Phénoménologie du transport des espèces chargées dans la Galaxie

David Maurin (LPNHE & IAP)
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Bibliographie succinte...

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- Berezinskii et al.: Astrophysics of Cosmic Rays - Sect. I-III (North-Holland, 1990)

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Autres :
- Document introductif
- Ma thÃ¨se

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projo.

I. Généralités sur le Rayonnement Cosmique (RC)

II. Notre Galaxie du point de vue du RC

III. Notion de grammage et « Leaky-Box Model »

IV. Equation de diffusion : quelques propriétés

V. Solution dans des cas idéalisés

tableau

VI. Trucs tièdes et chauds du RC aujourd'hui

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I. Généralités sur le Rayonnement Cosmique (RC)

1. Bref historique : RC et physique des particules

2. Spectre, composition,...

3. Vue globale du RC galactique

Références utiles

Simpson, ARNPS 33, 323 (1983)

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Ecole de Physique des Astroparticules

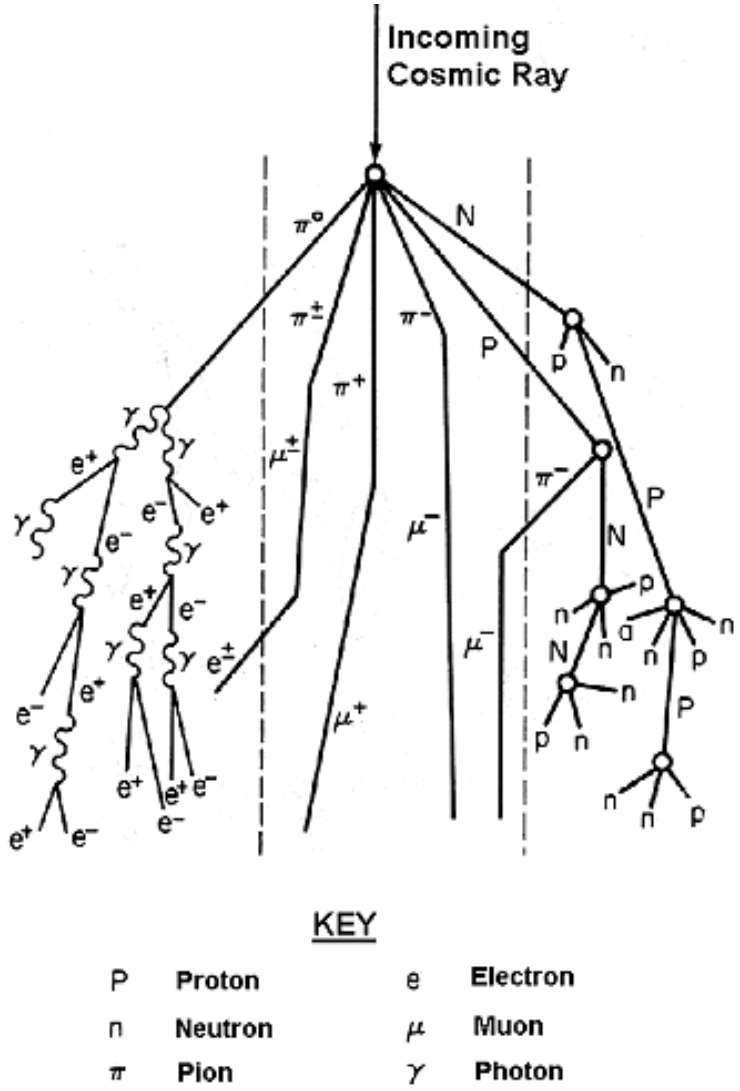
OHP – 7 septembre 2009

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

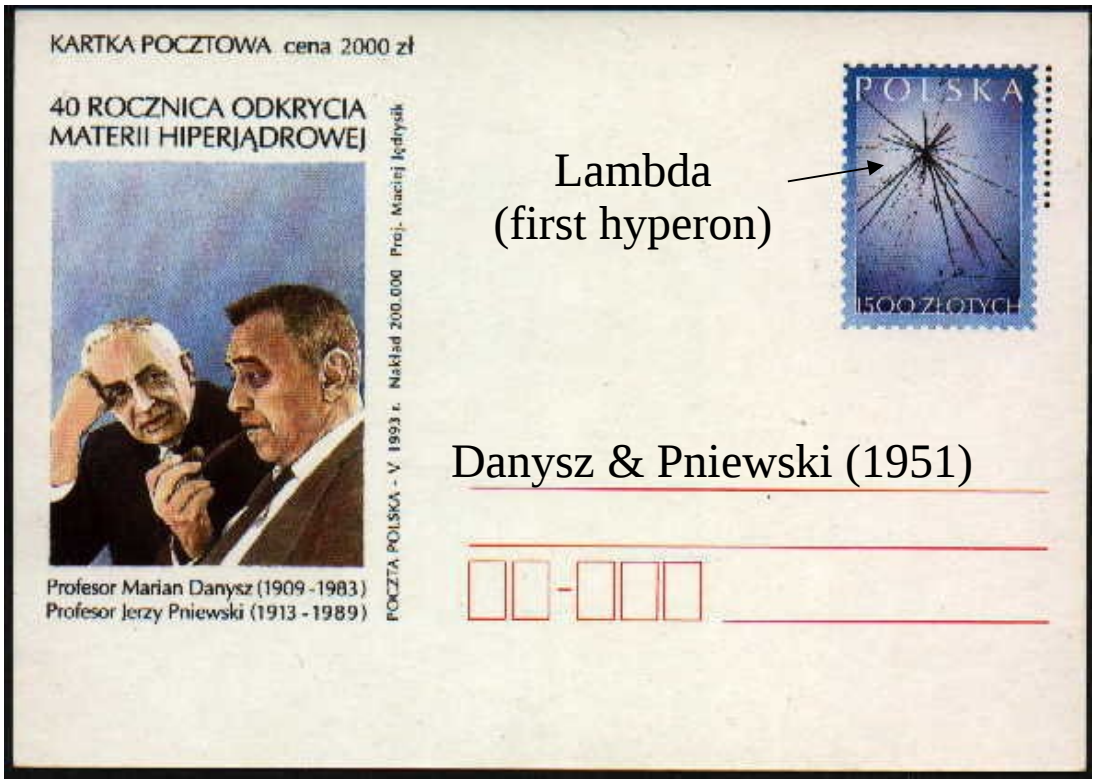


CRs through the Earth atmosphere: air showers

Discovery of new particles in CR showers:

