Explanation for the Anisotropies at Small and Medium Angular Scales

Gwenael Giacinti

University of Oxford, Clarendon Laboratory

Based on :

<u>GG & G.Sigl Phys. Rev. Lett. 109, 071101(2012)</u>

GG, M.Kachelriess, D.Semikoz Phys. Rev. Lett. 108, 261101(2012)
Phys. Rev. D 88, 023010 (2013)

UNIVERSITY OF OXFORD

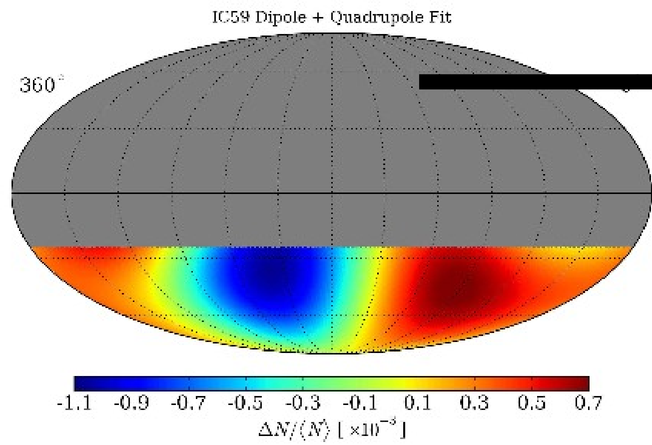
With thanks to Tony Bell, Brian Reville & Klara Schure for discussions

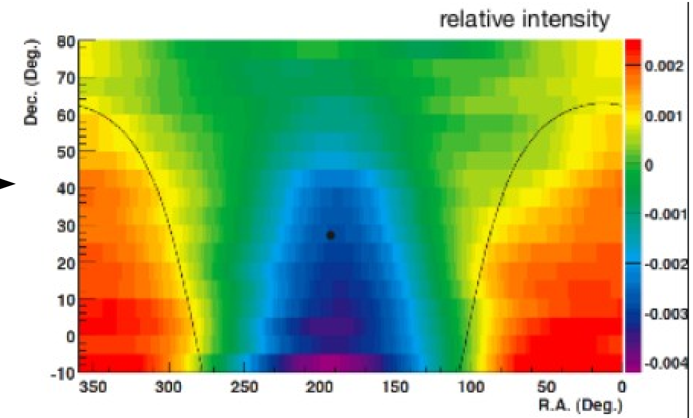
erc

Observations

IceCube results, here

~0.1%

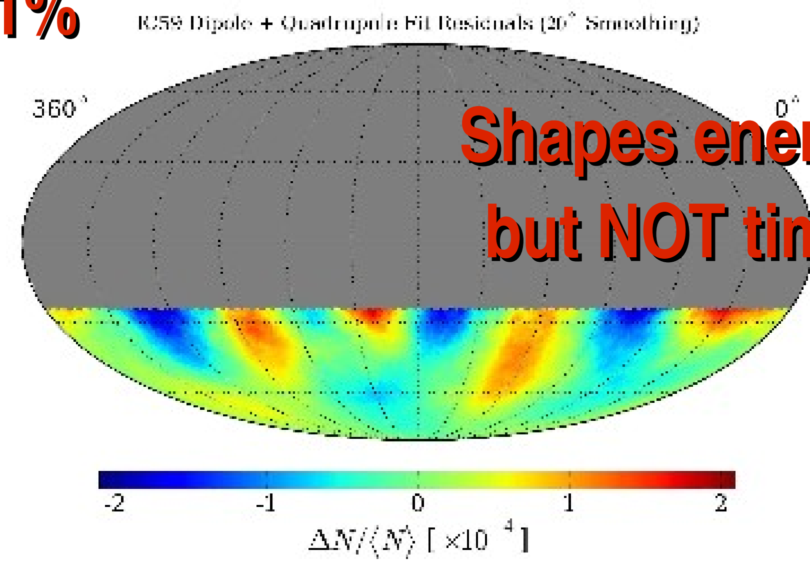


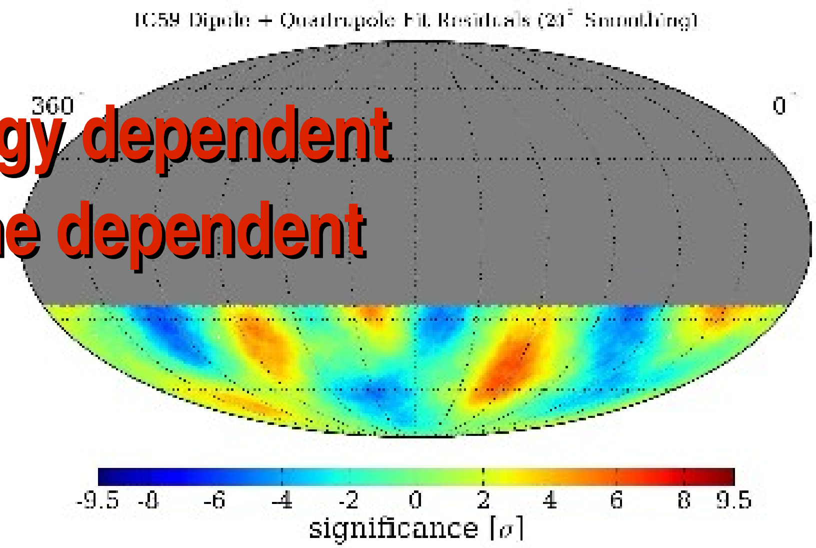


1105.2326

Milagro

~0.01%



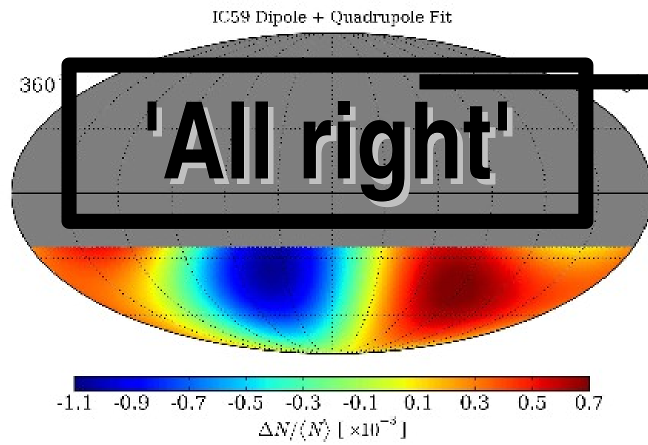


Shapes energy dependent
but NOT time dependent

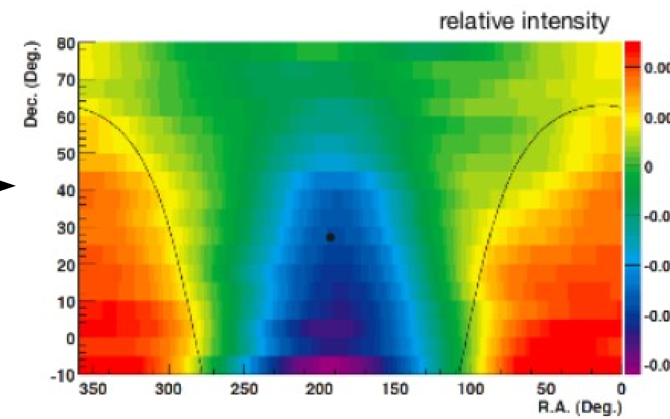
Observations

IceCube results, here

~0.1%



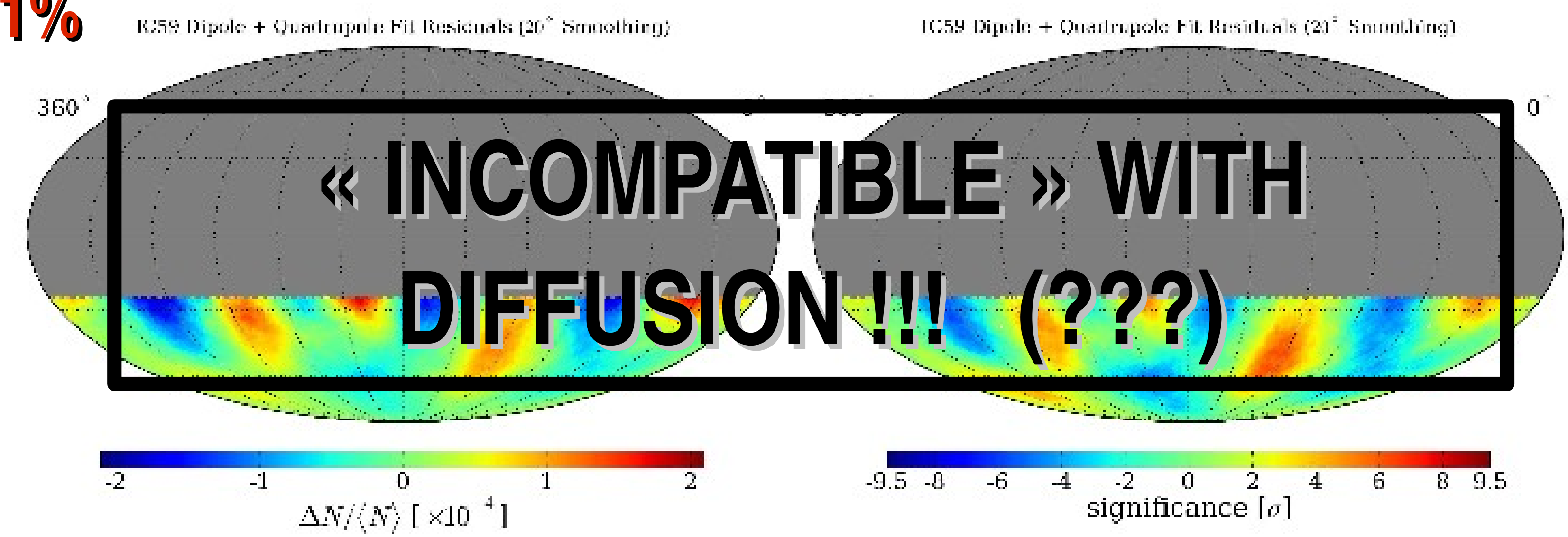
'All right'



1105.2326

Milagro

~0.01%



« INCOMPATIBLE » WITH DIFFUSION !!! (???)

The Galactic turbulent magnetic field

Satisfies : <**B**(**x**)> = **0**, <**B**(**x**)^2> = B_{rms}^2, and div **B** = 0

+ ω t

Fourier transform : $$B_i(\mathbf{x}) = \int \frac{\mathrm{d}^3 k}{(2\pi)^3} B_i(\mathbf{k}) e^{i(\mathbf{k}\cdot\mathbf{x}+\phi_\mathbf{i}(\mathbf{k}))}$$

with $|\boldsymbol{B}(\boldsymbol{k})|^2 \propto k^{-\alpha-2}$

Power spectrum : $\mathcal{P}(k) \propto k^{-\alpha}$ (α = 5/3, 3/2 plausible)

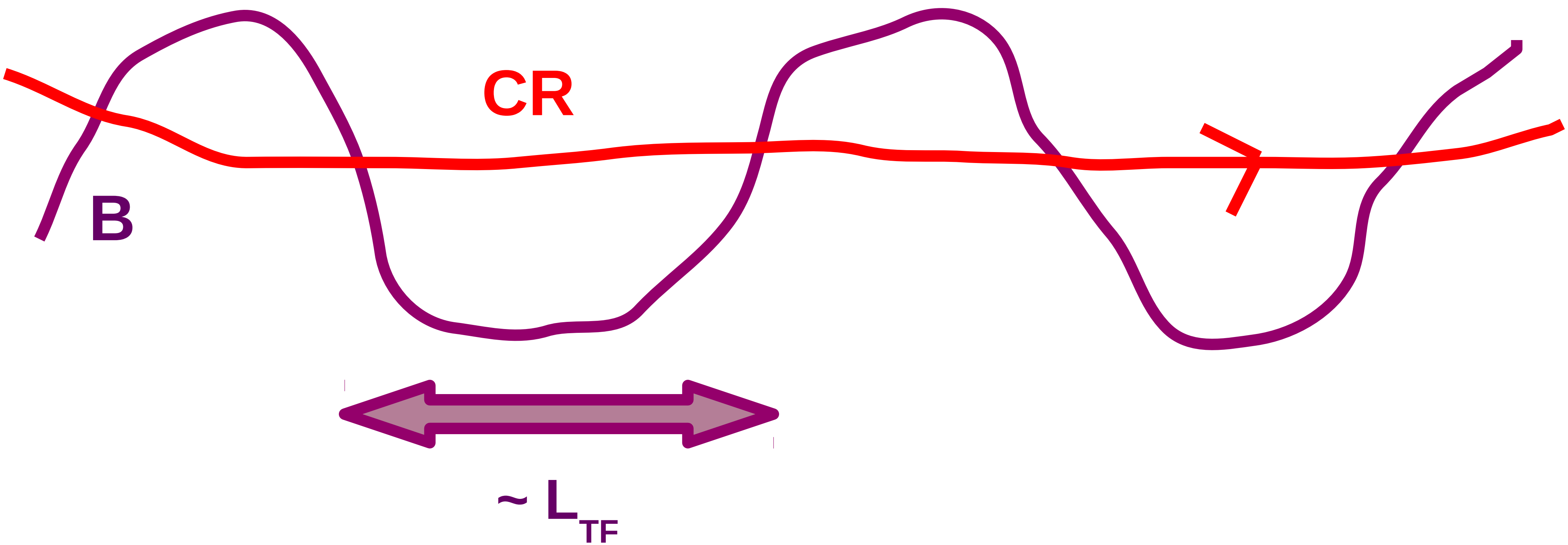
for $2\pi/L_{max} \leq k \leq 2\pi/L_{min}$ with L_{min} < 1 AU, L_{max} ~ 100 pc

Coherence length : L_c ~ few 10s pc.

