A Markov Chain Monte Carlo technique to sample transport and source parameters of Galactic cosmic rays

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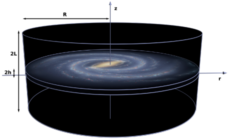
Phenomenology of nuclear cosmic rays

Why study cosmic-ray propagation?

- Study of the standard cosmic-ray astrophysics;
- Indirect search for dark matter.

Propagation models: USINE



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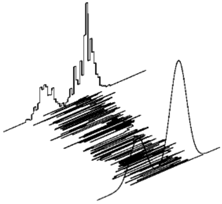
Statistical tools: MCMC



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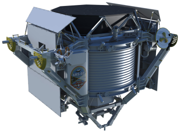
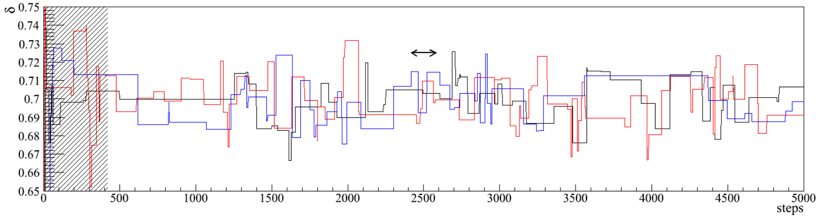
Experimental data: AMS



used for the first time in the context of cosmic-ray physics [Putze *et al.*, A&A (2009–2011)].

Metropolis-Hastings algorithm

Chain spends more time in more probable regions!



Evaluation of the burn-in and correlation lengths for independent sample extraction

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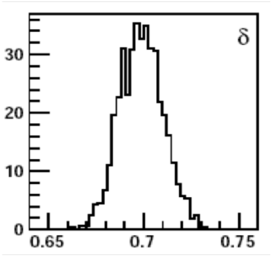

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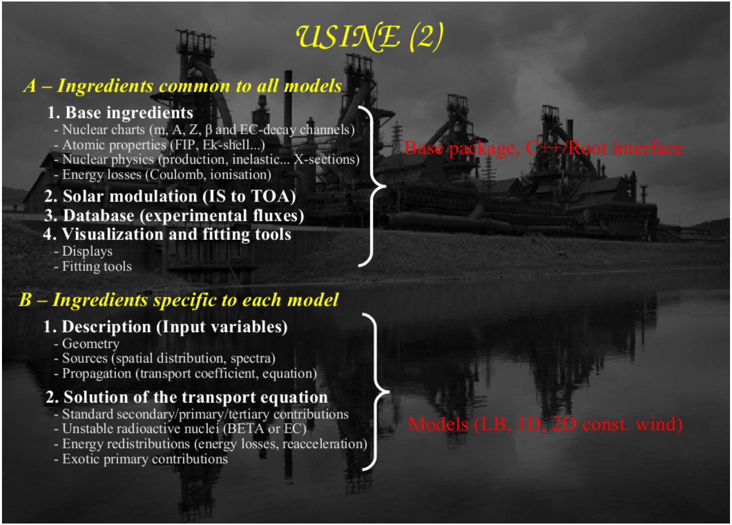
Estimation of the posterior PDF

The USINE propagation code

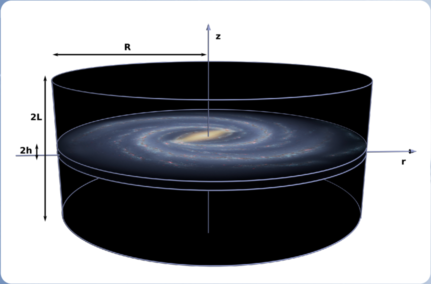
Slide from D. Maurin



Diffusion Model

USINE — semi-analytical propagation code [D. Maurin]

Diffusion model with minimal reacceleration, constant Galactic wind



Galaxy is divided into two zones:

1. a thin disk of size h;
2. a diffusive halo of size $L \gg h$.

