Cosmic Ray (CR) Propagation

I. Early history: CRs and particle physics

II. Facts and questions

III. Models & parameters: phenomenology

IV. Background calculations (& limitations)

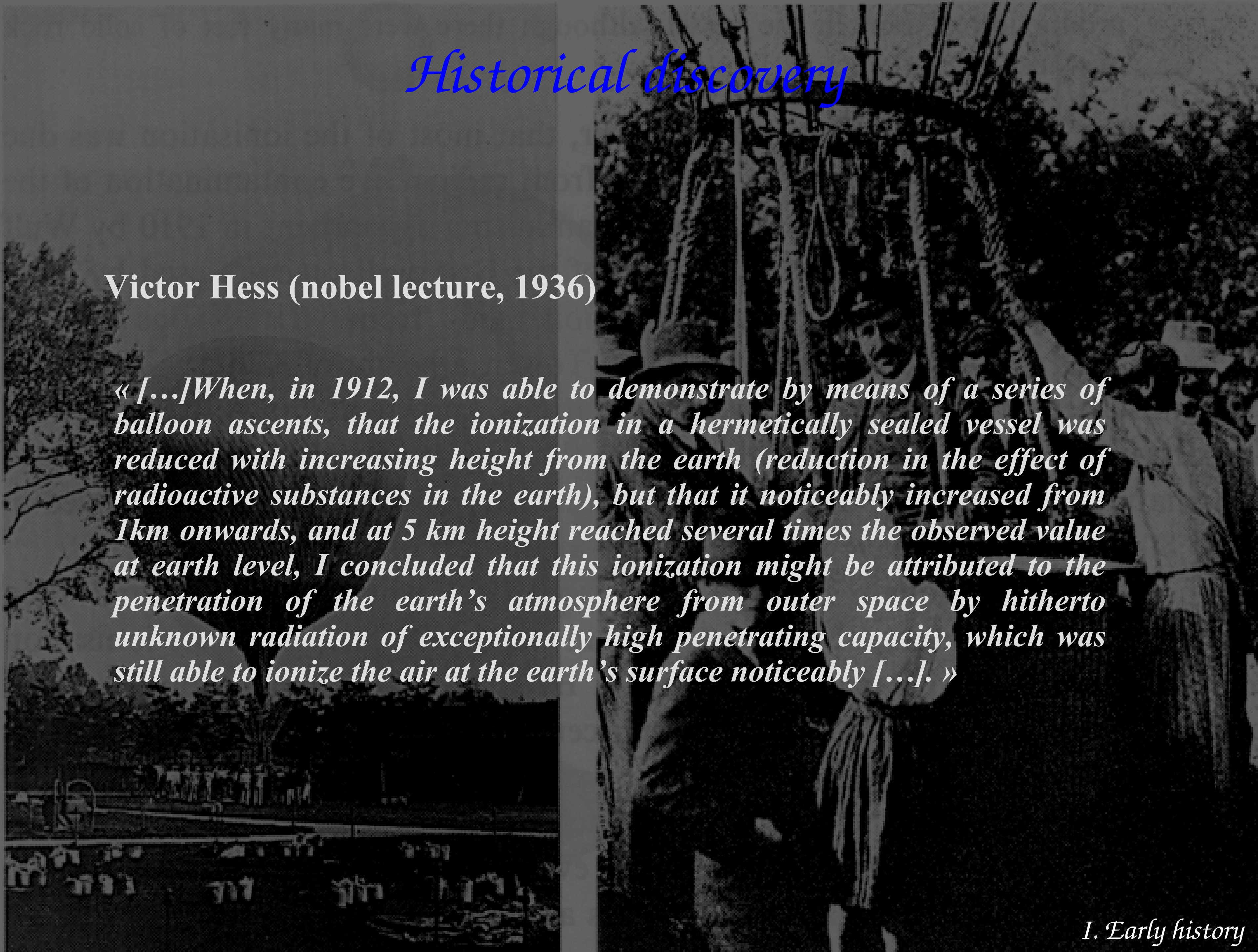
V. Systematics (parameters)

VI. Conclusions

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

CR background in DM searches
AlbaNova, 26/01/2010

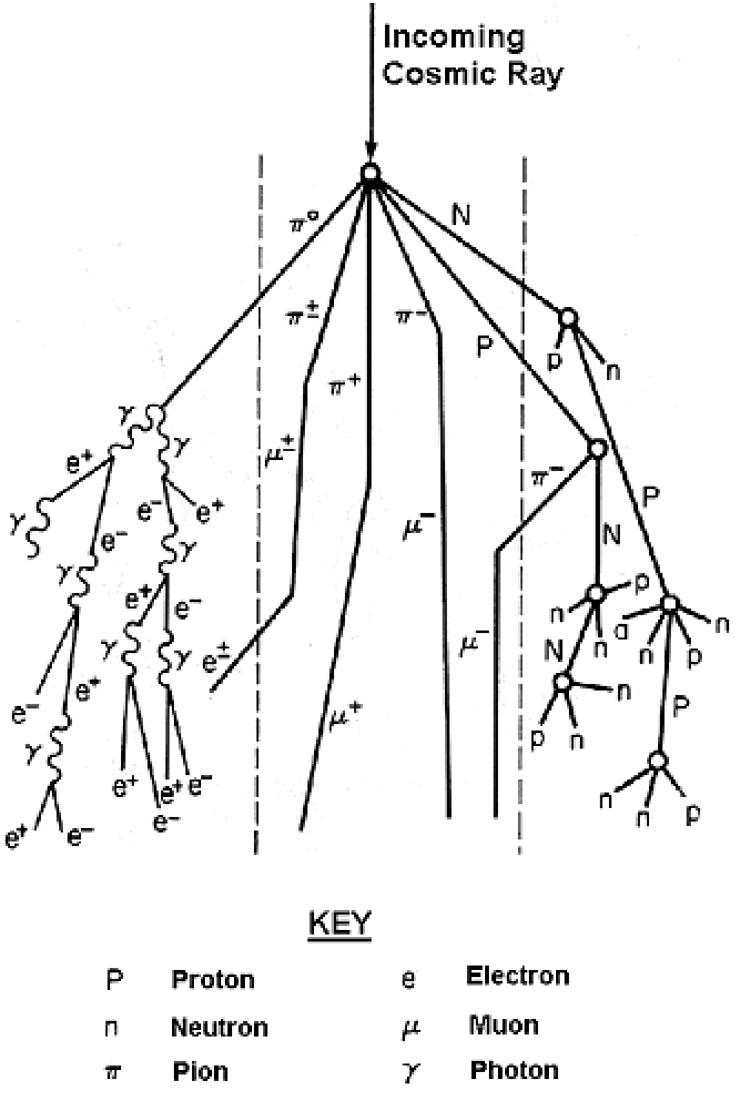
Historical discovery



Victor Hess (nobel lecture, 1936)

> ***« […]When, in 1912, I was able to demonstrate by means of a series of balloon ascents, that the ionization in a hermetically sealed vessel was reduced with increasing height from the earth (reduction in the effect of radioactive substances in the earth), but that it noticeably increased from 1km onwards, and at 5 km height reached several times the observed value at earth level, I concluded that this ionization might be attributed to the penetration of the earth's atmosphere from outer space by hitherto unknown radiation of exceptionally high penetrating capacity, which was still able to ionize the air at the earth's surface noticeably […]. »***

CRs through the Earth atmosphere: air showers

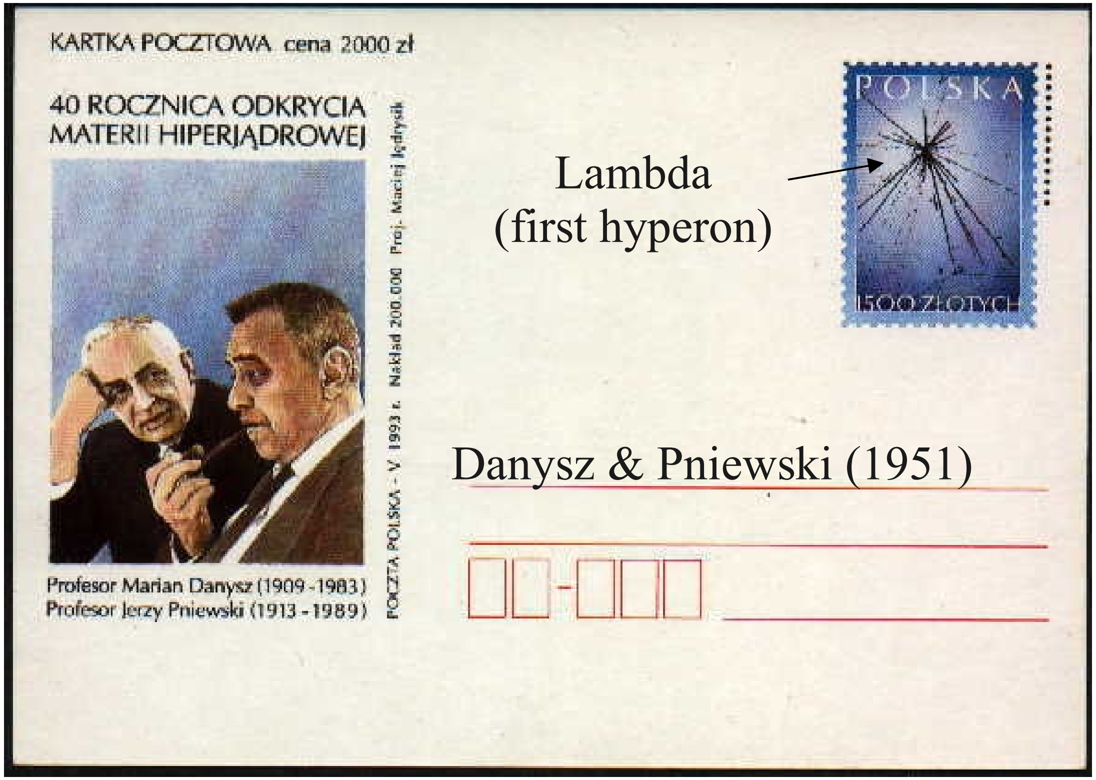


CRs through the Earth atmosphere: air showers

Discovery of new particles in CR showers:

- Positron: Anderson (1932)
- Muon: Anderson & Neddermeyer (1936)
- Pion: Powell (1947)
- Kaon [strange particle]: Rochester & Butler (1947)

and…



KARTKA POCZTOWA cena 2000 zł

40 ROCZNICA ODKRYCIA
MATERII HIPERJĄDROWEJ

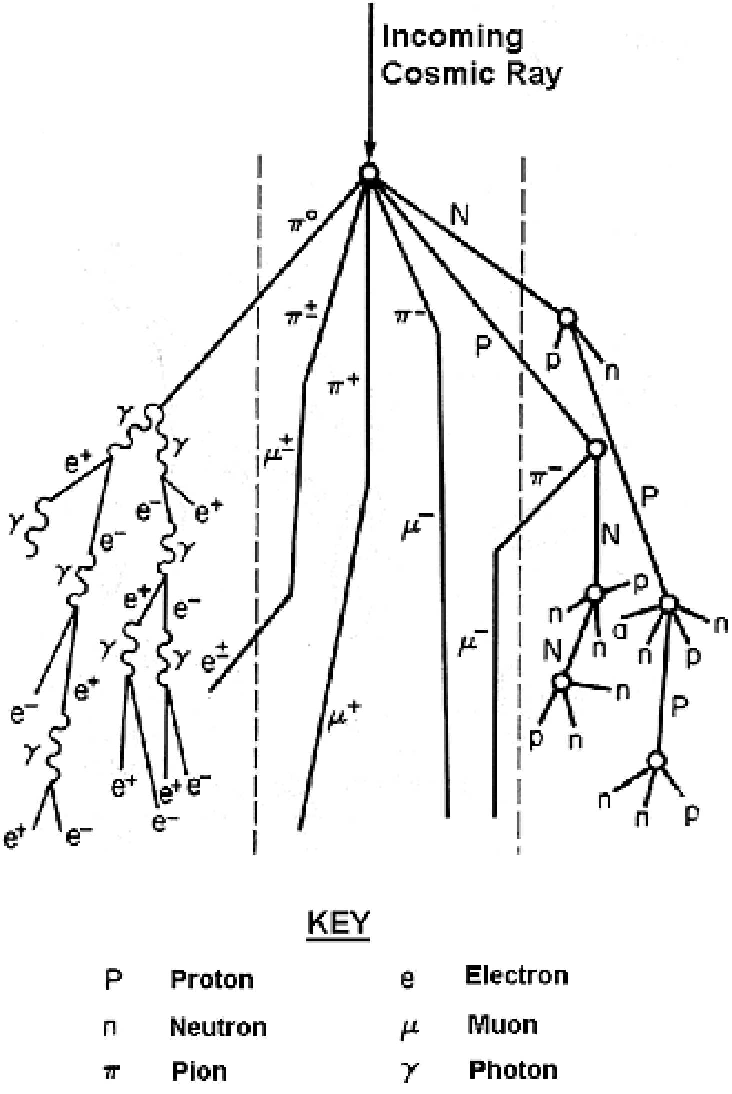
Profesor Marian Danysz (1909-1983)
Profesor Jerzy Pniewski (1913-1989)

POCZTA POLSKA - V 1993 r. Nakład 200.000 Proj. Marcin Jędrysik

POLSKA
1500 ZŁOTYCH

Lambda
(first hyperon)

Danysz & Pniewski (1951)



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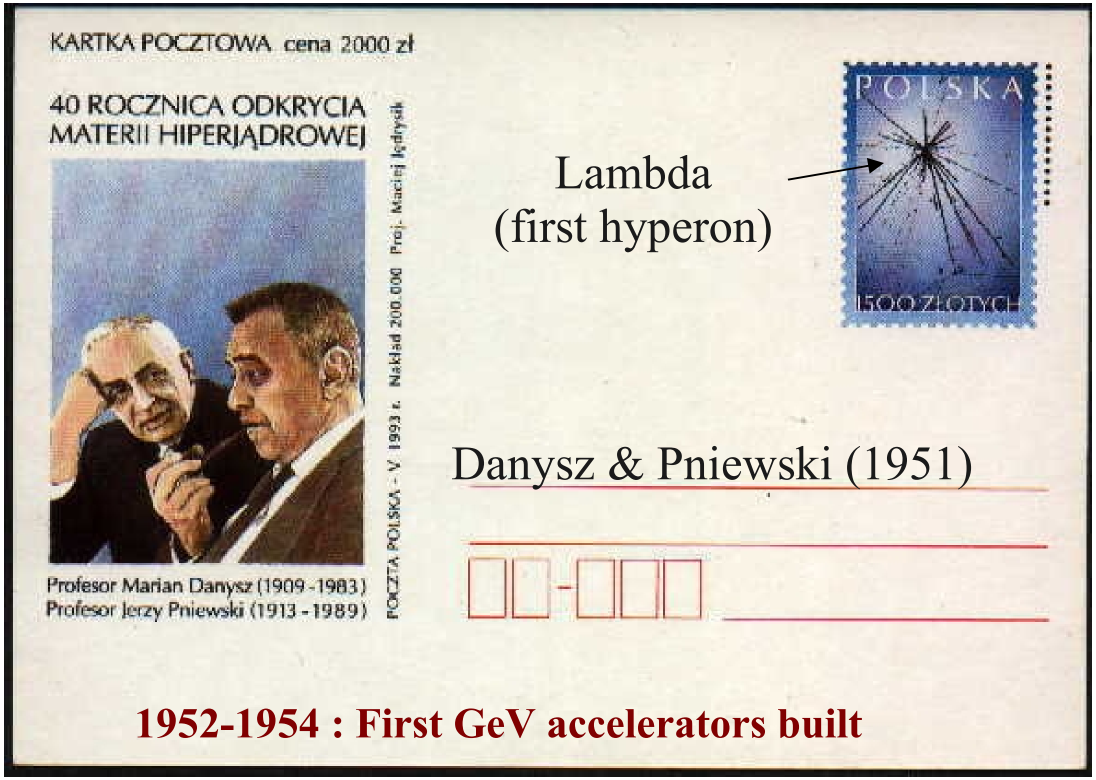

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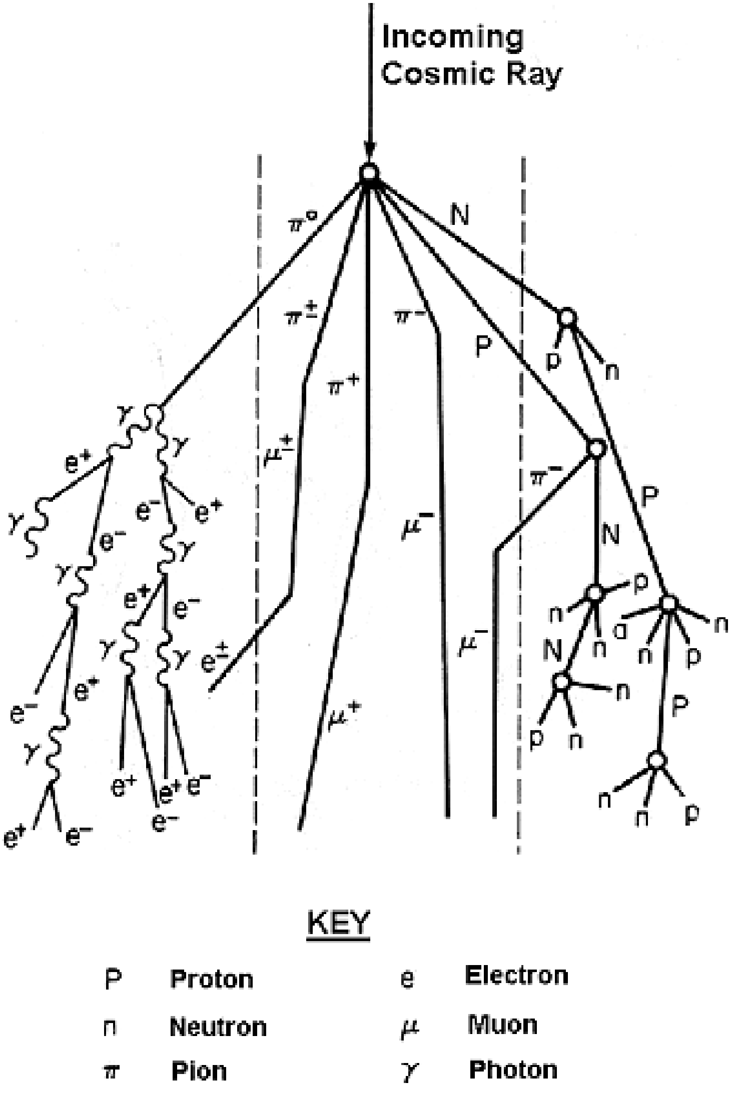
Danysz & Pniewski (1951)