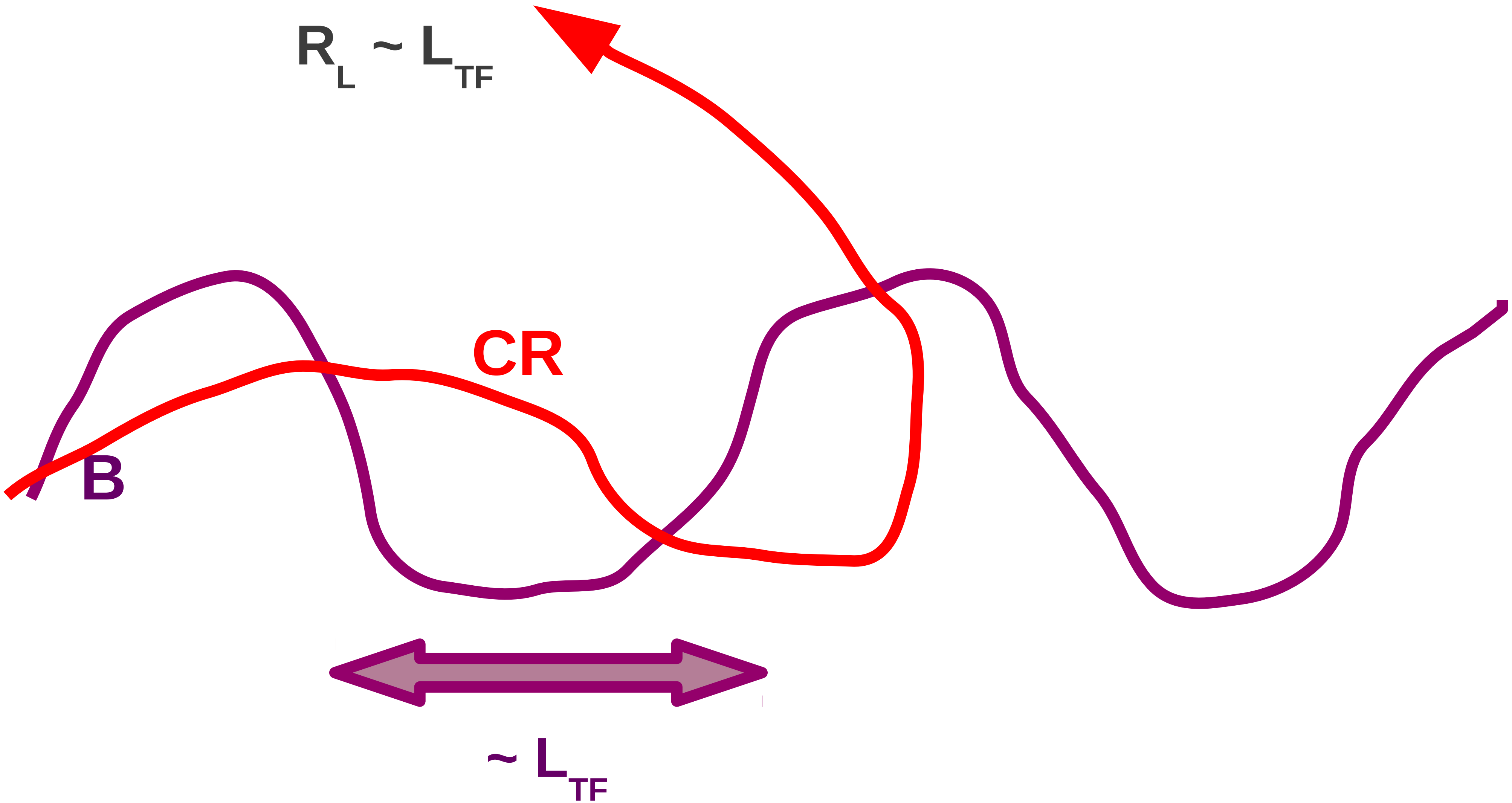
Locally : See works of P. Frisch

CR propagation in magnetic turbulence

$R_L \gg L_{TF}$



CR propagation in magnetic turbulence

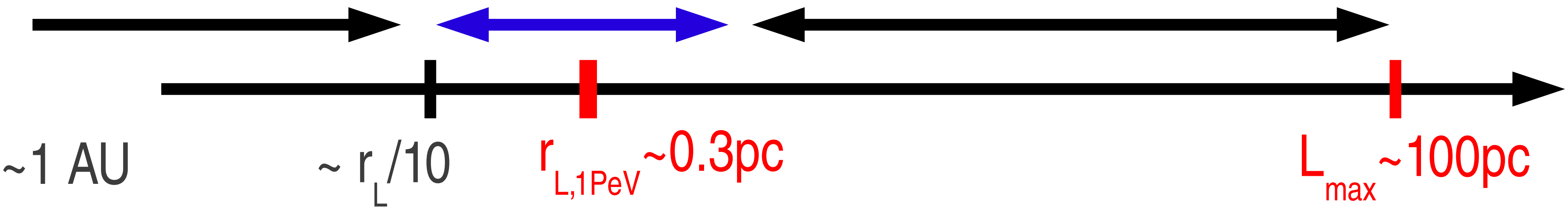


Diffusion approximation

« No » effect

Resonant scattering of CRs

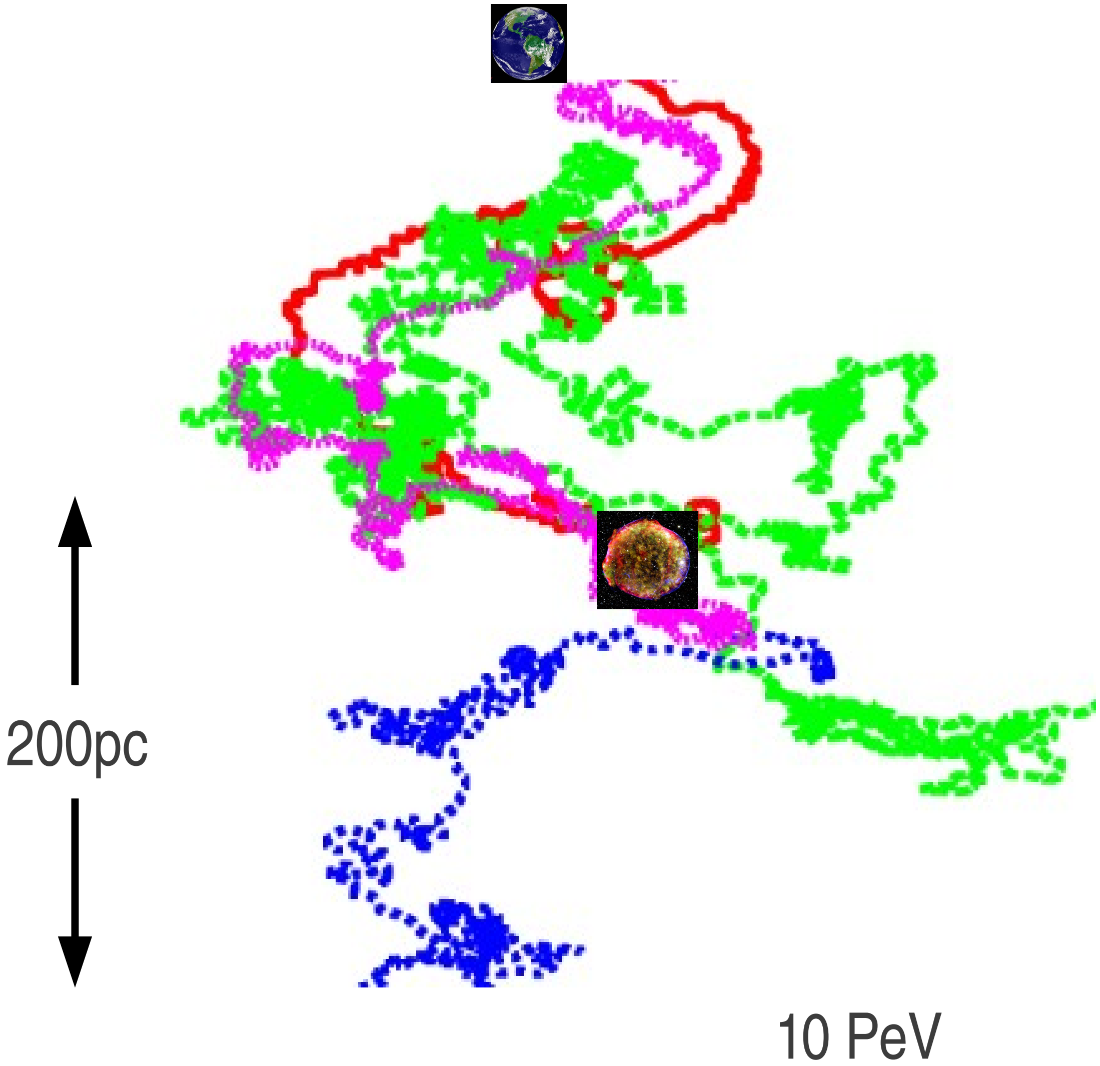
Act as local regular fields



CR propagation in magnetic turbulence can be regarded as a **Markovian process**

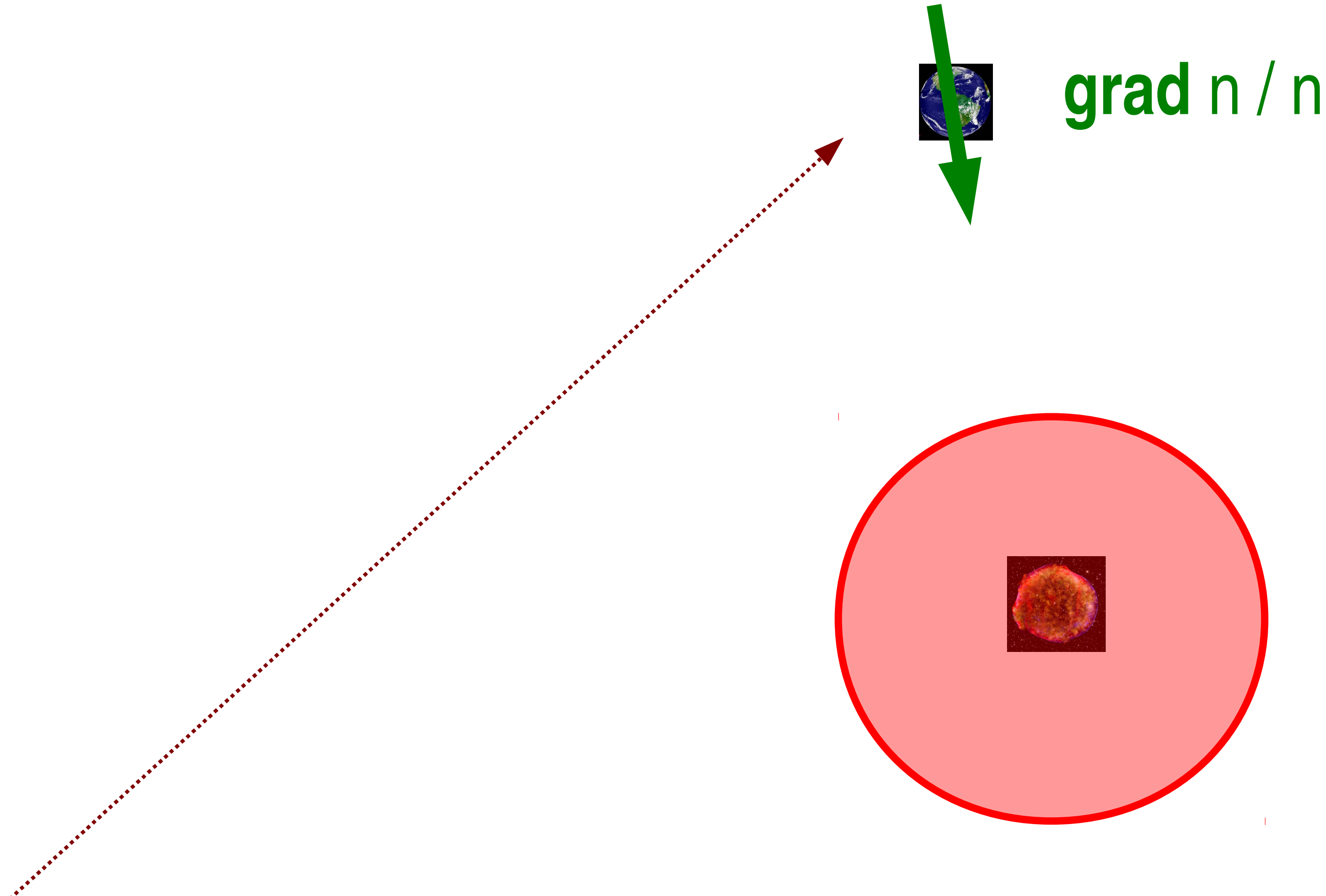
=> **diffusion approximation**

Diffusion approximation



Globally /
effective picture :
All right

Diffusion approximation

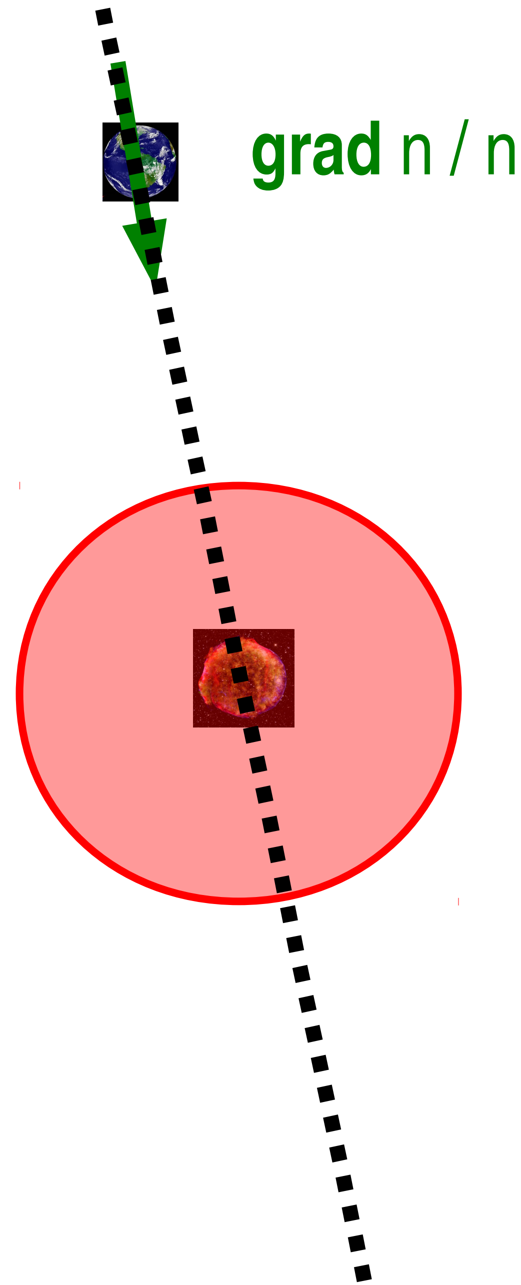


$$\boldsymbol{\delta}(p) \simeq -\frac{3}{c_0}\frac{\mathbf{j}}{n} = \frac{3D(p)}{c_0}\frac{\boldsymbol{\nabla} n}{n}$$

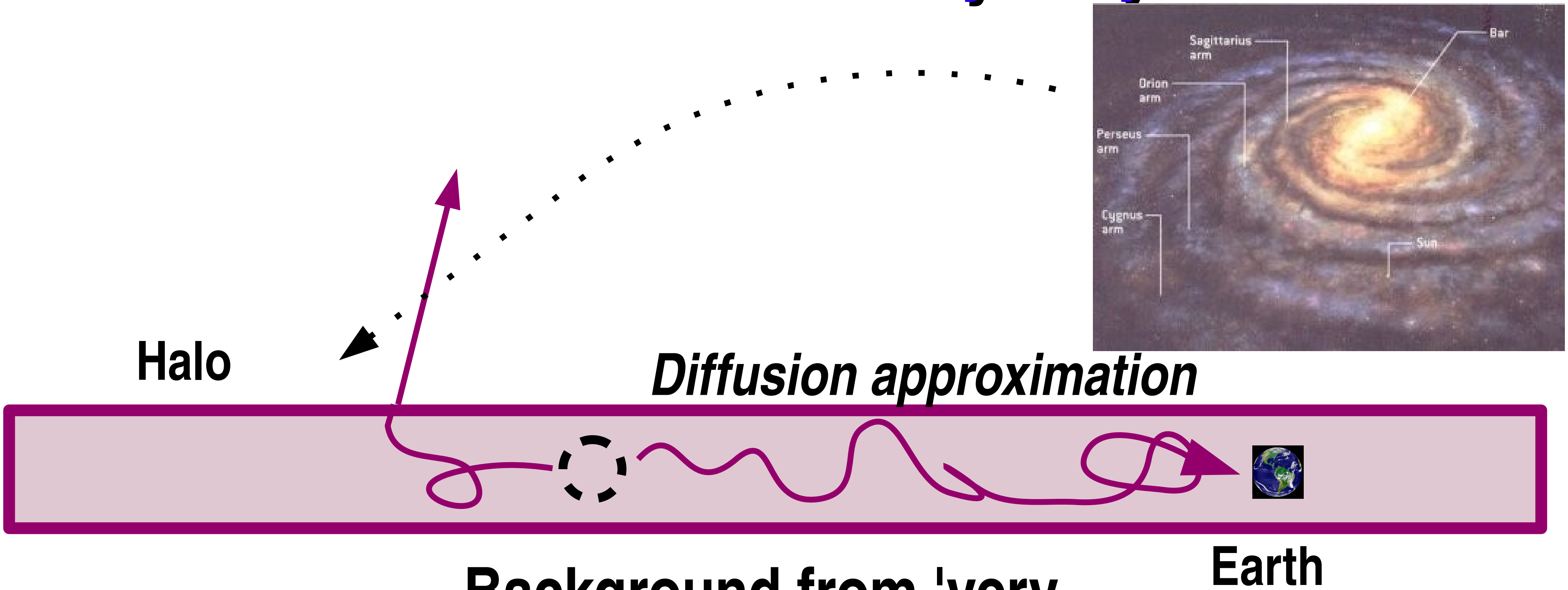
where $\mathbf{j}(\mathbf{r}, p) = -D(p)\boldsymbol{\nabla} n$ is the CR current

DIPOLE δ '~' $(E/Z)^{1/3;\ 1/2}$

Diffusion approximation



CR diffusion in the Milky Way



Background from 'very old' sources

Rather isotropic

CR diffusion in the Milky Way

Background from 'very old' sources

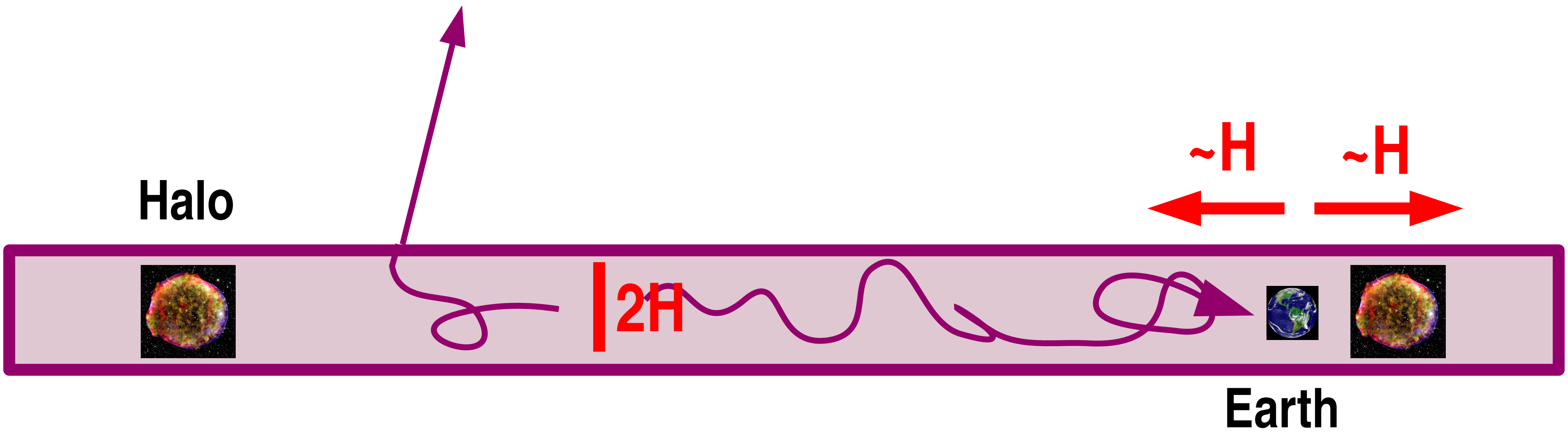
+

Flux from 'more recent' sources: ***More anisotropic***

---> CR anisotropy at Earth due to 'most recent' sources

CR diffusion in the Milky Way

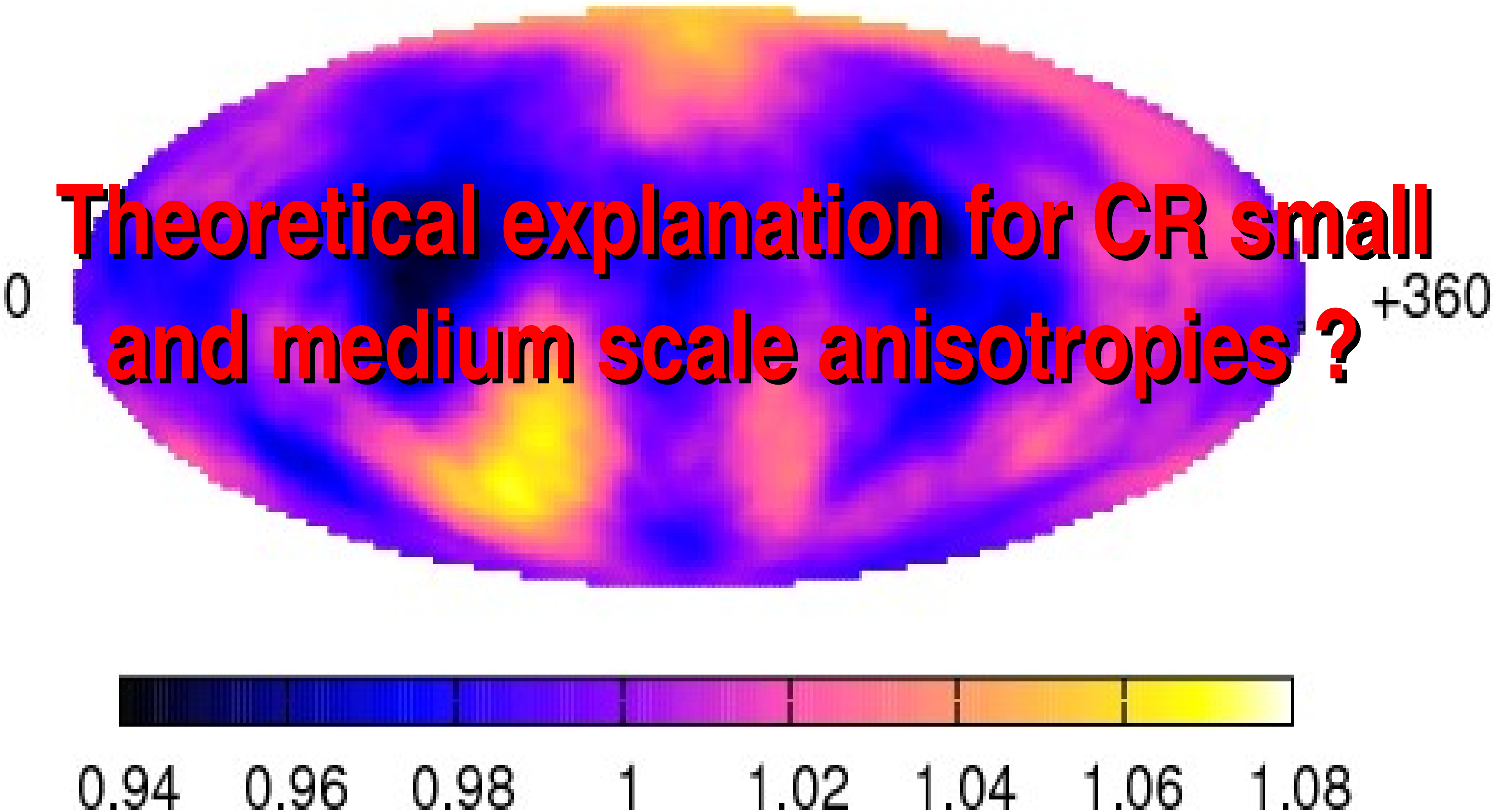
(Erlykin & Wolfendale '06, Blasi & Amato '11)



CR anisotropy at Earth mostly due to 'most recent' and 'nearby' sources

=> DIPOLE $\delta \sim (E/Z)^{2-\alpha} \sim (E/Z)^{1/3;\ 1/2}$

Theoretical explanation for CR small and medium scale anisotropies ?



Based on : Giacinti & Sigl Phys. Rev. Lett. 109, 071101 (2012)

Small scale anisotropies : 'mysterious'

In magnetic turbulence, only a dipolar anisotropy should be detected => Additional effects needed.

- ~~Related to sources ?~~ CRs do not point back to their sources

Small scale anisotropies : Suggestions

Magnetic funnelling (Drury & Aharonian '08)

Astroparticle Physics 29 (2008) 420–423

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/ast

ELSEVIER

The puzzling MILAGRO hot spots

L.O'C. Drury *, F.A. Aharonian

Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland

A R T I C L E I N F O

Article history:
Received 2 April 2008
Received in revised form 18 April 2008
Accepted 21 April 2008
Available online 10 May 2008

Keywords:
Cosmic ray anisotropy
Local sources

A B S T R A C T

We discuss the reported detection by the MILAGRO experiment of localised hot spots in the cosmic ray arrival distribution and the difficulty of interpreting these observations. A model based on secondary neutron production in the heliotail is shown to fail. An alternative model based on loss-cone leakage through a magnetic trap from a local source region is proposed.

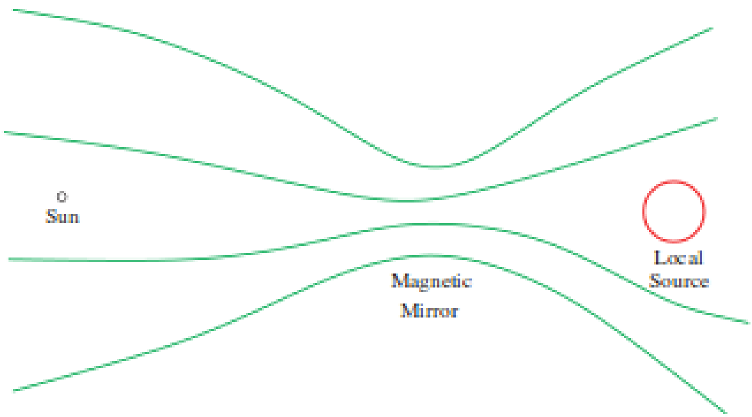


Fig. 1. A cartoon representation of the suggested model. The magnetic field near the sun is linked through a strong field region where most particles are mirrored to a region containing a slightly higher amplitude and harder spectrum of cosmic rays, presumably as a result of a local source event such as a supernova explosion. Only particles with pitch angles closely aligned to the field can penetrate through the mirror and emerge as a field-aligned beam on the other side (another possibility would be to locate the source inside the strong field region itself rather than behind the trap).

