Effect of the primary cosmic ray flux uncertainties on the secondary positron flux

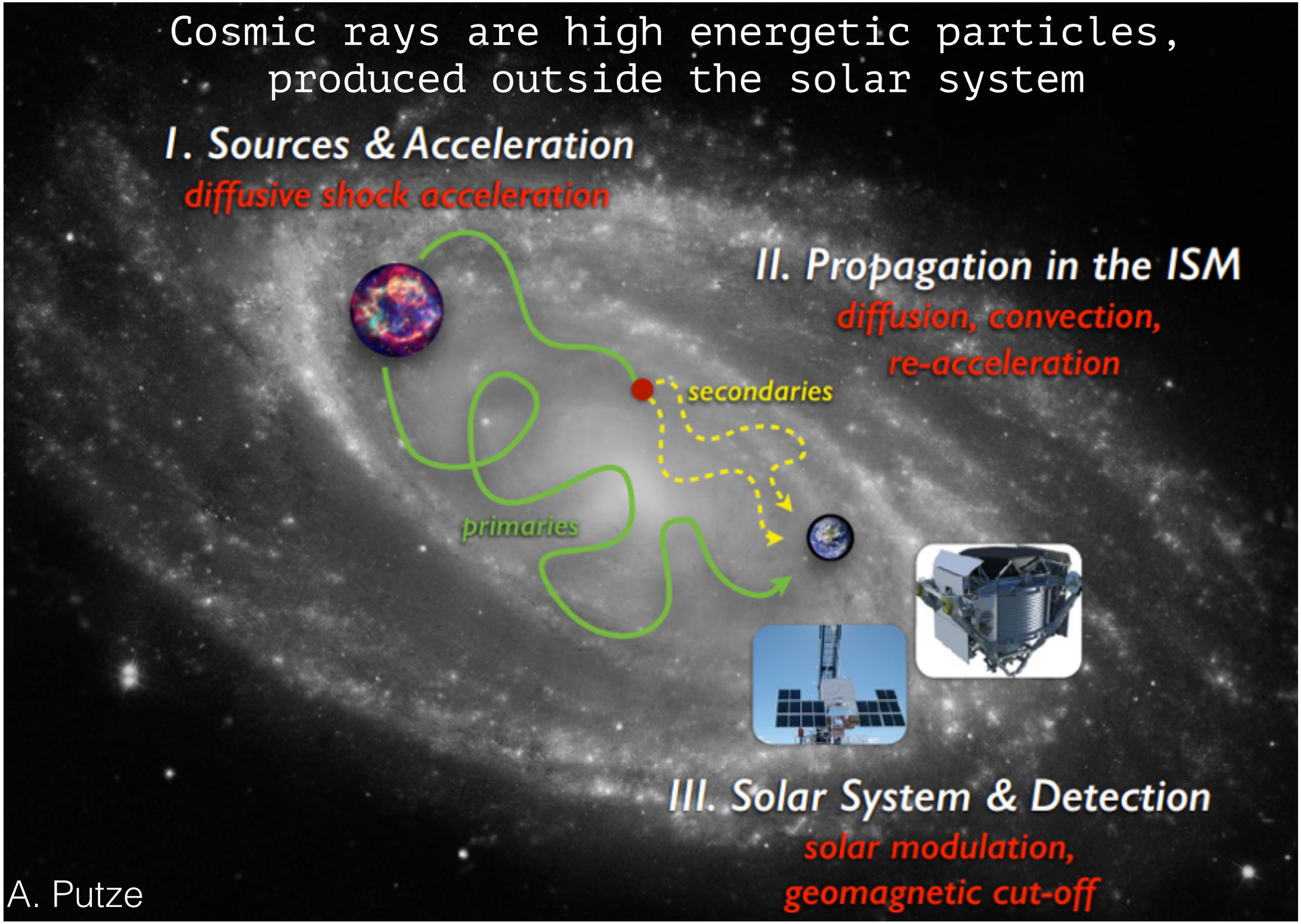
Manuela Vecchi[1], Mathieu Boudaud[2], Sami Caroff[3], Yoann Genolini[2], Vivian Poulin[2], Pierre Salati[2], Vincent Poireau[3], Antje Putze[2,3], E. F. Bueno[1]

aka Cosmic Rays Alpine Collaboration

1, Instituto de Física de São Carlos, Universidade de São Paulo (IFSC)
2, Laboratoire d'Annecy-le-Vieux de Physique Théorique (LAPTh)
3, Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP)

IFSC UNIVERSIDADE DE SÃO PAULO
Instituto de Física de São Carlos

The life of cosmic rays



Ingredients for secondary e+ spectra determination

Secondary positrons are created by the interaction of primary cosmic rays with the interstellar medium composed of hydrogen and helium.

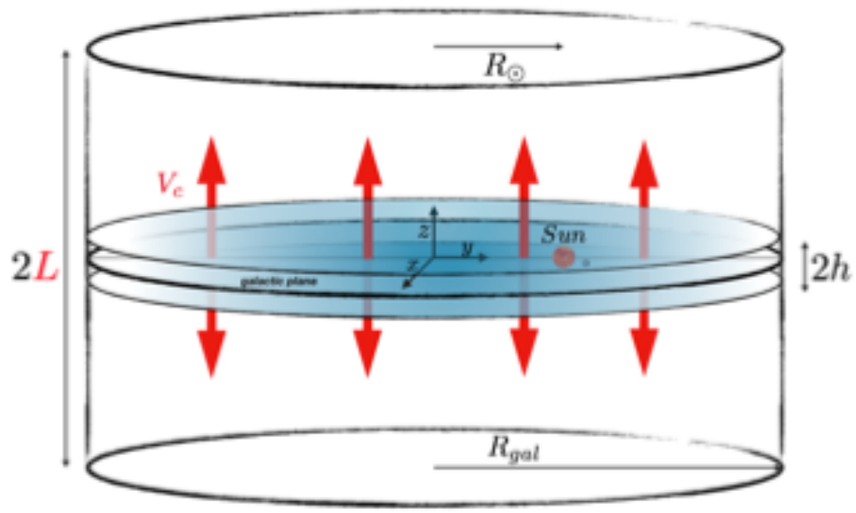
$$p + p_{\mathrm{ism}} \rightarrow \pi^+ + \ldots$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

To obtain the secondary positron flux prediction we have to take into account:

- Spectra of primary cosmic rays
- Interaction cross section CR+ISM
- Description of the galactic environment
- Solar modulation
- Propagation processes