1952-1954 : First GeV accelerators built



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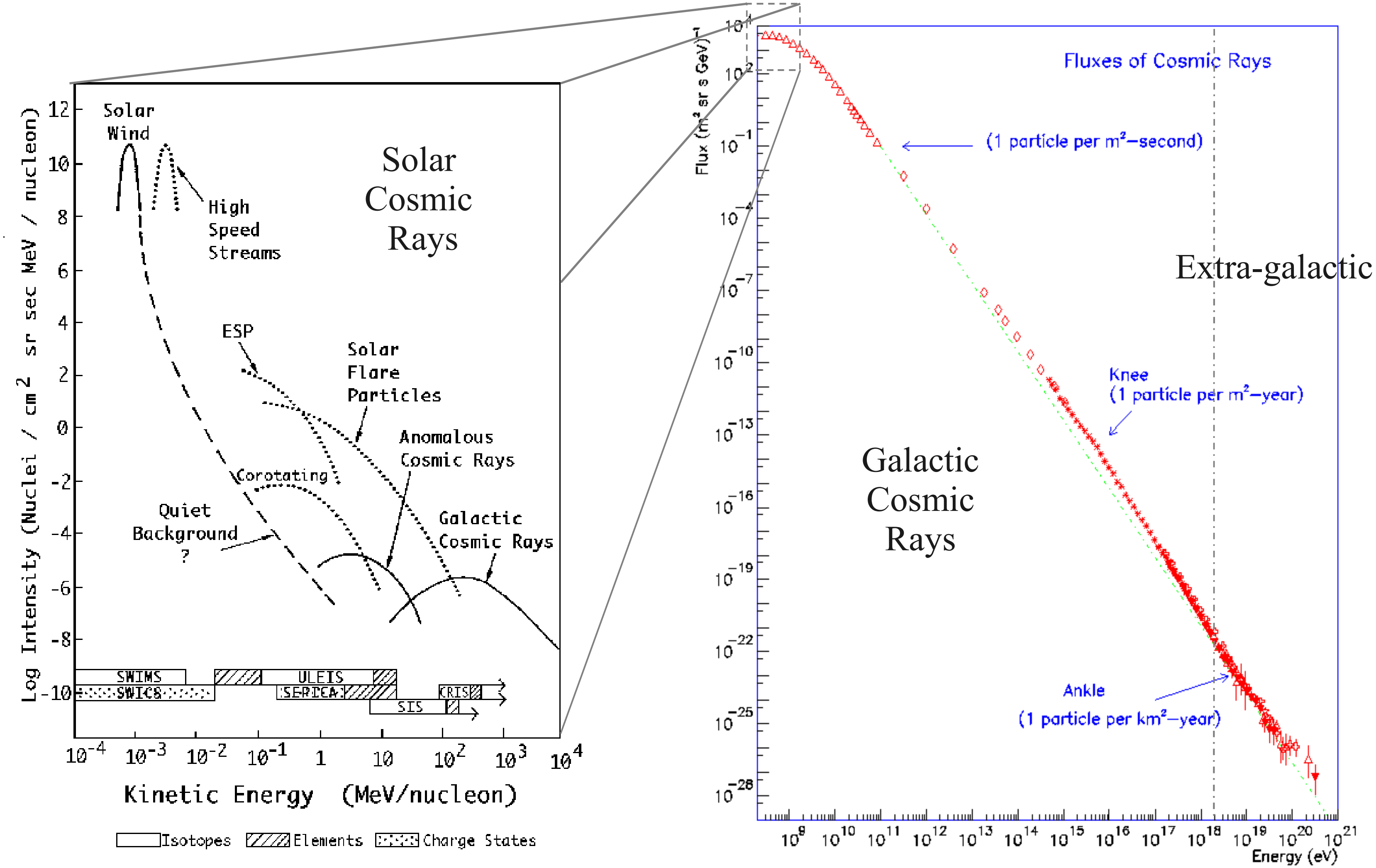
CR spectrum: from Solar to extragalactic origin

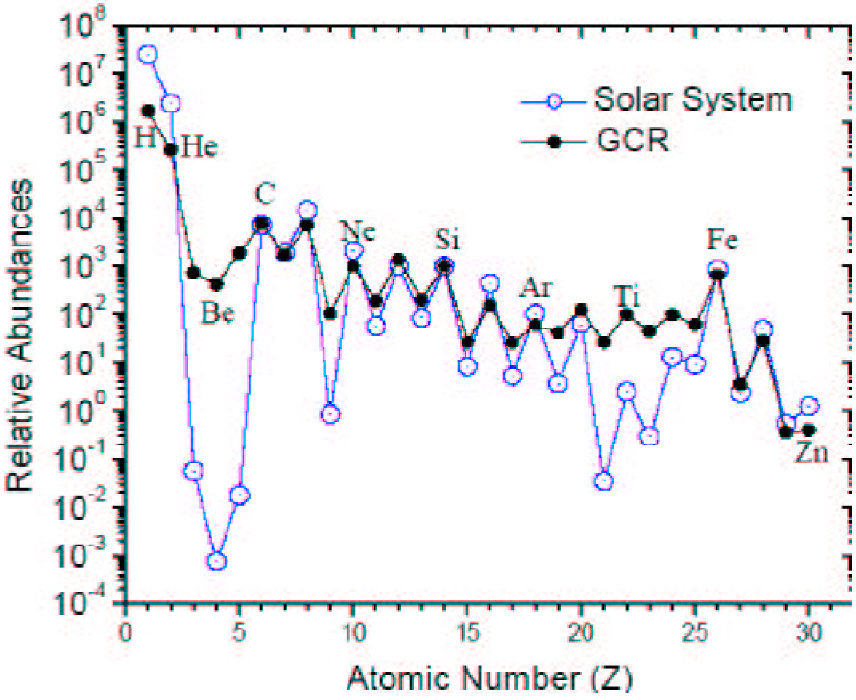


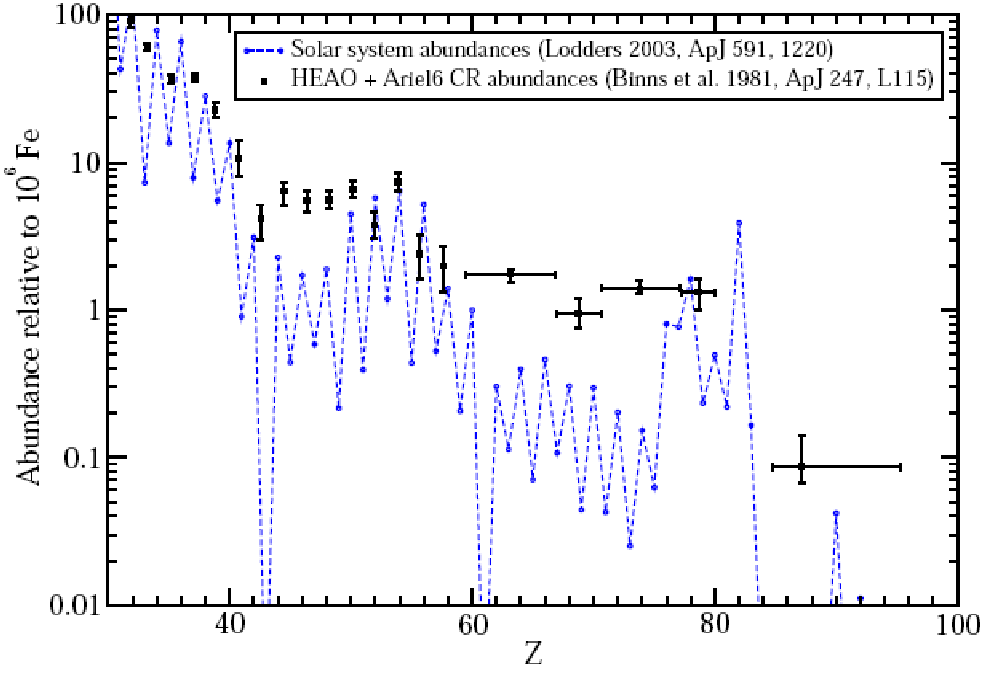
N.B.: Solar modulation of GCRs below GeV/amu energies

→ We focus on the GeV-TeV region: GCRs

Abundances: GCR vs Solar System

(secondary species to "calibrate" propagation)





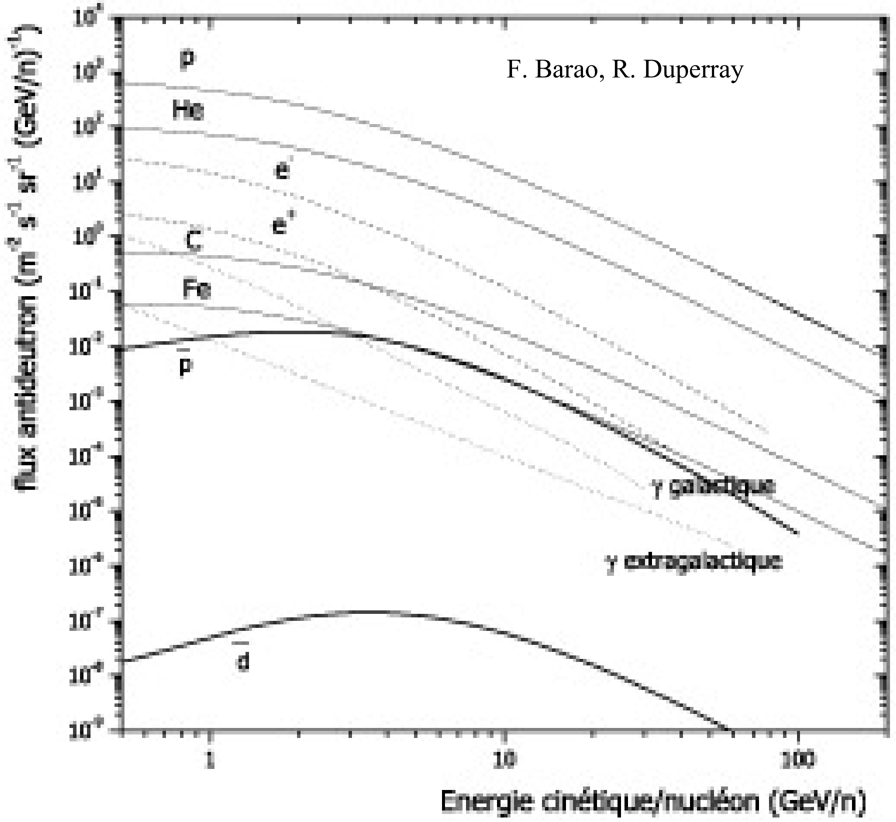
=> Primary species are present in sources (CNO, Fe)

- Stellar nucleosynthesis
- Acceleration in SN shocks ($\geq 10^4$ yr after nucleosynthesis, from radioactive primary Co/Ni)

=> Secondary species are absent of sources (LiBeB, SubFe)

- Produced during propagation of primaries (cross ~10 g cm^{-2} @ GeV/amu)
- Propagation timescale (confinement) ~ 10 Myr from ^{10}Be flux

Also γ, ν, antimatter…



GCR content

Nuclei: H, He, CNO, Fe…
- Light, heavy, VH and UH
- Stable, β and EC rad.

Electons *[e/p ~ 1% @ GeV]*

Matter

Anti-nuclei: pbar, dbar…
Positrons *[e^{+}/e^{-} ~ 10%]*

Anti-Matter

γ and ν

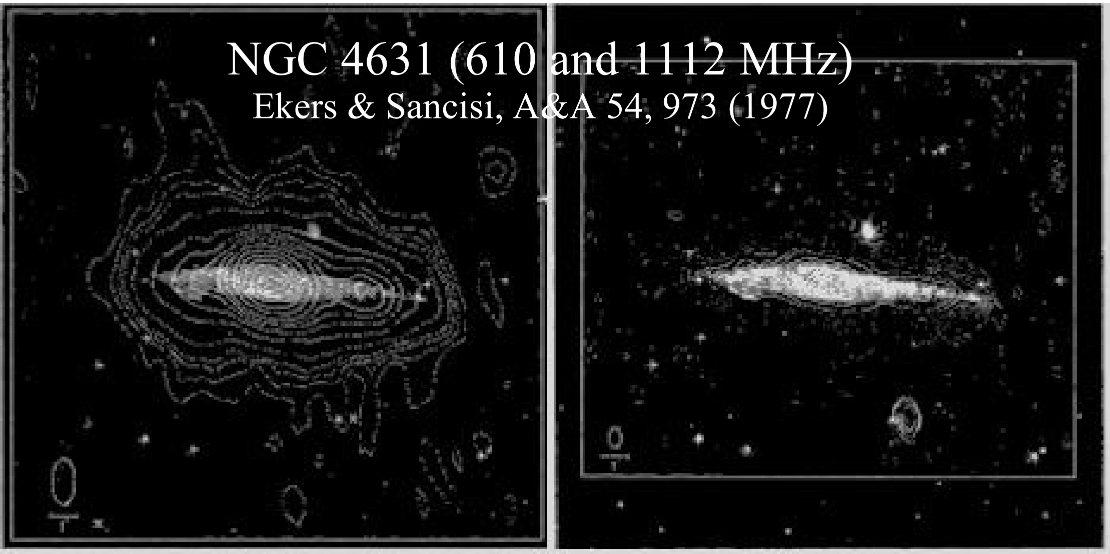
Neutral

N.B.: Information carried by neutral or charged particles is different!

=> gamma-rays are measured along a line of sight

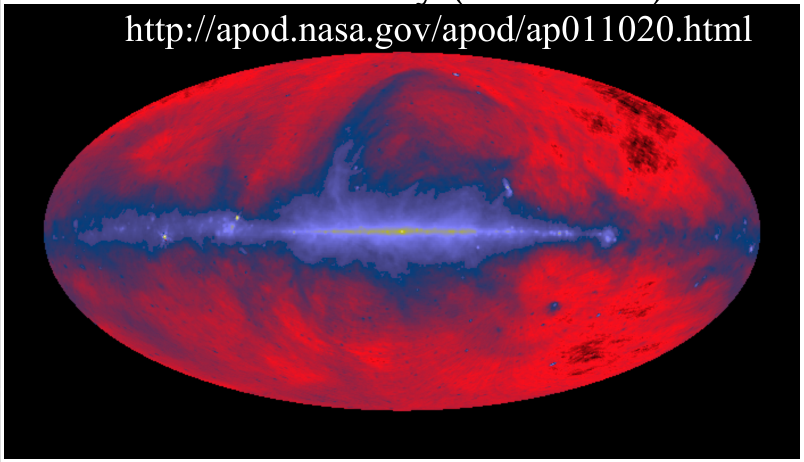
=> Charged particles diffuse: only a local measurement

Spatial distribution of GCRs



NGC 4631 (610 and 1112 MHz)
Ekers & Sancisi, A&A 54, 973 (1977)

Our Galaxy (408 MHz)



http://apod.nasa.gov/apod/ap011020.html

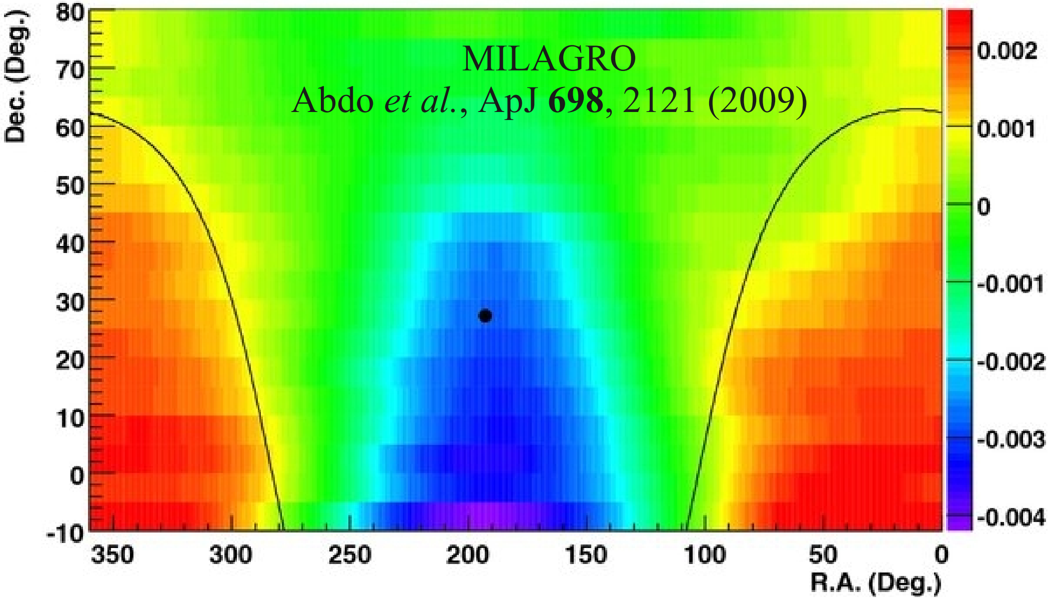
Cosmic radio waves are generated by high energy electrons spiralling along magnetic fields. In the Milky Way, many of the bright sources near the plane are distant pulsars, star forming regions, and SN remnants. The grand looping structures are pieces of bubbles blown by local stellar activity.

