Lectures & objectives

ISAPP 2014
(Belgirate)
21-30 July 2014

Transport of cosmic rays in the Galaxy and in the heliosphere (~ 4h30)

- What is GCR (Galactic Cosmic Ray) physics and transport
- Relevant time scales: ≠ species have ≠ phenomenology
- Main modelling ingredients: key parameters and uncertainties
- Tools to solve the transport equation

Charged signals: electrons/positrons, antibaryons (~1h30)

- What is astroparticle physics and DM (Dark Matter) indirect detection
- What are the astrophysical backgrounds + uncertainties [nuclear]
- Phenomenology of DM signals + uncertainties [transport and dark matter]
- Pros and Cons of DM indirect detection with charged GCRs

David Maurin (LPSC)
dmaurin@lpsc.in2p3.fr

Previous episodes

Lecture II: processes, ingredients, characteristic times

→ Different time scales for nuclei and leptons

Lecture III: solving the transport equations and phenomenology

- Microphysics complex (diffusion) → use of simple (effective?) models
- Stable and radioactive nuclei data → constrain source and transport parameters
- High energy e± → local sources matter (steady-state not valid)

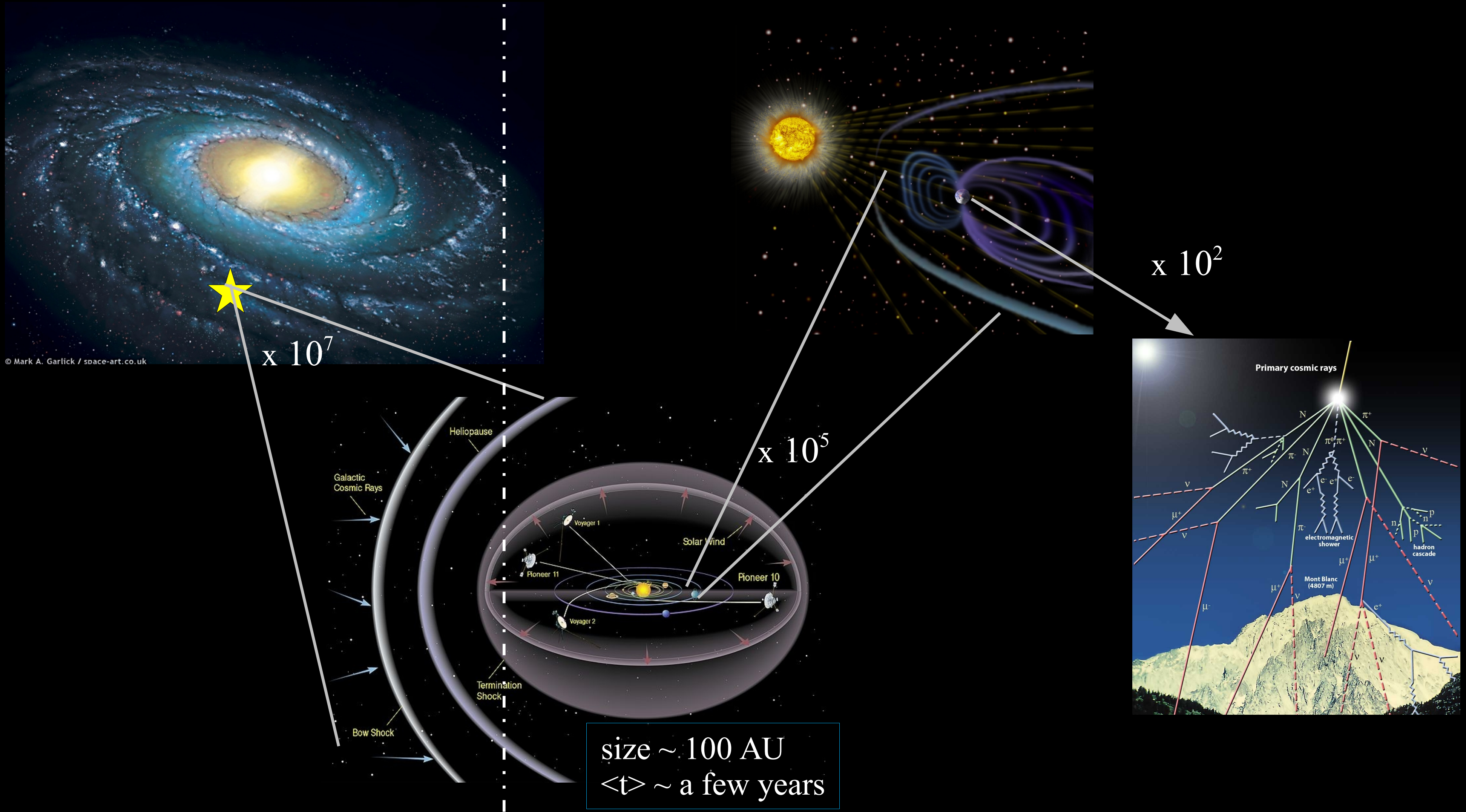
Charged signals: electrons/positrons, antibaryons

Lecture-IV.pdf

An unexpected journey: solar modulation

Interstellar (IS) fluxes
[time independent]

Top-of-atmosphere (TOA) fluxes
[Solar cycle time dependent]



size ~ 100 AU
<t> ~ a few years

→ Unknown at low energy

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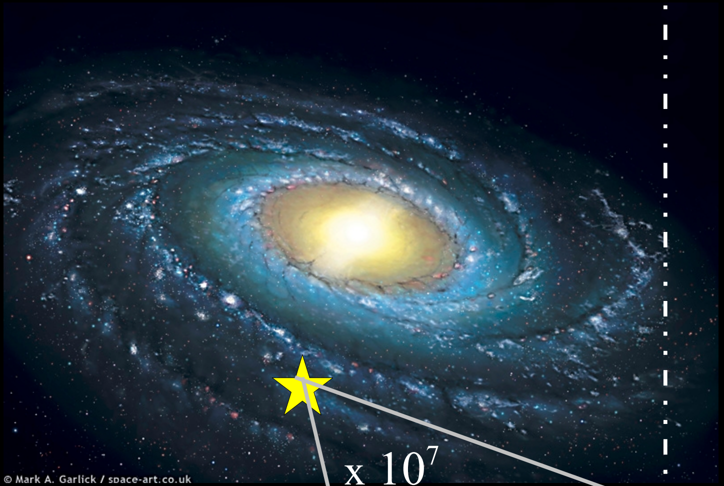
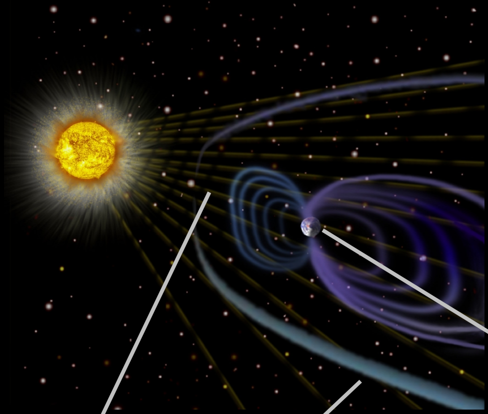
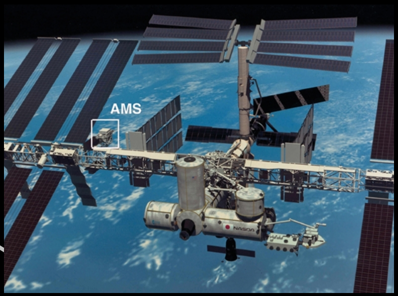
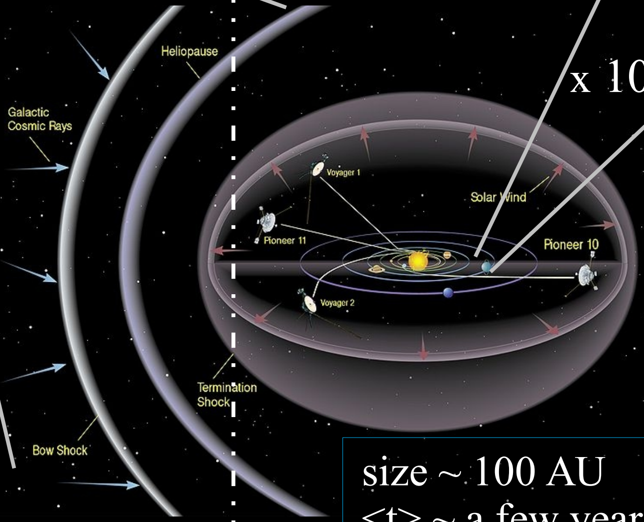


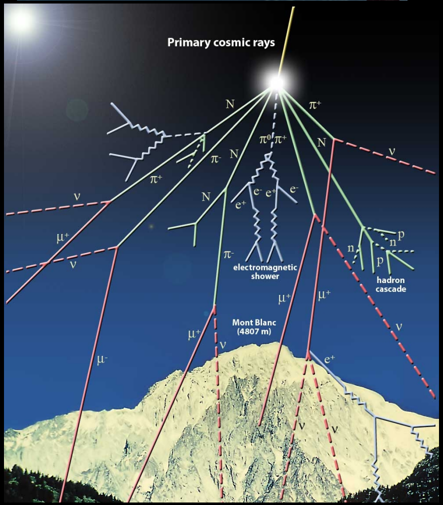
x 10^7





x 10^5





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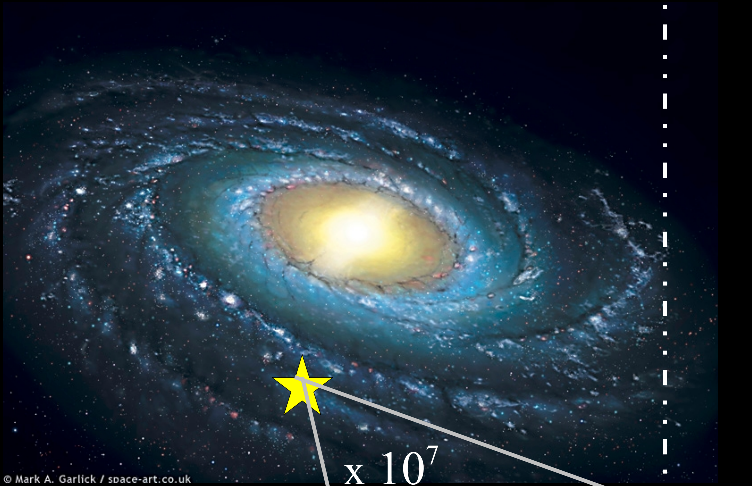

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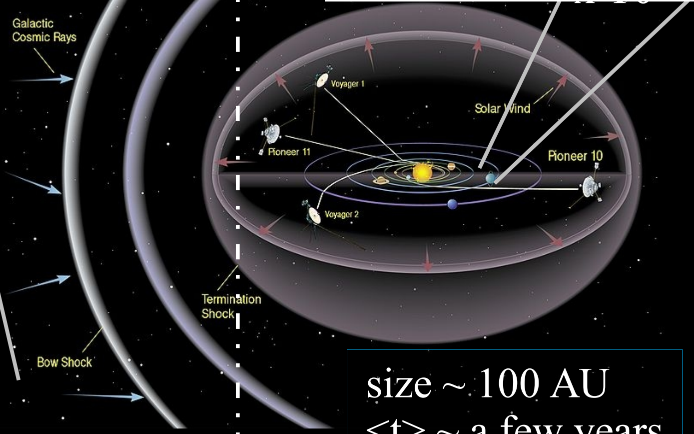

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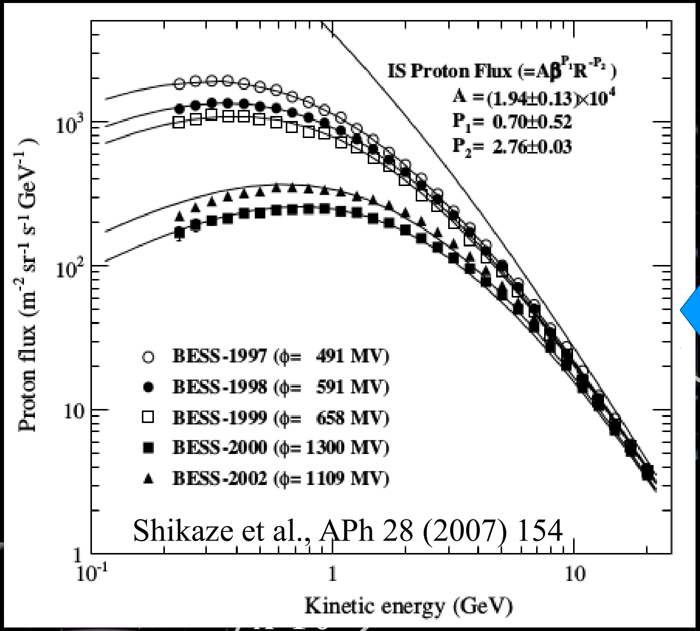
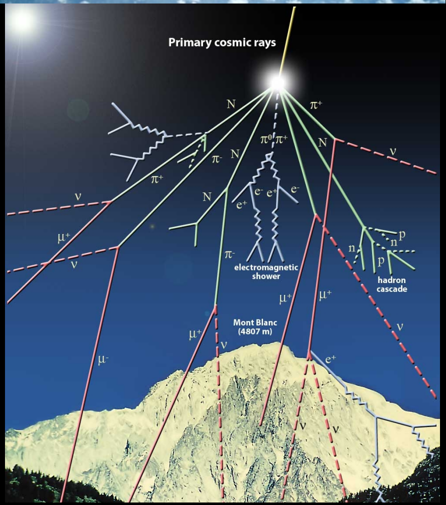
Top-of-atmosphere (TOA) fluxes
[Solar cycle time dependent]



Shikaze et al., APh 28 (2007) 154



Q1: is a low GCR flux associated to a quiet or active sun?
Q2: what about the time evolution of secondary particles in ground detectors?

An unexpected journey: solar modulation

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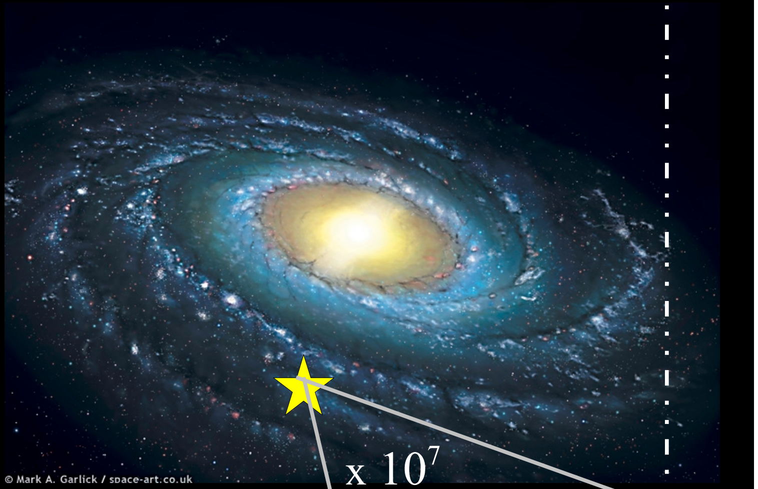
[Solar cycle time dependent]



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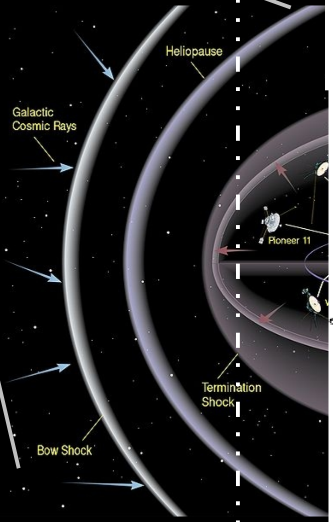

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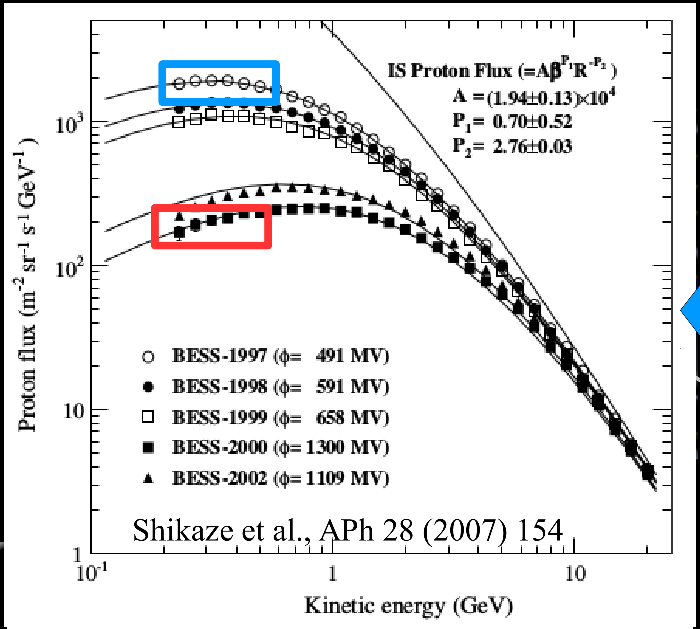

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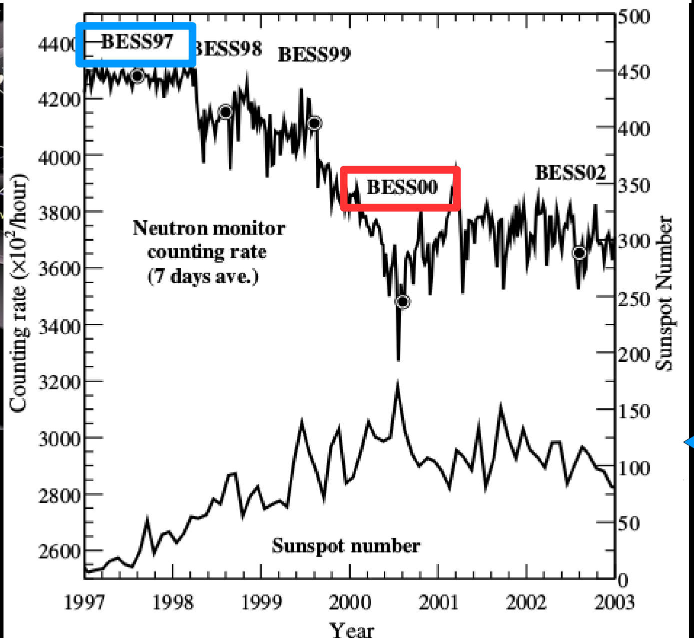

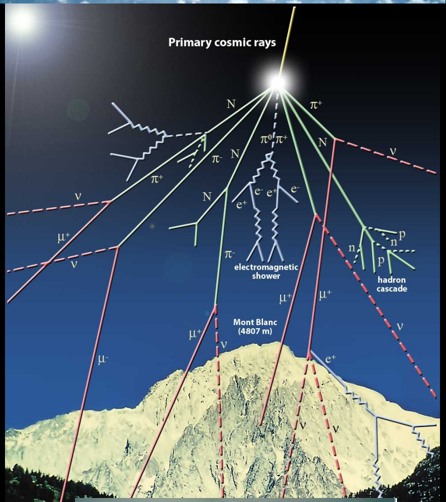

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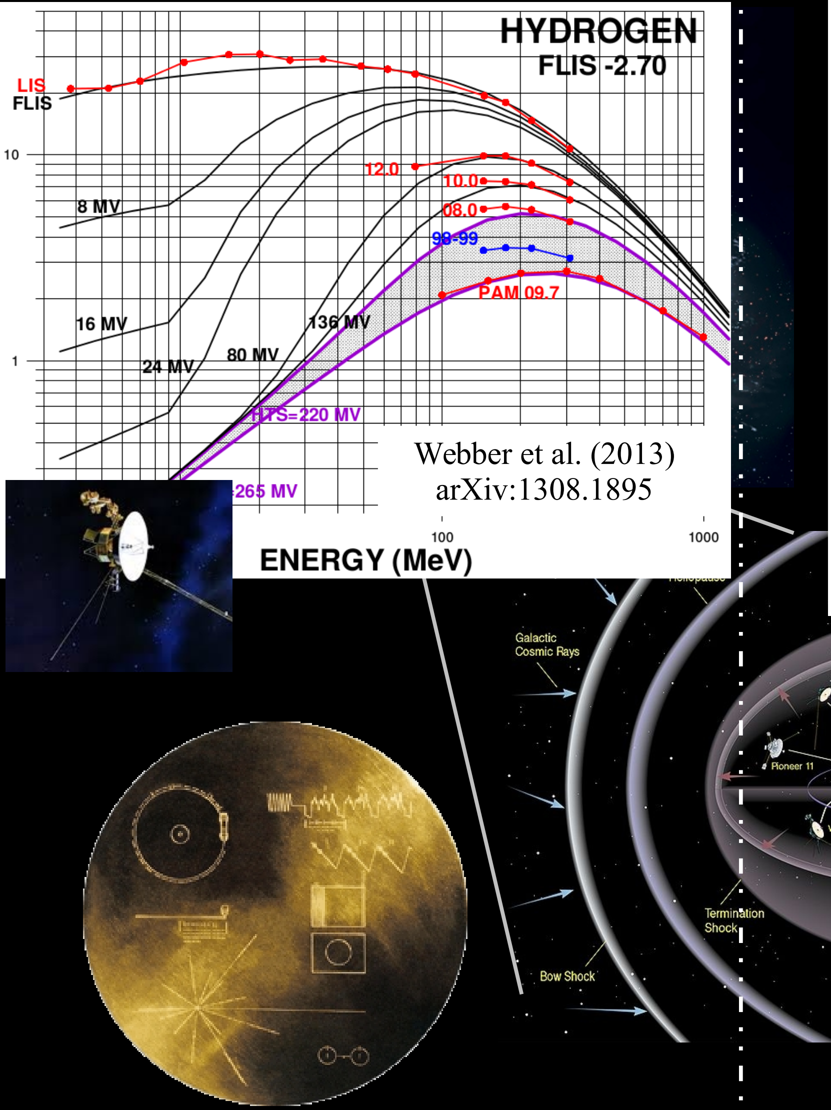

Webber et al. (2013)
arXiv:1308.1895

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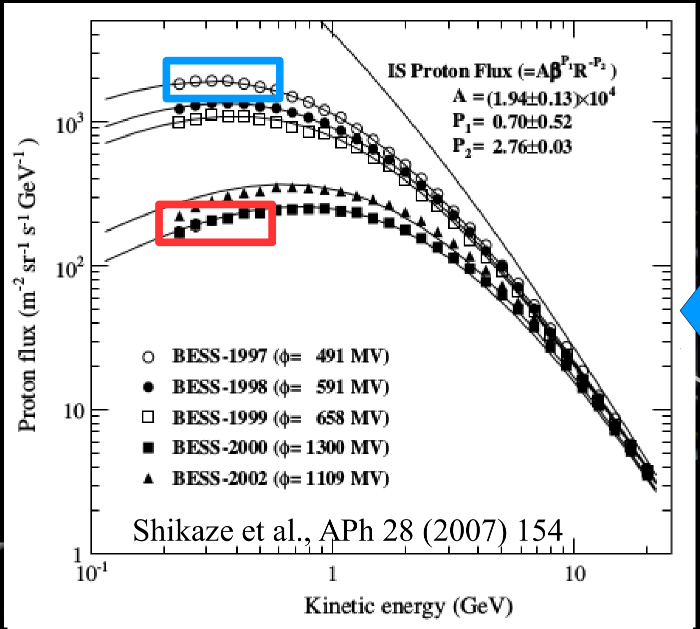
Top-of-atmosphere (TOA) fluxes
[Solar cycle time dependent]



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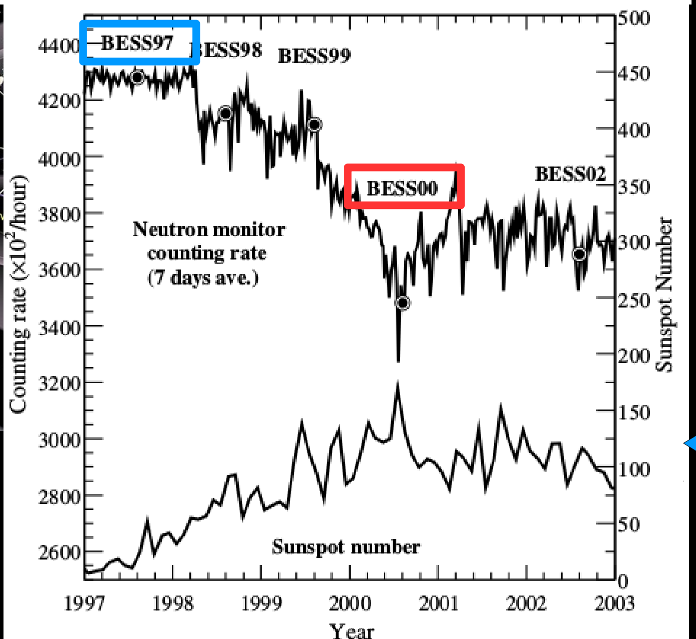
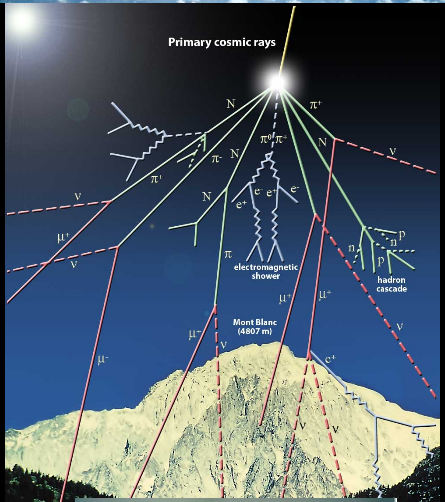


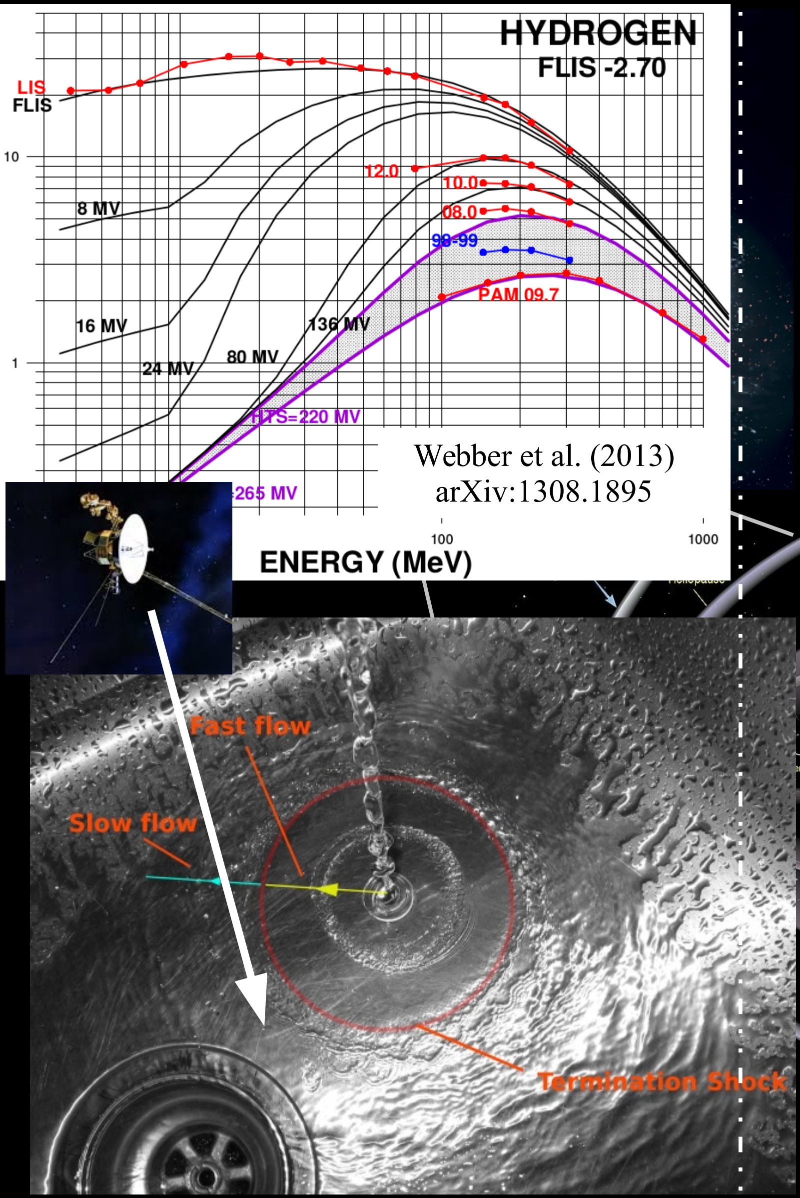
Balloon experiment



Neutron Monitors

An unexpected journey: solar modulation

Interstellar (IS) fluxes
[time independent]



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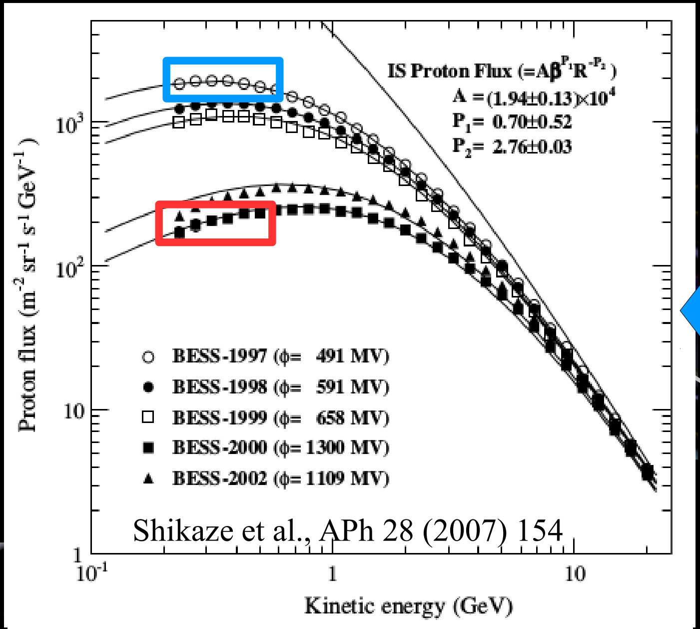

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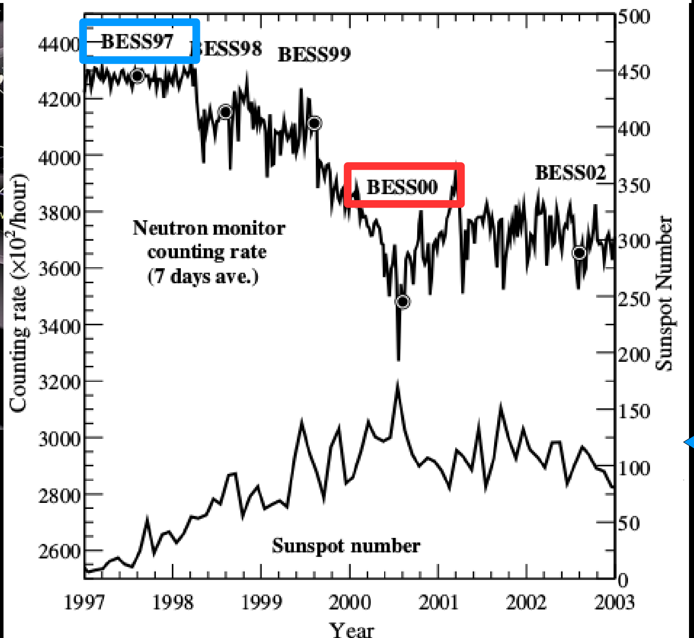

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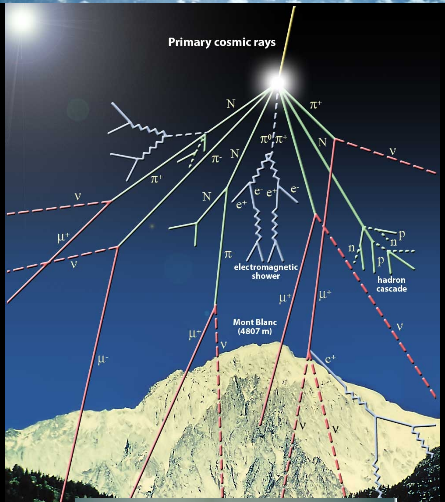


Neutron Monitors

Some useful references

Living Reviews in Solar Physics

- G. Usoskin: A History of Solar Activity over Millennia (LRSP 10, 2013-1)
- Charbonneau: Dynamo Models of the Solar Cycle (LRSP 7, 2010- 3)
- Bruno and Carbone: The Solar Wind as a Turbulence Laboratory (LRSP 10, 2013-2)
- Owens & Forsyth: The Heliospheric Magnetic Field (LRSP 10, 2013-5)
- M. Potgieter: Solar Modulation of Cosmic Rays (LRSP 10, 2013-3)

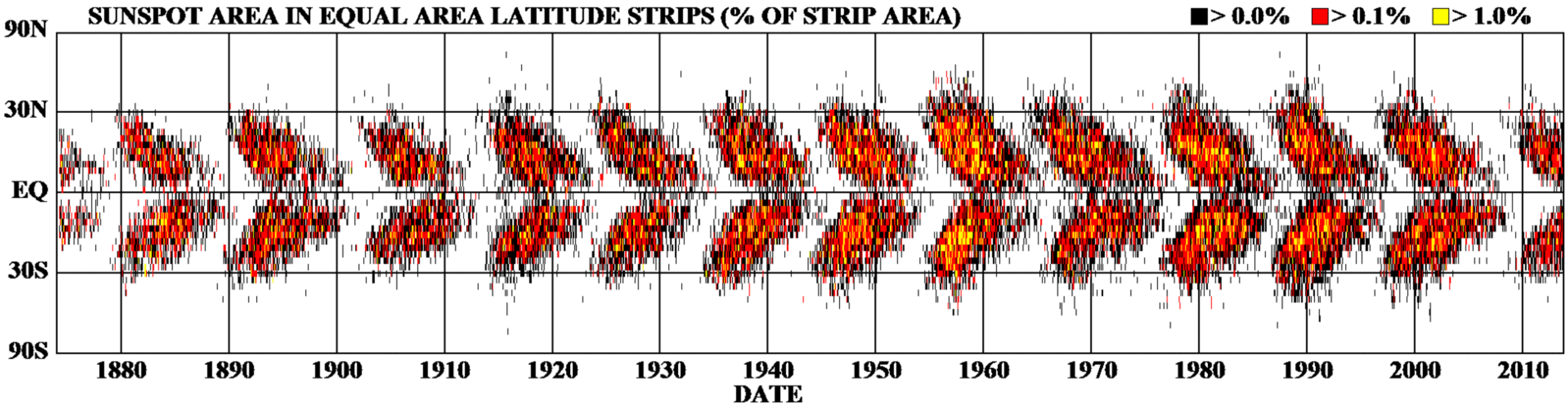
+ Caballero-Lopez & Moraal, JGR 109 (2004) A01101
Limitations of the force field equation to describe cosmic ray modulation

N.B.: whenever the plot reference is not specified below, it is taken from one of these reviews

Solar activity: early observations

Maunder "butterfly" diagram
(naked eye observation)

→ 11-yr (average) periodicity
1st solar cycle: 1755-1766



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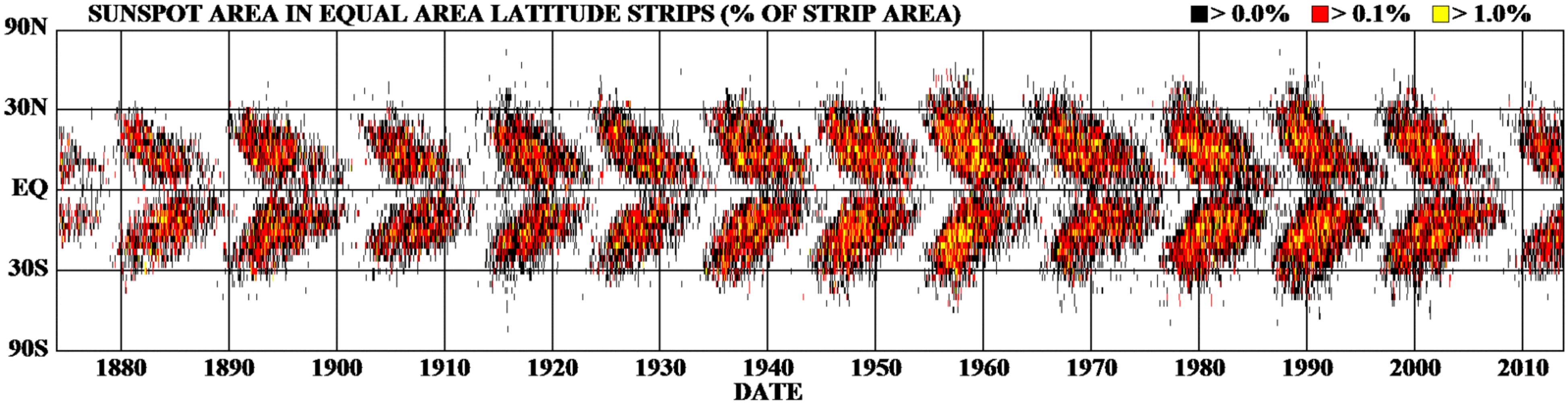
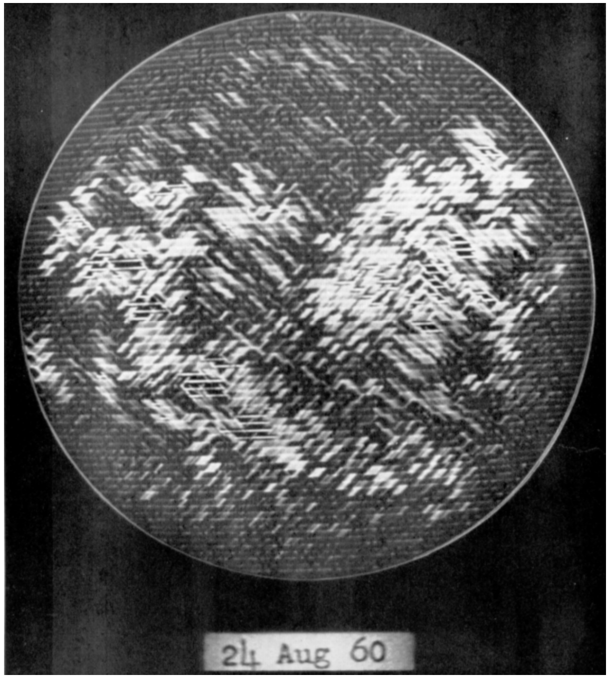


