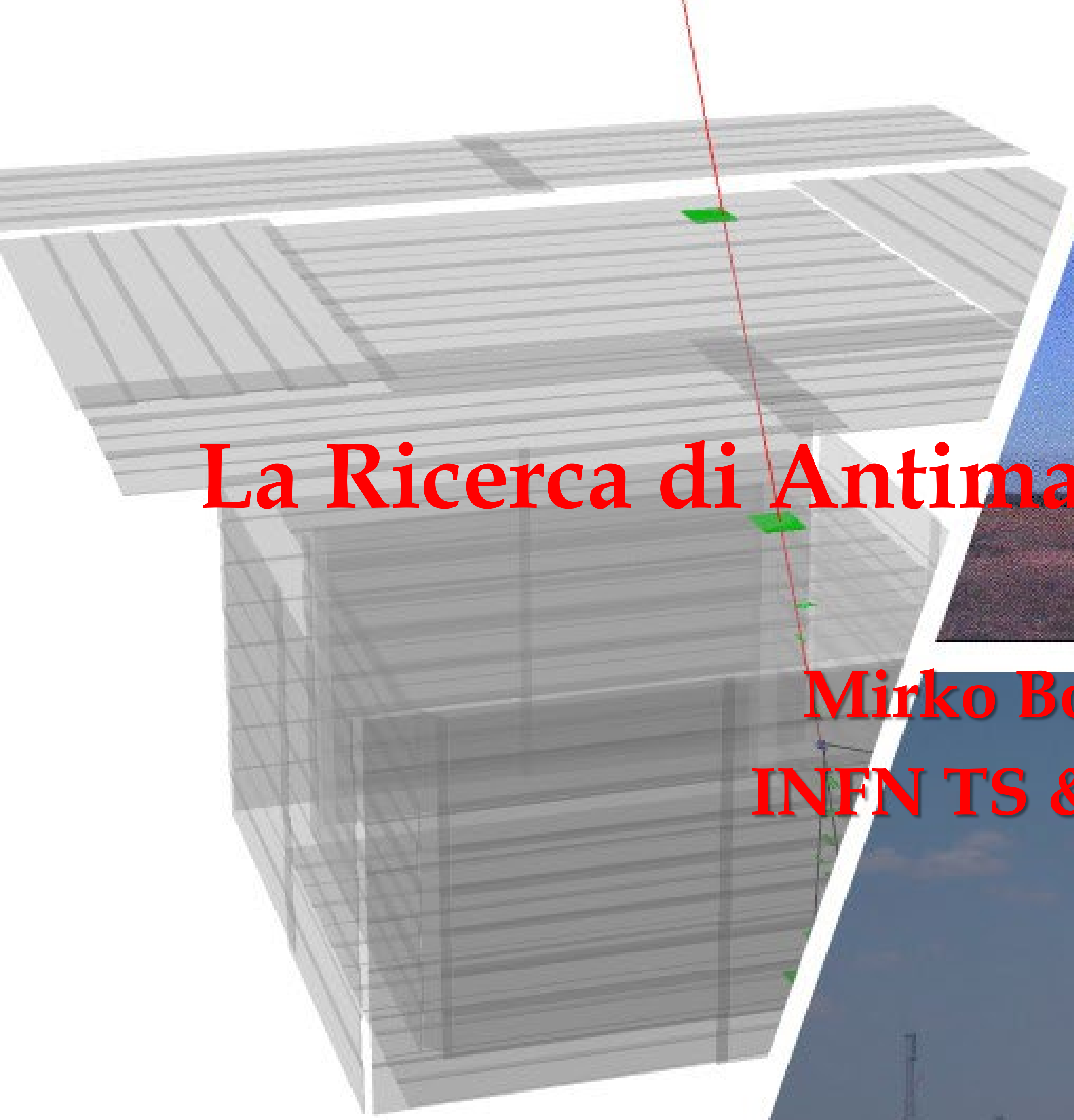
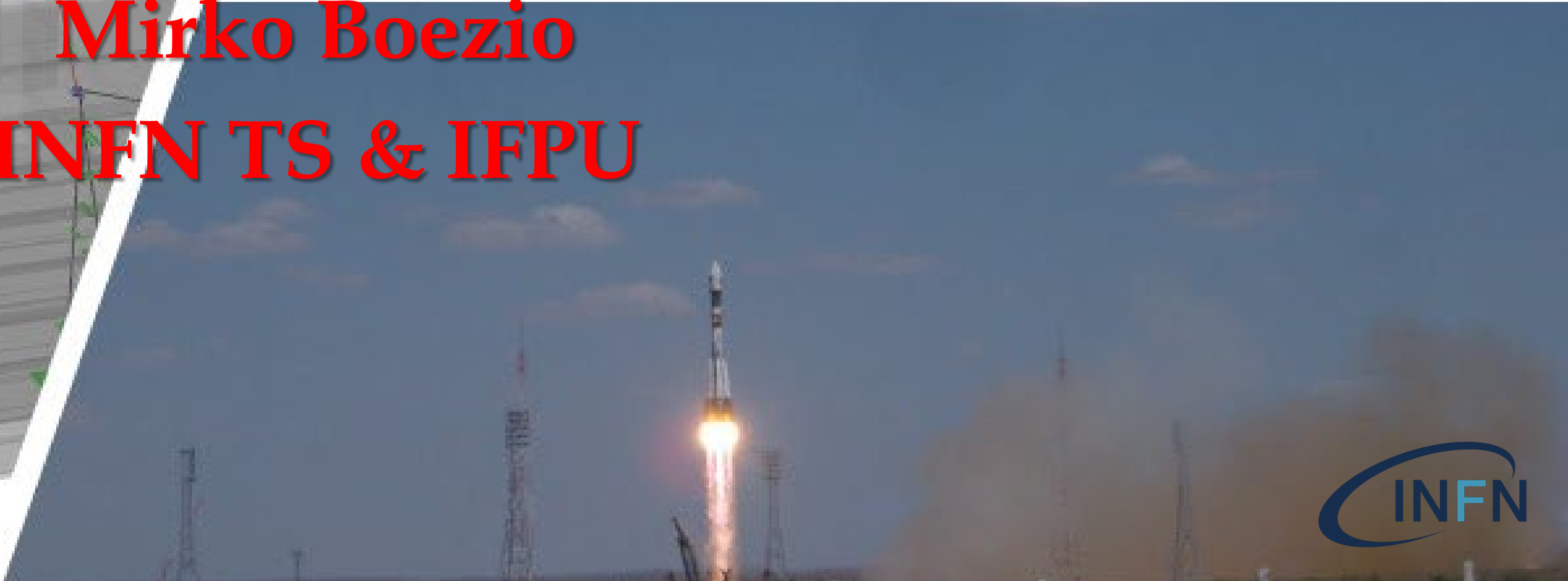
La Ricerca di Antimateria nello Spazio

