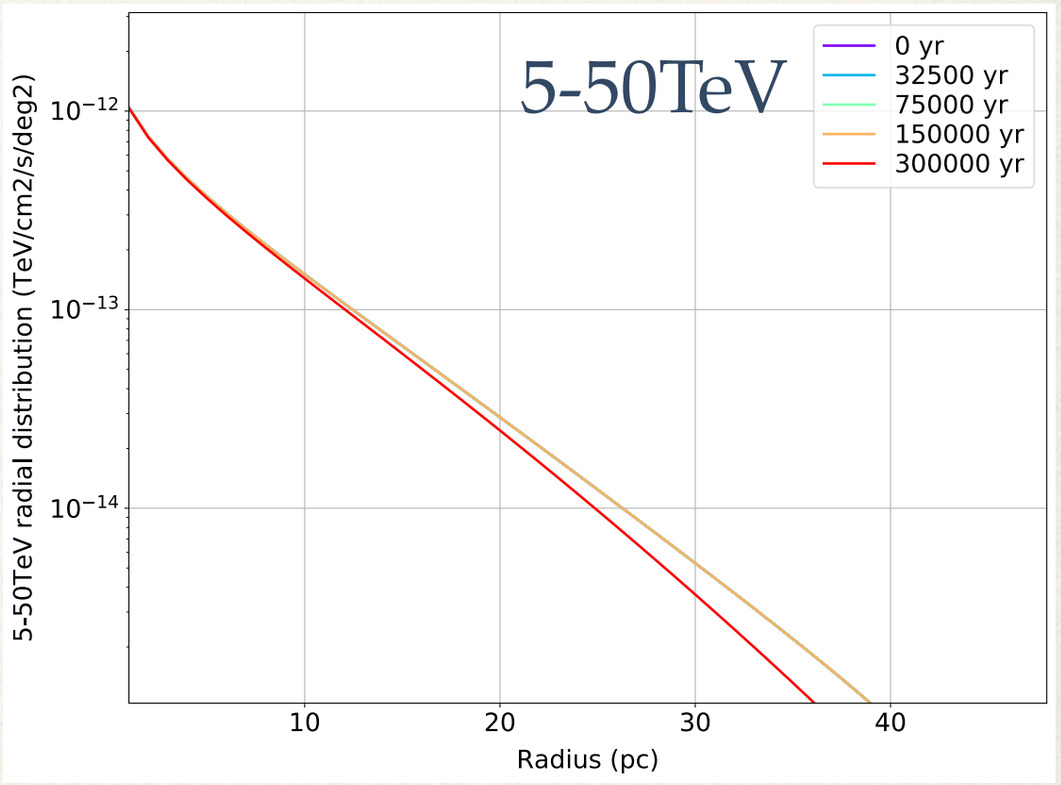
recent injection and transport

<0.1-1TeV: diffusion-limited regime

integrated injection history

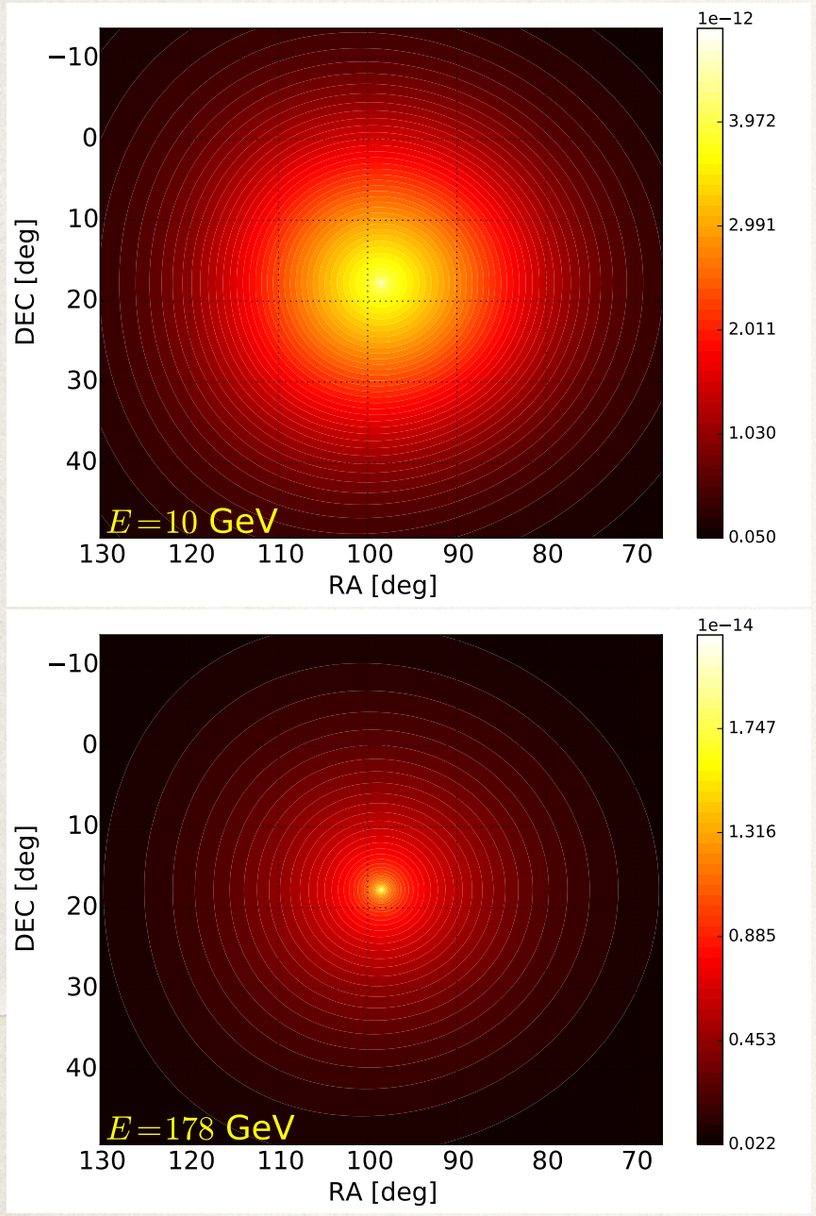
past transport conditions (incl. proper motion)