$$K(R) = K_0 \beta^{\eta_T} R^{\delta}$$

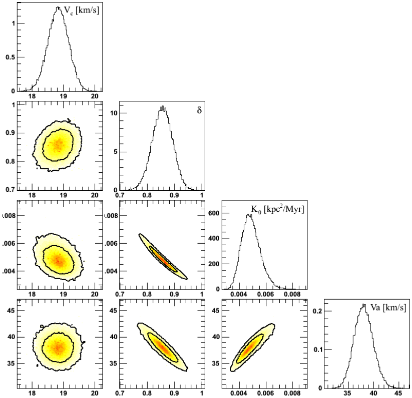
$$Q(R) = q \beta^{\eta_S} R^{-\alpha}$$

$$n_d = n, \quad n_h = 0$$

Free parameters

- 6 transport par.: K_0 [kpc^2/Myr], η_T, δ, V_c and V_a [km/s], L [kpc].
- 3 source par.: q in $(\mathrm{m^3\,s\,GeV/n})^{-1}$, η_S, α

Stable nuclei: constraining transport parameters – B/C



[Putze *et al.*, A&A **516** (2010), A66]

- Configuration with V_c and V_a preferred:

$$L = 4\,\text{kpc fixed}$$
$$V_c = 18.8^{+0.3}_{-0.3}\,\text{km/s}$$
$$\delta = 0.86^{+0.04}_{-0.04}$$
$$K_0 = 0.0046^{+0.0008}_{-0.0006}\,\text{kpc}^2/\text{Myr}$$
$$V_a = 38^{+2}_{-2}\,\text{km/s}$$

- Kolmogorov spectral index ($\delta = 1/3$) disfavoured.

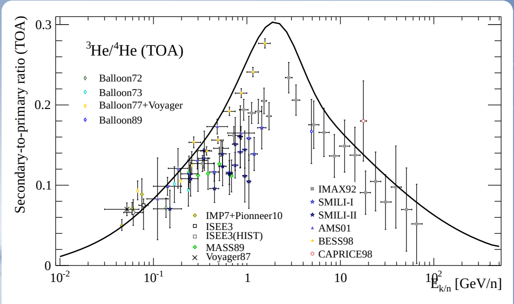
Stable nuclei: constraining transport parameters – $^3He/^4He$

B/C:

- abundant;
- elemental separation.

$^3He/^4He$:

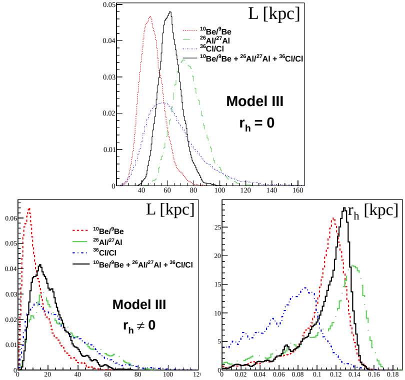
- very abundant;
- isotopic separation.



[Coste *et al.*, in preparation]

Data	V_c (km s^{-1})	δ -	$K_0 \times 10^2$ (kpc^2 Myr^{-1})	V_a (km s^{-1})
$^3He/^4He$	$17.3^{+0.3}_{-0.4}$	$0.79^{+0.05}_{-0.04}$	$0.50^{+0.05}_{-0.06}$	40^{+2}_{-3}
B/C	$18.9^{+0.3}_{-0.4}$	$0.86^{+0.04}_{-0.04}$	$0.46^{+0.08}_{-0.06}$	38^{+2}_{-2}

Radioactive secondaries: constraining the halo size L



[Putze *et al.*, A&A **516** (2010), A66]