Mirko Boezio
INFN TS & IFPU





The Existence of Antimatter

Paul A.M. Dirac

Theory of electrons and positrons

Nobel Lecture, December 12, 1933

Relativity:

$$\frac{W^2}{c^2} - p_{r^2} - m^2 c^2 = 0$$

Quantum Theory:

$$\left[\frac{W^2}{c^2} - p_{r^2} - m^2 c^2\right]\Psi = 0$$

$$m^2 = (m)(m) = (-m)(-m)$$

Dirac asked: What is (-m) ➡ Theory of antimatter

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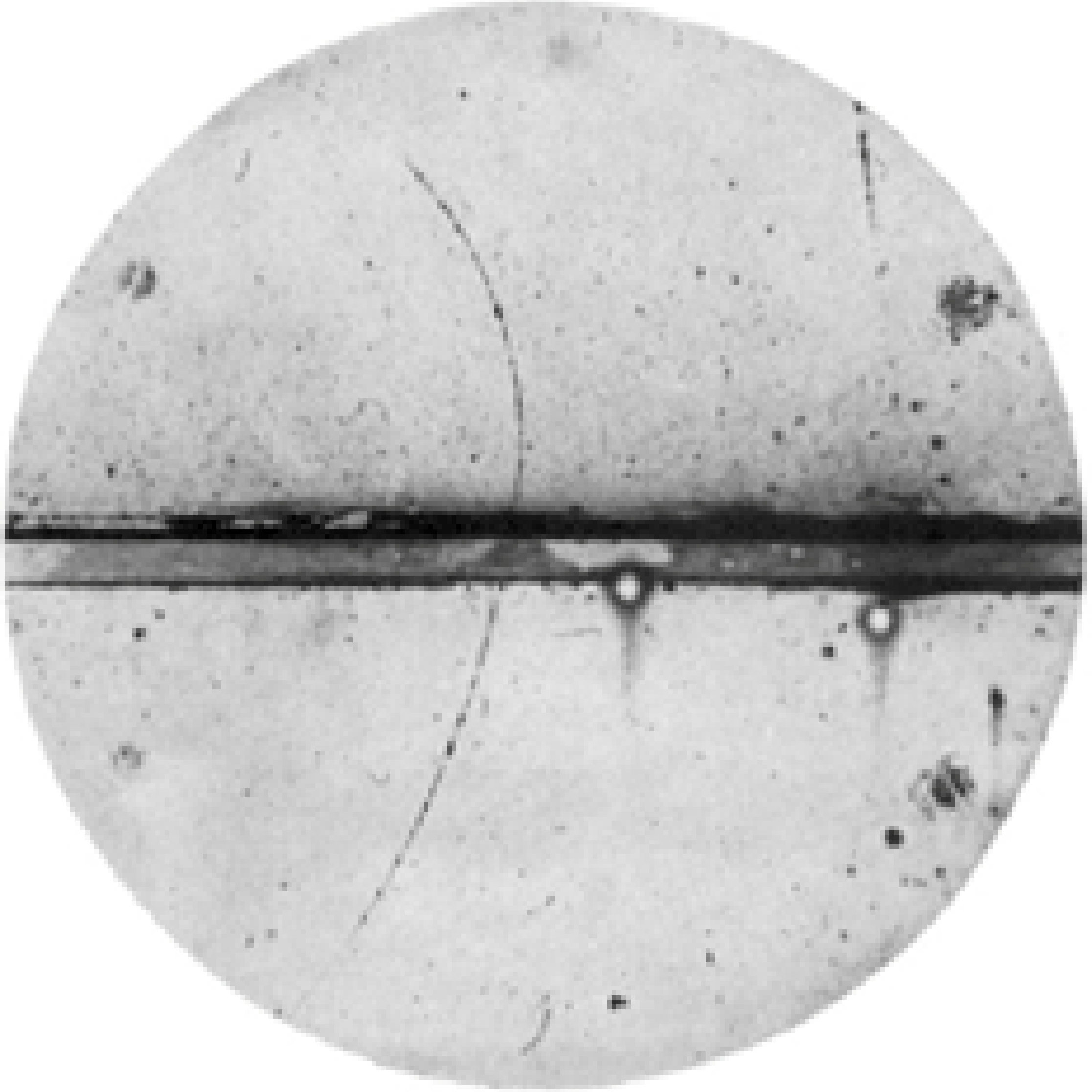
1933 Scoperta dell' antielettrone nei raggi cosmici. C. Anderson Nobel 1936



Le leggi della Natura sono le stesse per la materia e l’antimateria

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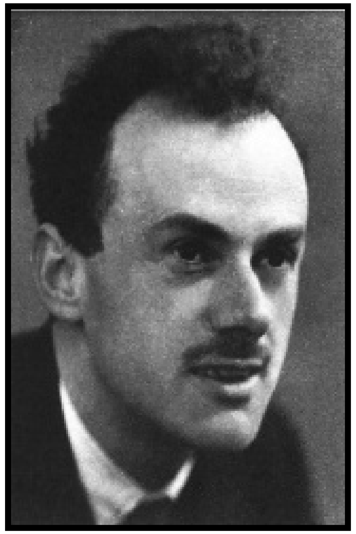
Universo Simmetrico in Materia ed Antimateria?

Noi dobbiamo considerare piuttosto un caso che la Terra e forse tutto il Sistema Solare contengano una preponderanza di elettroni negativi e protoni positivi. E' del tutto possibile che per qualcuna delle stelle avvenga il contrario



P. Dirac, Nobel lecture (1933)

Esiste un Universo di Antimateria?

Baryogenesis, matter and antimatter

Theoretically:

- There is an almost exact symmetry between matter and antimatter.

Experimental facts:

- There is no evidence for significant amounts of antimatter in the Universe, e.g.:
    - The primary cosmic ray nuclei are found to be completed dominated by nuclei rather than antinuclei
    - No evidence for the intense γ- and X-ray emissions expected from matter in galaxies colliding with 'clouds' of antimatter

Simple Big Bang Model

The early Universe was a hot expanding plasma with equal number of baryons, antibaryons and photons. In thermal equilibrium the two-ways reaction was:

$$B + \text{anti-}B \longleftrightarrow \gamma + \gamma$$

As the Universe expands, the density of particles and antiparticles falls, annihilation process ceases, effectively freezing the ratio:

- baryon/photon = antibaryon/photon ~ 10^{-18}.
- Annihilation catastrophe.

Instead, in the present real Universe:

- Baryon/photon ~ 10^{-9} (from direct observ. & microwave background);
- Antibaryon/baryon < 10^{-4}.

