# Messengers of the universe as (astro)physical probes

(Deep dream take on Camille Flammarion's "l'astronomie populaire")

Pasquale Dario Serpico (Annecy)

Remise du Prix Friedel-Volterra 2022
26ème Congrès Général de la SFP - 04/07/2023

# Thanks to all my collaborators in the two countries!

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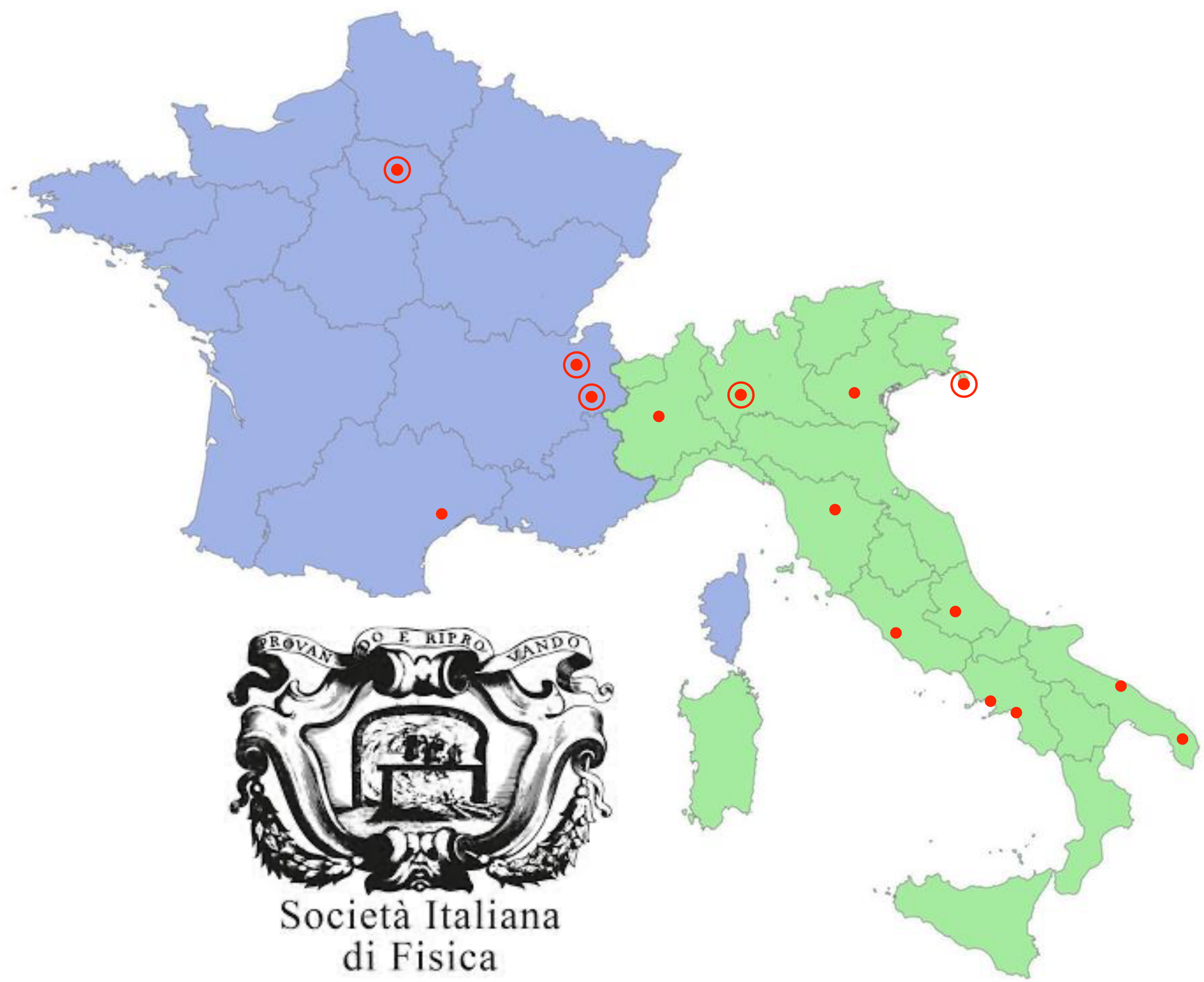
Société Française de Physique



Società Italiana di Fisica

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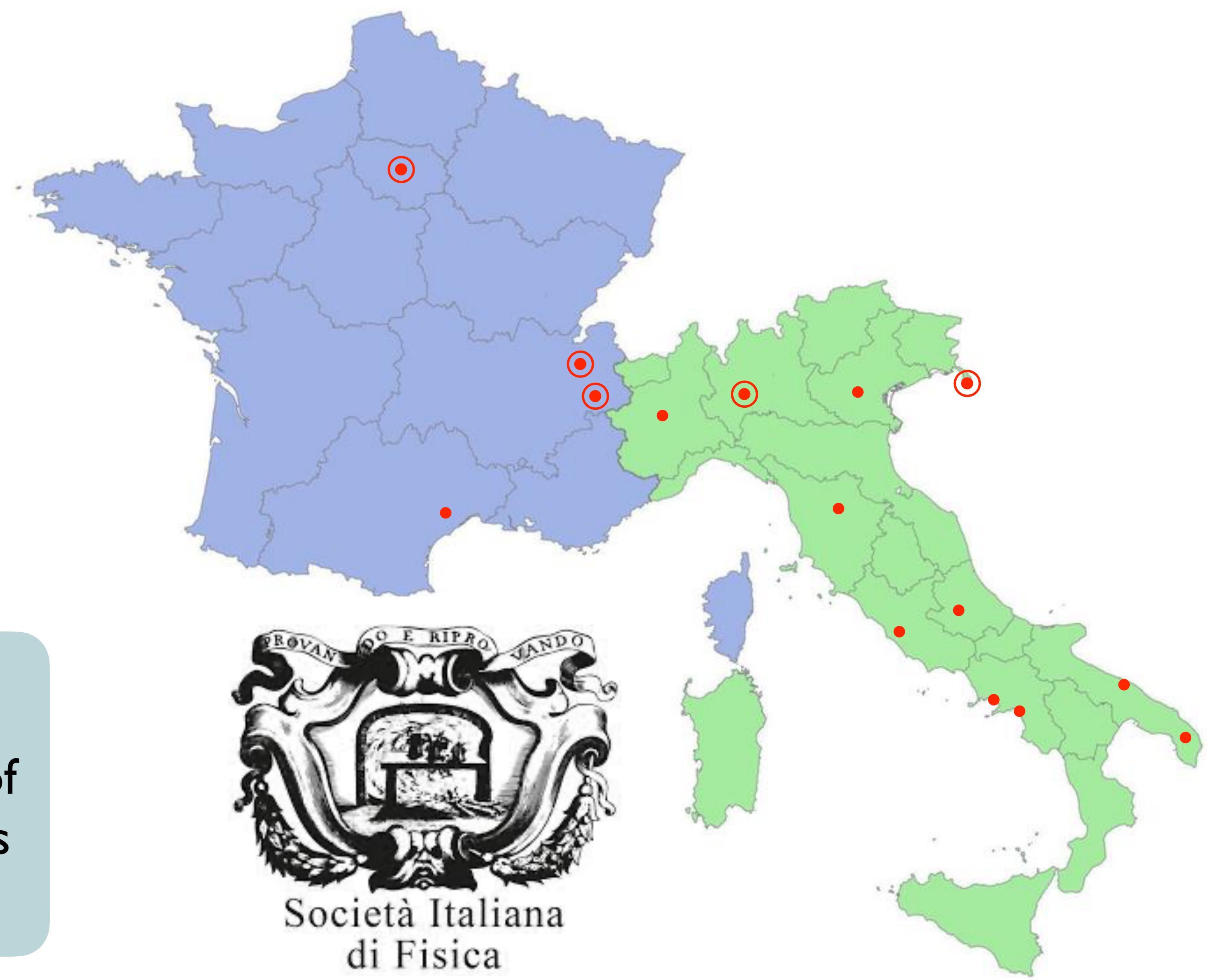

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**GOAL HERE**

glimpse of the revolution in the field of cosmic rays over the last ~15 years its new challenges and opportunities

# A long story of cosmic rays & fundamental physics

**~1932-53**

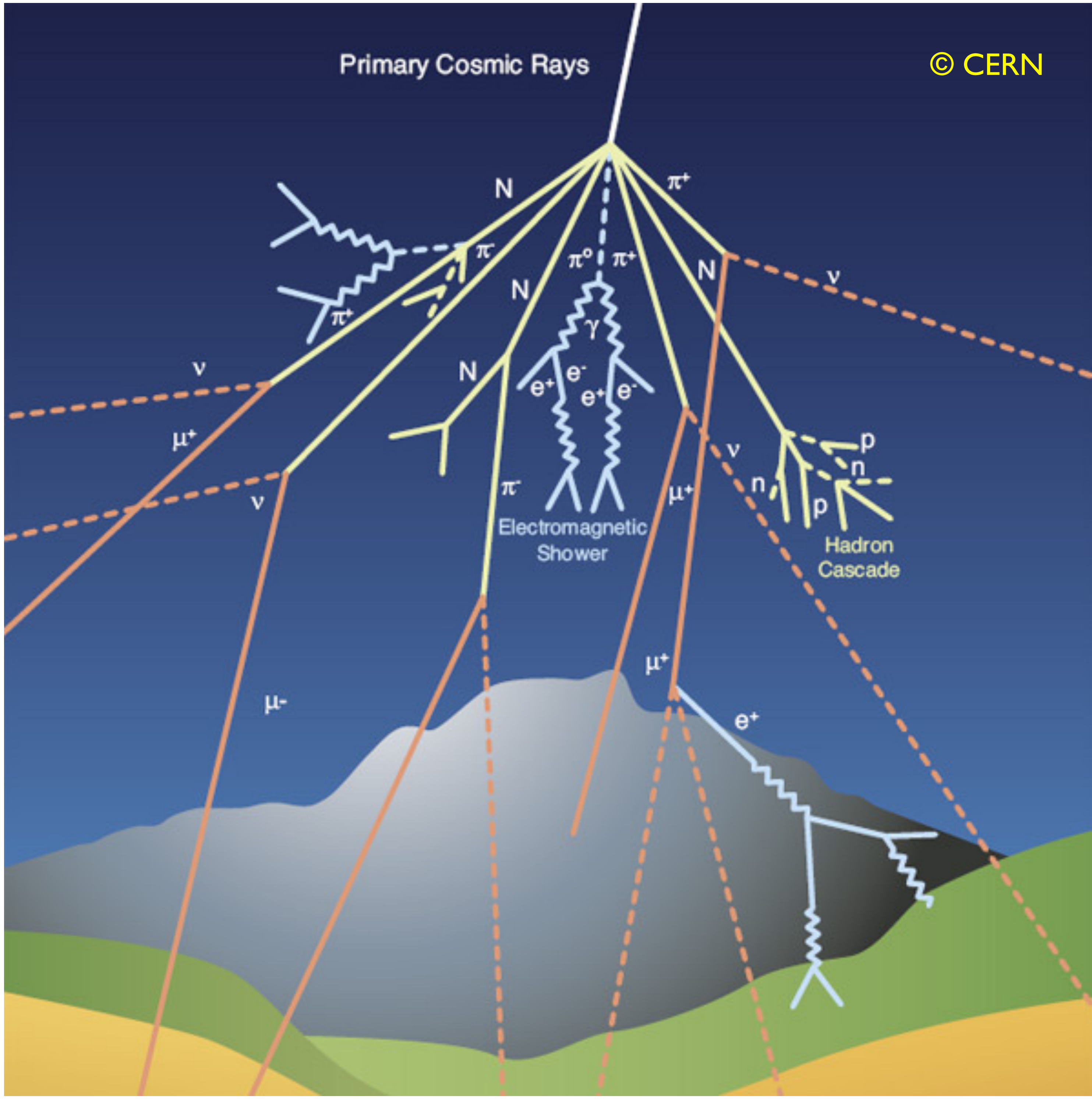
**“Particle zoo” among <u>secondary</u> particles**

