Multi-messenger Approaches to Cosmic Rays: Origin and Space Frontiers

Proton and Helium anomalies

Timur Delahaye
in collaboration with
Guilhem Bernard, Pierre Salati, Richard Taillet, Wei Liu and Yong-Yeon Keum

Stockholm University

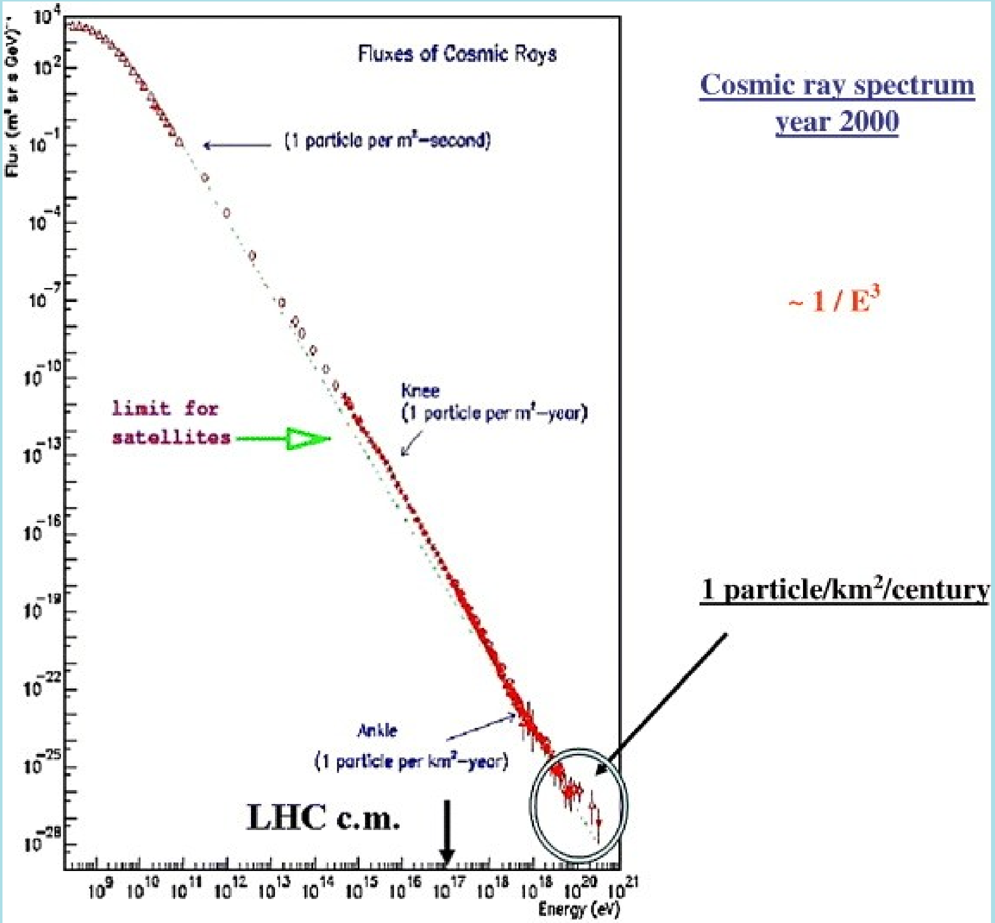
Oskar Klein centre

Based on

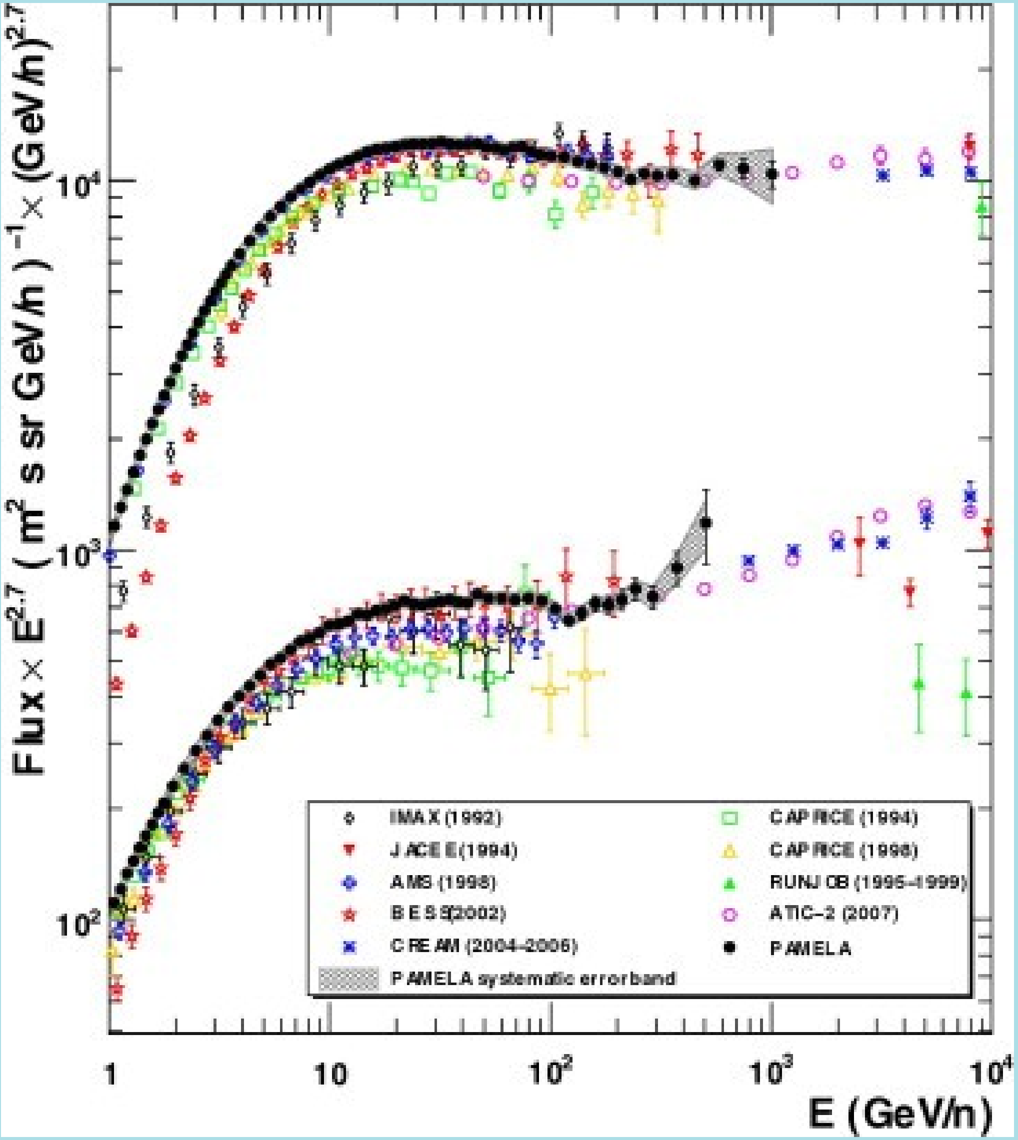
- **Variance of the Galactic nuclei cosmic ray flux** by Bernard, TD, Salati & Taillet *Astronomy & Astrophysics (2012), Volume 544, id.A92*

- **TeV cosmic-ray proton and helium spectra in the myriad model** by Bernard, TD, Keum, Liu, Salati & Taillet *Astronomy & Astrophysics (2013), Volume 555, id.A48*

Is low energy boring ?