Sakharov criteria

To account for the predominance of matter over antimatter, Sakharov (1967) pointed out the necessary conditions:

- *B violating interactions;*
- *non-equilibrium situation;*
- *CP and C violation*.

GUT theories ?

Leptogenesys ?

The processes really responsible are not presently understood!

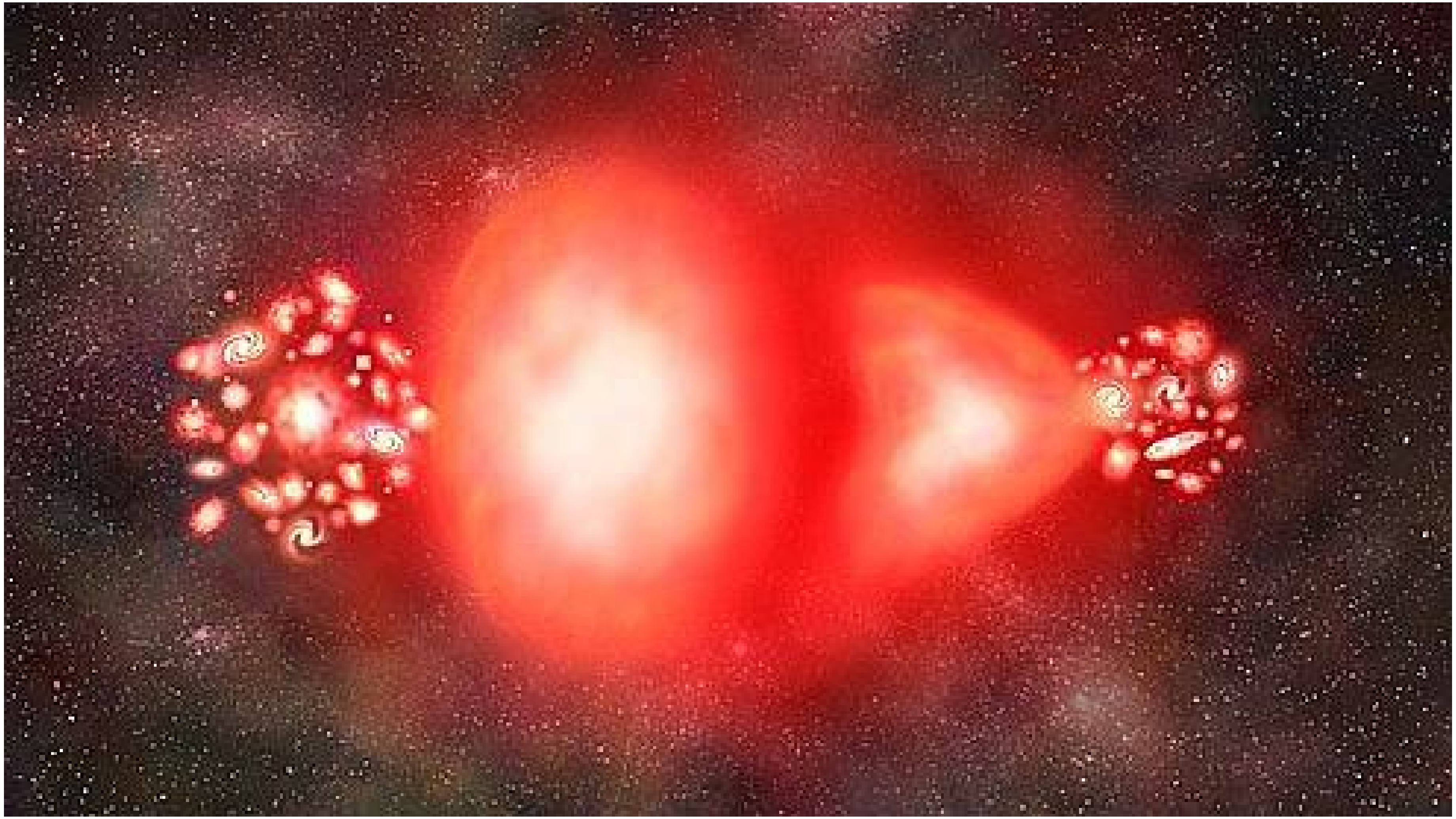
What about the observations?

- Indirect ->
- By measuring: the spectrum of the Cosmic Diffuse Gamma emission

- Direct ->
- By searching for Antinuclei
- By measuring anti-p and e^+ energy spectra

PAMELA
AMS-02
GAPS

Galassia e Antigalassia

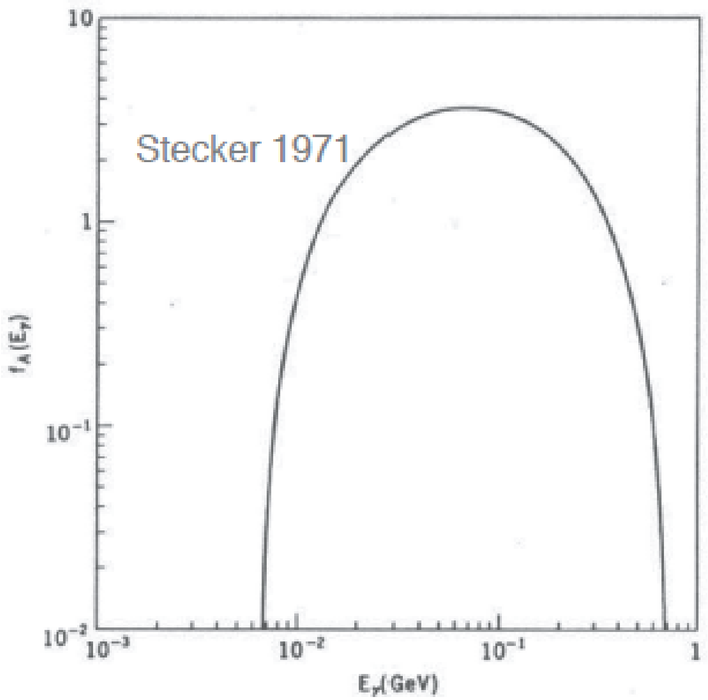


gamma rays from nucleon-antinucleon annihilation

$$N-\overline{N} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma+\gamma \\ \pi^\pm \rightarrow \mu^\pm + \nu_\mu(\overline{\nu}_\mu) \end{cases}$$

$$\hookrightarrow \pi^\pm \rightarrow e^\pm + \nu_e(\overline{\nu}_\mu) + \nu_\mu(\overline{\nu}_\mu)$$

