The Moon (same scale)

TeV γ-RAY HALOS CLASSIFIED BY THE DOMINANT ENERGETICS IN THE REGION

Gwenael Giacinti (MPIK Heidelberg)

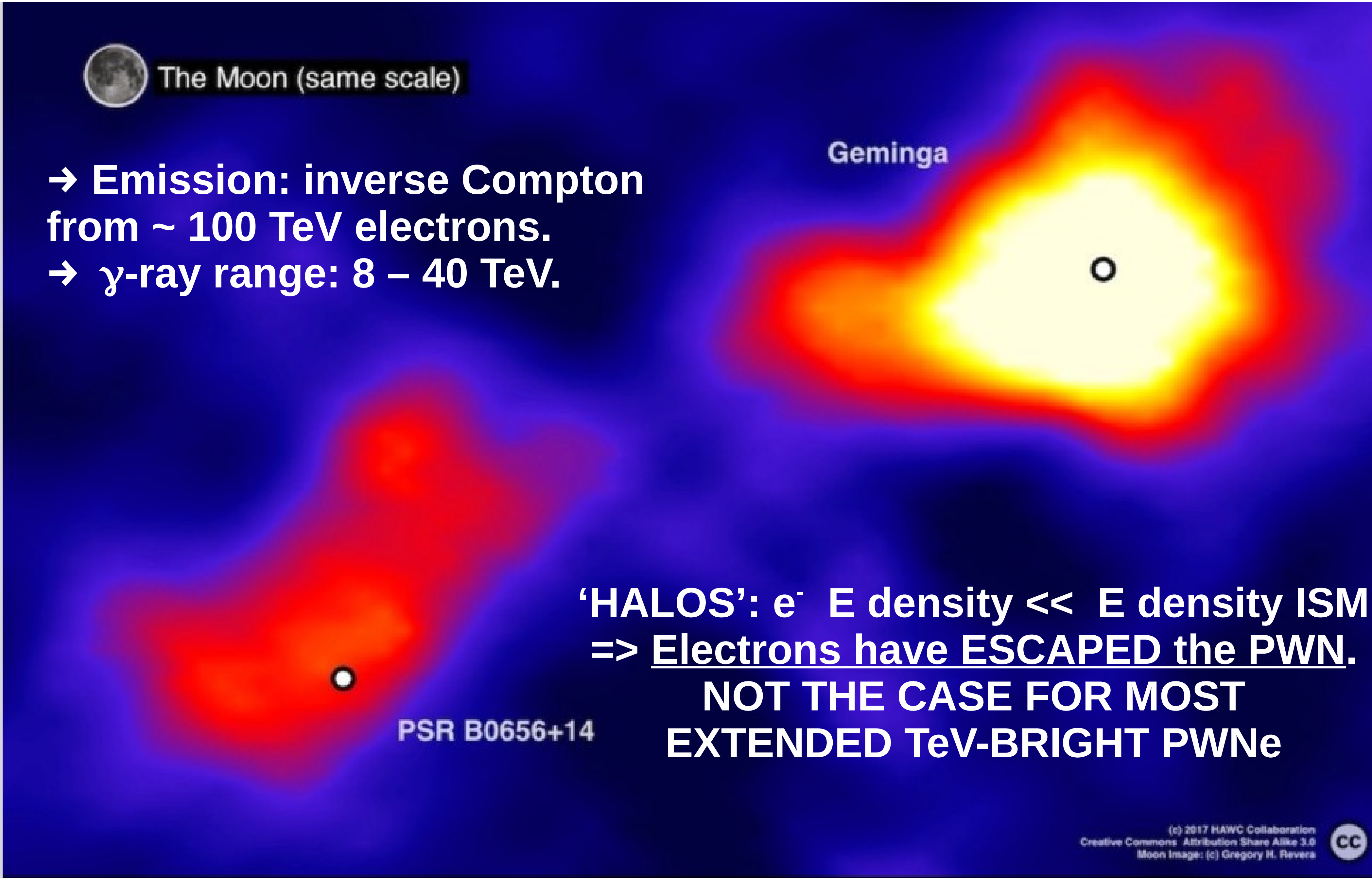
Partly based on :

→ Giacinti, Mitchell, Lopez-Coto, Joshi, Parsons & Hinton, A&A 636, A113 (2020) [arXiv:1907.12121],

→ Lopez-Coto & Giacinti, MNRAS 479, 4526 (2018) [arXiv:1712.04373].

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

HAWC observ. of Geminga & Monogem

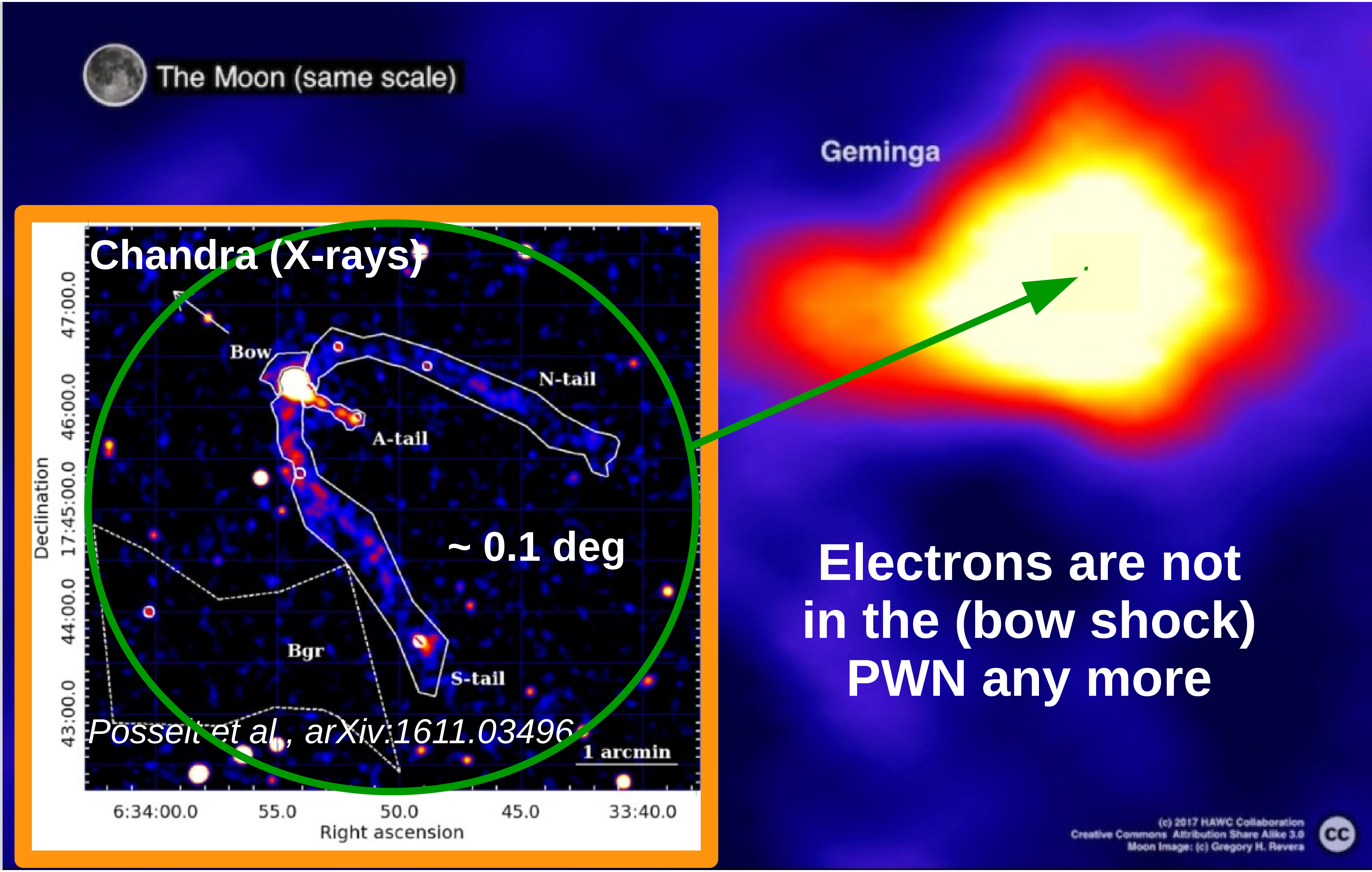


➜ **Emission: inverse Compton from ~ 100 TeV electrons.**

➜ **γ-ray range: 8 – 40 TeV.**

'HALOS': e^- E density << E density ISM
=> <u>Electrons have ESCAPED the PWN</u>.
NOT THE CASE FOR MOST EXTENDED TeV-BRIGHT PWNe

HAWC observ. of Geminga & Monogem

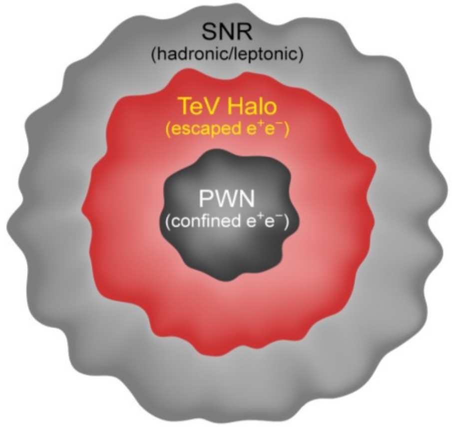


How to define ‘escape from the PWN’ ?

→ Tim’s talk + Sudoh et al., arXiv:1902.08203 :

* "Halos" : Diffusion instead of advection

* Evoli + (2019) : Electron-driven instabilities possible.



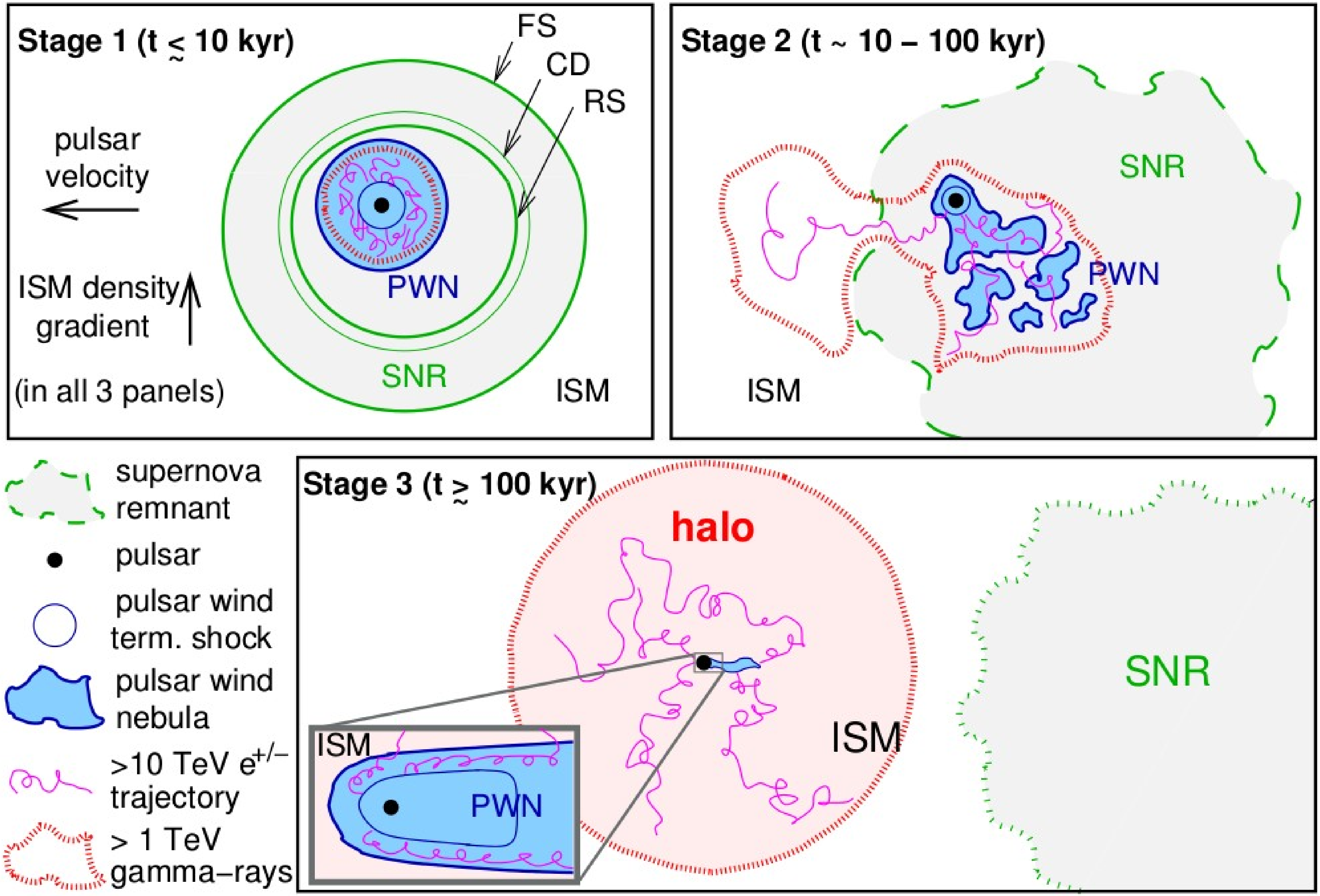
→ Giacinti, Mitchell, Lopez-Coto, Joshi, Parsons & Hinton, A&A 636, A113 (2020)

*** "Halos" : e^- energy density << ISM energy density.**
(Otherwise, could include standard TeV-bright PWNe)

* Large majority of known TeV sources: Emission from the zone energetically dominated by the pulsar (= the PWN), rather than from a halo of particles freely diffusing in the ISM.