PAMELA, ATIC & CREAM



Spectral break around 230 GeV/nuc

$\Delta\alpha_p = +0.2$

$\Delta\alpha_\alpha = +0.3$

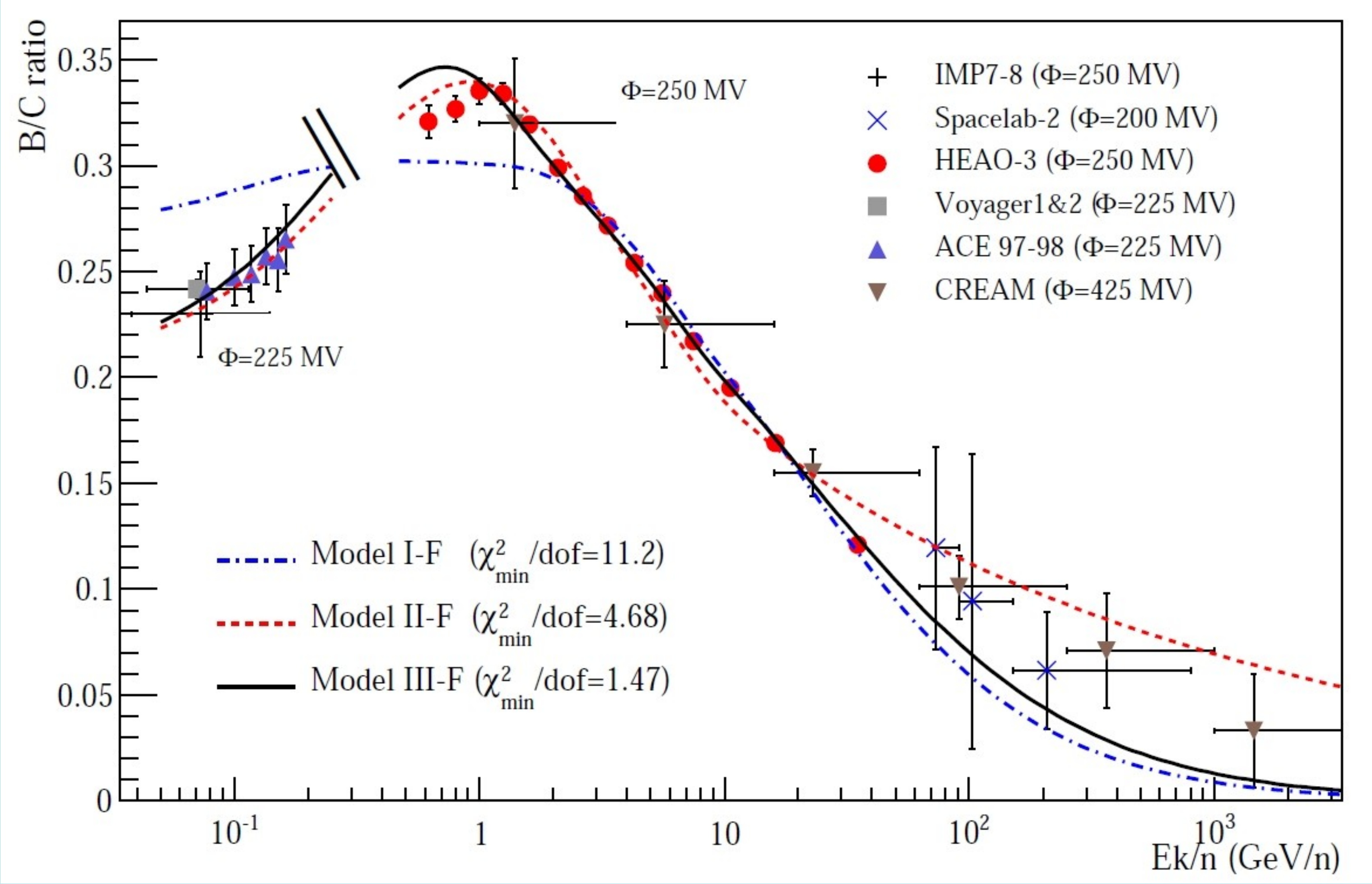
Consistent with Kascade Grande data

Possible explanations

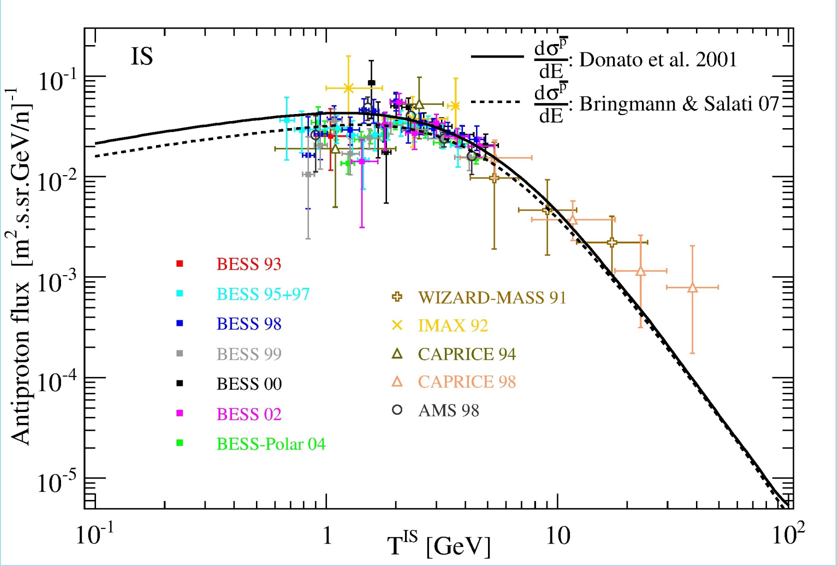
- Modified acceleration mechanisms *(Malkov et al. 2012, Ohira & Ioka 2011)*
- New class of source *(Stanev et al. 1993 2006, Biermann et al. 2010)*
- Very strong spallation *(Blasi & Amato 2011, Hörandel et al. 2007)*
- Energy dependance of propagation coefficients *(Ave et al. 2009)*
- Local propagation effects *(Evoli et al. 2012, Tomassetti 2012)*
- Local sources *(Erlykin & Wolfendale 2011, Thoudam & Hörandel 2012)*