1/3 of $2m_Nc^2 \rightarrow$ 200 MeV γ's



1/2 of $2m_Nc^2 \rightarrow$ ν's

1/6 of $2m_Nc^2 \rightarrow$ 100 MeV e^- / e^+

typical rest-frame spectrum produced by p-$\overline{\text{p}}$ annihilation with π° decay

maximum intensity at $m_\pi c^2/2 \sim 70$ MeV

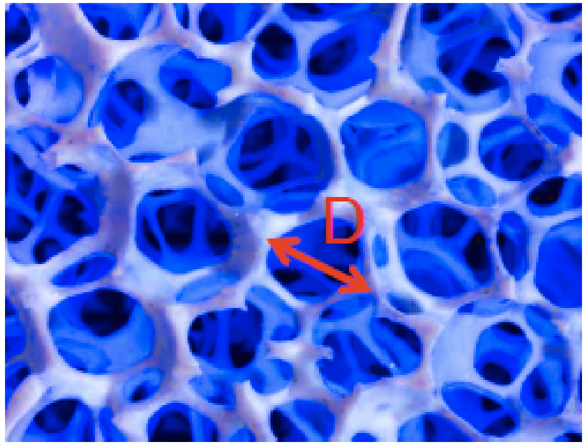
antimatter domains and the diffuse gamma-ray background

Annihilation radiation from the boundaries of matter-antimatter regions, emitted in the early Universe before - and/or - after recombination.

Stecker et al. (1971) solved the cosmological photon transport equation accounting for pair production and Compton scattering at high z.

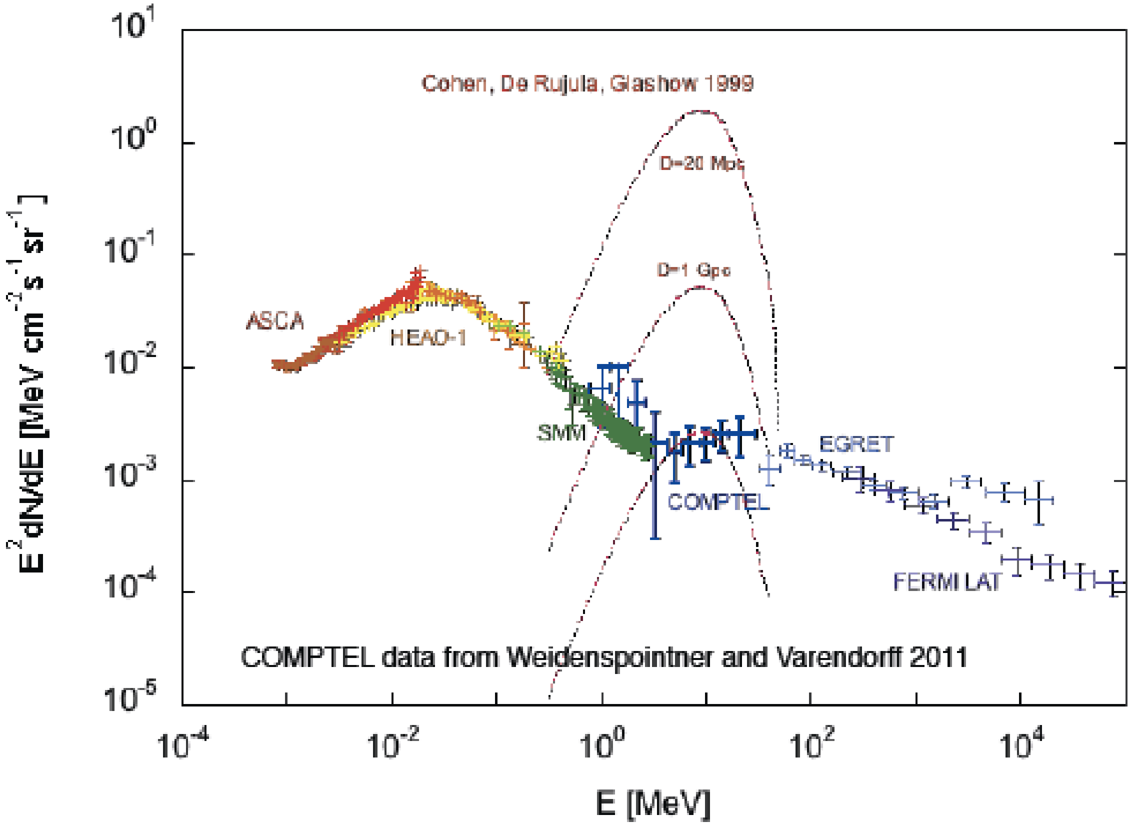
$$y\frac{\partial I}{\partial y}+\epsilon\frac{\partial I}{\partial \epsilon}=2I+\frac{y^2\Omega\nu}{[1+\Omega(y-1)]^{1/2}}\left[A(\epsilon)I-\int_{\epsilon}^{b(\epsilon)}d\epsilon' B(\epsilon|\epsilon')I(\epsilon',y)-\xi^2\Omega n_c y^3 v(T(y))\frac{\sigma_A(T(y))}{\pi r_e^2}G_A(\epsilon)\right]\ldots$$

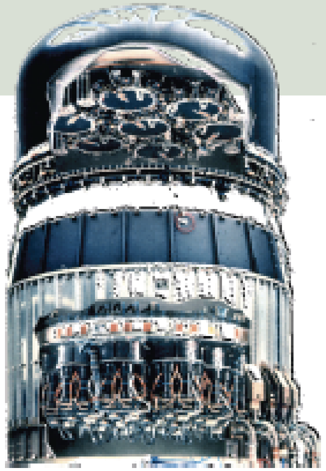
=> redshifted gamma-ray "bump" above ~ 1 MeV



what domain-size D (> 20 Mpc)
is compatible with
the observed MeV gamma-ray sky ?

Cosmic diffuse X- and Gamma-Ray Background





COMPTEL

- no MeV bump
- transition from a softer to a harder component at ~ 5 MeV
- no deviation from isotropy within statistics

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Direct searches: current status

- Antiprotons: DETECTED! secondary production

$P_{CR}+H_{ISM}$
$P_{CR}+He_{ISM}$
$\alpha_{CR}+H_{ISM}$
$\alpha_{CR}+He_{ISM}$ ⇒ p + anti-p <u>secondary antiprotons</u>

- **Positrons: DETECTED! secondary production**

$P_{CR}+ ISM$
$N_{CR}+ISM$ ⇒ π+ -> μ+ -> e+ <u>secondary positrons</u>

- **Anti-nuclei: <u>never detected!</u>**

They would be the real signature of antistars because their production by "spallation" is negligible

AMS-02?

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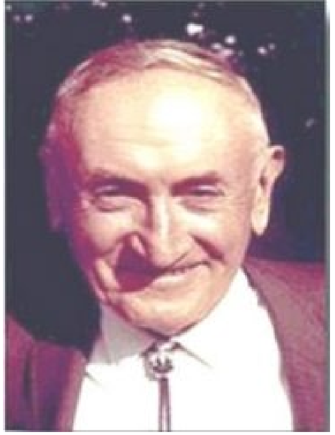
Il Mistero della Materia Oscura



Fritz Zwicky
14/2/1898, Varna (Bulgaria)
8/2/1974 Pasadena

Nel 1933 Zwicky, osservando il movimento delle galassie nell'ammasso Coma, dedusse la presenza di materia non visibile che teneva maggiormente unite le galassie tra loro.

