Stat./systematic uncertainties in CR parameters

Putze *et al.*, A&A **497**, 991 (2009)
Putze, Derome & Maurin, arXiv:1001.0551
Maurin, Putze & Derome, arXiv:1001.0553

I. CR in the Galaxy: context and models

II. Sample results and limitations

III. MCMC technique and results

IV. Statistical vs systematic uncertainties

V. Conclusions

David Maurin (LPNHE)
dmaurin@lpnhe.in2p3.fr

Atelier du GDR PCHE
Emission diffuse
IAS, 9/06/2010

Open questions in CR physics

1. Do we understand the “standard” galactic fluxes?

- **Sources (SN, pulsars, SB...)**
- **Nucleosynthesis (r and s-process for heavy nuclei)**
- **Acceleration mechanisms (injection, B amplification)**
- **Propagation mechanisms (link to turbulence, spatial dependence, isotropy)**
- **Magneto-cosmico-gaseo properties of the Galaxy (MHD description)**
    - i) GCRs here/in the whole Galaxy (linked to diffuse emissions)
    - ii) GCRs now/in the past/future (linked with massive extinctions?)

2. Do we understand Solar Modulation?

3. Are GCRs a good laboratory to search for new physics?

- **Dark matter/new physics ?**
- **Just standard astrophysics?**

~ Milestones ~

Measurements

1946 First air shower experiments
1948 Discovery that CRs contain nuclei of a whole series of elements
1953 Synchrotron nature of a significant part of the cosmic radio emission is established
1960 First measurement of Cosmic Ray electrons
1962 First 10^{20} eV cosmic ray detected
1965 Identification of positrons in CRs
1972 First identification of γ diffuse emission in the Galaxy
1973 First detection of GeV $Z > 90$ group
1979 First measurement of GeV anti-protons
1993 Highest energy particle ever detected at 3×10^{20} eV
2005 HESS first direct probe of proton acceleration in shocks
? First detection of anti-deuterons?
? First detection of a diffuse ν emission?
2010+ AMS, CREAM, FERMI, PAMELA, TRACER, ...

Acceleration

1949 Fermi's theory of cosmic rays (first and second order acceleration)
1978 Charge particle acceleration mechanism in shocks (1^{st} order Fermi) in agreement with observations
2000 Non-linear magnetic field amplification in diffusive shocks (*à la* Bell & Lucek)

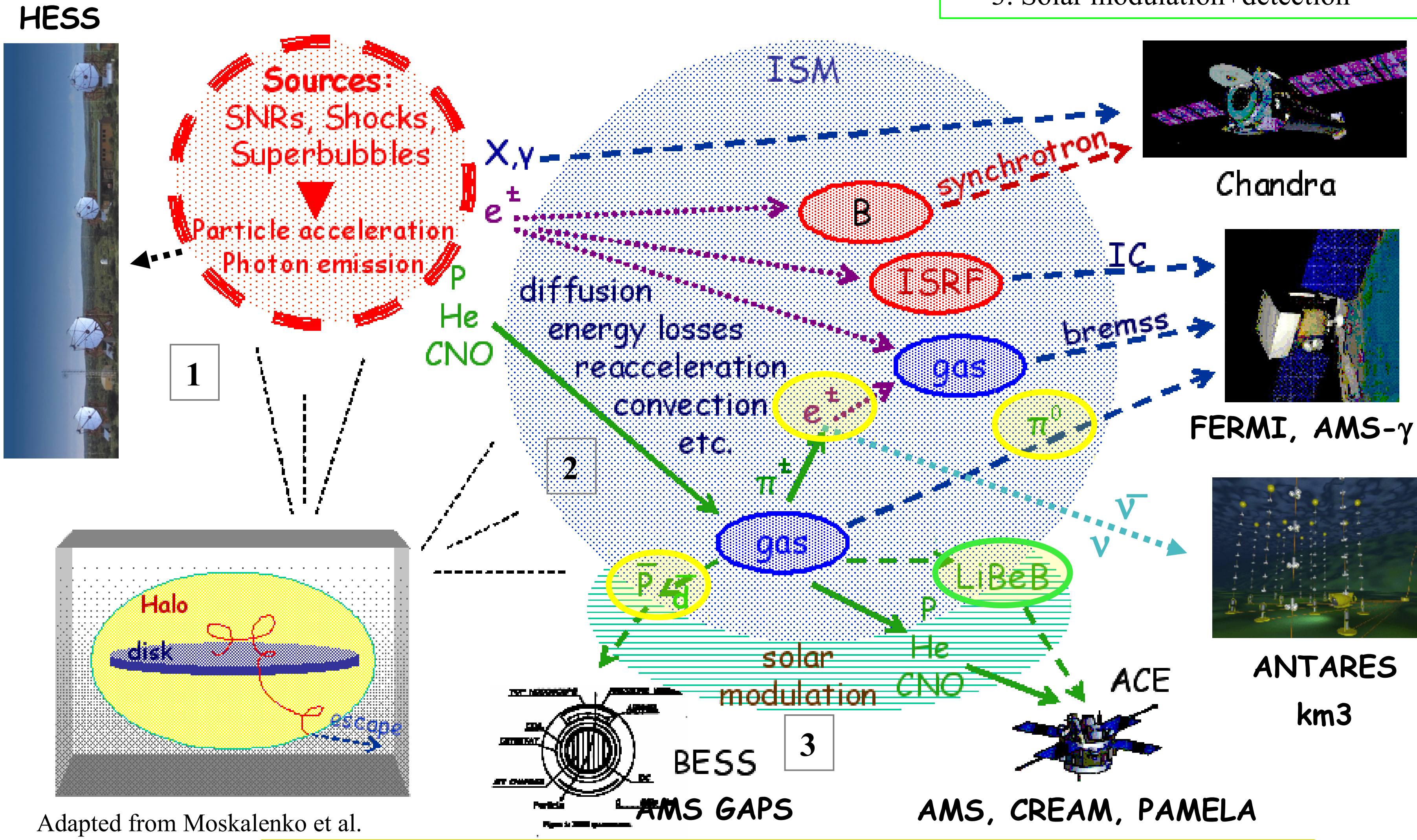
Transport

1953 Hypothesis of the existence of a CR halo around the gaseous disk
1960 Leaky Box: an Exponential Path Length Distribution to fit the data
1964 First reference textbook on CRs: The origin of CRs (Ginzburg & Syrovatskii)
1970 Demonstration of the validity of the Leakage Lifetime Approximation (for stable nuclei) deduced from the general diffusion/convection equation (it does not apply to e^-)!
1974 Why the LB fails with radioactive species; first measurement of the $^{10}Be/Be$ ratio that hints at a halo model for propagation
90's First attempts to built self-consistent complete models for CR propagation (nuclei, e^+/e^-, γ)
2000's Necessity to take into account time-dependent effects and local sources?
2010's Inhomogeneous transport, MHD self-consistent approaches?

Requirement: consistent description of all fluxes (electrons, nuclei and gamma)

Cosmic Ray journey in 3 steps:

1. Synthesis and acceleration
2. Transport (diffusion & interactions)
3. Solar modulation+detection



Adapted from Moskalenko et al. (2004)

=> Search for DM where "standard" production is rare (secondary)

=> Use LiBeB to calibrate the transport coefficients

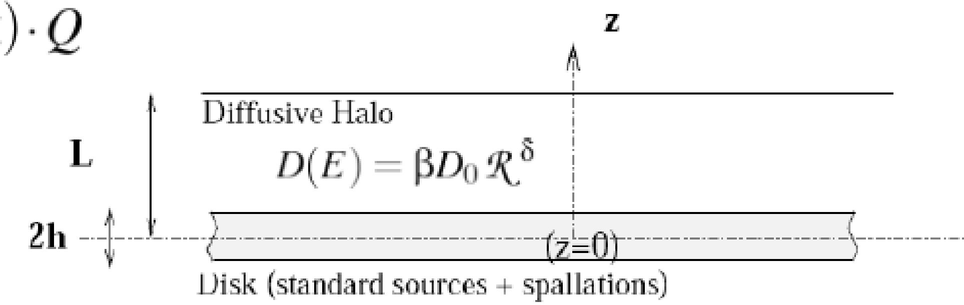
Basics on transport: diffusion and source slope

$$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \nabla \cdot (D_{xx} \nabla \psi - \mathbf{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\nabla \cdot \mathbf{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

