Propagation of Galactic Cosmic Rays

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DMAstroLHC (ANR-12-BS05-0006)

What do we know about nuclear cosmic rays today?

Nuclear cosmic rays are

- energetic particles
  [Bothe & Kolhörster, Z. Phys. (1929)]
- of extraterrestrial origin
  [Hess, Sitzungsberichte der kaiserl. Akademie (1912)]
- bombarding Earth's atmosphere, and
- producing atmospheric particle showers
  [Auger *et al.*, Rev. Mod. Phys. (1939)]

[Lee & Kirby, Marvel Comics (1961)]

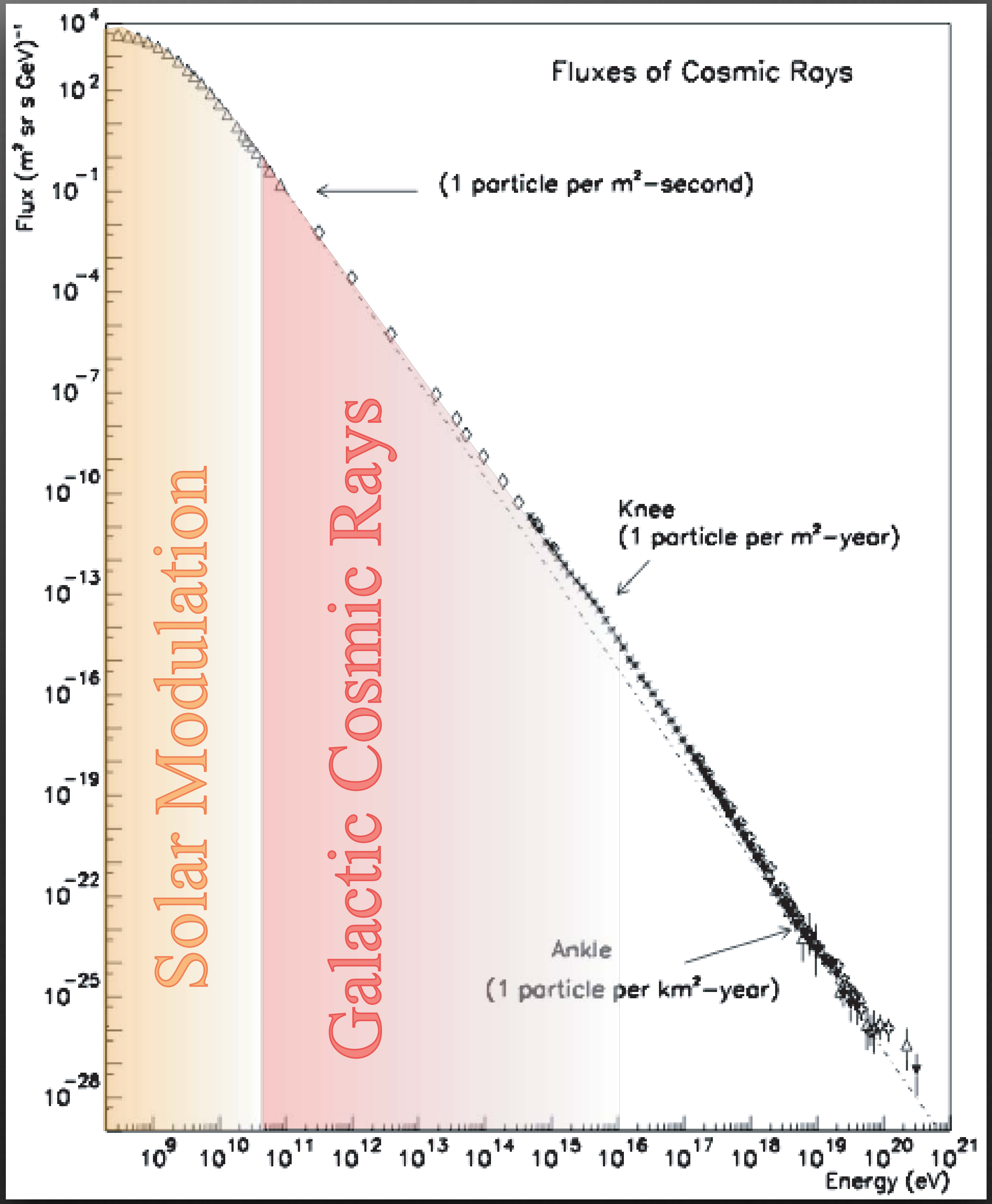
Energy spectrum

The cosmic-ray spectrum

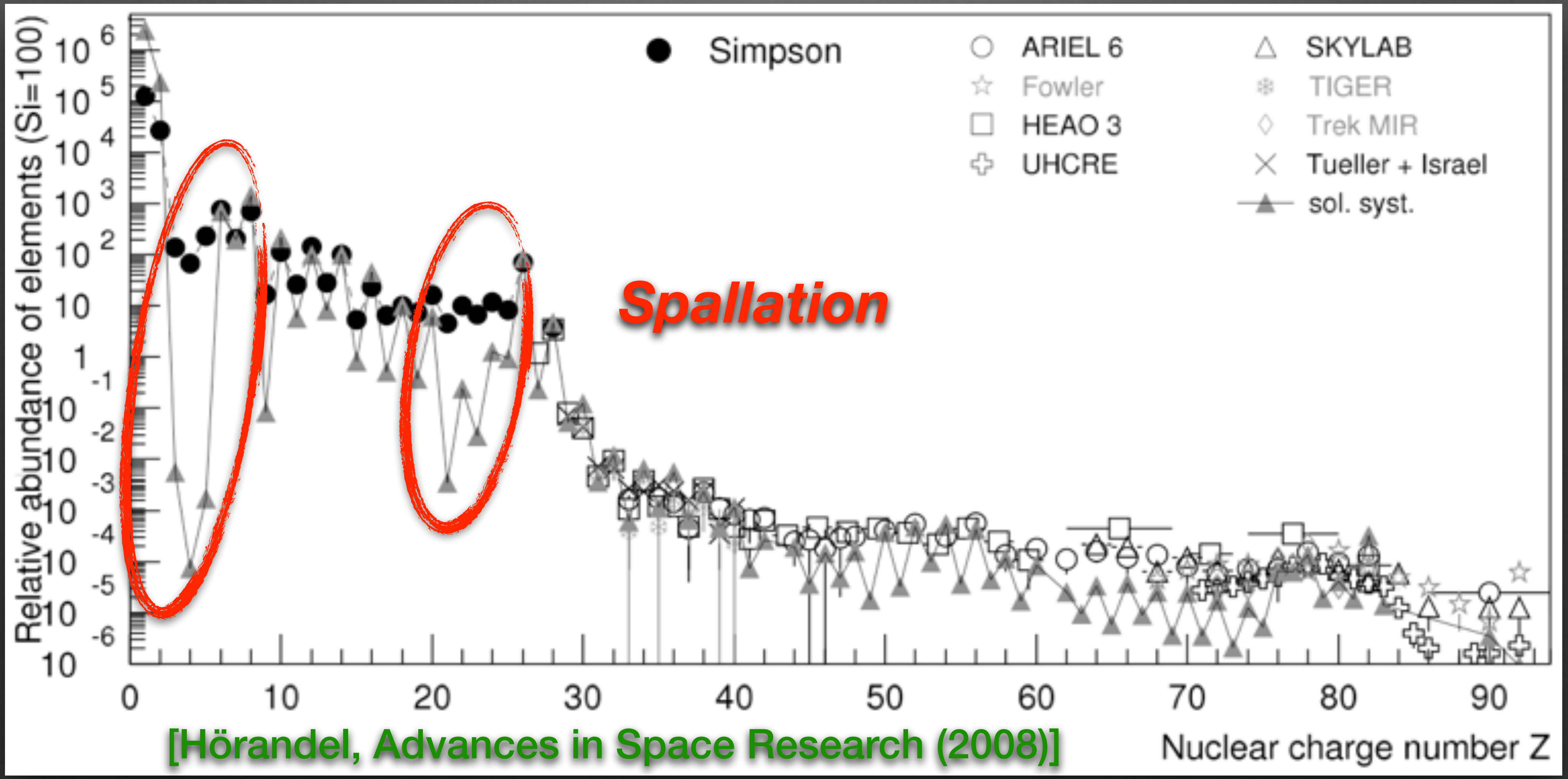
- extends over 12 orders of magnitude in energy and 32 of magnitude in intensity,
- can be described by a simple power law:

$$\frac{\mathrm{d}N(E)}{\mathrm{d}E} \propto E^{-\gamma}$$

- has three major features:
  - the knee at ~ $4.5 \cdot 10^{15}$ eV
  - the ankle at ~ $4 \cdot 10^{18}$ eV
  - a cut-off at ~ $4 \cdot 10^{19}$ eV