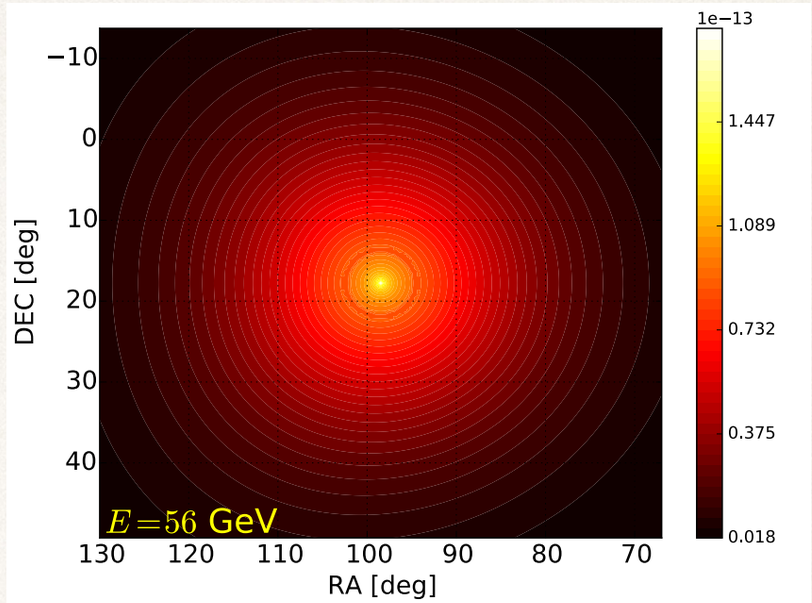


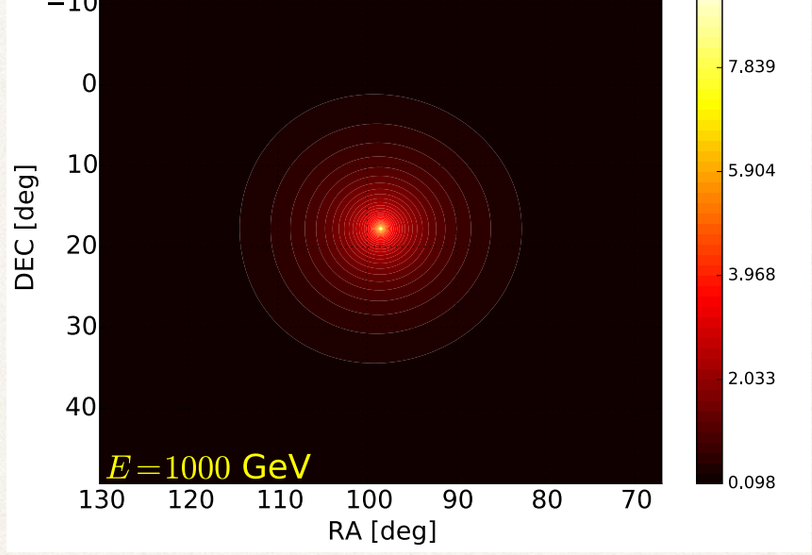


Decomposition of spectrum and profiles as function of injection start time

Halo morphology



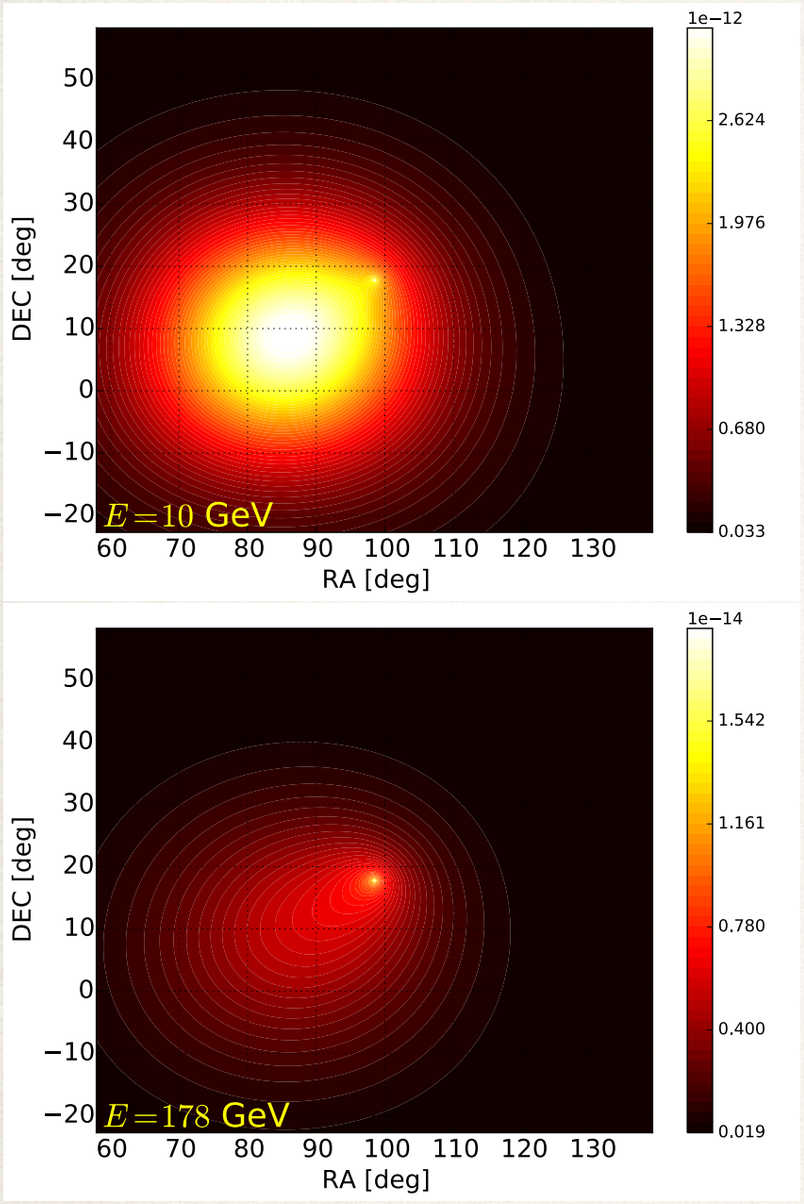


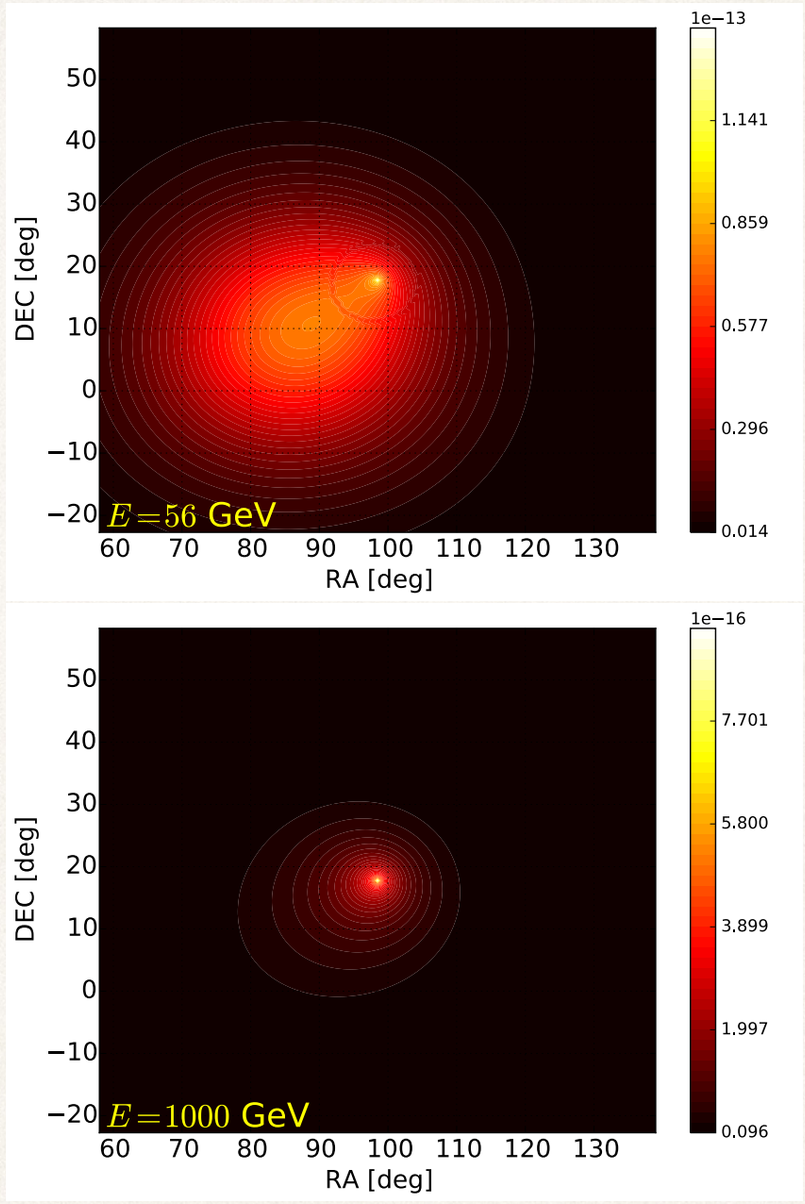


Di Mauro et al. 2019
One-zone diffusion model

energy-dependent morphology (both extent and profile)
maximum extent reached from <100GeV to >1TeV (**age-dependent**)

Effects of proper motion





Di Mauro et al. 2019
One-zone diffusion model

Geminga halo detected in Fermi-LAT observations

Proper motion evidenced with significance $> 4\sigma$

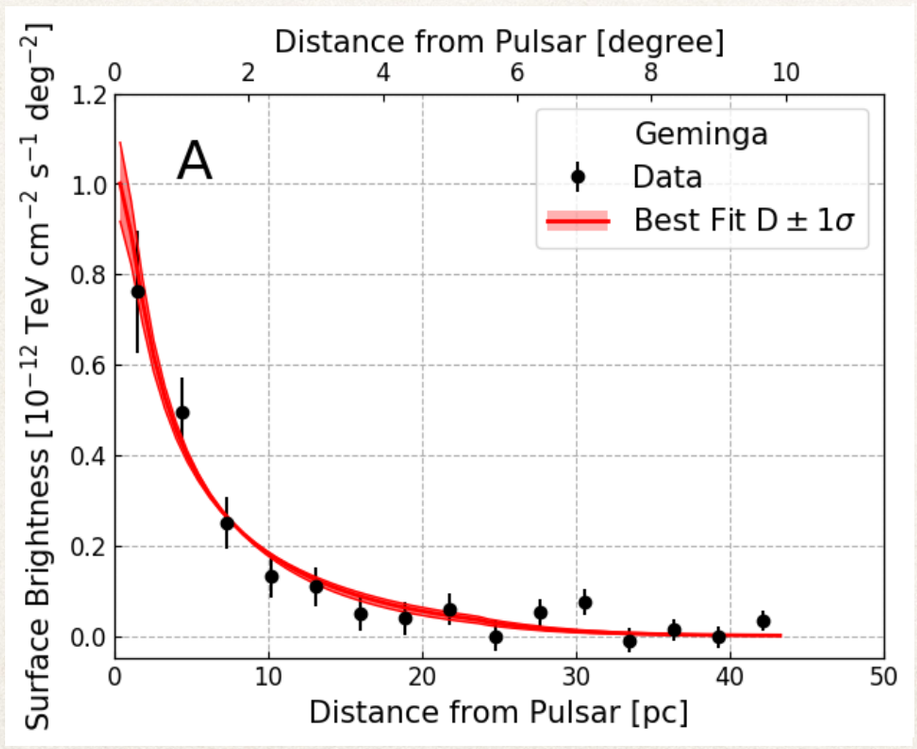
Variety of source **morphologies** and **pulsar offsets** depending on
injection history (spin-down history+ injection parameters)
diffusive properties of the medium (self-confinement or externally-driven)