Steady-state: 1D Diffusion Model *vs* LeakyBox Model

$$1\mathrm{D}: \quad -KN'' + 2h\delta(z) \cdot nv\sigma \times N = 2h\delta(z) \cdot Q$$

$$\begin{cases} N(z) = N(0) \cdot \dfrac{L - z}{L} \\ \dfrac{2D}{2hL} \cdot N(0) + nv\sigma N(0) = Q \end{cases}$$



LB equation : $\dfrac{N}{\tau_{\mathrm{esc}}} + \bar{n} v \sigma N = Q$ => Link between LBM and diffusion models

Degeneracy: Models with the same D_0/L are equivalent (secondary-to-primary production)
=> referred to as *"the degeneracy"* in the following

Simple case: secondary-to-primary ratio

High energy: $N^p \propto \dfrac{Q}{D} \propto \dfrac{E^{-\alpha}}{E^{\delta}}$, and $N^s \propto \dfrac{N^p}{D} \quad \Rightarrow \quad \dfrac{N^s}{N^p} (e.g.\ B/C) \propto D^{-1} \propto E^{-\delta}$

I. *CR in the Galaxy: context and models*

II. *Sample results and limitations*

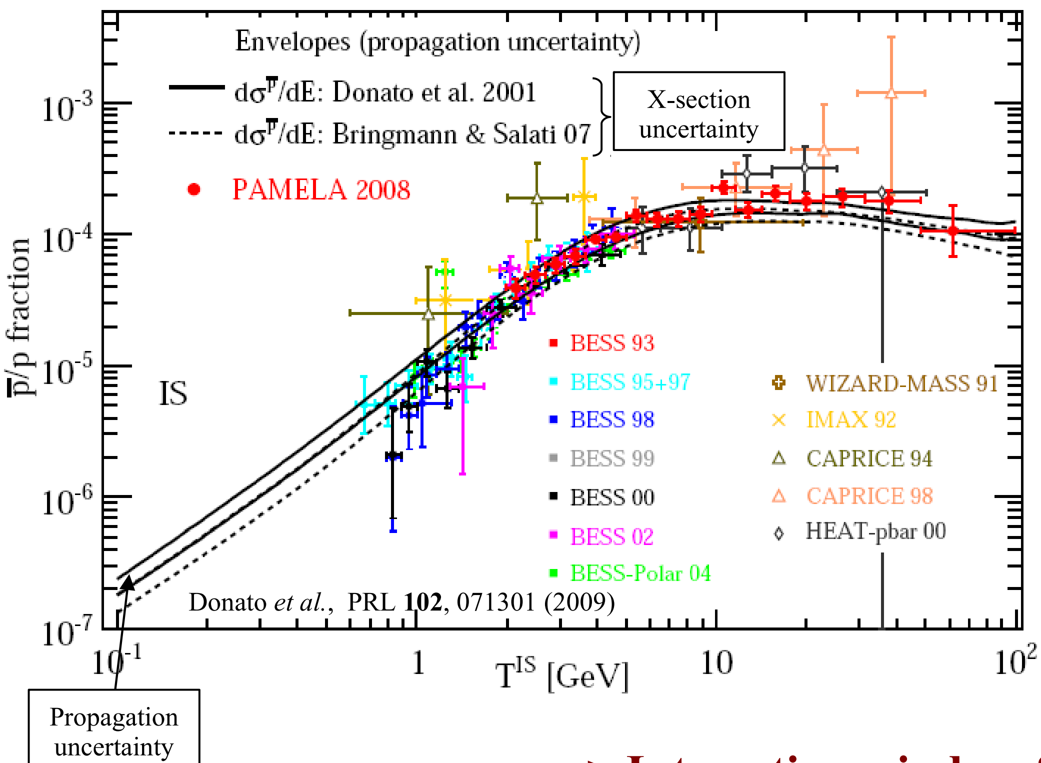
III. *MCMC technique and results*

IV. *Statistical vs systematic uncertainties*

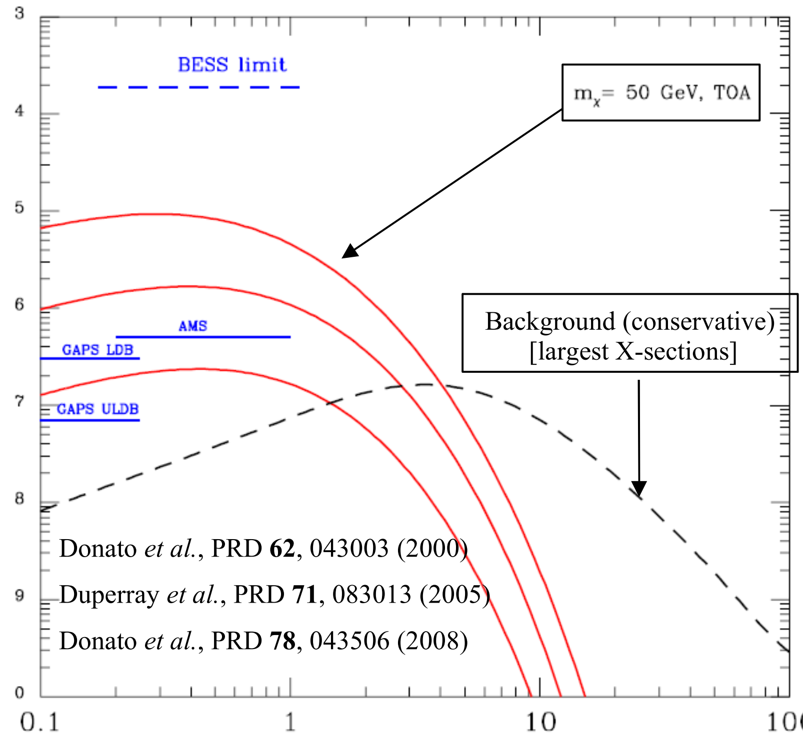
V. *Conclusions*

Antiproton and antideuteron flux

Antiproton/proton



Antideuterons



=> Interesting window for antideuterons

GAPS: Mori et al., ApJ **566**, 604 (2002), Hailey et al., PRD **01**, 007 (2006)

=> Recent PAMELA data consistent with pure background

N.B.: theoretical prediction limited by production cross-section accuracy

e+/e-: see Julien Lavalle's talk

Sample of models/effects inspected in the literature

Bloemen *et al.* A&A **267**, 372 (1993) => Semi-analytical (homogeneous D, linear wind)
Erlykin & Wolfendale, J. Phys. G **28**, 2329 (2002) => Semi-analytical (use $\delta(r)$, liked to turbulence level)
Jones *et al.,* ApJ **547**, 264 (2001) => Semi-analytical (homogeneous D, constant wind)
Ptuskin & Soutoul, A&A **337**, 859 (1998) => Semi-analytical (radioactive nuc. and LISM)
Shibata *et al.*, ApJ **642**, 882 (2006) => Semi-analytical (inhomog. D, no V)