Small scale anisotropies : Suggestions

Anisotropic turbulence (Malkov *et al.* '10)

THE ASTROPHYSICAL JOURNAL, 721:750–761, 2010 September 20 doi:10.1088/0004-637X/721/1/750

PROBING NEARBY COSMIC-RAY ACCELERATORS AND INTERSTELLAR MEDIUM TURBULENCE WITH MILAGRO HOT SPOTS

M. A. MALKOV[1], P. H. DIAMOND[1], L. O'C. DRURY[2], AND R. Z. SAGDEEV[3]
[1] CASS and Department of Physics, University of California, San Diego, La Jolla, CA 92093-0424, USA
[2] Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland
[3] University of Maryland, College Park, MD 20742-3280, USA
Received 2010 May 7; accepted 2010 July 28; published 2010 September 1

ABSTRACT

Both the acceleration of cosmic rays (CRs) in supernova remnant shocks and their subsequent propagation through the random magnetic field of the Galaxy are deemed to result in an almost isotropic CR spectrum. However, the MILAGRO TeV observatory discovered sharp ($\sim 10^\circ$) arrival anisotropies of CR nuclei. We suggest a mechanism for producing a weak and narrow CR beam which operates en route to the observer. The key assumption is that CRs are scattered by a strongly anisotropic Alfvén wave spectrum formed by the turbulent cascade across the local field direction. The strongest pitch-angle scattering occurs for particles moving almost precisely along the field line. Partly because this direction is also the direction of the minimum of the large-scale CR angular distribution, the enhanced scattering results in a weak but narrow particle excess. The width, the fractional excess, and the maximum momentum of the beam are calculated from a systematic transport theory depending on a single scale l which can be associated with the longest Alfvén wave, which efficiently scatters the beam. The best match to all three characteristics of the beam is achieved at $l \sim 1$ pc. The distance to a possible source of the beam is estimated to be within a few 100 pc. Possible approaches to the determination of the scale l from the characteristics of the source are discussed. Alternative scenarios of drawing the beam from the galactic CR background are considered. The beam-related large-scale anisotropic CR component is found to be energy independent, which is also consistent with the observations.

Key words: acceleration of particles – cosmic rays – diffusion – ISM: supernova remnants – magnetohydrodynamics (MHD) – scattering – shock waves – turbulence

Small scale anisotropies : Suggestions

A local source in the heliotail (Lazarian & Desiati '10)

THE ASTROPHYSICAL JOURNAL, 722:188–196, 2010 October 10 doi:10.1088/0004-637X/722/1/188

MAGNETIC RECONNECTION AS THE CAUSE OF COSMIC RAY EXCESS FROM THE HELIOSPHERIC TAIL

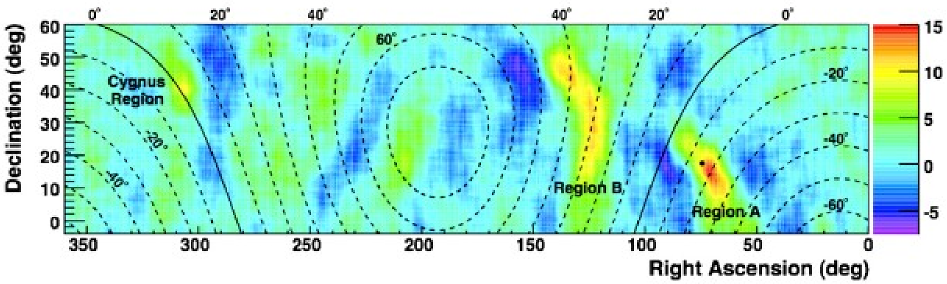
A. LAZARIAN[1] AND P. DESIATI[2]
[1] Astronomy Department, University of Wisconsin, Madison, WI 53706, USA
[2] Department of Physics, University of Wisconsin, Madison, WI 53706, USA
Received 2010 May 10; accepted 2010 August 1; published 2010 September 17

ABSTRACT

The observation of a broad excess of sub-TeV cosmic rays compatible with the direction of the heliospheric tail and the discovery of two significant localized excess regions of multi-TeV cosmic rays by the MILAGRO Collaboration, also from the same region of the sky, have raised questions on their origin. In particular, the coincidence of the most significant localized region with the direction of the heliospheric tail and the small angular scale of the observed anisotropy ($\sim 10^\circ$) is suggestive of a local origin and of a possible connection to the low-energy broad excess. Cosmic ray acceleration from magnetic reconnection in the magnetotail is proposed as a possible source of the energetic particles.

Key words: acceleration of particles – cosmic rays – magnetic fields – magn
solar wind

Online-only material: color figures



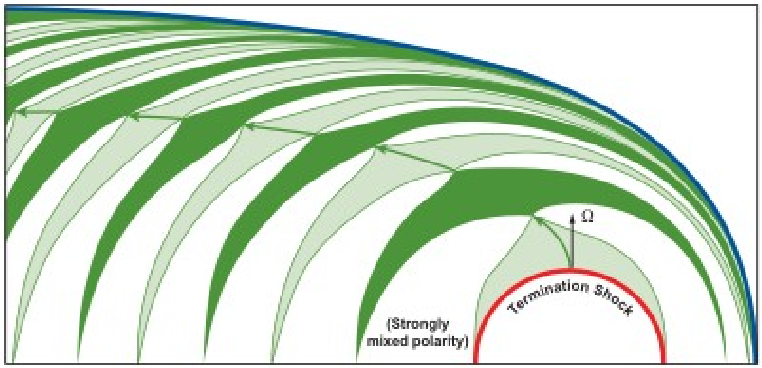


Figure 4. Meridional view of the boundary sectors of the heliospheric current sheet and how the opposite sectors get tighter closer to the heliopause and into the heliotail. The thickness of the outflow regions in the reconnection region depends on the level of turbulence. The length of the outflow regions L depends on the mean geometry of magnetic field and turbulence. Adapted from Nerney et al. (1995) and also Lazarian & Opher (2009).

Small scale anisotropies : Suggestions

Strangelets – Molecular Clouds (Kotera *et al.* '13)

Strangelets and the TeV-PeV cosmic-ray anisotropies

Kumiko Kotera[1,*], M. Angeles Perez-Garcia[2,†], and Joseph Silk[1,‡]
[1] *Institut d'Astrophysique de Paris, UMR 7095 - CNRS, Université Pierre & Marie Curie, 98 bis boulevard Arago, 75014, Paris, France*
[2] *Department of Fundamental Physics and IUFFyM, University of Salamanca, Plaza de la Merced s/n 37008 Salamanca*
(Dated: March 7, 2013)

Several experiments (e.g., Milagro and IceCube) have reported the presence in the sky of regions with significant excess in the arrival direction distributions of Galactic cosmic rays in the TeV to PeV energy range. Here we study the possibility that these hotspots are a manifestation of the peculiar nature of these cosmic rays, and of the presence of molecular clouds near the sources. We propose that stable quark matter lumps or so-called *strangelets* can be emitted in the course of the transition of a neutron star to a more compact astrophysical object. A fraction of these massive particles would lose their charge by spallation or electron capture in molecular clouds located in the immediate neighborhood of their source, and propagate rectilinearly without decaying further, hence inducing anisotropies of the order of the cloud size. With reasonable astrophysical assumptions regarding the neutron star transition rate, strangelet injection and neutralization rates, we can reproduce successfully the observed hotspot characteristics and their distribution in the sky.

Several experiments have reported strong anisotropy measurements in the arrival direction distributions of Galactic cosmic rays (CRs) in the TeV to PeV energy range (Super-Kamiokande, Tibet III, Milagro, ARGO-YBJ, and IceCube [1, 2]). The data reveal the presence of large scale anisotropies of amplitude $\sim 0.1\%$. Smaller scale anisotropies of size $\sim 10^\circ - 30^\circ$ are also detected with amplitude a factor of a few lower. Milagro has reported the detection at significance $> 10\sigma$ of two *hotspots* (regions with enhanced CR intensity) with amplitude $\approx 10^{-4}$, at a median energy of 1 TeV. ARGO-YBJ report similar excesses. IceCube observes localized regions of angular scale $\sim 15^\circ$ of excess and deficit in CR flux with significance $\sim 5\sigma$ around a median energy of 20 TeV [2].

gies. Various phenomena, such as heliospheric tion, neutron sources, nearby pulsars, peculiar s of the local Galactic magnetic fields have been but none seem to give an obvious explanation [

In this work we study the possibility that the hotspots in the skymap are a manifestation of the peculiar nature of CRs, and of the presence of molecular clouds (MCs) near the sources. We propose that quark matter lumps or so-called *strangelets* could be produced and accelerated while a neutron star (NS) transitions to a quark star (QS). A fraction of these heavy particles would suffer spallation or electron capture in molecular clouds located in the immediate neighborhood of their source, and produce neutral fragments that would propagate rectilinearly without decaying further, hence inducing

COMPARISON WITH DATA AND SIGNATURES

Most observed hotspots could be produced by MCs in the Gould Belt (a star forming region concentrating many MCs, that forms a ring at a distance from the Sun of $\sim 0.7-2$ kpc), at the location where NS-QS transitions may have occurred. Interestingly, the Milagro hotspot labelled "Region A" [1] lies in the direction of the Taurus Molecular Cloud, the nearest star formation region located at 140 pc, and that covers $\sim 100\,\mathrm{deg}^2$ in the sky [19]. "Region 1" of IceCube [2] is also in the direction of a remarkable MC: the Vela Molecular Ridge, located at $0.7-2$ kpc distance, of size $\sim 15^\circ$ in sky [19].

Small scale anisotropies : Suggestions

Dark Matter (Harding '13)

The TeV Cosmic-Ray Anisotropy from Local Dark Matter Annihilation

J. Patrick Harding*
Physics Division, Los Alamos National Laboratory, Los Alamos, NM, USA

(Dated: July 25, 2013)

Several experiments have reported regions in the TeV sky with an excess of cosmic rays. Here we consider the possibility that the excess cosmic rays are coming from dark matter annihilation in nearby subhalos. We provide motivation for dark matter as the source of the excess and show that dark matter annihilations can naturally produce the cosmic ray anisotropy without the need for exotic dark matter models. We show that viable dark matter explanations of the cosmic ray excess are consistent with current measurements of antiprotons, positrons, and gamma-rays. Additionally, we show that the dark matter interpretation of the observed anisotropy predicts detections in several cosmic ray channels by the next generation of experiments.

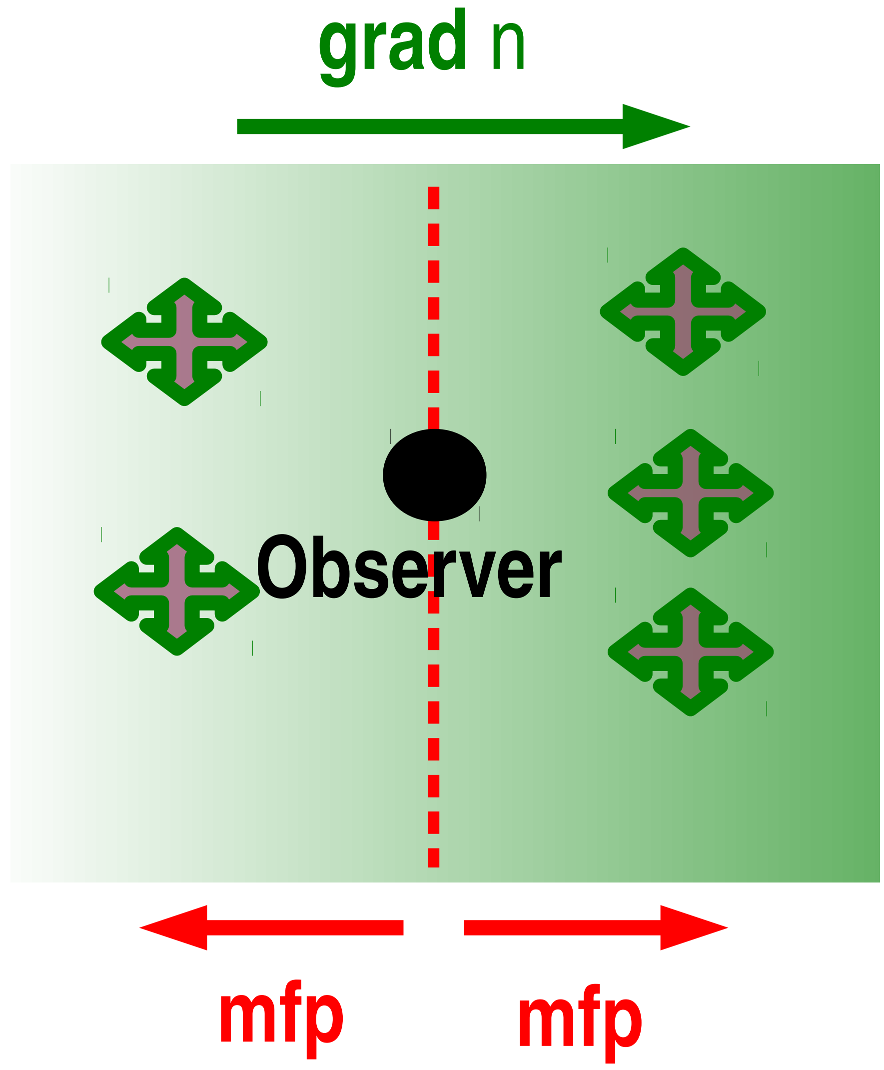
Solution we propose:

~~**In magnetic turbulence, only a dipolar anisotropy should be detected => Additional effects needed.**~~

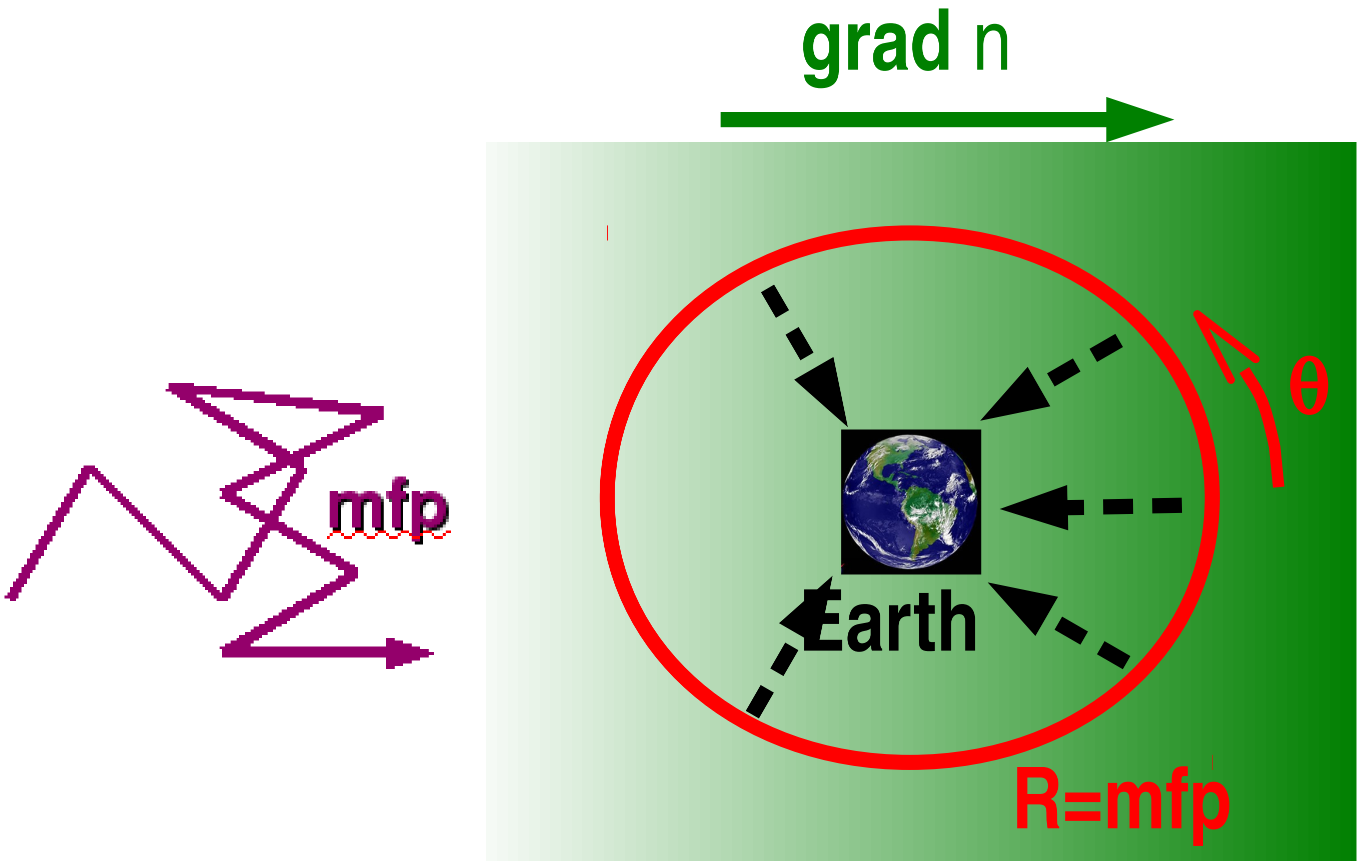
- Energy-dependent smaller scales must ***automatically*** appear at multiple angular scales, provided a large scale anisotropy exists... *even* in pure *isotropic turbulence*

- ***No additional assumption***

Diffusion approximation (1D)



Diffusion approximation - Dipole

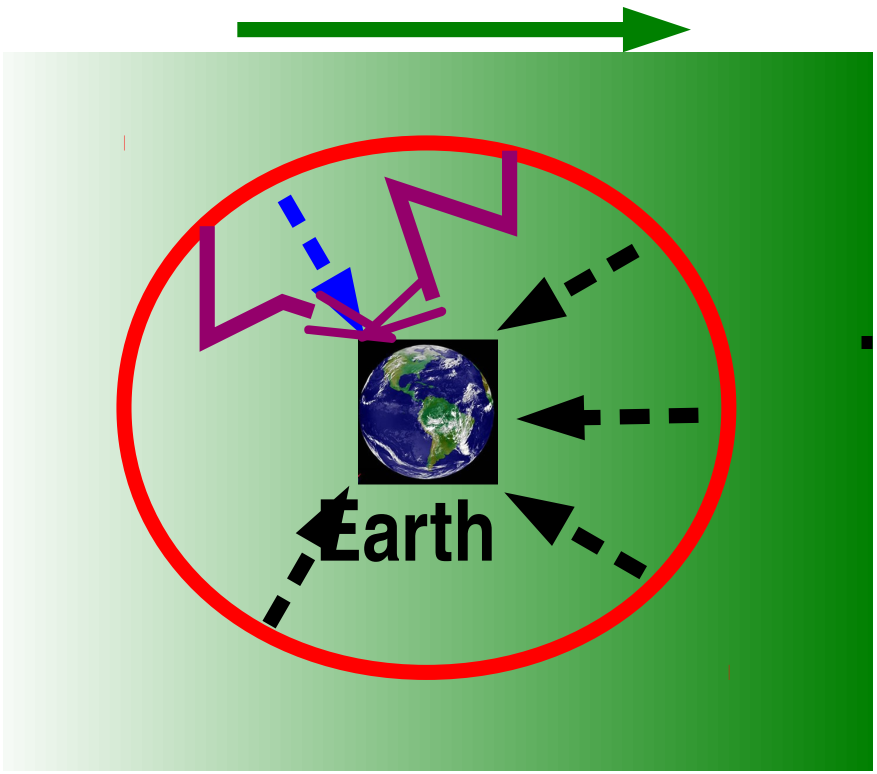


$F = F_0\,(1+\delta \cos\theta)$

$$\boldsymbol{\delta}(p) \simeq -\frac{3}{c_0}\frac{\mathbf{j}}{n} = \frac{3D(p)}{c_0}\frac{\boldsymbol{\nabla} n}{n}$$

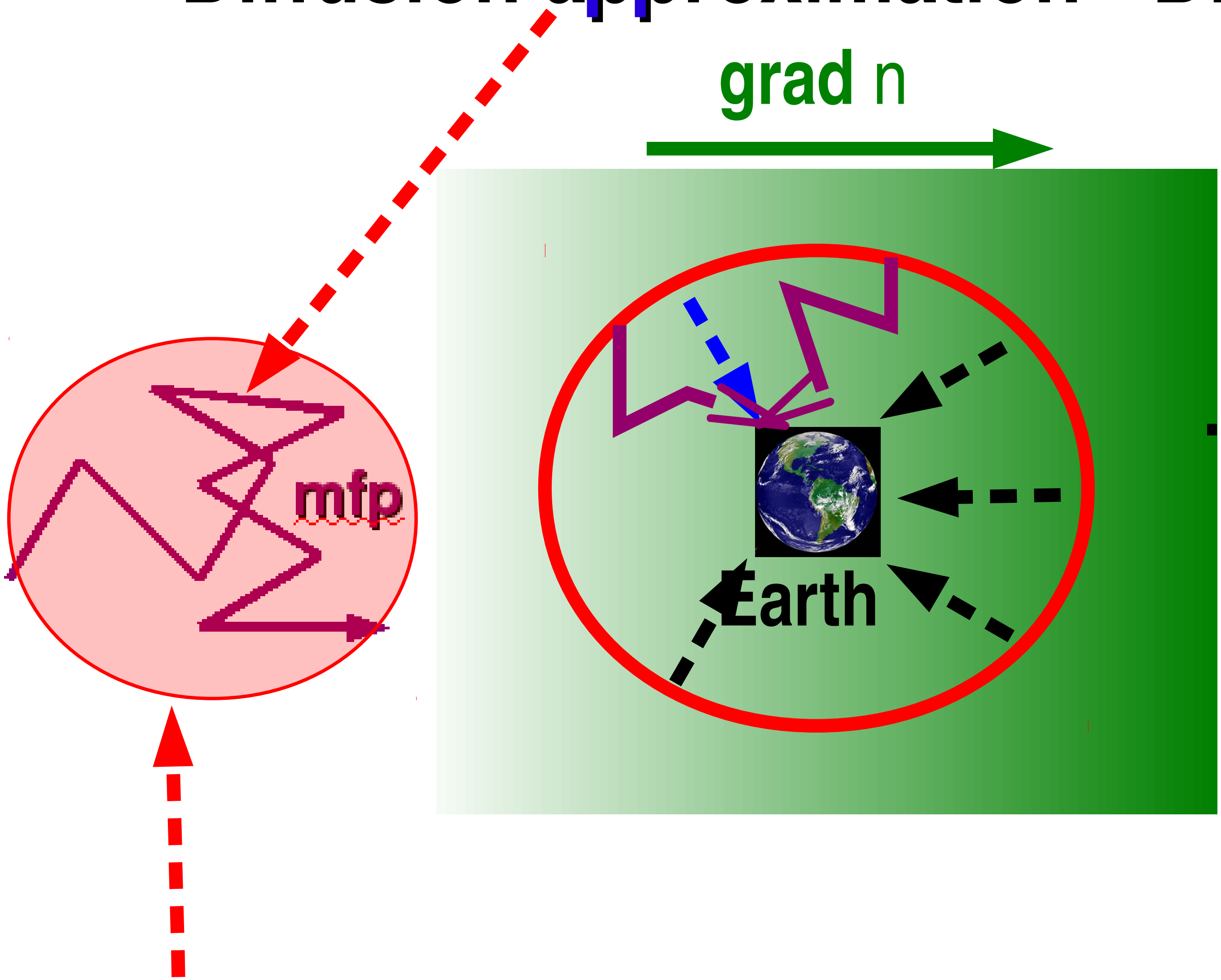
where $\mathbf{j}(\mathbf{r},p) = -D(p)\boldsymbol{\nabla} n$ is the CR current

