Le code de propagation USINE

(et quelques mots sur les autres codes)

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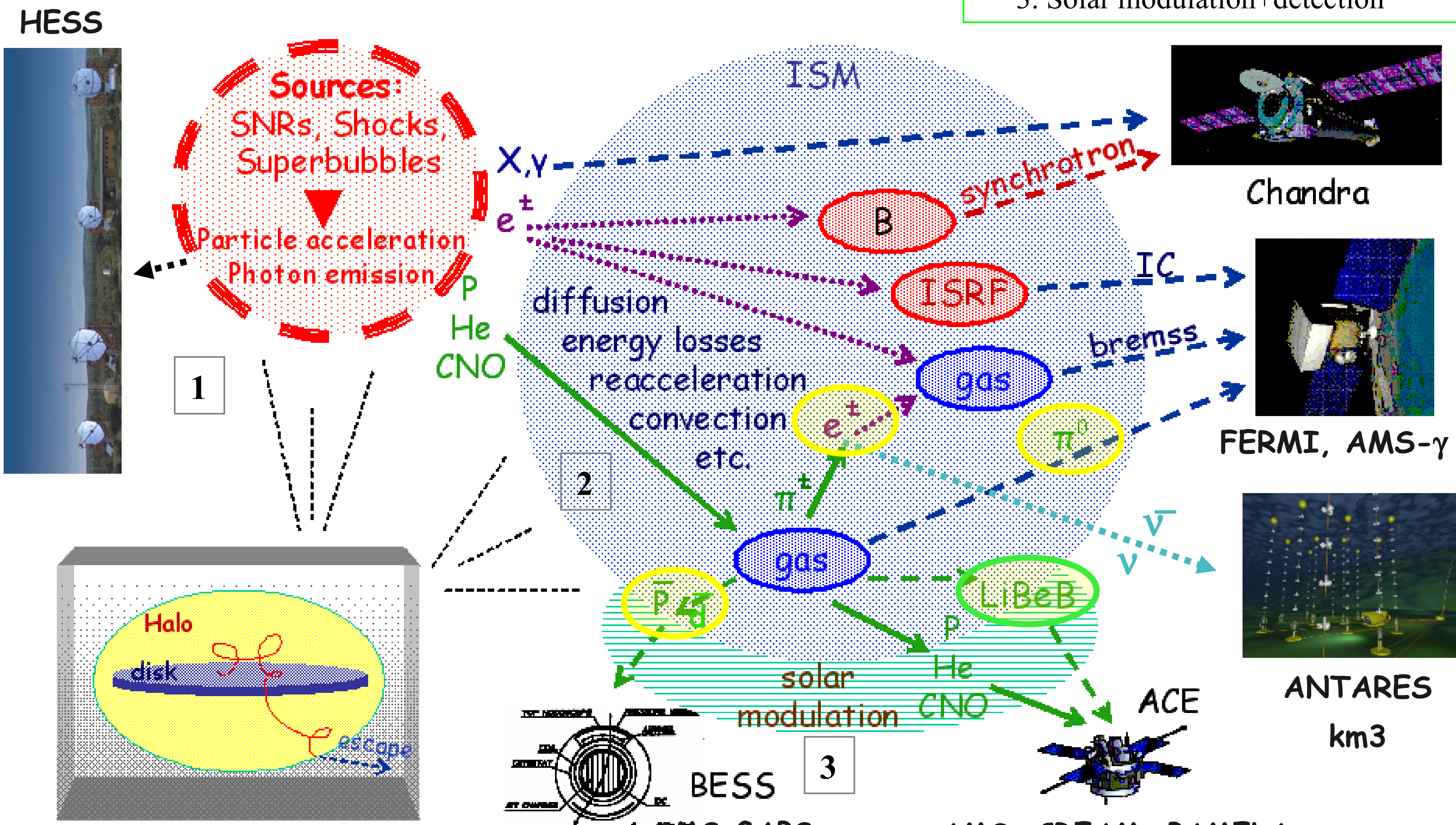
AMS – issues and prospects
LAPP, 9th march 2010

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

I. Zeste d'intro.

~ Milestones ~

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, ...

