Model dependence of cosmic rays propagation parameters

Yoann Génolini

December 17th, 2015

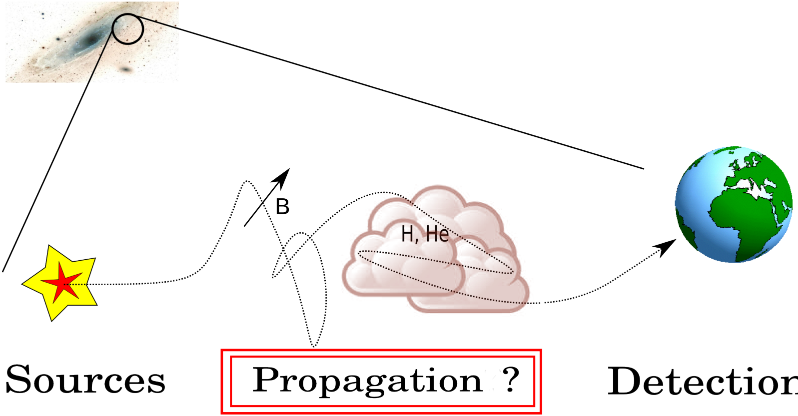
LAPTh

Y. Genolini, A. Putze, P. Salati, and P. D. Serpico, A&A 580, A9 (2015) [arXiv:1504.03134]

Outline

1. Why propagation is interesting ?
2. Modeling the propagation
3. Measuring CRs parameters
4. Quantifing uncertainties

We don't measure directly the sources !



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The model has to take into account :

- Sources spectra :
  $\rightarrow Q\left(E_k\right) \propto R^{\alpha}$, with $R(E_k) = p/(Ze)$ and $\alpha \in [-2.5, -2.0]$
- Transport (In the case of a weak electromagnetic turbulence) :
  $\rightarrow$ Diffusion in phase space $(\boldsymbol{x}, \boldsymbol{p})$ $D_x = D_0.\beta.R^{\delta}$
  $\rightarrow$ Convective wind $\boldsymbol{u}$.
- Interaction with the ISM :
  $\rightarrow$Energy losses
  $\rightarrow$Spallation $(\sigma_{\alpha}, \sigma_{\alpha\rightarrow\beta})$

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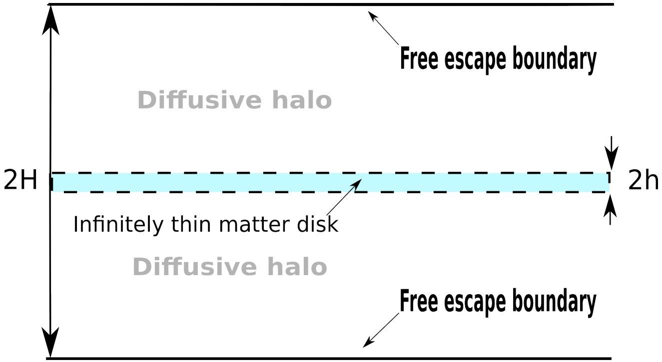
A Simplified propagation equation for : Ek>10GeV/nuc

- Interaction with the ISM
- Radioactivity
- Diffusion in space
- Source term

$$\frac{\partial f_a}{\partial t} + \sigma_a v_a n_{ISM} f_a + \frac{f_a}{\tau_a} - \nabla_{\boldsymbol{x}}.(D_x \nabla_{\boldsymbol{x}} f_a) = q_a + \sum_{Z_\beta \geqslant Z_a}^{Z_{max}} \sigma_{b\to a} v_b n_{ISM} f_b + \frac{f_b}{\tau_b}$$

Galaxy model :



Surface density of the disc $\mu = 2.4\ \mathrm{mg.cm^{-2}}$.

Analytical resolution of the propagation equation :

For a stable nucleus :

$$\mathcal{J}_a(E_k) = \left\{ Q_a + \sum_{Z_b \geqslant Z_a}^{Z_{max}} \sigma_{b\to a}\, \mathcal{J}_b \right\} / \left\{ \sigma^{\rm diff} + \sigma_a \right\} \qquad (1)$$

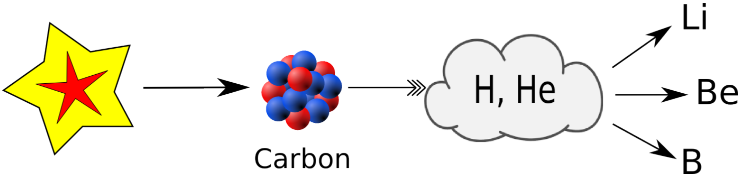
Primary and secondary source terms.