Diffusion approximation - Dipole



...or <=> several time-dependent random scattering centers

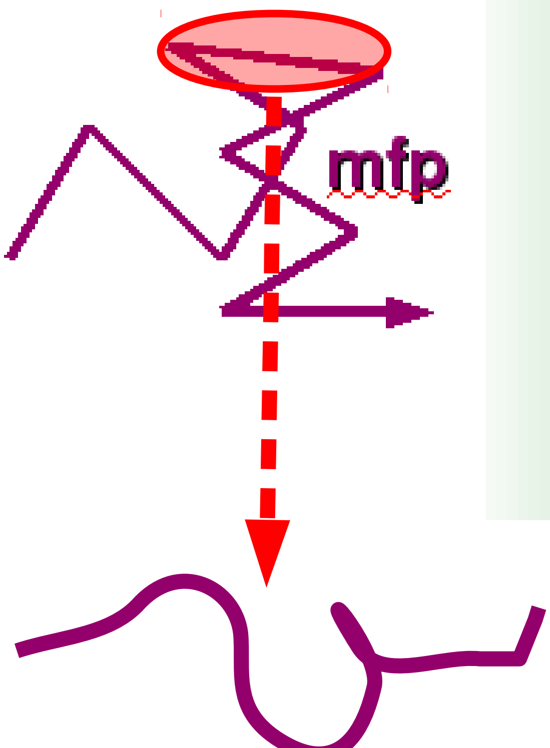
Diffusion approximation - Dipole

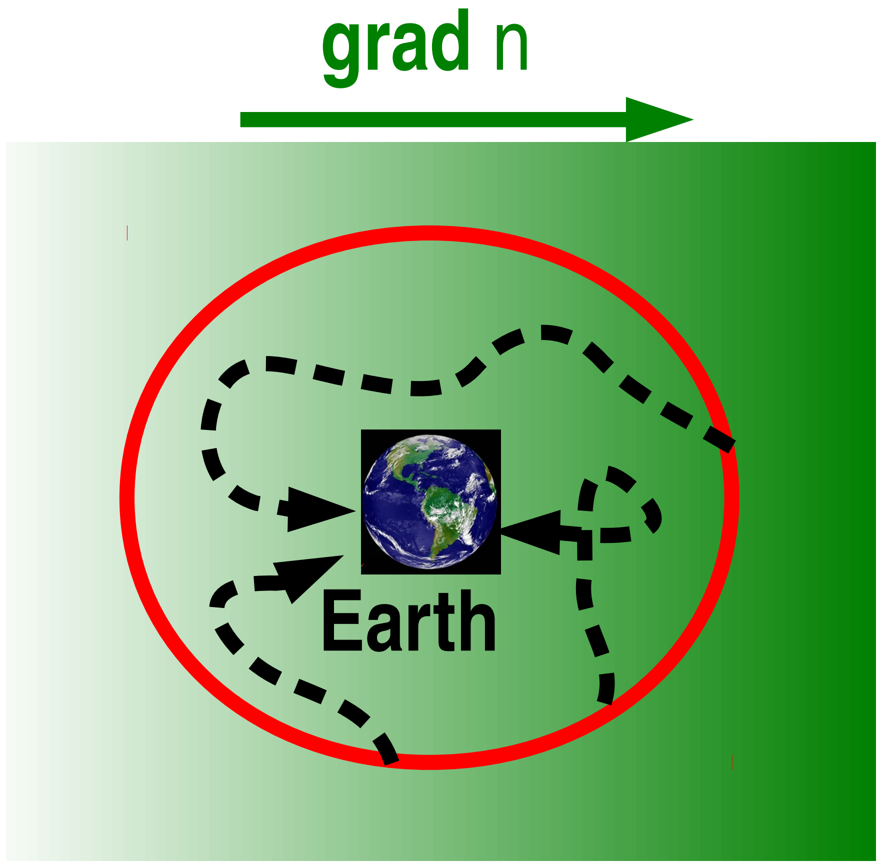


...or <=> several time-dependent random scattering centers

<u>'Globally' : Markovian process</u>

In reality :

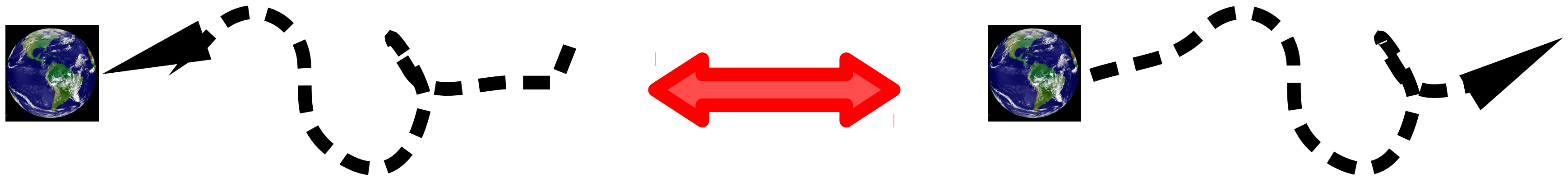




1) The local field does not vary signif. within λ/c (10 km/s << c)

Not diffusion -> Need individual trajectories

In reality :

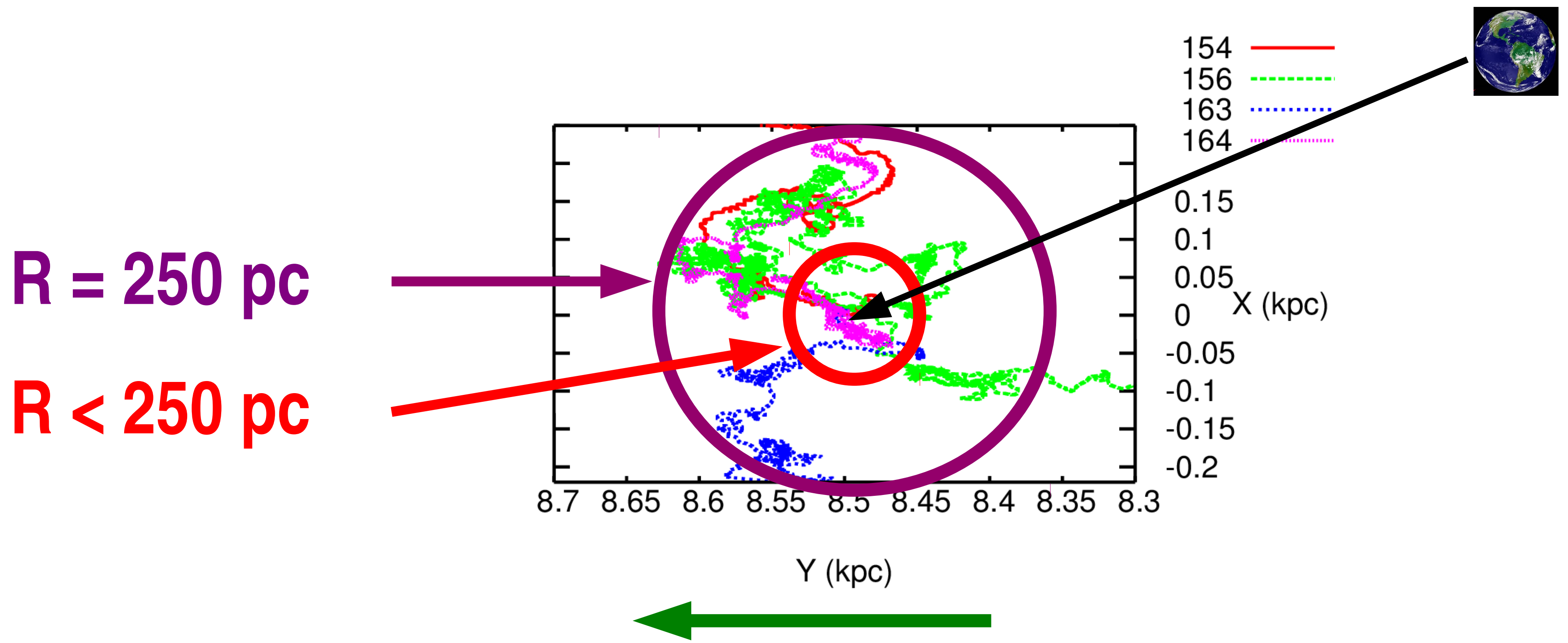


Equivalence between forward- and back-tracking of individual cosmic rays

… the process is locally non-Markovian

2) The Earth is point-like (/r_L)

Numerical simulations



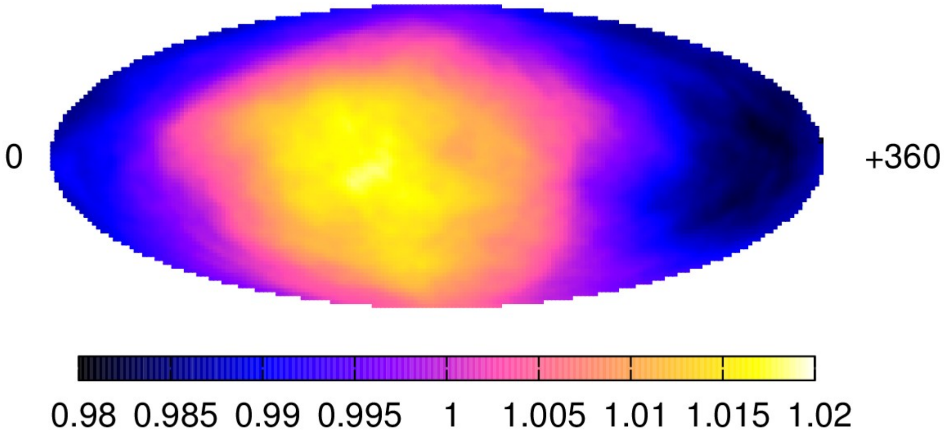
|(**grad** n)/n| ~ (290 pc)$^{-1}$ *-> (1kpc)$^{-1}$*

and E/Z = 10^{16} eV *-> 10^{13} eV*

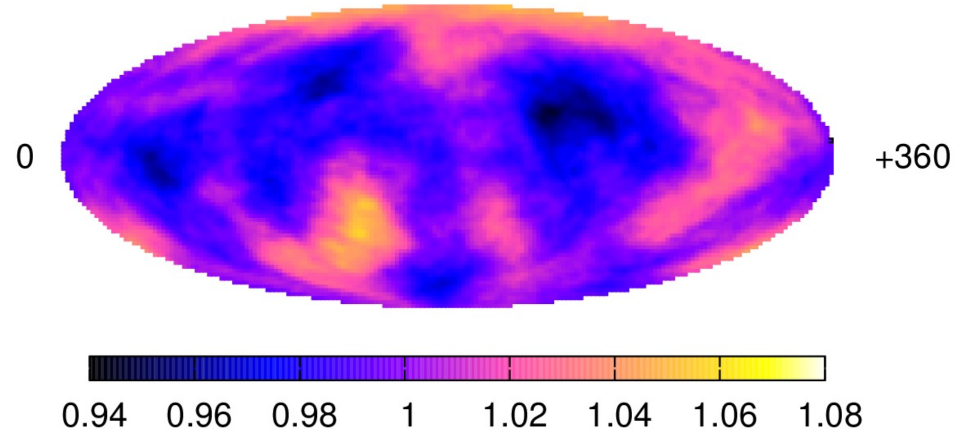
*Can be extrapolated to lower (**grad** n)/n and E/Z*

Dipole / Smaller scales

90°smoothing



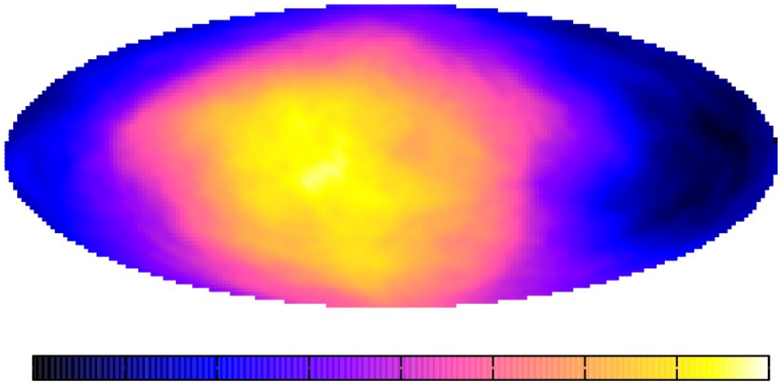
20°smoothing - Dipole



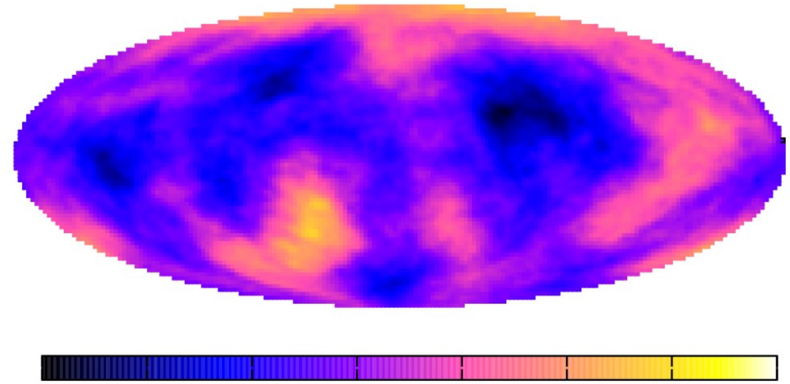
Amplitude ~ 6 % here

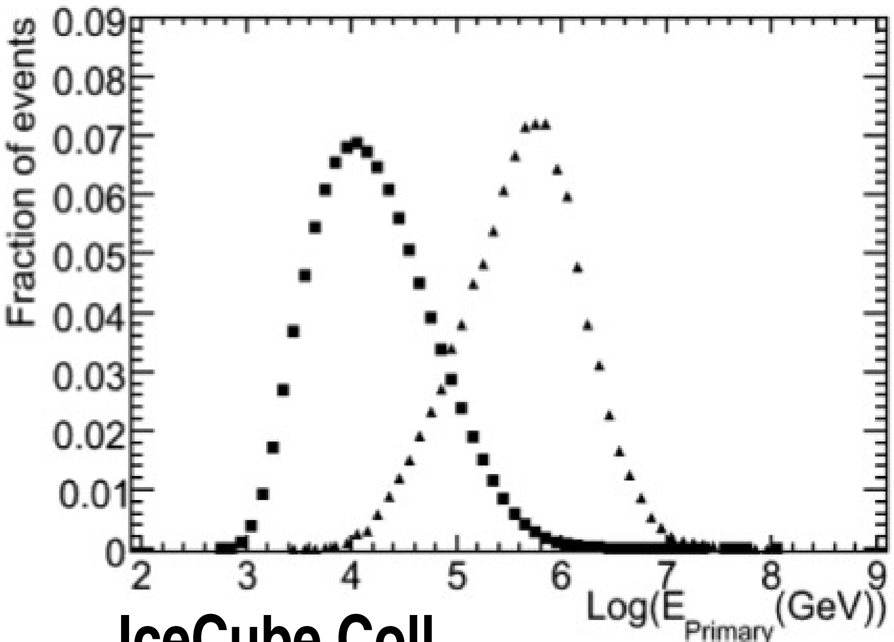
Dipole / Smaller scales

90°smoothing



20°smoothing - Dipole





IceCube Coll.

Different E/Z add non-constructively

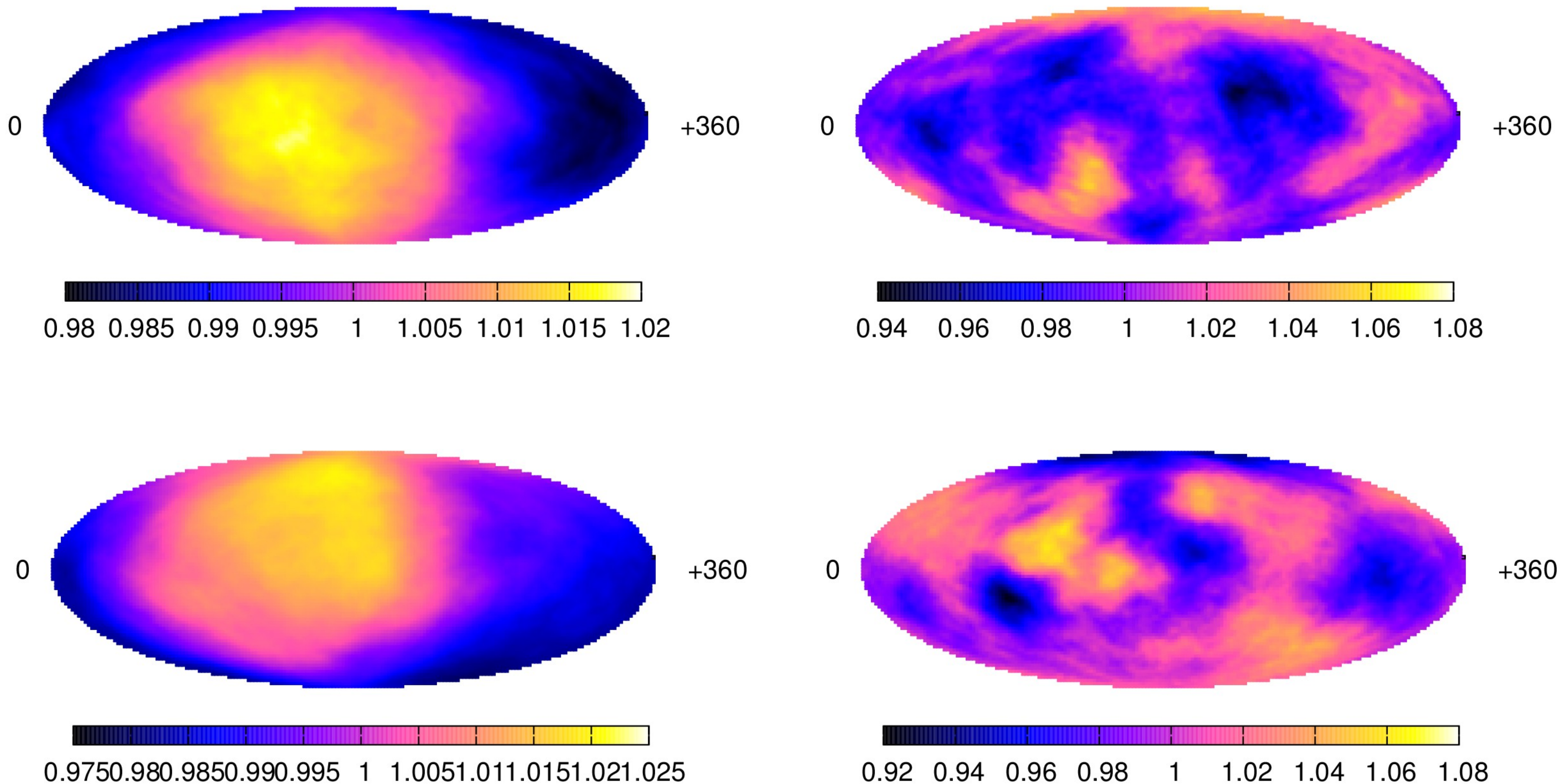
→ Smaller (~10x)

(Giacinti, PPCF '13)