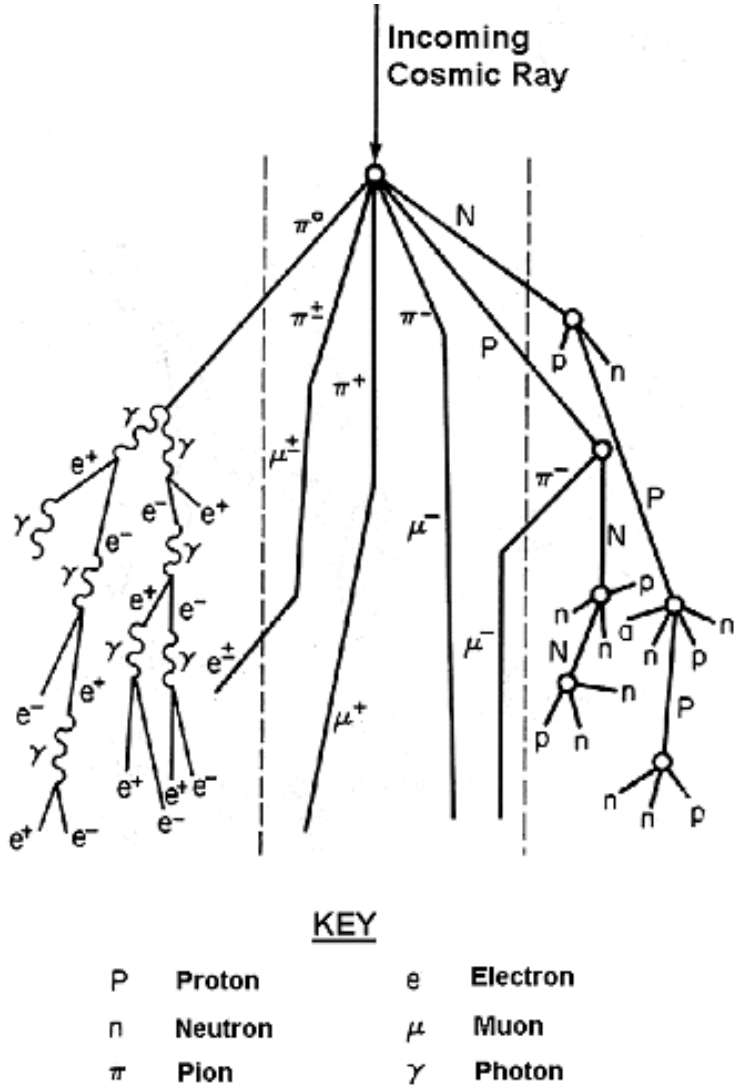
- Positron: Anderson (1932)
- Muon: Anderson & Neddermeyer (1936)
- Pion: Powell (1947)
- Kaon [strange particle]: Rochester & Butler (1947)

and…



Lambda
(first hyperon)

Danysz & Pniewski (1951)



