

## Can the local sources of cosmic rays explain the proton flux ?

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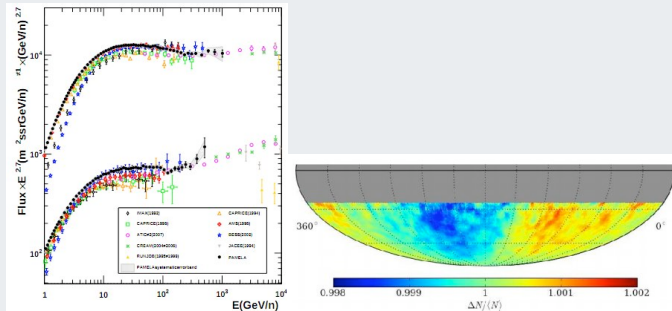
September 4, 2012

## Motivations

Indirect detection of dark matter

→ Predict the signal

→ Understand the background



**Figure:** Proton Flux as observed by PAMELA Colaboracion. Adriani et al arxiv:1103.4055, Cosmic rays anisotropy as observed by IceCube Toscano et al arxiv:1110.207

# Outline

- 1 Framework
- 2 Diffusion equation
- 3 Standard deviation of the flux
- 4 Variance is infinite but confidence levels are finite
- 5 Catalog of sources

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# Diffusion Model

The propagation of charged particles in the interstellar medium is determined by the structure of the galactic magnetic field.

- Regular component (around  $2 \mu\text{G}$ )
- Stochastic component

→ Fluctuations of the magnetic field on every scale

Turbulence  $\sim$  Larmor Radius

## Slightly turbulent regime

→ Diffusion process

Defined by a diffusion coefficient

$$D = D_0 \beta R^\delta$$

$D_0$  Related to the amplitude of turbulence

$\delta$  Related to the kind of magnetic turbulence

## The diffusion equation

We solve a diffusion equation taking into account :

- diffusion (diffusion coefficient ? anisotropic ? inhomogeneous ?)
- escape (boundary conditions, geometry of diffusion volume)
- spallations (creation/destruction, cross-sections, interstellar medium)
- energy losses
- diffusive reacceleration
- galactic wind (convection)
- Sources (distribution, spectra)

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## Diffusion parameters

- $D_0$  and  $\delta$
- L height of the diffusive halo
- $V_c$  convective wind
- Distribution of sources (supernova, sometimes we use pulsars distribution)
- Explosion rate of supernova

## Previous work

The results will be presented for three benchmark sets of diffusion parameters, consistent with the energy dependance of the B/C ratio

**Table:** Diffusion parameters for the three benchmark models

model	$D_0$ (kpc $\cdot$ My $^{-1}$ )	$\delta$	$L$ (kpc)	$V_c$ (km $\cdot$ s $^{-1}$ )
min	0.0016	0.85	1	13.5
med	0.0112	0.7	4	12
max	0.0765	0.46	15	5



## The myriad model

We treat supernova explosions as point-like events

Production rate of protons given by :

$$q_{\text{acc}}(\mathbf{x}_S, t_S) = \sum_{n \in \mathcal{P}} q_n \delta^3(\mathbf{x}_S - \mathbf{x}_n) \delta(t_S - t_n) , \quad (1)$$

Each source  $n$  belonging to the population  $\mathcal{P}$  of supernovae contributes a factor  $q_n$  at position  $\mathbf{x}_n$  and time  $t_n$ .

→ Infinite set of realisation possible in the range  $t_{\min} < t_n < t_{\max}$  and  $R_{\min} < r_n < R_{\max}$

Is it possible that a statistical variation of the flux gives rise to observed structures ?