Dipole / Smaller scales

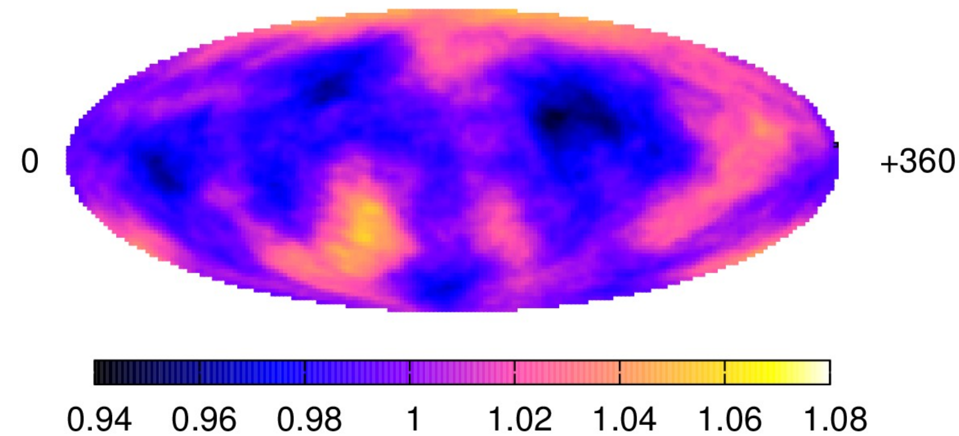
90°smoothing

20°smoothing - Dipole

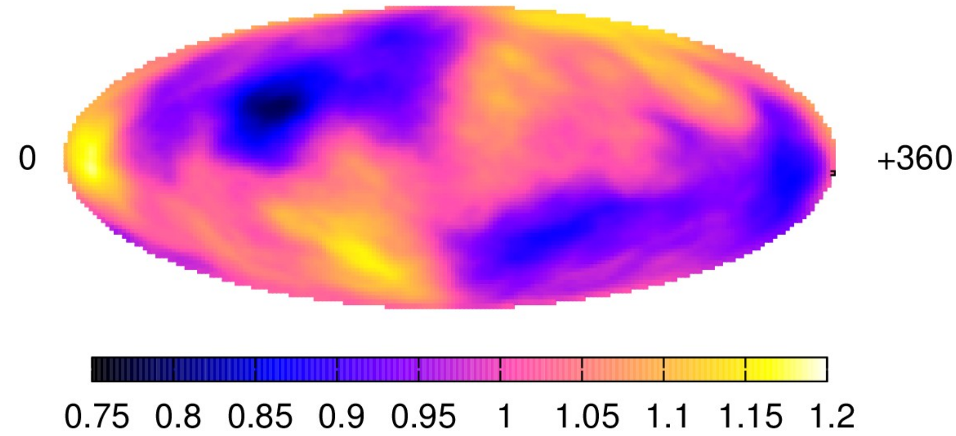


Dependence on the CR rigidity E/Z

E/Z = 10^{16} eV

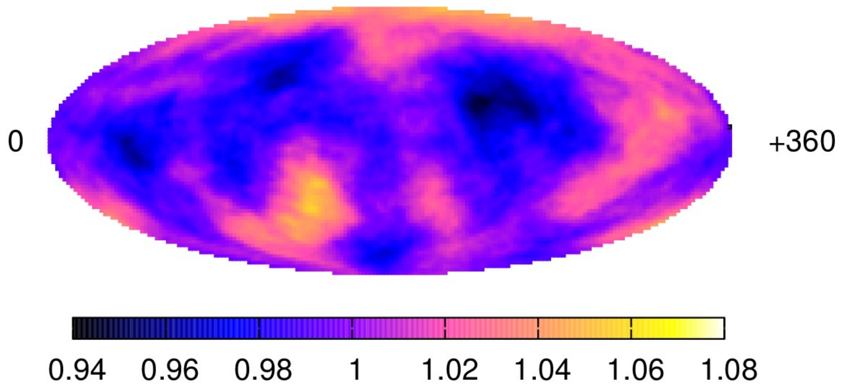


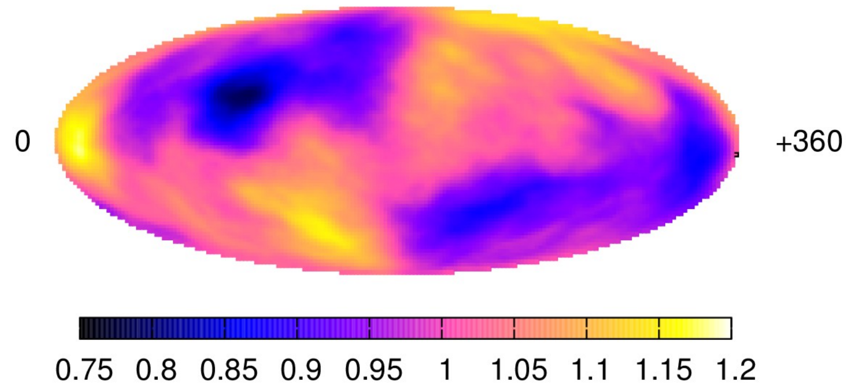
E/Z = 5 x 10^{16} eV

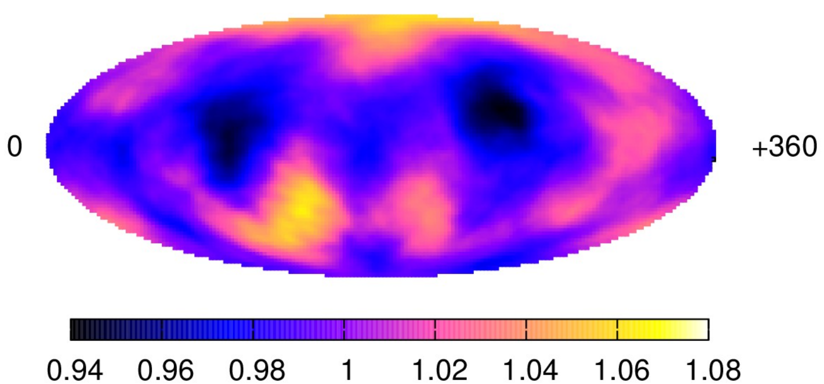


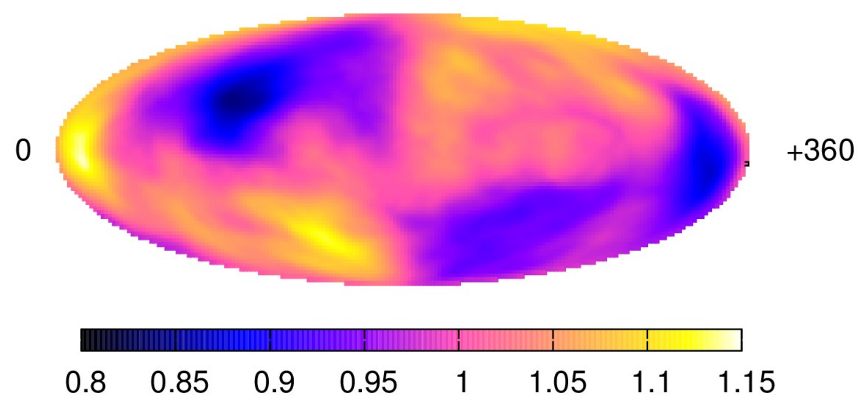
Dependence on the 'domain' size

250 pc





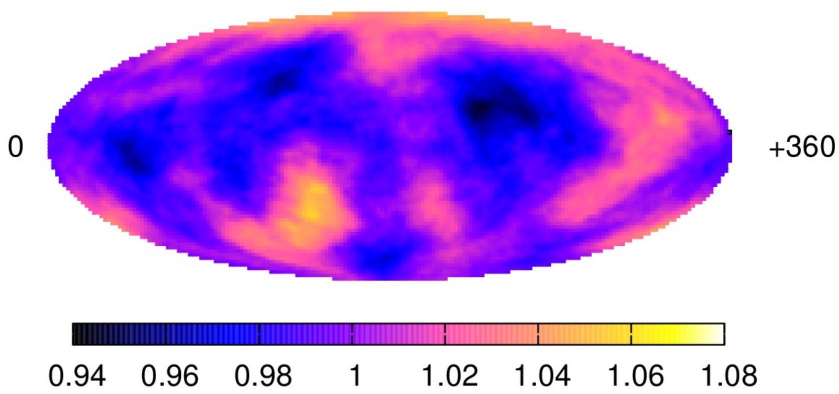


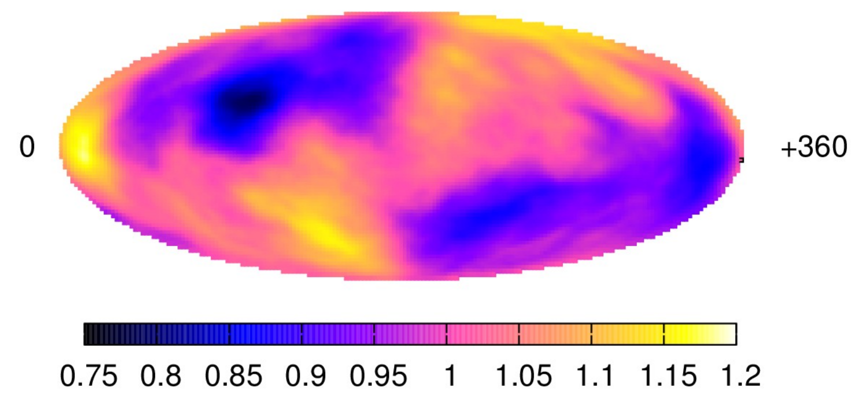


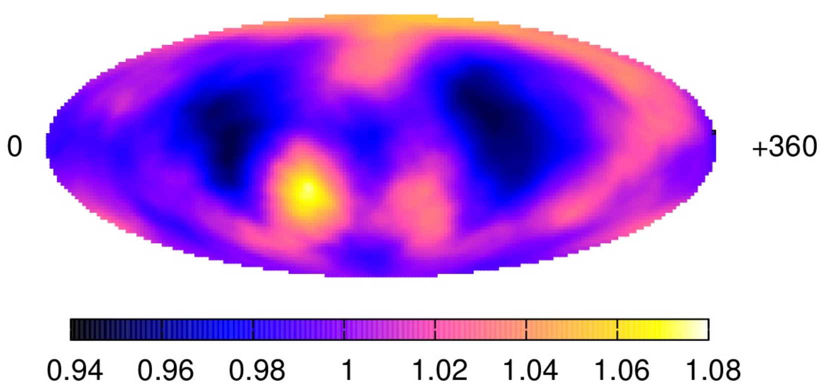
100 pc

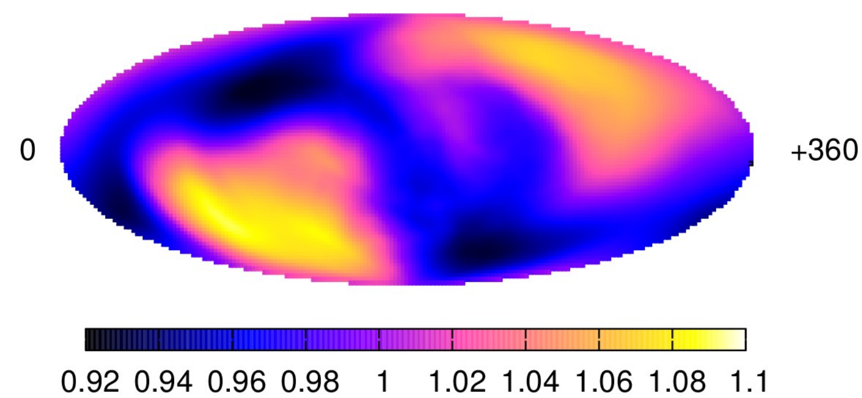
Dependence on the 'domain' size

250 pc





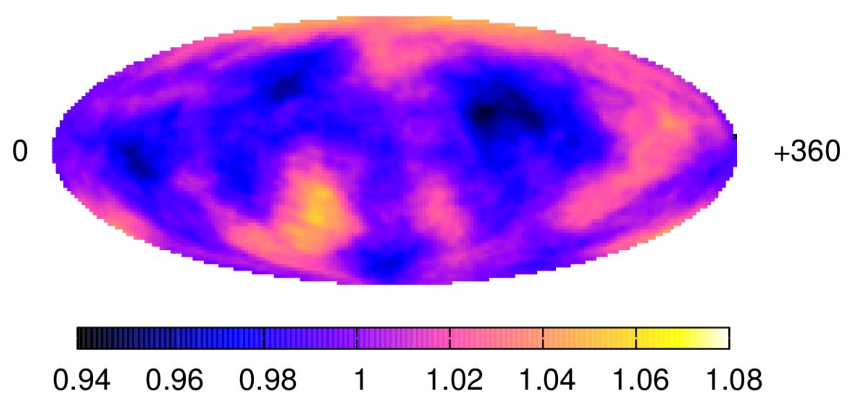


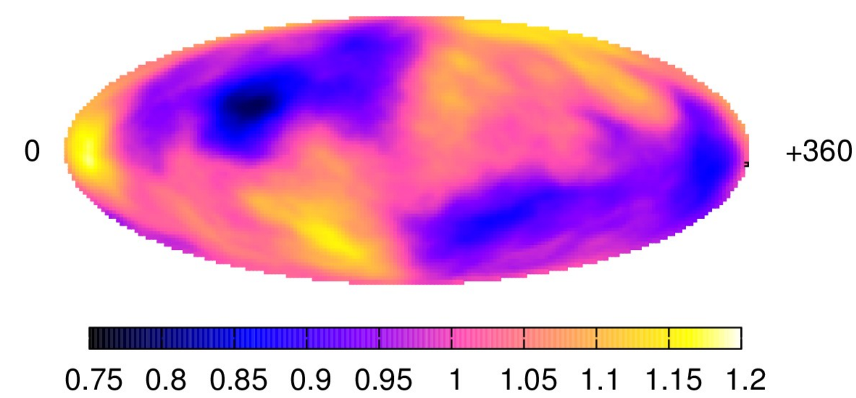


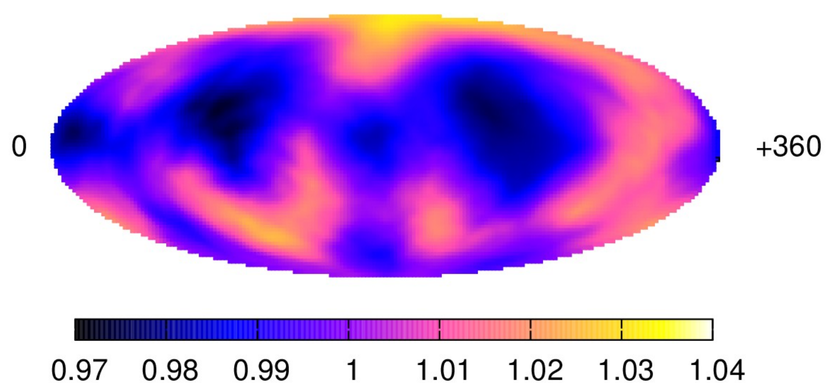
50 pc

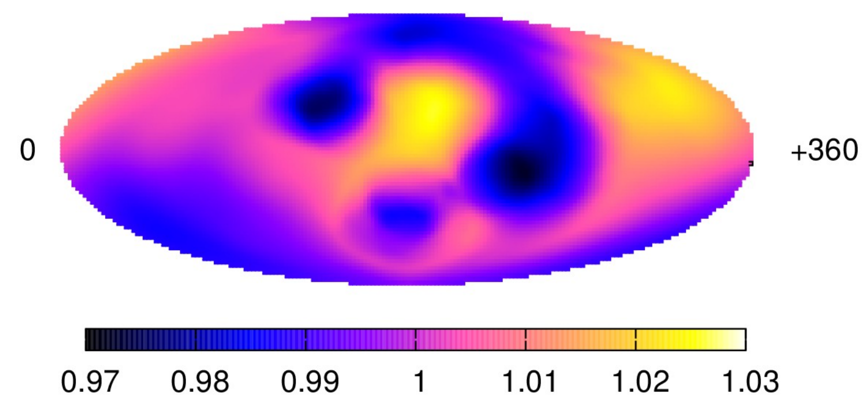
Dependence on the 'domain' size

250 pc





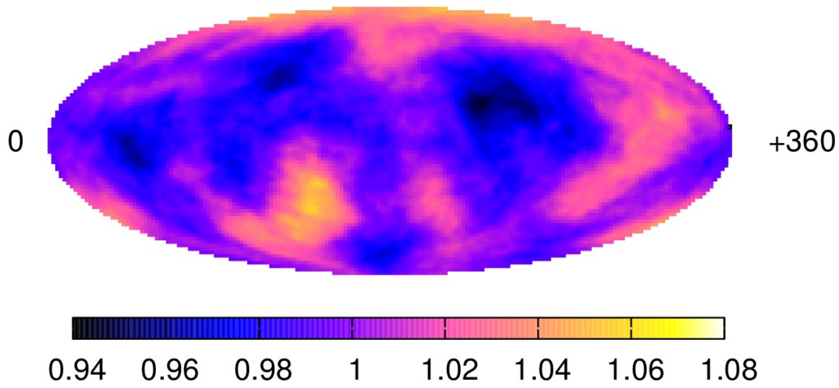


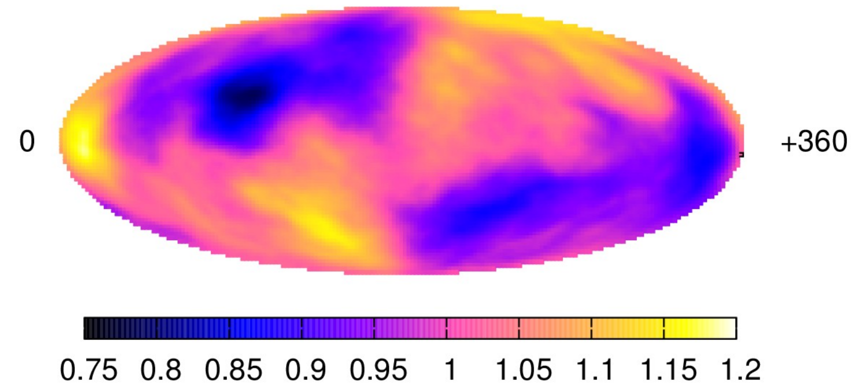


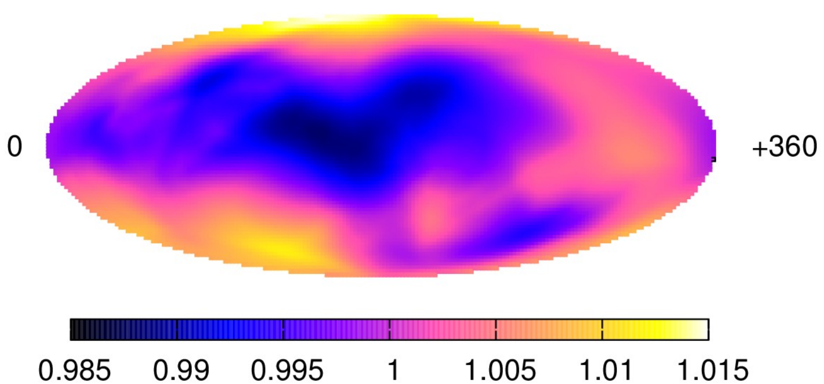
25 pc

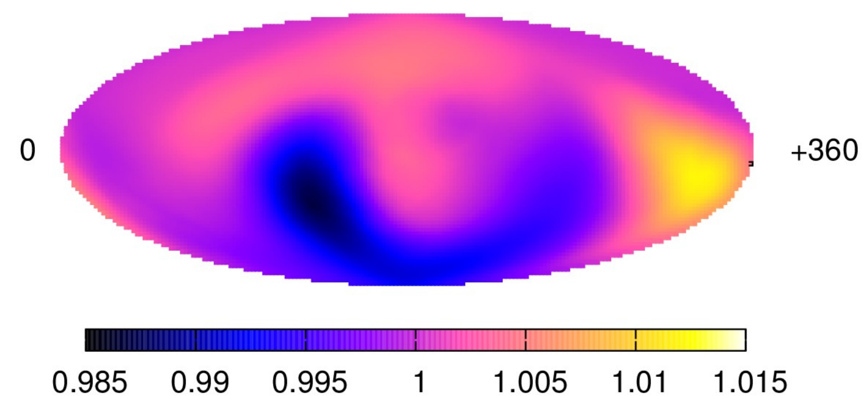
Dependence on the 'domain' size

250 pc



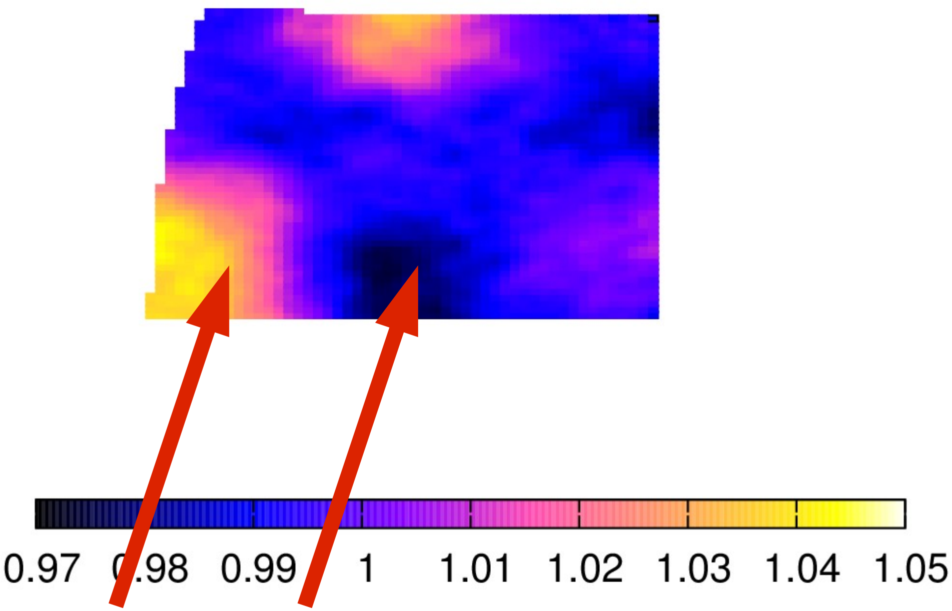


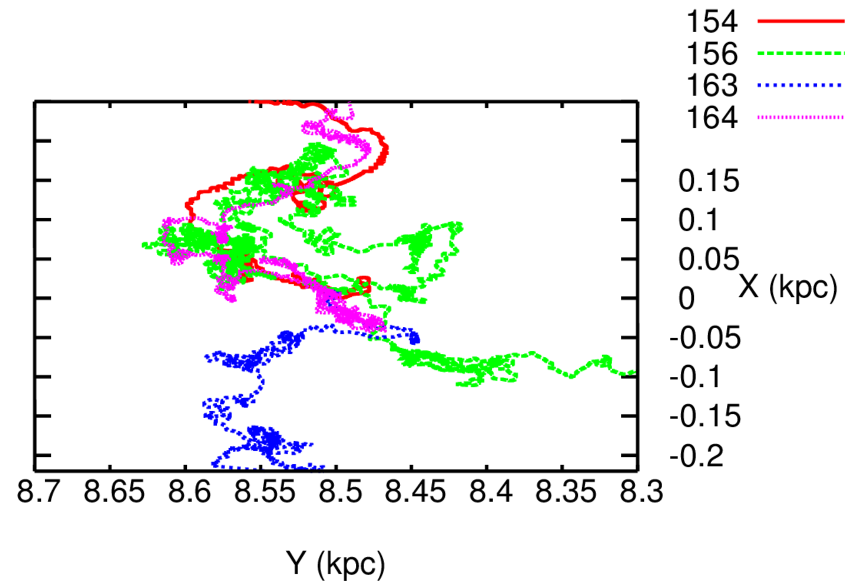




10 pc

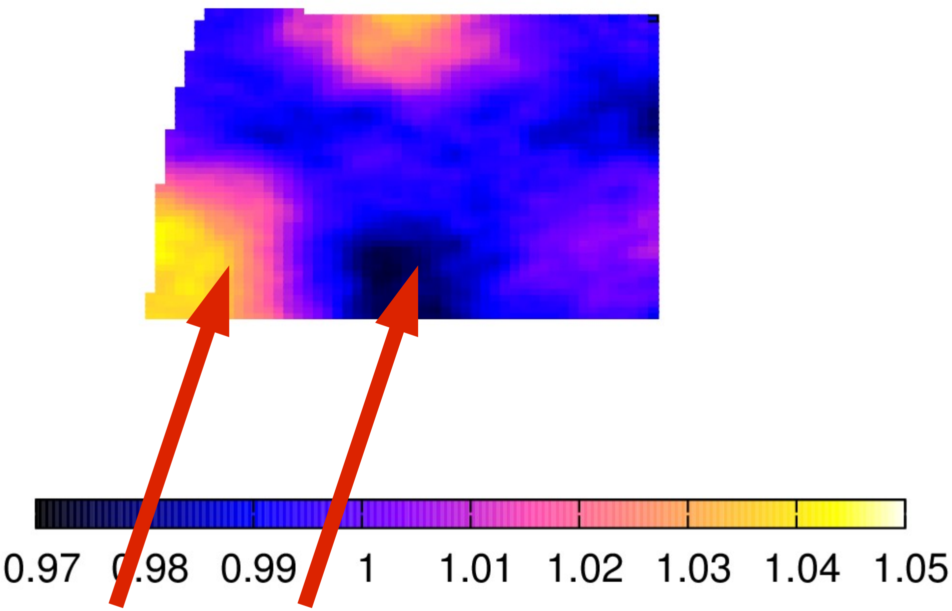
Local trajectories

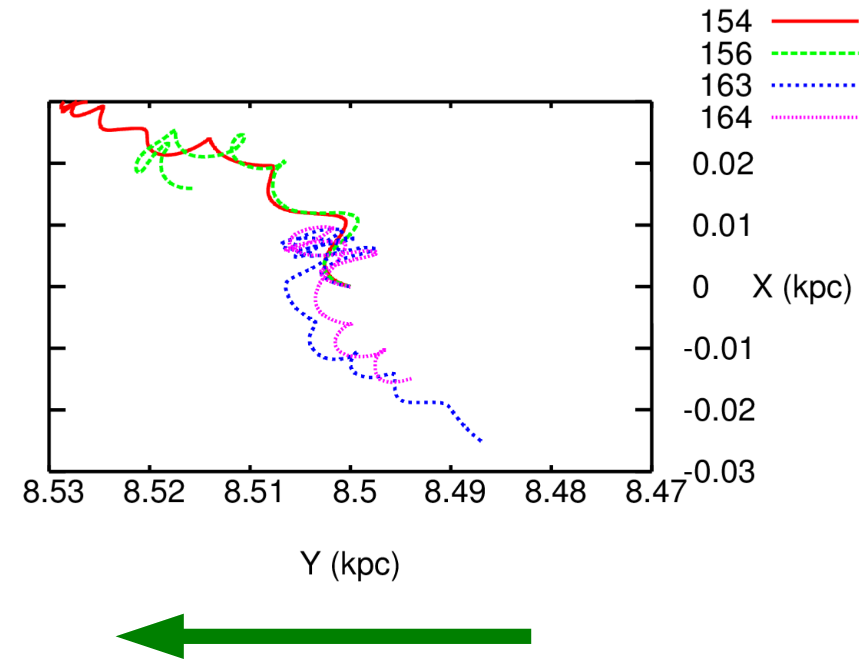




grad n

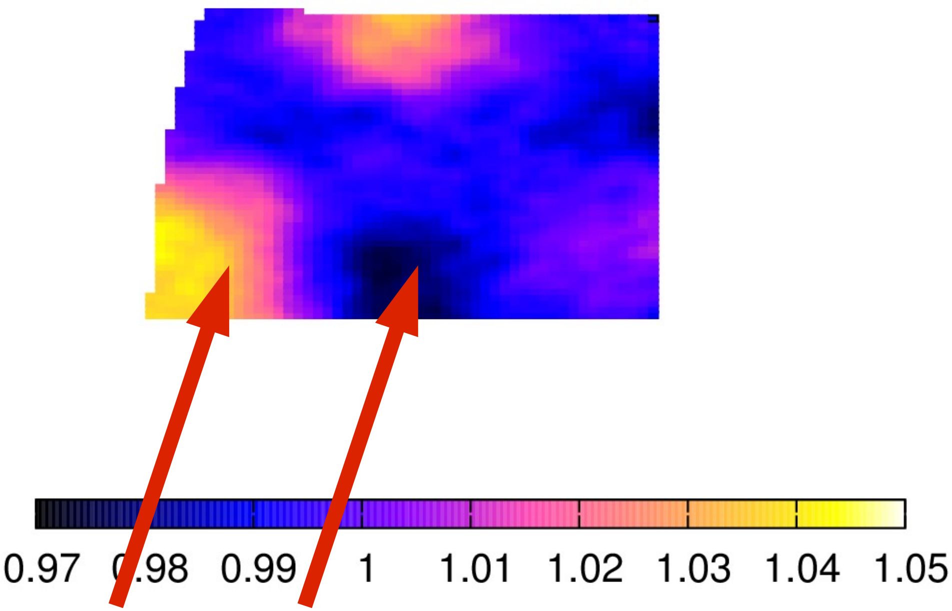
Local trajectories

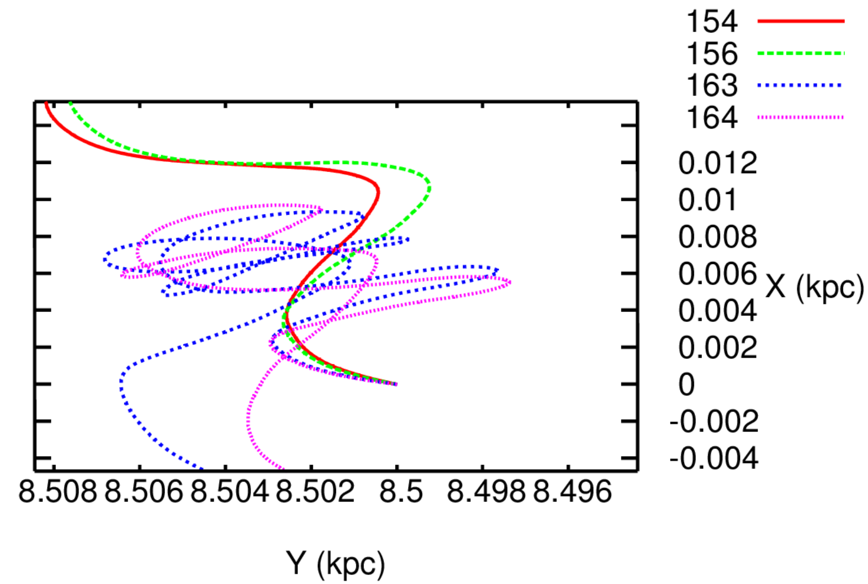




grad n

Local trajectories





grad n

Heliospheric B fields at ~ TeV energies ?

At PeV energies : probe ISMF up to ~10s of pc

At 1 - 10 TeV energies : Same argument ; may start to probe fields in the heliosphere, see P. Desiati and A. Lazarian, Astrophys. J. 762, 44 (2013).

The Astrophysical Journal, 762:44 (10pp), 2013 January 1 doi:10.1088/0004-637X/762/1/44

ANISOTROPY OF TeV COSMIC RAYS AND OUTER HELIOSPHERIC BOUNDARIES

P. Desiati[1] and A. Lazarian[2]
:Cube Particle Astrophysics Center (WIPAC), Department of Astronomy, University of Wisconsin, Mad
[2] Department of Astronomy, University of Wisconsin, Madison, WI 53706, USA
Received 2012 June 19; accepted 2012 October 9; published 2012 December 14

ABSTRACT

in the energy range from about tens of GeV to several hundreds of TeV are o
gy-dependent anisotropy of order 0.01%–0.1% and a consistent topology that appe
gher energy. The nearest and most recent galactic cosmic-ray sources might stoch
on and possibly explain a change in orientation of the anisotropy as a function of en
roximation is not able to explain its non-dipolar structure and, in particular, the signi
ılar scale features. Particle propagation within the mean free path in the local interste
role in determining the properties of galactic cosmic rays, such as their arrival distribu