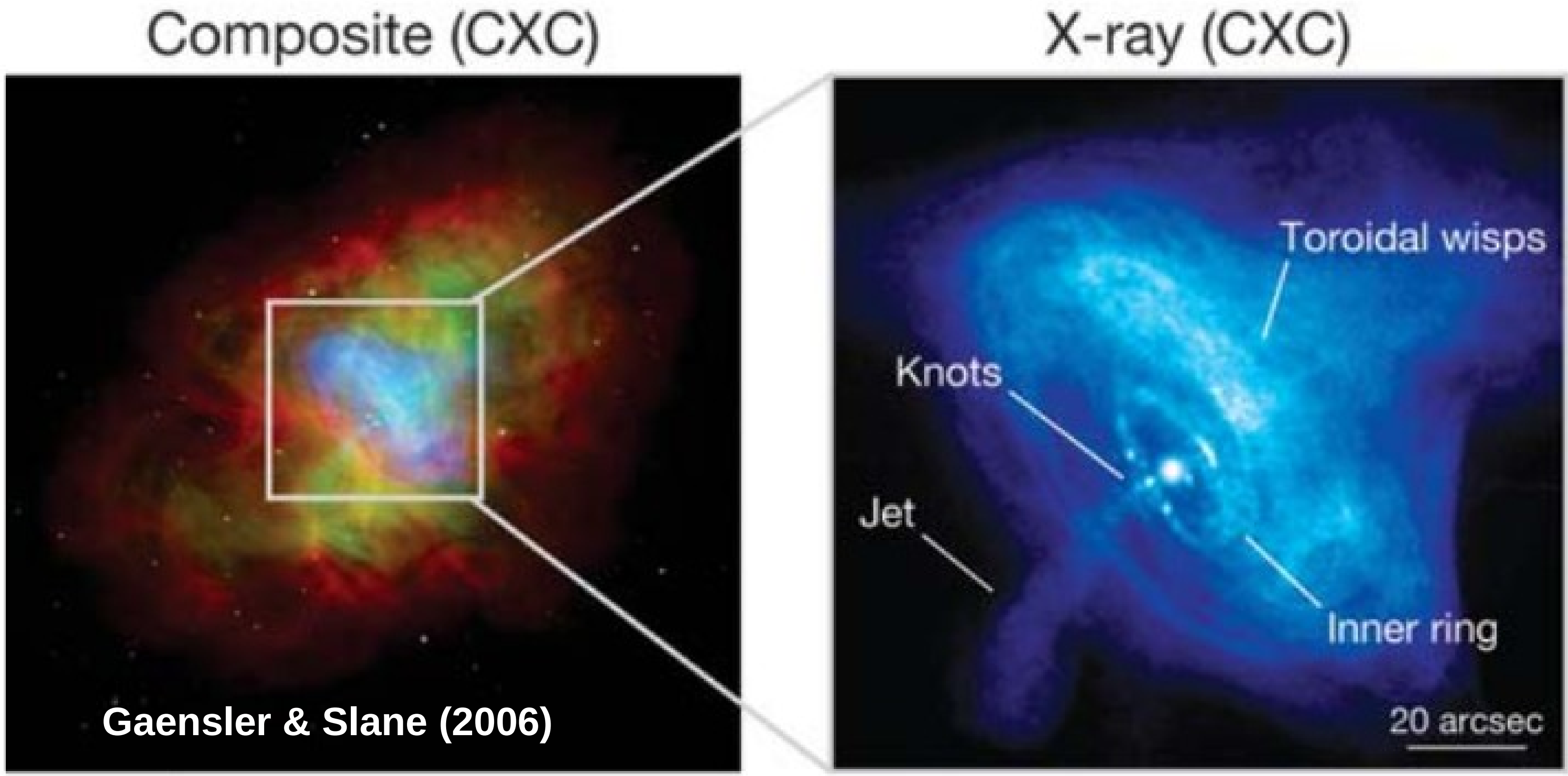
Evolutionary stages of a PWN :

Giacinti, Mitchell, Lopez-Coto, Joshi, Parsons & Hinton,
A&A 636, A113 (2020), arXiv:1907.12121:



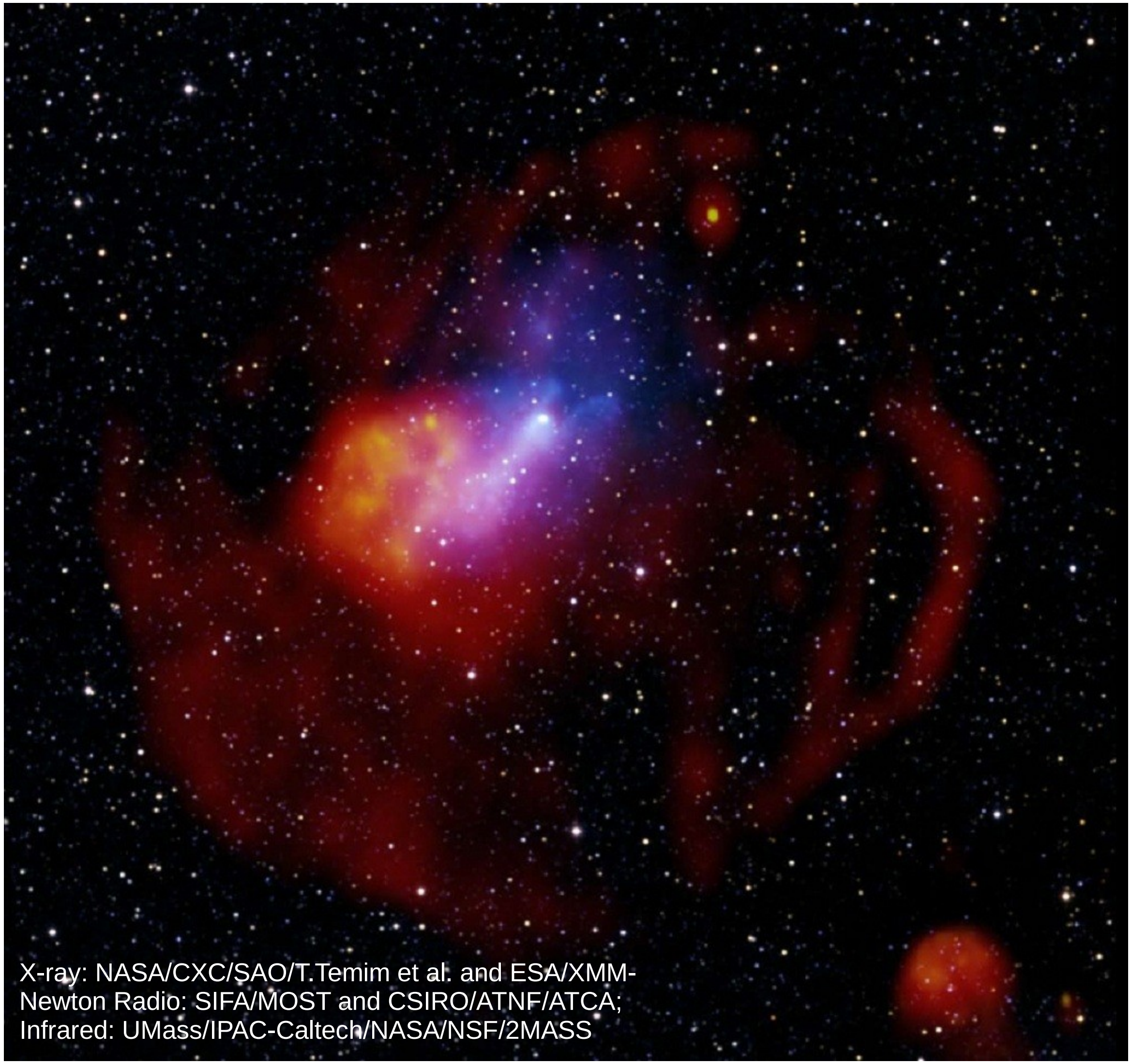
Evolutionary stages of a PWN :

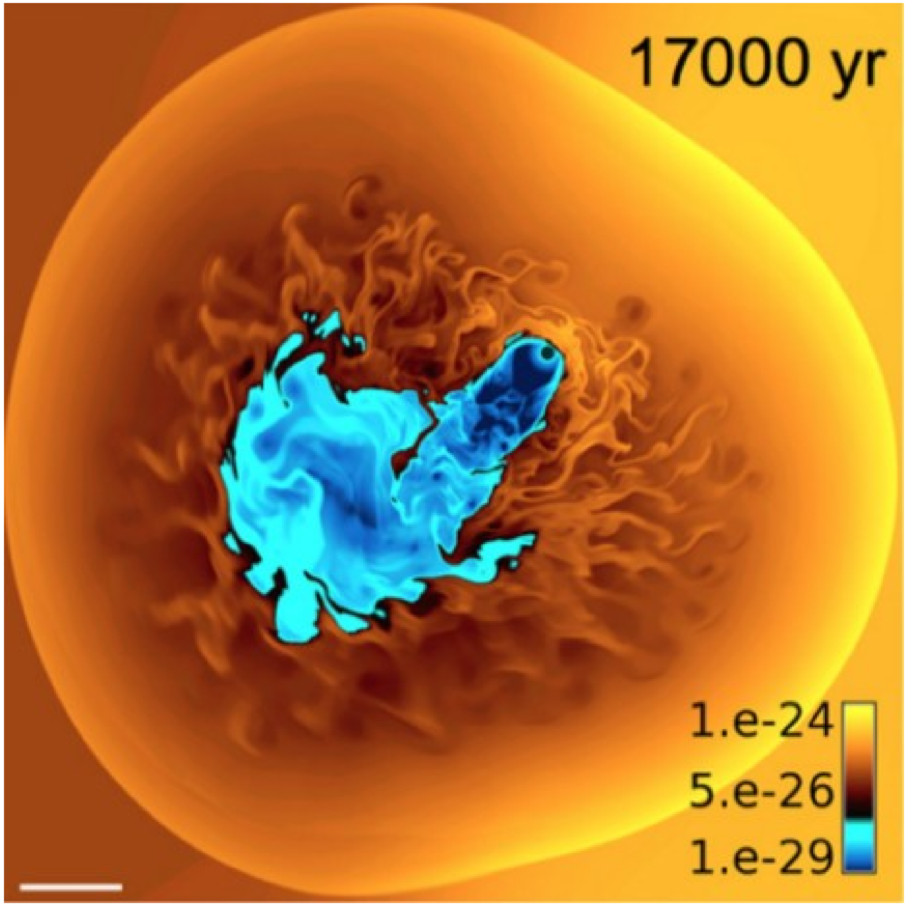
Stage 1 : e.g. Crab Nebula (0.94 kyr)



Evolutionary stages of a PWN :

Stage 2 : e.g. G327.1-1.1 (17 kyr)



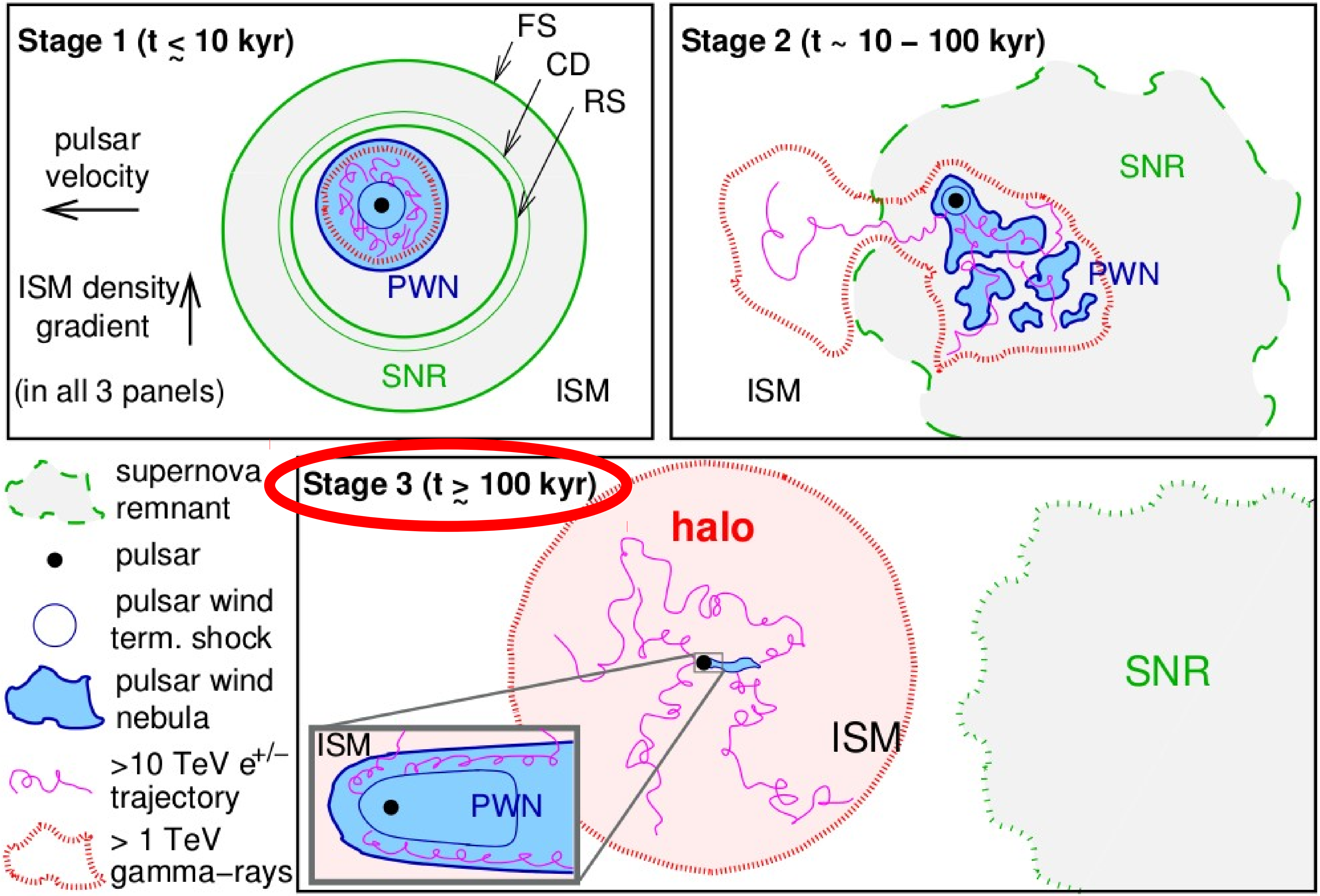


Simulation -Temim et al. (2015)