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## Diffusion equation

$$\frac{\partial \psi}{\partial t} + \partial_z(V_C \psi) - K \Delta \psi = \sum_i q_i \delta^3(\mathbf{x}_S - \mathbf{x}_i) \delta(t_S - t_i) - 2 h \delta(z_S) \Gamma_p \psi(\mathbf{x}_S, t_S) . \quad (2)$$

$$\psi(\mathbf{x}, t) = \int_{-\infty}^t dt_S \int_{\text{DH}} d^3 \mathbf{x}_S \mathcal{G}_p(\mathbf{x}, t \leftarrow \mathbf{x}_S, t_S) q_{\text{acc}}(\mathbf{x}_S, t_S) , \quad (3)$$

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## Mean value

$$\langle \mathcal{G}_N \rangle = NA \int 2\pi r_s dr_s \int d\theta_s \int dz_s \int dt_s f_\theta(\theta) f_r(r_s) f_z(z_s) f_t(t_s) \mathcal{G}_N(r_s, \theta_s, t_s)$$

The source distribution in space are those from Yusifov and Küçük (2004)

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## Variance of the propagator

The second order momentum of the distribution diverges if we chose  $R_{\min} = 0$  and  $t_{\min} = 0$

$$\langle \mathcal{G}_1^2 \rangle \sim \frac{A}{4\pi D} \sum_{n,m} \langle \mathcal{G}_z^2 \rangle_{n,m} \ln R_{\min} \quad (4)$$

how bad is it ?

Does it mean that the actual value of the flux had a disturbingly large probability to be very far from the mean value.

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## Regularisations

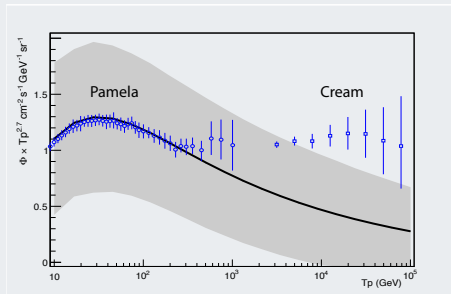
- Regularisation using a cut-off (Blasi et Amato (2011))
- Confidence intervals
- Catalog

## Regularisation introducing a cut off

Allowing sources to explode in the solar neighborhood is not physical : we put a cut-off on the ages of sources.

We choose  $t_{\min} = 100\text{yr}$ , physical limit of the diffusion at high energies.

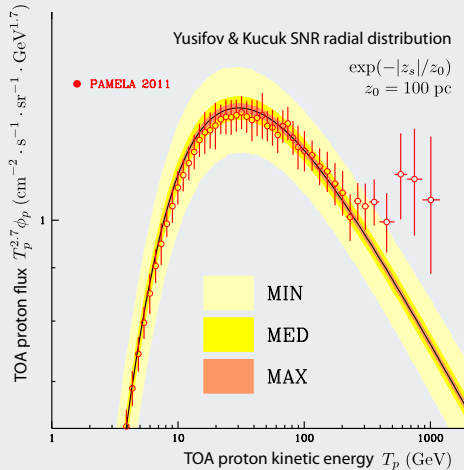
→ At  $10^5$  GeV, solutions of the propagation equation for sources younger than 100 yr are non physical because of the non-relativistic nature of the equation



Variance of the flux computed with a 100 yr cut-off



## Regularisation introducing a cut off

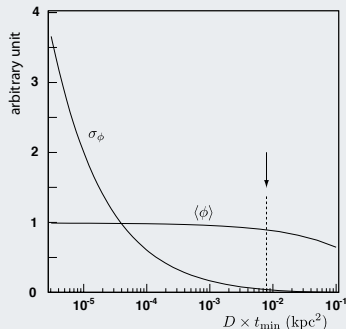


Variance for each set of parameters

## Energy dependant cut-off

Work of Blasi et Amato(2011)  $t_{\min} = R_{\max} / \sqrt{4\nu D(E)}$  corresponds to the limit for which sources contribute very weakly to the flux

## Influence of the cut-off



The value of  $\sigma_{\phi} / \langle \phi \rangle$  depends sensitively on the chosen cut-off  $t_{\min}$ .

For a very low value of  $t_{\min}$ , the standard deviation is very large and vice versa

**This confusing situation, where some rare events have a very small contribution to the mean, but give rise to a very large standard deviation, is not uncommon (Cauchy distribution).**

→ The distribution of fluxes is such that the central limit theorem is not valid in its usual form.