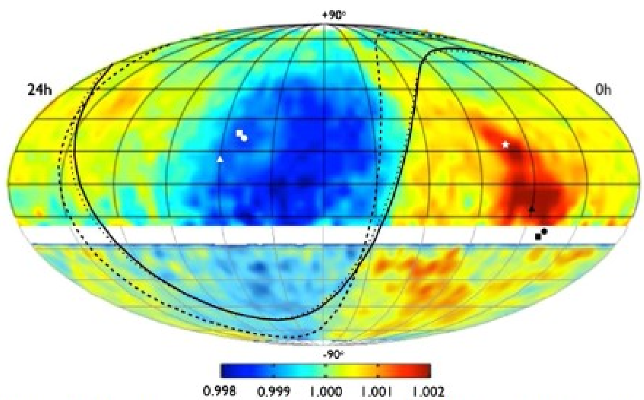


Figure 1. Map in equatorial coordinates constructed by combining relative intensity distributions of cosmic-ray counts independently normalized within

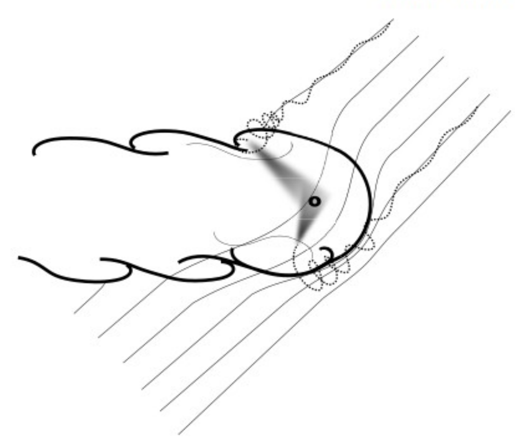


Figure 4. Illustration of the turbulent ripples at large scale on the outer

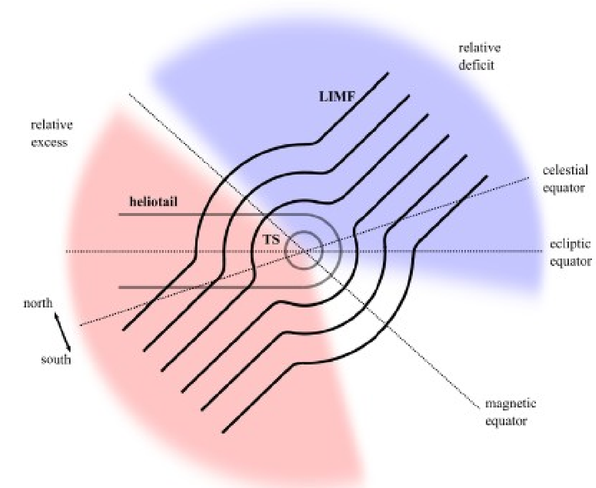


Figure 2. Schematic representation of the elongated heliosphere with respect

Heliospheric B fields at ~ TeV energies ?

Alternative possibility at 1 – 10 TeV : heliospheric electric fields , see L. Drury, arXiv:1305.6752 [astro-ph.HE].

33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

The problem of small angular scale structure in the cosmic ray anisotropy data

L. O'C. DRURY

Dublin Institute for Advanced Studies
School of Cosmic Physics
31 Fitzwilliam Place
Dublin 2
Ireland

ld@cp.dias.ie

Abstract: Recent observations have revealed structure on small angular scales in the anisotropy data of cosmic rays at multi TeV energies. Even though the absolute amplitudes are very small, these effects are somewhat surprising and a wide range of possible causes have been discussed. A possible origin associated with heliospheric electric fields is proposed.

Keywords: anisotropies

1 Introduction

Our knowledge of directional variations (usually referred to as anisotropies) in the flux of cosmic rays reaching the Earth at TeV energies and above has greatly improved in recent years, largely because of the need to control the charged cosmic ray background in experiments searching

targets, have no difficulty with
but fail because they require
densities in close proximity to th
by astronomical observations [1
A recent fascinating but high
is that the anisotropy might be d

s of a few nT. Thus above about a TeV cosmic ray particles are expected to penetrate the heliosphere with relatively little deflection. Such particles arriving at the Earth will thus have seen an effective potential shift due to induction fields in the heliosphere of

$$\int -V \times B \cdot ds \qquad (2)$$

where the integral is taken along the trajectory of the incoming particle out from Earth through the heliosphere and into the local ISM. It is important that all these particles arriving in a given direction and energy band will have essentially the same trajectory through the heliosphere. If

tant w
Giacin

Refe

[1] G.
[2] M
[3] A.
[4] A.
[5] S.
[6] R.
[7] R.
[8] M

Conclusions and perspectives

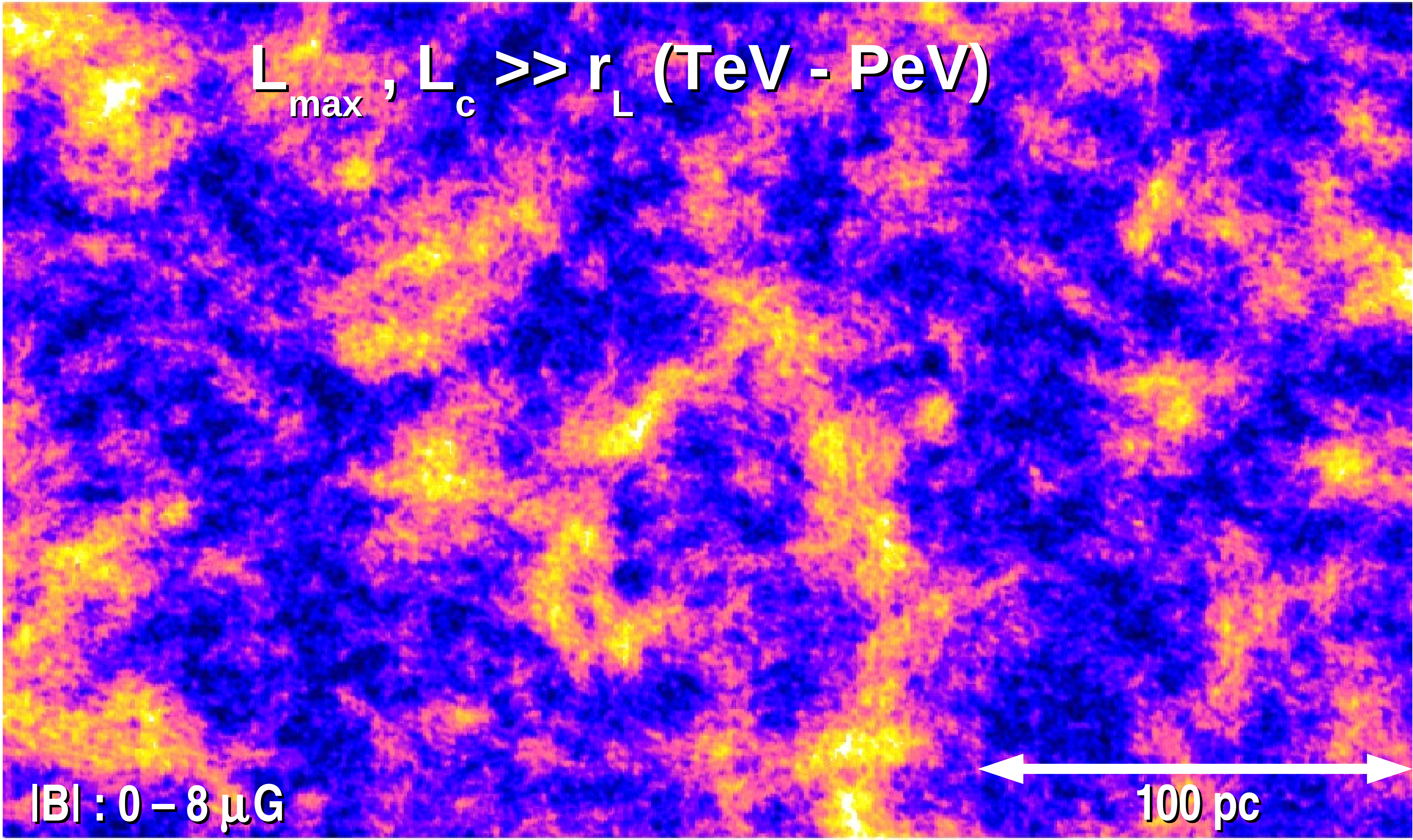
Medium and small scale CRA must be present because of the MF structure within ~ a CR mean free path

---> May become (one of) the best way(s) to probe the structure of local magnetic fields in the ISM in the future.