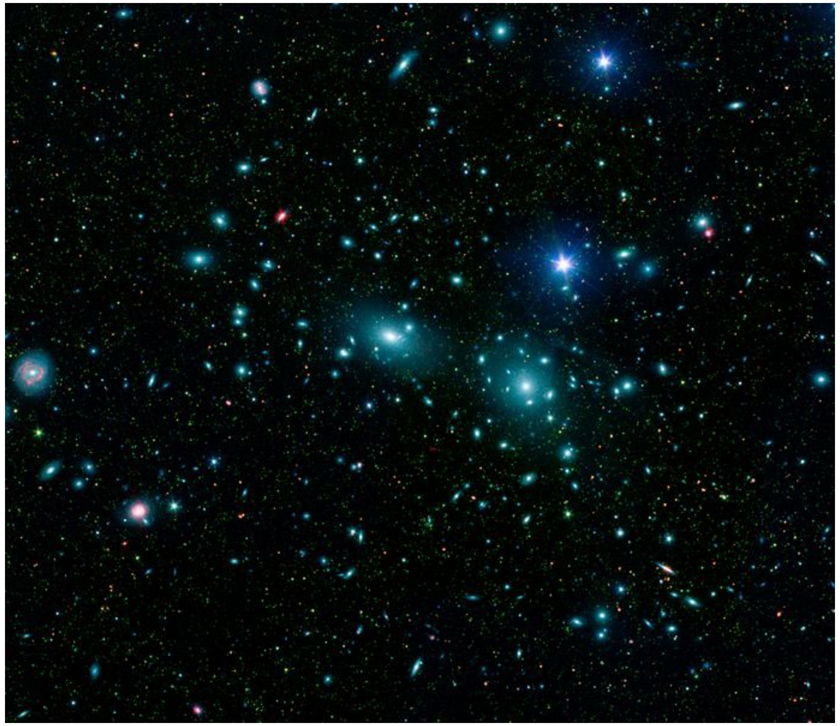
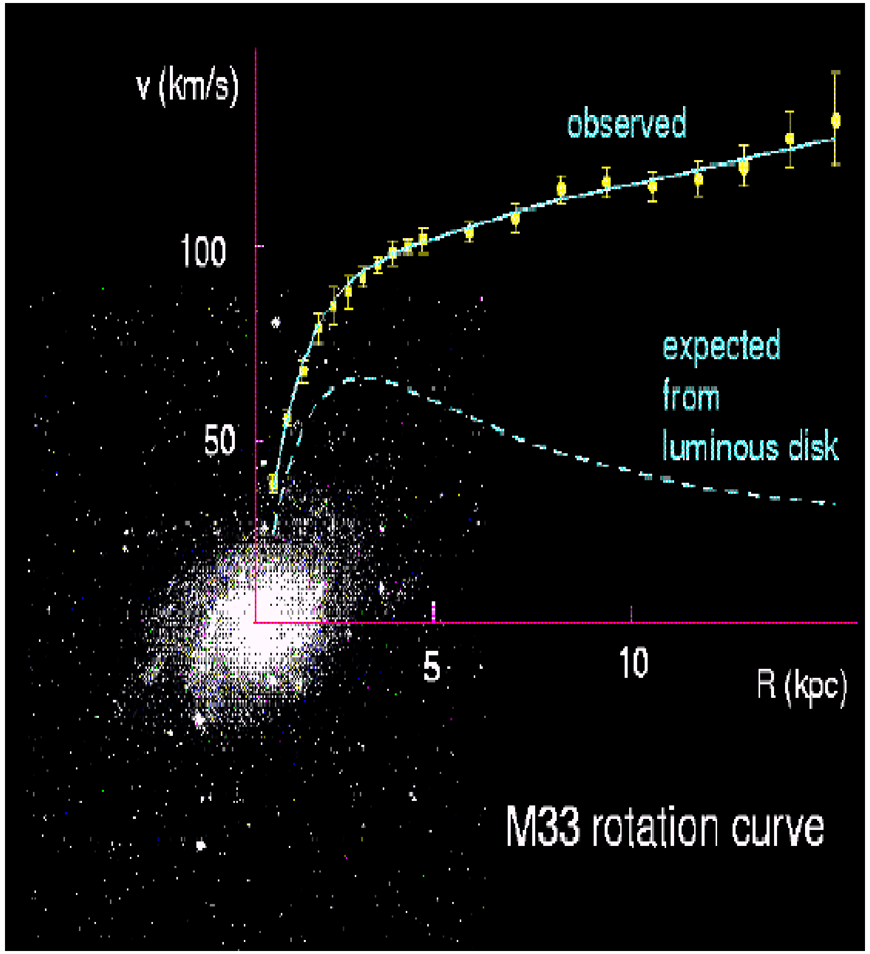


Immagine a falsi colori: blu – visibile (Sloan Digital Sky Survey)
Rosso e verde - Infrarosso (NASA's Spitzer Space Telescope)

…nessuno lo ascoltò per anni…

Eppur si muove!