Cosmic rays propagation

Two-zone model and semi-analytic method



$$1 < L < 15 \text{ kpc}$$

$$K(E) = K_0\, \beta \left(\frac{R}{R_0}\right)^{\delta}$$

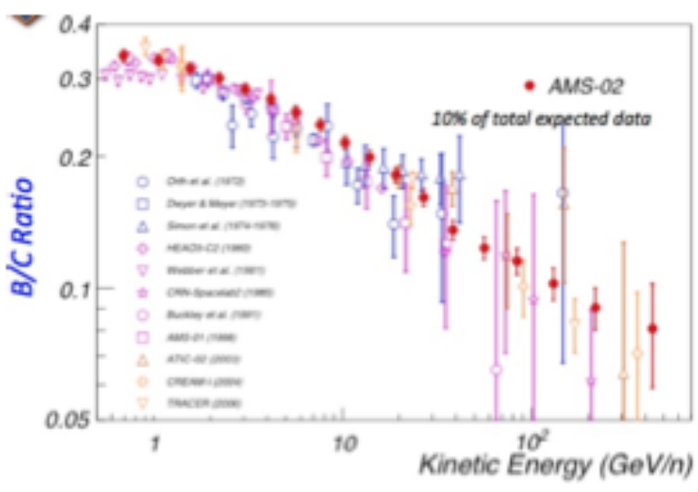
$$\vec{V}_c = V_c\, sign(z)\vec{e}_z$$

$$K_{EE}(E) = \frac{2}{9} {V_a}^2 \frac{E^2\beta^2}{K(E)}$$

Cosmic rays transport equation

$$\partial_t\psi - K(E)\nabla^2\psi + \partial_z\left[V_c\, sign(z)\psi\right] + \partial_E\left[b(E,\vec{x})\psi - K_{EE}(E,\vec{x})\partial_E\psi\right] = Q(E,t,\vec{x})$$

$$Q(E,t,\vec{x}) = Q^{source}(E,t,\vec{x}) - Q^{sink}(E,\vec{x})$$



Maurin et al. (2001)
Donato et al. (2003)
$\Rightarrow$

Case	δ	K_0 [kpc^2/Myr]	L [kpc]	V_C [km/s]	V_a [km/s]
MIN	0.85	0.0016	1	13.5	22.4
MED	0.70	0.0112	4	12	52.9
MAX	0.46	0.0765	15	5	117.6

M. Boudaud

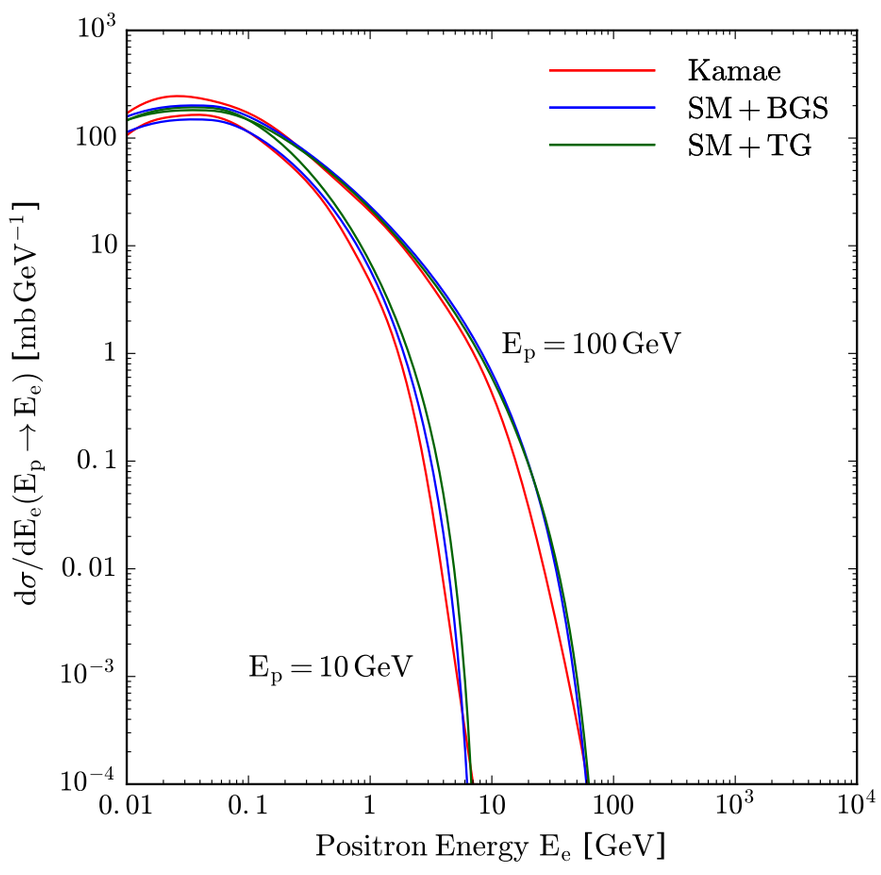
Source term: the primary CR fluxes

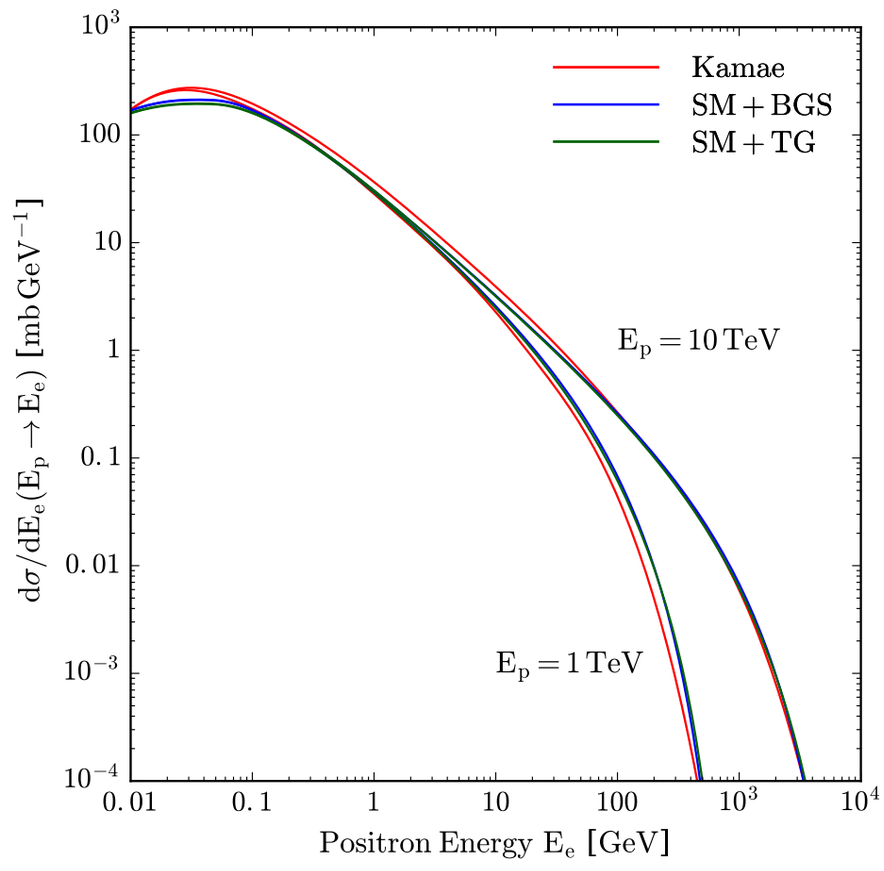
- The source term for proton-hydrogen collisions is given by:

$$Q^{\rm II}(E,\vec{x}) = 4\pi\, n_H\, f(r,z) \int dE_p \frac{d\sigma}{dE}(E_p \to E)\, \Phi_p(E_p,\vec{x}),$$