$e^+$, $\mu$, $\pi$, strange particles (K, Λ, Ξ, Σ)…

Conversi-Pancini-Piccioni    Leprince-Ringuet

*Many pioneering French & Italian researchers!*

Tradition rejuvenated with the discovery of atmospheric $\nu$ oscillations ~30 yrs ago



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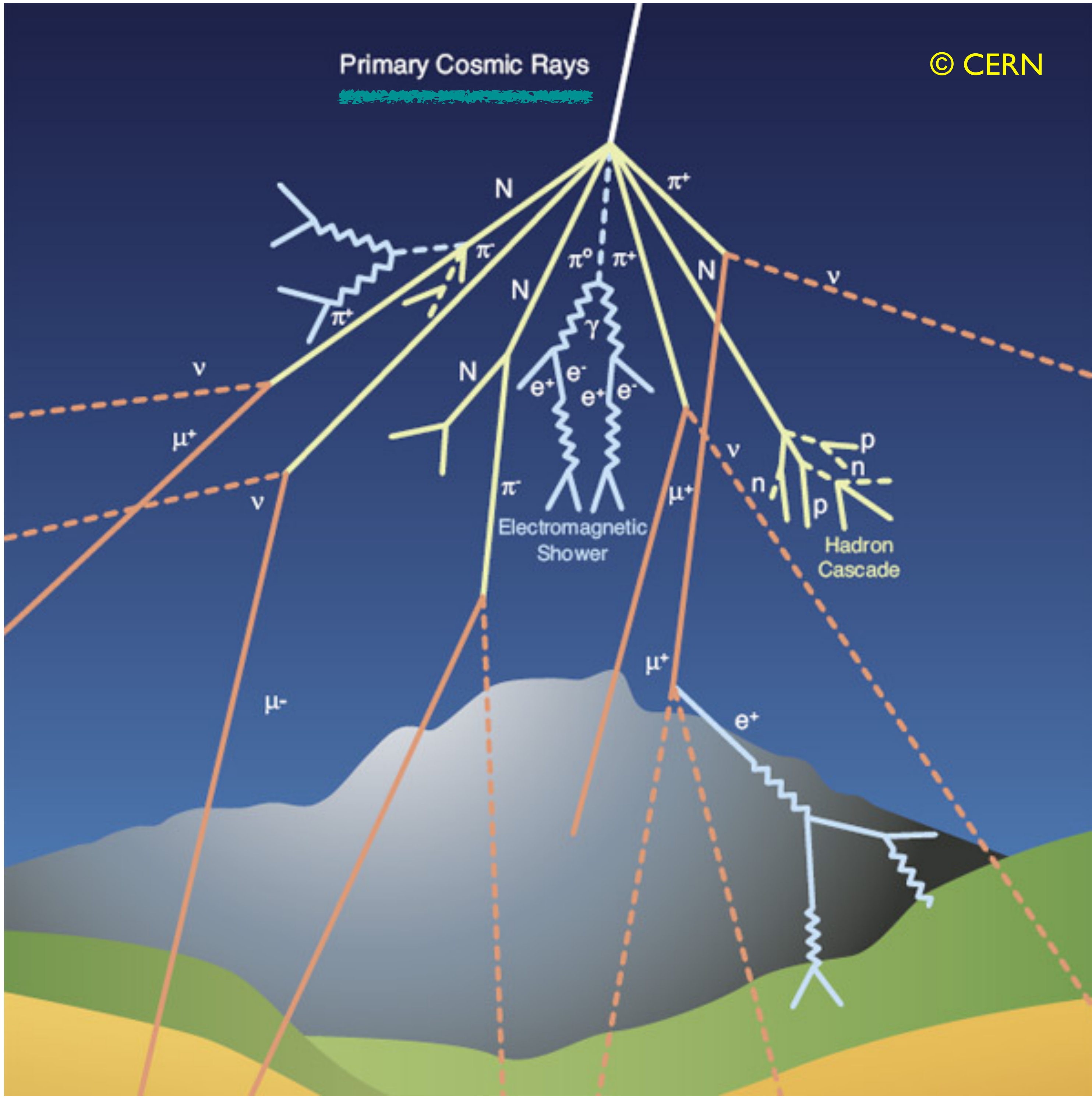
What about primaries?

**(The detail of) their origin still not completely elucidated**

**Can they be used as (astro)physical probes?**

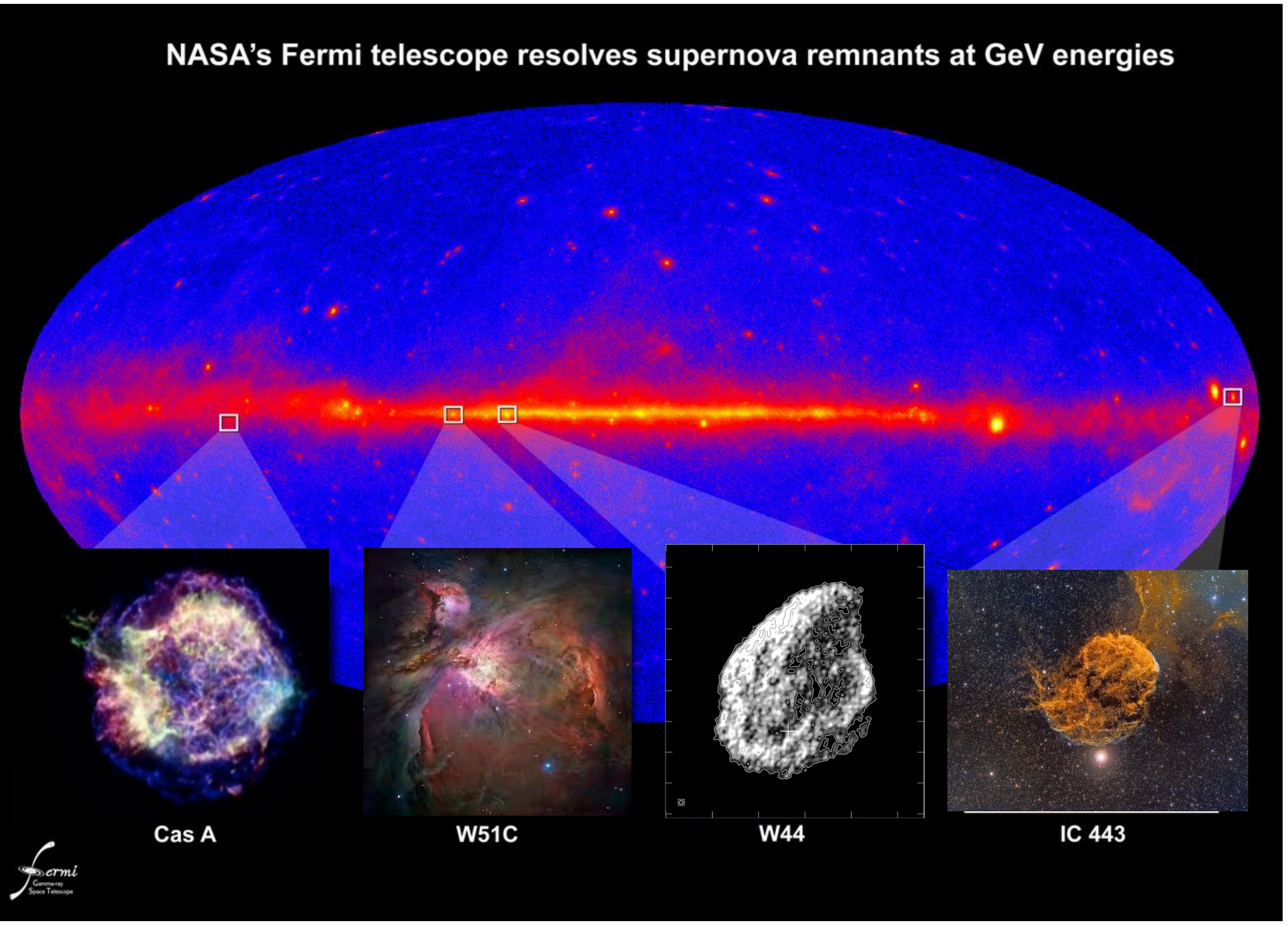


# Two directions for progress

## Indirect understanding

neutrals ($\gamma$,$\nu$) via primary *E*-losses (sources, propagation)

Birth of $\nu$ astronomy; Development of IACTs, Fermi-LAT…




- Basic confirmation of Baade & Zwicky 's 1934 idea of supernovae as CR accelerators
- Driving progress e.g. on acceleration theory (notably non-linear effects), major advances wrt first theory by Fermi in 1949

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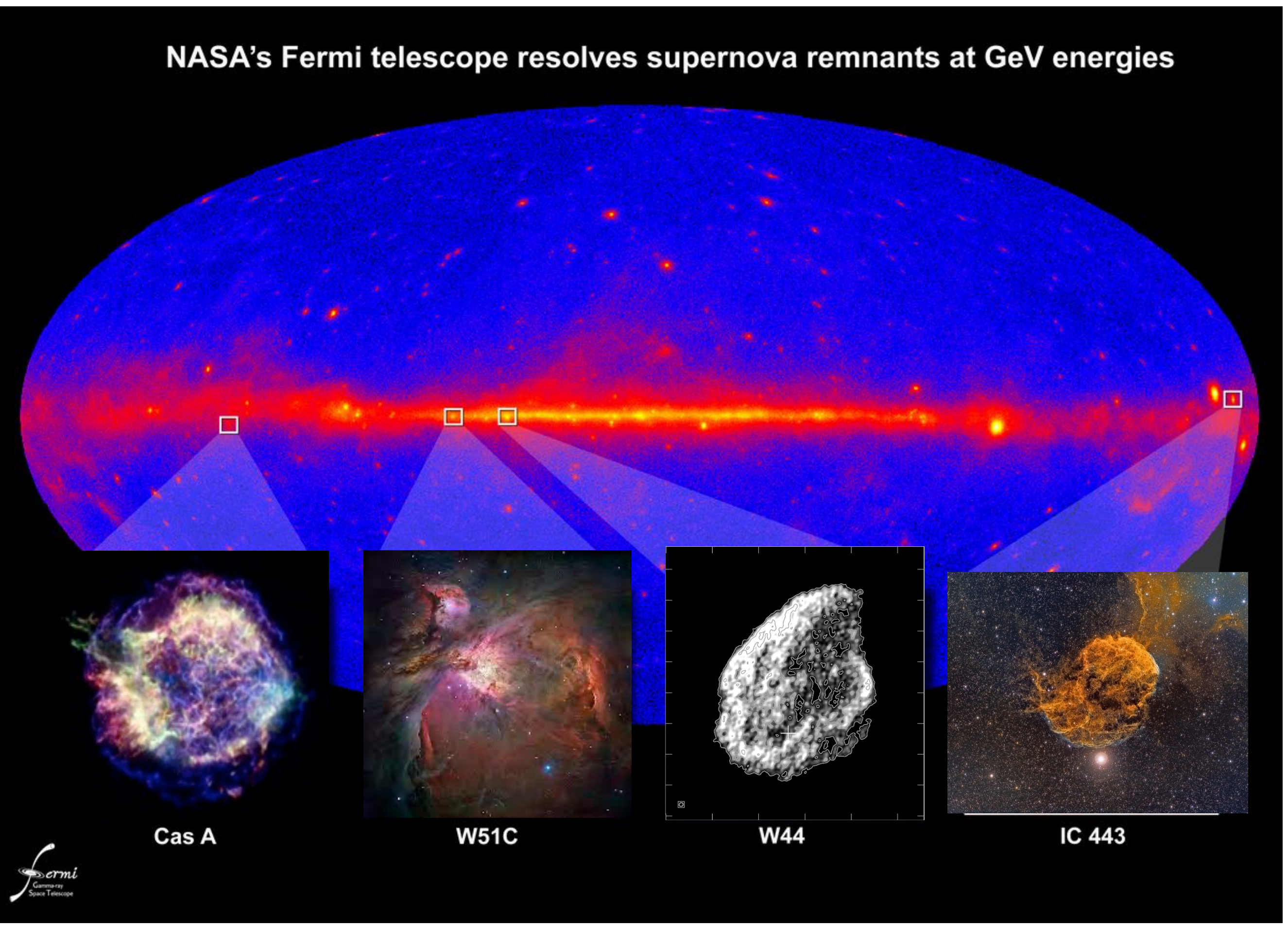