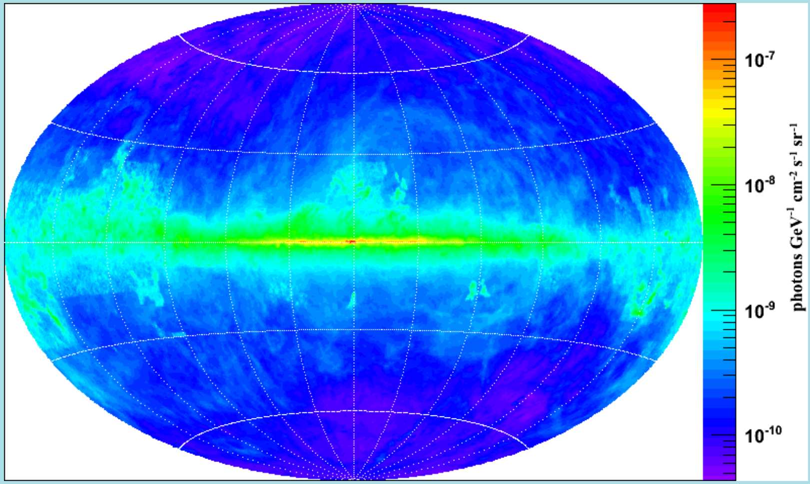
Cosmic ray propagation

$$\partial_t \Psi + \vec{\nabla} \cdot \left(\vec{V}_c \Psi - K \vec{\nabla} \Psi \right) + \partial_E \left(b_{loss} \Psi - D_{EE} \partial_E \Psi \right) = Q - D$$



A very successful model





Cosmic ray variance

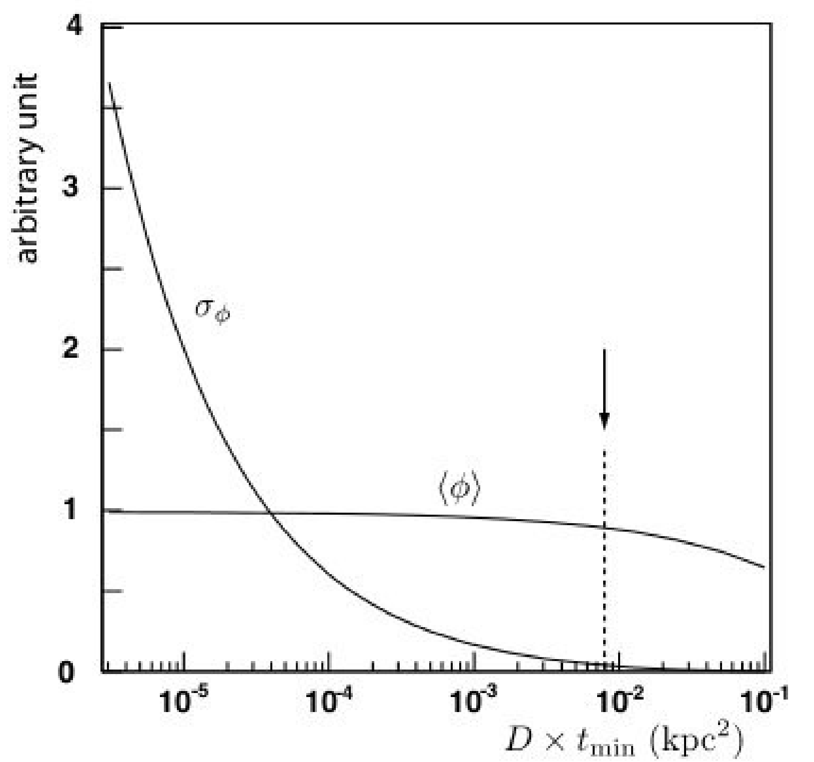
- The mean flux coming from a large number of point-like sources is the same as the one obtained from a smooth distribution.
- But the distribution has a heavy tail so the central limit theorem does not apply : the second moment of the propagator $\langle G^2 \rangle$ diverges

Cosmic ray variance

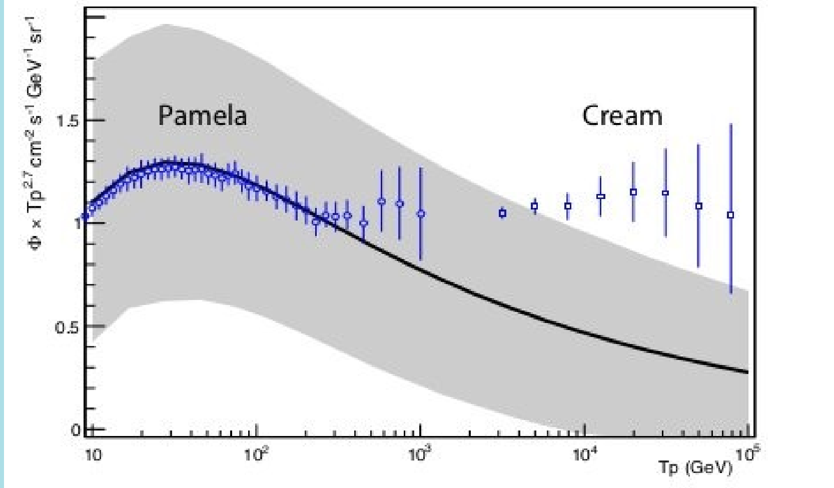
- The mean value is hence hard to estimate because it takes a long time to converge
- The variance is even worse
- Because there is a non zero probability of having a nearby young source
  - Cut the distribution
  - Study the quantiles
  - Use the catalogue

