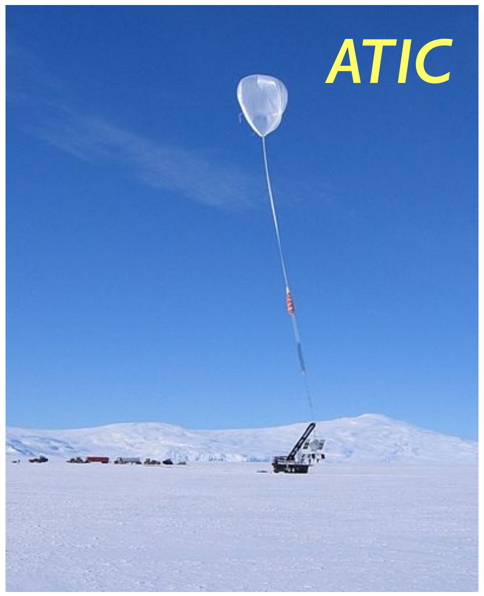
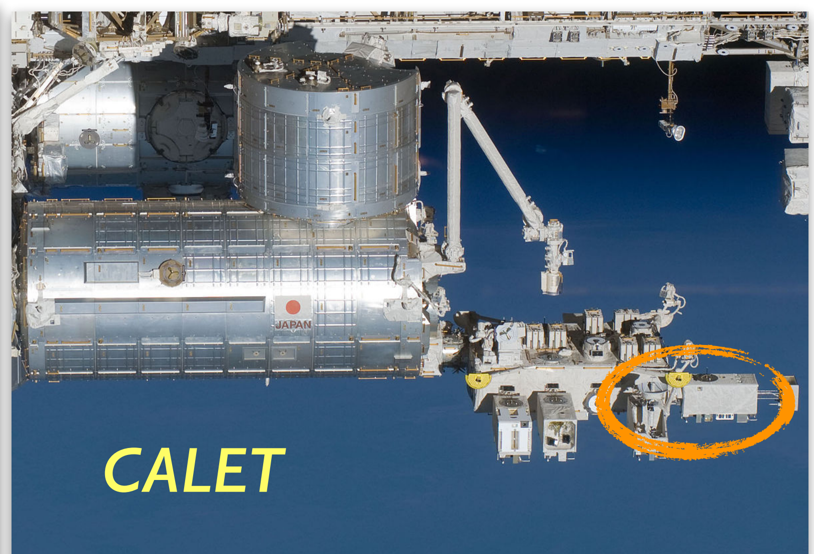
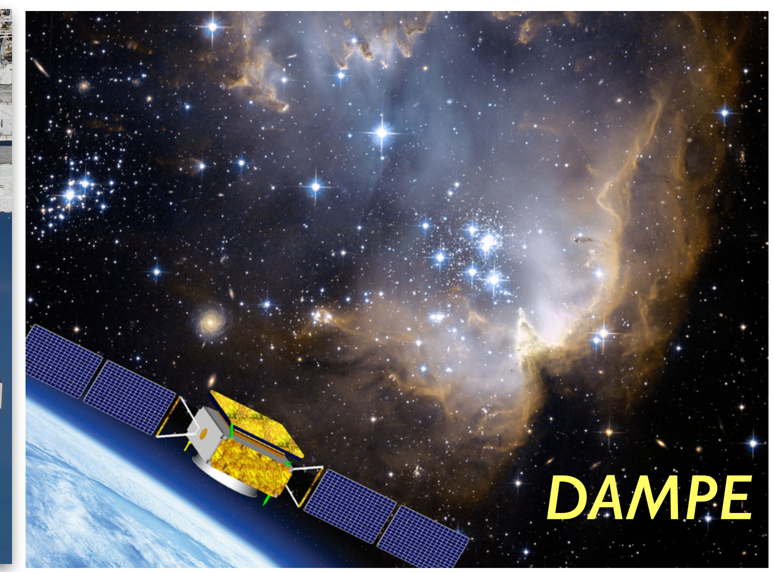
Antiprotons from dark matter ?

Pasquale Dario Serpico (Annecy, France)
DarkWin, Natal, September 3rd 2019

Cosmic ray propagation & antiproton flux predictions in the "CR precision era"







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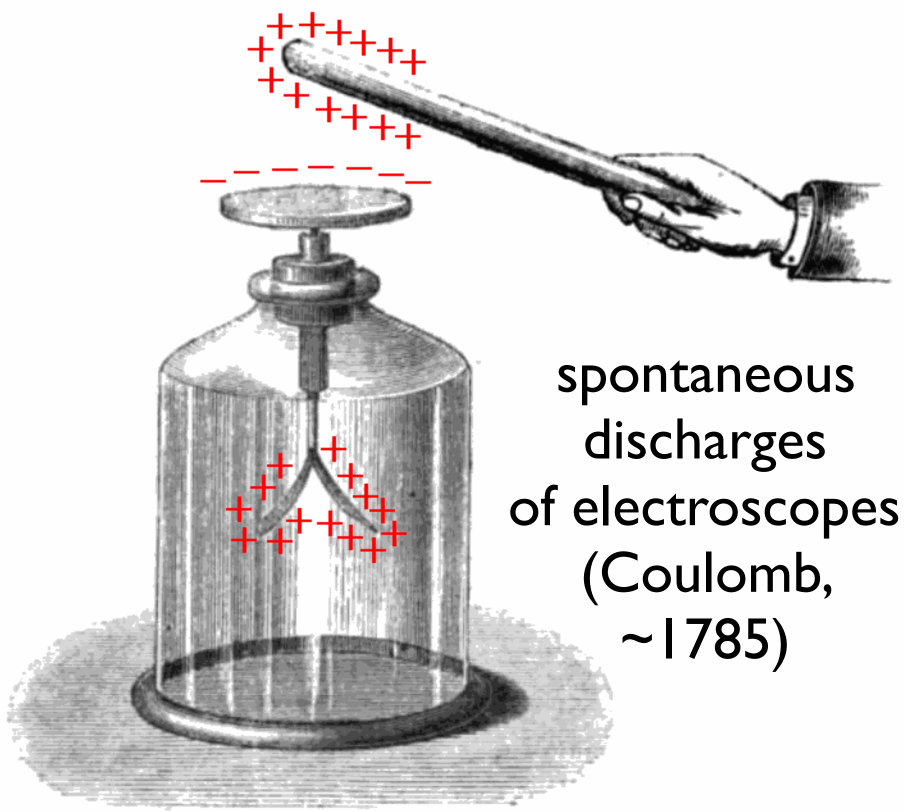
Broad outline

- Intro to cosmic rays (CR) and the interest in anti-particles
- The "standard model" of CRs
- Predicting (secondary) antiprotons…
- …A few percent-level anti-p flux measurement by AMS-02…
- … and the debate on the "hints for DM": a critical assessment

Introduction

A bit of history



spontaneous
discharges
of electroscopes
(Coulomb,
~1785)

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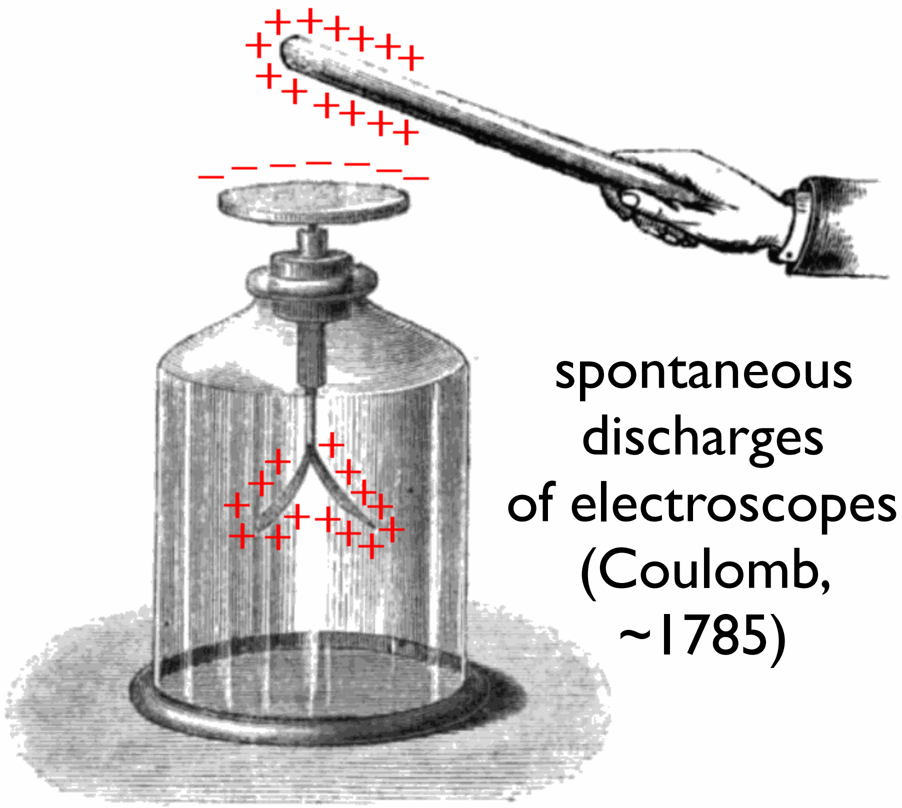

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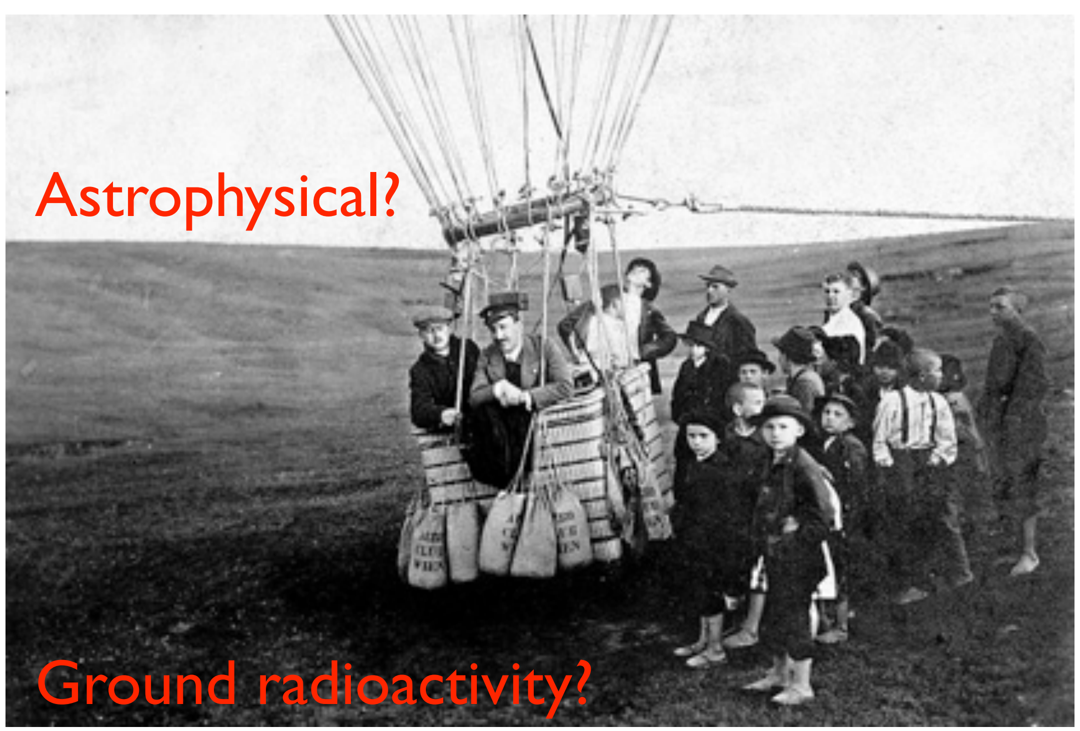
V. Hess (outside Vienna, 1911)



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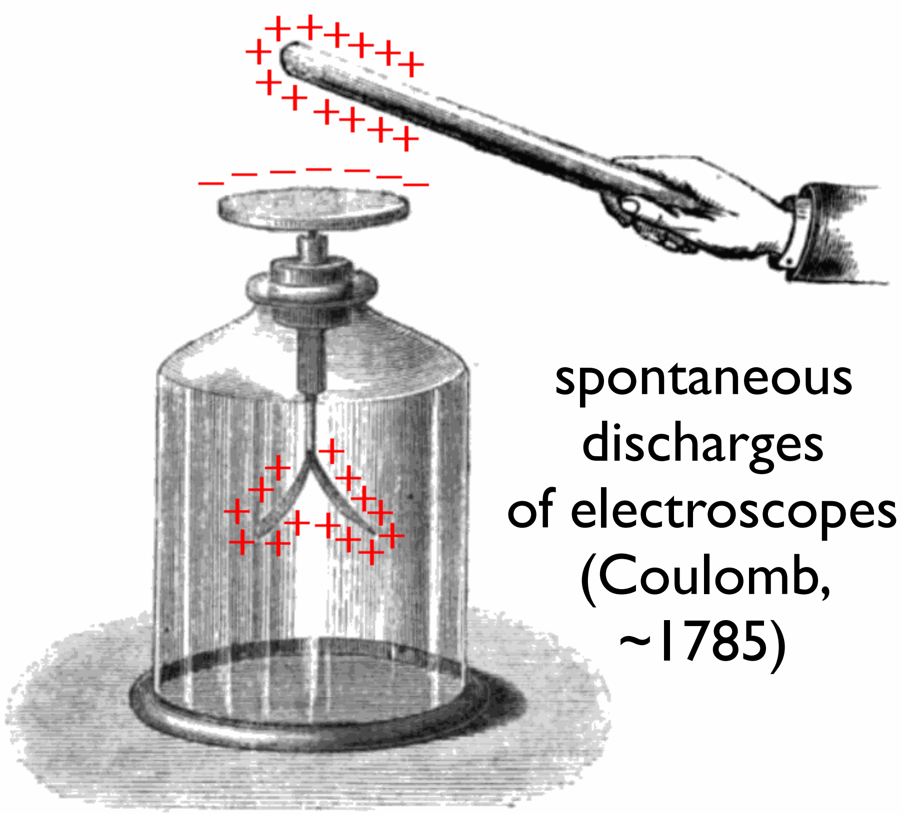
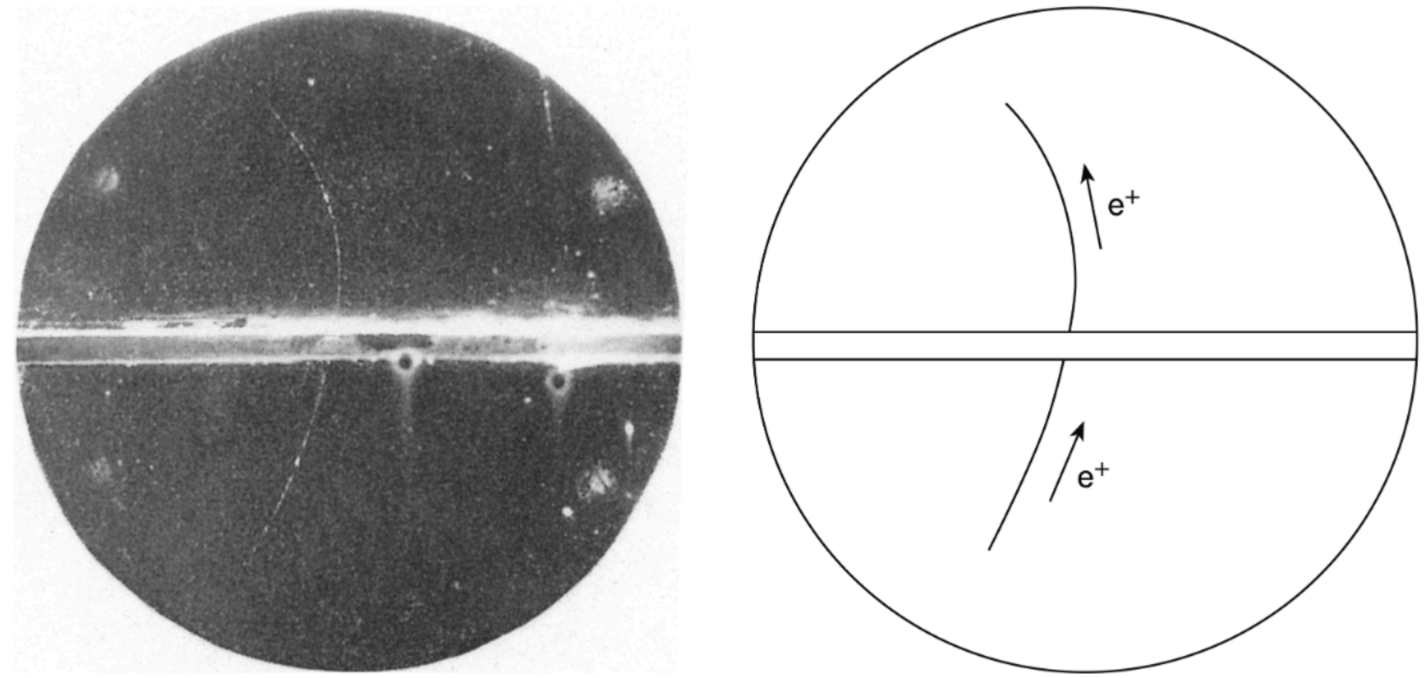


spontaneous discharges of electroscopes (Coulomb, ~1785)

positron discovery (Anderson ’32)