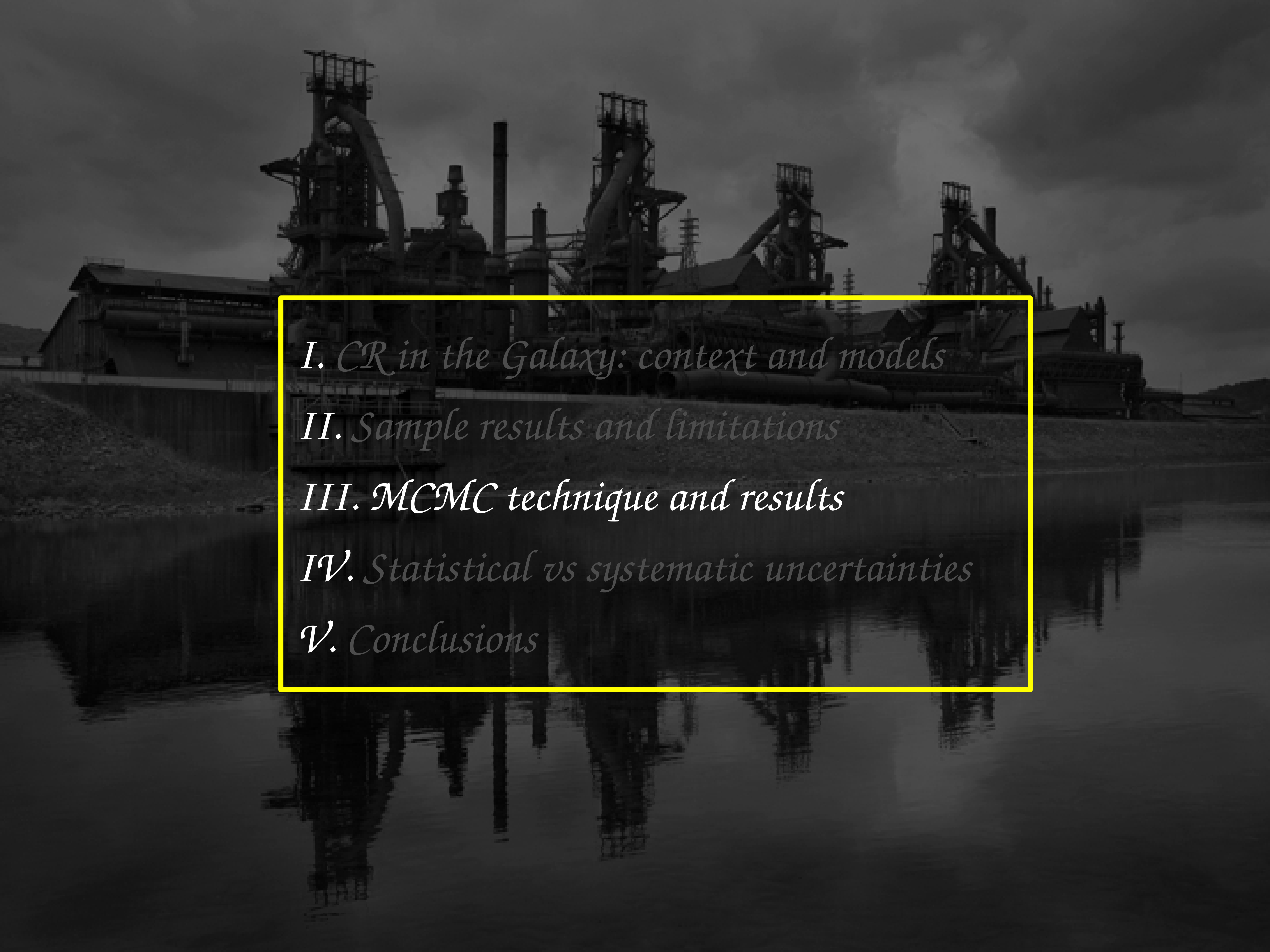
Berezhko *et al.,* A&A **410**, 189 (2003) => Secondary production in source
Breitschwerdt *et al.*, A&A **385**, 216 (2002) => Numerical (homog. D, but V(r,z))
Evoli *et al.* JCAP **10**, 18 (2008) => Numerical (inhomogeneous D, no V, no E losses)
Farahat *et al.*, ApJ **681**, 1334 (2008) => Numerical (backward Markov stochastic processes)
Strong & Moskalenko, ApJ **509**, 212 (1998) => Numerical (cst + linear wind)

+ anisotropic diffusion (e.g., to explain the knee)
+ time-dependent effects (HE leptons)
+ MHD couplings of magnetic fields, CRs and gas...

General caveats

- Each model developed generally not suitable for all species
- Different refinements required for different species (nuclei, leptons, γs)

=> Up-to-date/optimised models describing all CRs are likely to be a mixture of the above approaches



I. CR in the Galaxy: context and models

II. Sample results and limitations

III. MCMC technique and results

IV. Statistical vs systematic uncertainties

V. Conclusions

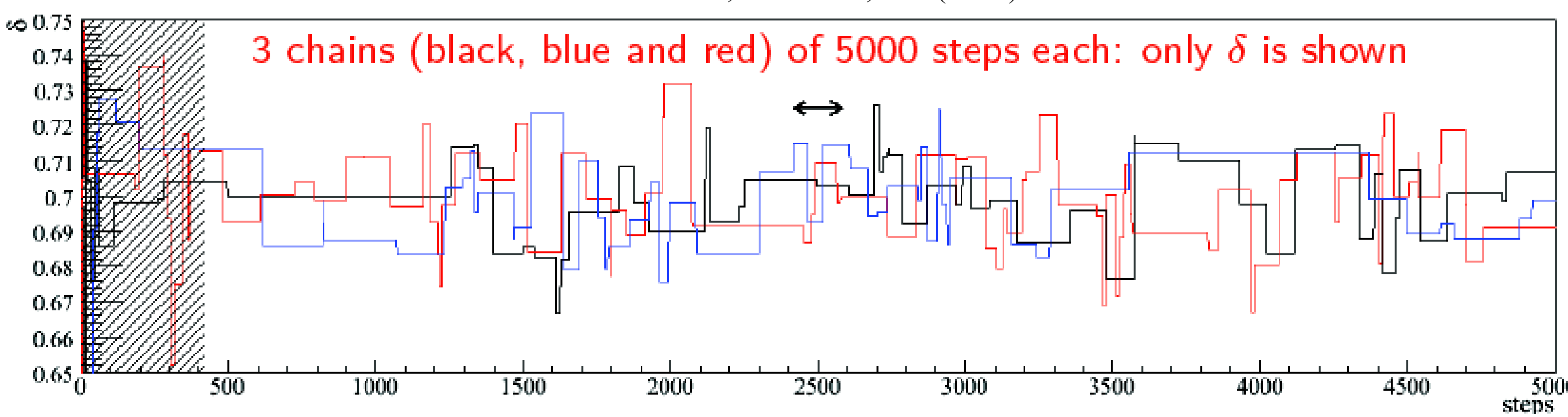
The MCMC technique: basics

Principle: Given some prescription, a Markov chain in evolved in the parameter space
=> with the right algorithm (e.g., Metropolis-Hastings), ensures that the time spent in regions of the parameter space is proportional to the parameter probability density function

Advantages: Waterproof (robust, statistically sound, effective, ...) and handy (tackles large parameter space, parallel processing of chains)

Illustration:

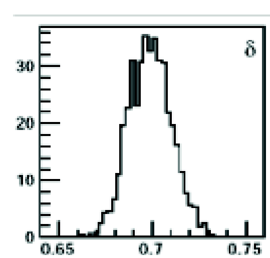
Putze *et al.*, A&A **497**, 991 (2009)



- Discard burn-in length (hatched area)
- Keep only 1/l point, where l is the correlation length (arrow)

⇒ stack values of the chain in an histogram (marginalising is easy!)

⇒ PDF of the parameter



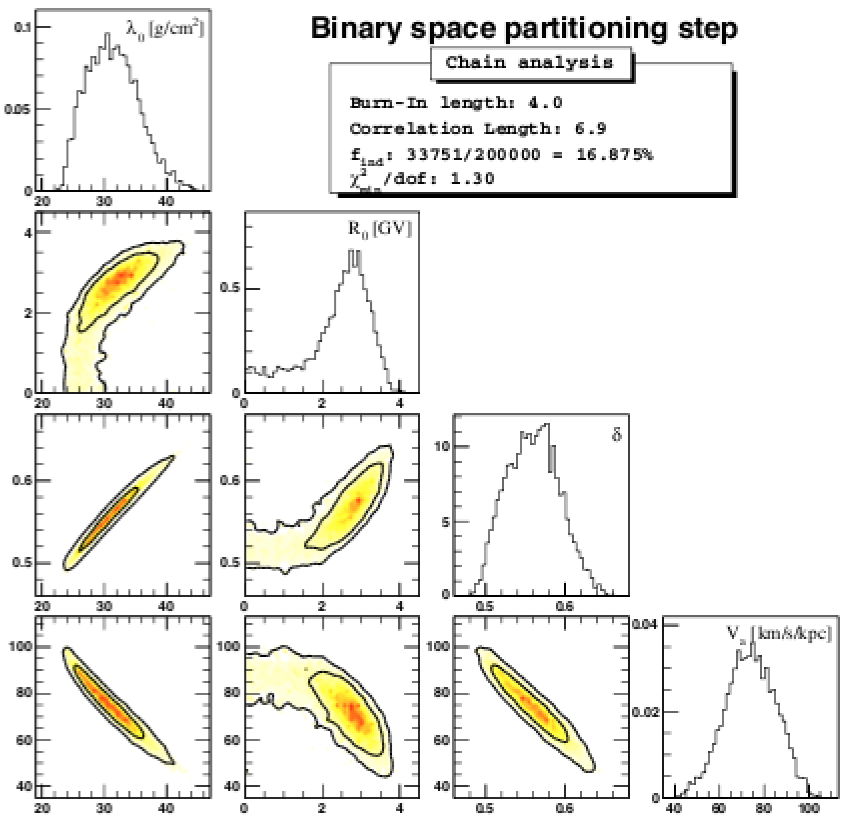
⇒

- Extract mean value
- Extract confidence intervals/levels

$$\mathrm{CL}(x) \equiv \int_{\Delta_x} \mathcal{P}(\theta_i)\mathrm{d}\theta_i = 1 - x$$