Cutting the distribution

Comparision with Blasi & Amato 2011



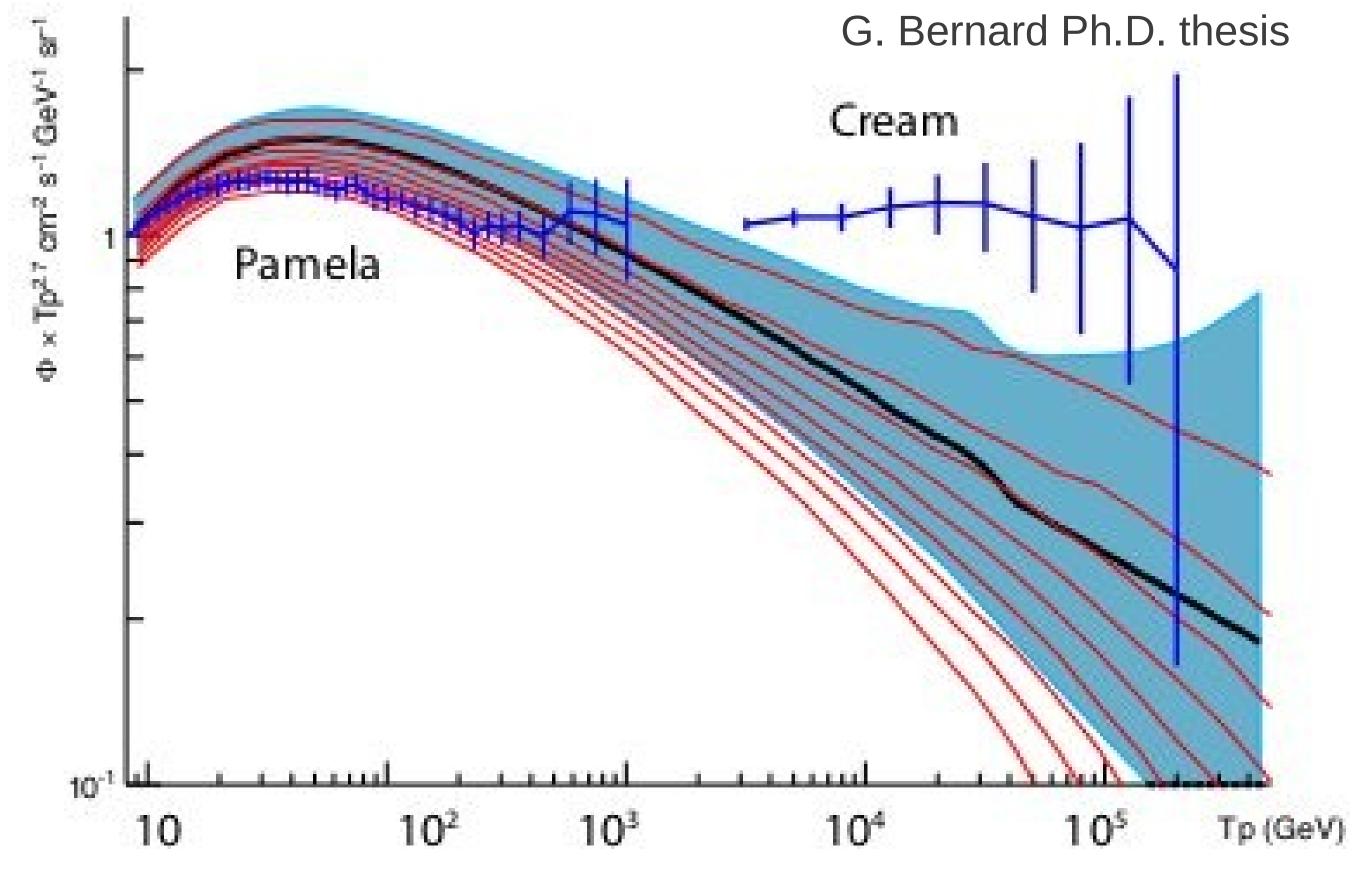
$T_{min} = R_{max} / \sqrt{(4\nu D)}$



T_{min} = 100 years

However the flux coming from far away sources has a very small variance

Quantiles



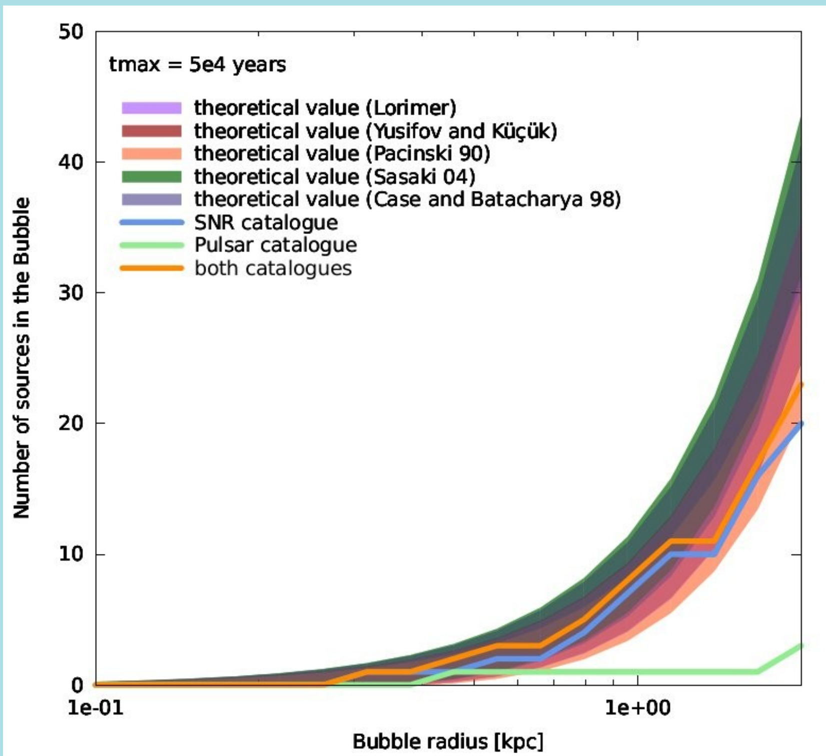
The variance may be infinite but the confidence levels are finite.

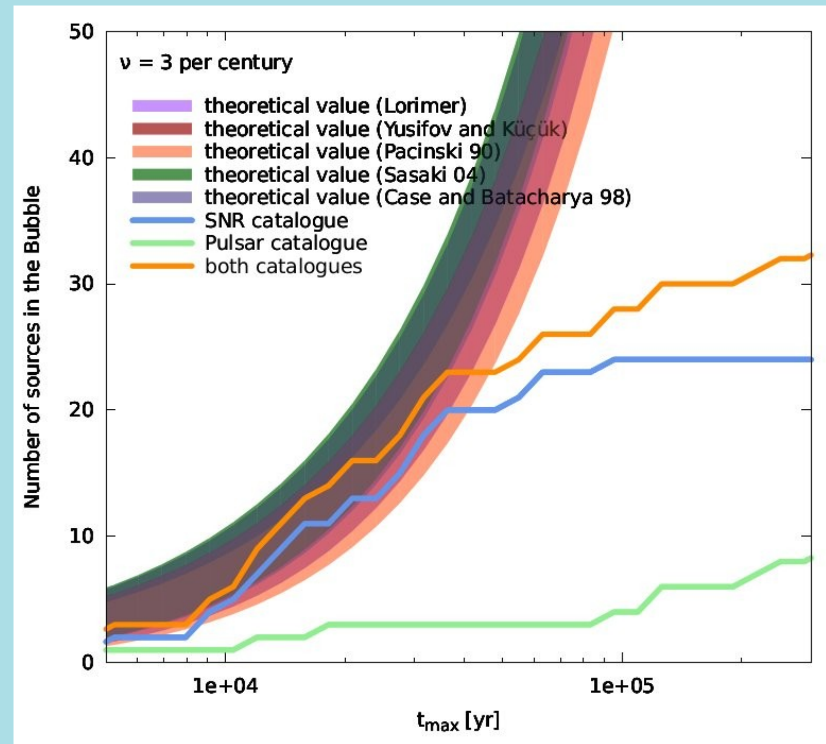
Decreasing the supernovæ explosion rate increases the size of the deciles.