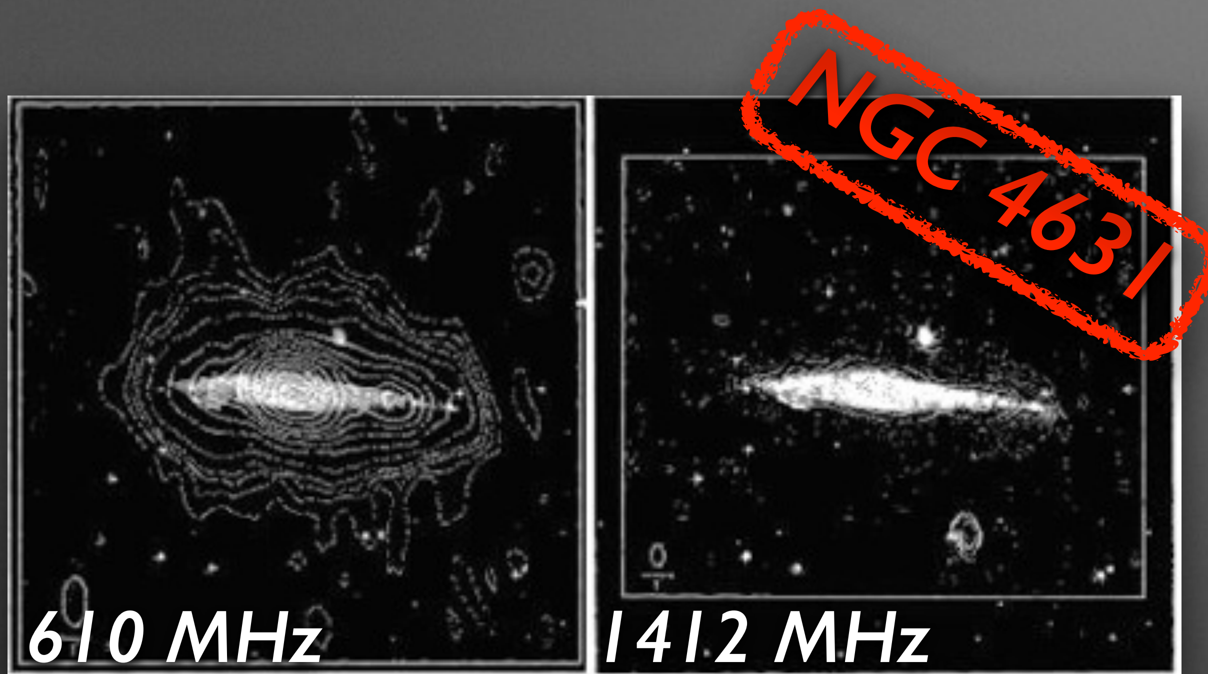
Composition & abundances



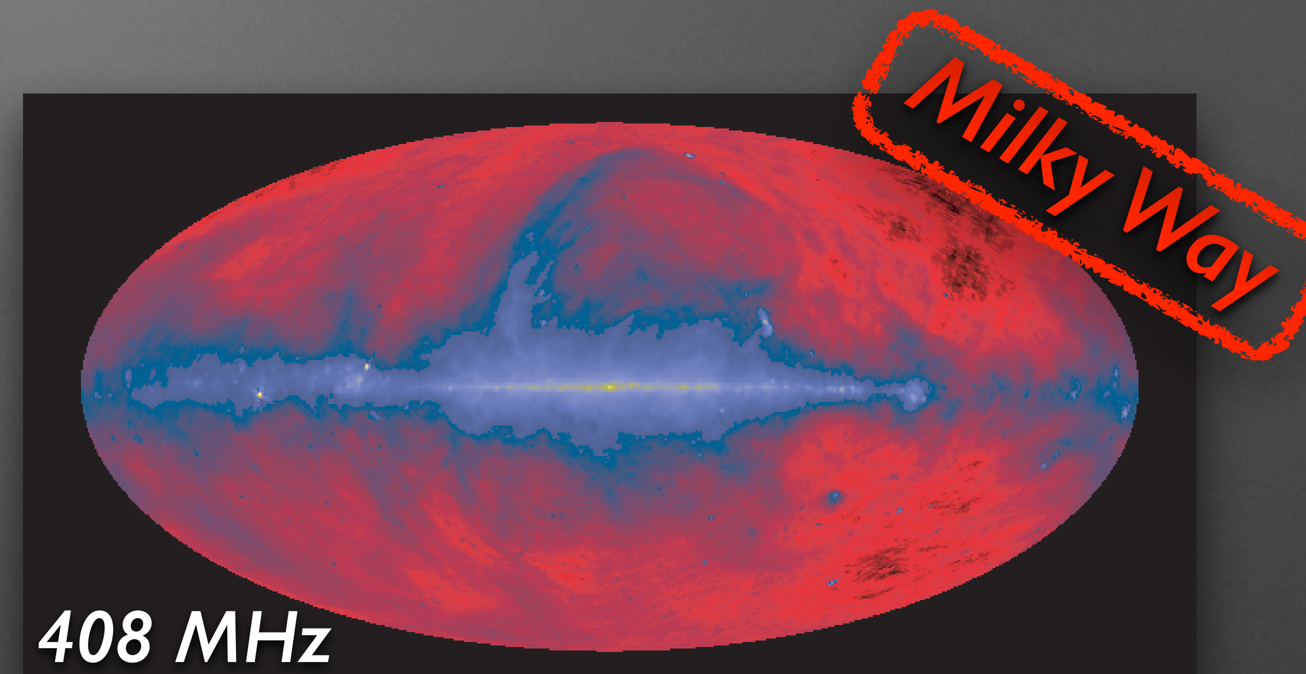
- 87% Hydrogen
- 12% Helium
- 1% heavier nuclei

similar abundances to those in the solar system, but overabundances for elements Z = 3 — 5, 20 — 25, …

Spatial distribution of Galactic cosmic rays



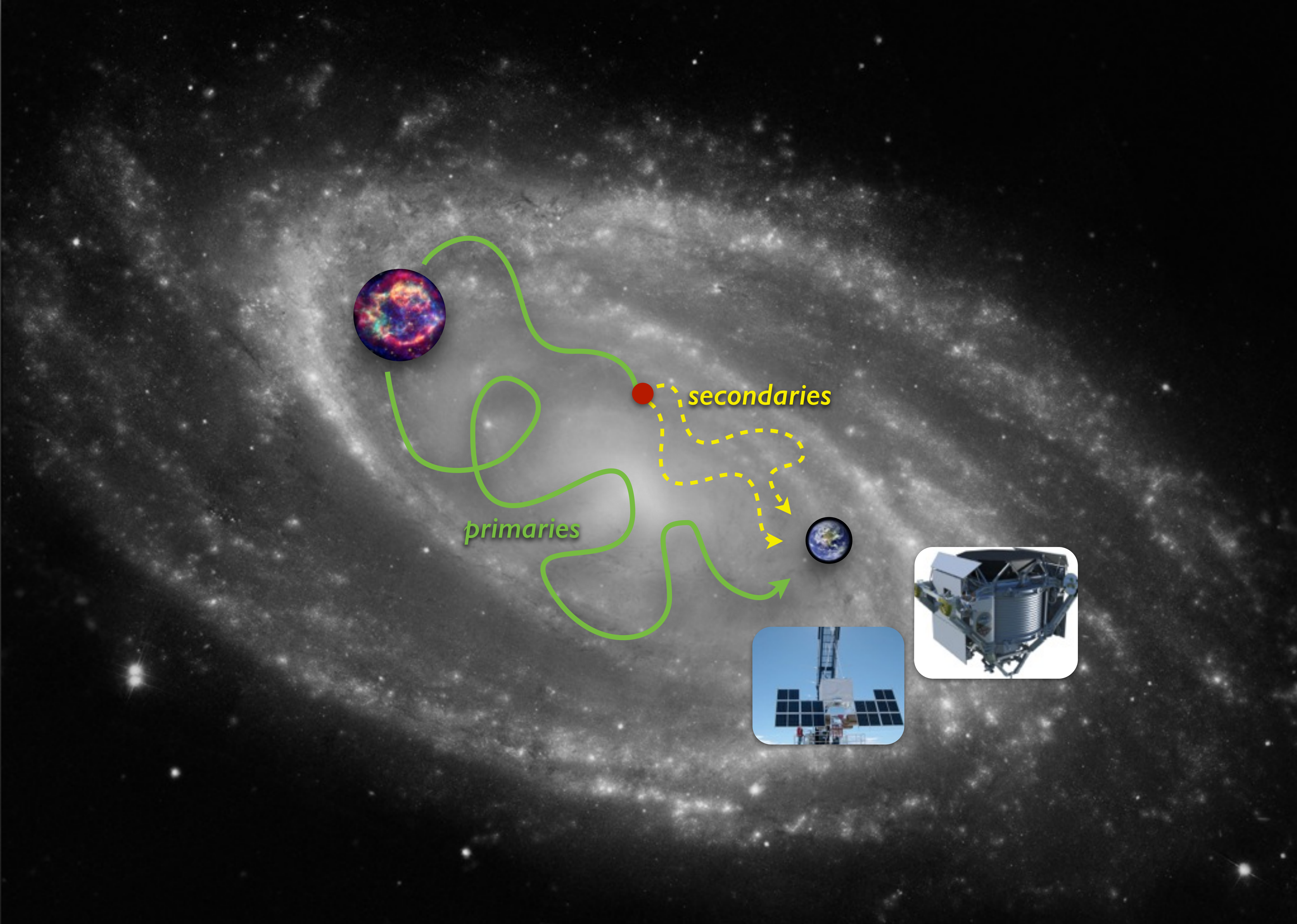
[Ekers & Sancisi, A&A (1977)]



[Haslam *et al.*, A&AS (1982)]

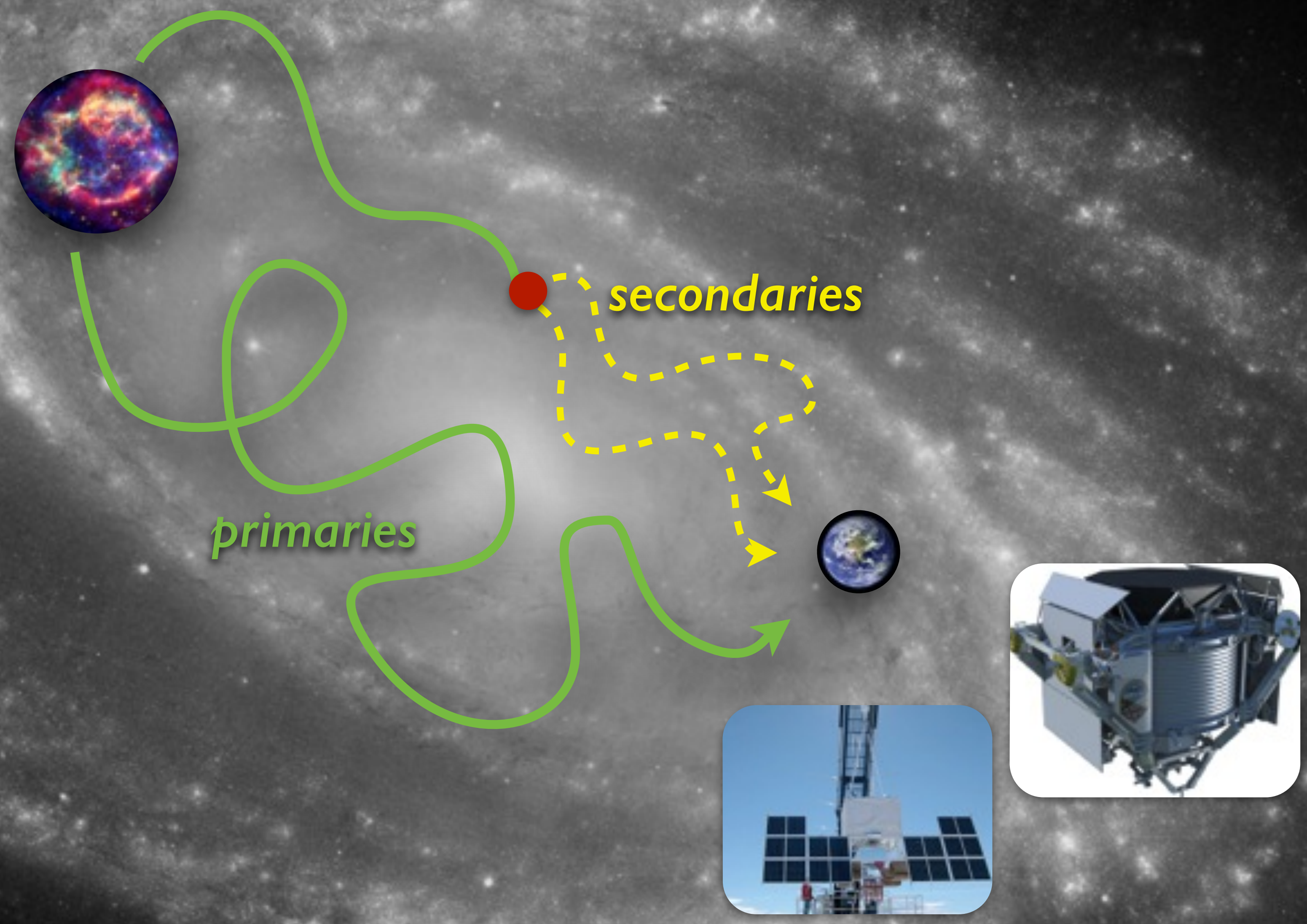
radio halo (few kpc) due to cosmic rays around the galactic disc