Measurements

Acceleration

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

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?

Transport

I. Zeste d'intro.

Propagation codes: what for?

Astrophysics

- Extract transport parameters (diffusion, convection...)
- Extract source parameters (abundances, spectra)
- Check all secondary productions (positrons, anti-protons, γ-rays)

Issues: solar modulation, nuclear cross-sections, spatial dependence of param.
N.B.: even GALPROP-like codes are pheno. (see Alex's talk on diffusion)

Indirect dark matter searches (tomorrow's session)

- Calculate Dark Matter contribution to secondary fluxes

Issues: same as astrophysics (background), but worse (DM distribution, PP...)

=> code must be multi-GeV + multi-messenger
+ DM-enabled
+ fast + user friendly + versatile

I. Zeste d'intro.

I. Un zeste d'introduction

II. Un poil de phénoménologie

III. Analytique vs numérique

IV. Galprop, Dragon & Usine

V. Conclusions

Basics on transport: equation

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

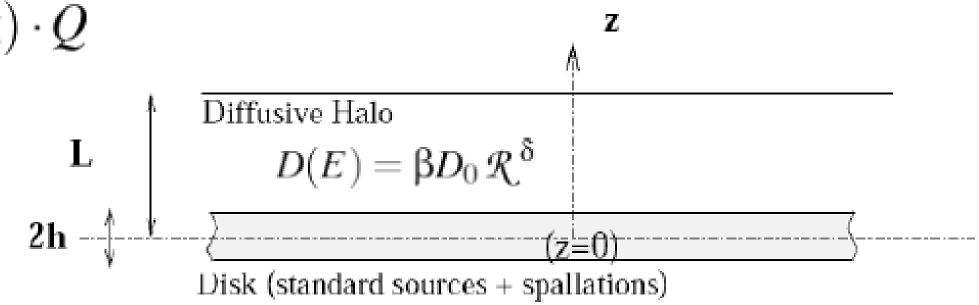
Basics on transport: simplifying assumptions

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

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

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

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



Basics on transport: Do/L degeneracy

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

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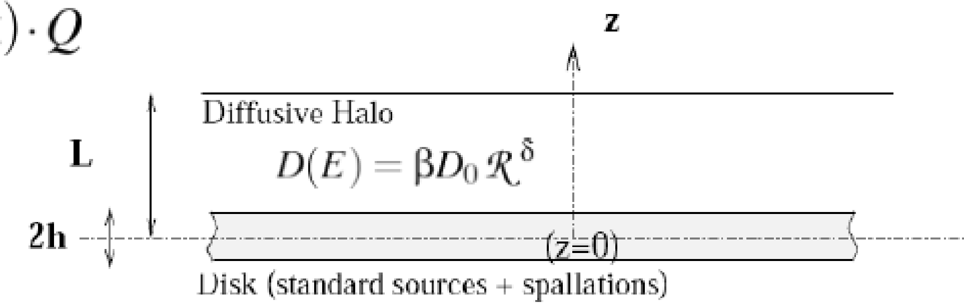

$$\text{LB equation}: \quad \frac{N}{\tau_{esc}} + \bar{n}v\sigma N = Q$$

=> 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

Basics on transport: diffusion and source slope

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

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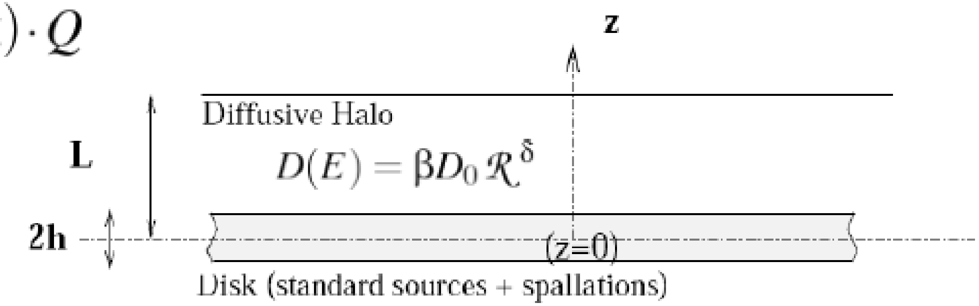