Magnetogram: trace proportional to B (5-40 G)

Babcock, ApJ 133 (1961) 572
The Topology of the Sun's Magnetic Field and the 22-yr cycle

→ 22-yr (average) periodicity
for polarity reversal



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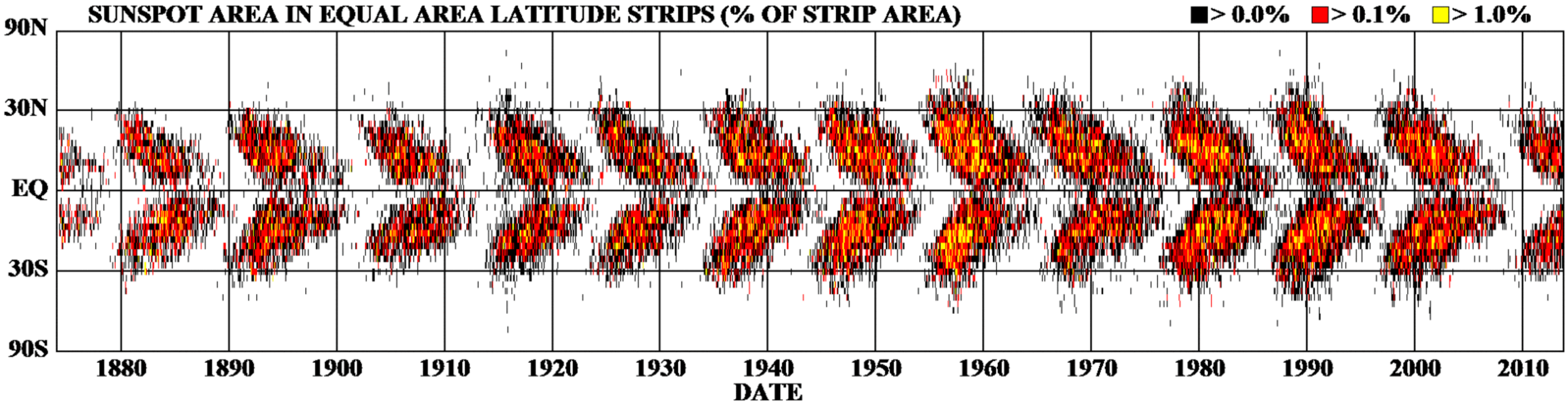

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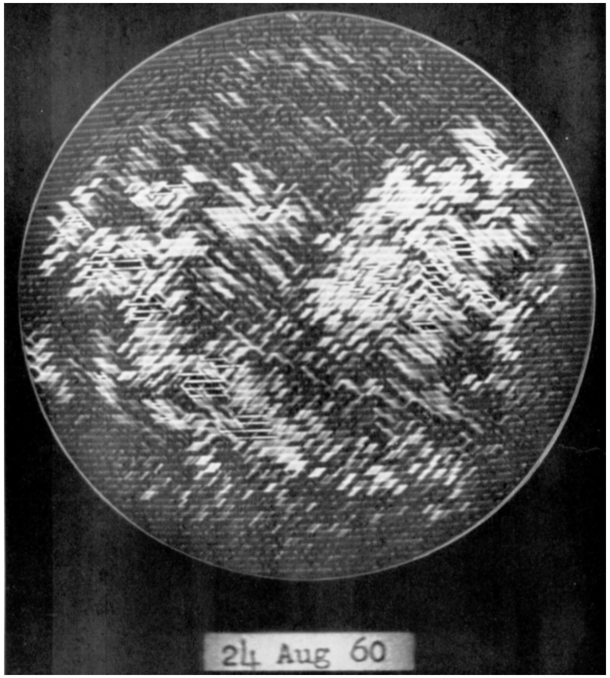

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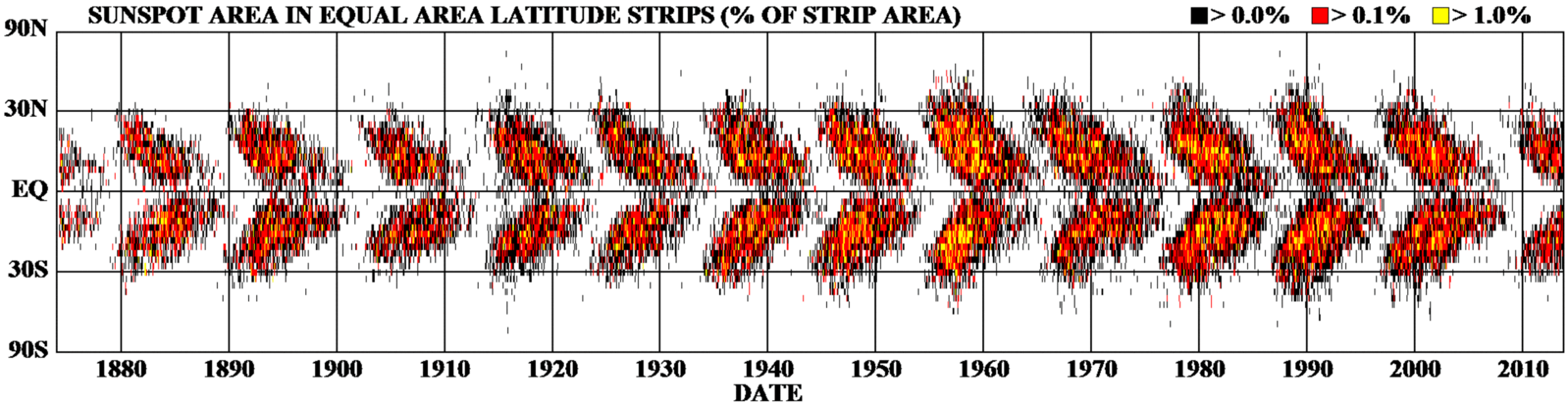

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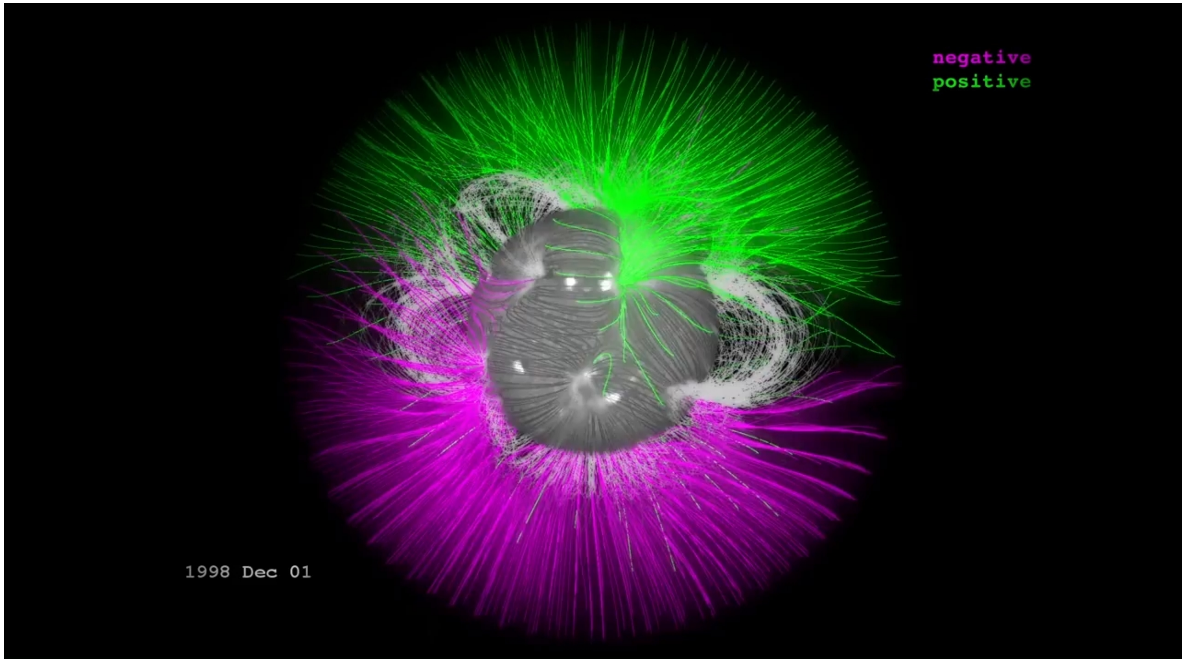
(Cycle 24 : 1997-2013)



Solar activity: polarity reversal in cycle 24

Maunder "butterfly" diagram
(naked eye observation)

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Babcock, ApJ 133 (1961) 572
The Topology of the Sun's Magnetic Field and the 22-yr cycle

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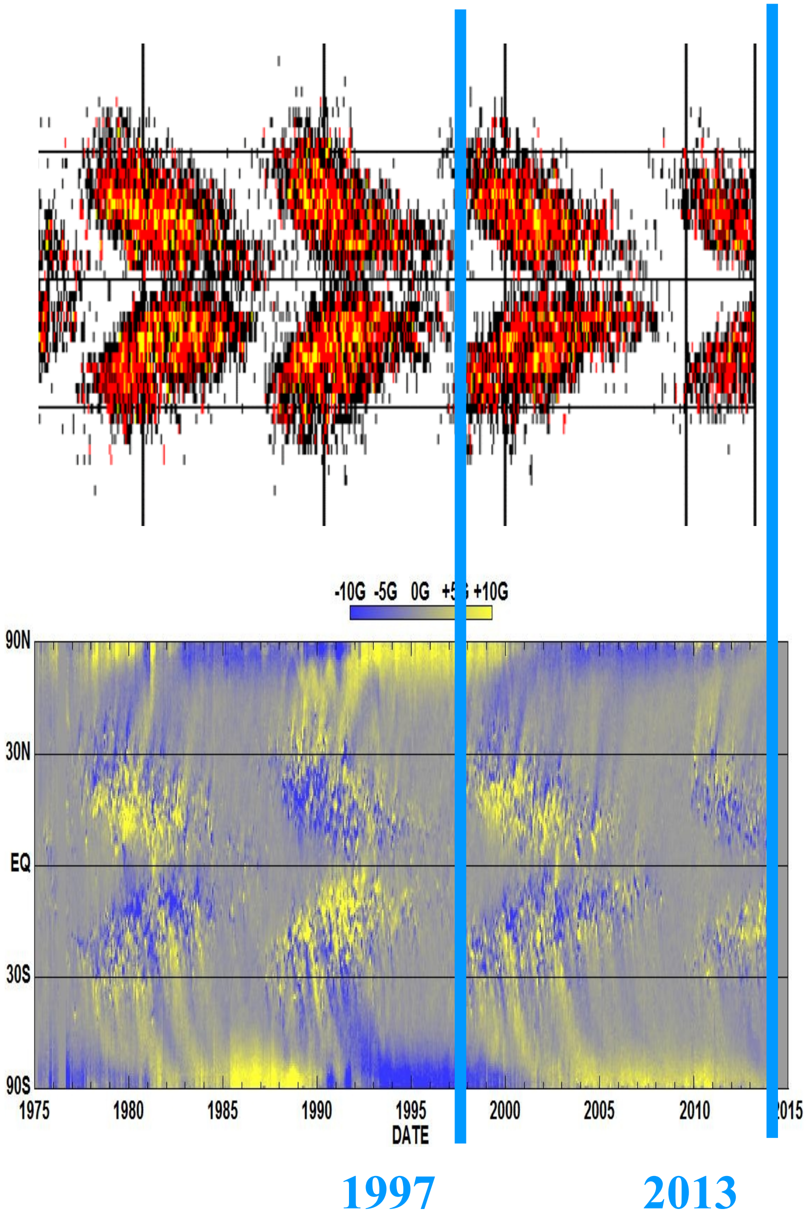
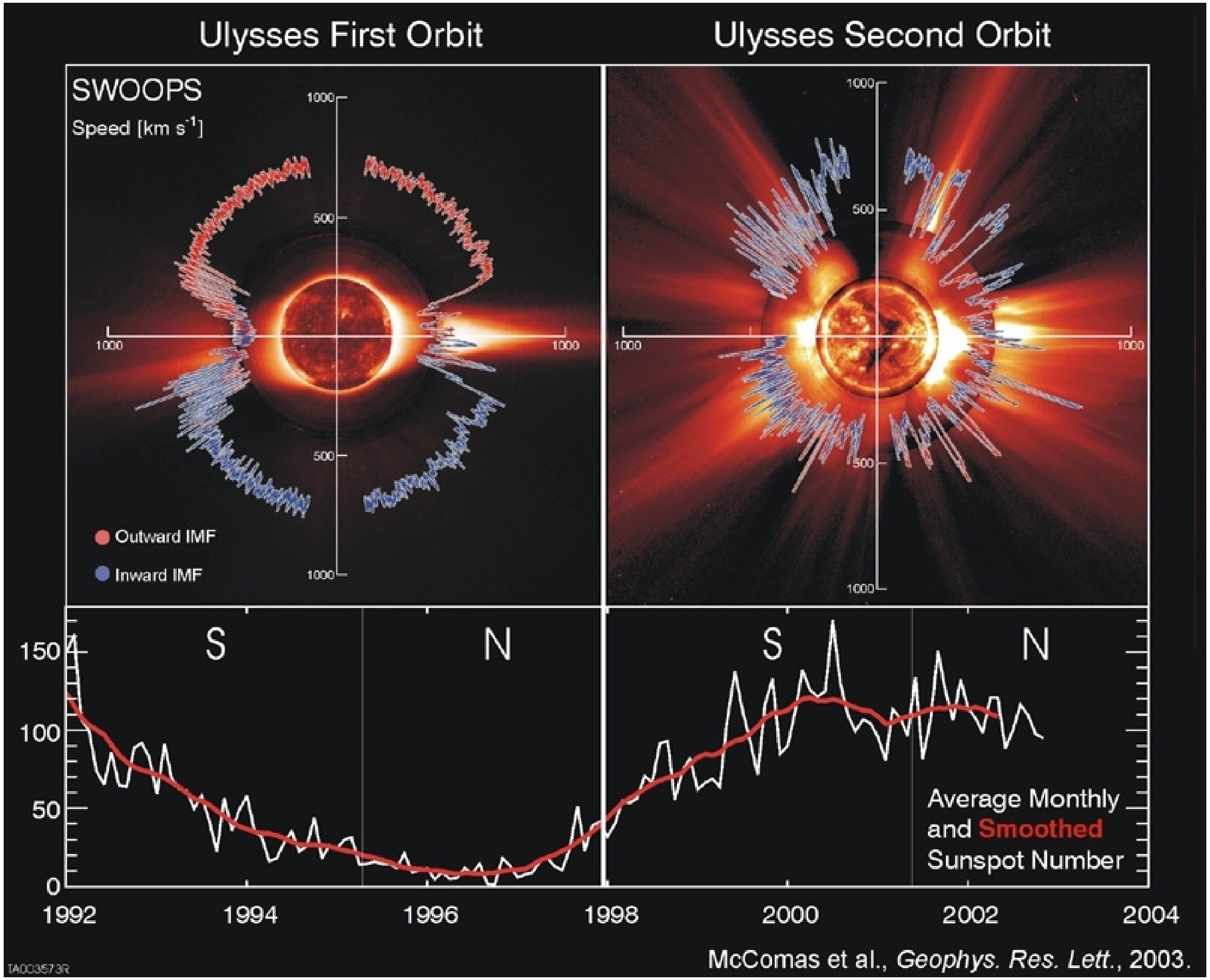


Solar activity: solar wind

→ A continuous flow of charged particles with velocities ~ 400 km/s

- Mostly electrons and protons (10^{12} particles m^{-2} $s^{-1)}$
- First continuous observations by Mariner 2 (1962) + 3 orbits by Ulysses



McComas et al., *Geophys. Res. Lett.*, 2003.

→ Solar wind is spherically symmetric (at first order)

Solar activity: solar wind turbulence

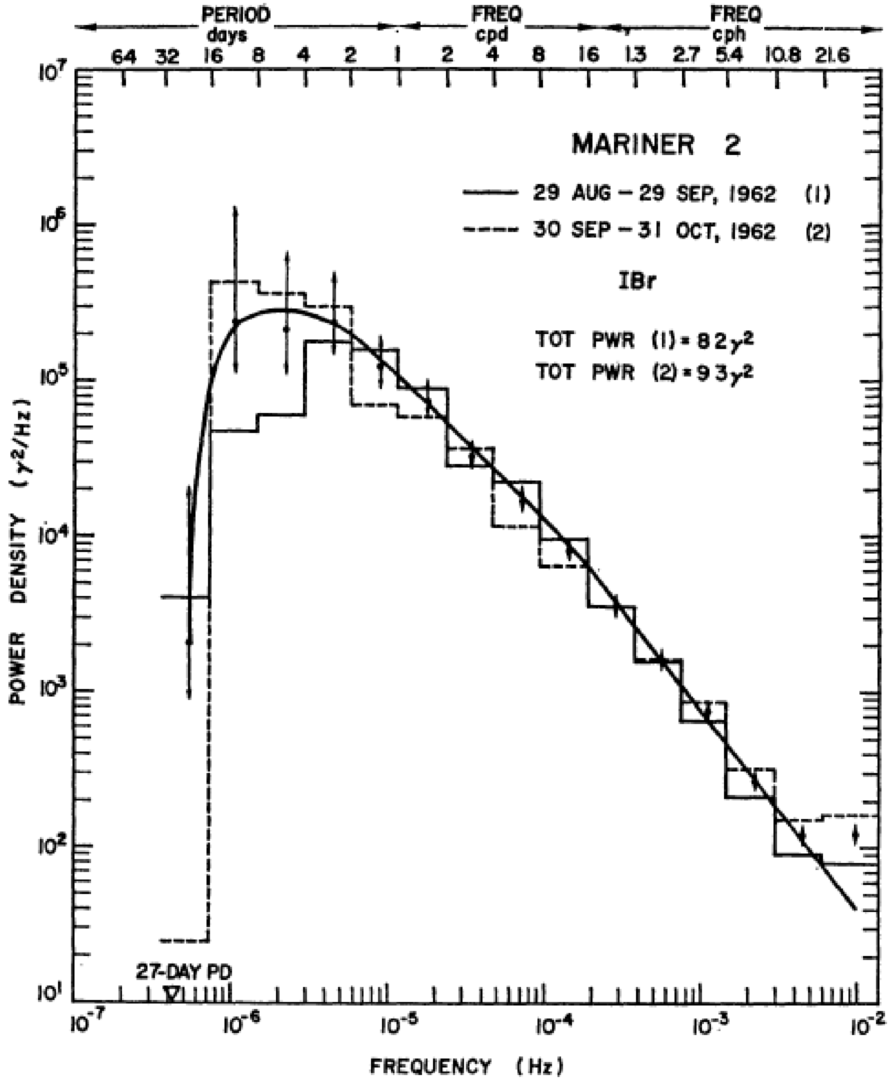


Figure 20: The magnetic energy spectrum as obtained by Coleman (1968).

→ Turbulence in the solar wind (Kolmogorov = 3/2)

Solar activity

How can we describe GCRs in the Solar cavity?

Advection/diffusion transport in the Solar cavity!

Caballero-Lopez & Moraal, JGR 109 (2004) A01101

$$\partial f/\partial t + \mathbf{V} \cdot \nabla f - \nabla \cdot (\mathsf{K} \cdot \nabla f) - \frac{1}{3}(\nabla \cdot \mathbf{V})\partial f/\partial \ln p = Q$$

Force-field solution

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Force-field approximation:

- No source
- Steady state
- No adiabatic losses

$$\frac{\partial f}{\partial r} + \underbrace{\frac{VP}{3\kappa}}_{\text{GV/m (E field)}}\frac{\partial f}{\partial P} = 0$$

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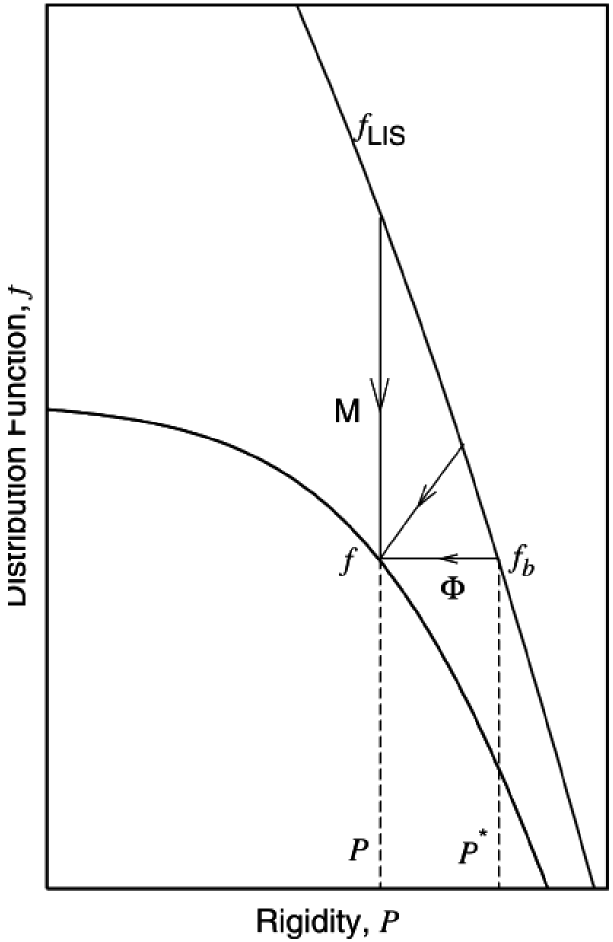
→ Solution

$$\boxed{\begin{gathered}\frac{E^{\rm TOA}}{A} = \frac{E^{\rm IS}}{A} - \frac{|Z|}{A}\phi \\ \frac{J^{\rm TOA}\left(E^{\rm TOA}\right)}{J^{\rm IS}\left(E^{\rm IS}\right)} = \left(\frac{p^{\rm TOA}}{p^{\rm IS}}\right)^2,\end{gathered}}$$

$$\frac{\phi}{\beta\kappa_2} = \frac{1}{3}\int_r^{r_b}\frac{V}{\kappa}dr$$



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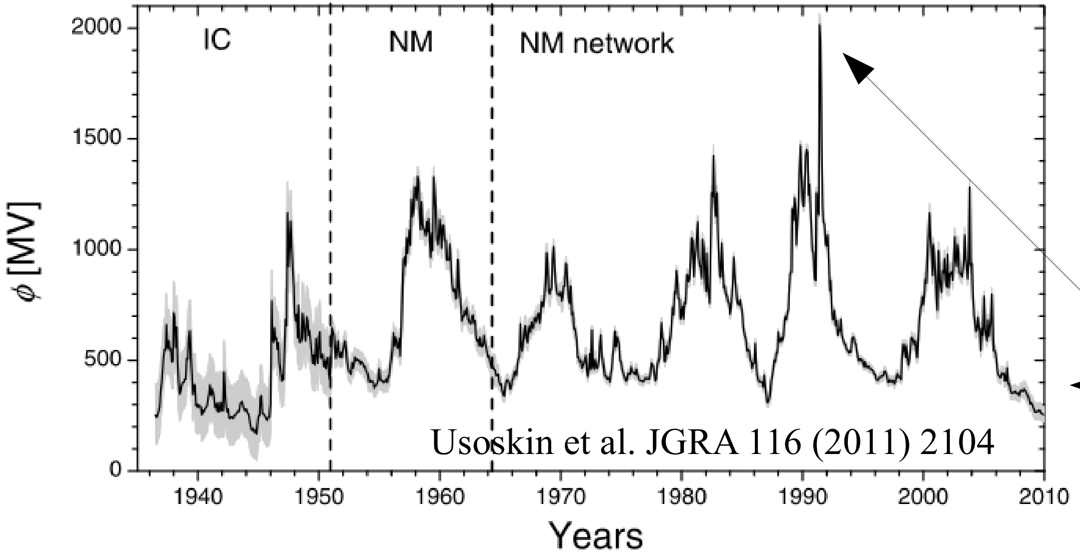
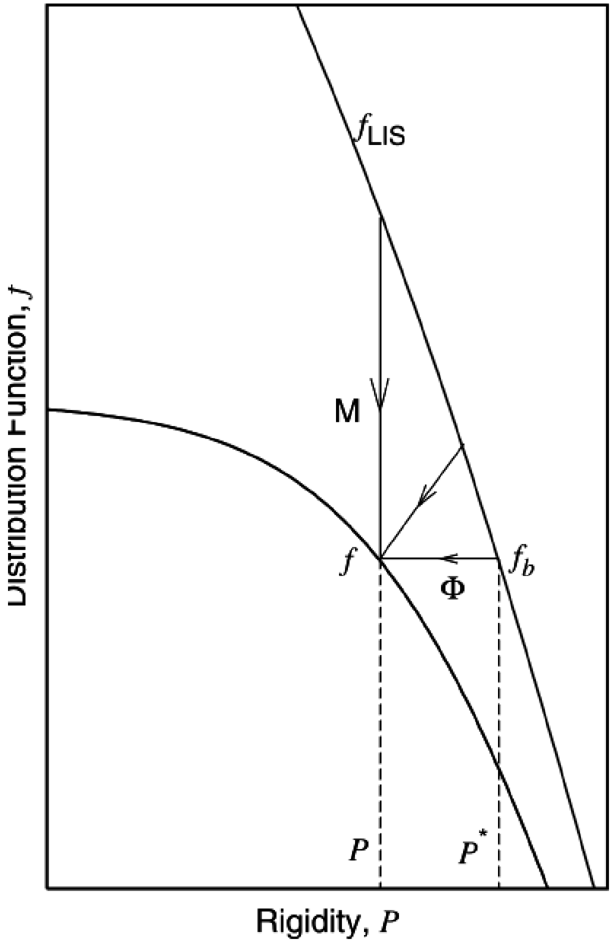


Usoskin et al. JGRA 116 (2011) 2104



What is the minimal IS kinetic energy we can measure on “Earth”?

Force-field solution

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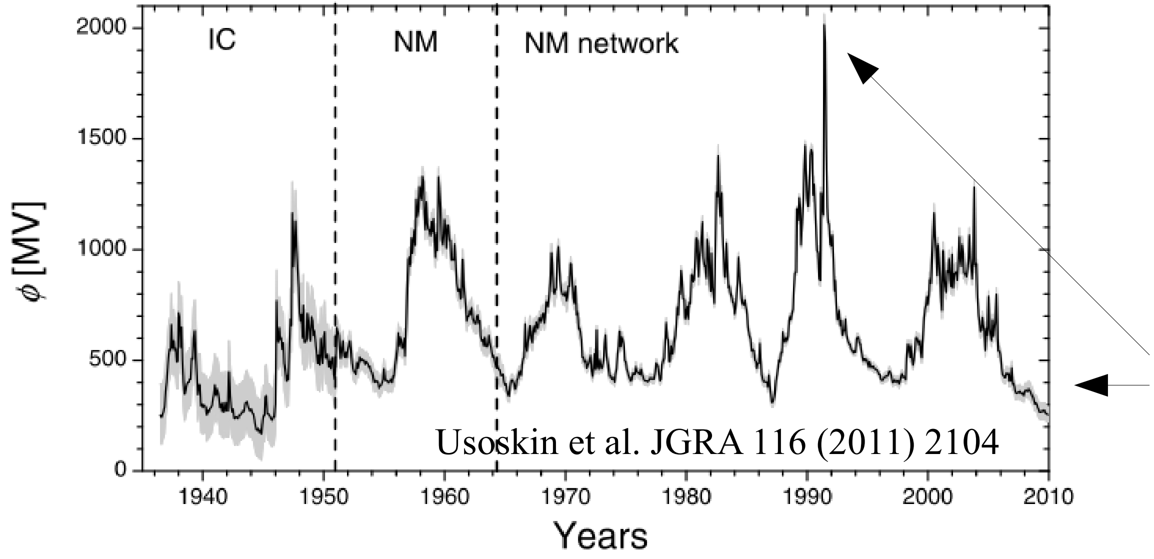
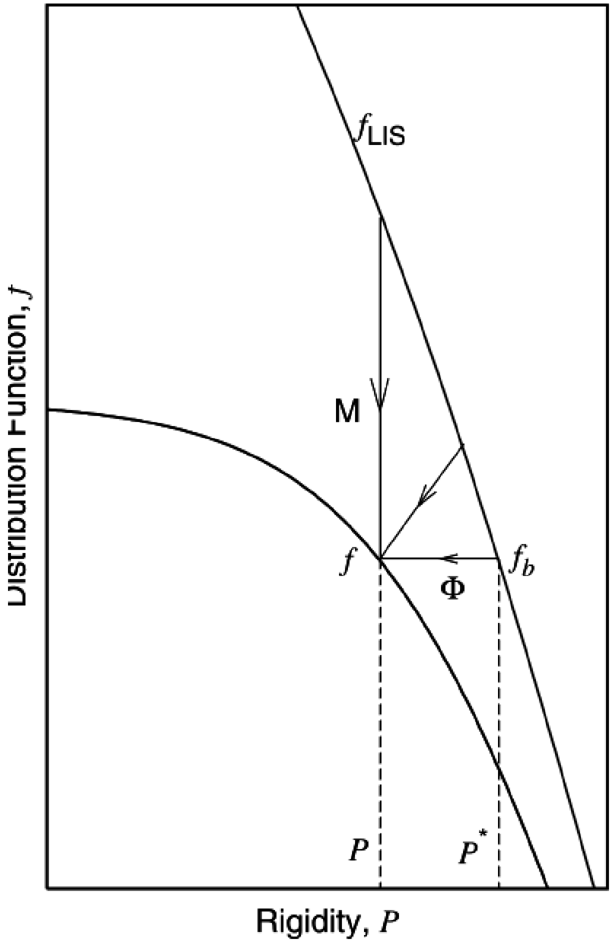


Usoskin et al. JGRA 116 (2011) 2104

2 GeV

400 GeV



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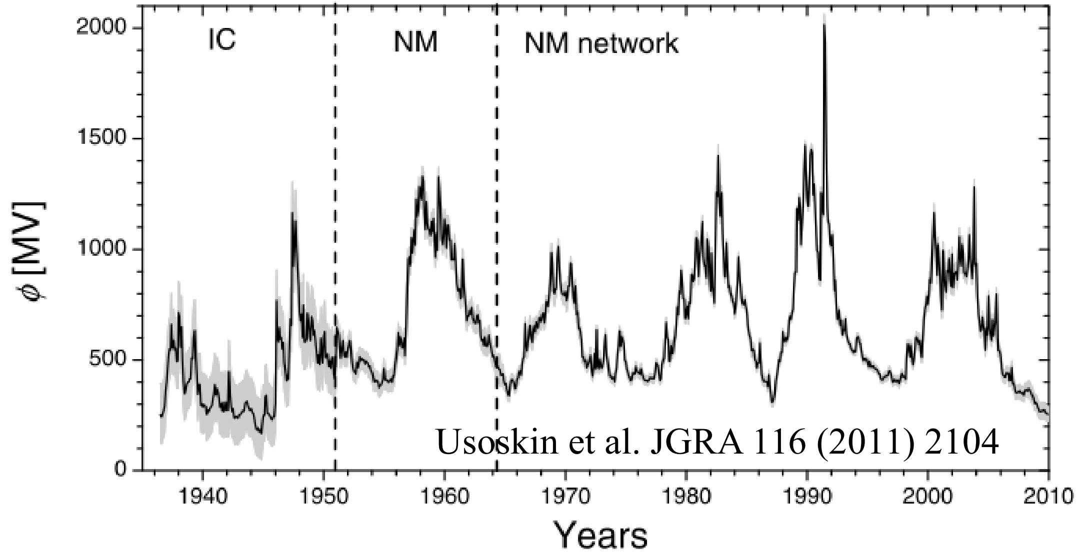

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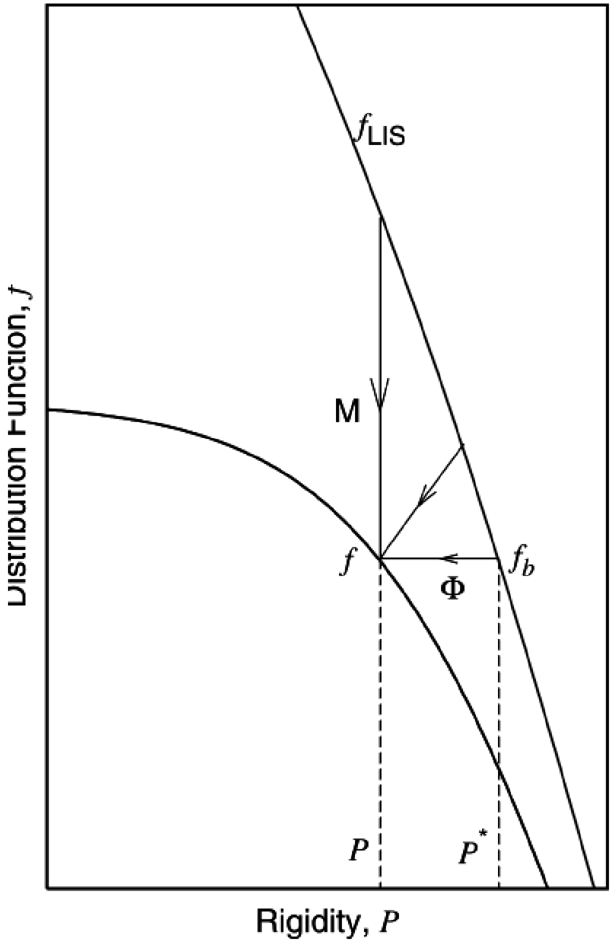

N.B.: Force-Field works because the FF energy loss is an upper limit of the true adiabatic loss

Force-field vs 1D spherically symmetric solution

N.B.: 1D solution uses the full equation below

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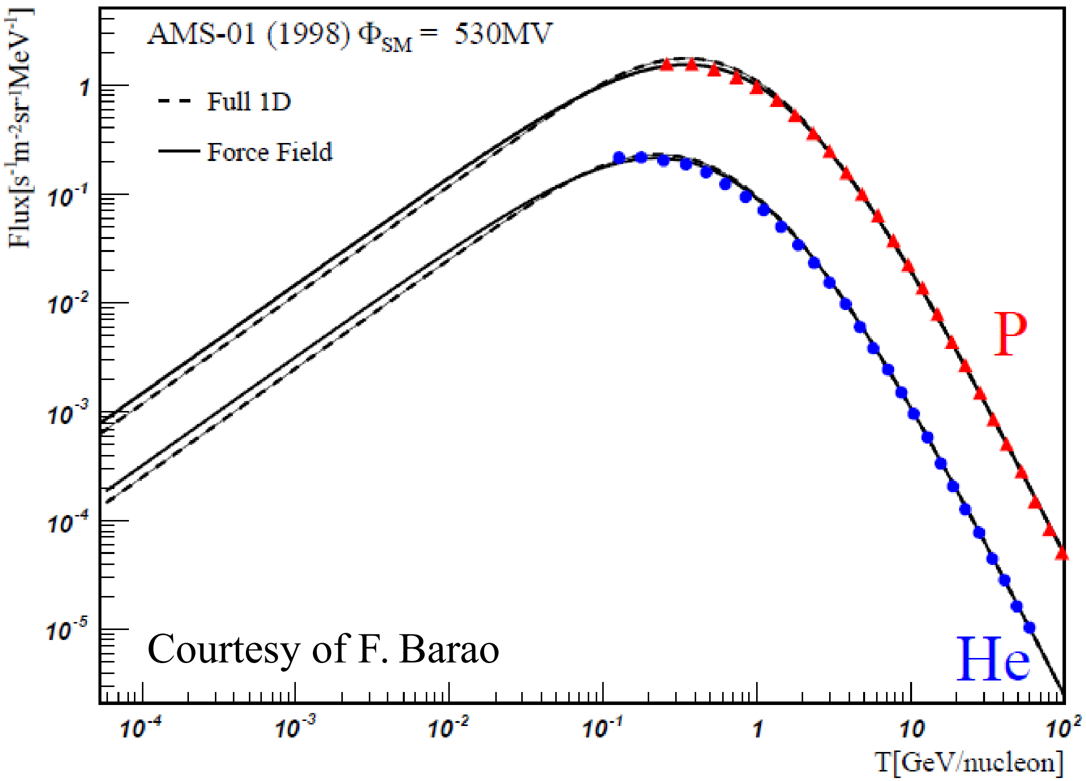
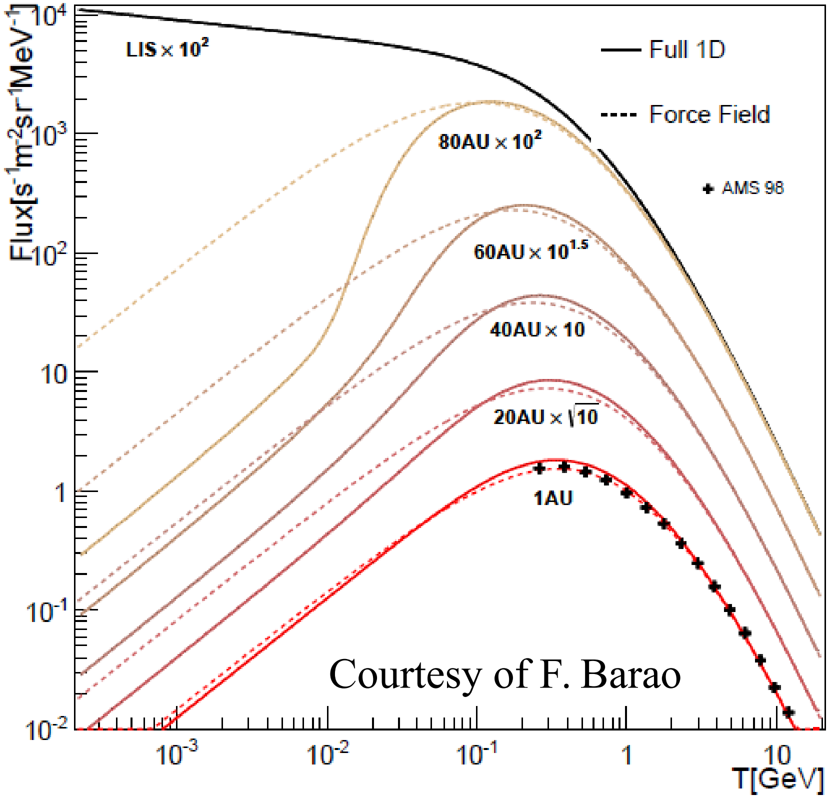
Fit to GCR data to determine ϕ