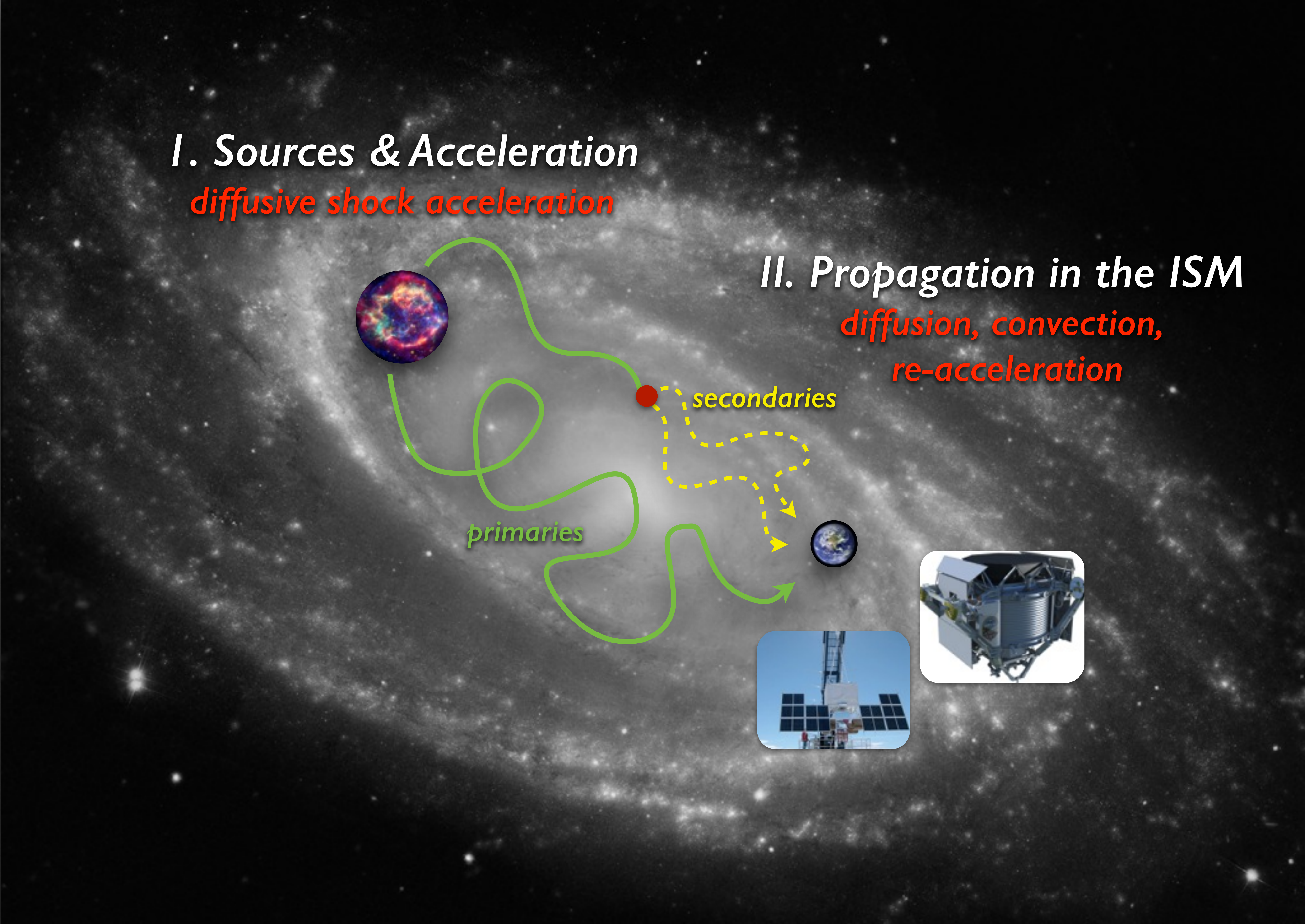
→ galactic diffusive halo

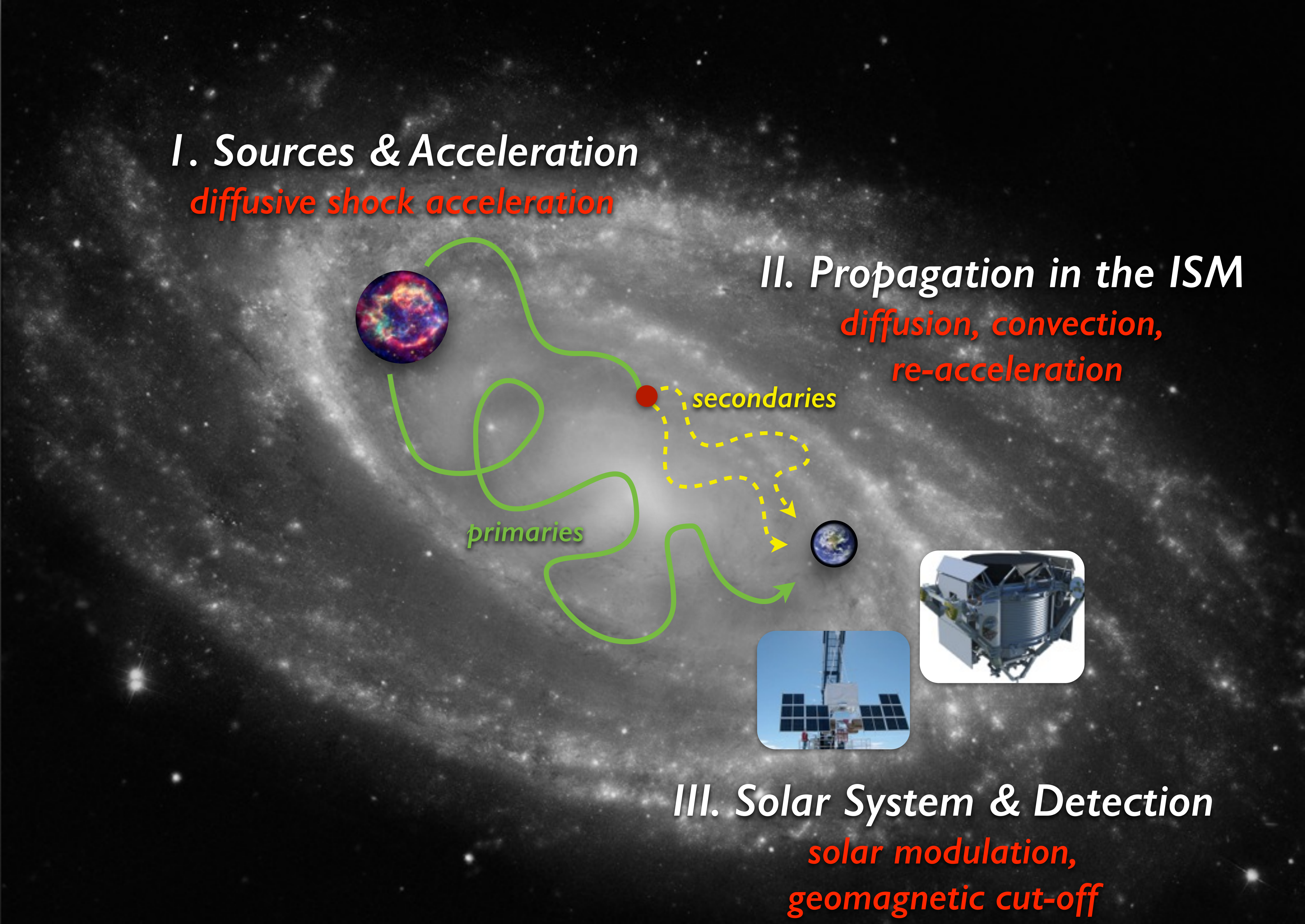

secondaries
primaries

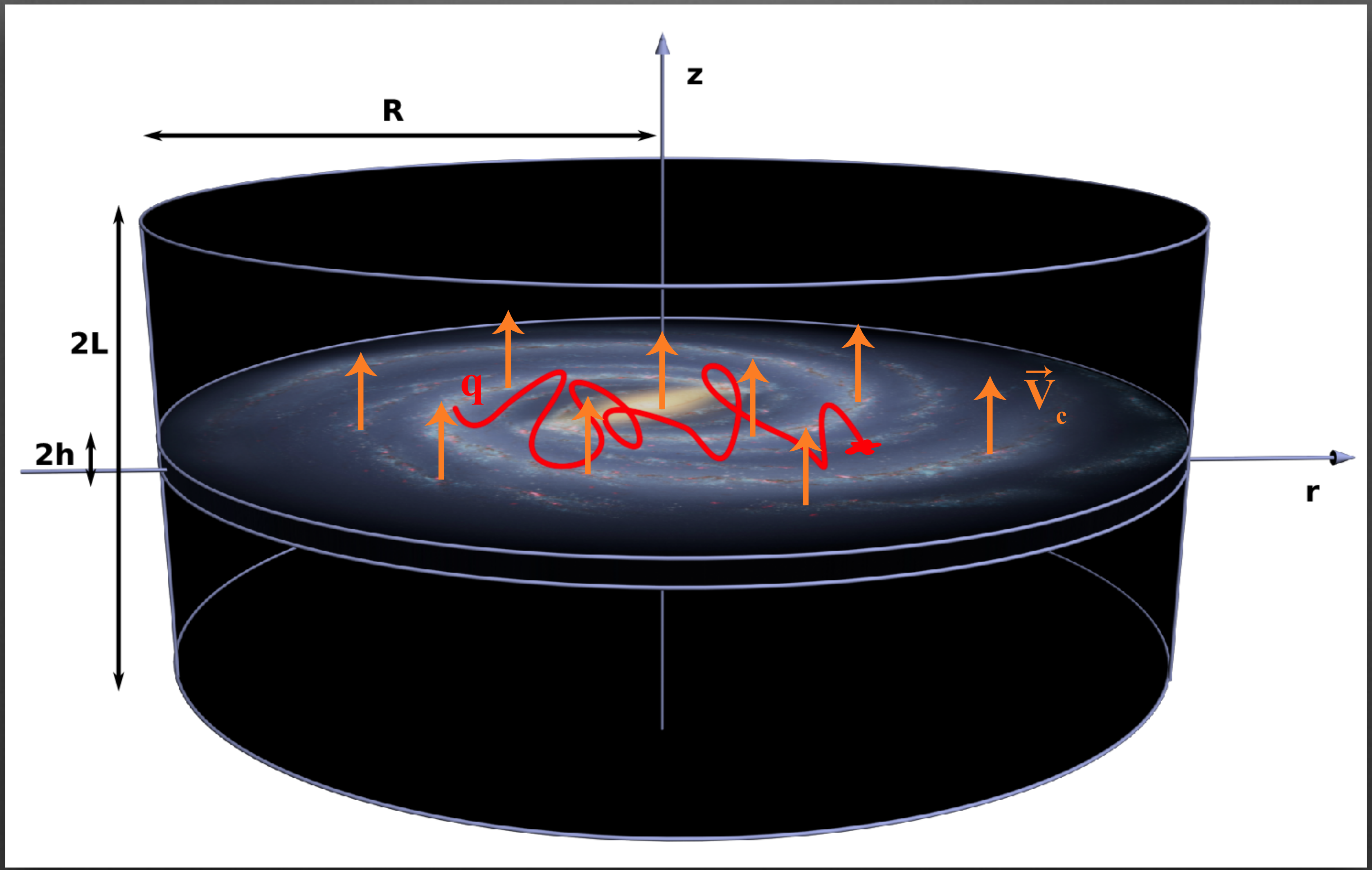
I. Sources & Acceleration

diffusive shock acceleration




I. Sources & Acceleration
diffusive shock acceleration
II. Propagation in the ISM
diffusion, convection,
re-acceleration
secondaries
primaries


I. Sources & Acceleration
diffusive shock acceleration
II. Propagation in the ISM
diffusion, convection,
re-acceleration
secondaries
primaries
III. Solar System & Detection
solar modulation,
geomagnetic cut-off



$$\frac{\partial N}{\partial t} = \underbrace{q}_{\text{sources}} + \underbrace{\vec{\nabla}\cdot(\hat{K}_{xx}\vec{\nabla}N - \vec{V}_c N)}_{\text{spatial diffusion \& convection}} + \underbrace{\frac{\partial}{\partial p}p^2 K_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}N}_{\text{momentum diffusion}}$$

$$- \underbrace{\frac{\partial}{\partial p}\left[\frac{\partial p}{\partial t}N - \frac{p}{3}\left(\vec{\nabla}\vec{V}_c\right)N\right]}_{\text{energy losses}} - \underbrace{\frac{1}{\tau_s}N}_{\text{spallation}} - \underbrace{\frac{1}{\tau_r}N}_{\text{radioactive decay}}$$