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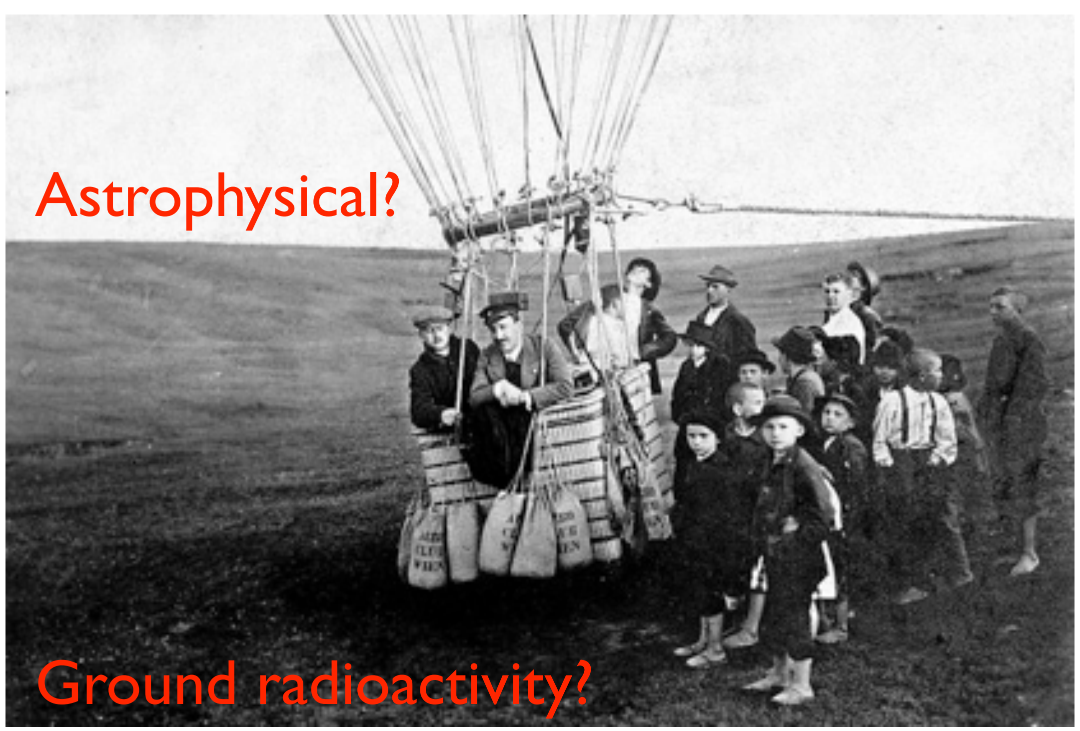
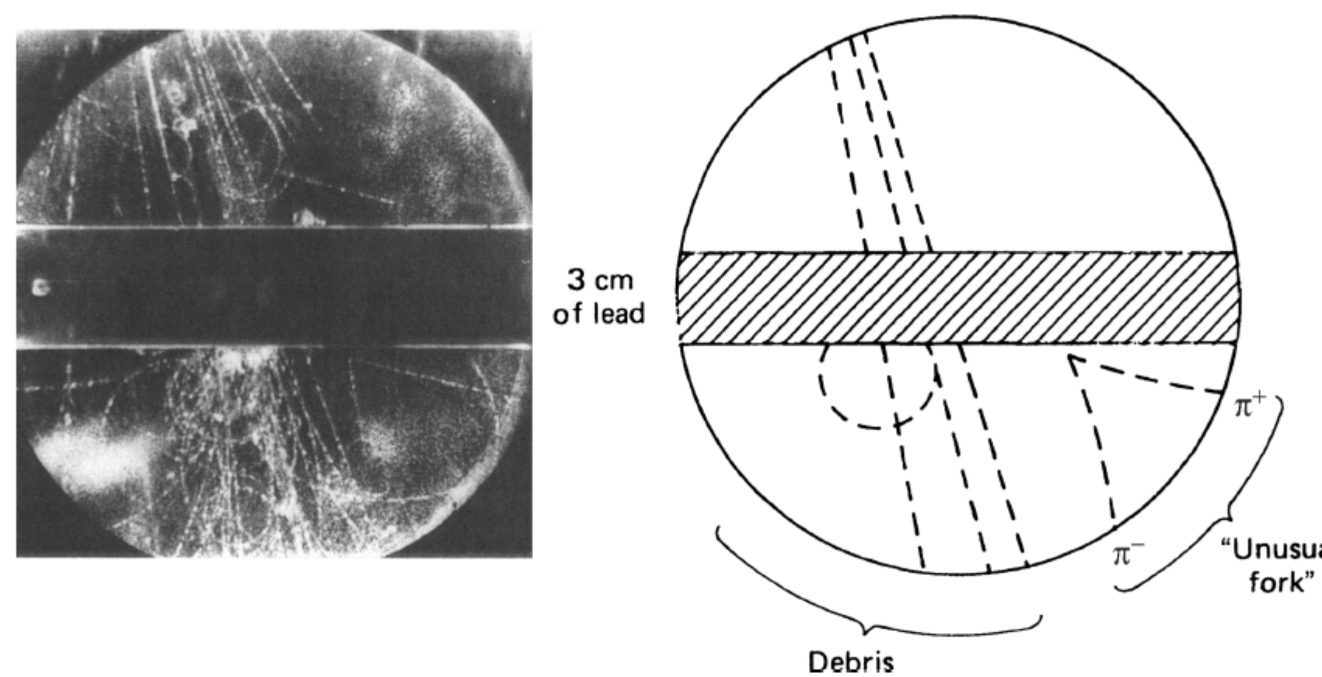


1st strange particle, Kaon ($\rightarrow 2\pi$, Rochester & Butler ’47)



~1932-53: the first golden age of particle physics: e^+, μ, π, *strange* particles K, Λ, Ξ, Σ

Including antiprotons, actually!

E. Amaldi *et al.*, “Unusual event produced by cosmic rays,” *Nuovo Cimento* **1** (1955), 492 (**received 18/02/1955**)

Unusual Event Produced by Cosmic Rays.

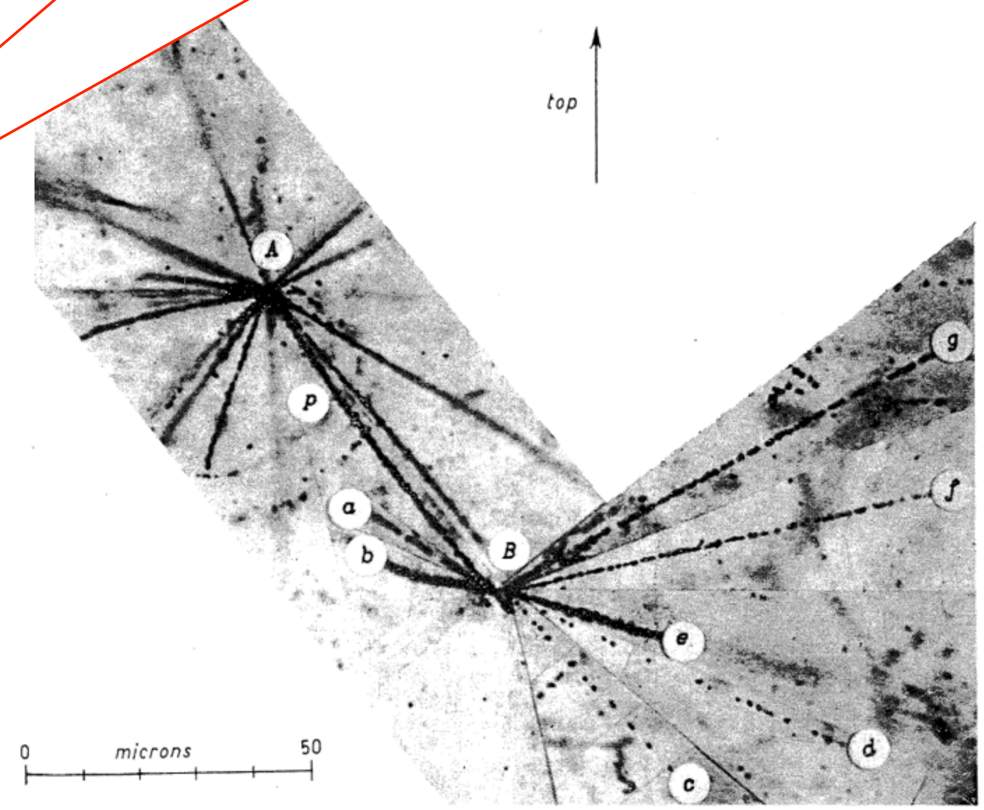
E. AMALDI, C. CASTAGNOLI, G. CORTINI, C. FRANZINETTI and A. MANFREDINI

Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(ricevuto il 18 Febbraio 1955)

Summary. — The authors describe an event consisting of two stars respectively of about 5 and 1-2 GeV energy. The probable value of the number of accidental space coincidences that one expects to observ in the scanned volume, is about $4 \cdot 10^{-4}$. This value, although it d not allow us to exclude an accidental process, justifies the consider-ation of interpretations in terms of some physical process. Special attention is devoted to the production, capture and annihilation of a negative proton.

although it does not allow us to exclude an accidental process, justifies [...] interpretations in terms of some physical process [...] capture and annihilation of a negative proton.



To be compared with Chamberlain *et al.*
“Observation of Antiprotons” [@ Berkeley's Bevatron]
Phys. Rev. 100, 947 (1955)
Received 24/10/1955
(Nobel Prize to Chamberlain & Segrè in 1959)

These are *secondary* cosmic rays!

i.e. byproducts of astrophysical 'primary' particles hitting the upper atmosphere

Once man-made accelerator made controlled particle physics studies possible, CR field moved towards "astro" questions (1953, Bagnères de Bigorre)

For an account, see *James W. Cronin, 1111.5338*

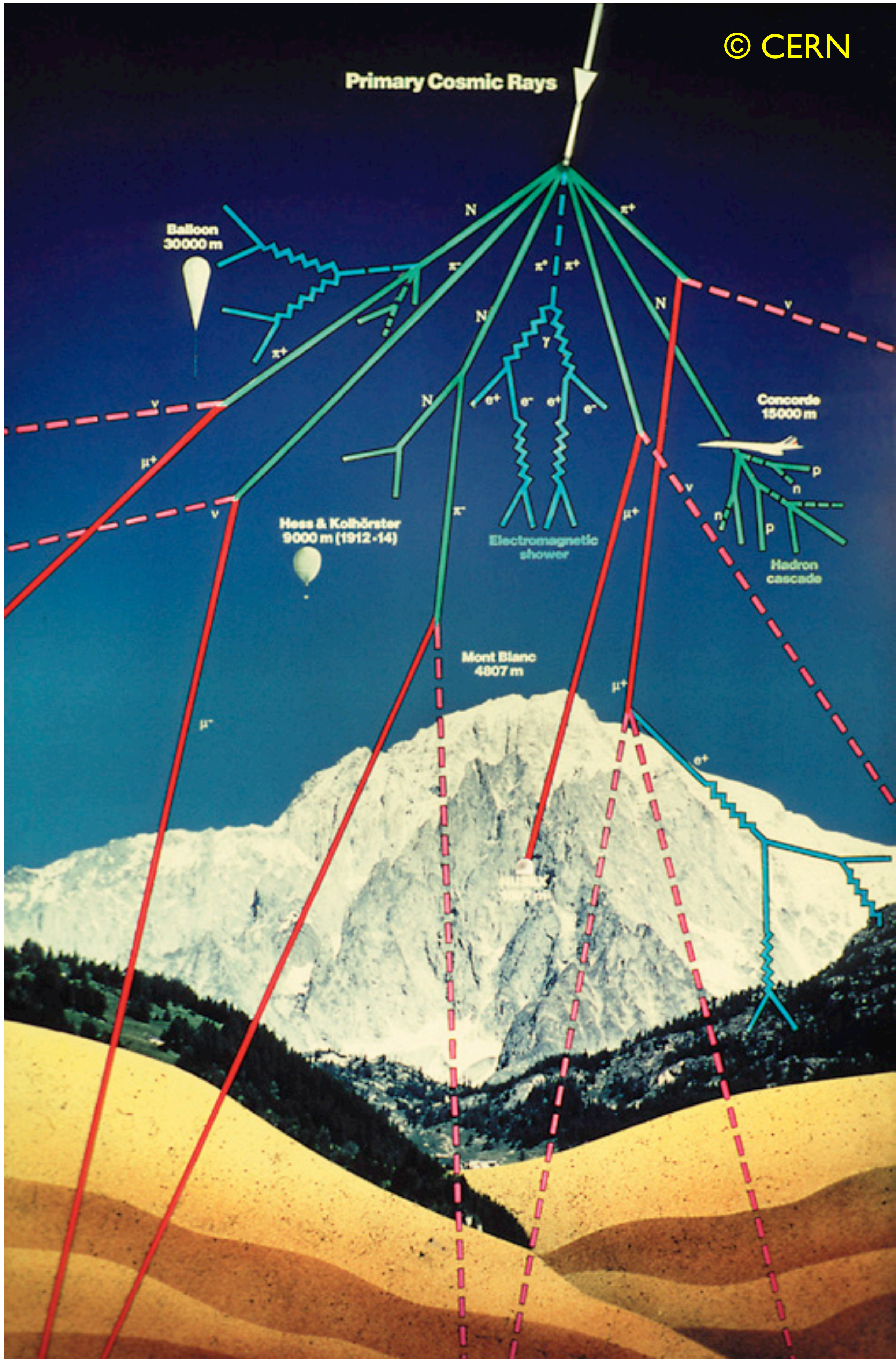
How is CR acceleration taking place?

In what type of objects?

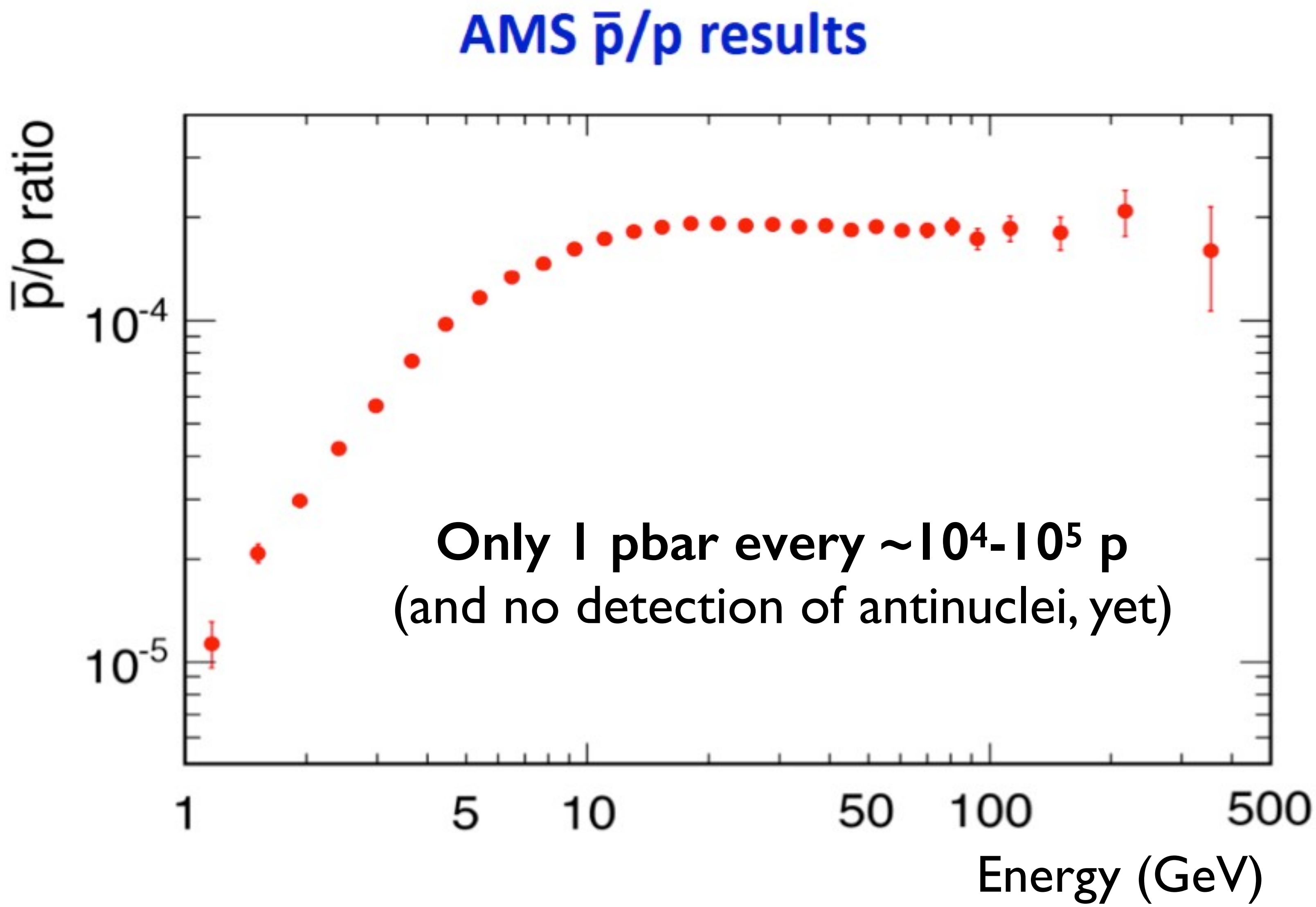
Where and when?

How do CRs propagate to us?

more easily addressed by high-altitude (or above the atmosphere) detectors as the gallery in my opening slide



One thing clearly confirmed by these experiments



Opportunity for IDM searches:

WIMP annihilations produce equal amounts and spectra of p and pbar's: searches much easier in pbar due to huge 'astro' background suppression!

Baseline hypothesis

pbar flux fully accounted for by rare collisions in the interstellar gas, Galactic analogous of secondaries in the atmosphere leading to particle discoveries in 1930-50

To which extent is the baseline true? Any hints for excesses attributable to "primary" contribution from DM annihilation? Rest of the talk!