Monte Carlo with populations ~3000 SNR
ν = 1 /century

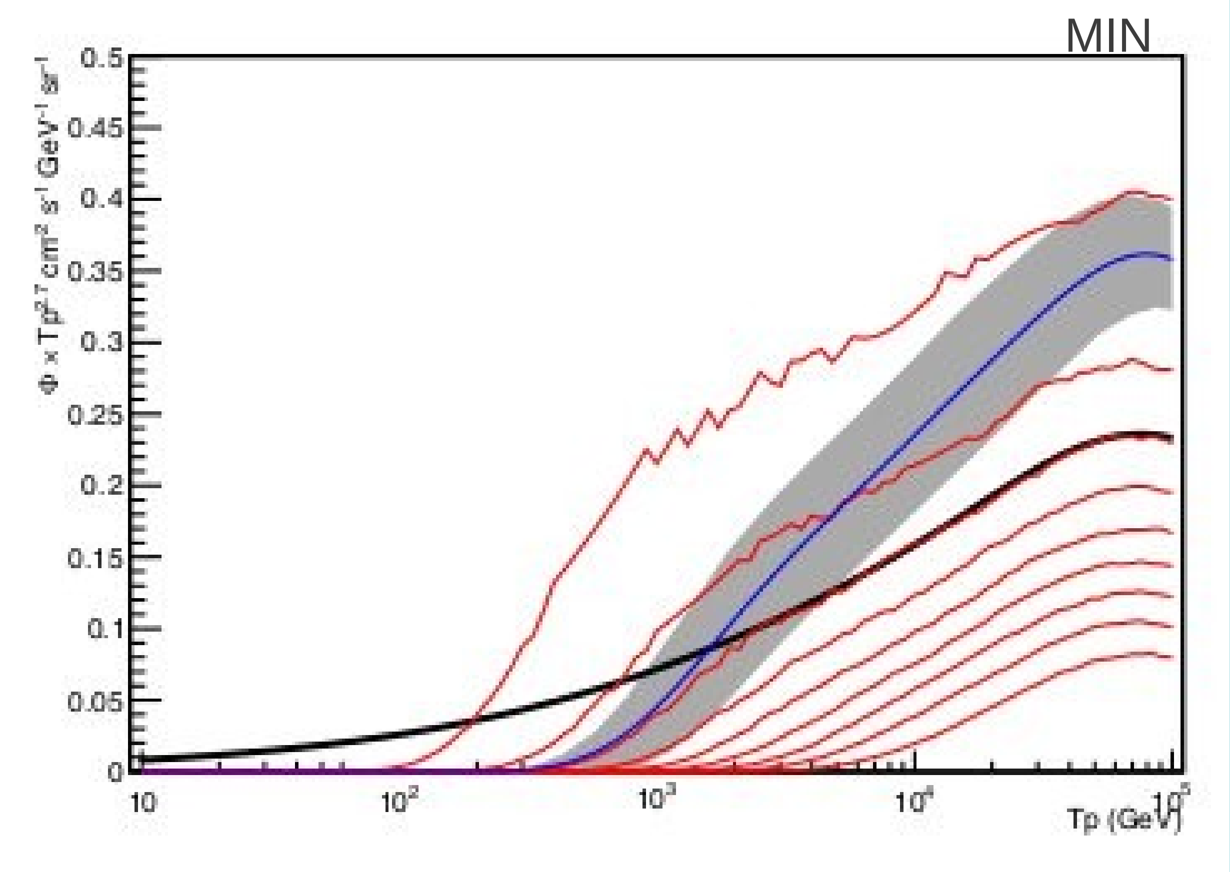
Catalogues

Green 2009 (27 SNR) & ATNF (Manchester et al. 2005, 157 pulsars)
d < 2 kpc & t < 50,000 years