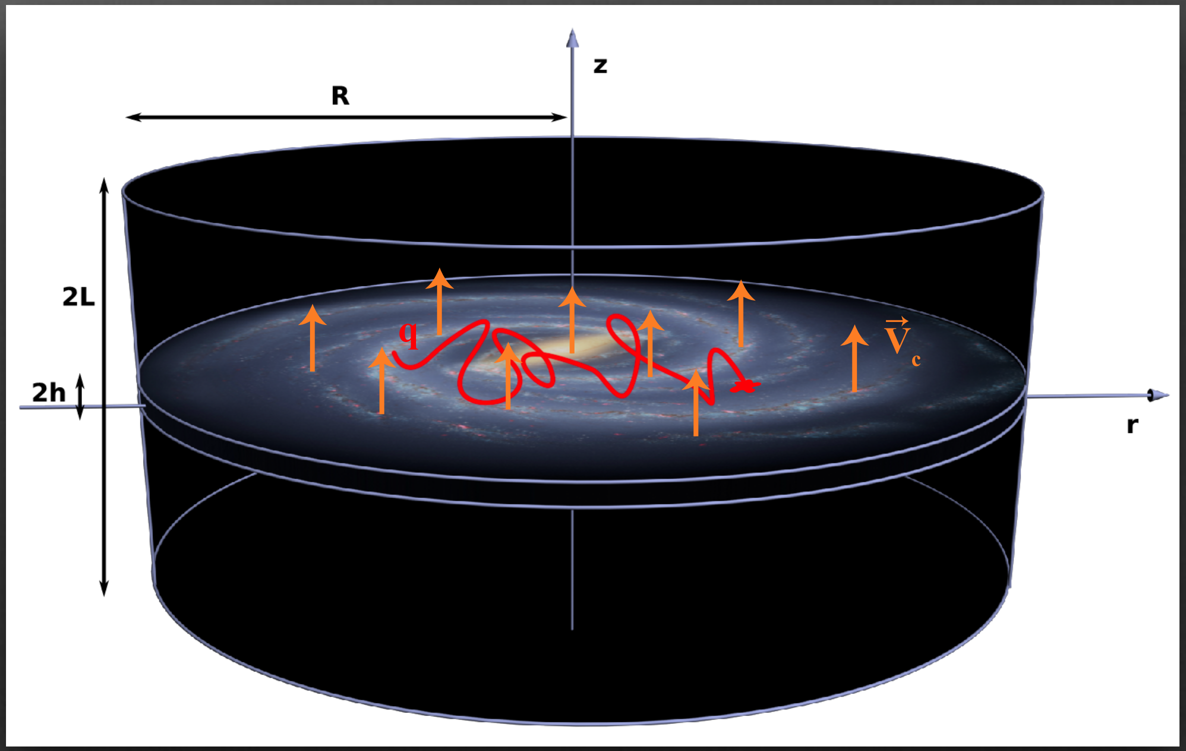
Cosmic-ray transport equation

Diffusion Model

Diffusion equation becomes solvable assuming a cylindrical geometry of the Galaxy with 2 zones: the galactic disc & the diffusive halo

- Semi-analytical approach
  e.g. USINE @ lpsc.in2p3.fr/usine
  ✅ fast computation
  ⛔ simplified description of the interstellar medium

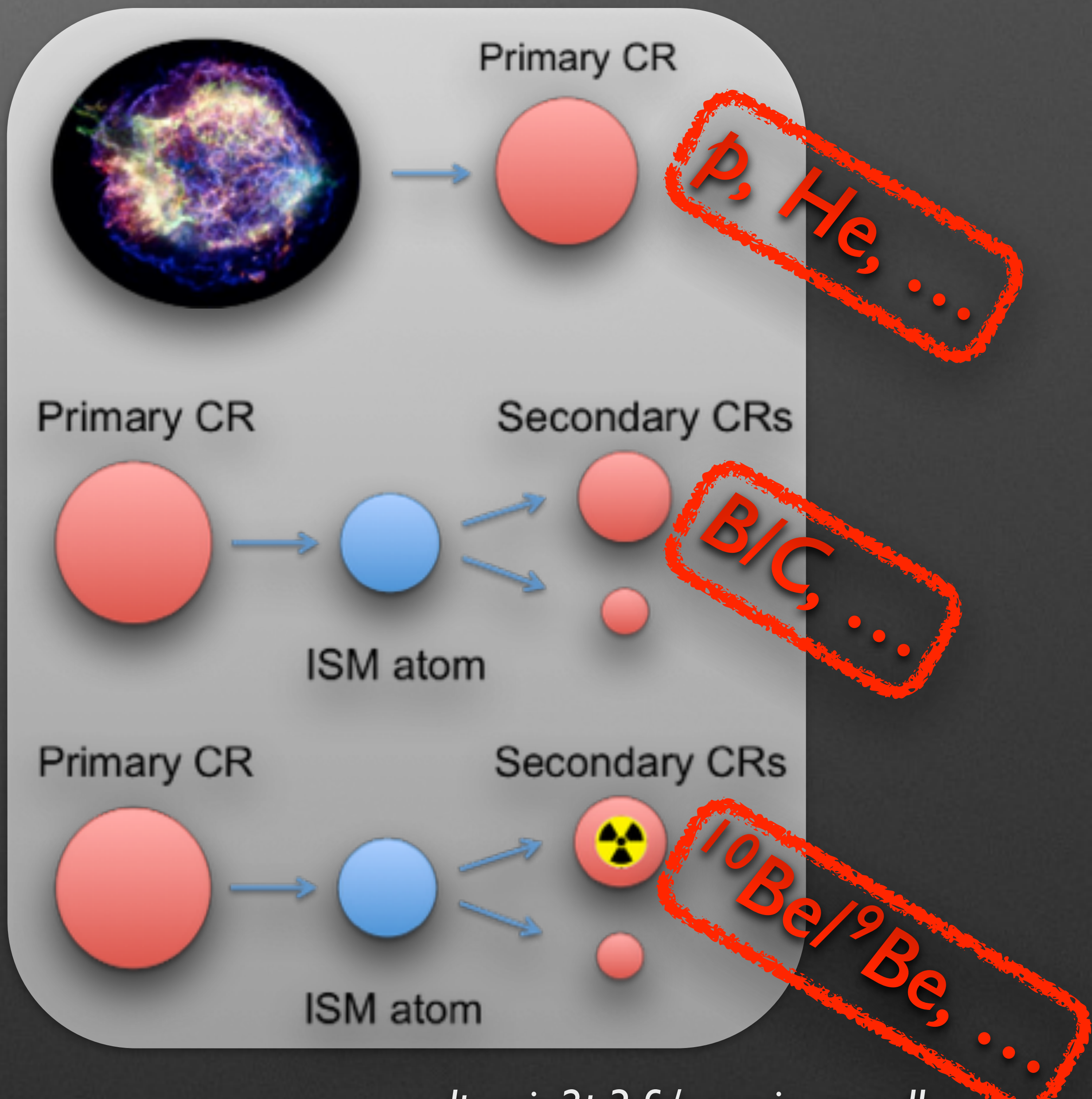
- Numerical approach
  e.g. GALPROP @ galprop.stanford.edu
  ✅ data based description of the interstellar medium
  ⛔ very slow



Parameters and observables

The most important parameters are linked to

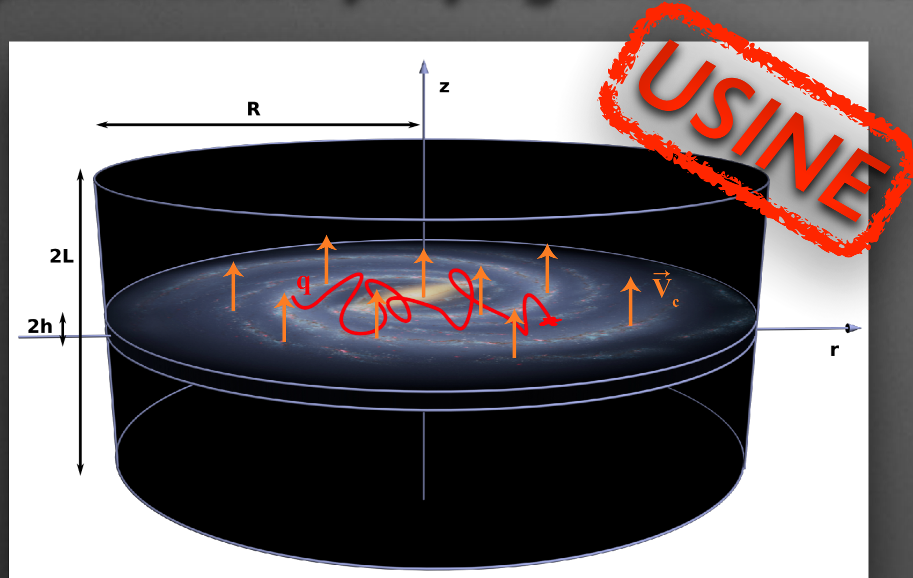
- the acceleration mechanisms
  injection spectrum: $Q(R) \propto qR^{-\alpha}$
- the propagation mechanisms
  diffusion: $K(R) \propto K_0 R^{\delta}$
  convection: V_C
  re-acceleration: V_A
- the geometry of the Galaxy
  diffusive halo size: L



lpsc.in2p3.fr/cosmic-rays-db

Constraining propagation models

sophisticated propagation models



precise experimental data

sophisticated statistical tools

parameters

observables

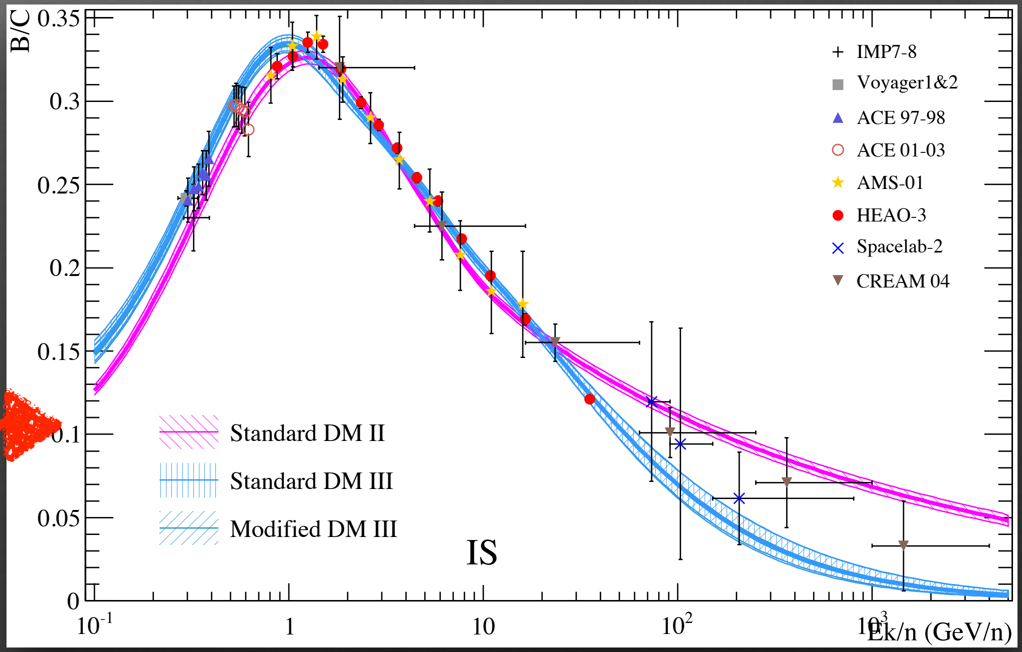
6 publications [AP, Coste, Derome, Donato, Maurin, Perotto, Taillet (2009 - 2014)]

Which model is the best?