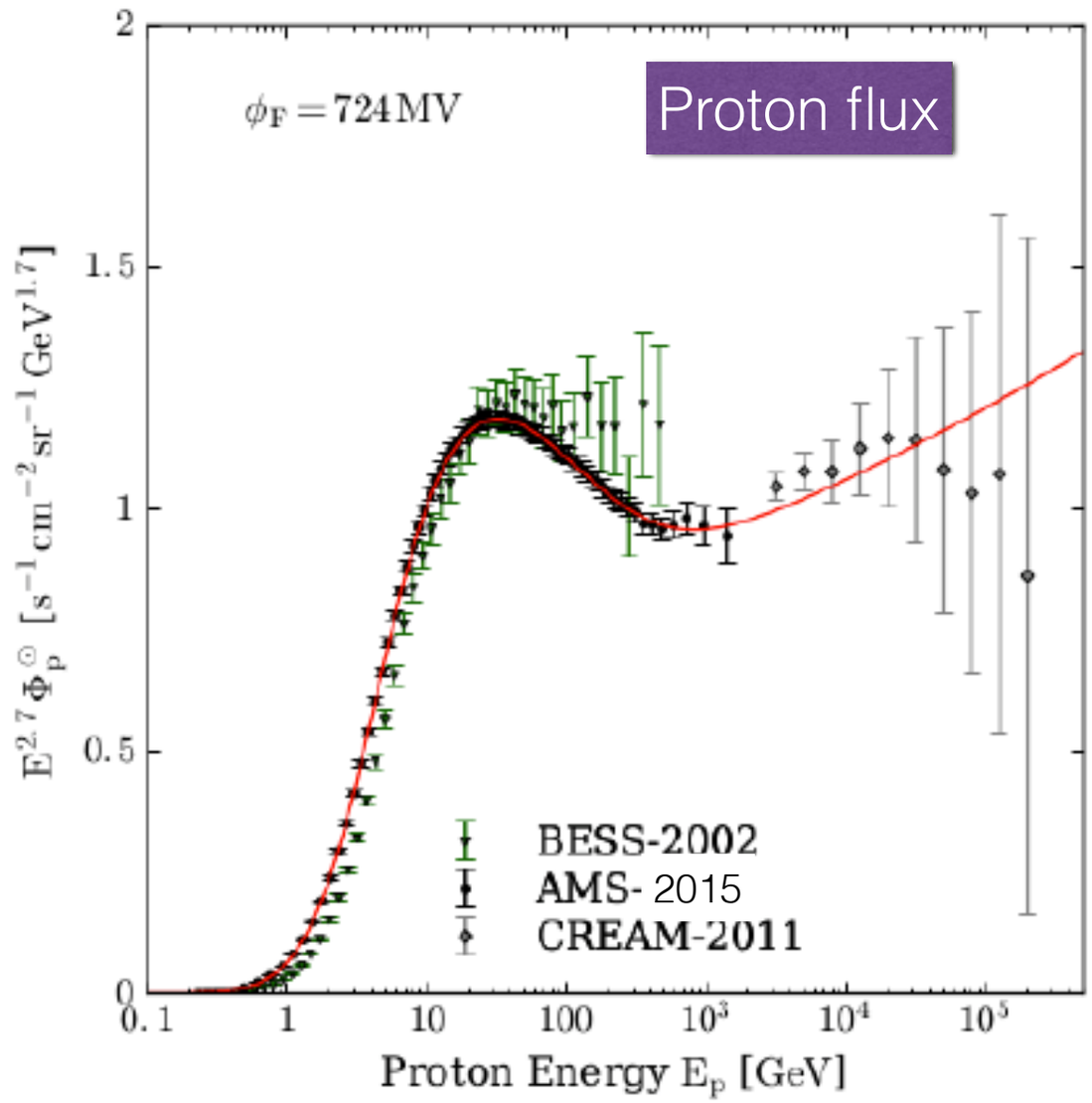
CR-ISM cross-section

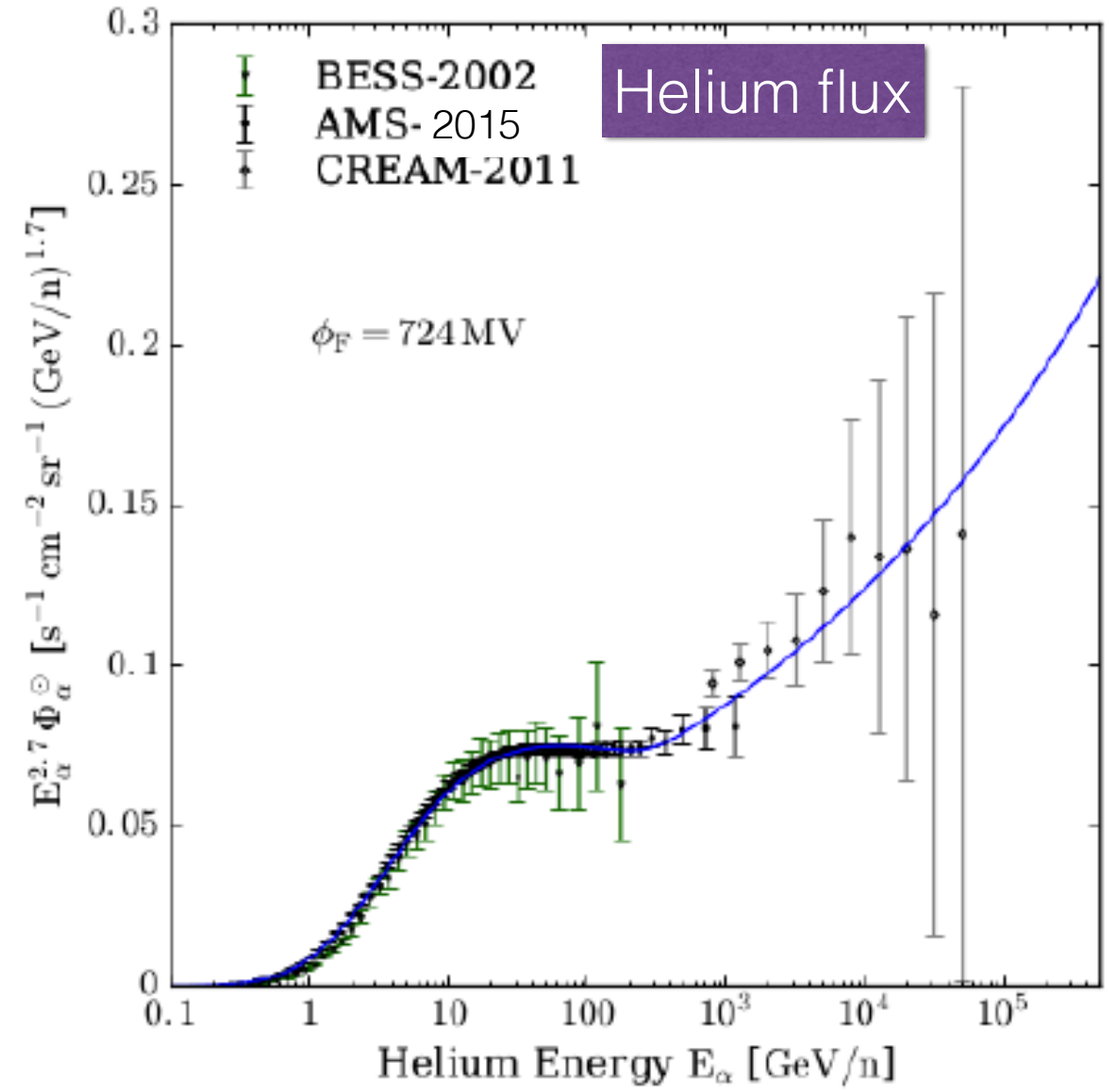
CR proton flux





Primary cosmic ray fluxes





$$\Phi_{IS,p}(R) = C\beta(R)\left(1 - e^{\alpha R}\right) R^{\gamma}\left(1 + \left(\frac{R}{R_b}\right)^{\frac{\Delta\gamma}{s}}\right)^{s}$$