LB equation : $\dfrac{N}{\tau_{\text{esc}}} + \bar{n}v\sigma N = Q$ => Link between LBM and diffusion models

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 $N^s \propto \dfrac{N^p}{D}$ $\Rightarrow$ $\dfrac{N^s}{N^p}(e.g.\ B/C) \propto D^{-1} \propto E^{-\delta}$


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Semi-analytical models

1. Performances:
    - In general, less prone to numerical instabilities
    - Faster

    => Easier to sample the parameter space of a given models

2. Direct benefits:
    - Uncertainties on the propagation parameters
    - Uncertainties on any quantity derived from these parameters

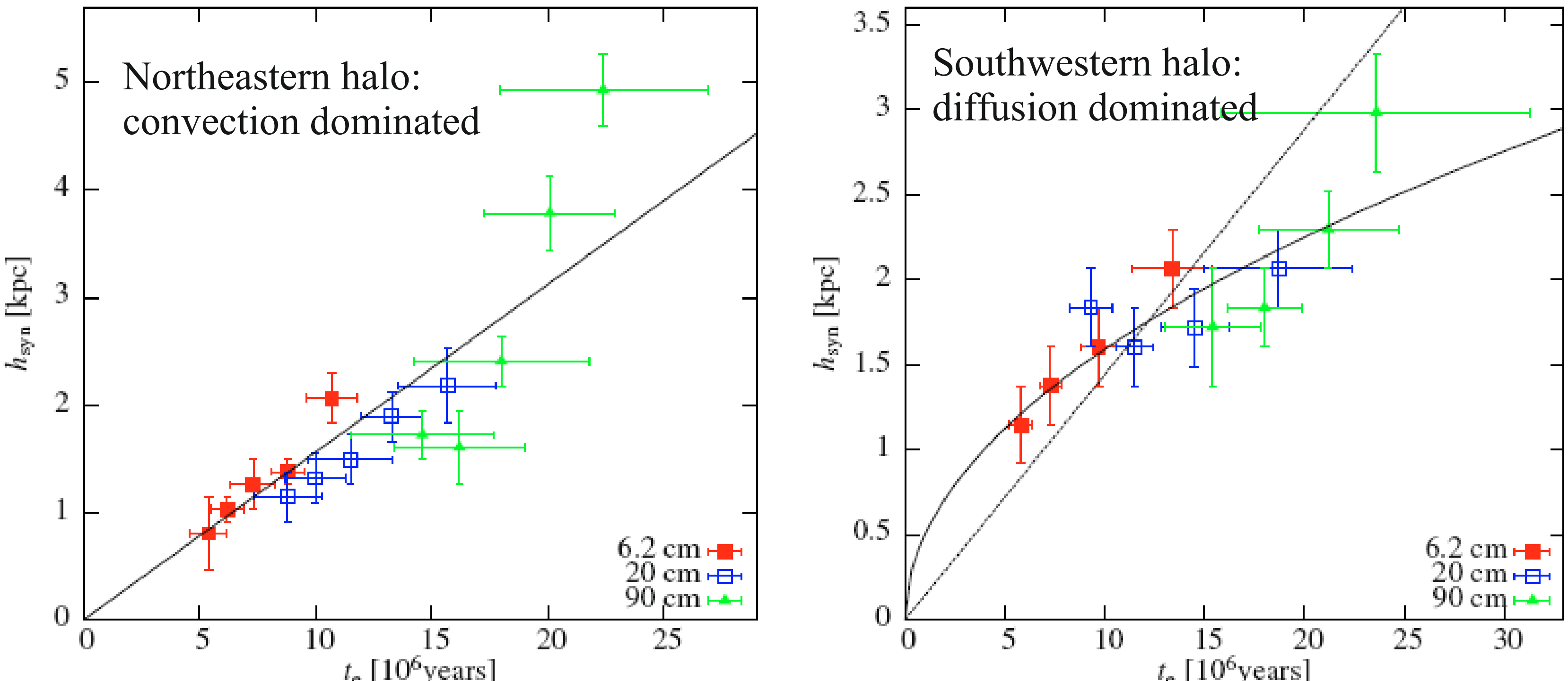
    => allows to understand which are the relevant physical parameters