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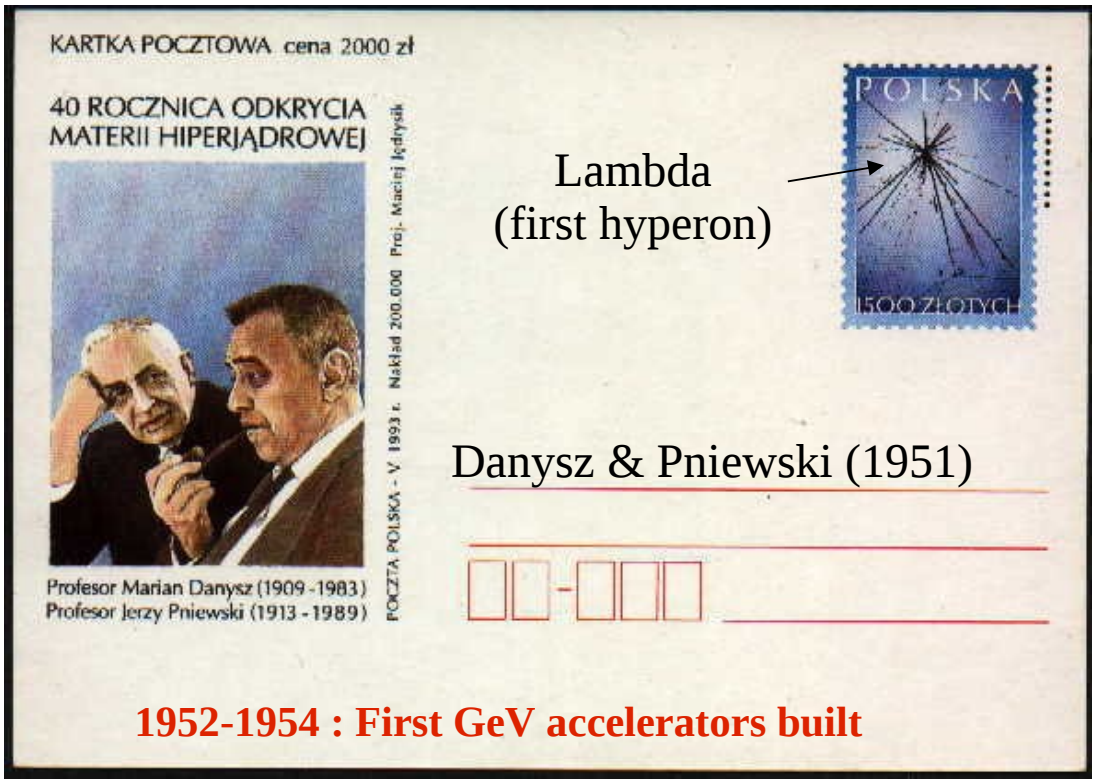
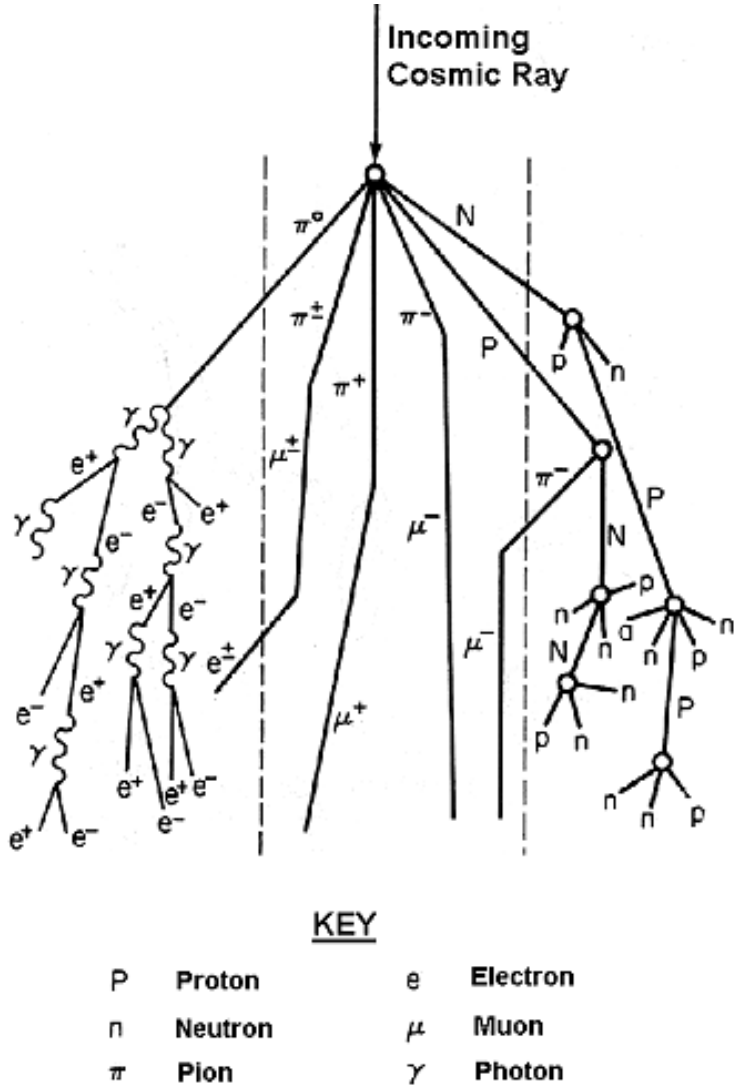
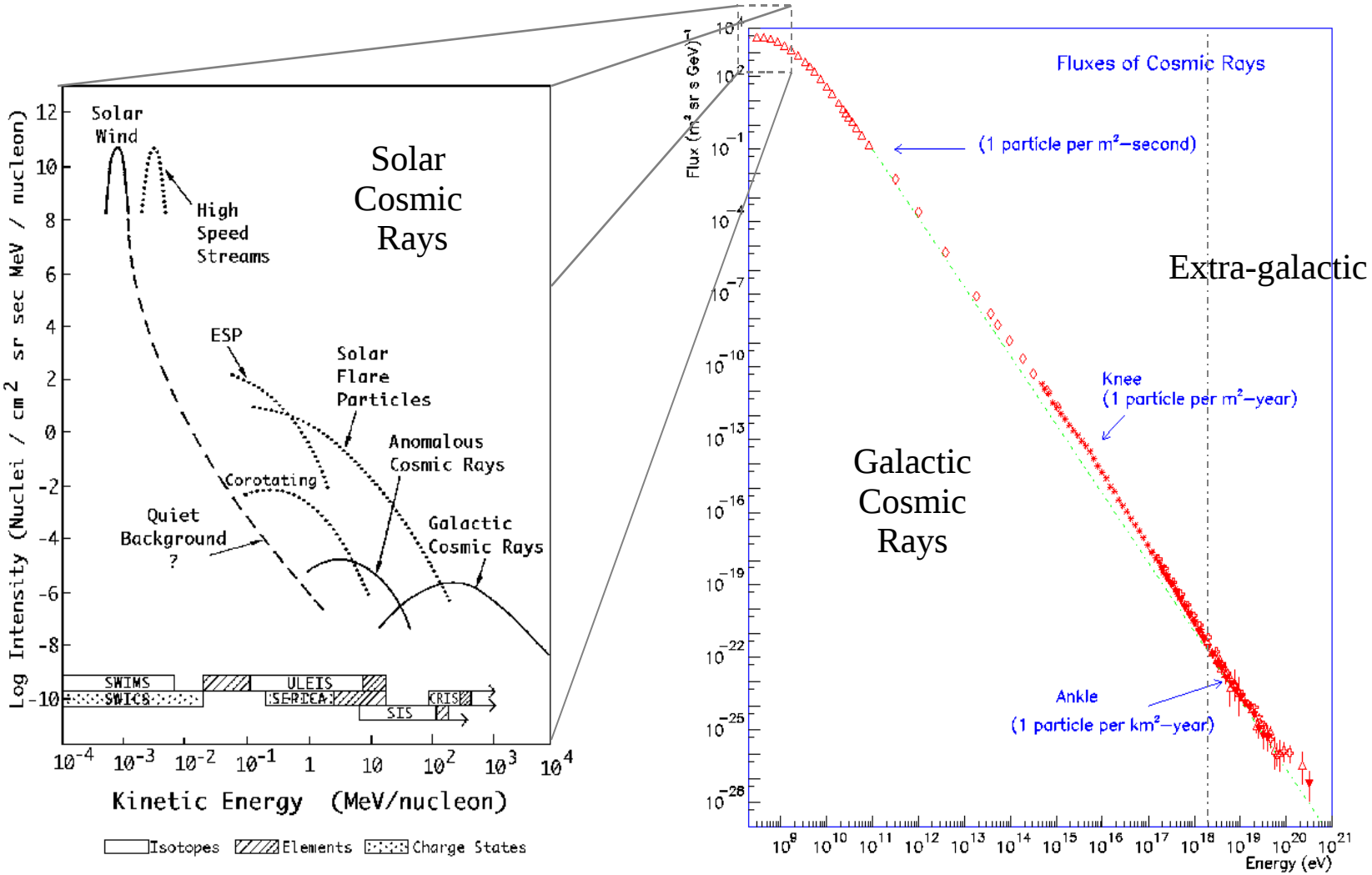