Courtesy of F. Barao

Modulation at different r positions



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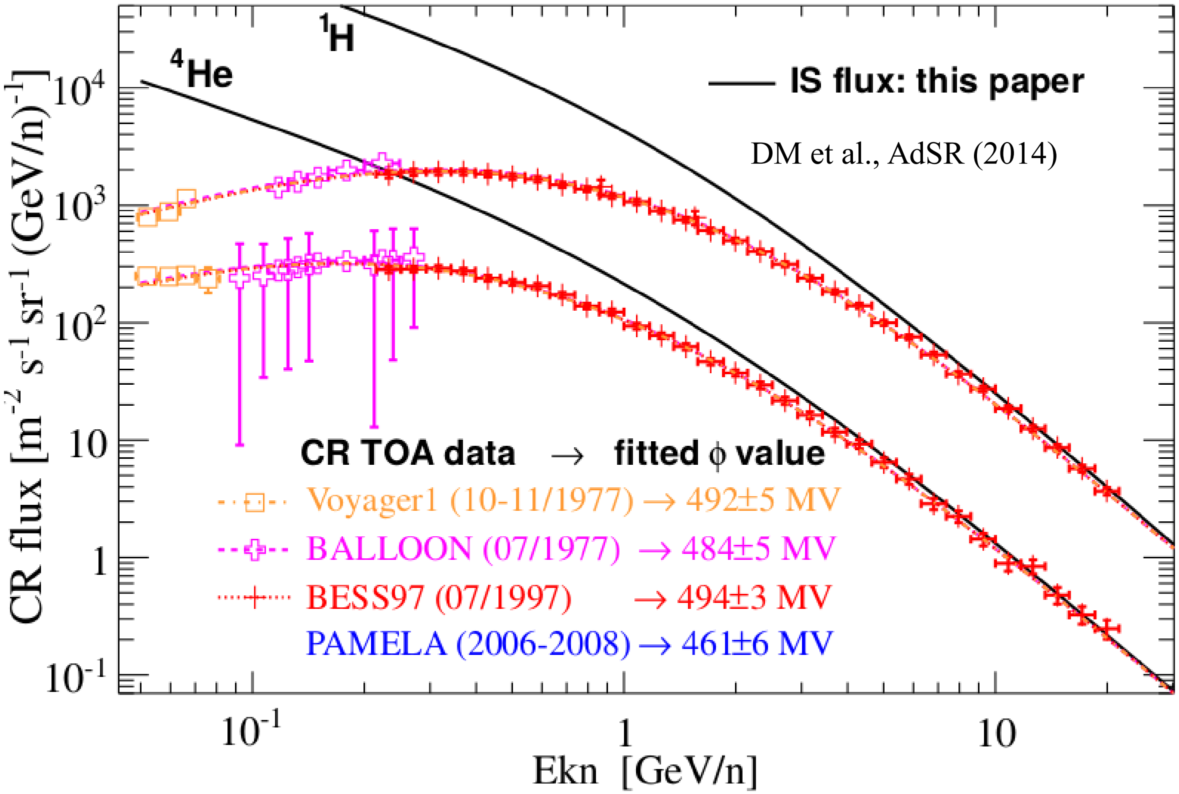
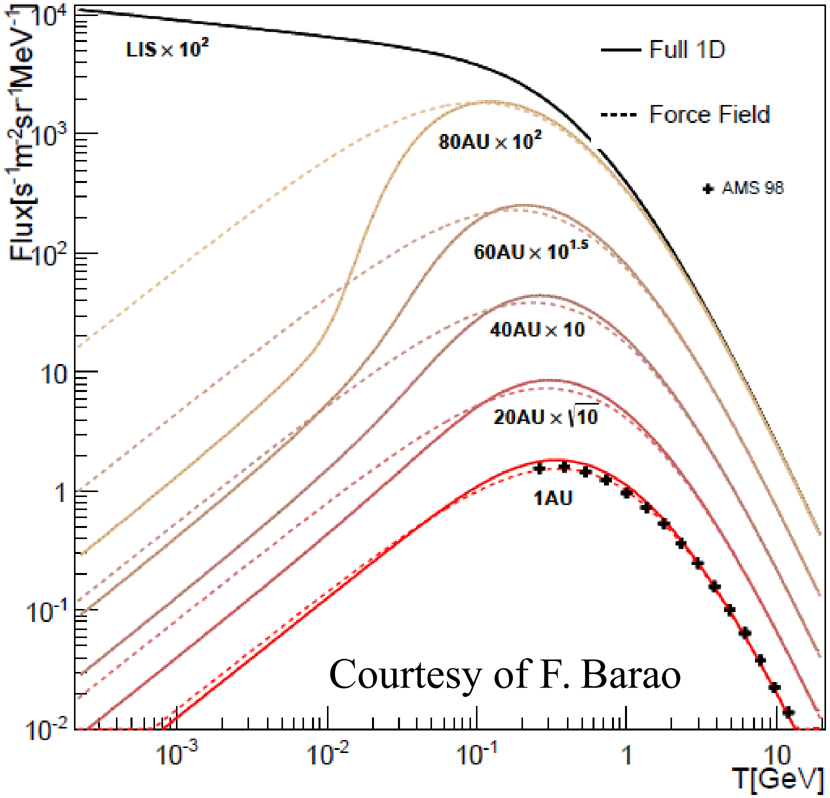
At similar minimum, same modulation level



DM et al., AdSR (2014)

Modulation at different r positions



Courtesy of F. Barao

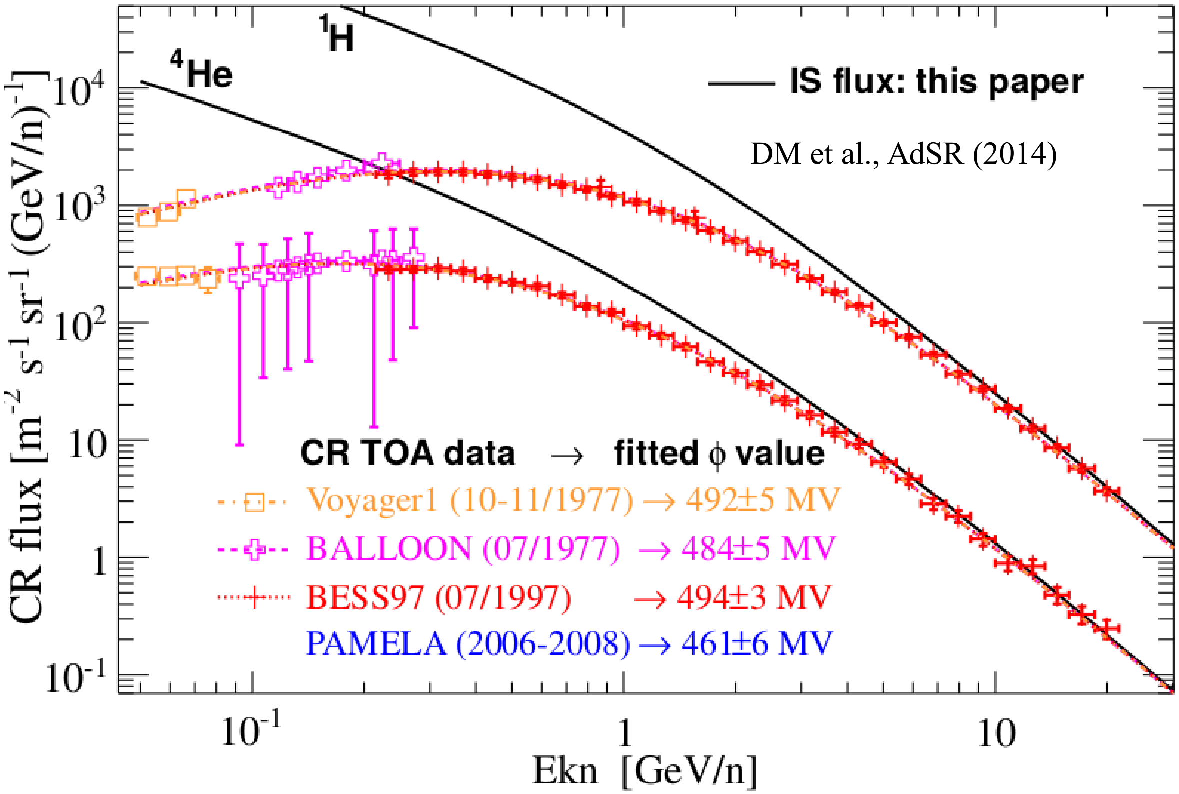
Modulation level reconstructed with NMs vs AMS-02 data
→ Alexandre Ghelfi's poster

Force-field vs 1D spherically symmetric solution

N.B.: 1D solution uses the full equation below

$$\partial f/\partial t + \mathbf{V}\cdot\nabla f - \nabla\cdot(\mathsf{K}\cdot\nabla f) - \frac{1}{3}(\nabla\cdot\mathbf{V})\partial f/\partial \ln p = Q$$

At similar minimum, same modulation level



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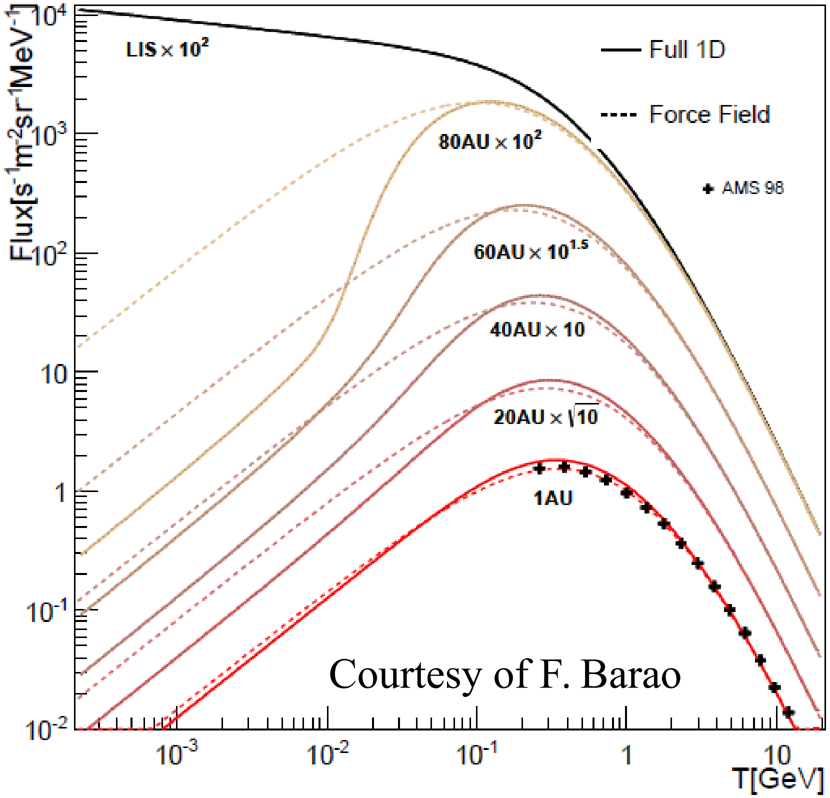


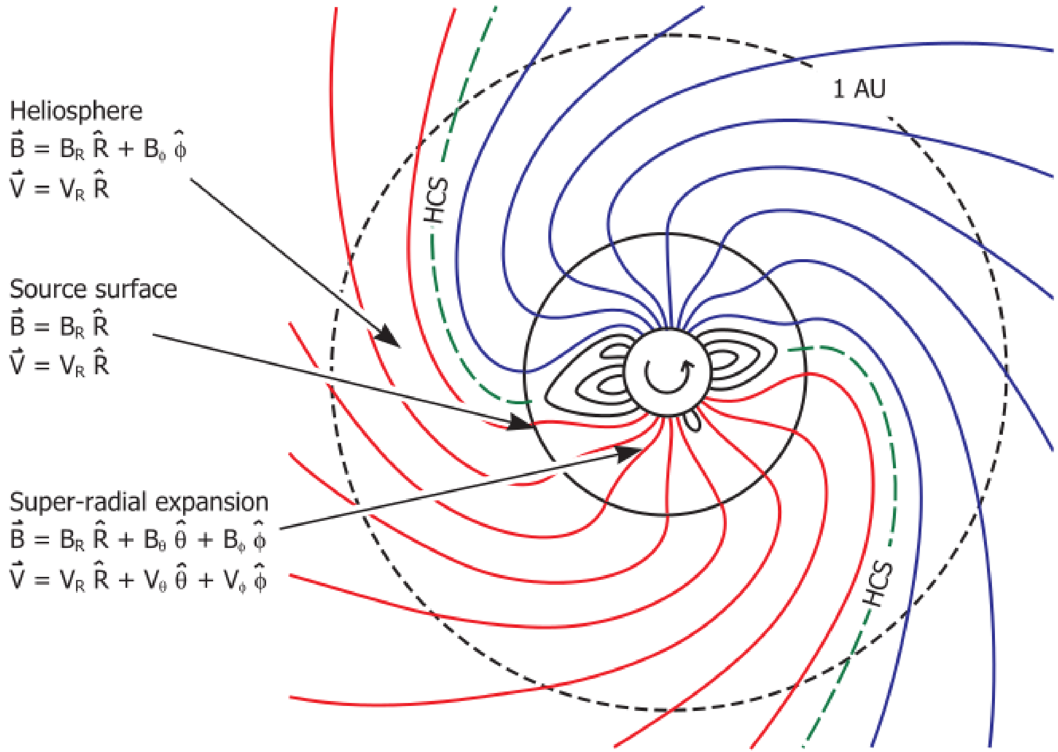
Courtesy of F. Barao

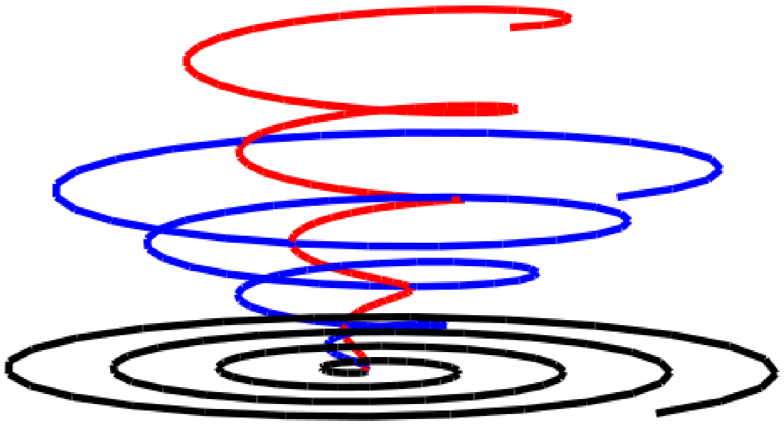
→ Force field OK @ Earth + not too low energy

More realistic model: archimedean structure

Magnetic field is assumed to be frozen in solar wind plasma
→ Archimedean spiral in the solar equatorial plane

Parker, AJ 128 (1958), 664





Ideal Parker spiral magnetic field lines between 0 and 25 AU for a solar wind speed of 450 km s^{-1}. Black, blue, and red lines show heliographic latitudes of 0, 30, and 60 degrees, respectively

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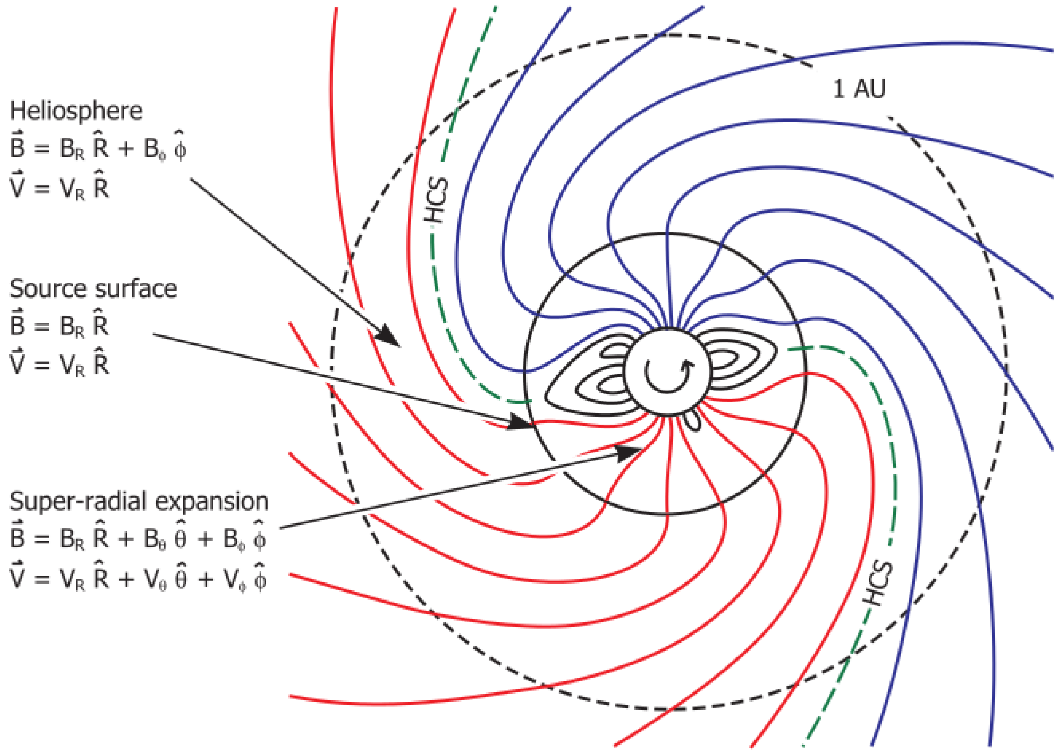
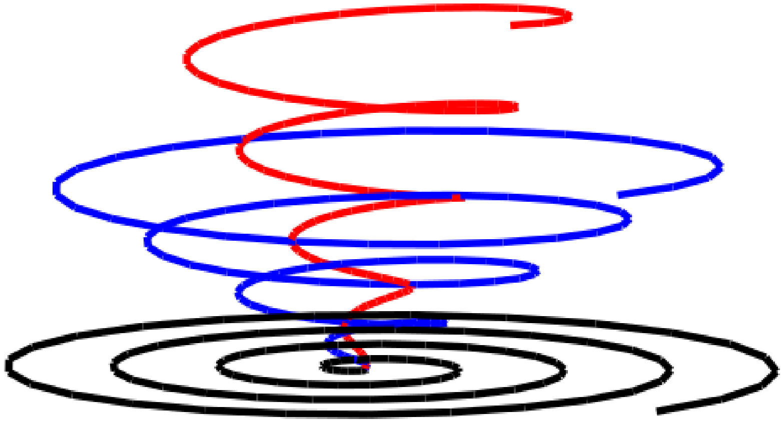




Ideal Parker spiral magnetic field lines between 0 and 25 AU for a solar wind speed of 450 km s^{-1}. Black, blue, and red lines show heliographic latitudes of 0, 30, and 60 degrees, respectively

$$V(r,\theta) = V_0 \left[1 - \exp\left(13.33\left(\frac{r_\odot - r}{r_0}\right)\right)\right] \left[1.475 \mp 0.4 \tanh\left(6.8\left(\theta - \frac{\pi}{2} \pm \theta\right)\right)\right] \left[\left(\frac{s+1}{2s}\right) - \left(\frac{s-1}{2s}\right) \tanh\left(\frac{r - r_{\mathrm{TS}}}{L}\right)\right]$$

$$\mathbf{B} = B_o \left(\frac{r_0}{r}\right)^2 \left(\mathbf{e}_r - \tan\psi\, \mathbf{e}_\phi\right)$$

$$\tan\psi = \frac{\Omega\,(r - r_\odot)\sin\theta}{V}$$

More realistic model: 3D diffusion equation to solve

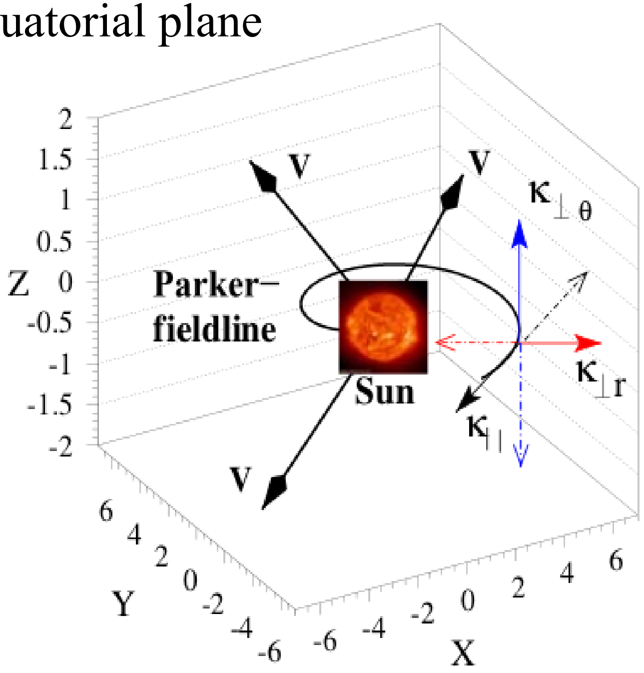
$$
\begin{aligned}
&\overbrace{\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 K_{rr}\right)+\frac{1}{r\sin\theta}\frac{\partial K_{\phi r}}{\partial \phi}\right]\frac{\partial f}{\partial r}+\left[\frac{1}{r^2\sin\theta}\frac{\partial}{\partial \theta}\left(K_{\theta\theta}\sin\theta\right)\right]\frac{\partial f}{\partial \theta}}^{\text{diffusion}} \\
&+\overbrace{\left[\frac{1}{r^2\sin\theta}\frac{\partial}{\partial r}(rK_{r\phi})+\frac{1}{r^2\sin^2\theta}\frac{\partial K_{\phi\phi}}{\partial \phi}-\Omega\right]\frac{\partial f}{\partial \phi}}^{\text{diffusion}} \\
&+\overbrace{K_{rr}\frac{\partial^2 f}{\partial r^2}+\frac{K_{\theta\theta}}{r^2}\frac{\partial^2 f}{\partial \theta^2}+\frac{K_{\phi\phi}}{r^2\sin^2\theta}\frac{\partial^2 f}{\partial \phi^2}+\frac{2K_{r\phi}}{r\sin\theta}\frac{\partial^2 f}{\partial r\partial \phi}}^{\text{diffusion}} \\
&+\overbrace{\left[-\langle \mathbf{v}_d\rangle_r\right]\frac{\partial f}{\partial r}+\left[-\frac{1}{r}\langle \mathbf{v}_d\rangle_\theta\right]\frac{\partial f}{\partial \theta}+\left[-\frac{1}{r\sin\theta}\langle \mathbf{v}_d\rangle_\phi\right]\frac{\partial f}{\partial \phi}}^{\text{drift}} \\
&-\overbrace{V\frac{\partial f}{\partial r}}^{\text{convection}} \\
&+\overbrace{\frac{1}{3r^2}\frac{\partial}{\partial r}\left(r^2 V\right)\frac{\partial f}{\partial \ln p}}^{\text{adiabatic energy losses}}=0.
\end{aligned}
\tag{7}
$$

Here K_{rr}, $K_{r\theta}$, $K_{r\phi}$, $K_{\theta r}$, $K_{\theta\theta}$, $K_{\theta\phi}$, $K_{\phi r}$, $K_{\phi\theta}$, and $K_{\phi\phi}$, are the nine elements of the 3D diffusion tensor, based on a Parkerian type HMF. Note that K_{rr}, $K_{r\phi}$, $K_{\theta\theta}$, $K_{\phi r}$, $K_{\phi\phi}$ describe the

$$
\begin{aligned}
K_{rr} &= K_{\parallel}\cos^2\psi + K_{\perp r}\sin^2\psi, \\
K_{\perp\theta} &= K_{\theta\theta}, \\
K_{\phi\phi} &= K_{\perp r}\cos^2\psi + K_{\parallel}\sin^2\psi, \\
K_{\phi r} &= \left(K_{\perp r} - K_{\parallel}\right)\cos\psi\sin\psi = K_{r\phi}
\end{aligned}
$$

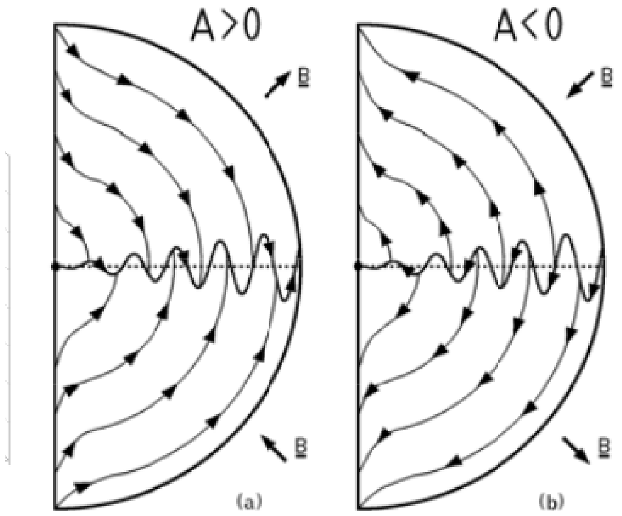
More realistic model: drift effect

Magnetic field is assumed to be frozen in solar wind plasma
→ Archimedean spiral in the solar equatorial plane



- Sun rotates with a period of ≃ 27.27 days (Carrington rotation - started on Nov 9, 1853)
- The magnetic field at the solar magnetic poles approximates that of a dipole
- Offset between the sun magnetic and rotation axis → tilt angle increases with Sun activity

→ Drift velocity depend on particle charge (Z) and solar magnetic field polarity (A)



Crucial parameters: polarity and tilt angle

Magnetic field is assumed to be frozen in solar wind plasma
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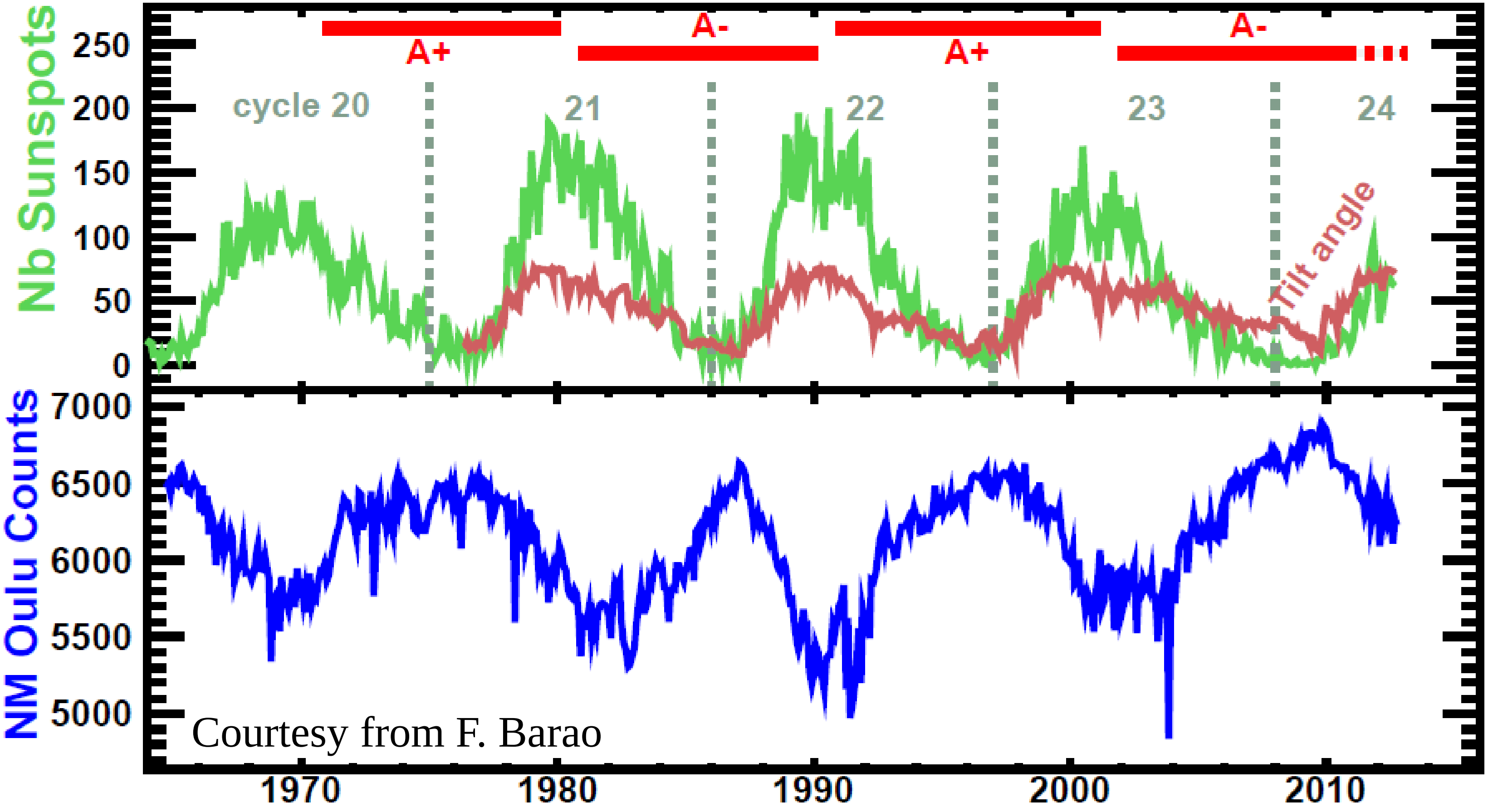

Courtesy from F. Barao

→ Different modulation of positive and negative particles (if small tilt angle)

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- Sun rotates with a period of $\simeq$ 27.27 days (Carrington rotation - started on Nov 9, 1853)
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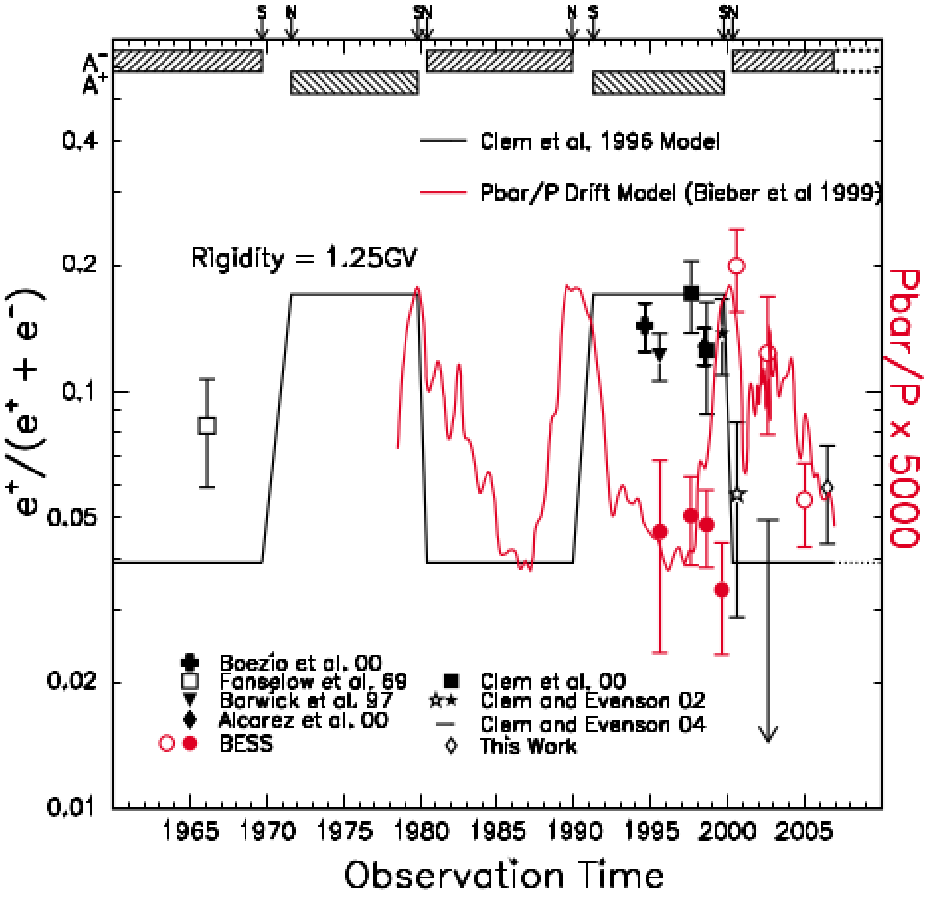
- Offset between the sun magnetic and rotation axis → tilt angle increases with Sun activity

→ Drift velocity depend on particle charge (Z) and solar magnetic field polarity (A)
→ Too much gaps in the data time coverage to draw firm conclusions

Clem & Evenson, ApJ 568, 216 (2002)



Conclusions on Solar modulation

Solar modulation changes low energy fluxes

→ Force-Field is simple (algebraic expressions) and still used

- Single effective parameter ϕ (between 400 and 2000 MV)
- Determined from GCR data or NM data

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AMS-02 data will provide a crucial test for the theory
- High accuracy measurements (for p, statistics $< 1\%$)
- Dayly or weakly fluxes over several years (tilt angle/polarity)
- Simultaneous data on p(bar), e±

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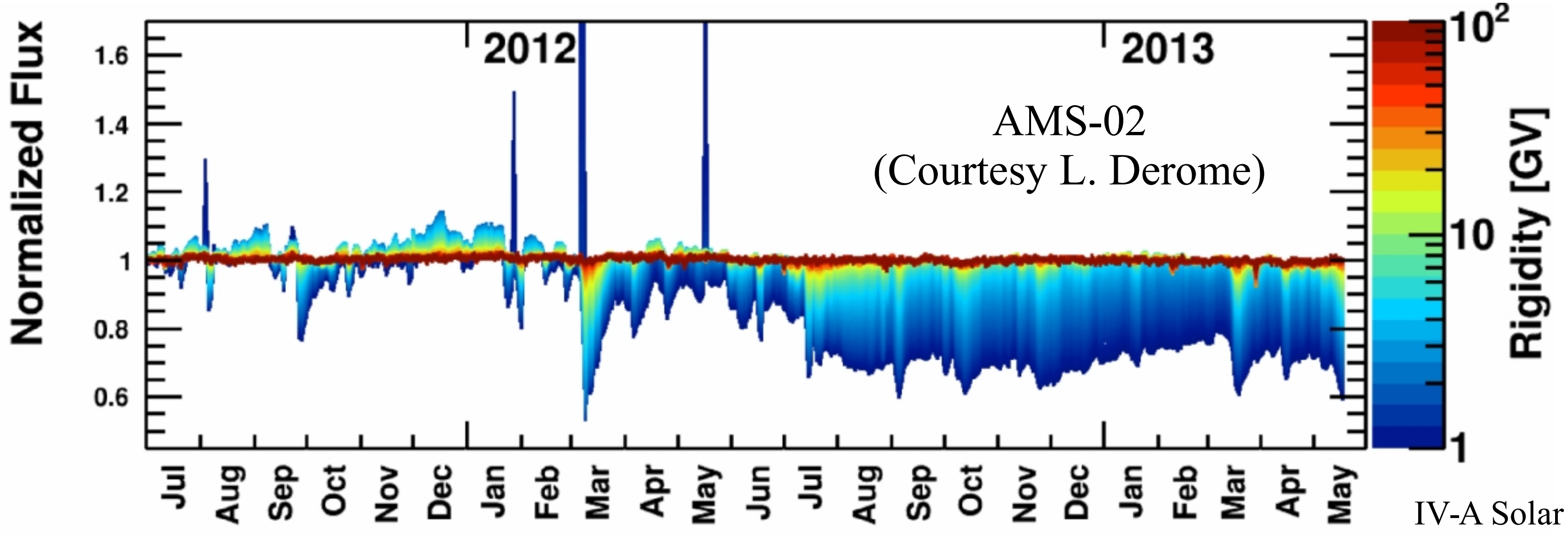

Charged signals: electrons/positrons, antibaryons

IV - Transport in the heliosphere
Charged signals: electrons/positrons, antibaryons

IV-A Propagation in the heliosphere
IV-B CRDB
IV-C Anti-p, anti-d, and positron fraction
1. Where to look for new physics in GCRs
2. “Backgrounds” from secondary production
3. Uncertainties on DM signals (propagation, DM)
4. Positron fraction
5. Summary and perspectives

CRDB: why?

http://lpsc.in2p3.fr/crdb

Usefulness for

- GCR phenomenology: astrophysics or DM searches
- GCR experiments: comparison to previous data
- Solar physics: comparison to past measurements

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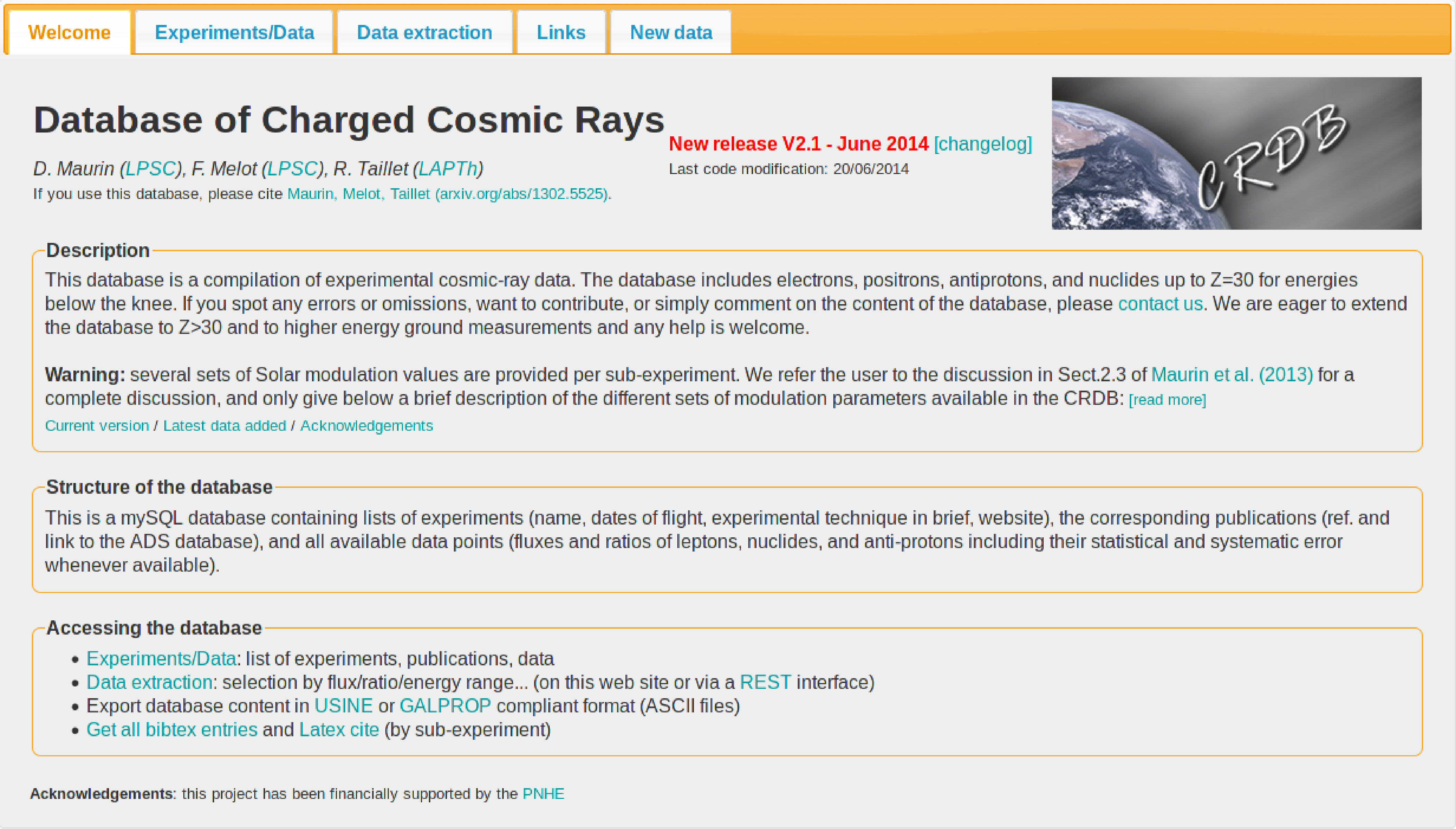
Because it is a waste of resource when every researcher has to find and gather again and again the same data sets!