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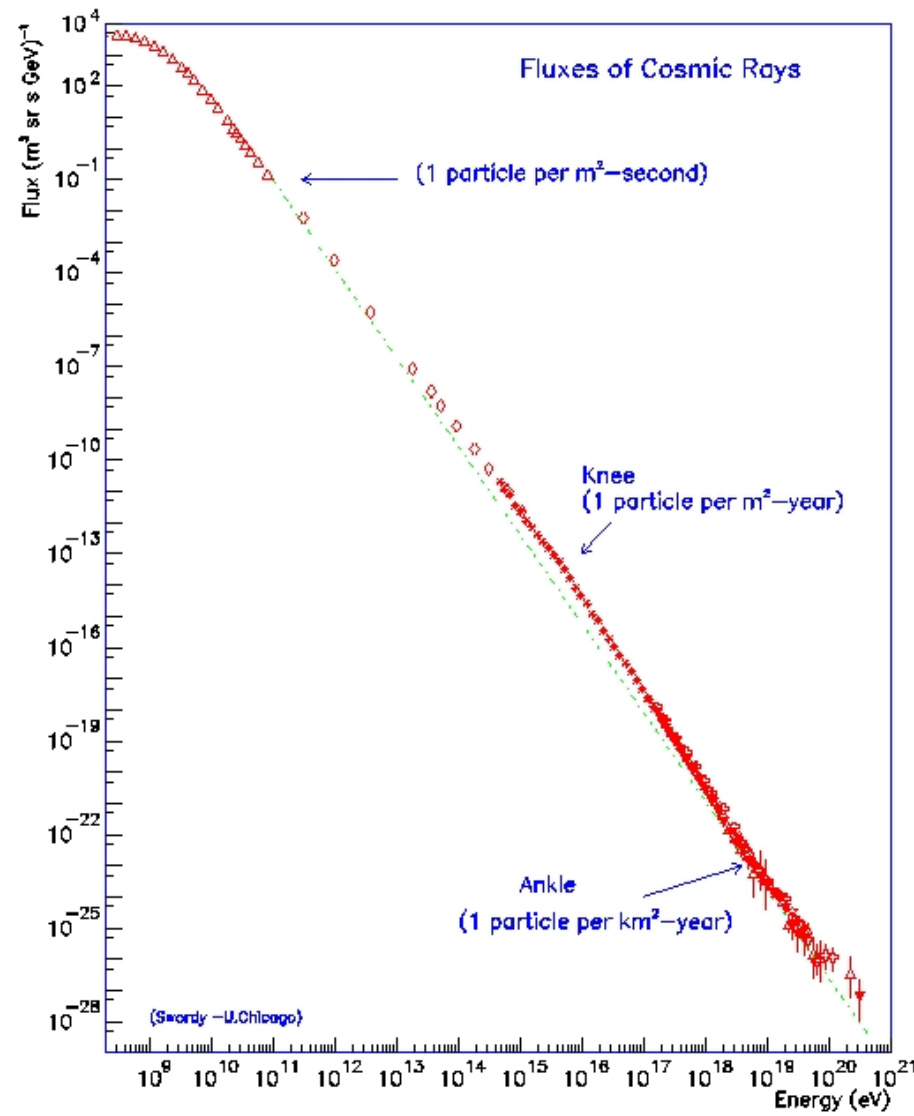
## Direct understanding

For decades, slow progress:
Isotropization in interstellar B-fields
~featureless spectrum
some chemical info



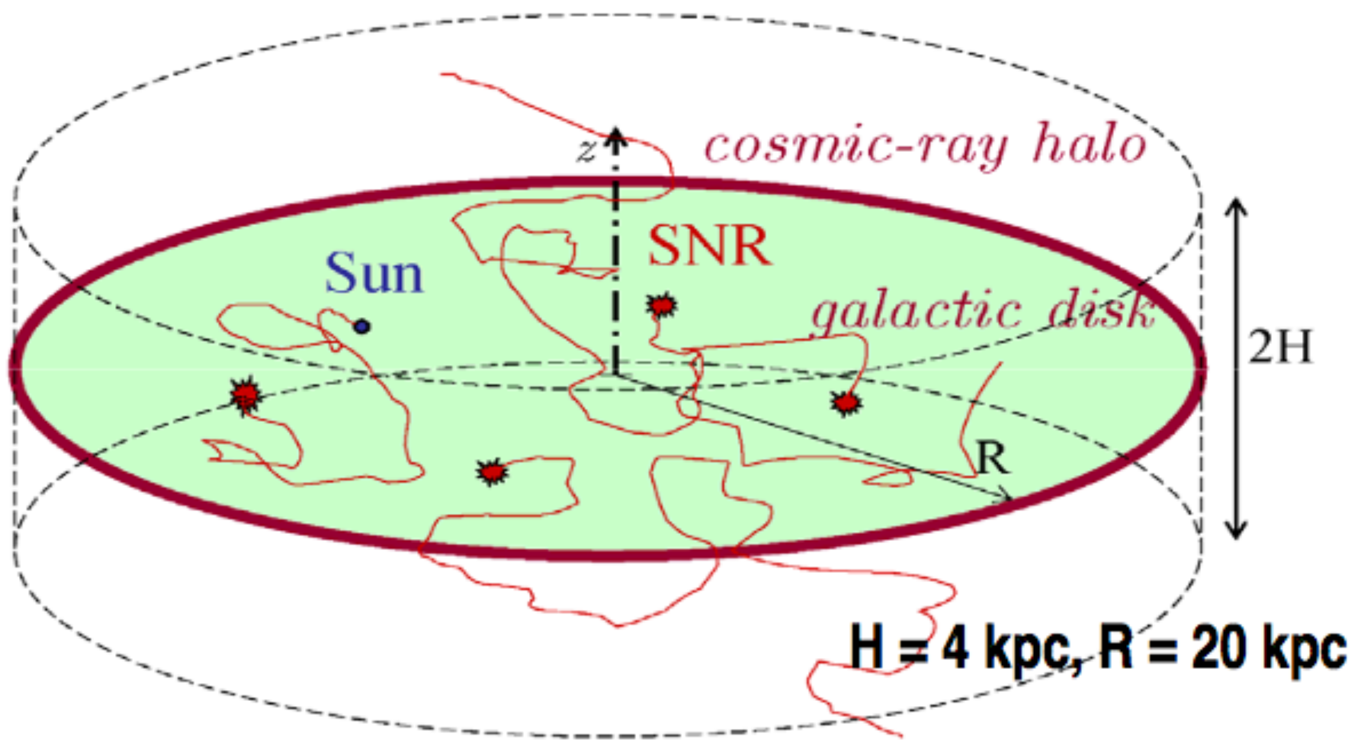

Example of Mar's Law?
*"Everything is linear if plotted on a log-log scale with a fat magic marker."*

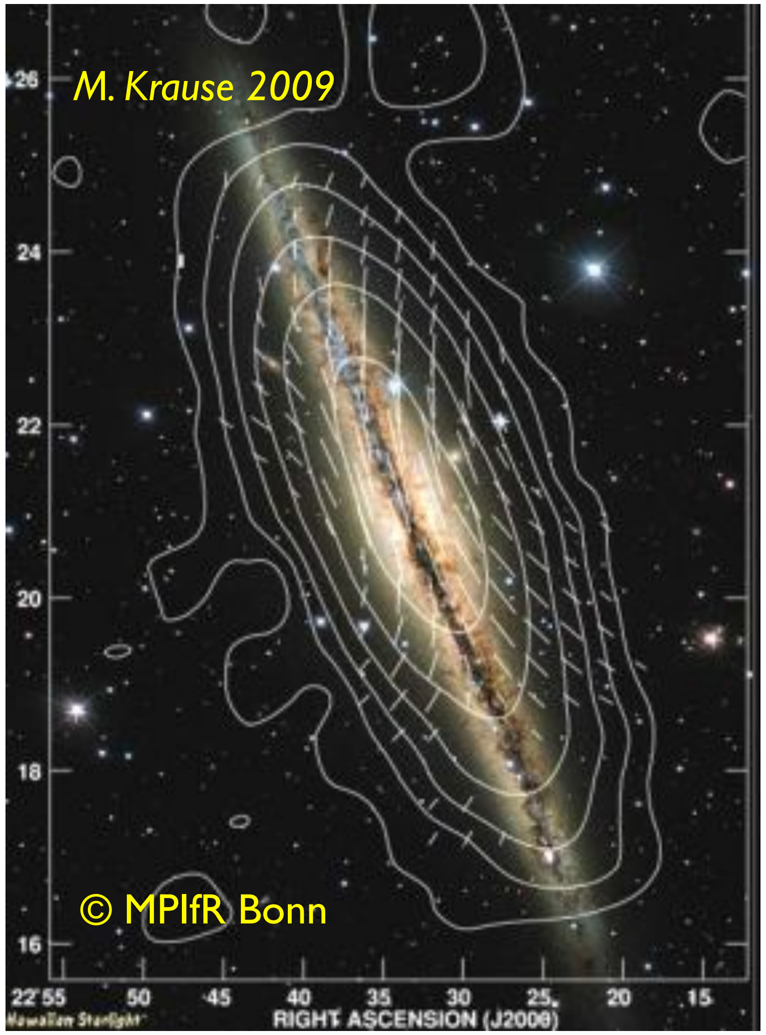
# Context: Sketch of the "CR standard model"

**Key hypothesis**

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

Simplified geometry inspired by actual galactic magnetic halos




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

Sources typically reduced to a(n inhomogeneous) "jelly" over volume of **continuously injected** particles with power-law spectra

Propagation into a diffusive/convective region threaded by **externally assigned** turbulent B-fields, with low 'target' density

# A symbolic look at the master equations

Linear (***x*** & *t*-dependent) “Fokker-Planck like” PDEs (coupled) for fluxes $\mathbf{\Phi}$ of species *i*

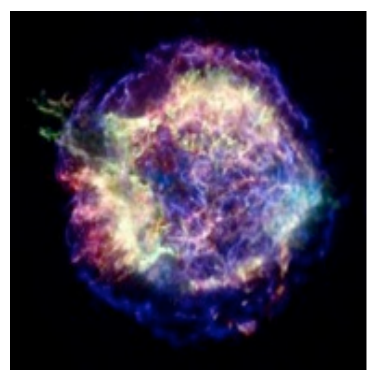
often seeking steady state solution

$$\left(P + L^{(i)}\right)\Phi_i = Q_i + A_{ij}\Phi_j$$

**Spatial + *p* diffusion+ advection… operators**

**species-specific losses**

*e.g. ionisation*

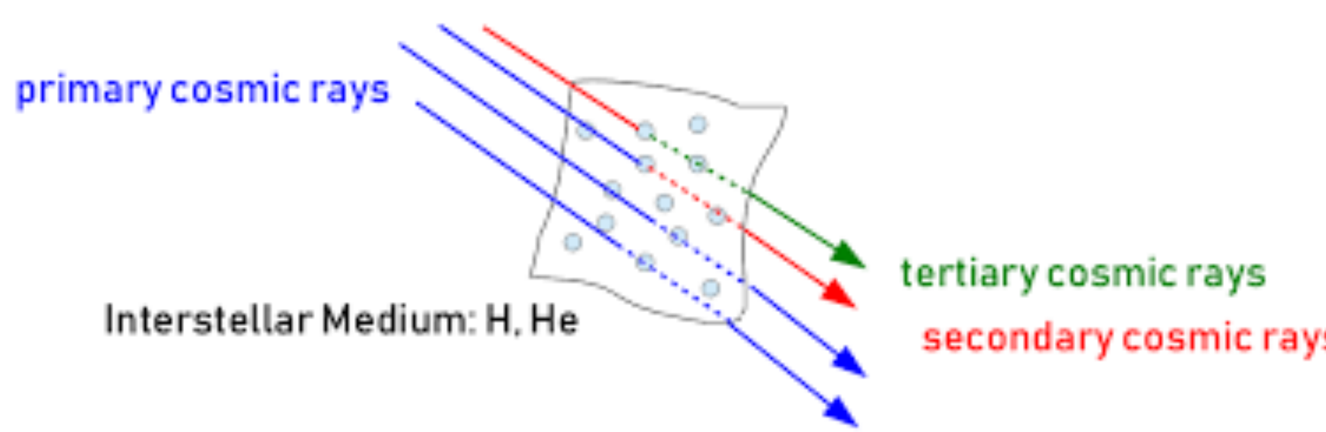


**Primary sources**

*acceleration e.g. at SNRs*

**Secondary sources**

*Byproducts of collisions in the ISM*




Solved numerically (GALPROP, DRAGON…) or semi-analytically (USINE…)

Agreement obtained, but data not very precise. Rough modelling enough!