1952-1954 : First GeV accelerators built



CR spectrum: from Solar to extragalactic origin

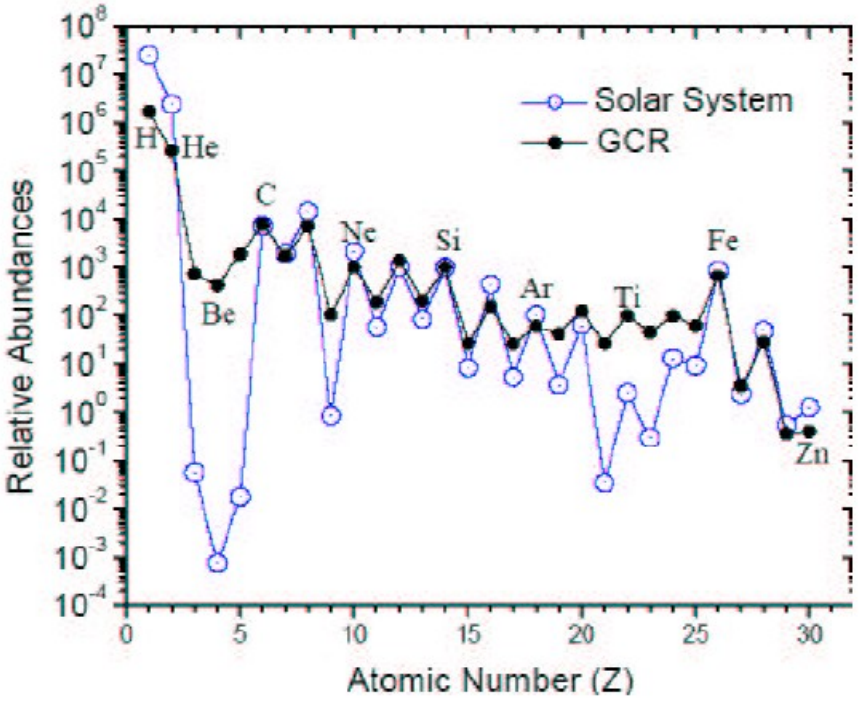


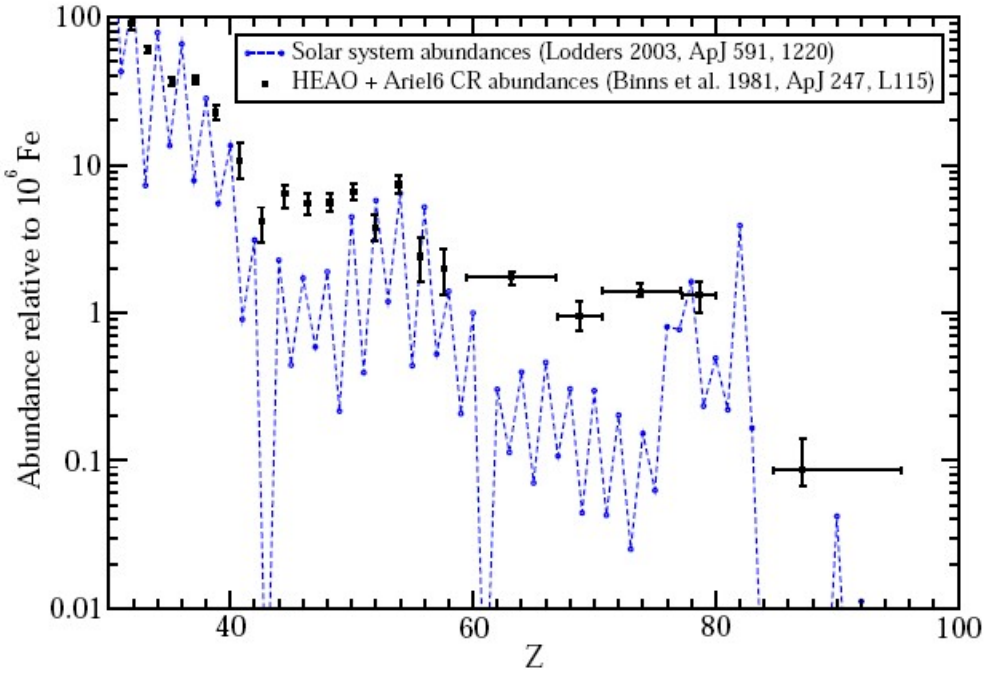
N.B.: Solar modulation of GCRs below GeV/amu energies

→ We focus on the GeV-TeV region: GCRs

Abundances: GCR vs Solar System

(secondary species to "calibrate" propagation)