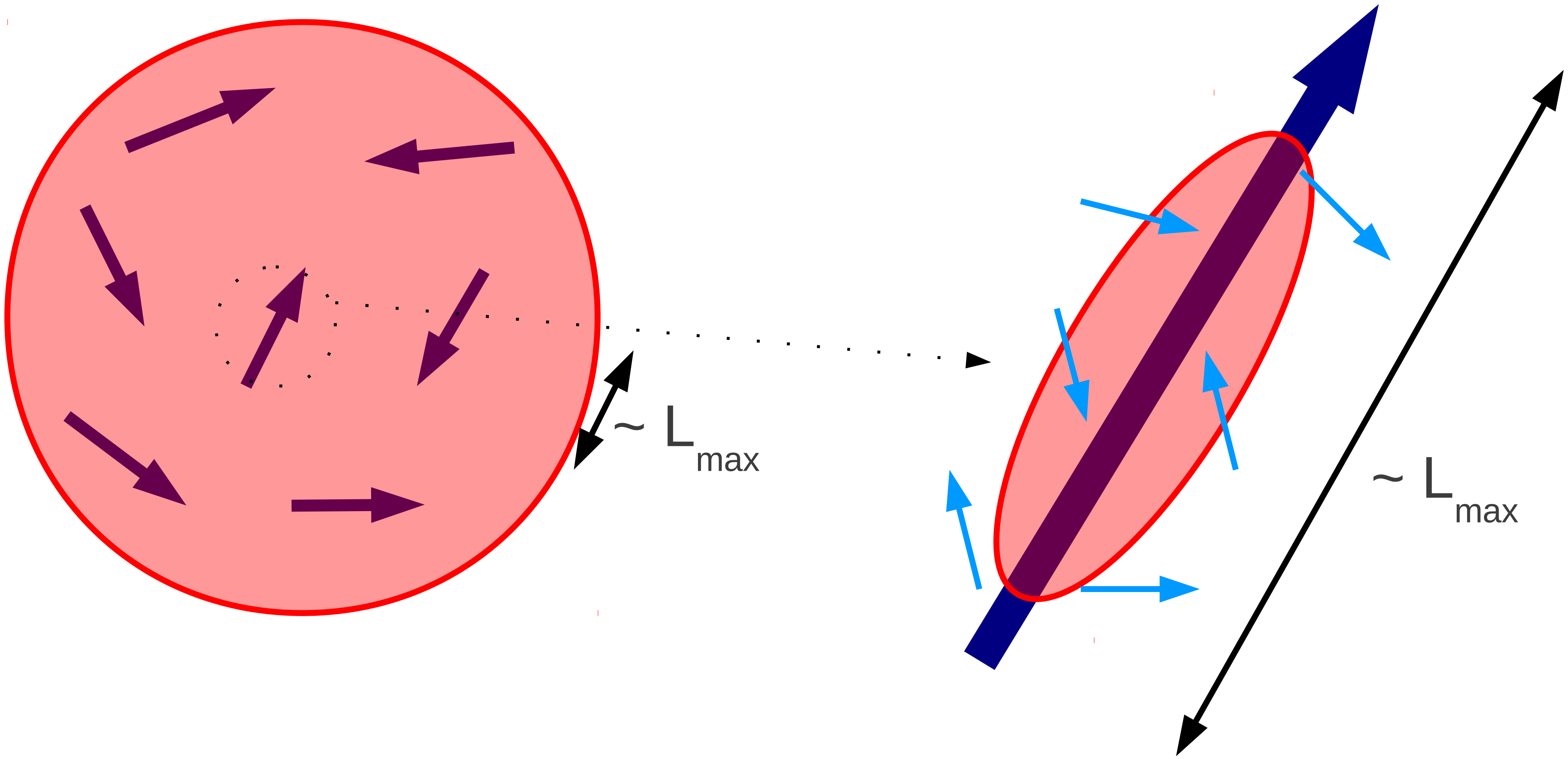
---> Once this question is solved : Potential for other interesting discoveries.

NEXT WORKS : Local MFs (ISM, Heliosphere) → CRA maps

Generated magnetic turbulence



Anisotropic diffusion in *isotropic* turbulence

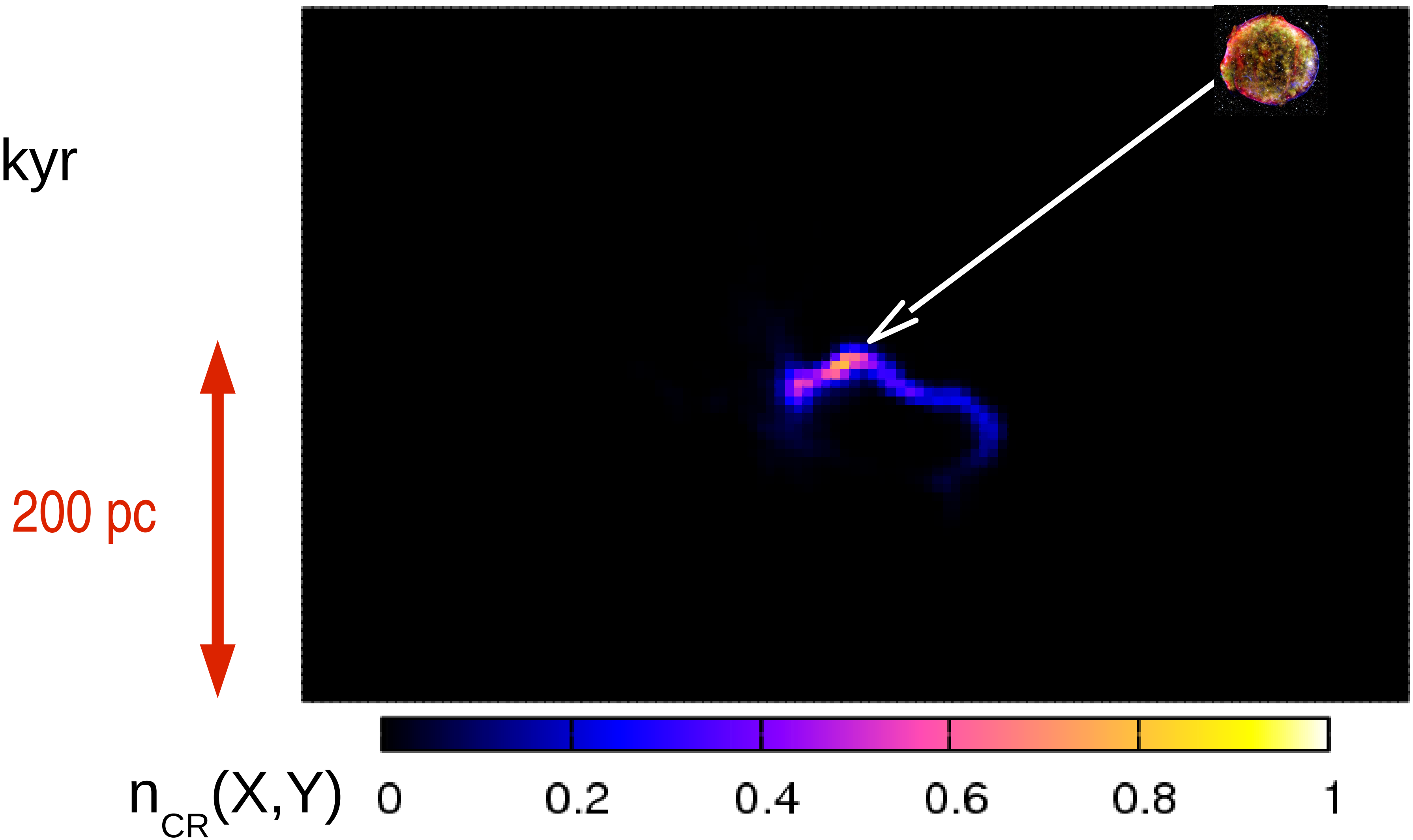


For Δt ~ 1 kyr, $v_{10km/s}\Delta t$ ~ 0.01 pc << $(6D_{1PeV}\Delta t)^{1/2}$ ~ few 10s pc

Results of numerical simulations

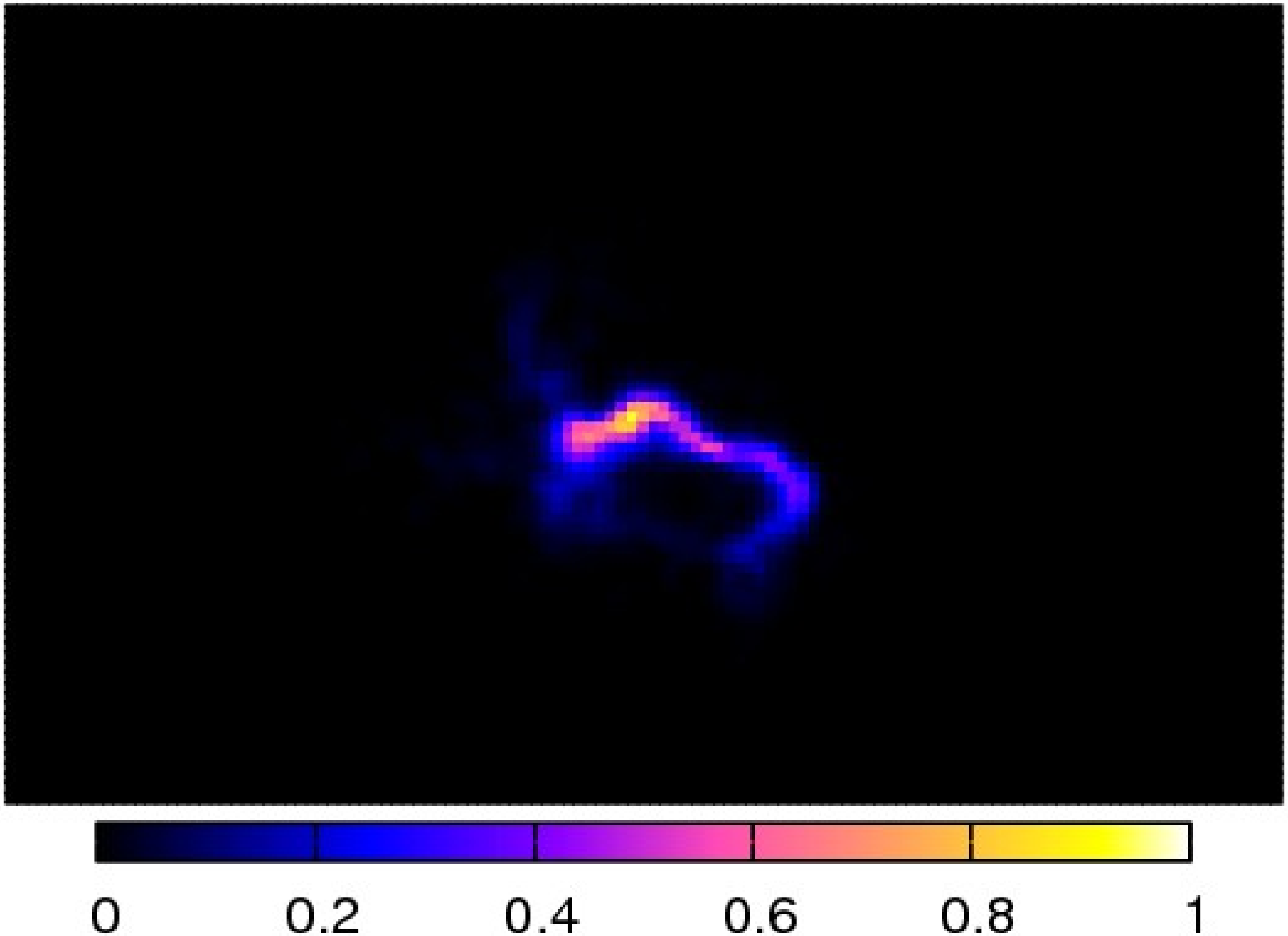
E/Z=1PeV, Kolmogorov spectrum, L_{max}=150pc

t = 1kyr



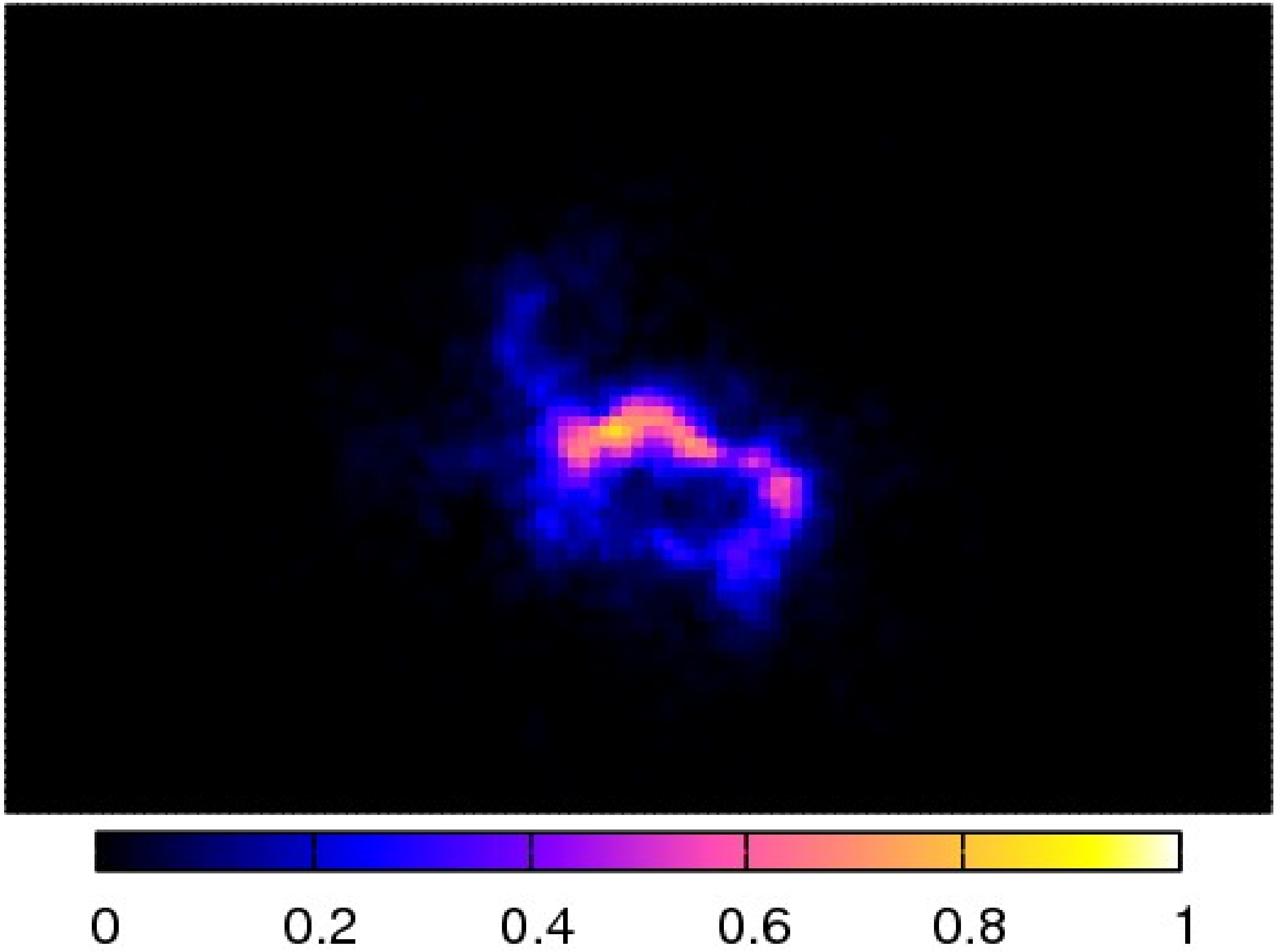
Results of numerical simulations

t = 2kyr



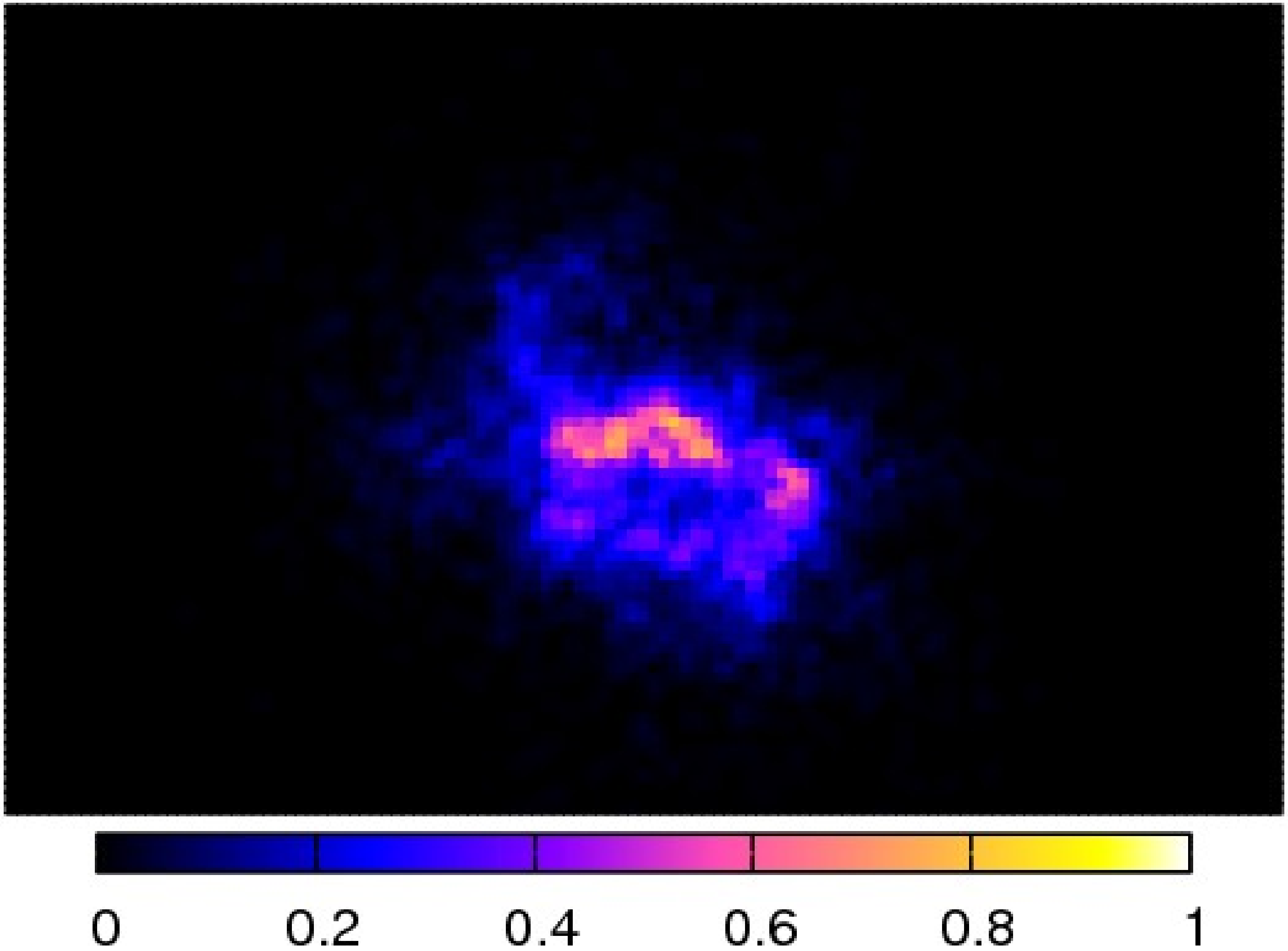
Results of numerical simulations

t = 4kyr



Results of numerical simulations

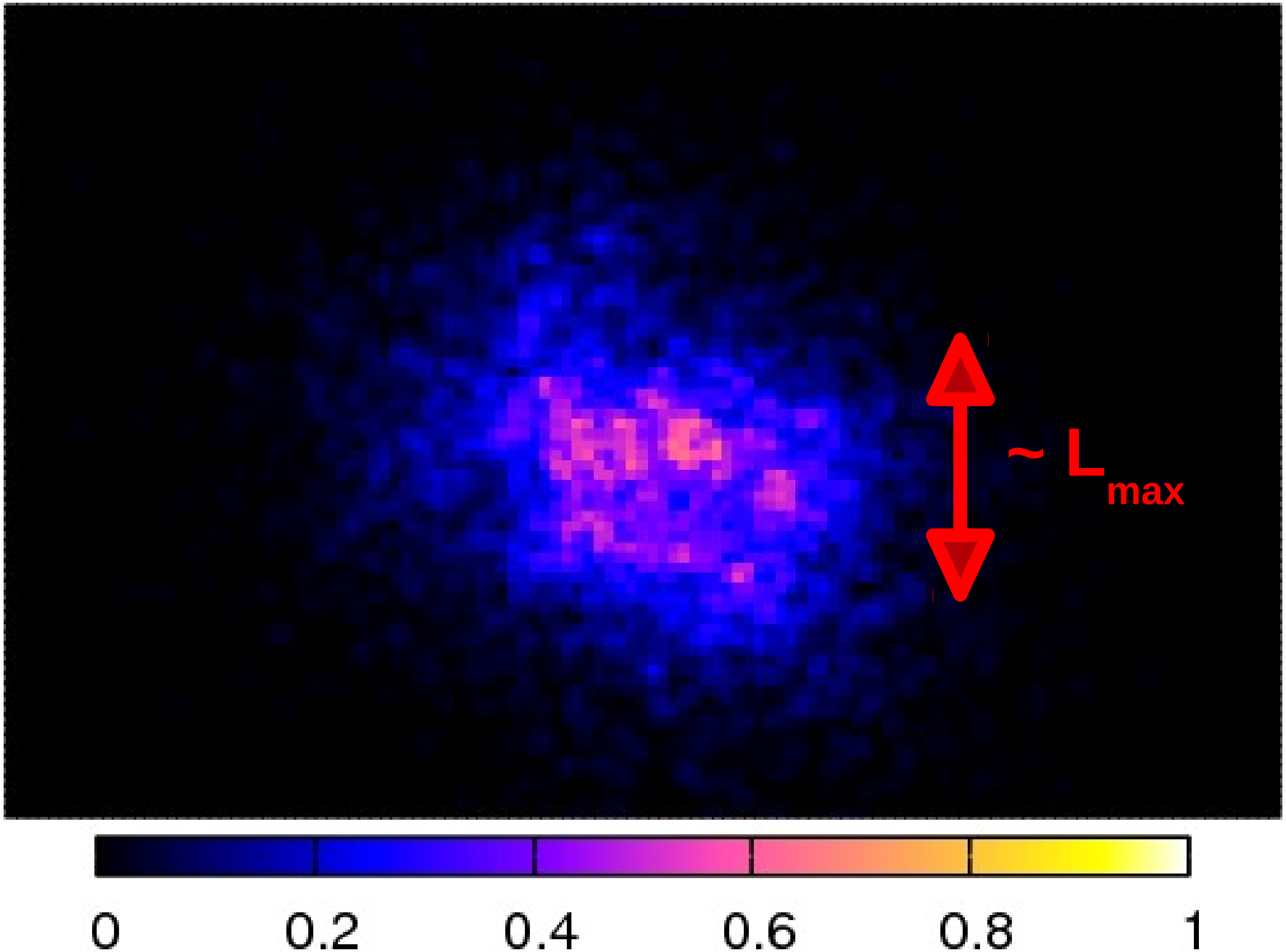
t = 6kyr



Results of numerical simulations

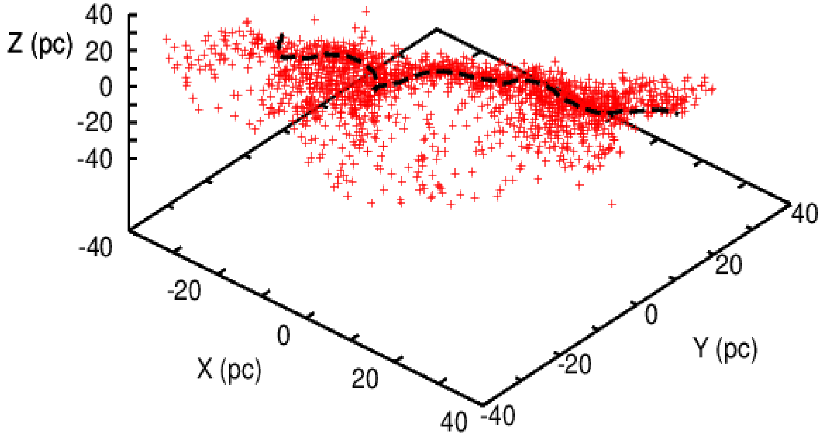
... then starts to tend towards the $r \propto t^{1/2}$ behaviour