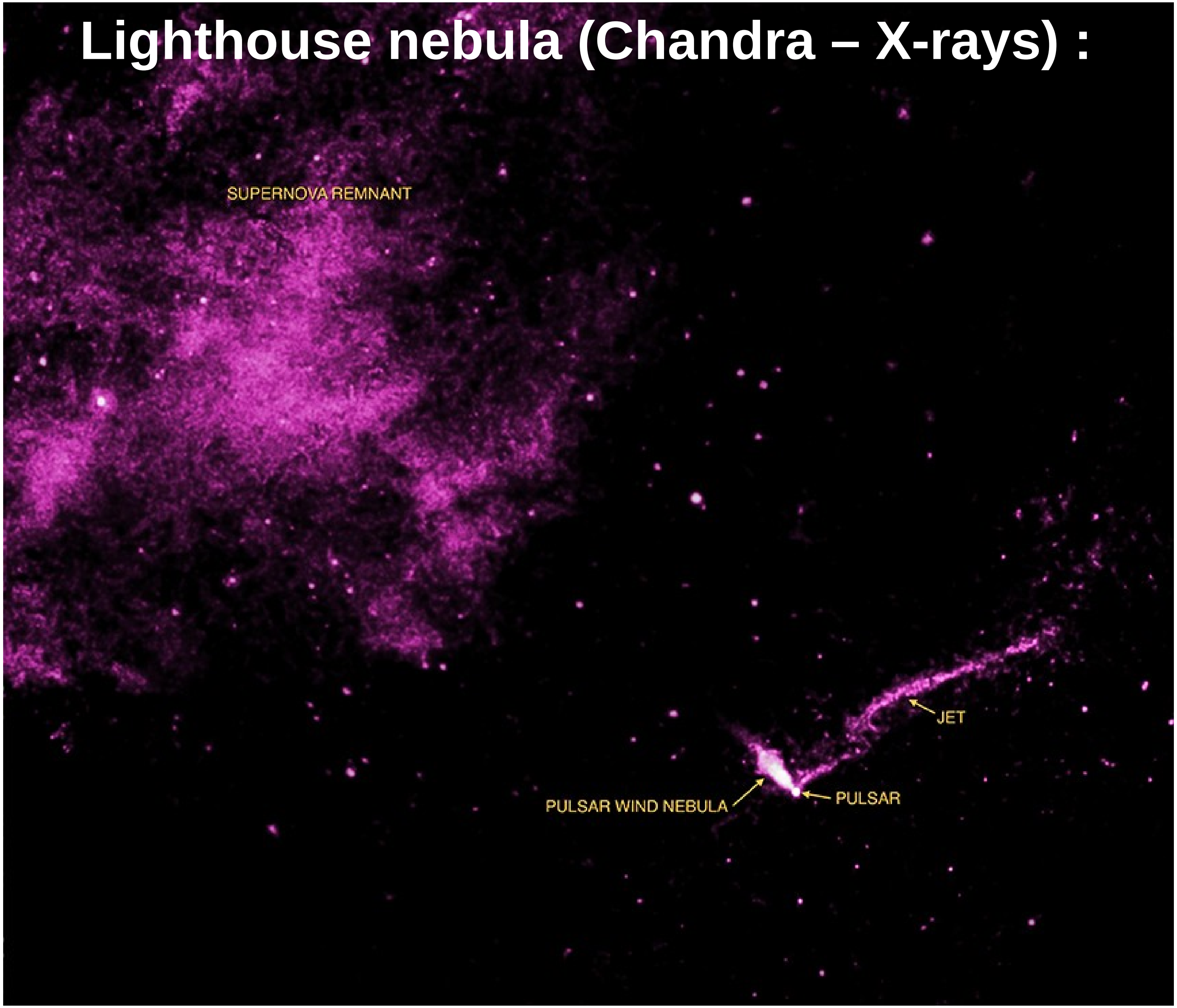
Stage 3 : e.g. Geminga (342 kyr)

e⁻ can escape in to the ISM; Weak; Low e⁻ density

=> Only then a "halo" may form within our definition.

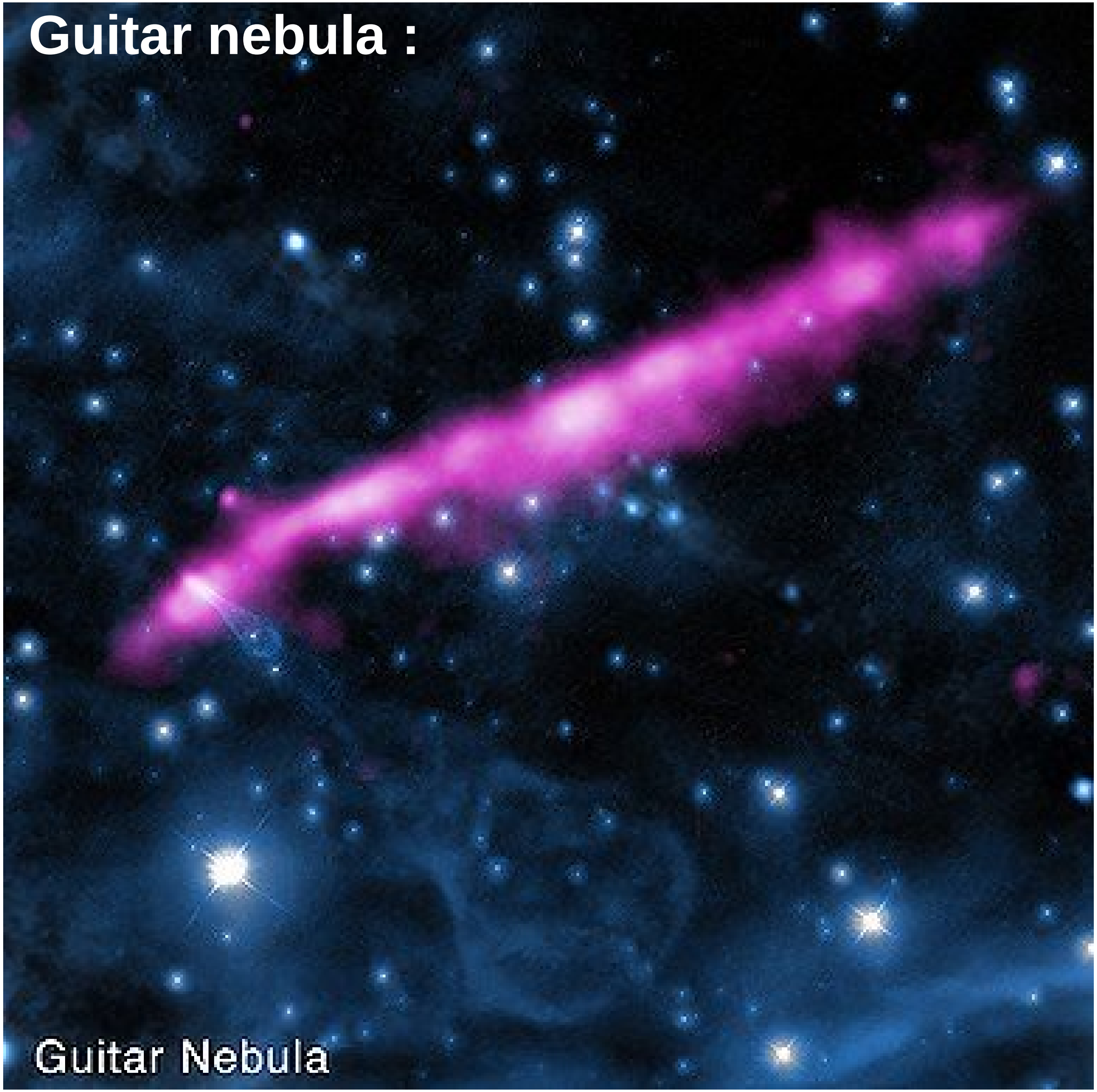


HE electron escape :



Theory escape : See e.g. works of Barkov + ; Bucciantini +

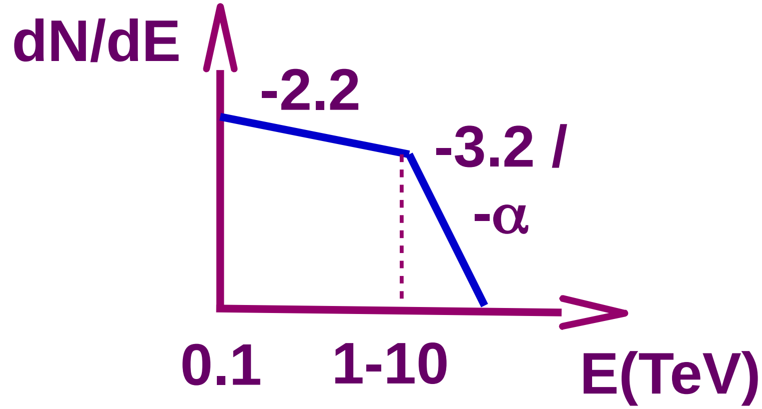
HE electron escape :

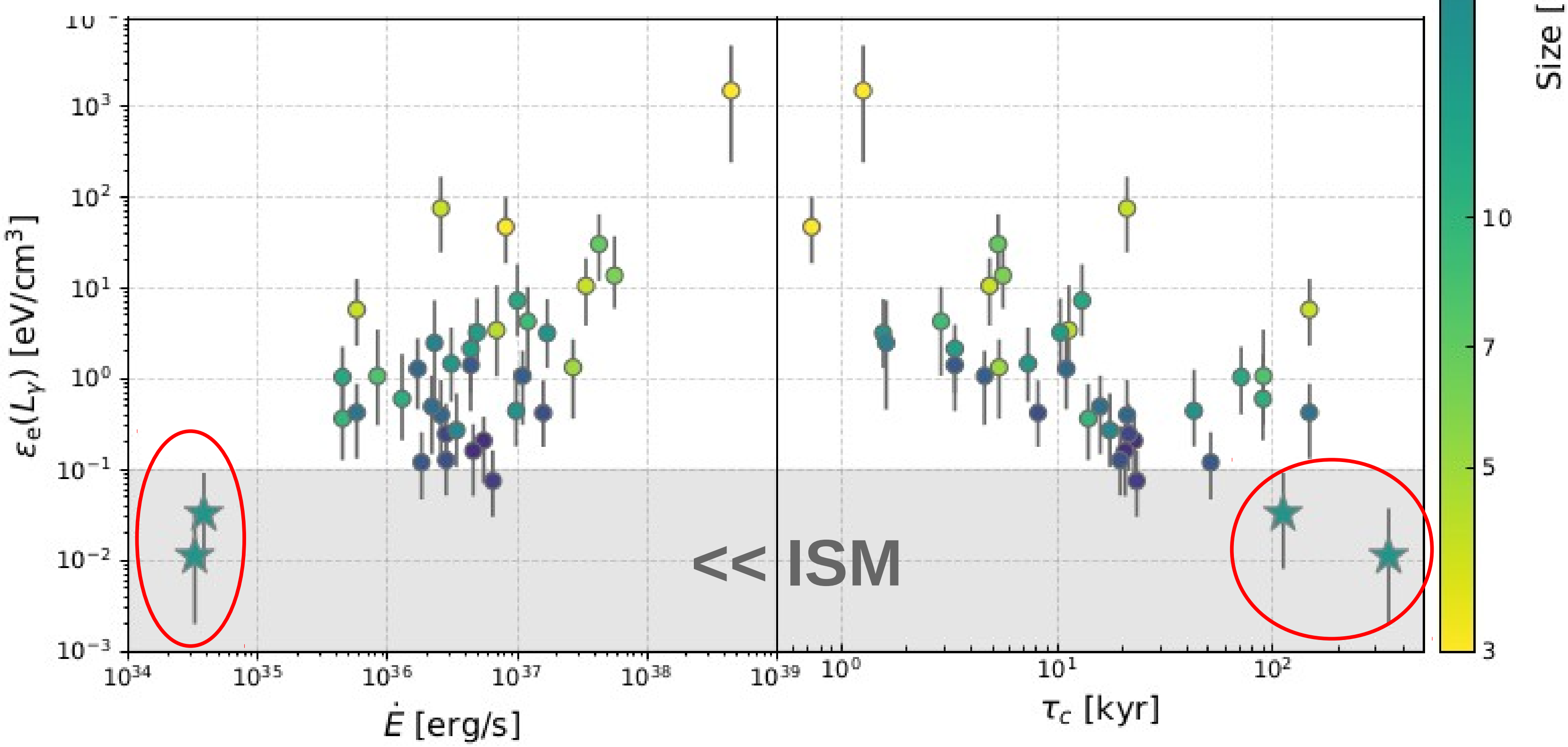


e^- Energy Densities (A&A 636, A113 (2020)) :

- Take the TeV sources identified as PWNe by the HESS Coll. (Abdalla et al. 2018) + Geminga and PSR B0656+14 from HAWC.