CRDB snapshots: main page

http://lpsc.in2p3.fr/crdb



Database of Charged Cosmic Rays

D. Maurin (LPSC), F. Melot (LPSC), R. Taillet (LAPTh)

If you use this database, please cite Maurin, Melot, Taillet (arxiv.org/abs/1302.5525).

New release V2.1 - June 2014 [changelog]

Last code modification: 20/06/2014

Description

This database is a compilation of experimental cosmic-ray data. The database includes electrons, positrons, antiprotons, and nuclides up to Z=30 for energies below the knee. If you spot any errors or omissions, want to contribute, or simply comment on the content of the database, please contact us. We are eager to extend the database to Z>30 and to higher energy ground measurements and any help is welcome.

Warning: several sets of Solar modulation values are provided per sub-experiment. We refer the user to the discussion in Sect.2.3 of Maurin et al. (2013) for a complete discussion, and only give below a brief description of the different sets of modulation parameters available in the CRDB: [read more]

Current version / Latest data added / Acknowledgements

Structure of the database

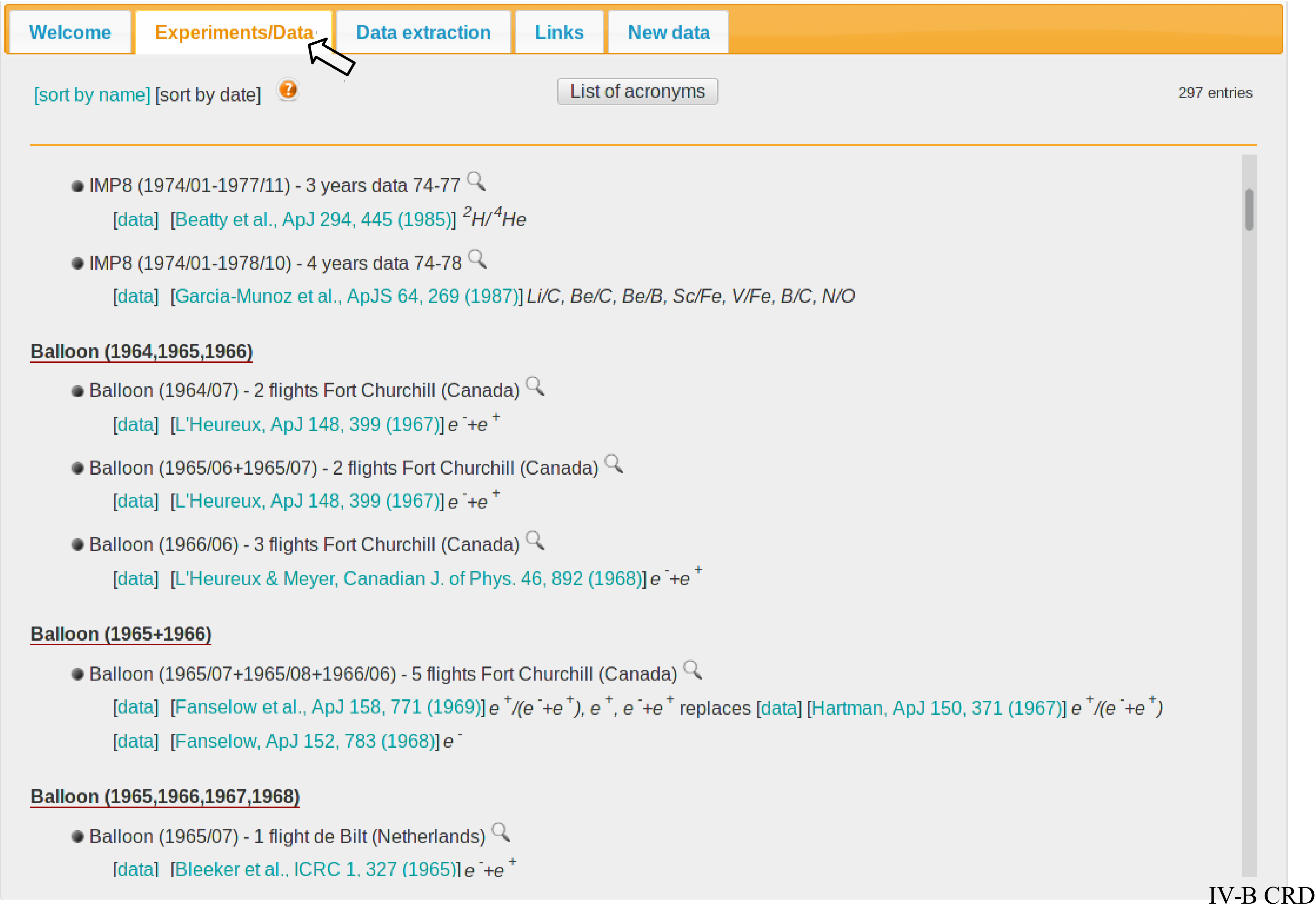
This is a mySQL database containing lists of experiments (name, dates of flight, experimental technique in brief, website), the corresponding publications (ref. and link to the ADS database), and all available data points (fluxes and ratios of leptons, nuclides, and anti-protons including their statistical and systematic error whenever available).

Accessing the database

- Experiments/Data: list of experiments, publications, data
- Data extraction: selection by flux/ratio/energy range... (on this web site or via a REST interface)
- Export database content in USINE or GALPROP compliant format (ASCII files)
- Get all bibtex entries and Latex cite (by sub-experiment)

Acknowledgements: this project has been financially supported by the PNHE

CRDB snapshots: 'Experiment/Data' tab (1)



- IMP8 (1974/01-1977/11) - 3 years data 74-77
  [data] [Beatty et al., ApJ 294, 445 (1985)] $^{2}H/^{4}He$
- IMP8 (1974/01-1978/10) - 4 years data 74-78
  [data] [Garcia-Munoz et al., ApJS 64, 269 (1987)] *Li/C, Be/C, Be/B, Sc/Fe, V/Fe, B/C, N/O*

Balloon (1964,1965,1966)

- Balloon (1964/07) - 2 flights Fort Churchill (Canada)
  [data] [L'Heureux, ApJ 148, 399 (1967)] e^-+e^+
- Balloon (1965/06+1965/07) - 2 flights Fort Churchill (Canada)
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- Balloon (1966/06) - 3 flights Fort Churchill (Canada)
  [data] [L'Heureux & Meyer, Canadian J. of Phys. 46, 892 (1968)] e^-+e^+

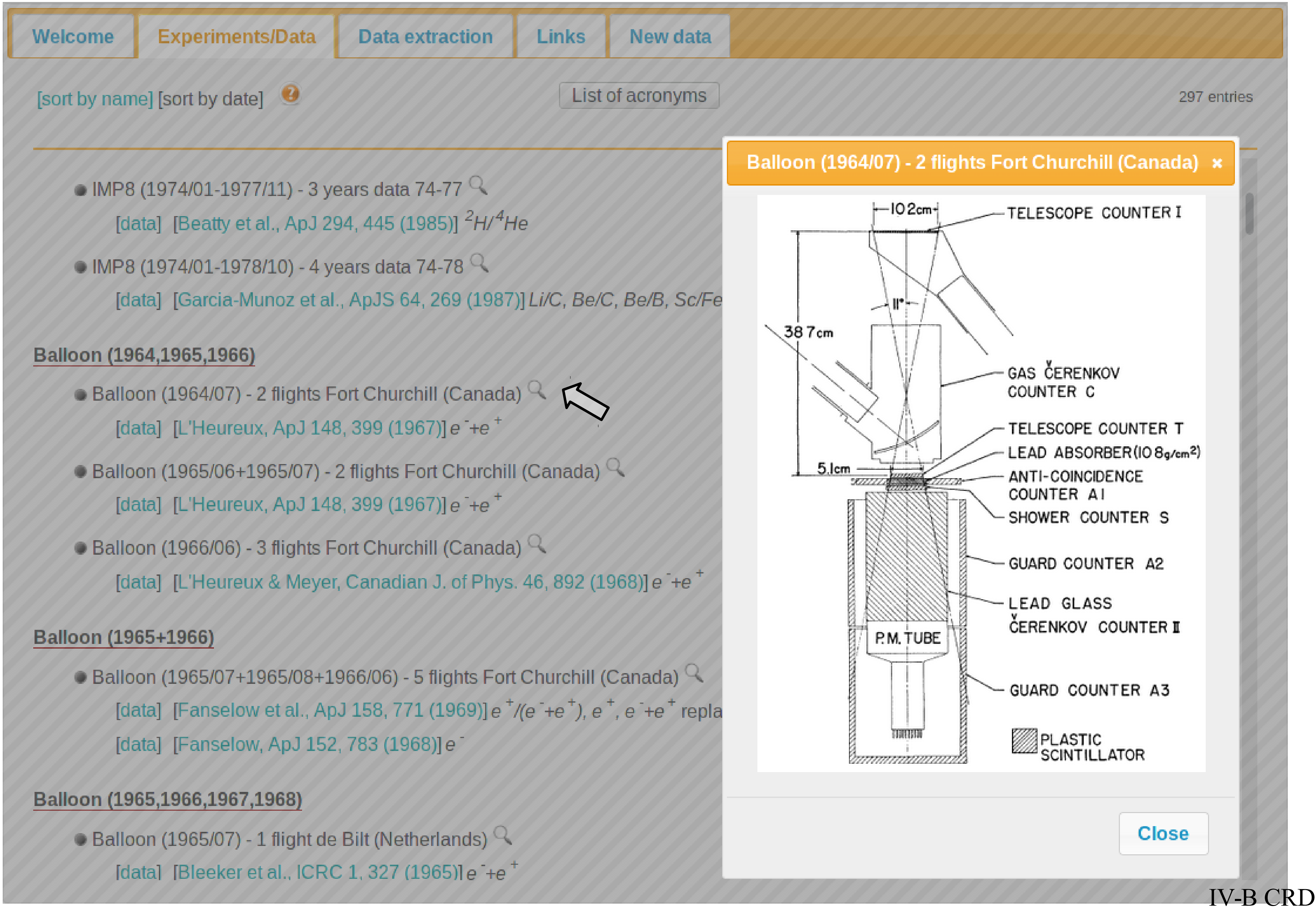
Balloon (1965+1966)

- Balloon (1965/07+1965/08+1966/06) - 5 flights Fort Churchill (Canada)
  [data] [Fanselow et al., ApJ 158, 771 (1969)] $e^+/(e^-+e^+)$, e^+, e^-+e^+ replaces [data] [Hartman, ApJ 150, 371 (1967)] $e^+/(e^-+e^+)$
  [data] [Fanselow, ApJ 152, 783 (1968)] e^-

Balloon (1965,1966,1967,1968)

- Balloon (1965/07) - 1 flight de Bilt (Netherlands)
  [data] [Bleeker et al., ICRC 1, 327 (1965)] e^-+e^+

CRDB snapshots: 'Experiment/Data' tab (2)



[sort by name] [sort by date]

297 entries

- IMP8 (1974/01-1977/11) - 3 years data 74-77
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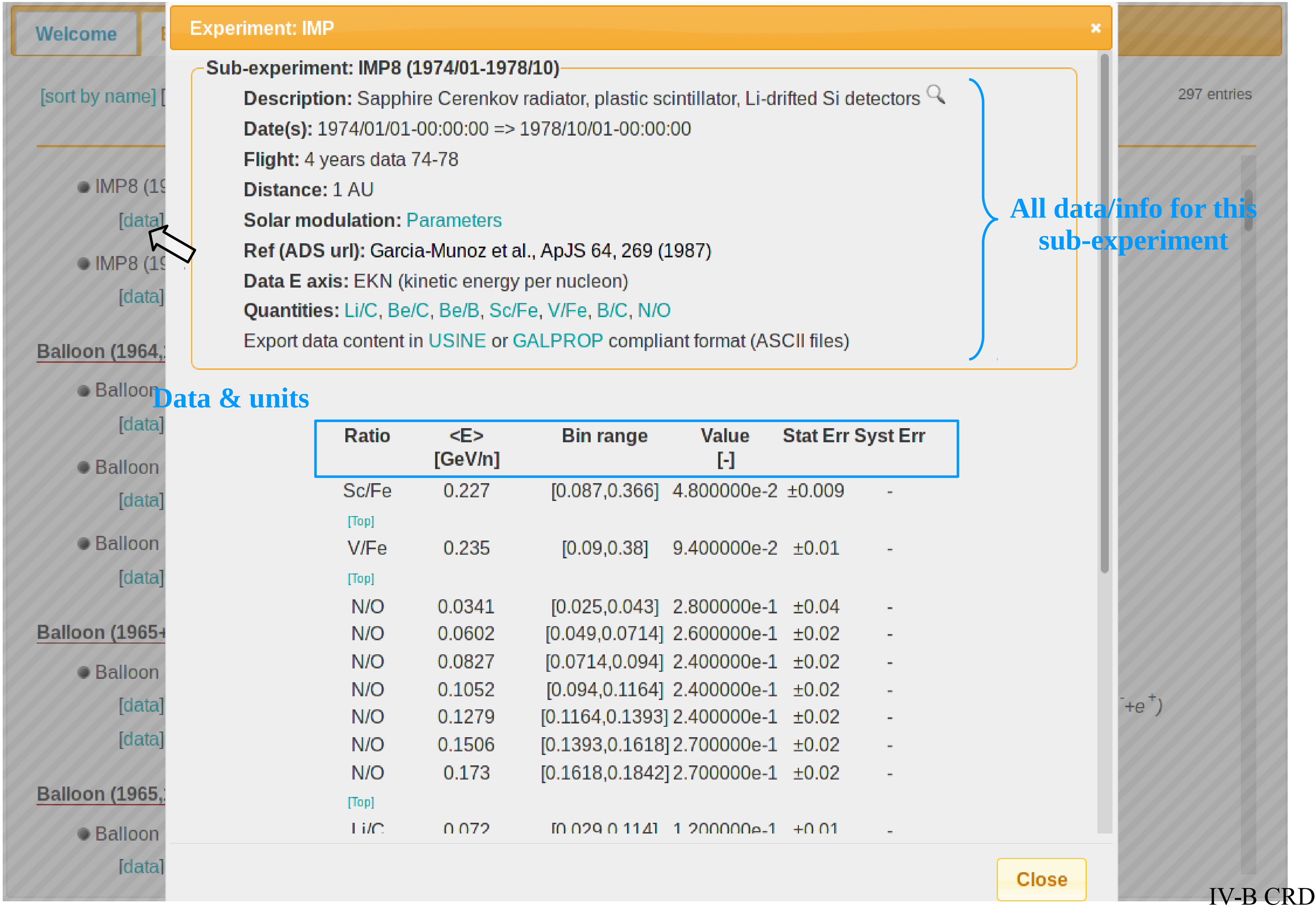
CRDB snapshots: 'Experiment/Data' tab (3)



Experiment: IMP

Sub-experiment: IMP8 (1974/01-1978/10)

Description: Sapphire Cerenkov radiator, plastic scintillator, Li-drifted Si detectors

Date(s): 1974/01/01-00:00:00 => 1978/10/01-00:00:00

Flight: 4 years data 74-78

Distance: 1 AU

Solar modulation: Parameters

Ref (ADS url): Garcia-Munoz et al., ApJS 64, 269 (1987)

Data E axis: EKN (kinetic energy per nucleon)

Quantities: Li/C, Be/C, Be/B, Sc/Fe, V/Fe, B/C, N/O

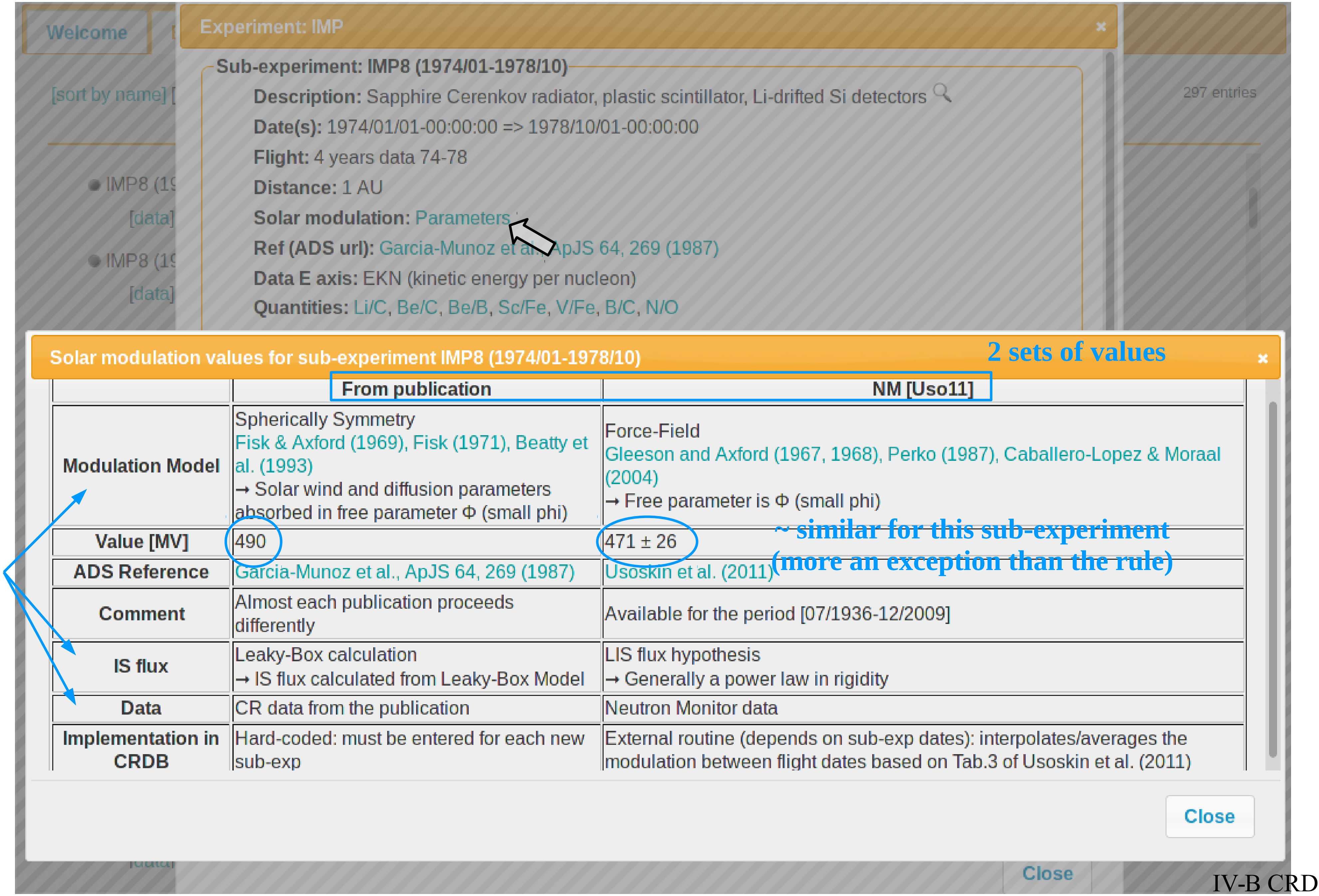
Export data content in USINE or GALPROP compliant format (ASCII files)

All data/info for this sub-experiment

Data & units

Ratio	<E> [GeV/n]	Bin range	Value [-]	Stat Err	Syst Err
Sc/Fe	0.227	[0.087,0.366]	4.800000e-2	±0.009	-
[Top]					
V/Fe	0.235	[0.09,0.38]	9.400000e-2	±0.01	-
[Top]					
N/O	0.0341	[0.025,0.043]	2.800000e-1	±0.04	-
N/O	0.0602	[0.049,0.0714]	2.600000e-1	±0.02	-
N/O	0.0827	[0.0714,0.094]	2.400000e-1	±0.02	-
N/O	0.1052	[0.094,0.1164]	2.400000e-1	±0.02	-
N/O	0.1279	[0.1164,0.1393]	2.400000e-1	±0.02	-
N/O	0.1506	[0.1393,0.1618]	2.700000e-1	±0.02	-
N/O	0.173	[0.1618,0.1842]	2.700000e-1	±0.02	-
[Top]					
Li/C	0.072	[0.029,0.114]	1.200000e-1	±0.01	-

CRDB snapshots: 'Experiment/Data' tab (4)



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Flight: 4 years data 74-78

Distance: 1 AU

Solar modulation: Parameters

Ref (ADS url): Garcia-Munoz et al., ApJS 64, 269 (1987)

Data E axis: EKN (kinetic energy per nucleon)

Quantities: Li/C, Be/C, Be/B, Sc/Fe, V/Fe, B/C, N/O

Solar modulation values for sub-experiment IMP8 (1974/01-1978/10)

2 sets of values

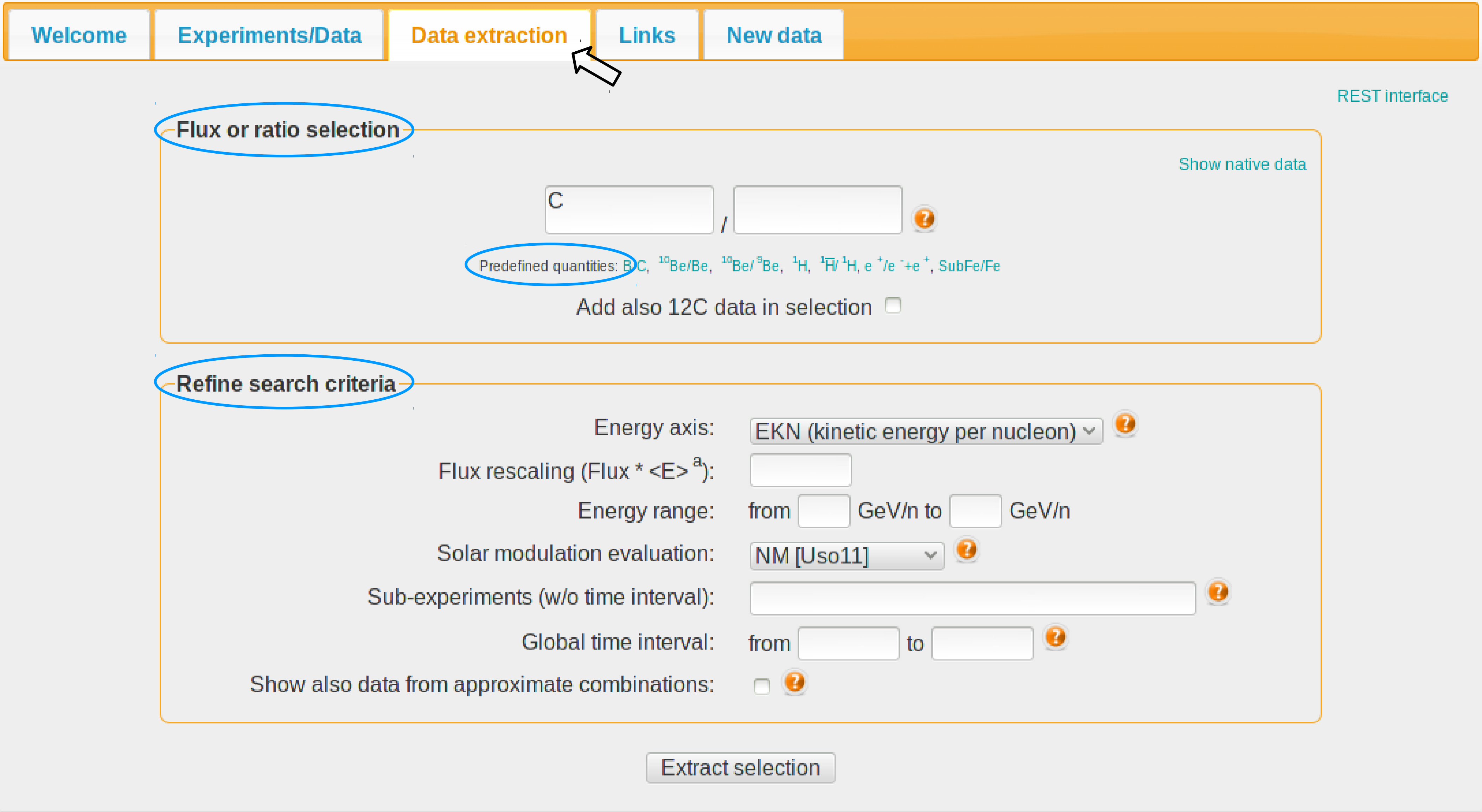
	From publication	**NM [Uso11]**
Modulation Model	Spherically Symmetry Fisk & Axford (1969), Fisk (1971), Beatty et al. (1993) → Solar wind and diffusion parameters absorbed in free parameter Φ (small phi)	Force-Field Gleeson and Axford (1967, 1968), Perko (1987), Caballero-Lopez & Moraal (2004) → Free parameter is Φ (small phi)
Value [MV]	490	471 ± 26
ADS Reference	Garcia-Munoz et al., ApJS 64, 269 (1987)	Usoskin et al. (2011)
Comment	Almost each publication proceeds differently	Available for the period [07/1936-12/2009]
IS flux	Leaky-Box calculation → IS flux calculated from Leaky-Box Model	LIS flux hypothesis → Generally a power law in rigidity
Data	CR data from the publication	Neutron Monitor data
Implementation in CRDB	Hard-coded: must be entered for each new sub-exp	External routine (depends on sub-exp dates): interpolates/averages the modulation between flight dates based on Tab.3 of Usoskin et al. (2011)

~ similar for this sub-experiment (more an exception than the rule)

Hypotheses

Close

CRDB snapshots: 'Data extraction' tab (1)



Flux or ratio selection

C /

Predefined quantities: B/C, ^{10}Be/Be, ^{10}Be/^{9}Be, ^{1}H, $^{1}\overline{H}$/^{1}H, e^{+}/e^{-}+e^{+}, SubFe/Fe

Add also 12C data in selection ☐

Refine search criteria

Energy axis: EKN (kinetic energy per nucleon)

Flux rescaling (Flux * <E>^{a}):

Energy range: from GeV/n to GeV/n

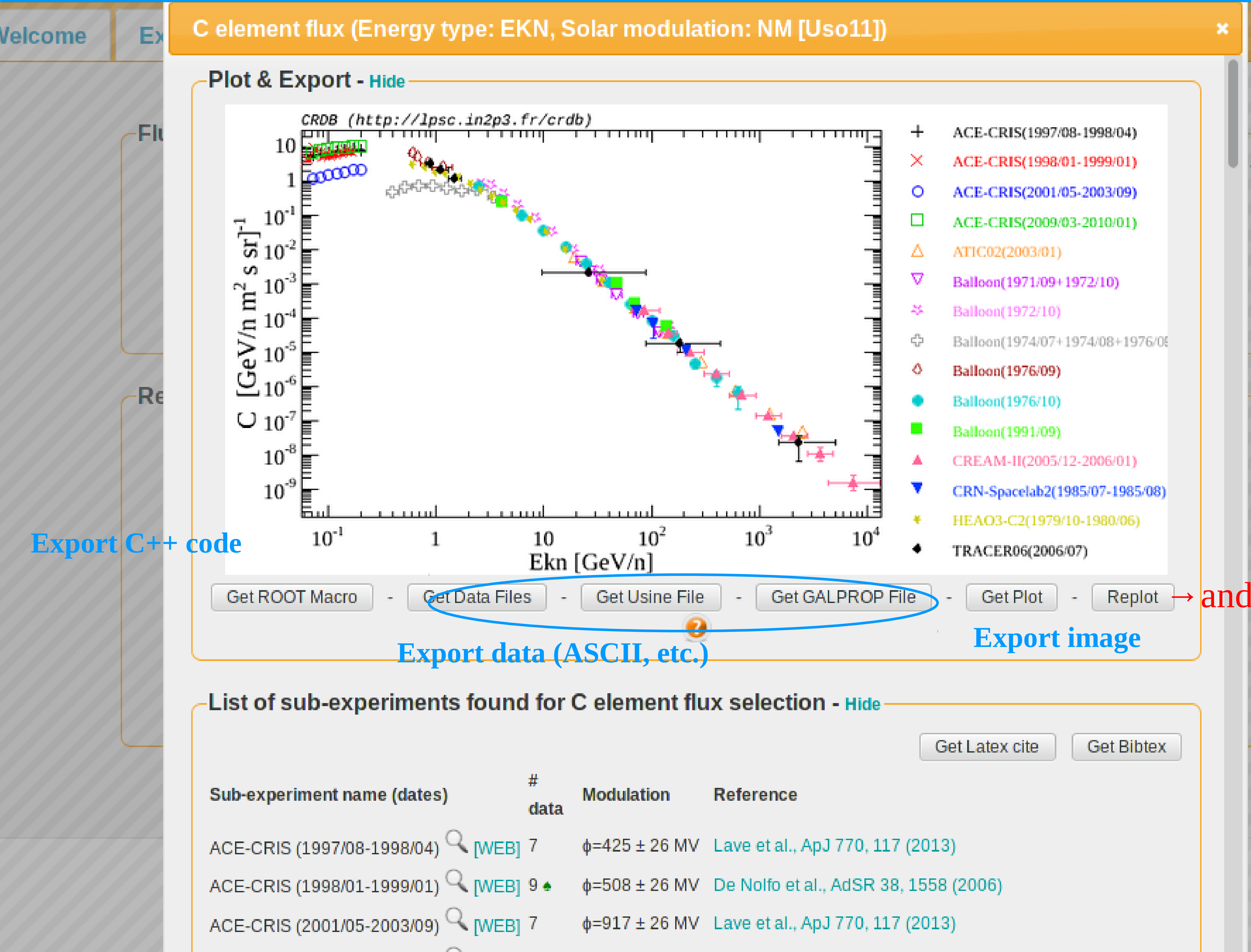
Solar modulation evaluation: NM [Uso11]

Sub-experiments (w/o time interval):

Global time interval: from to

Show also data from approximate combinations: ☐

CRDB snapshots: 'Data extraction' tab (2)



C element flux (Energy type: EKN, Solar modulation: NM [Uso11])

Plot & Export - Hide

Export C++ code

→ and click to get.

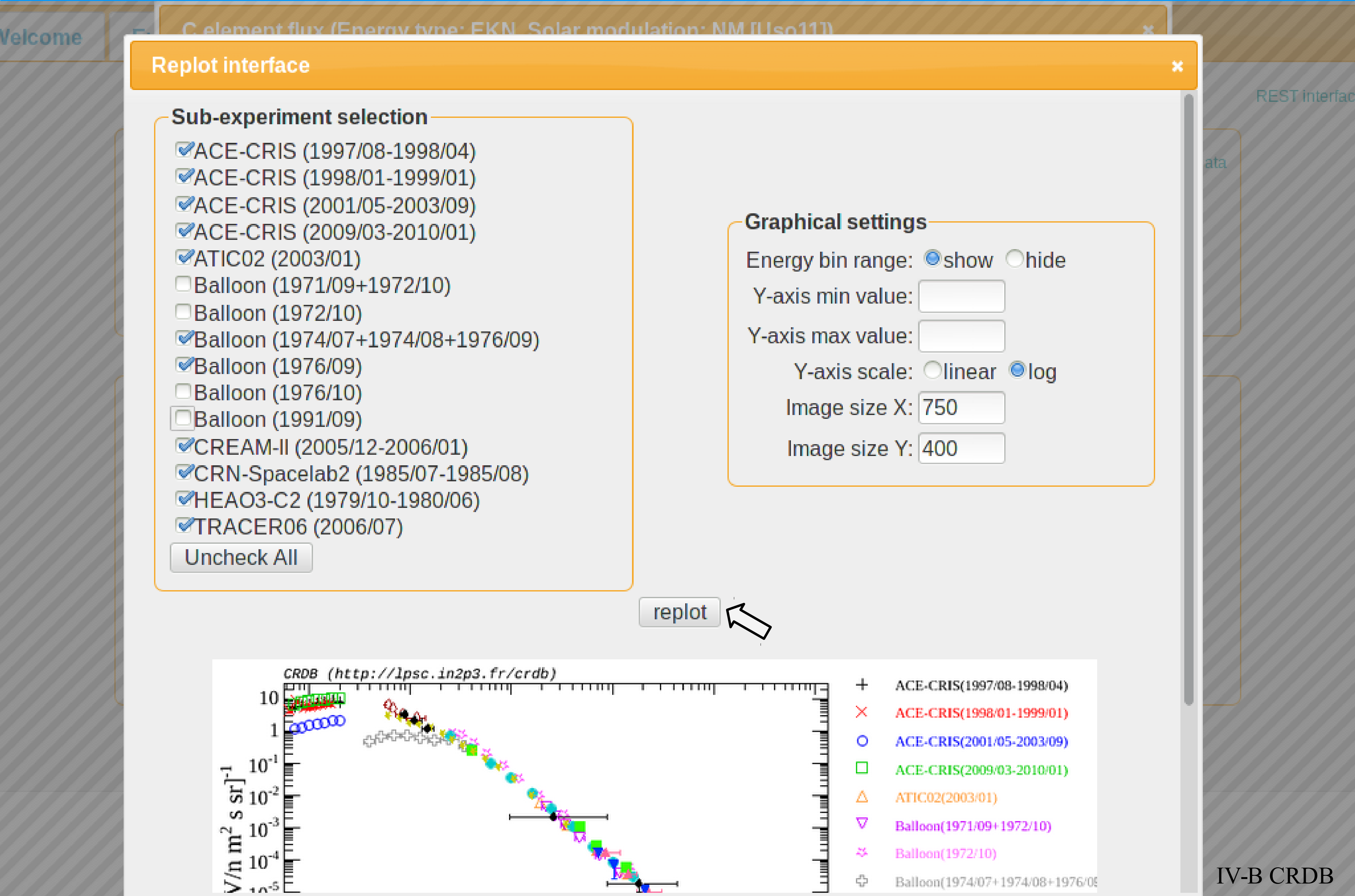
Export image

Export data (ASCII, etc.)

List of sub-experiments found for C element flux selection - Hide

Sub-experiment name (dates)	# data	Modulation	Reference
ACE-CRIS (1997/08-1998/04) [WEB]	7	ϕ=425 ± 26 MV	Lave et al., ApJ 770, 117 (2013)
ACE-CRIS (1998/01-1999/01) [WEB]	9 ♠	ϕ=508 ± 26 MV	De Nolfo et al., AdSR 38, 1558 (2006)
ACE-CRIS (2001/05-2003/09) [WEB]	7	ϕ=917 ± 26 MV	Lave et al., ApJ 770, 117 (2013)

CRDB snapshots: 'Data extraction' tab (3)



Replot interface

Sub-experiment selection

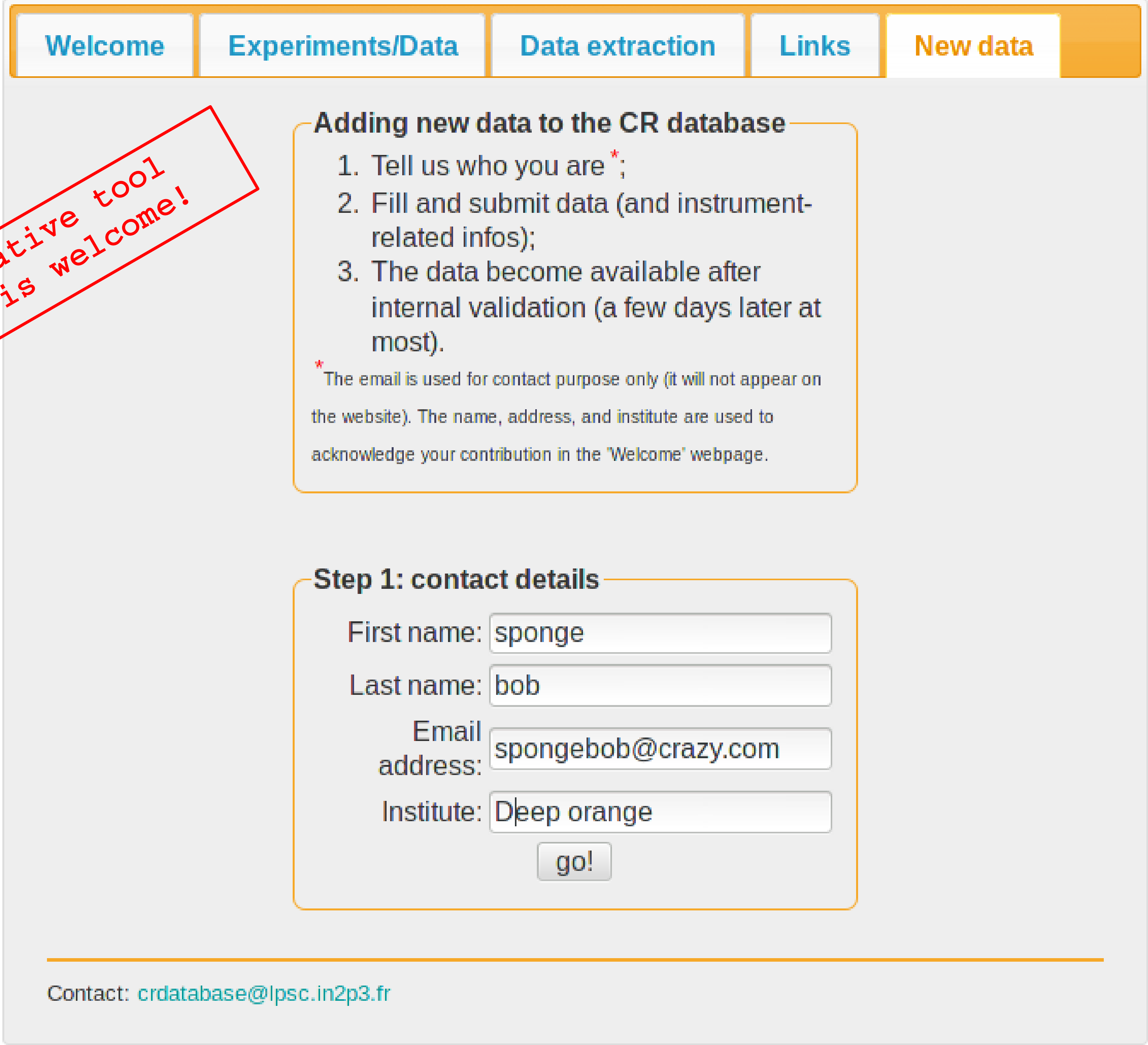
- ☑ ACE-CRIS (1997/08-1998/04)
- ☑ ACE-CRIS (1998/01-1999/01)
- ☑ ACE-CRIS (2001/05-2003/09)
- ☑ ACE-CRIS (2009/03-2010/01)
- ☑ ATIC02 (2003/01)
- ☐ Balloon (1971/09+1972/10)
- ☐ Balloon (1972/10)
- ☑ Balloon (1974/07+1974/08+1976/09)
- ☑ Balloon (1976/09)
- ☐ Balloon (1976/10)
- ☐ Balloon (1991/09)
- ☑ CREAM-II (2005/12-2006/01)
- ☑ CRN-Spacelab2 (1985/07-1985/08)
- ☑ HEAO3-C2 (1979/10-1980/06)
- ☑ TRACER06 (2006/07)

Graphical settings

Energy bin range: ● show ○ hide
Y-axis min value:
Y-axis max value:
Y-axis scale: ○ linear ● log
Image size X: 750
Image size Y: 400

CRDB: 'New data' tab

→ collaborative tool
your help is welcome!