3. Indirect benefits:
    - The derived range of parameters can be used "as is" in limiting cases
    - Studies: spatial "origin" of sources, radioactive & local bubble, exotic fluxes

Exemple of limitation: inhomogeneous transport

NGC 253 (starburst Galaxy, SFR ~ 5 Milky Way, Fermi source)

- Inhomogeneous spatial diffusion/convection
- Convective transport dominates over diffusive one in the northeastern halo



Heesen *et al.*, A&A **494**, 563 (2009)

=> "Homogeneous" models may be a good approximation, but are we touching their limit?

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 δ(r), linked 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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GALPROP (1)

Cosmic ray studies with GALPROP

Andy Strong
MPE Garching

Cosmic-ray backgrounds in Dark Matter Searches

Alba Nova, Stockholm
25-27 Jan 2010

GALPROP (2)

Propagation models

A main advantage is the physical interpretation in terms of diffusion, convection etc. related to the real Galaxy. Intuitive understanding of meaning of terms.

1D, 2D, or 3D
Both analytical and numerical, and hybrids, all have their proponents.

Analytical	Numerical
Mainly 1D, some 2D	2D or 3D
complex (but impressive) formulae	simple formulae (computer does the work)
simplified energy losses	full energy losses
simplified gas distribution	gas based on HI, CO surveys in 3D
simplified magnetic field	any magnetic field model
gamma rays only in simple way	full gamma ray calculation
synchrotron only in simple way	full synchrotron calculation

GALPROP (3)

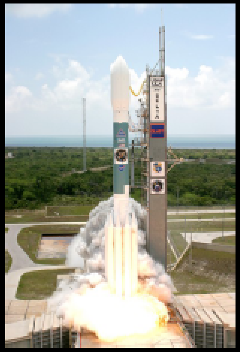
GALPROP

Public code (but new release slow in coming, sorry !)

Dedicated website *galprop.stanford.edu* for code and forum, ~90 registrations

Used in many papers / year

Adopted as standard model for Fermi, for both diffuse and source analysis



Need such a model to do justice to the quality of Fermi data

Other applications include contribution to Planck Galaxy model.

GALPROP (4)

How the propagation is computed:.

Linear equation, easy to solve.

2D or 3D grid, resolution down to 100 pc

$\Delta n = dn/dt\ \Delta t$ "

stabilized by Crank-Nicolson scheme

dn/dt = source terms + propagation terms

Δt = eg 1000 yrs

for steady-state, follow until $dn / dt=0$
(trick : start with large Δt and decrease Δt: finds steady-state fast)

or time-dependent solution if required eg for stochastic sources.

nuclei: start from ^{64}Ni and work down in (A, Z)
including secondary production
plus secondary positrons, electrons, pbar

primary electrons: separate species

DRAGON (1)

CR propagation with DRAGON

Luca Maccione (DESY)

in collaboration with (in alphabetical order)
G. Di Bernardo, C. Evoli, D. Gaggero, D. Grasso

Stockholm -- Mini-Workshop on DM searches -- 26.01.2010

DRAGON (2)

CR propagation

CRs obey essentially a diffusion equation (**Ginzburg & Syrovatsky, 1964**)