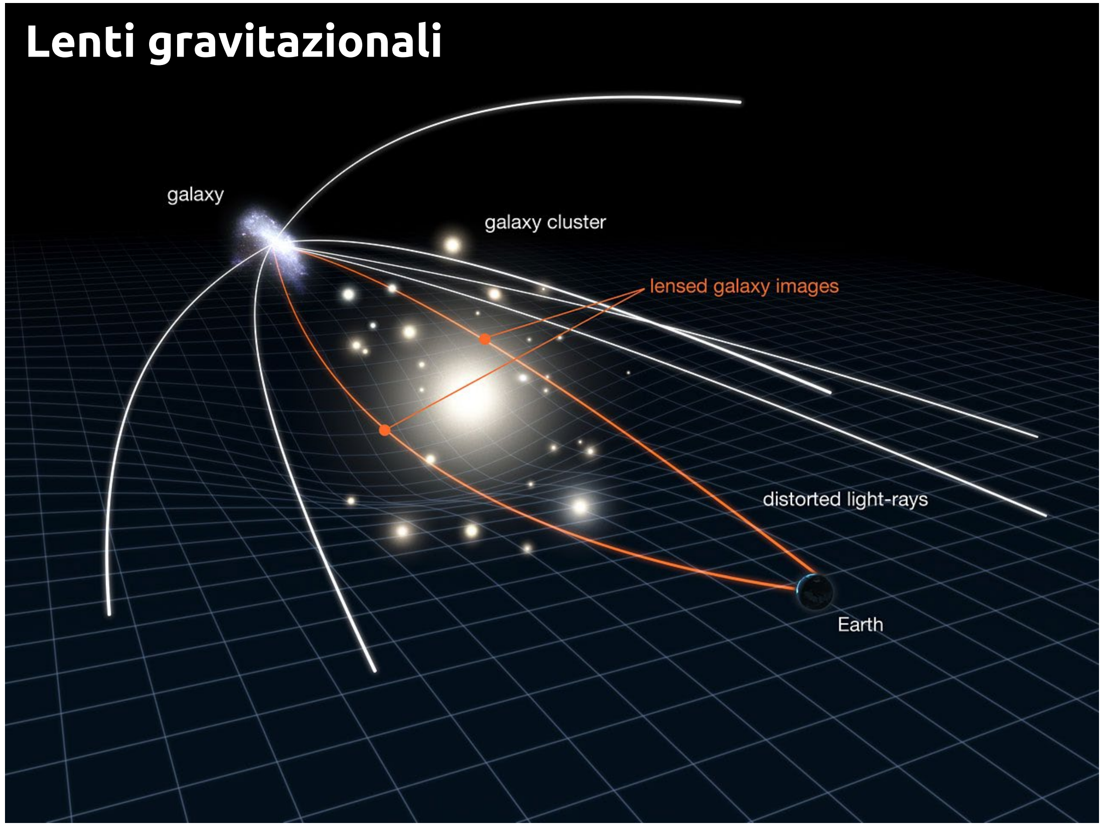
Come “vediamo” la materia oscura?



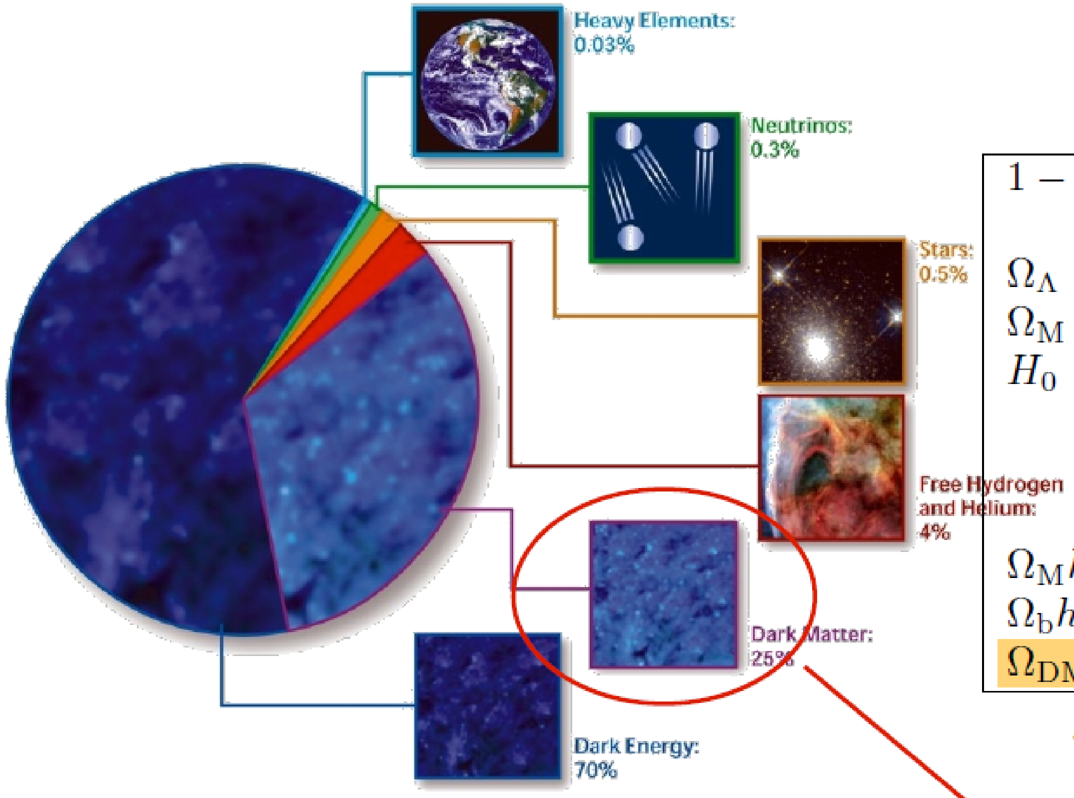
- Red-shift variation of the galaxy is explained as a velocity distribution.
- Newtonian dynamics based on only the luminous mass would predict a decline in the velocity as distance increase from galaxy center.
- On the contrary rotational curve is increasing indicating that the galaxy is inside a halo of “dark matter’ that does neither radiates nor absorbe radiation.

Come "vediamo" la materia oscura?

Non possiamo vederla con i telescopi perche` non emette luce! Come sappiamo che esiste? Attraverso indicazioni indirette, cioe` fenomeni che possono essere spiegati solo grazie alla presenza di una grande quantita di materia non visibile: sappiamo che esiste grazie ai suoi effetti gravitazionali.



Dark Matter



$1 - \Omega_{TOT}$	-0.0105 ± 0.061	[95% C.L.]
Ω_Λ	0.693 ± 0.019	[68% C.L.]
Ω_M	0.307 ± 0.019	[68% C.L.]
H_0	67.9 ± 1.5	[95% C.L.]
	73.8 ± 2.4	[*]
	74.3 ± 2.6	[+]
$\Omega_M h^2$	0.1414 ± 0.0029	[68% C.L.]
$\Omega_b h^2$	0.02217 ± 0.00033	[68% C.L.]
$\Omega_{DM} h^2$	0.1186 ± 0.0031	[68% C.L.]

Ade et al. (Planck Collab.), arXiv: 1303.5076
[*] Riess et al., Ap. J. 730 (2011) 119
[+] Freedmann et al., Ap. J. 758 (2012) 24

DM points towards New Physics:

- Non-baryonic (cold) dark matter

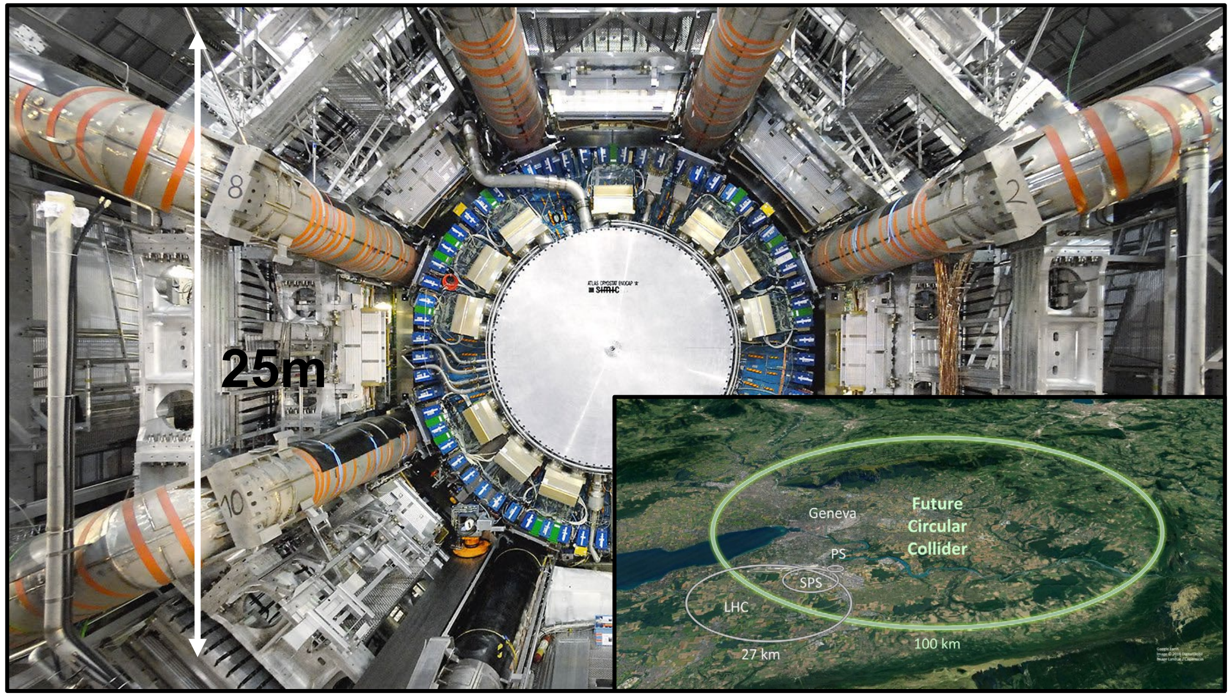
One hypothesis: the solution is a particle, a WIMP (weakly interacting massive particle)

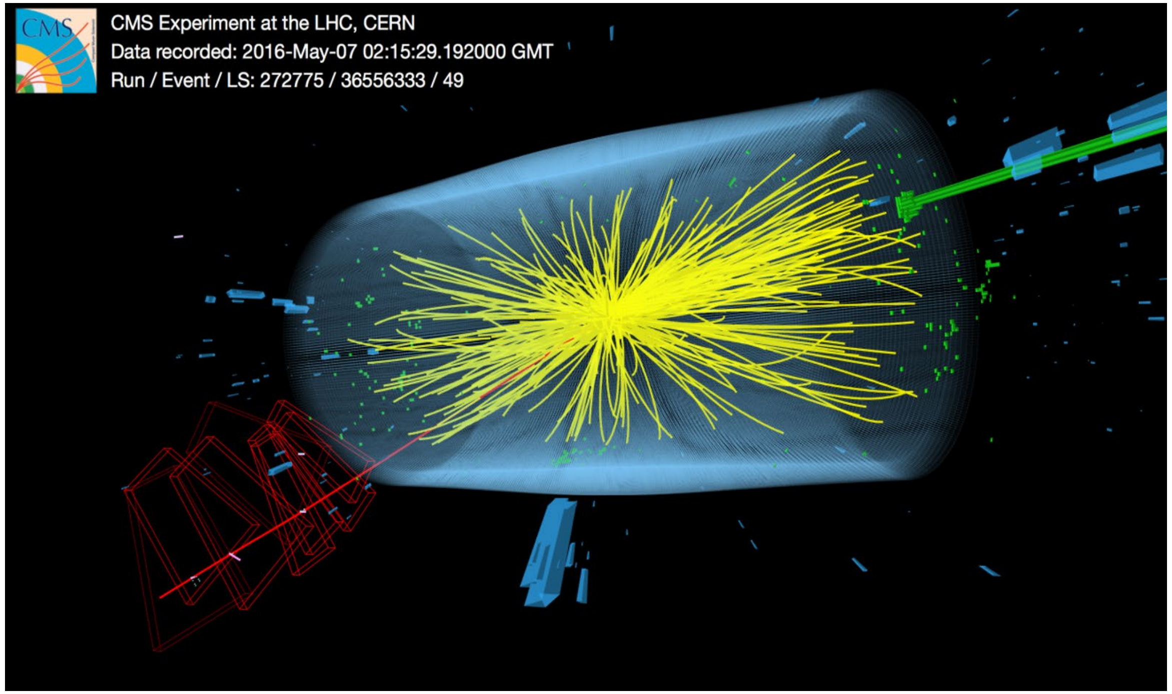
Two fundamental questions:

- Identify the particle candidate
- Identify a non-gravitational signal

Courtesy by N. Fornengo

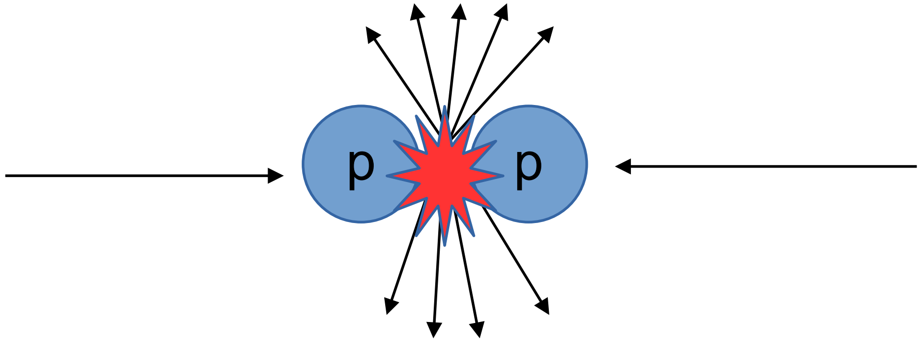
Come rivelarla? 1) Produrla in laboratorio