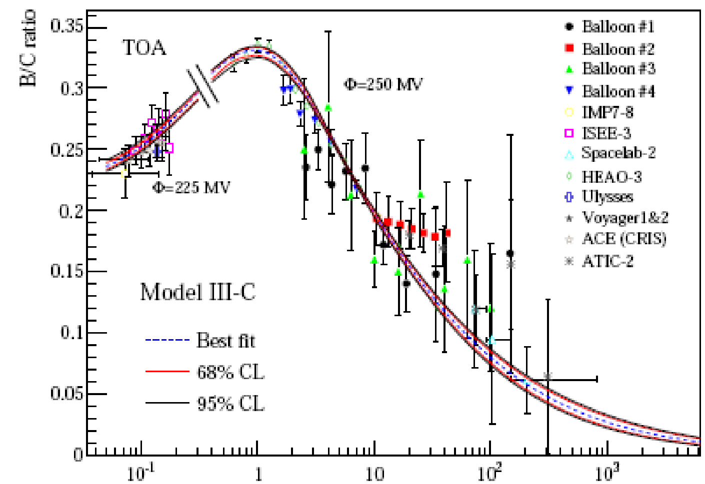
The MCMC technique: results (1)

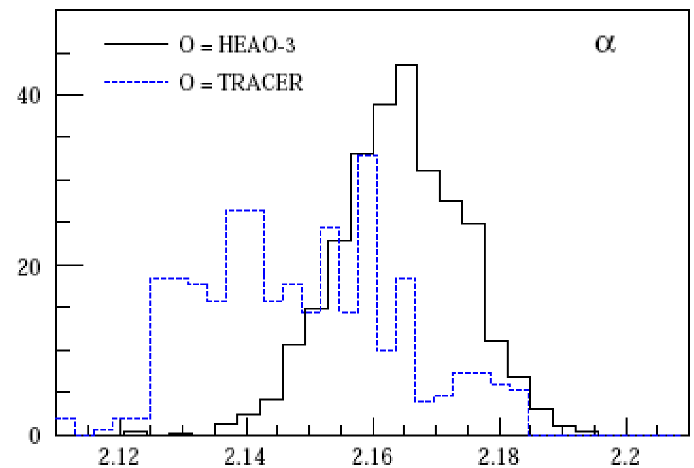
Leaky Box Model
Putze *et al.*, A&A **497**, 991 (2009)



Posterior distribution of the LBM parameters
(λo, Ro, δ, Va)

- Diagonal: PDF of the parameter
- Off-diagonal: 2D correlations for the PDFs





Possible studies

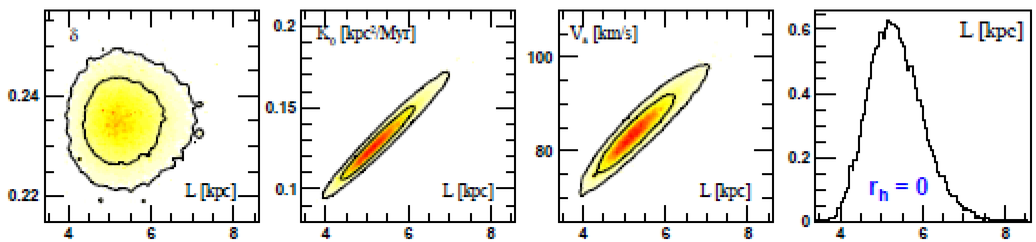
- δ=0.53 (+0.02,-0.03) => δ=1/3 excluded
- "Unbiased" determination of α~2.15
- Envelopes, constraints from ≠ datasets,...

The MCMC technique: results (2)

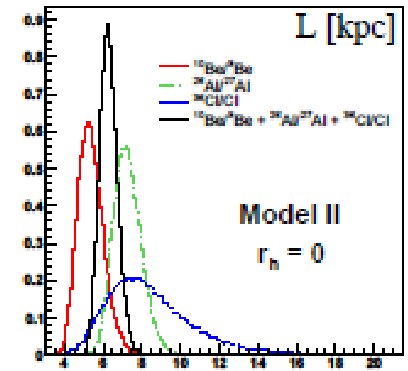
1D diffusion model (B/C + ^{10}Be/Be)

Maurin, Putze & Derome, **arXiv:1001.0553** (2010)