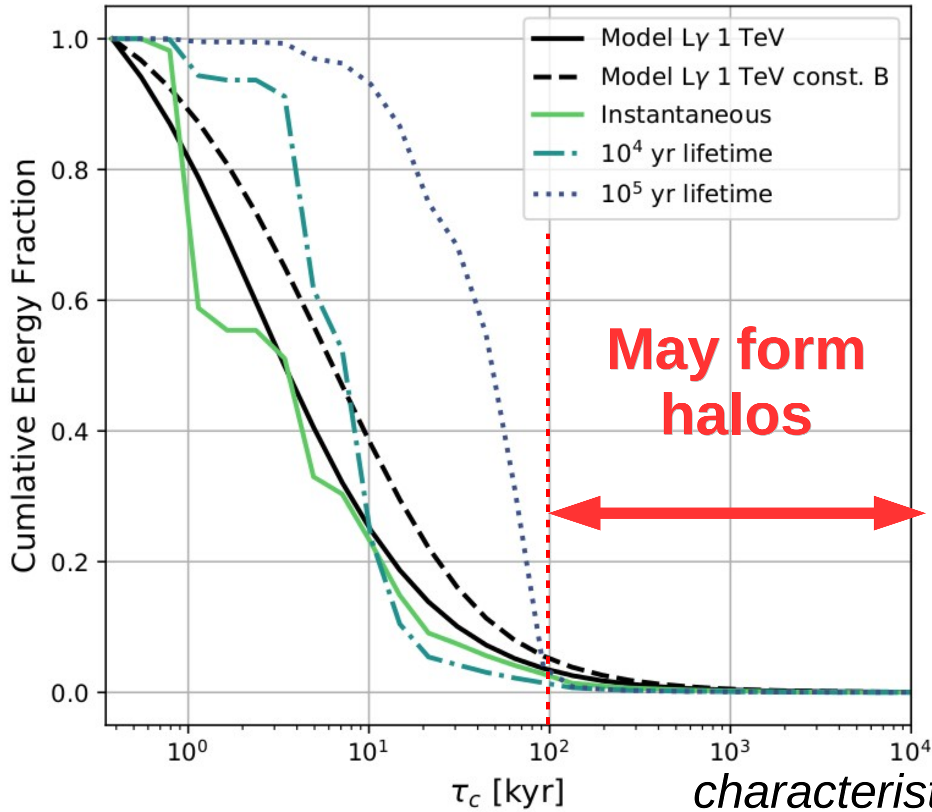
- Use measured $L_{\gamma,\ 1\text{-}10\ /\ 8\text{-}40\mathrm{TeV}}$





Halos: Prospects for future detections

Unlikely that halos contribute significantly to the ***total TeV γ-ray luminosity from e⁻ accelerated in PWN*** :

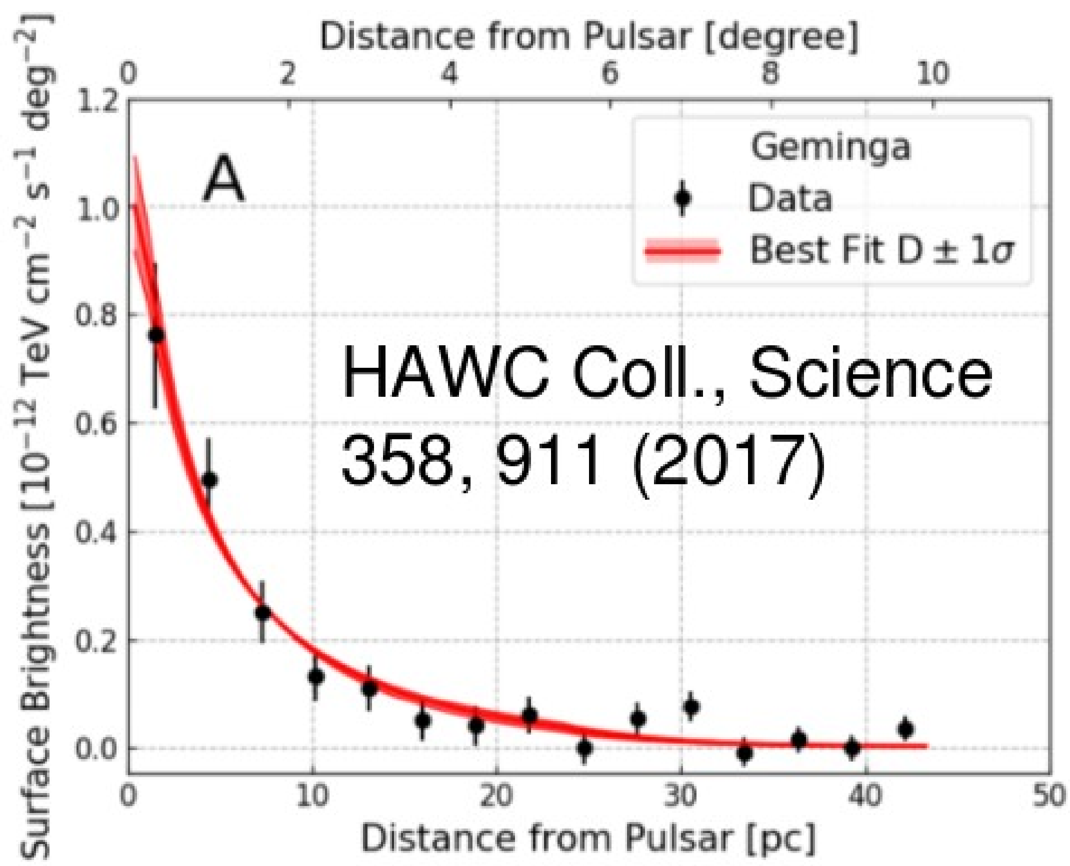


Cumulative fraction of the energy output of the known pulsar population (ATNF catalogue)

characteristic age of the pulsar

Halos should be a common feature of > 100 kyr pulsars, but should remain a small fraction of all detected TeV-bright PWNe.
(Halos dim & large => hard to detect => Sees nearby ones)

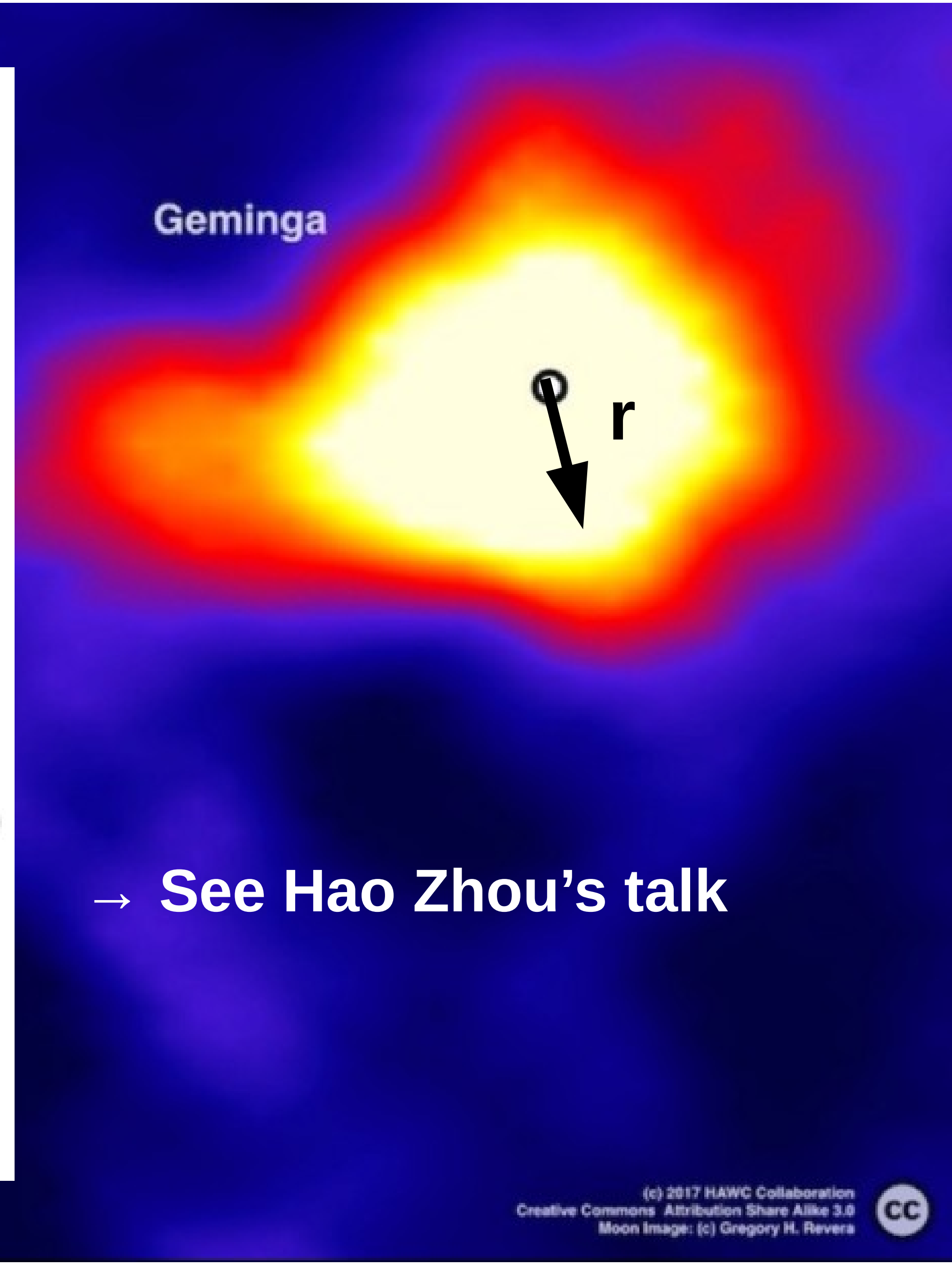
« Small » Diffusion Coefficient !



$B = 3\ \mu\mathrm{G}$

$$D_{100} = (4.5 \pm 1.2) \times 10^{27}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$$

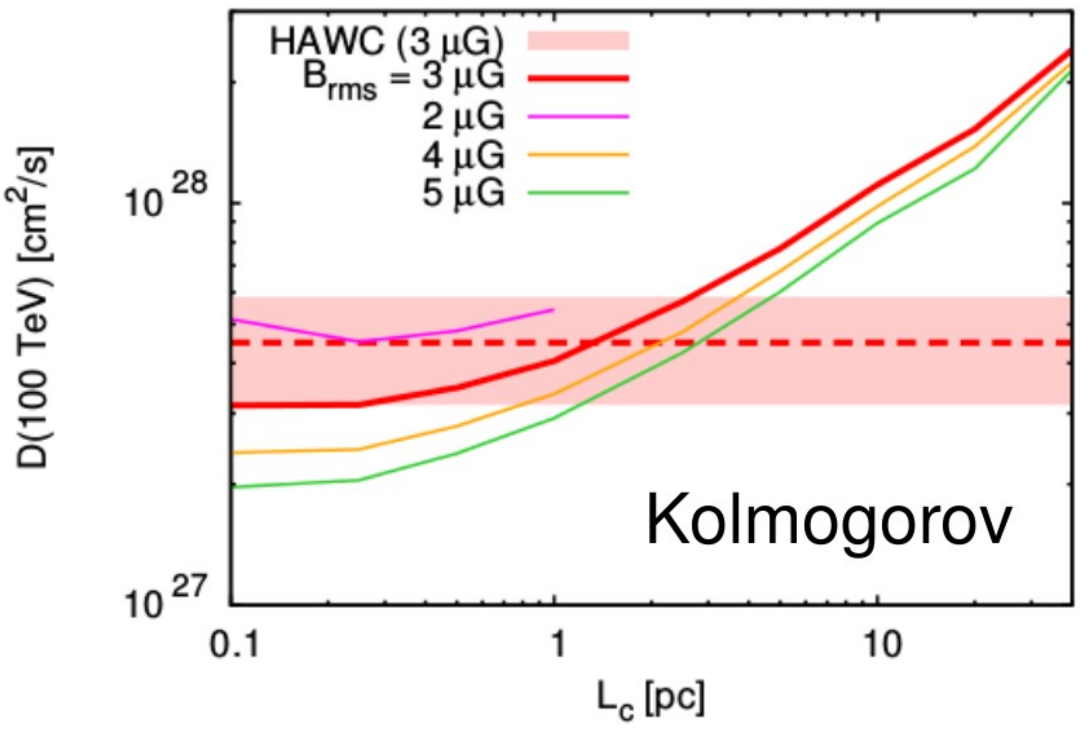
at 100TeV.



