



The Moon (same scale)

Geminga

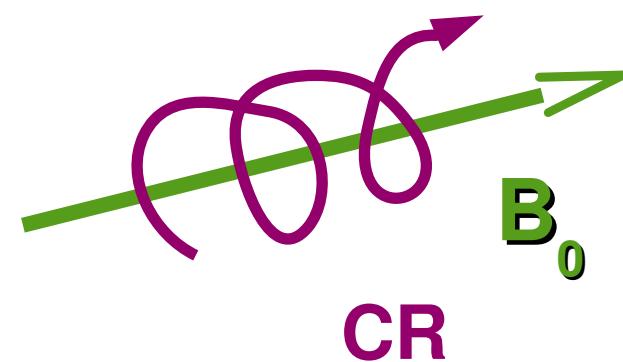
GAMMA-RAY INSIGHTS INTO COSMIC-RAY TRANSPORT

Gwenael Giacinti
(MPIK Heidelberg)

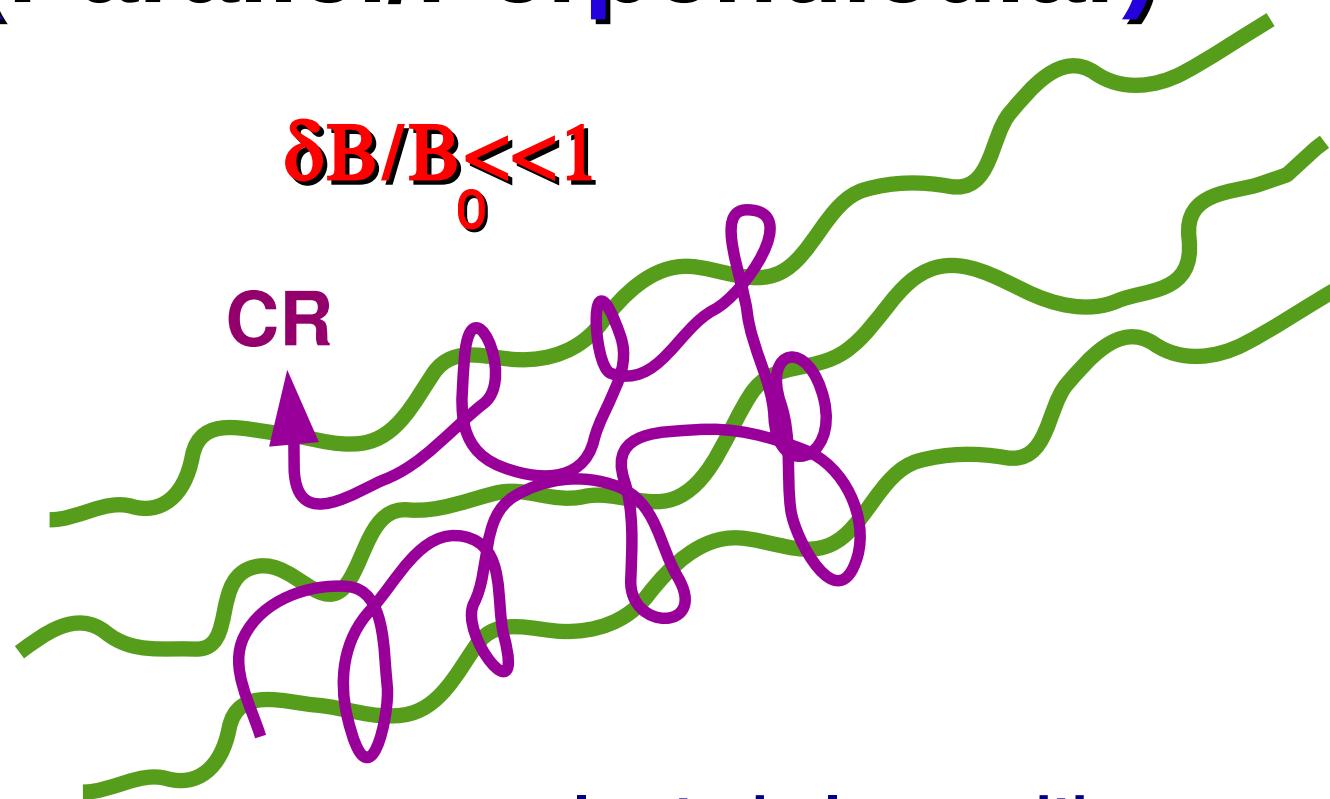


CR diffusion (Parallel/Perpendicular)

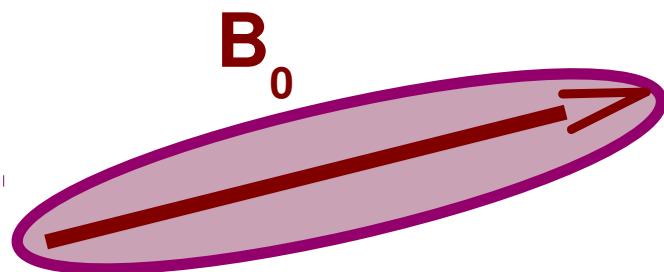
$\delta B = 0$



$\delta B/B_0 \ll 1$



Iso turbulence with power-law spectrum $\rightarrow D(E) \propto E^\delta$

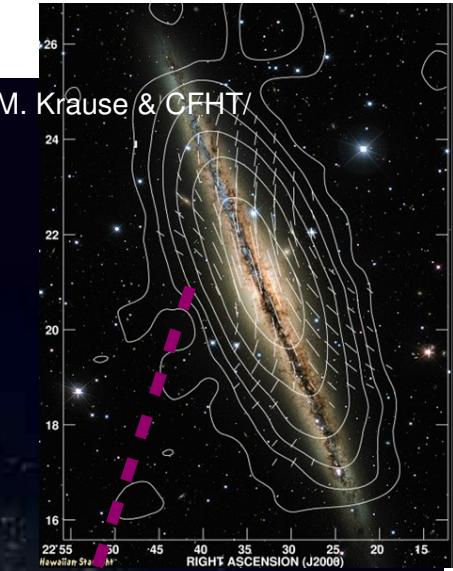


Increasing turbulence

$\delta B/B_0 \ll 1$

$\delta B/B_0 \gg 1$

MPIfR, M. Krause & CFHT/
Coelum



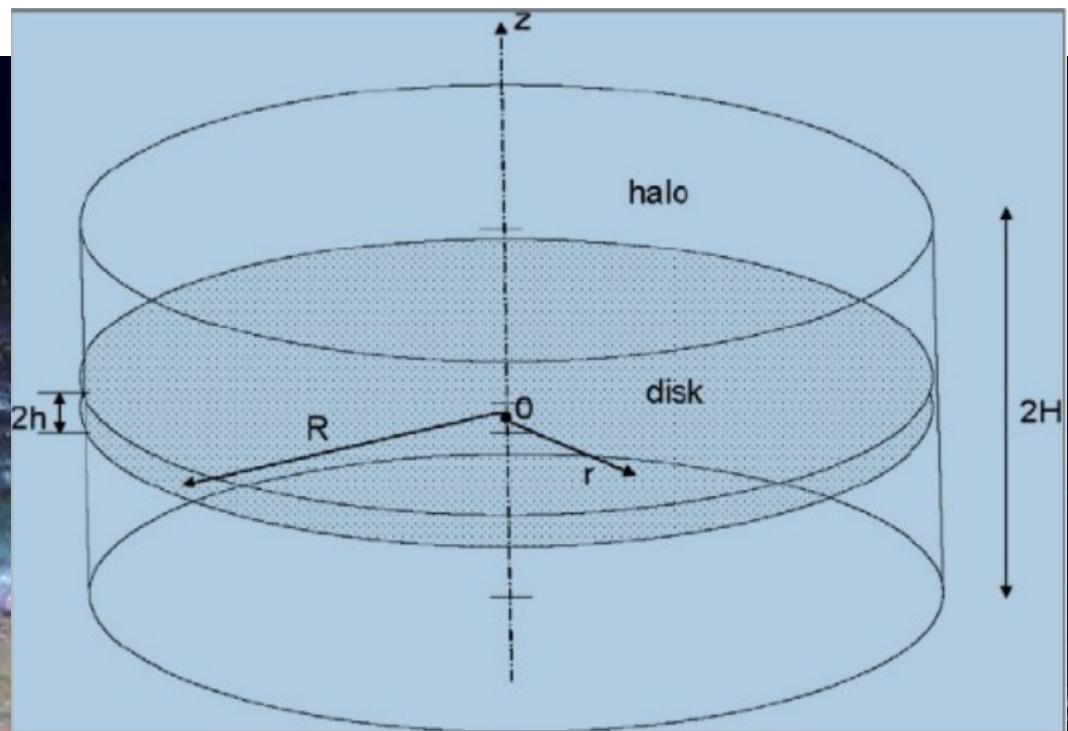
Larmor radius at 1 TeV:

~ a few 10^{-4} pc

ESA/Hubble & NASA

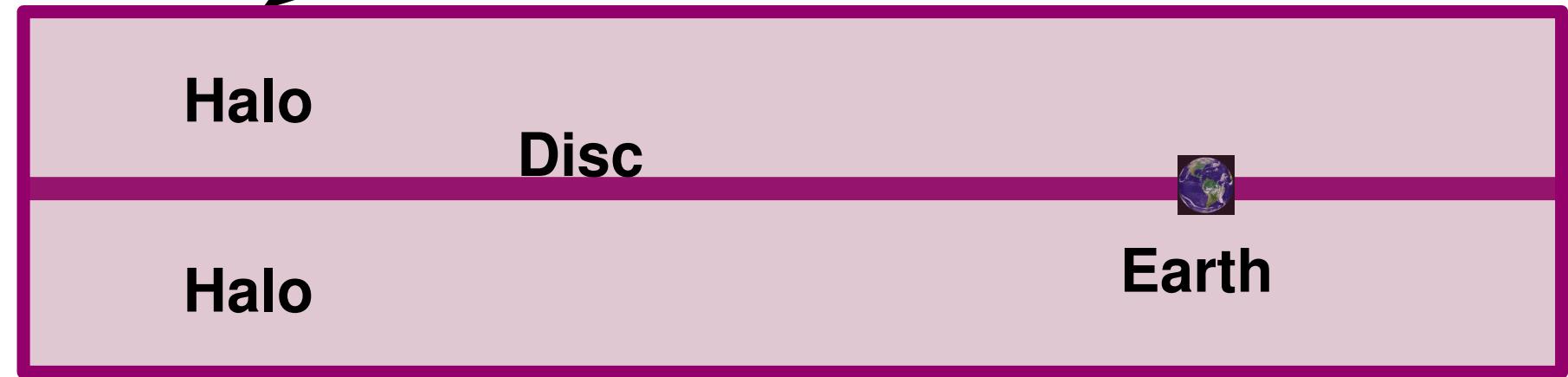


H ~ several kpc

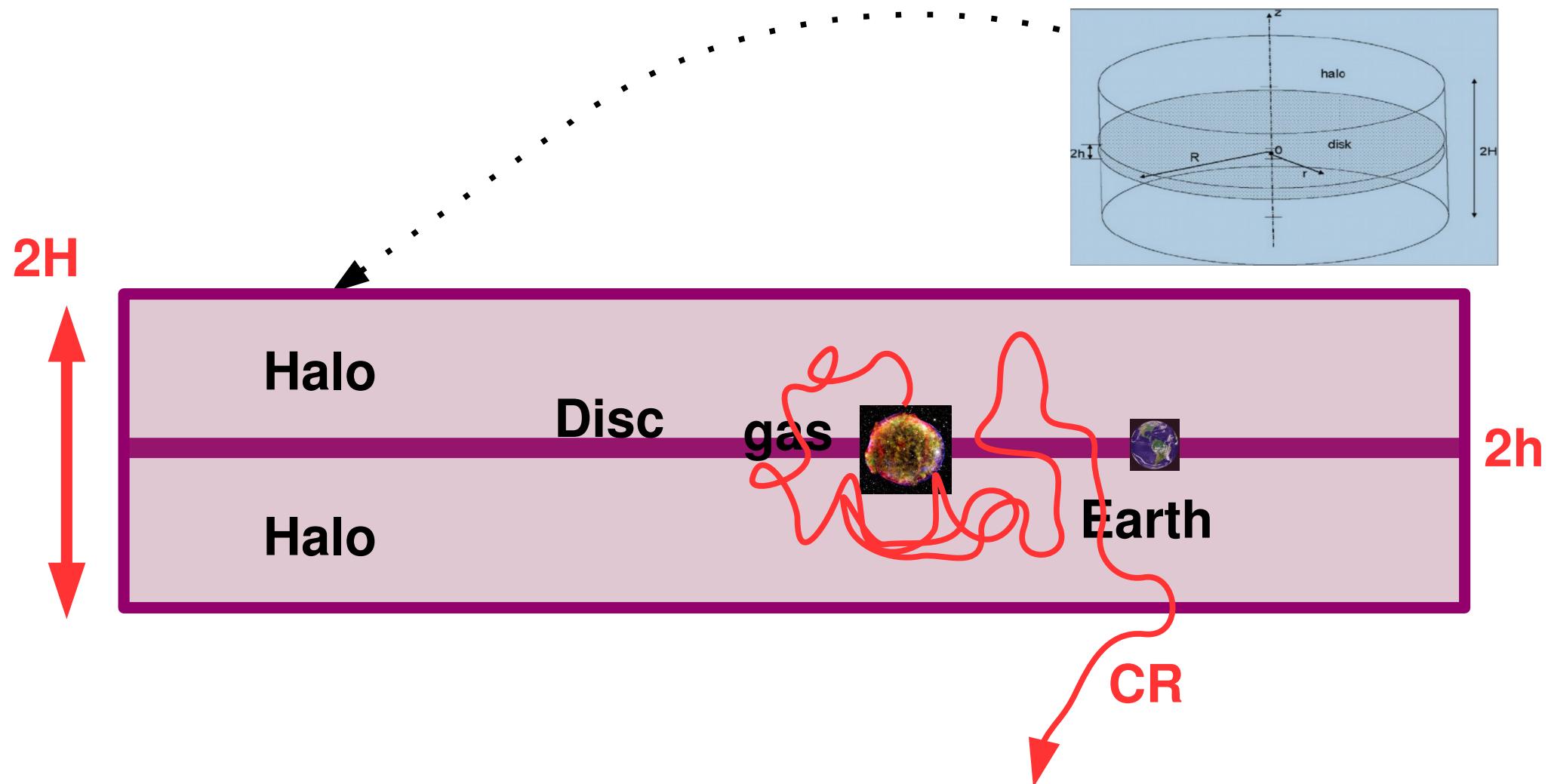


Simplified Milky Way seen edge-on :

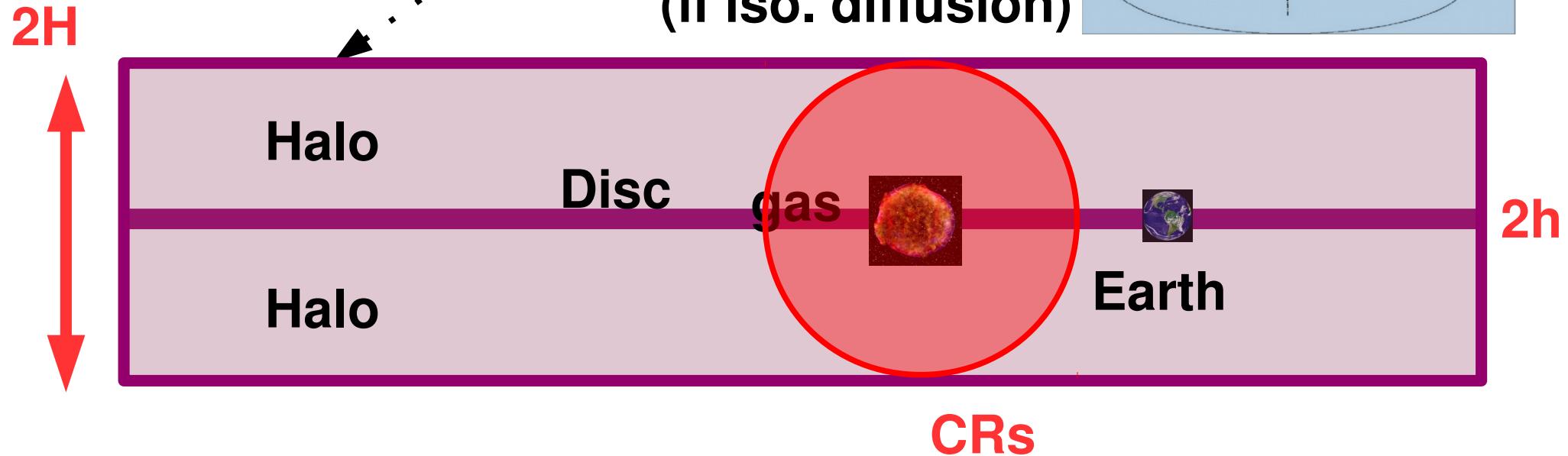
$2H$



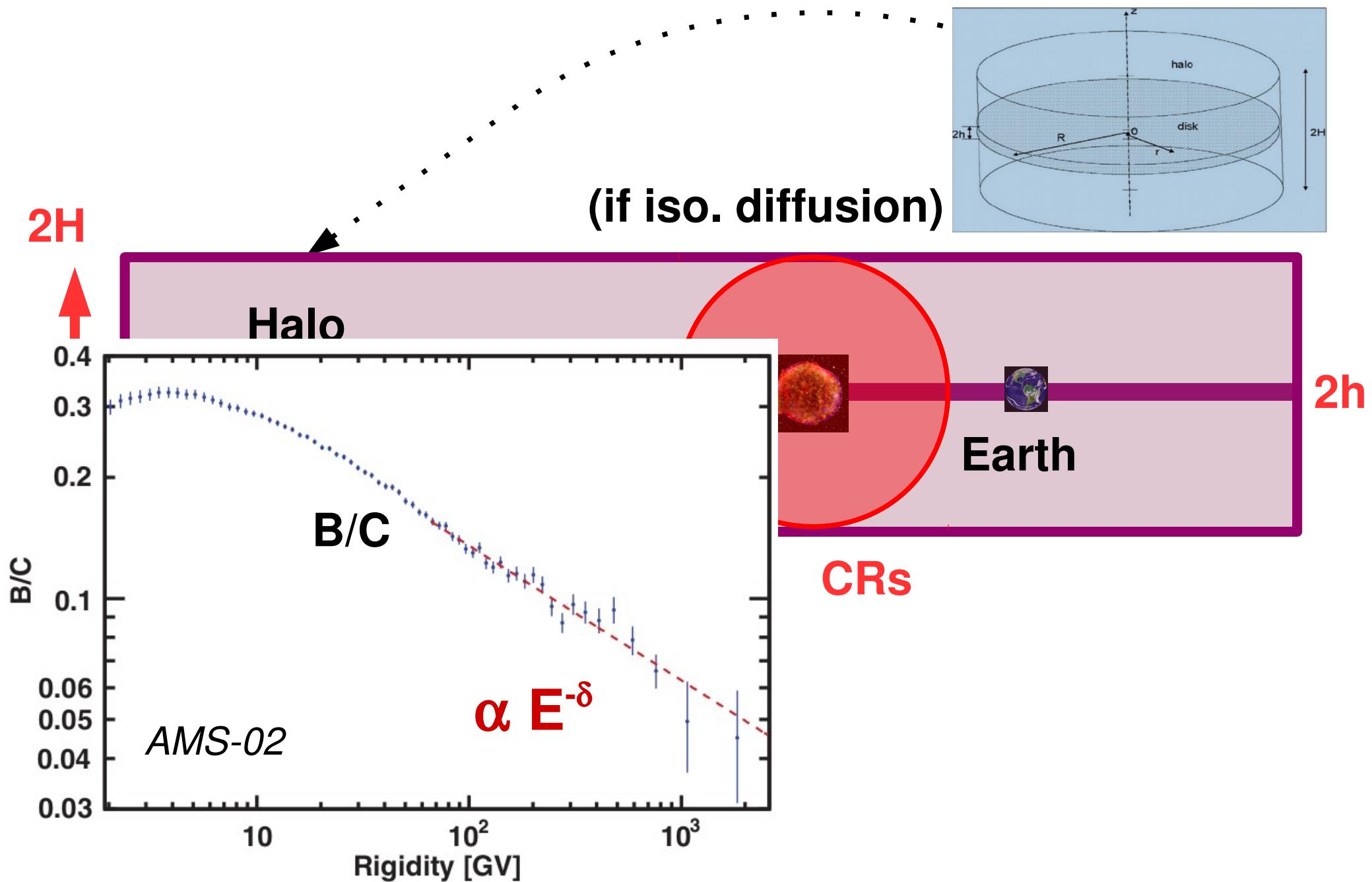
Simplified Milky Way seen edge-on :



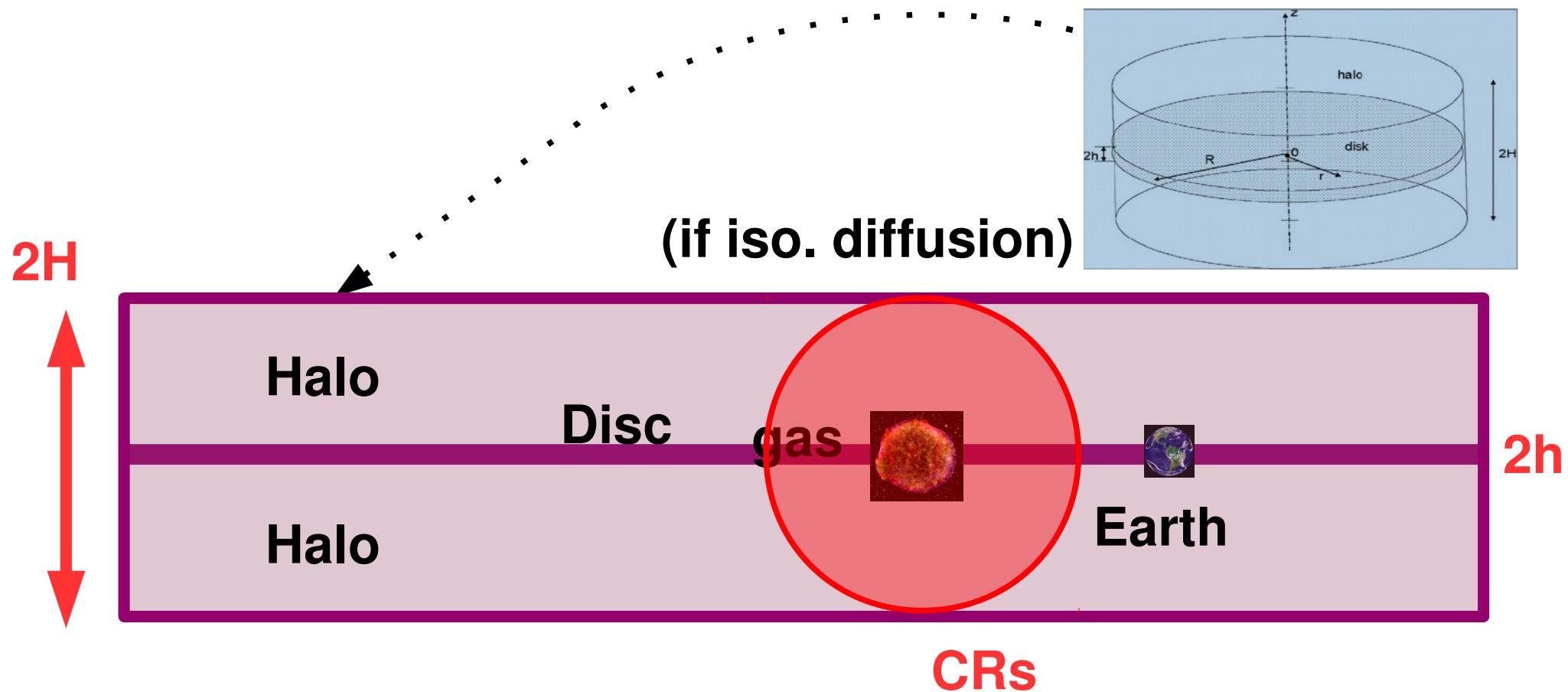
Simplified Milky Way seen edge-on :



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Simplified Milky Way seen edge-on :



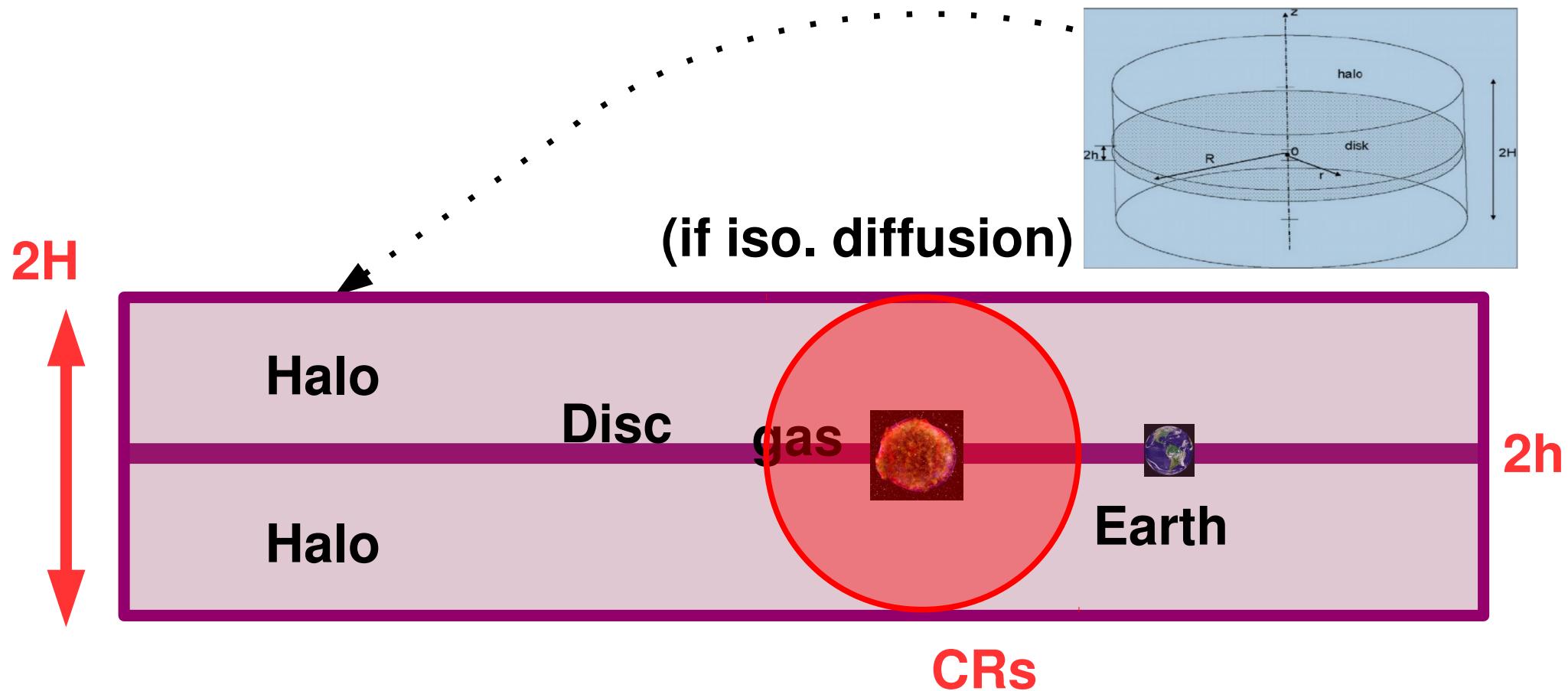
CR spectrum at sources: $\propto E^{-\beta}$

D: $\propto E^\delta$; B/C, conf. time: $\propto E^{-\delta}$

CR spectrum at Earth: $\propto E^{-\beta-\delta}$

("no wind" case)