The CR “Standard Model”

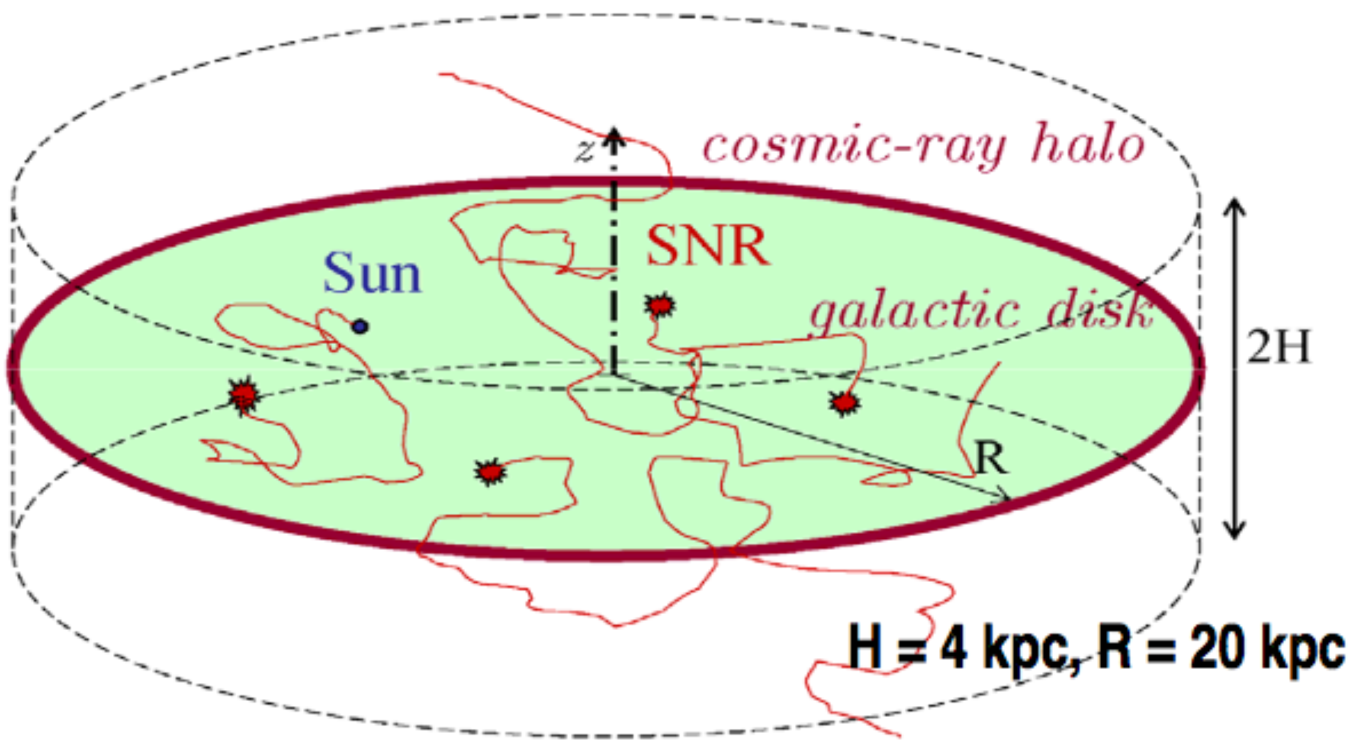
Sketch of the "CR standard model"

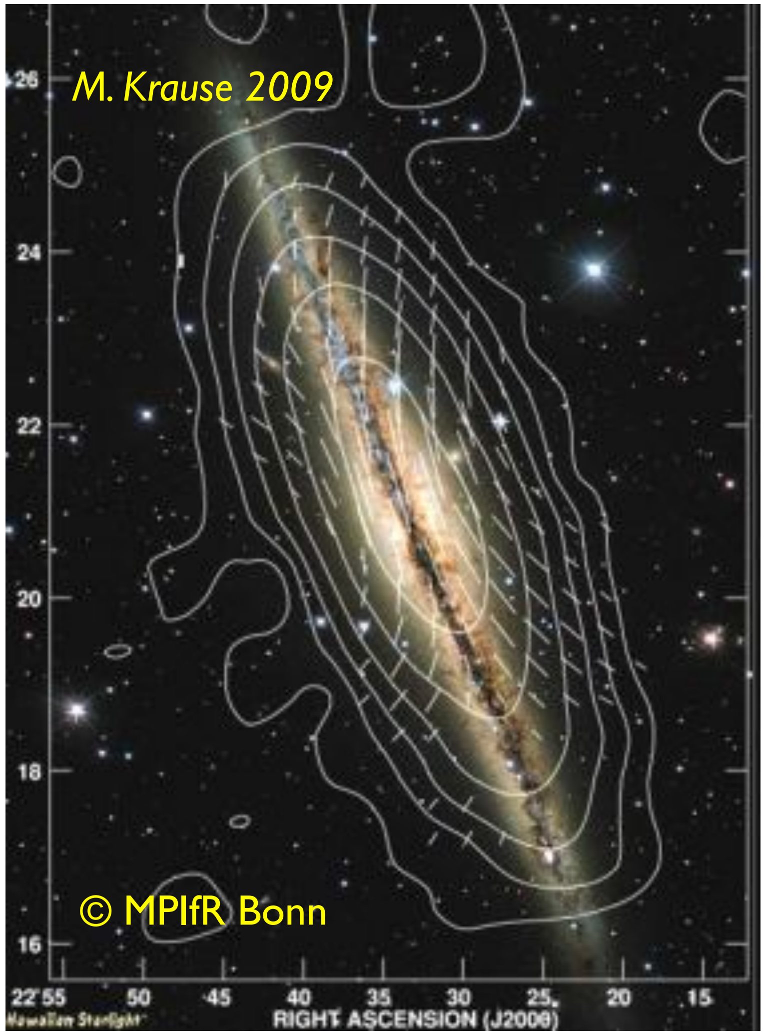
Key hypothesis

Factorized problem (differences in time and spatial scales):
Sources ⊗ Propagation ⊗ Solar System effects *(solar modulation)*

Each block has a 'fiducial framework', if not a complete model

Often simplified geometry inspired by actual galactic magnetic halos



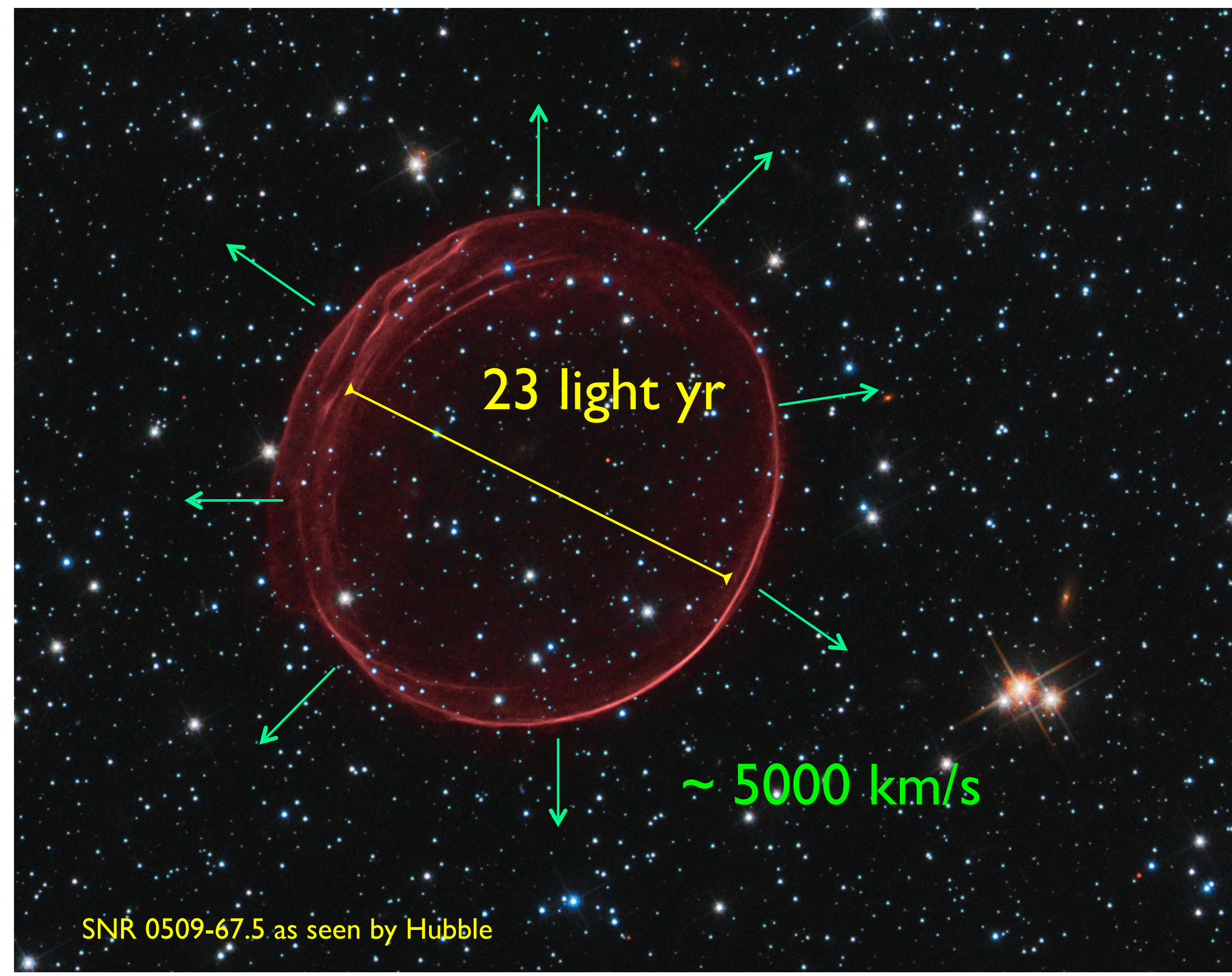


radio-contours and B-field direction
of NGC 891, MW-like Galaxy

Sketch of the “standard model”: sources

need to satisfy several requirements (like for artificial accelerators!)

Energetics:
need to supply 2 10^{41} erg/s; supernova explosions are the only class of sources providing 5-10 times more energy in the Galaxy in kinetic form (high-velocity remnants)
(possibly some contributions from pulsars & stellar winds…)



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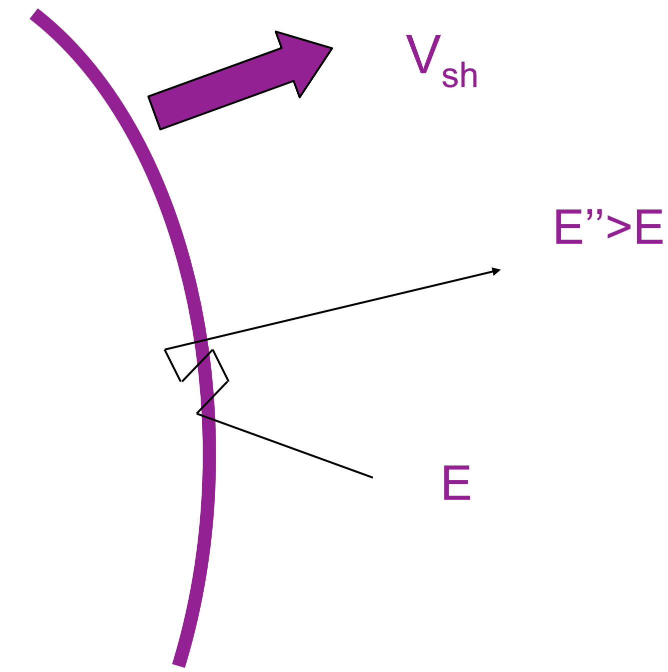

Mechanism for Energy Transfer:

how to transfer energy from macroscopic objects into the (microscopic) acceleration of particles?

Diffusive shock acceleration provides

I. 1^{nd} order acceleration in the large shock velocity: efficient!

II. spectral index is universal for strong ($\mathscr{M}$>>1) shocks in ordinary matter

III. Spectral index value close to what inferred

$$\frac{\Delta E}{E} \simeq \frac{V_{\rm sh}}{c} \simeq 10^{-3} - 10^{-2}$$

$$E^{-\gamma} \qquad \gamma = 2 + \frac{4}{\mathscr{M}^2}$$

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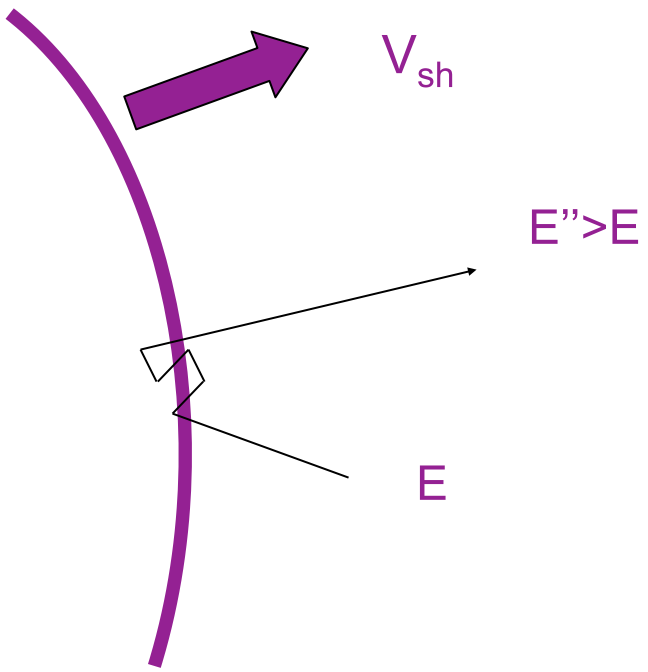

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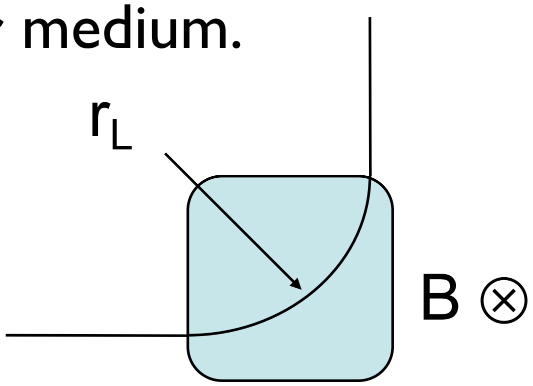
Confinement: need to check that the particle stays in the accelerator for the time needed to accelerate it.

Lack of (significant) E-losses: accelerating particles is useless for explaining CRs if they lose energy too quickly…

Sketch of the SM: How do CRs propagate?

Charged particles deflected in B-fields, known to permeate the interstellar medium. Their "Larmor Radius" is

$$r_L = \frac{p_\perp}{Z\,e\,B} \approx \frac{1\,\mathrm{pc}}{Z}\left(\frac{p_\perp}{\mathrm{PeV}/c}\right)\left(\frac{1\mu\mathrm{G}}{B}\right)$$



Even for protons, this distance is comparable to distance between neighboring stars up to ~PeV and smaller than Galactic Sizes up to EeV.

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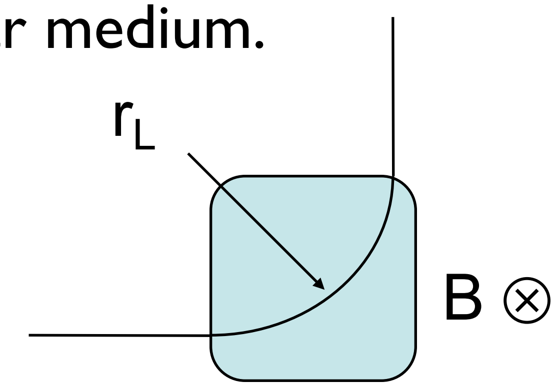

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CRs probe thus "small-scale inhomogeneities" in the field, changing direction by what appear "random kicks", similar to Brownian motion