=> Proof that cosmic rays (at least electrons)
pervade a larger zone (~ few kpc) than the disc thickness

Anisotropy

Very low anisotropy (dipole estimate): ~ 0.1%

- Supports diffusive transport
- Prediction from B/C fits uncomfortably high [e.g. Jones et al., ApJ 547, 264 (2001)]
- Skymap anisotropy (MILAGRO, Tibet III...) + EAS-TOP: δ=0.74±0.42 [ApJ **692**,L130 (2009)]



MILAGRO
Abdo *et al.*, ApJ **698**, 2121 (2009)

Figure 7. Result of a harmonic fit to the fractional difference of the CR rates from isotropic in equatorial coordinates as viewed by Milagro for the years 2000–2007. The color bin width is 1.0×10^{-4} reflecting the average statistical error. The two black lines show the position of the Galactic equator and the solid circle shows the position of the Galactic north pole. This map is constructed by combining 18 individual profiles of the anisotropy projection in R.A. of width 5° in decl. It is not a two-dimensional map of the sky. The median energy of the events in this map is 6 TeV.

Dipole anisotropy
(Compton-Getting effect)?

- Earth's motion (~10^{-4})
- Solar system's motion?
- Heliosphere?

...or preferential diffusion
along regular B ?
[Battaner *et al.*, ApJ **703**, L90 (2009)]

=> Multi-E anisotropy
skymaps are another
powerful tracer...

Open questions

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?

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

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)

~ *Milestones* ~

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? 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 (1st order Fermi) in agreement with observations

2000 Non-linear magnetic field amplification in diffusive shocks (*à la* Bell & Lucek)

Transport

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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?

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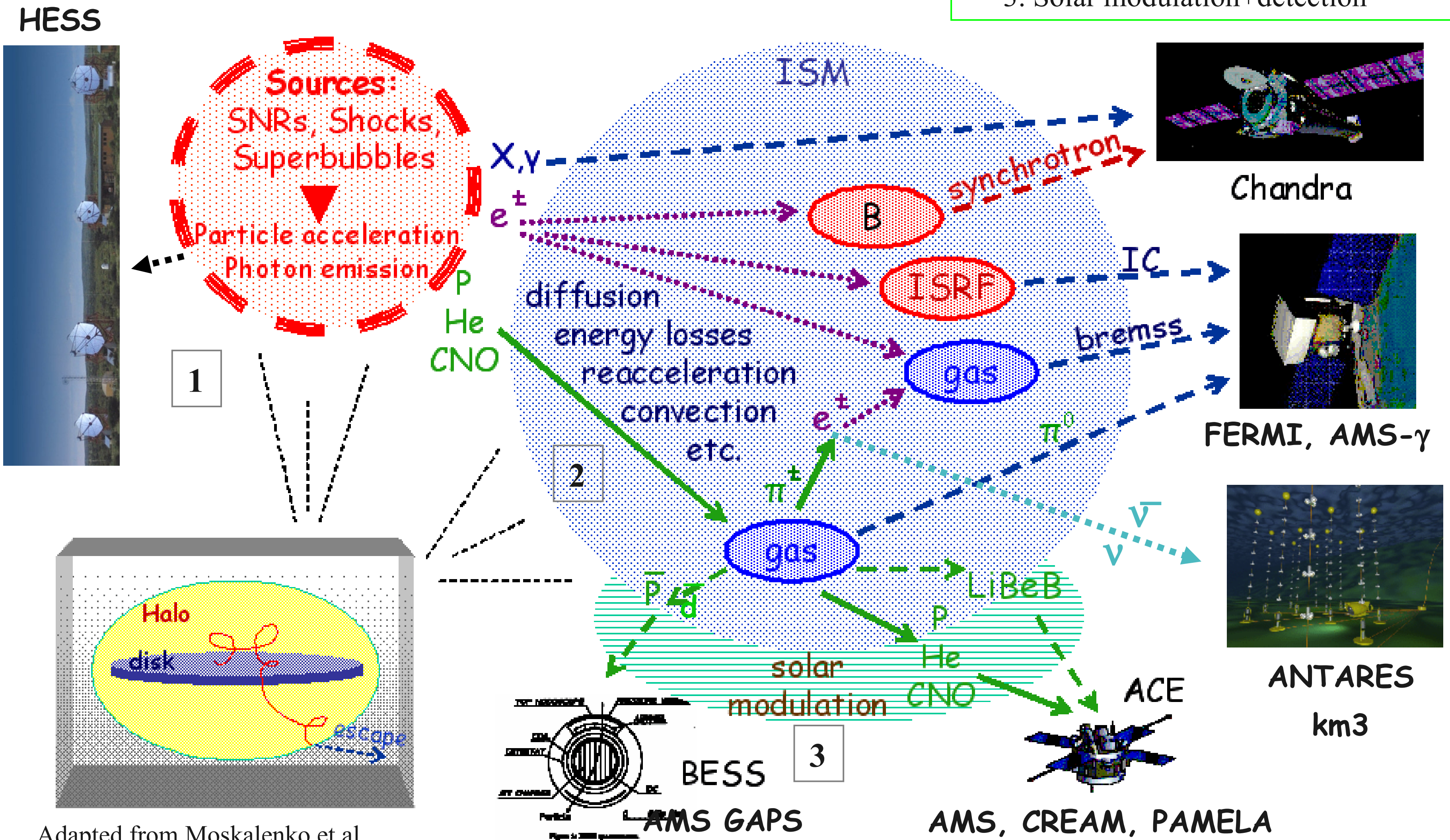
Requirement: consistent description of all fluxes (electrons, nuclei and gamma)

Cosmic Ray journey in 3 steps:

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



Adapted from Moskalenko et al. (2004)

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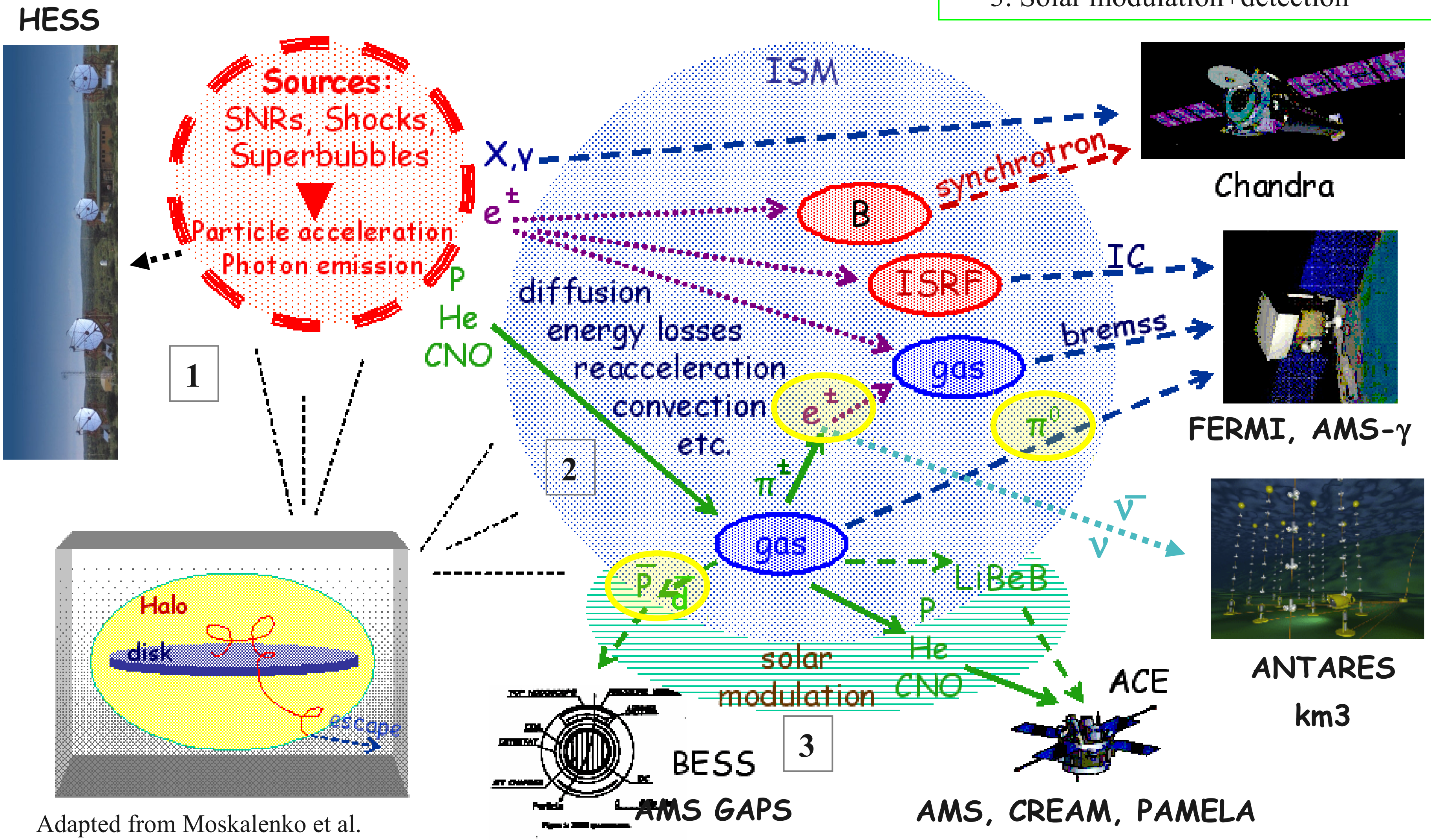

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=> Search for DM where "standard" production is rare (secondary)

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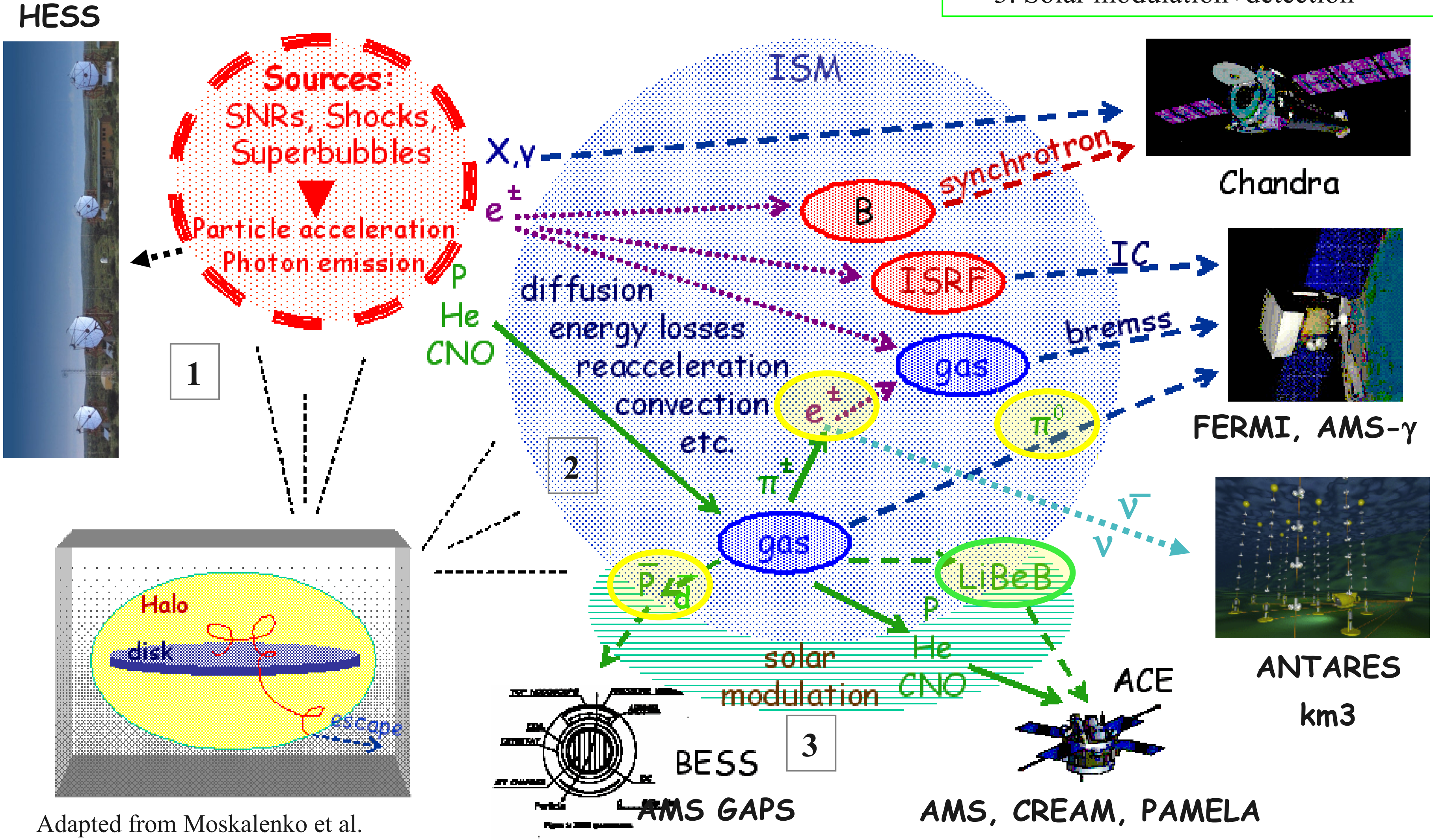


Adapted from Moskalenko et al. (2004)

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

=> Use LiBeB to calibrate the transport coefficients

Basics on transport: equation

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

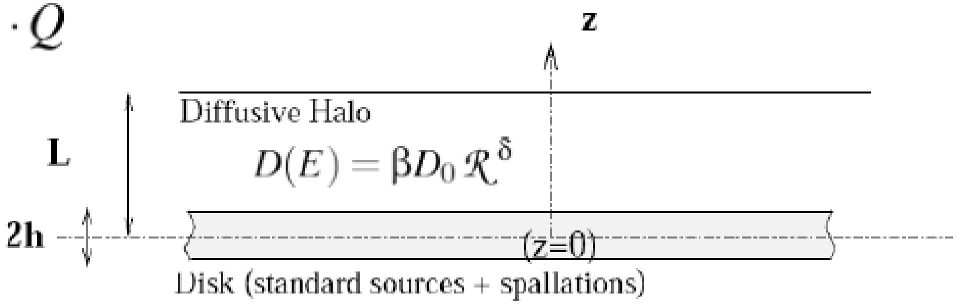
Basics on transport: simplifying assumptions

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

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

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

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



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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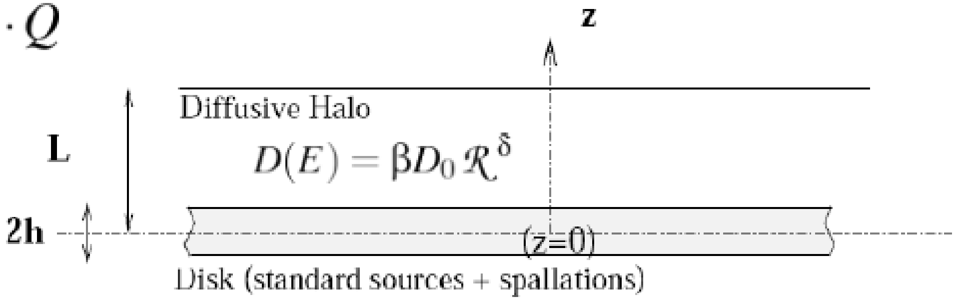

$$\text{LB equation}: \quad \frac{N}{\tau_{\mathrm{esc}}} + \bar{n}v\sigma N = Q$$

=> Link between LBM and diffusion models

Degeneracy: Models with the same *D₀/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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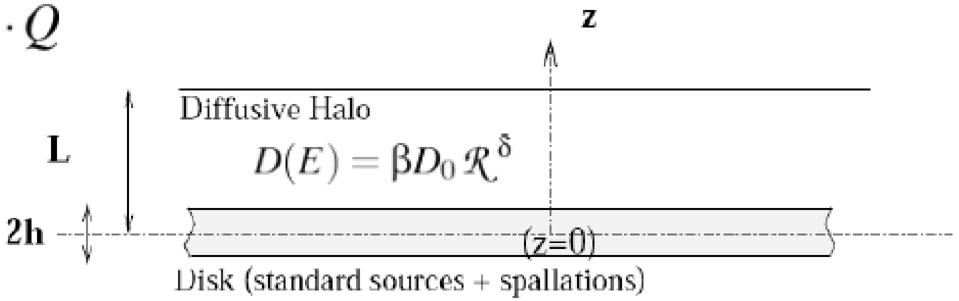


LB equation : $\dfrac{N}{\tau_{esc}} + \bar{n}v\sigma N = Q$ => Link between LBM and diffusion models