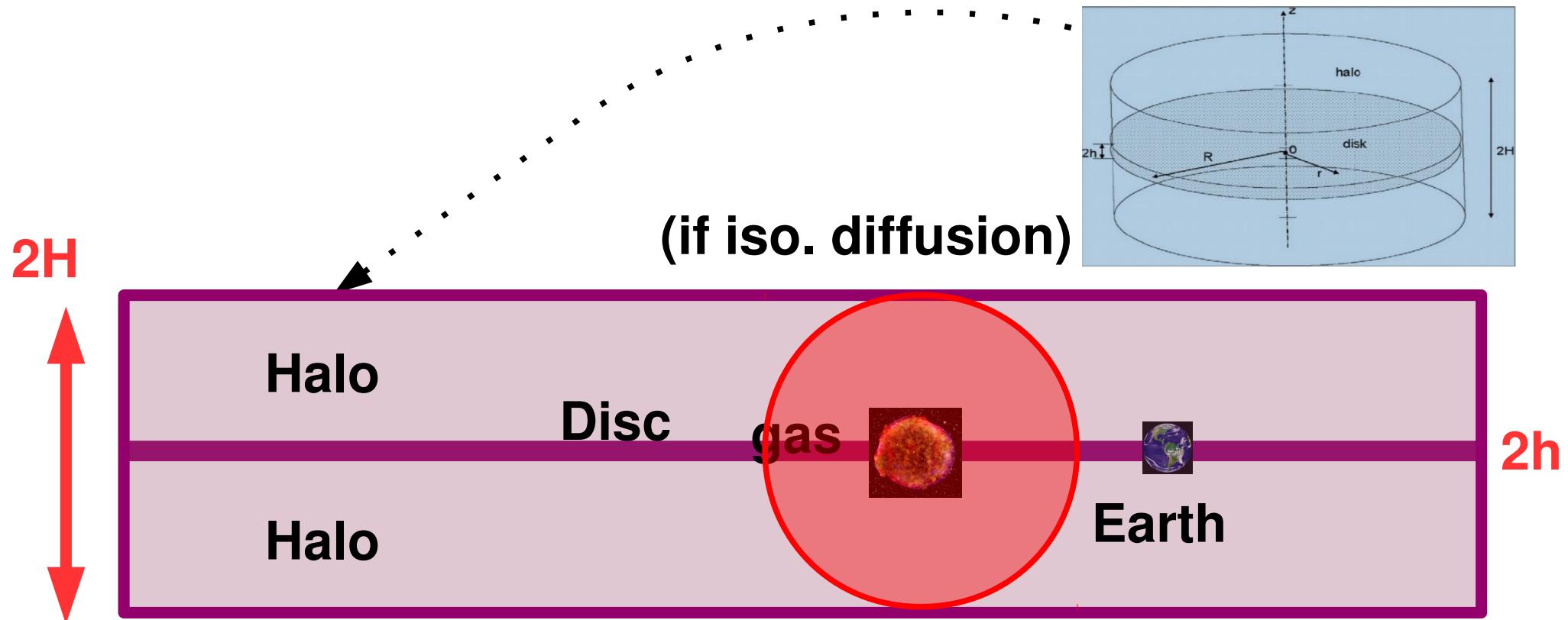
Simplified Milky Way seen edge-on :



Grammage : $X = c\rho h H / D_z$ ~ several g/cm² at GeV

D ~ 10^{28} cm²/s at GeV for H ~ several kpc

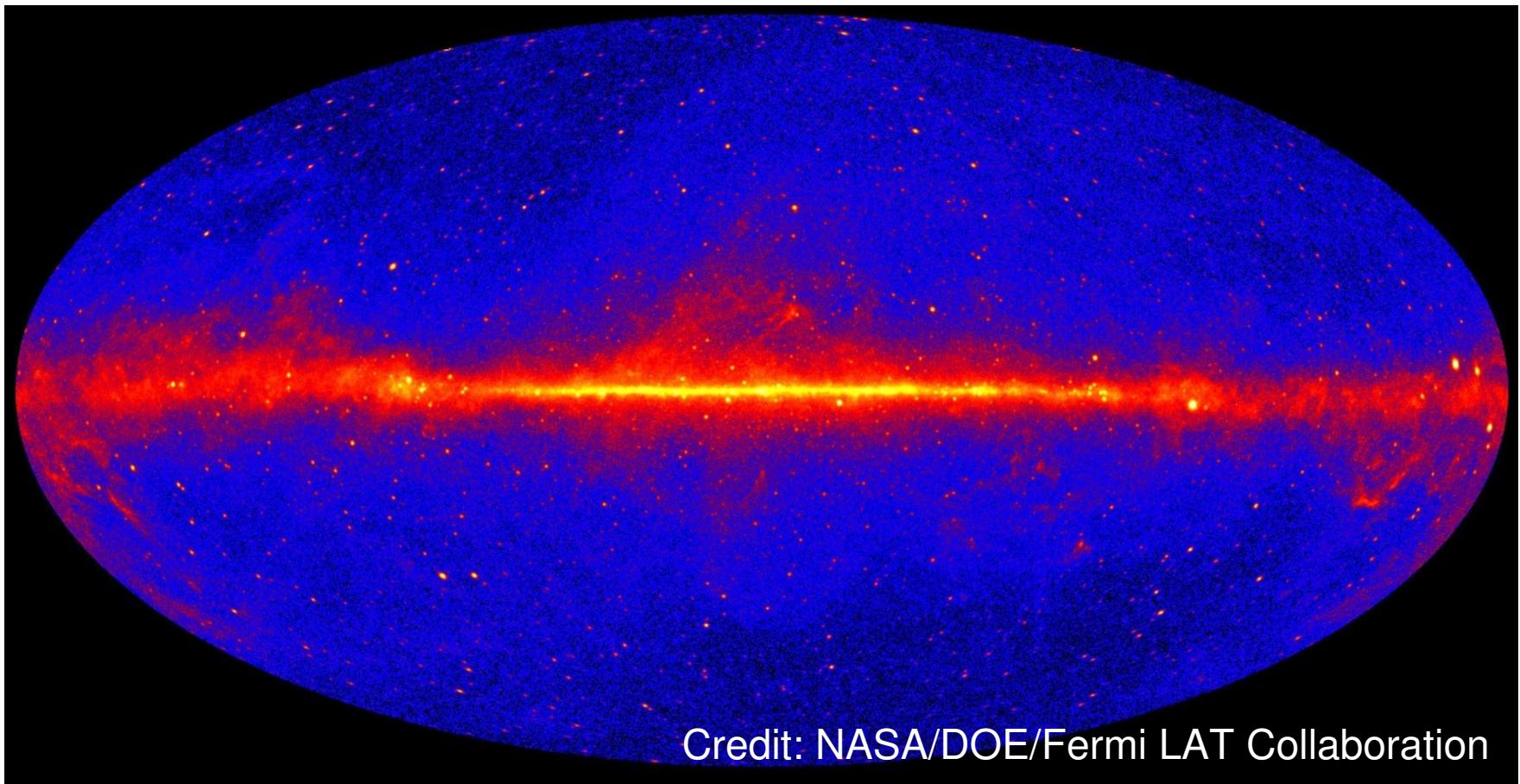
Simplified Milky Way seen edge-on :



CR propagation codes (GALPROP, DRAGON, ...) :

$$\begin{aligned}
 \frac{\partial \psi(\vec{r}, p, t)}{\partial t} &= q(\vec{r}, p, t) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) \\
 \text{CRs} \quad &+ \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi
 \end{aligned}$$

Fermi, 2008 – 2017 :



Point sources + Neutral pion + Inverse Compton + Bremsstrahlung + iso bkg + FBs + ...

Diffuse emission :

- Constrains models,
 - Globally in agreement with B/C, & SNR paradigm in terms of injected CR power... (γ -rays from nearby galaxies too)
- & radioactive nuclei & synchrotron ...

CRs versus Galactocentric radius :

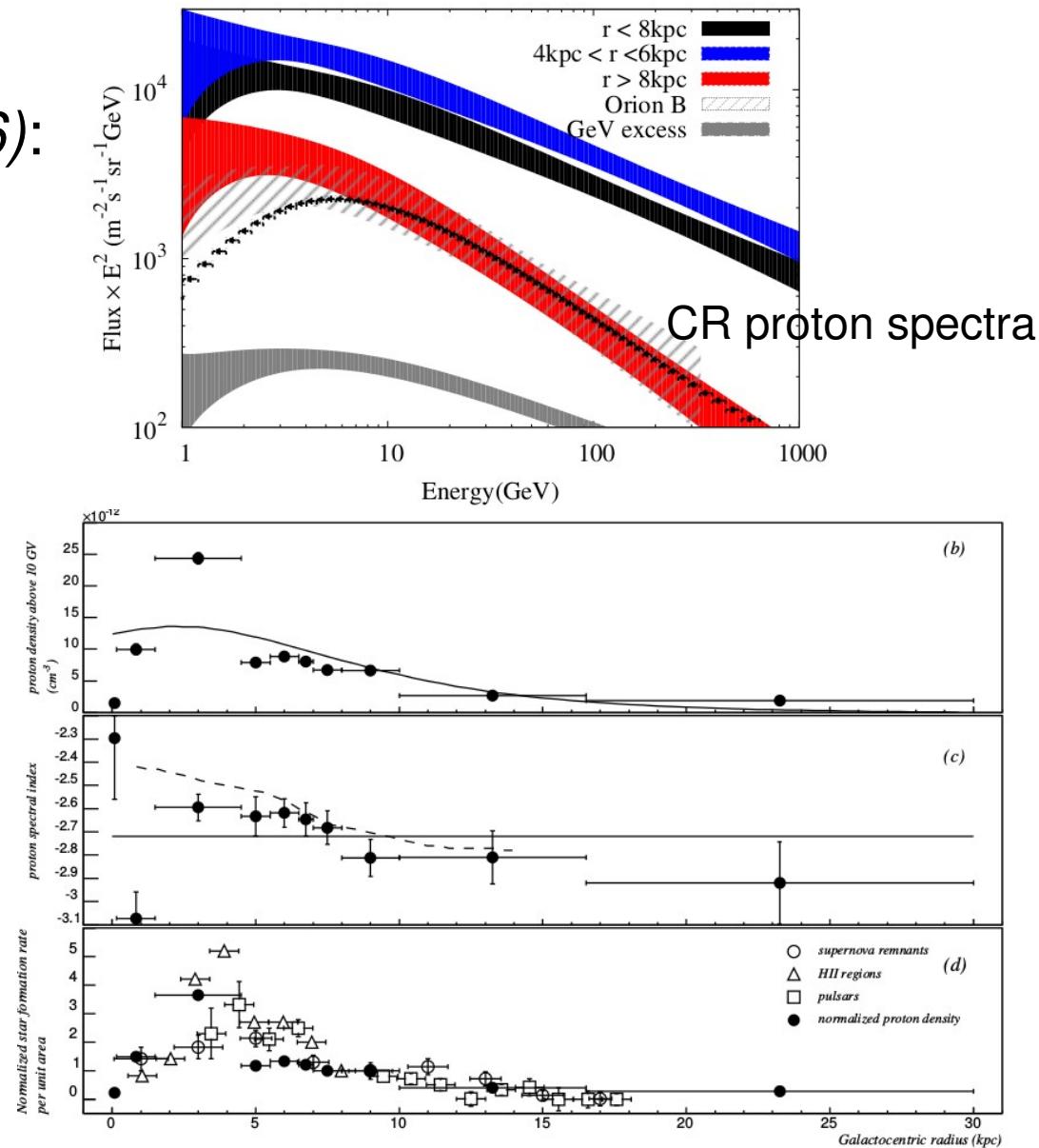
→ Yang, Aharonian & Evoli (2016):

(Fermi-LAT diffuse emission in GP)

→ Acero et al. (2016):

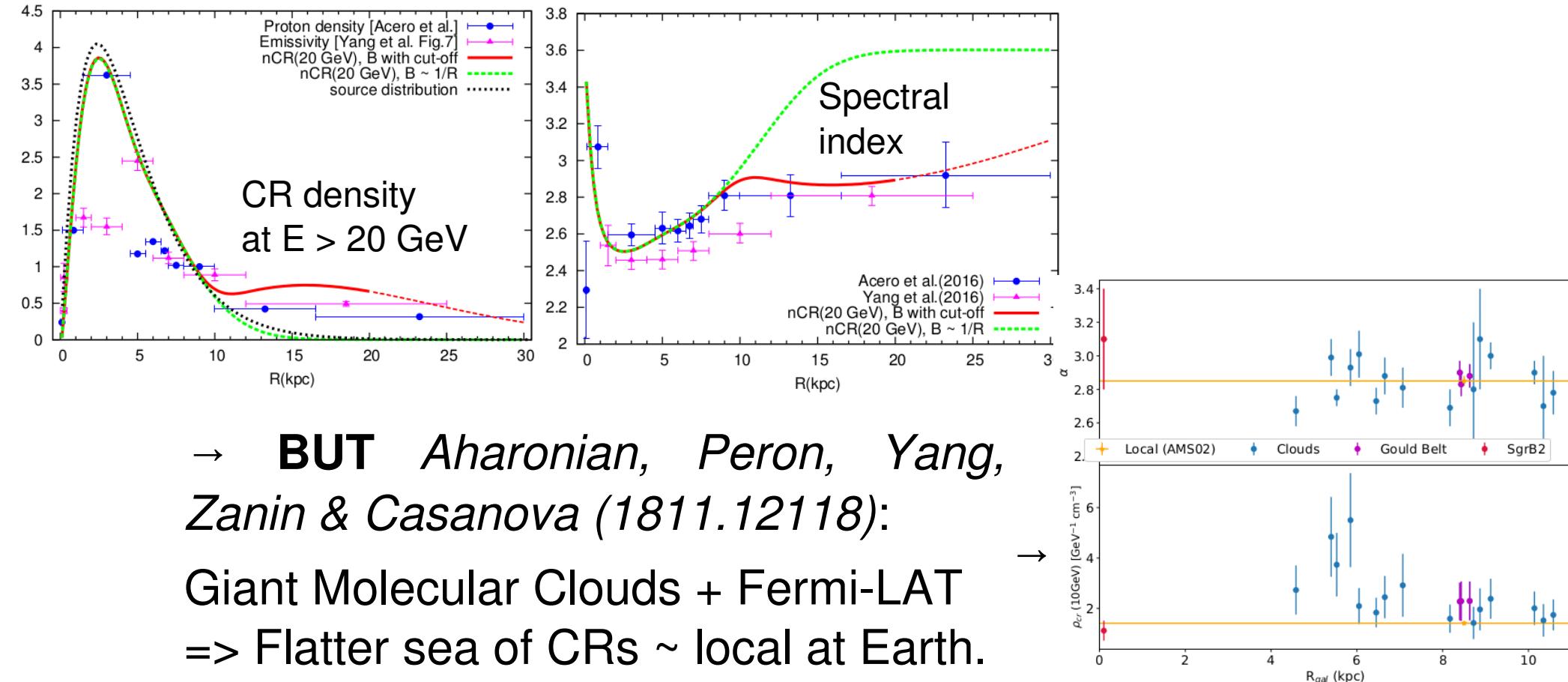
* CR proton density decreases with Galactocentric distance beyond 5kpc from the GC.

* Also suggest a softening of the proton spectrum with Galactocentric distance.



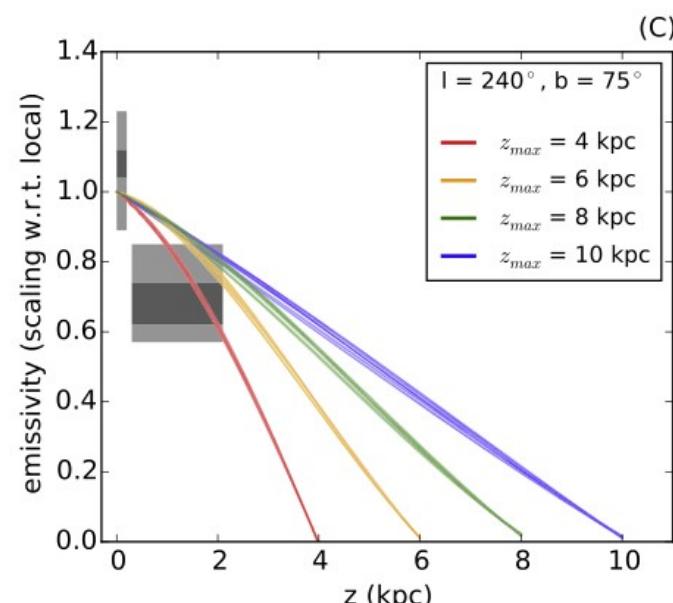
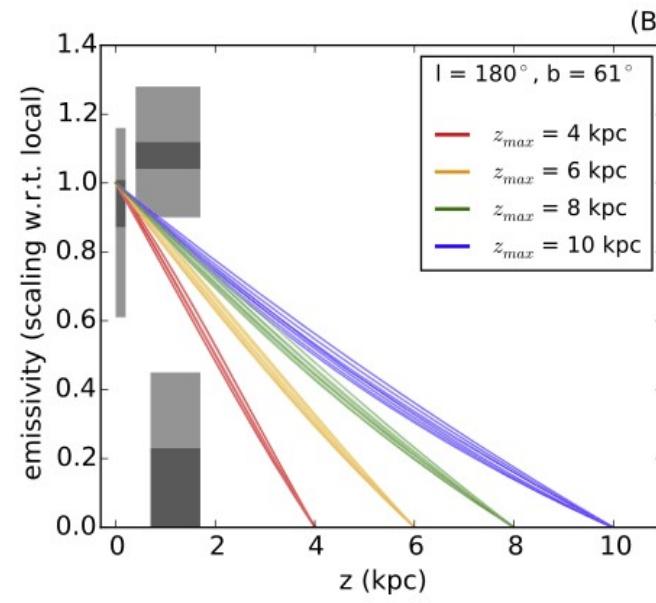
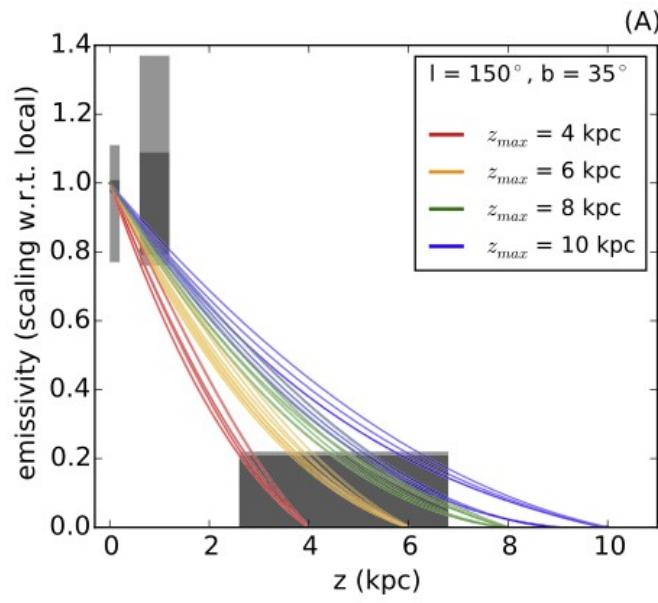
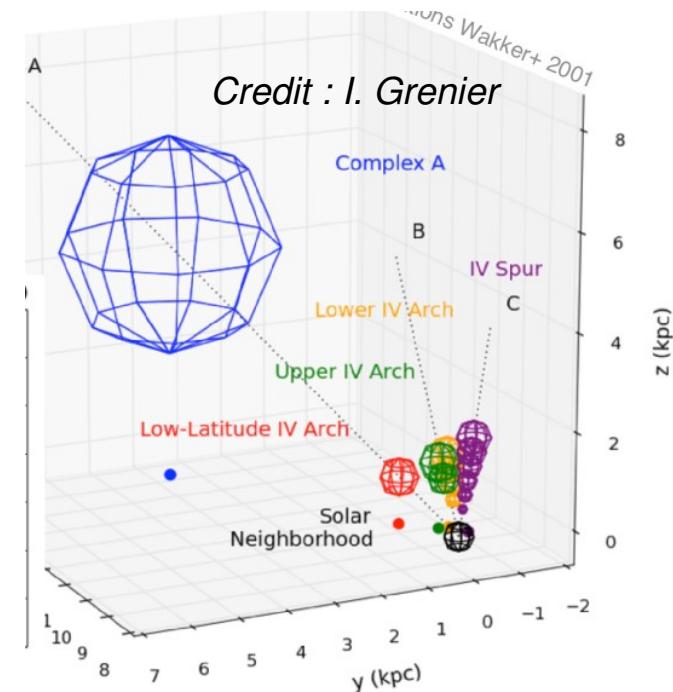
=> Challenge for standard CR propagation models w/ uniform diffusion coefficient within the Galaxy !

- *Evoli + (2012)*: Solution for density profile → Anisotropic diffusion.
 - DRAGON code papers : Solution for index → $D(E,R) \propto E^{-\beta(R)}$.
 - *Recchia, Blasi & Morlino (2016)*: Model of **non-linear CR propagation** (transport is due to CR scattering & advection off self-generated turbulence).
- => Radial distribution of CRs & softening of spectral index reproduced :



CRs in the Galactic halo :

→ *Tibaldo et al. (2015)* : Fermi-LAT observations (300 MeV-10 GeV) of high-/intermediate-velocity clouds in the halo.



Insights from Imaging Atmospheric Cherenkov Telescopes (IACTs)

MAGIC



H.E.S.S.



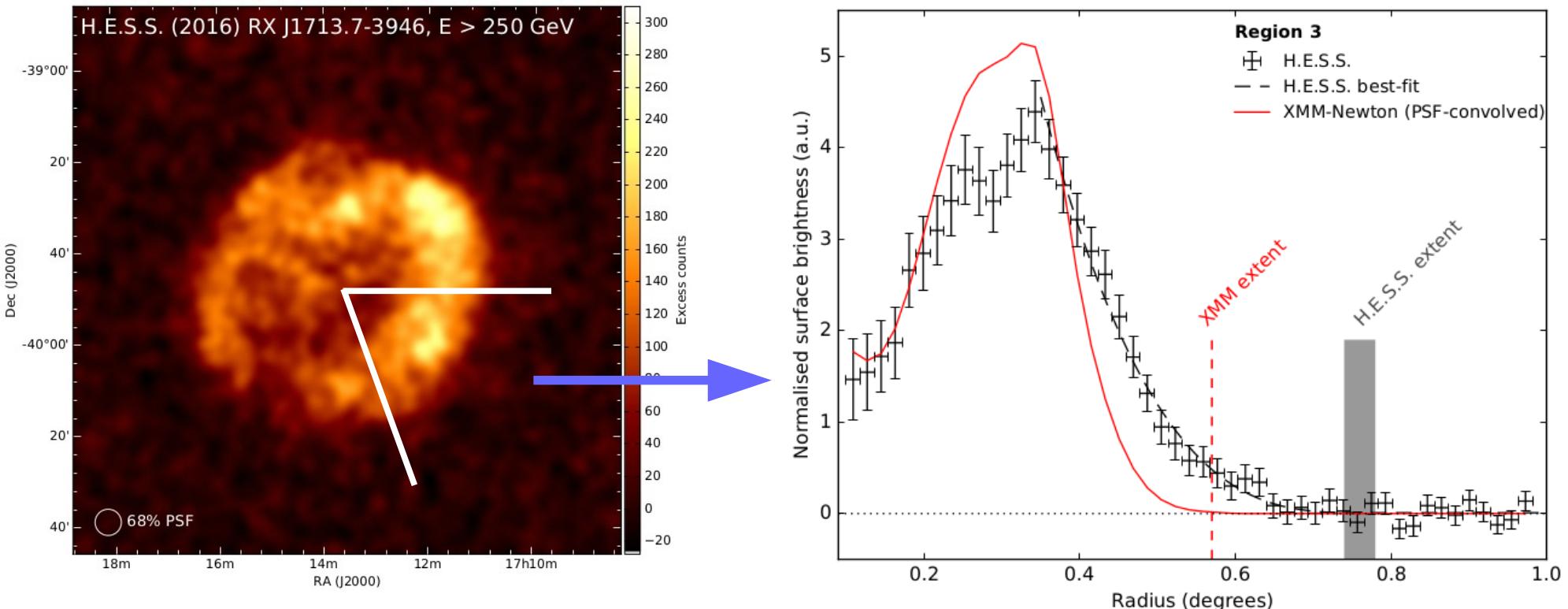
(Image credits: the collaborations)

VERITAS



~ TeV emission outside SNRs :

→ RX J1713.7–3946: CRs (p/e⁻?) escaping their accelerator?

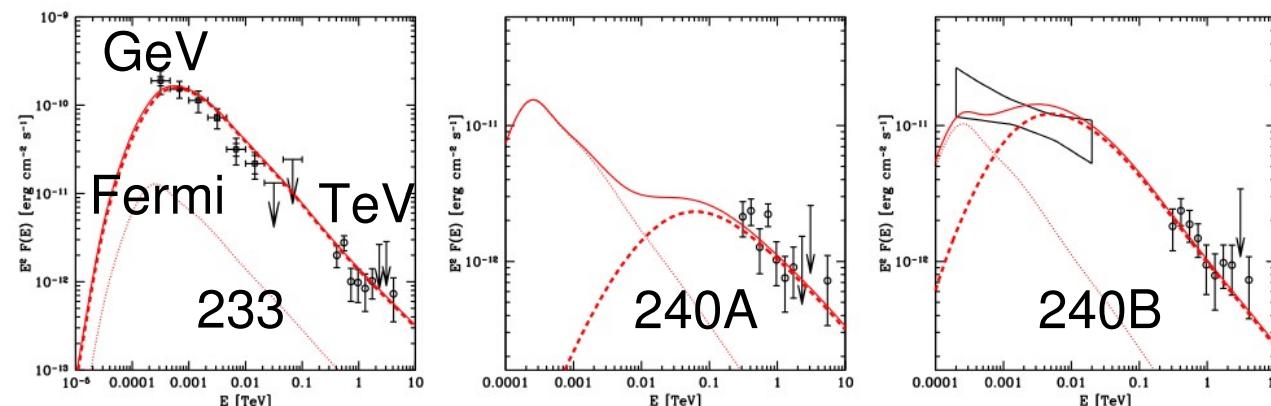
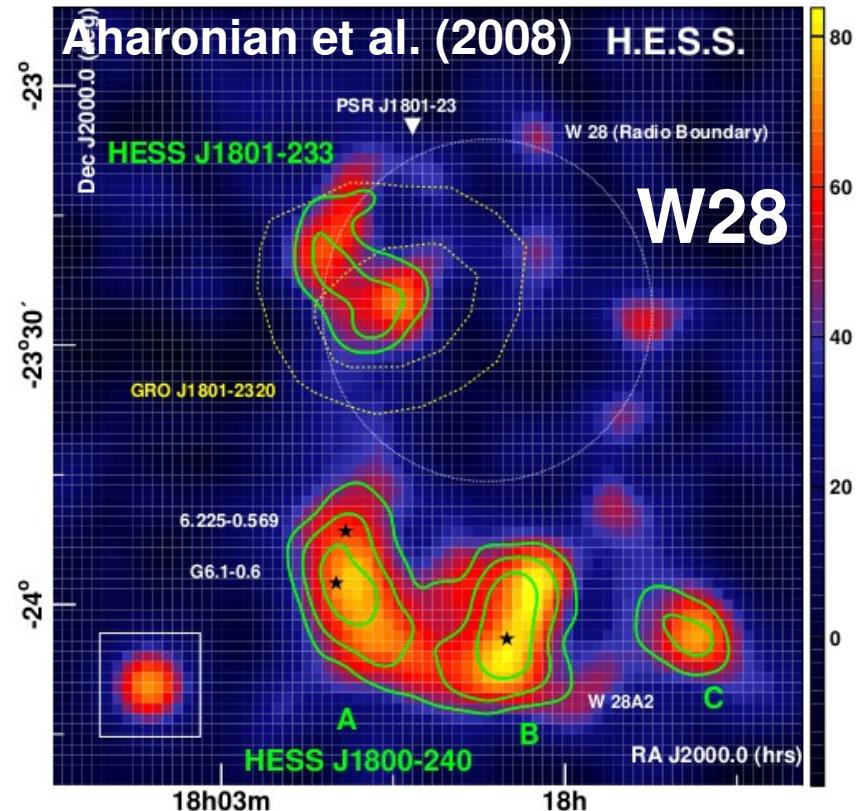


H.E.S.S. Coll., A&A, 612, A6 (2018)

TeV beyond the keV shell ! X-ray extent (close to shock) vs more extended γ -rays (escaped or precursor ?)

~ TeV emission outside SNRs :

- Emission from neighbouring **molecular clouds** (W28, W51C, W44):
- *Gabici, Casanova, Aharonian & Rowell, in Proc. SF2A 2010* :
- * Assuming **isotropic diffusion** :
γ-ray observations explained only if the CR diffusion coefficient in the region surrounding the SNR is **significantly suppressed with respect to the average Galactic one (6%)**.