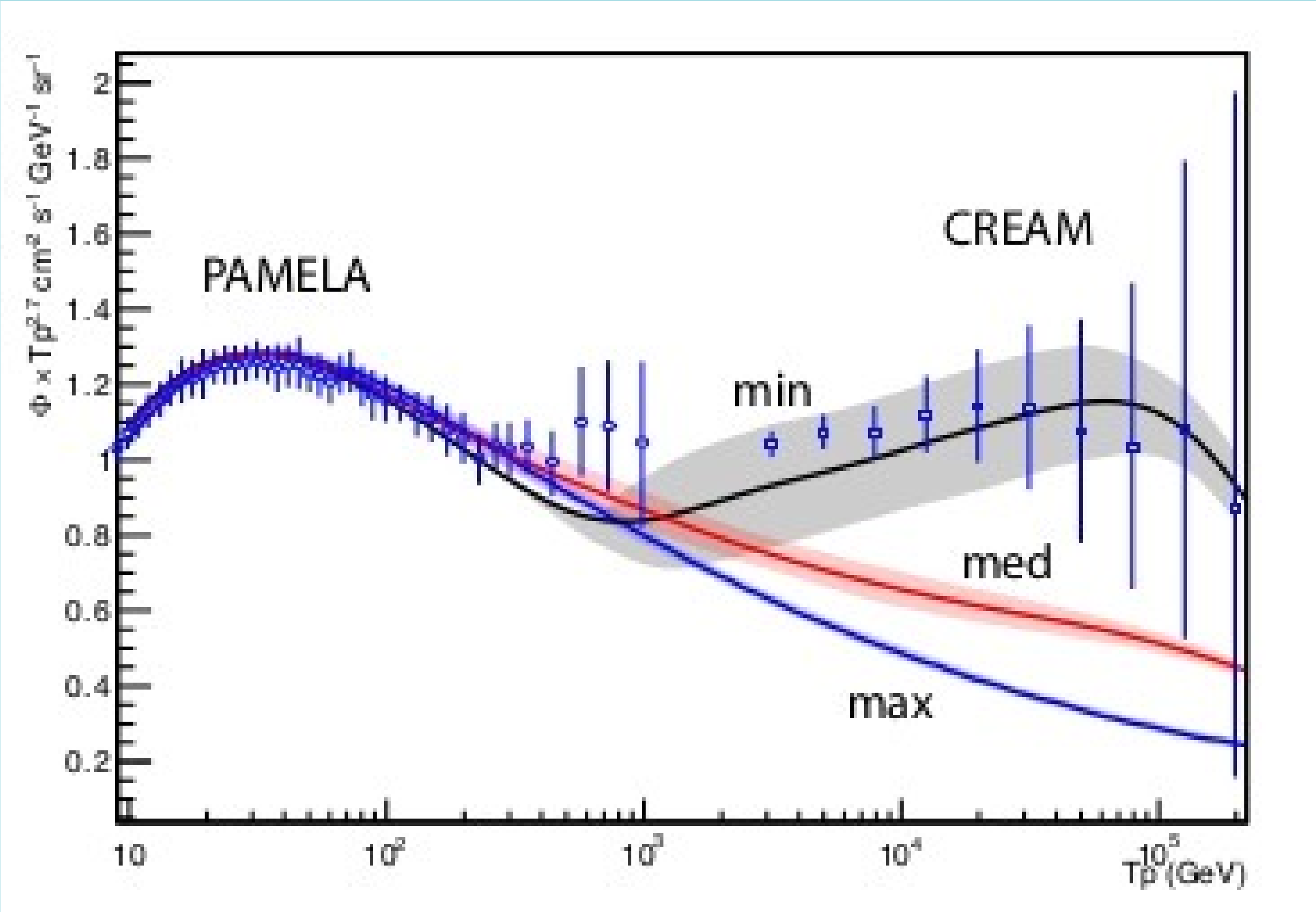


Catalogue



The real sources do not give the same results as the mean

Error from the catalogue

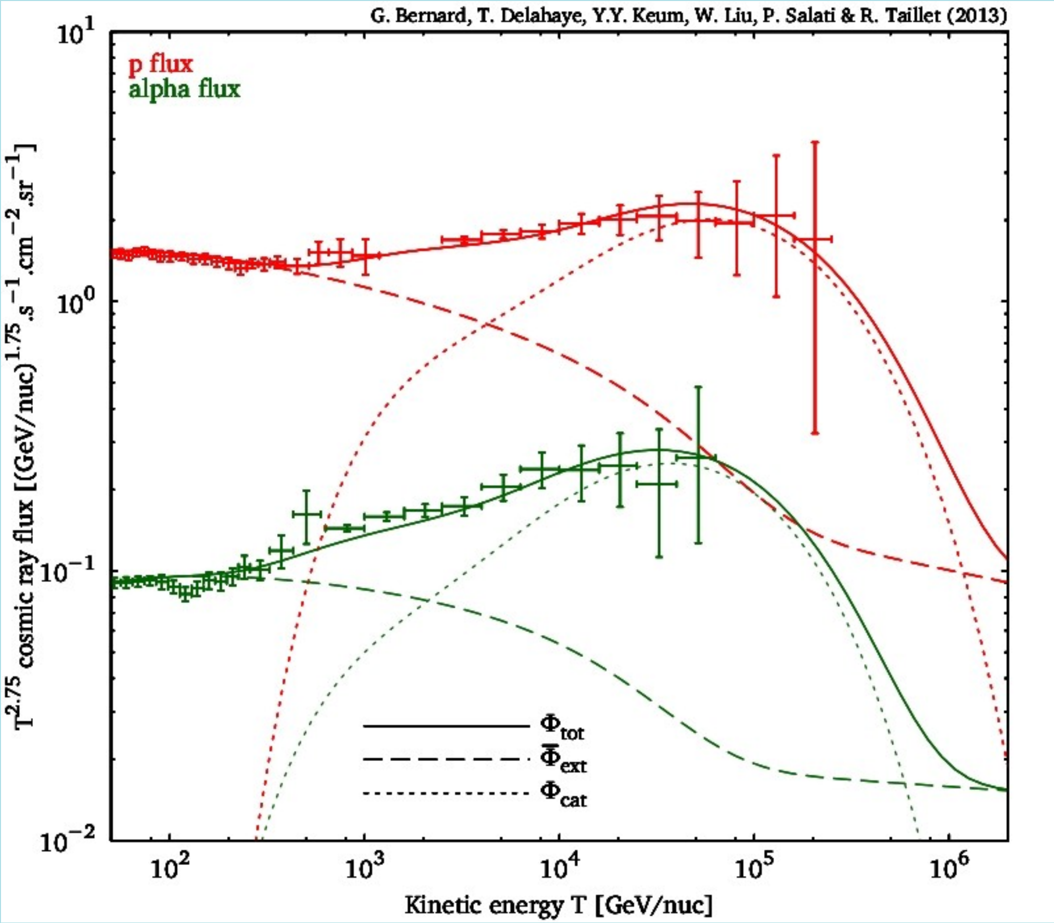


Fits results

model	K_0 [kpc^2/yr]	δ	L [kpc]	V_c [kpc/yr]	$q^0_{\rm p}$ [GeV^{-1}]	$q^0_{\rm He}$ [(GeV/n)$^{-1}$]
A	2.4×10^{-9}	0.85	1.5	1.38×10^{-8}	1.17×10^{52}	3.22×10^{51}
B	2.4×10^{-9}	0.85	1.5	1.38×10^{-8}	0.53×10^{52}	1.06×10^{51}
MED	1.12×10^{-9}	0.7	4	1.23×10^{-8}	15.8×10^{51}	3.14×10^{51}
model	$\alpha_{\rm p} + \delta$	$\alpha_{\rm He} + \delta$	ν [century^{-1}]	H injection	He injection	χ^2/dof
A	2.9	2.8	0.8	0.19	0.05	0.61
B	2.85	2.7	1.4	0.12	0.07	1.09
MED	2.85	2.7	0.8	0.148	0.07	1.3

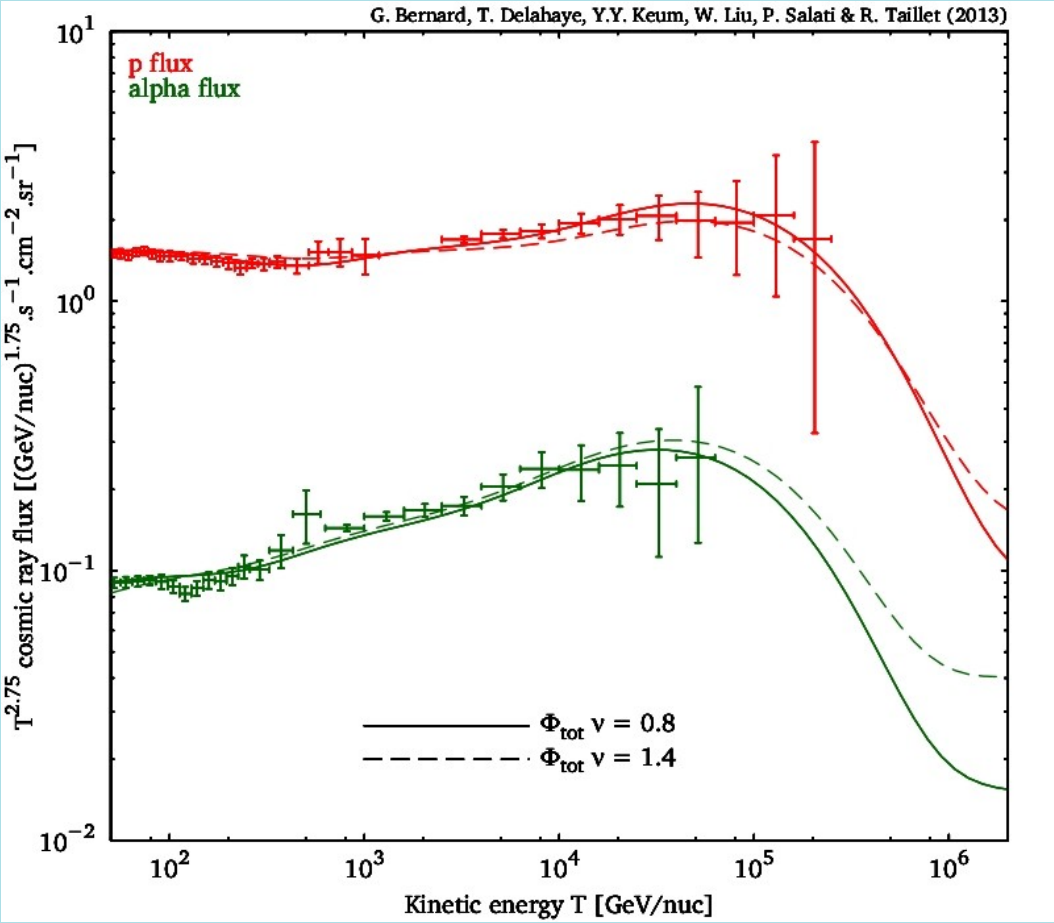
- Fits go from 50 GeV/nuc to 100 TeV/nuc
- A : propagation parameters are free
- B : same propagation parameters and fixed ν