# “ The Times They Are a-Changin' ”

Bonanza of new measurements:
AMS-02, ATIC, CALET, CREAM, DAMPE, PAMELA…


Increased precision, extended dynamical range
→**Features in *E* and chemical species**!

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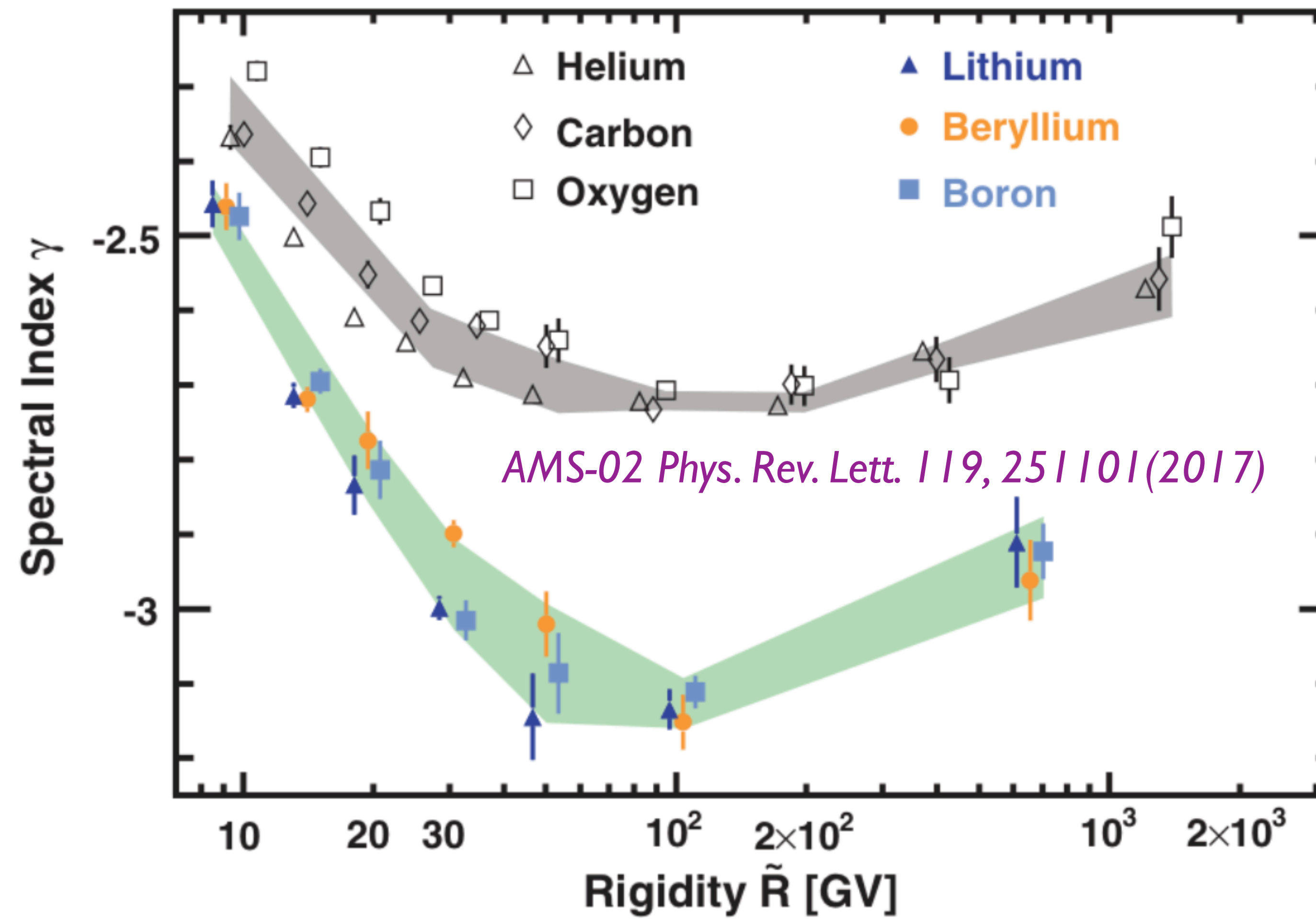
**One example:**
Spectral hardening ‘universal by groups’
Fragile, ‘secondary’ nuclei, steeper but ‘harden more’




Properties consistent with diffusive origin of these features. *Phys. Rev. Lett. 119 (2017), 241101 [w CRAC collab.]*

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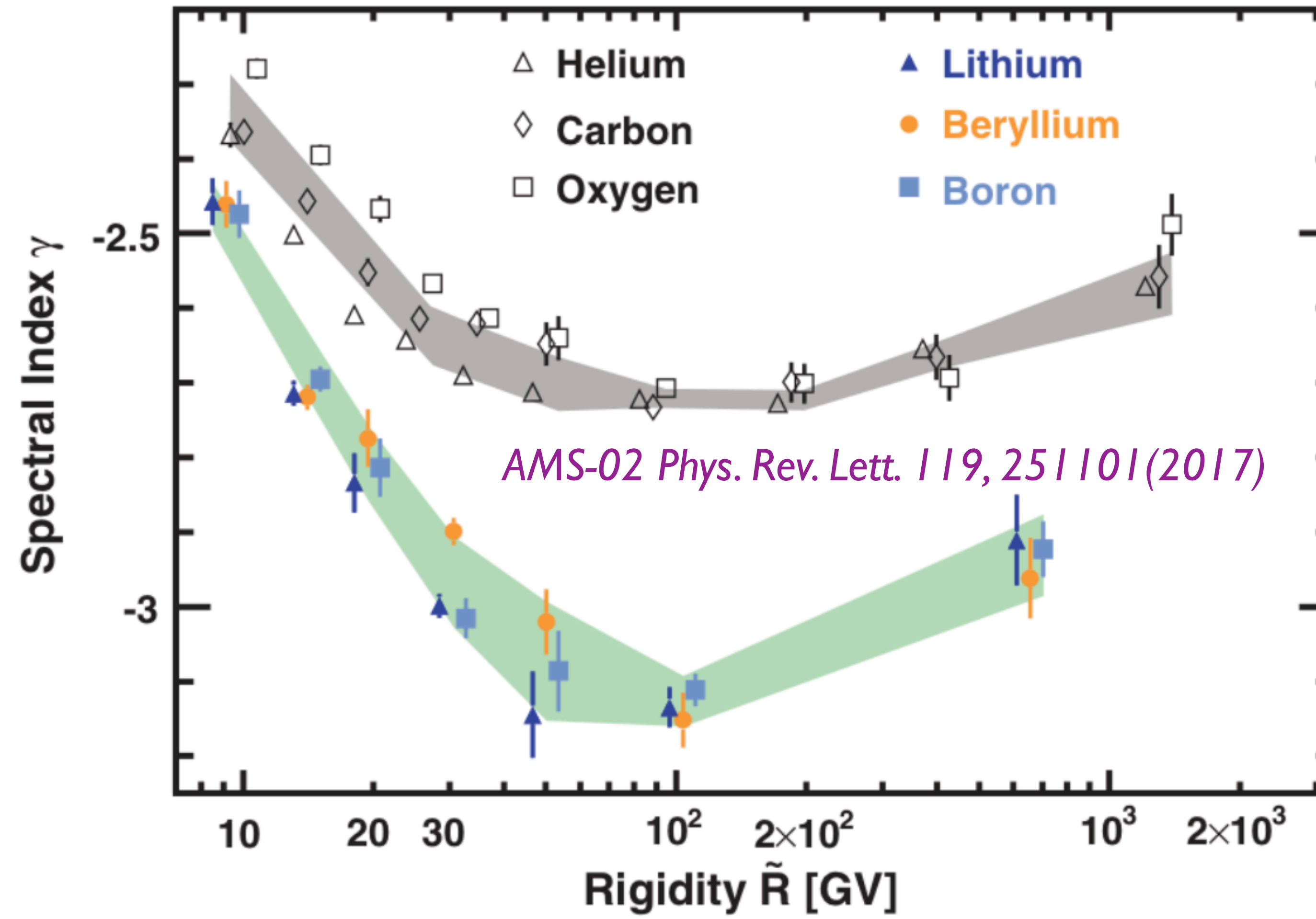


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Possible fascinating hypothesis for its physical origin:

**Non-linear effects, coupling CRs - magnetic turbulence:**

CR below the break diffuse on waves generated by CRs themselves, above the break onto external turbulence (SNR stirred one)

*Phys. Rev. Lett. 109, 061101 (2012), with collaborators in Florence*

# Tight test of 'secondary' origin of antiprotons

**Standard lore**

Anti-p above the atmosphere due to CR occasionally interacting in the rarefied interstellar medium

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

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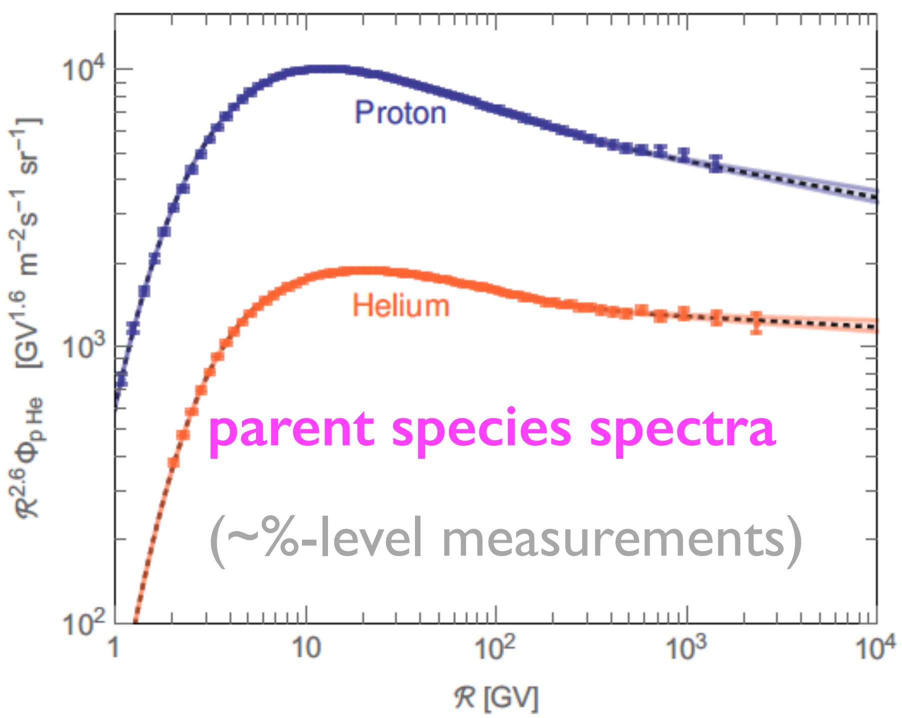