Actually, D_{HAWC} = Theoretical D

Lopez-Coto & Giacinti, MNRAS (2018):

Individual particles propagated numerically in 3D synthetic turbulence.



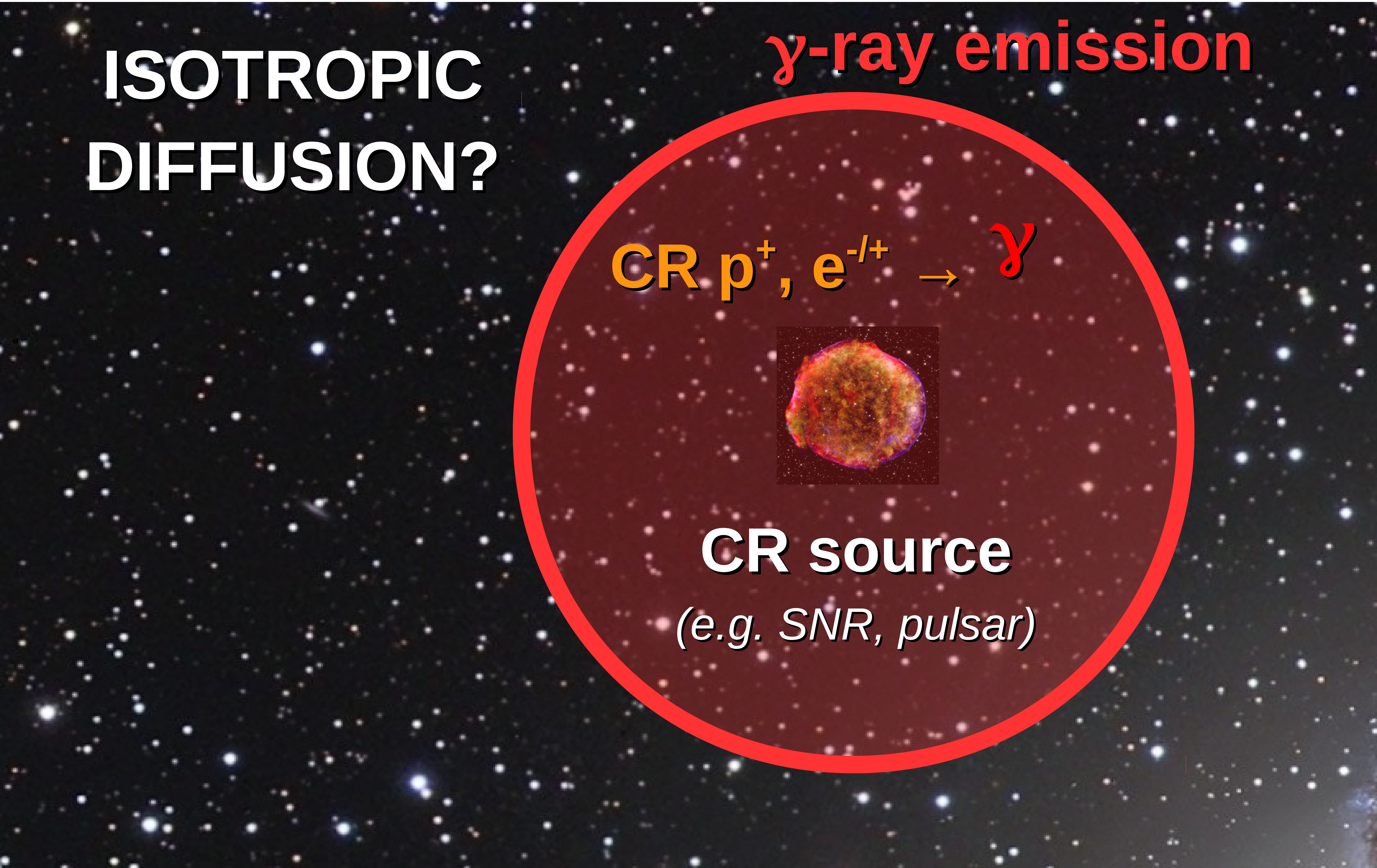
=> HAWC findings agree with theoretical expectations :

(a) For a **strongly turbulent** magnetic field (i.e. regular B negl.),

(b) For coherence lengths ~ a few pc.

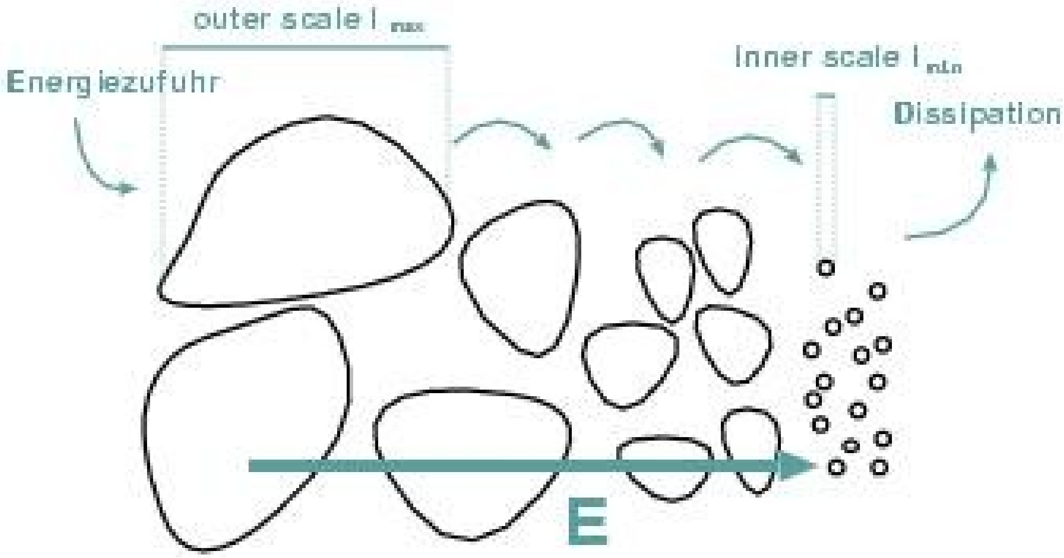
Tensions with B/C solved if faster diff in the halo. GG+ JCAP (2018)

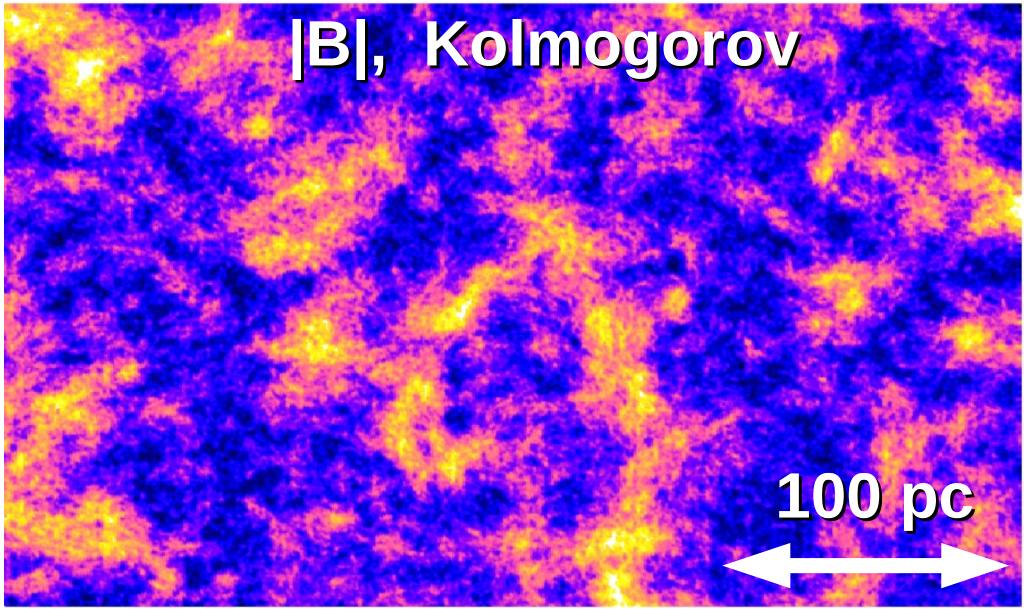
But is CR diffusion (ever) isotropic ?

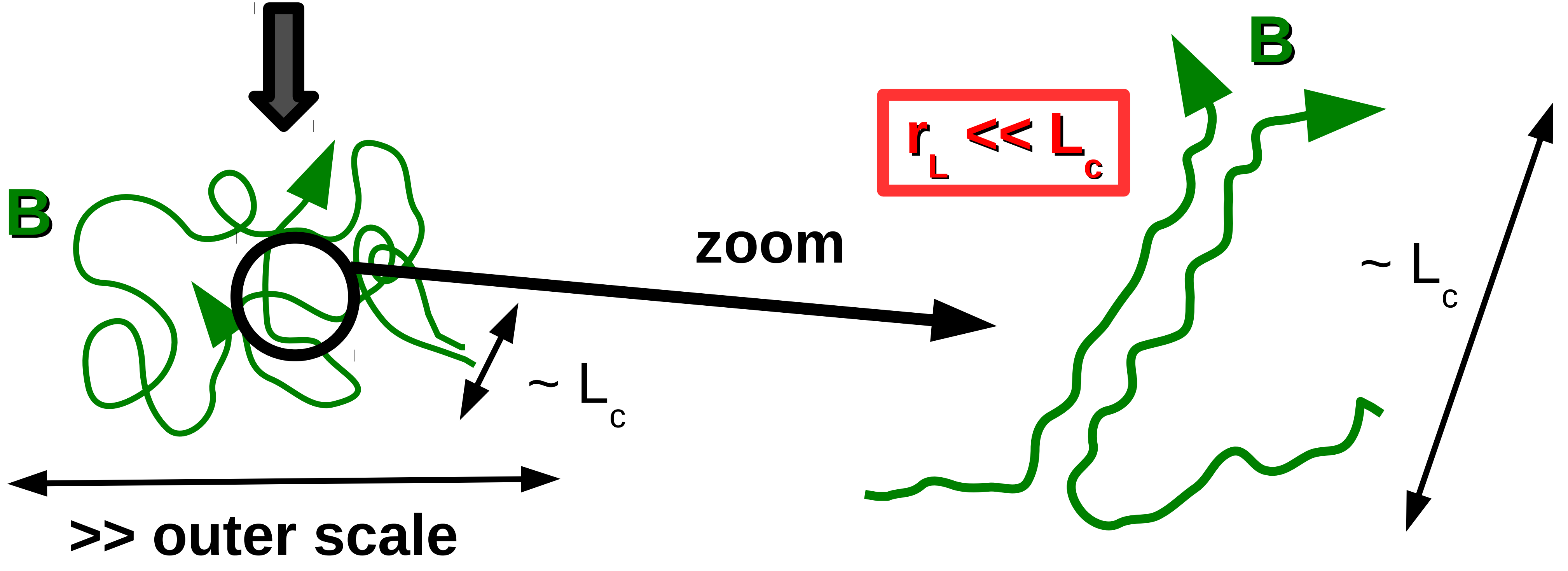


But is CR diffusion (ever) isotropic ?