I. Diffusion/reacceleration (no convection)



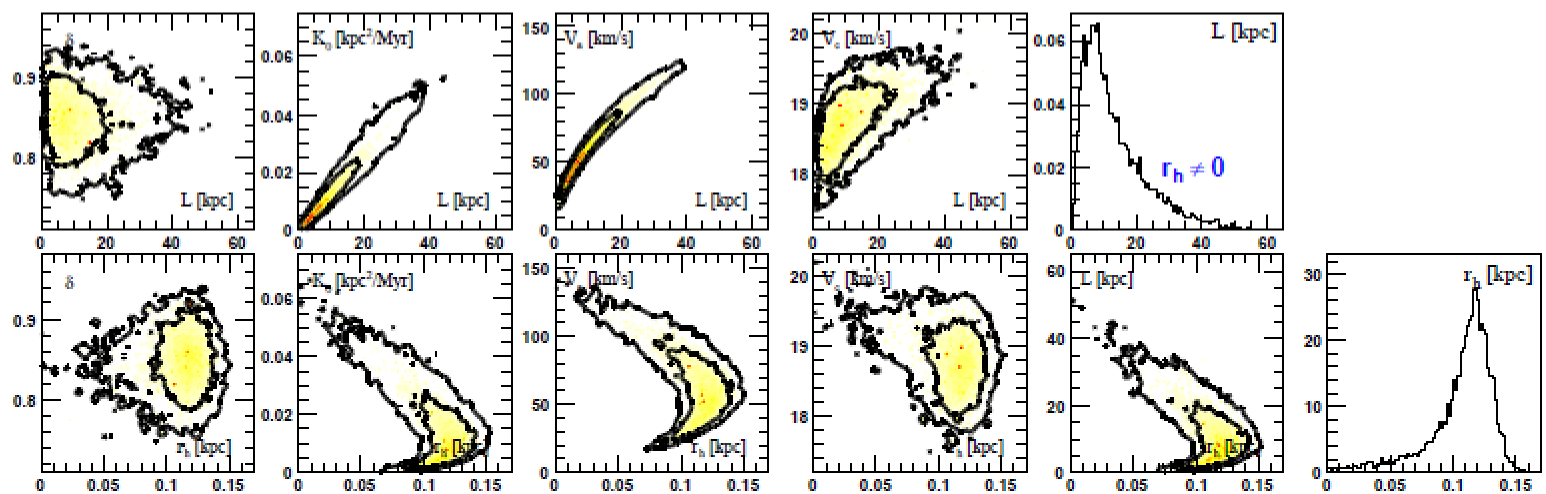
...or using various radioactive species



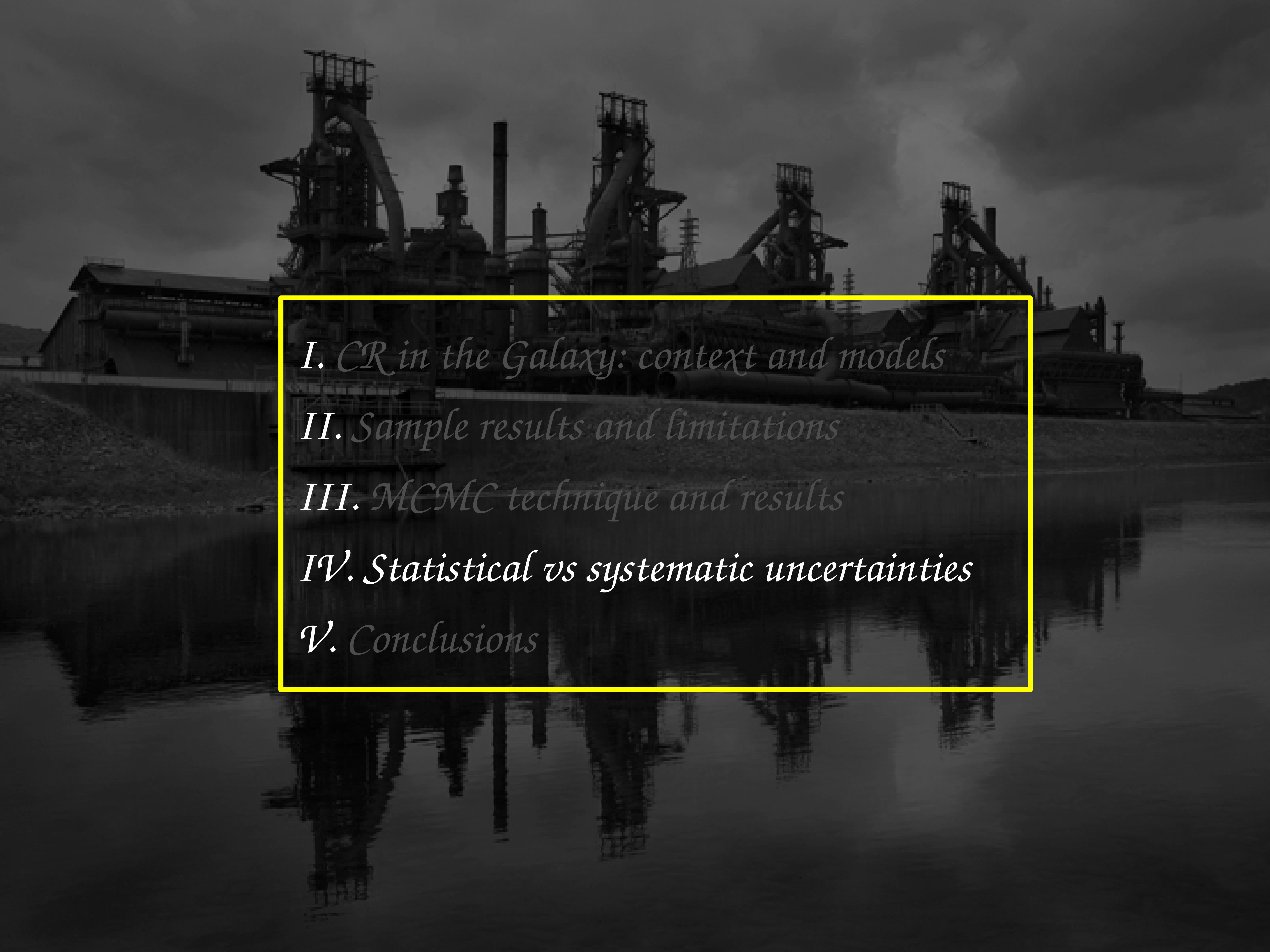
II. Diffusion/convection/reacceleration + local underdensity (~100 pc)

Ptuskin & Soutoul, A&A **337**, 859 (1998)

Lallement *et al*, A&A **411**, 447 (2003, Welsh *et al*, A&A **510**, 54 (2010)



+ Putze, Donato & Maurin (in preparation) for primary fluxes



I. CR in the Galaxy: context and models

II. Sample results and limitations

III. MCMC technique and results

IV. Statistical vs systematic uncertainties

V. Conclusions

Systematic uncertainties: methodology

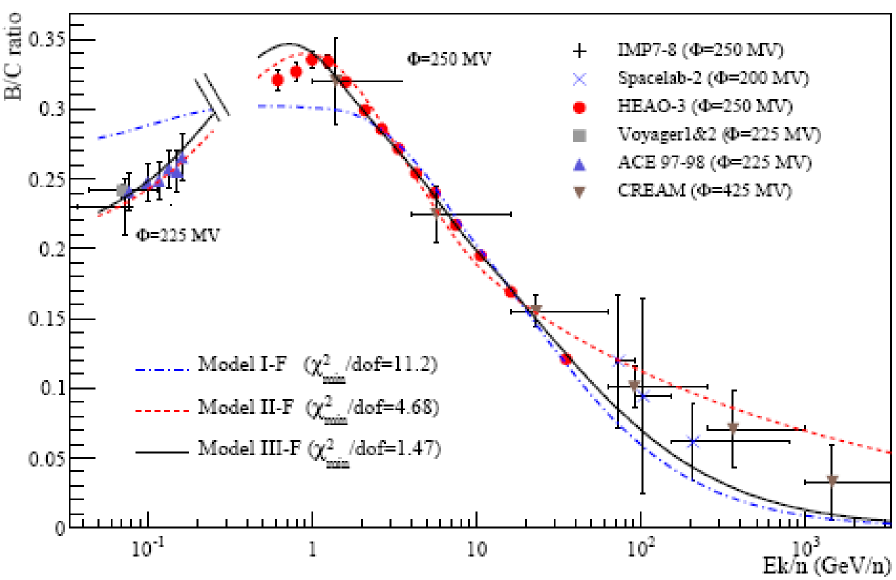
Maurin, Putze & Derome, **arXiv:1001.0553** (2010)

- Goal

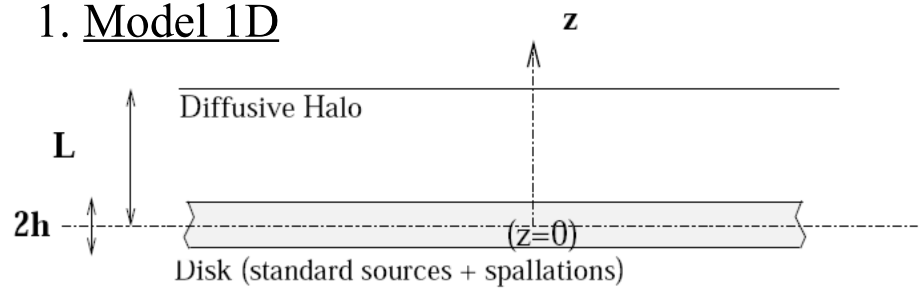
Exists uncertainties in the ingredients
=> How does it affect the derived parameters?
+ how it affects δ?

- Data

HEAO-3 + low-energy
+ HE (CREAM, Spacelab)



1. Model 1D



N.B.: L set to 4 kpc

2. Default configuration

Input name	Default value/dependence/set
Gas	$\Sigma = 6.17 \cdot 10^{20}$ cm^2, $f_H = 90\%$
Source spectrum	$\eta Q^j(E) = q_j \beta^{\eta_S} R^{-\alpha}$
$K(E)$ and $K_{pp}(E)$	Slab Alfvén (SA): Eqs. (5) & (6)
Cross-sections	W03 (Webber et al. 2003)
Data	B/C, dataset F†

† 31 data points from IMP7-8, Voyager 1&2, ACE, HEA0-3, Spacelab, and CREAM04

3. Minimisation from Minuit (CERN) lib.

Systematic uncertainties: ISM

$$\Sigma^{new} = x \times \Sigma^{ref}$$

Table 2. Best-fit transport parameters for different ISM.