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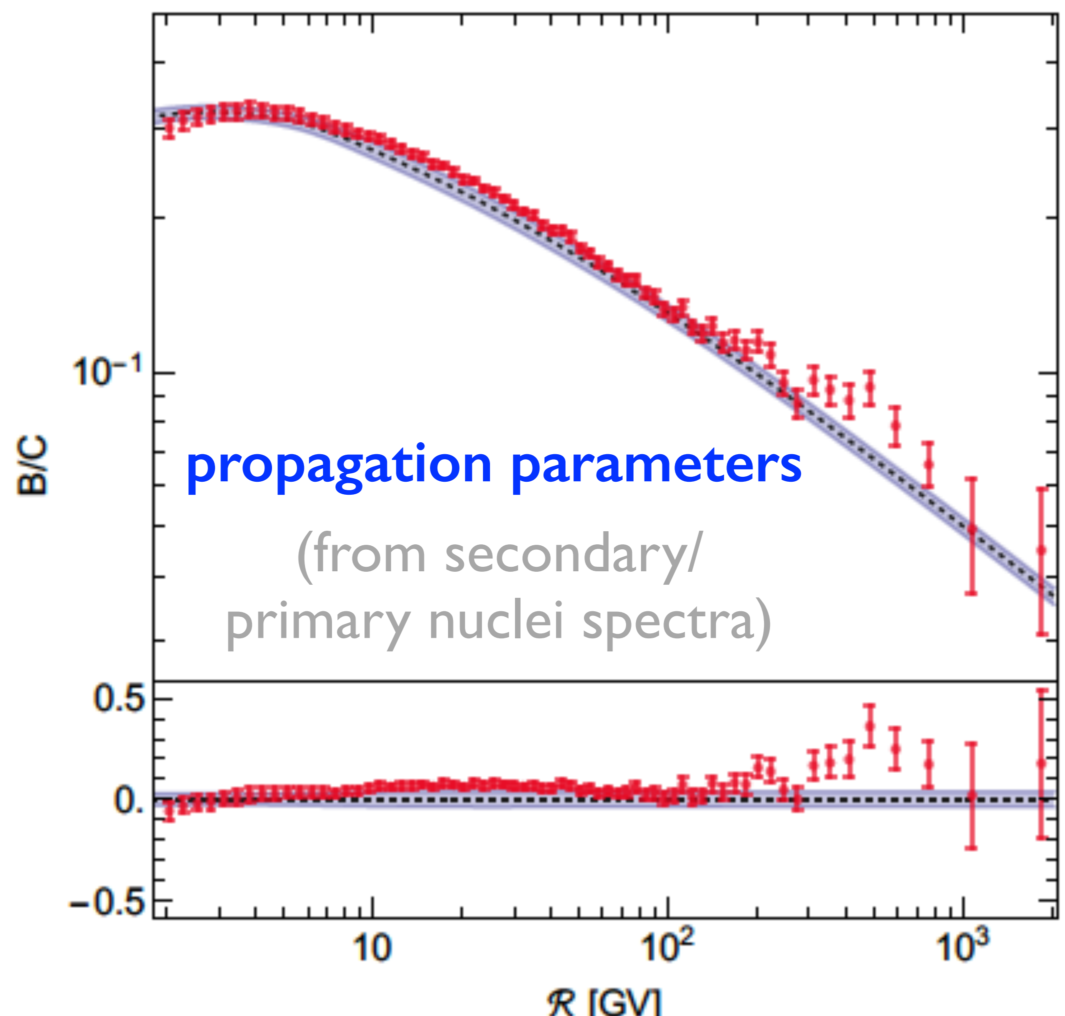


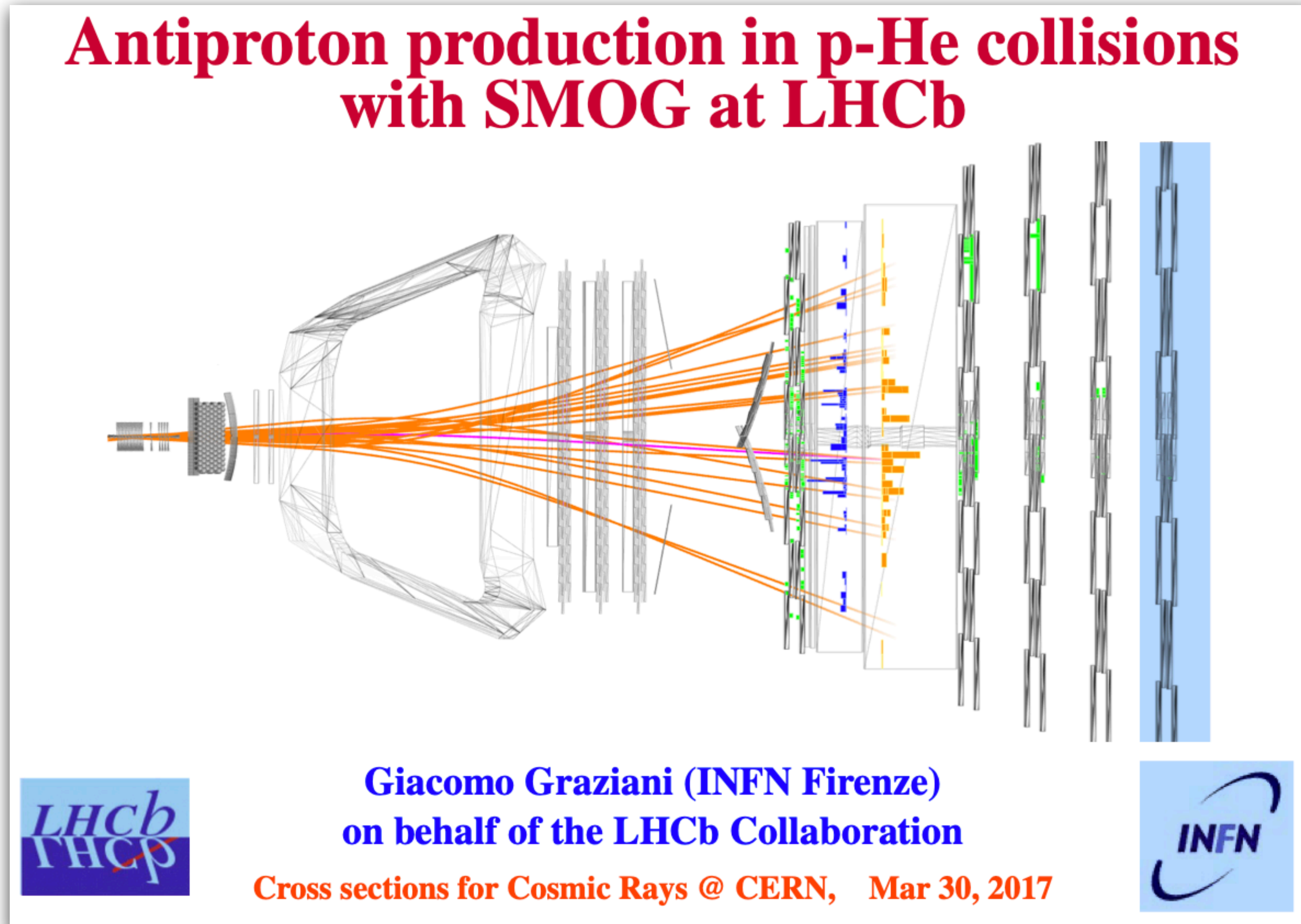

+ cross-sections

**predict secondary antiproton CR flux**

# A parenthesis

**Renewed interest in understanding, fitting, and measurement of relevant cross sections!**

History of theorist-experimentalist workshops @ CERN led by people in Grenoble, Turin & Annecy



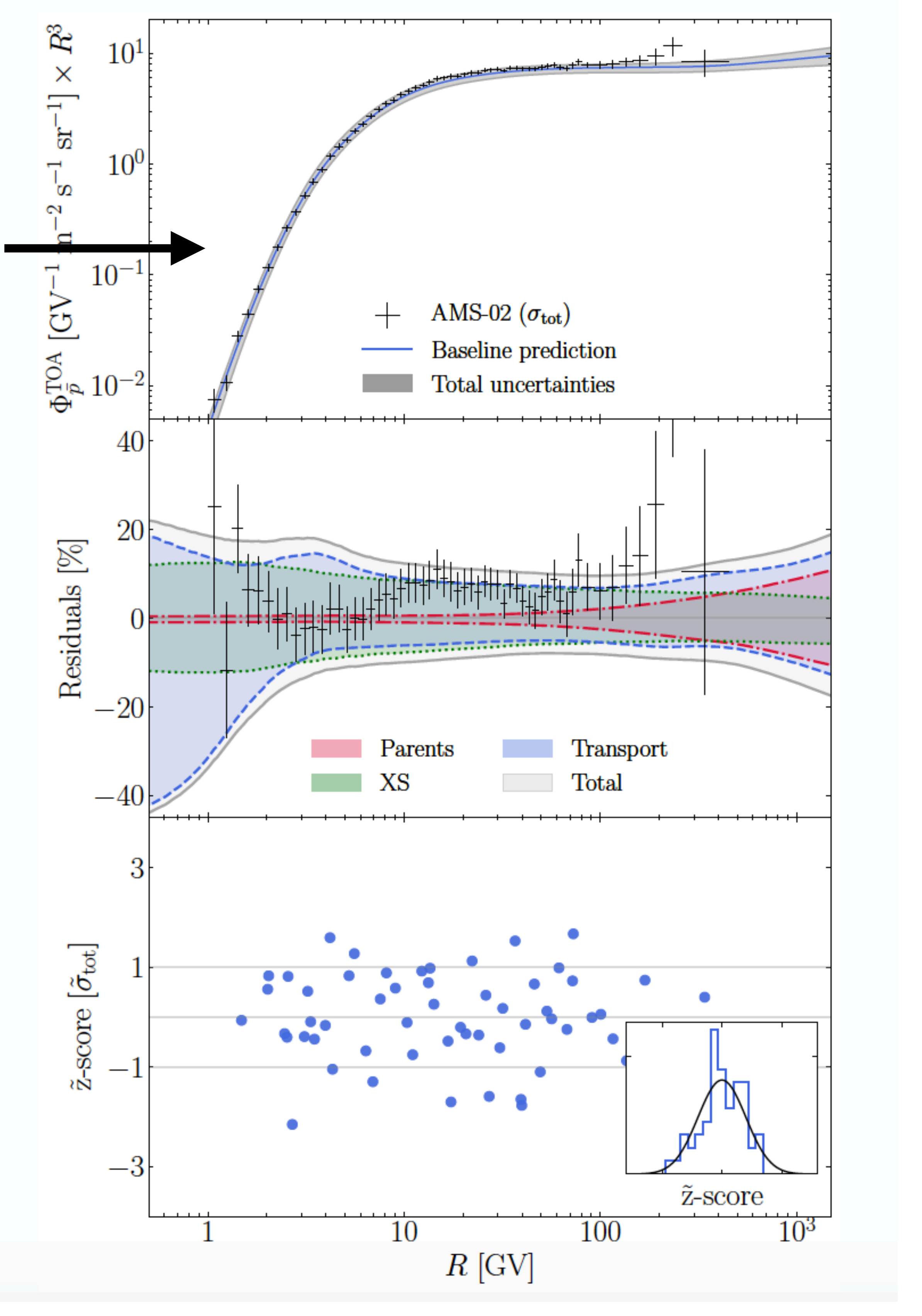

As far as I am concerned, initiated in a Annecy-Turin collaboration (with co-supervised PhD)
*1408.0288, PRD, with M. di Mauro, F. Donato, A. Goudelis*