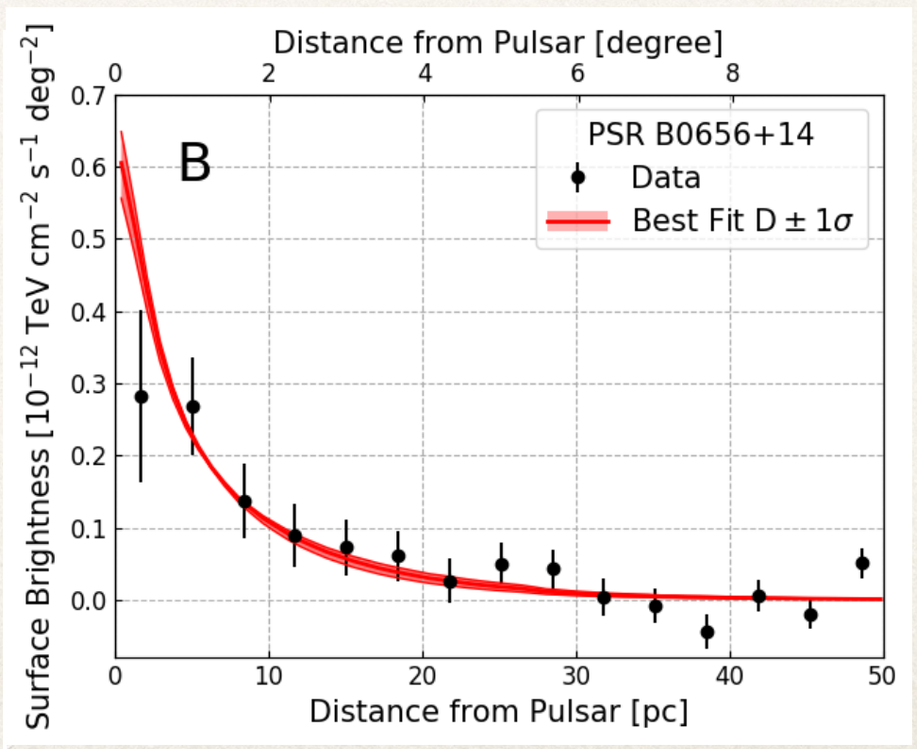
Zhang et al. 2020

Questions raised by the HAWC observations

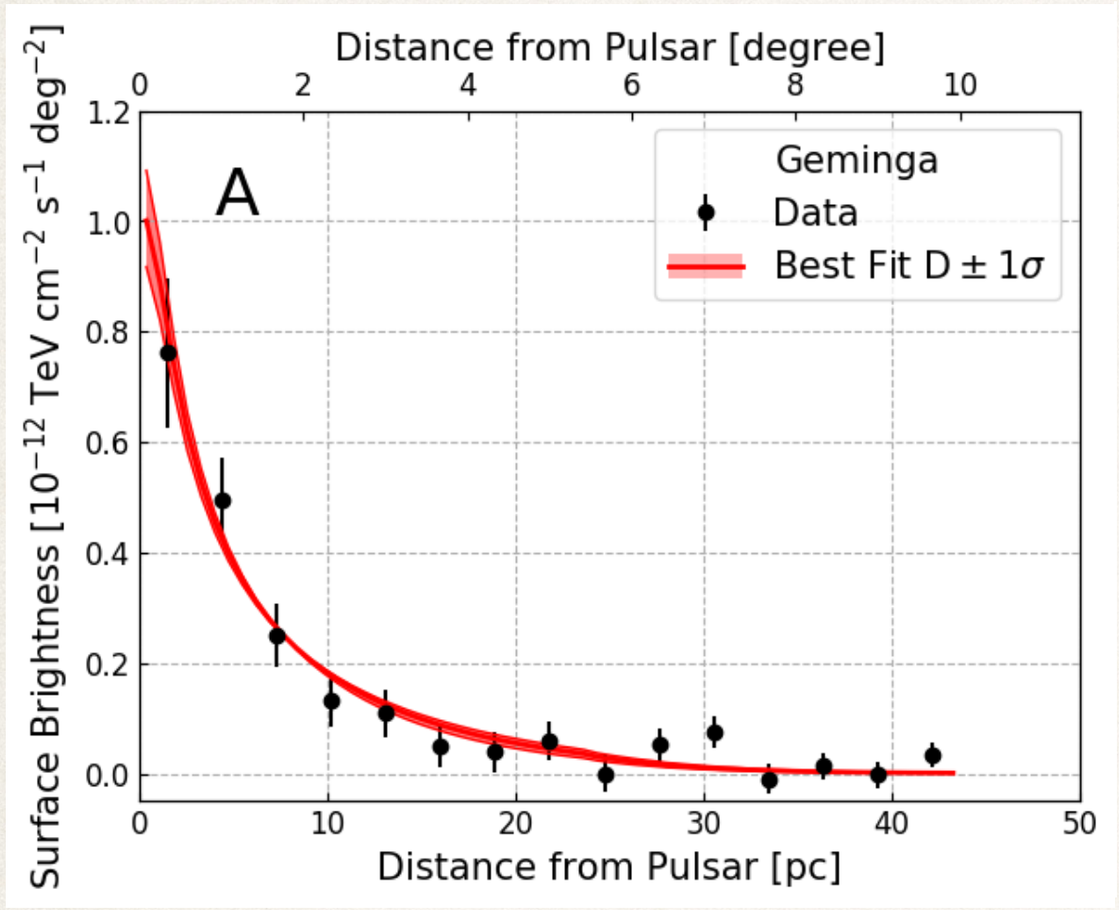
- Observationally
  - **Full extent** of the phenomenon (in space/energy) ?
  - Are these two objects **representative** of a (much) larger population ?

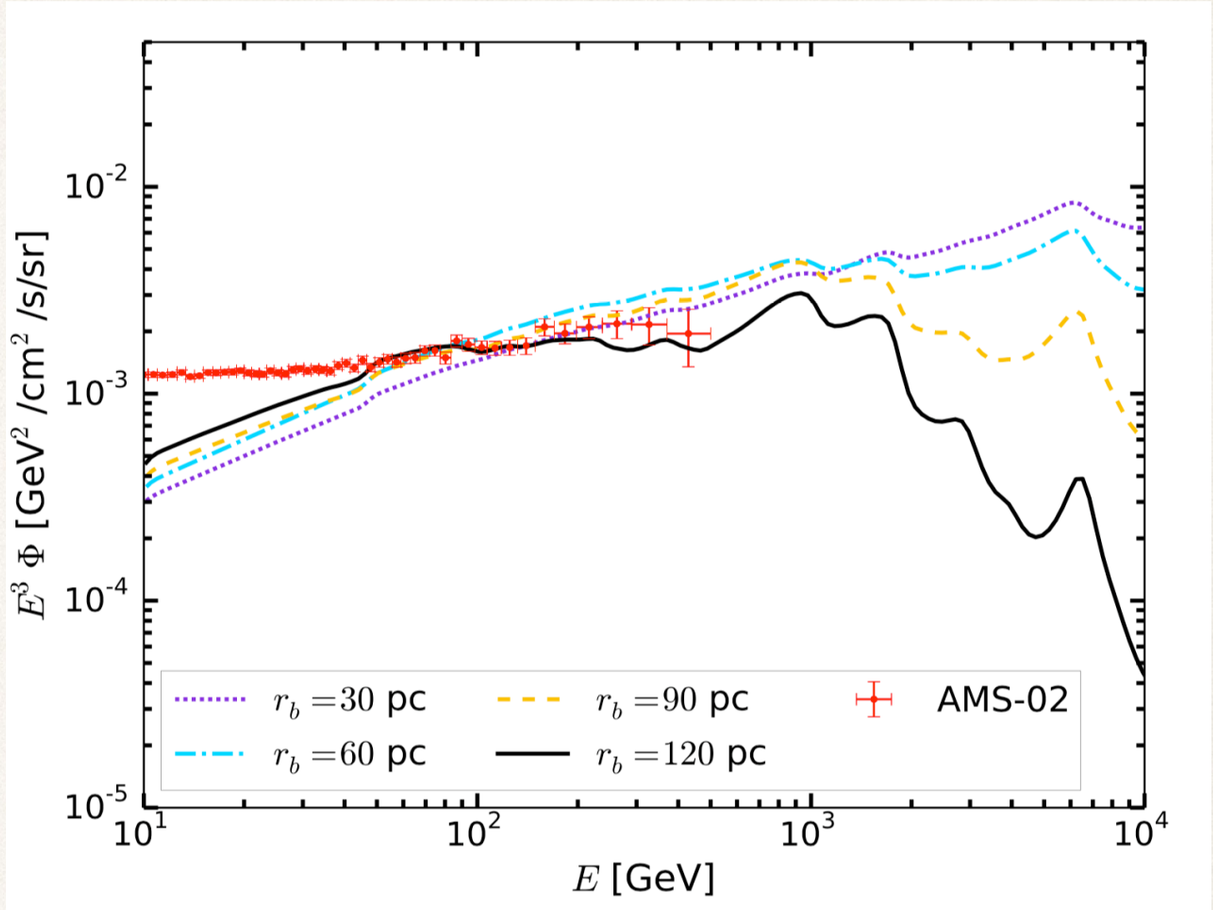
- Physically
  - How is such an extended and **long-lasting confinement** achieved ?
  - Are the pulsars playing any role in this ?
  - … or do they just happen to be located in **specific environments** ?