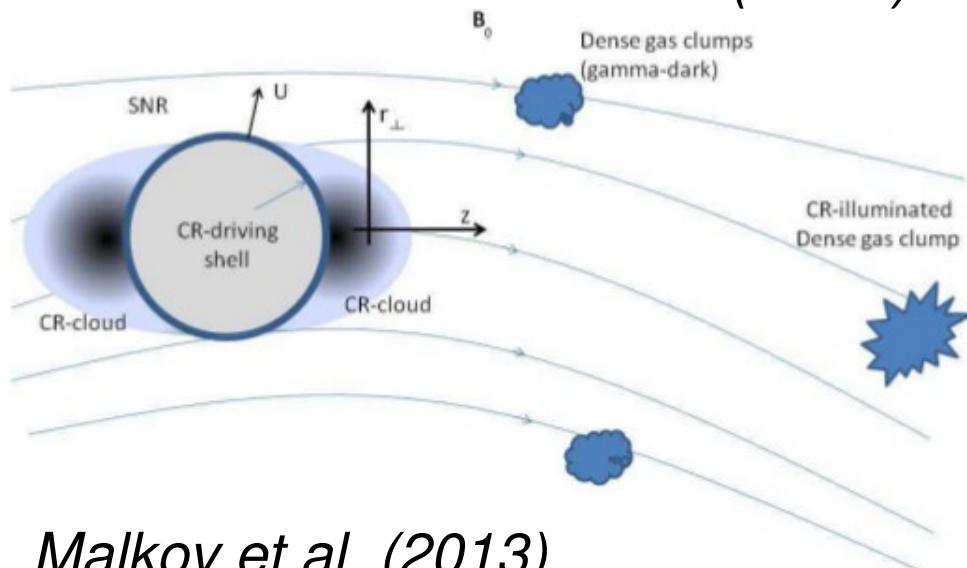


Gabici et al. (2010)

→ **Several other observations:**

- * Ackermann *et al.*, *Science* (2011) : **Low-diffusion** region in the Cygnus superbubble (Fermi-LAT).
 - * Aharonian *et al.*, *Nat. Astron.* (2019) : **Reduced diff. coeff. (1 – 2 orders of magnitude)** inferred from the radial profile of γ -ray emission around a few Galactic clusters (Fermi-LAT & HESS)
- *Gabici et al. (2010)* : Due to **CR-driven instabilities ?**

See *Ptuskin, Zirakashvili, Plesser (2008); Malkov, Diamond, Sagdeev, Aharonian & Moskalenko (2013)* :



Escaping CRs excite Alfvén waves →
Slow down their own propagation

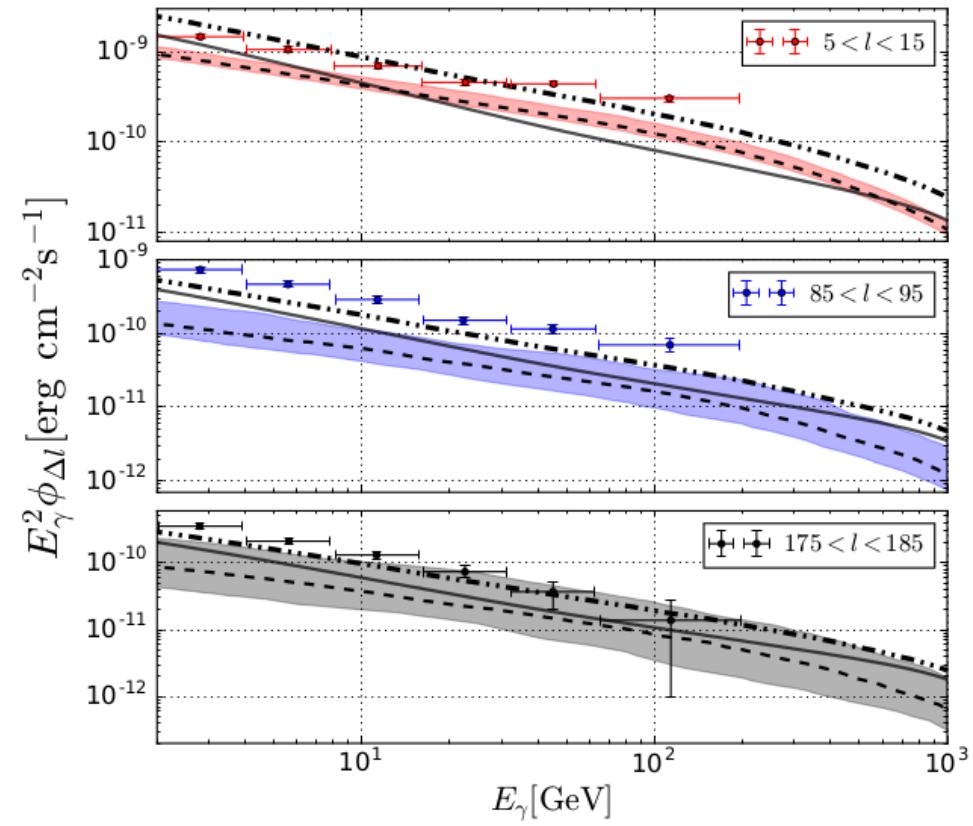
Malkov *et al.* (2013)

→ Recent works :

- * *D'Angelo + (2016)*: CR grammage around sources may be **non-negligible**.
- * *Nava + (2016)*: Presence of neutrals (=> damping), **Impact on γ -rays from MCs**.
- * *Nava + (2019)*: Fully ionized – Negligible grammage accumulated.

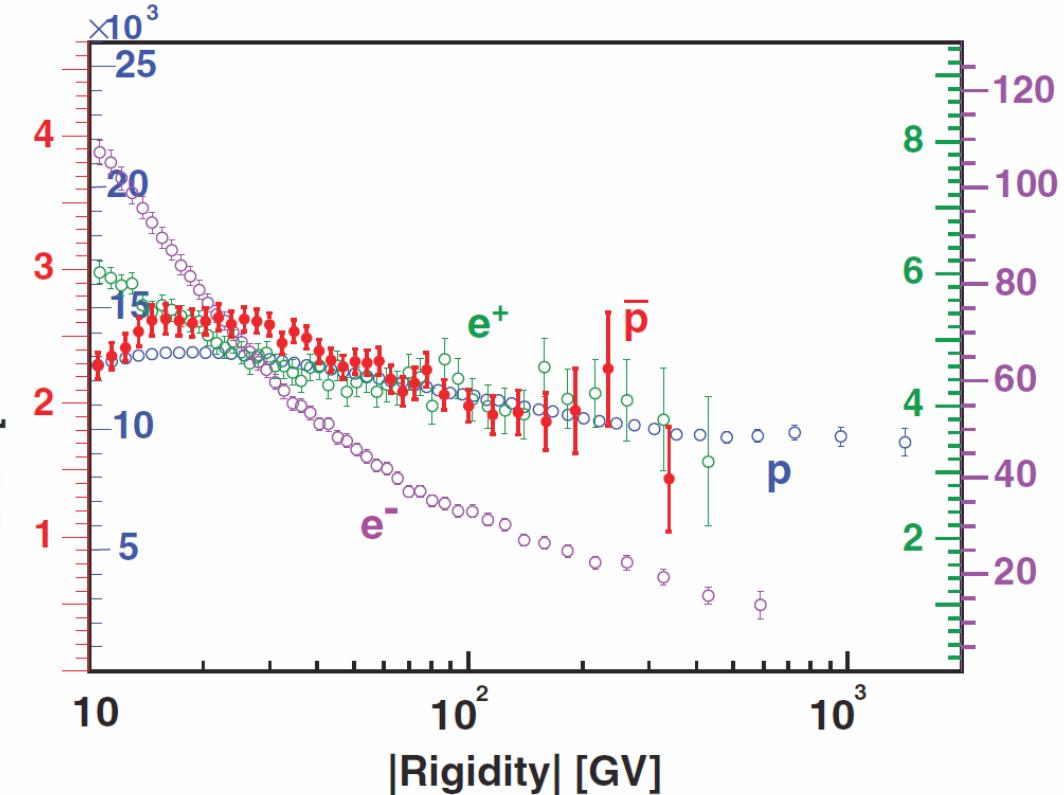
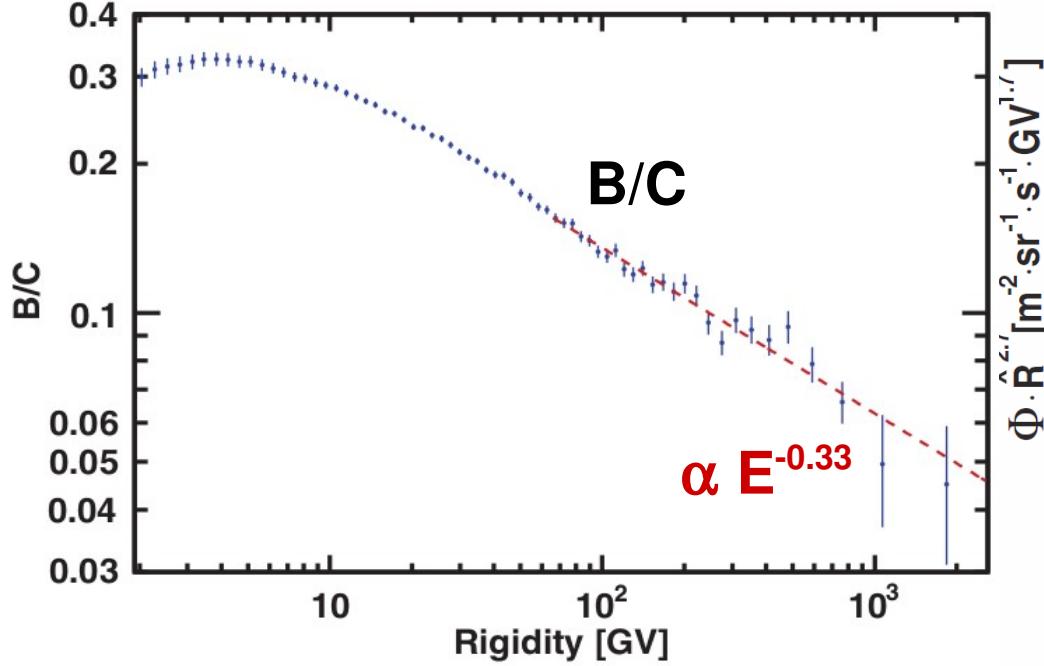
→ *D'Angelo + (2018)* :
Diffuse γ -ray emission from self-conf
CRs around Galactic sources (poss.
substantial).

γ -rays may **help solve CR transport**.



CR self-confinement around sources & CR fluxes at Earth ?

- B/C ratio suggests energy-dependent escape of CRs from the Galaxy... BUT (e.g. Lipari 2017):
 - (1) spectra of p, pbar, and e⁺ have similar slopes, contrary to standard expectations;
 - (2) ratio of fluxes of e⁺ and pbar is ~ the ratio of their production cross sections.



CR self-confinement around sources & CR fluxes at Earth ?

- B/C ratio suggests energy-dependent escape of CRs from the Galaxy... **BUT (e.g. Lipari 2017):**
 - (1) spectra of p , $p\bar{}$, and e^+ have similar slopes, contrary to standard expectations;
 - (2) ratio of fluxes of e^+ and $p\bar{}$ is \sim the ratio of their production cross sections.

Possible solution ? : Model of *Cowsik et al. (2016)*, where :

- (i) CRs accumulate an E-dependent grammage around their sources, rather than on Galactic scales.
- (ii) > 100 GeV CRs escape the source regions quickly and accumulate grammage in the Galaxy in an E-independent manner.

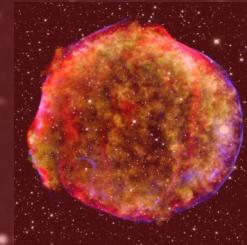
=> Potential links with **CR self-confinement close to CR sources. (?)**

But is CR diffusion (ever) isotropic ?

ISOTROPIC
DIFFUSION?

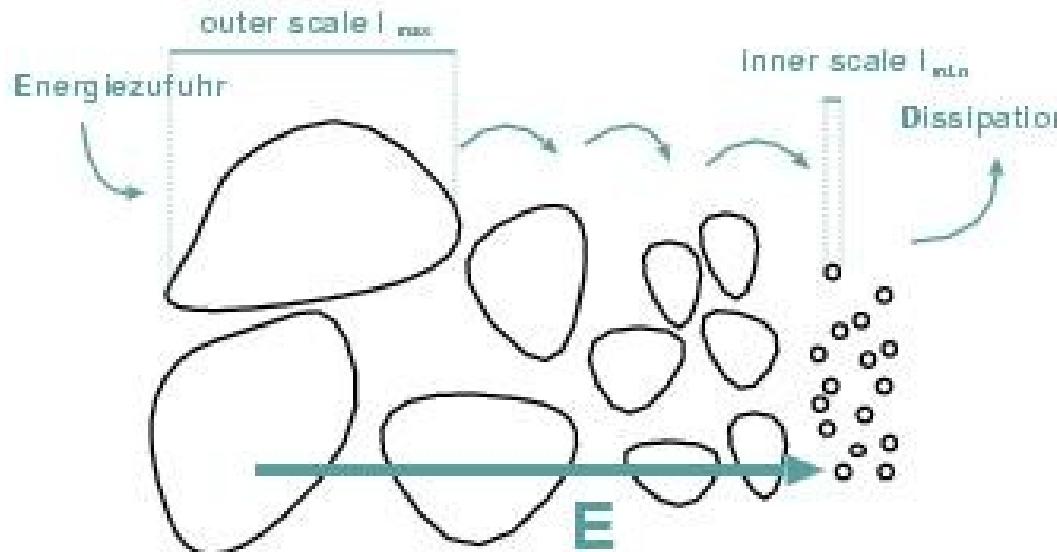
γ -ray emission

CR $p^+, e^{-/+} \rightarrow \gamma$



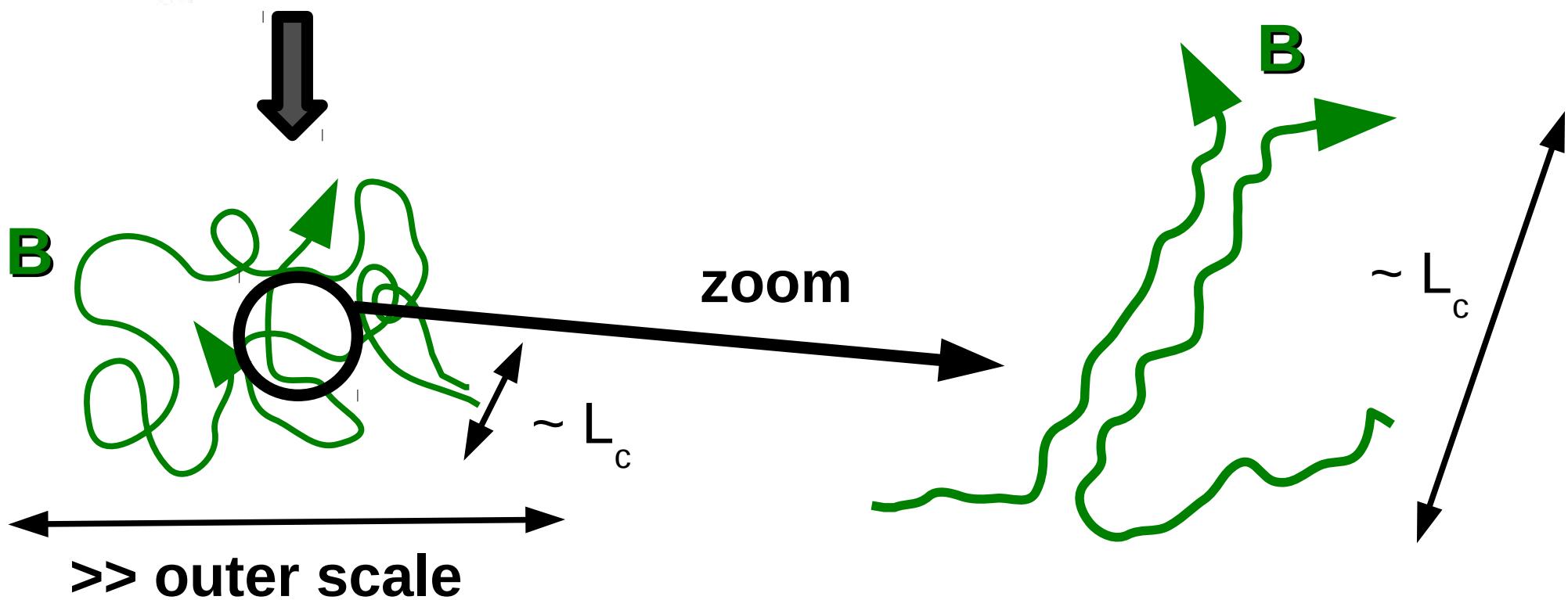
CR source
(e.g. SNR, pulsar)

But is CR diffusion (ever) isotropic ?

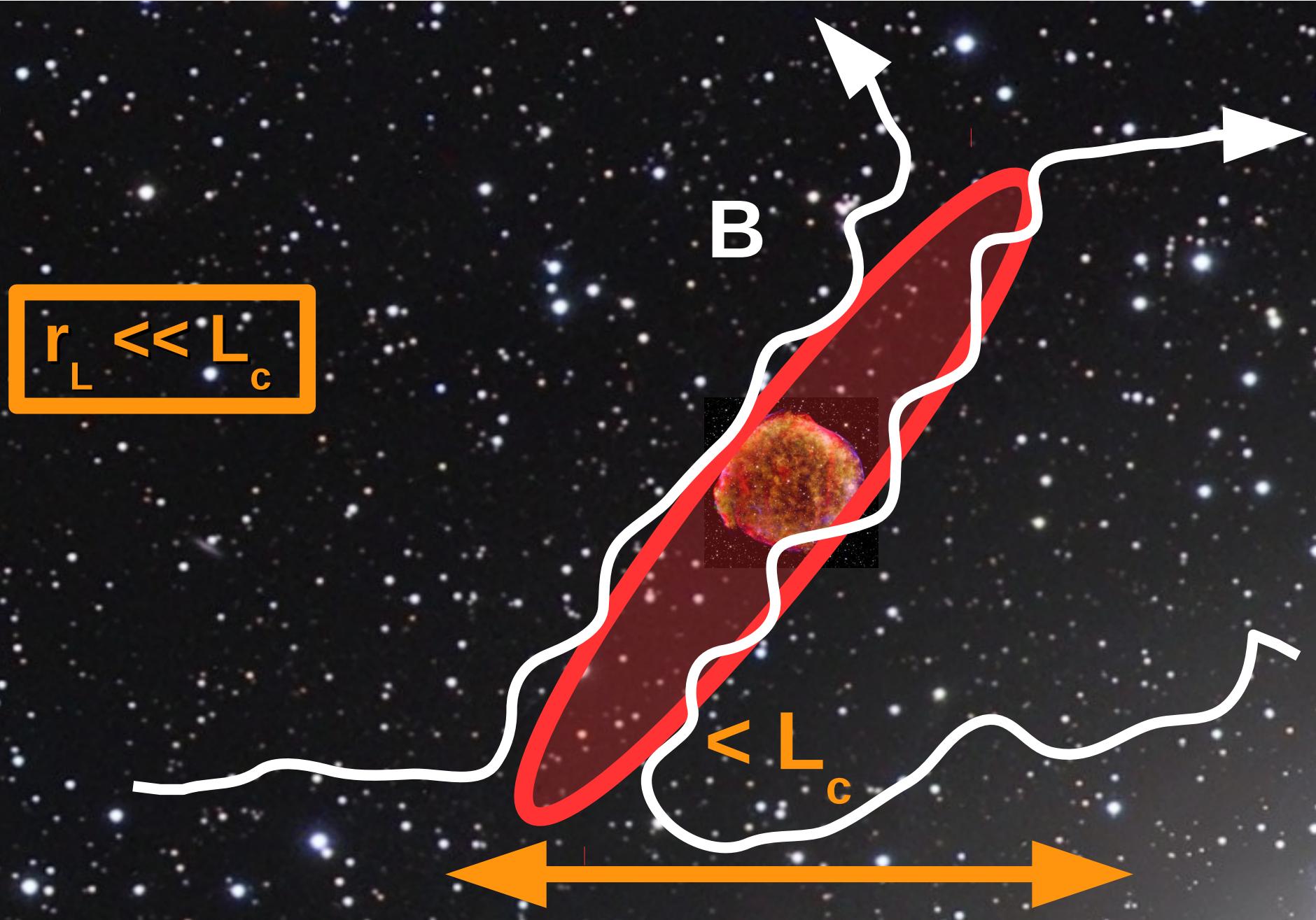


From <http://www.lsw.uni-heidelberg.de/users/sbrinkma/thesis/node5.html>

$$r_L \ll L_c$$



But is CR diffusion (ever) isotropic ?



But is CR diffusion (ever) isotropic ?

$$r_L \ll L_c$$



Anisotropic diff. in *isotropic* turbulence

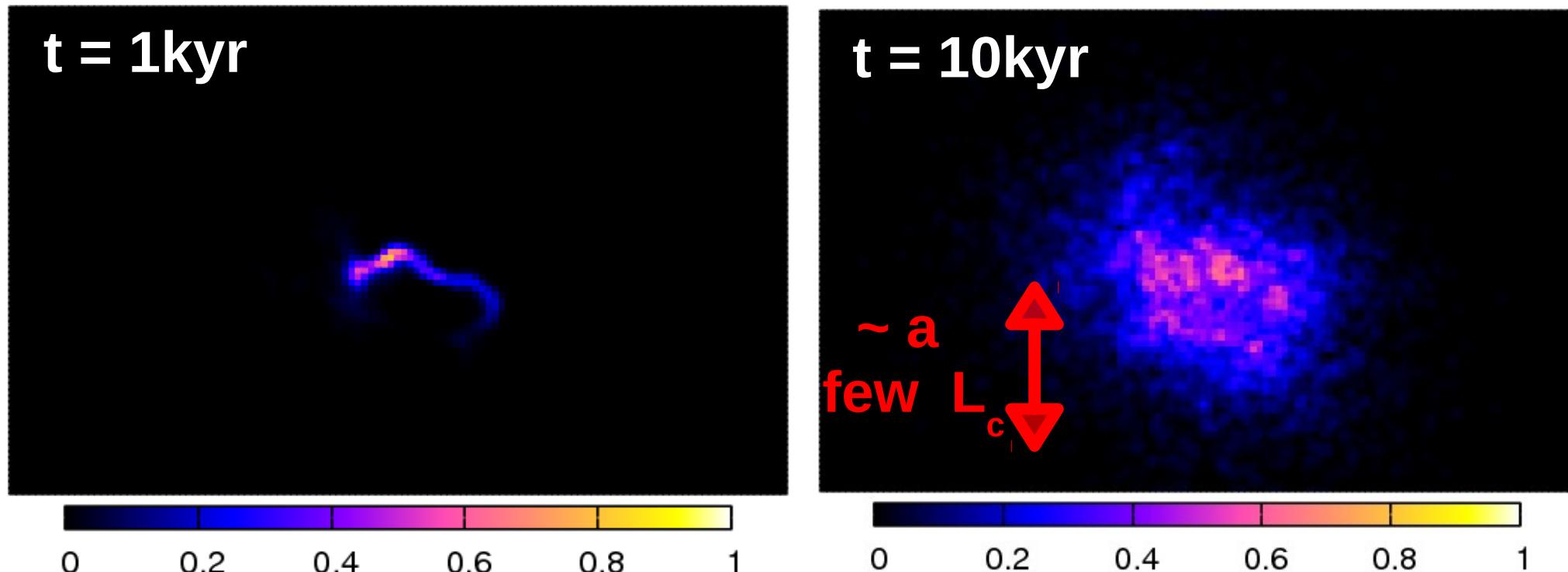
PRL 108, 261101 (2012)

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} + GG et al. (2013)

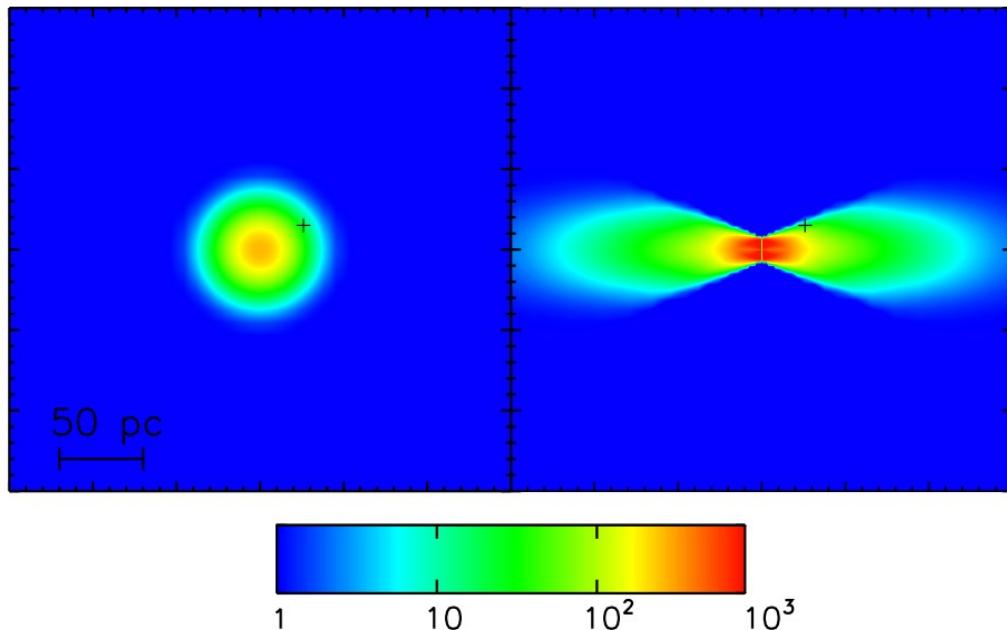


Individual (1PeV) CR propagated in 3D synthetic
Kolmogorov turbulence ($L_{\max} = 150$ pc, Plot size : 400 pc)

=> Expect intrinsically ASYMMETRIC emissions too!

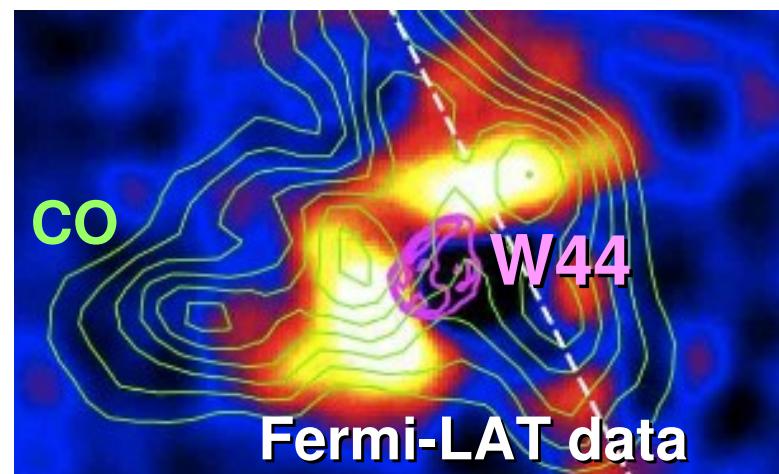
→ Nava & Gabici (2013) :

Estimates of the D from γ -ray observations strongly depend on the assumptions made on the isotropy, or anisotropy, of diffusion.



→ Malkov et al. (2013) : May be visible around W44 :

Uchiyama et al. (2012) →



Insights from a gamma-ray air shower array, HAWC



HAWC Collaboration

HAWC observ. of Geminga & Monogem



The Moon (same scale)

- Emission: inverse Compton from ~ 100 TeV electrons.
- γ -ray range: 8 – 40 TeV.