Nowadays, even greater 'sophistication' accounting for production from heavy nuclei, 'non-prompt' production (essentially anti-hyperons), isospin violation effect & uncertainties…

# Prediction of the secondary antiproton flux (not a fit!)

M. Boudaud et al. Phys. Rev. Research 2, 023022 (2020) [1906.07119]

*How often do you see that in astrophysics?*




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

- Production cross-sections
- Transport
- Parent CR fluxes

Residuals which actually matter

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

in terms of "decorrelated" dof's

**AMS-02 pbar data consistent with secondary origin!**

# Can constrain exotic sources

Solve master equation now including extra source e.g. from dark matter annihilation

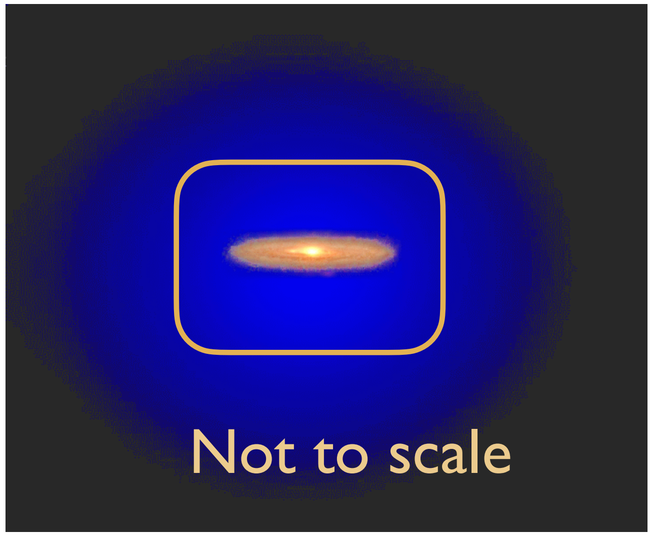
$$Q_{\rm tot}(E,\mathbf{x}) = Q_{\rm astro}(E,\mathbf{x}) + Q_{\rm DM}(E,\mathbf{x})$$

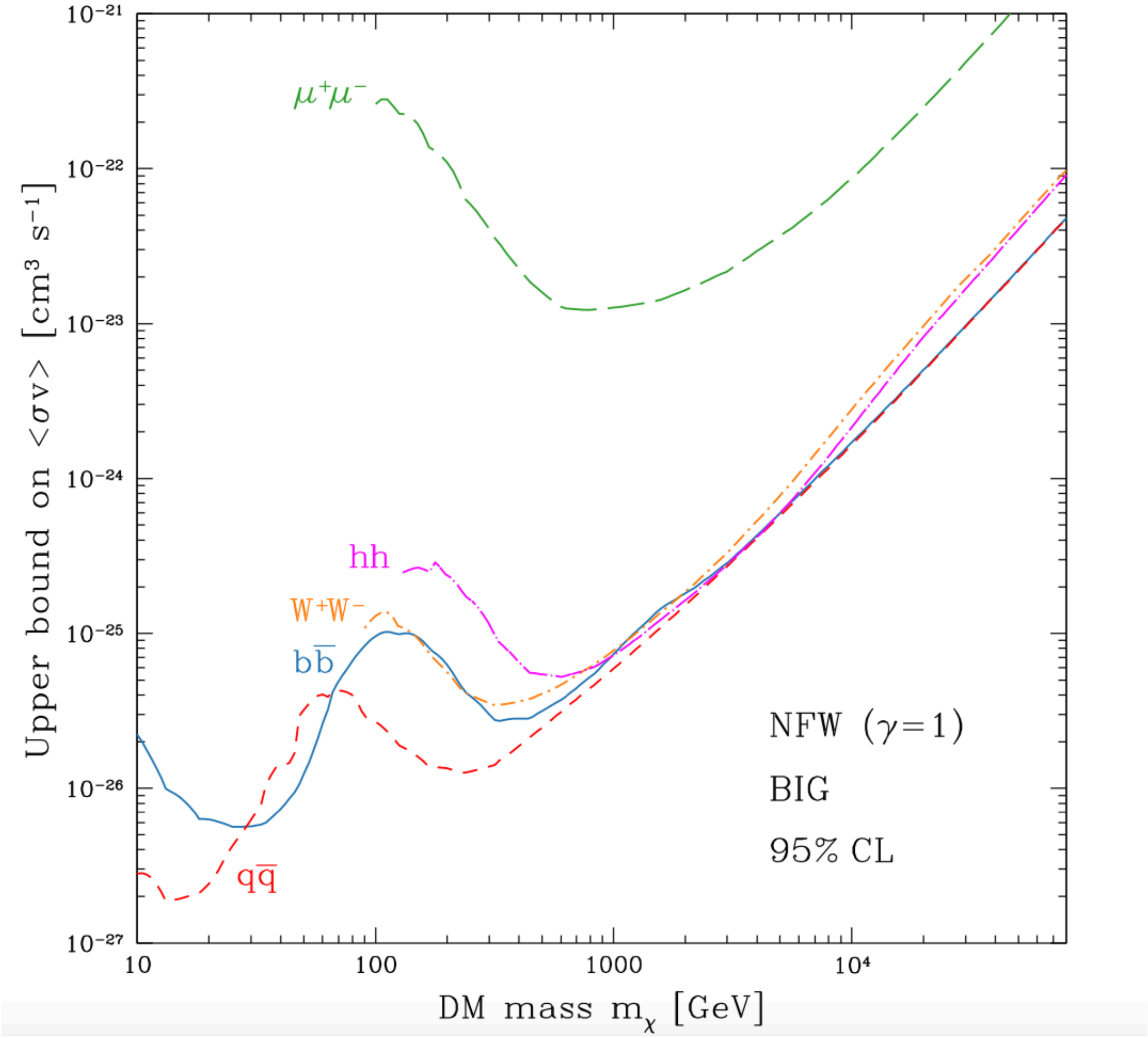
$$Q_{\rm DM}(E,\mathbf{x}) = \frac{\langle\sigma v\rangle \rho^2(\mathbf{x})}{8\pi m_X^2}\frac{\mathrm{d}N}{\mathrm{d}E}$$

Particle model fixes x-sec, spectrum, mass…

**Density of DM**

*Resort to simulations with parameters fitted to astro data*




*With people from Annecy, Grenoble and Paris*
*"AMS-02 antiprotons and dark matter: Trimmed hints and robust bounds," SciPost Phys. 12 (2022) no.5, 163 [arXiv:2202.03076]*