Results with ^{10}Be/^{9}Be data

without local bubble:

$$L = 46^{+9}_{-8}\ \text{kpc}$$

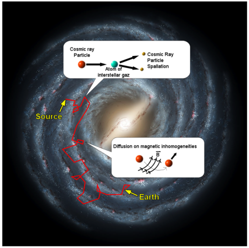
with local bubble:

$$L = 8^{+8}_{-7}\ \text{kpc},\ r_h = 120^{+20}_{-20}\ \text{pc}$$

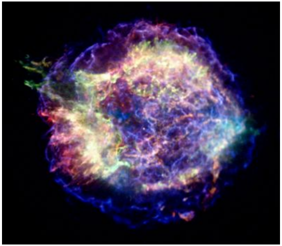
Local bubble

- underdensity in the LISM modelled as a hole in the disc
- exponential decrease of radioactive fluxes [Donato *et al.*, A&A **381** (2002), 539]

Primary nuclei: constraining source parameters



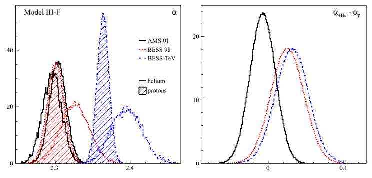
$\Longrightarrow$



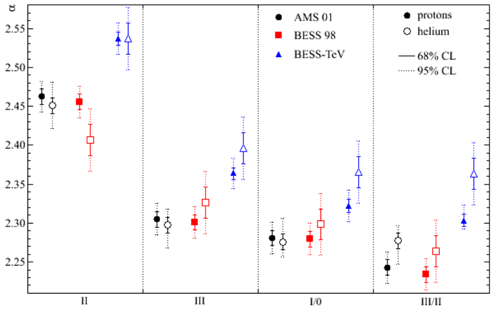
Model	η_T	$K_0^{\text{best}} \times 10^2$ (kpc^2 Myr^{-1})	δ^{best}	V_c^{best} (km s^{-1})	V_a^{best} (km s^{-1})	χ^2/d.o.f
II	1.	9.76	0.23	0.	73.2	4.73
III	1.	0.48	0.86	18.8	38.0	1.47
I/0	-2.6	2.05	0.61	0.	0.	3.29
III/II	-1.3	3.16	0.51	0.	45.4	2.26

[Maurin *et al.*, A&A **516** (2010), A67]

Primary nuclei: p and He



[Putze *et al.*, A&A **526** (2011), A101]

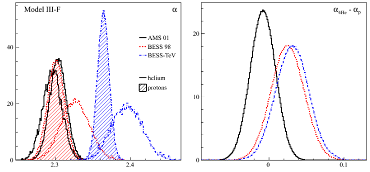


[Putze *et al.*, A&A **526** (2011), A101]

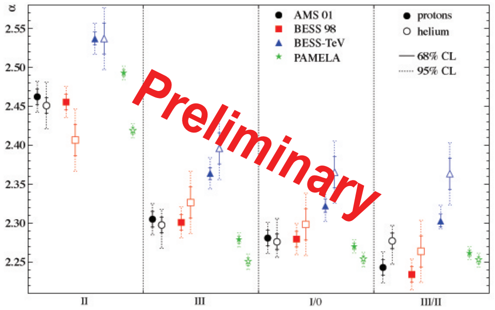
α well constrained between 2.2 and 2.5 (independent of model and data)
asymptotic regime ($\gamma_{\text{asymp}} = \alpha + \delta$) not reached

same results for heavier nuclei

Primary nuclei: p and He



[Putze *et al.*, A&A **526** (2011), A101]



[Putze *et al.*, in preparation]

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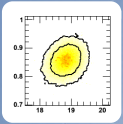
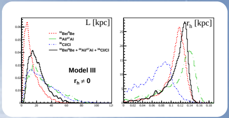
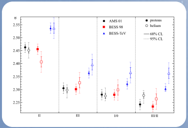
Conclusion



Successful posterior PDF extraction of the propagation parameters of the one dimensional diffusion model

First estimation of the Galactic halo size L and the radius r_h of the local bubble





Good constraints of the spectral slope α implicating a universality for primary nuclei

MCMC is a robust tool allowing an excellent parameter estimation in high dimensional parameter spaces.