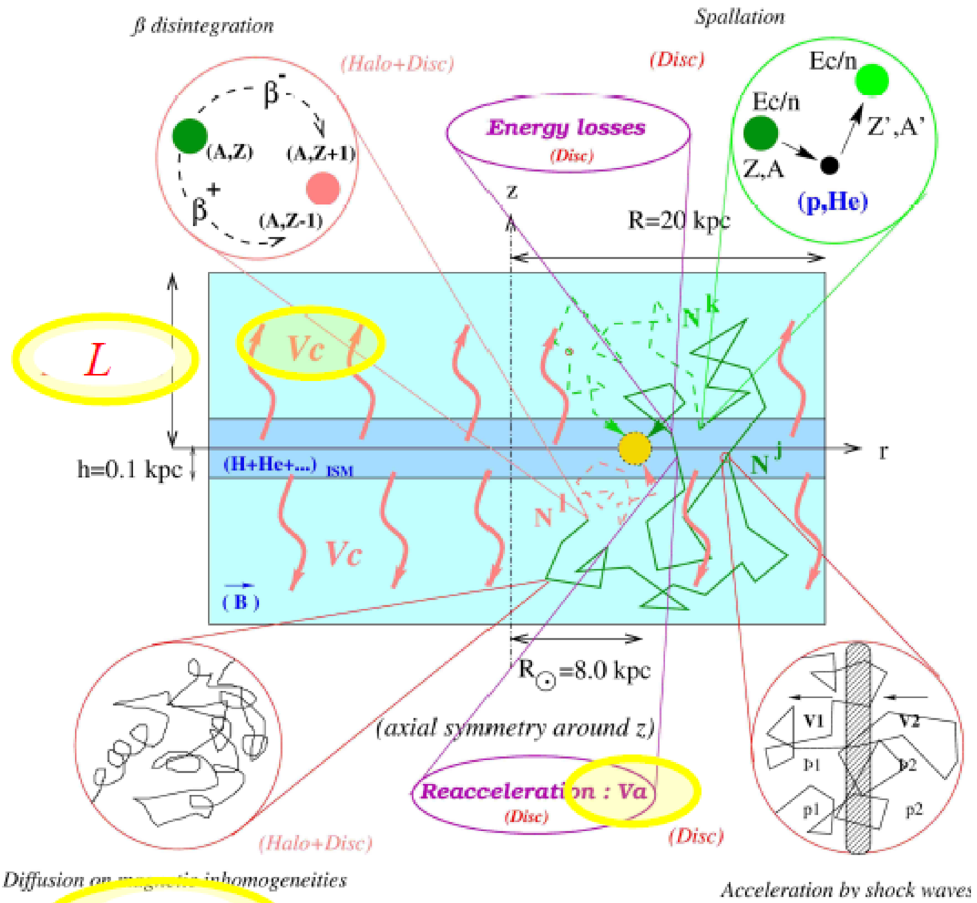
Degeneracy: Models with the same D_0/L are equivalent (secondary-to-primary production)
=> referred to as *"the degeneracy"* in the following

Simple case: secondary-to-primary ratio

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

A two-zone diffusion model (1D or 2D)

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



$D=\beta D_0 R^{\delta}$

$Q(E) \propto R^{-\alpha}$

➔ **Analytical or numerical solution**

i) Simplified geometry (cylindrical symmetry)
- Gas distribution (thin disk)
- Source distribution (thin disk)
- Diffusive halo (L)

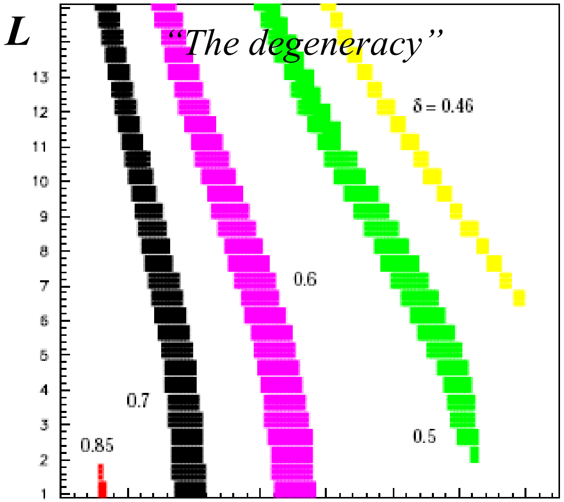
ii) Steady-state sources
- Spectrum
- Isotopic abundances

iii) Transport coef. (independent of position)
- Diffusion/convection
- Coulomb./Ion./Adiab. losses + reacc.

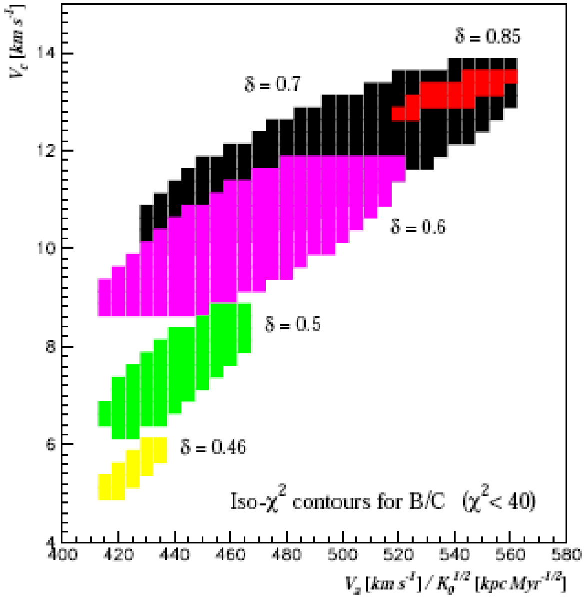
=> B/C constrains transport parameters (L, D_0, δ, V_c and V_a)

Allowed range for the propagation parameters

Degeneracies



Maurin *et al.*, Apj **555**, 585 (2001)



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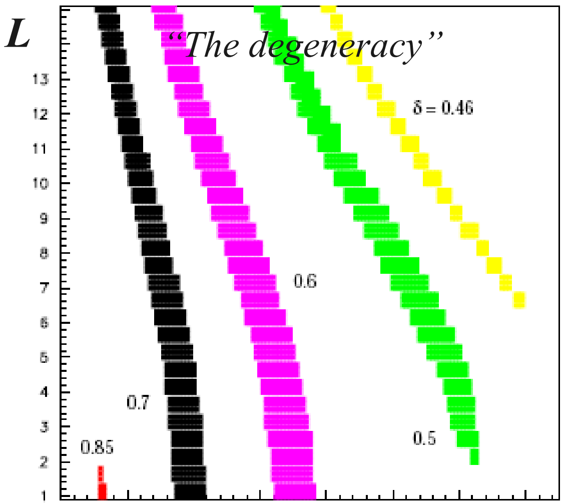
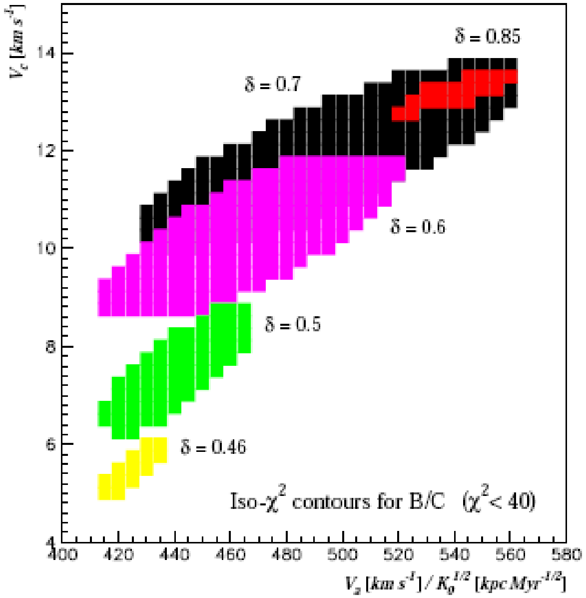
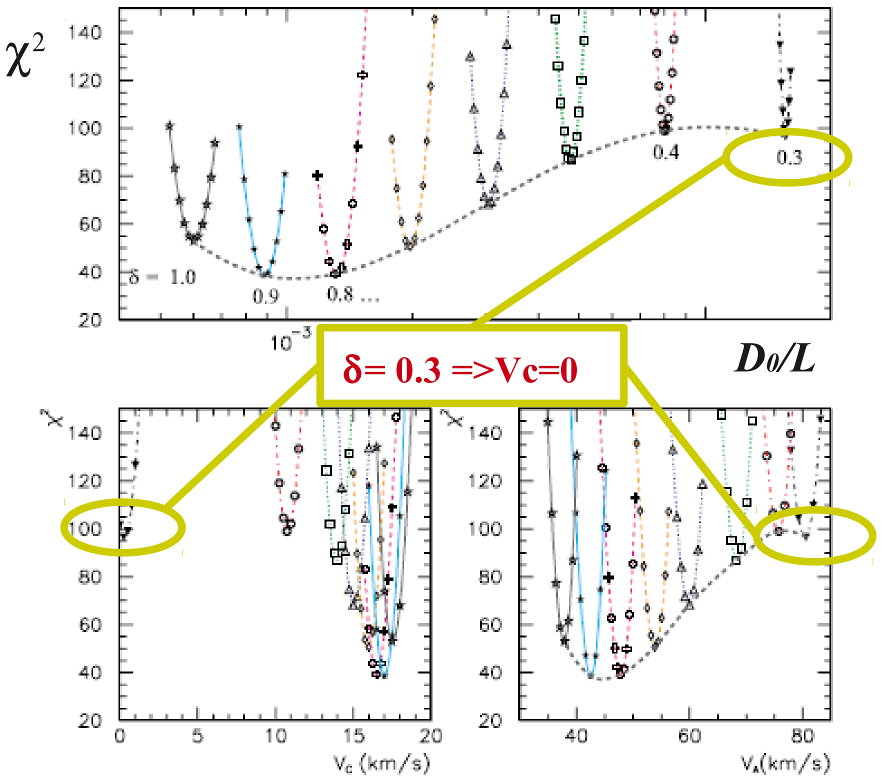


Maurin *et al.*, Apj **555**, 585 (2001) ***D₀/L***



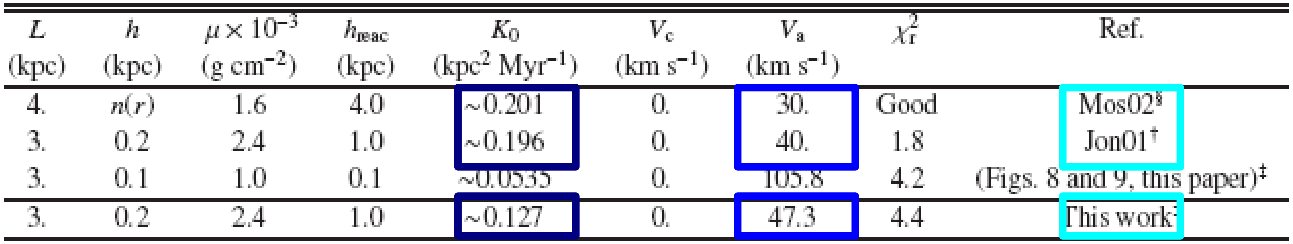
Best-fit diffusion slope δ



δ= 0.3 =>Vc=0

Maurin *et al.*, A&A **394**, 1039 (2002)

Comparison of models for δ=0.3 and L~3-4 kpc



L (kpc)	h (kpc)	$\mu\times10^{-3}$ (g cm^{-2})	$h_{\rm reac}$ (kpc)	K_0 (kpc^2 Myr^{-1})	V_c (km s^{-1})	V_a (km s^{-1})	χ^2_r	Ref.
4.	$n(r)$	1.6	4.0	~0.201	0.	30.	Good	Mos02§
3.	0.2	2.4	1.0	~0.196	0.	40.	1.8	Jon01†
3.	0.1	1.0	0.1	~0.0535	0.	105.8	4.2	(Figs. 8 and 9, this paper)‡
3.	0.2	2.4	1.0	~0.127	0.	47.3	4.4	This work

=> All models consistent

=> δ =0.3 (local minimum) excluded

Basics on transport: convection

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

Effect of convection (low energy only)

Jones, ApJ 222, 1097 (1978)

For a particle to reach z and diffuse back: $t_D \approx z^2/D$

In the same time, convection: $t_C = z/V_C$

A particle at z can come back to the disk, if $t_C < t_D \Rightarrow z_{\max} \equiv L^* = D/V_C$

Transport: LE radioactive nuclei & HE leptons

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Local origin for some species

N.B: Leaky Box not to be used for these species!

$l_{\max} \sim \sqrt{Dt}$ => limited distance travelled in a finite time

Radioactive nuclei: $t_{\mathrm{rad}} = \gamma \cdot \tau_0 = \gamma \cdot \ln 2 \cdot t_{1/2}$

$\text{Below GeV/n energy}: D \sim 10^{28}\ \mathrm{cm}^2\ \mathrm{s}^{-1}, t^{^{10}\mathrm{Be}} = 1.51\ \mathrm{Myr} \Rightarrow l_{\mathrm{rad}} \sim 100\ \mathrm{pc}$

Only sensitive to *D* => breaks the *D₀/L* degeneracy!

Leptons: $t_{\mathrm{loss}} \sim 300\ \mathrm{Myr} \cdot (1\ \mathrm{GeV})/E$ Above 10 GeV, $d_{e^+,e^-} \sim 1\ \mathrm{kpc}$

Basics on transport: probing various time/space scales

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

Effect of convection (low energy only)

Jones, ApJ 222, 1097 (1978)

For a particle to reach z and diffuse back: $t_D \approx z^2/D$

In the same time, convection: $t_C = z/V_C$

A particle at z can come back to the disk, if $t_C < t_D \;\Rightarrow\; z_{\max} \equiv L^* = D/V_C$

Local origin for some species

N.B: Leaky Box not to be used for these species!

$l_{\max} \sim \sqrt{Dt}$ => limited distance travelled in a finite time

Radioactive nuclei: $t_{\rm rad} = \gamma \cdot \tau_0 = \gamma \cdot \ln 2 \cdot t_{1/2}$

$$\text{Below GeV/n energy} : D \sim 10^{28}\ \text{cm}^2\ \text{s}^{-1}, t^{^{10}\text{Be}} = 1.51\ \text{Myr} \;\Rightarrow\; l_{\rm rad} \sim 100\ \text{pc}$$

Only sensitive to *D* => breaks the D_0/L degeneracy!

Leptons: $t_{\rm loss} \sim 300\ \text{Myr} \cdot (1\ \text{GeV})/E$ Above 10 GeV, $d_{e^+,e^-} \sim 1$ kpc

Keep in mind: different species, different processes, different space/timescales probed

I. Early history: CRs and particle physics

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IV. Background calculations (& limitations)

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Benefit of 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:

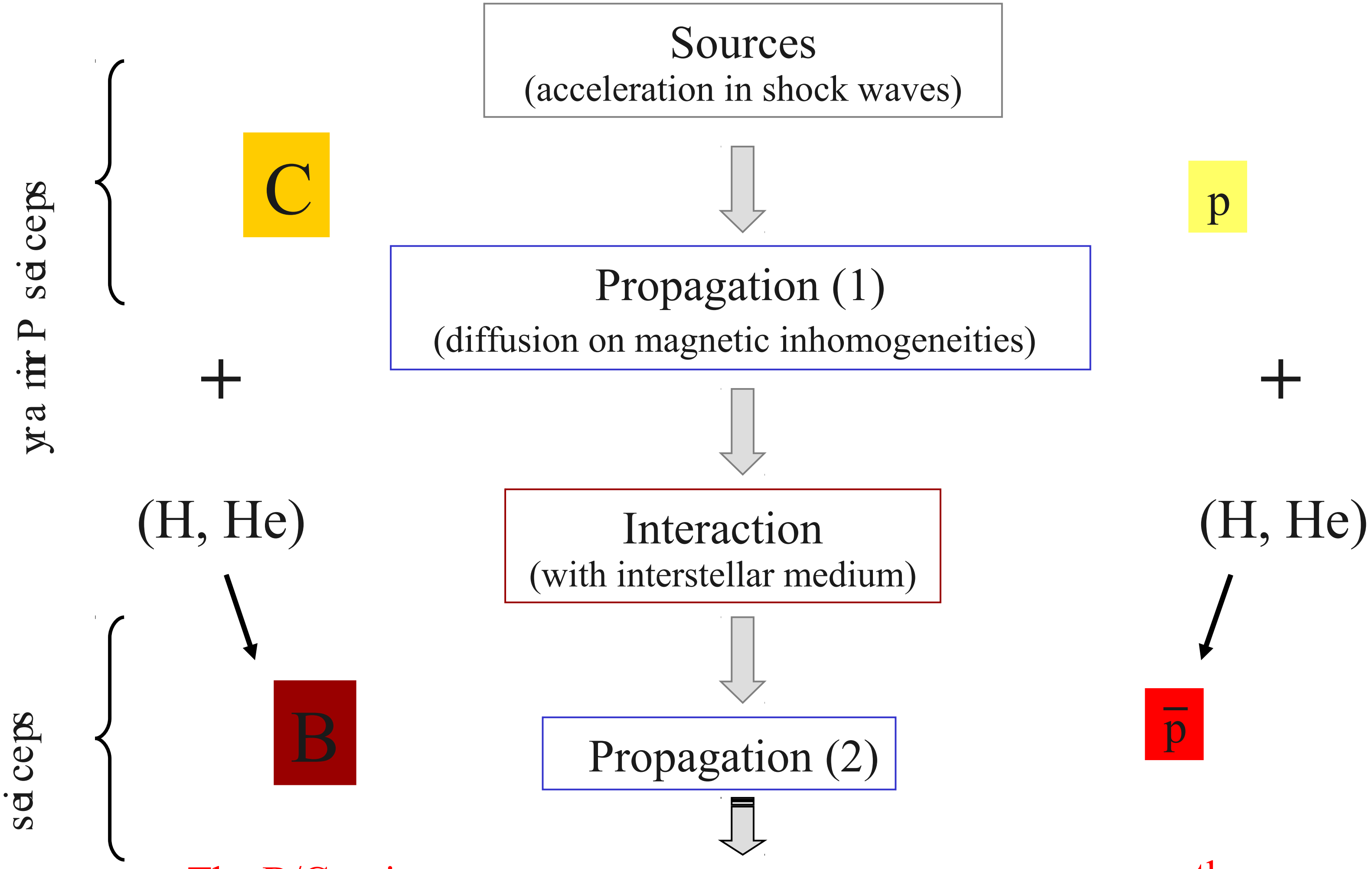
- Uncertainties on the propagation parameters
- Uncertainties on any quantity derived from these parameters