Uncertainty on the primary fluxes

The uncertainty on the primary CR flux implies an uncertainty on the secondary positron flux

$$Q^{\mathrm{II}}(E,\vec{x}) = 4\pi\, n_H\, f(r,z) \int dE_p \frac{d\sigma}{dE}(E_p \to E)\, \Phi_p(E_p,\vec{x}),$$

- We could simply use the uncertainties of various parameters derived by the fit to our model, however this strategy has several weak points:
  - the correlation between parameters is not taken into account
  - the statistical and systematic uncertainties cannot be treated in the same way: while statistical uncertainties are uncorrelated between different data points and follow a normal distribution, the systematic one can be correlated and follow a non-normal distribution.

The Monte Carlo method we developed takes into account both aspects.

Description of the method

For each AMS-02 and CREAM p-He flux data point a new, random, value is randomly generated according to the following strategy:

To take into account the statistical error:

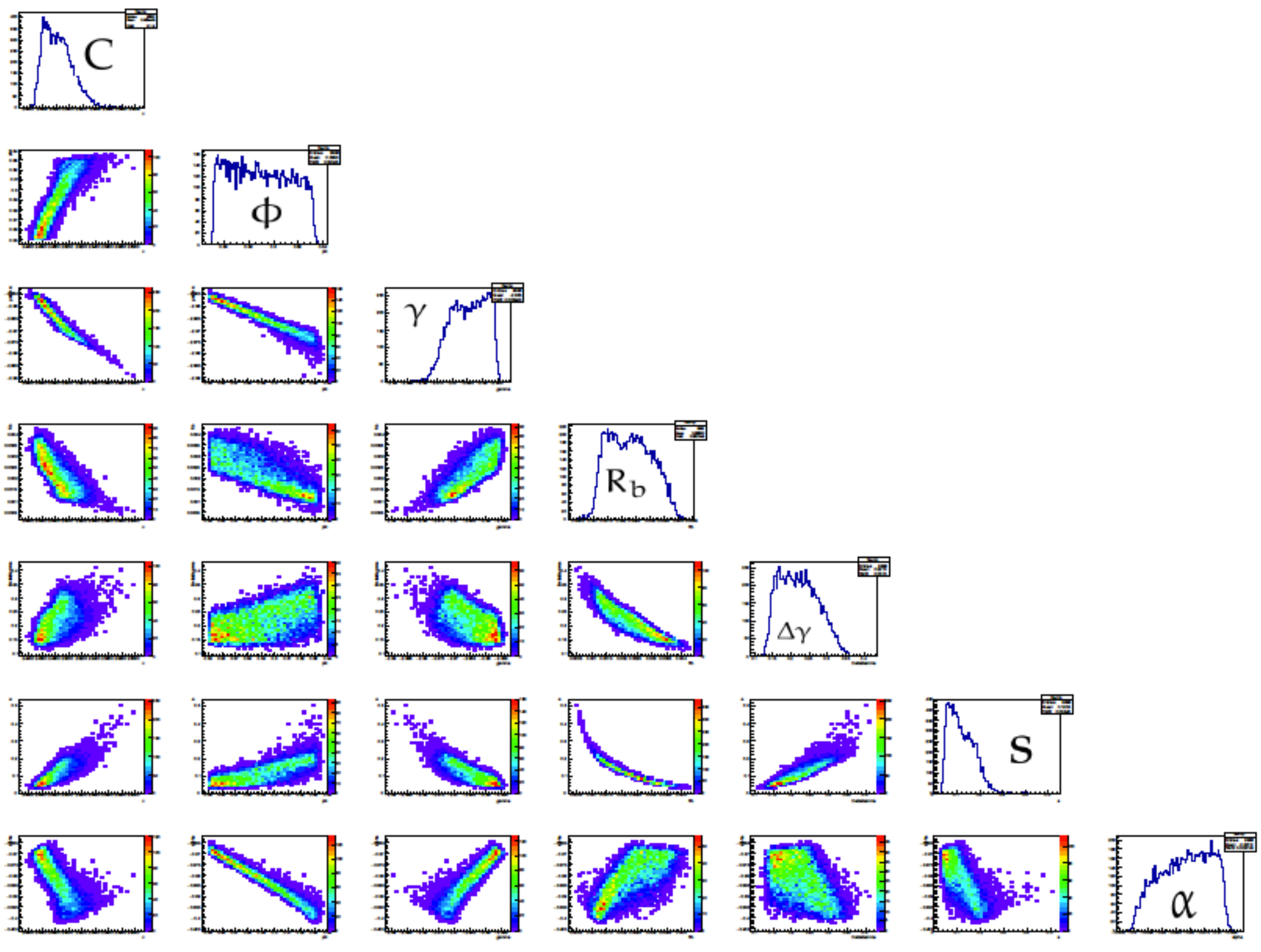
It follows a normal distribution centred on the value of data point and its standard deviation is equal to the statistical uncertainty.

To take into account the systematic error:

We assume that the systematic uncertainties are totally correlated, and we generate a random value following a uniform function (rectangular function), centered on the primary flux and whose width is equal to twice the systematic uncertainty. Two random values are generated, independently for the AMS-02 and CREAM data, since they are uncorrelated.