Model A



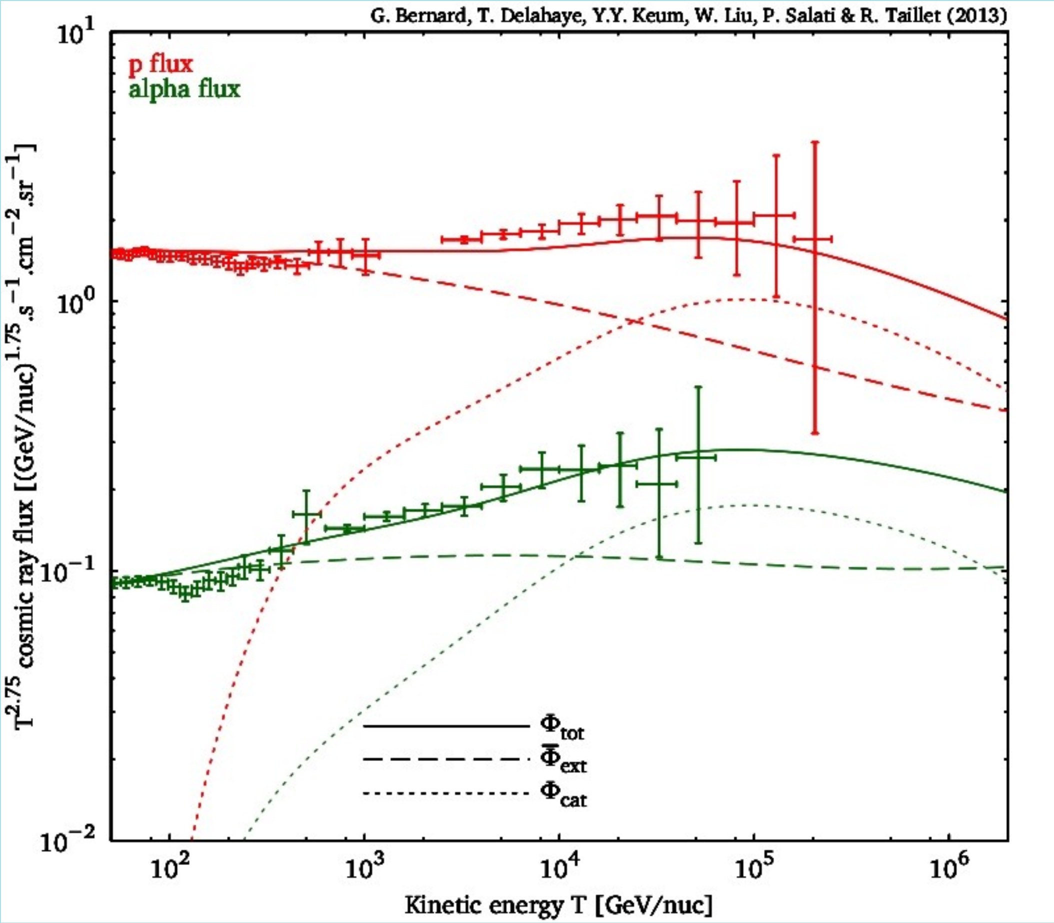
G. Bernard, T. Delahaye, Y.Y. Keum, W. Liu, P. Salati & R. Taillet (2013)
p flux
alpha flux
Φ_{tot}
Φ_{ext}
Φ_{cat}
$T^{2.75}$ cosmic ray flux [(GeV/nuc)$^{1.75}$.s^{-1}.cm^{-2}.sr^{-1}]
Kinetic energy T [GeV/nuc]

Model B



G. Bernard, T. Delahaye, Y.Y. Keum, W. Liu, P. Salati & R. Taillet (2013)
p flux
alpha flux
$T^{2.75}$ cosmic ray flux [(GeV/nuc)$^{1.75}$.s^{-1}.cm^{-2}.sr^{-1}]
10^1
10^0
10^{-1}
10^{-2}
Φ_{tot} ν = 0.8
Φ_{tot} ν = 1.4
10^2
10^3
10^4
10^5
10^6
Kinetic energy T [GeV/nuc]

MED


G. Bernard, T. Delahaye, Y.Y. Keum, W. Liu, P. Salati & R. Taillet (2013)
p flux
alpha flux
$T^{2.75}$ cosmic ray flux [(GeV/nuc)$^{1.75}$.s^{-1}.cm^{-2}.sr^{-1}]
Kinetic energy T [GeV/nuc]
Φ_{tot}
$\overline{\Phi}_{ext}$
Φ_{cat}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}