Where : $\sigma^{\rm diff} = \dfrac{2D\, m_{\rm ISM}}{\mu v H}$.

and $Q_a = \dfrac{1}{4\pi} \dfrac{q_a}{n_{ISM}} \equiv N_a \left(\dfrac{\mathcal{R}}{1\,{\rm GV}} \right)^{\alpha}$.

Outline

Secondary nuclei :



Li, B, Be are said secondary.

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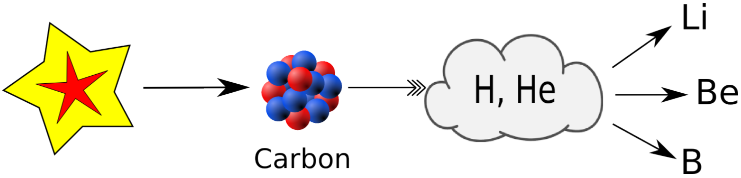

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Secondary/primary ratio :

$$\mathcal{J}_B(E_k) = \left\{ Q_B + \sum_{Z_b \geqslant Z_B}^{Z_{max}} \sigma_{b\to B}\, \mathcal{J}_b \right\} / \left\{ \sigma^{\rm diff} + \sigma_B \right\} \quad (2)$$

Hypothesis :

- $Q_B = 0$
- Double nuclei system (B,C)

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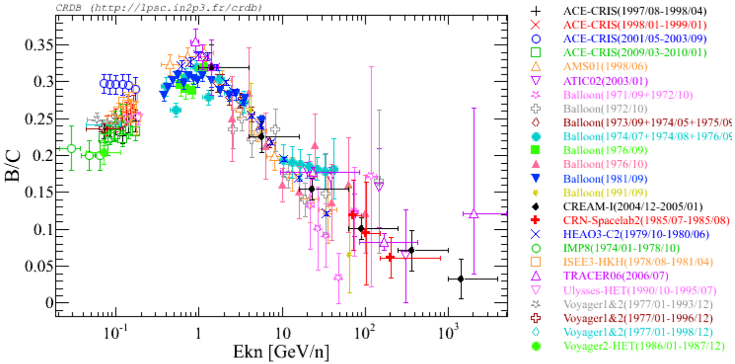
$$\frac{\mathcal{J}_B(E_k)}{\mathcal{J}_C(E_k)} = \sigma_{C\to B} / \left\{\sigma^{\text{diff}} + \sigma_B\right\}.$$

When : $\sigma_B << \sigma^{diff} \Rightarrow \boxed{\frac{\mathcal{J}_B}{\mathcal{J}_C} \propto R^{-\delta}}$

Experimental data :



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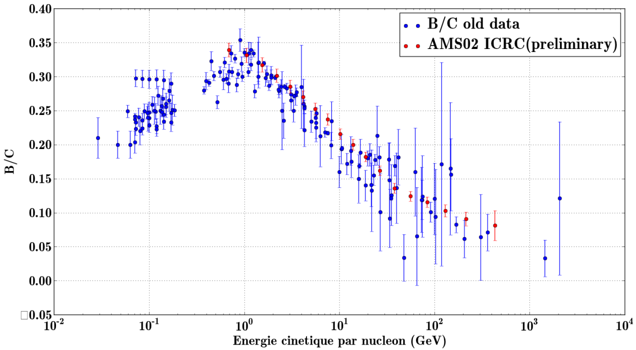
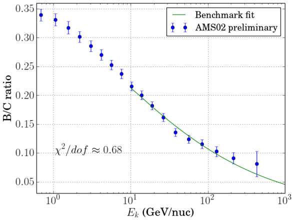


New data with AMS02 !..and soon CALET !