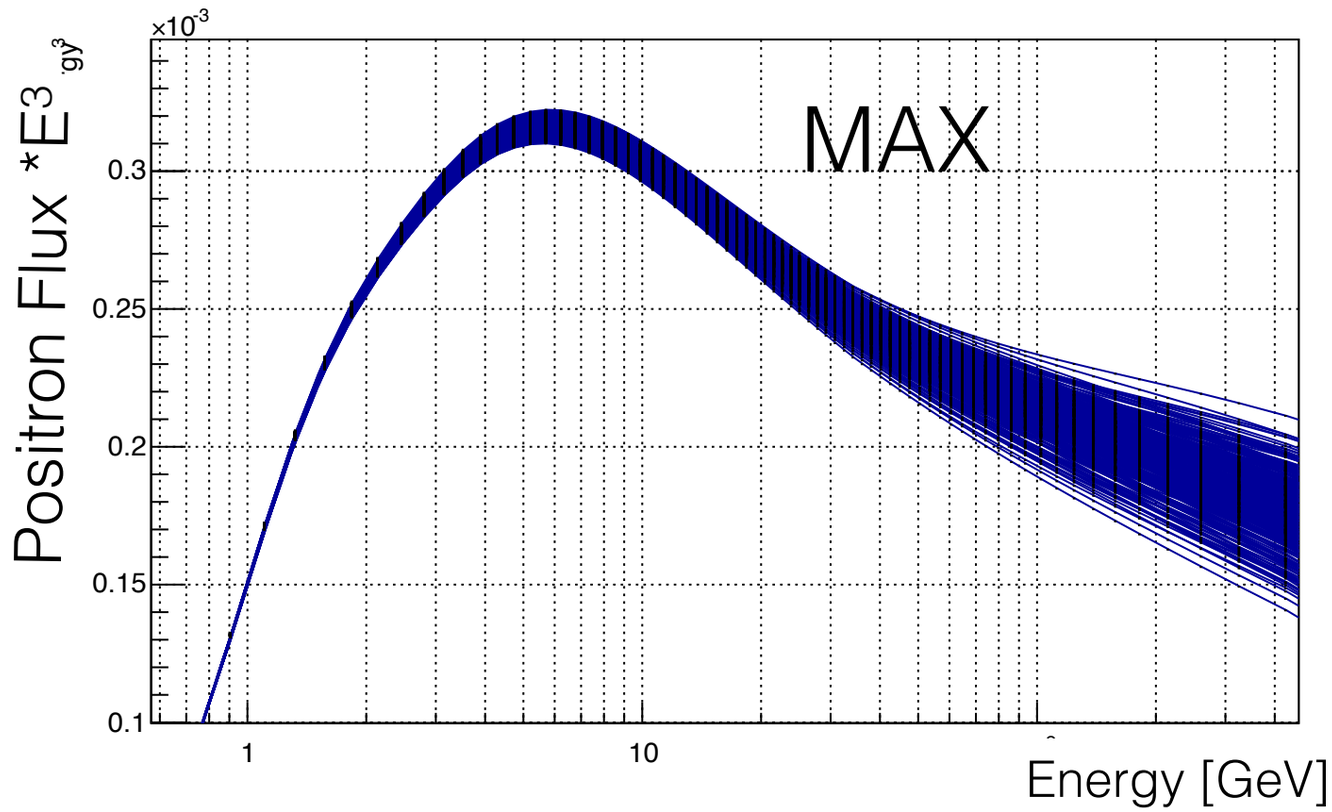
Each *randomised* primary flux is fit to our model, so that we get a pdf for each individual parameter of the fit.

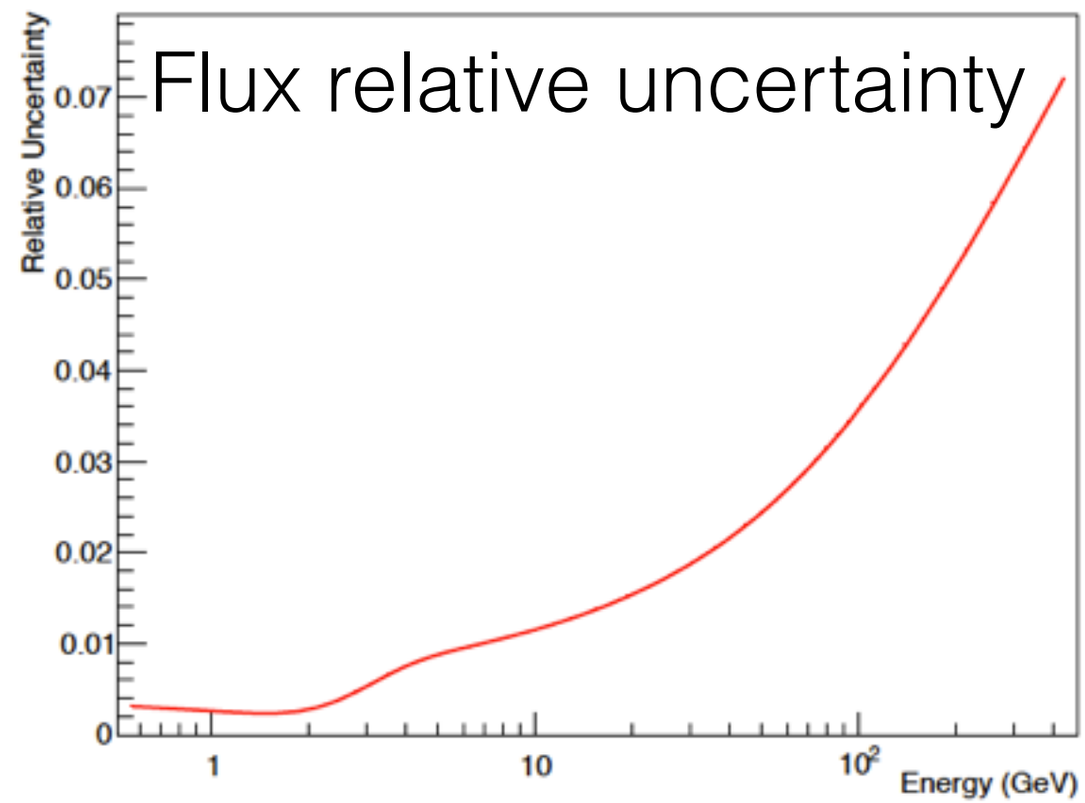
Fit Parameters distributions



Effect on the secondary positrons

The uncertainty caused by the experimental error on the primary fluxes has no great impact on studies of secondary positrons.





Ingredients for secondary e+ spectra determination

To obtain the secondary positron flux prediction we have to take into account:

Propagation processes

Interaction cross section CR+ISM

Description of the galactic environment

Solar modulation

Spectra of primary cosmic rays

Cosmic ray positrons propagation

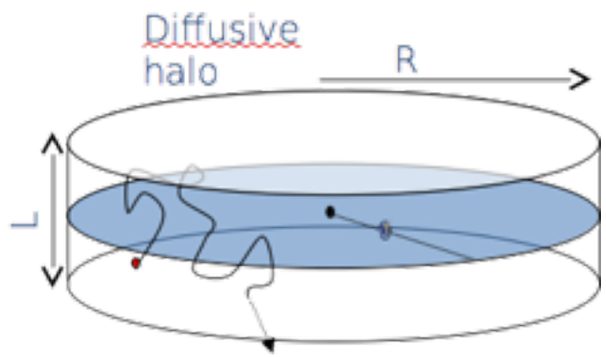
M. Boudaud @IDM2

- The transport equation (steady state) reads:

$$V_C\,\partial_z[\mathrm{sign}(z)]\,\psi - K(E)\Delta\psi + \partial_E[b_{halo}(E)] + 2h\,\delta(z)\,\partial_E\left[b_{disc}(E)\,\psi - D(E)\,\partial_E\psi\right] = Q(E,\vec{x}).$$

$b_{disk} = b_{ion} + b_{adia} + b_{Coul} + b_{Brem}$

dominant below few GeV



$b_{halo} = b_{IC} + b_{Sync}$

dominant above few GeV

- If we want to take all energy losses into account, it is hard to solve the propagation equation when energy losses do not take place in the same region. To solve this issue, we developed a method that allows us to consider the halo energy losses to take place in an effective way in the galactic disk.