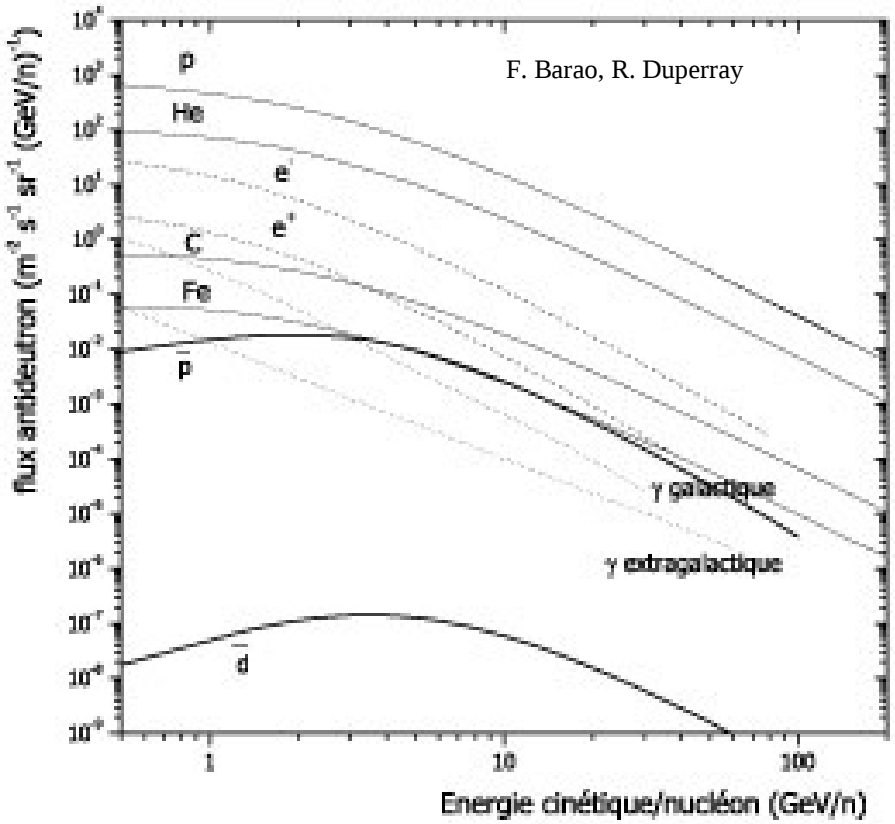
=> Primary species are present in sources (CNO, Fe)

- 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

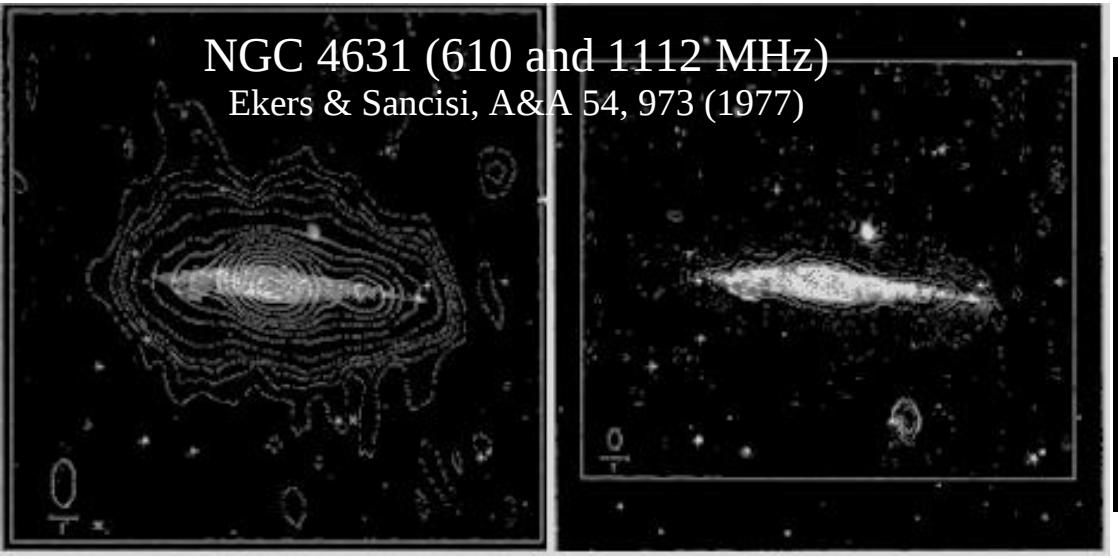
Neutral

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

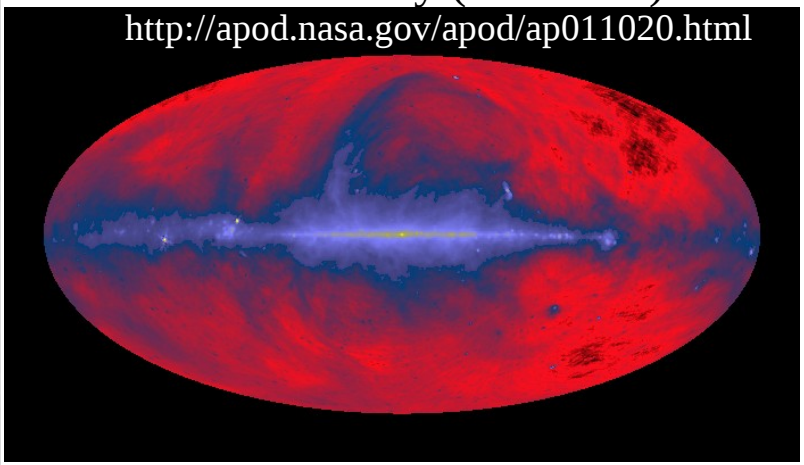
=> gamma-rays are measured along a line of sight

=> Charged particles diffuse: only a local measurement

Spatial distribution of GCRs



Our Galaxy (408 MHz)



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

N.B. : + very small anisotropy ($<10^{-3}$) not understood yet

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?