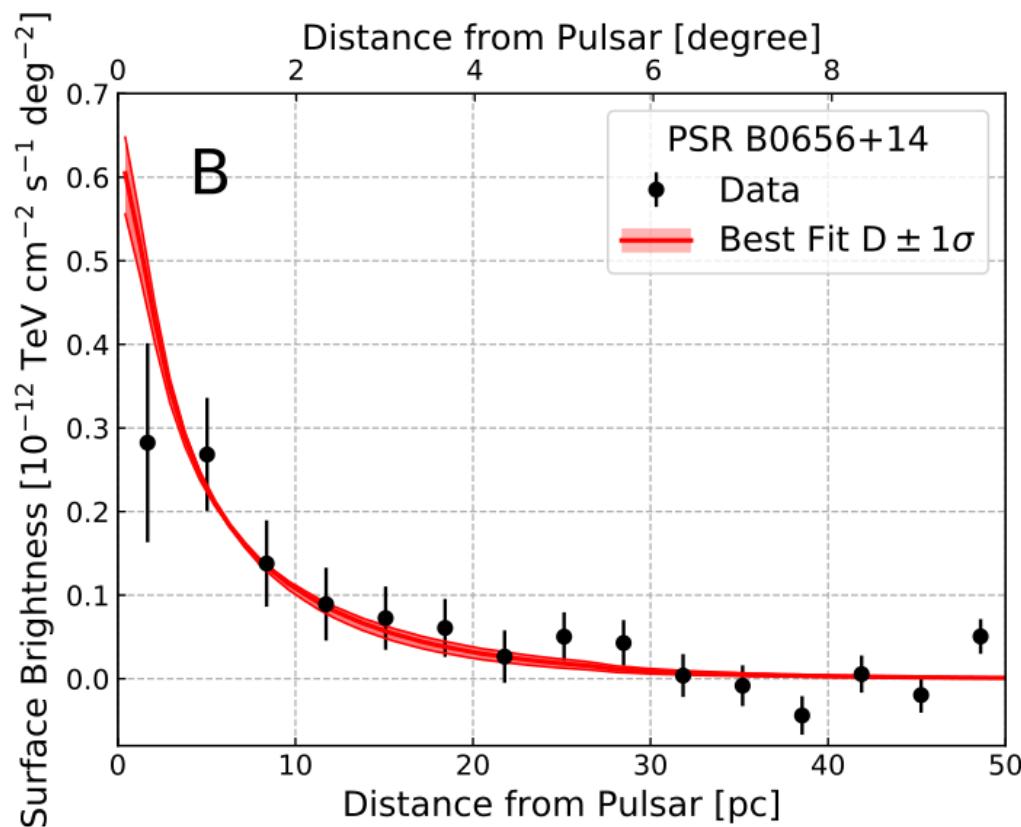
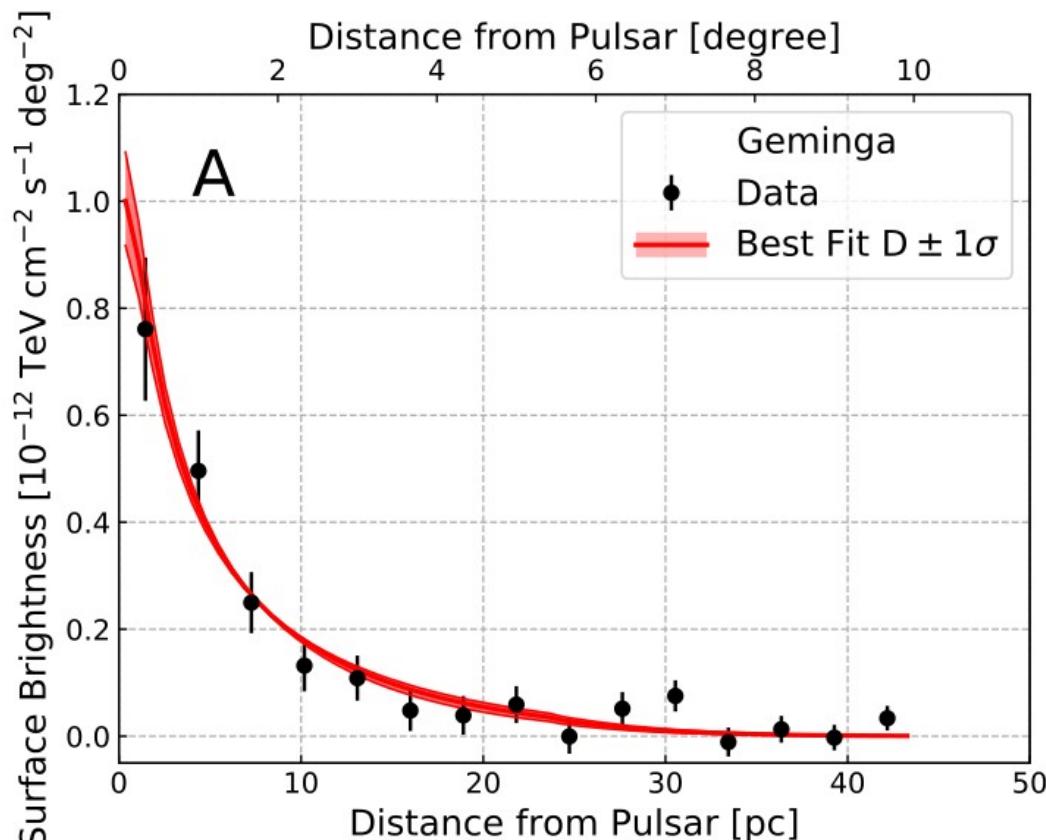
PSR B0656+14

Geminga

'HALOS': e^- E density \ll E density ISM
=> e^- outside PWN.
NOT THE CASE FOR MOST
EXTENDED TeV-BRIGHT PWNe



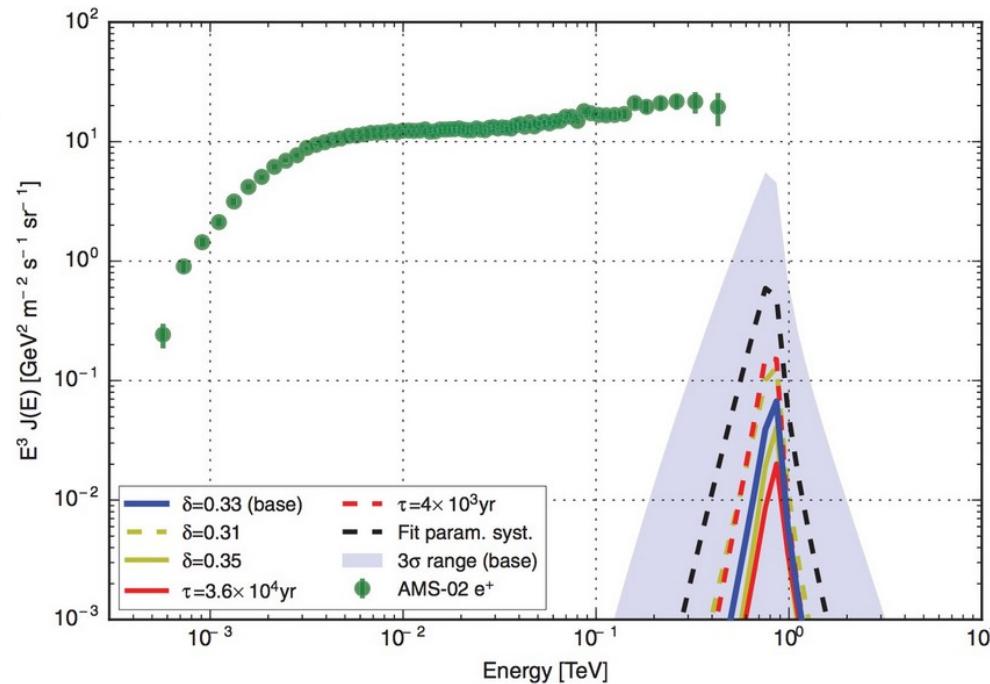
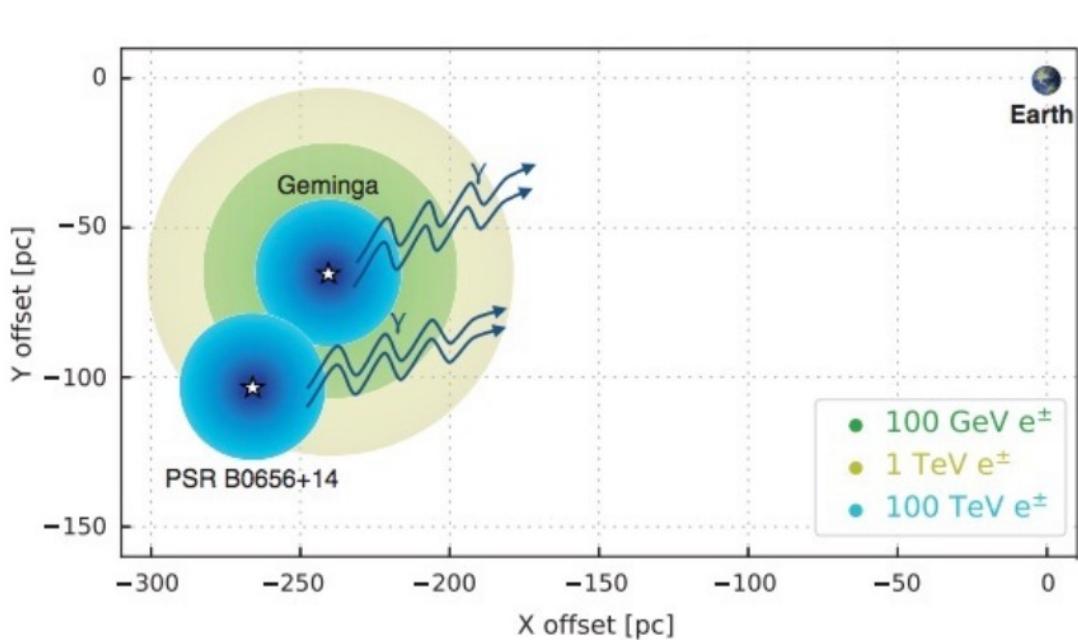
→ Diffusion + synchrotron/IC energy losses :



Best fit provides: $D(100 \text{ TeV}) = 4.5 \times 10^{27} \text{ cm}^2/\text{s}$

2 orders of magnitude smaller than value from the B/C ratio !

Electrons + Symmetry => No room for MC + L_c explanations !



Assuming the same D in our local environment, Geminga and Monogem cannot explain the local positron flux.

Di Mauro et al.(2019): GeV halo around Geminga (Fermi) → <20% e^+ flux.

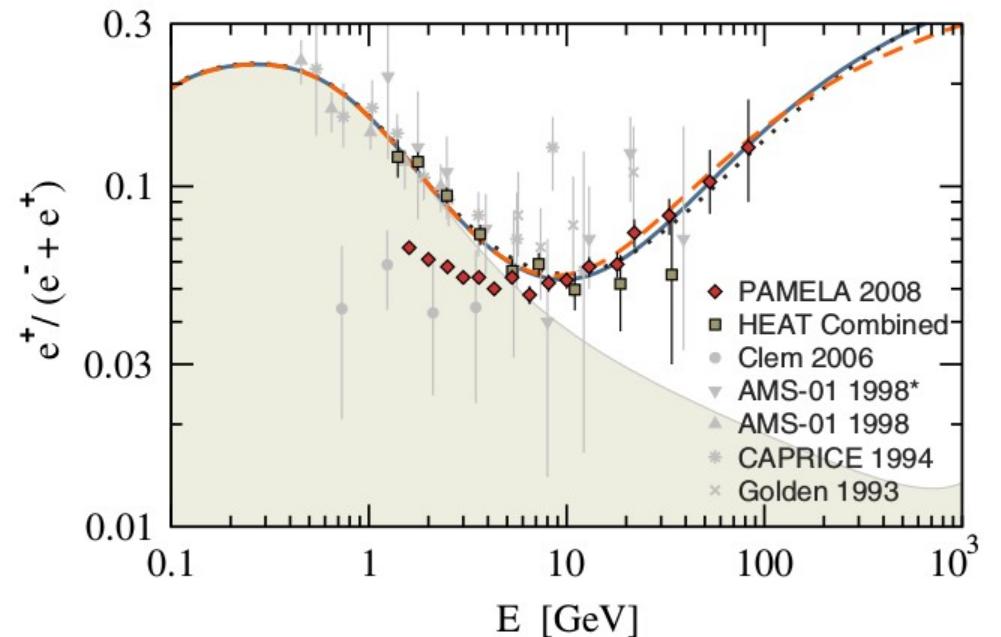
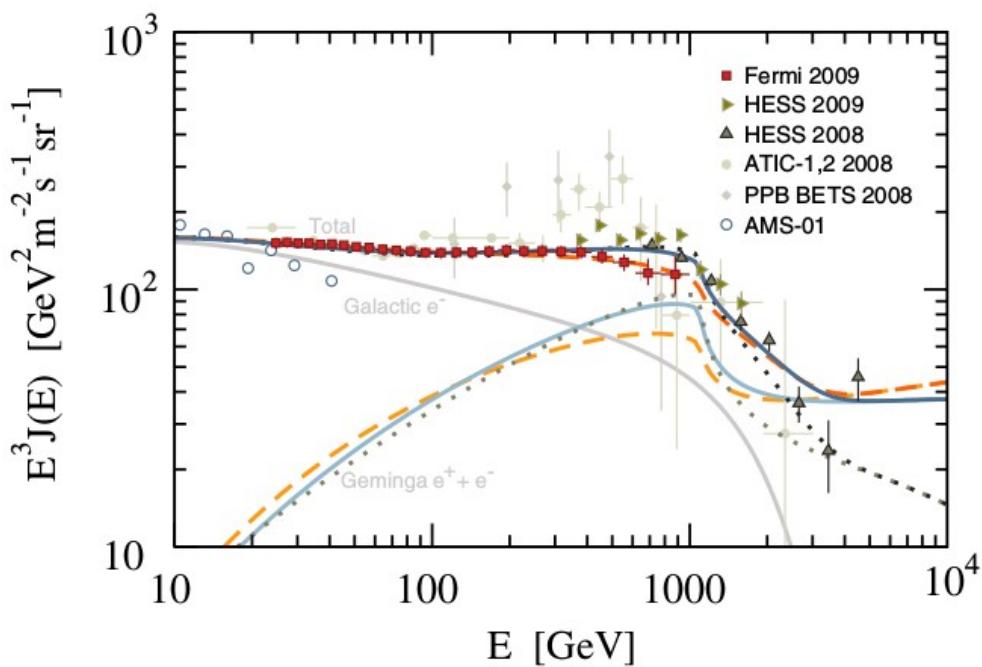
" Who ordered that ? "

- How can we now explain electron and positron spectra at Earth ?
- How can we now explain the B/C ratio ?

→ Indeed, with a standard D: Geminga & Monogem best candidates within known pulsars for the electron and positron fluxes at HE

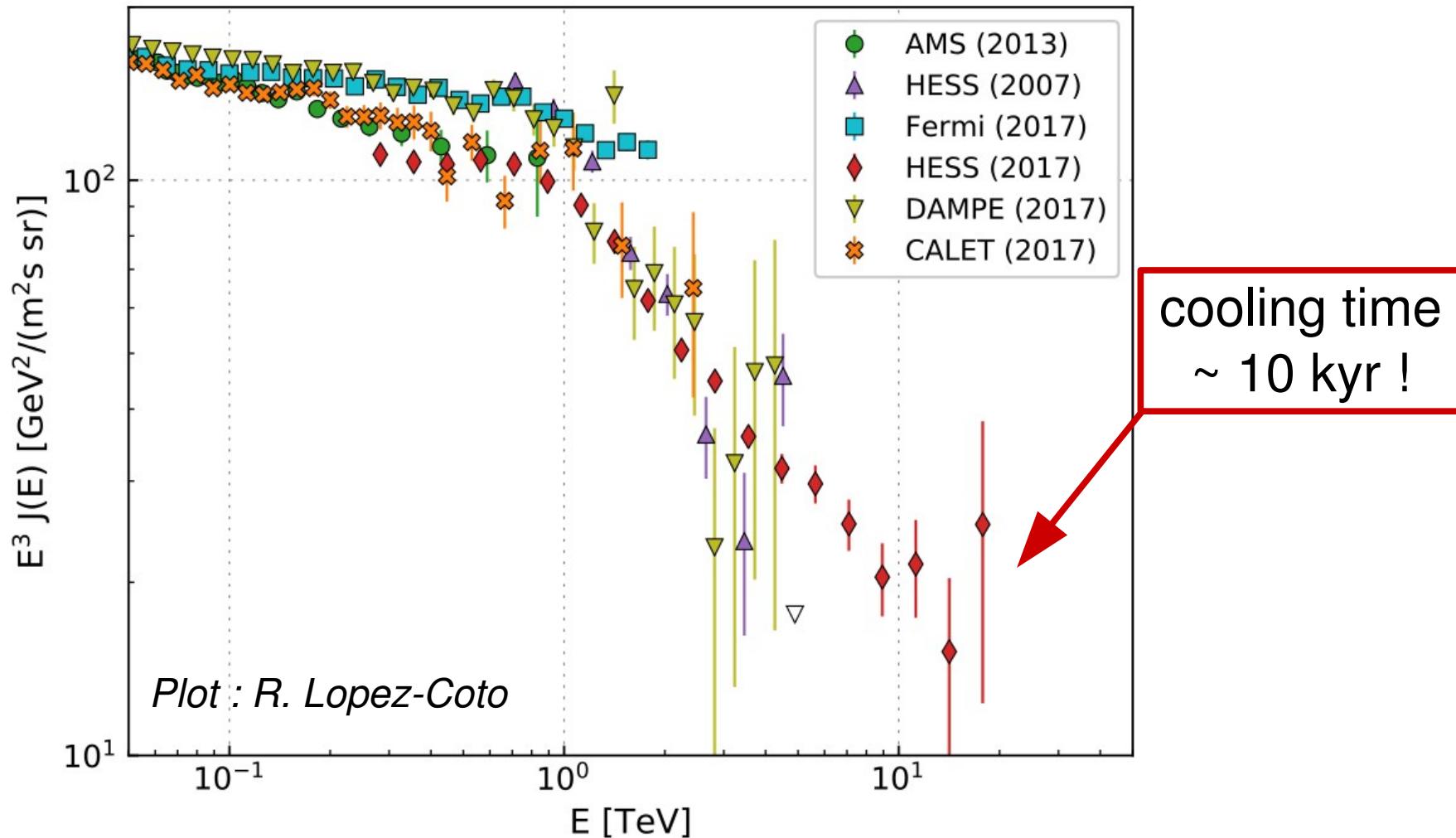
Aharonian et al. (1995) ;

Yuksel et al.(2009) [w/ Milagro flux] :



H.E.S.S. (2017) all-electron spectrum

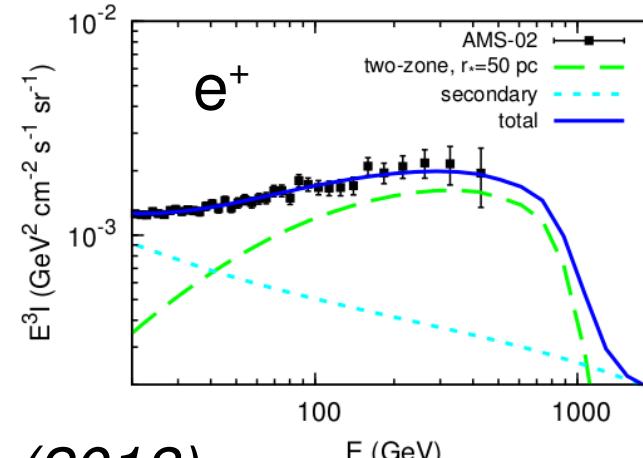
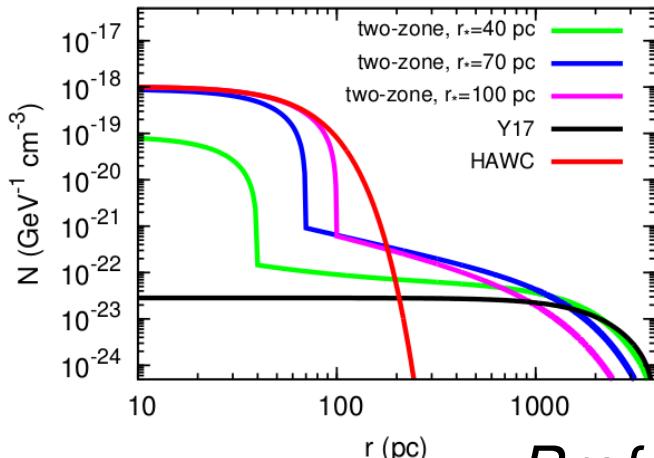
Power-law between 1 and 20 TeV. Spectral index ~ 3.8



Hooper & Linden (2018): Cannot be explained with known pulsars and HAWC's D coeff. => The slow diffusion regions must be very small.

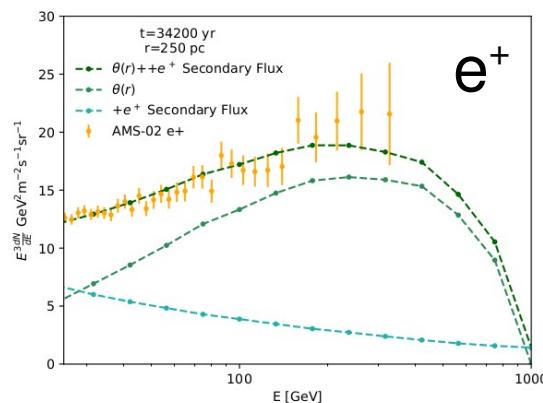
Possible solutions :

- Hooper et al. (2017) : Can explain the $e^{+/-}$ fluxes w/ **strong advection**,
... but large velocities ($> 100s$ km/s) \gg than any measured.
- **Two-zone models**: - Fang et al. (2018) :



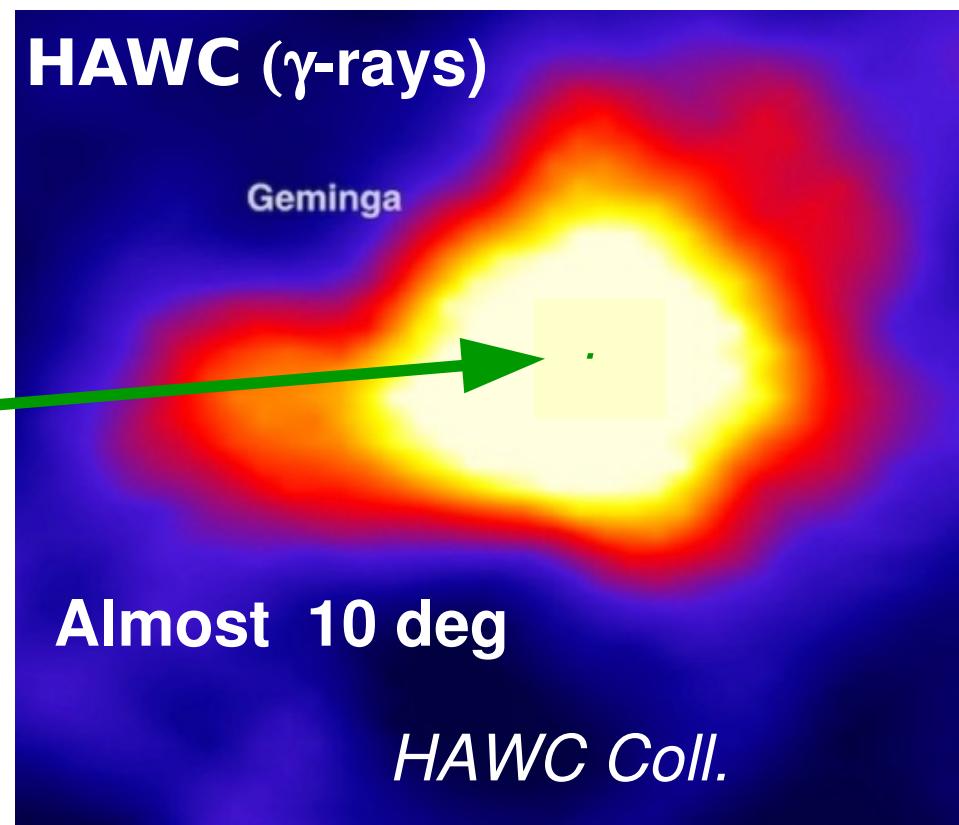
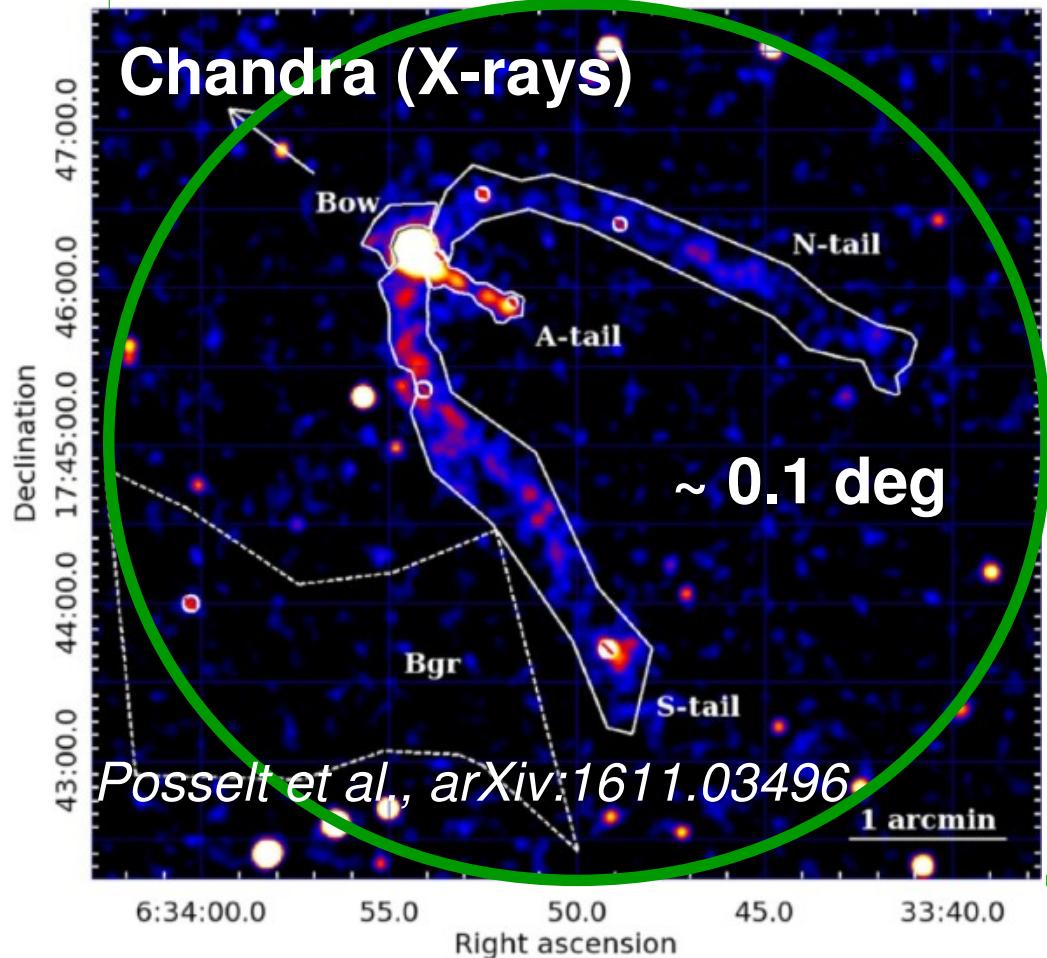
- Profumo et al. (2018) :

Lessons from HAWC PWNe observations: the diffusion constant is not a constant; Pulsars remain the likeliest sources of the anomalous positron fraction; Cosmic rays are trapped for long periods of time in pockets of inefficient diffusion



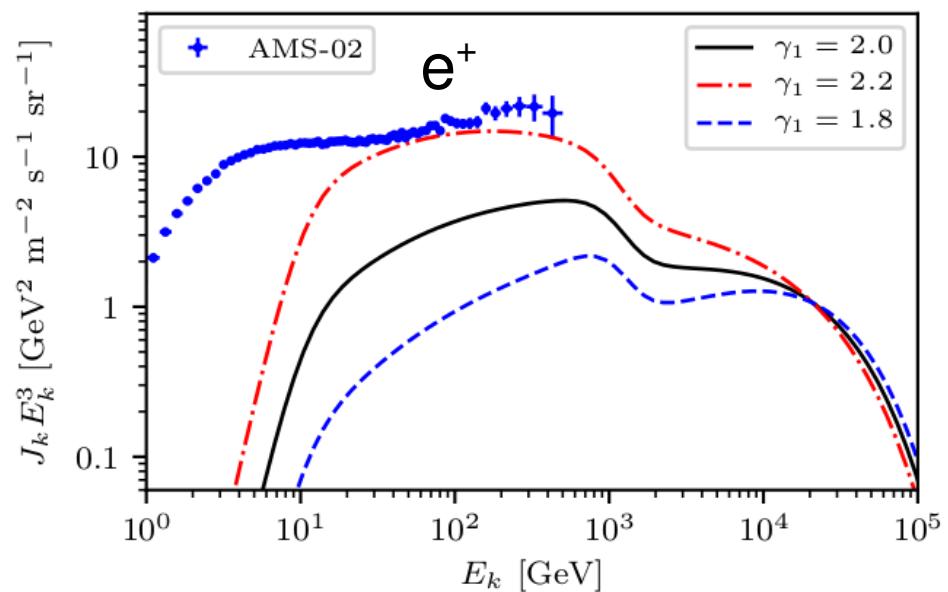
"... region at distances smaller than 20 pc ... likely still within the PWN."

BUT e^- are not in the (bow shock) PWN any more :

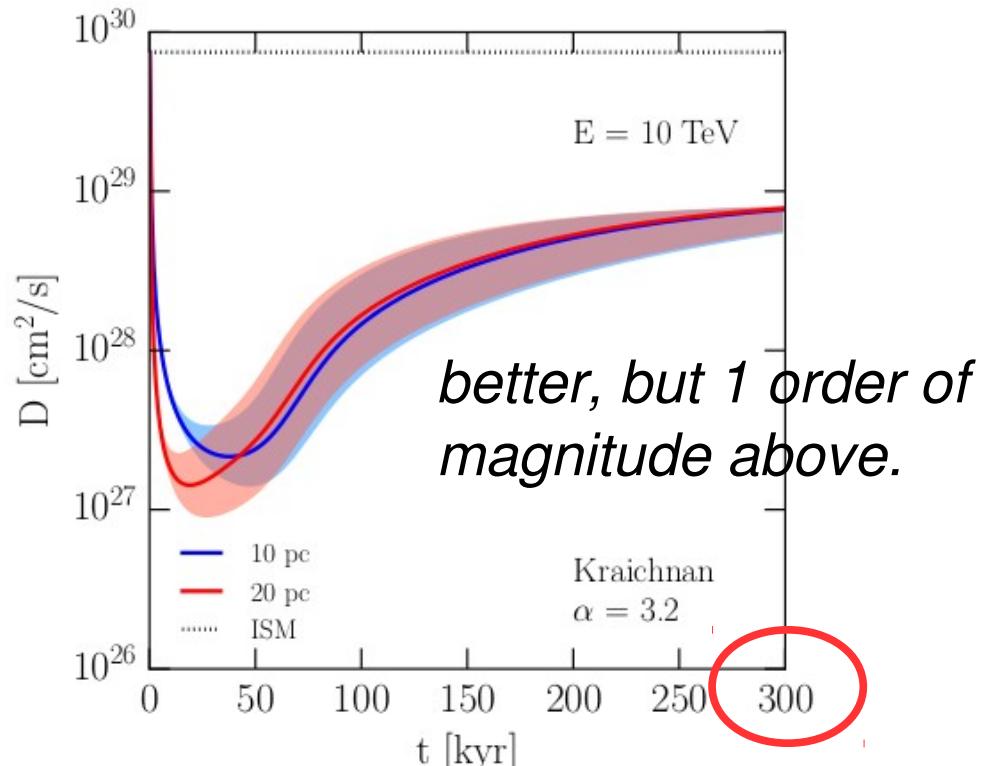
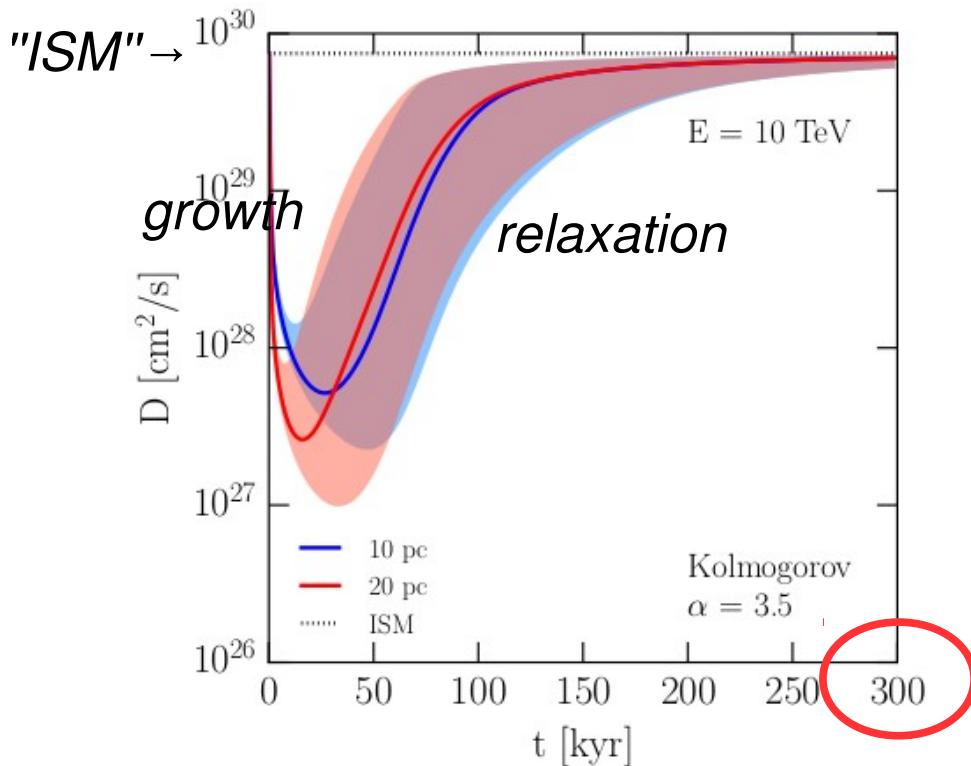


→ Johannesson, Porter & Moskalenko
(arXiv:1903.05509) :

- * Two-zone model with GALPROP →
- * Influence on low E γ -ray emission around Geminga (→ Fermi-LAT).