Gas Σ	f_H	$K_0^{best} \times 10^2$ ($kpc^2\,Myr^{-1}$)	δ^{best}	V_c^{best} ($km\,s^{-1}$)	V_a^{best} ($km\,s^{-1}$)	χ^2/d.o.f
Σ^{ref}	f_H^{ref}	*0.48*	*0.86*	*18.8*	*38.0*	*1.47*
Σ^{ref}	95%	0.53	0.83	18.6	38.1	1.24
Σ^{ref}	80%	0.41	0.90	19.3	37.7	2.14
$\frac{1}{2}\,\Sigma^{ref}$	f_H^{ref}	0.25	0.85	9.5	19.4	1.45
$2\,\Sigma^{ref}$	f_H^{ref}	0.92	0.86	37.3	74.6	1.51

$$\Sigma^{new} = x \times \Sigma^{ref}$$

and $$\langle x \rangle^{pure-DM} = \frac{\Sigma_{ISM}\bar{m}vL}{2K}$$ => $$K_0^{new} = x \times K_0^{ref}$$

and $$\langle x \rangle^{V_c} \equiv \frac{\Sigma_{ISM}\bar{m}v}{2V_c}\left[1 - e^{-\frac{V_c L}{K}}\right]$$ => $$V_c^{new} = x \times V_c^{ref}$$

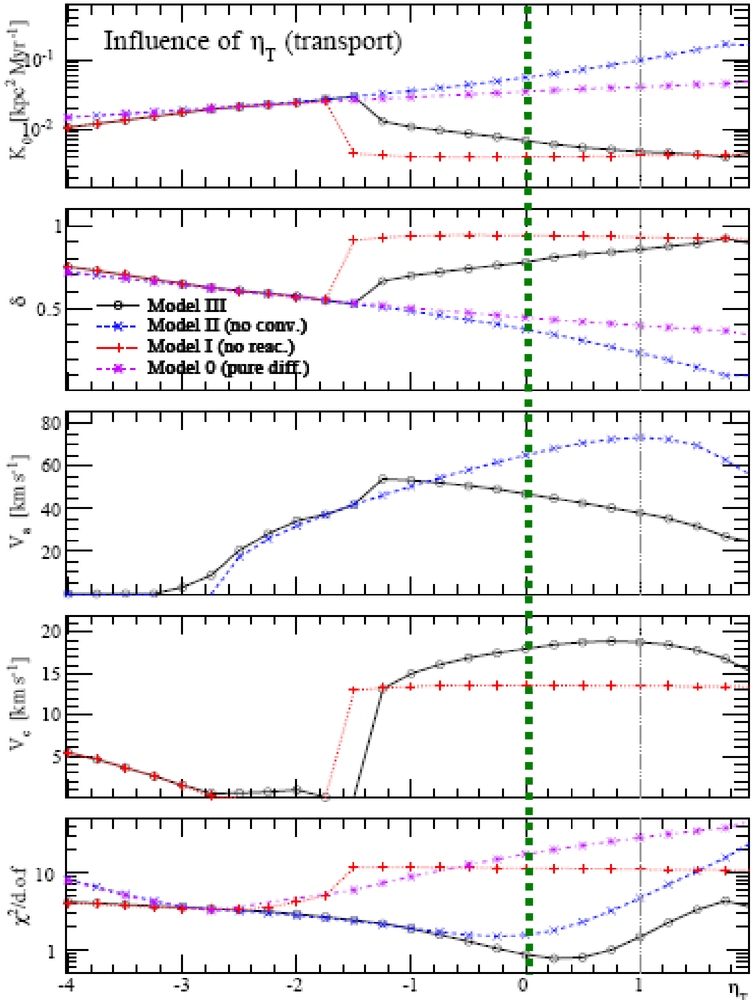
Systematic uncertainties: low-energy transport η_T

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

Ptuskin *et al.*, ApJ, **642**, 902 (2006)
(sharp turn-off at low energy possible)

Type of turbulence		η_T	$\frac{K_{pp}K_{xx}}{4/3\, p^2 V_a^2}$
LBI	Leaky Box Inspired	0	$\frac{1}{\delta(4-\delta^2)(4-\delta)}$
SA	*Slab Alfvén*	*1*	$\frac{1}{\delta(4-\delta^2)(4-\delta)}$
IFM	Isotropic fast magnetosonic	$2-\delta$	$\beta^{1-\delta}\ln(\frac{v}{V_a})$
Mix	Mixture SA and IFM	$1-\delta$	$\beta^{1-\delta}\ln(\frac{v}{V_a})$

Type	$K_0^{\rm best}\times 10^2$ (kpc^2 Myr^{-1})	$\delta^{\rm best}$	$V_c^{\rm best}$ (km s^{-1})	$V_a^{\rm best}$ (km s^{-1})	χ^2/d.o.f
0: LBI	3.48	0.45	...	...	17.5
0: SA	*4.08*	*0.40*	...	...	*28.8*
0: IFM	4.30	0.38	...	...	36.7
0: Mix	3.71	0.43	...	...	23.7
I: LBI	0.40	0.94	13.6	...	12.0
I: SA	*0.42*	*0.93*	*13.5*	...	*11.2*
I: IFM	0.42	0.93	13.5	...	11.6
I: Mix	0.41	0.94	13.5	...	12.0
II: LBI	5.50	0.38	...	65.0	1.61
II: SA	*9.76*	*0.23*	...	*73.1*	*4.73*
II: IFM	14.0	0.16	...	18.9	6.86
II: Mix	7.13	0.32	...	12.8	2.03
III: LBI	0.70	0.78	18.0	47.1	0.87
III: SA	*0.48*	*0.86*	*18.8*	*38.0*	*1.47*
III: IFM	0.49	0.85	18.9	45.6	1.25
III: Mix	0.73	0.77	17.8	57.4	0.93



=> δ is extremely sensitive to η_T !