Measurements

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

Acceleration

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)

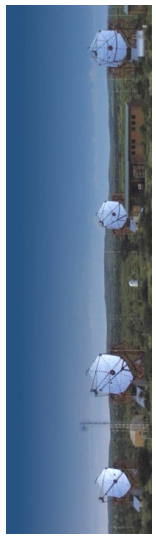
Transport

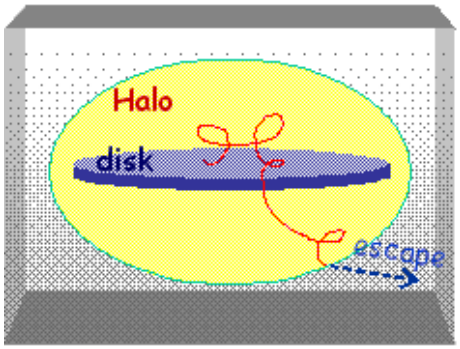
00's Necessity to take into account time-dependent effects and local sources?

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





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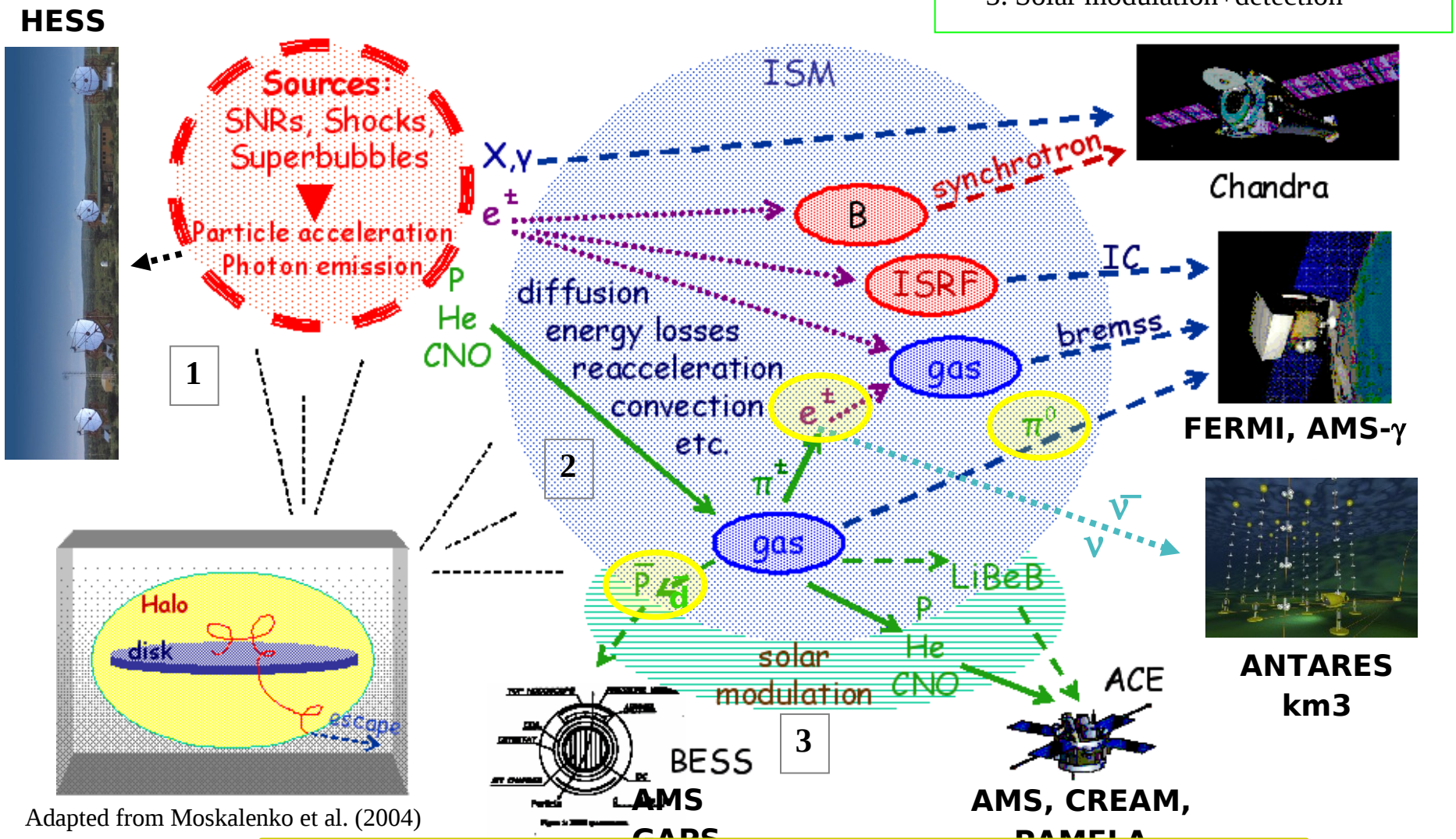

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=> Search for DM where "standard" production is rare (secondary)