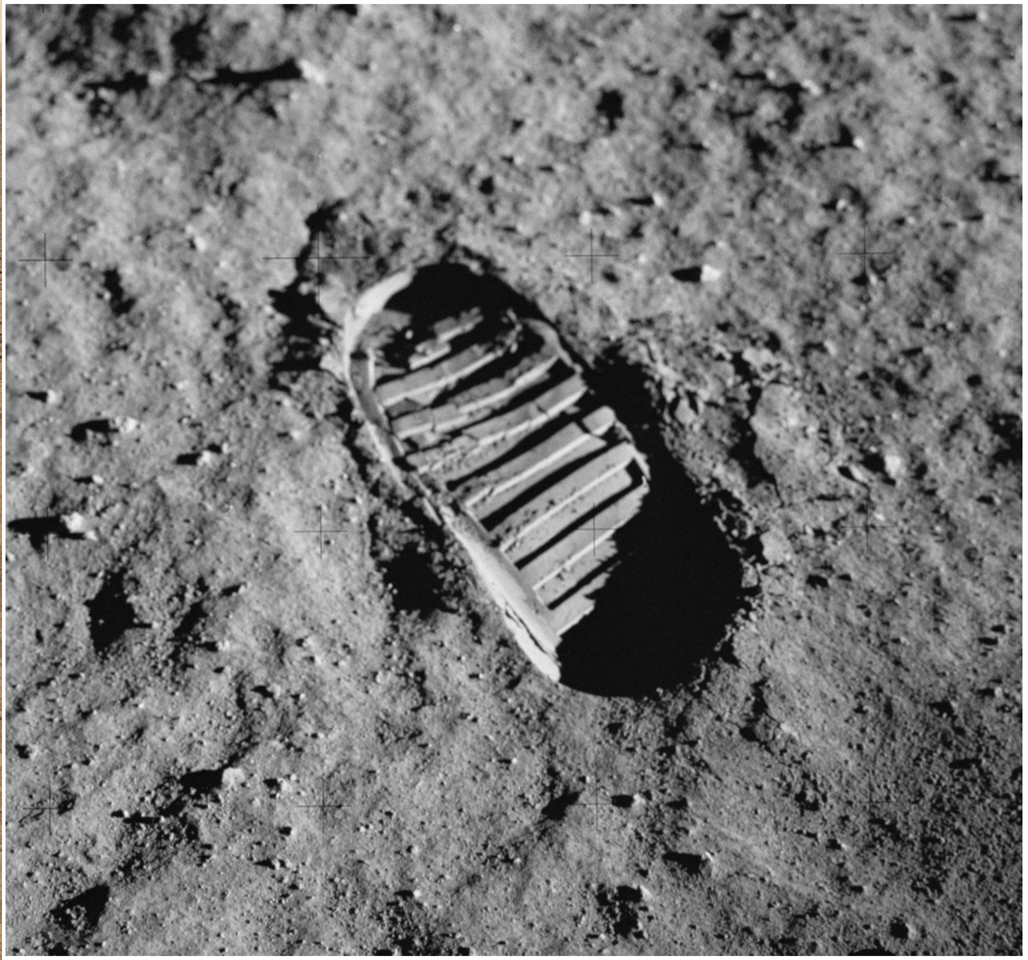
# To conclude, a reminder

**Something really exotic we ALREADY learned from CRs that we give for granted…**

# Sure, the solar system exclusively made by matter…

Cassini, Titan

Curiosity self-portrait, Mars

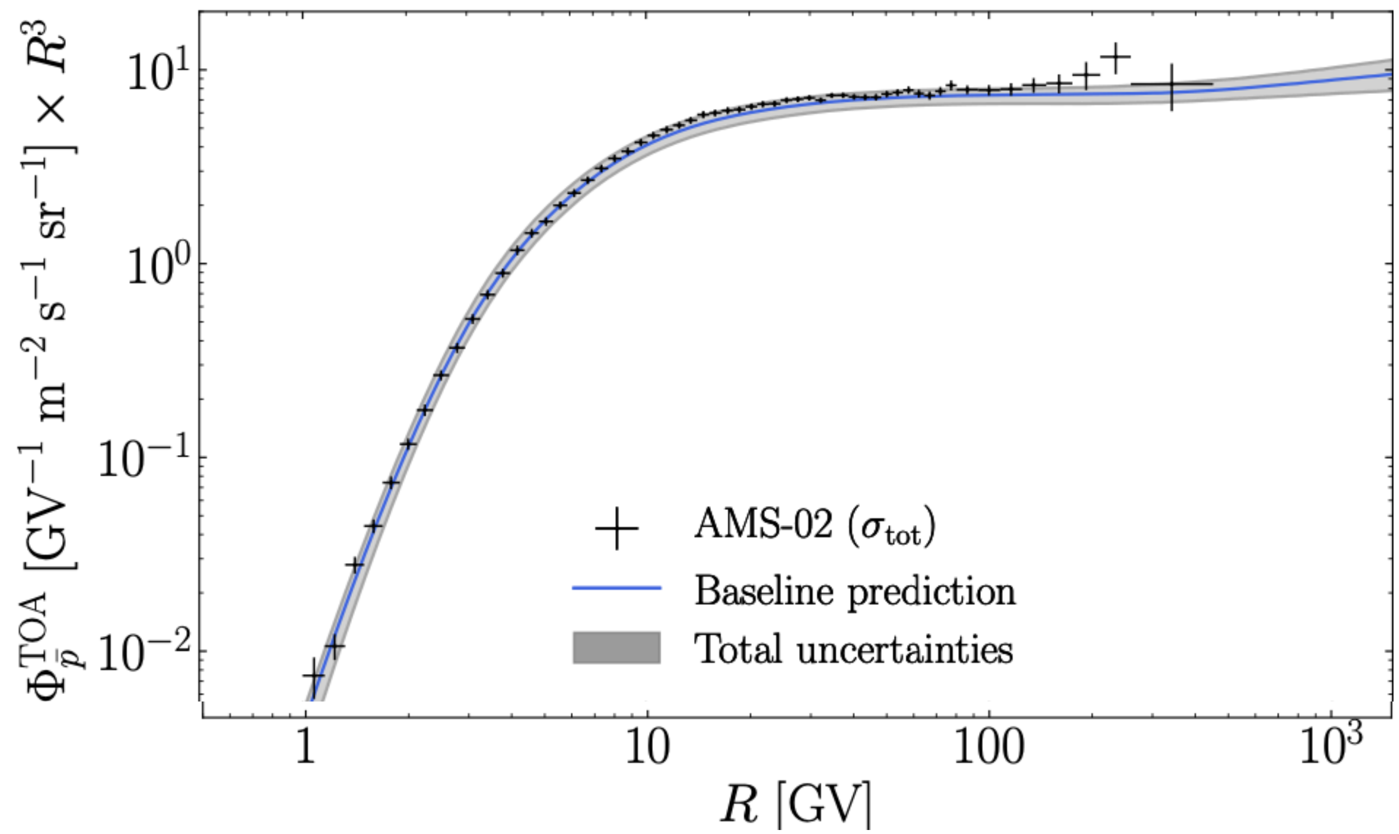


Apollo 11, Moon

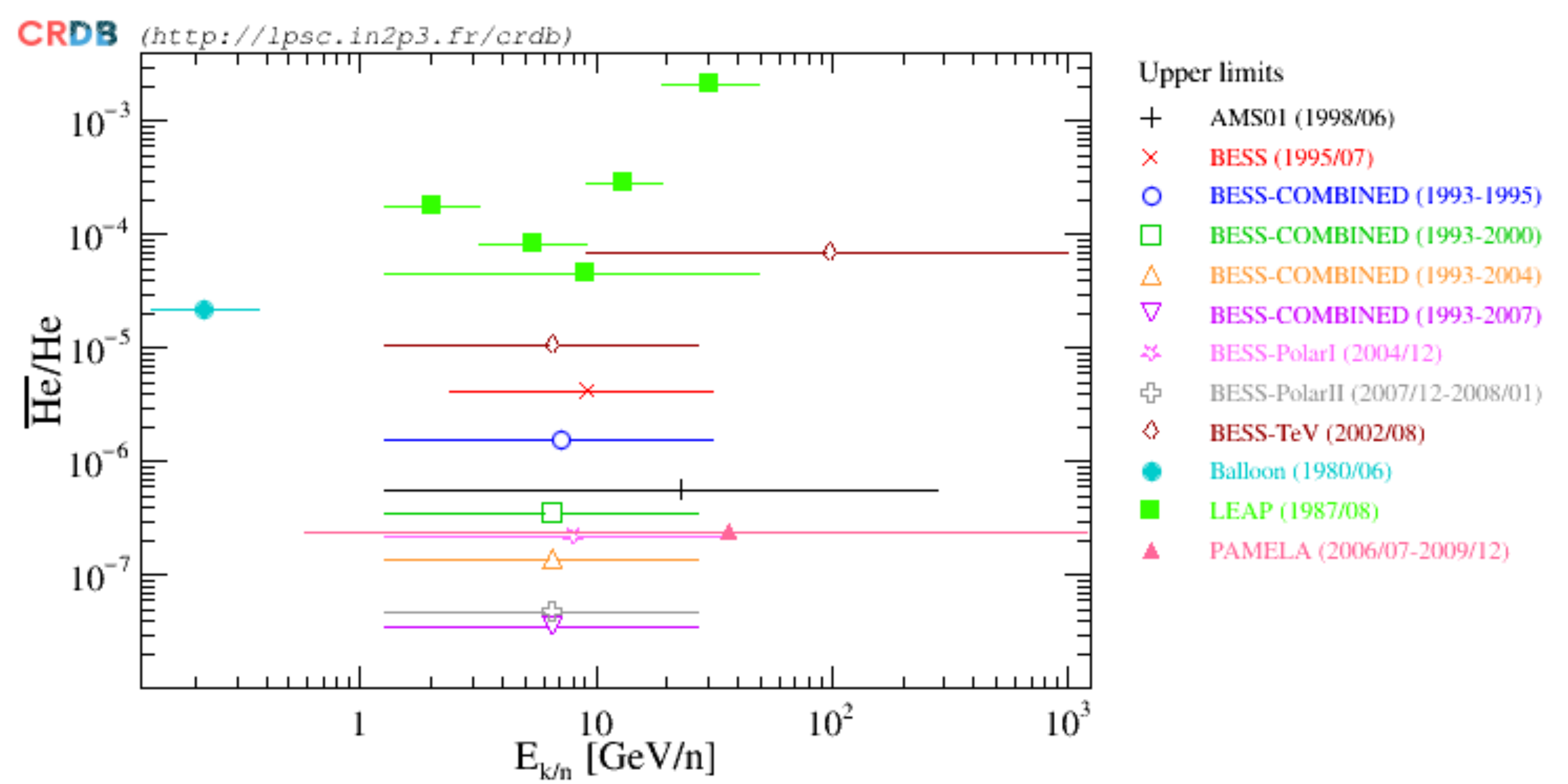
**…What about the rest of the universe?**

# CRs: Little to no antimatter in the galaxy

Traces in CRs ; ~ 1 in 10000 ($e^+$, anti-p) are fully accounted for via rare collisions of cosmic rays (protons, nuclei) in the rarefied interstellar medium

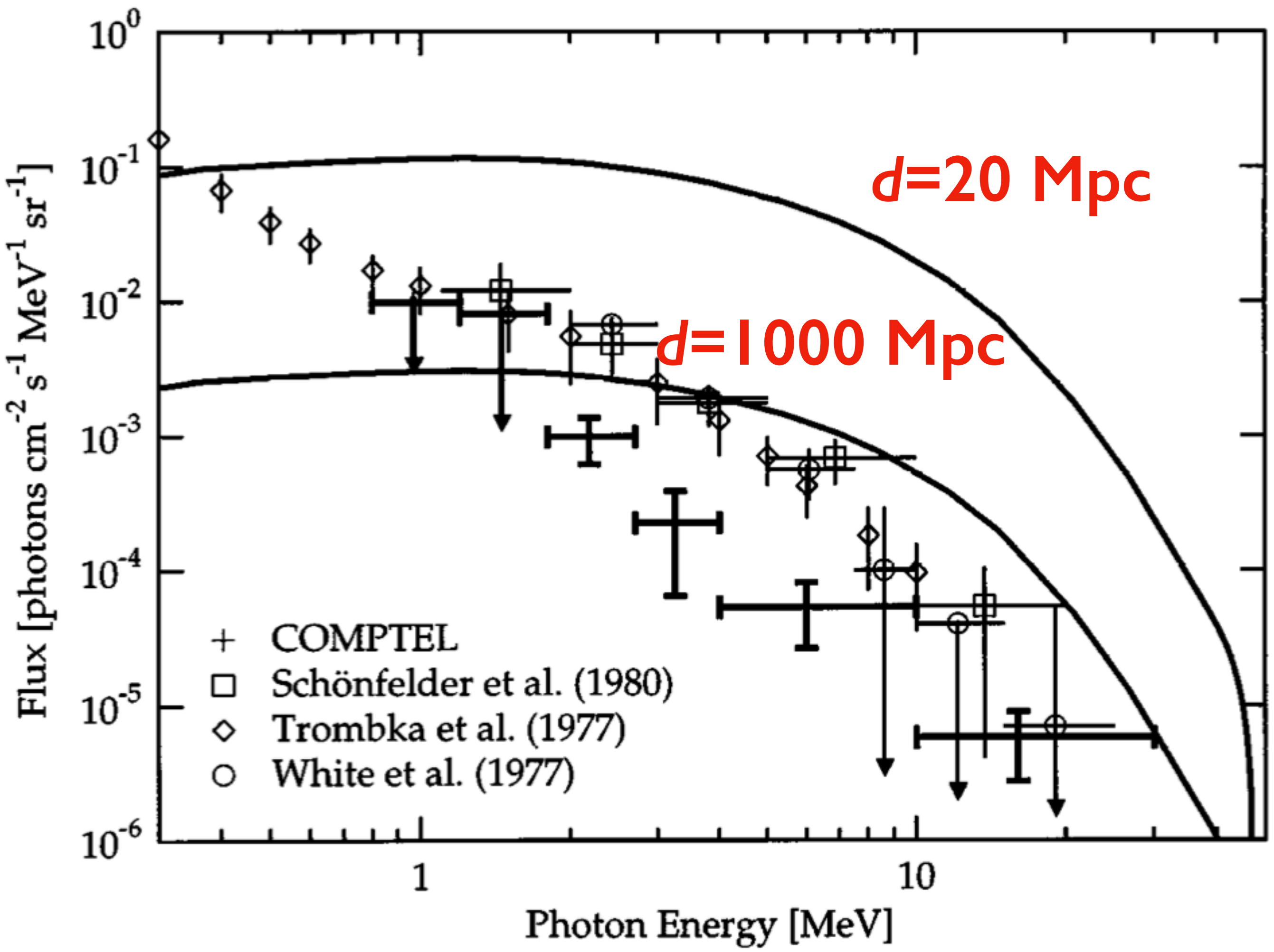



With a comparable number of stars & antistars, one should collect a similar flux of protons & antiprotons, helium & anti-helium, etc.



# At cosmological scale, from gamma-ray background

No signs of sizeable traces of antimatter e.g. via gamma annihilation spectra at the borders of matter/antimatter domains of size ***d***




*A. G. Cohen, A. De Rujula and S. L. Glashow Astrophys. J. 495 (1998), 539-549 [astro-ph/9707087]*

**Empirical Fact** (here on Earth's labs!):

*In any reaction creating matter, antimatter particles are also created in equal amounts.*

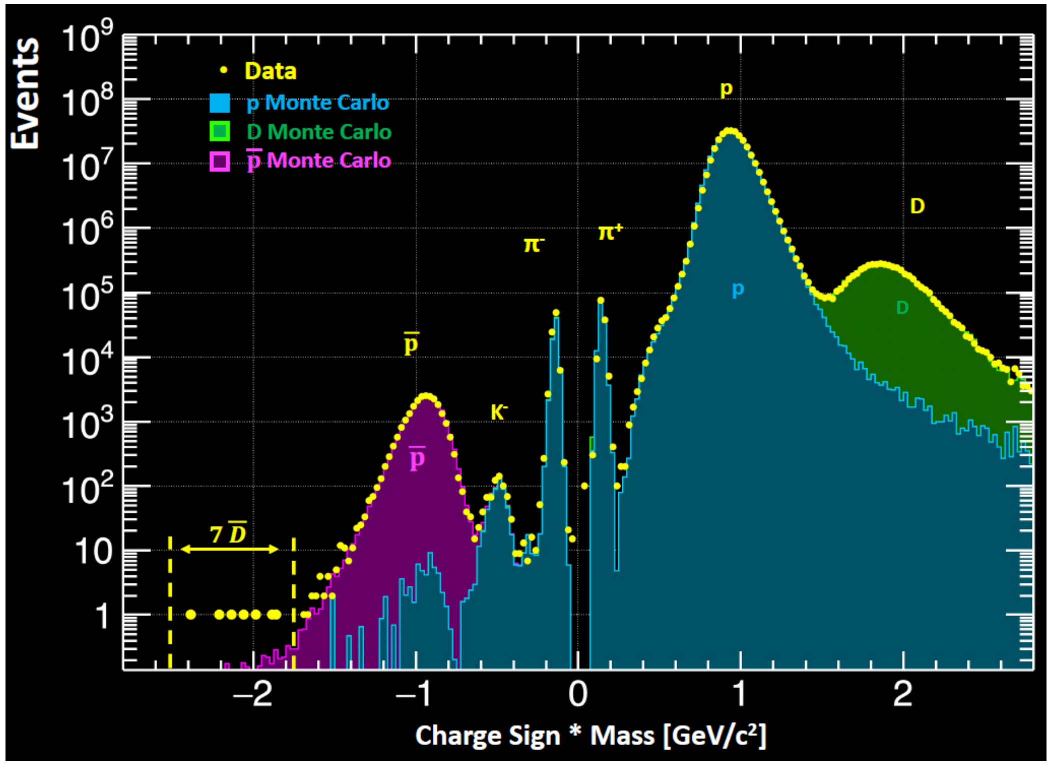
*How is it that we live in a Universe dominated by matter?*