http://www.lsw.uni-heidelberg.de/users/sbrinkma/thesis/node5.html

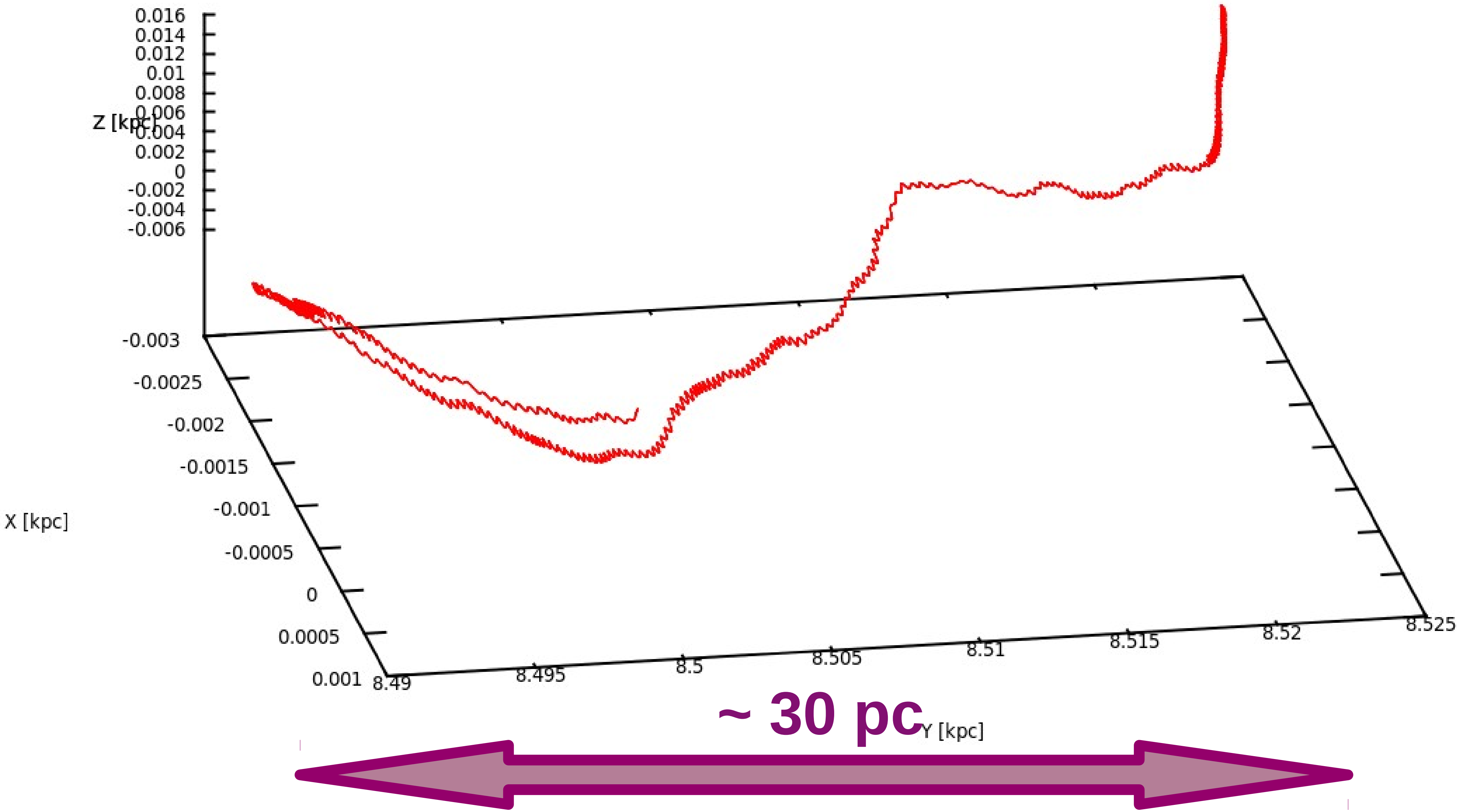




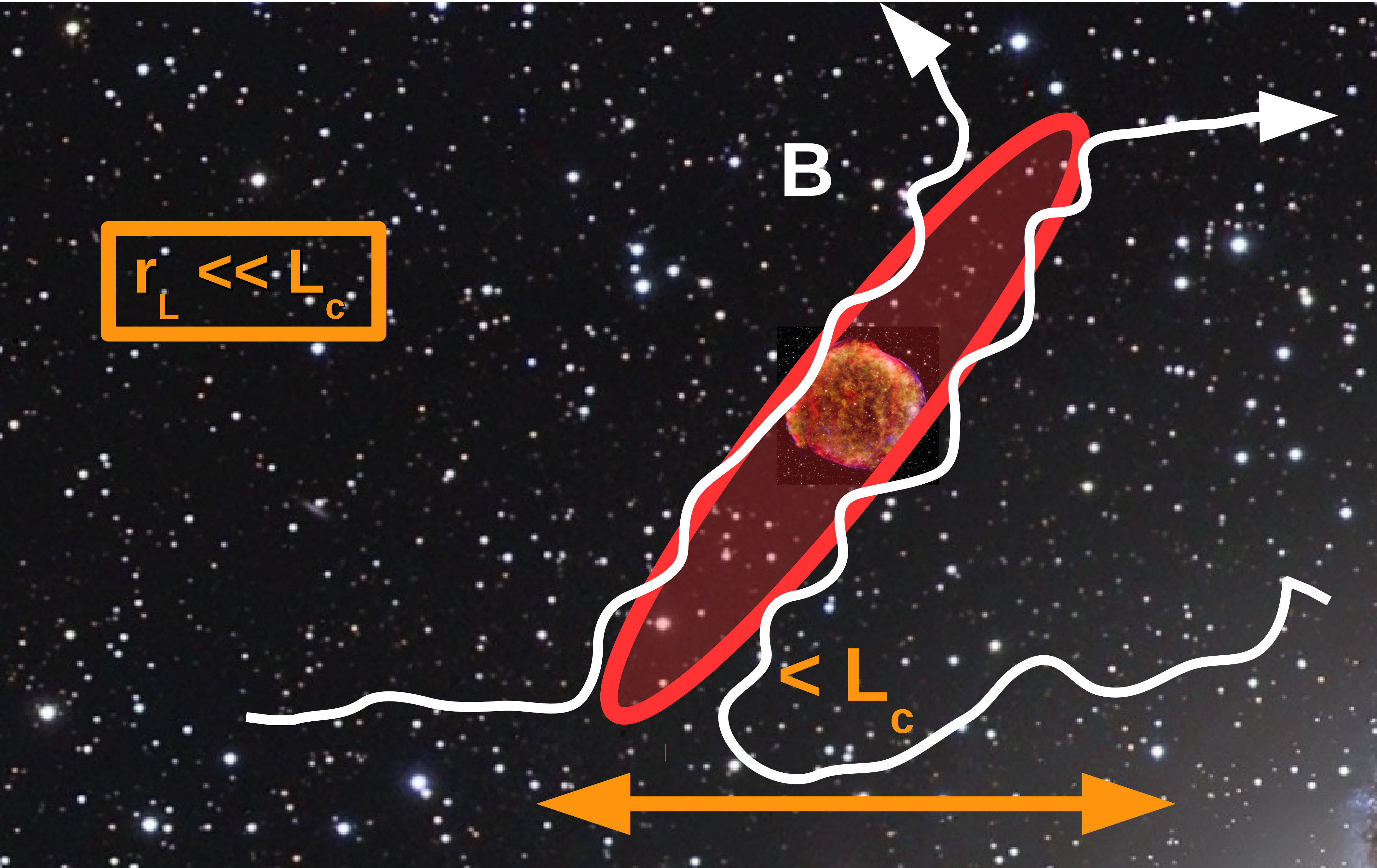


Individual CR trajectories

300 TeV, Kolmogorov, L_c = 30 pc, B_{rms} = 4 μG.



But is CR diffusion (ever) isotropic ?



But is CR diffusion (ever) isotropic ?

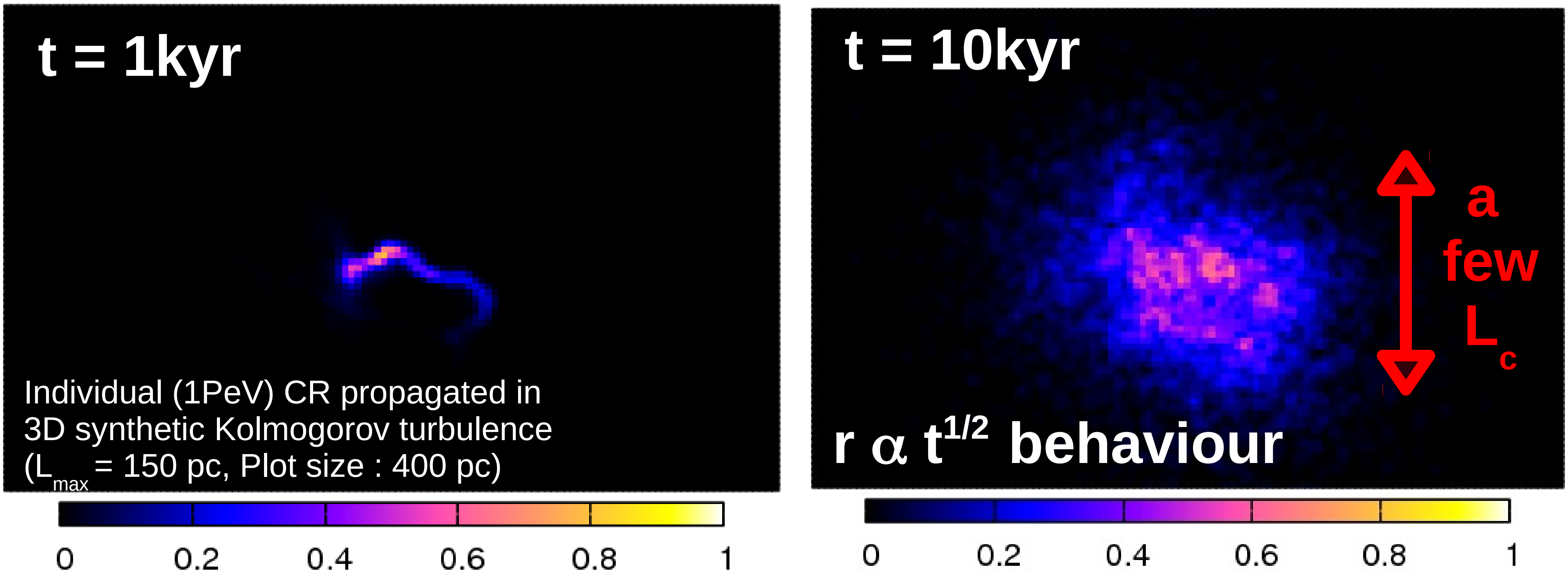
$r_L << L_c$

If emission symmetric: Can put <u>upper limits</u> on the <u>coherence length</u> of the turbulence

PRL 108, 261101 (2012) PHYSICAL REVIEW LETTERS week ending 29 JUNE 2012

Filamentary Diffusion of Cosmic Rays on Small Scales

G. Giacinti,[1] M. Kachelrieß,[1] and D. V. Semikoz[2,3]



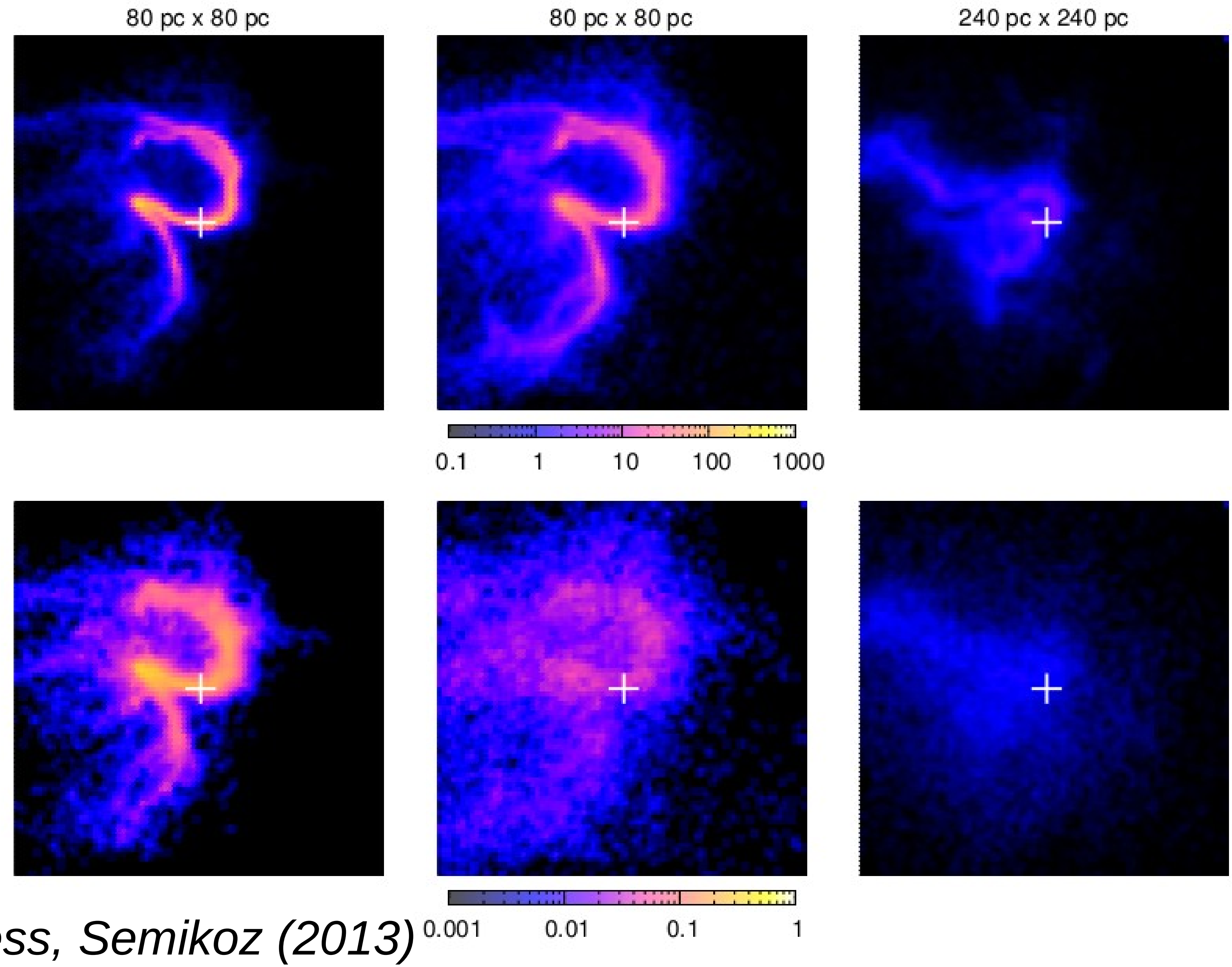
- See also Malkov et al., ApJ (2013).
- See Ruoyu's talk.
- Hints of anisotropic diffusion around W44: Peron et al., ApJ (2020).