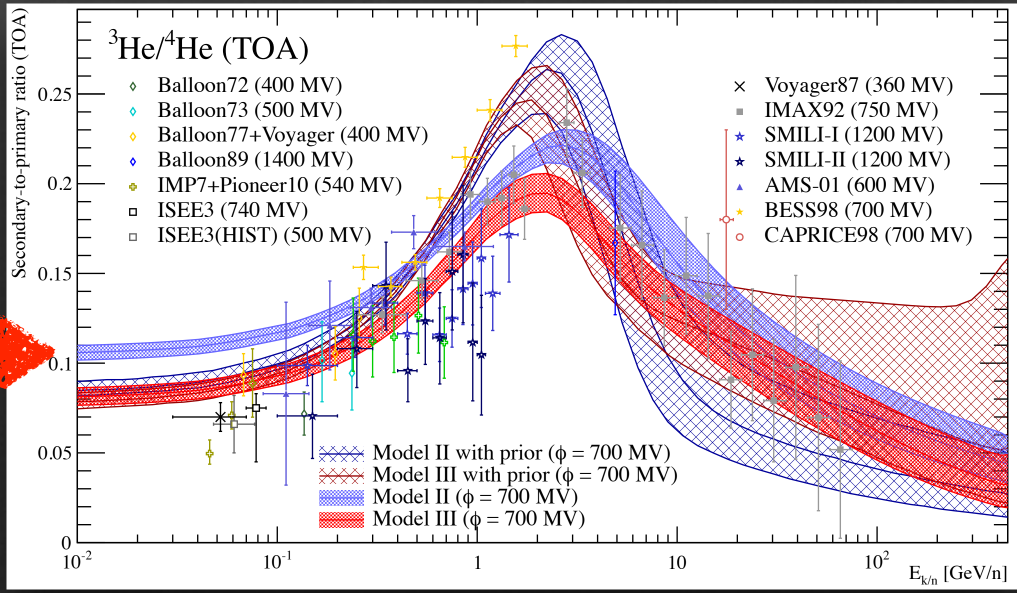
Diffusion models with re-acceleration and/or convection preferred, but diffusion slope δ varies from 0.3 to 0.8

Same results for

- B/C
  ✅ abundant
  ✅ elemental separation needed
  [AP, Derome, Maurin, A&A (2010)]



- ^{3}He/^{4}He
  ✅ very abundant
  ⛔ isotopic separation needed
  [Coste, Derome, Maurin, AP, A&A (2012)]



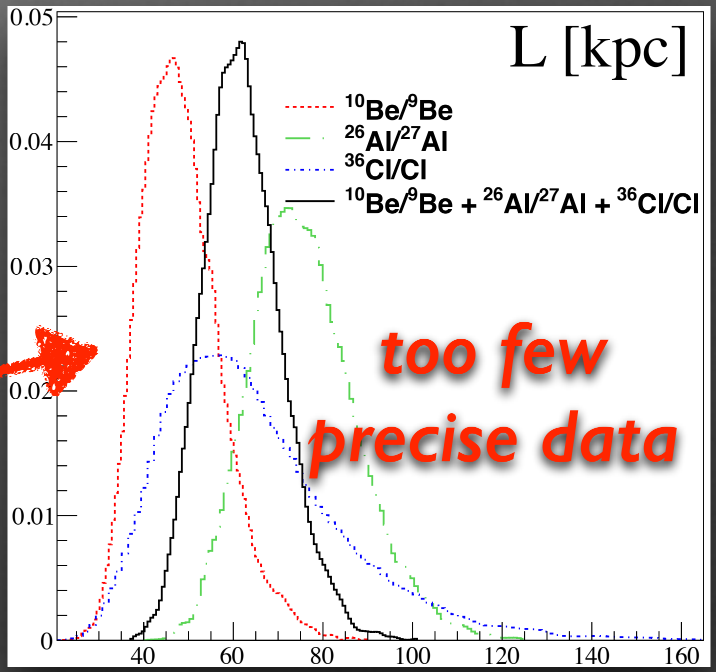
How big is the diffusive halo?

L determines the amount of dark matter in cosmic rays!

first PDF of L from an MCMC analysis with radioactive secondaries

very sensitive to the LISM

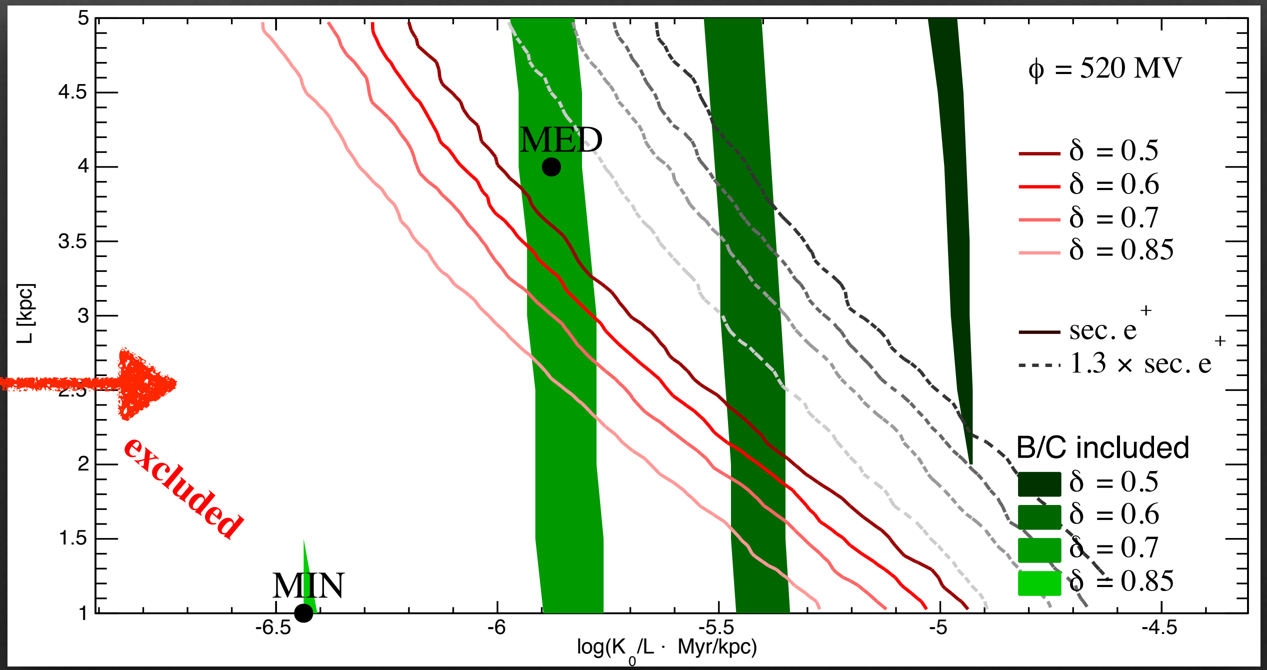
[AP, Derome, Maurin, A&A (2010)]



first direct exclusion of small values of L with low-energy secondary positrons

sensitive to solar modulation

[Lavalle, Maurin, AP, arXiv:1407.2540]

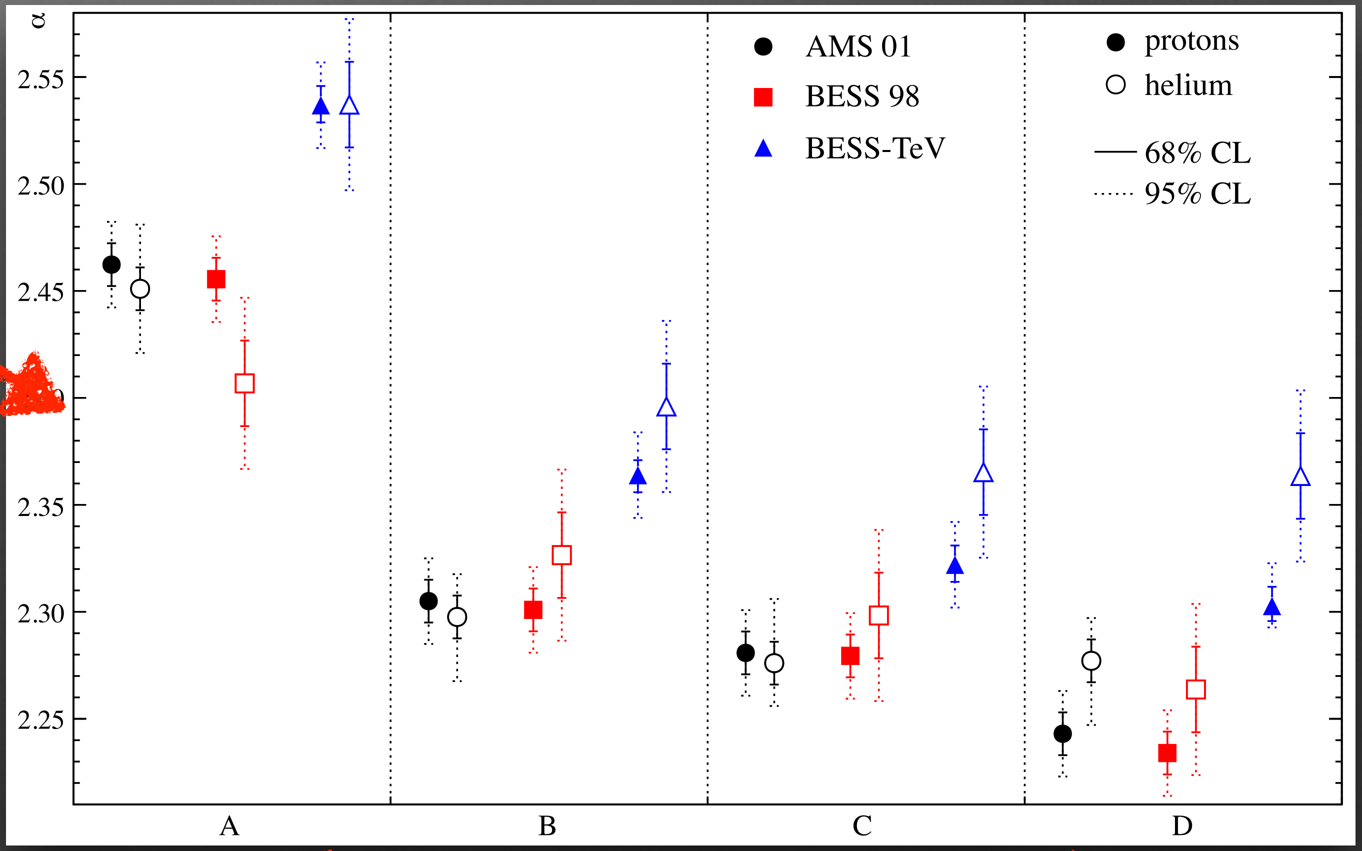


What the primaries tell us...