Physical extent of halos

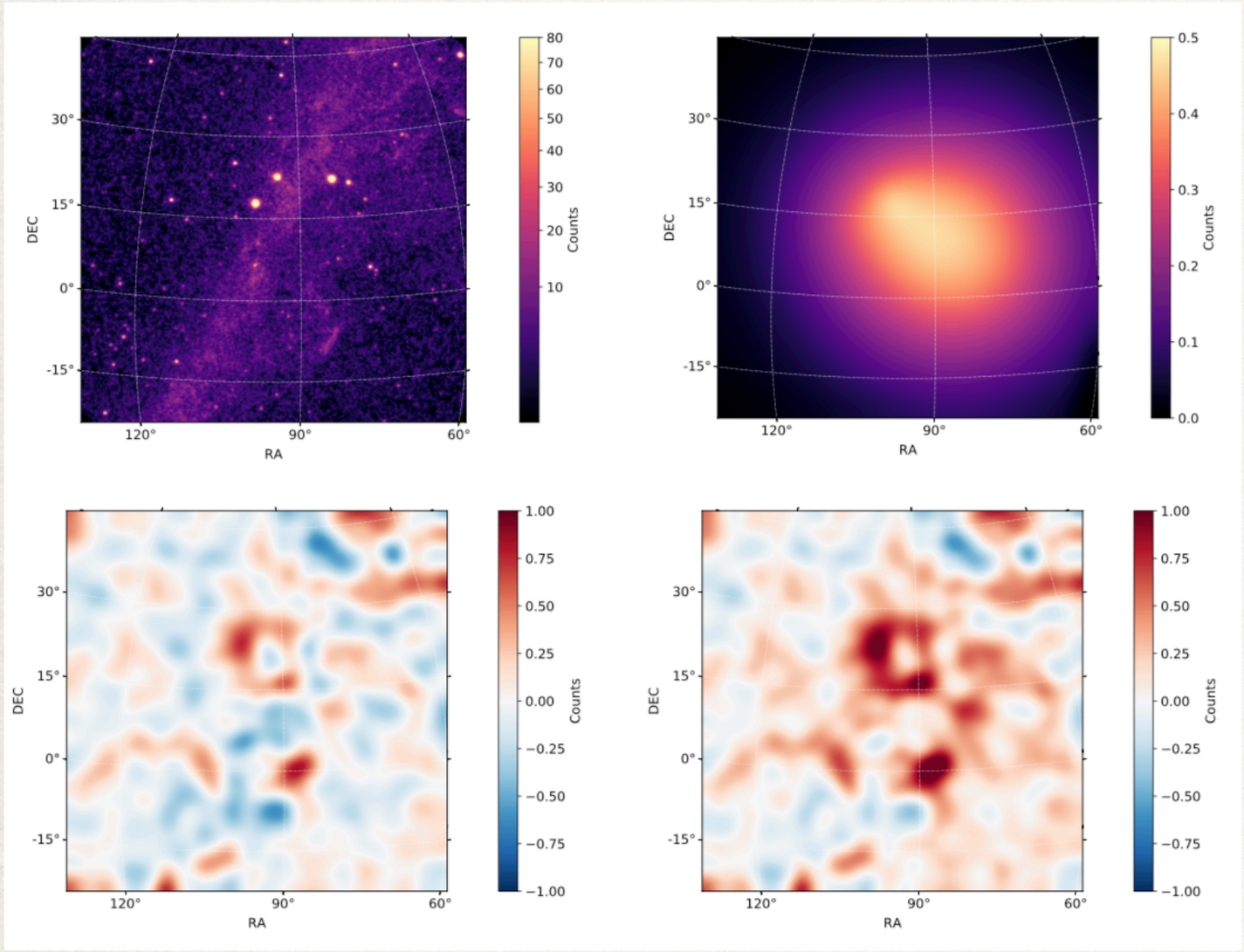


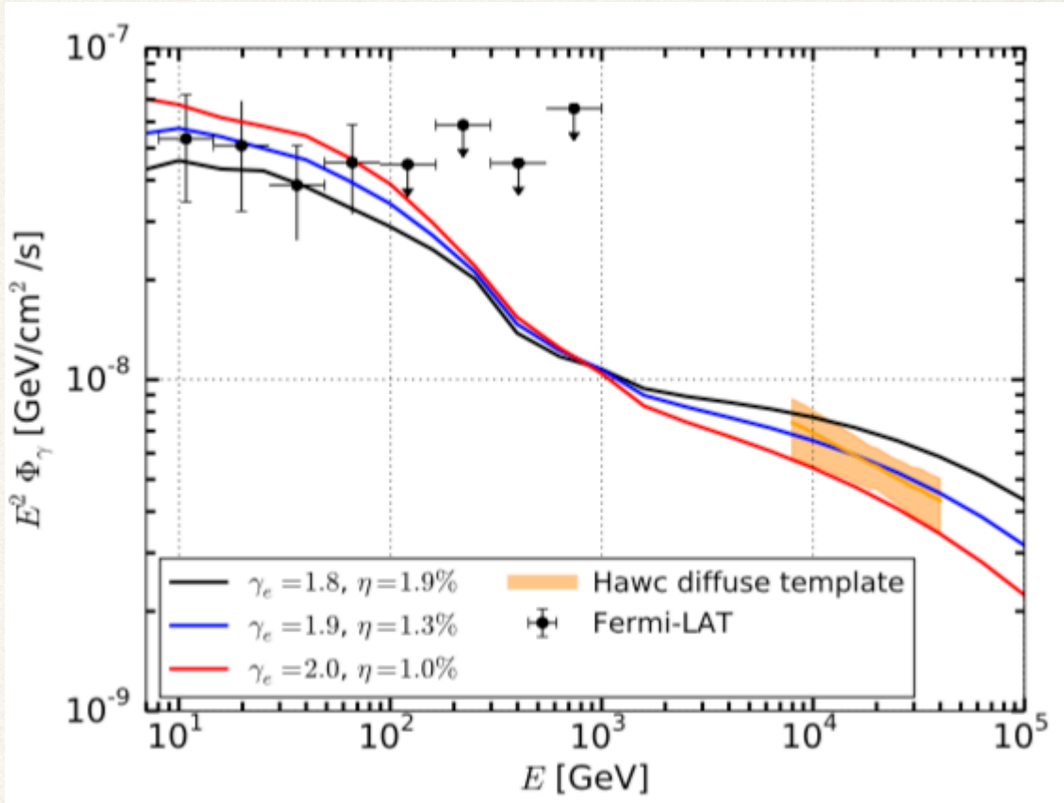


- Bounds on the low-diffusion region
  - **>20-30pc**: HAWC intensity profile (+AMS-02)
  - **<50-100pc**: LAT and MAGIC measurements
  - <kpc: average Galactic diffusion coefficient (from B/C,…)

Johannesson et al. 2019, Tang&Piran 2019,
Profumo et al. 2018, Di Mauro et al. 2019b, Manconi et al. 2020