Evoli, Linden & Morlino (2018): A proper physical suggestion! → Alfvén waves from escaping $e^{+/-}$ generate a region of low D around pulsars



Relaxes too rapidly to confine e^- around Geminga.

→ *Fang, Bi & Yin (2019)* : No, Geminga is too weak to generate enough $e^{+/-}$ to generate turbulence. May be downstream of the SNR shock.

(... Unsure because of kick velocity. But maybe from escaped SNR protons.)

An undiscovered pulsar in the Local Bubble as an explanation of the local high energy cosmic ray electron spectrum

Lopez-Coto, Parsons, Hinton & GG , Phys. Rev. Lett. **121**, 251106 (2018)

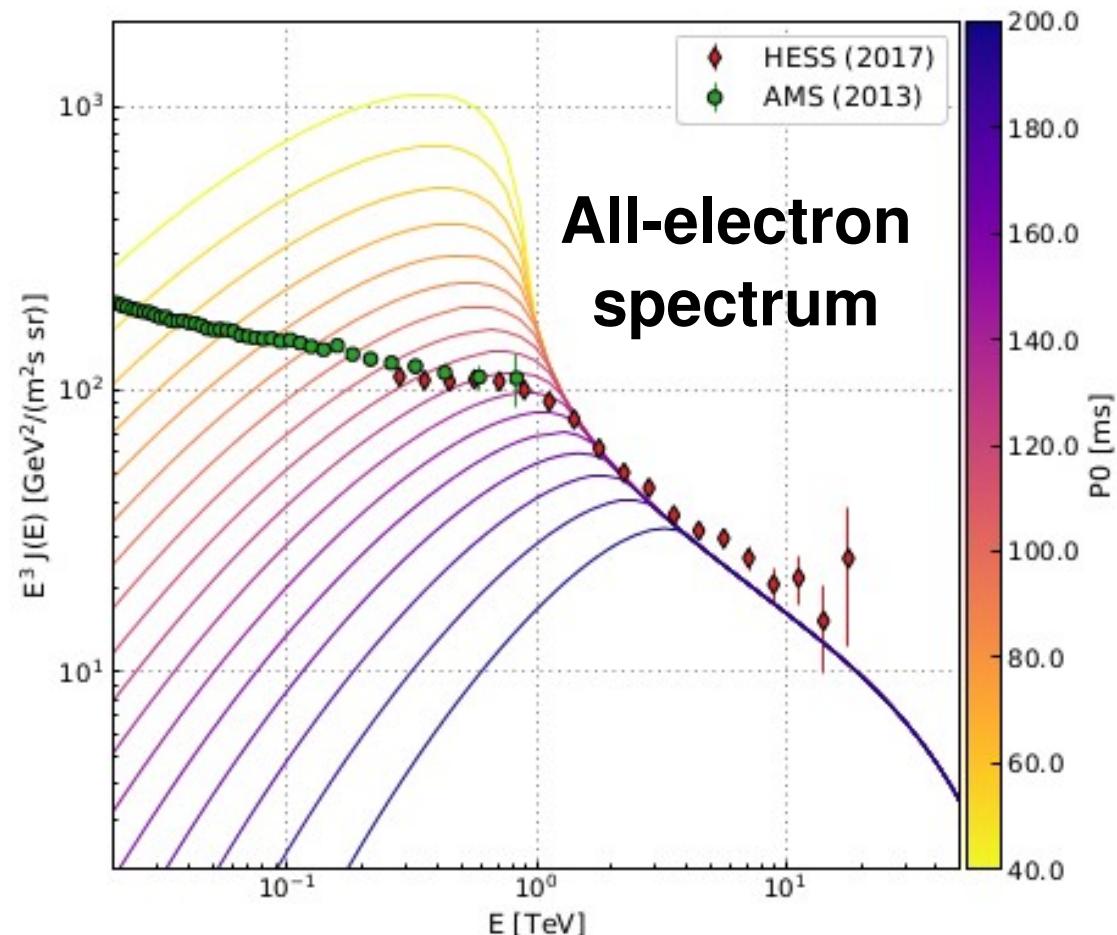
Can a nearby, old, undiscovered pulsar reproduce the HE $e^{-/+}$ spectra, with a HAWC-like diff. coeff. in the entire local ISM ? **YES !**

- Required characteristics :
 - Age > 300 kyr,
 - Distance < 90 pc,
 - Spin-down power
 $\sim 10^{33} - 10^{34}$ erg/s.

Consistent with known population.

Breitschwerdt+, Nature (2016):
SN 2.2 Myr ago at 60 – 130 pc.

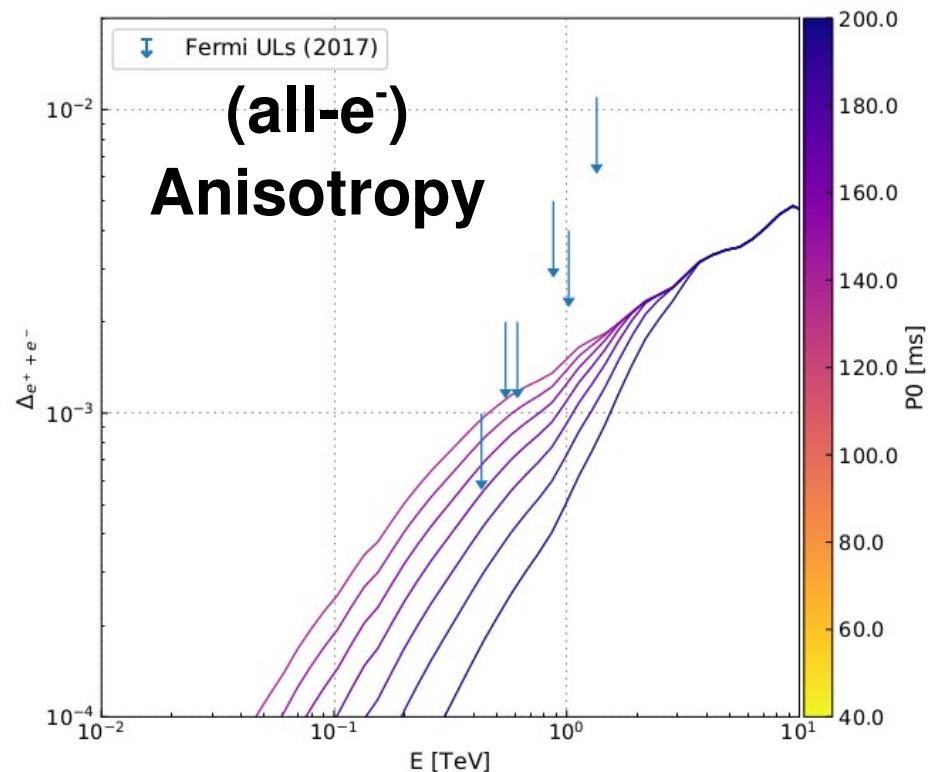
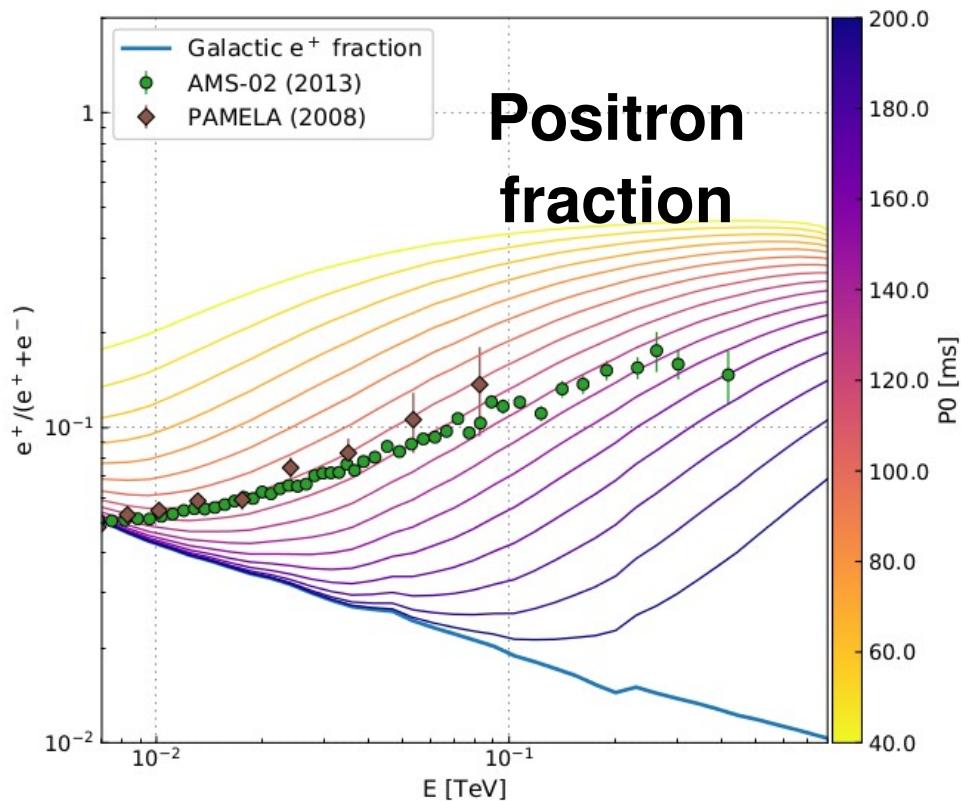
Fang+, arXiv:1906.08542: PSR
B1055-52, if $d \sim 90$ pc (??)



$d = 50$ pc, $E = 1.3 \times 10^{33}$ erg/s, $\alpha = 2.4$, $B = 3 \mu\text{G}$.

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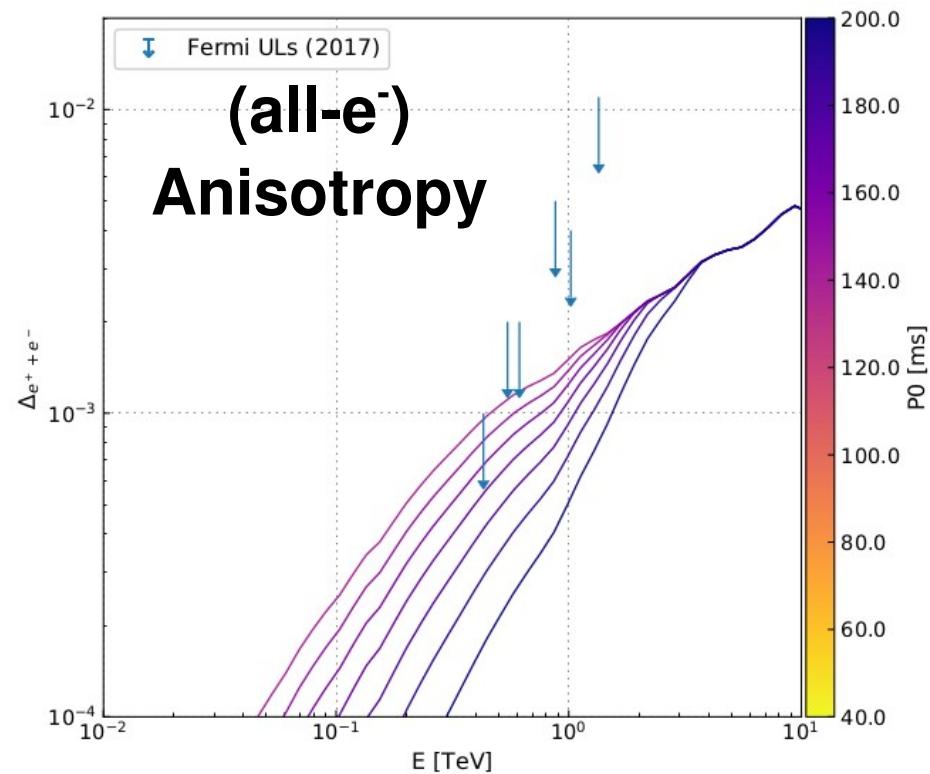
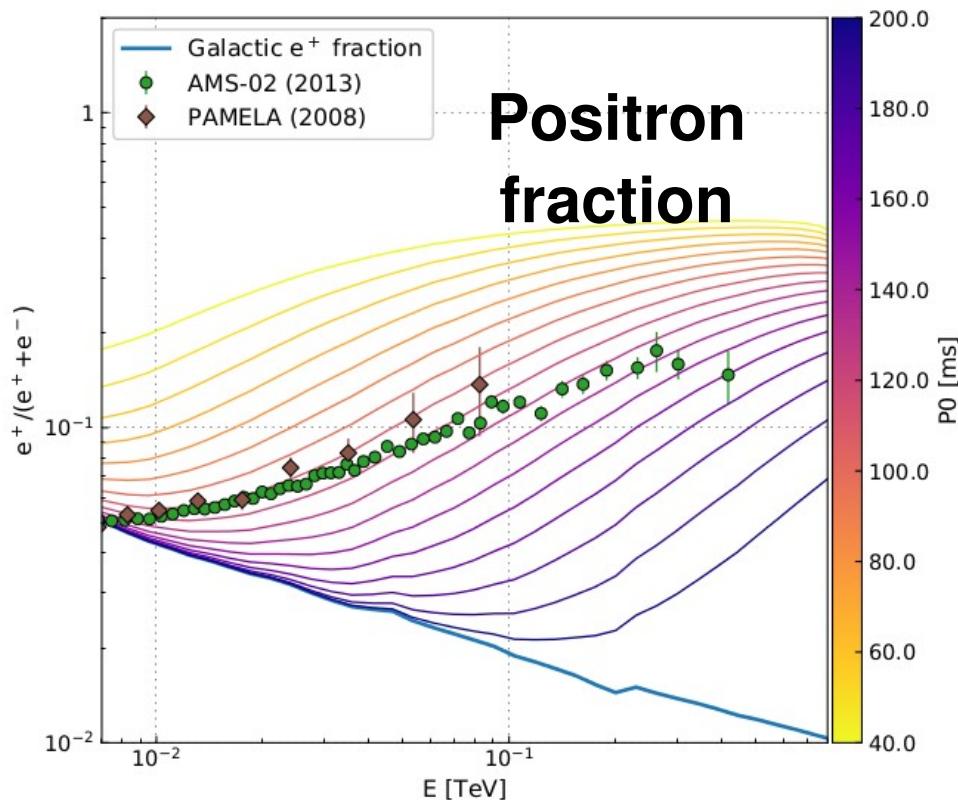


But Recchia, Gabici, Aharonian & Vink (2019) argue that the flattening/decrease at HE in the AMS-02 e^+ fraction data **rules out pulsars**.

→ Very good point, but **assumes 50/50 e^+ / e^- accelerated at PWNe.**

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Lopez-Coto, Parsons, Hinton & GG , Phys. Rev. Lett. **121**, 251106 (2018)



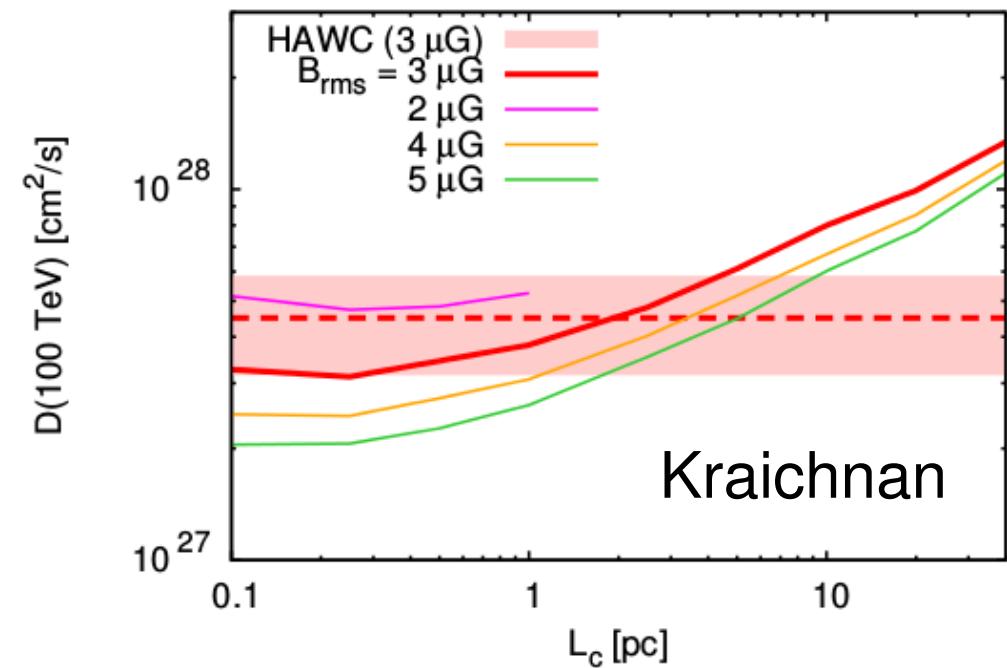
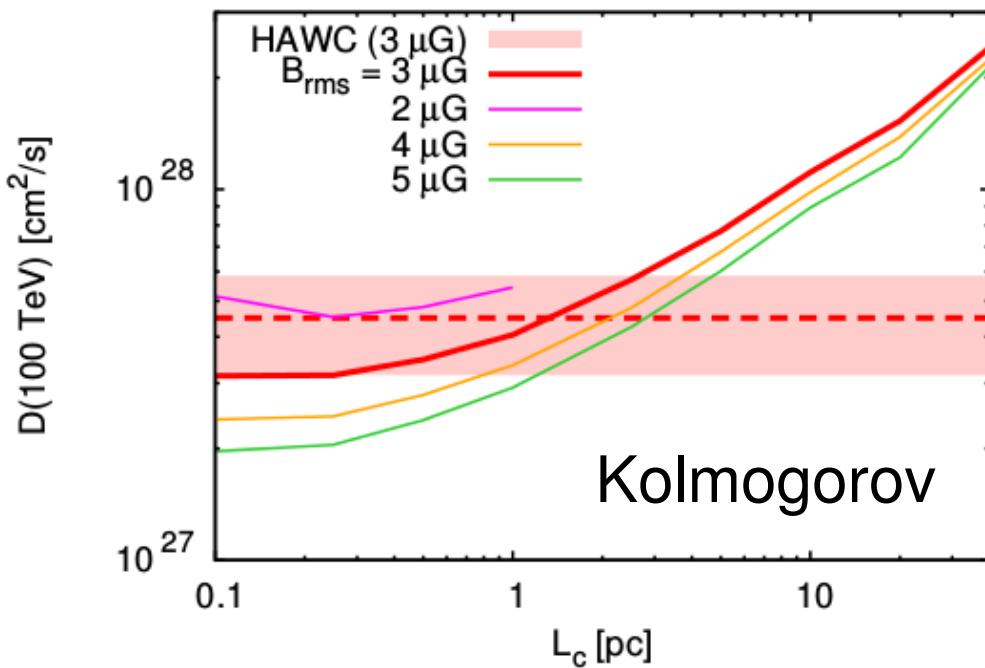
→ See GG & Kirk (2018) : **Pulsars may come in two categories and accelerate either e^+ or e^- to HE, but not both!**

Major implications for the e^+ fraction ! If < 0.5 , means local " e^- -pulsar".

Actually, $D(\text{HAWC}) = \text{Theoretical } D$!!!

Lopez-Coto & GG (2018):

Individual particles propagated numerically in 3D synthetic turbulence.



=> HAWC findings agree perfectly with theoretical expectations :

- (a) For a strongly turbulent magnetic field (i.e. regular B negl.),
- (b) For coherence lengths \sim a few pc.

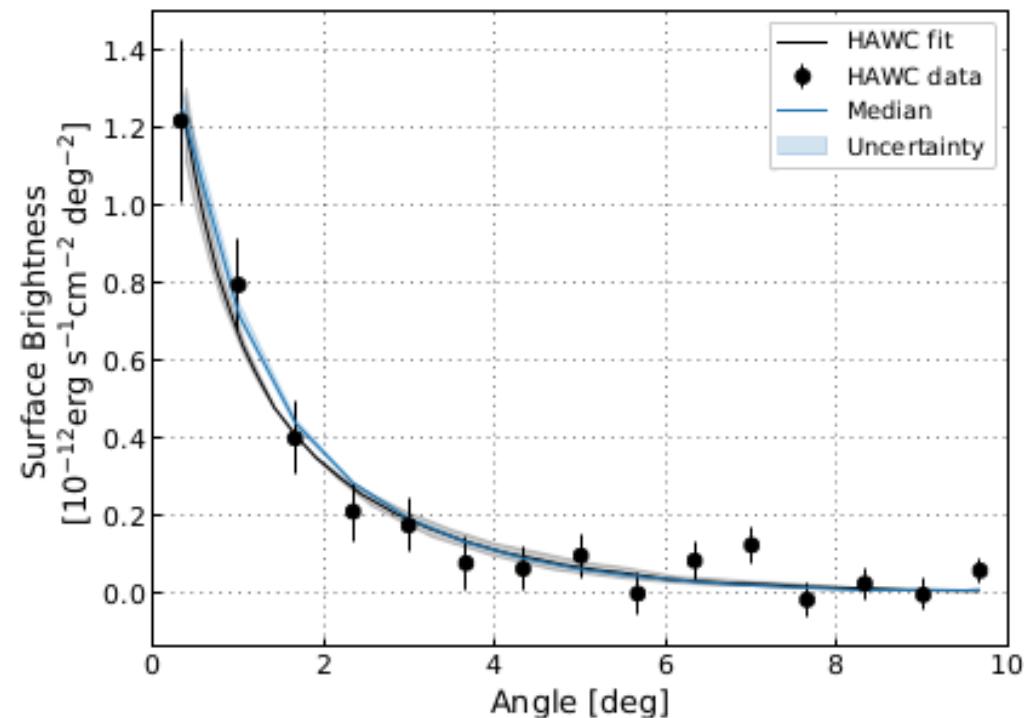
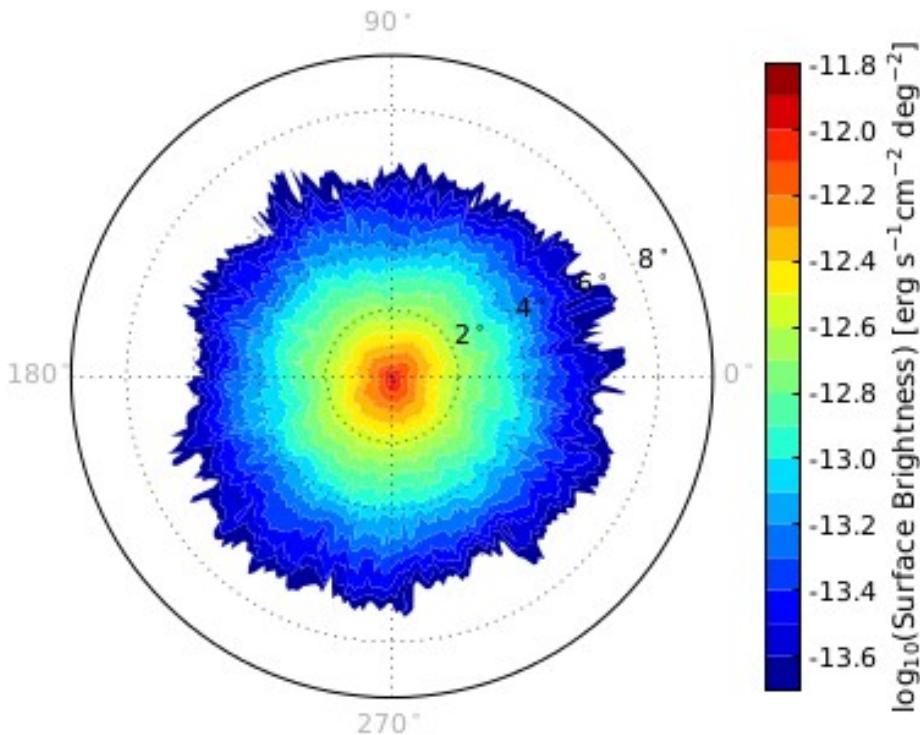
=> Is this the actual D_{ISM} (at least in the disc) ?

Actually, D(HAWC) = Theoretical D !!!

Lopez-Coto & GG (2018)

- Individual e⁻ propagated in 3D synthetic turbulence, taking into account synchrotron + IC losses .
- Best fit to HAWC measurements ($\chi^2/\text{ndf} < 1$) :

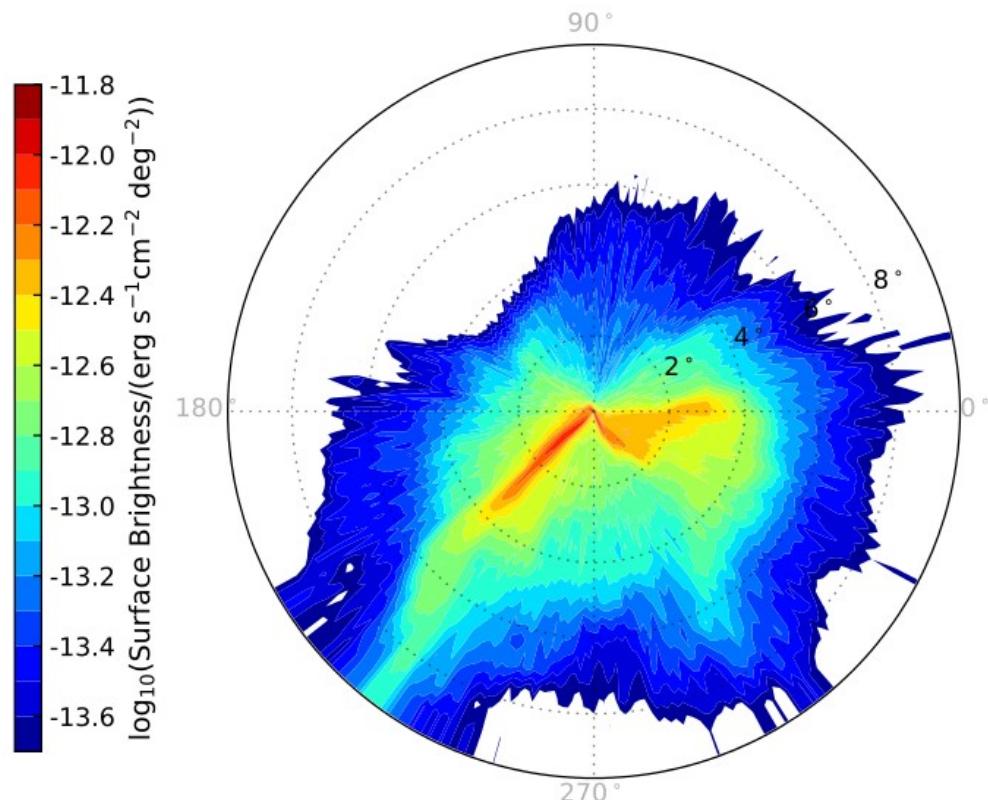
Kolmogorov / Kraichnan, $B = 3\mu\text{G}$, $L_c = 1 \text{ pc}$



Actually, D(HAWC) = Theoretical D !!!