Diffusion tensor
$D(E) = D_0\,(\rho/\rho_0)^{\delta}$
$\rho = \text{rigidity} \sim p/Z$

Convection term

Energy loss

Reacceleration
$D_{pp} \propto \frac{p^2 v_A^2}{D}$

$$\frac{\partial N^i}{\partial t} - \nabla\cdot(D\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla\cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} =$$
$$= Q^i(p,r,z) + \sum_{j>i} c\beta n_{\mathrm{gas}}(r,z)\sigma_{ji}N^j - c\beta n_{\mathrm{gas}}\sigma_{\mathrm{in}}(E_k)N^i$$

SN source term.
We assume everywhere
a power law energy spectrum

Spallation cross section. Appearance of nucleus i due to spallation of nucleus j

Total inelastic cross section.
Disappearance of nucleus i

The height of the propagation/diffusion region is z_t $\quad D_0(z) \propto e^{z/z_t}$

Several approximations: stationary solution, smoothed source distribution... Turn out to be surprisingly good for hadronic cosmic rays.

DRAGON (3)

Equation solvers...

Several ways of solving the diffusion equation:

- **leaky-box models**: $D(E) \leftrightarrow \tau_{esc}(E)$
  Analytic and surprisingly meaningful solutions. Benchmark model!

- **semi-analytic models** assume simplified distributions for sources and gas, and try to solve the diffusion equation analytically (Maurin, Salati, Donato et al)
- **numerical models** (Galprop) try to use more realistic distributions

A new numerical model: DRAGON (Diffusion of cosmic RAys in the Galaxy modelizatiON)

Features (w.r.t. Galprop):
- same fragmentation cross sections
- position dependent, anisotropic diffusion
- boundary conditions in momentum and at R=0
- independent injection spectra for each nuclear species
- same results in same conditions
- faster (improved treatment of decays)
- interfaced with DarkSUSY
- only 2D
- not public (yet)

References:
C. Evoli et al. JCAP 0810 (2008) 018
G. Di Bernardo et al. arXiv:0909.4548
and works in preparation