Broadband/multiwavelength objects



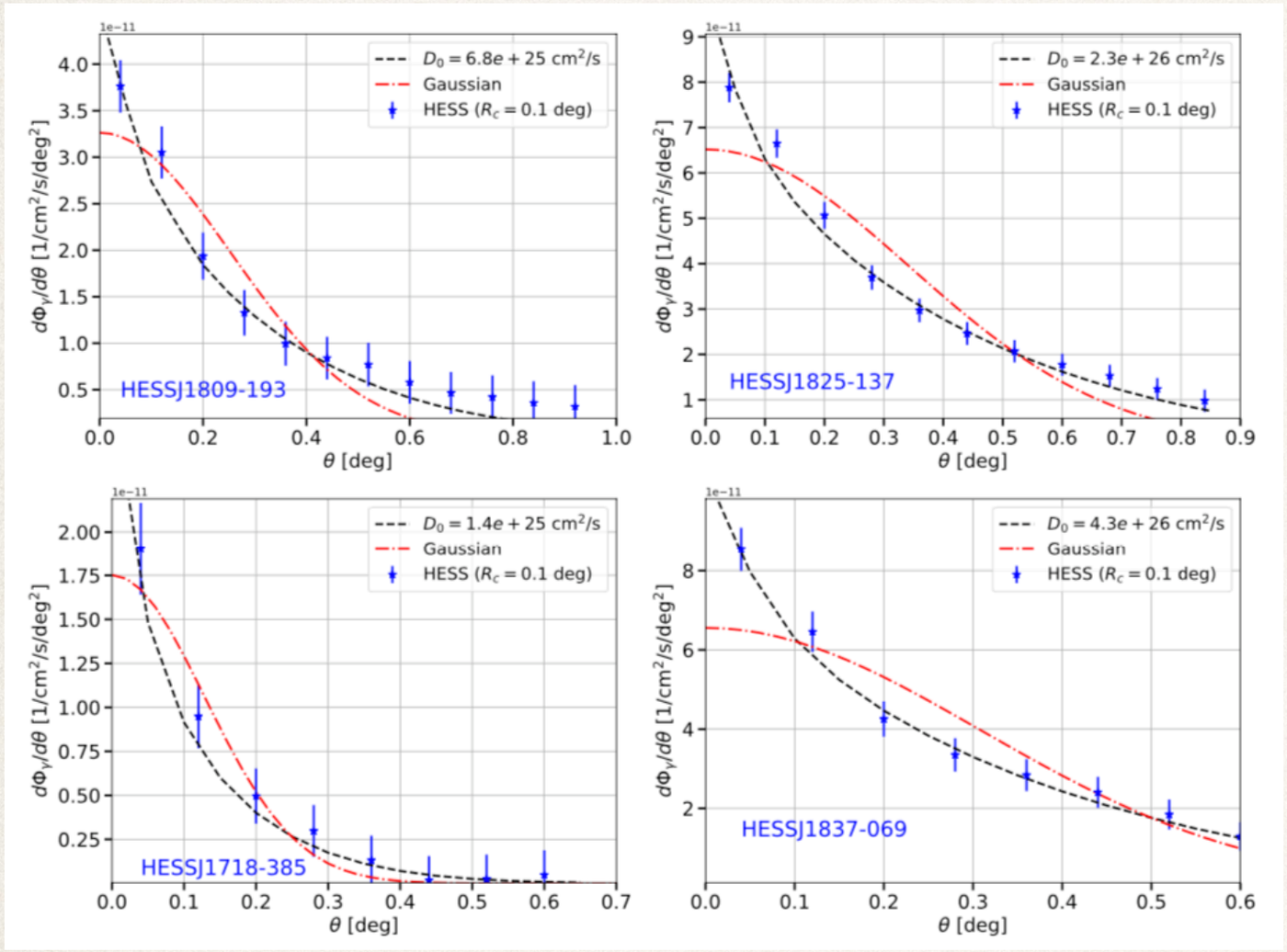


Geminga halo detected in Fermi-LAT observations
Proper motion evidenced with significance > 4σ

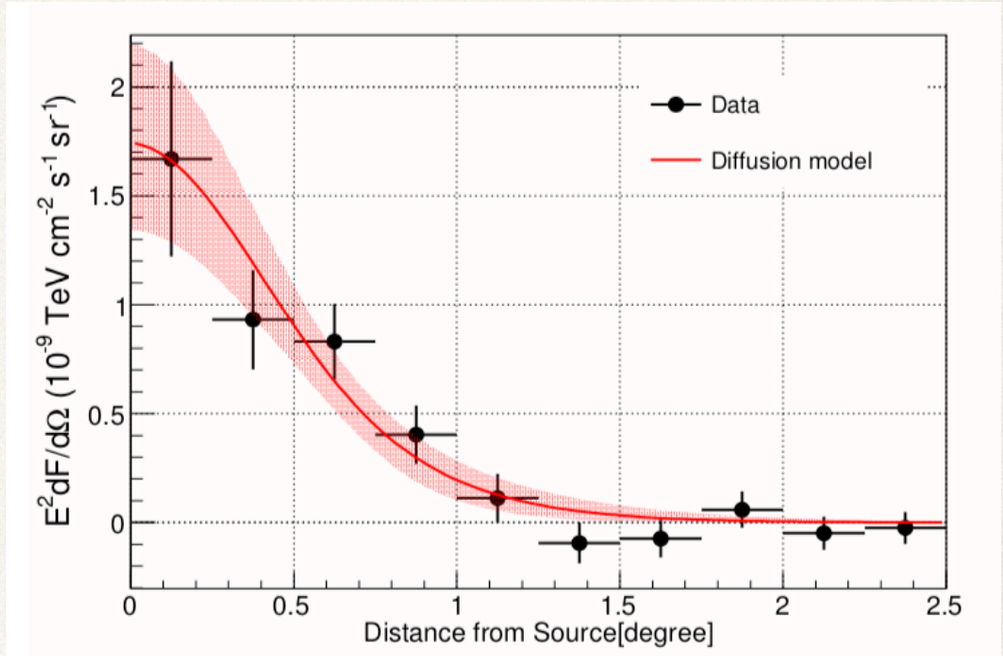
Di Mauro et al. 2019a

- At lower energies
  - No diffuse X-rays around Geminga, B<1microgauss (Liu et al. 2019)
  - Prospects for detection with eRosita sub-pc to 10s pc (Li et al. 2021)

Rapidly growing population ?



Di Mauro et al. 2019b



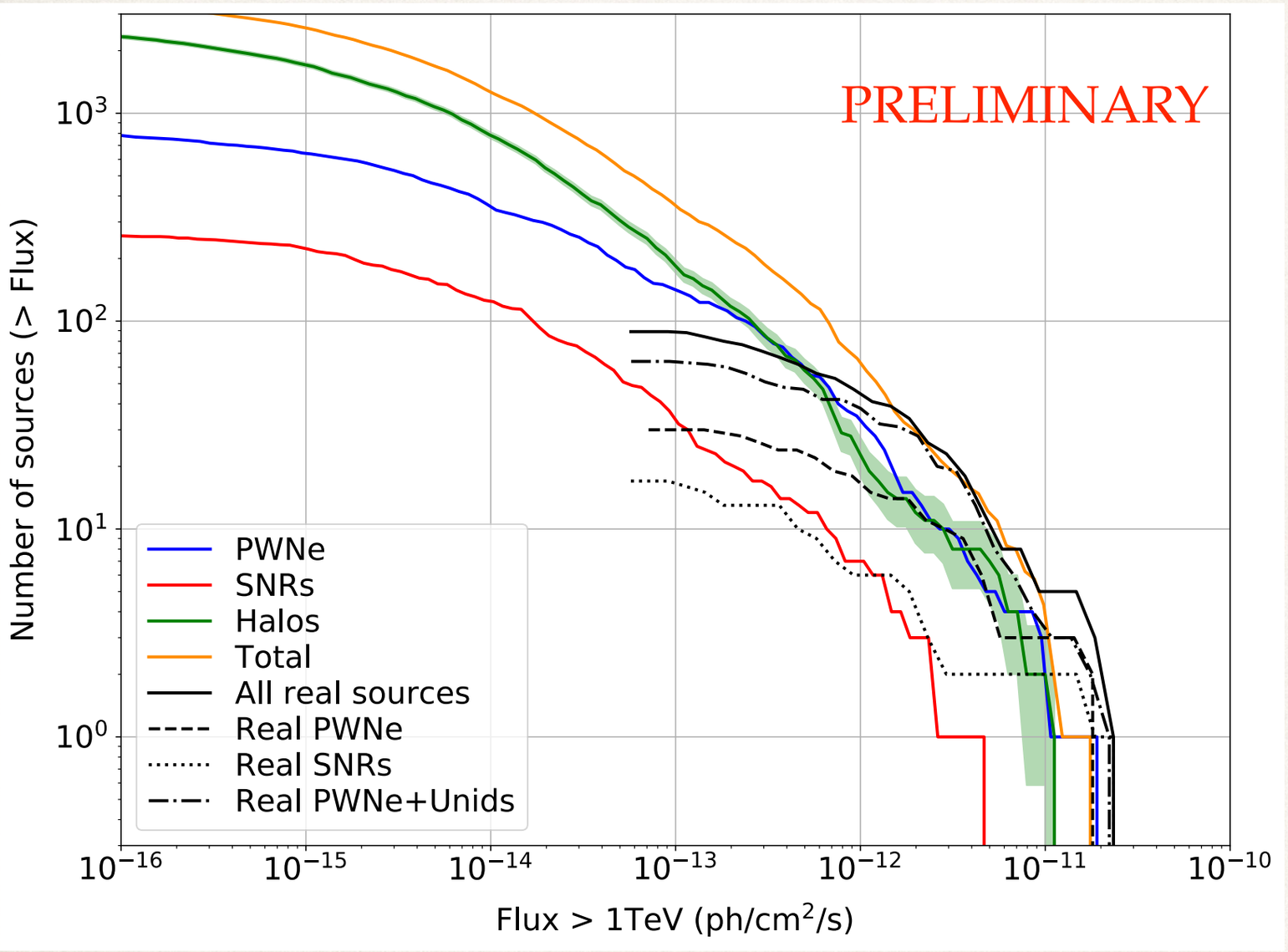
LHAASO collab. 2021
PSR J0622+3749, ~200kyr