Systematic uncertainties: production cross-sections

GALPROP 09, Webber 03, or energy biased X-sections

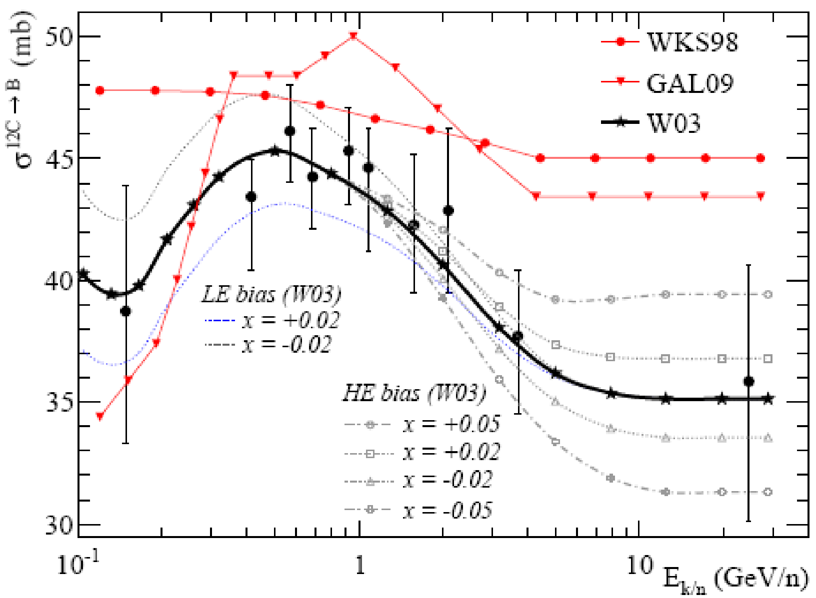
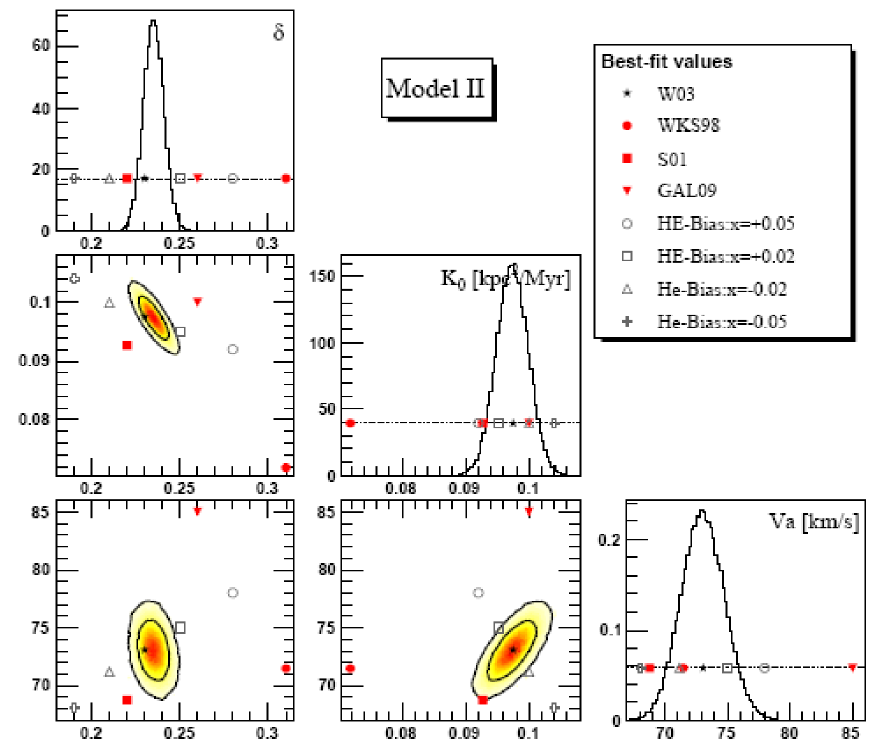
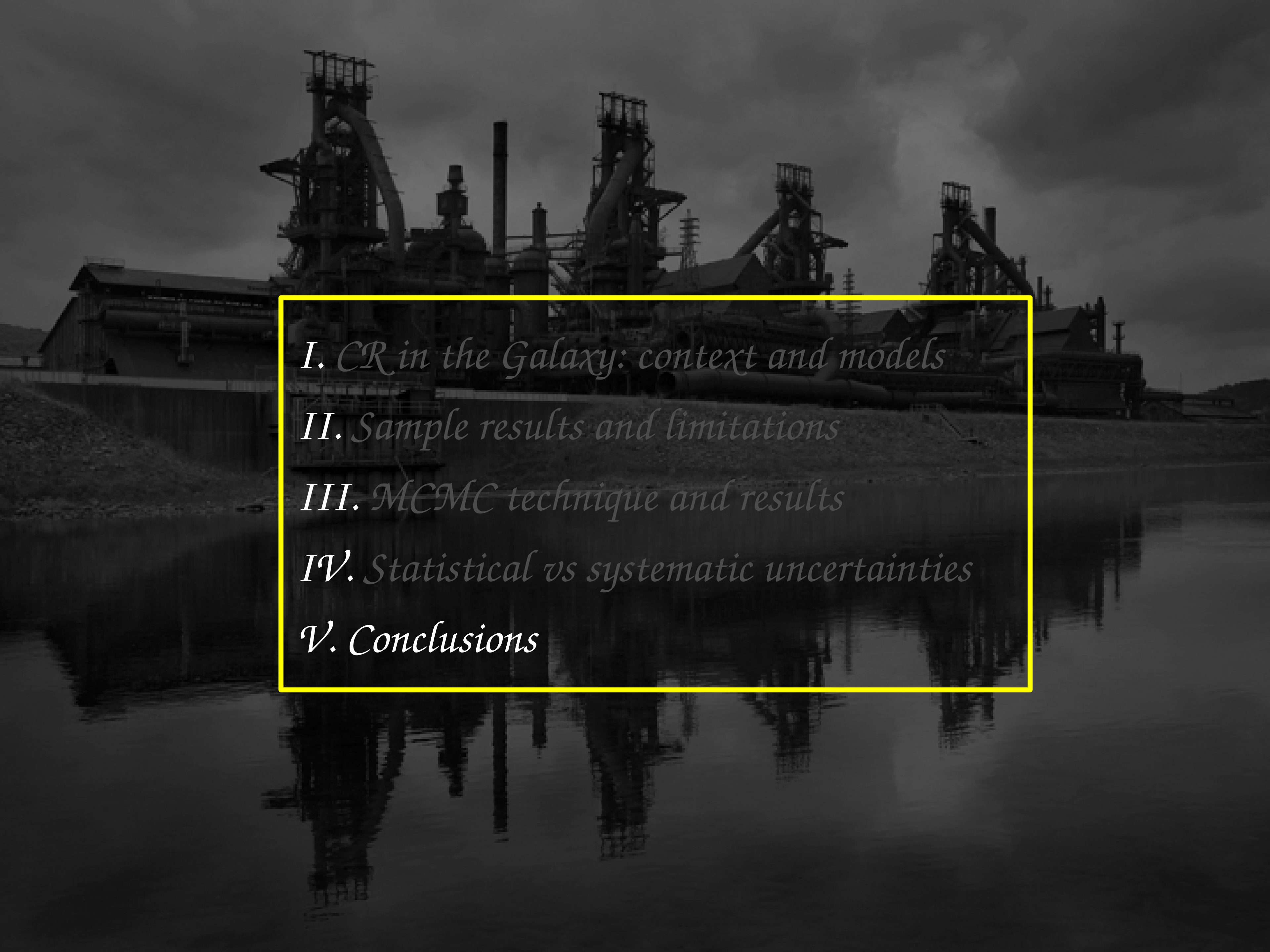


Fig. 3. Production cross-section for $^{12}C+H \rightarrow ^{10,11}B$ (adapted from Webber et al. 2003). The standard sets are shown as solid lines (WKS98: red dots; GAL09: red down triangles; W03: black stars), and the biased sets in dotted ($|x| = 0.02$) and dashed ($|x| = 0.05$) lines.



=> Systematics uncertainties > "statistical uncertainties"



I. CR in the Galaxy: context and models

II. Sample results and limitations

III. MCMC technique and results

IV. Statistical vs systematic uncertainties

V. Conclusions

Conclusions: pros and cons

- Present-day situation
  - Wealth of new data after the ~80's-00's "gap": nuclei, leptons, MeV-TeV γ
  - Clearer picture of transport in magnetic fields (numerical/analytical/data)
  - Better knowledge of the Galactic environment

=> Global propagation models are necessary tools to go further
Specific studies can help (time-dependent effects, inhomogeneity...)

Yet, simple models with a few parameters still suffer from large uncertainties
=> DM backgrounds (~OK except HE e+), messy for signals

USINE

- V1.0 public release
- Database (MySQL)
- Website (simple model calculation online)

… we are working hard to make it happen (~ July-August 2010)

[LPNHE – LAPTH – LIP – LPSC – Università di Torino]

=> to be thought as a toolbox to implement your own models

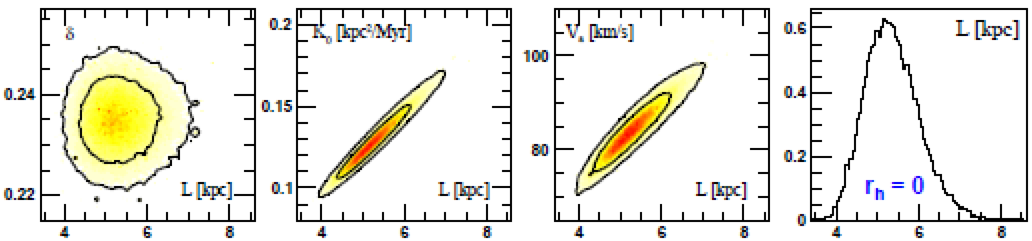
N.B: if not in the first release, MCMC and e+/e-
should be made public quickly after the first release...