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## Very simple framework

We computed the probability for a flux from one source to be higher than a given value  $\Phi$  reads

$$P(> \Phi) = \frac{\langle \phi \rangle^2}{4\Phi^2} \Theta \left( \Phi - \frac{1}{2} \langle \phi \rangle \right)$$

The probability that  $\Phi > 10\langle \phi \rangle$  is only 1/400

For N source the effect is even more important. Considering 100 sources,

$$P(> 2\langle \Phi \rangle) = 2.5 \cdot 10^{-3}$$

## Very simple framework

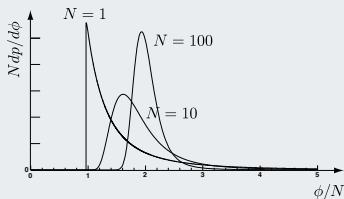
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$$P(> 2\langle \Phi \rangle) = 2.510^{-3}$$



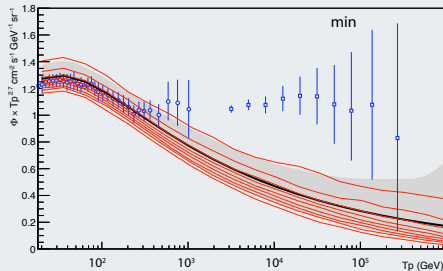
Probability distribution of  $\Phi/N$  for  $N = 1, 10$  and  $100$  sources.

## Quantiles

Using this information, we rather draw 68% confidence intervals, we also show 10% quantiles as a good estimator of theoretical uncertainties. (Monte-Carlo simulation)

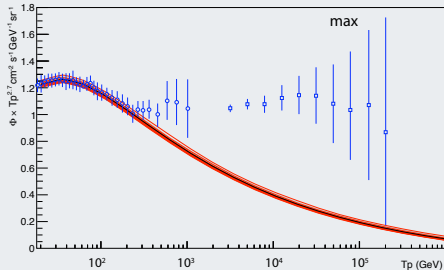
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Flux in the 'min' set of parameters





Flux in the 'max' set of parameters

The flux is very unlikely to be far from the mean value

The spread of the distribution is very sensitive to the thickness 'L' of the diffusive halo

Changing the cut-off  $t_{\min}$  will only change extremal deciles.

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## We know local sources

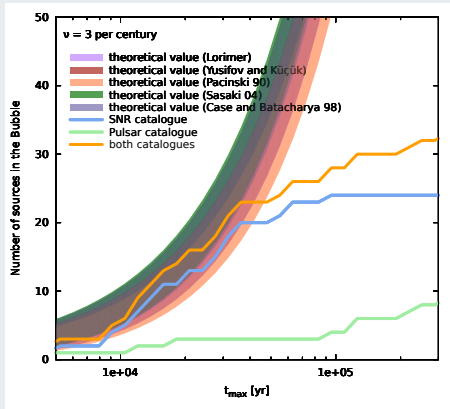
There are strong arguments to think that sources responsible for spread quantiles or large variance, are located in a region nearby the Sun. Following Delahaye et al. (2010), we have made use of two catalogs:

- Green catalog of supernova (Green (2009))
- ATNF pulsar catalog (Manchester (2005))

These catalogs are used to describe sources younger than  $10^5$  yr in a region of radius 2 kpc around the sun.

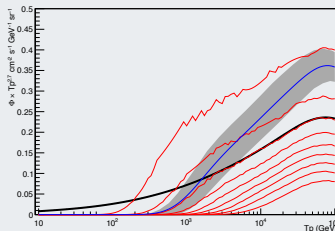
We created a new statistical set excluding this region, → **no divergence**

## Are these sources representative of the local environment ?



Theoretical number of sources and sources from the catalog considering an explosion rate of 3 supernova per century in a 2kpc region around solar system.