+3HWC candidates
+LAT candidates

- Under the (strong) assumption that all pulsars develop halos:
  - Highly **populated source class**
  - Several 10s already **detected as unIDs** in HGPS/HAWC surveys
  - Non-negligible **contribution as diffuse** from unresolved sources
  - Now also including **MSPs ?**

Di Mauro et al. 2019b, Sudoh et al. 2019, Linden et al. 2017, Linden et&Buckmann 2018, Hooper & Linden 2021

A promising source class

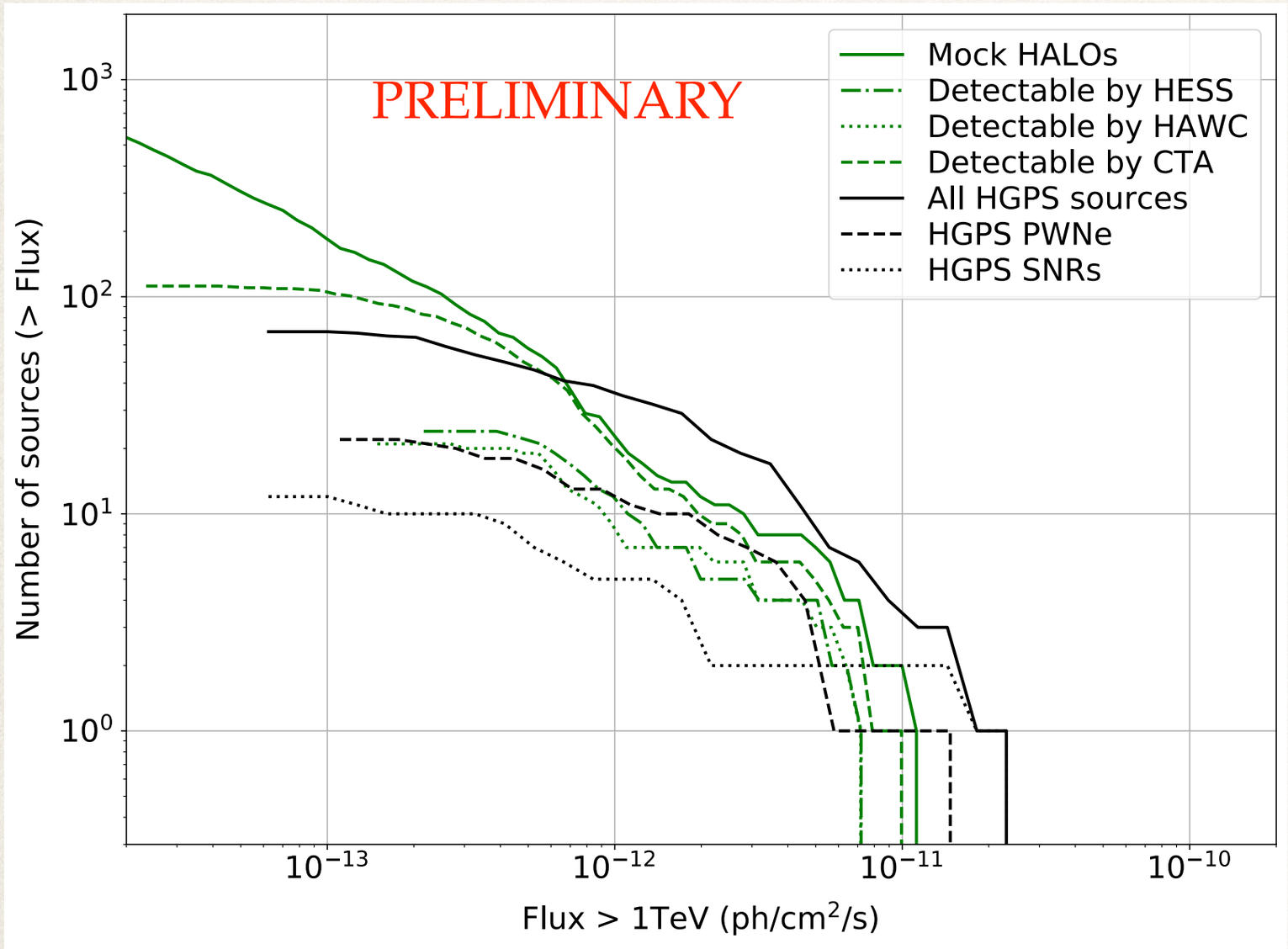


Galactic model of
SNRs+PWNe+Halos
Mock population
of normal pulsars
PWN stage ~0-50kyr
Halo stage ~50-400kyr
Geminga-like 50pc halo model
ISRF and B-field Galactic models

Martin et al. (in prep.)

- Synthetic halo population (~2600 objects)
  - Flux distribution similar to PWNe down to 10mCrab
  - PWNe+Halos saturating the known population (incl. unIDs)

A promising source class



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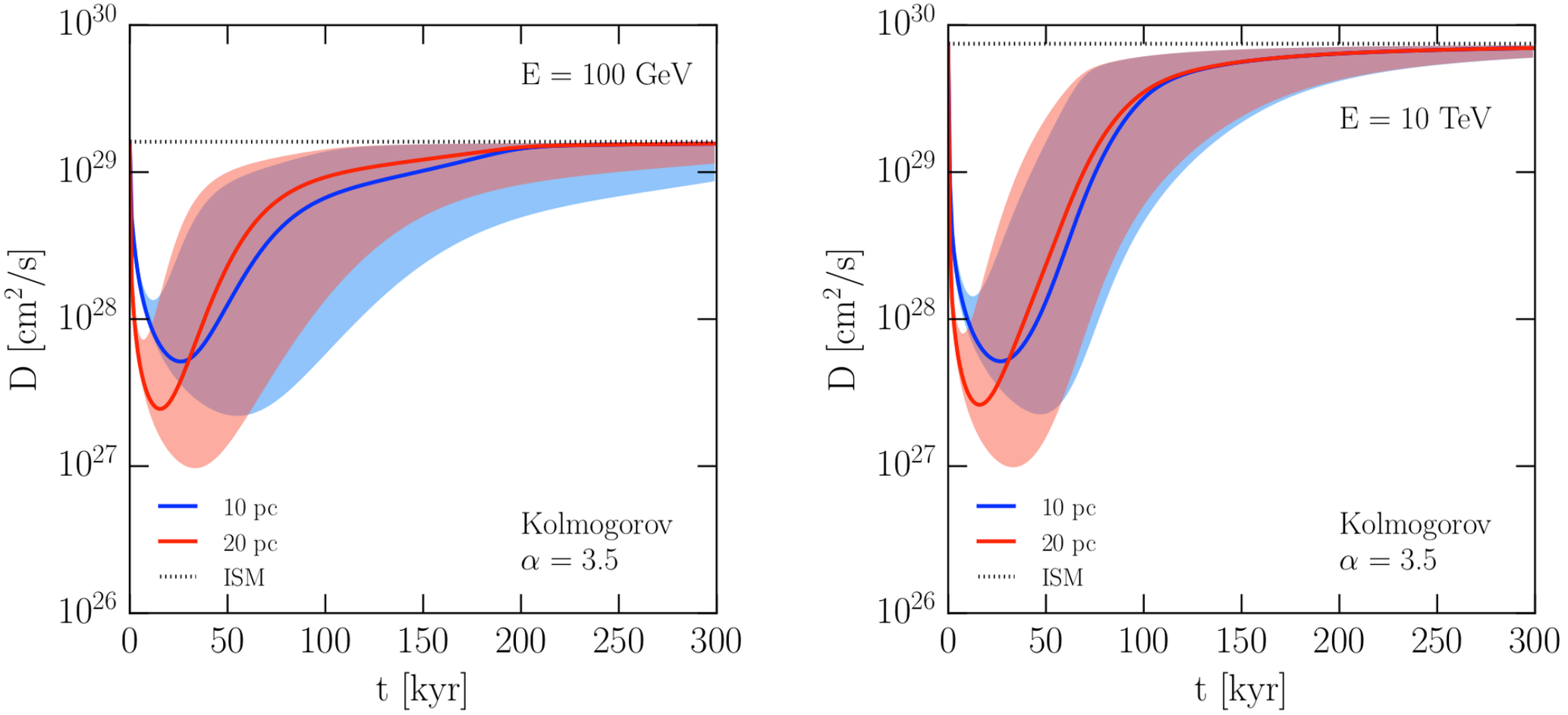
Martin et al. (in prep.)

- Detectable halo population
  - ~20 already in 3HWC, ~30 already in HGPS, >100 in reach of CTA
  - Note: flux > sensitivity only (extension accounted for)
  - Actual data analysis: lots of confusion, non-trivial morphologies, backgrounds

Turbulence (kinetic)

Evoli et al. 2018

Watch out for Mukhopadhyay et al.