=> 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

Parameters for the background calculation: principle



Primary species

C

\+

(H, He)

Secondary species

B

The B/C ratio characterises propagation

Sources

(acceleration in shock waves)

Propagation (1)

(diffusion on magnetic inhomogeneities)

Interaction

(with interstellar medium)

Propagation (2)

Detection on Earth…

p

\+

(H, He)

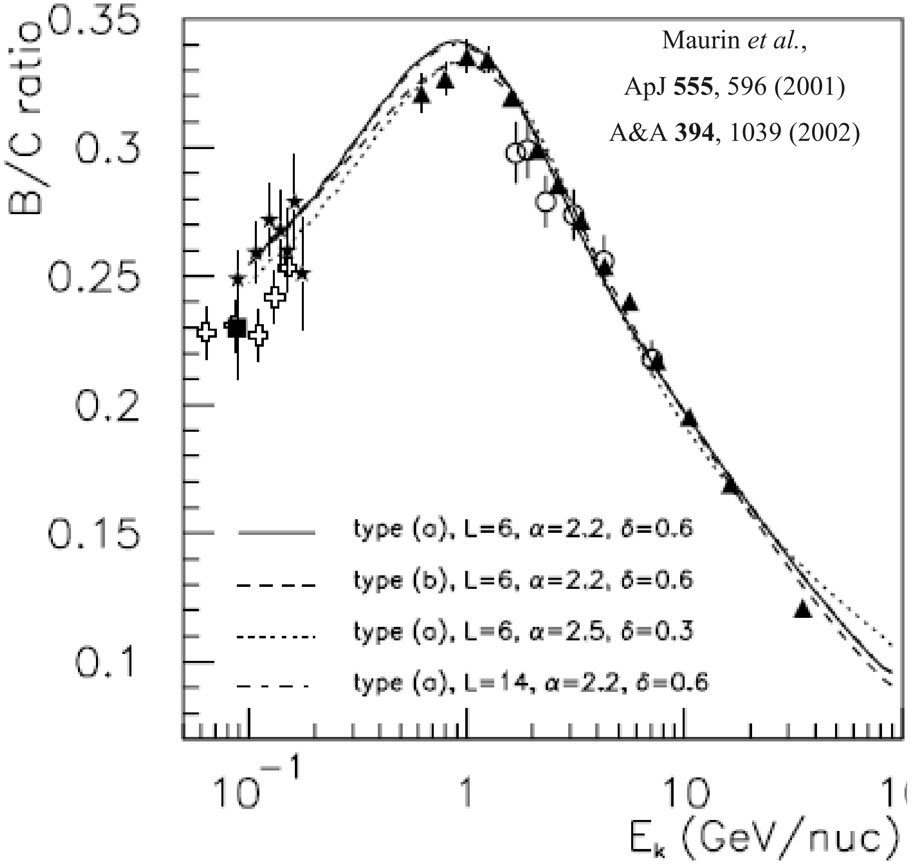
$\bar{p}$

can thus be evaluated…

=> Same propagation history

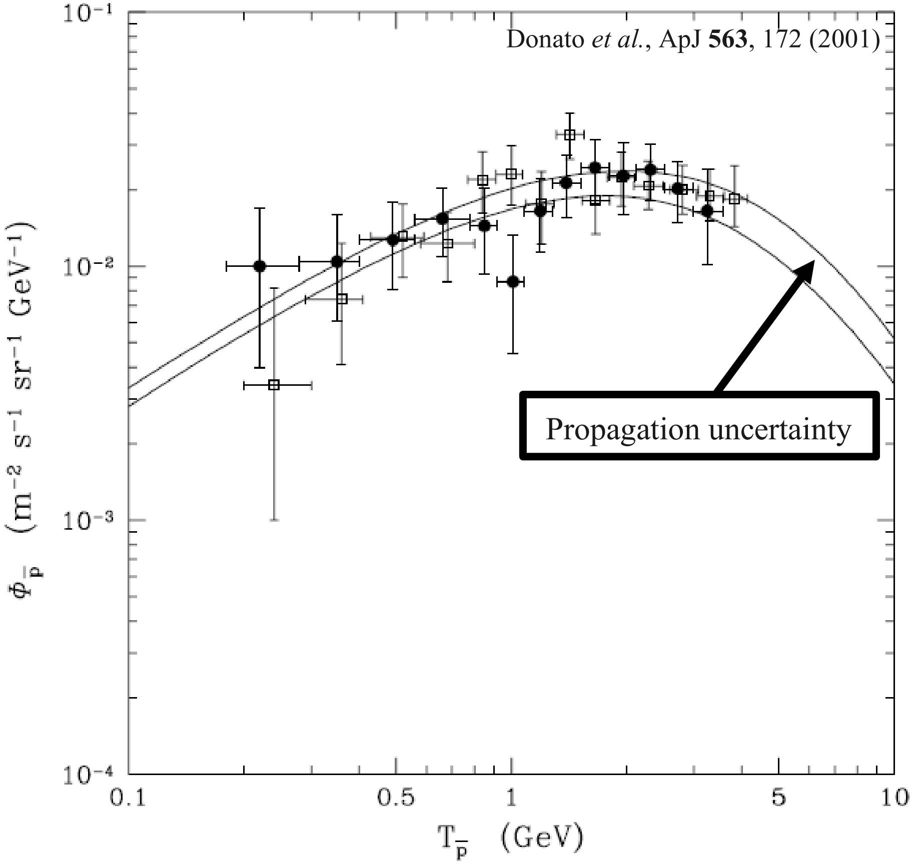
Antiproton "standard" flux

Propagation parameters
adjusted to fit the data



Maurin *et al.*,
ApJ **555**, 596 (2001)
A&A **394**, 1039 (2002)

=> no free parameters!!!



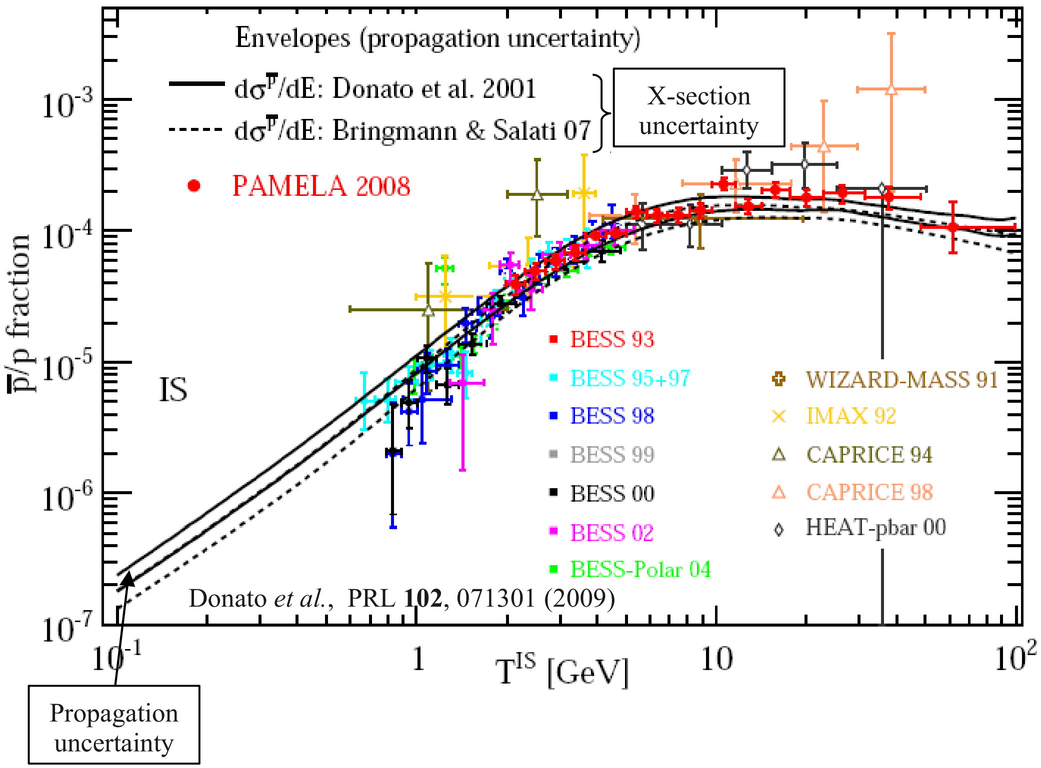
Donato *et al.*, ApJ **563**, 172 (2001)

Propagation uncertainty

=> Excellent agreement
=> Small astrophysical uncertainty on the antiproton background

Antiproton and antideuteron flux

Antiproton/proton



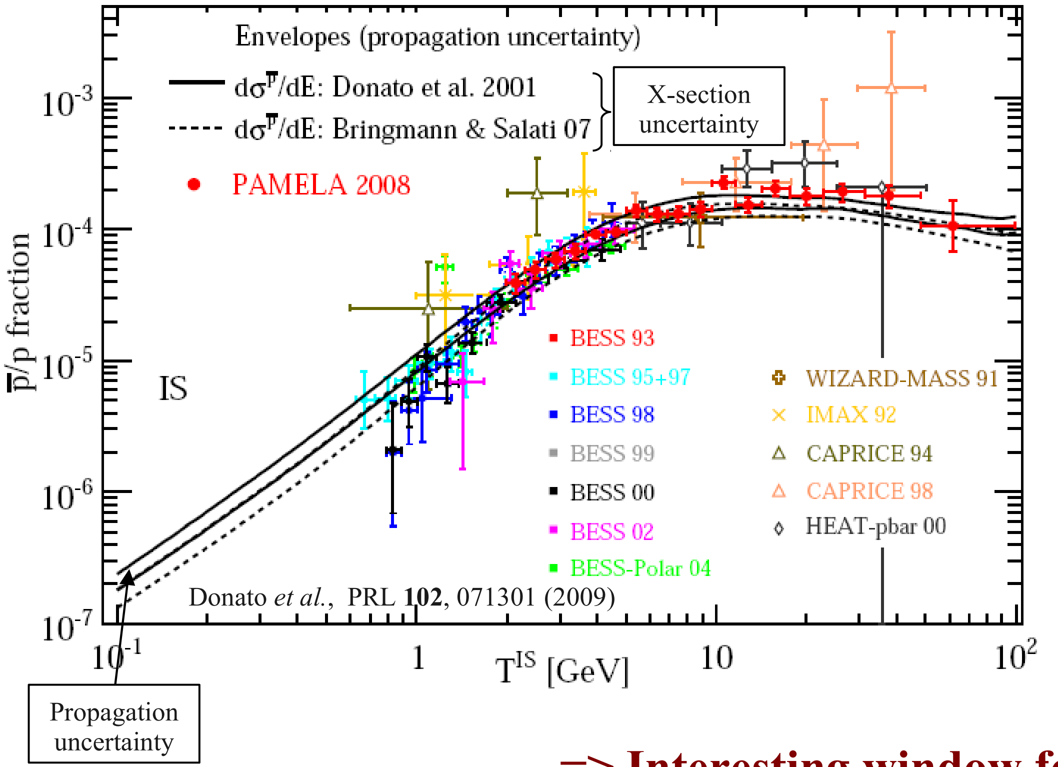
=> Recent PAMELA data consistent with pure background

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

See Fiorenza Donato's talk

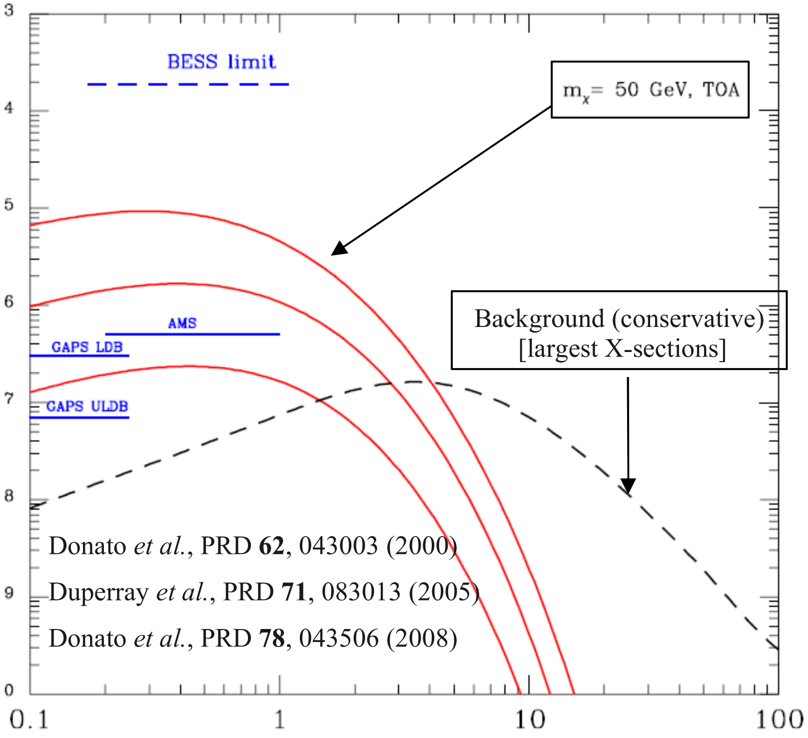
Antiproton and antideuteron flux

Antiproton/proton



Donato *et al.*, PRL **102**, 071301 (2009)

Antideuterons



Donato *et al.*, PRD **62**, 043003 (2000)

Duperray *et al.*, PRD **71**, 083013 (2005)

Donato *et al.*, PRD **78**, 043506 (2008)

=> Interesting window for antideuterons

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

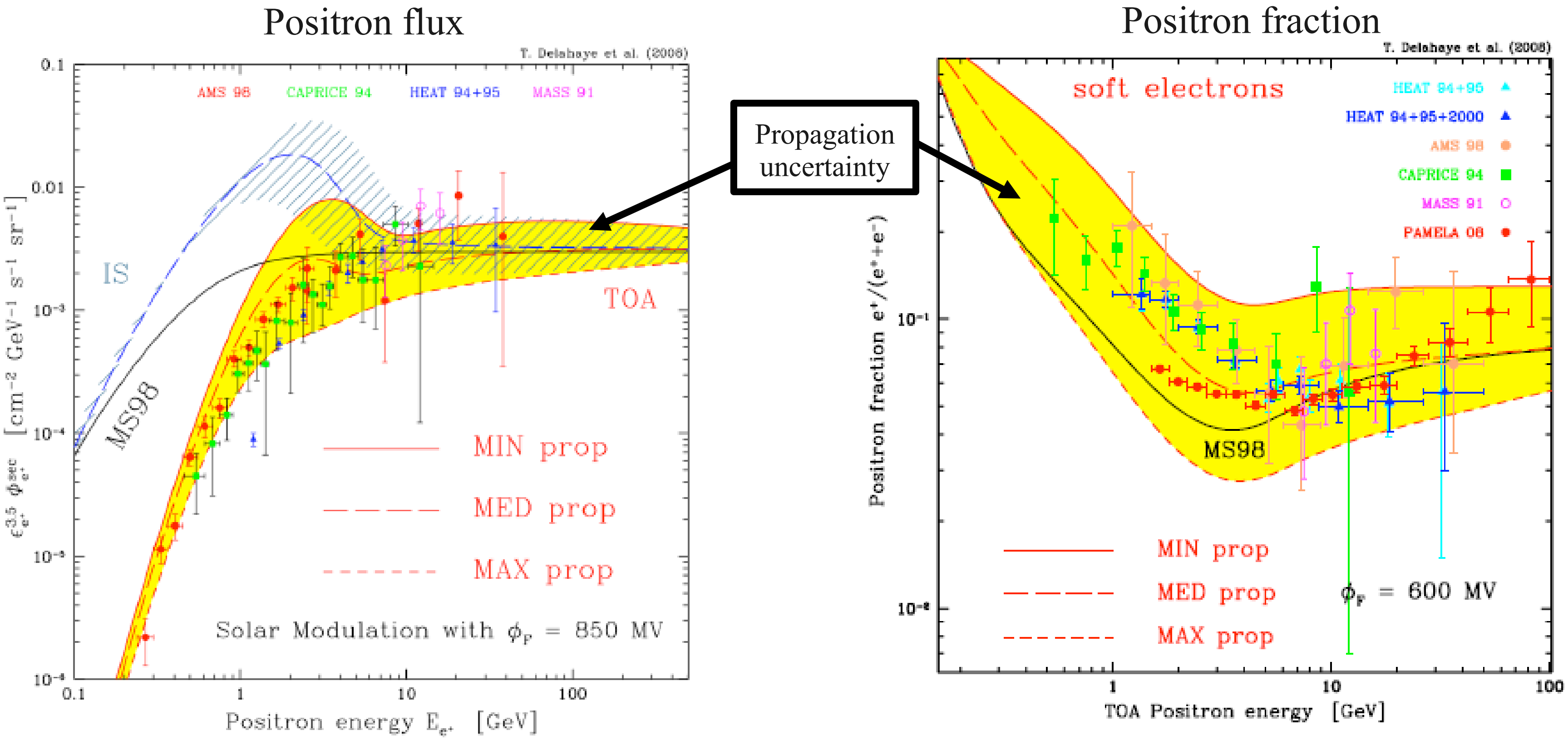
=> Recent PAMELA data consistent with pure background

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

See Fiorenza Donato's talk

Positron flux and positron fraction: uncertainties

Delahaye, Donato, Fornengo, Lavalle, Lineros, Salati, and Taillet
A&A **501**, 821 (2009)