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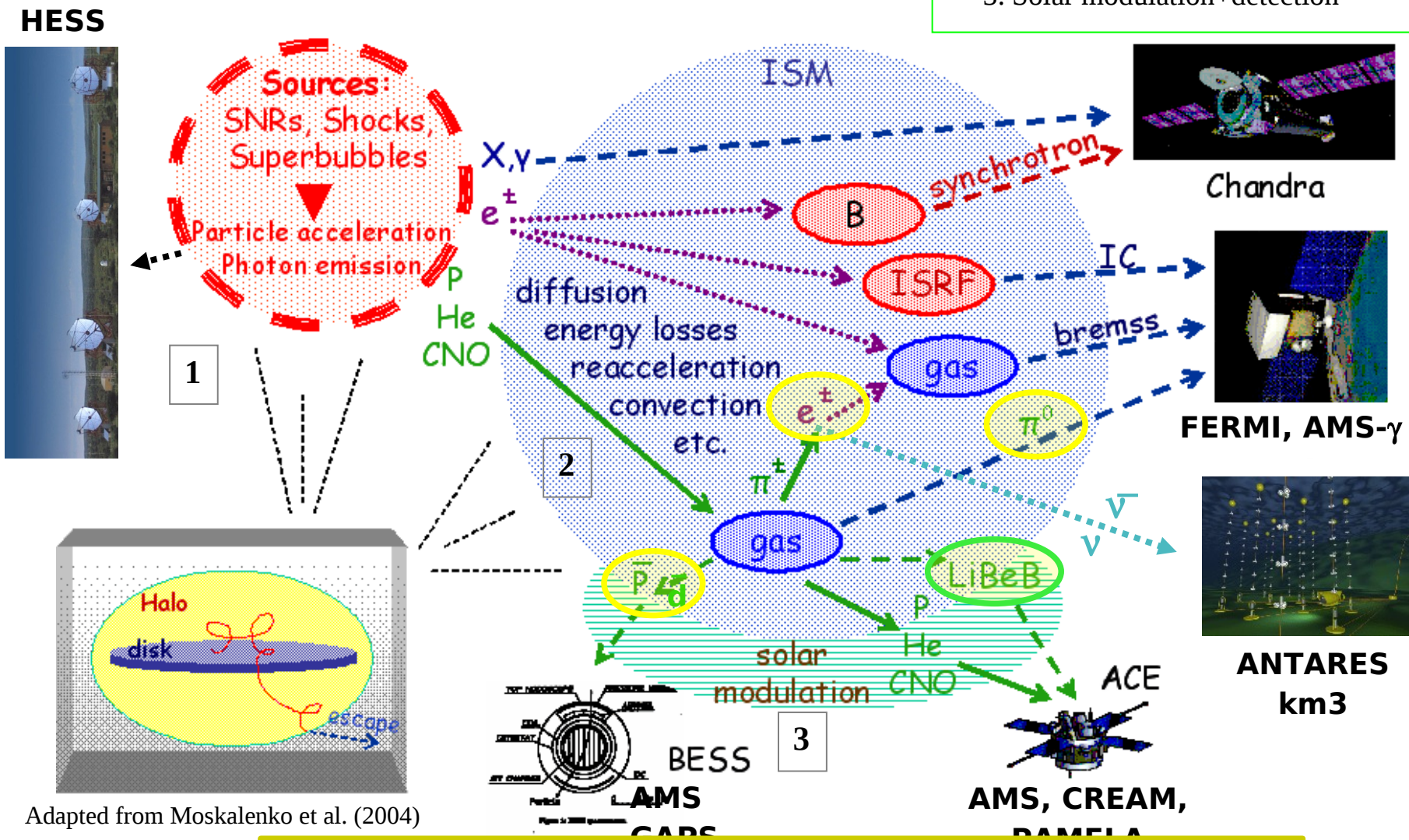

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=> Search for DM where "standard" production is rare (secondary)

=> Use LiBeB to calibrate the transport coefficients

Open questions

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?)

Are GCRs a good laboratory to search for new physics?

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

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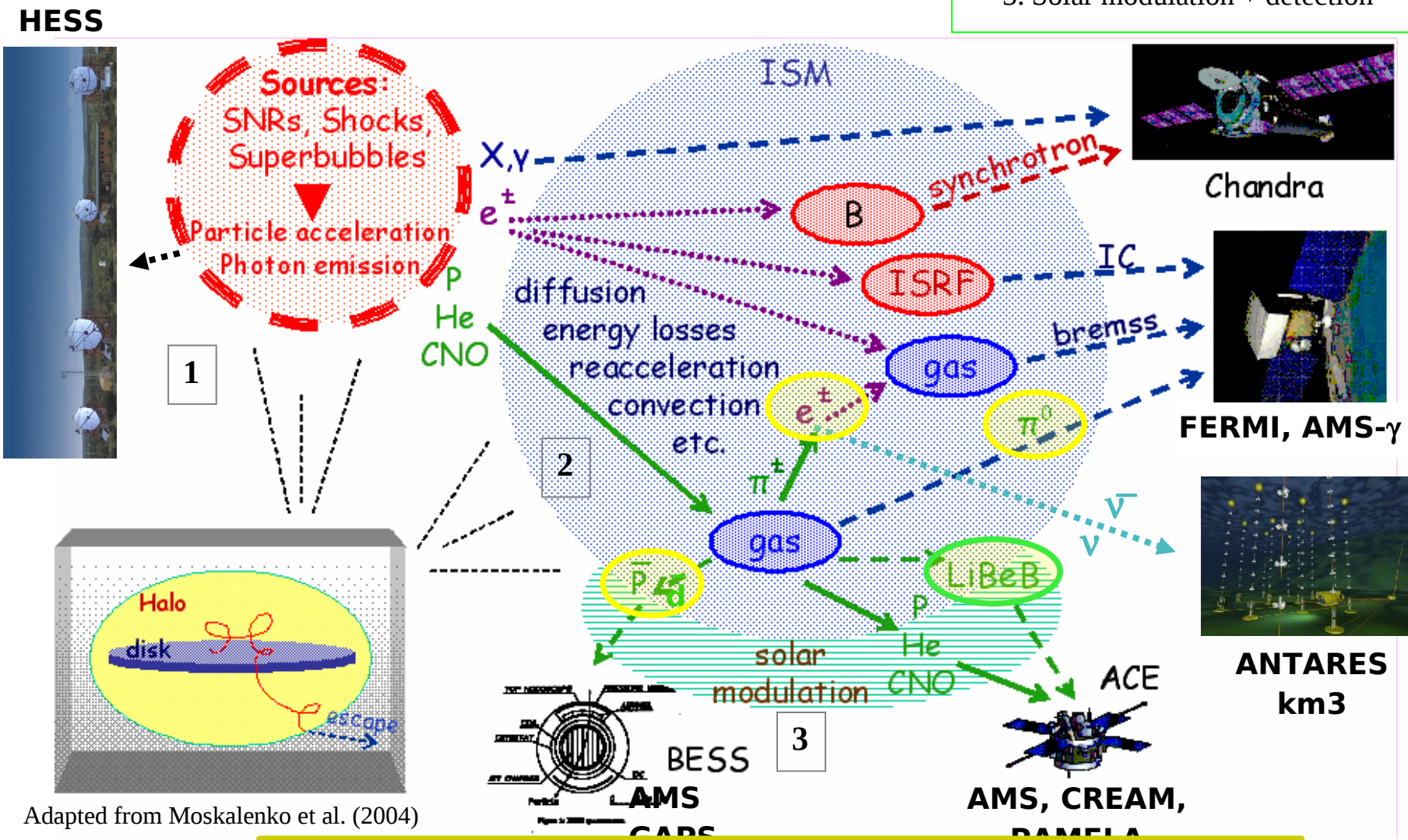