Lopez-Coto & GG (2018)

- Individual e⁻ propagated in 3D synthetic turbulence, taking into account synchrotron + IC losses.
- Large coherence lengths ruled out :

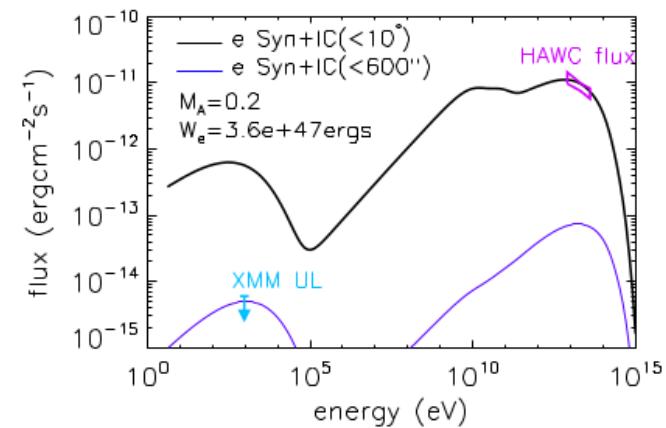
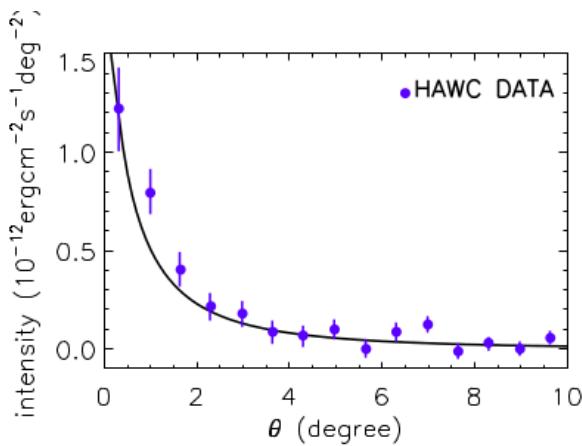
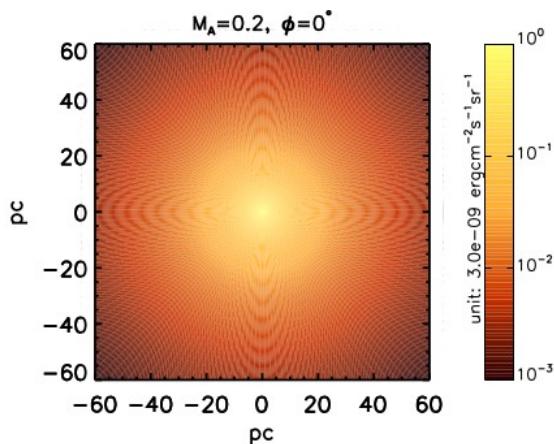


$L_c = 40 \text{ pc}$: Too asymmetric
(no strong asymmetry in HAWC measurements)

=> Everything in agreement, then!

Or could the local L_c be $>> 40$ pc ?

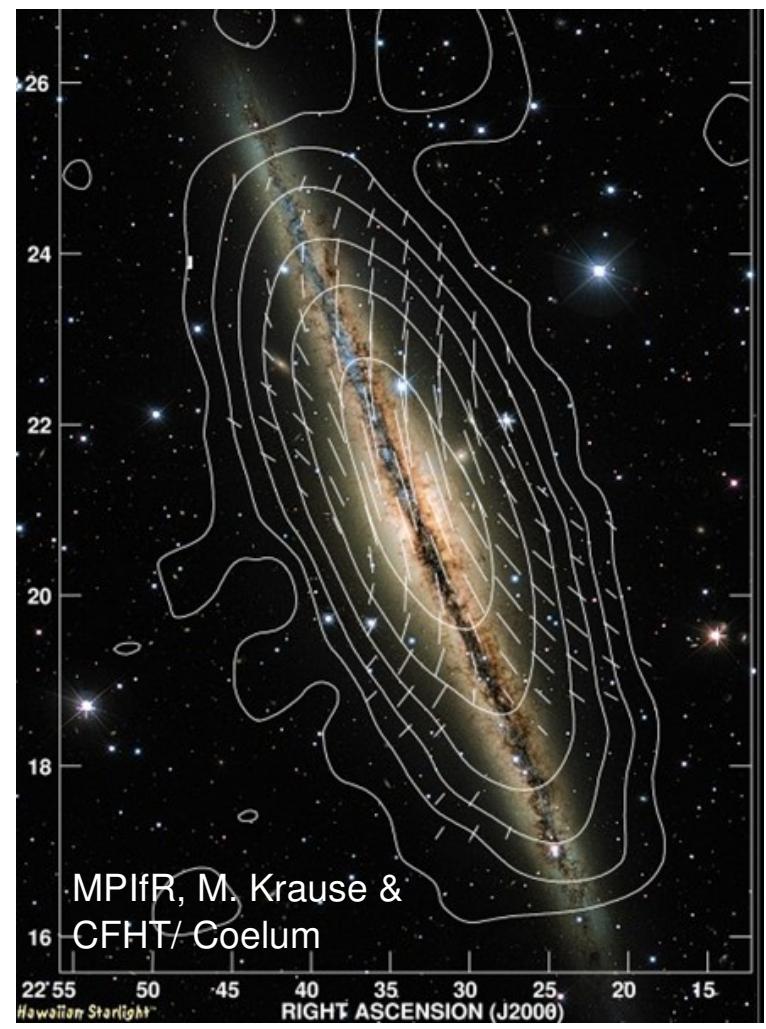
- Liu, Ge, Sun & Wang (2019) : Discrepancy between IC γ -rays and X-ray synchrotron (Chandra/XMM) in a small region around Geminga.
=> B field aligned towards us?
- Liu, Yan & Zhang (2019) : sub-Alfvenic turbulence, with such a large-scale B field → Find no need for a small D.



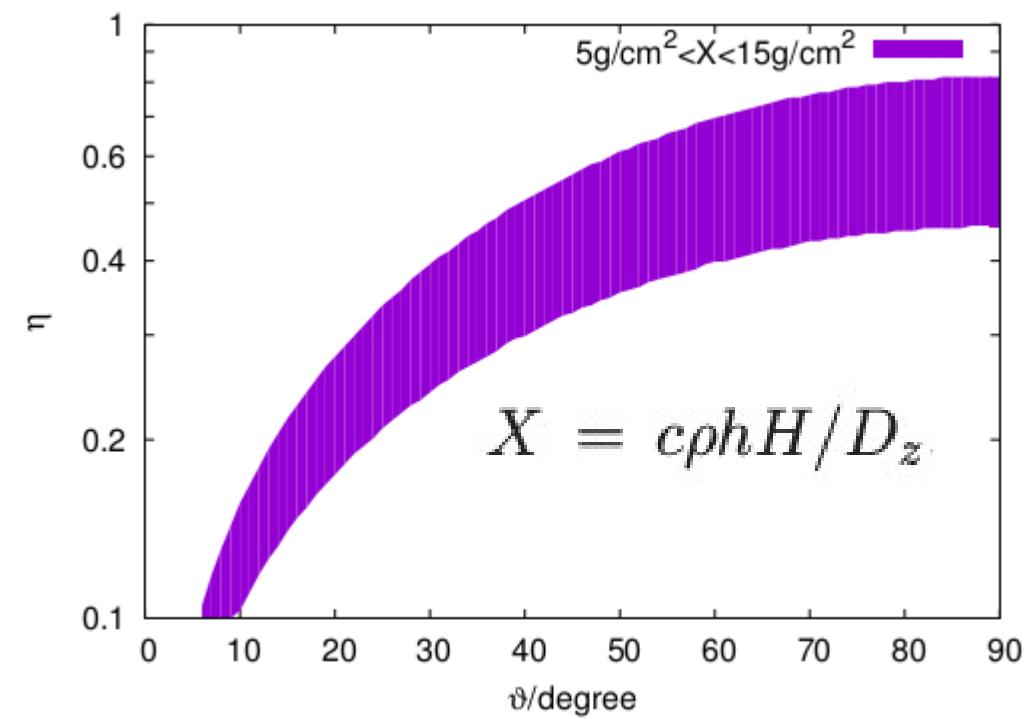
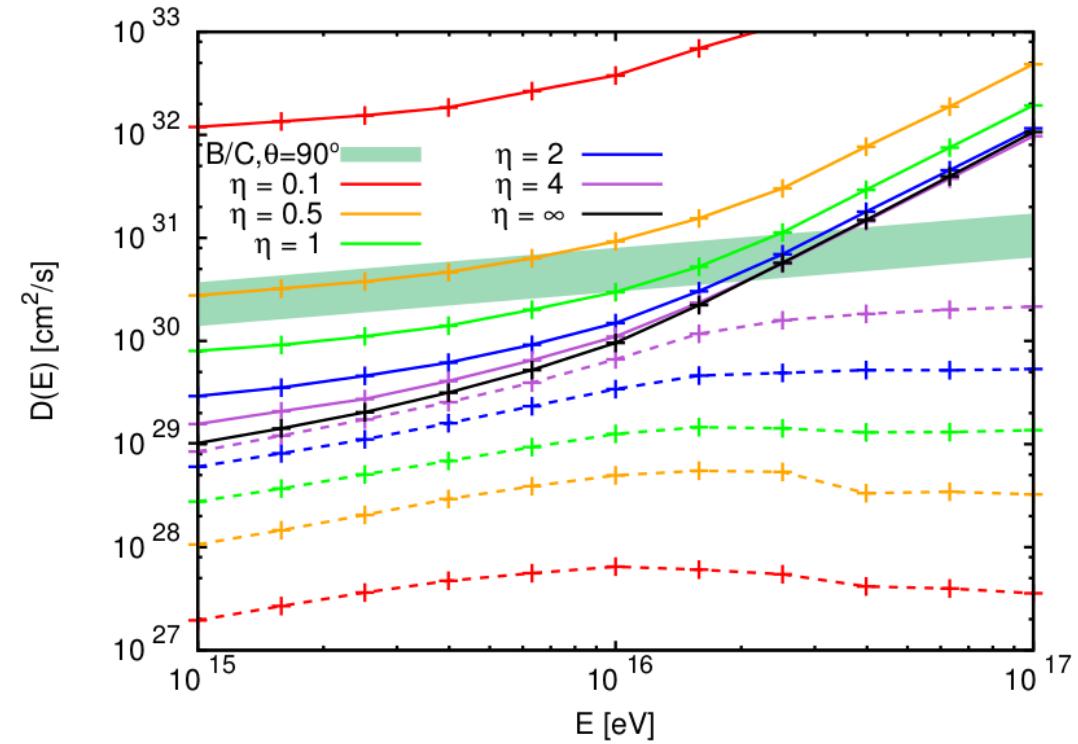
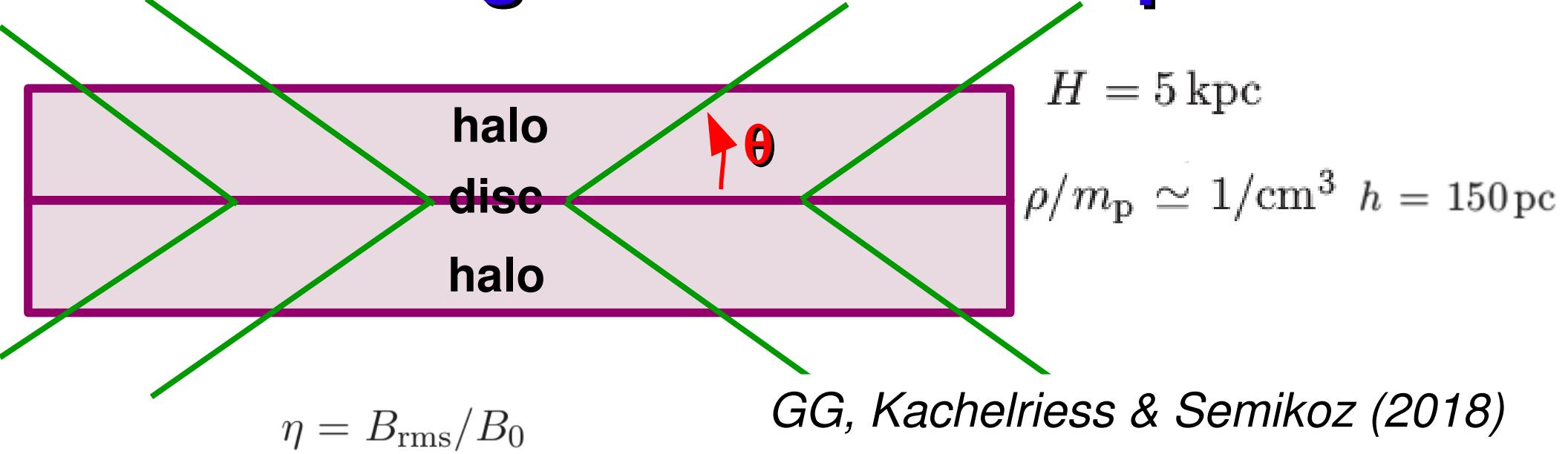
- Impact field line wandering=> Ruled out for Lopez-Coto & GG (2018)'s turbulence. Does it work for another? Need to check in this model.
- Further X-ray/ γ -ray analyses welcome. IACTs pointed to Geminga may still see some asymmetries, even in Lopez-Coto & GG's best fit.

And the B/C ratio ?

- Probes CR propagation on **kpc scales**.
- => Small D in the disc might be viable as long as CRs are removed from the Galaxy sufficiently quickly, **e.g. faster diffusion in the Galactic halo (or advection, etc.)**.
- => Quick CR escape by parallel diffusion along a large-scale field ?



Grammage with an out-of-plane B

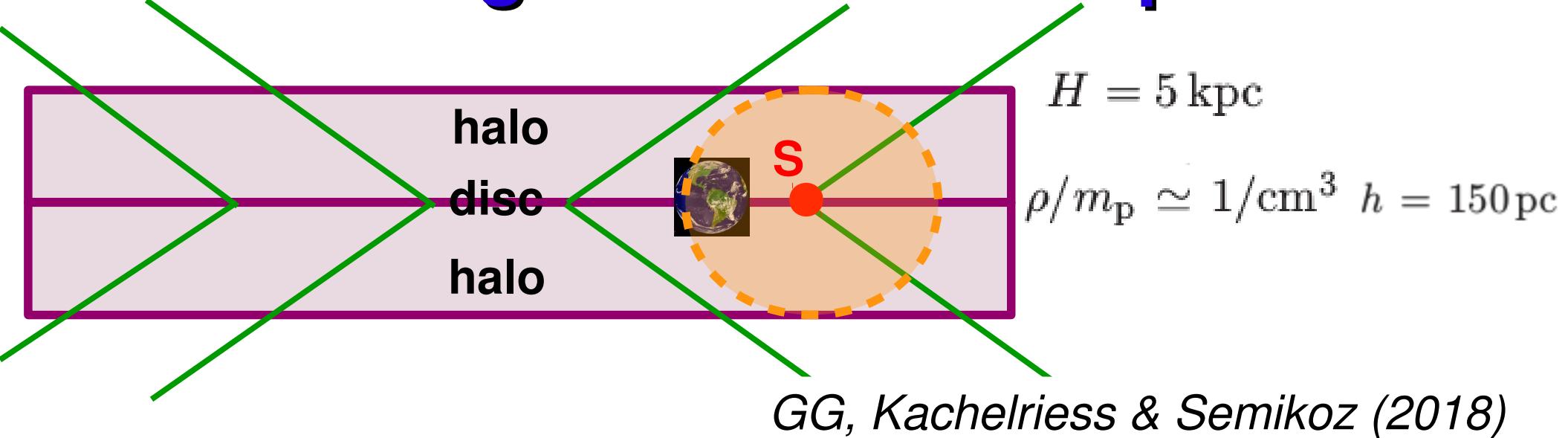


$$\mathcal{P}(k) \propto k^{-5/3}$$

$$L_{\max} = 100 \text{ pc}$$

$$B_{\text{tot}} = \sqrt{B_{\text{rms}}^2 + B_0^2} = 1 \mu\text{G}$$

Grammage with an out-of-plane B

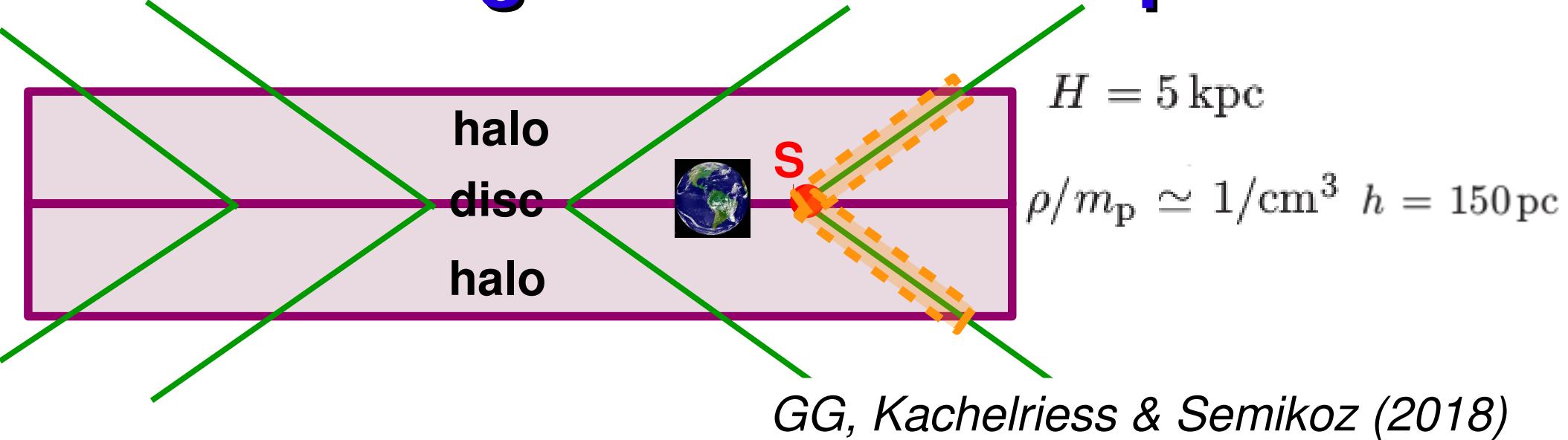


Isotropic diffusion:

CRs occupy a large volume. B/C constraints on D

=> Needs $>\sim 100$ s sources for the local $> 10 \text{ TeV}$ CR flux.

Grammage with an out-of-plane B



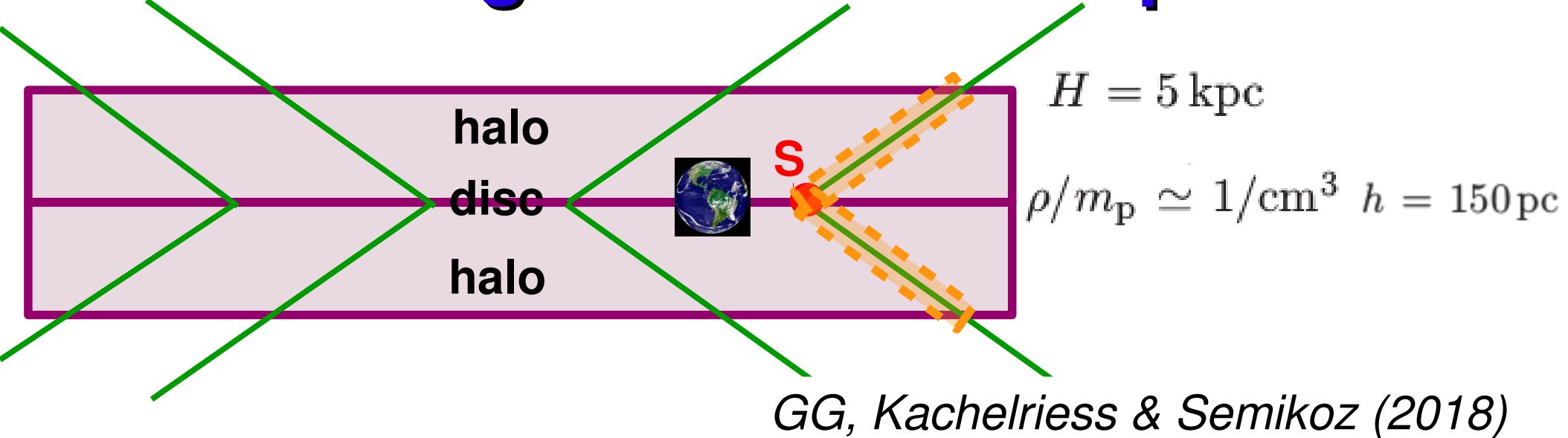
Anisotropic diffusion:

If takes D_{\parallel} ($\rightarrow D_{\perp}$) that satisfy B/C, the volume $V(t)$ is reduced by ~ 200

=>One local source ($\sim 200 \text{ pc}$) may dominate the CR flux at $>\sim 10 \text{ TeV}$

Erlykin&Wolfendale ; Explanation for e^+ , $p\bar{p}$ (Kachelriess & Semikoz)

Grammage with an out-of-plane B



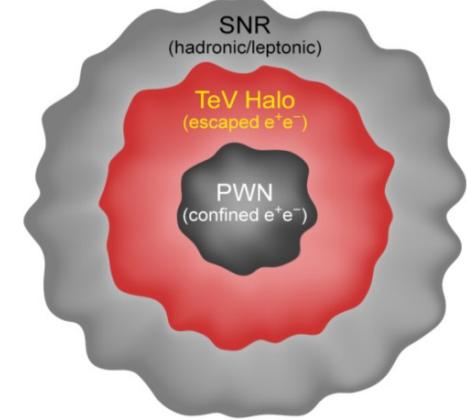
- but still needs to fit γ -rays and synchrotron => Could need some fine tuning.
- Or more physical picture : Galactic wind ? CRs streaming in the Galactic halo ? (cf. E. Zweibel's talk)

How to define a "TeV Halo" ? :

→ Sudoh et al., arXiv:1902.08203 :

* "Halos" : e^- that have escaped from the PWN, but remain trapped in a region where diffusion is inhibited.

* More in HESS catalog.



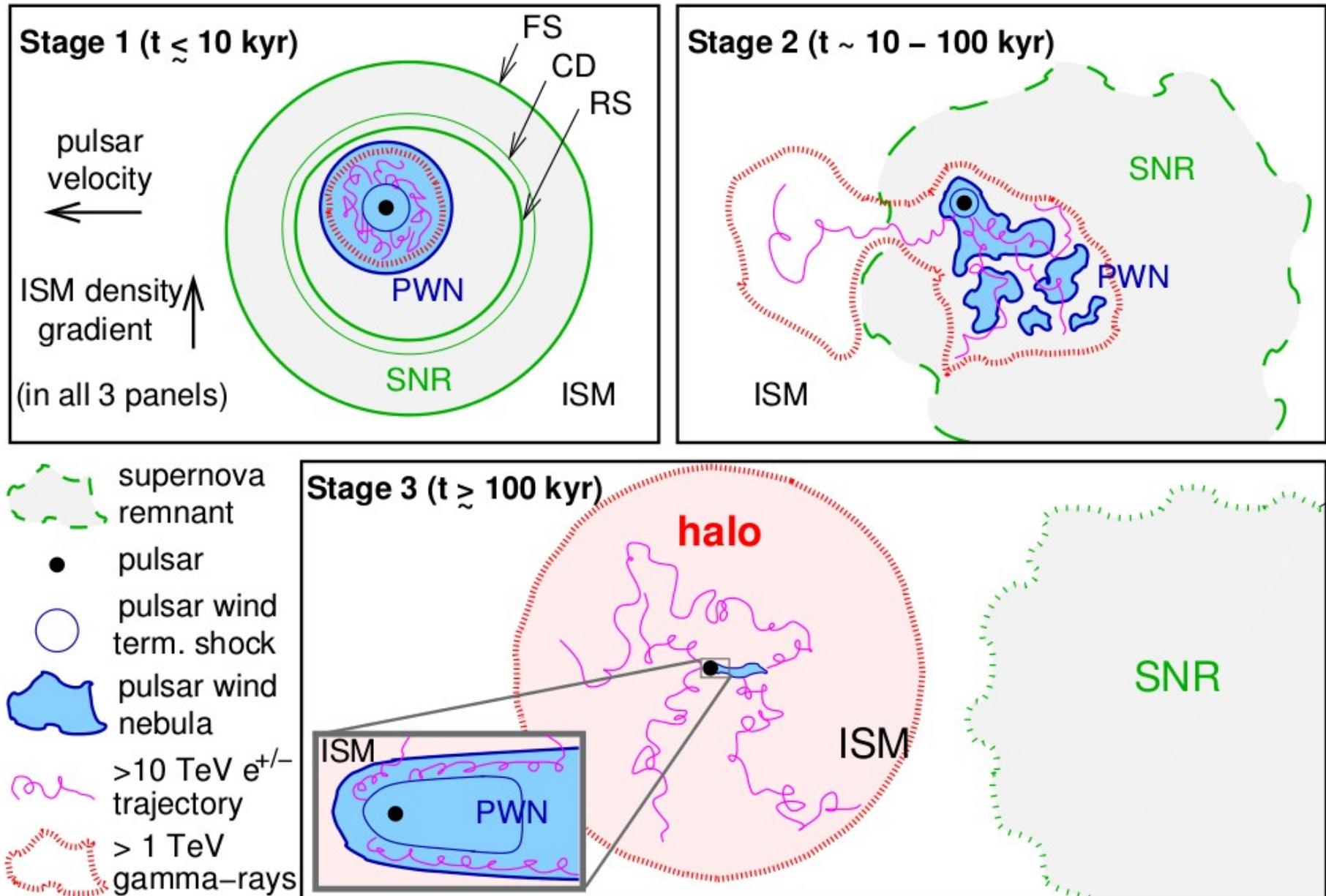
→ GG, Mitchell, Lopez-Coto, Joshi, Parsons & Hinton, arXiv:1907.12121:

* **"Halos"** : e^- energy density \ll 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.