The MCMC technique: results (2)

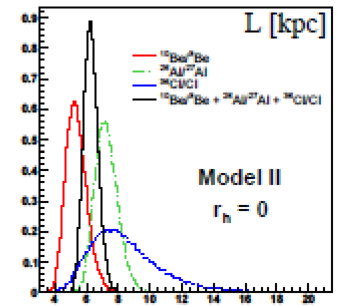
1D diffusion model (B/C + ^{10}Be/Be)

Putze, Derome & Maurin, A&A **xxx**, xxx (2010)

I. Diffusion/reacceleration (no convection)

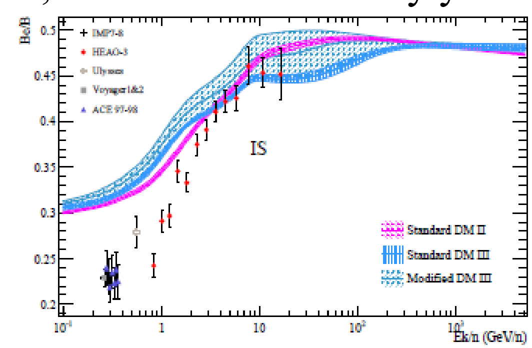


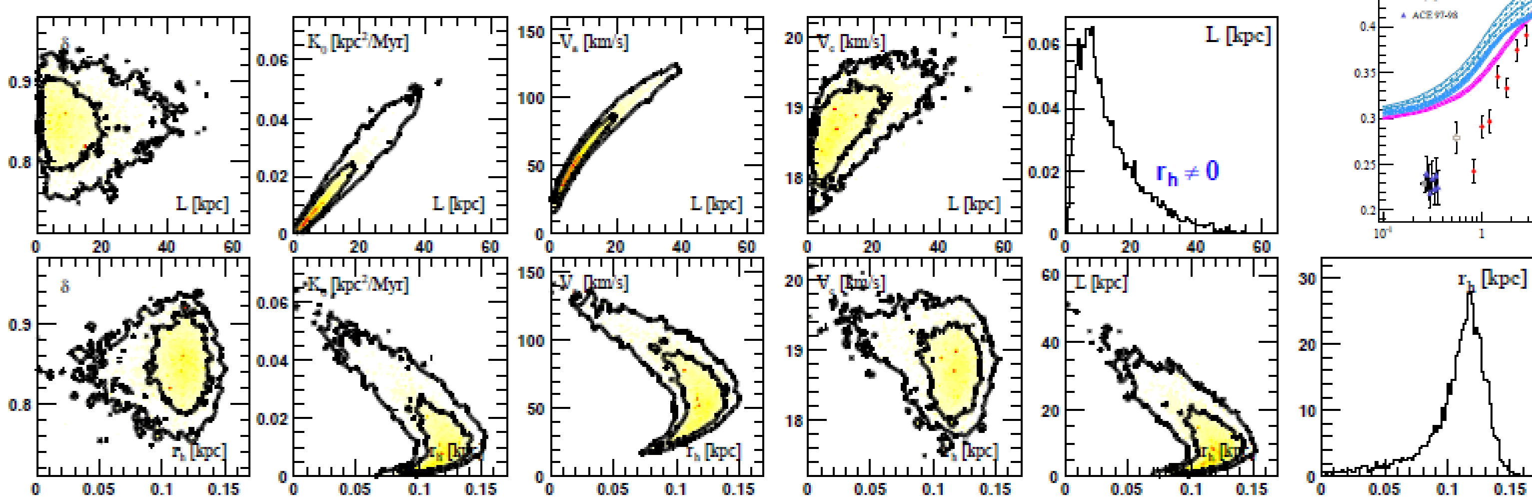
...or using various radioactive species



II. Diffusion/convection/reacceleration + local underdensity (~100 pc)

but still, no model satisfactory yet!





+ Putze, Donato & Maurin (in preparation) for primary fluxes

~ Interlude ~

Flux anomalies as DM signals: déjà vu?

Antiprotons

- first measurements, be it at low energy or at high energy, proven wrong
- first theoretical calculation underestimated

  => *Present status: no excess from PAMELA data*

γ-ray GeV excess

- EGRET excess (1997-2008): astrophysical or DM?
- High latitude excess proven wrong by FERMI data

  => *Present status: awaiting FERMI results for the disc*

Positron fraction

- Rise at 10 GeV (HEAT) controversial, needed large boost if DM
- No DM boosts: now, is it a particle physics boost?

  => *Present status: p contamination? Local sources?DM?*

511 keV line

- Variable source, then positronium fountain (OSEE)...
- Hundreds of papers on light dark matter

  => *Present status: spatial correlation LMXB (issues with intensity?)*

TeV electron flux

- First measurement ATIC& PPP-BETS (2008)
- Local sources, DM [~*O*(100) papers], or incorrect measurements?

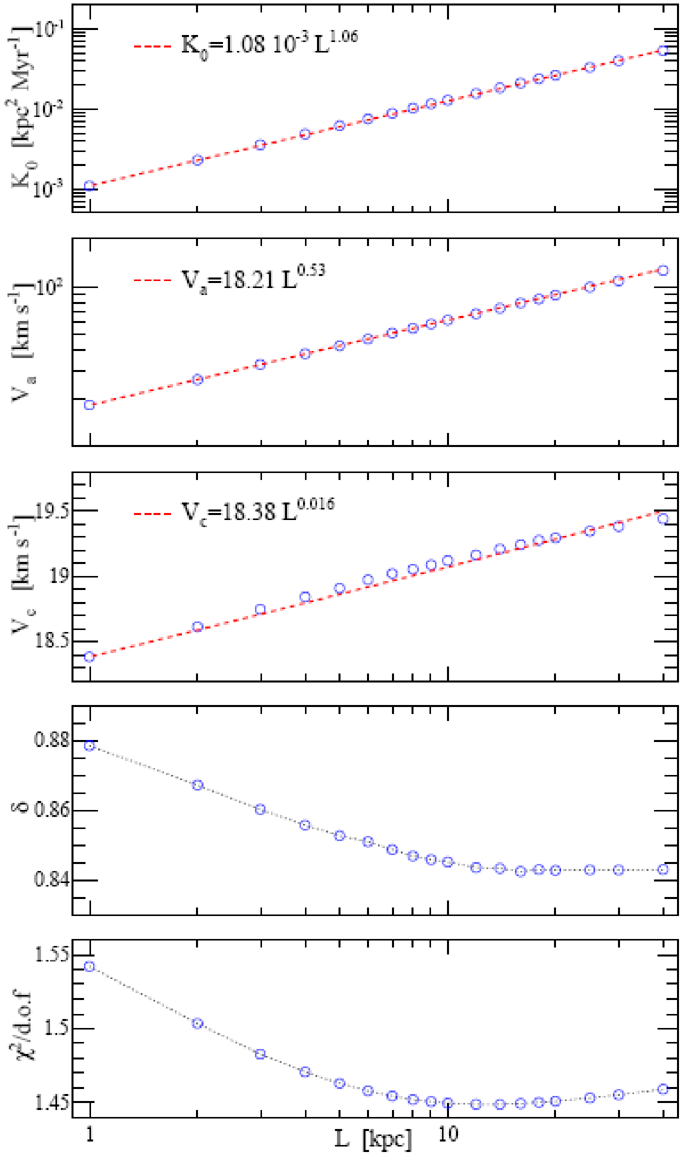
  => *Status: neither confirmed by HESS nor by FERMI*

=> More and more “DM” papers... but the recent CR “history” is deceiving, so be careful...

~ Interlude ~

How do the parameters scale with L?

Putze, Derome & Maurin, **ArXiv:1001.0551** (2010)



← Ko/L degeneracy

← Va α (Ko)$^{1/2}$, $K_{pp} \times K = \frac{4}{3}\, V_a^2\, \frac{p^2}{\delta\,(4-\delta^2)\,(4-\delta)}$,

← ~ no effect on Vc

← ~ no effect on the diffusion slope

← ~ no effect on χ^2

=> all conclusions hold for any L (only rescaling)

USINE (2)

A – Ingredients common to all models

1. Base ingredients
- Nuclear charts (m, A, Z, β and EC-decay channels)
- Atomic properties (FIP, Ek-shell...)
- Nuclear physics (production, inelastic... X-sections)
- Energy losses (Coulomb, ionisation)

2. Solar modulation (IS to TOA)

3. Database (experimental fluxes)

4. Visualization and fitting tools
- Displays
- Fitting tools

Base package, C++/Root interface

[NEW]
Markov Monte Carlo Chain (MCMC) technique
=> PDF of parameters

Putze et al., A&A **497**, 991 (2009)
Putze et al., **arXiv:1001.0551** (2010)

See Antje Putze's talk

B – Ingredients specific to each model

1. Description (Input variables)
- Geometry
- Sources (spatial distribution, spectra)
- Propagation (transport coefficient, equation)

2. Solution of the transport equation
- Standard secondary/primary/tertiary contributions
- Unstable radioactive nuclei (BETA or EC)
- Energy redistributions (energy losses, reacceleration)
- Exotic primary contributions

Models (LB, 1D, 2D const. wind)