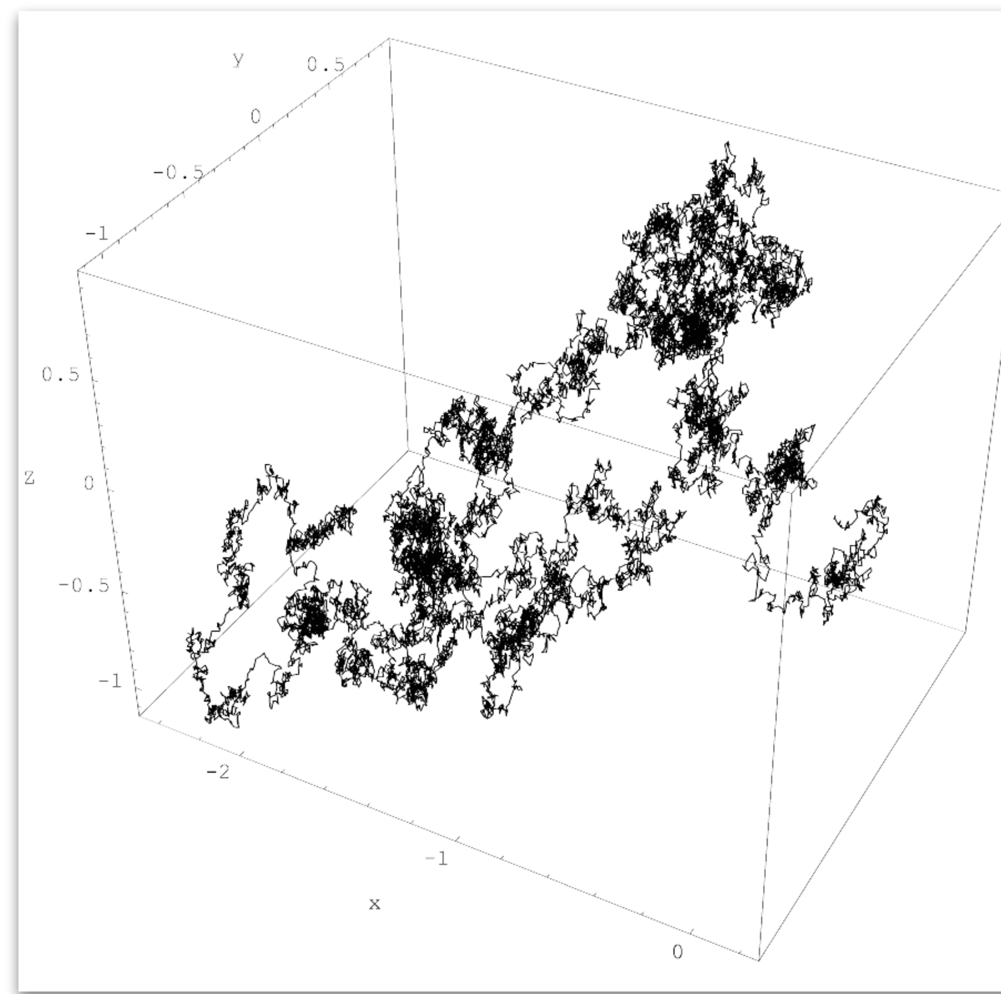
Macroscopically described as ***diffusion (+ a drift)***

$$\frac{\partial \Phi}{\partial t} + \nabla\cdot\mathbf{J}_\Phi = Q$$

Continuity Equation

$$\mathbf{J}_\Phi = -D(\mathbf{x}, \Phi, E\ldots)\nabla\Phi$$

Fick's law

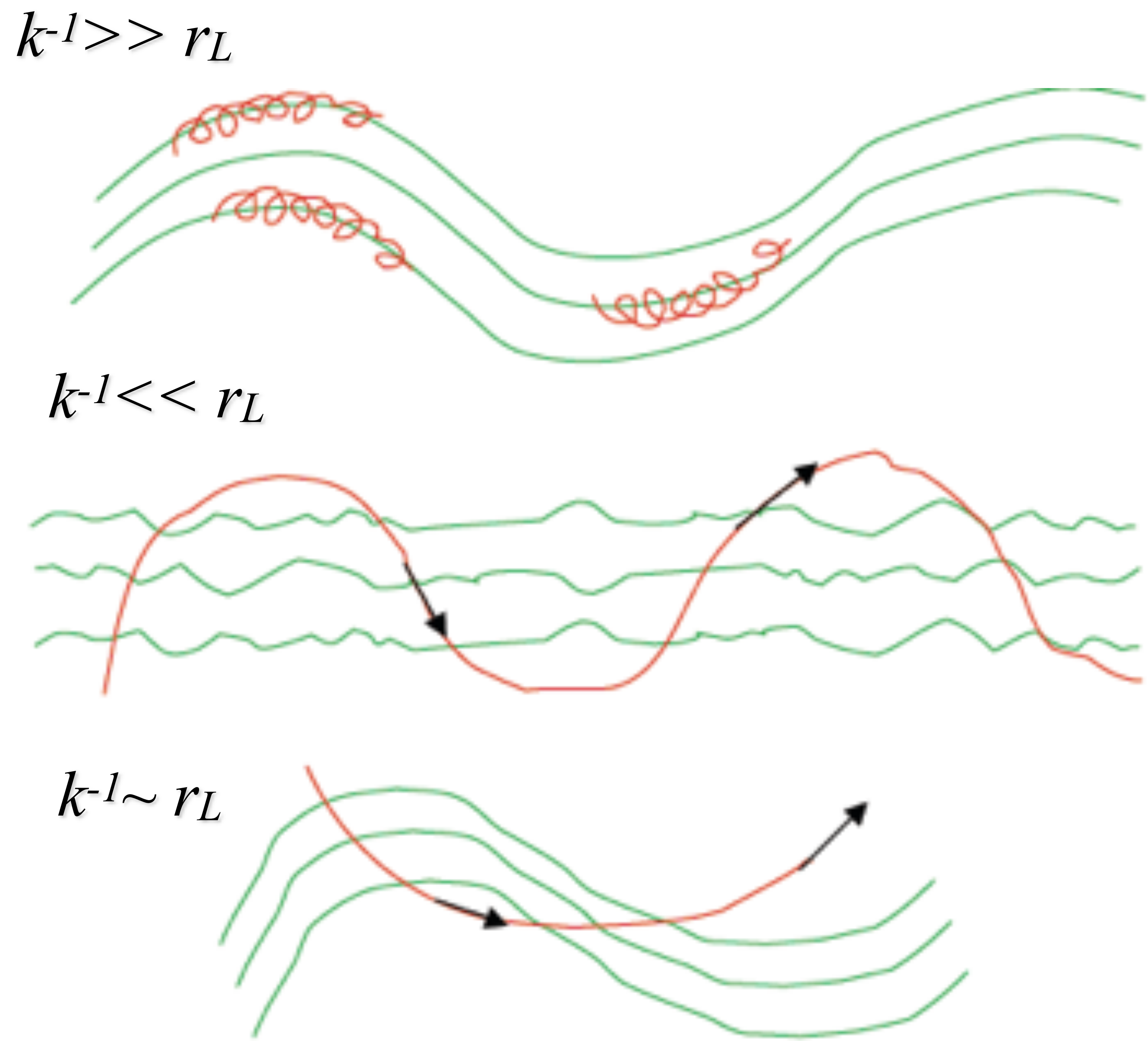


Collisionless diffusion

if $k^{-1} >> r_L$ the CRs surf adiabatically the waves,

if $k^{-1} << r_L$ the CRs hardly feel their presence

If $k^{-1} \sim r_L$ ('resonance'), the CR changes pitch angle by $\delta B/B$ with random sign



The momentum-dependence of the diffusion depends on how large field fluctuations are at different scales (their "power spectrum")

Benchmark: "Kolmogorov" energy spectrum ~ $k^{-5/3}$

unique dissipation rate at "inertial" scales, far from both injection (large) & viscous ones (small)

Slight complications

Add sources, energy losses… and account for the fact that the scattering centers (inhomogeneities/waves) are not static with respect to the Galactic frame.

In one dimension, CR distribution function f obeys:

$$\frac{\partial f}{\partial t} - \frac{\partial}{\partial z}\left(\mathsf{K}\frac{\partial f}{\partial z}\right) + u\frac{\partial f}{\partial z} - \frac{du}{dz}\frac{p}{3}\frac{\partial f}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{\rm loss} f\right] - \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\,\mathsf{D}\frac{\partial f}{\partial p}\right) = q_0 - \mathsf{L}[f]$$

Spatial diffusion

Advection

Adiabatic losses/gains

Continous losses

V. L. Ginzburg S. I. Syrovatskii, "The Origin of Cosmic Rays" (1964)

Fragmentation and decay terms, of "collisional" nature *(symbolic)*

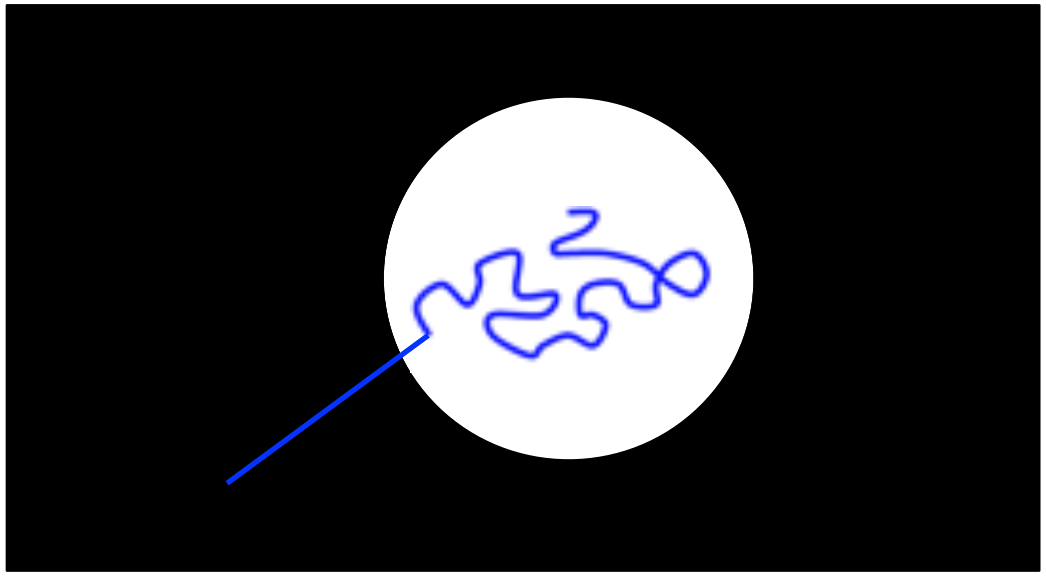
Source term (t, **x**, **p** -dep.)
Includes dec./frag. for heavier nuclei

Reacceleration

Typically solved (in 1 or 2D) with numerical (GALPROP, DRAGON…) or semianalytical codes (USINE)

CR propagation for dummies

The most important effect is diffusion, especially at high-rigidity



For ***stationary, homogeneous & isotropic*** problems & observations at a single location, the diffusion operator can be effectively replaced by an effective "diffusive confinement" time $\tau_{\rm diff}$

$$\frac{\partial \Phi}{\partial t} - K\nabla^2\Phi = Q \Rightarrow \frac{\partial \Phi}{\partial t} + \frac{\Phi}{\tau_{\rm diff}(E)} = Q$$

At steady state

$$\Phi = Q(E)\tau_{\rm diff}(E)$$

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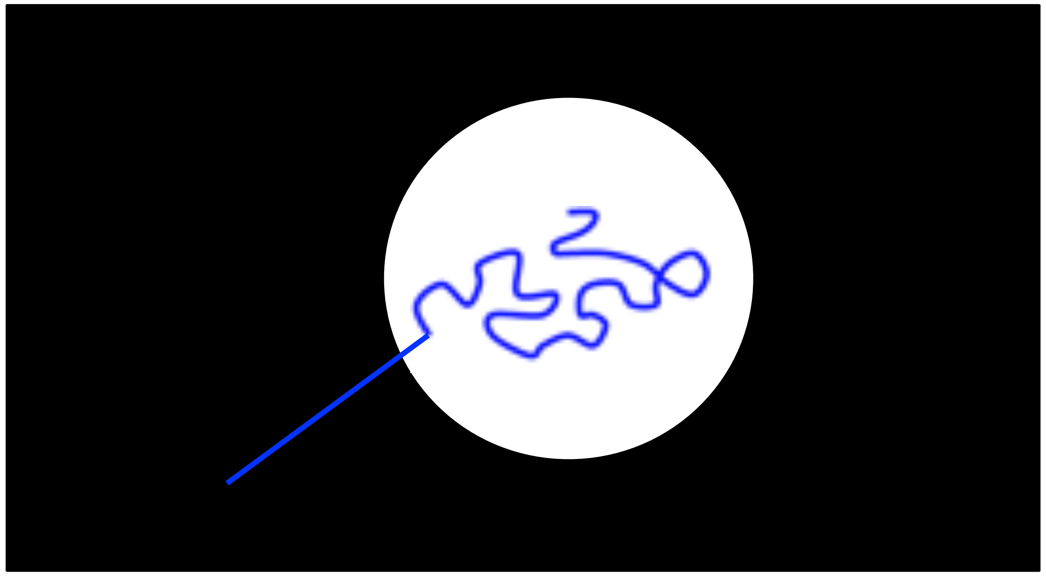

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If a nucleus is not accelerated directly (***primary***) but only produced via primary collisions (***secondary***)

$$\Phi_s = Q_s\,\tau_{\rm diff} \propto \sigma_{p\to s}\Phi_p\tau_{\rm diff}$$

(more in general, convolution of σ and $\boldsymbol{\Phi}_p$)

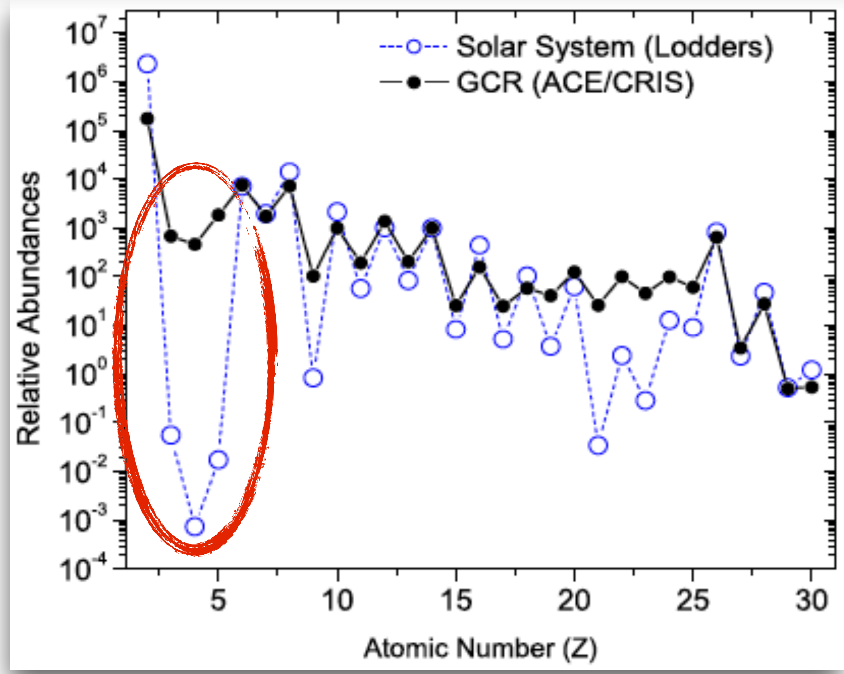
- **If diffusion and/or σ is E-dependent, secondaries and primaries differ in spectral shape**
- **Since there are no (significant) antiprotons in SNRs or the ISM, anti-*p* are secondaries (in the standard model); DM, as 'direct' source of anti-*p*, would be a primary channel!**

“Fixing” the propagation parameters

Fragile nuclei such as Li, Be, B… present but in traces in stellar astrophysical environments, while in sizable fractions in CRs:

➡ interpreted as result of spallation of “primary” nuclei, accelerated at sources (e.g. SNRs) during the CR diffusive propagation in the ISM.

Above ~GeV scale, σ has little energy dependence



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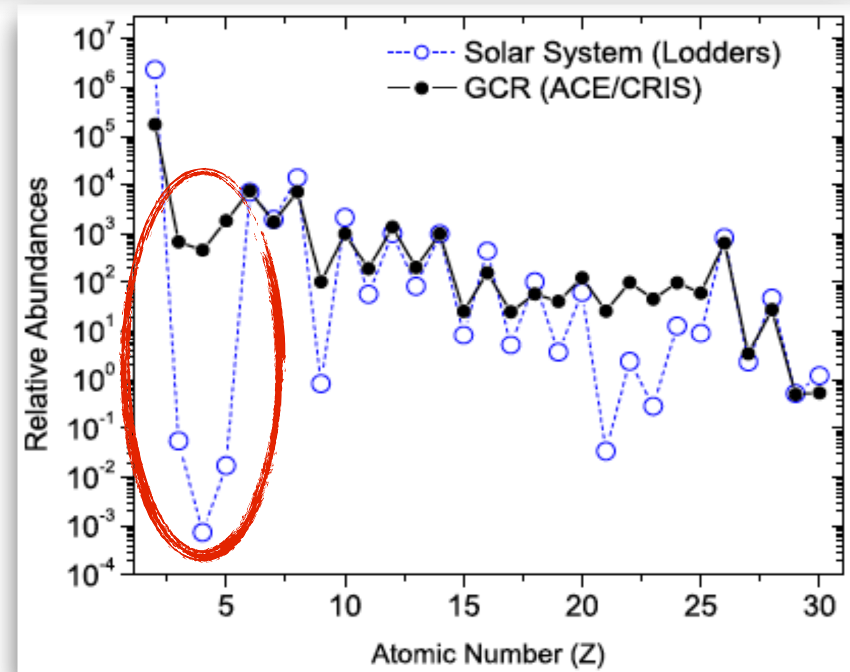


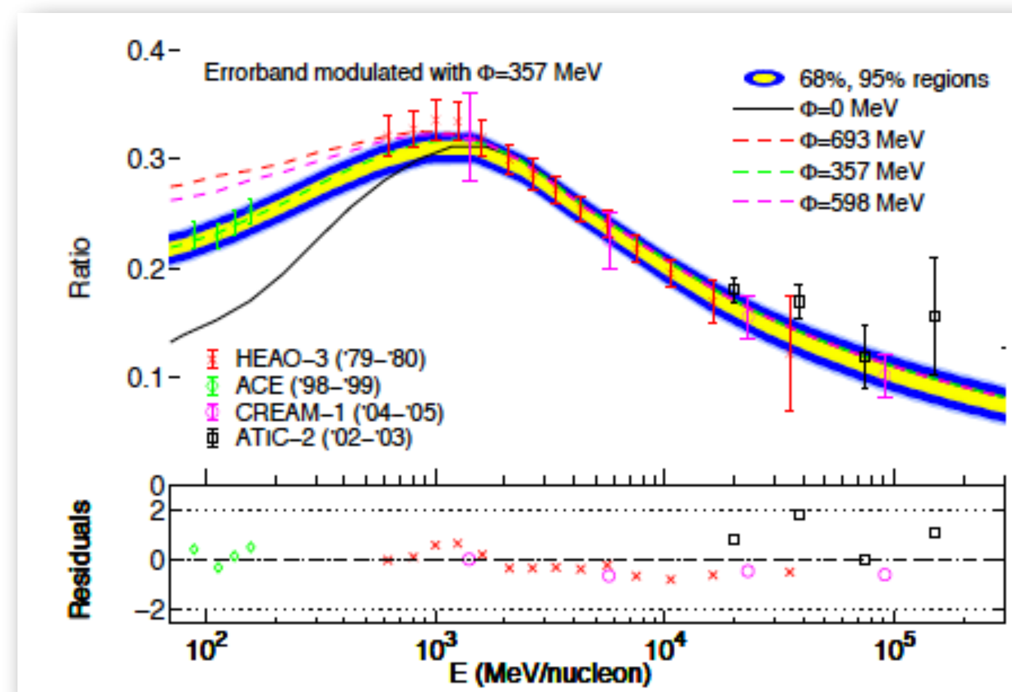
a secondary/primary comparison yields

$$\frac{\Phi_s}{\Phi_p} \propto \tau_{\rm diff}(E) \propto 1/K(E) \propto E^{-\delta}$$