Adding new data to the CR database

1. Tell us who you are *;
2. Fill and submit data (and instrument-related infos);
3. The data become available after internal validation (a few days later at most).

* The email is used for contact purpose only (it will not appear on the website). The name, address, and institute are used to acknowledge your contribution in the 'Welcome' webpage.

Step 1: contact details

First name: sponge
Last name: bob
Email address: spongebob@crazy.com
Institute: Deep orange

Contact: crdatabase@lpsc.in2p3.fr

Charged signals: electrons/positrons, antibaryons

IV - Transport in the heliosphere
Charged signals: electrons/positrons, antibaryons

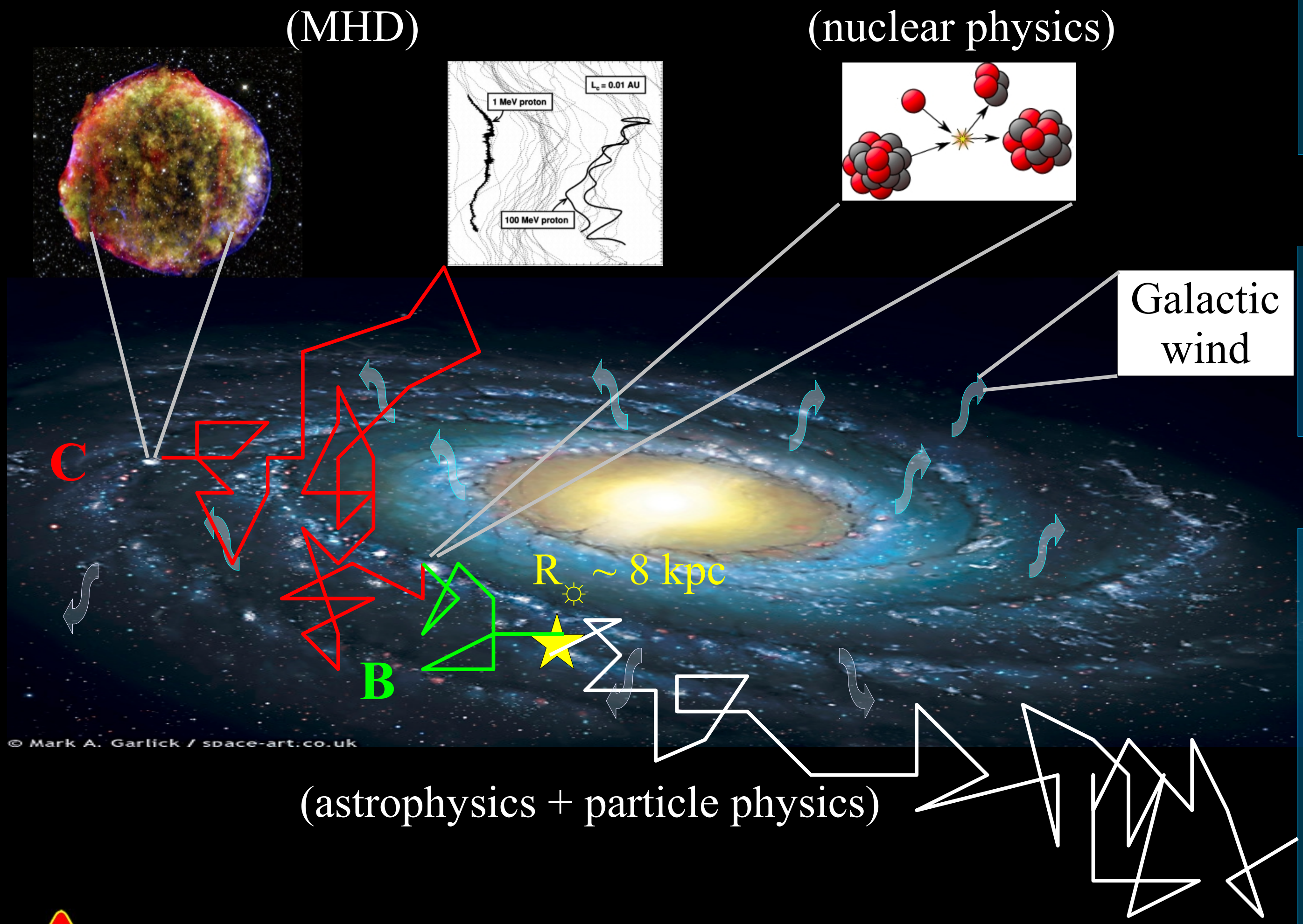
Charged cosmic rays in the Galaxy

1. Source injection

- spectrum ~ R^{-2}
- abundances

2. Transport in the Galaxy

- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay



What about dark matter?

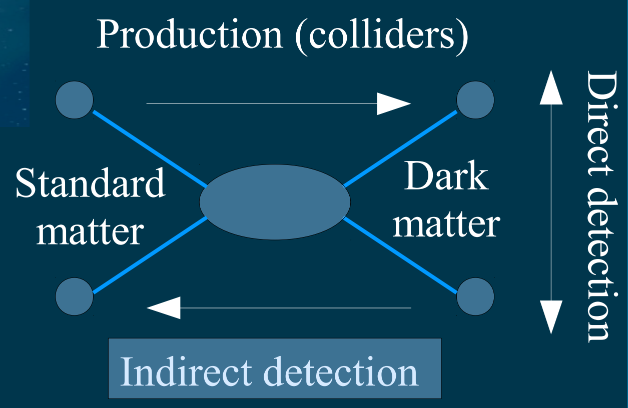
Universe (after Planck)

- 68.3 % dark energy
- 26.8 % dark matter
- 4.9 % ordinary matter

MW dark matter halo

- ~ spherical halo
- radius ~300 kpc

How to detect dark matter?



Where to look for new physics in GCRs: which species?

Charged cosmic rays in the Galaxy

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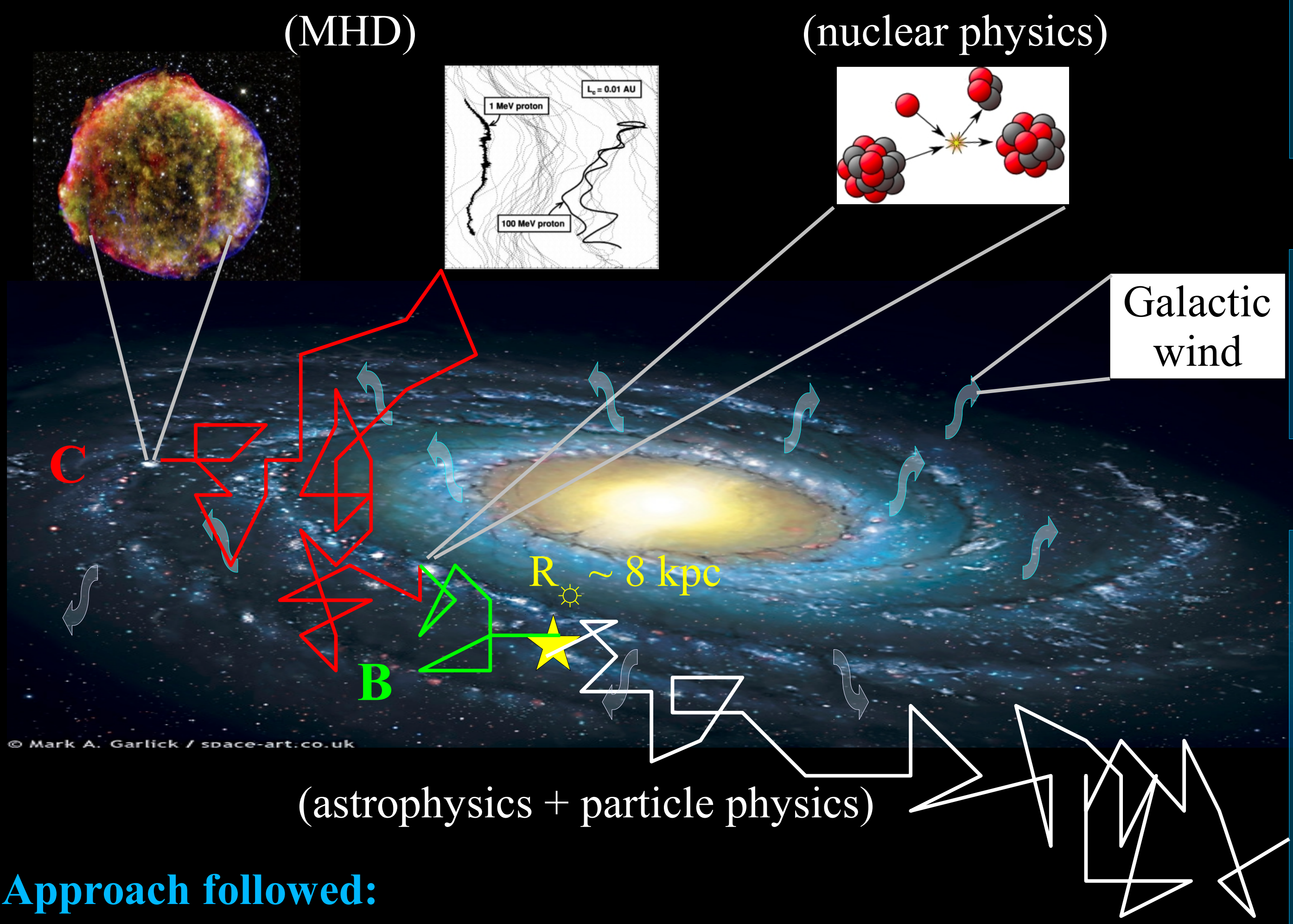

© Mark A. Garlick / space-art.co.uk

Approach followed:

→ Calibrate transport (model vs data): B/C, $^{10}Be/^{9}Be$

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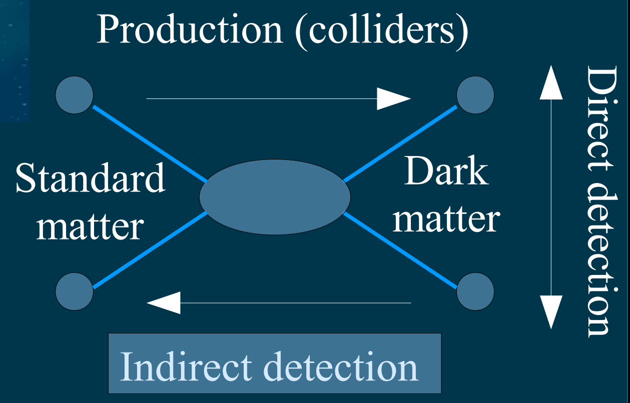

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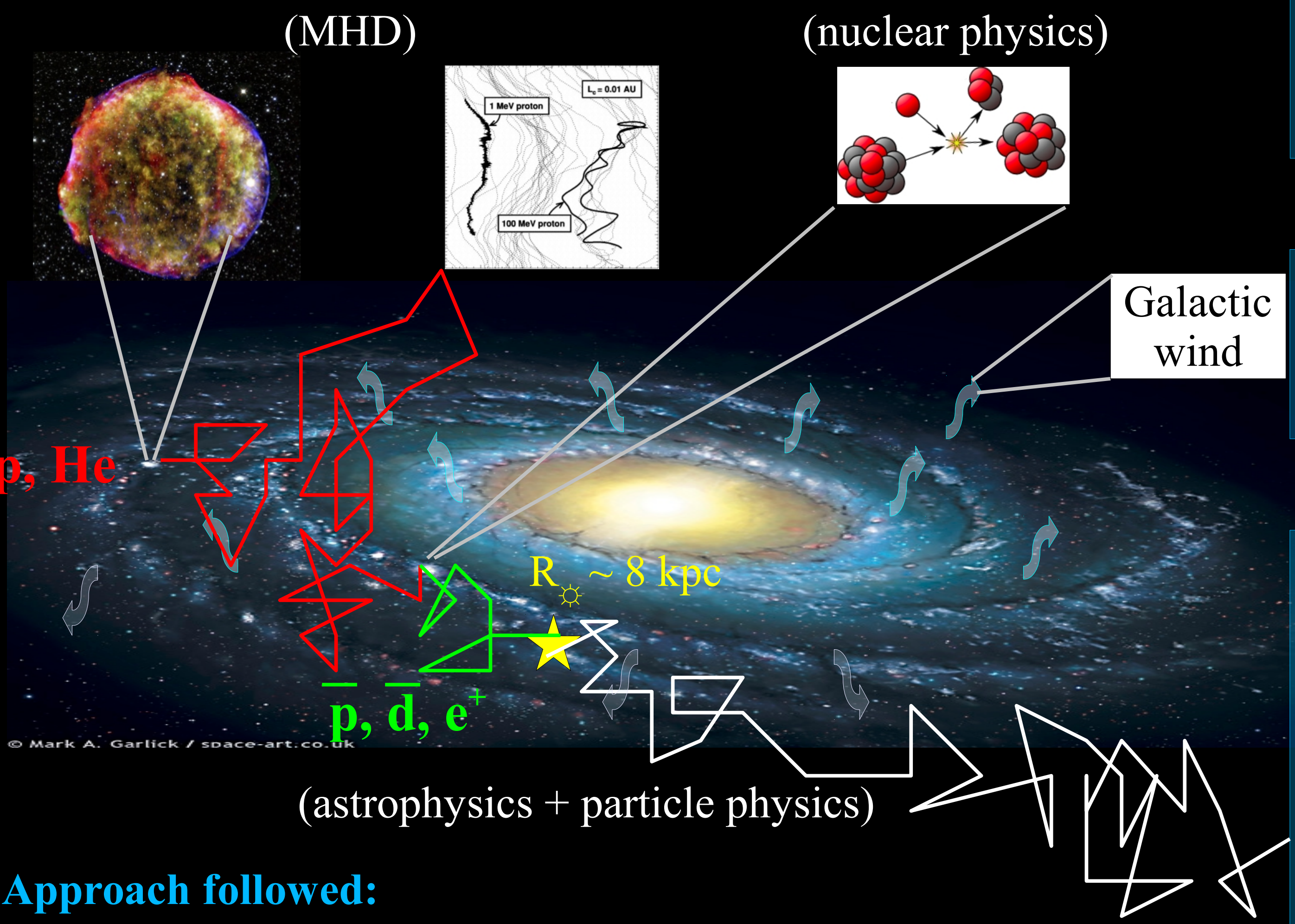

Approach followed:

→ Calibrate transport (model vs data): B/C, ^{10}Be/^{9}Be
→ Calculate rare secondary fluxes (e^+, antiproton, antideuteron)

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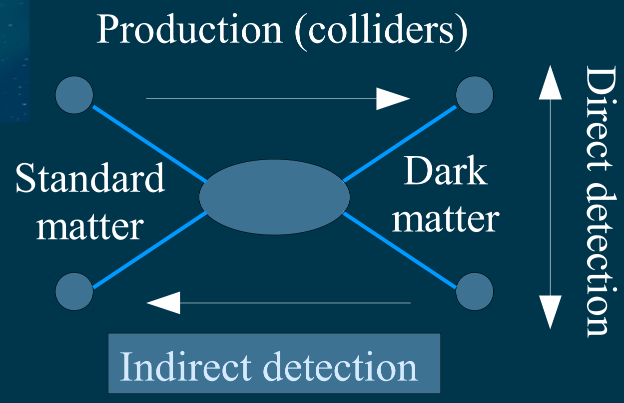

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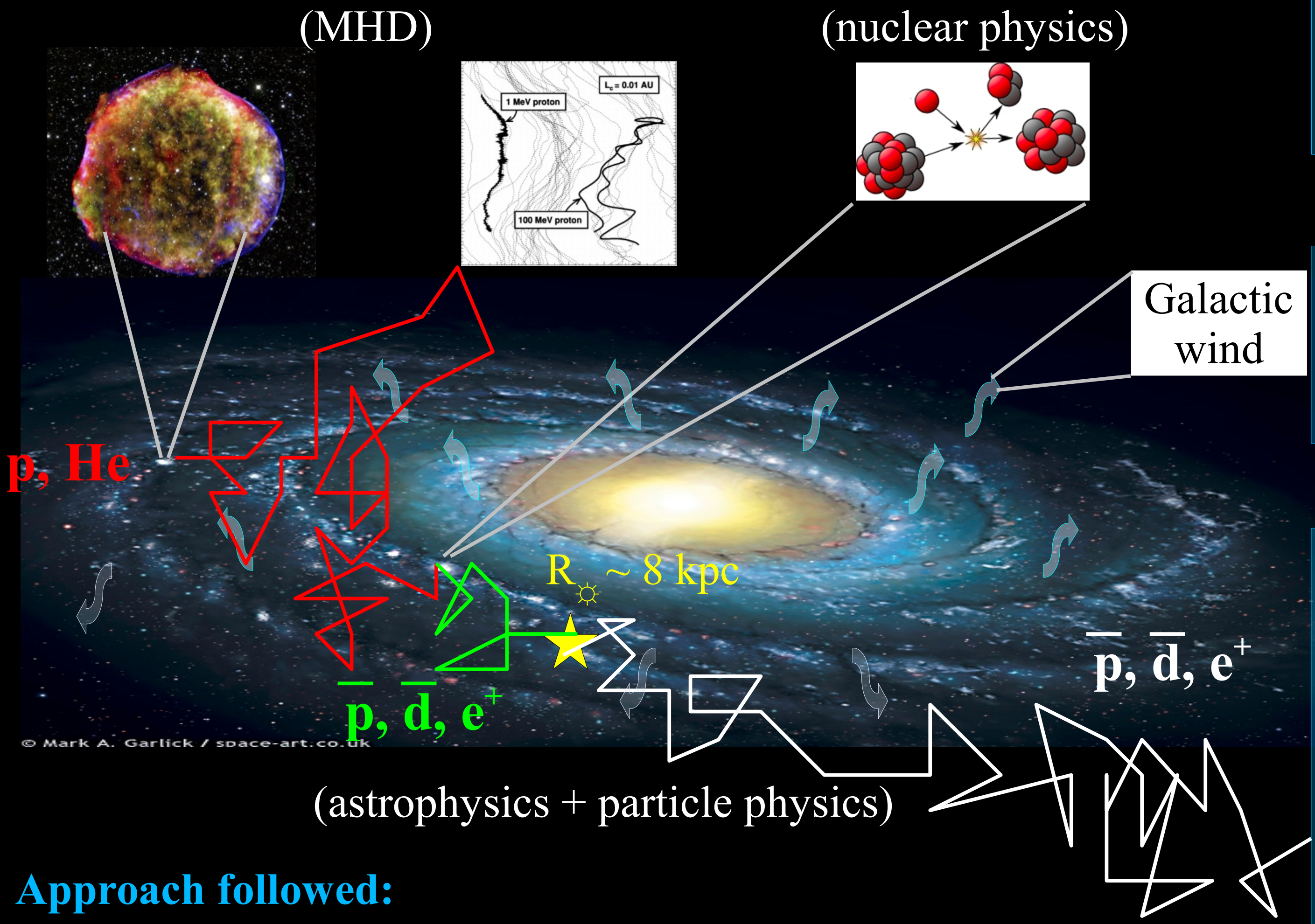

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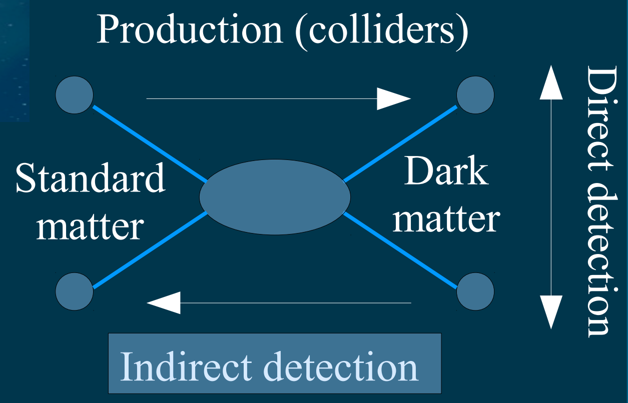


Approach followed:

→ Calibrate transport (model vs data): B/C, ^{10}Be/^{9}Be

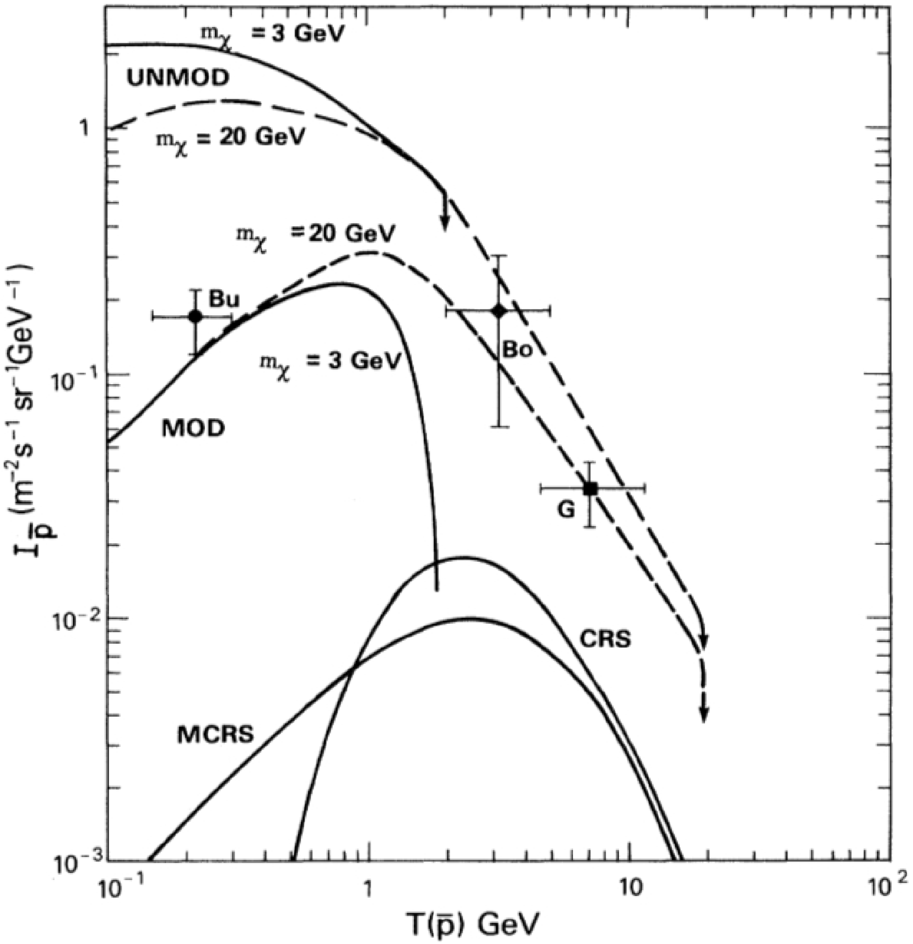
→ Calculate rare secondary fluxes (e^+, antiproton, antideuteron)

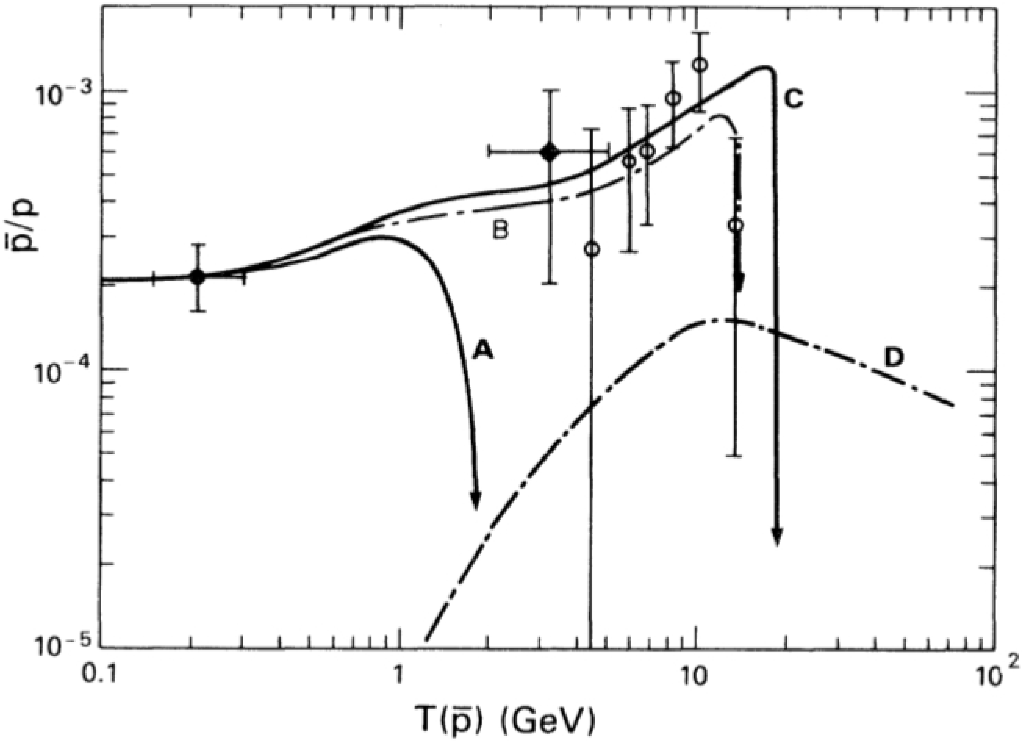
→ Excess from DM annihilation?

Initial motivation for DM in antiprotons

Excess in the antiproton flux?

Stecker, Rudaz & Walsh, Phys. Rev. Lett. **55**, 2622 (1985)





What are the 3 possible conclusions?

Charged signals: electrons/positrons, antibaryons

IV - Transport in the heliosphere
Charged signals: electrons/positrons, antibaryons

IV-A Propagation in the heliosphere

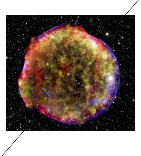
IV-B CRDB

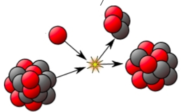
IV-C Anti-p, anti-d, and positron fraction

1. Where to look for new physics in GCRs
2. "Backgrounds" from secondary production
3. Uncertainties on DM signals (propagation, DM)
4. Positron fraction
5. Summary and perspectives

Astrophysical backgrounds: source terms to consider

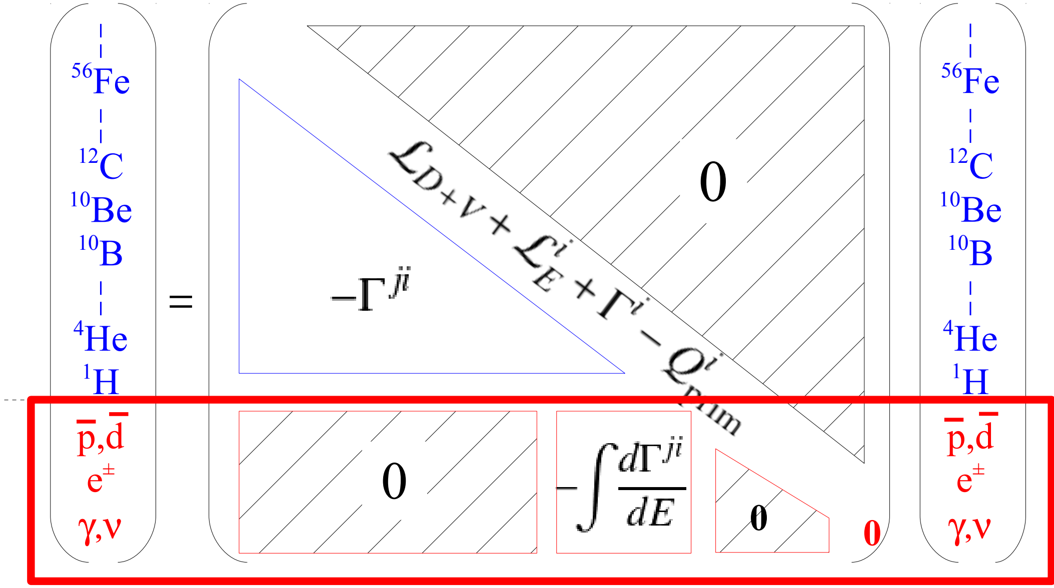
$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(D(E,\vec{r})\vec{\nabla}\right)+\vec{\nabla}\cdot\vec{V}_c(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - D_{EE}\frac{\partial N^j}{\partial E}\right)}^{\text{E losses and gains}} + \overbrace{\left(\Gamma_{\text{rad}}+\Gamma_{\text{inel}}\right)}^{\text{Catastrophic losses}} N^j = \boxed{\overbrace{Q^j(t,E,\vec{r})}^{\text{Source}}}$$





$$\left.\begin{array}{l} Q^{\text{primary}}_{\text{continuum}}(r,E) \approx q^j R^{-\alpha^j} \times [f_{\text{SNR}}(r)]^{(\text{disc})} \\ \boxed{\left[Q^{\text{primary}}_{\text{e}\pm}{}_{;}(t,\delta(r-r_s),E)\right]} \end{array}\right\}$$

$$\left.\begin{array}{l} \boxed{Q^{\text{secondary}}_{\bar{\text{p}},\bar{\text{d}},\text{e}^\pm,\gamma,\nu}(r,E) = \sum_{(p,He)+(H,He)} \int nv' \frac{d\sigma}{dE} N^{p,He}(E')dE} \\ Q^{\text{secondary}}_{\text{N}}(r,E) = \sum_{m_p>m_s} n_{(H,He)} v\sigma^{ps}(E) N^p(r,E) \end{array}\right\}$$



→ Calculate p, $e^\pm$, γ, ν from p, He

Antiprotons and antideutons: secondary source term

$$Q^{\rm sec}(T_{\bar{p}}) = 2 \sum_{\rm i=CRs}^{\rm p,He,CNO} \sum_{\rm j=ISM}^{\rm H,He,CNO} 4\pi n_j \int_{\rm m_{thresh}}^{\infty} \frac{d\sigma^{\rm i+j}}{dT_{\bar{p}}} \times (T_{\bar{p}}, T_i)\Phi_i(T_i)dT_i,$$

p+p ⟶ pbar + ?

What is the threshold to create a pbar?

What is the threshold to create a dbar?

$$A + B \rightarrow C + X$$

$$s = P_A^2 + P_B^2 = m_A^2 + m_B^2 + 2E_A E_B - 2\vec{p}_A \cdot \vec{p}_B$$

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$$p+p \rightarrow \bar{p}+ppp$$

$$p+p \rightarrow \bar{d}(=\bar{p}\bar{n})+pppn$$

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CR framework: p+H with H at rest
CMS: all particles at rest @ threshold

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p+p ⟶ pbar + ?
What is the threshold to create a pbar?
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$$p+p \to \bar{p}+ppp \qquad E_p = 7\ m_p$$

$$p+p \to \bar{d}(=\bar{p}\bar{n})+pppn \qquad E_p = 17 m_p$$

$$A+B \to C+X$$

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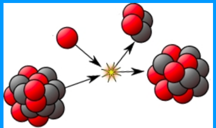

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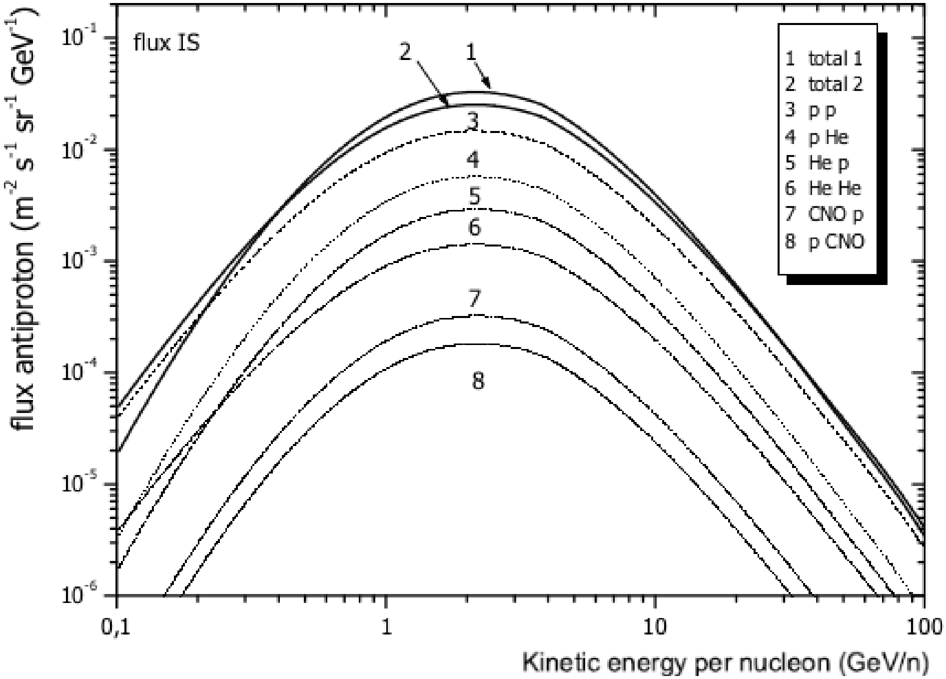
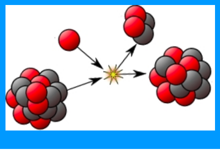
Duperray et al., PRD **71,** 083013 (2005)

Anti-protons



→ Dominant contributors: H and He (GCRs and ISM)

Antiprotons and antideutons: secondary source term



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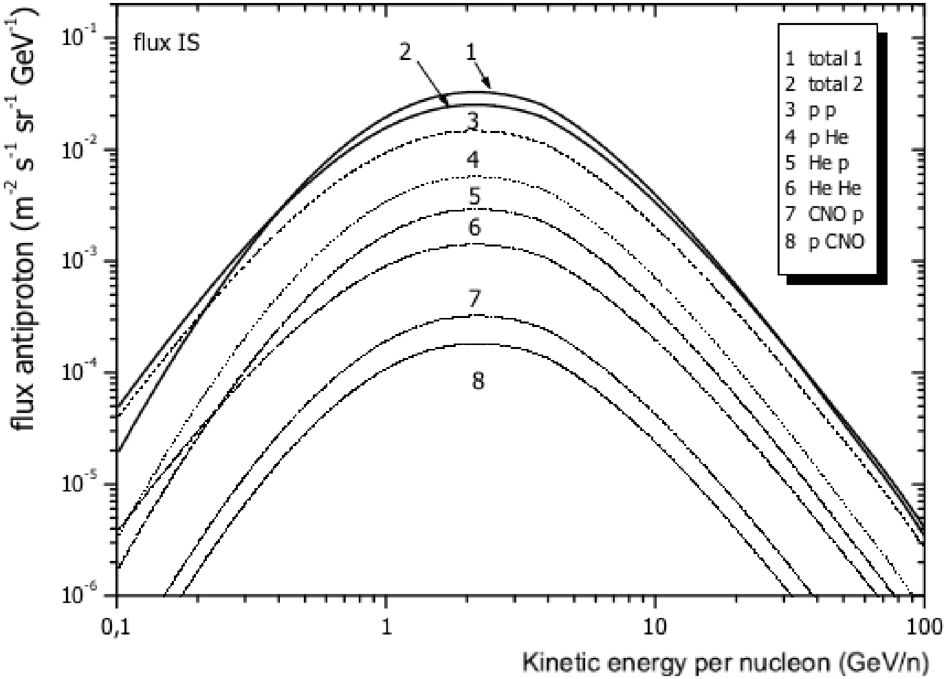
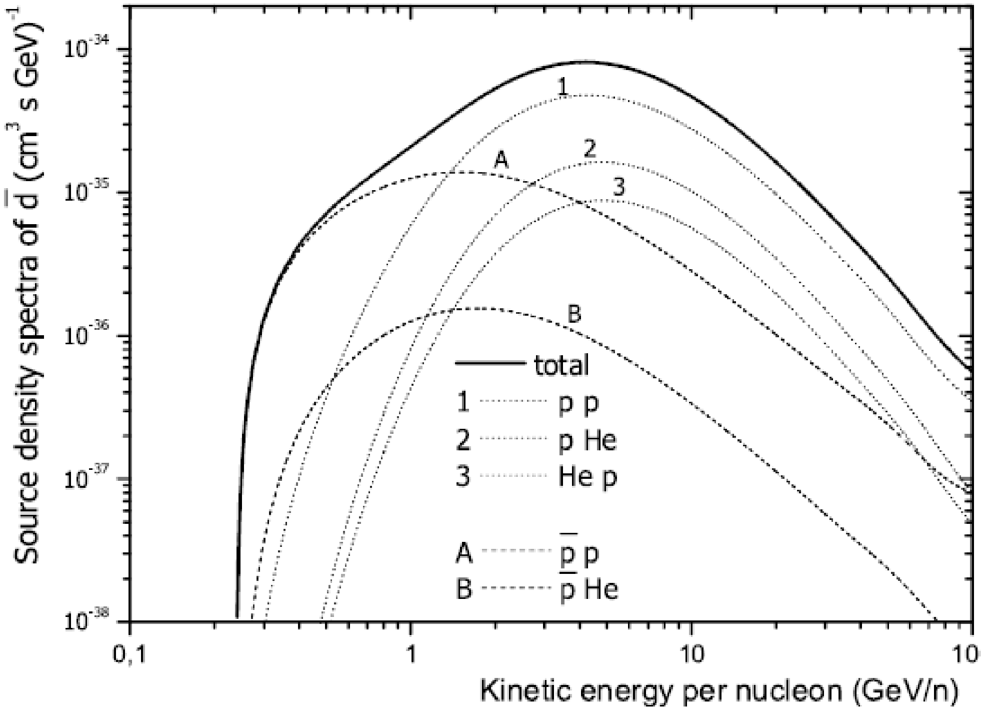