$b_{eff}(E,E_S) = \xi(E, E_S)b(E)$

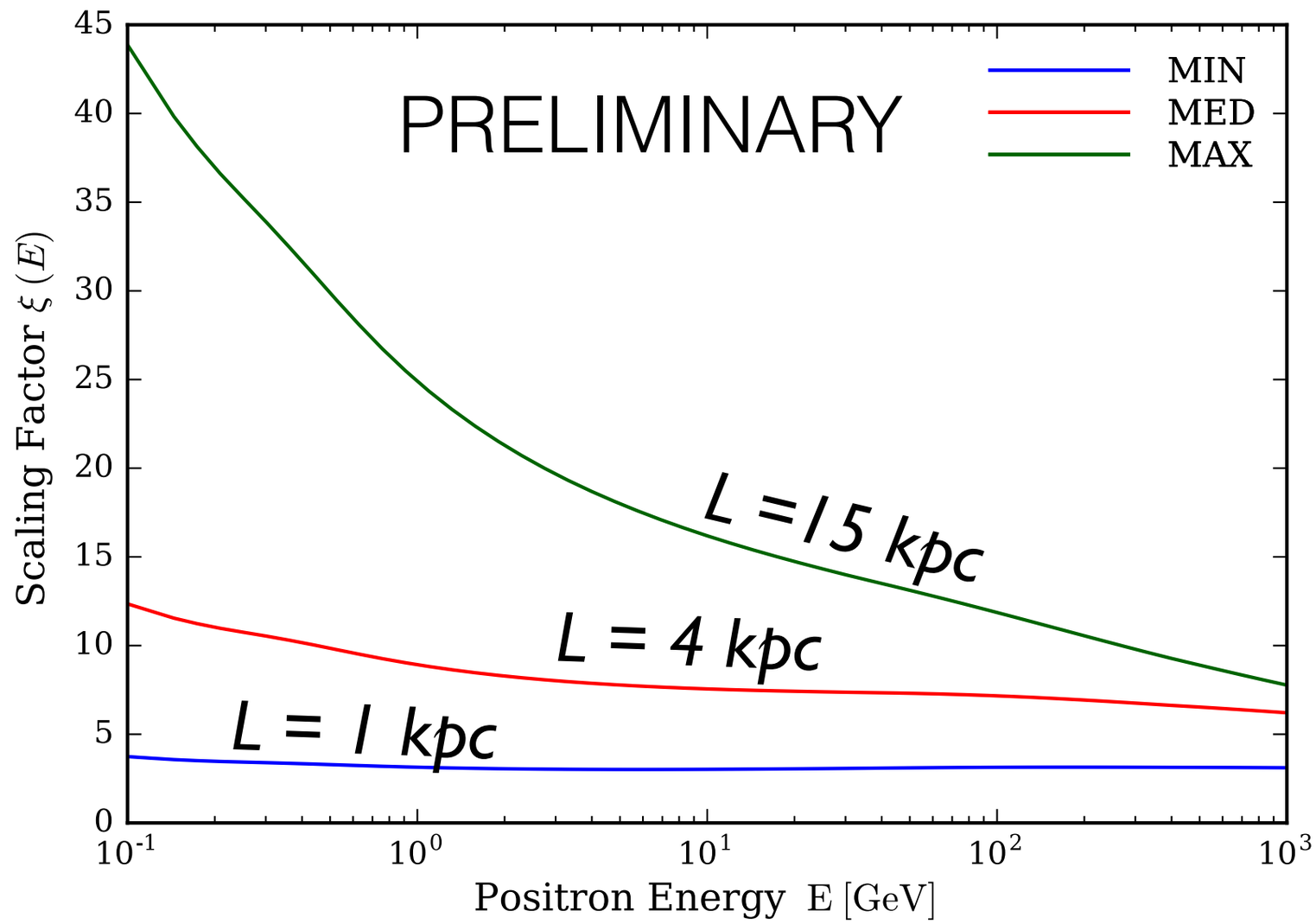
M. Vecchi *et al*, TeVPA 2016

Pinching method

- Besides energy losses, other relevant processes are convection, diffusion and diffusive reacceleration, all taking place in the halo.
- We want the processes taking place in the halo to take place in an effective way in the galactic disk.
- We want to reproduce this effect assuming that the positron lose energy only in the galactic disc.
- To do this, we need to boost the intensity of the energy losses processes occurring only in the disc in order to obtain the same effect on the positron.
- The way to do that is to replace in equation b(E) by the function $b_{eff}(E,E_S)$ that ensure that the solution of the transport equation is the same both in the disk and in the halo. The key factor in order to determine $b_{eff}(E,E_S)$ is the function $\xi(E, E_S)$ defined by $b_{eff}(E,E_S) = \xi(E, E_S)b(E)$