(modulo uncertainties in the x-section!)

often inferred from B/C, with typical results

$$K(R) \sim 10^{28} \div 10^{29} \left(\frac{R}{3\,{\rm GV}}\right)^{0.2\div0.6} {\rm cm}^2/{\rm s}$$



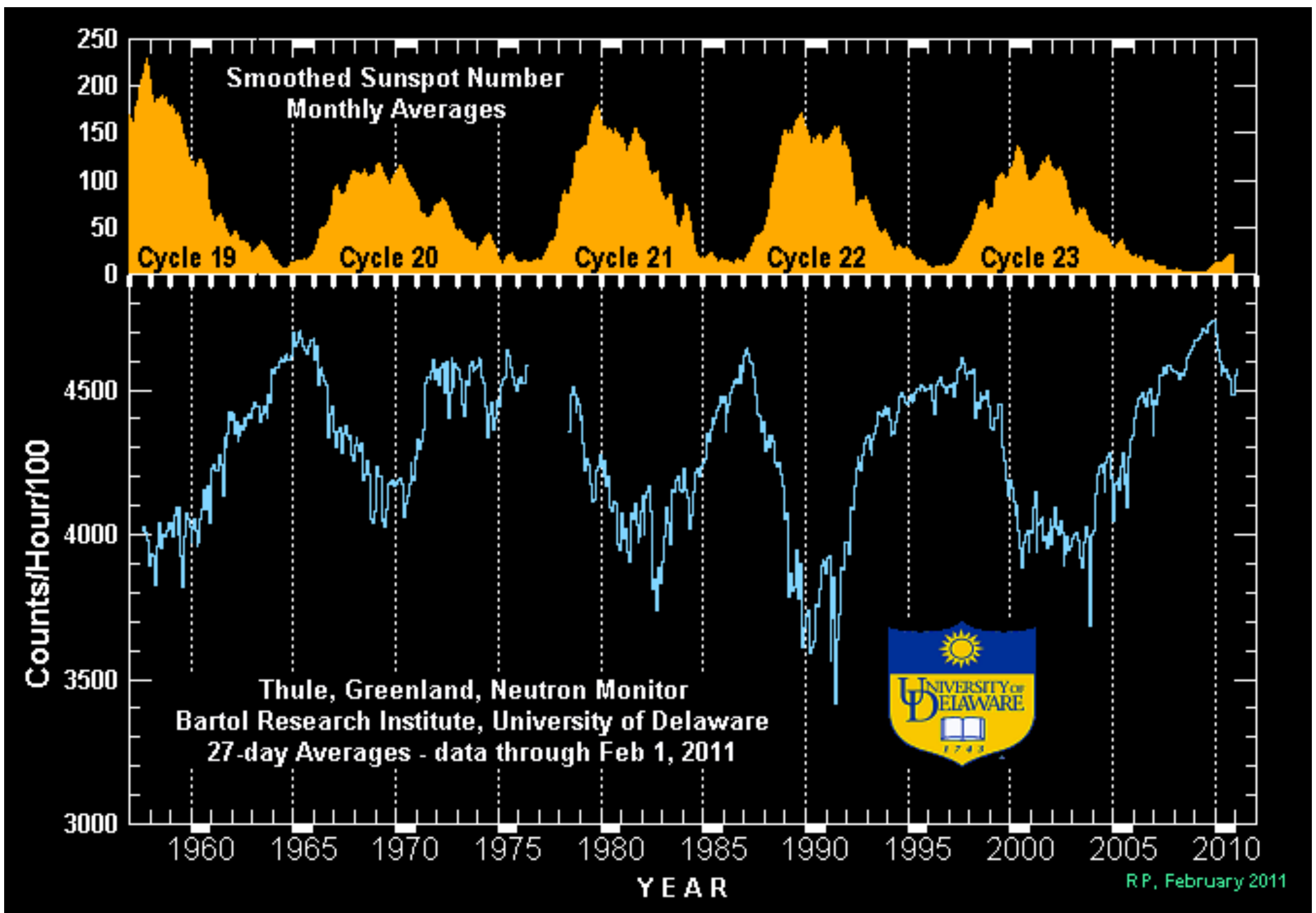
see e.g. Trotta, Johannesson, Moskalenko et al. ApJ 729, 106 (2011)

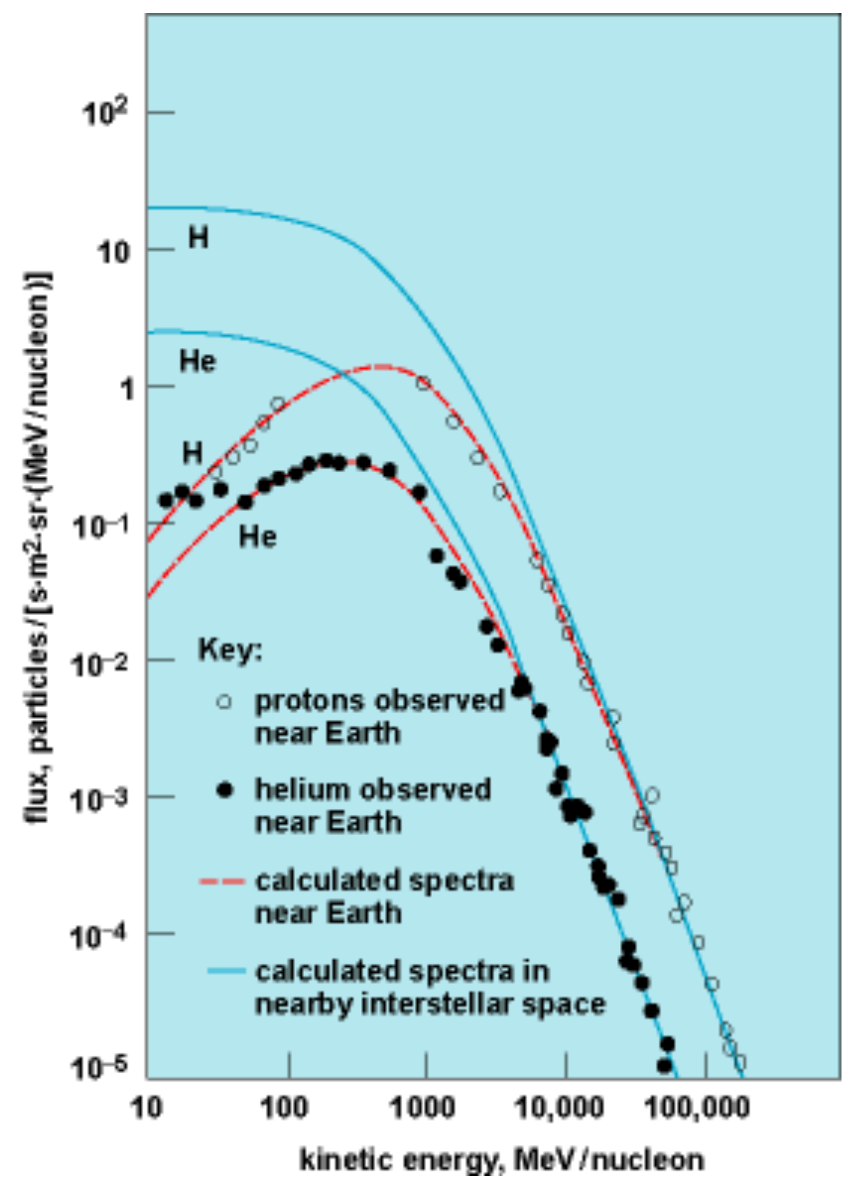
Sketch of the SM: Solar modulation

Result of balance between inward diffusion of Galactic CRs and outward convection and adiabatic cooling by the solar wind. Usually treated in the force-free approximation with φ~O(100-1000) MV, in reality a 3D transport phenomenon in the heliosphere

Gleeson, L. J.; Axford ApJ 154, 1011 (1968)

$$J_{\oplus}(T-\varphi) = J_{\infty}(T)\frac{(T-\varphi)(T-\varphi+2\,m)}{T(T+2\,m)}$$





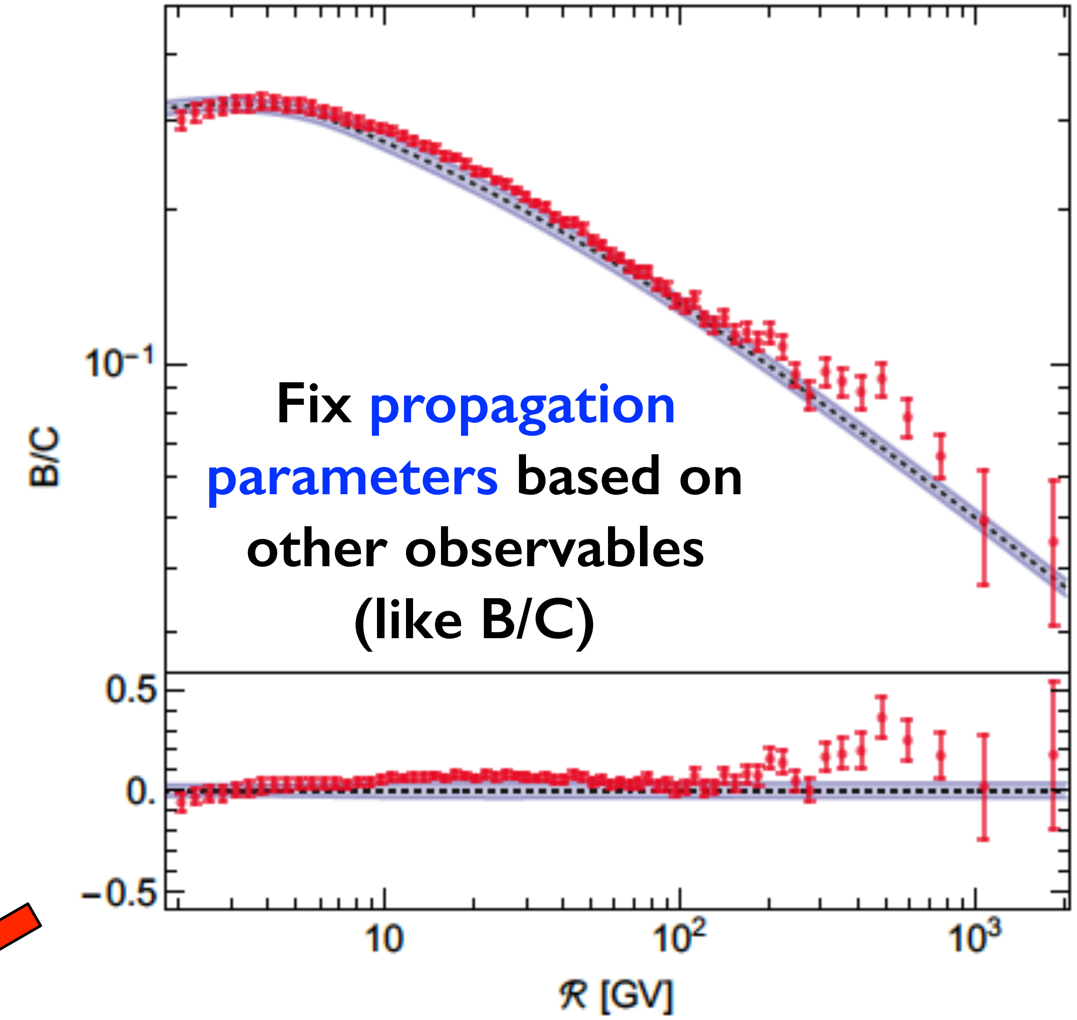
Antiprotons

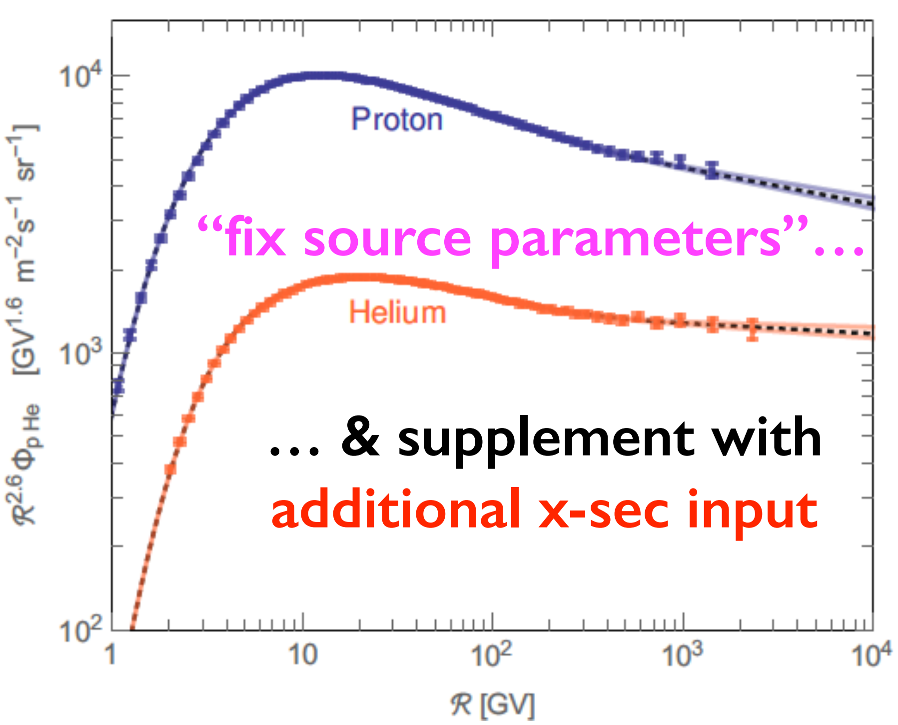
Predicting secondary antiprotons

$$\Phi_{\bar{p}} \sim \tau \otimes \sum_{\alpha,i} n_i \Phi_\alpha \otimes \sigma_{\alpha,i\to\bar{p}}$$

Parameterize the injection fluxes and fit injection & propagation parameters (more or less) simultaneously to B/C, p,He…

differently from B, Li, Be… inelasticity low, hence sensitive to fluxes at significantly higher energies





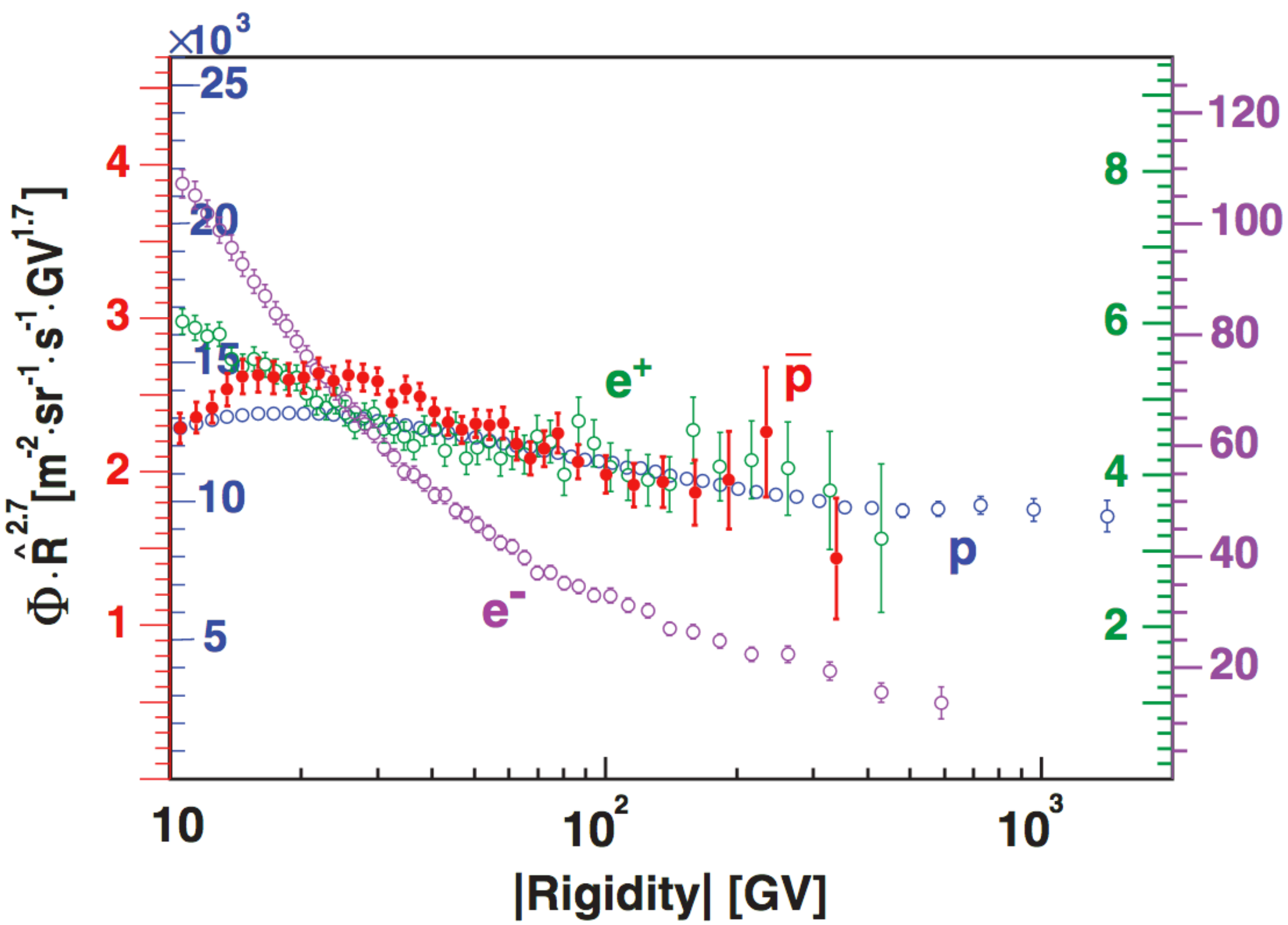
predict antiprotons and constrain models