Benchmark model :

The goal is to minimize :

$$\chi^2_{\mathrm{B/C}} = \sum_i \left\{ \frac{\mathcal{F}_i^{\mathrm{exp}} - \mathcal{F}_i^{\mathrm{th}}(Parameters..)}{\sigma_i} \right\}^2$$



Reference parameter values	
D_0 [kpc^2/Myr]	$(5.8 \pm 0.7) \cdot 10^{-2}$
δ	0.44 ± 0.03
$\chi^2_{\mathrm{B/C}}/\mathrm{dof}$	$5.4/8 \approx 0.68$
$\gamma = \alpha - \delta$ (fixed)	-2.78

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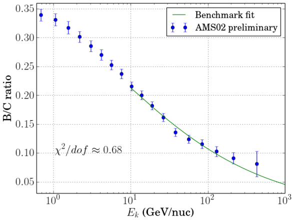

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- Primary boron contribution
- Production cross-section uncertainties
- Destruction cross-section uncertainties
- Geometry framework

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Primary boron ?

[Blasi, 2009], [Blasi and Serpico, 2009],
[Mertsch and Sarkar, 2009], [Mertsch and Sarkar, 2014]
→ **Secondary species may be formed at sources !**

- Confinement inside a SNR at TeV/nuc :

$$X_{SNR} \approx 0.17 \text{ g cm}^{-2} \frac{n_{ISM}}{\text{cm}^{-3}} \frac{T_{SNR}}{2.10^4 \text{ yr}}$$

- Galactic diffusion at TeV/nuc :

$$X_{Diff} \approx 1.2 \text{ g cm}^{-2}$$

⇒ **Order of 10% !**

Primary boron ?

At high energy...

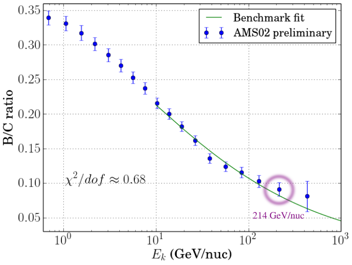
$$\frac{\mathcal{J}_B(E_k)}{\mathcal{J}_C(E_k)} = \left\{ \frac{Q_B}{\mathcal{J}_C} + \sigma_{C\to B} + \sum_{Z_b > Z_C}^{Z_{max}} \sigma_{b\to B} \frac{\mathcal{J}_b}{\mathcal{J}_C} \right\} / \left\{ \sigma^{\text{diff}} + \sigma_B \right\}$$

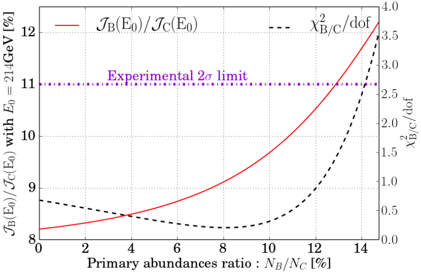
$$\underset{HE}{\propto} \quad \frac{N_B}{N_C}$$

...it leads to a plateau.

Primary boron ?

Constraining $\frac{N_B}{N_C}$:





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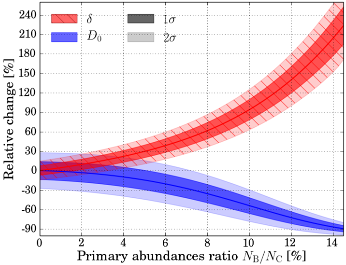
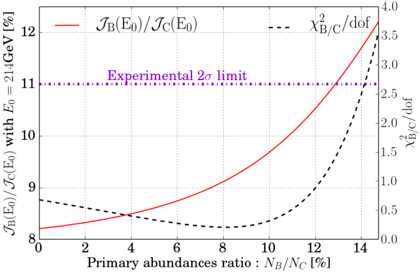
Primary boron ?

Scan on $\frac{N_B}{N_C}$:





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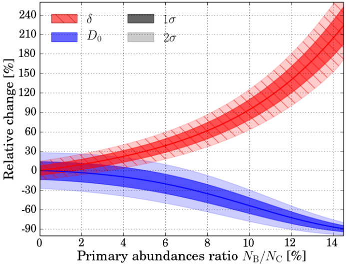

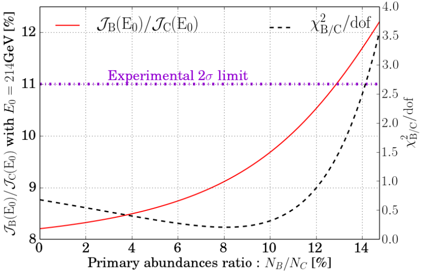

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Models of cross sections :

The different models for calculating cross section :

- are based on old data.
- extrapolate values to high energy.
- in some cases data do not exist at all.