Pair halos as **dynamical objects**

t<10kyr: powerful pulsar, **turbulence growth**, particles can still escape

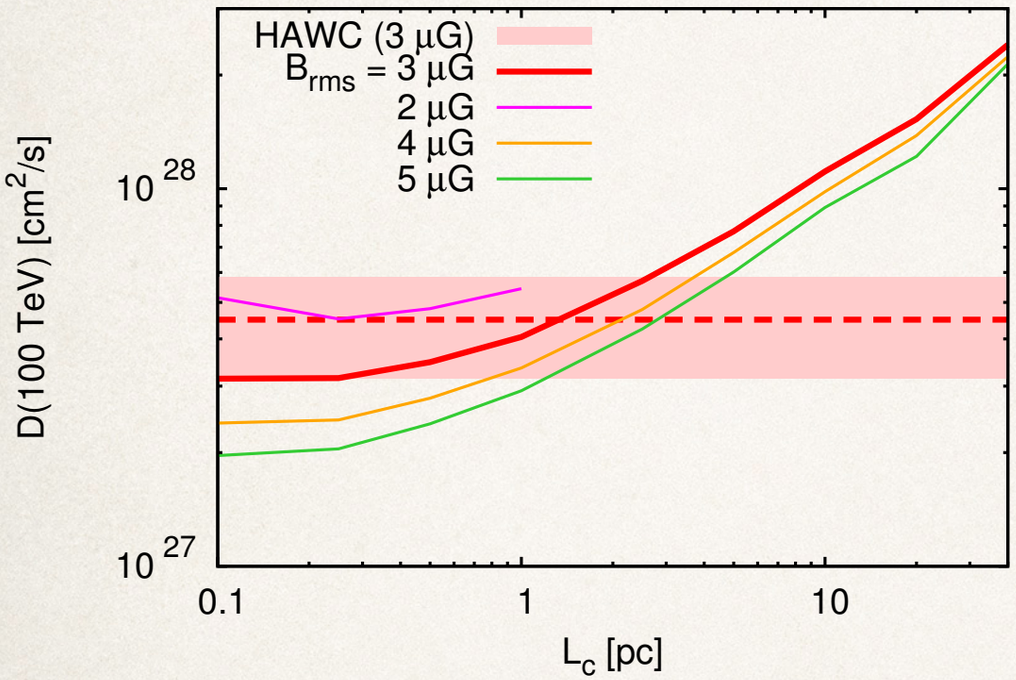
10kyr<t<100kyr: weaker pulsar, turbulence **damping, relaxation**

Dependent on injection history and spectrum, turbulence model for wave damping

Problems: 1) growth in PWN stage, 2) rapid relaxation, 3) proper motion (for maximum injection efficiency, hard injection spectrum, 1D)

Turbulence (fluid)

- Fluid option: externally-driven



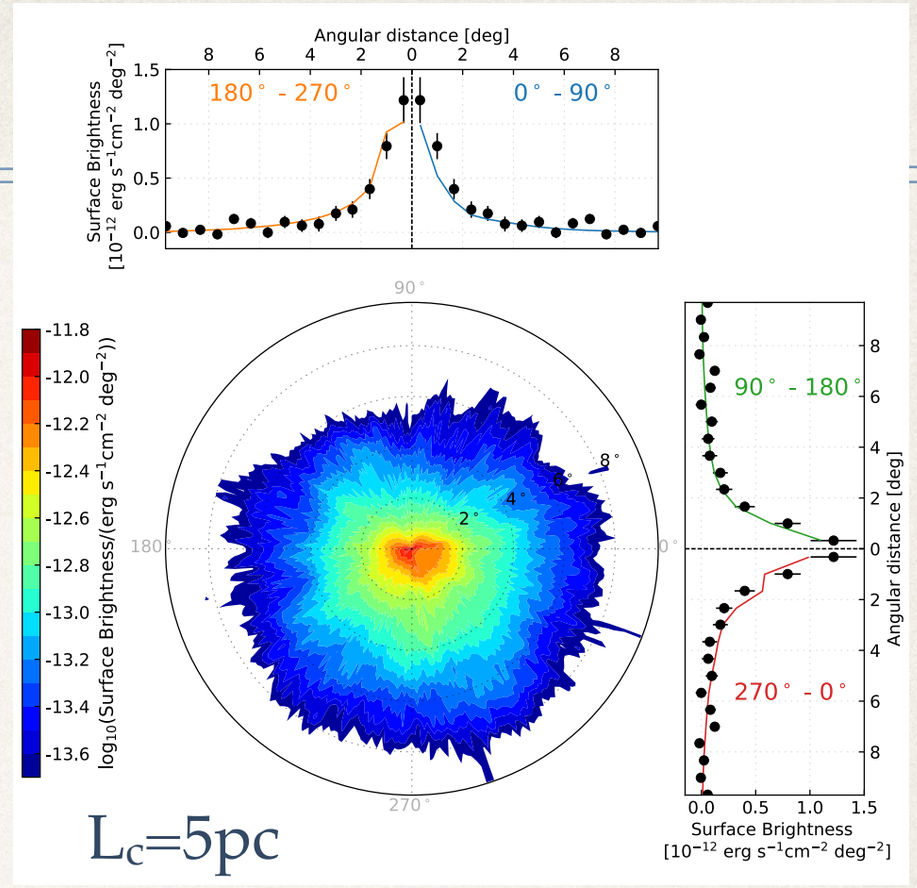
From individual 40-500TeV electron trajectories in 3D realizations of turbulence

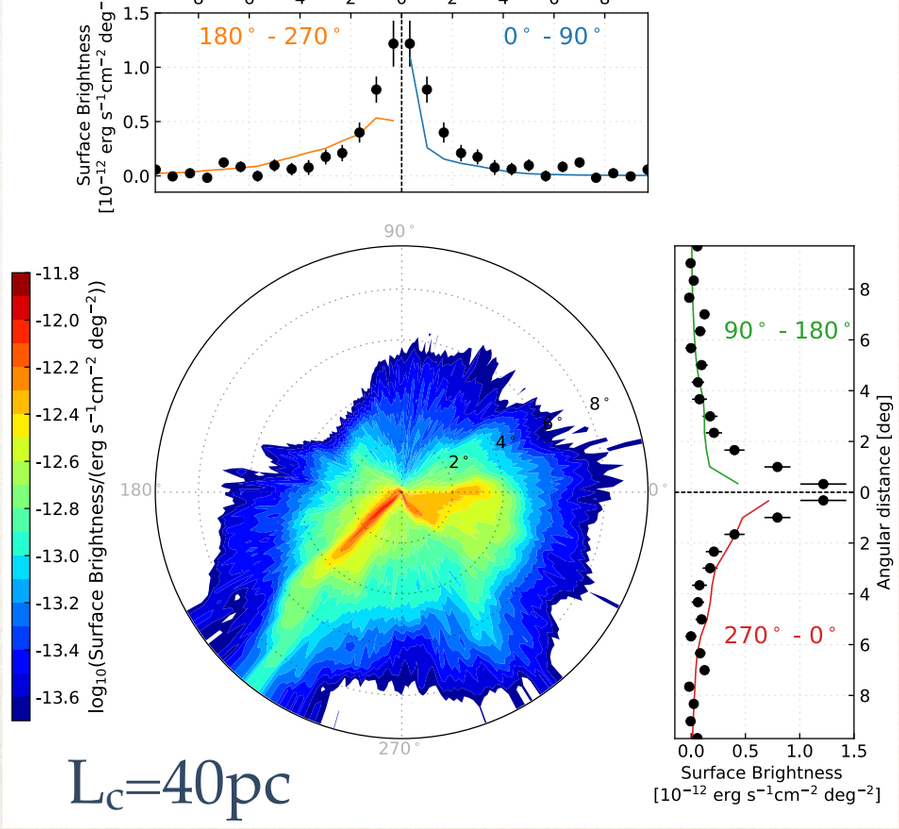
HAWC measurement compatible with turbulence with **B_{rms}=3μG** and **L_c<5pc**