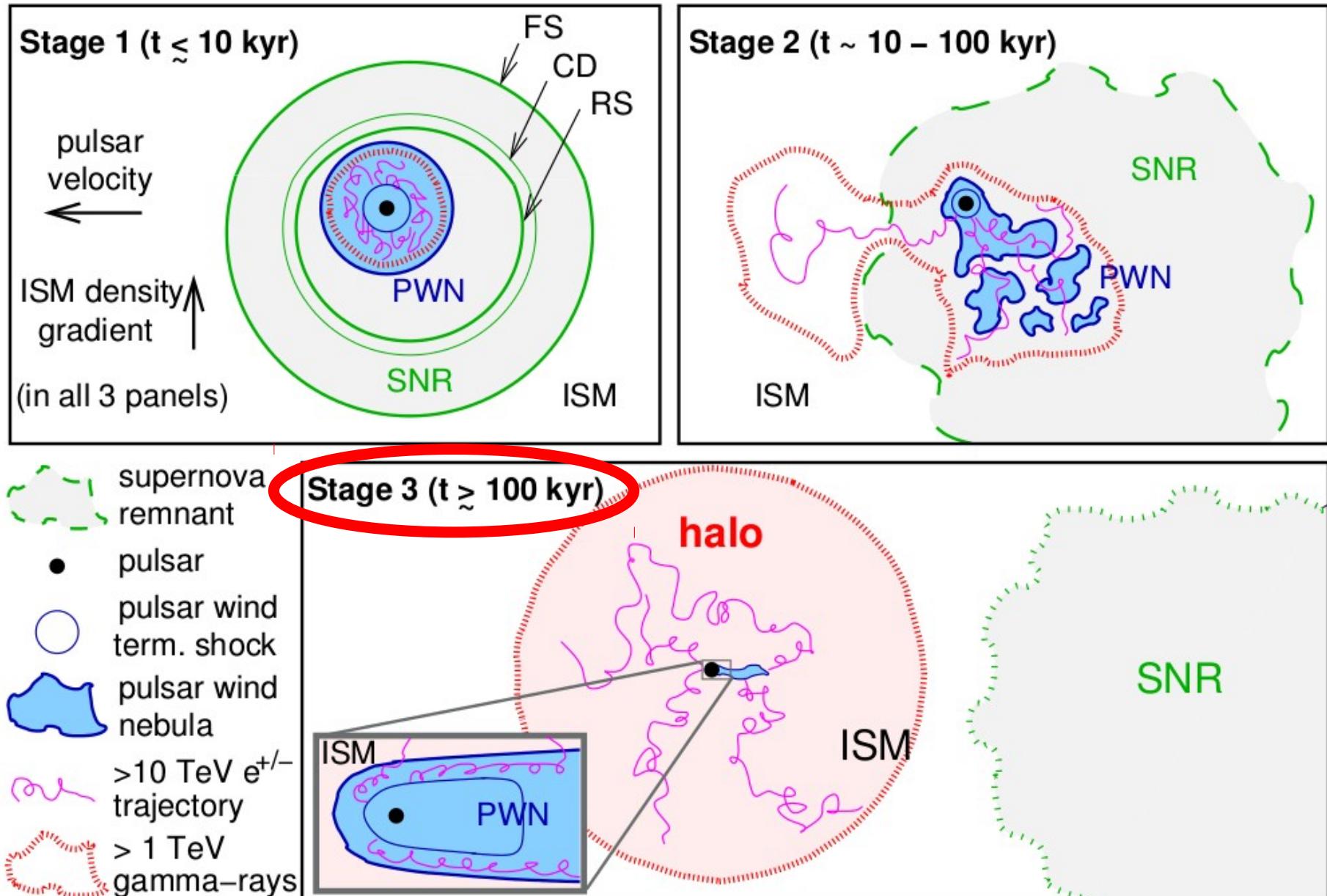
Evolutionary stages of a PWN :

GG, Mitchell, Lopez-Coto, Joshi, Parsons & Hinton, arXiv:1907.12121:



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

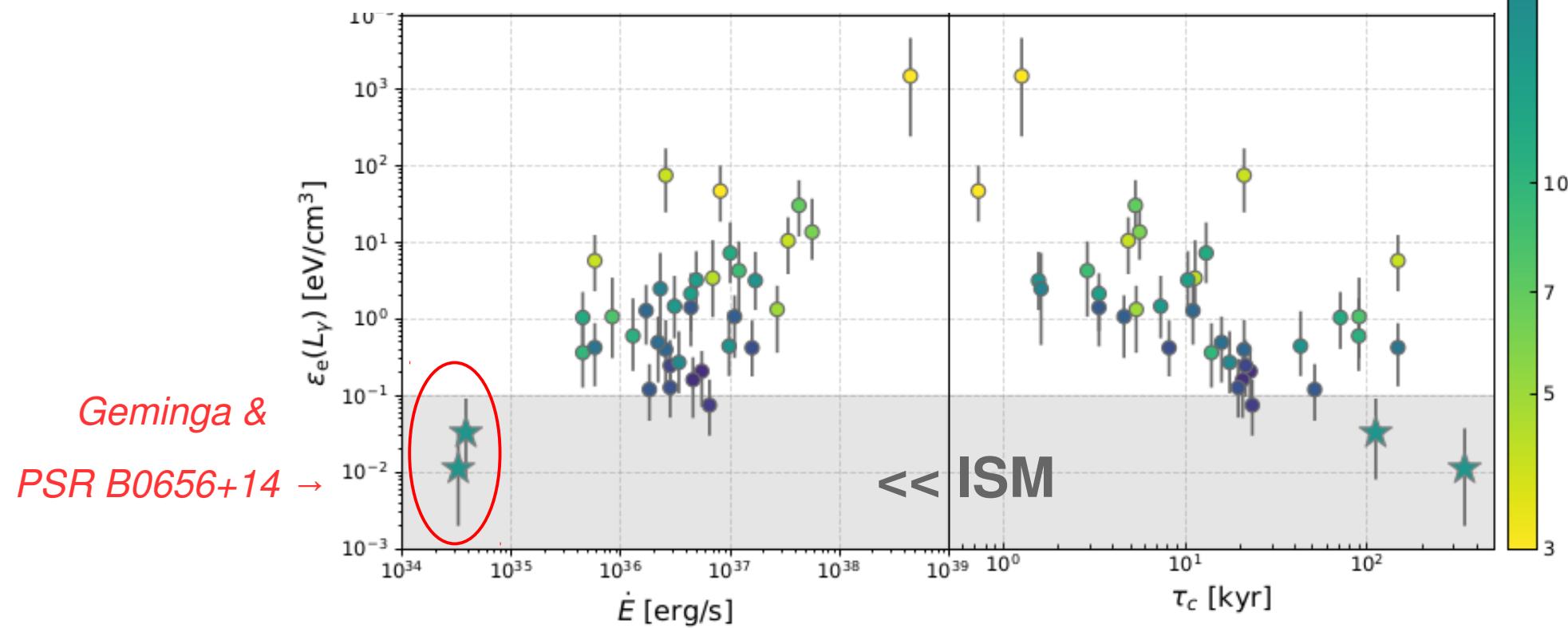
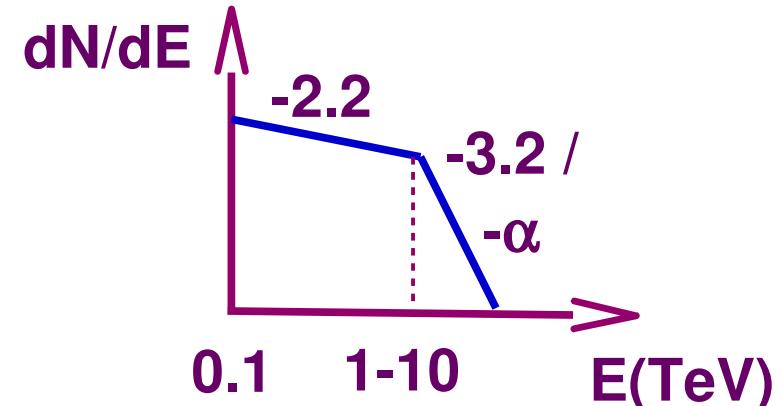
e⁻ can escape in to the ISM; Weak; Low e⁻ density
=> Only then a "halo" may form.



e^- Energy Densities (arXiv:1907.12121) :

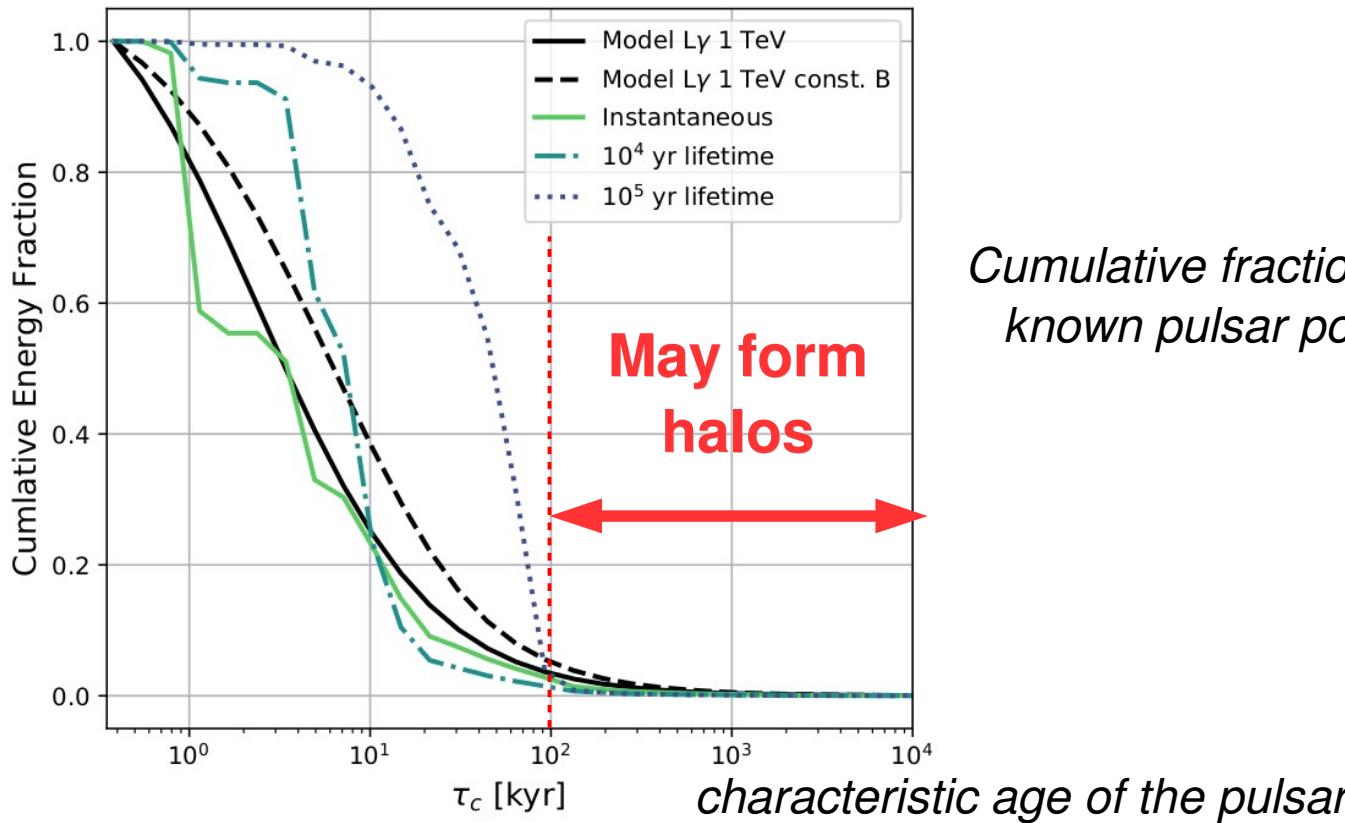
- Take the TeV sources identified as PWNe by the HESS Coll. (Abdalla et al. 2018) + Geminga and PSR B0656+14 from HAWC.

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



Halos: Prospects for future detections

Unlikely that halos contribute significantly to the *total TeV γ -ray luminosity from e^- accelerated in PWN*: (arXiv:1907.12121)



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)

Halos: Prospects for future detections

→ *Linden et al. (2017)*:

Observations by HAWC and Milagro have detected bright and spatially extended TeV γ -ray sources surrounding the Geminga and Monogem pulsars. We argue that these observations, along with a substantial population of other extended TeV sources coincident with pulsar wind nebulae, constitute a new morphological class of spatially extended TeV halos. We show that HAWCs wide field-of-view unlocks an expansive parameter space of TeV halos not observable by atmospheric Cherenkov telescopes. Under the assumption that Geminga and Monogem are typical middle-aged pulsars, we show that ten-year HAWC observations should eventually observe 37^{+17}_{-13} middle-aged TeV halos that correspond to pulsars whose radio emission is not beamed towards Earth. Depending on the extrapolation of the TeV halo efficiency to young pulsars, HAWC could detect more than 100 TeV halos from mis-aligned pulsars. These pulsars have historically been difficult to detect with existing multiwavelength observations. TeV halos will constitute a significant fraction of all HAWC sources,

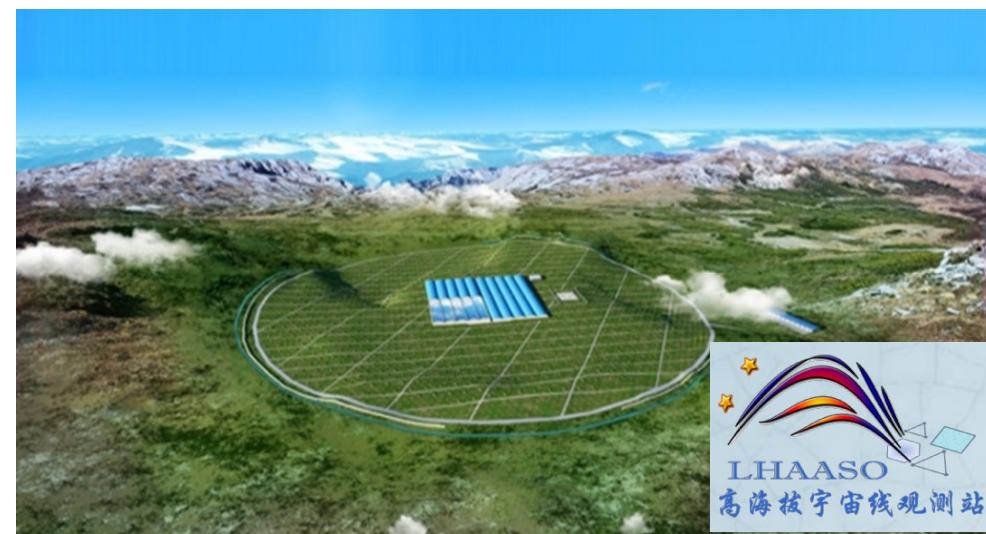
... Two new halos may have been detected !

- HAWC J0543+233 around PSR B0540+23 (*Riviere et al. 2017*), and
- HAWC J0635+070 around PSR J0633+0632 (*Brisbois et al. 2018*).

* Pulsars older than a few 10s of kyr.

* Energy densities: $\sim 0.6 \text{ eV/cm}^3$ and $\sim 0.09 \text{ eV/cm}^3$ for HAWC J0543+233 and HAWC J0635+070 resp.

In the future: CTA, SWGO/SGSO, LHAASO should detect halos too.



Science case SWGO [wide FoV in Southern Hemisphere]:

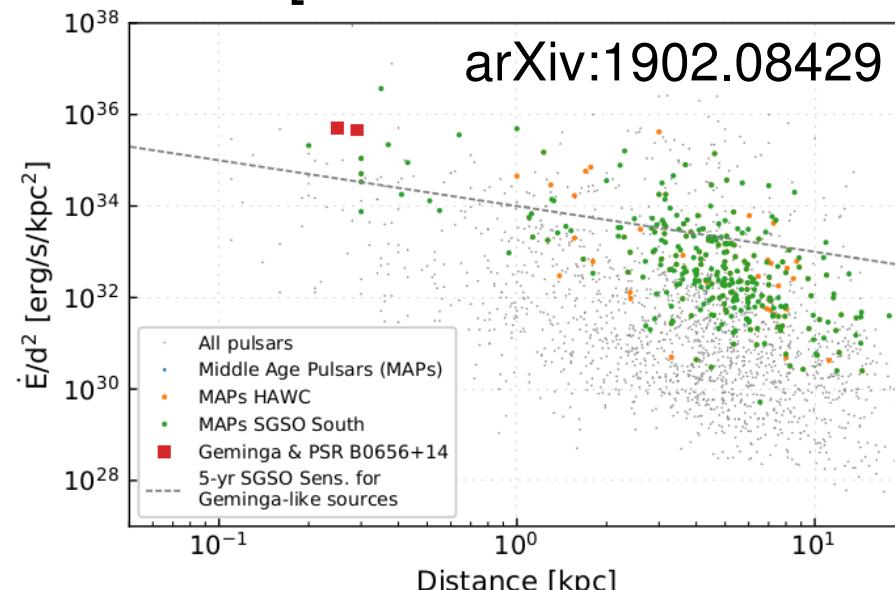


Figure 4.3: Pulsar spin-down power divided by d^2 as a function of the distance. Green points are the MAPs accessible by SGSO and orange points those accessible by HAWC. Grey points indicate the rest of the pulsars from ATNF. The gray line indicates the sensitivity to detect these sources if they produce a TeV halo similar to that produced by Geminga. This sensitivity does not take into account the limiting angular resolution of the instrument.

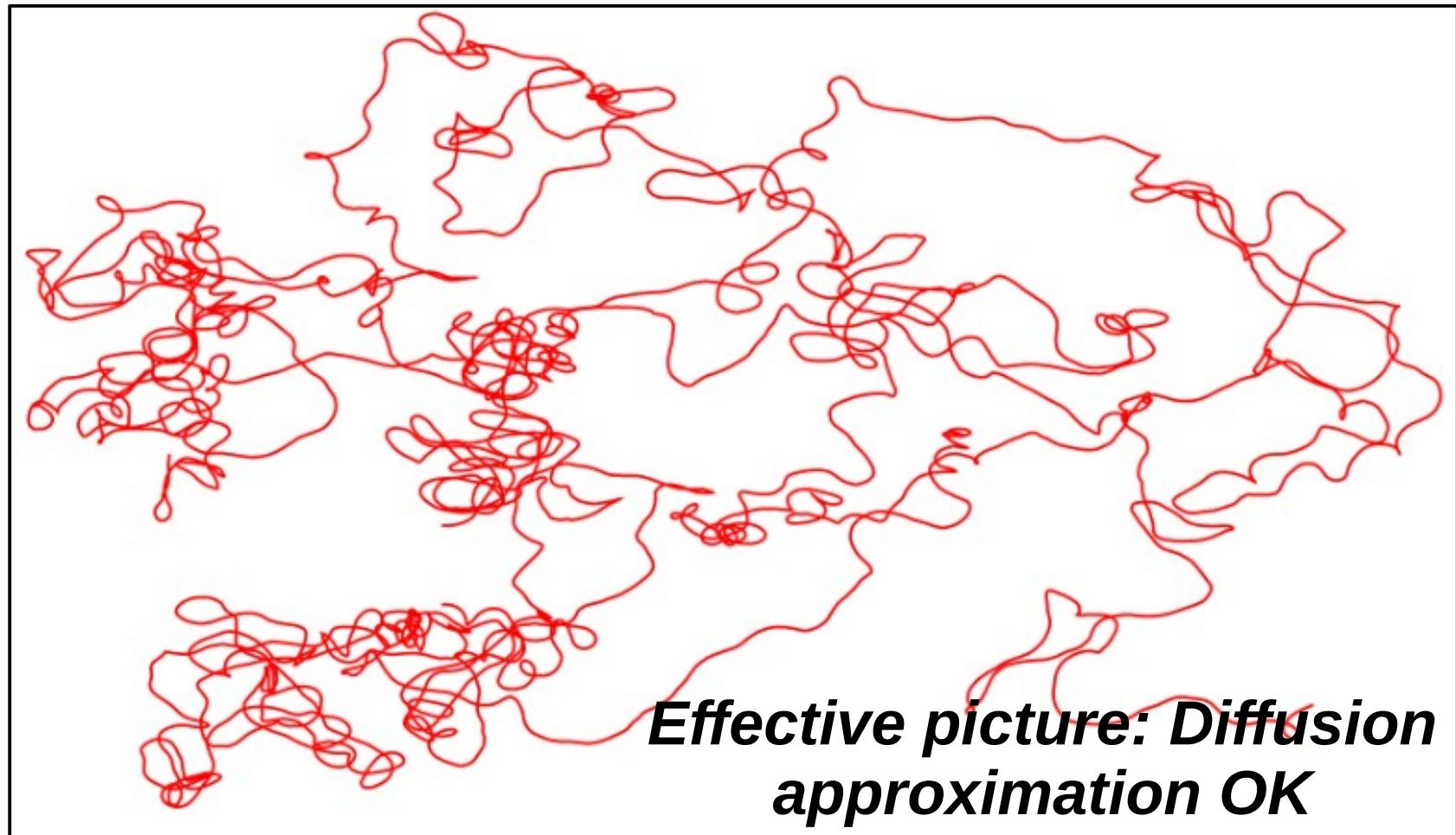
Conclusions and perspectives

- Gamma-ray observations : Crucial to constrain / improve our understanding of CR transport in the Galaxy (some observations fit basic versions of our phenomenological models, other do not).
- Have started to become new probes of the properties of the interstellar turbulence (symmetric vs asymmetric emissions)
- HAWC's TeV halos ! More should be detected !
- Around SNRs + in HAWC's TeV halos : Small D.
 - CR self-confinement ?
 - Small D in disc because of strong interstellar turbulence ?
- Unclear yet, but groundbreaking / important implications either way.

EXTRA SLIDES

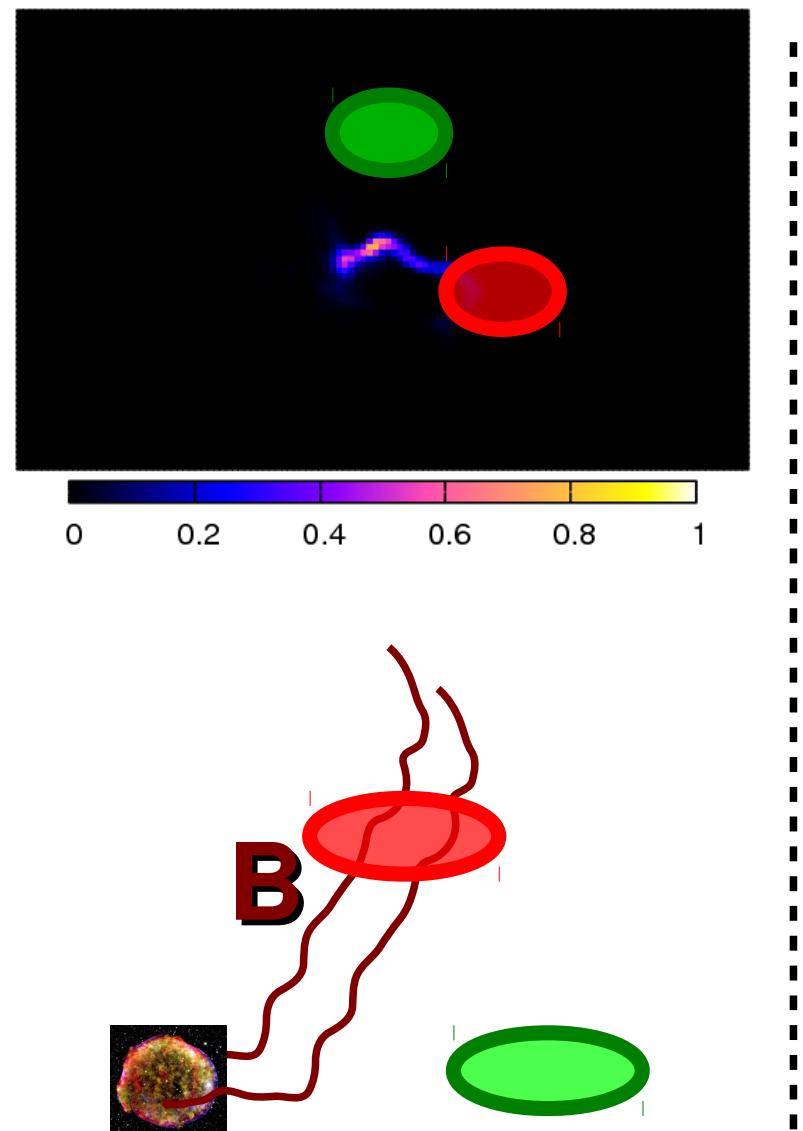
3D CR trajectories in turbulence

Numerical simulation:



Iso turbulence with power-law spectrum $\rightarrow D(E) \propto E^\delta$

Molecular Clouds : Spectrum in / out of the MF flux tube



GG, Kachelriess, Semikoz (2013)

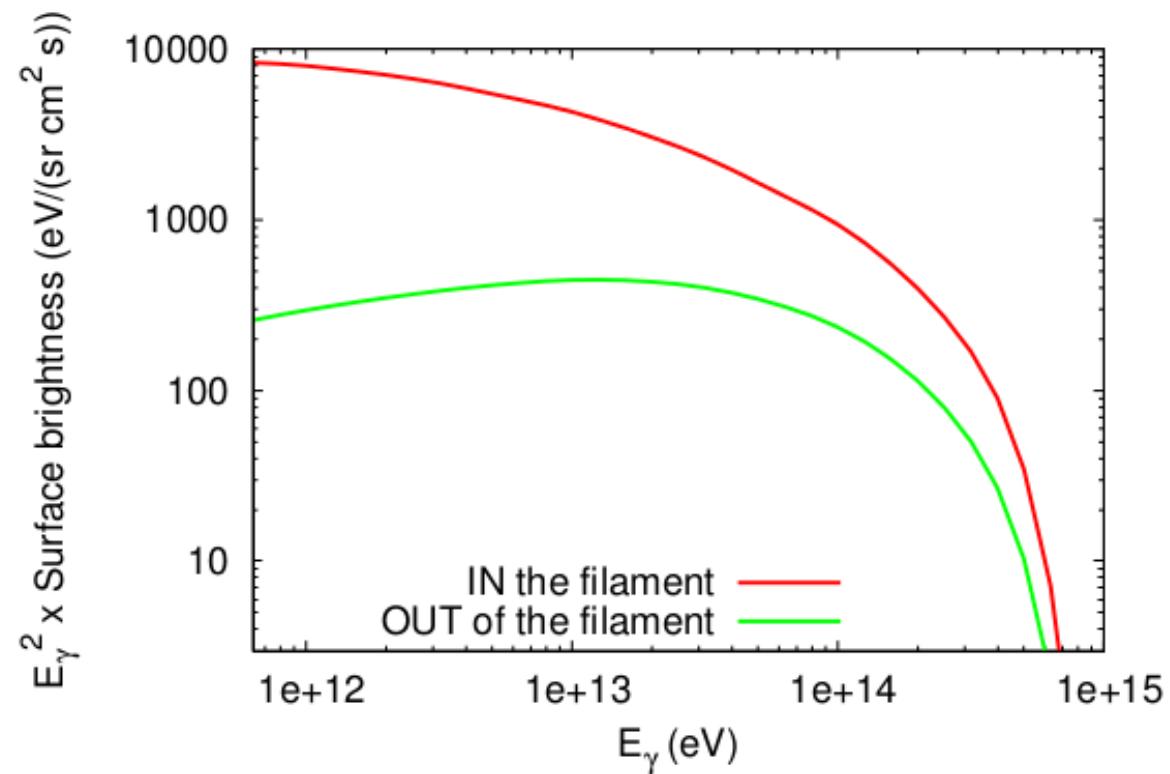


Table 1. Properties of selected well-known PWN systems in different evolutionary stages, ordered according to the system age.

System	Crab	MSH 15-52	G21.5-0.9	G0.9+0.1	Vela X	G327.1-1.1	J1825-137	Geminga
Age (kyr) ^a	0.94	1.56	4.85	5.31	11.3	18	21.4	342
PSR ^b	B0531+21	B1509-58	J1833-1034	J1747-2809	B0833-45	^c	B1823-13	J0633+1746
$\log(\dot{E})$ (erg/s)	38.65	37.23	37.53	37.63	36.84	36.49	36.45	34.51
Distance (kpc)	2	4.4	4.1	8.5	0.28	9	3.93	0.25
R _{SNR} (pc)	? ^d	38.4	2.98	19.8	19.5	22	120	?
R _{PWN} (pc) ^e	2.8	19.2	0.8	2.5	12.2	10.5	?	0.01
$v \times t$ (pc) ^f	0.27	0.45	1.4	1.5	3.3	5.2	6.2	100
R _{TeV} (pc) ^g	< 3	11	< 4	< 7	2.9	3	50	16.2
R _{X-ray} (pc)	0.24	10.2	0.8	4.9	3.08	13	9.1	0.15
Stage ^h	1	1	1b	1b	2	2	2b	3
Refs. ⁱ	I	II	III	IV	V	VI	VII	VIII

^a The pulsar characteristic age is used for the age of the system, except where historical values are known.

^b Associated pulsar (PSR). Pulsar properties are taken from Manchester et al. (2005).

^c Putative pulsar candidate identified, without pulsed emission detected Temim et al. (2009)

^d Unknown quantities are marked by “?”

^e R_{PWN} is the size of the PWN in radio (as opposed to the radio SNR shell).

^f $v \times t$ is the pulsar kick velocity multiplied by the age of the system, where a value of 300 km/s is adopted for the velocity, corresponding to the average of known values (Hansen & Phinney 1997).

^g R_{TeV} is the one sigma radius taken from Abdalla et al. (2018b) for sources within the H.E.S.S. Galactic Plane Survey (HGPS), unless a reference is provided.