source slope **2.25** $\leqslant \alpha \leqslant$ **2.5** for diverse propagation models

source slope α similar for all primaries Z = 1, ..., 26

→ universality of the acceleration mechanism

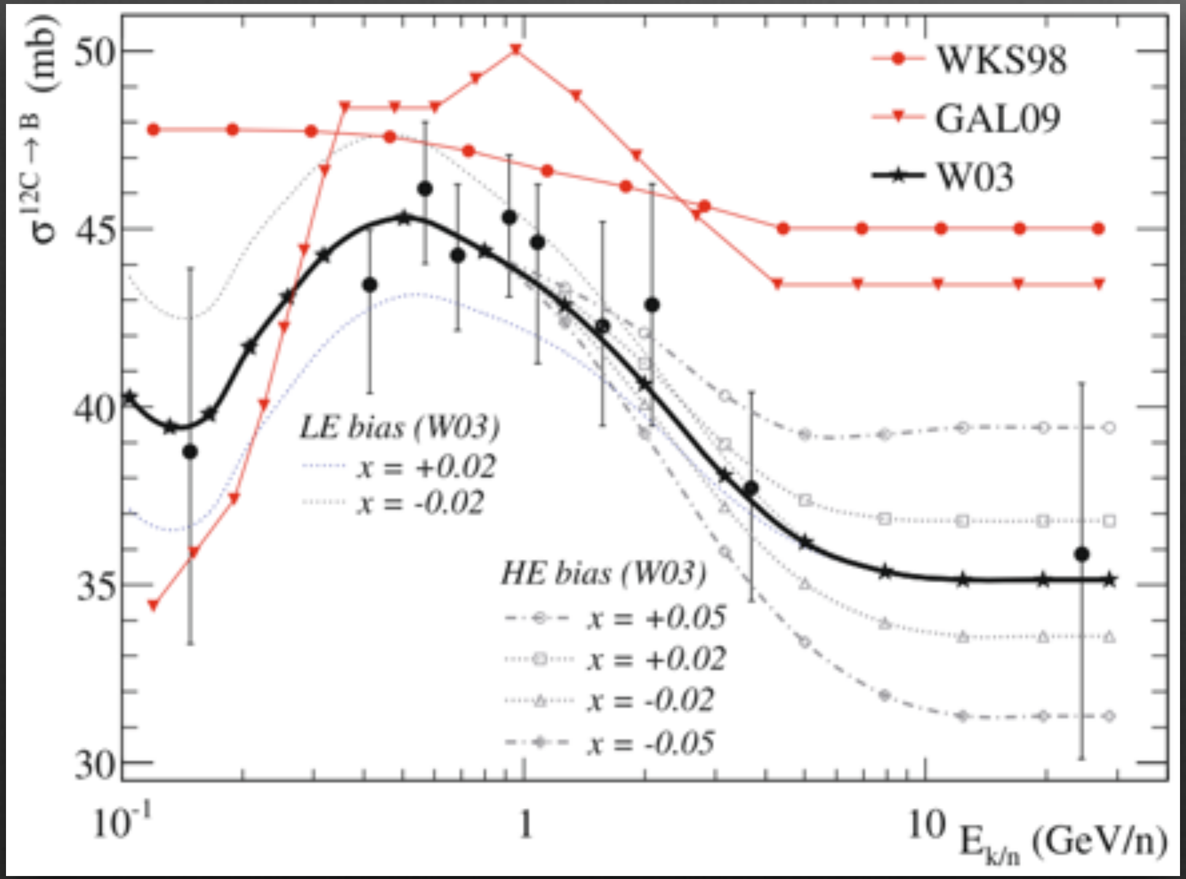


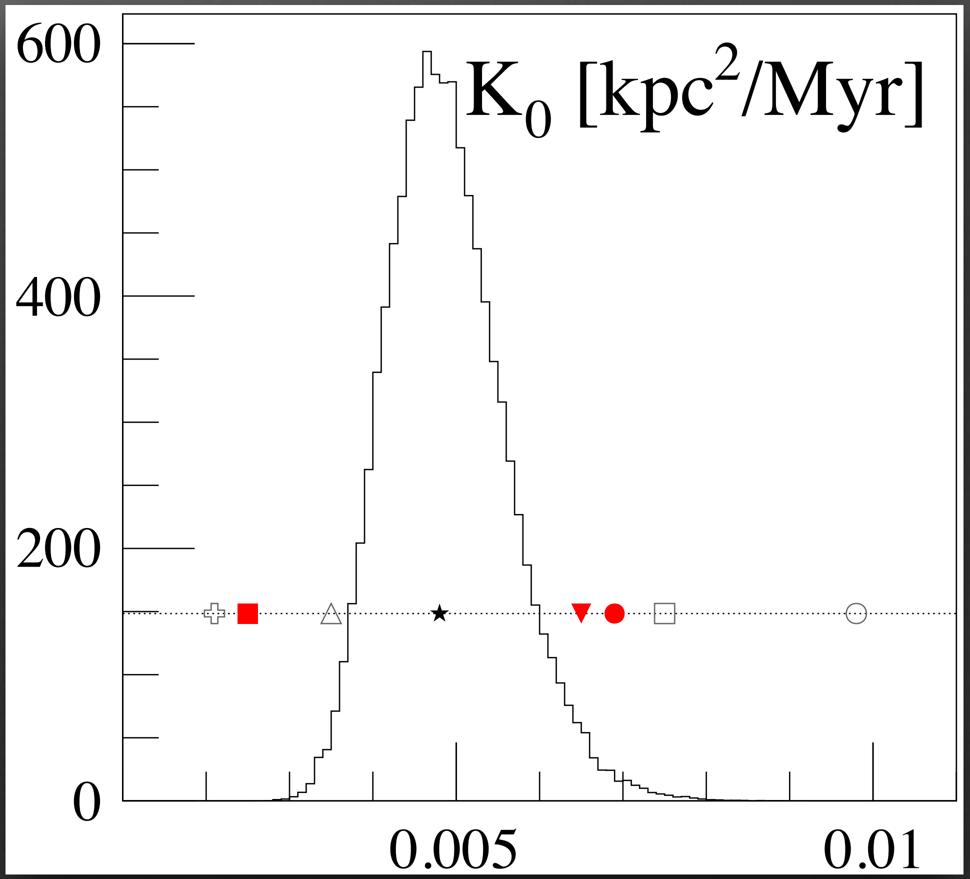
different propagation models

[AP, Maurin, Donato, A&A (2011)]

What about systematics?

Precise cosmic-ray measurements give small statistical uncertainties, and systematic uncertainties from model ingredients are dominating!

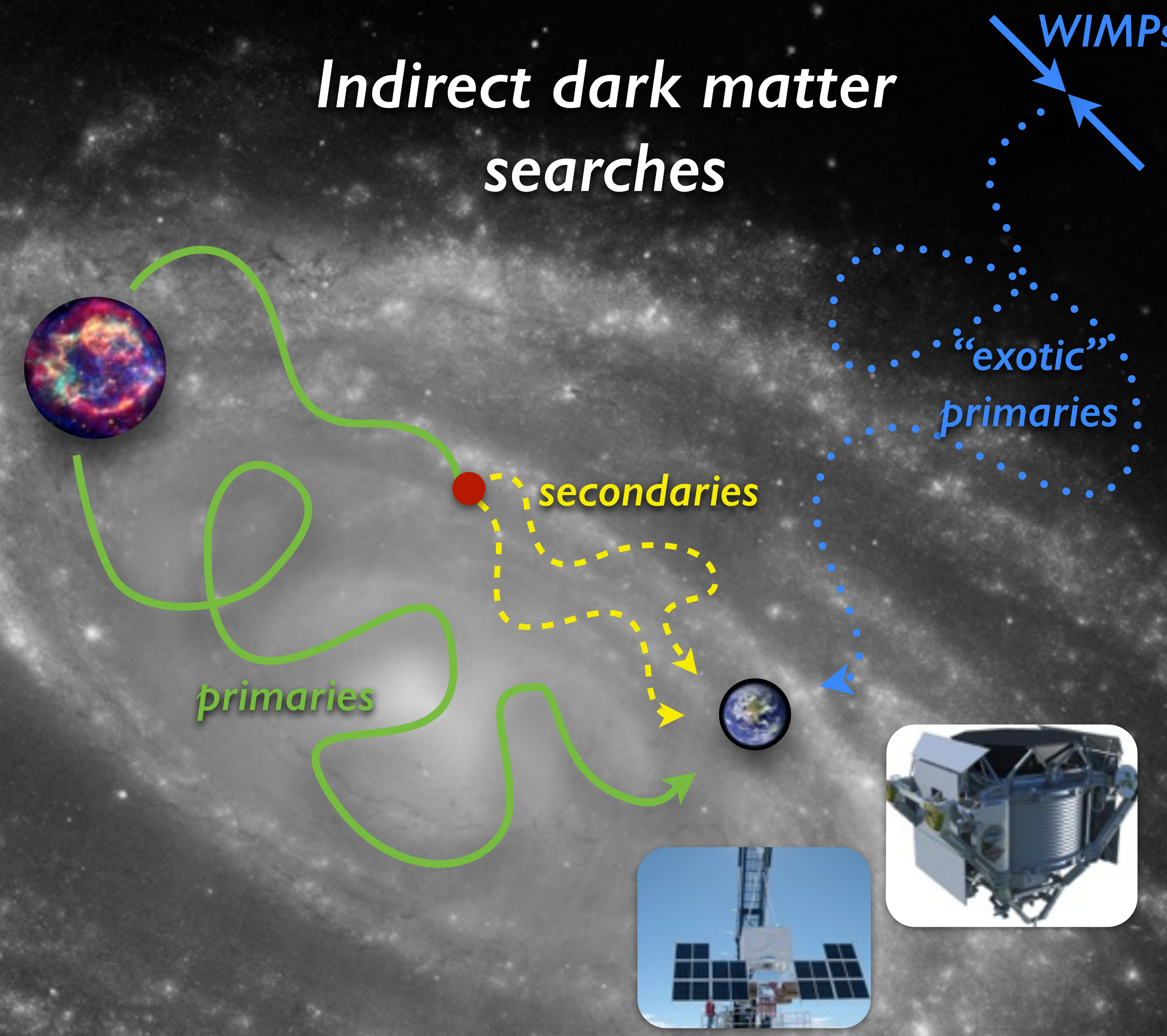




Parameter estimation already very tricky in a simple configuration…

[Maurin, AP, Derome, A&A (2010)]

Indirect dark matter searches



charged cosmic-ray channels: $e^+, \bar{p}, \bar{d}, \ldots$

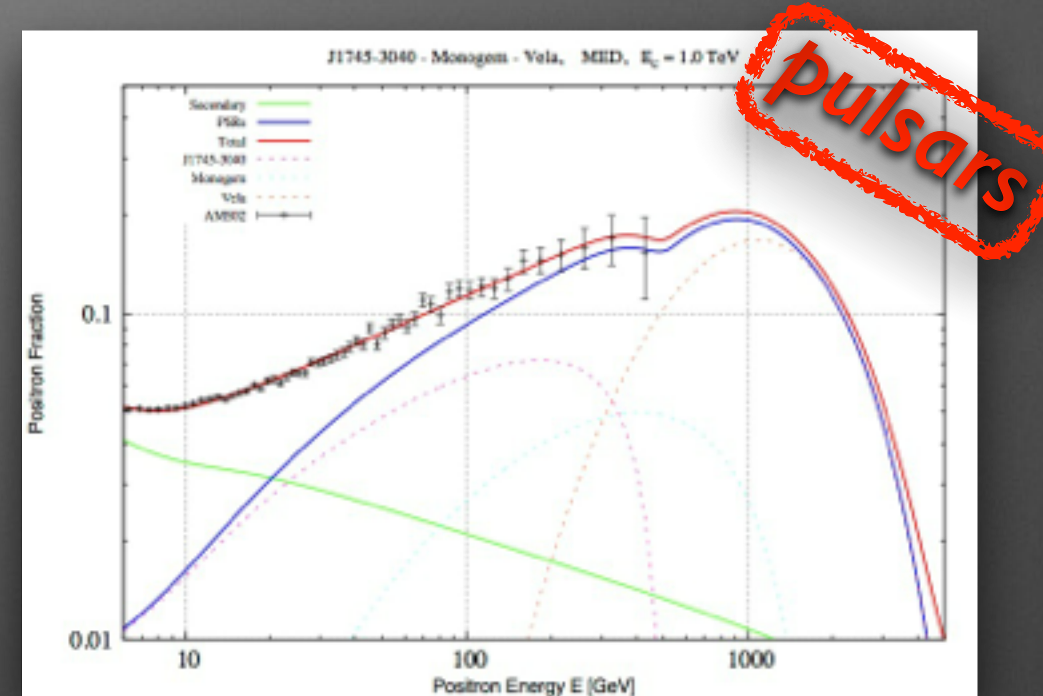
Positrons — difficult probes for dark matter searches