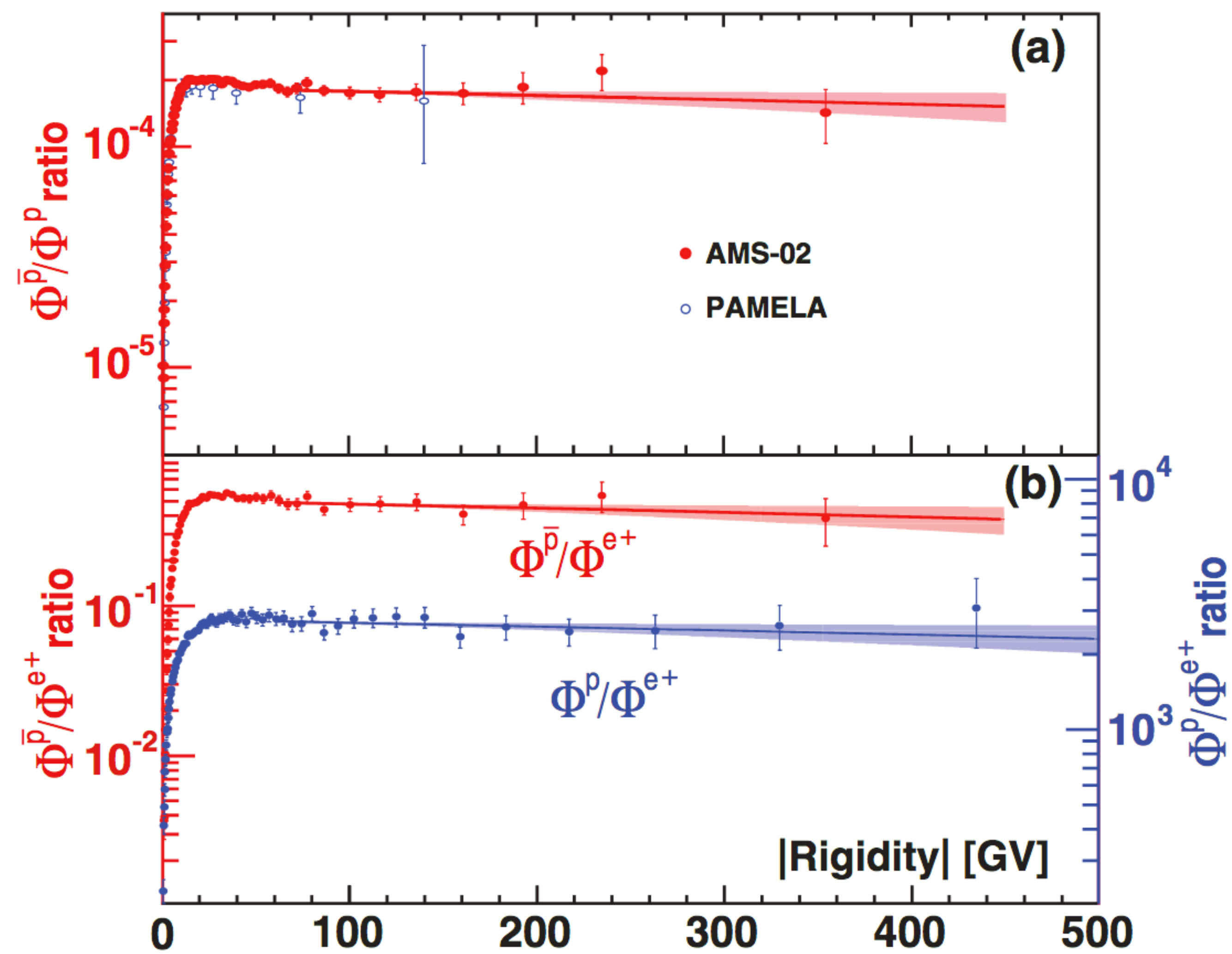
Plots taken from

A. Reinert and M.W. Winkler, "A Precision Search for WIMPs with Charged Cosmic Rays," JCAP 1801, 055 (2018) [1712.00002]

The AMS-02 data

M. Aguilar et al. [AMS Collaboration], "Antiproton Flux, Antiproton-to-Proton Flux Ratio, and Properties of Elementary Particle Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station," Phys. Rev. Lett. 117, 091103 (2016)

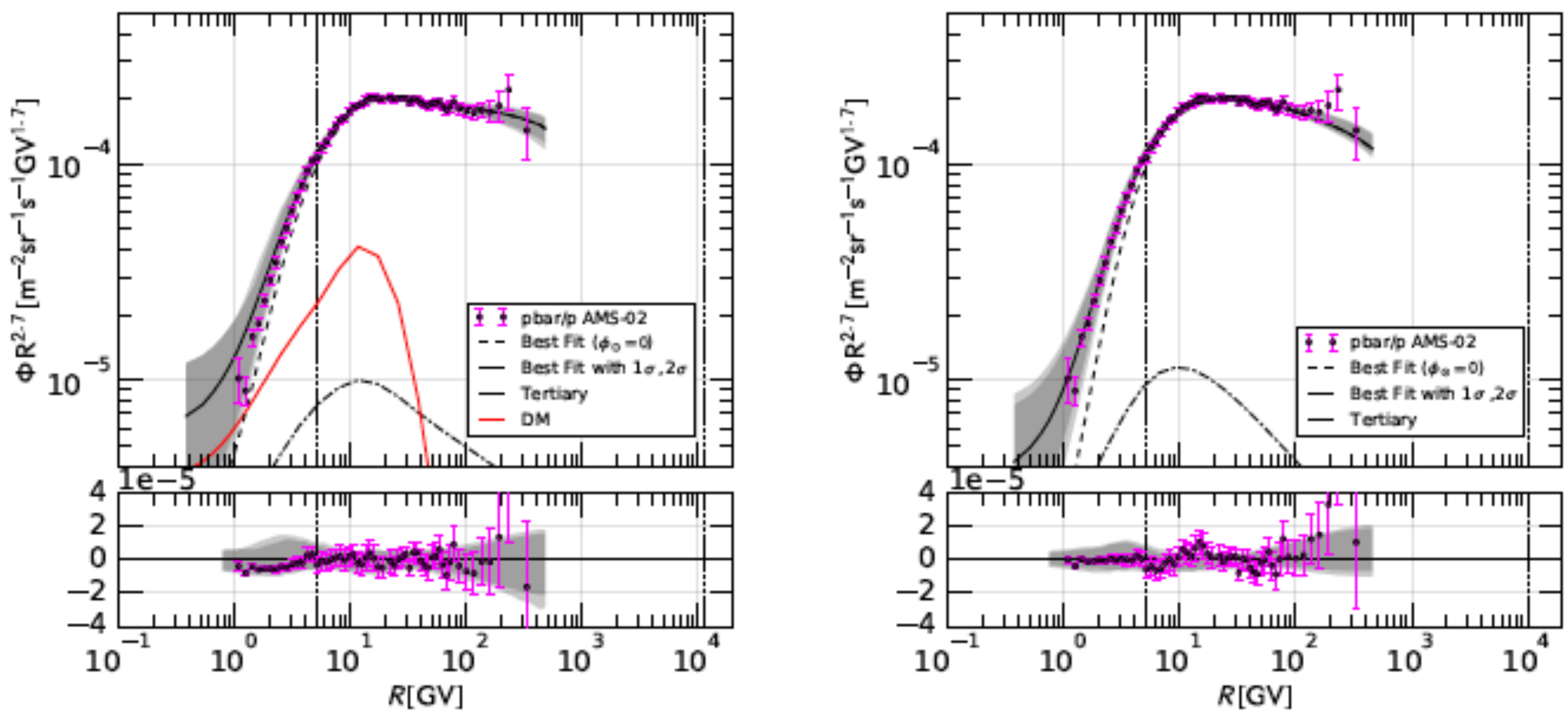




A DM signal hidden in the data?

A. Cuoco, M. Krämer, M. Korsmeier, "Novel dark matter constraints from antiprotons in the light of AMS-02," Phys. Rev. Letters 118, 191102 (2017) [1610.03071]

"DM favored at around 4.5 sigmas"



See also
M.Y. Cui, Q. Yuan, Y. L. S. Tsai and Y. Z. Fan, "A possible dark matter annihilation signal in the AMS-02 antiproton data," Phys. Rev. Letters 118, 191101 (2017) [1610.03840]

…much smaller effect (~2.2 sigma local, 1.1 sigma global) found in

A. Reinert and M.W. Winkler, "A Precision Search for WIMPs with Charged Cosmic Rays," JCAP 1801, 055 (2018) [1712.00002]

2019: sequel(s)

A.Cuoco, J. Heisig, L. Klamt, M. Korsmeier, M. Krämer, "Scrutinizing the evidence for dark matter in cosmic ray antiprotons," 1903.01472

Confirmed excess, but at 3 sigma level (number of technical improvements and checks)

I. Cholis, T. Linden, D. Hooper, "A Robust Excess in the Cosmic-Ray Antiproton Spectrum: Implications for Annihilating Dark Matter" 1903.02549

Hint claimed at the 4.7 sigma level

S. J. Lin, X.J. Bi, Y. P. F.Yin, "Investigating the dark matter signal in the cosmic ray antiproton flux with the machine learning method" 1903.09545

From very significant to below 1 sigma, depending on model for cross sections and treatment of solar modulation.

Let’s check! Our B/C analysis

L. Derome et al. “Fitting B/C cosmic-ray data in the AMS-02 era: a cookbook,” Astron. Astrophys. 627, A158 (2019) [1904.08210]

Y. Genolini et al. “Cosmic-ray transport from AMS-02 B/C data: benchmark models and interpretation,” Phys. Rev. D 99, 123028 (2019) [1904.08917]

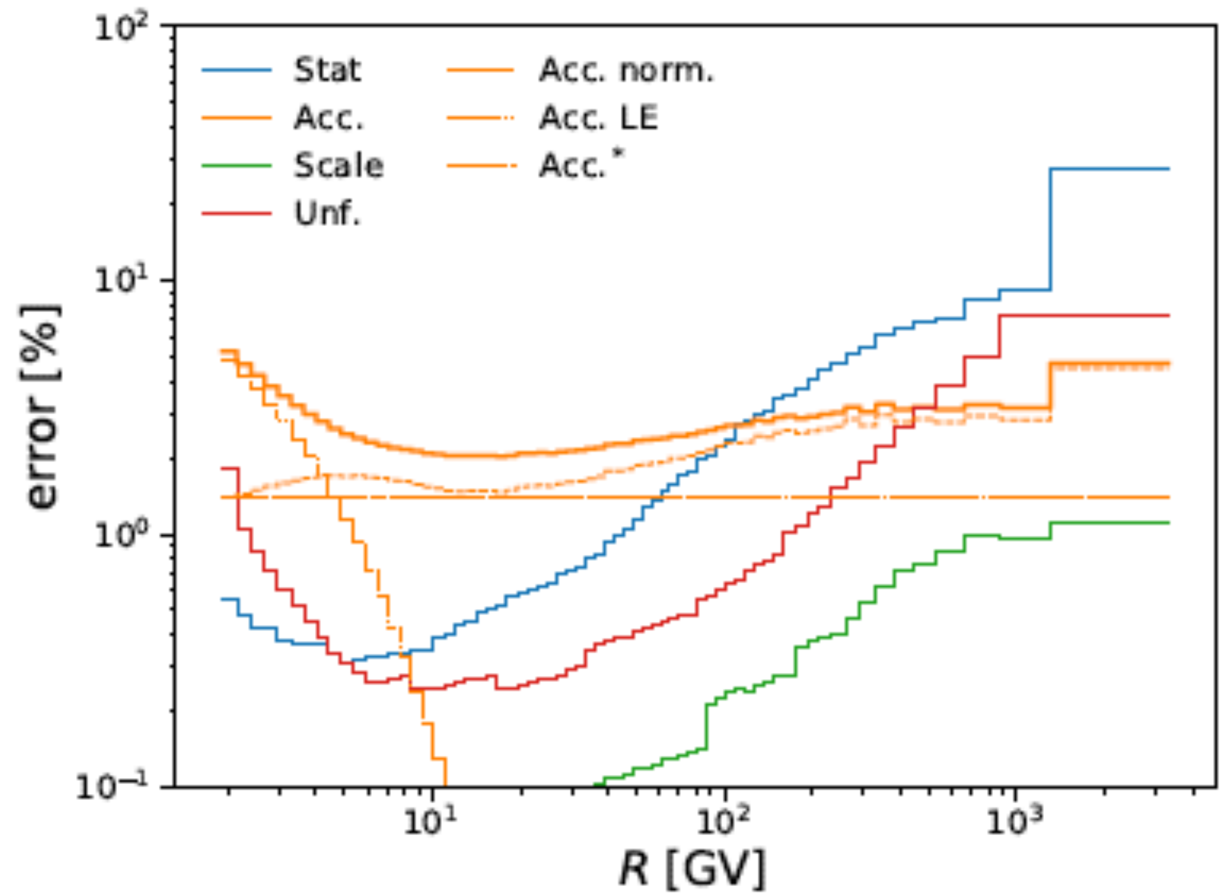
- **Takes into account a physics motivated model of correlation in AMS-02 errors.**
- Nuclear cross sections parametrized… and treated as nuisance.
- Tries to avoid multiplication of parameters (probably crucial in p,He overfitting manifest in Cuoco et al.'s analyses): proves that simple power-laws work for C,O when accounting for high-rigidity spectral break in diffusion coefficient.
- Extend down to low-rigidities, modulation described with neutron monitor data and then normalization marginalized over.
- We confirm spectral break at high-rigidity, but also highlight likely presence of flattening in diffusion coefficient at low-R (wave damping?)

On error correlations

L. Derome et al. "Fitting B/C cosmic-ray data in the AMS-02 era: a cookbook," Astron. Astrophys. 627, A158 (2019) [1904.08210]

- Error decomposition extracted from AMS-02 publications
- correlation lengths from educated guesses (e.g. 0 for statistical errors, 'infinite' for scale error) but for the data/Montecarlo calibration of the acceptance error, fitted with a single parameter

$$\mathscr{C}_{ij} = \sum_\alpha \exp\left(-\frac{\log[(R_i/R_j)]^2}{2\ell_\alpha^2}\right)\sigma^\alpha_{\text{sys},i}\sigma^\alpha_{\text{sys},j}$$