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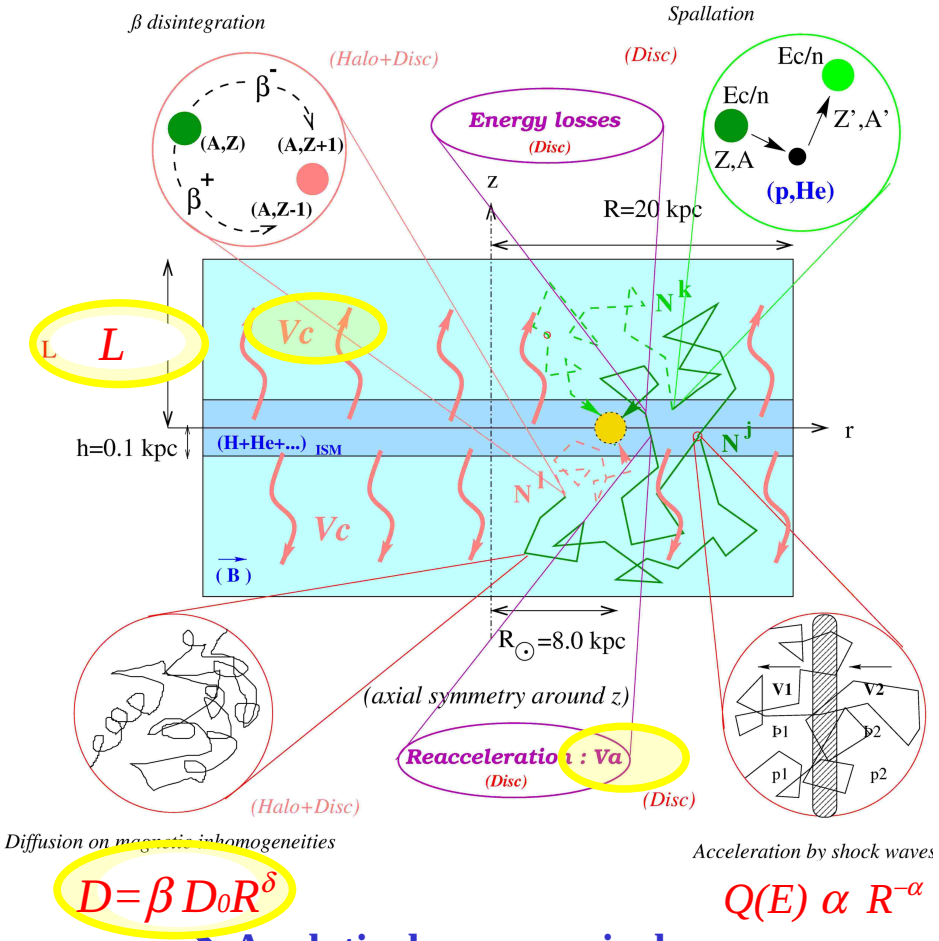
A two-zone diffusion model (1D or 2D)

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



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

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

➔ **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)

VI. En bref + trucs tièdes et chauds du RCG aujourd'hui

Q1 : les flux standards sont-ils compris ?

- **Sources (SN, pulsars, SB...)**
- **Nucléosynthèse (processus r et s pour les noyaux lourds)**
- **Mécanisme d'accélération (injection, amplification de B)**
- **Mécanisme de propagation (lien turbulence, dépendance spat., isotropie)**

R1 : *l'essentiel* semble avoir été *compris* il y a ~30 ans...
mais les preuves *directes* et les *détails* manquent toujours !

Observables :

- multi-longueur d'ondes : radio, X, TeV
- multi-messagers : noyaux (stables, rad.), électrons, ν, γ

Obervatoires/expériences :

- PAMELA, HESS, CREAM, ATIC... (chargés : GeV-TeV)
- AUGER (> PeV)
- FERMI, H.E.S.S. (γ du GeV au TeV)
- ANTARES, km3, IceCube (ν)

=> Il n'y a jamais eu autant de mesures simultanées d'observables du RCG

Q2 : peut-on trouver facilement de la nouvelle physique ?

R2 : oui, euh..., mais non !

Antiprotons
- first measurements, be it at low energy or at high energy, proven wrong
- first theoretical calculation underestimated
  => *Present status: no excess (PAMELA data)*

Excès γ au GeV
- EGRET excess (1997-2008): astrophysical or DM?
- High latitude excess proven wrong by FERMI data
  => *Present status: awaiting FERMI data in the disc*

Fraction positron
- 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?*

Raie 511 keV
- Variable source, then positronium fountain (OSEE)...
- Hundreds of papers on light dark matter
  => *Present status: spatial correlation LMXB (issues with intensity?)*

Flux électron TeV
- First measurement ATIC & PPP-BETS (2008)
- Local sources, DM [~*O*(100) papers], or incorrect measurement?
  => *Status: Disproved (?) by HESS and/or FERMI*

=> Beaucoup de papiers « matière noire » ... Pas beaucoup de choses convaincantes

– Il reste du pain sur la planche –