Anti-deutérons



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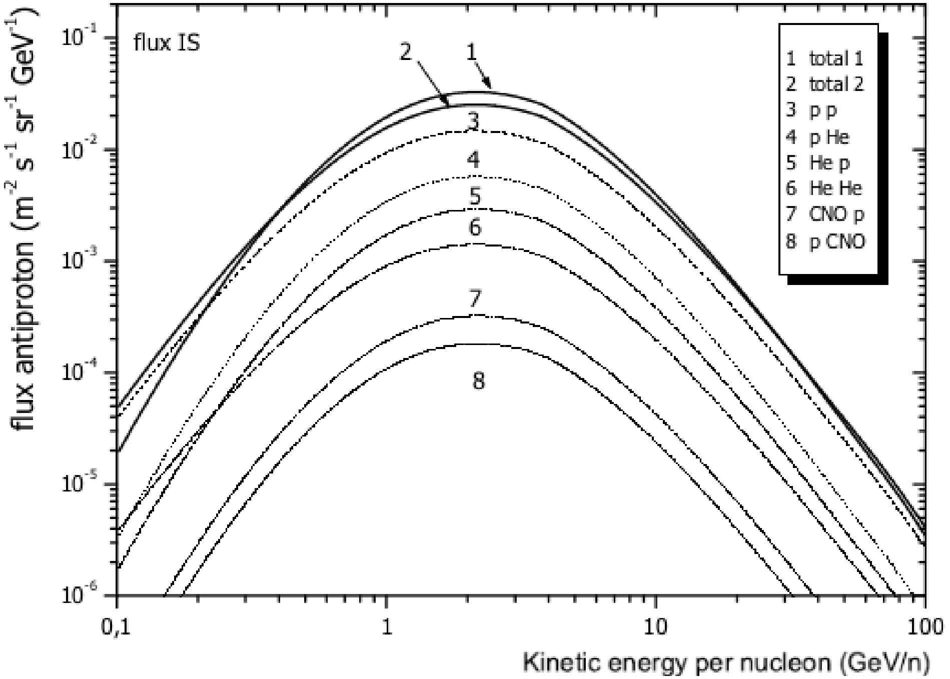


Anti-deutérons

Coalescence: pbar and nbar must be produce close in momentum space

$$\gamma \frac{d^3N_d}{d\vec{p}_d^{\,3}} = \frac{4\pi}{3} p_0^3 \left(\gamma \frac{d^3N_p}{d\vec{p}_p^{\,3}}\right)\left(\gamma \frac{d^3N_n}{d\vec{p}_n^{\,3}}\right)$$

$$\gamma \frac{d^3N_d}{d\vec{p}_d^{\,3}} = \frac{4\pi}{3} p_0^3 \left(\gamma \frac{d^3N_p}{d\vec{p}_p^{\,3}}\right)^2.$$

→ Coalescence momentum fitted on few data (~ 20% uncertainty on p_0)

Antiprotons and antideutons: tertiary source term

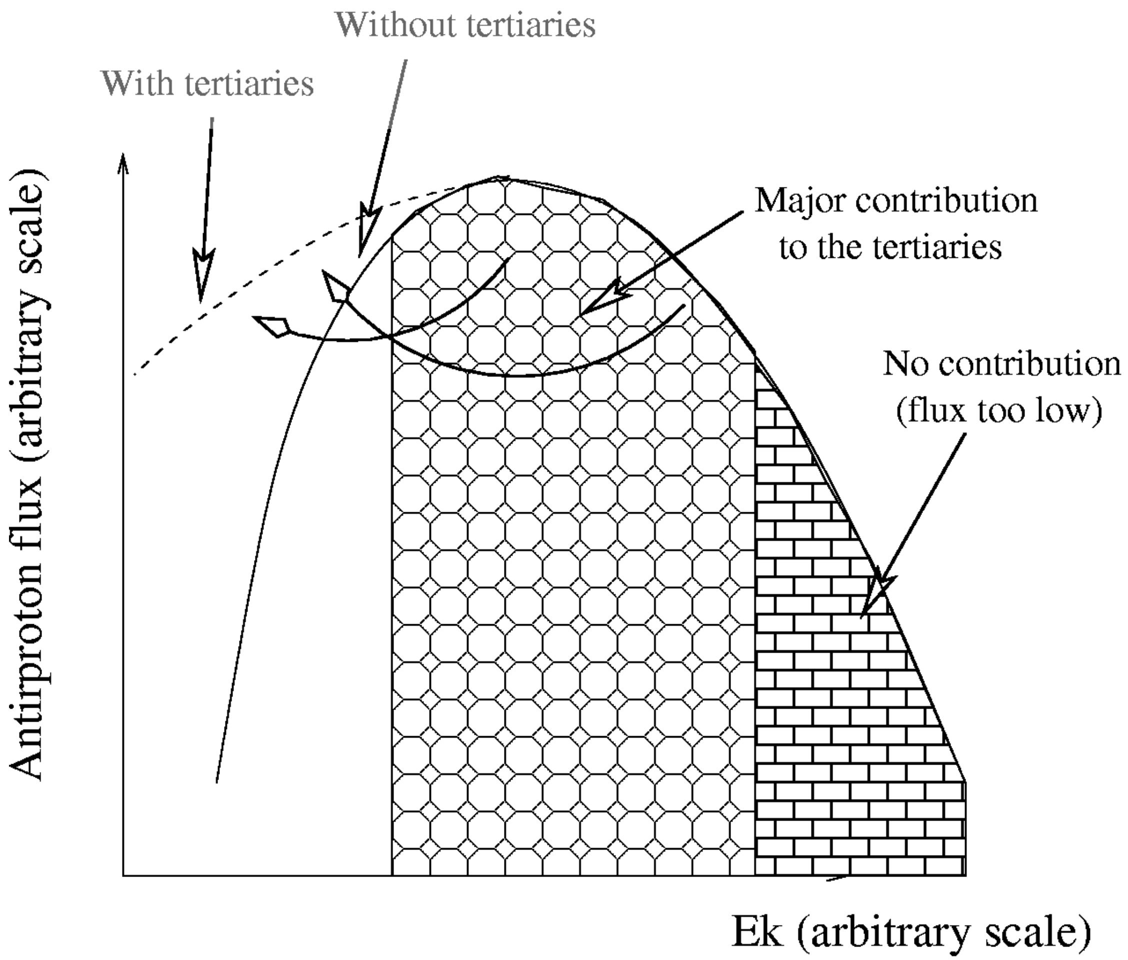
$$Q^{\rm ter}(T_{\bar p}) = 4\pi . n_p\left[2\int_{T_{\bar p}}^{\infty}\frac{d\sigma^{\bar p p\to\bar p X}}{dT_{\bar p}}(T'_{\bar p}, T_{\bar p})\Phi_{\bar p}(T'_{\bar p})dT'_{\bar p}\right. \\ \left. - 2\sigma_{\rm NAR}^{\bar p p\to\bar p X}(T_{\bar p})\Phi_{\bar p}(T_{\bar p})\right],$$

pbar(T) + p ⟶ pbar(T'<T) + X (resonances)

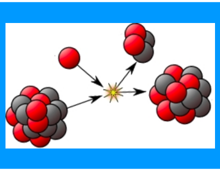
What is the effect on the pbar low energy spectrum?

Antiprotons and antideutons: tertiary source term

$$Q^{\text{ter}}(T_{\bar p}) = 4\pi . n_p \Bigg[2 \int_{T_{\bar p}}^{\infty} \frac{d\sigma^{\bar p p \to \bar p X}}{dT_{\bar p}} (T'_{\bar p}, T_{\bar p}) \Phi_{\bar p}(T'_{\bar p}) dT'_{\bar p} - 2\sigma_{\text{NAR}}^{\bar p p \to \bar p X}(T_{\bar p}) \Phi_{\bar p}(T_{\bar p}) \Bigg],$$



Antiprotons and antideutons: tertiary source term



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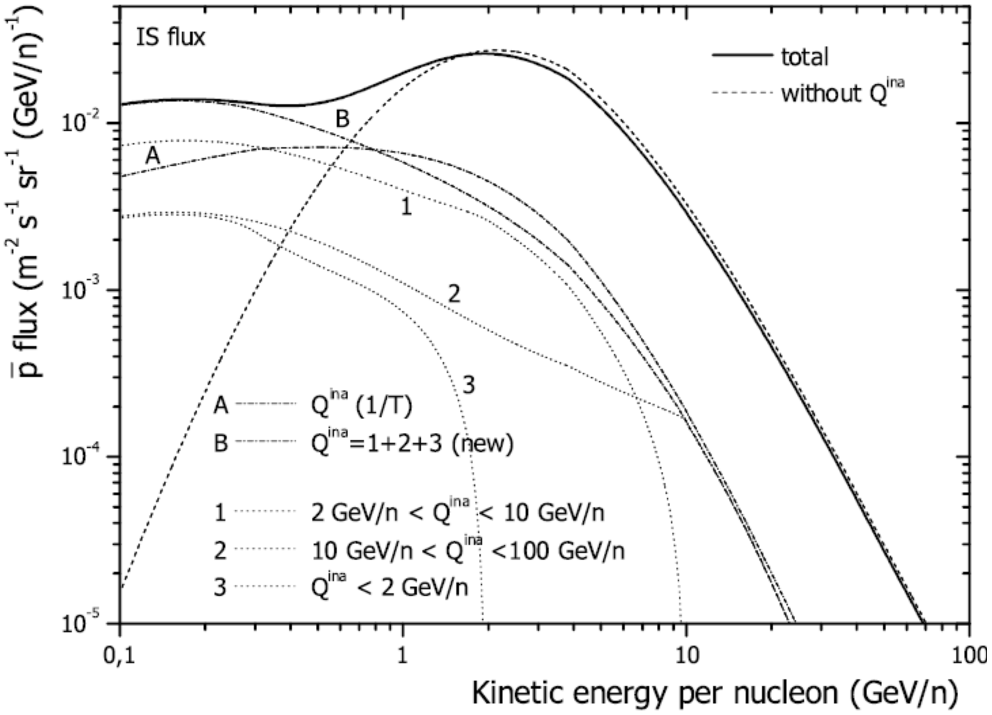
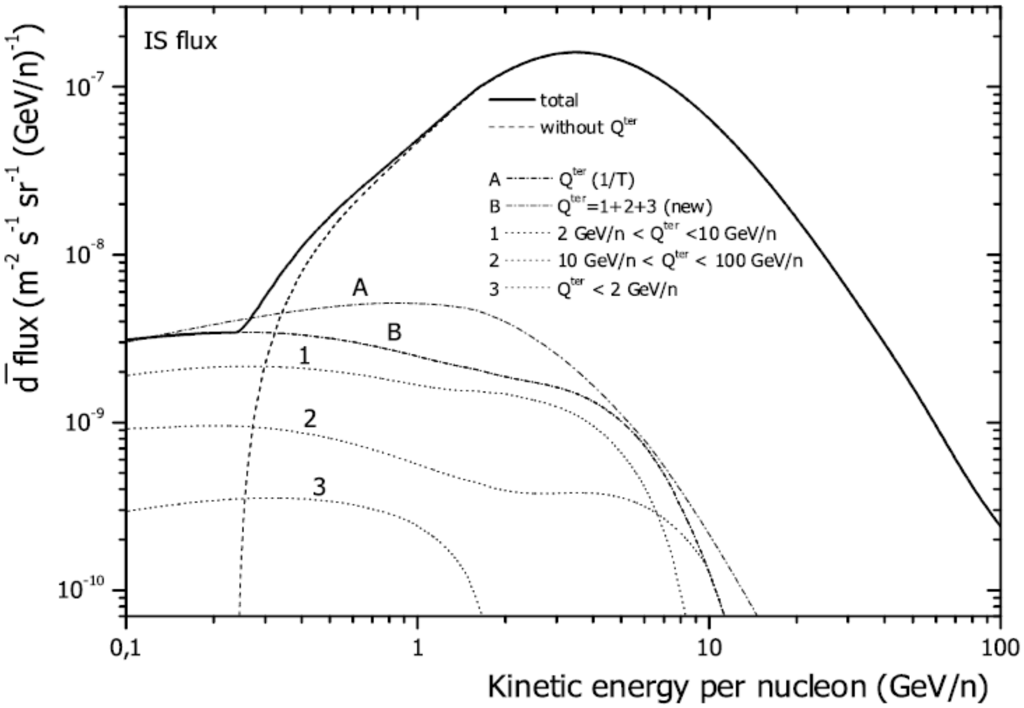
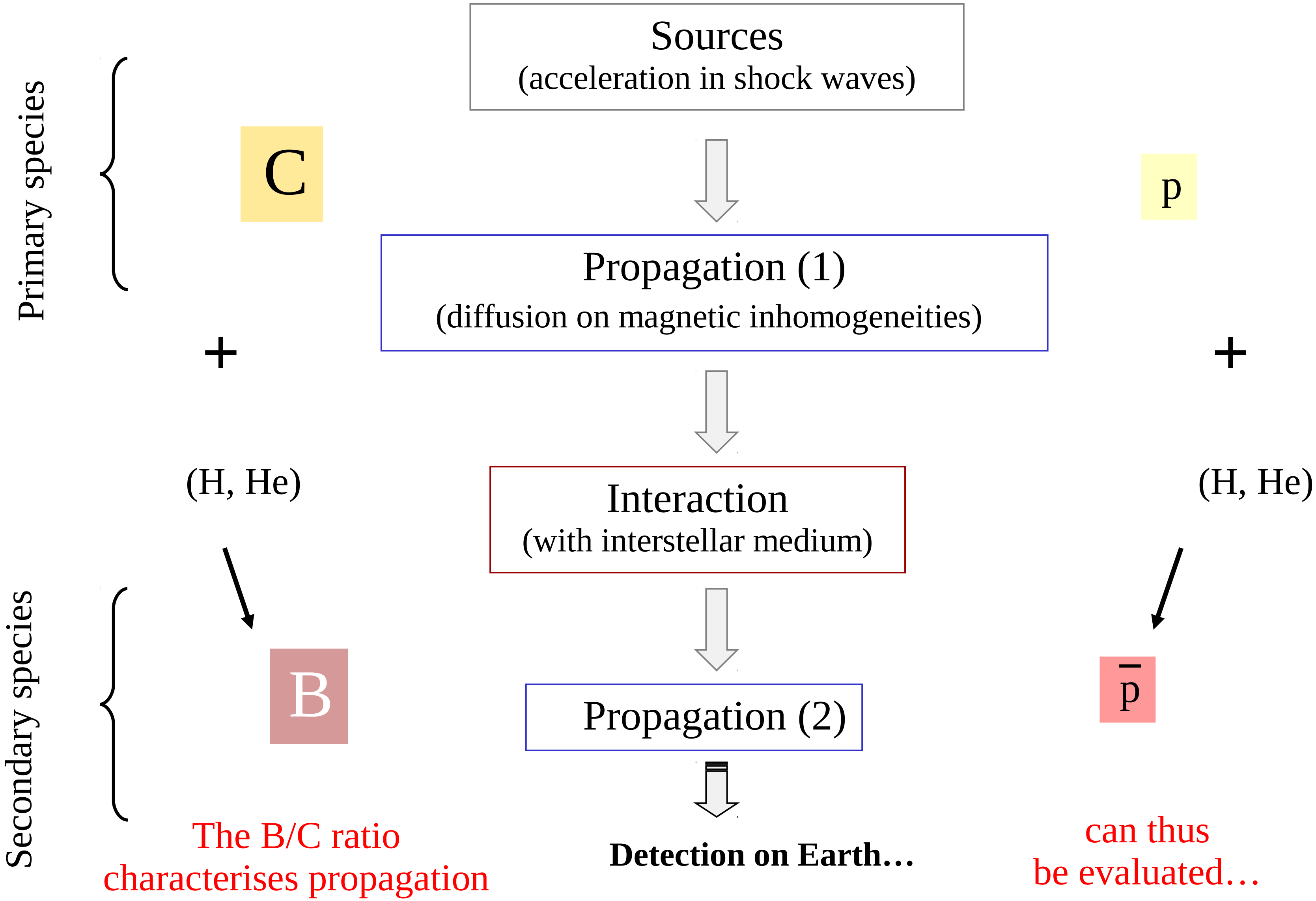


Anti-deutérons



→ Inelastic non-annihilating cross section: fill low energy

Antiprotons and antideutons: propagation is fixed form B/C



Sources
(acceleration in shock waves)

Propagation (1)
(diffusion on magnetic inhomogeneities)

Interaction
(with interstellar medium)

Propagation (2)

Detection on Earth…

The B/C ratio characterises propagation

can thus be evaluated…

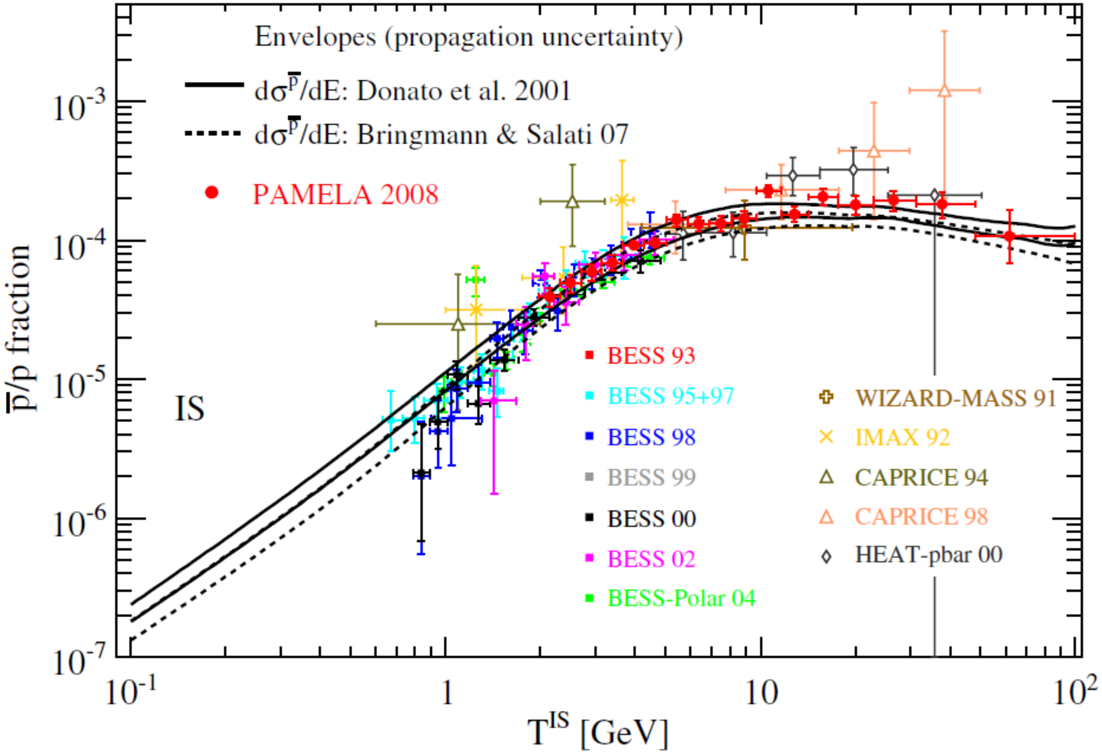
→ Same propagation history

Do we expect large or small propagation uncertainties?

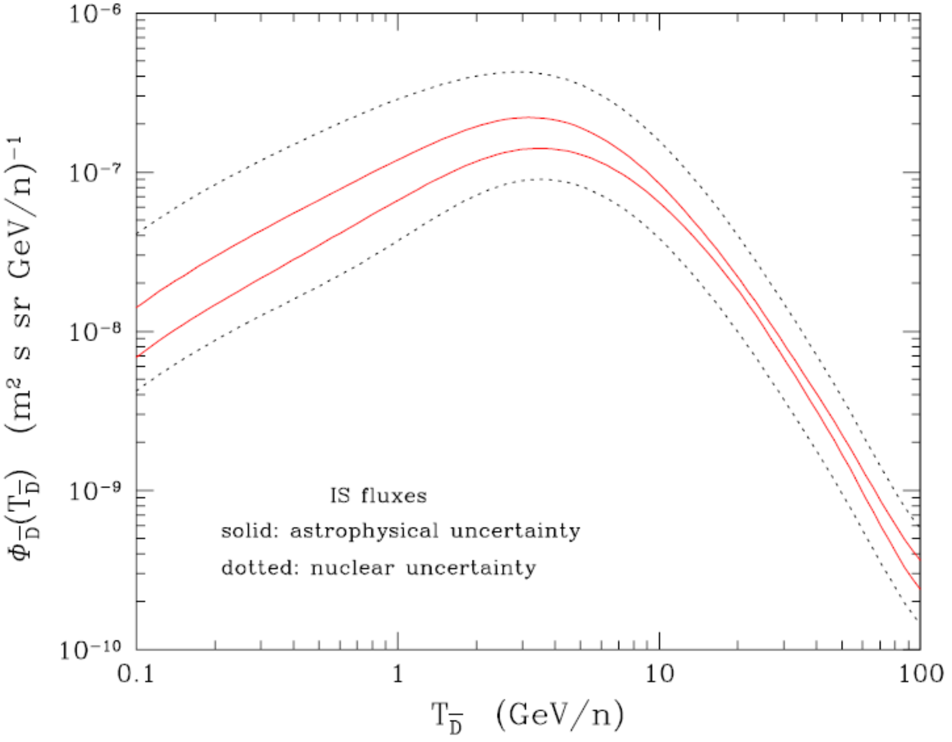
“Background” uncertainties

Previous transport parameters (no free parameters) + nuclear X-sections

Donato et al., PRL 102 (2009) 071301



Donato et al. PRD 78 (2008) 043506



1. Good agreement between model and data (no dark matter needed)
2. Nuclear physics uncertainties > propagation uncertainties

→ Due to uncertainties (including solar modulation), constraints on non-detection difficult to improve

Charged signals: electrons/positrons, antibaryons

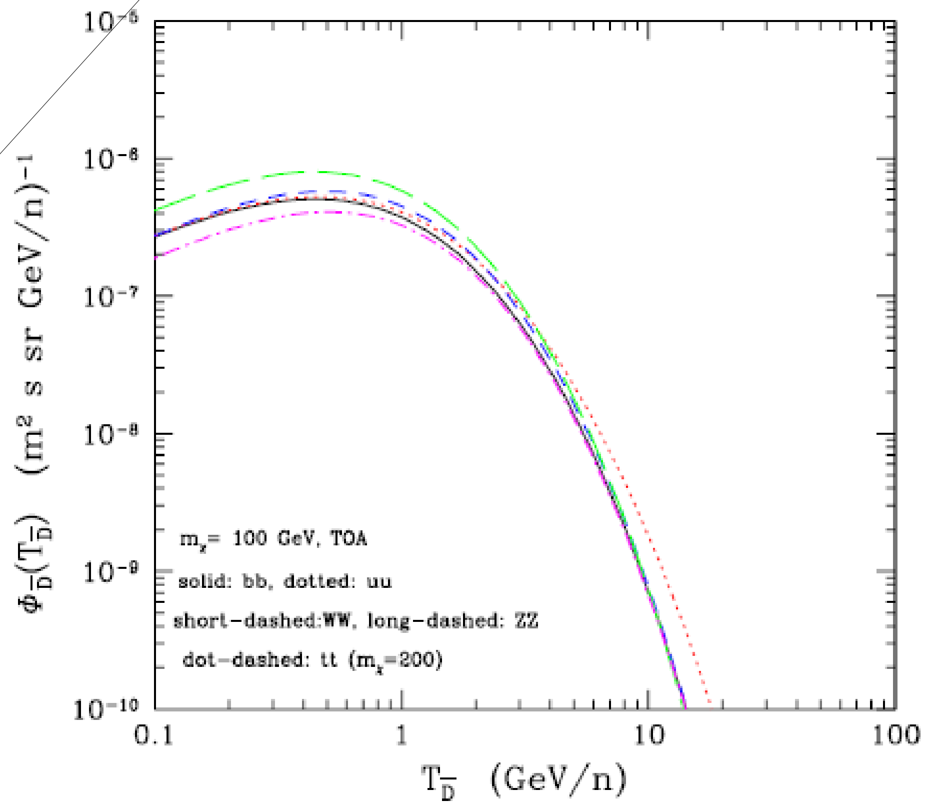
IV - Transport in the heliosphere
Charged signals: electrons/positrons, antibaryons

Dark matter contribution: primary source term in the halo

$$q_{\bar{d}}^{\rm prim}(r,z,E) = \eta\,\xi^2\,\langle\sigma_{\rm ann}v\rangle_0\,\frac{dN_{\bar{d}}}{dE_{\bar{d}}}\left(\frac{\rho_{\rm DM}(r,z)}{m_\chi}\right)^2$$

$$\frac{dN_{\bar{p}}}{dE_{\bar{p}}} = \sum_{\rm F,h} B_{\chi\rm h}^{(\rm F)}\,\frac{dN_{\bar{p}}^{\rm h}}{dE_{\bar{p}}}$$

- Sub-dominant DM candidate
- Annihilation cross section
- Annihilation spectrum
- Dark matter density in the Galaxy
- Mass of the DM candidate

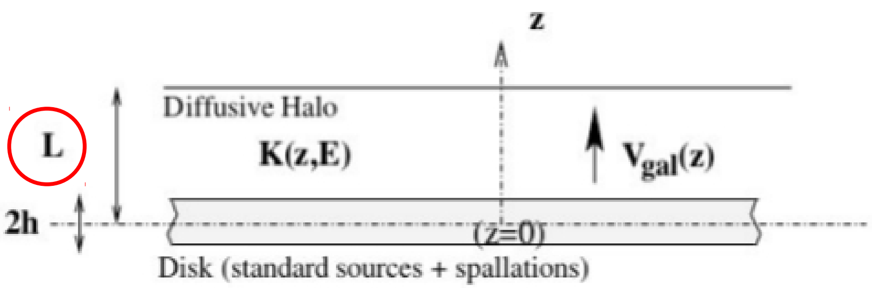


D0/L degeneracy: impact on dark matter signal

$$-\frac{d}{dz}\left\{K(z)\frac{dN}{dz}\right\}+\frac{d}{dz}[V_{\mathrm{gal}}(z)N]+nv\sigma 2h\delta(z)N=q(z,E)$$

\+ isotropic diffusion
\+ no galactic wind

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



Transport parameters from B/C analysis

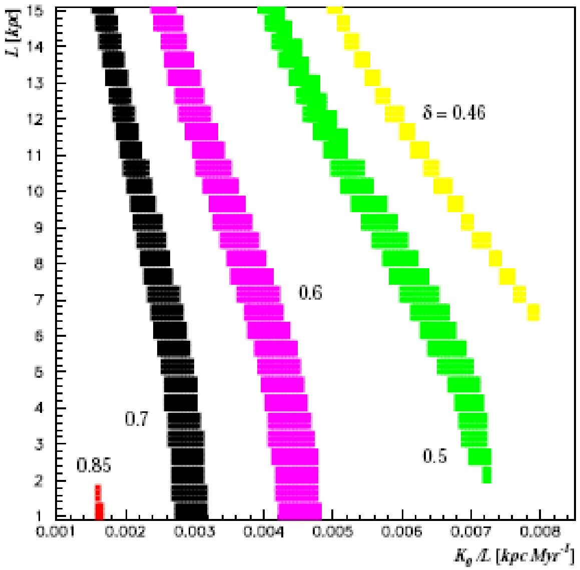
$$-KN'' + nv\sigma 2h\delta(z)\times N = 2h\delta(z)Q(E)$$

$$\frac{N^s}{N^p}(z=0)\propto \frac{L}{K_0}\mathcal{R}^{-\delta}$$

Parameters matching B/C data

↓

K0/L degeneracy



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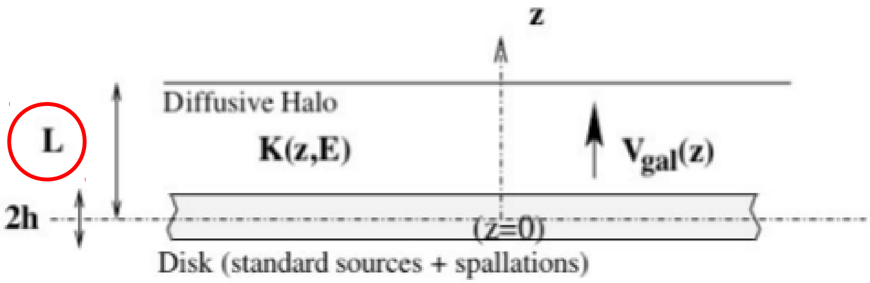

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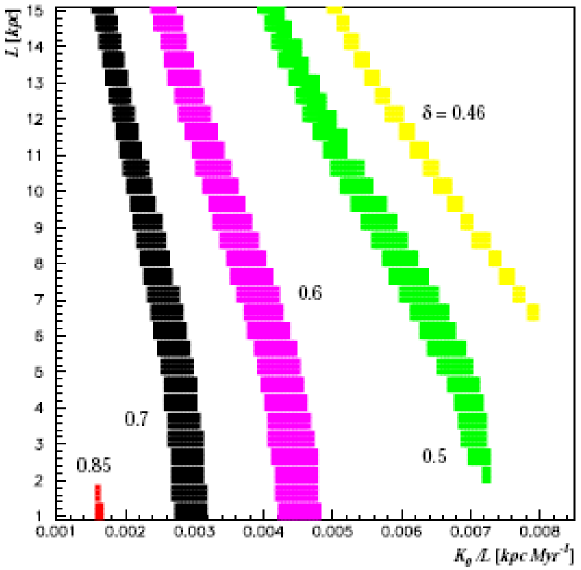

Dark matter signal

Solve 1D (pure diffusion) equation with a constant distribution of DM
→ How does the signal scale?

D0/L degeneracy: impact on dark matter signal

$$-\frac{d}{dz}\left\{K(z)\frac{dN}{dz}\right\}+\frac{d}{dz}[V_{\rm gal}(z)N]+nv\sigma 2h\delta(z)N=q(z,E)$$

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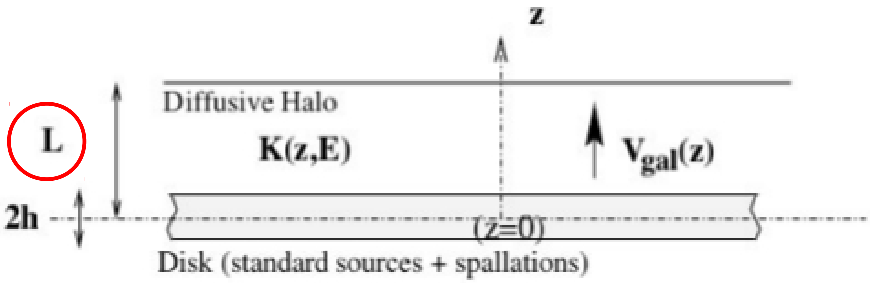

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Parameters matching B/C data

↓

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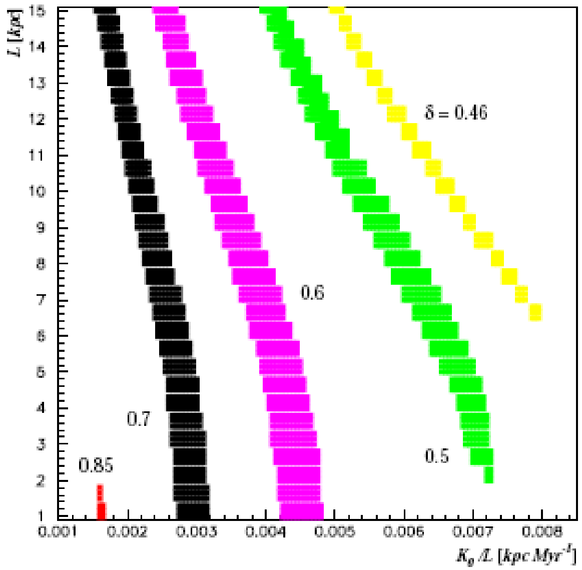


Dark matter signal

$$-KN'' = q \quad \Rightarrow \quad N_{(\bar{p},\,\bar{d})}(z=0) = \frac{q\,L^2}{2K}$$

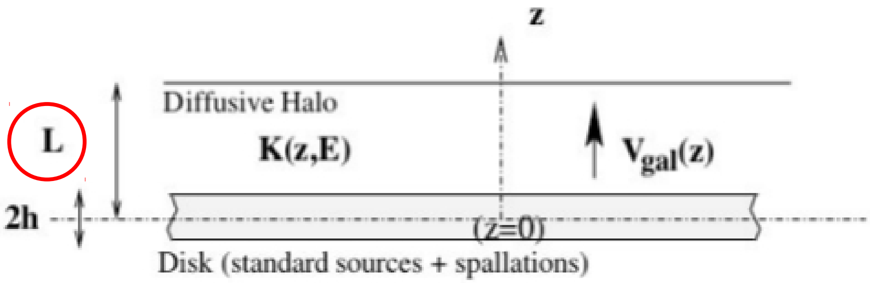
Solve 1D (pure diffusion) equation
with a constant distribution of DM
→ How does the signal scale?