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$\Rightarrow$ Typical differences of 10 % are commonly observed.

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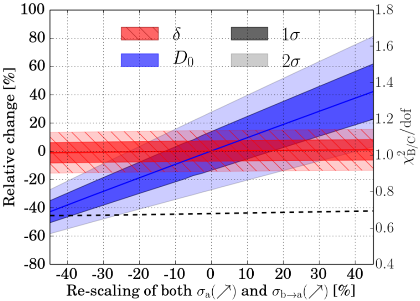
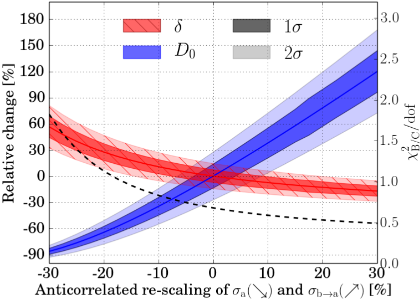
Dependence of propagation parameters on a systematic rescaling :





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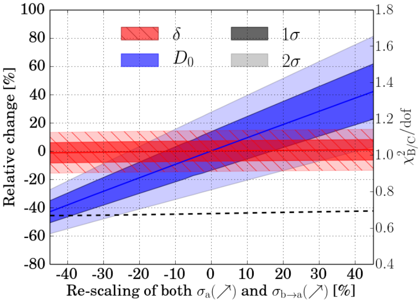

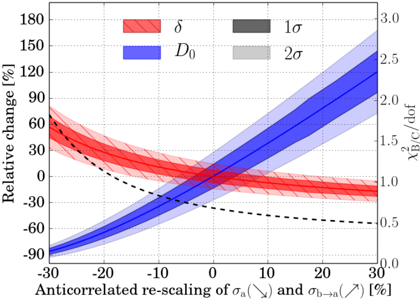

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Summary of the main systematics :

	Wind	1D/2D geometry	Cross-sections	Primary boron
$\Delta D_0/D_0$	-40%	-2 to -13%	$\pm 60\%$	0 to -90%
$\Delta\delta/\delta$	$+15\%$	0 to $+1\%$	$\pm 20\%$	0 to $+100\%$

Prospects, what we need at zero order :

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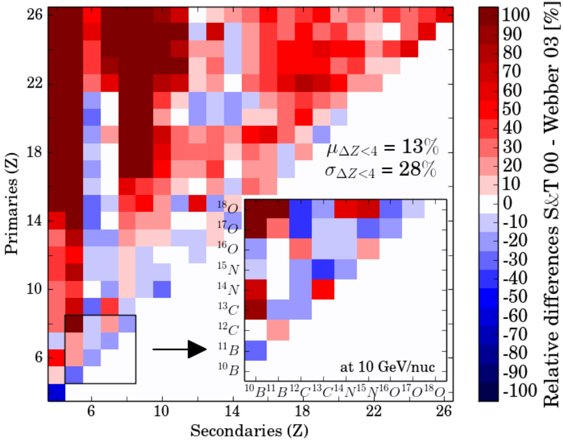
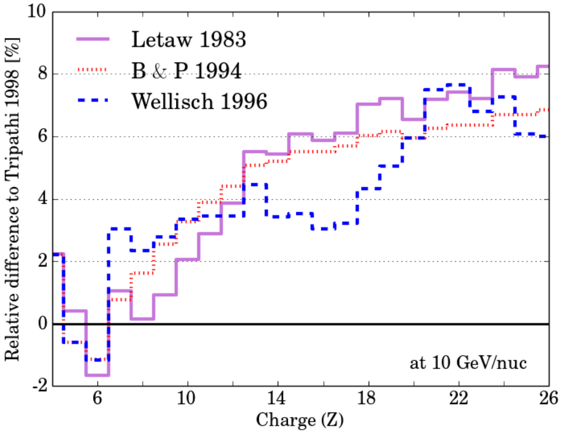
Thanks for listening !