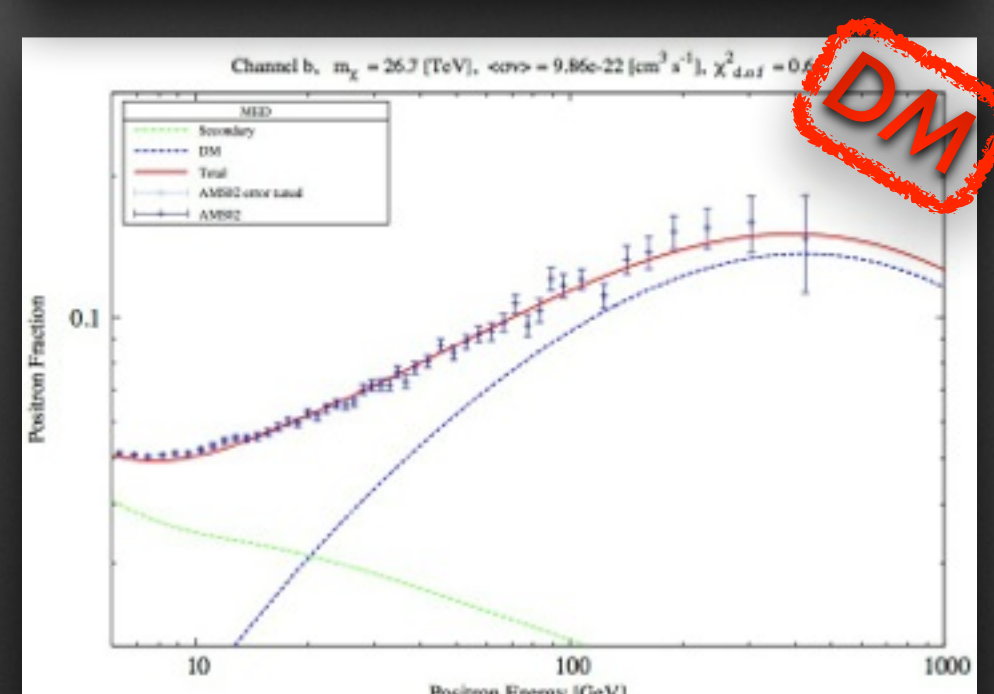
Well modelled with

- secondaries:
  ✅ diffusion models
  ⛔ uncertainties on propagation parameters

- primaries:
  ✅ pulsars, dark matter annihilation/decay, acceleration of secondaries in sources, …
  ⛔ very large uncertainties
  ⛔ large boost factor needed for dark matter interpretation

but no unique interpretation…

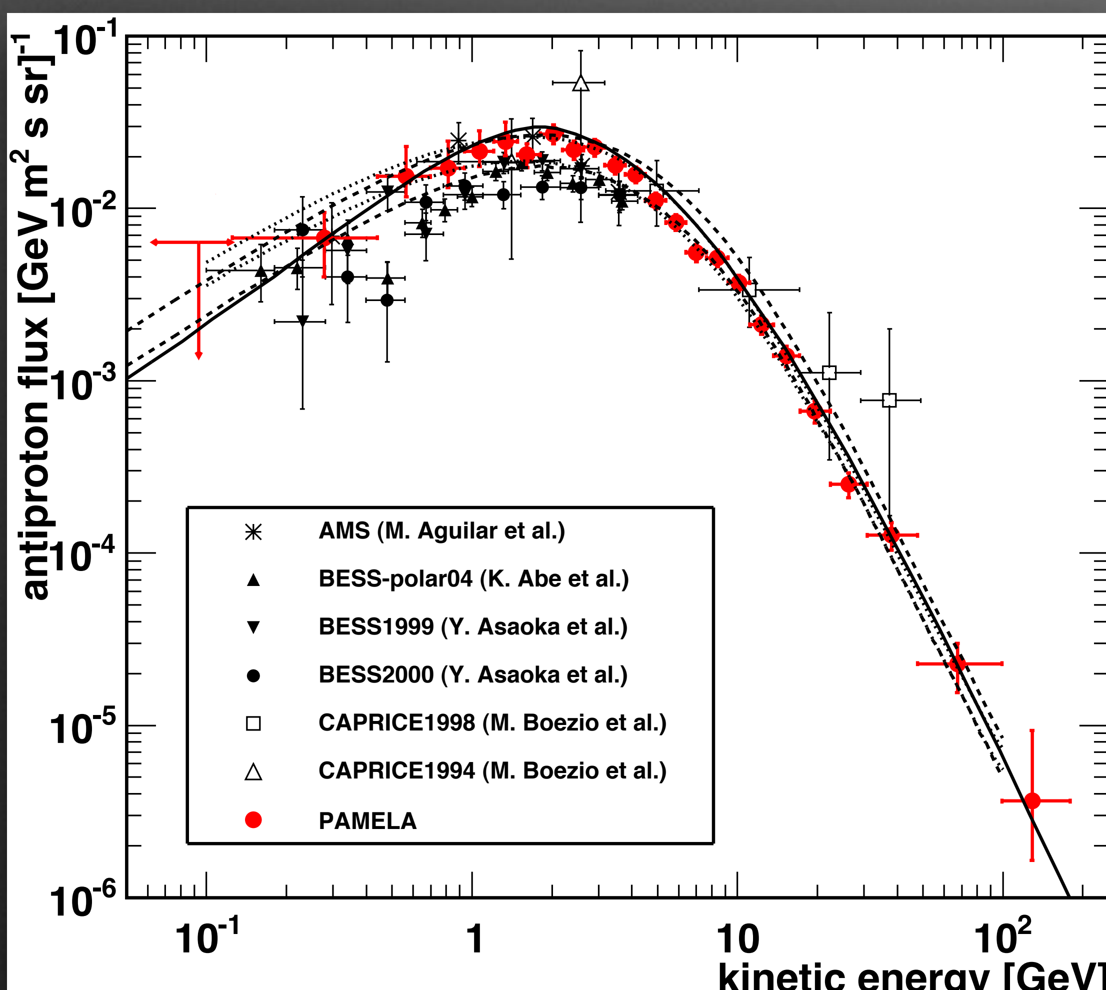


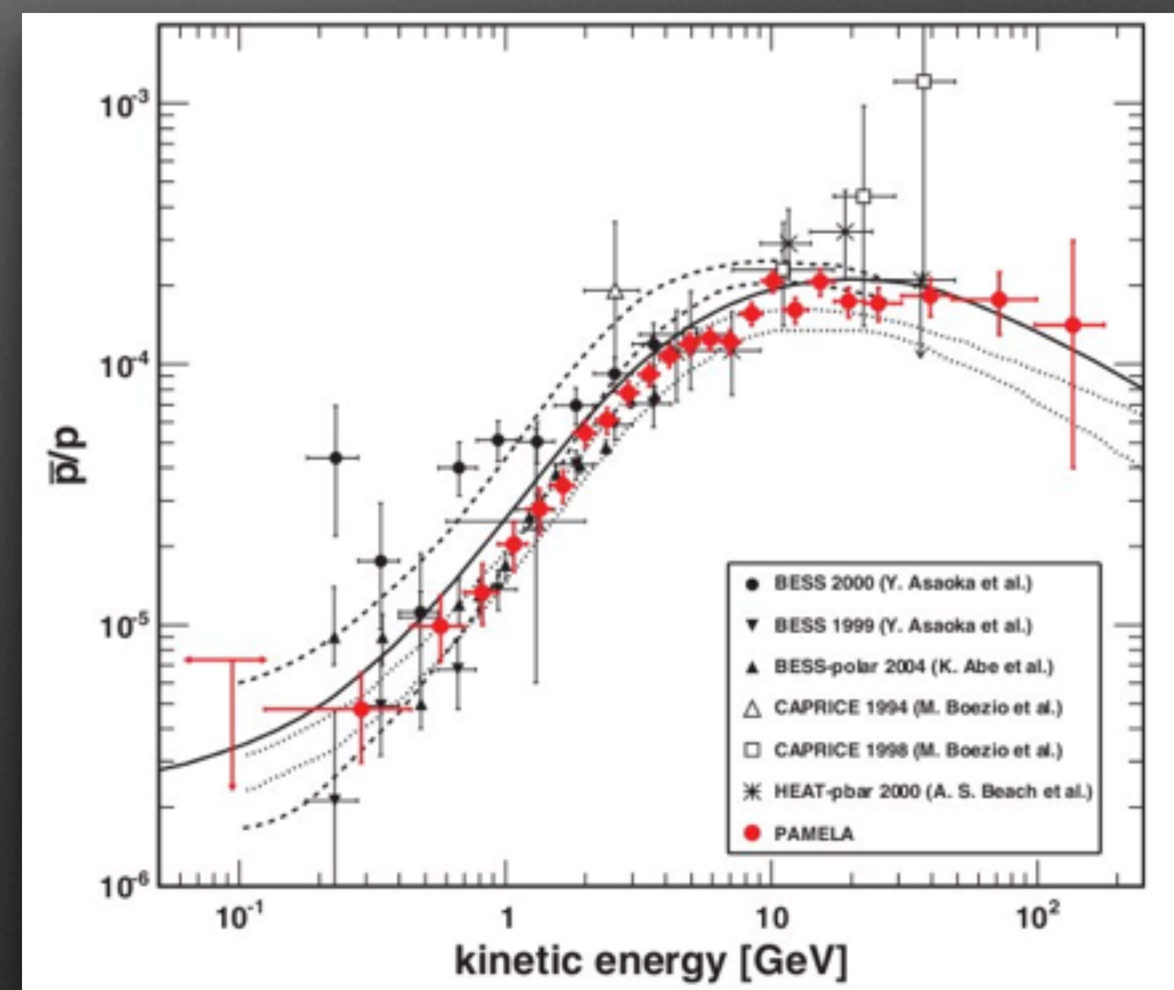


[Boudaud, AP, *et al.*, A&A (in preparation)]

Antiprotons — strong constraints for dark matter

Recent antiproton measurements in very good agreement with a pure secondary origin