Positron flux

Positron fraction

Propagation uncertainty

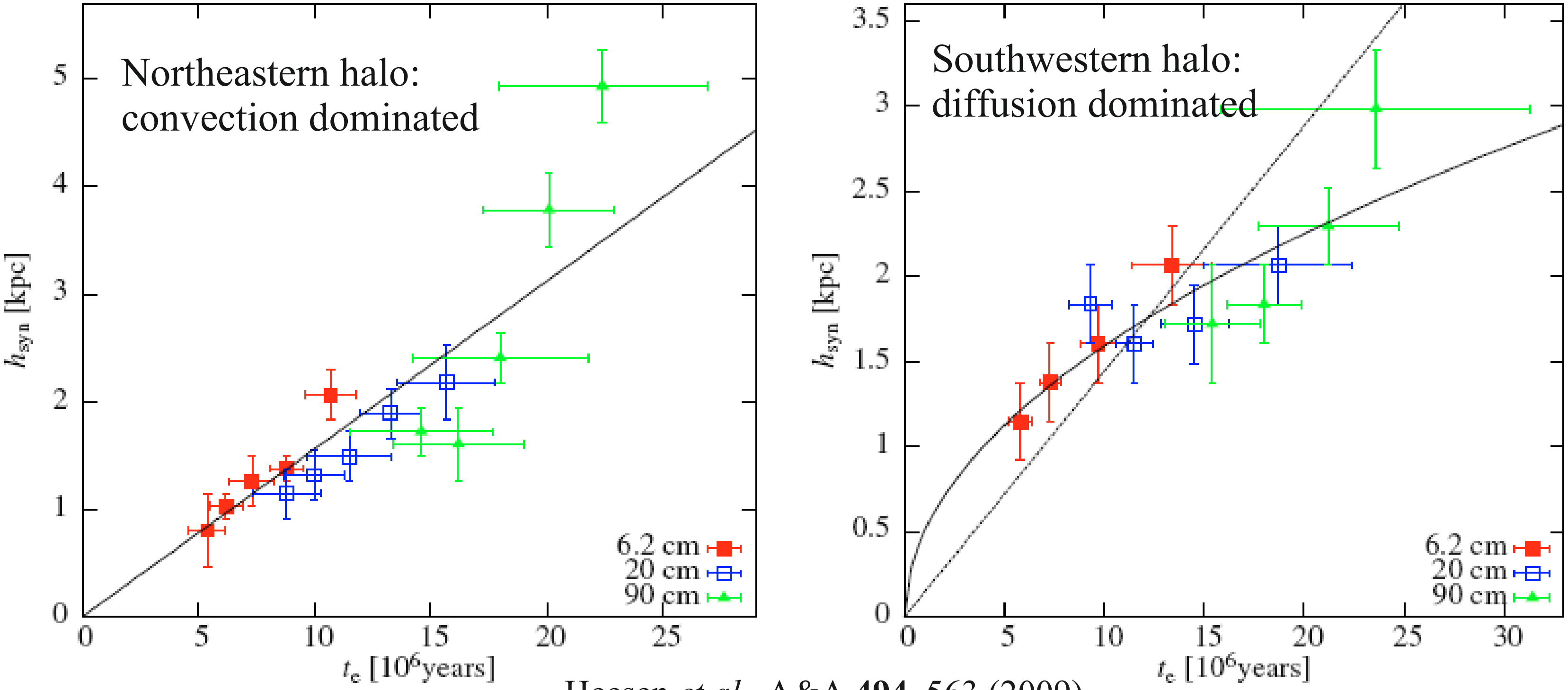
- Larger propagation uncertainties on positrons than on antinuclei (not the same key transport parameters)
- **Steady-state regime fails at high energy**

See Timur Delahaye's talk

Exemple of limitation: inhomogeneous transport

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

- 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), 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

~ *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?)*

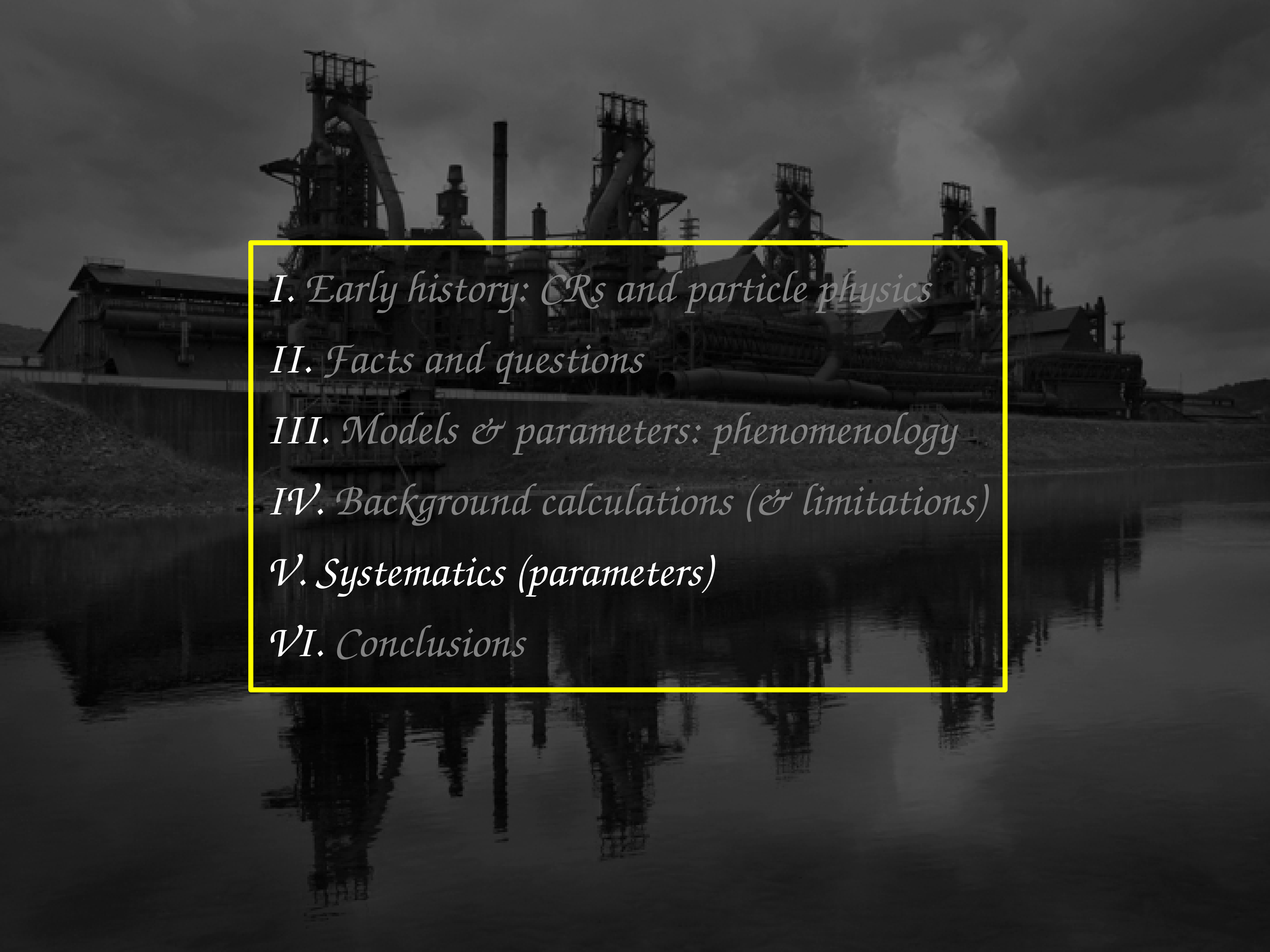
TeV electron flux

- 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* ~



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Systematic uncertainties: methodology

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

Systematic uncertainties on the cosmic-ray transport parameters

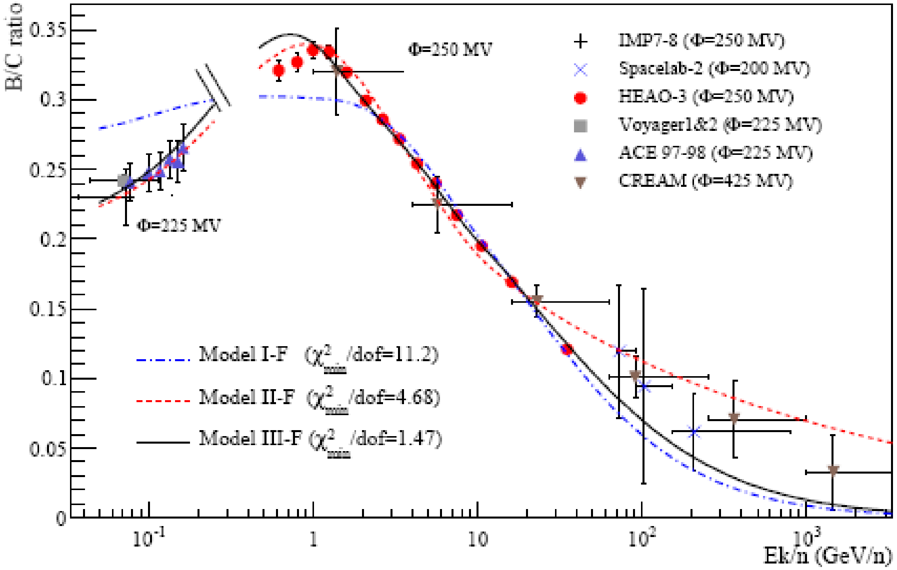
Is it possible to reconcile B/C data with δ=1/3 or δ=1/2?

- 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)



Systematic uncertainties: methodology

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

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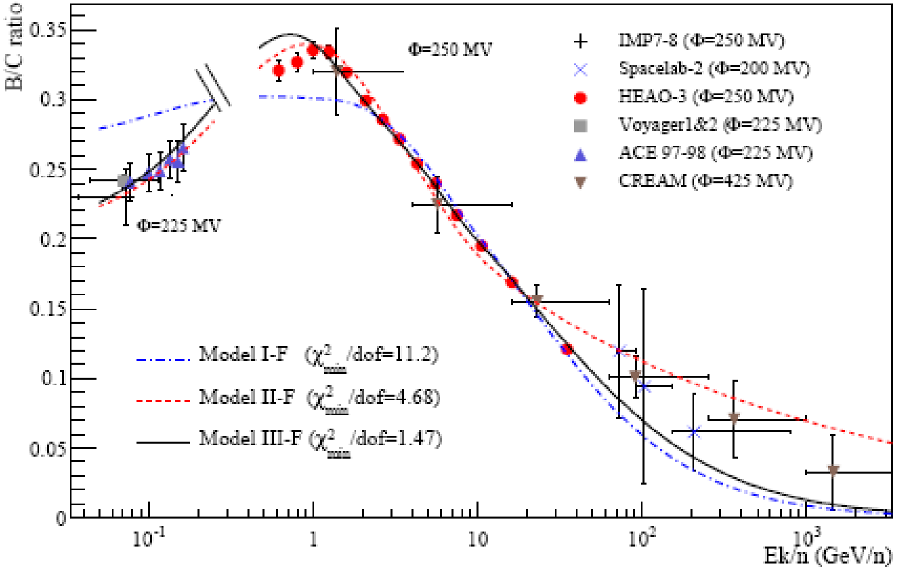
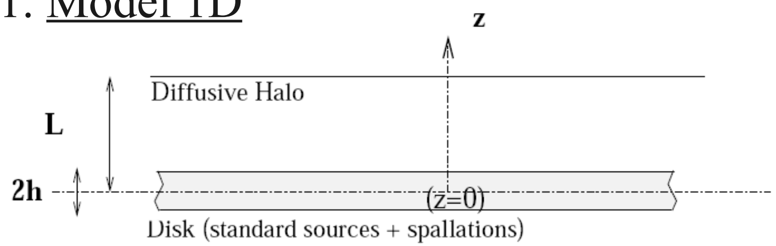


1. Model 1D



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, $f_{\rm H} = 90\%$
Source spectrum	$\eta_S = -1$, $\alpha + \delta = 2.65$
$K(E)$ 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

$$Q^j(E) = q_j \beta^{\eta_S} R^{-\alpha}$$

3. Models/methodology: Minuit (CERN) lib.

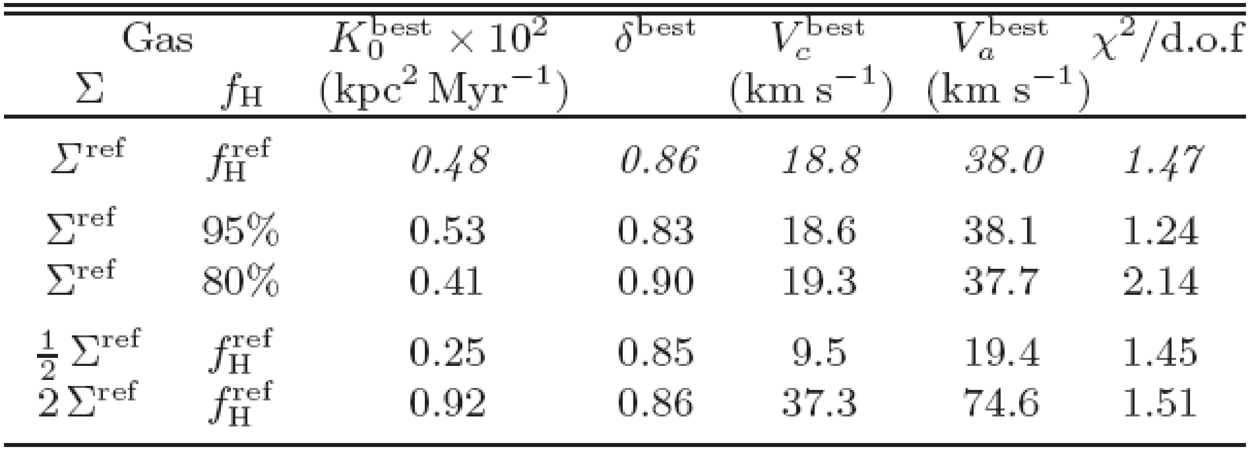
- Model 0 = $\{K_0, \delta\}$, i.e. pure diffusion ($V_a = V_c = 0$);
- Model I = $\{K_0, \delta\ V_c\}$, i.e. no reacceleration ($V_a = 0$);
- Model II = $\{K_0, \delta, V_a\}$, i.e. no convection ($V_c = 0$);
- Model III = $\{K_0, \delta, V_c, V_a\}$.

Systematic uncertainties: ISM

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

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

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



Gas Σ	 $f_{\rm H}$	$K_0^{\rm best} \times 10^2$ (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
$\Sigma^{\rm ref}$	$f_{\rm H}^{\rm ref}$	*0.48*	*0.86*	*18.8*	*38.0*	*1.47*
$\Sigma^{\rm ref}$	95%	0.53	0.83	18.6	38.1	1.24
$\Sigma^{\rm ref}$	80%	0.41	0.90	19.3	37.7	2.14
$\frac{1}{2}\,\Sigma^{\rm ref}$	$f_{\rm H}^{\rm ref}$	0.25	0.85	9.5	19.4	1.45
$2\,\Sigma^{\rm ref}$	$f_{\rm H}^{\rm ref}$	0.92	0.86	37.3	74.6	1.51

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

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

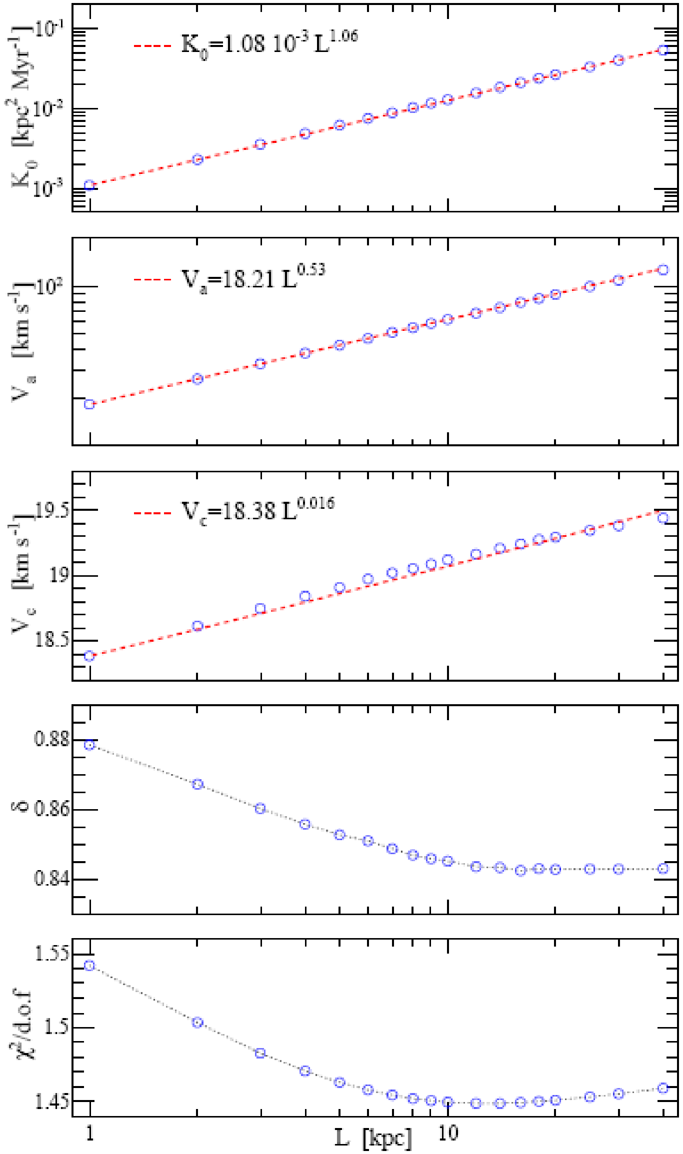
and $$\langle x \rangle^{V_c} \equiv \frac{\Sigma_{\rm ISM}\bar{m}v}{2V_c}\left[1 - e^{-\frac{V_c L}{K}}\right]$$ =>

$$\boxed{\begin{array}{l} K_0^{\rm new} = x \times K_0^{\rm ref} \\ V_c^{\rm new} = x \times V_c^{\rm ref} \end{array}}$$

=> Systematics ~ uncertainty on the gas surface density

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)