Lopez-Coto & Giacinti 2018

Turbulence inherited from **parent SNR** or stellar-wind bubble

Fang et al. 2019





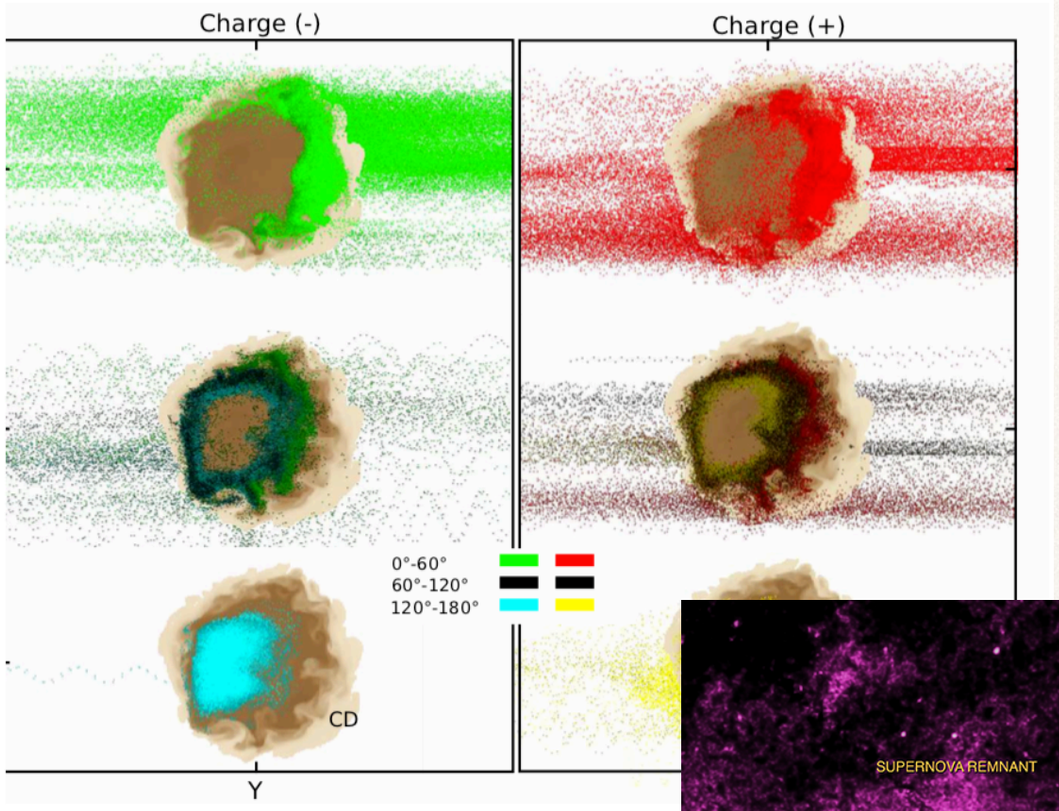
Open questions and challenges
(certainly a non-exhaustive list)

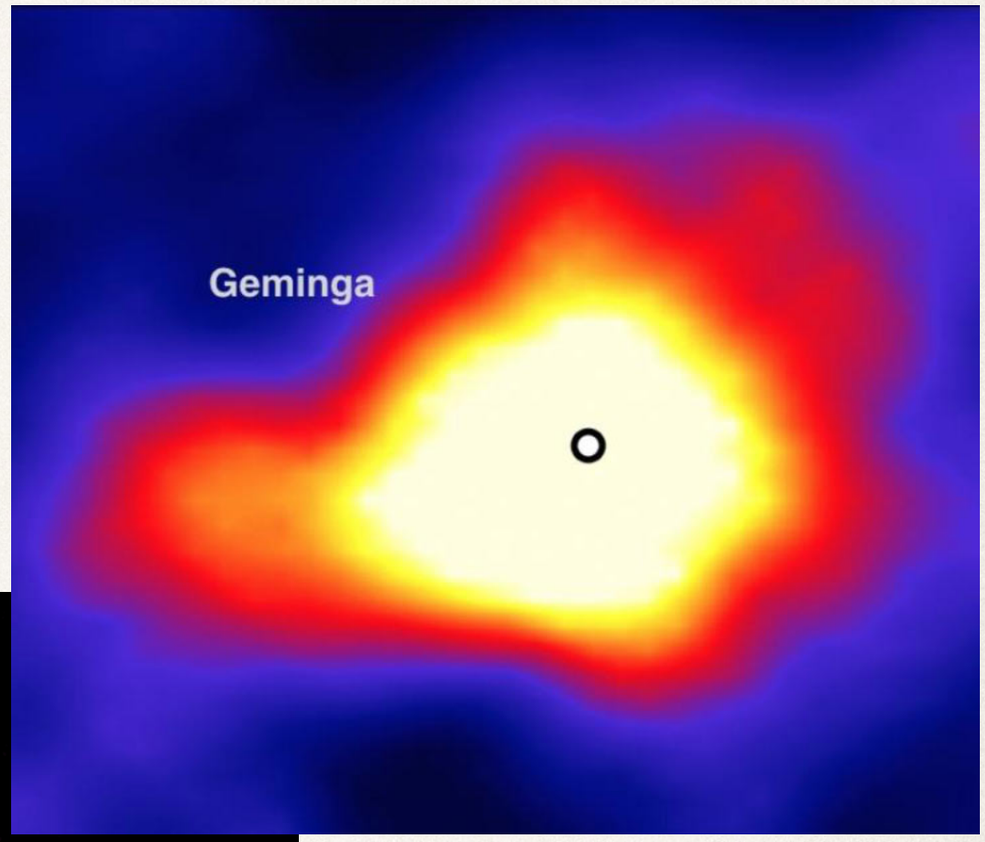
Theory/Modeling

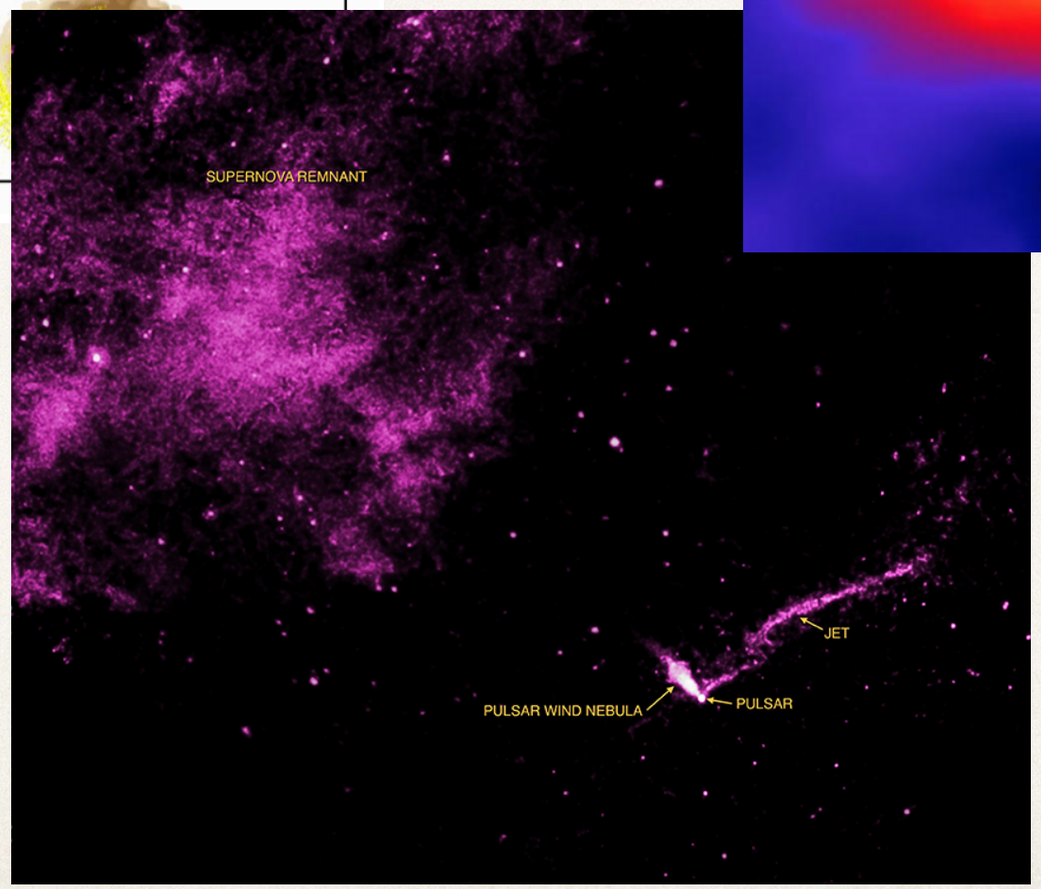
- What is the origin of the efficient confinement around (some) pulsars ?
  - Kinetic option:
    - Is turbulence generation by streaming pairs a possible solution at all ?
    - Power problem if injection starts after few 10 kyr with typical PWN spectrum
    - Magnetic turbulence saturation levels and spectrum including cascade ?
    - Could there be an additional role of accelerated protons ?
    - Could non-resonant streaming instability help ?
    - … numerical simulations produce some charge separation (Bucciantini 2020)
    - Other instabilities e.g. firehose ?
    - Time evolution of the injection term, spectrum and efficiency
  - Fluid option:
    - Are known halos probing regions of turbulence with reduced coherence length ?
    - What would be their origin ? How often can they be found ?
    - If turbulence was imparted by parent SNR, can it last long until ~300-500kyr ?
    - Impact on other observables, e.g. direct CR measurements ?

Serious challenges on the numerical side
owing to the variety of time/spatial scales involved

Theory/Modeling







Bucciantini 2020, Pavan et al. 2015, Abeysekara et al. 2017

Observations/Data analysis

- What are the properties of halos as a population ?
  Do most pulsars go through a halo phase ?
  - Gamma-rays
    - How to tell PWNe apart from halos in existing/forthcoming observations ?
    - What fraction can we hope to detect/identify/exploit ?
    - …HESS J1825-137 illustrates the challenge
    - What is the potential/added value of IACTs here ?
  - Other wavelengths
    - X-ray halos: problems with extension, absorption, backgrounds
    - Radio halos: more or less the same issues
  - Probes of interstellar turbulence
    - What are the prospects for a better understanding of turbulence in the disc ?

Very likely that gamma-rays cannot do it alone