Simulated γ-ray images of a source :

t = 0.5 kyr **2 kyr** **10 kyr after escape**

> 300 GeV

> 30 TeV



GG, Kachelriess, Semikoz (2013)

Simulations

→ **Propagate individual e⁻ in 3D synthetic turbulence :**

62 x10 realizations : $\{\mathcal{P}(k), L_c, B_{rms}\}$ $B_{rms} \equiv \sqrt{\langle B^2 \rangle}$.

Injection spectrum (40 – 500 TeV) :

$$dN/dE = f_e(E/E_0)^{-\alpha} \text{ with } \alpha = 2.24$$

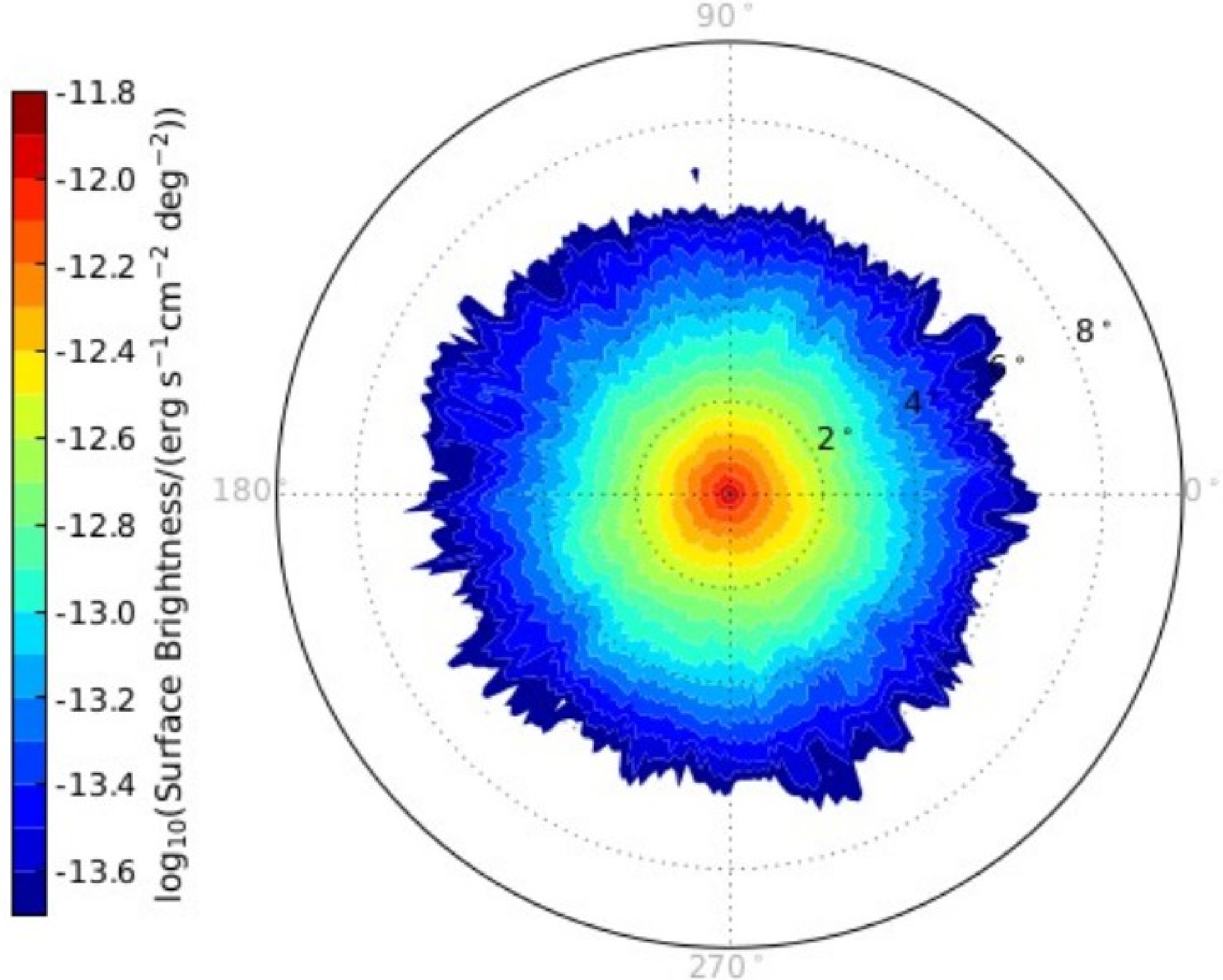
→ Take into account synchrotron + IC losses (/CMB) :

$$\left|\frac{dE}{dt}\right| \simeq 2.53 \times 10^{-15}\,\text{TeV/s}\left[\left(\frac{B}{\mu\text{G}}\right)^2 + 10.1\left(1 + \frac{E}{99\,\text{TeV}}\right)^{-1.5}\right]\left(\frac{E}{\text{TeV}}\right)^2$$

→ Calculate gamma-ray emission : IC on CMB photons.
(full Klein-Nishina treatment of the cross section)

Predicted γ-ray surface brightness

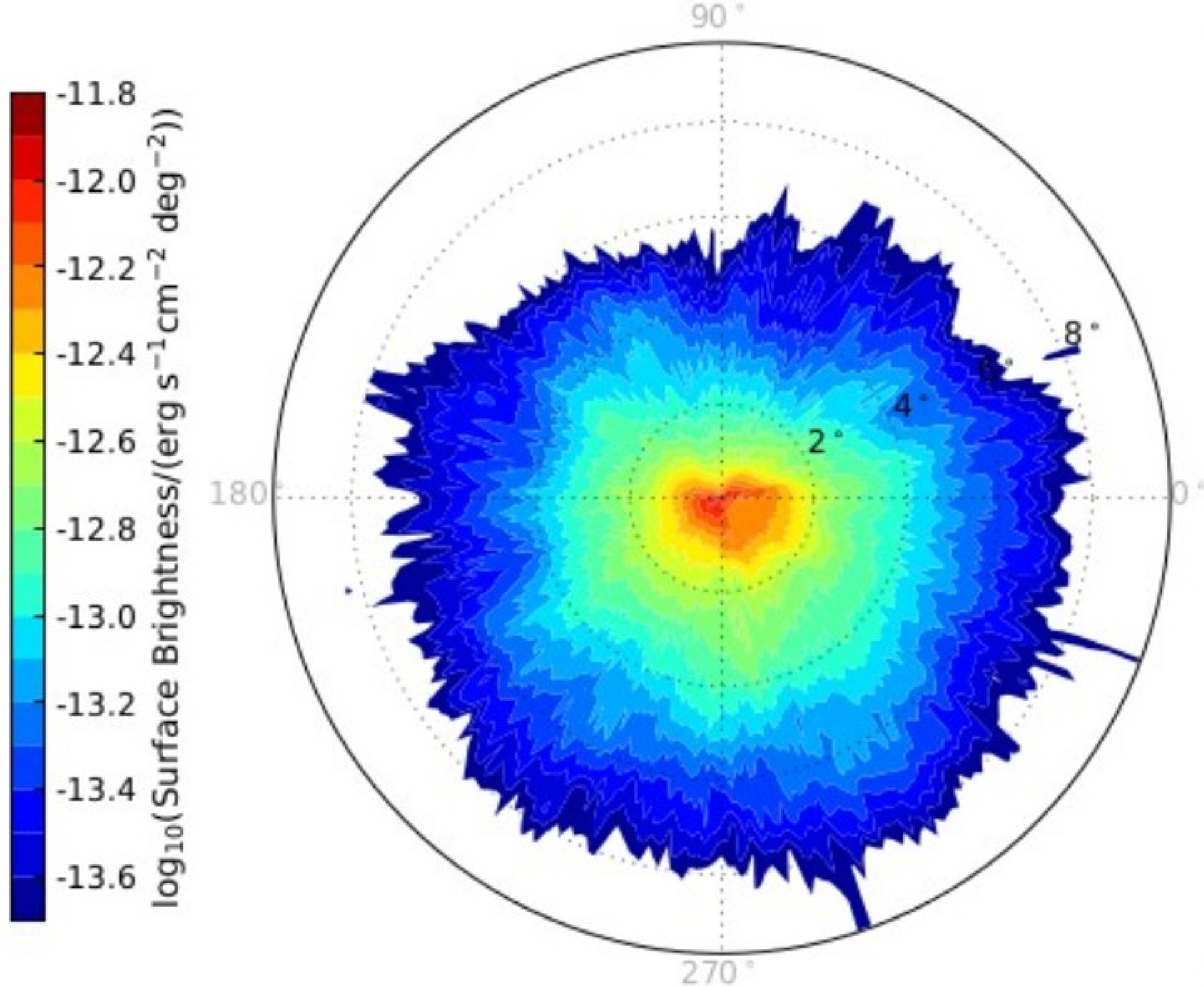
Kolmogorov, B_{rms}=3 μG, $\mathbf{L_c}$ **= 0.25 pc** :



Lopez-Coto & Giacinti, MNRAS 479, 4526 (2018) [arXiv:1712.04373]

Predicted γ-ray surface brightness

Kolmogorov, B_{rms}=3 μG, $\mathbf{L_c}$ **= 5 pc** :

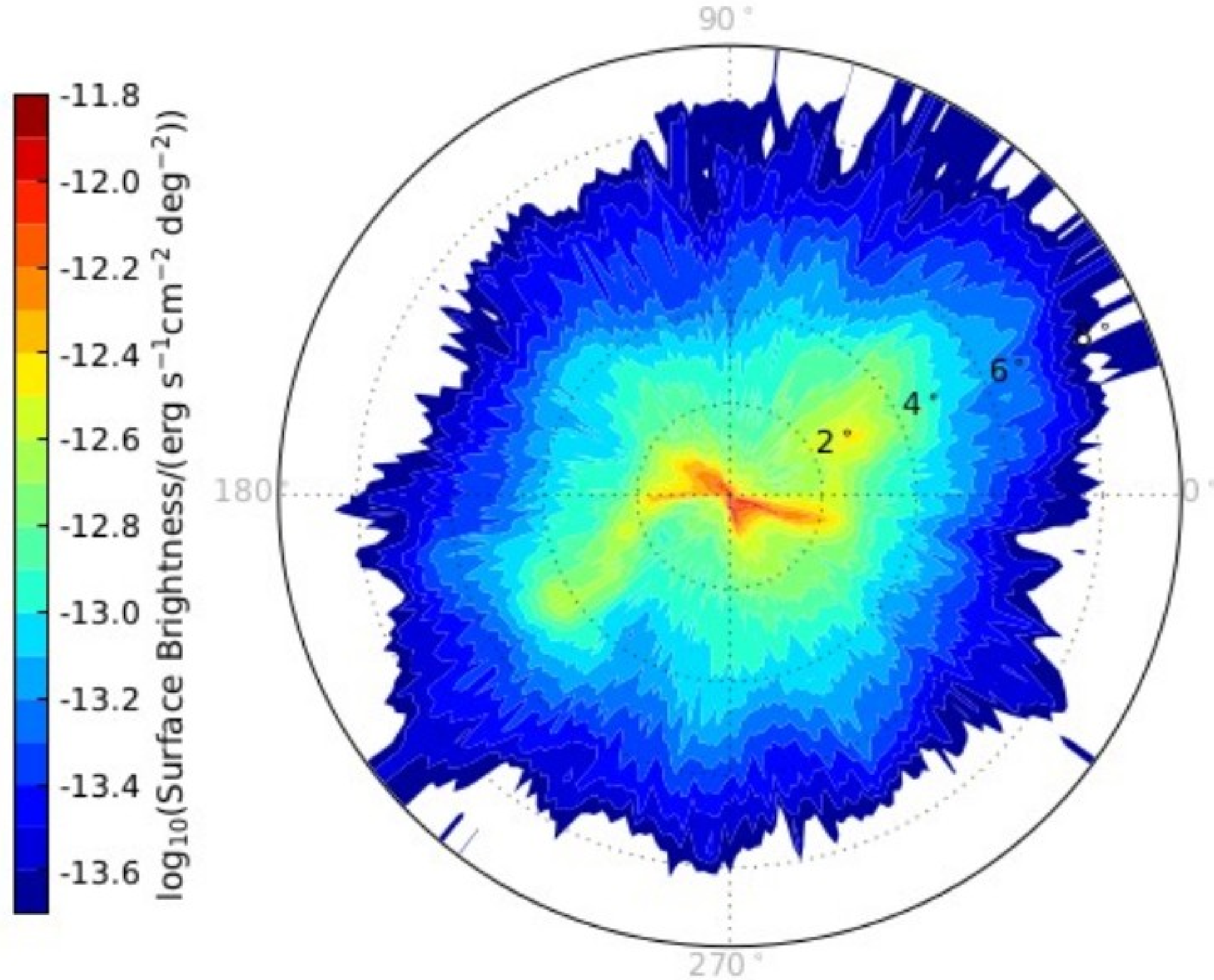


OK

Lopez-Coto & Giacinti, MNRAS 479, 4526 (2018) [arXiv:1712.04373]

Predicted γ-ray surface brightness

Kolmogorov, B_{rms}=3 μG, $\mathbf{L_c}$ **= 10 pc** :