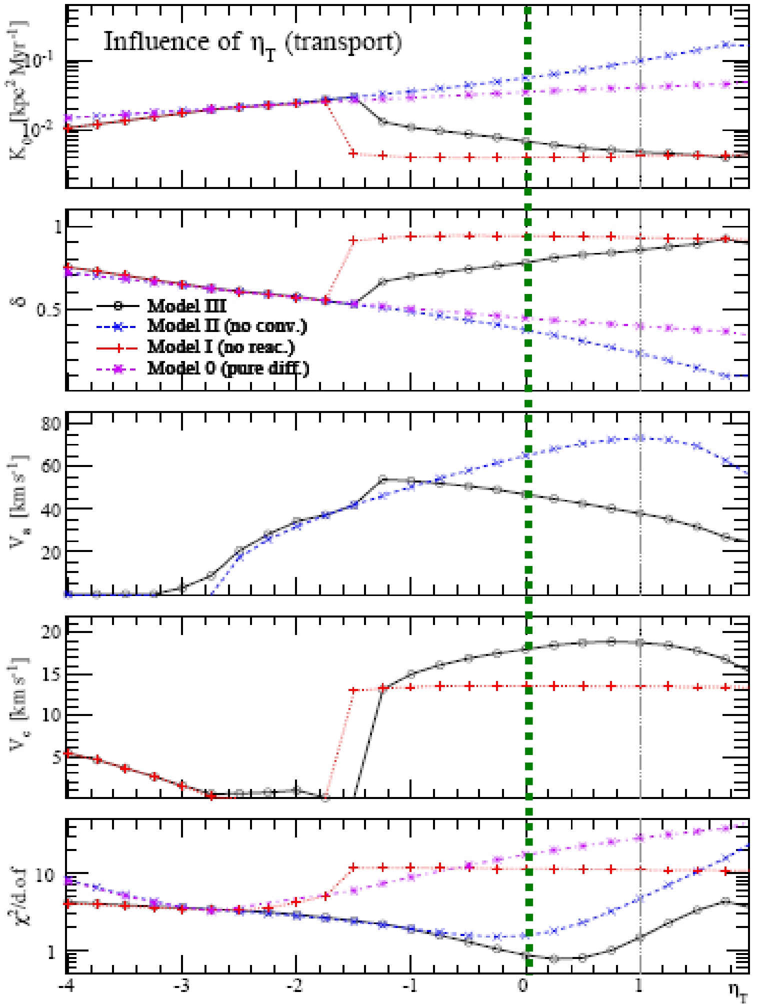
Systematic uncertainties: low-energy transport η_T

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

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

Type of turbulence		η_T	$\frac{K_{pp}K_{xx}}{4/3\,p^2V_a^2}$
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	$K_0^{\rm best}\times 10^2$ ($\rm kpc^2\,Myr^{-1}$)	$\delta^{\rm best}$	$V_c^{\rm best}$ ($\rm km\,s^{-1}$)	$V_a^{\rm best}$ ($\rm km\,s^{-1}$)	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

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

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

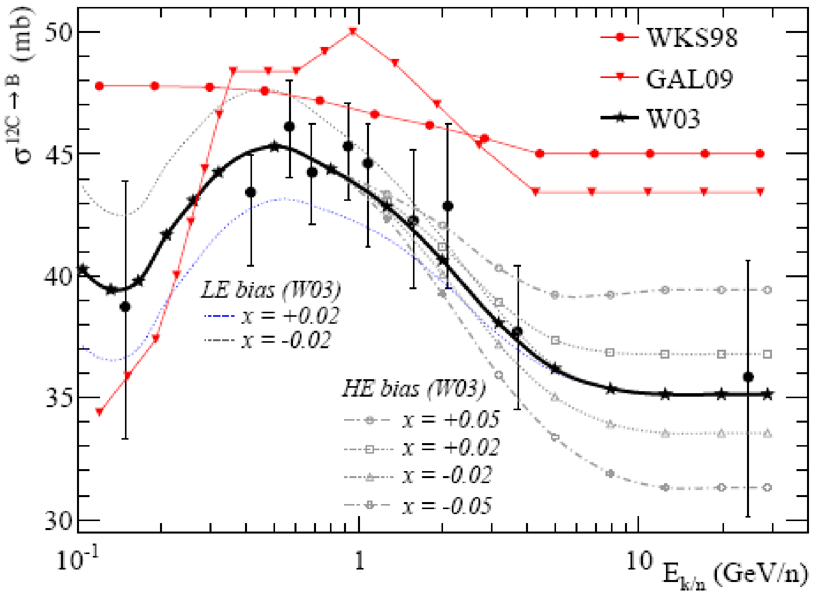
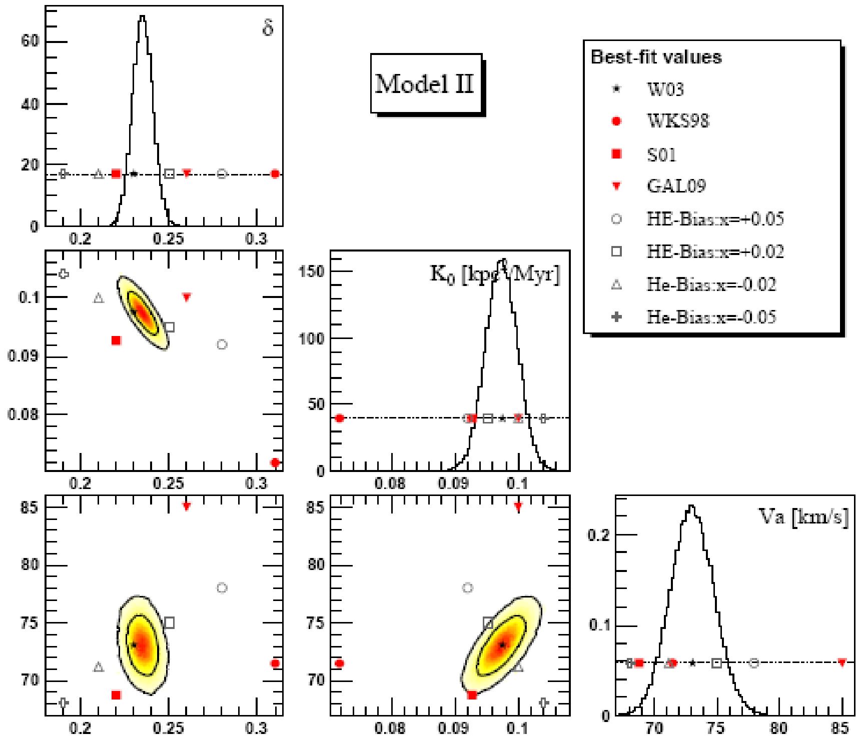


Fig. 3. Production cross-section for $^{12}C+H\to^{10,11}B$ (adapted from Webber et al. 2003). The standard sets are shown as solid lines (WKS98: red dots; GAL09: red down triangles; W03: black stars), and the biased sets in dotted ($|x| = 0.02$) and dashed ($|x| = 0.05$) lines.

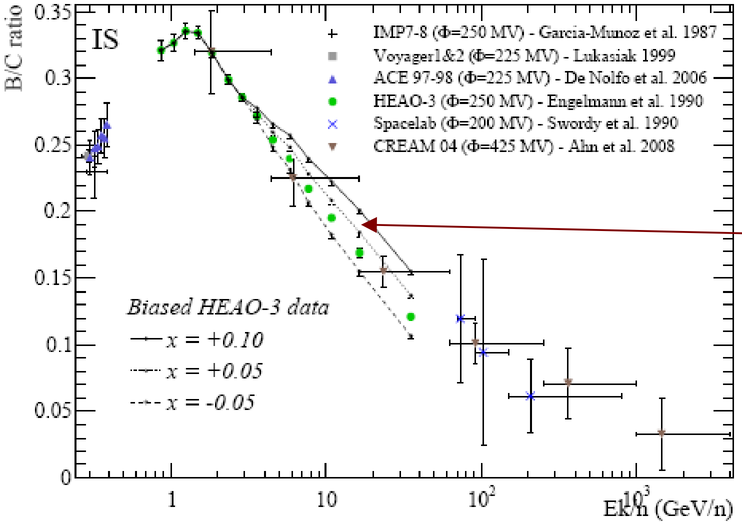


=> Systematics uncertainties > "statistical uncertainties" (fit from data)

What about the data?

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

Simple energy bias in the data?



Why most publications use large error bars for HEAO-3 at high energy?

[which are inconsistent with Engelmann *et al.*, A&A **233**, 96 (1990)]

HEAO-3 HE bias x	$K_0^{\rm best} \times 10^2$ (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
II: +0.10	10.1	0.17	...	56.6	4.54
II: +0.05	9.95	0.20	...	64.8	4.27
II: +0.00	*9.76*	*0.23*	...	*73.1*	*4.73*
II: −0.05	9.56	0.27	...	81.5	5.79
III: +0.10	0.31	0.85	19.1	30.0	1.32
III: +0.05	0.42	0.83	19.0	34.8	1.16
III: +0.00	*0.48*	*0.86*	*18.8*	*38.0*	*1.47*
III: −0.05	0.50	0.90	18.7	40.0	2.18

=> does not help to have δ~ 0.3 in conv. models

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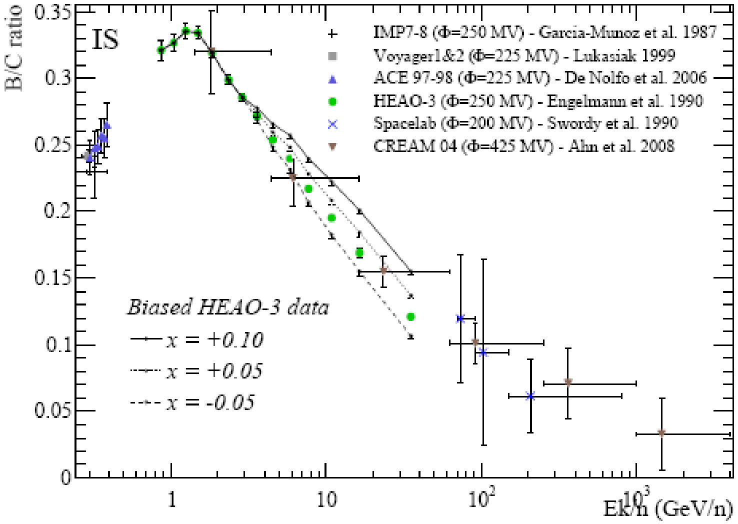

HEAO-3 HE bias x	$K_0^{\rm best} \times 10^2$ (kpc^2 Myr^{-1})	$\delta^{\rm best}$	$V_c^{\rm best}$ (km s^{-1})	$V_a^{\rm best}$ (km s^{-1})	χ^2/d.o.f
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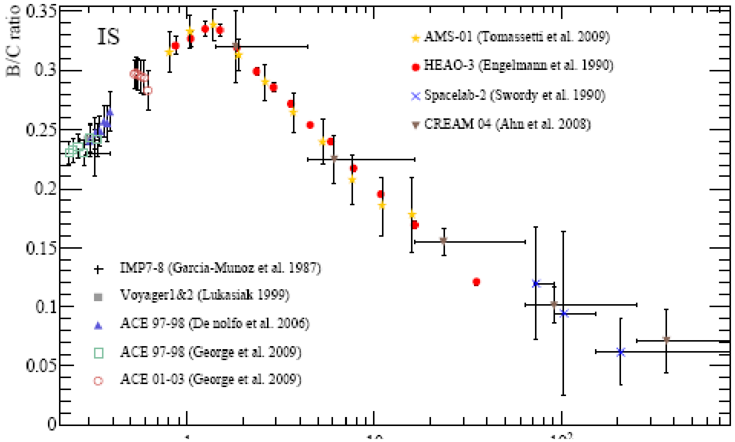
=> does not help to have δ~ 0.3 in conv. models

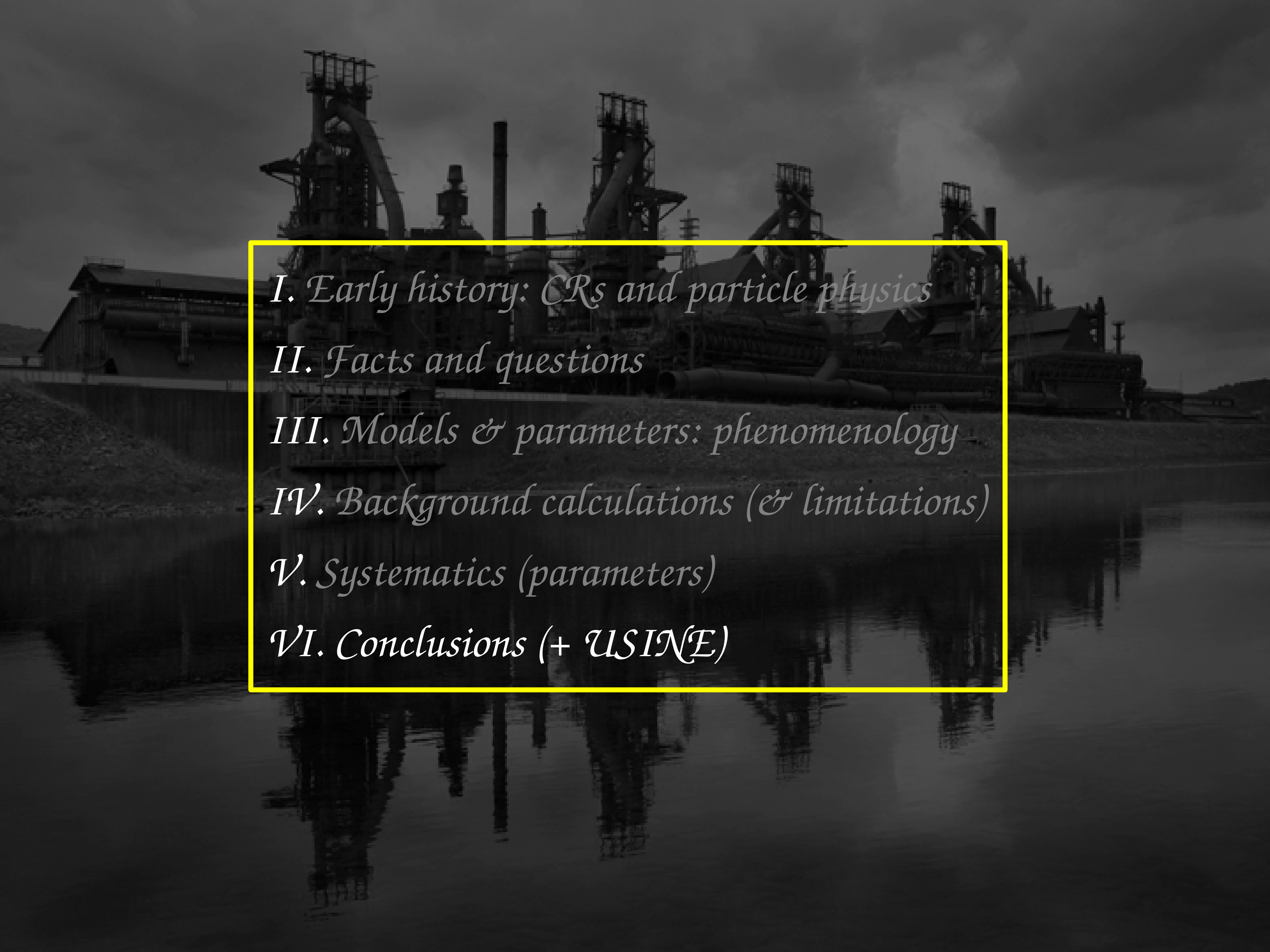
Or more complicated biases?



Model Data	$K_0^{\rm best} \times 10^2$ (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
III-A	2.51	1.00	21.7	35.4	2.11
III-C	0.43	0.89	18.9	36.7	1.72
III-F	0.48	0.86	18.8	38.0	1.47
III-G1	0.53	0.84	18.0	37.4	1.80
III-G2	0.46	0.85	20.0	39.6	2.73
III-G1/2	0.53	0.83	19.0	39.1	2.94
III-H	1.85	0.51	18.1	54.1	0.25

- A: HEAO-3 [0.8 – 40 GeV/n], 14 data points;
- C: HEAO-3+low energy [0.3–0.5 GeV/n], 22 data points;
- F: HEAO-3 + low + high energy [0.2 – 2 TeV/n], 31 data
- G1: as F, but with new ACE 1997-1998 data, 31 data
- G2: as F, but with new ACE 2001-2003 data only, 31
- G1/2: using both 1997-1998 and 2001-2003 ACE data,
- H: as F, but HEAO-3 replaced by AMS-01 data, 27 data

=> New B/C data desired!!!