Backup slides !

2-Models of production cross sections :



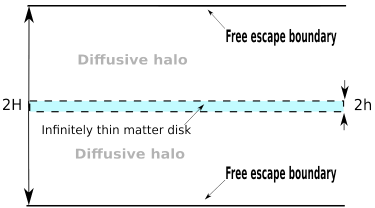
3-Models of destruction cross sections :



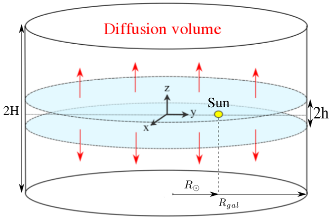
4-1D/2D diffusion models ?

The two commonly used geometries :

1D



2D



1D/2D diffusion models ?

Geometry	Plane – 1D	Cylindrical – 2D homogeneous source distribution	Cylindrical – 2D realistic source distribution
D_0 [kpc^2/Myr]	$(5.8 \pm 0.7) \cdot 10^{-2}$	$(5.7 \pm 0.7) \cdot 10^{-2}$	$(5.0 \pm 0.6) \cdot 10^{-2}$
$\Delta D_0^{\mathbf{1D}} / D_0^{\mathbf{1D}}$	N/A	-2%	-13%
δ	0.441 ± 0.031	0.439 ± 0.031	0.445 ± 0.032
$\Delta \delta^{\mathbf{1D}} / \delta^{\mathbf{1D}}$	N/A	0%	$+1\%$
$\chi^2_{\mathbf{B/C}}$/ndof	$5.4/8 \approx 0.68$	$5.4/8 \approx 0.68$	$5.5/8 \approx 0.69$

→ Tiny impact !

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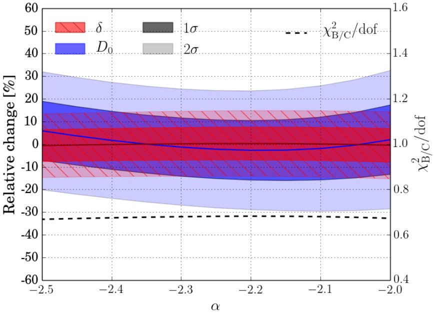
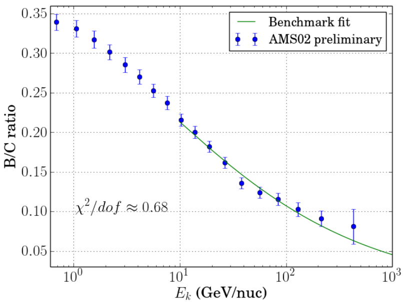
$\rightarrow$ **Tiny impact !**

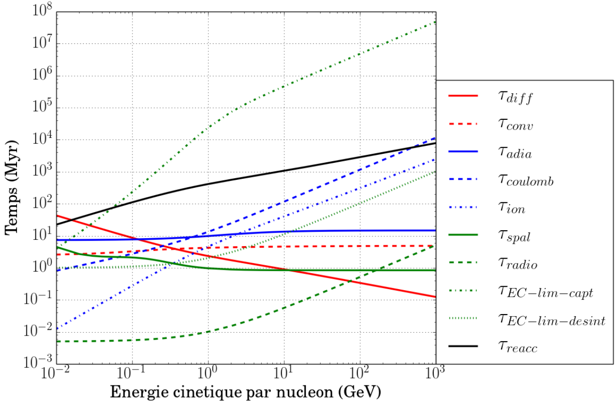
Test of the model

Independence of the spectral index α :





Simplifying the equation :



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Models of production cross sections :