Pinching factor VS energy

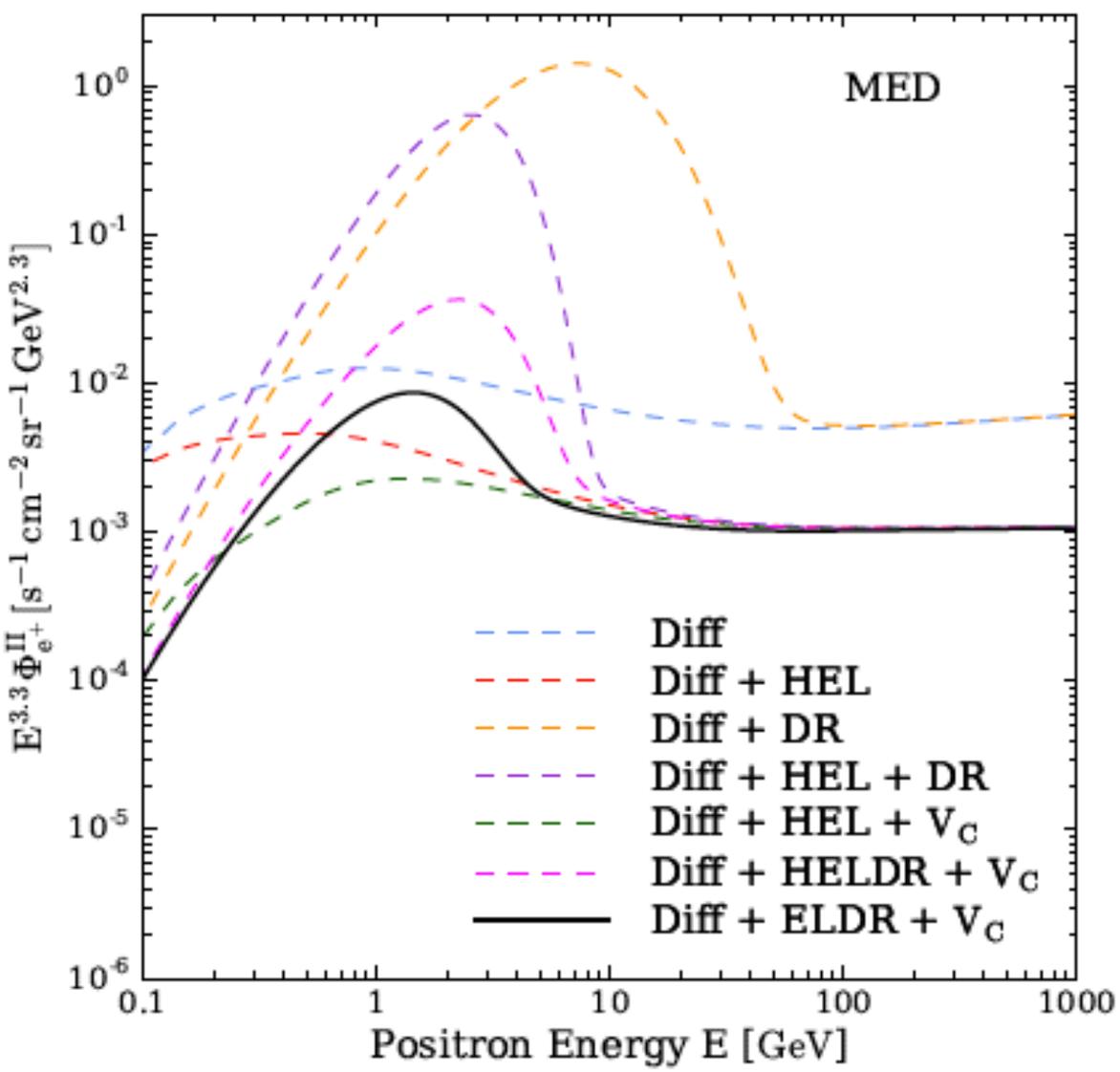
$b_{eff}(E,E_S) = \xi(E, E_S)b(E)$

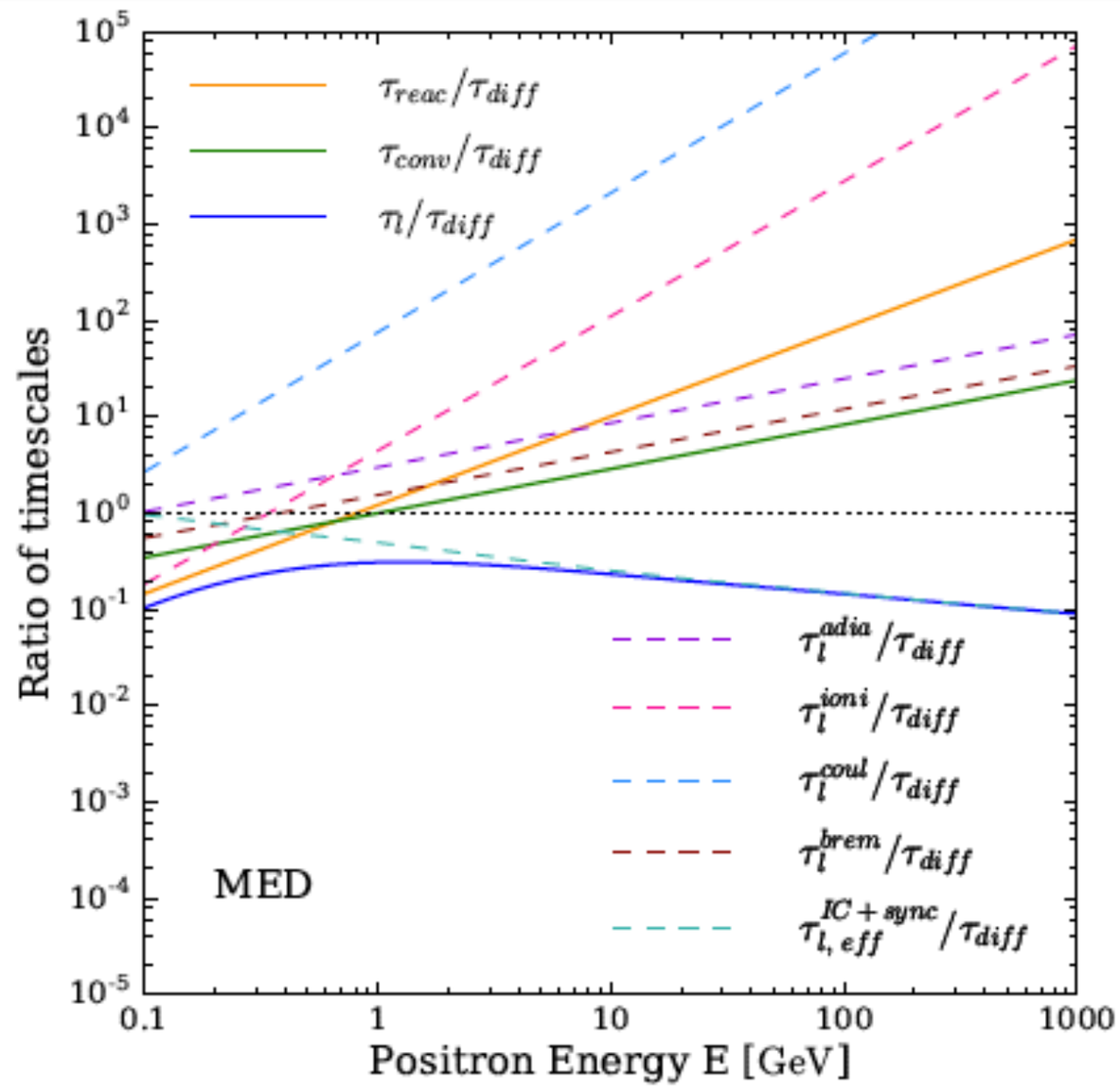


Propagation effects and typical times

Thanks to the pinching method, all energy losses processes are considered to be effective in the galactic disc.

We are therefore able to solve analytically the full transport equation taking into account all the effects positrons undergo when they propagate in the Galaxy.





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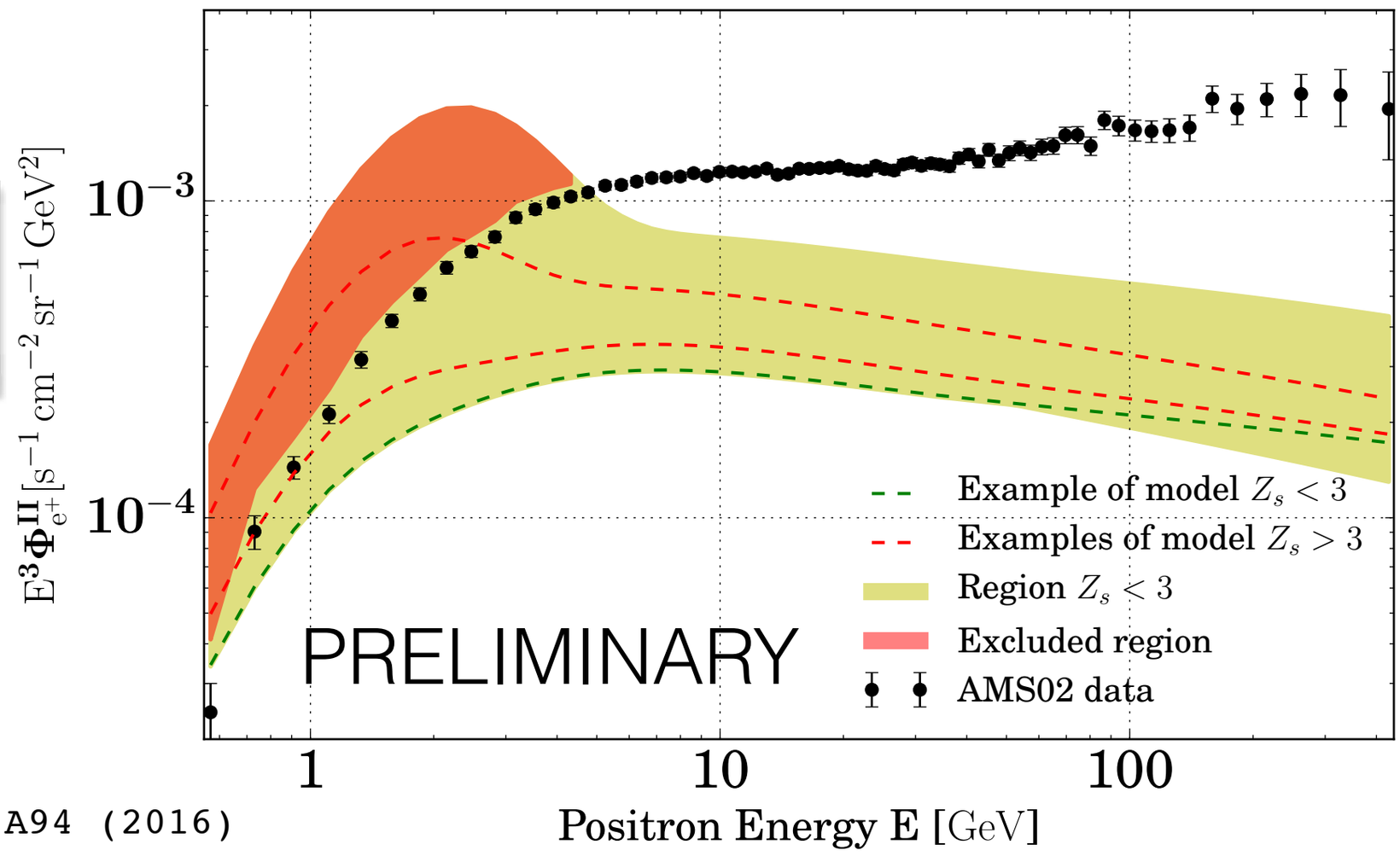
Constraints on the propagation parameters