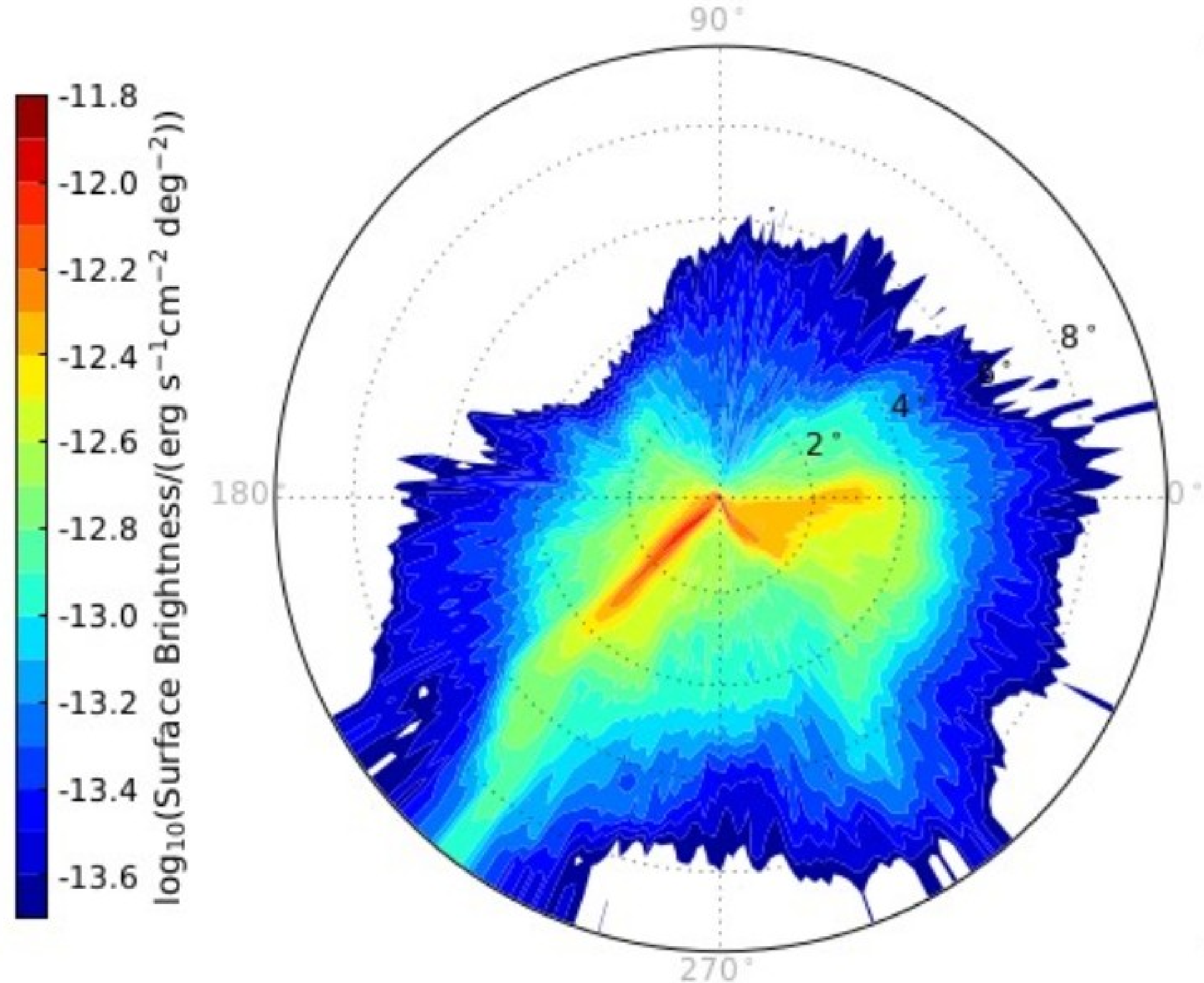


ALMOST INCOMPATIBLE WITH HAWC MEASUREMENTS

Lopez-Coto & Giacinti, MNRAS 479, 4526 (2018) [arXiv:1712.04373]

Predicted γ-ray surface brightness

Kolmogorov, B_{rms}=3 μG, **L_c = 40 pc** :



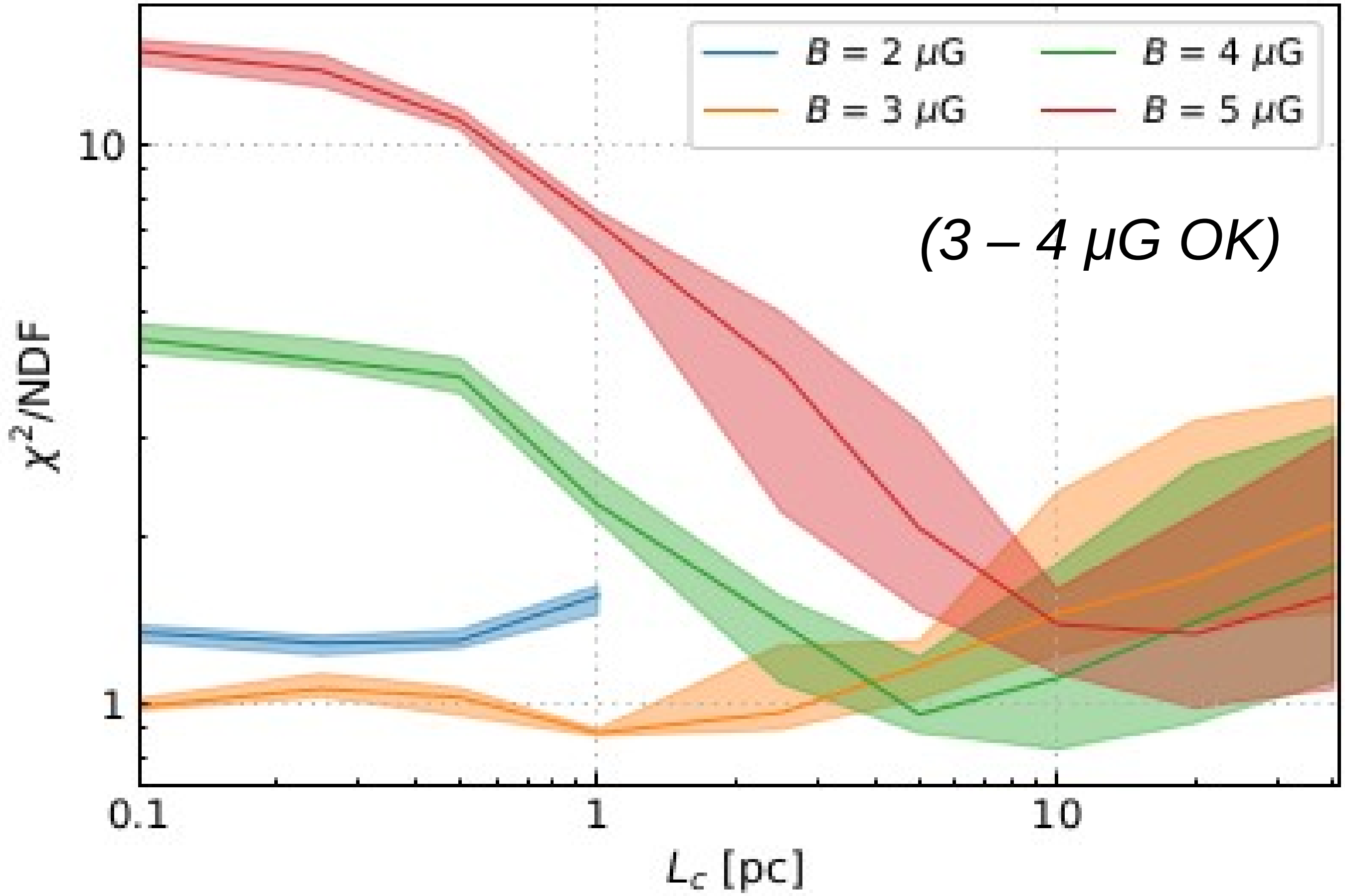
INCOMPATIBLE WITH HAWC MEASUREMENTS

Large coherence lengths (> 10 pc) ruled out (Too asymmetric)

χ^2/ndf as a function of L_c

Kolmogorov

(Kraichnan similar)

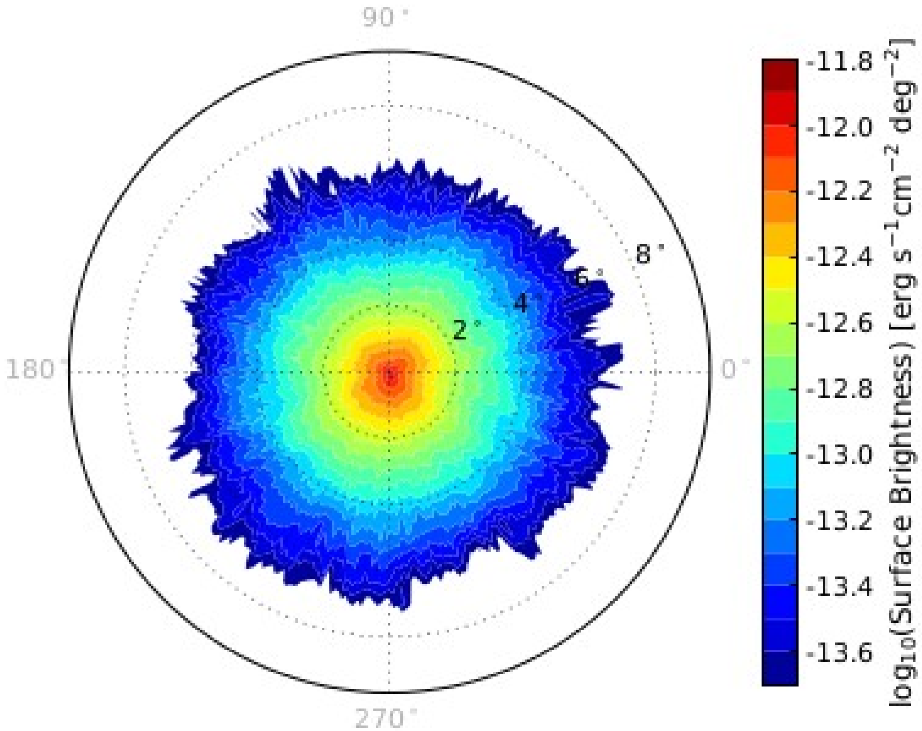


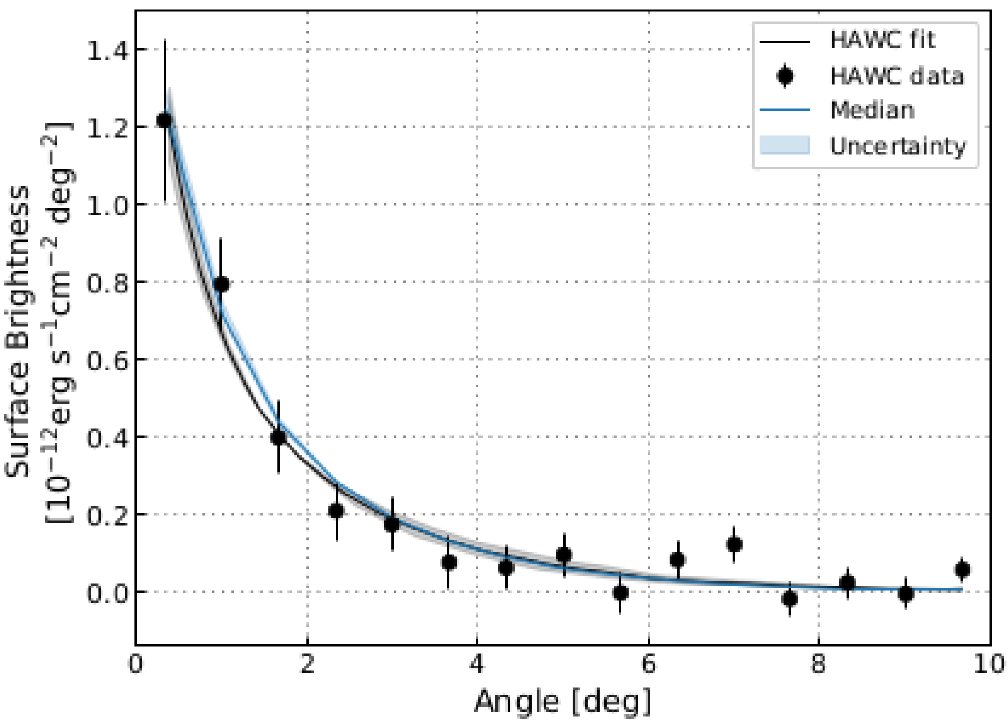
Lopez-Coto & Giacinti, MNRAS 479, 4526 (2018) [arXiv:1712.04373]

Best fit to HAWC measurements (χ^2/ndf<1)

→ Kolmogorov / Kraichnan, B = 3 μG, L_c = 1 pc

(comp. w/ radio observations in spiral arms)





Lopez-Coto & Giacinti, MNRAS 479, 4526 (2018) [arXiv:1712.04373]

Conclusions and perspectives

- Halos : Propose a classification based on the dominant energetics in the emitting region → **Relativistic e^- energy density subdominant (test particles in the ISM).**
- → Distinguishes from regular TeV γ-ray bright PWNe.
  → Highlights the novelty of HAWC's discovery.
  → Based on underlying/relevant physics.
- **HAWC measurements compatible with e^- in ISM turb. :**

  $B_{rms} \sim 3\ \mu G$ $L_c <\sim 5$ pc
- **γ-ray observatories as a probe of** :
  → **Turbulent interstellar magnetic fields**
  → Future : CR-driven instabilities around CR sources.

Future analyses: → 2D on sky, → function of E_γ