D_0/L degeneracy: impact on dark matter signal

$$-\frac{d}{dz}\left\{K(z)\frac{dN}{dz}\right\} + \frac{d}{dz}[V_{\rm gal}(z)N] + nv\sigma 2h\delta(z)N = q(z,E)$$

+ isotropic diffusion
+ no galactic wind

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



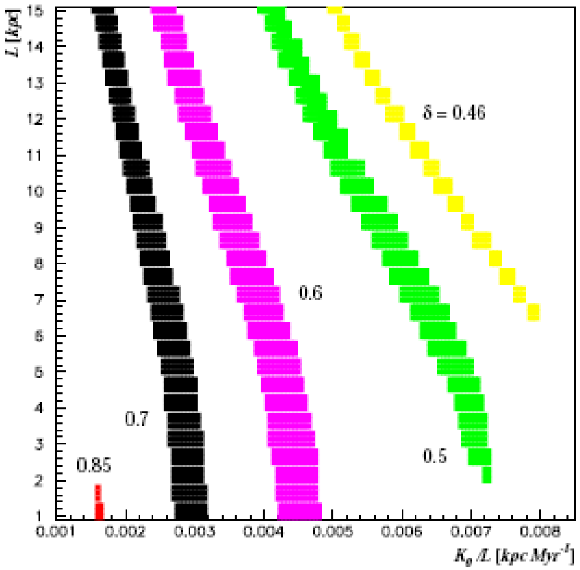
Transport parameters from B/C analysis

$$-KN'' + nv\sigma 2h\delta(z) \times N = 2h\delta(z)Q(E)$$

$$\frac{N^s}{N^p}(z=0) \propto \frac{L}{K_0}\mathcal{R}^{-\delta}$$

Parameters matching B/C data

K0/L degeneracy



Dark matter signal

$$-KN'' = q \quad \Rightarrow \quad N_{(\bar{p},\,\bar{d})}(z=0) = \frac{q\,L^2}{2K}$$

→ for fixed D_0/L (from B/C), signal scales with L, hence the min/med/max parameters

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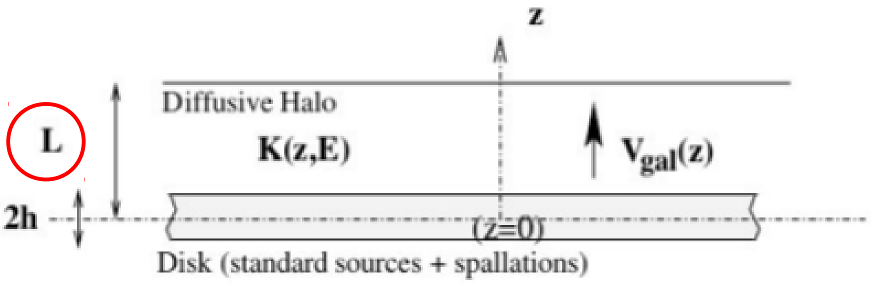

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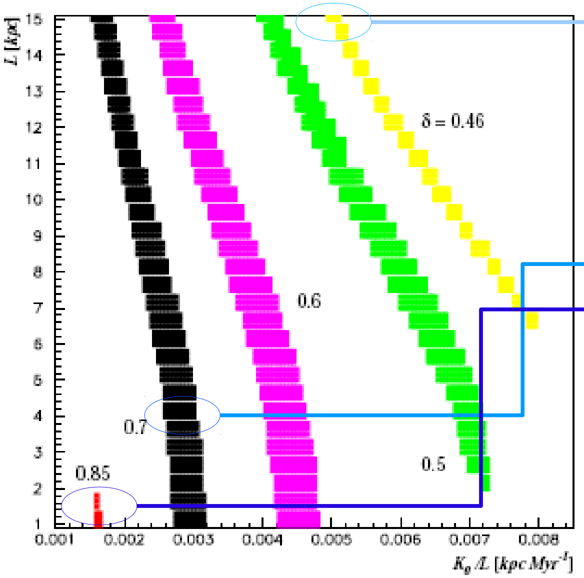

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Donato et al. (2004)

Case	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)	V_A (km/s)	$\chi^2_{B/C}$
max	0.46	0.0765	15	5	117.6	39.98
med	0.70	0.0112	4	12	52.9	25.68
min	0.85	0.0016	1	13.5	22.4	39.02

N.B.: K0/L degeneracy also broken for positrons
Delahaye et al. (2009)

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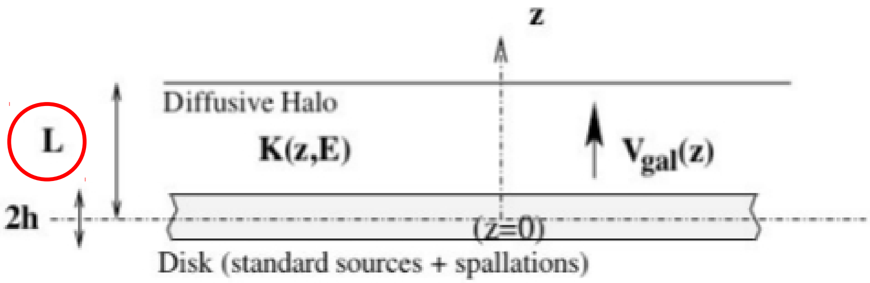

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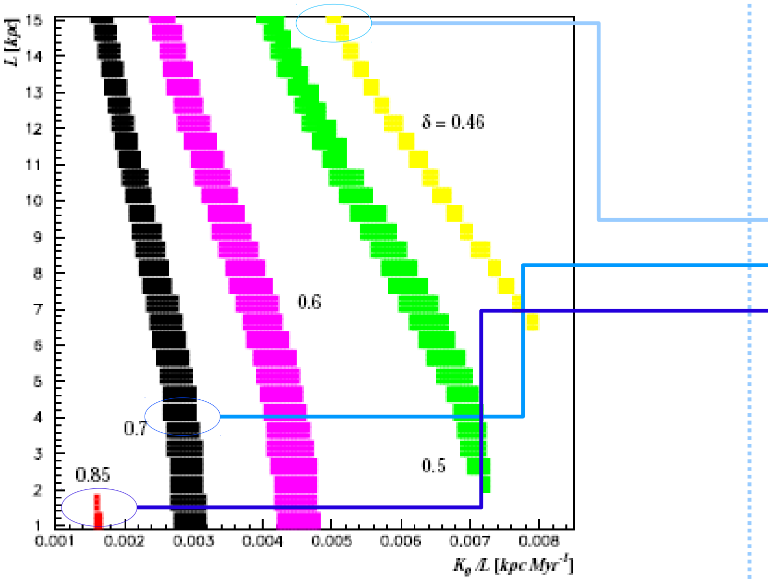
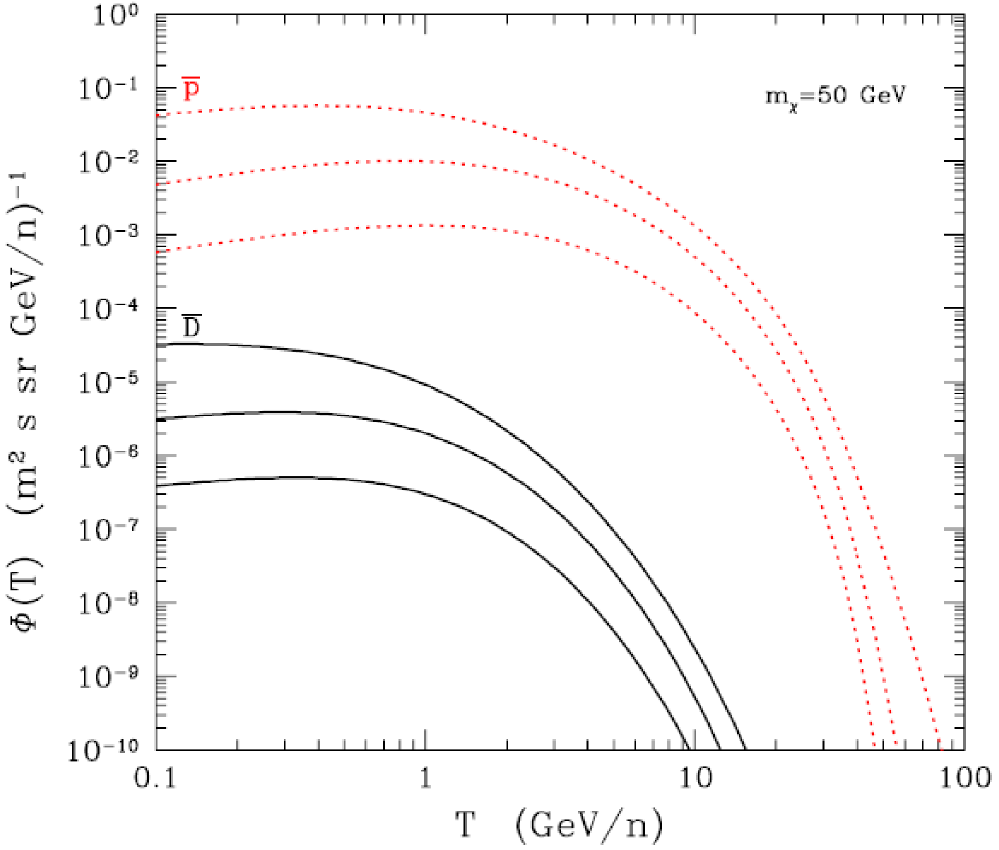


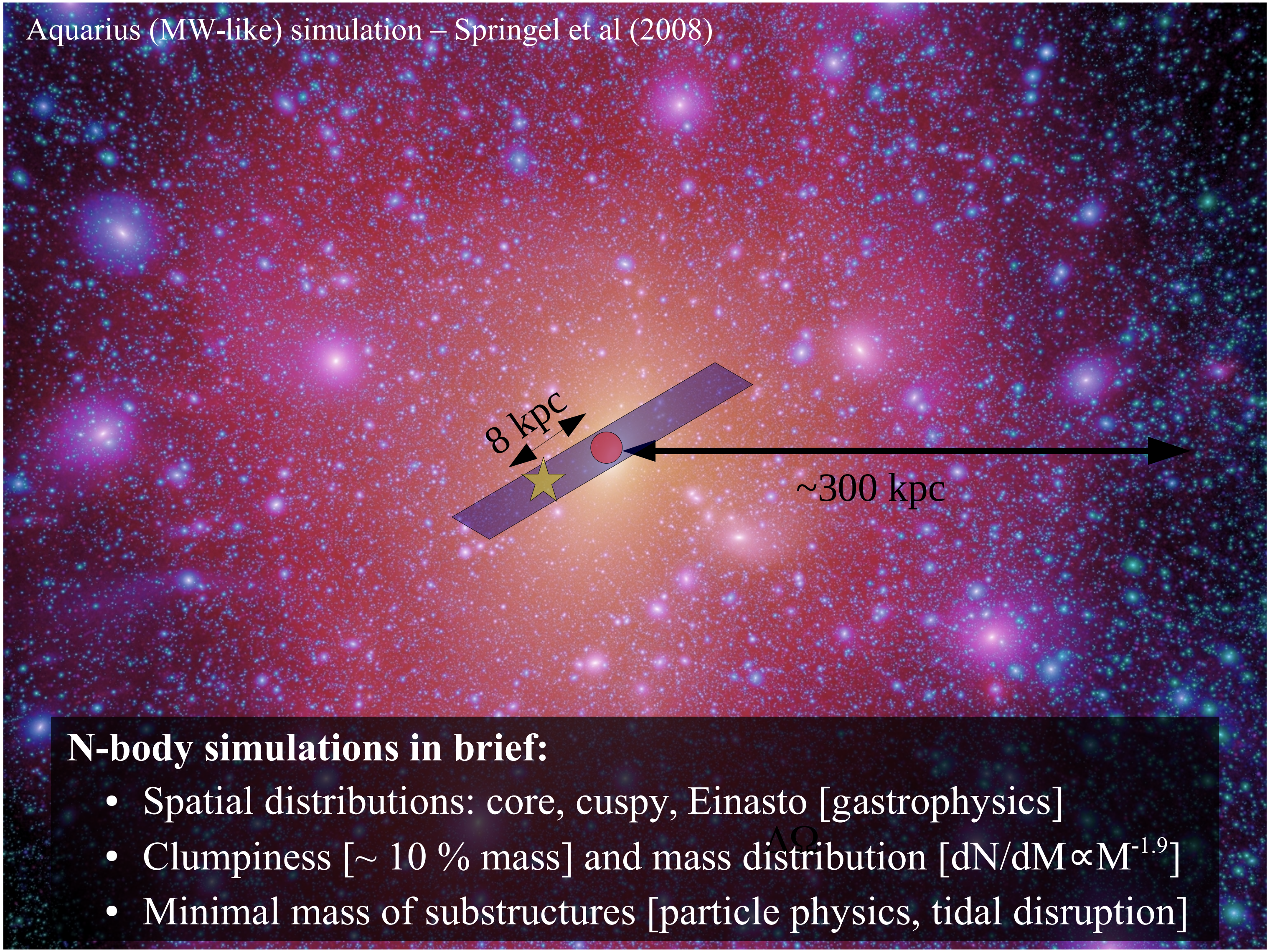


- ~ factor 100 uncertainty on DM pbar and dbar
- Similar (though smaller) efect for positrons

[Delahaye et al., A&A 501 (2009) 821]

Dark matter distribution

Hierarchical formation of structures in the Universe: from micro-haloes to galaxy clusters



Aquarius (MW-like) simulation – Springel et al (2008)

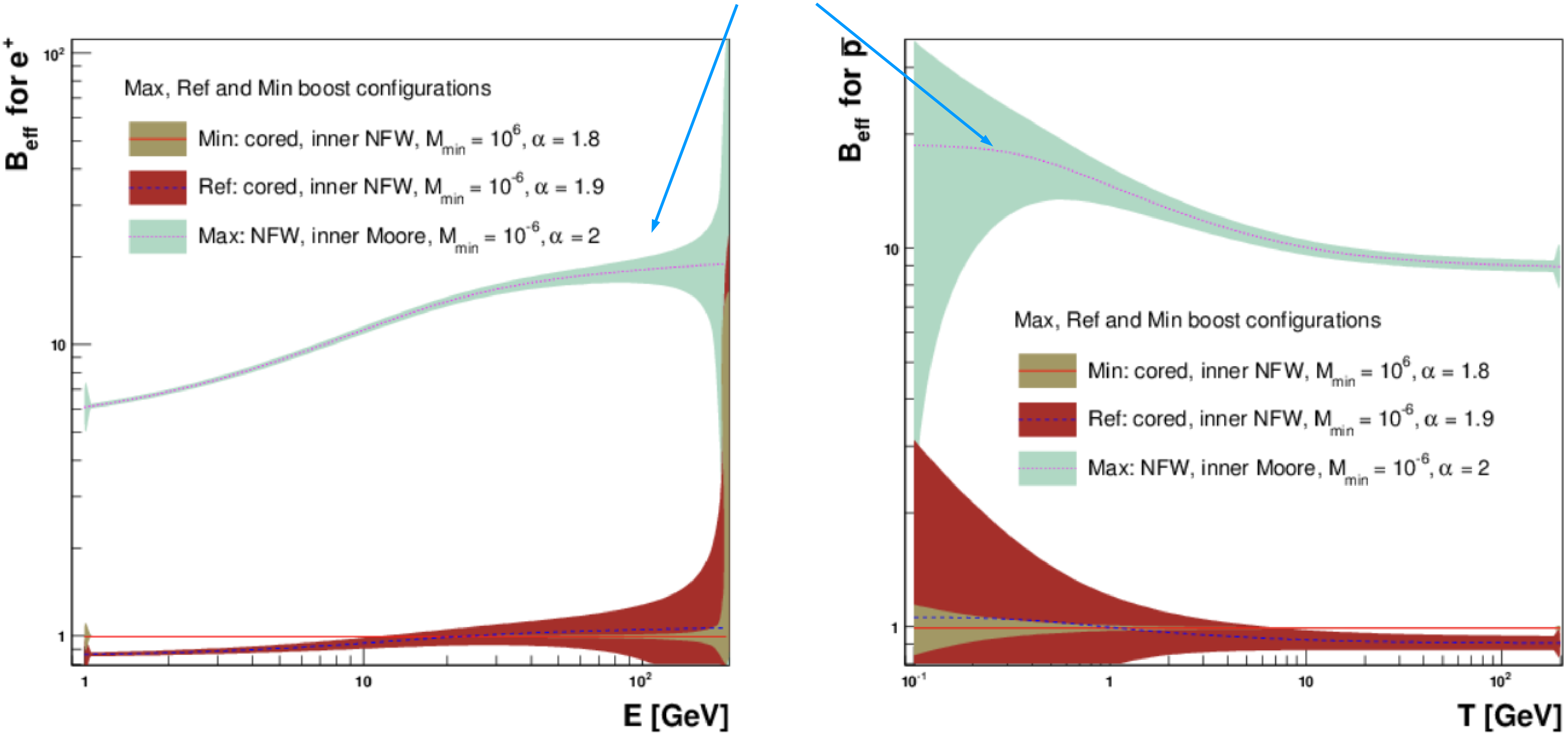
N-body simulations in brief:

- Spatial distributions: core, cuspy, Einasto [gastrophysics]
- Clumpiness [~ 10 % mass] and mass distribution [$dN/dM \propto M^{-1.9}$]
- Minimal mass of substructures [particle physics, tidal disruption]

Boost factor of the signal from substructures

Lavalle et al., A&A 479 (2008) 427

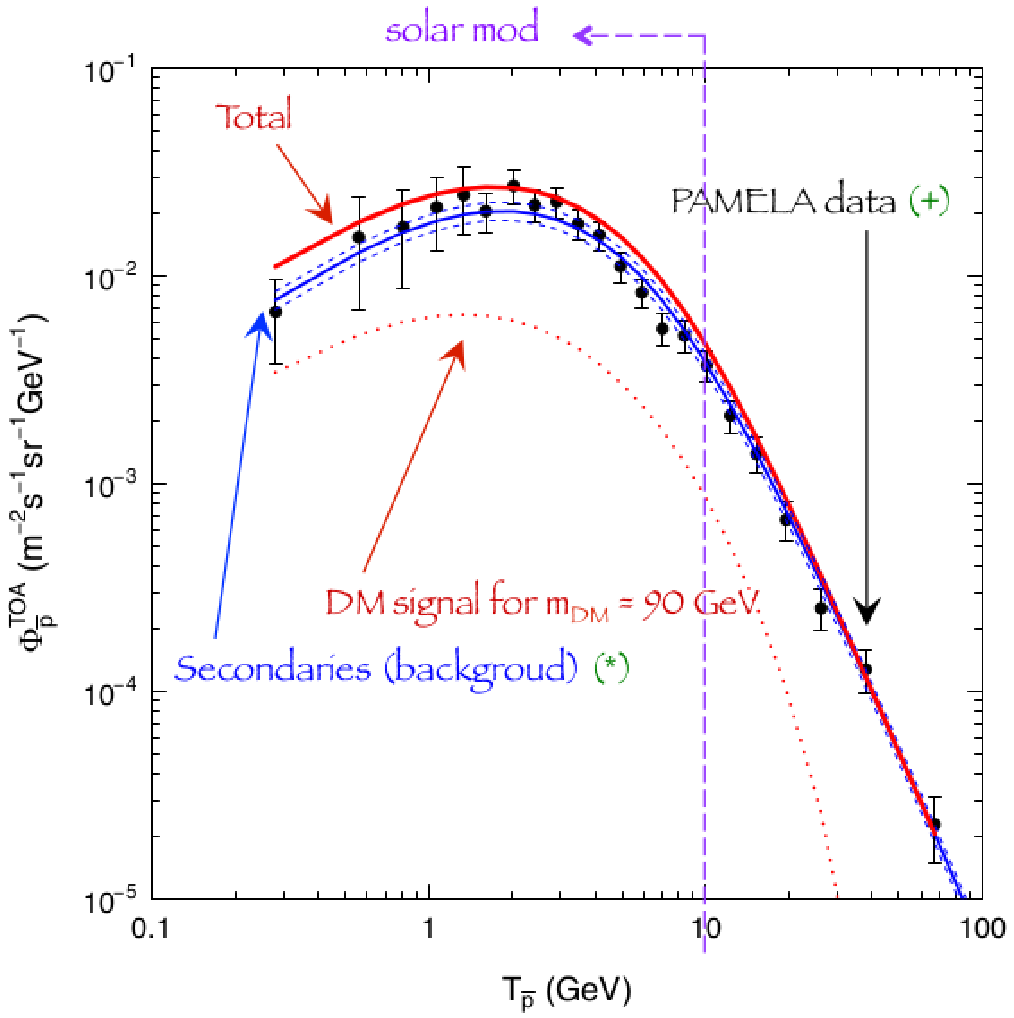
Excluded by more recent simulations

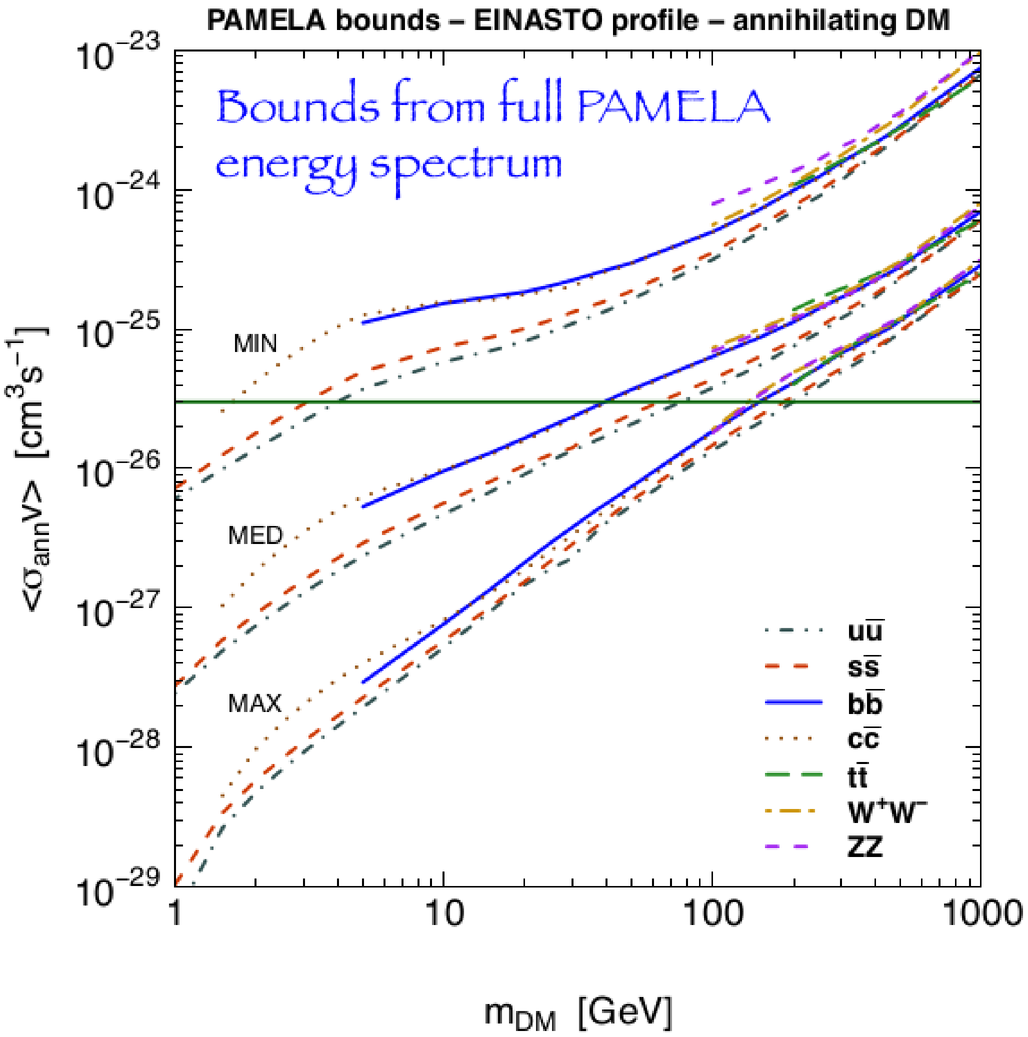


→ No boost from DM substructures
→ Mildly sensitive to DM distribution in the GC (too far away)

Prospects for antiprotons

[slide from N. Fornengo]





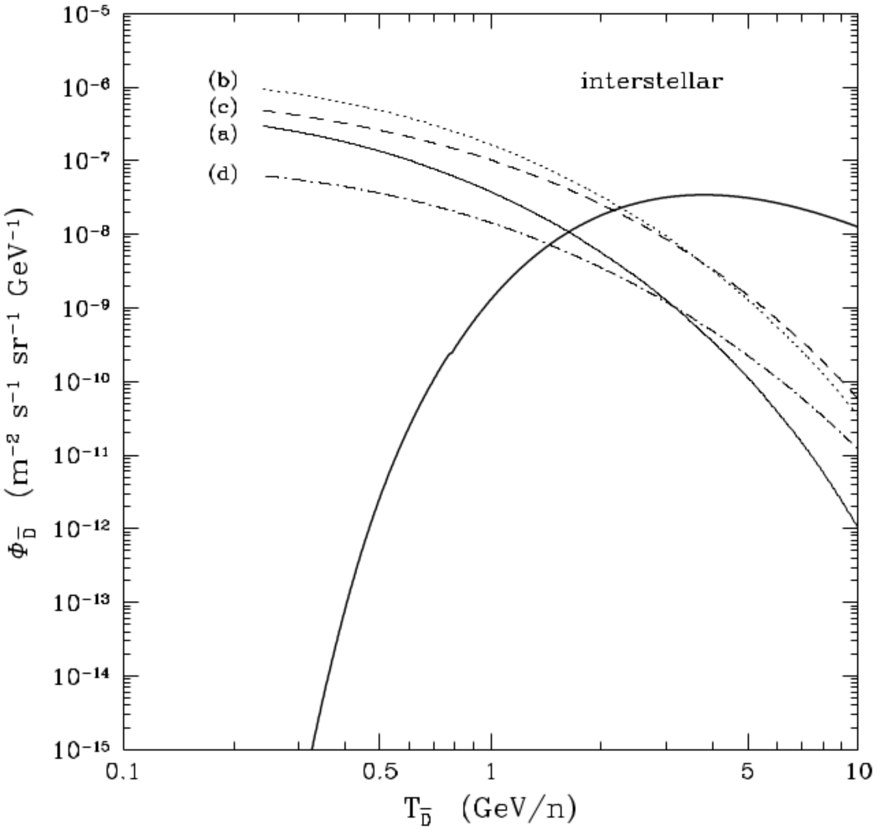
(*) Donato, Maurin, Brun, Delahaye, Salati, PRL 102 (2009) 071301
(+) Adriani et al. (PAMELA Collab.), PRL 105 (2010) 121101

Fornengo, Maccione, Vittino, JCAP 09 (2013) 031

Caveat: the bounds are reported (as is usual) under the hypothesis that the DM candidate is the dominant DM component, regardless of its thermal properties in the early Universe

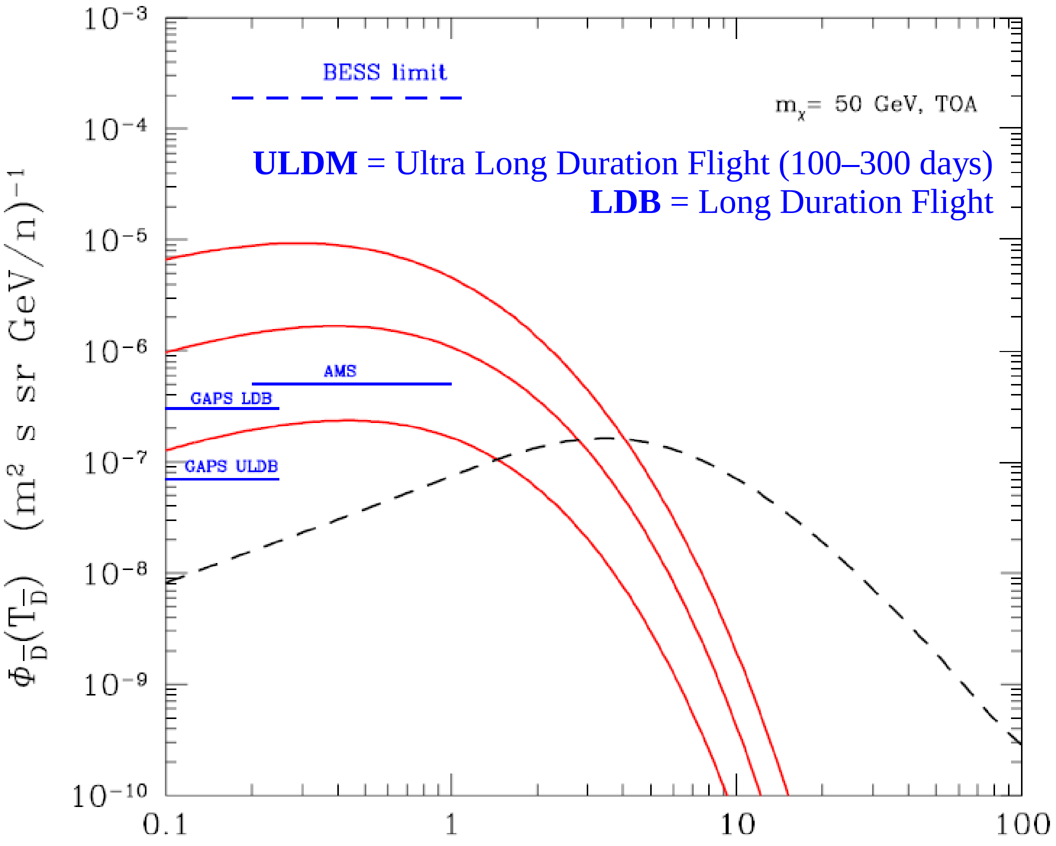
Prospects for antideuterons (low energy)

First study



Donato, Fornengo, Salati, PRD 62 (2000) 043003

With improved "background"



ULDM = Ultra Long Duration Flight (100–300 days)
LDB = Long Duration Flight

Donato et al. PRD 78 (2008) 043506

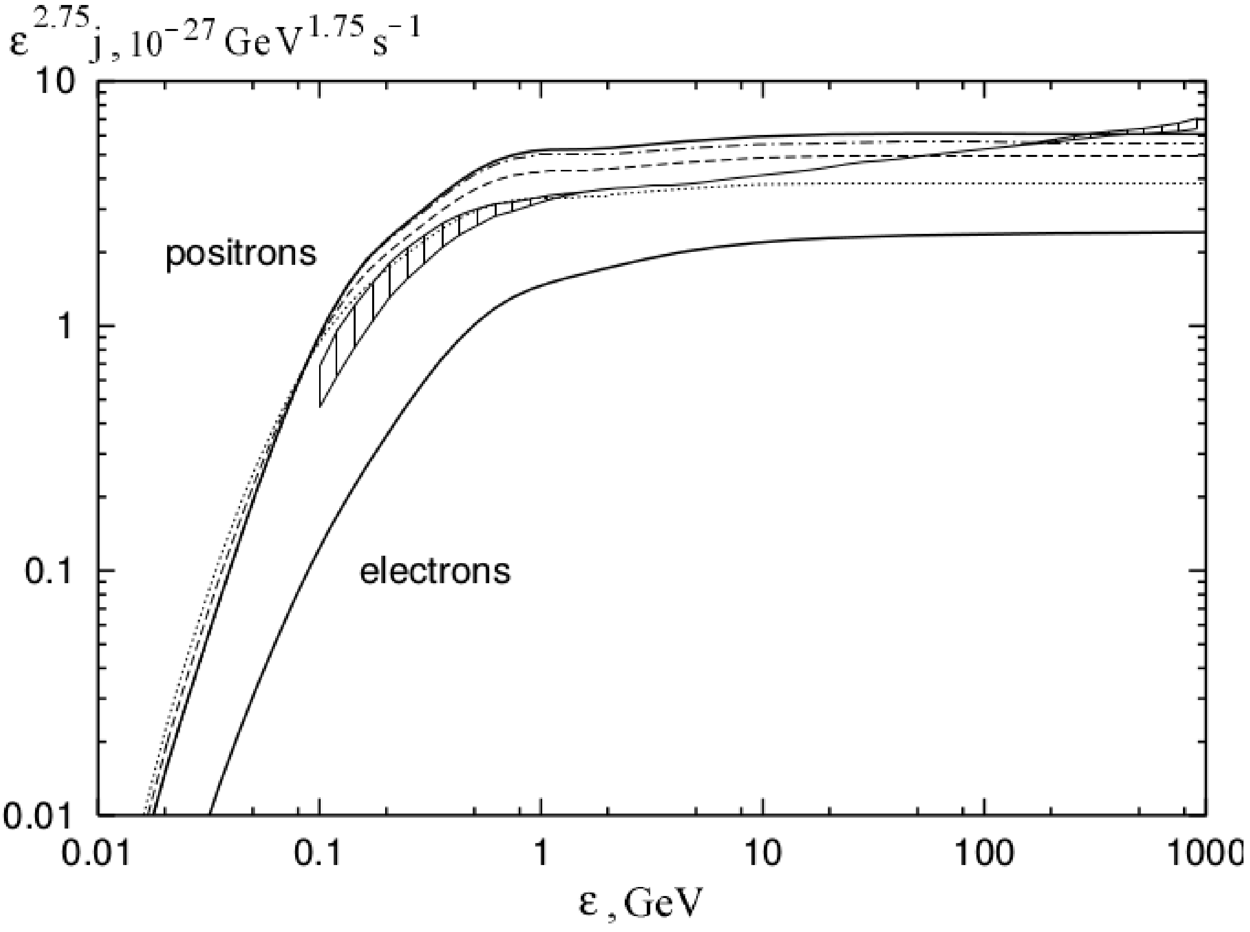
Enhanced production for Heavy DM
Kadastik et al. (2010), Dal & Kachelriess (2012)

→ Very good perspectives for the near future (GAPS and AMS-02 experiments)

IV - Transport in the heliosphere
Charged signals: electrons/positrons, antibaryons

Secondary production of e±

Strong et al. (1998)

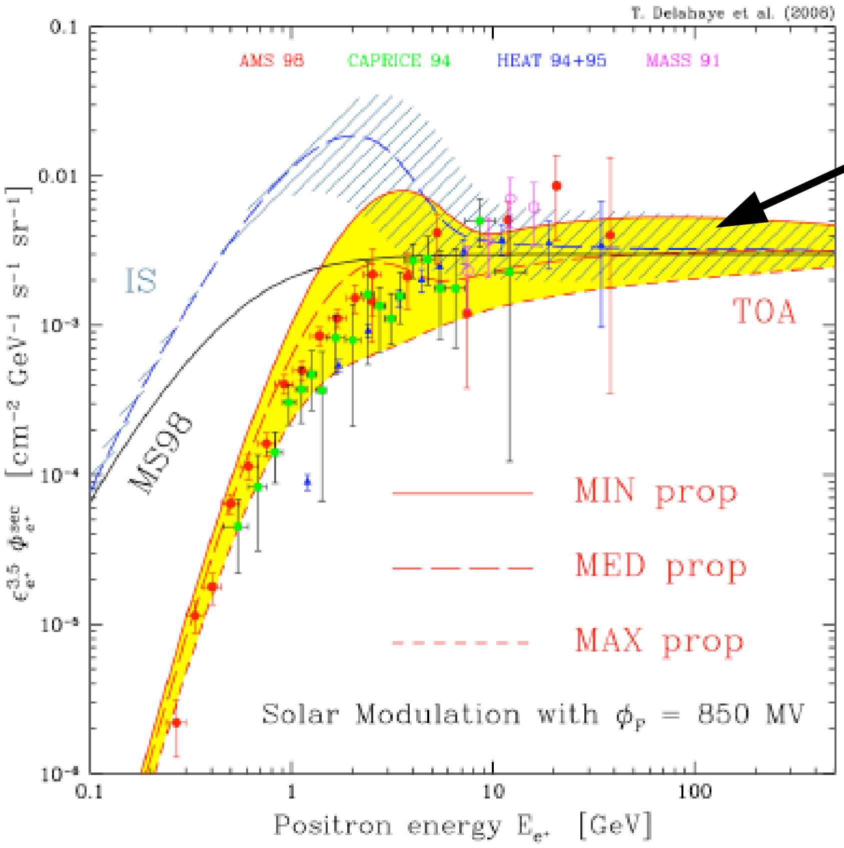


Secondary e+/e- ~ 2.5

Propagation uncertainties for secondary positrons

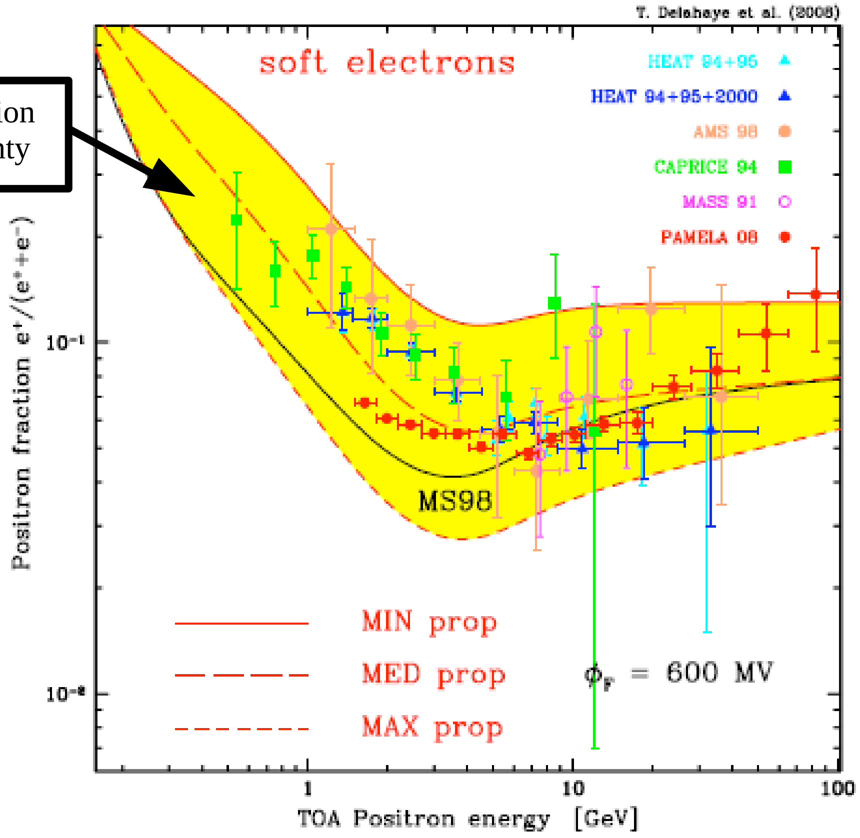
Delahaye et al., A&A 501 (2009) 821

Positron flux



Propagation uncertainty

Positron fraction



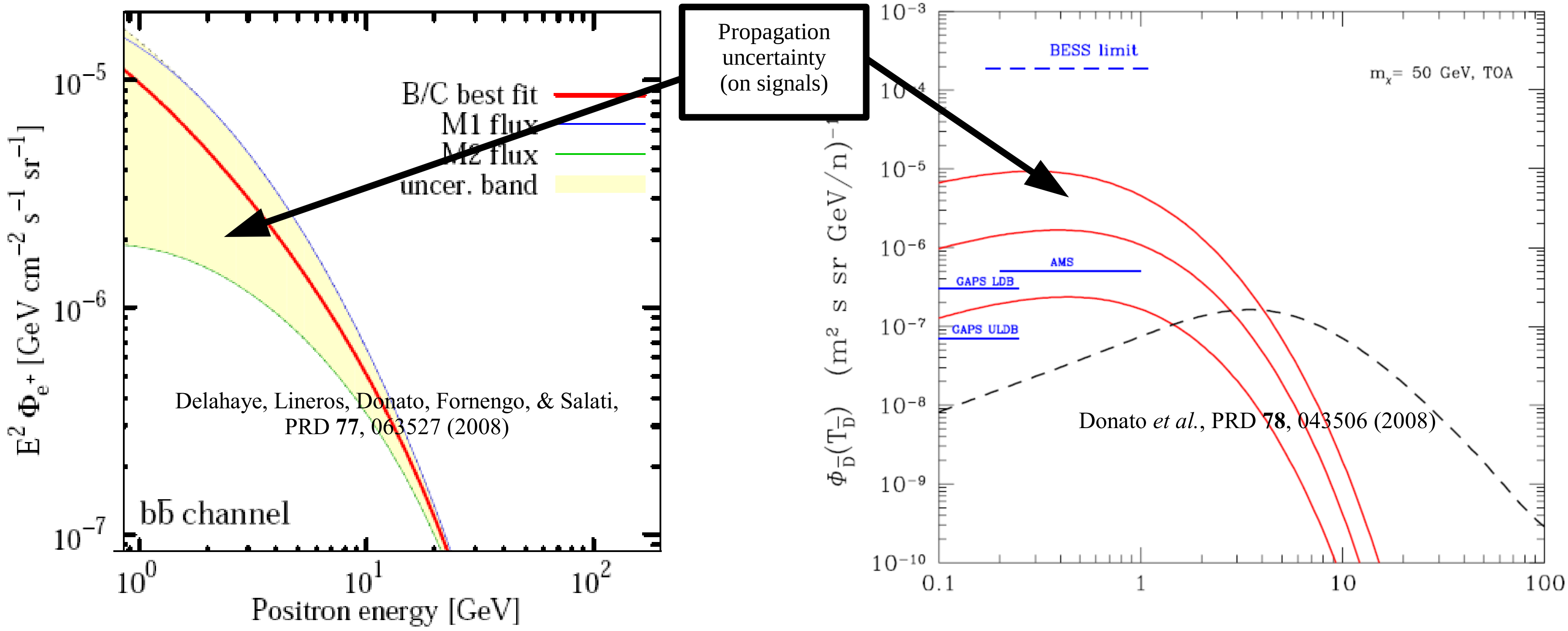
N.B.: larger propagation uncertainties on positrons than on antinuclei
(not the same key transport parameters)

→ Uncertainties (in addition to propagation ones)

- Production cross-sections: ~factor of 2-3 above a few 10 GeV (positron flux)
- Slope of the electron spectrum: ~ factor of 4 at 100 GeV (positron fraction)

Propagation uncertainties for primary positrons

$$\frac{d\phi_{\mathrm{prim}}}{dE} = \delta\,\frac{B_{\mathrm{prim}}\times <\sigma v>}{8\pi m_\chi^2} \times \int dE_S \int d^3\vec{x}_S\,\mathcal{G}(\vec{x}_\odot, E \leftarrow \vec{x}_S, E_S)\times\rho^2_{\mathrm{mn}}(\vec{x}_S)\times\frac{dN_{\mathrm{prim}}}{dE_S}$$