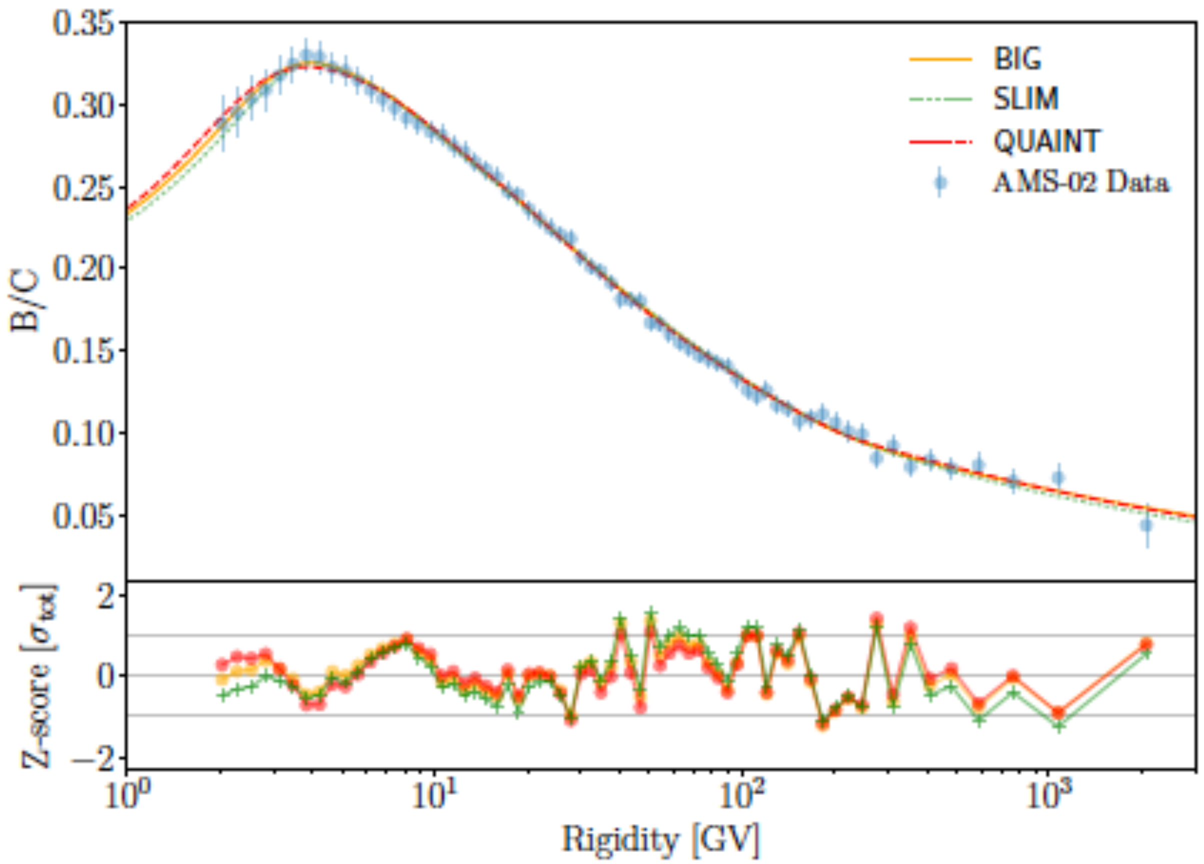


See 1904.08210 for a number of checks with mock data

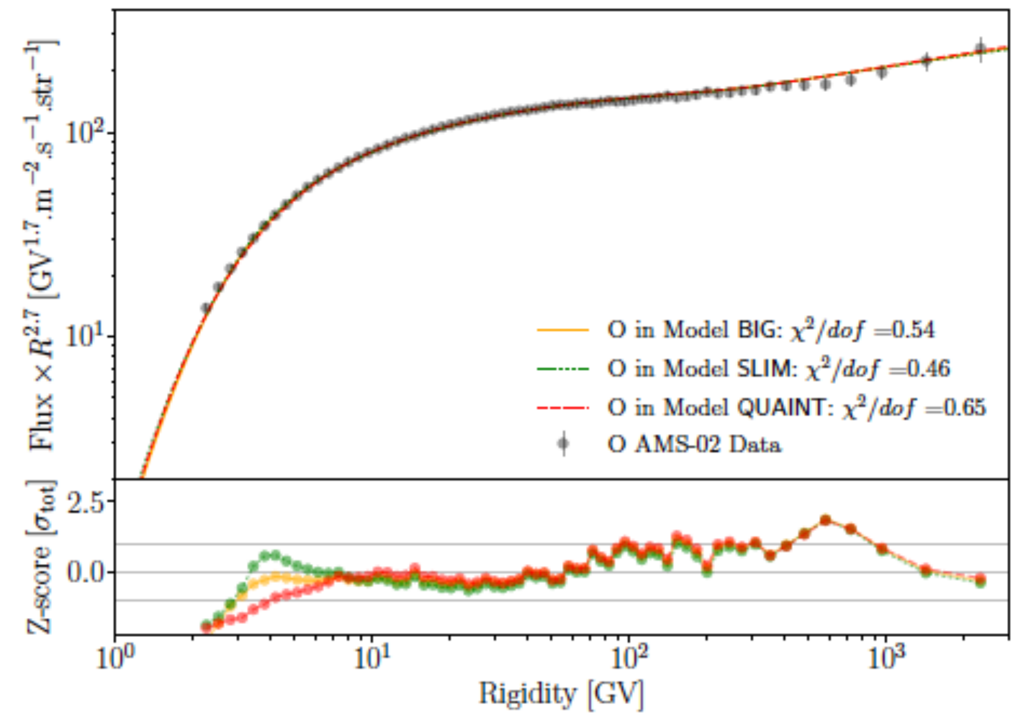
Our B/C analysis

Y. Genolini et al. "Cosmic-ray transport from AMS-02 B/C data: benchmark models and interpretation," 1904.08917

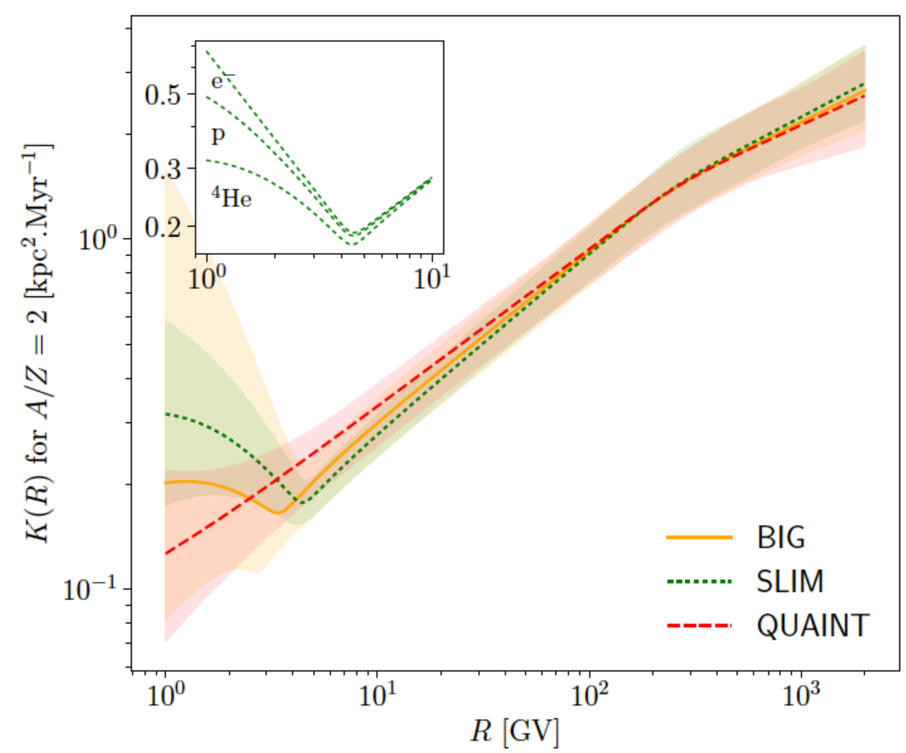
- Excellent fits obtained in different models



- Good agreement with primary fluxes with simple power-law injections



- Inferred constraints e.g. on diffusion coefficient, to be reused for the secondary antiproton flux calculation



Consequences for antiprotons

M. Boudaud et al. "AMS-02 antiprotons are consistent with a secondary astrophysical origin," arXiv:1906.07119

some ingredients to pay attention to

- Contribution of different CR nuclei and targets
- Satisfactory and detailed fits the contributing nuclei (p, He, C, O…) at R>10 GV.
- Accounting for 'non-prompt' production (essentially from anti-hyperons) and uncertainty
- Accounting for the isospin violation effect & uncertainty
- **Careful treatment and propagation of experimental and model uncertainties**

Prediction of the antiproton flux (<u>not a fit!</u>)

1. IMHO, it looks remarkably close, for being an astro prediction!

2. Yet, is there an excess?

Intermediate rigidity 'broad bump'… compatible with the one found e.g. by *Cuoco et al.*?

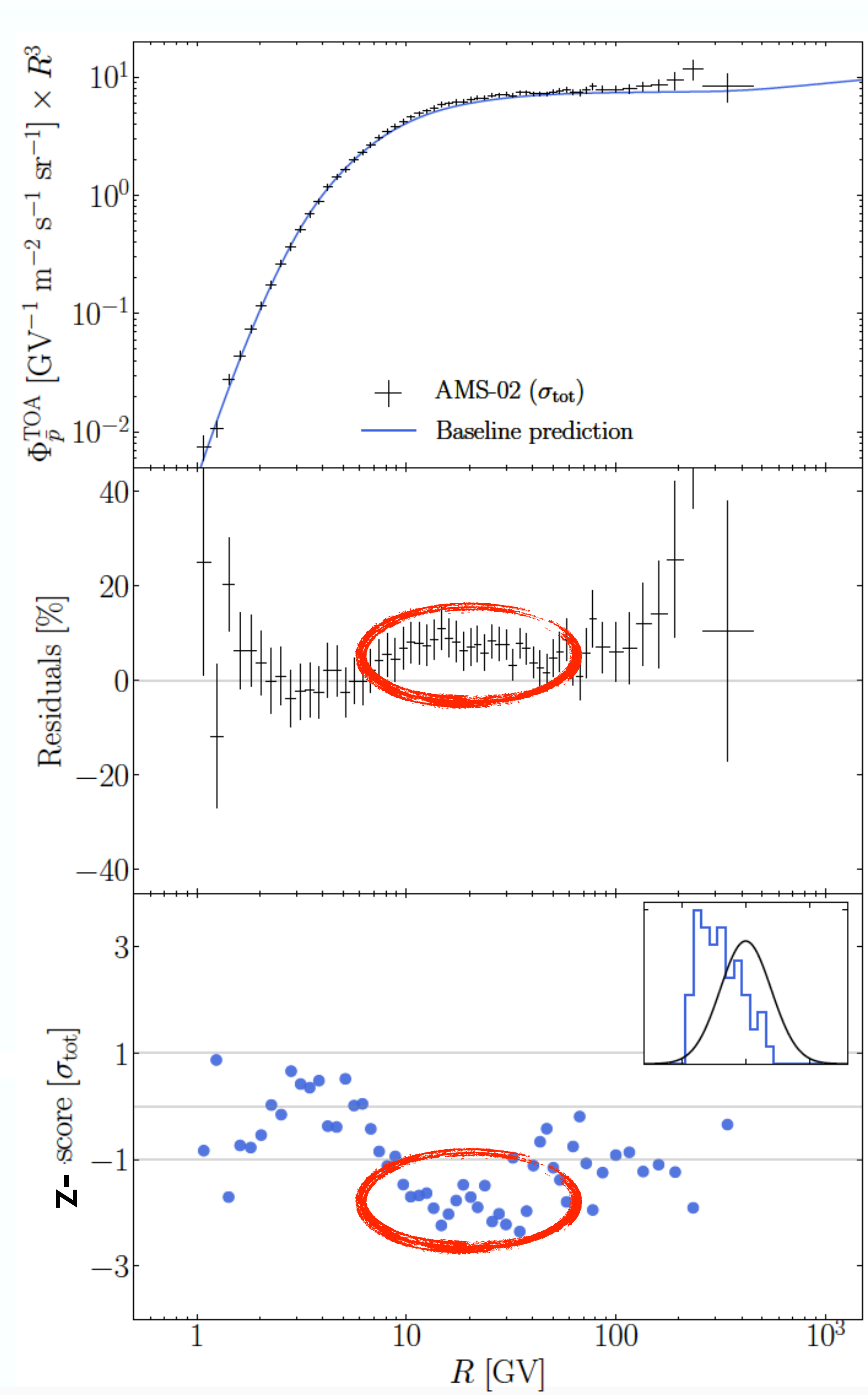
Data-model distance usually quantified via χ^2

$$x_i = \text{data}_i - \text{model}_i$$

$$\mathscr{C} = \text{covariance matrix}$$

$$\chi^2 = \sum_{ij} x_i (\mathscr{C}^{-1})_{ij} x_j$$

Visual inspection of residuals via $z_i = x_i / \sigma_i$



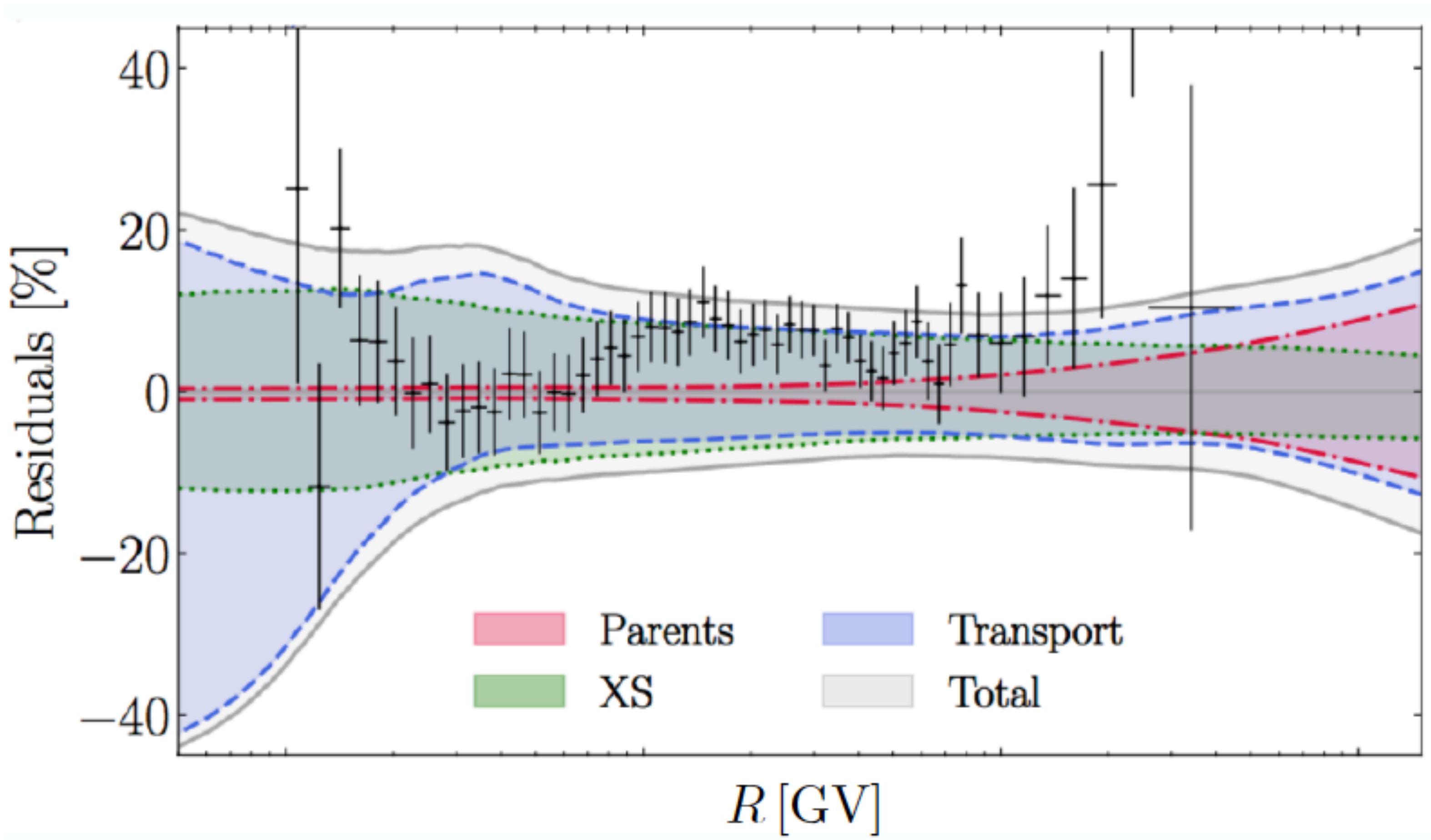
Wait!

- no model uncertainties, yet
- no account for correlated errors in AMS-02 data, in visual inspection!

Model Errors

Monte Carlo simulations to determine the errors (and correlations!) due to

- Production XS (fits to collider data)
- Transport (fit B/C)
- Parent CR fluxes



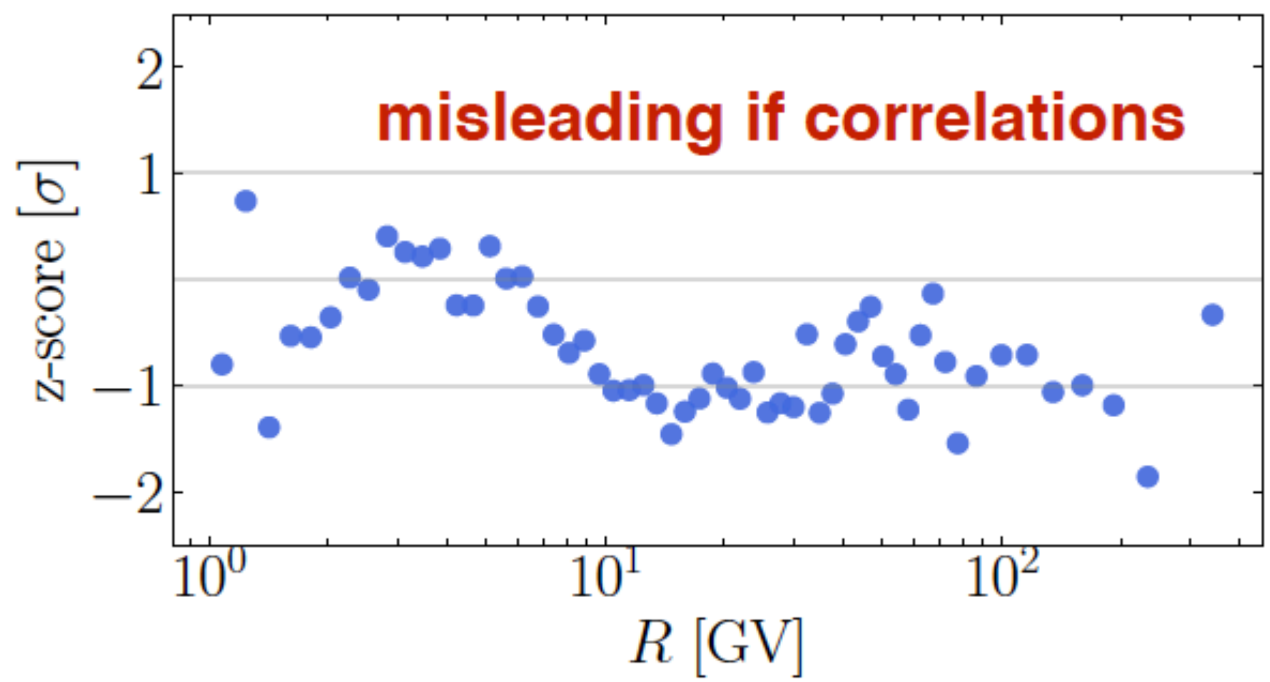
Already by eye, looks less impressive, since σ_{tot} grows, lower significance

but beware of ‘features by eye’

(notably if correlations are present!)