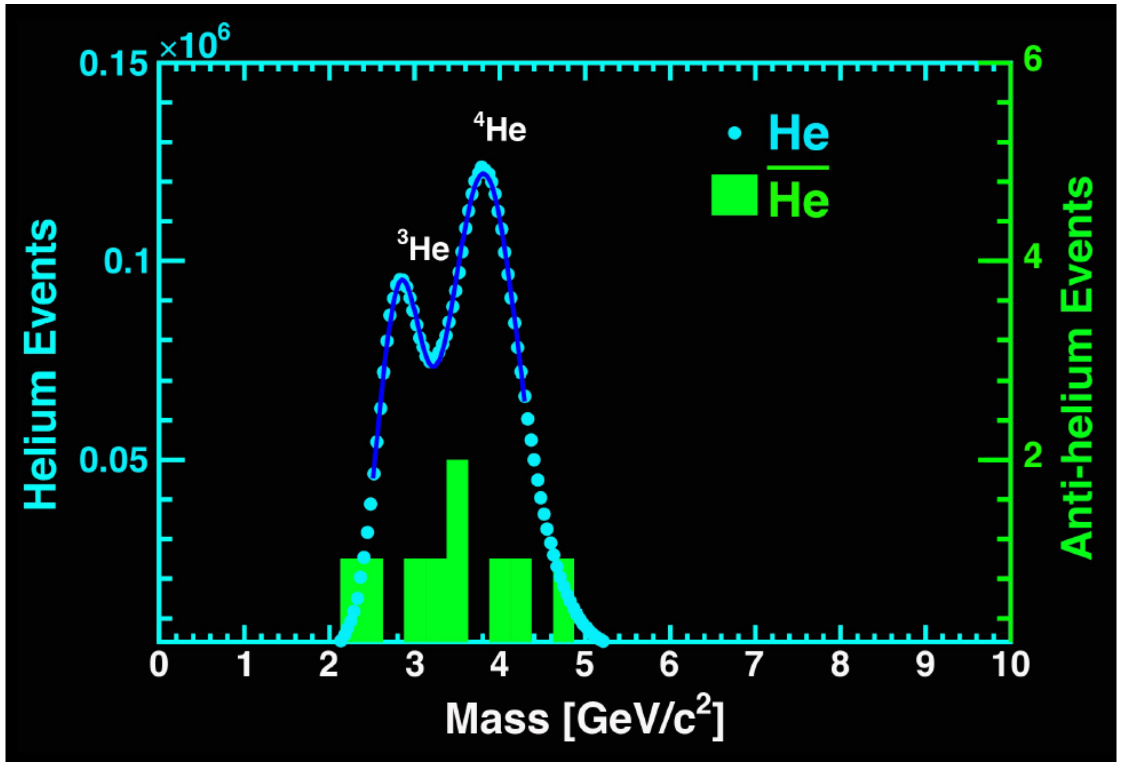
One of the biggest mysteries in fundamental physics

**Matter-Antimatter Asymmetry**

# Searches for CR antinuclei is ongoing!

Paolo Zuccon on behalf of AMS-02 collaboration MIAPP 2021




~9 anti-He, ~7 anti-D candidates, hard to reconcile even with a DM origin!

Hard to understand systematics to the required level, but certainly exciting time ahead

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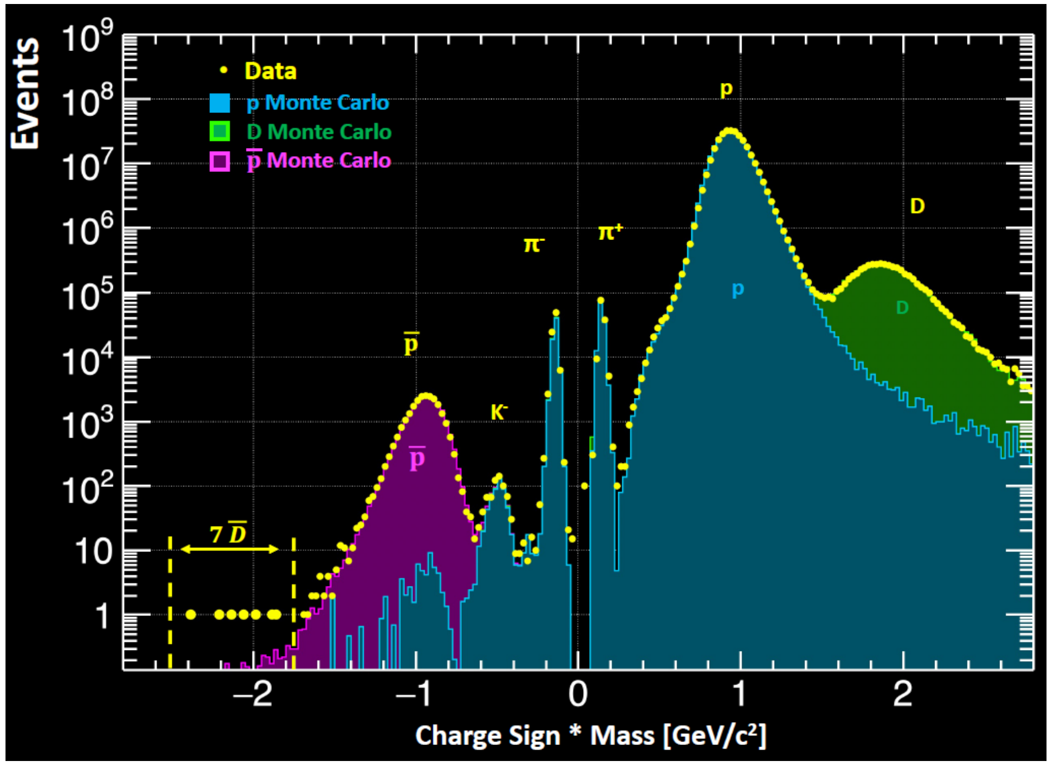


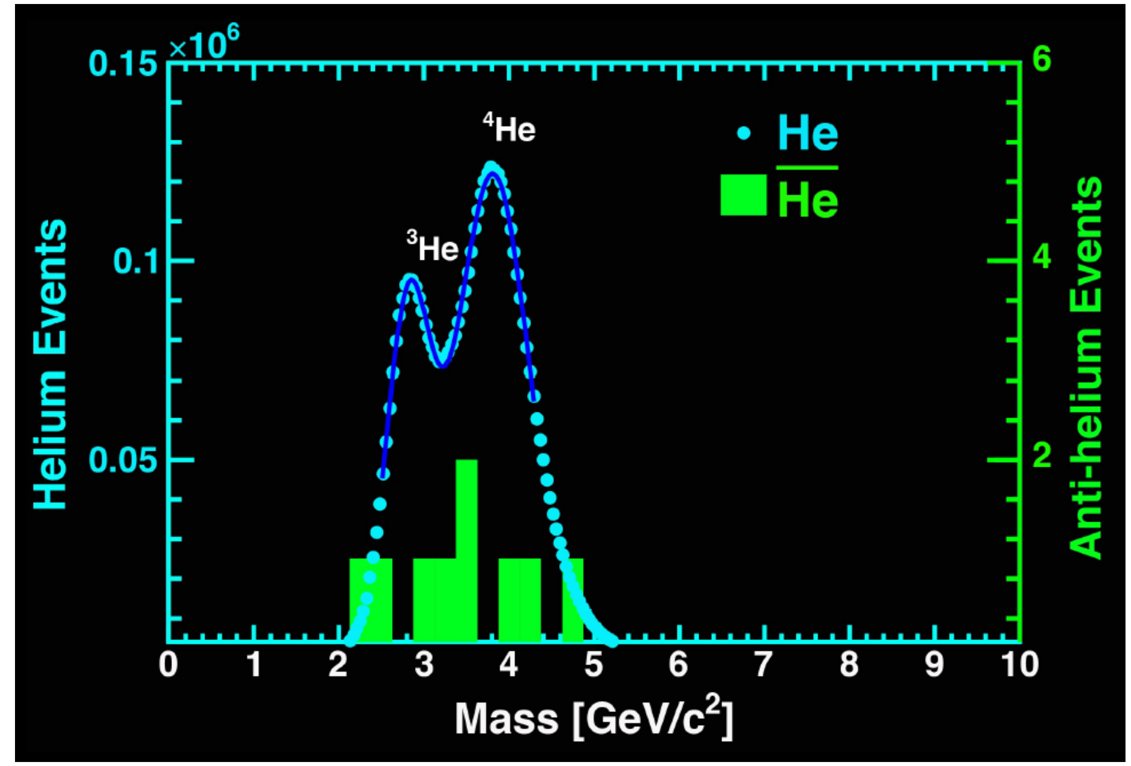


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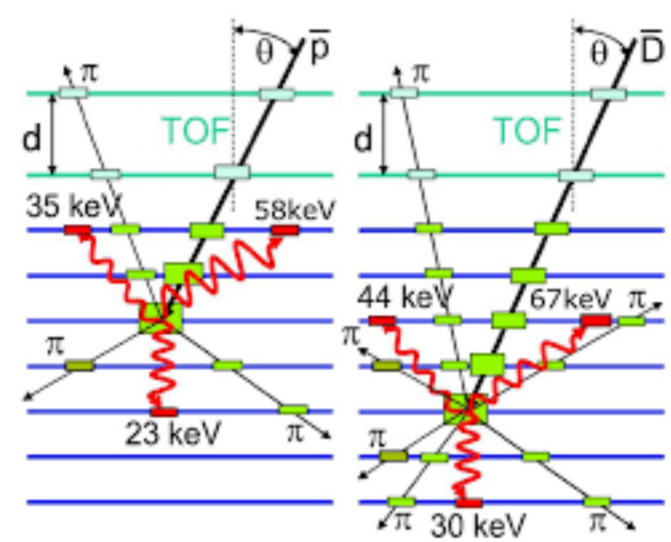
## Even new detector type

Incident cosmic-ray antinucleus slowed by the tracker, forms exotic atom with Silicon.

Characteristic X-rays and annihilation products emitted from the decay and annihilation of the exotic atom



# A bright future ahead…or perhaps a revolution?

En vous remerciant de votre attention, je souhaite que ces mots puissent incarner bientôt les années à venir !

Forse agli occhi dei nostri posteri il momento storico attuale apparirà come a noi quello del Rinascimento, in cui il concetto di sistema del mondo cambiò la base stessa su cui era poggiato.

Peut-être aux yeux de notre postérité le moment historique actuel apparaîtra comme celui de la Renaissance, dans lequel le concept de système du monde a changé la base même sur laquelle il reposait.

Perhaps in the eyes of posterity the current historical moment will appear as that of the Renaissance to us, in which the concept of the world system changed the very basis on which it was standing.

Vito Volterra, 1907