Main production channels $\sigma_{\mathsf{CNO}\to\mathsf{B}}$ at 10 GeV/nuc	Webber 03 [mb]	S&T 2000 [%]	Webber 98 [%]	Webber 93 [%]
$\boldsymbol{\sigma\left({}^{12}_{6}\mathrm{C}\to{}^{10}_{5}\mathrm{B}\right)}$	14.0	-2.2	22	26
$\boldsymbol{\sigma\left({}^{12}_{6}\mathrm{C}\to{}^{11}_{5}\mathrm{B}\right)}$	47.0	13	14	18
$\sigma\left({}^{13}_{6}\mathrm{C}\to{}^{10}_{5}\mathrm{B}\right)$	4.70	48	-2.1	0
$\sigma\left({}^{13}_{6}\mathrm{C}\to{}^{11}_{5}\mathrm{B}\right)$	40.0	-26	2.2	4.3
$\boldsymbol{\sigma\left({}^{14}_{7}\mathrm{N}\to{}^{10}_{5}\mathrm{B}\right)}$	9.90	40	0.14	1.0
$\boldsymbol{\sigma\left({}^{14}_{7}\mathrm{N}\to{}^{11}_{5}\mathrm{B}\right)}$	27.2	1.8	-8.9	-11
$\sigma\left({}^{15}_{7}\mathrm{N}\to{}^{10}_{5}\mathrm{B}\right)$	9.20	-7.0	-71	-71
$\sigma\left({}^{15}_{7}\mathrm{N}\to{}^{11}_{5}\mathrm{B}\right)$	28.0	-0.40	-27	-28
$\boldsymbol{\sigma\left({}^{16}_{8}\mathrm{O}\to{}^{10}_{5}\mathrm{B}\right)}$	10.7	-22	-7.7	8.4
$\boldsymbol{\sigma\left({}^{16}_{8}\mathrm{O}\to{}^{11}_{5}\mathrm{B}\right)}$	24.0	2.8	-9.4	-11
$\sigma\left({}^{17}_{8}\mathrm{O}\to{}^{10}_{5}\mathrm{B}\right)$	3.60	56	0.27	0
$\sigma\left({}^{17}_{8}\mathrm{O}\to{}^{11}_{5}\mathrm{B}\right)$	19.7	22	1.4	0
$\sigma\left({}^{18}_{8}\mathrm{O}\to{}^{10}_{5}\mathrm{B}\right)$	0.70	89	6.3	4.3
$\sigma\left({}^{18}_{8}\mathrm{O}\to{}^{11}_{5}\mathrm{B}\right)$	12.0	53	2.2	0.80

Propagation equation :

- Convection
- Interaction with the ISM
- Radioactivity
- Diffusion in phase space
- Source term

$$\frac{\partial f_a}{\partial t} + \boldsymbol{u}.\nabla_{\boldsymbol{x}} f_a - \frac{1}{3}(\nabla_{\boldsymbol{x}}.\boldsymbol{u})p\frac{\partial f_a}{\partial p} + \nabla_{\boldsymbol{p}}(b(\boldsymbol{p})f_a) + \sigma_a v_a n_{ISM} f_a +$$

$$\frac{f_a}{\tau_a} - \nabla_{\boldsymbol{x}}.(D_x \nabla_{\boldsymbol{x}} f_a) - \nabla_{\boldsymbol{p}}.(D_p \nabla_{\boldsymbol{p}} f_a) =$$

$$q_a + \sum_{Z_\beta \geqslant Z_a}^{Z_{max}} \sigma_{b\to a} v_b n_{ISM} f_b + \frac{f_b}{\tau_b}$$

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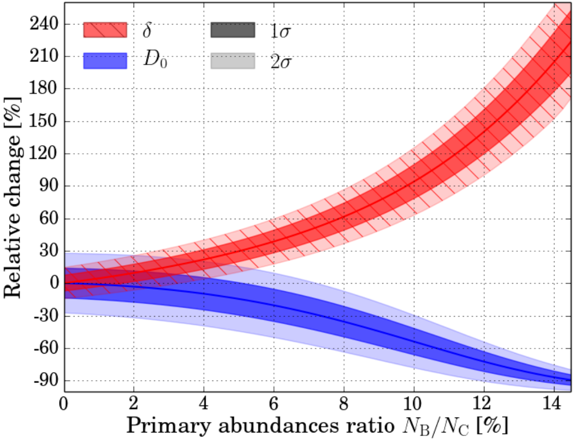
Primary boron ?

Scan on $\frac{N_B}{N_C}$:



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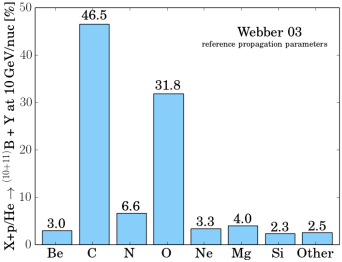
Different weights at $10 GeV/nuc$:



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