Visual inspection of residuals

standard z-score $z_i = x_i / \sigma_i$



What actually matters

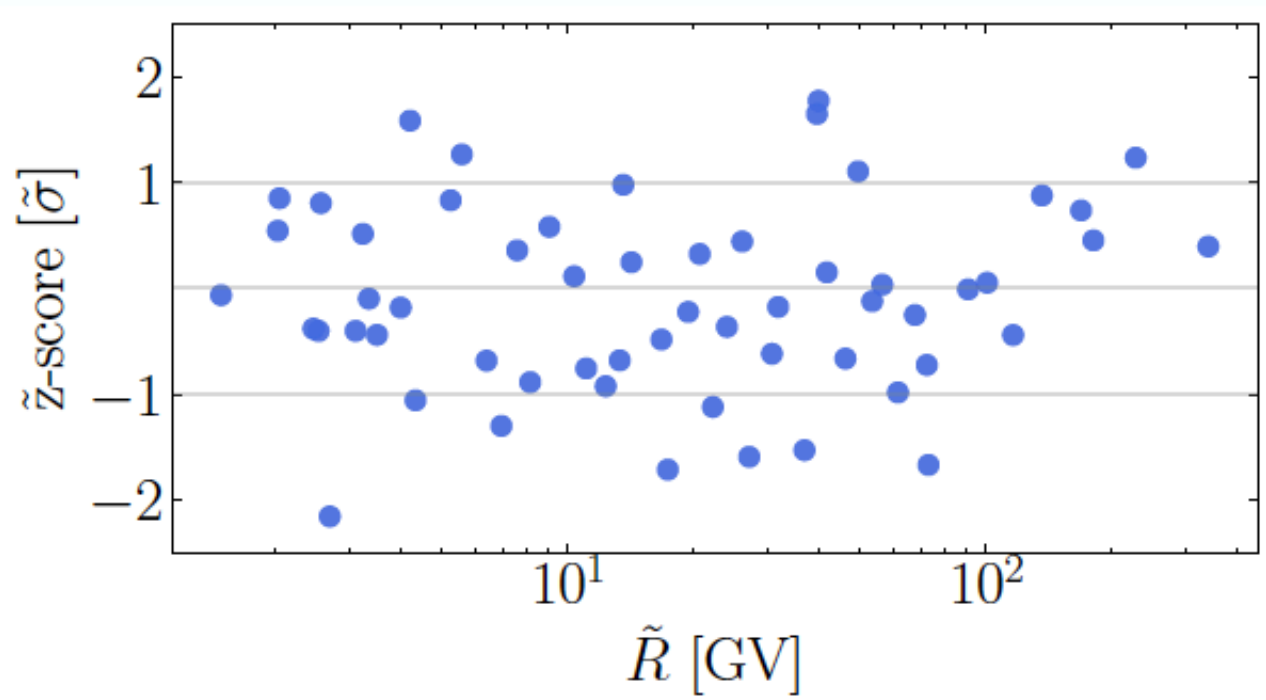
“rotated” z-score $\tilde{z}_i = \tilde{x}_i / \tilde{\sigma}_i$

where $\tilde{x}_i = U_{ij} x_j$ with U defined via

$\tilde{\mathscr{C}} = U \mathscr{C} U^T$ such that $\tilde{\mathscr{C}}$ is diagonal

with elements $\tilde{\mathscr{C}}_{ii} = \tilde{\sigma}_i^2$

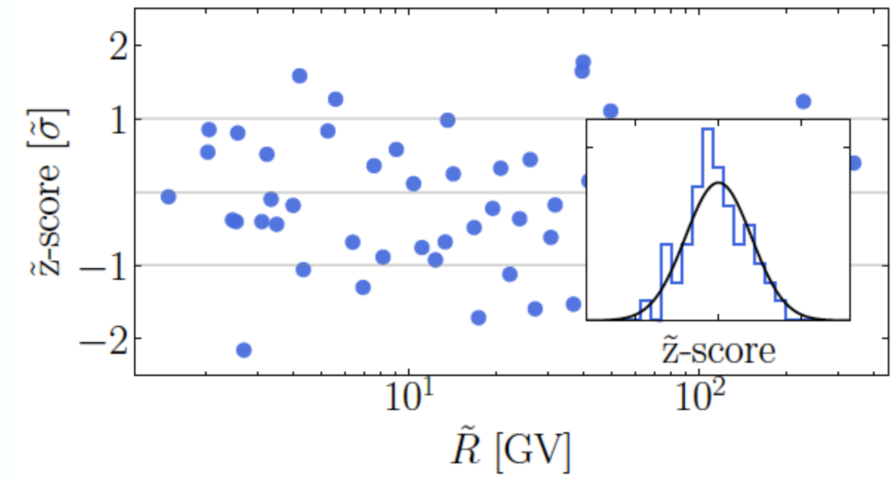
such that $\chi^2 = \sum_i \tilde{z}_i^2$



Statistical tests

χ^2 test
KS test (accounts e.g. for possible error overestimate)

w and w/o model errors



$$\chi^2 = \sum_{i,j} x_i \left(\mathcal{C}^{-1}\right)_{ij} x_j, \qquad x_i = \mathrm{data}_i - \mathrm{model}_i$$

$$\mathcal{C} = \mathcal{C}^{\mathrm{data}} + \mathcal{C}^{\mathrm{model}}$$

	Error considered	χ^2/dof	p-value (χ^2)	p-value (KS)
data uncertainties only	σ_{stat}	23	0	0
	σ_{tot}	1.69	8.3×10^{-4}	0
	$\mathcal{C}^{\mathrm{data}}$	0.84	0.79	0.98
data + model uncertainties	σ_{stat} and $\mathcal{C}^{\mathrm{model}}$	1.32	0.05	0.99
	σ_{tot} and $\mathcal{C}^{\mathrm{model}}$	0.37	1.0	0.04
	$\mathcal{C}^{\mathrm{data}}$ and $\mathcal{C}^{\mathrm{model}}$	0.77	0.90	0.27

$\left(\sigma_{\mathrm{tot}} = \sqrt{\sigma^2_{\mathrm{stat}} + \sigma^2_{\mathrm{syst}}} \right)$

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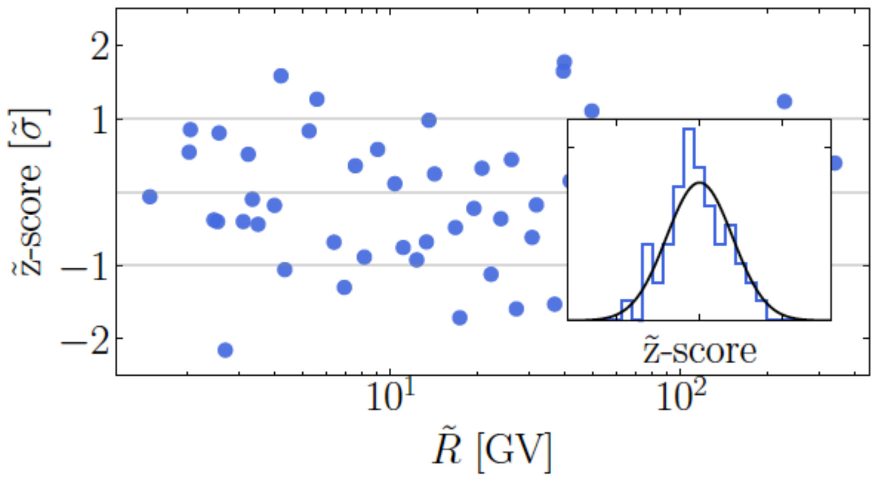

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Correlated errors in the data crucial for agreement

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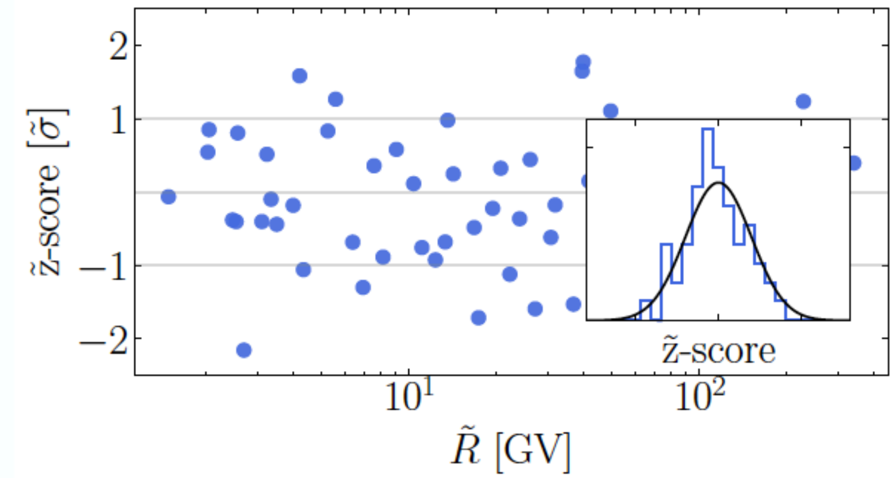

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Correlated errors in the data crucial for agreement

Exp. errors alone bring agreement within 1 sigma,
still true if most realistic treatment of model error considered

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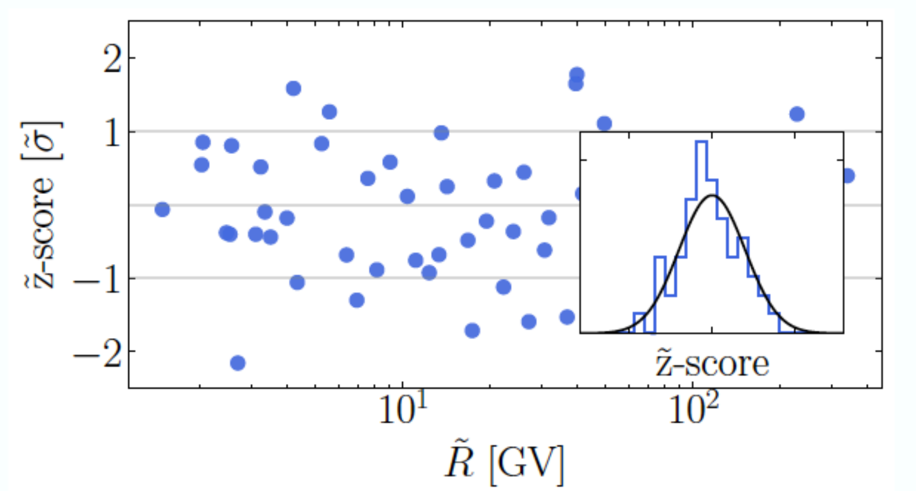

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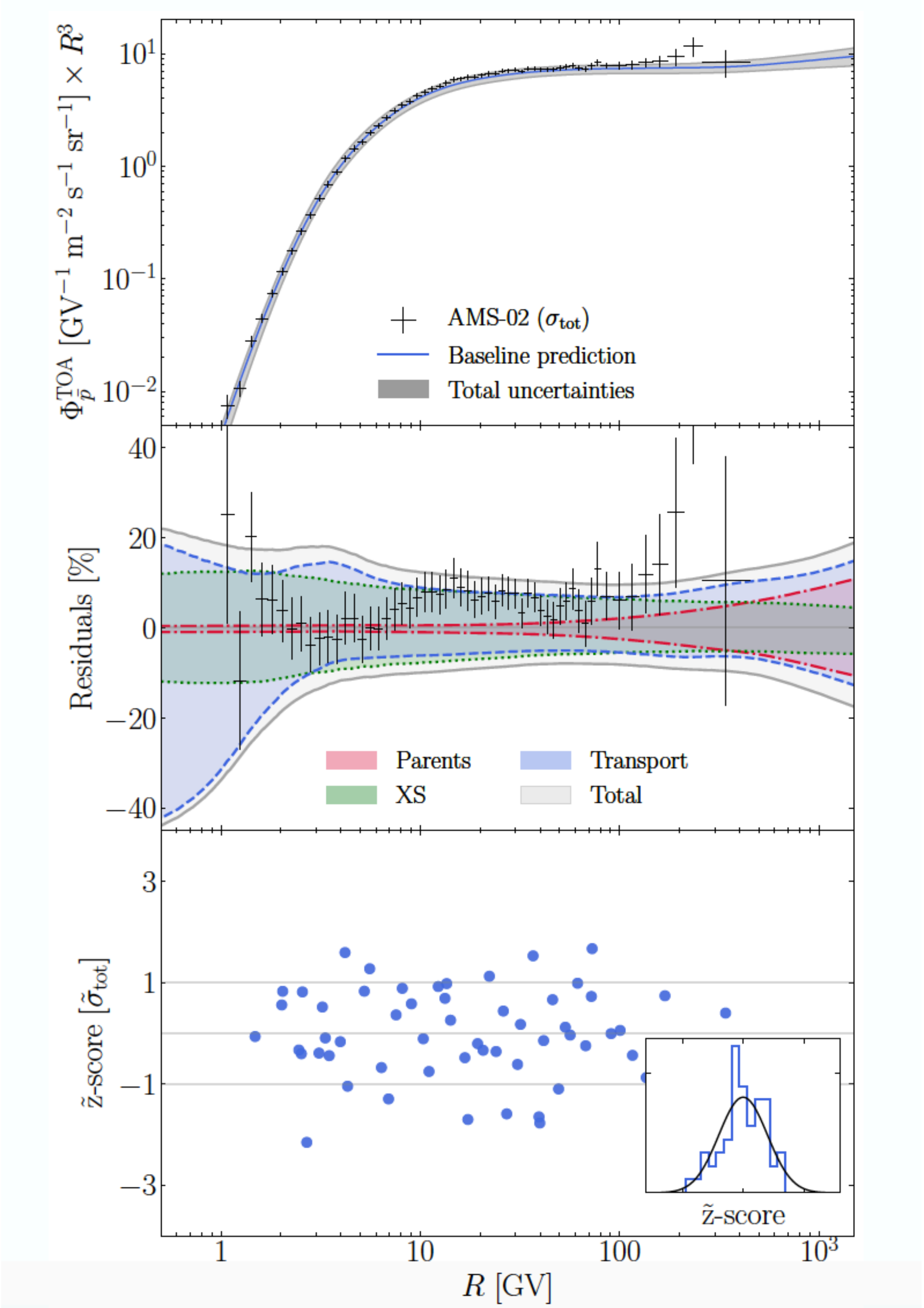
Correlated errors in the data crucial for agreement

Exp. errors alone bring agreement within 1 sigma,
still true if most realistic treatment of model error considered

using total errors in quadrature overestimate the uncertainties

Conclusion: AMS-02 data **are consistent** with a 2ary origin!



We used relatively simple propagation scenarios, and assumed no "primary" astro contribution, more realistic (hence rich) scenarios can only 'increase the dof's & broaden theory space".

Summary

The current *CR precision era* offers us new tools for DM searches (here I focused on the pbar's)

However, "Great responsibility inseparably follows from great power"

Une grande responsabilité est la suite inséparable d'un grand pouvoir

French Revolution Parliamentary Archives,
Tome 64 : Du 2 au 16 mai1793, Séance du mardi 7 mai 1793, page 287

with great power comes great responsibility

Amazing Fantasy #15 (1962)

- We argued that to analyse "features" at the level <~10 %, a number of effects must be taken into account (and some appear "irreducible errors" at the 1-2% level…)
- In particular, a bump-like antiproton excess attributable to DM seem to stem mostly from correlated errors incorrectly accounted for.

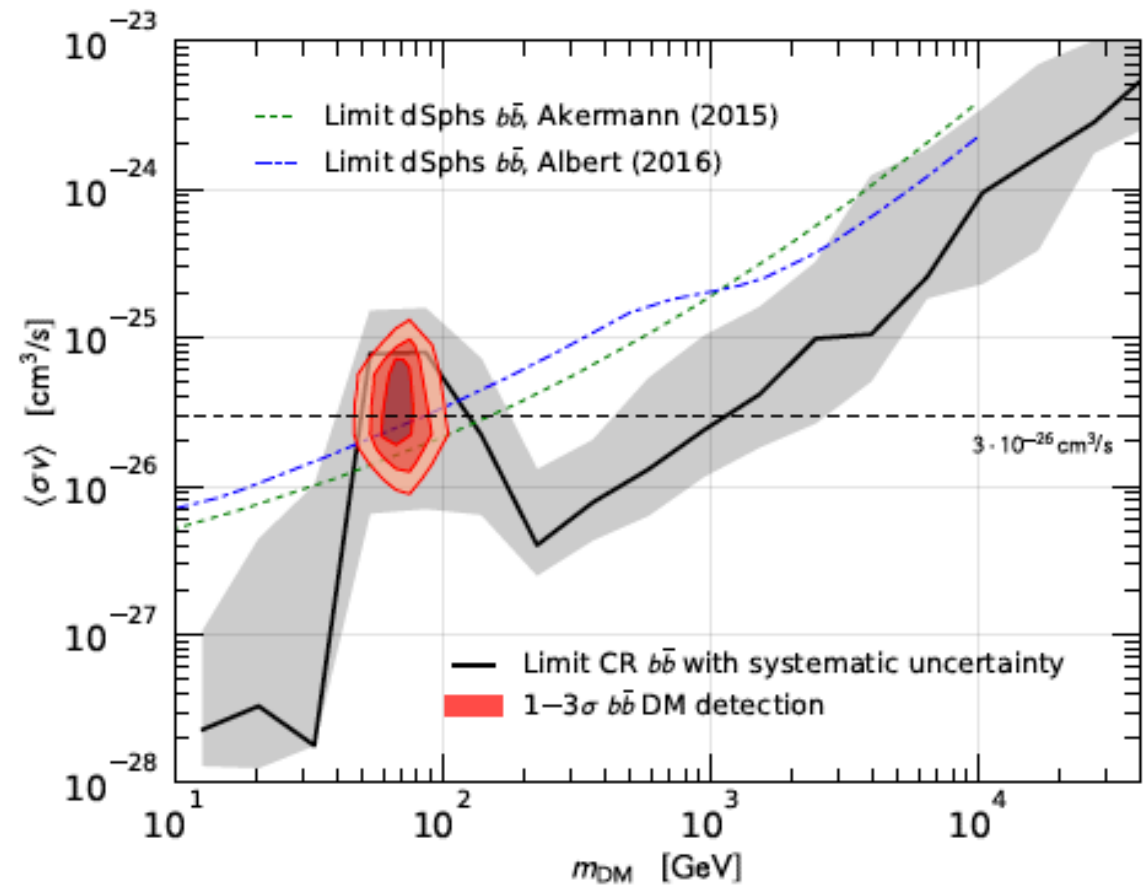
For the time being, no need for DM, but the constraints could be significant! Stay tuned…

Teaser: "naive" constraints in the literature

CR antiprotons have currently the greatest sensitivity to WIMP DM in the EW mass range

(to the extent you can trust the calculation)

A. Cuoco, M. Krämer, M. Korsmeier, "Novel dark matter constraints from antiprotons in the light of AMS-02," Phys. Rev. Letters 118, 191102 (2017) [1610.03071]



A. Reinert and M.W. Winkler, "A Precision Search for WIMPs with Charged Cosmic Rays," JCAP 1801, 055 (2018) [1712.00002]