Systematic uncertainties: production cross-sections

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

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

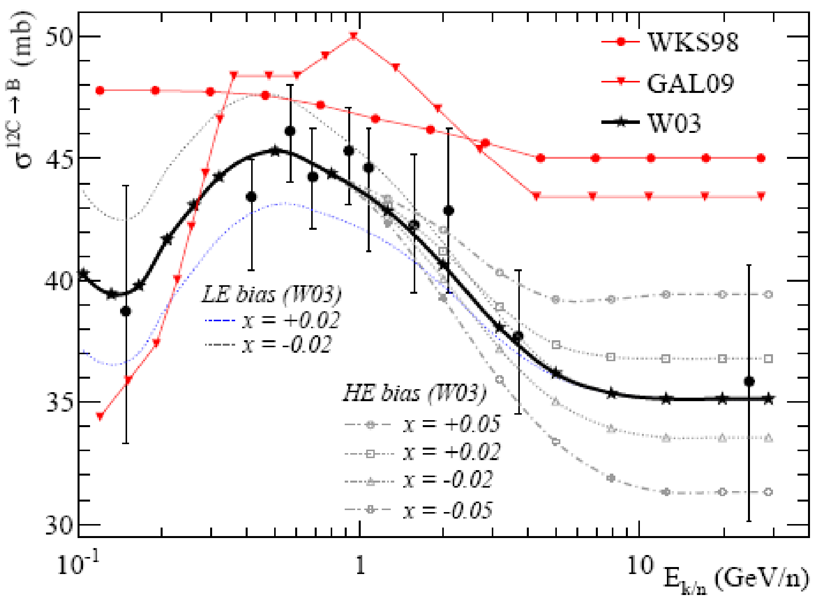
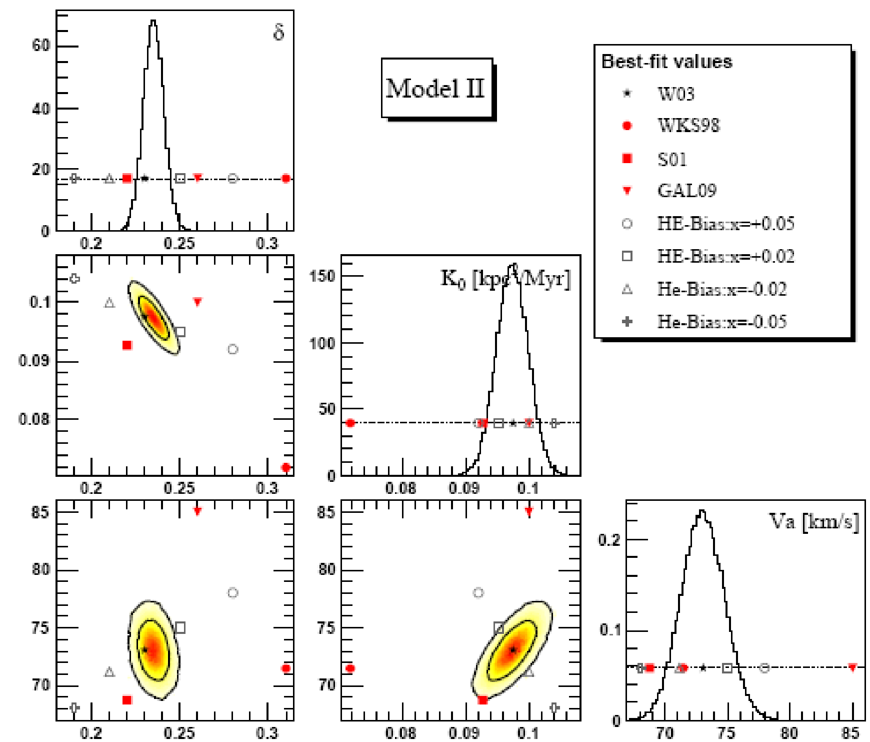


Fig. 3. Production cross-section for $^{12}C+H \to ^{10,11}B$ (adapted from Webber et al. 2003). The standard sets are shown as solid lines (WKS98: red dots; GAL09: red down triangles; W03: black stars), and the biased sets in dotted ($|x| = 0.02$) and dashed ($|x| = 0.05$) lines.



=> Systematics uncertainties > "statistical uncertainties" (fit from data)

USINE (1)

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

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)

USINE (2)

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Base package, C++/Root interface

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

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

See Antje Putze's talk

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

USINE (3)

We are working hard to go public (~April 2010)

- V1.0 public release
- Database (see Richard Taillet's talk)
- Website (simple model calculation online)

USINE-core (root-like documentation): D.M. (LPNHE)
Database: R. Taillet (LAPTh)
GUI: F. Barao (LIP)
MCMC: A. Putze (KTH), L. Derome (LPSC)

… and to improve it

e+/e-: T. Delahaye, F. Donato, J. Lavalle, R. Lineros, P. Salati
γ: in discussion...
More statistical tools: A. Putze & L. Derome
N'USINE (N'umerical USINE): B. Coste + others
Better Solar modulation: collaborations welcome...

+ to be thought as a toolbox to implement your own models

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~ Conclusions ~

1. Don't be fooled by any existing code (including USINE)

- They are phenomenological models
- What you get from depends on what you put in

=> You can often fit any data given enough ad hoc prescriptions

2. Always ask yourself: what do I need it for?

- Test a new model against standard parametrisation?
- Test your new data against standard models?
- Black-box analysis of some dark matter candidate?

=> DM analysis may be the most desired feature of propagation codes, but they are the most likely to be ill-estimated, if not plain wrong

3. Why should you use USINE?

- If you like ROOT, you'll feel comfortable with USINE
- Real C++: designed to be easy to adapt for your purpose (versatile)

=> As soon as public, your feedback and help will be welcome