## Is the catalog probable ?

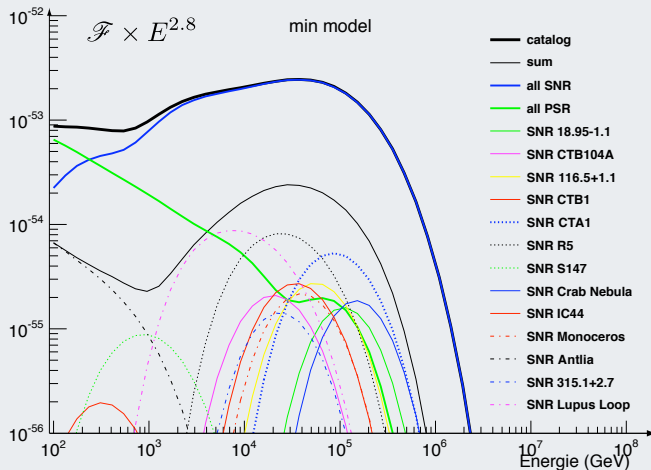


We compare the flux from the known sources to the flux from a random set of population.

→ The flux from the catalog is in the 68% confidence interval, including its theoretical uncertainties.

The flux from the local sources is very unlikely to produce important fluctuations at 200 GeV

## Contributions of the fluxes

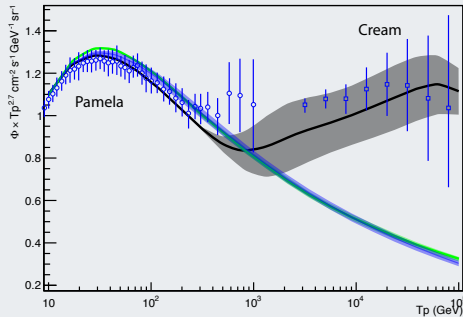


Contribution of the fluxes from each source

## Variing the explosion rate

We draw the flux considering the catalog and with an explosion rate of 1 supernova per century in the galaxy.

In this assumption : the local rate of explosion is higher than the mean explosion rate in the galaxy



We draw the flux including the catalog for the 'min' and 'max' benchmarks parameters considering an explosion rate of 1 supernova per century in the galaxy.

## conclusion

- Use of confidence interval rather than variance to compute the theoretical uncertainty of the flux
- The catalog is the best way to get rid of all divergence
- Only under certain assumptions (small  $L$ , small explosion rate) the confidence interval are high enough to allow sufficiently big fluctuations
- Local diffusion parameters seem to be a good way to provide an explanation to the bump.



## Can the local sources of cosmic rays explain the proton flux - Part II ?

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October 5, 2012

# Outline

1 Framework and parameters space

2  $\chi^2$  Test

3 Conclusion

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We investigate parameters compatible with Proton and Helium fluxes

### Our framework

Using our framework :

- point-like sources
- a catalog of known sources in the vicinity of the sun
- the mean value of the flux outside the catalog region

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### The parameter space

- $K_0$
- $\delta$
- $L$  (height of the diffusive halo)
- $\alpha_{\text{Proton}}$  (From the source injection spectra)
- $\alpha_{\text{Helium}}$  (Constrained to be very close from  $\alpha_{\text{Proton}}$ )
- $\nu$  (The rate of SNR in the galaxy)

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## Method

We perform a  $\chi^2$  test separately on both proton and Helium spectra in an energy range going from 80 GeV to  $10^5$  GeV.

→ No need to scan over convective wind or reaccelerations values at these energies