^h Stage of system evolution is assigned loosely based on age, to correspond to Fig. 1

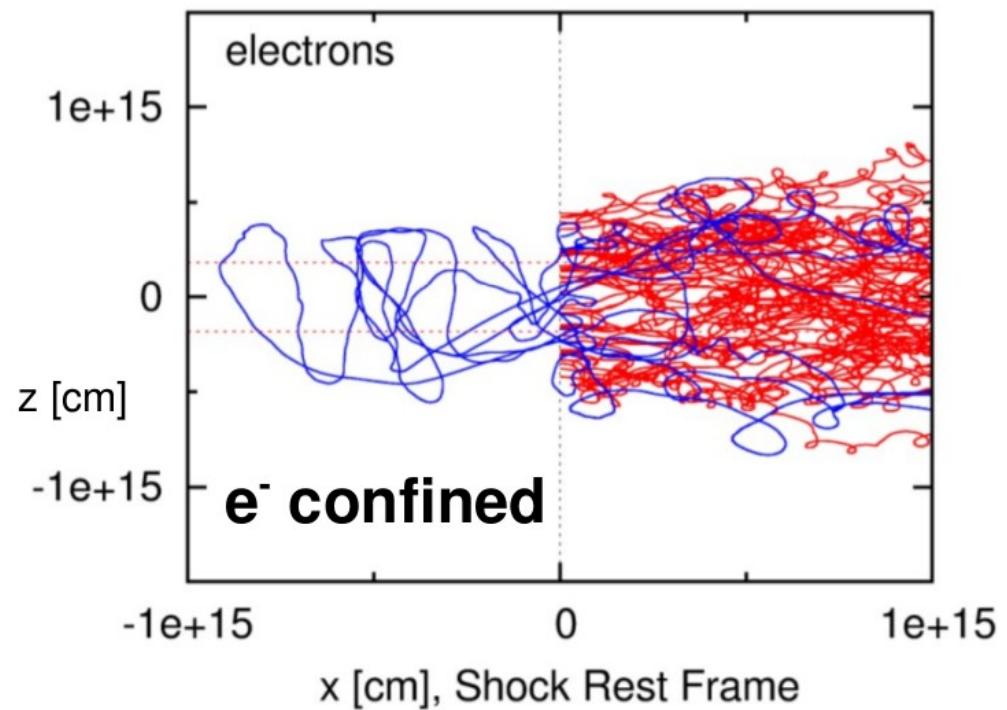
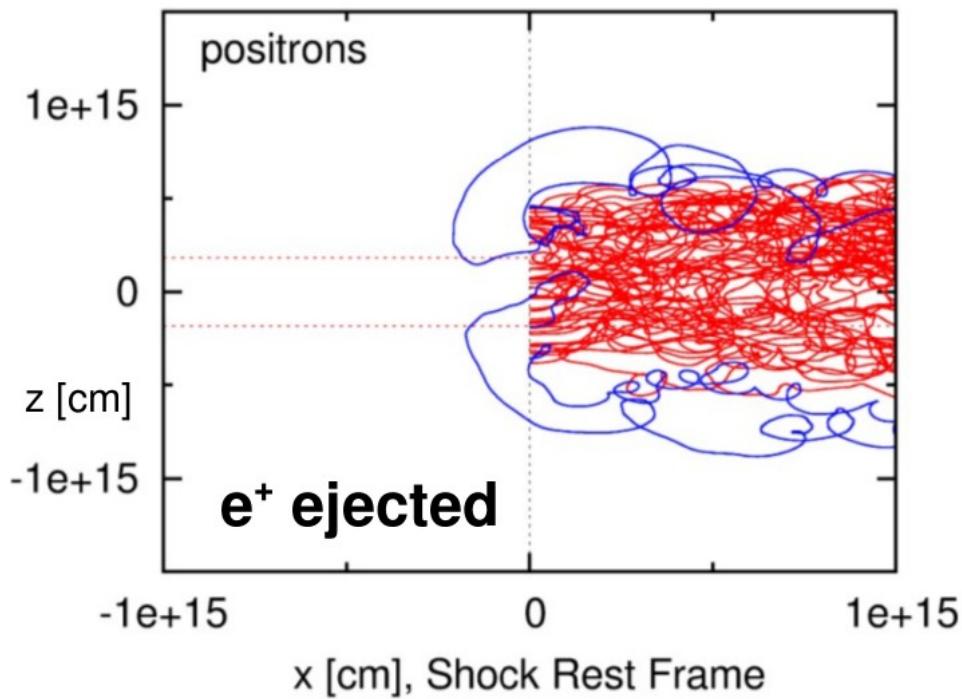
ⁱ References: **I:** Frail et al. (1995); Kargaltsev et al. (2015) **II:** Caswell et al. (1981); Du Plessis et al. (1995); Trussoni et al. (1996); Mineo et al. (2001) **III:** Matheson & Safi-Harb (2010); Safi-Harb et al. (2001) **IV:** Green (2014, 2017); Dubner et al. (2008); Porquet et al. (2003) **V:** Duncan et al. (1996); Dwarakanath (1991); Tibaldo et al. (2018) **VI:** Ma et al. (2016); Temim et al. (2015) **VII:** Stupar et al. (2008); Duvidovich et al. (2019); Pavlov et al. (2008); Uchiyama et al. (2009) **VIII:** Pellizzoni et al. (2011); Abeysekara et al. (2017a); Posselt et al. (2017); Caraveo et al. (2003)

Table 2. A compilation of TeV γ -ray sources with pulsar associations (i.e. PWN or associated Halos), together with estimated electron energy densities within the emission region (see notes below and text for details).

Name	ATNF Name	$\log_{10} \bar{E}$ (erg/s)	τ_e (kyr)	Distance (kpc)	Size (pc)	$\log_{10} E_{\text{Total}}$ (erg)	$\log_{10} \varepsilon_e(\bar{E})$ (eV/cm ³)	$\log_{10} \varepsilon_e(L_\gamma)$ (eV/cm ³)
Geminga	J0633+1746	34.51	342	0.25 ^[1]	16.2	47.5	-0.3	-2.0 ^{+0.5} _{-0.8}
B0656+14	B0656+14	34.58	111	0.29 ^[2]	16.2	47.1	-0.8	-1.5 ^{+0.4} _{-0.6}
CTA 1	J0007+7303	35.65	13.9	1.4	10.0	47.3	0.0	-0.4 ^{+0.4} _{-0.5}
J1858+020	J1857+0143	35.65	71.0	5.8	11.9	48.0	0.5	0.0 ^{+0.3} _{-0.4}
J1834-087	B1830-08 (2)	35.76	147	4.5	25.7	48.4	-0.1	-0.4 ^{+0.3} _{-0.5}
J1832-085	B1830-08 (1)	35.76	147	4.5	4.0	48.4	2.4	0.8 ^{+0.3} _{-0.4}
J1026-582	J1028-5819	35.92	90.0	2.3	8.0	48.4	1.4	0.0 ^{+0.5} _{-0.5}
J1718-385	J1718-3825	36.11	89.5	3.6	10.9	48.6	1.2	-0.2 ^{+0.5} _{-0.5}
J1303-631	J1301-6305	36.23	11.0	6.7	31.1	47.8	-1.0	0.1 ^{+0.3} _{-0.4}
J1809-193 (2)	J1809-1917	36.26	51.3	3.5	37.7	48.5	-0.5	-0.9 ^{+0.3} _{-0.4}
J1804-216	B1800-21	36.34	15.8	4.4	28.7	48.0	-0.6	-0.3 ^{+0.3} _{-0.5}
J1119-614	J1119-6127	36.36	1.61	8.4	21.1	47.1	-1.2	0.4 ^{+0.5} _{-0.7}
J1018-589A	J1016-5857 (1)	36.41	21.0	8.0	4.0	48.2	2.2	1.9 ^{+0.4} _{-0.5}
J1018-589B	J1016-5857 (2)	36.41	21.0	8.0	31.7	48.2	-0.5	-0.4 ^{+0.4} _{-0.5}
J1825-137	B1823-13	36.45	21.4	3.9	48.3	48.3	-1.0	-0.6 ^{+0.3} _{-0.4}
J1908+063	J1907+0602	36.45	19.5	3.2	41.1	48.2	-0.9	-0.9 ^{+0.4} _{-0.4}
J1356-645	J1357-6429	36.49	7.31	2.5	15.2	47.9	0.0	0.2 ^{+0.4} _{-0.4}
J1708-443	B1706-44	36.53	17.5	2.6	19.2	48.3	0.2	-0.6 ^{+0.4} _{-0.4}
J1641-462	J1640-4631 (2)	36.64	3.35	12.8	14.0	47.7	0.0	0.3 ^{+0.3} _{-0.5}
J1640-465	J1640-4631 (1)	36.64	3.35	12.8	37.7	47.7	-1.3	0.2 ^{+0.3} _{-0.5}
J1857+026	J1856+0245	36.66	20.6	9.0	61.9	48.5	-1.2	-0.8 ^{+0.3} _{-0.5}
J1418-609	J1418-6058	36.69	10.3	5.0 ^[3]	14.2	48.2	0.5	0.5 ^{+0.4} _{-0.4}
J1837-069	J1838-0655	36.74	22.7	6.6	61.9	48.6	-1.0	-0.7 ^{+0.3} _{-0.5}
J1809-193 (1)	J1811-1925	36.81	23.3	5.0	52.8	48.7	-0.8	-1.1 ^{+0.3} _{-0.4}
J0835-455	B0833-45	36.84	11.3	0.3	4.4	48.4	2.2	0.5 ^{+0.5} _{-0.5}
J1846-029	J1846-0258	36.91	0.73	5.8	3.0	47.3	1.6	1.7 ^{+0.3} _{-0.4}
J1849-000	J1849-0001	36.99	42.9	7.0 ^[4]	16.6	49.1	1.2	-0.4 ^{+0.5} _{-0.4}
J1420-607	J1420-6048	37.00	13.0	5.6	11.9	48.6	1.1	0.9 ^{+0.4} _{-0.4}
J1023-575	J1023-5746	37.04	4.60	8.0 ^[5]	35.0	48.2	-0.7	0.0 ^{+0.3} _{-0.5}
J1930+188	J1930+1852	37.08	2.89	7.0	9.0	48.0	0.9	0.6 ^{+0.4} _{-0.6}
J1616-508	J1617-5055	37.20	8.13	6.8	42.3	48.6	-0.5	-0.4 ^{+0.4} _{-0.4}
J1514-591	B1509-58	37.23	1.56	4.4	16.8	47.9	0.0	0.5 ^{+0.4} _{-0.4}
3C58	J0205+6449	37.43	5.37	2.0 ^[6]	5.0	48.7	2.3	0.1 ^{+0.3} _{-0.6}
J1833-105	J1833-1034	37.53	4.85	4.1	4.0	48.7	2.7	1.0 ^{+0.3} _{-0.4}
G0.9+0.1	J1747-2809	37.63	5.31	13.3	7.0	48.9	2.1	1.5 ^{+0.3} _{-0.4}
J1813-178	J1813-1749	37.75	5.60	4.7	6.0	49.0	2.4	1.1 ^{+0.4} _{-0.4}
Crab Nebula	B0531+21	38.65	1.26	2.0	3.0	49.2	3.6	3.2 ^{+0.5} _{-0.8}

Pulsars may come in two categories and accelerate either e^+ or e^- to HE, but not both!

GG & Kirk (2018) : $e^{+/-}$ trajectories at the pulsar-wind termination shock

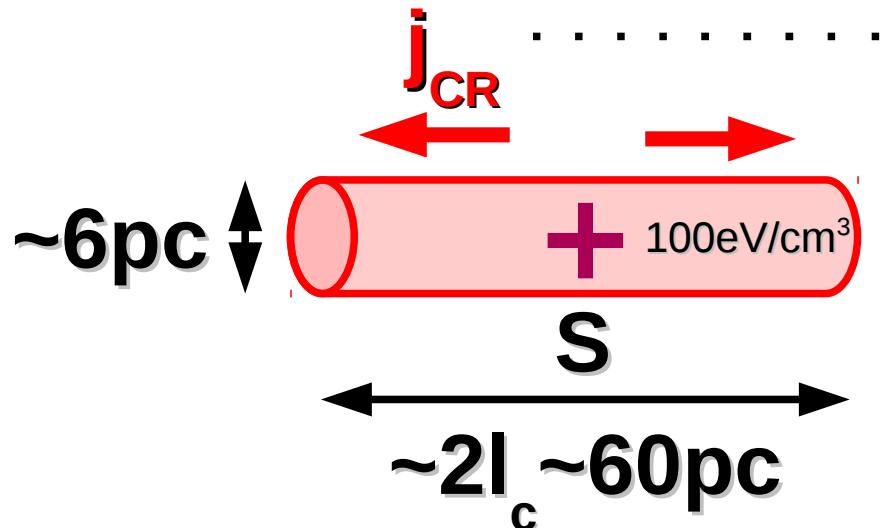


No/little acceleration

Acceleration

Major implications for the e^+ fraction ! If < 0.5 , means local "e⁻-pulsar".

CR-driven instabilities



$$\sim U_{\text{CR}} e D / (E l_c)$$

$$5\Gamma_{\text{BNRH}}^{-1} \approx 10\sqrt{\rho_{\text{ISM}}/\mu_0} E^{2/3} l_c / (U_{\text{CR}} e D_0)$$

$$\approx 1.4, 3.1, 14 \text{ and } 67 \text{ kyr}$$

$$3, 10, 100 \text{ and } 1000 \text{ TeV CRs}$$

$$t_c \sim l_c^2 / D$$

$$| E \gtrsim 0.1 \sqrt{\mu_0 / \rho_{\text{ISM}}} U_{\text{CR}} e l_c \approx 40 \text{ TeV} |$$

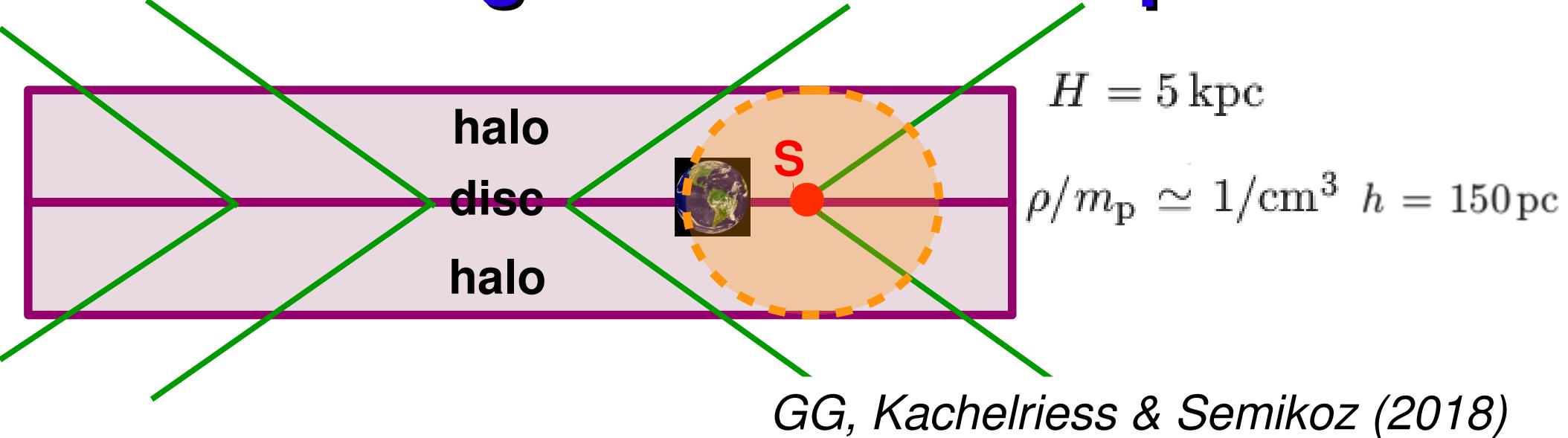
If e.g. 1 % neutrals
 \rightarrow damp. $\sim 1\text{kyr}$

NB : The CR pressure does not widen the filaments

$$\rho_{\text{ISM}} du/dt = |\nabla P_{\text{CR}}| \sim 100 \text{ eV}\cdot\text{cm}^{-3}/3\text{ pc}$$

$$t_{10k}^2 du/dt \approx 0.3 \text{ pc}$$

Grammage with an out-of-plane B



Isotropic diffusion:

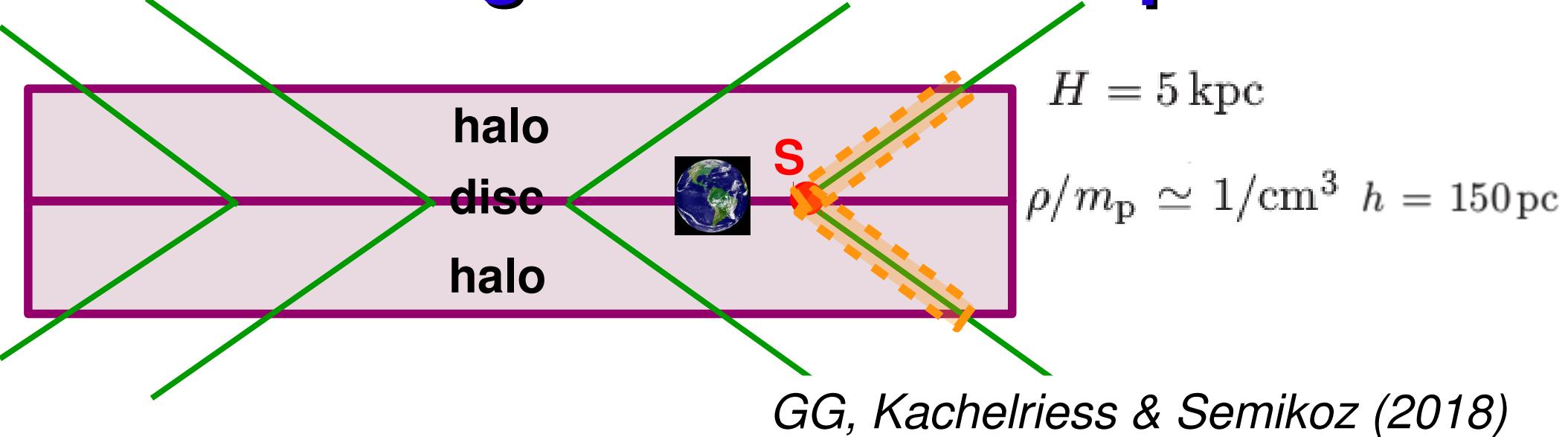
$D_{\text{iso}}(E_*) \sim 5 \times 10^{29} \text{ cm}^2/\text{s}$ at $E_* = 10 \text{ TeV}$ satisfies B/C ($H \sim 5 \text{ kpc}$)

Size of the diffusion front at $t = 2 \text{ Myr}$: $L(t) = \sqrt{2Dt} \simeq 2.5 \text{ kpc}$

$$\Rightarrow E_*^{2.8} I(E_*) \simeq 200 \text{ GeV}^{1.8} \text{ sr}^{-1} \text{ s}^{-1} \text{ m}^{-2}$$

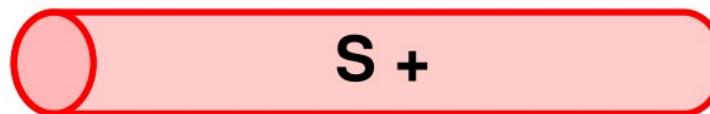
Only 1/100 of observed CR intensity $\Rightarrow >\sim 100$ s sources contribute.

Grammage with an out-of-plane B



Anisotropic diffusion:

$$I(E) \simeq \frac{c}{4\pi} \frac{Q(E)}{V(t)}$$



$$V(t) = \pi^{3/2} D_{\perp} D_{\parallel}^{1/2} t^{3/2} \quad \text{where} \quad 2Dt \sim L^2$$

If takes D_{\parallel} ($\rightarrow D_{\perp}$) that satisfy B/C, the volume $V(t)$ is reduced by ~ 200

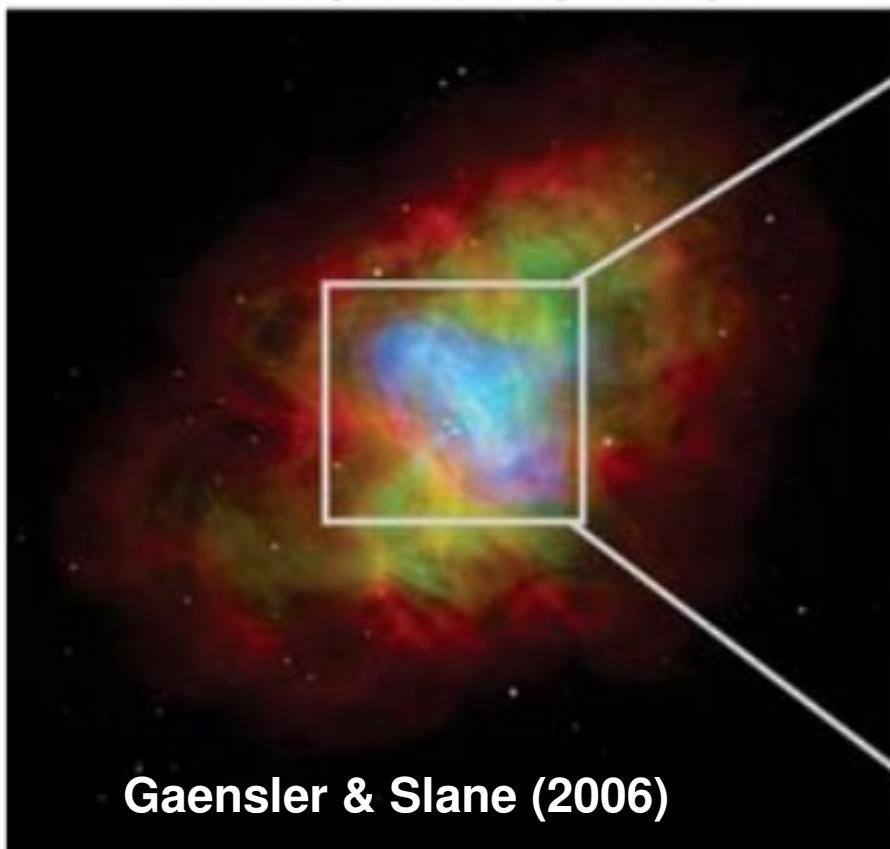
=>One local source ($\sim 200 \text{ pc}$) may dominate the CR flux at $>\sim 10 \text{ TeV}$

Erlykin&Wolfendale + explanation for e^+ , $p\bar{p}$ (Kachelriess & Semikoz)

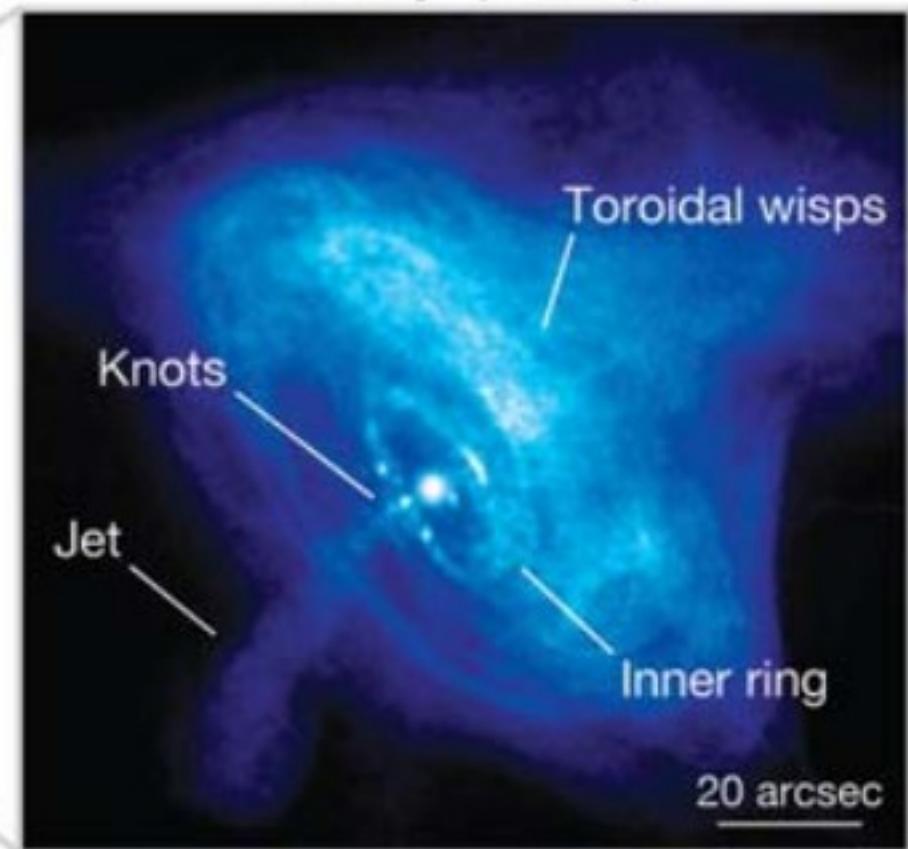
Evolutionary stages of a PWN :

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

Composite (CXC)

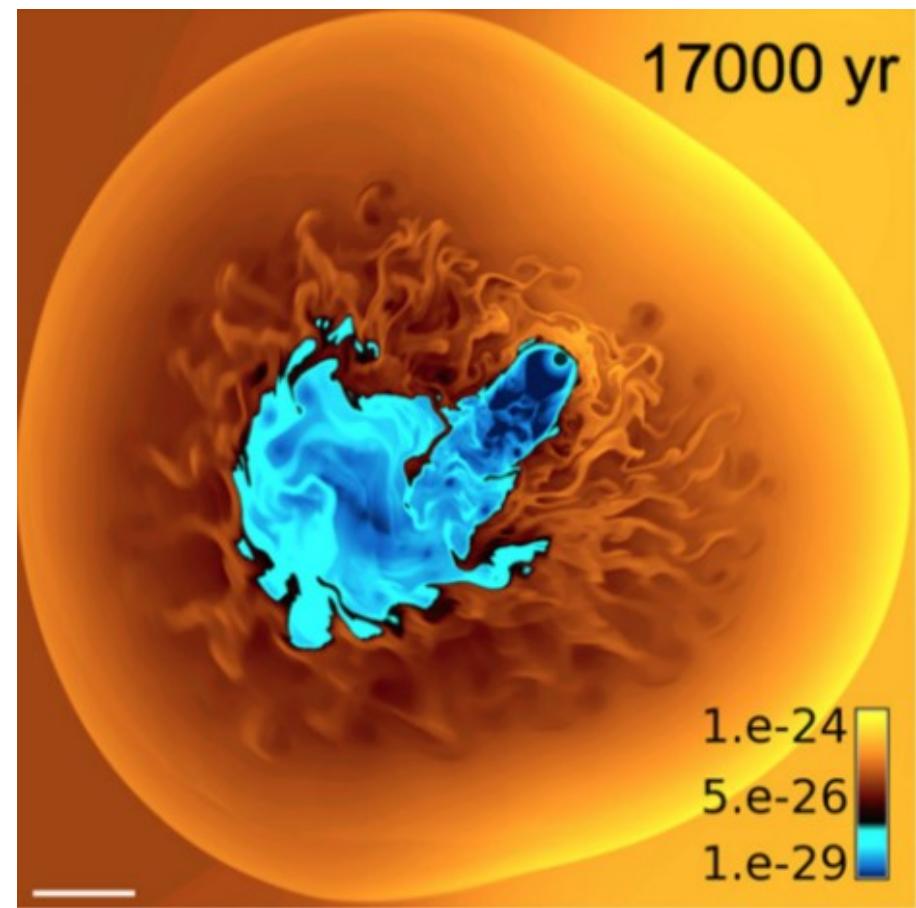


X-ray (CXC)



Evolutionary stages of a PWN :

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



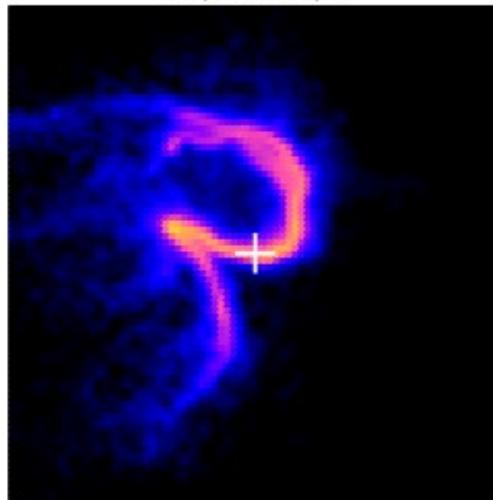
X-ray: NASA/CXC/SAO/T.Temim et al. and ESA/XMM-Newton Radio: SIFA/MOST and CSIRO/ATNF/ATCA;
Infrared: UMass/IPAC-Caltech/NASA/NSF/2MASS

Simulation -Temim et al. (2015)

Simulated γ -ray images of a source :

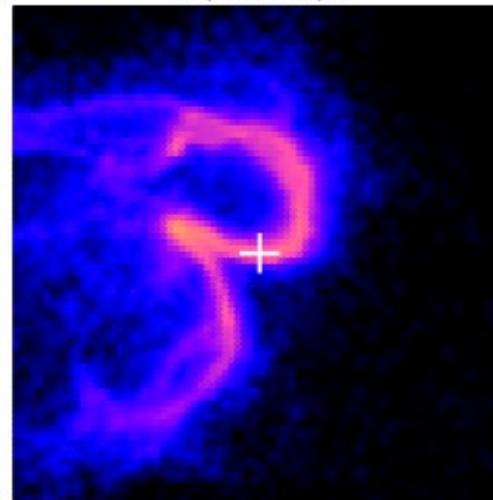
$t = 0.5 \text{ kyr}$

80 pc x 80 pc



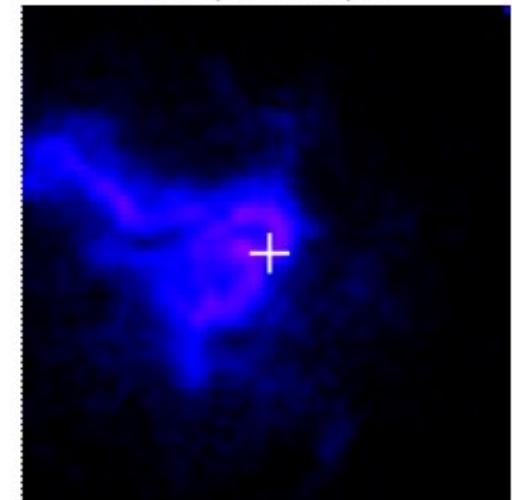
2 kyr

80 pc x 80 pc



10 kyr after escape

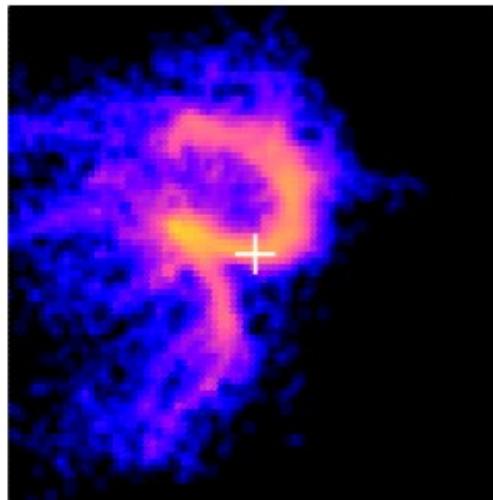
240 pc x 240 pc



$> 300 \text{ GeV}$

0.1 1 10 100 1000

$> 30 \text{ TeV}$



0.001 0.01 0.1 1

0.001 0.01 0.1 1

0.001 0.01 0.1 1