t = 10kyr



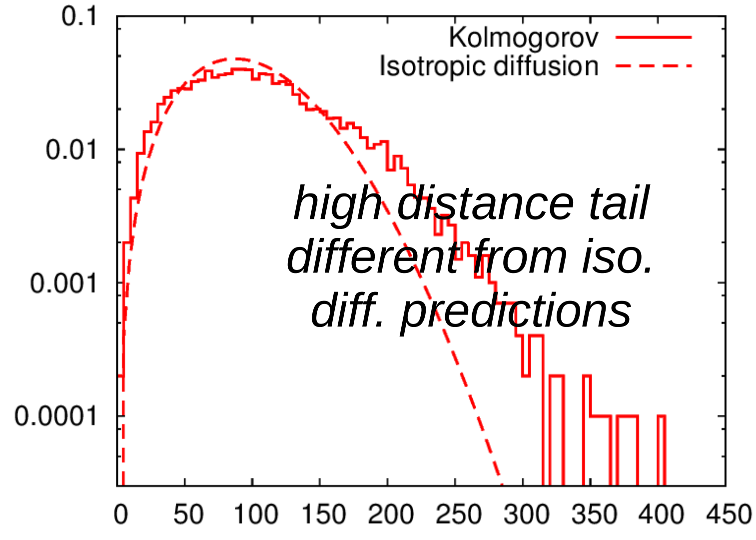
CRs and local configuration of the magnetic field

- t <~ t* /10 :

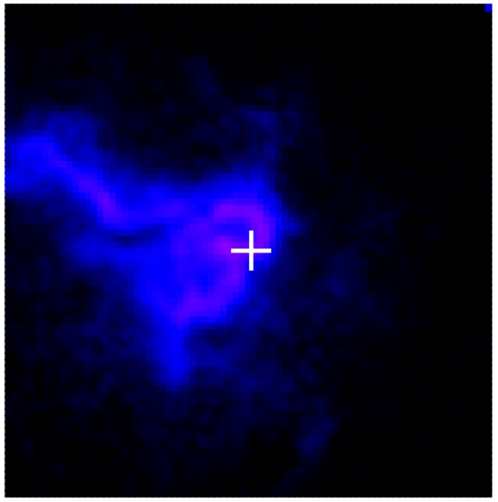


Nearby field lines coherent over ~L_c : CRs in a flux tube

- t ~ t* :



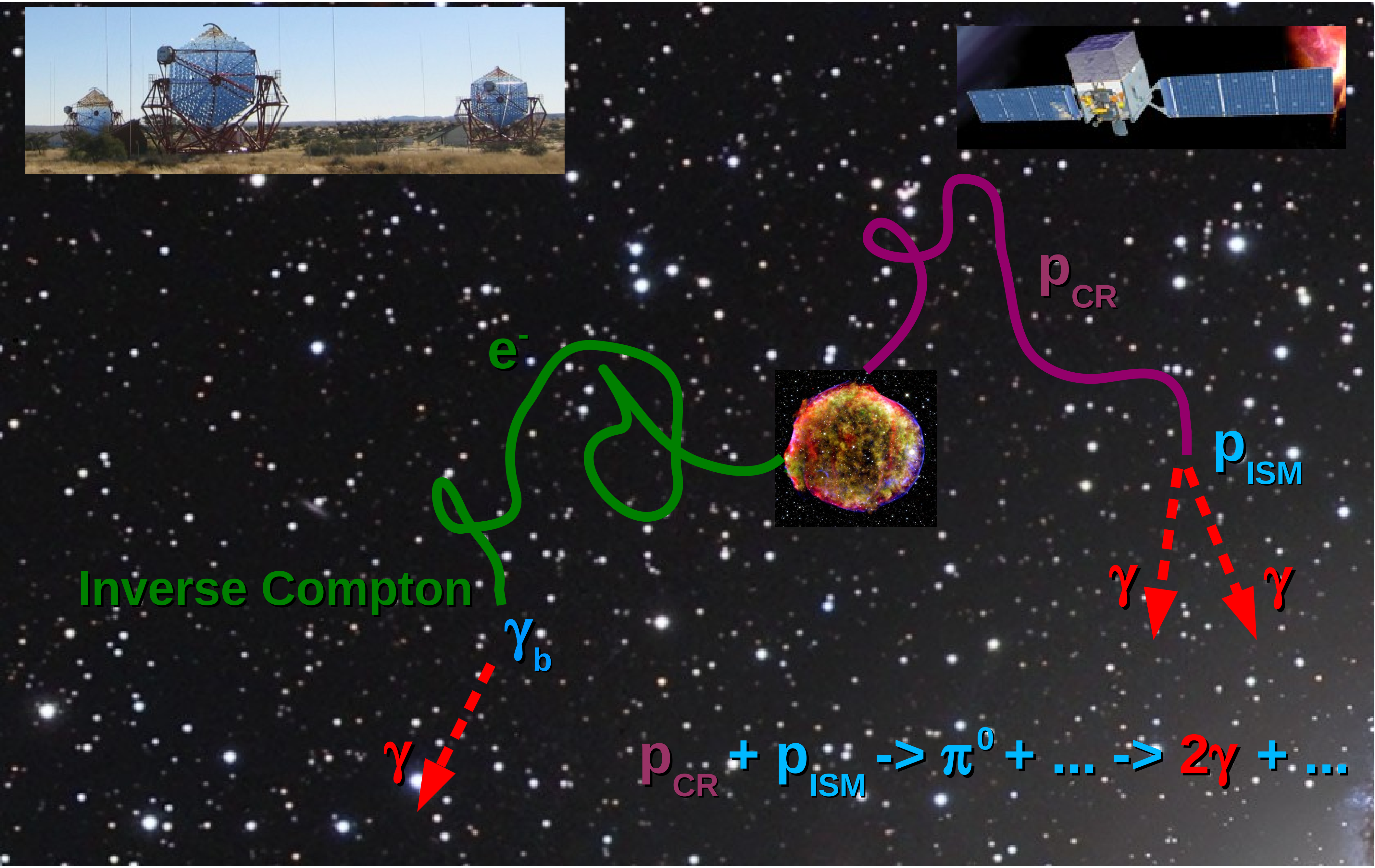
240 pc x 240 pc



- t >~ 10 t* :

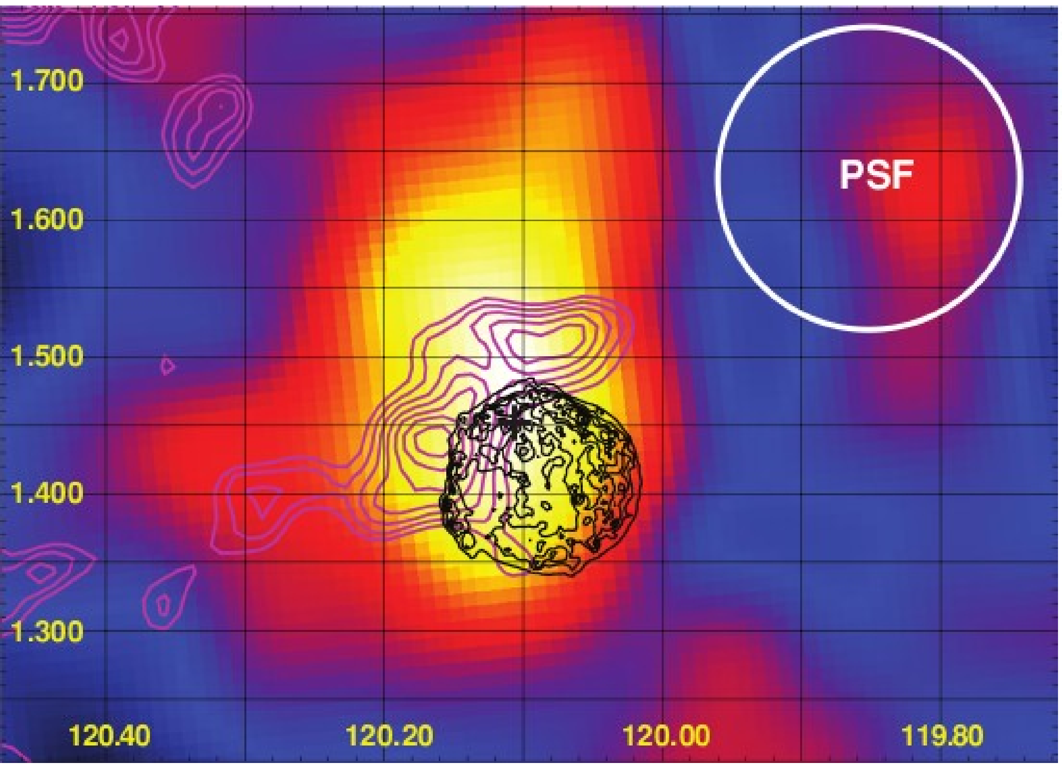
No visible difference

γ ray emission around sources



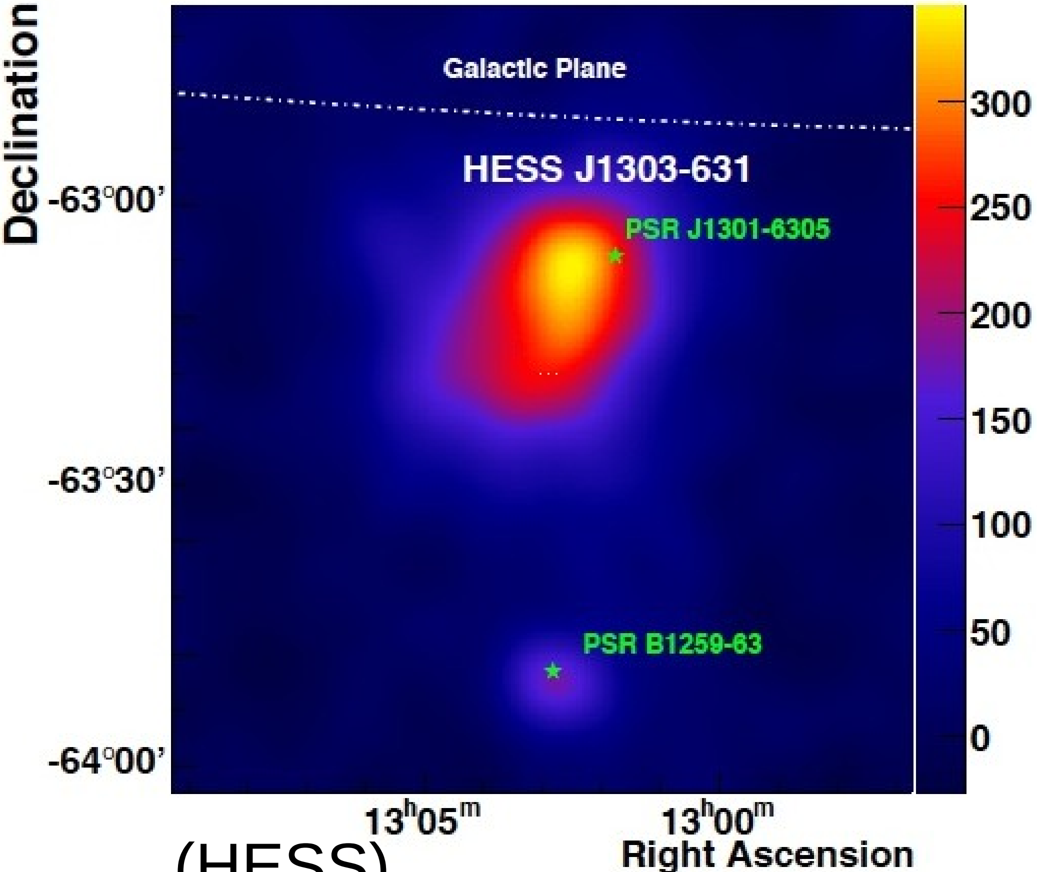
Observations : First hints at our findings ?

- Irregular images :



(Tycho - VERITAS)

-Offset from the source :



(HESS)

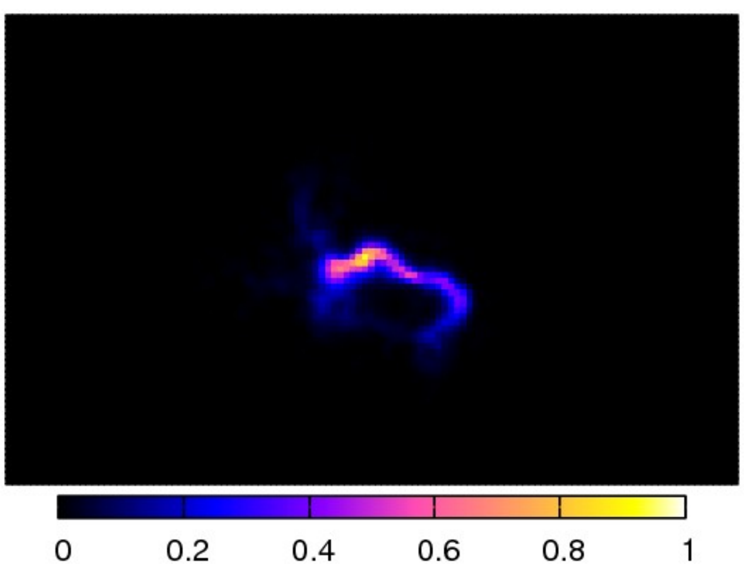
- Anisotropic diffusion around SNR W28 ? :
Nava & Gabici MNRAS '12

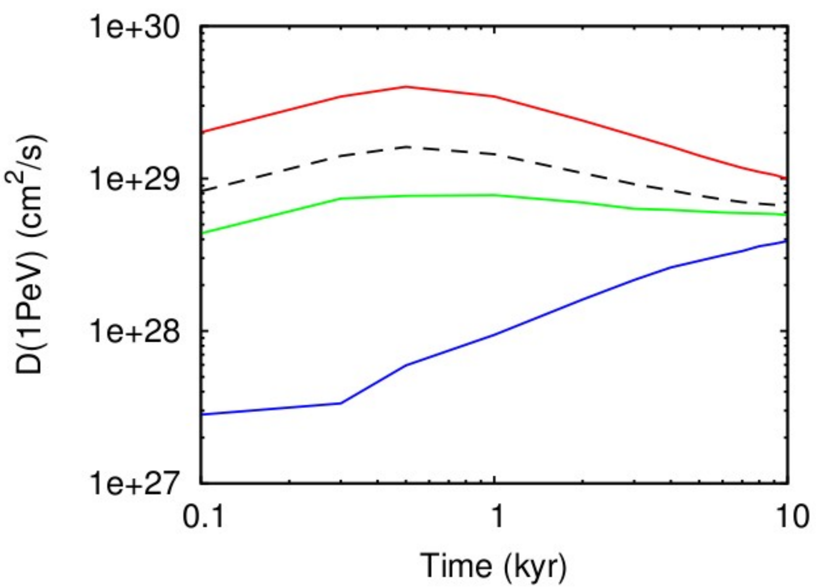
Eigenvalues of the diffusion tensor

Inject N particles at **x** = **0** in ***one single*** B field realization '*b*'

Calculate $$D_{ij}^{(b)} = \frac{1}{N}\sum_{a=1}^{N}\frac{x_i^{(a)}x_j^{(a)}}{2t}$$ (i, j = X, Y, Z)

Compute its eigenvalues : $d_1^{(b)} < d_2^{(b)} < d_3^{(b)}$



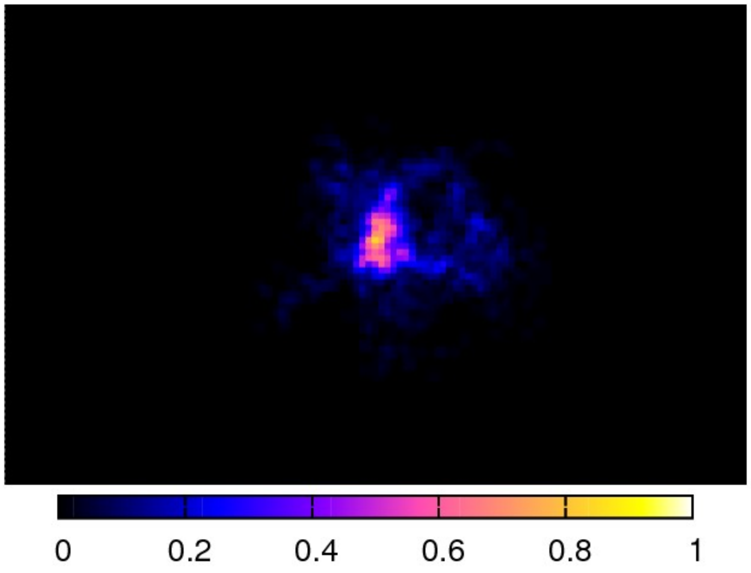


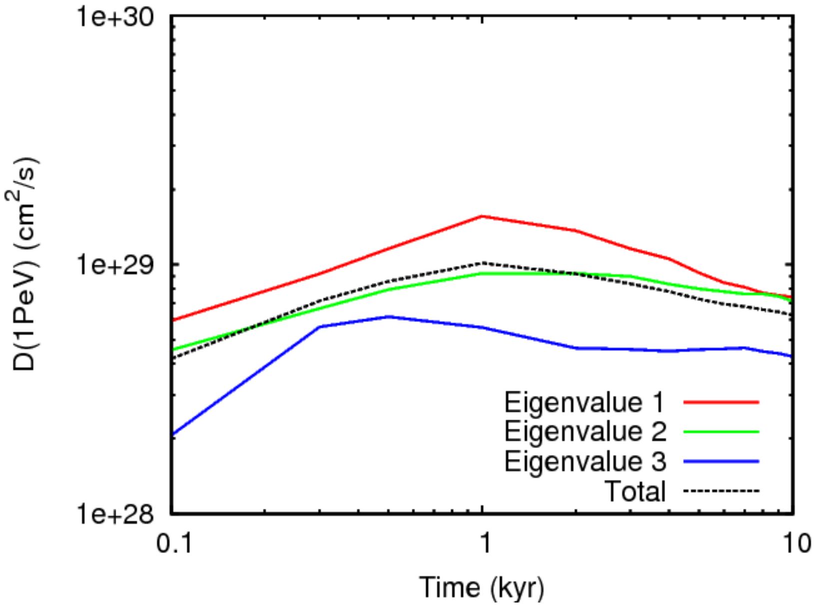
Eigenvalues of the diffusion tensor

Inject N particles at **x** = **0** in ***one single*** B field realization '*b*'

Calculate $$D_{ij}^{(b)} = \frac{1}{N}\sum_{a=1}^{N}\frac{x_i^{(a)}x_j^{(a)}}{2t}$$ (*i*, *j* = *X*,*Y*, *Z*)

Compute its eigenvalues : $d_1^{(b)} < d_2^{(b)} < d_3^{(b)}$





Eigenvalues of the diffusion tensor

Inject I

n '*b*'

Calcul

)

Compu

Averag