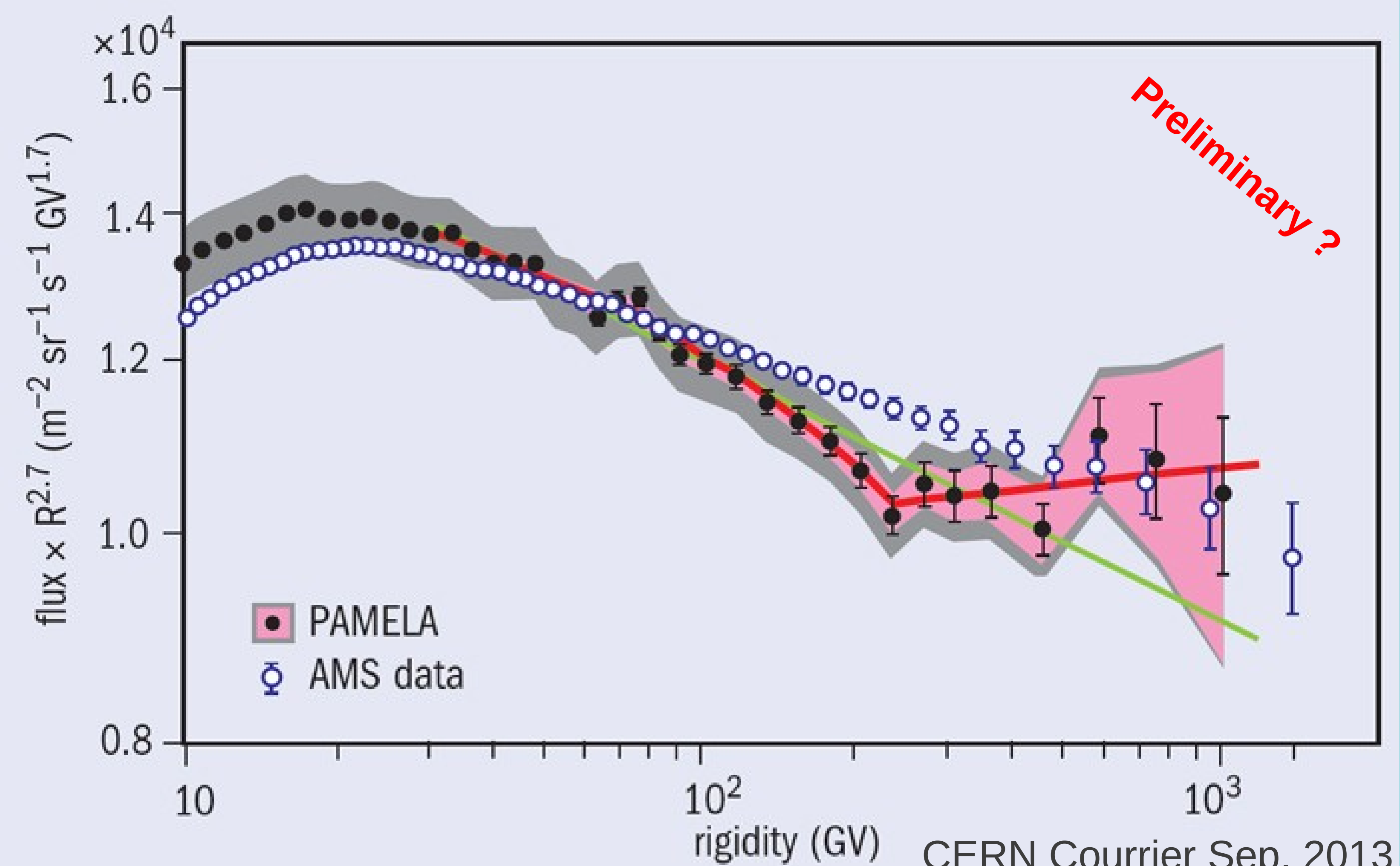
Results

- The data favours a local super nova explosion rate higher than the Galactic one.
- Miryad model requires small diffusive halo
- It requires slightly different injections for p & α

Conclusions

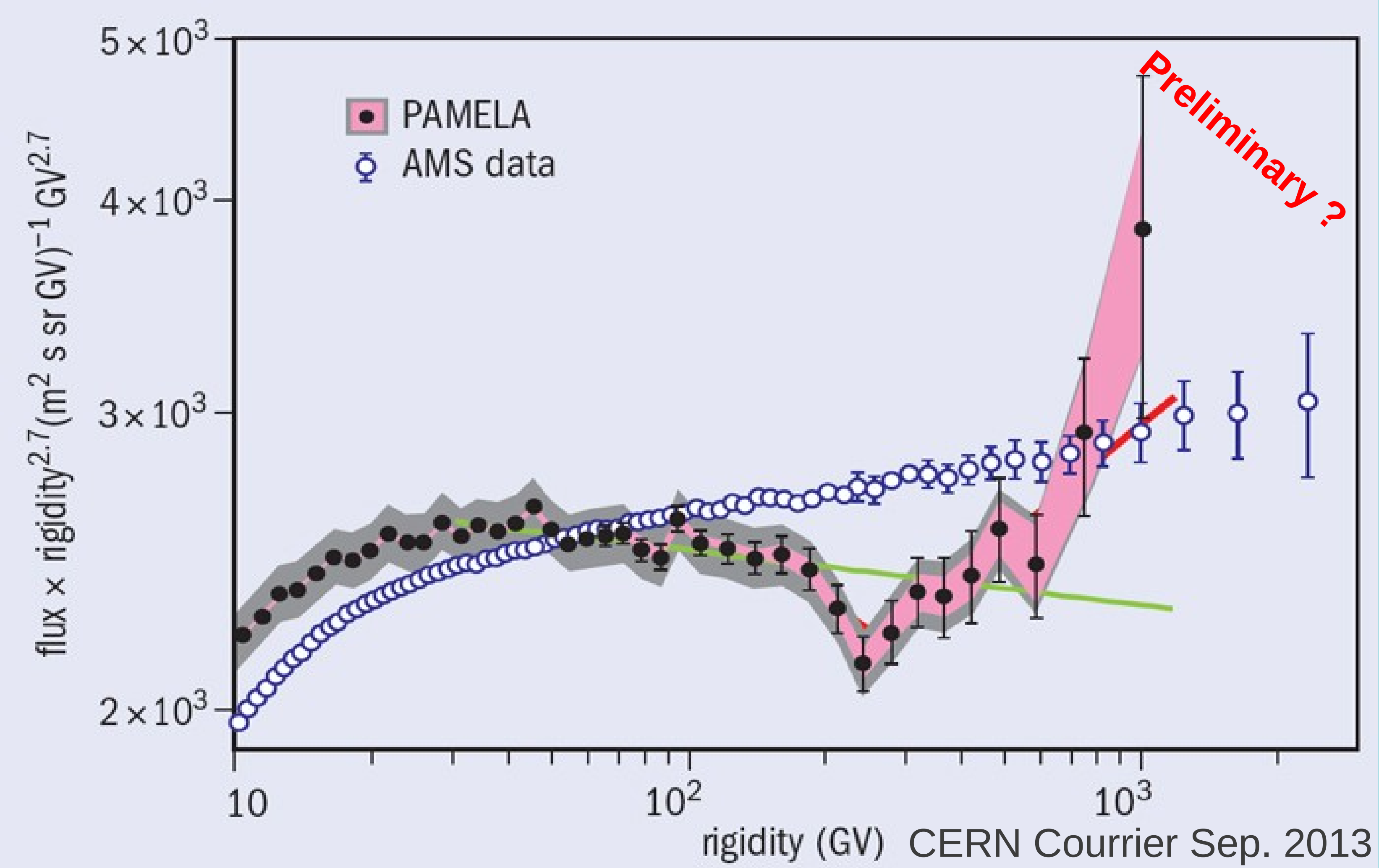
- Though not favoured, fluctuations of the flux, even strong, away from the mean value are possible in the myriad model
- This may question all previous models of cosmic rays : B/C, positrons, anti-protons γ-rays
- However...

AMS-02



CERN Courrier Sep. 2013

AMS-02



CERN Courrier Sep. 2013

So what ?

- Should the AMS-02 data be confirmed, it could help constraining propagation parameters.
- Anisotropies may bring interresting answers.