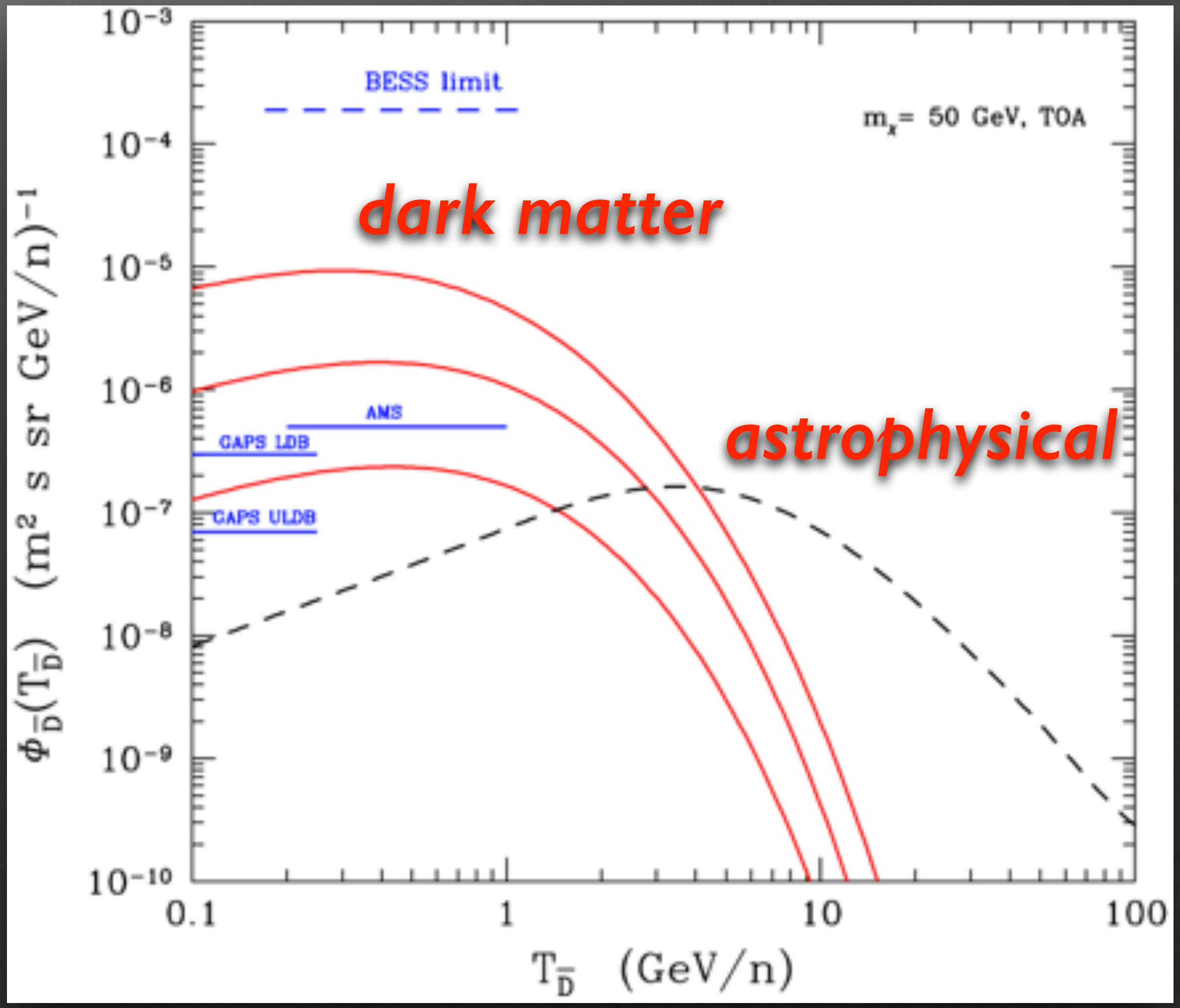


[Adriani *et al.*, PRL (2010)]

Anti-deuterons — the future?

excellent target for indirect dark matter searches due to its high signal-to-noise ratio [Donato, Fornengo, Salati, PRD 2000]

- high production threshold of ~17 m_p
- production at rest
  ✅ dark matter annihilation
  ⛔ astrophysical production
- low binding energy
  ✅ disintegration
  ⛔ energy losses

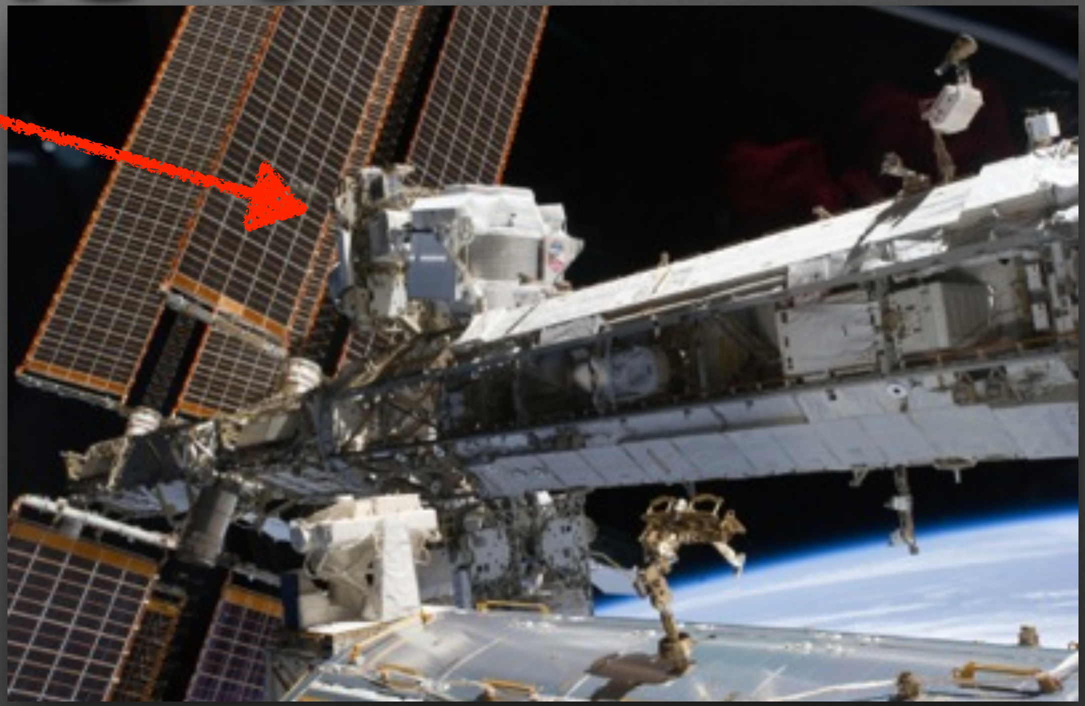


[Donato, Fornengo, Maurin, PRD 2008]

No cosmic-ray anti-deuteron detected so far, but GAPS is coming soon…

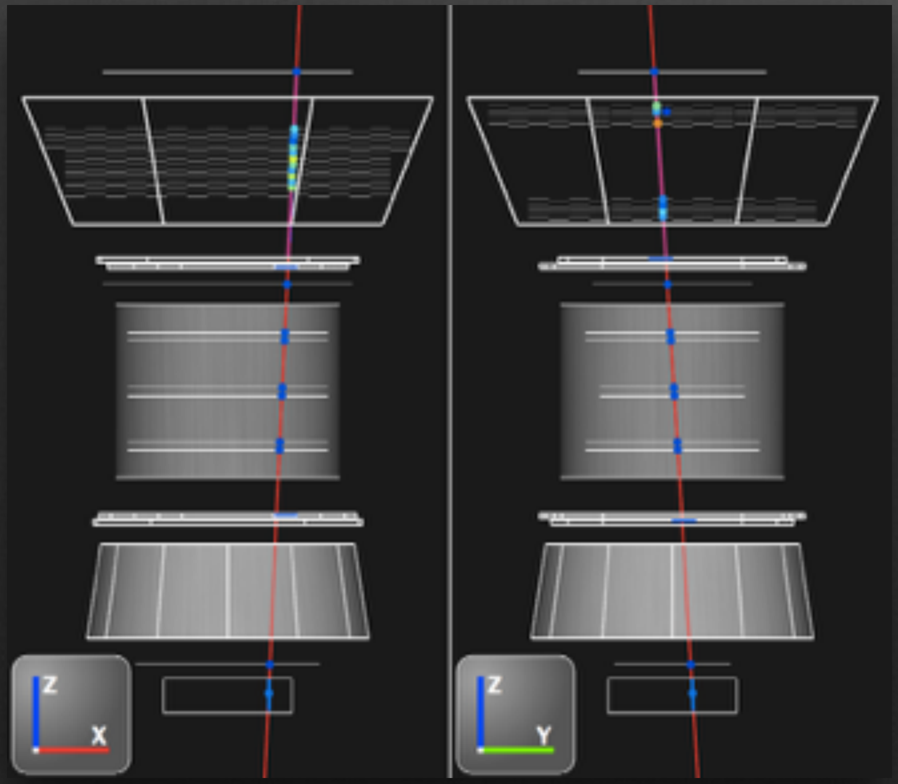
New data is coming ... from AMS-02

Alpha Magnetic Spectrometer



experiment installed on the ISS since 19 mai 2011

direct measurement elemental/isotopic fluxes of matter and anti-matter, $10^8 < E < 10^{12}$ eV



Principal sub-detectors and their specificities

TRD: electron-proton separation

TOF: trigger, velocity and charge

Tracker: rigidity, charge sign, charge

RICH: velocity and charge

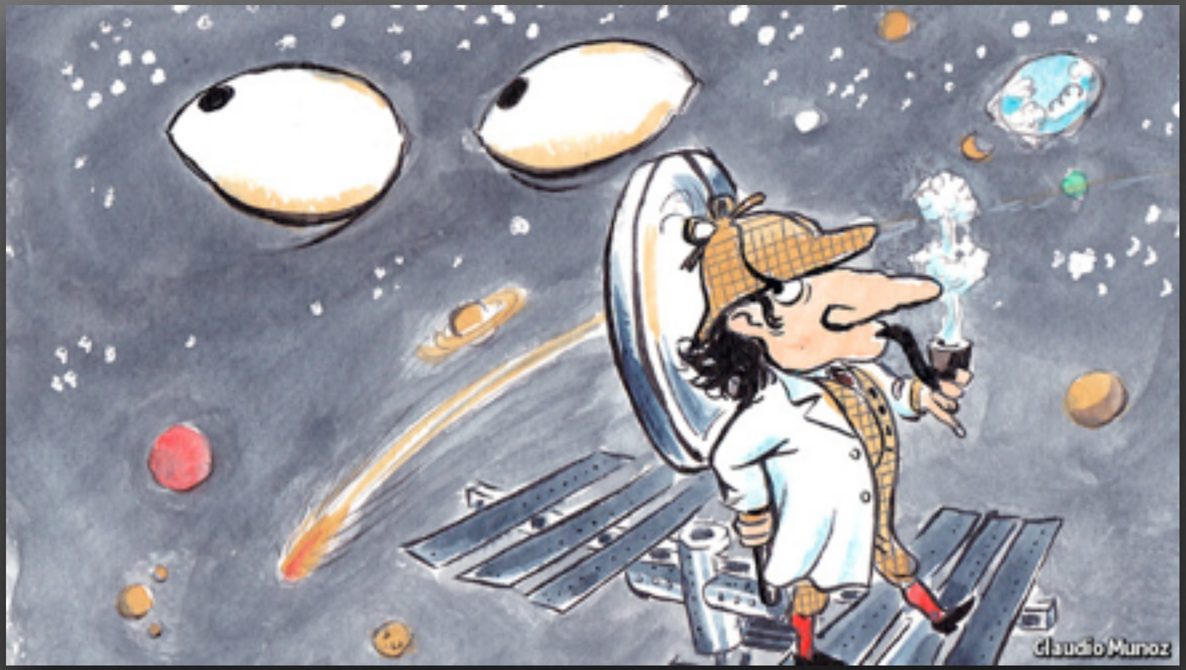
ECAL: electron-proton separation, energy

Conclusion

- Current propagation models suffer from large uncertainties on ingredients
  What you put in is what you get out…

- More and more precise cosmic-ray data will be available soon
  Need for better models/ingredients

- Cosmic rays are complementary and competitive with collider and direct dark matter searches



Are you hunting for dark matter?

- Your dark matter candidate should reproduce all the available data
  → global fits
  → GAMBIT

What is GAMBIT?

Global And Modular BSM Inference Tool

- Flexible and modular design for easy addition of new
  - models
  - experimental data sets and limits
  - scanning algorithms
- Frequentist or Bayesian methods with customisable
  - likelihoods
  - priors
  - nuisance parameters
- A smart and fast LHC likelihood calculator
- Plug'n'Play swapping of physics tools, scanners, likelihoods…
- Open source release

gambit.hepforge.org

Who is GAMBIT?

25 Members — 14 Institutes

P. Athron, C. Balázs, T. Bringmann, A. Buckley, J. Conrad,
J. Cornell, L.-A. Dal, J. Edsjö, B. Farmer, L. Hsu,
P. Jackson, A. Krislock, A. Kvellestad, F.N. Mahmoudi,
G. Martinez, M. Pato, A. Putze, A. Raklev, C. Rogan,
A. Saavedra, C. Savage, P. Scott (PI), N. Serra, C. Weniger,
M. White

10 Experiments

AMS-02, ATLAS, CTA, DARWIN, CDMS, DM-Ice, Fermi-LAT,
H.E.S.S., IceCube, LHCb