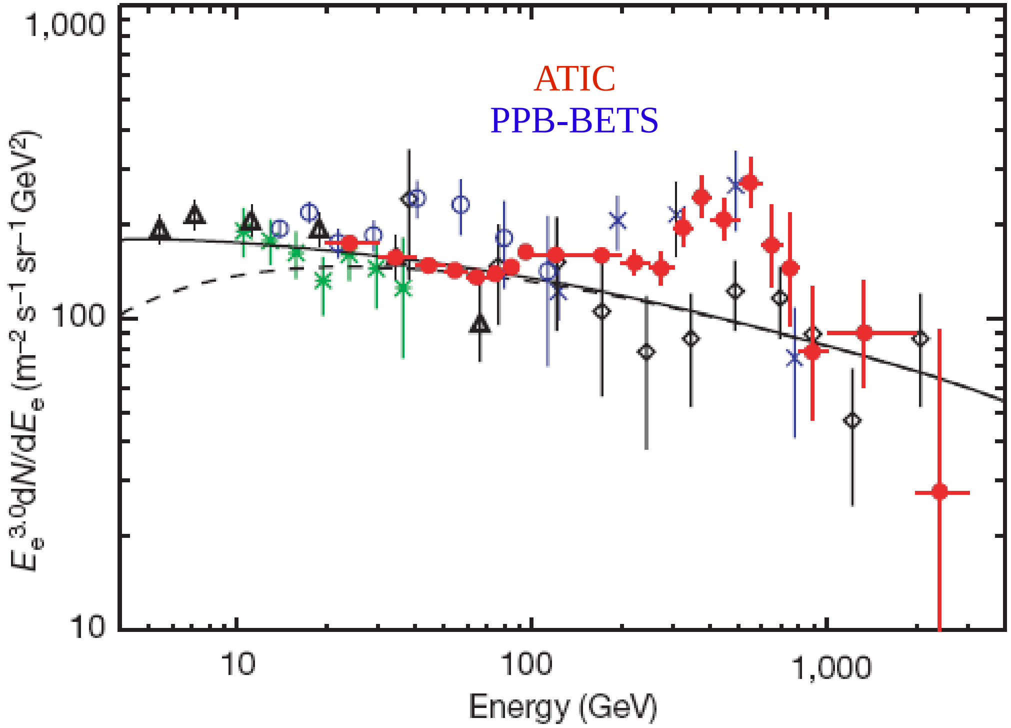
Propagation uncertainty (on signals)

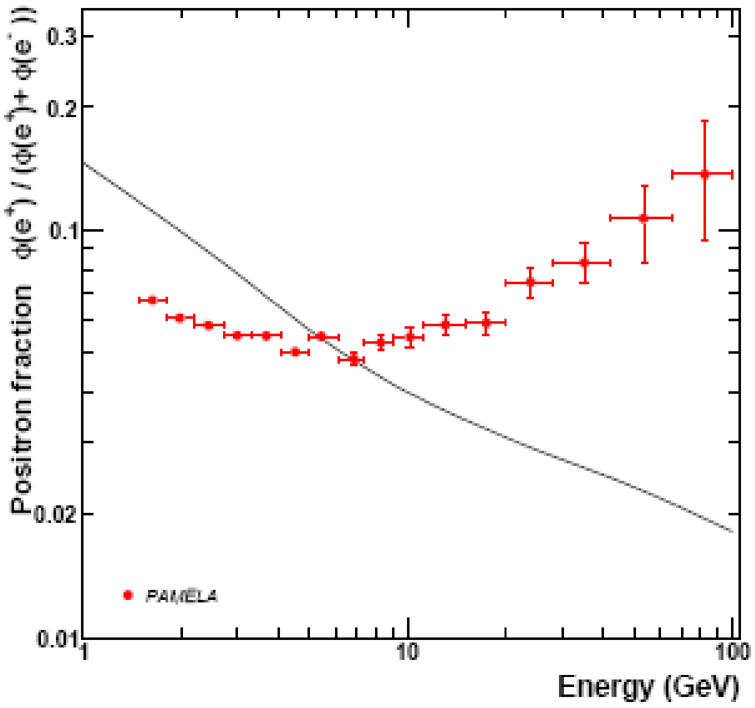
Delahaye, Lineros, Donato, Fornengo, & Salati, PRD **77**, 063527 (2008)

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

Standard (disc) and exotic (diffusive halo) sources have different propagation histories
=> degeneracy of propagation parameters lifted for DM sources

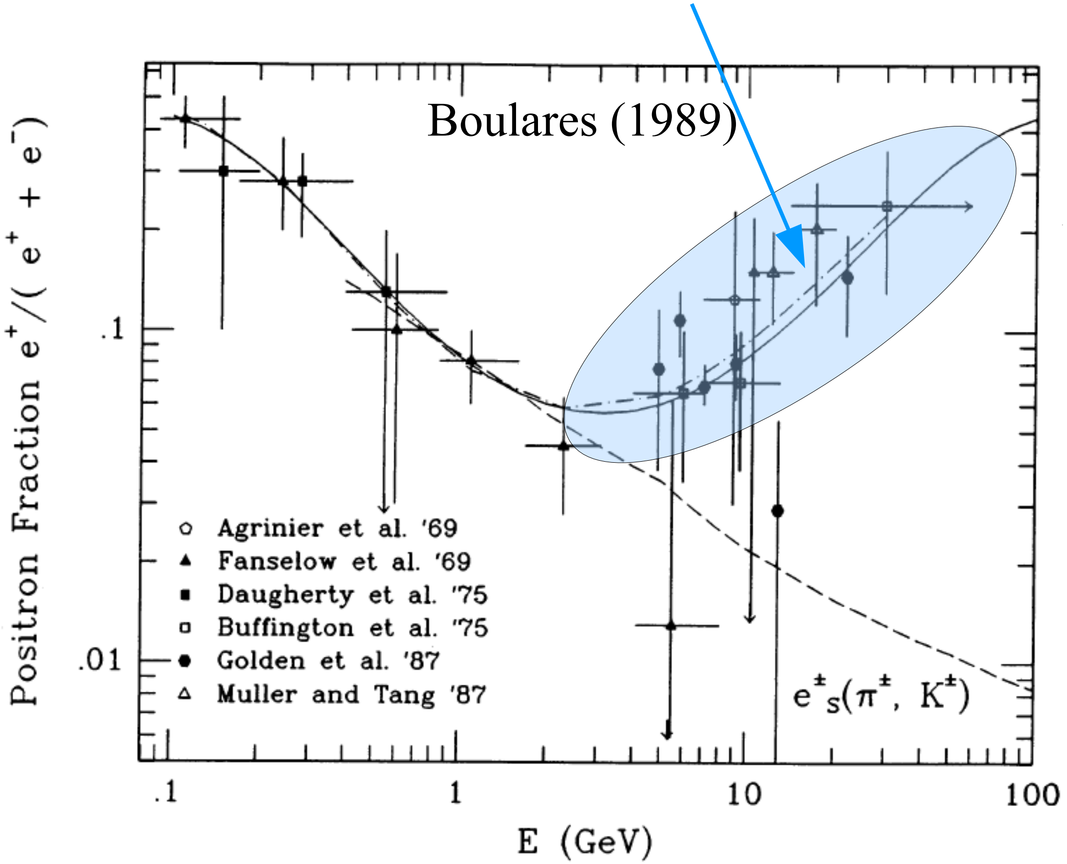
So, excess in the $e^+ + e^-$ spectrum and positron fraction?





Hum, there this guy...

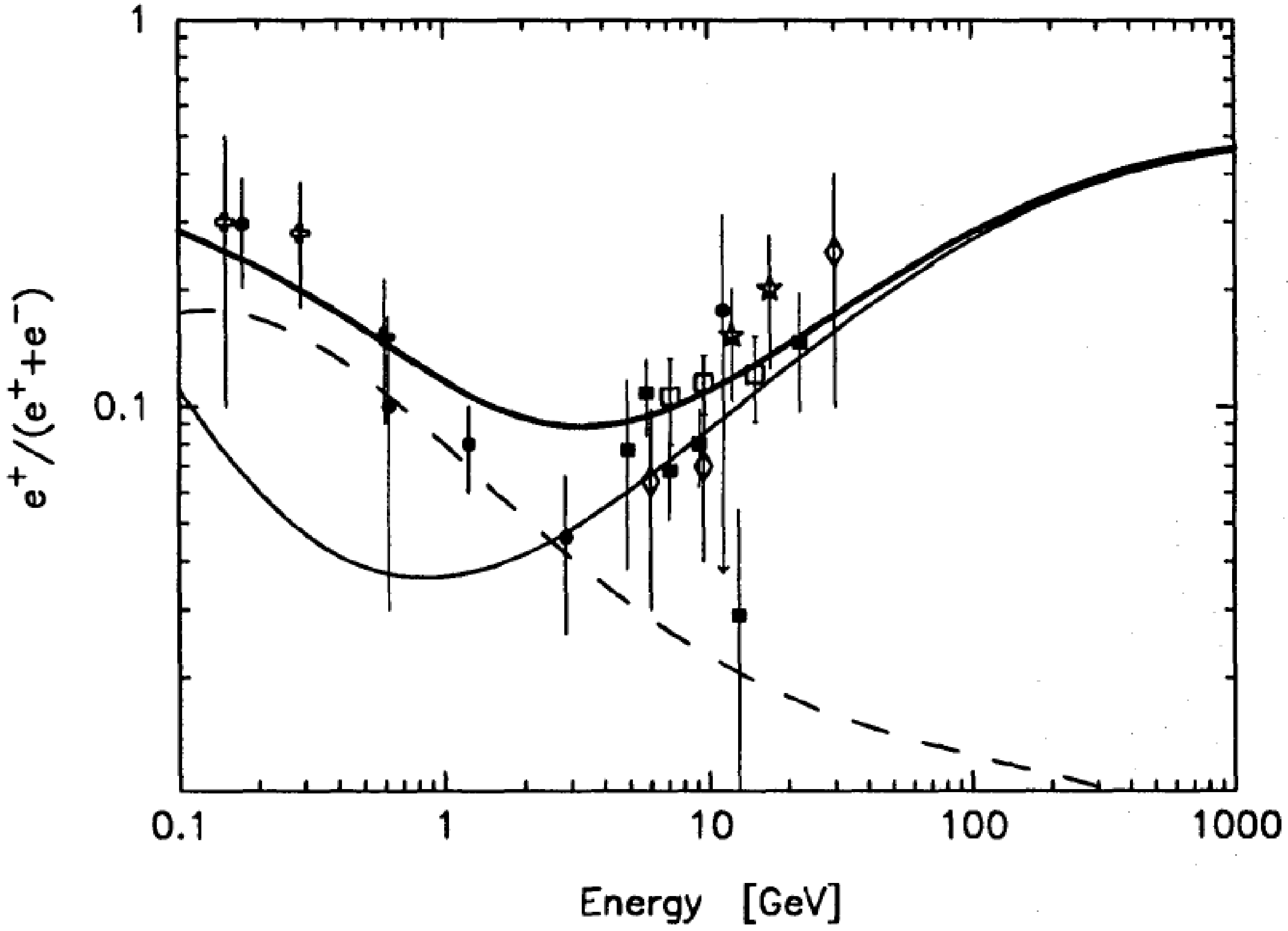
Positron fraction: origin of the rise at high energy



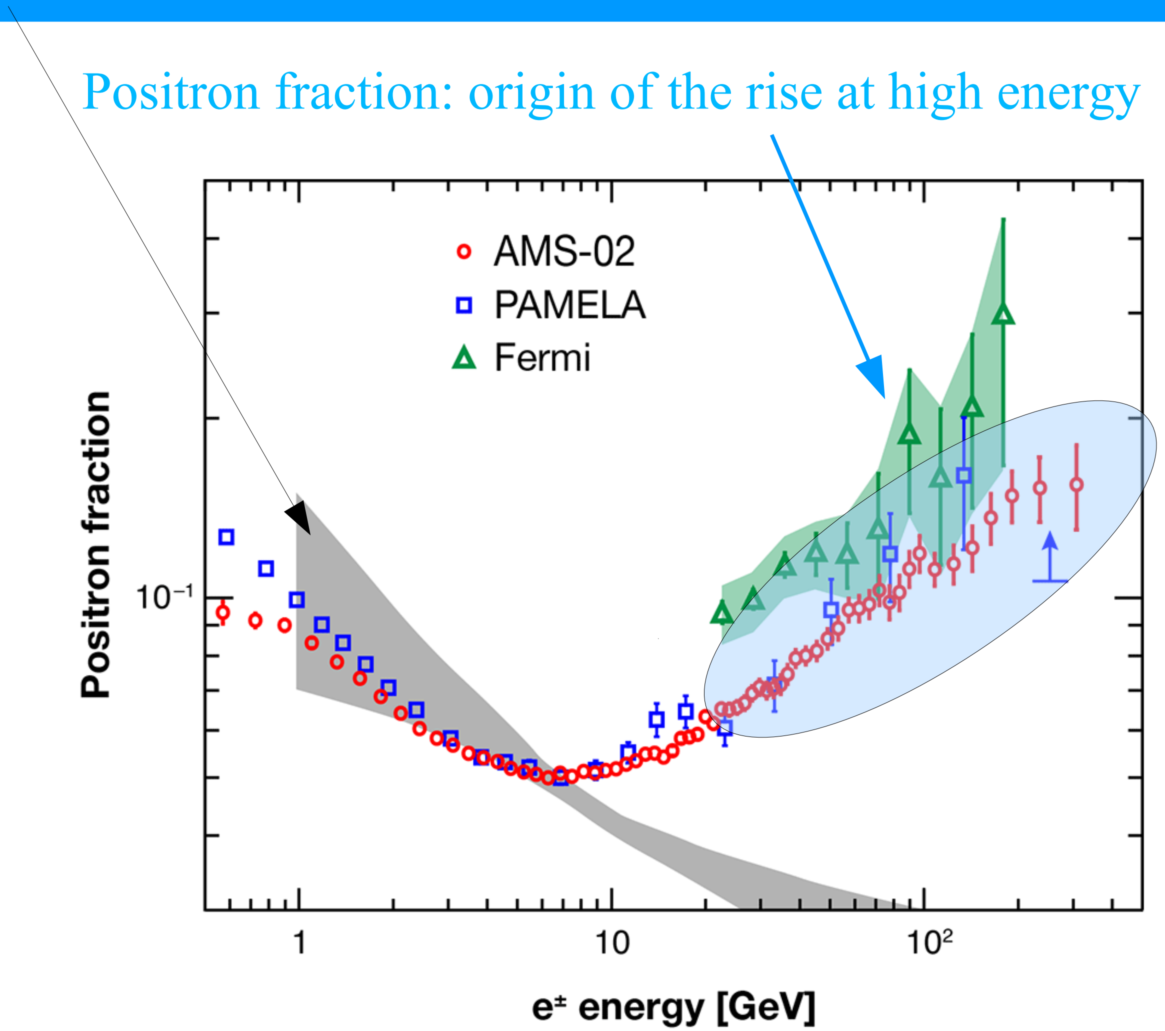
→ 'Natural' astrophysical prediction (local SNRs, pulsars)

… and this other guy

Aharonian et al., A&A 26 (1995) 41



… it is almost embarrassing


Positron fraction: origin of the rise at high energy

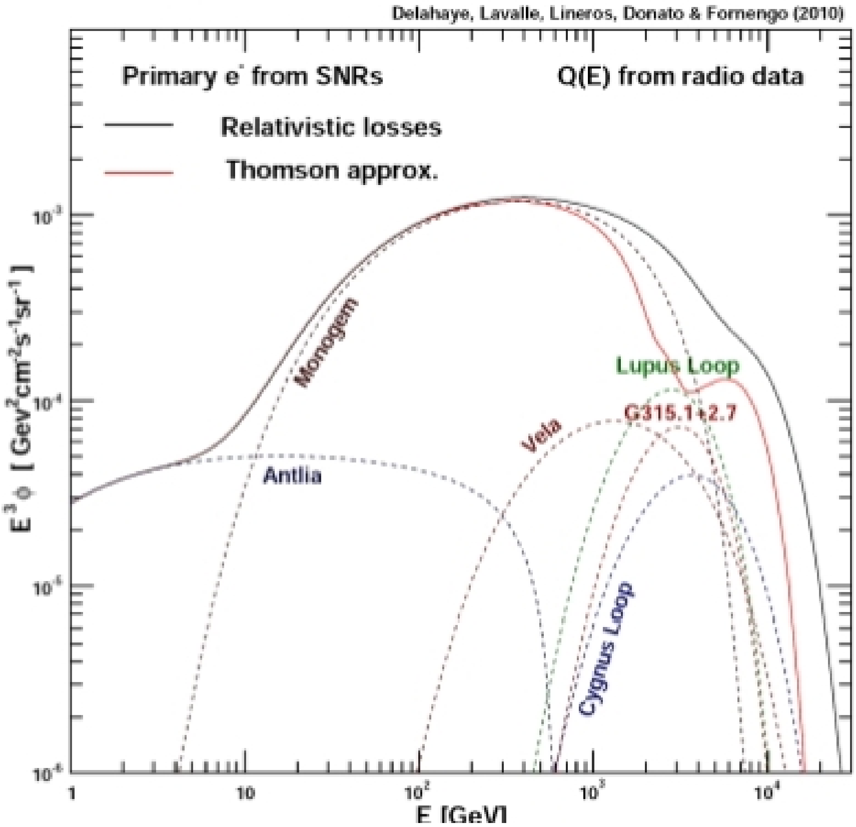
'Natural' astrophysical prediction
vs
leptophilic boosted dark matter post-diction

→ Last place to look for dark matter (local sources): no control on astro. background!

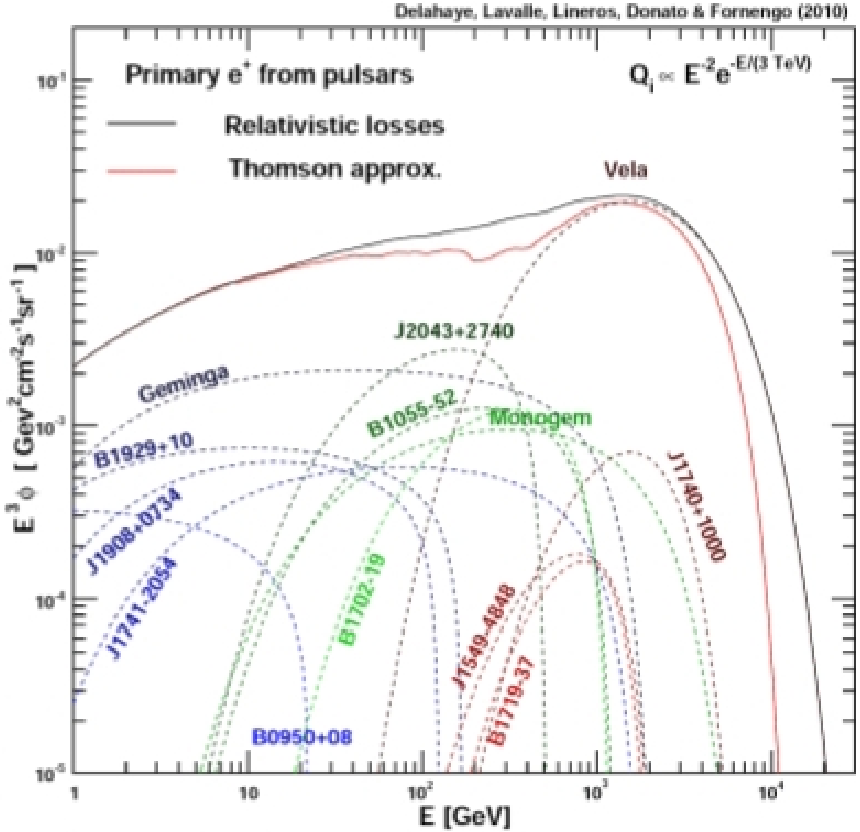
Remember: local sources

Delahaye et al., A&A 524 (2010) A51

e^-: 27 SNRs within 2 kpc



e^+:200 pulsars within 2 kpc

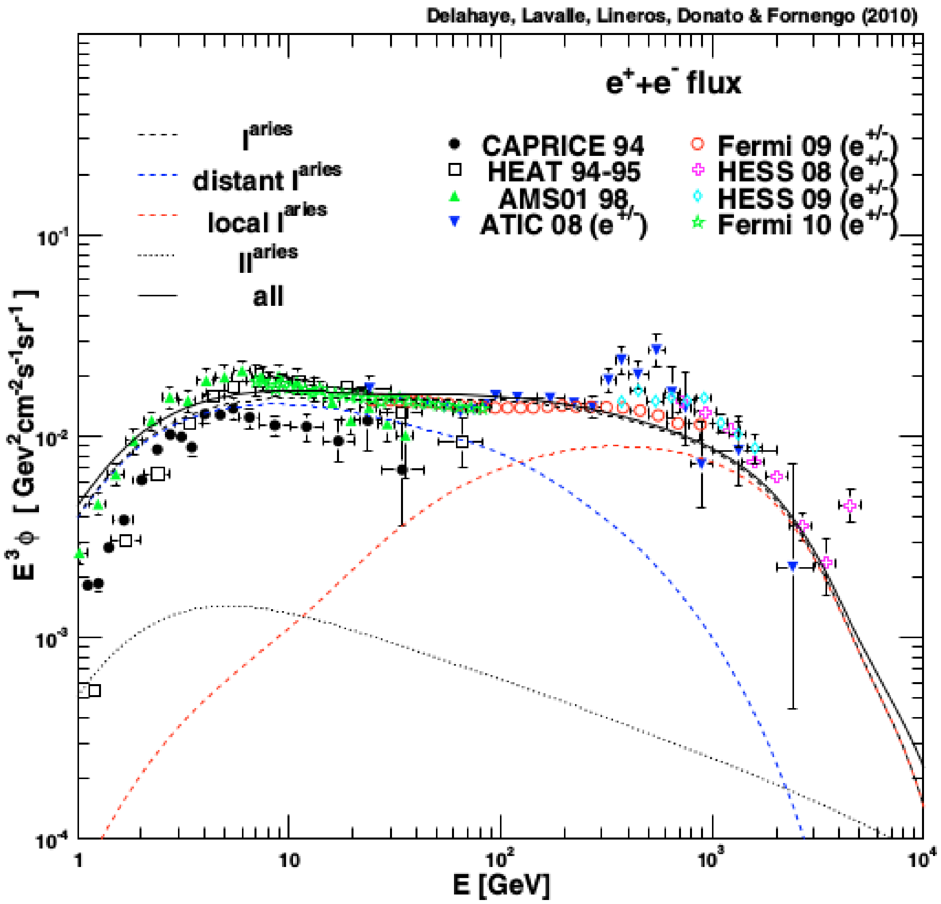


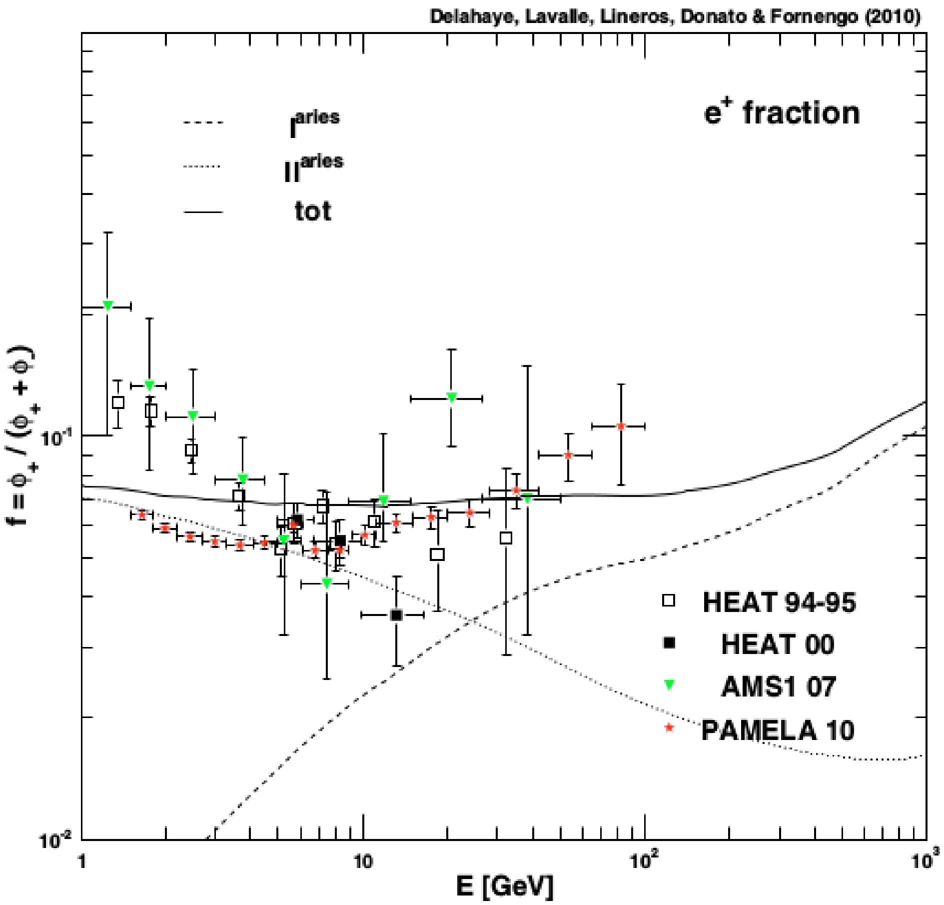
→ Primary astrophysical contributions enable to reproduce PAMELA data
(Large uncertainties on age, distance, efficiency, number of sources...)

→ high-energy e^+ and e^- spectra 'background' are hardly under control!

DM or astrophysics?

Delahaye et al., A&A 524 (2010) A51





→ it is useful to check where DM models lie, but always keep astro in mind!

Charged signals: electrons/positrons, antibaryons

IV - Transport in the heliosphere
Charged signals: electrons/positrons, antibaryons

Indirect dark matter searches with GCRs: summary

Antinuclei (low or high energy)

- Background
  → under control (dominated by nuclear uncertainties)
- DM signal
  → “DM distribution” uncertainties small: no boost, not sensitive to GC
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→ Credible signature requires: multi-messenger, multi-wavelength, cross-correlations...

Indirect dark matter searches: why so many claims?

Scarce data, data in extreme range of instrument capabilities, detector issue

- 1 GV & 10 GeV antiproton excess (in the 80's and 90's)
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- 130 GeV line in the Galactic center
- 110 and 130 GeV line in galaxy cluster
- XXX GeV line somewhere

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Inflation...

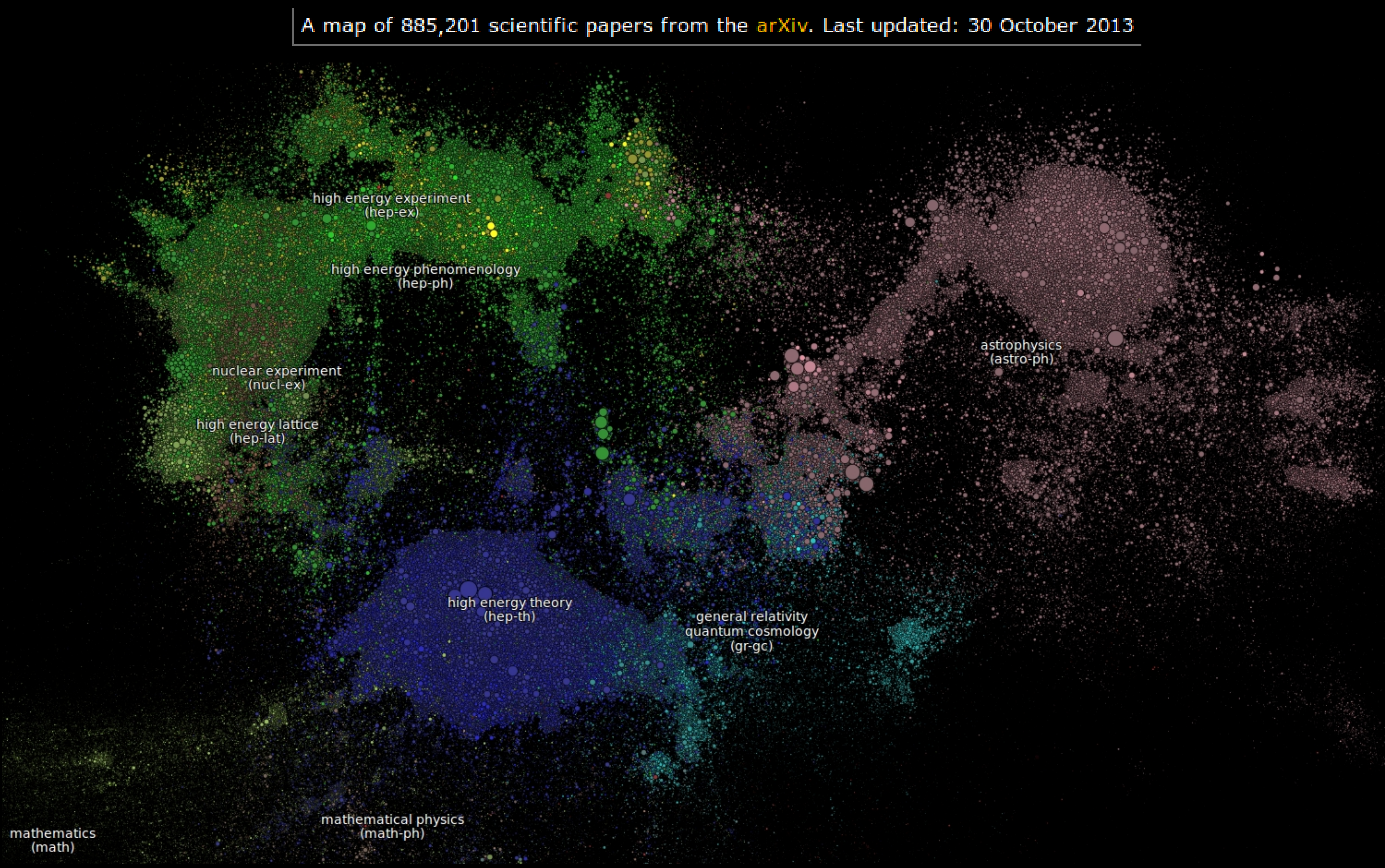
↓

Speculation bubble?

↓

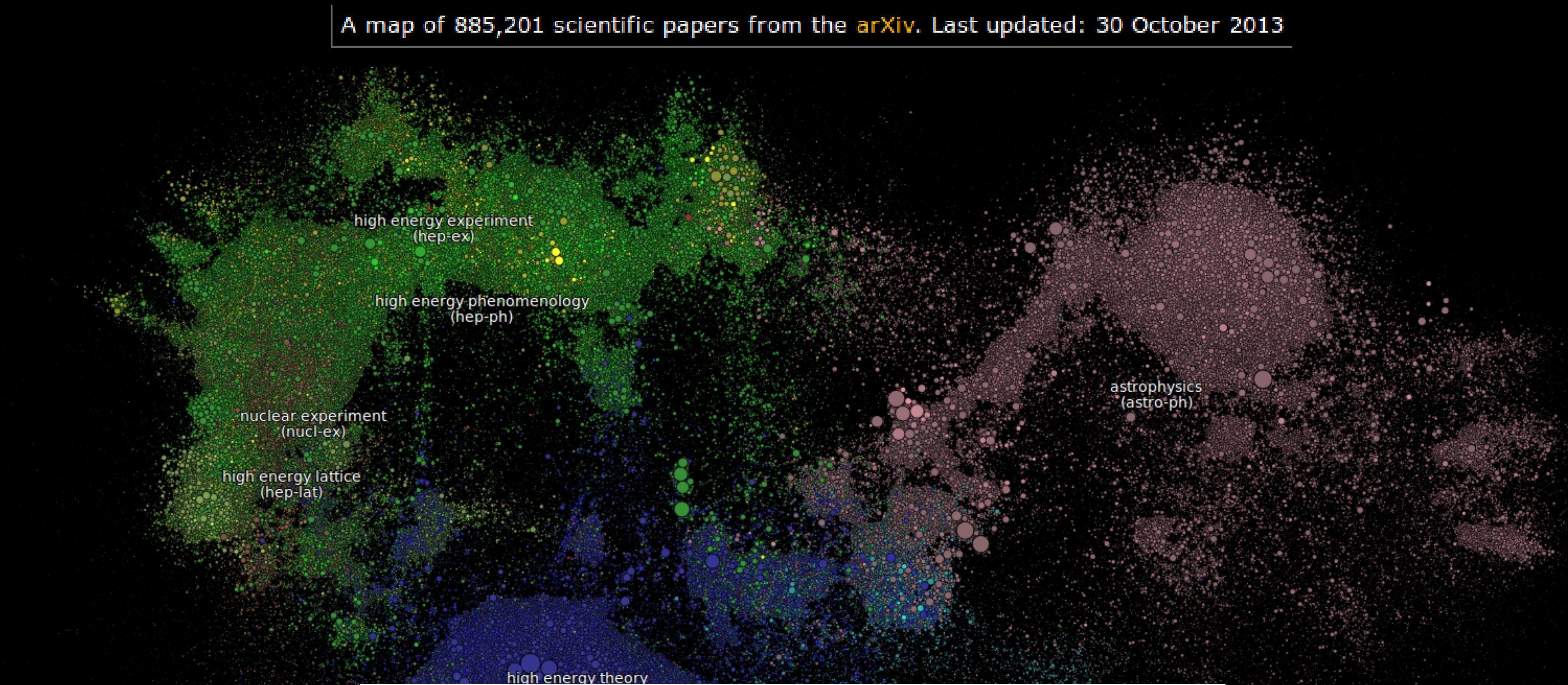
Impact on real science?

Physics landscape: `http://paperscape.org/`



A map of 885,201 scientific papers from the arXiv. Last updated: 30 October 2013

Physics landscape: `http://paperscape.org/`



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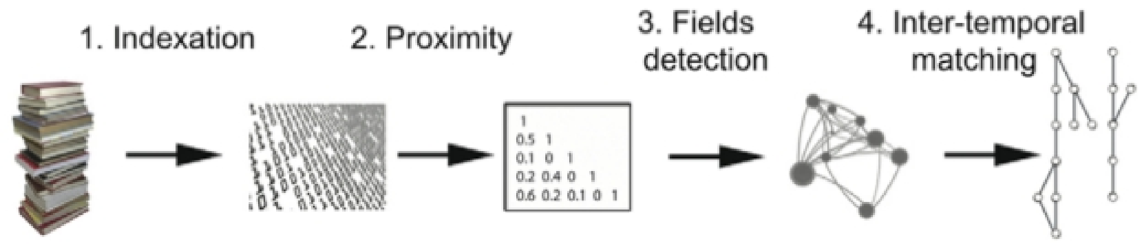

Figure 1. Steps contributing towards the reconstruction of a phylomemy.

→ Phylomemetic Patterns in Science Evolution—The Rise and Fall of Scientific Fields, Chavalarias & Cointet, Plos One (2013)

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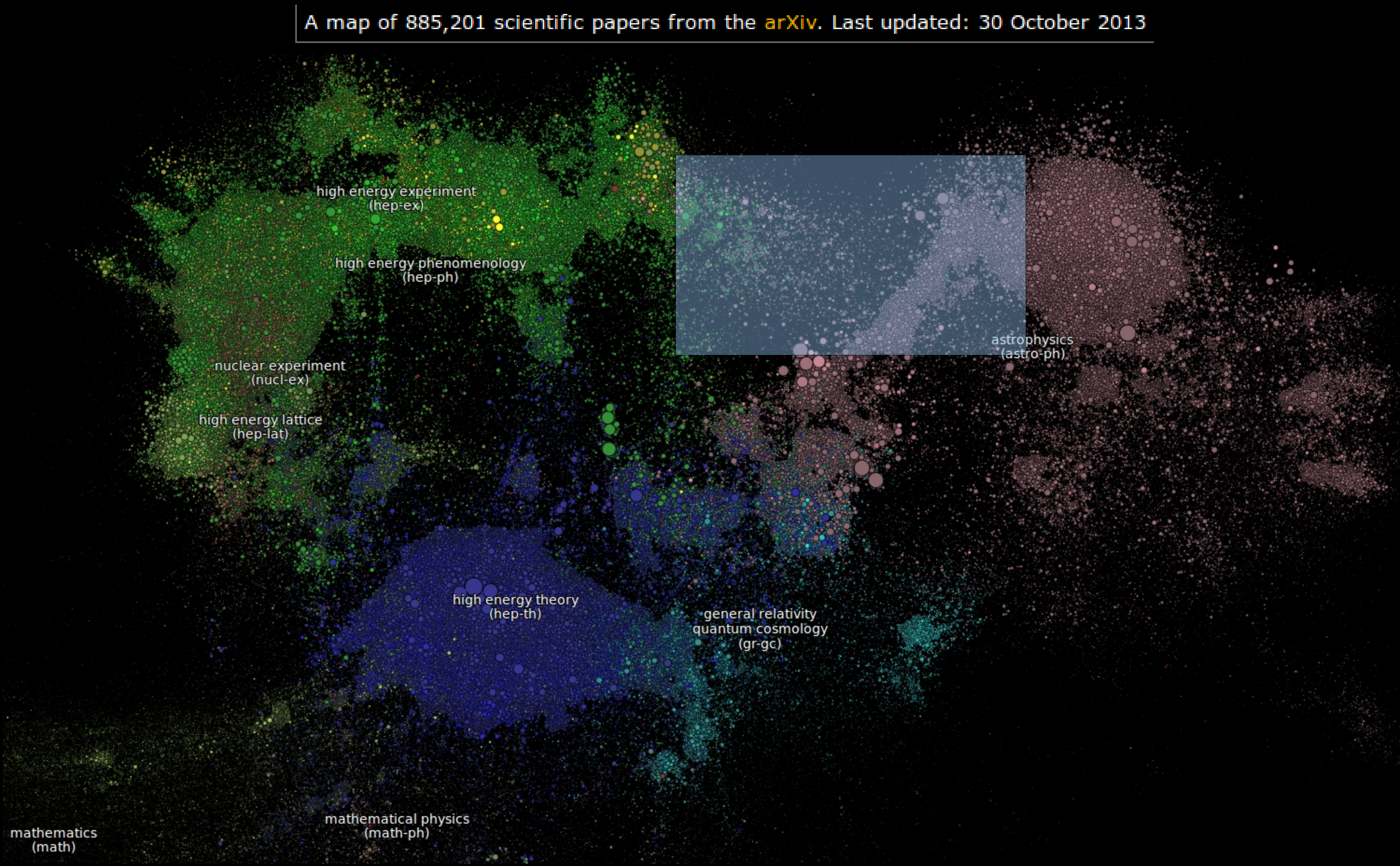

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→ Research 3.0: future tool to optimise 'research' efficiency?