I. Early history: CRs and particle physics

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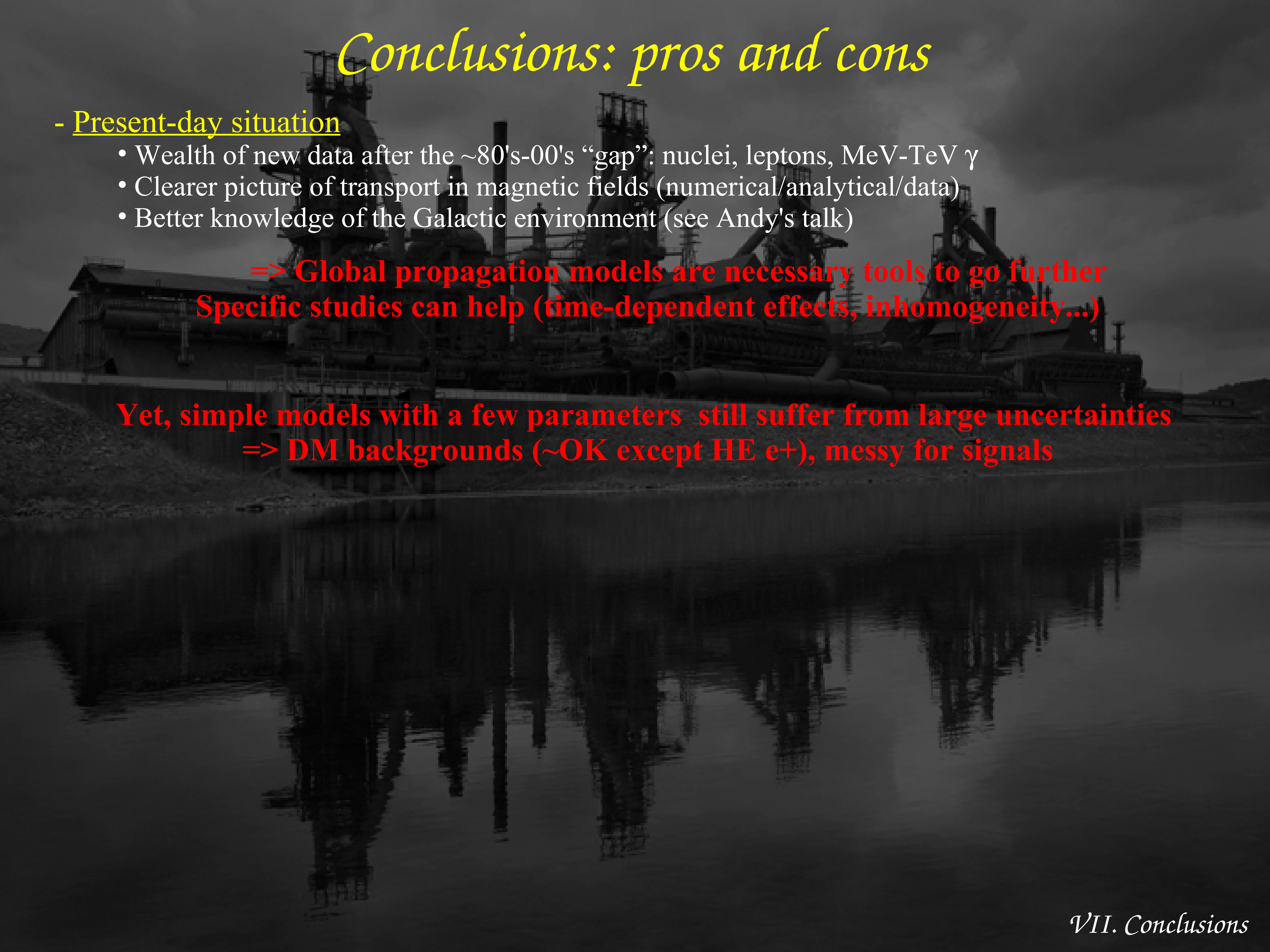
VI. Conclusions (+ USINE)

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 (see Andy's talk)

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



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 (see Andy's talk)

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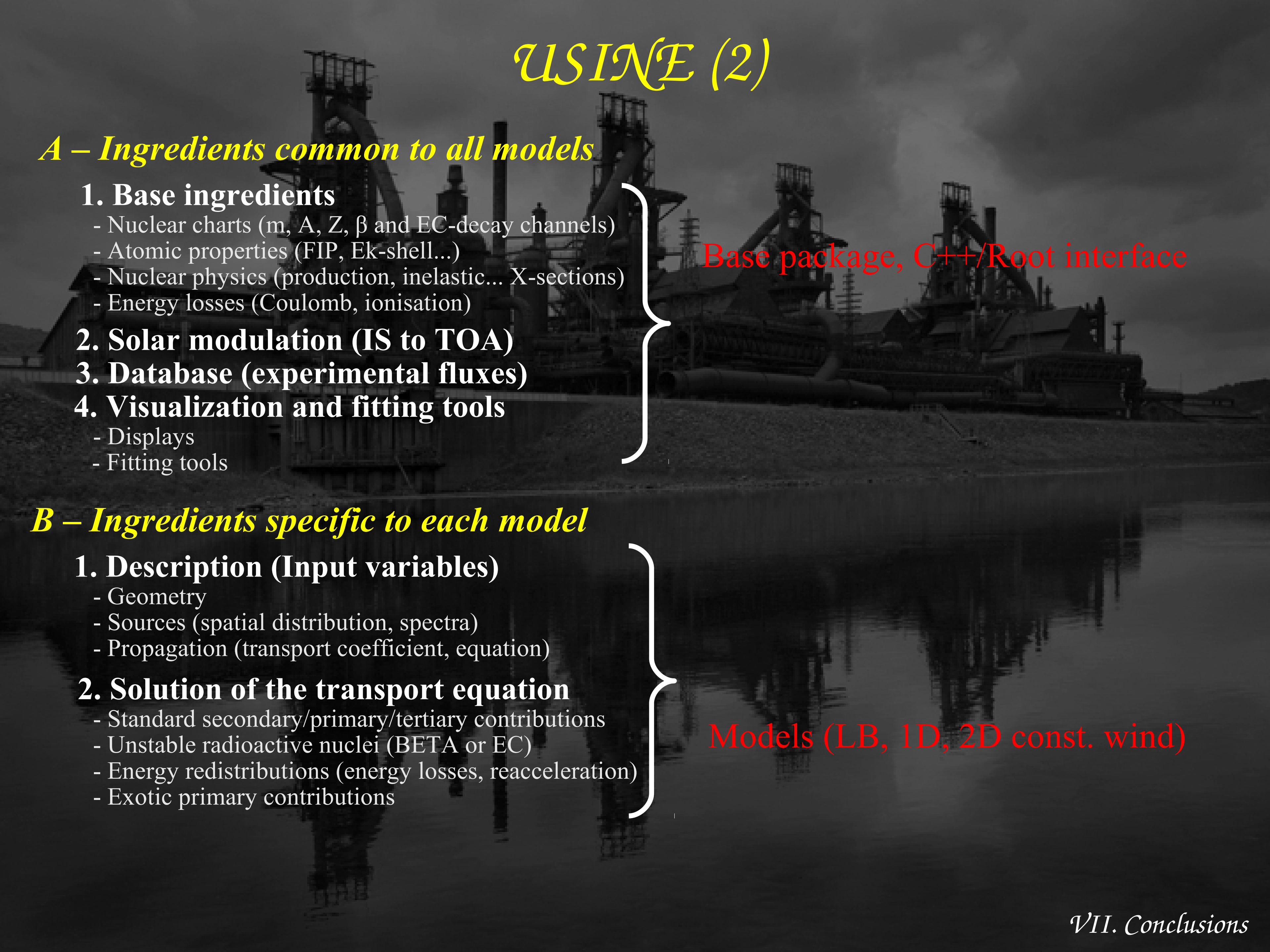
Yet, simple models with a few parameters still suffer from large uncertainties
=> DM backgrounds (~OK except HE e+), messy for signals

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

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)
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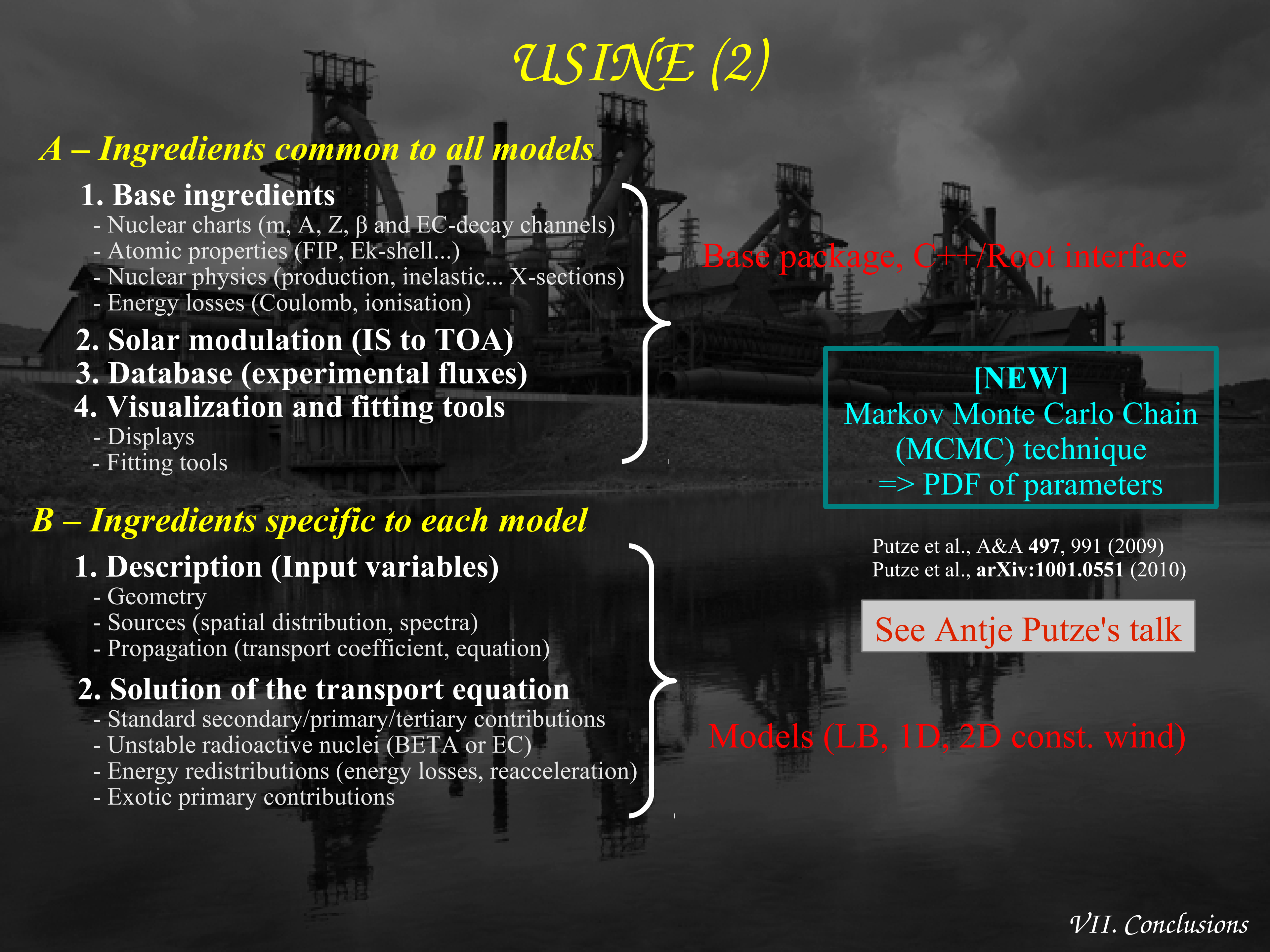
- Exotic primary contributions

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



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

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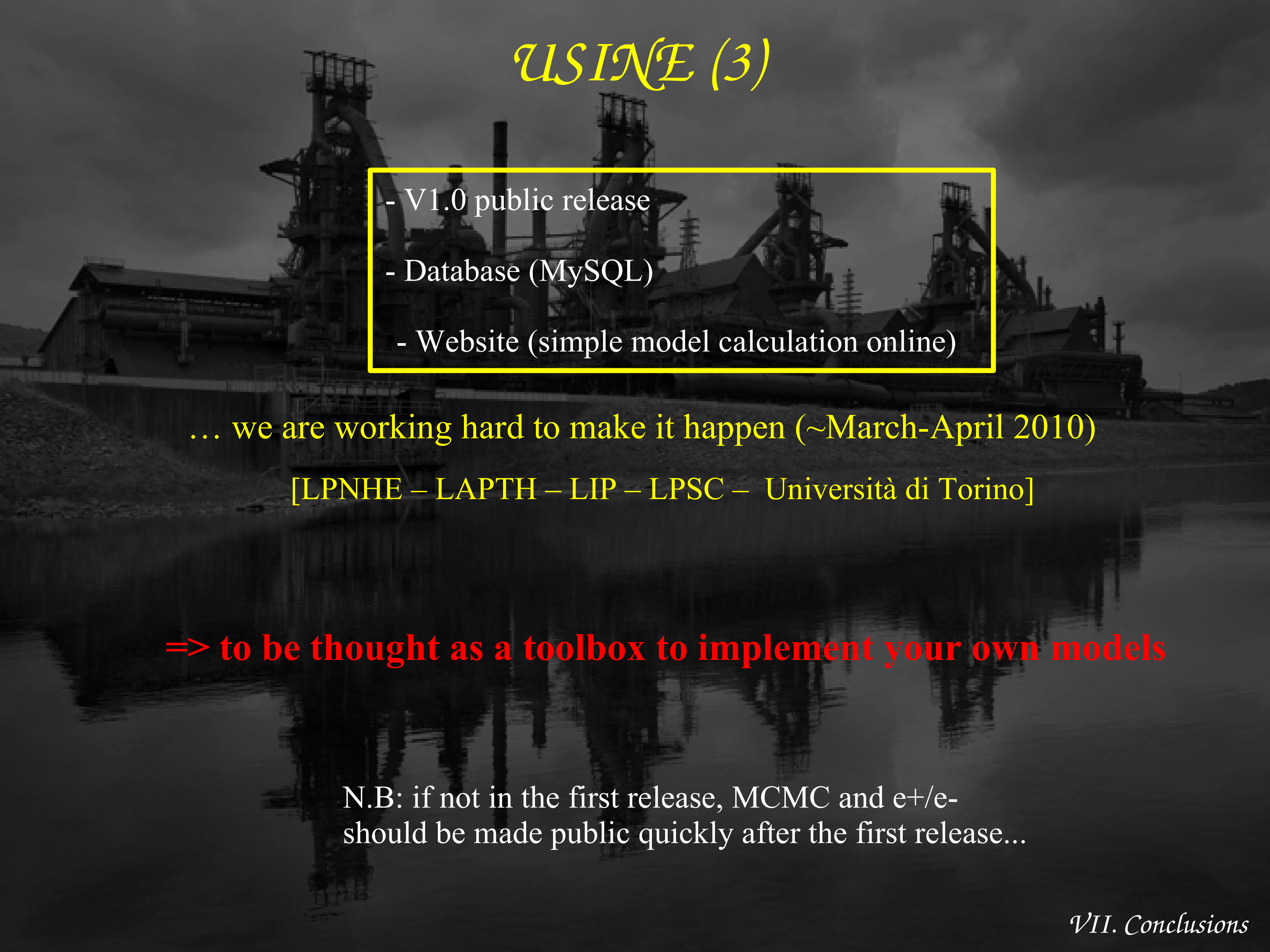
Putze et al., A&A **497**, 991 (2009)
Putze et al., **arXiv:1001.0551** (2010)

See Antje Putze's talk

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

USINE (3)



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

… we are working hard to make it happen (~March-April 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...

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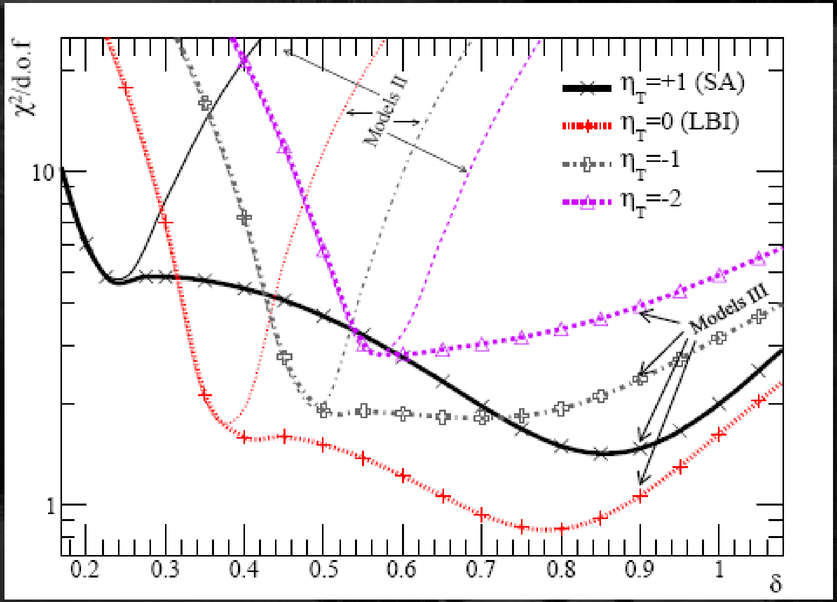

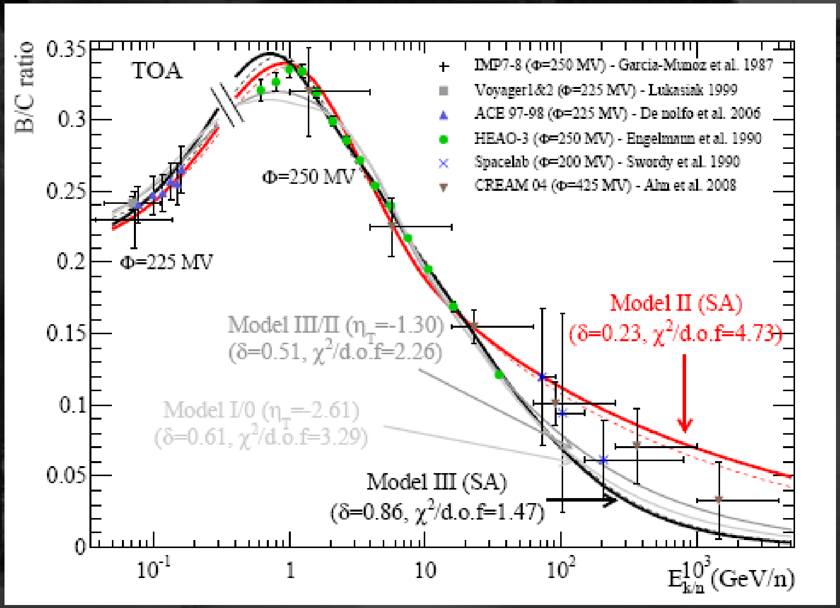

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