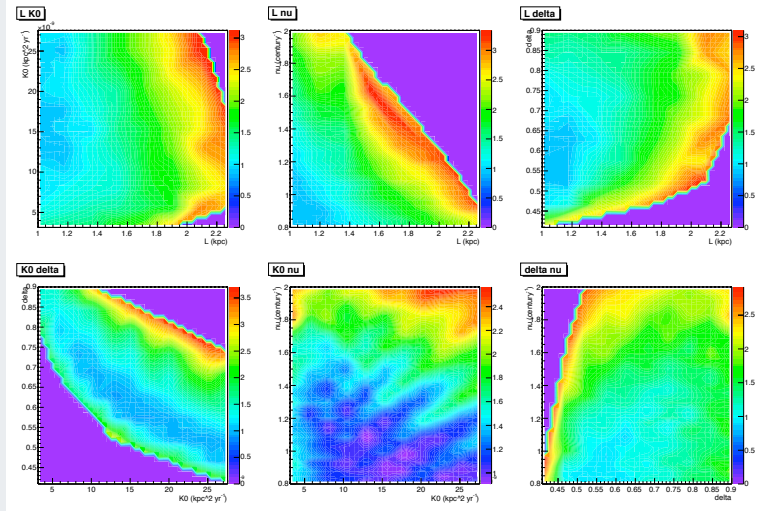
Each parameters set are kept only if :

$$(\chi^2/\text{ndof})_{\text{proton}} < 4 \text{ and } (\chi^2/\text{ndof})_{\text{Helium}} < 4$$

We allow  $\alpha_{\text{proton}}$  and  $\alpha_{\text{helium}}$  to be slightly different

→ The results drawn are  $(\chi^2/\text{ndof})_{\text{proton}} + (\chi^2/\text{ndof})_{\text{helium}}$

## Results



Values of the Best  $\chi^2/\text{ndof}$  for each couples of parameters



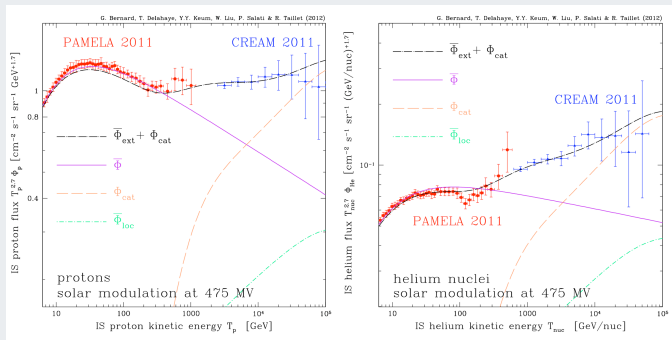
## Best fit parameters

The best fit parameters are :

$K_0 [\text{kpc}^2 \text{Myr}^{-1}]$	$\delta$	$L [\text{kpc}]$	$V_c [\text{km s}^{-1}]$	$\alpha_p$	$\alpha_{\text{He}}$	$\nu [\text{century}^{-1}]$
$1.29 \times 10^{-2}$	0.63	1	0	2.23	2.14	1.09

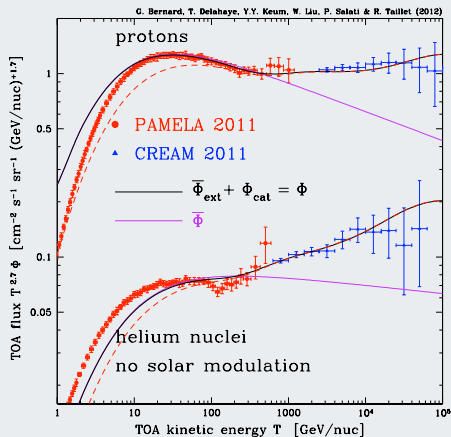
best fit are obtained for low values of  $L$ , which is fairly improbable

## Flux for best fit parameters



## Best fit obtained scanning over the B/C Grid

$K_0 [\text{kpc}^2 \text{Myr}^{-1}]$	$\delta$	$L [\text{kpc}]$	$V_c [\text{km s}^{-1}]$	$\alpha_p$	$\alpha_{\text{He}}$	$\nu [\text{century}^{-1}]$
$5.10 \times 10^{-3}$	0.75	2	11.5	2.11	2.0	0.8



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## Conclusion

- Results are in bad agreement at low energies (Region where the B/C is computed)
- But  $\chi^2$  test is performed only at high energies
- Need a new computation at low energies, considering  $V_c$  and diffusive reacceleration
- Good agreement only for little L