- Same approach as in `J. Lavalle et al, 2014`. If the flux of secondary positrons is larger than the flux measured by AMS-02, the propagation models used to derive it are necessarily wrong.

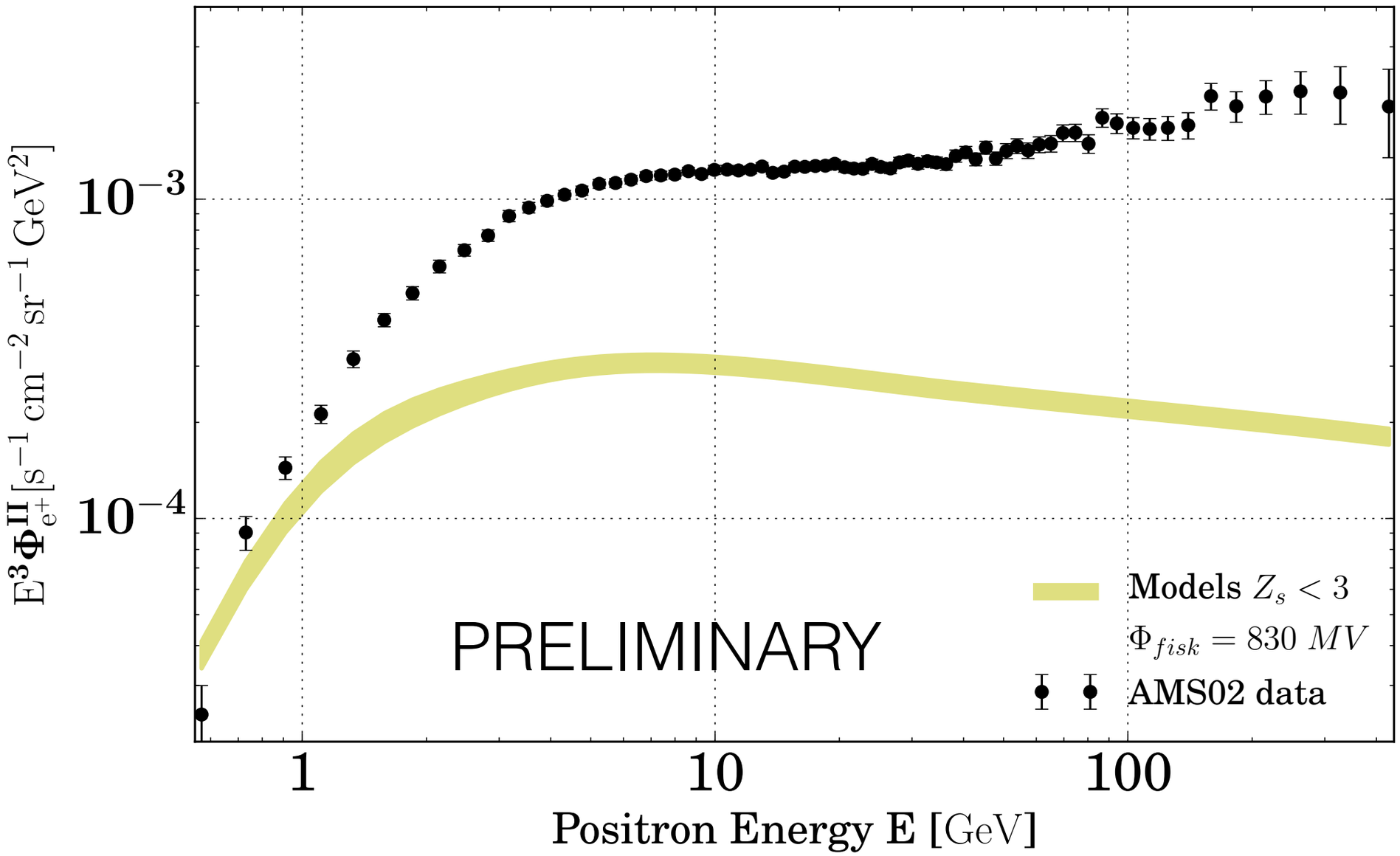
- The low energy part of the spectrum is affected by solar modulation: to be conservative, applying the maximal effect of solar modulation*, and we test 1623 sets of propagation parameters (allowed by B/C). Large halo size and small diffusion coefficients are allowed.

$$Z_j(E_i) = \frac{\Phi_j^{sec}(E_i) - \Phi^{exp}(E_i)}{\sigma^{exp}(E_i)}$$



*A. Ghelfi et al, A&A 591, A94 (2016)

Secondary e+ and AMS-02 data



AMS-02 data are incompatible with pure secondary hypothesis.
We need a primary positron source nearby the solar system.

Summary

- Secondary positrons are created by the interaction of primary cosmic rays with the interstellar medium composed of hydrogen and helium.
- A new method is developed to assess the effect of the primary CR experimental uncertainties on the secondary positron flux, taking into account both statistical and systematic errors. It is found to be below 1% up to 100 GeV, 7%@ 00 GeV).
- CR transport equation has been solved in a semi-analytic way over the whole energy range covered by AMS-02, providing a complete secondary positron flux prediction between 0.5 GeV and 500 GeV.
- The propagation models are constrained in a conservative way, scanning over a wide range of solar modulation parameters: large halo size and small diffusion coefficient are favoured.
- AMS-02 positron data are incompatible with pure secondary hypothesis: we need a primary positron source nearby the solar system to reproduce the measured flux.
- The results presented today are preliminary, final tests are ongoing.

Thank you for your attention!

Acknowledgements

- MV and EFB acknowledge the support of FAPESP (São Paulo Research Foundation) through the grant number 2014/19149-7 and 2014/50747-8.