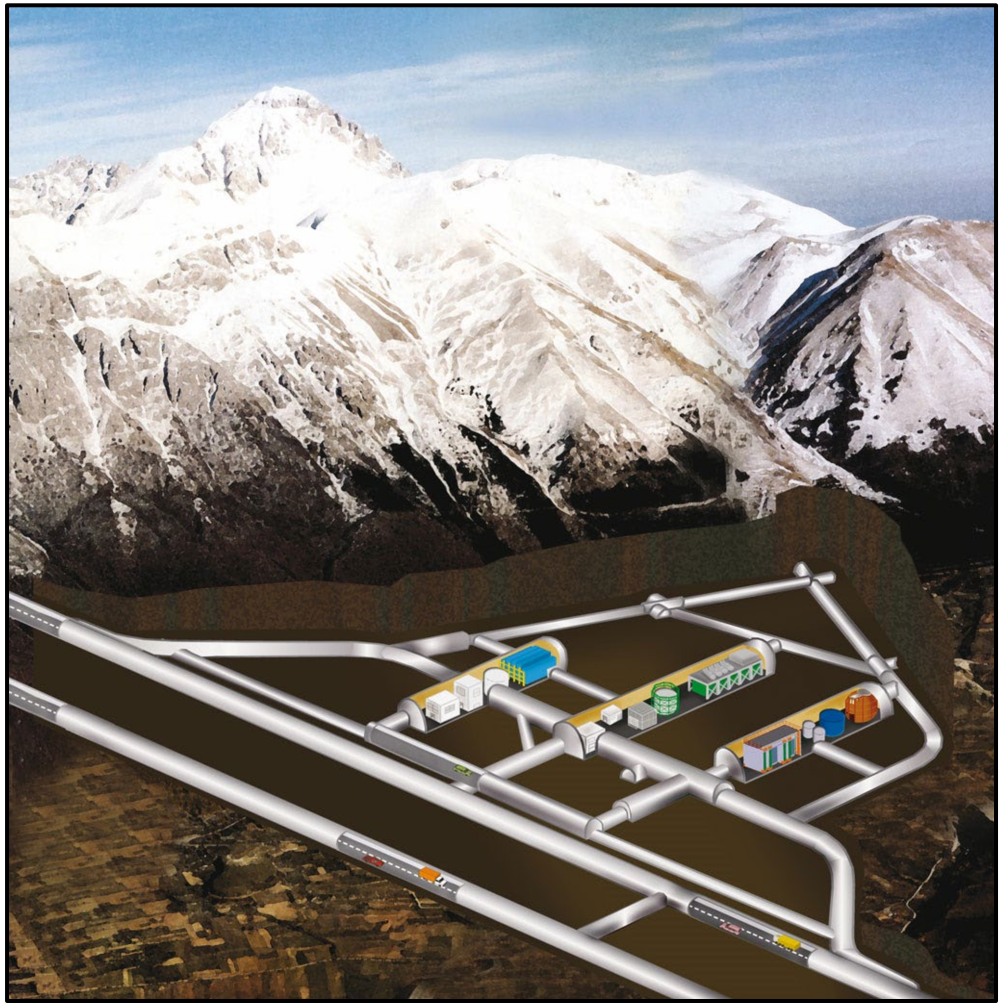


- I protoni vengono fatti scontrare ad altissime energie.
- L’energia viene trasformata in materia e altre particelle vengono prodotte.

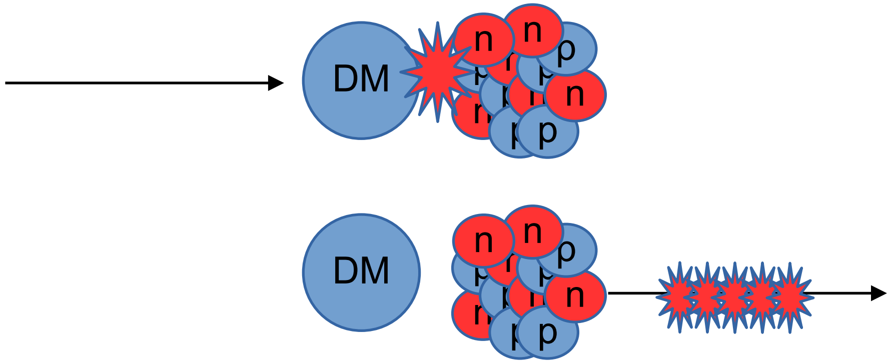
- I fisici cercano la presenza di nuove particelle, con caratteristiche diverse dalla materia ordinaria.



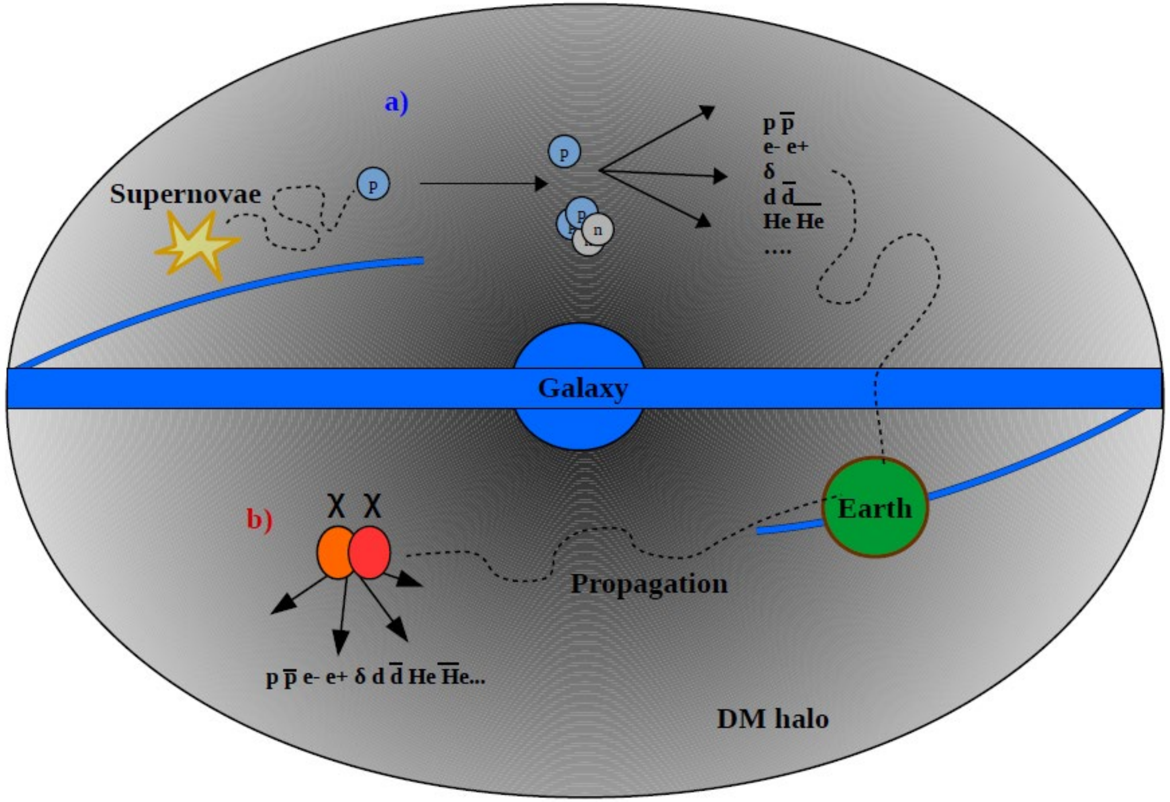
Come rivelarla? 2) Rivelazione diretta

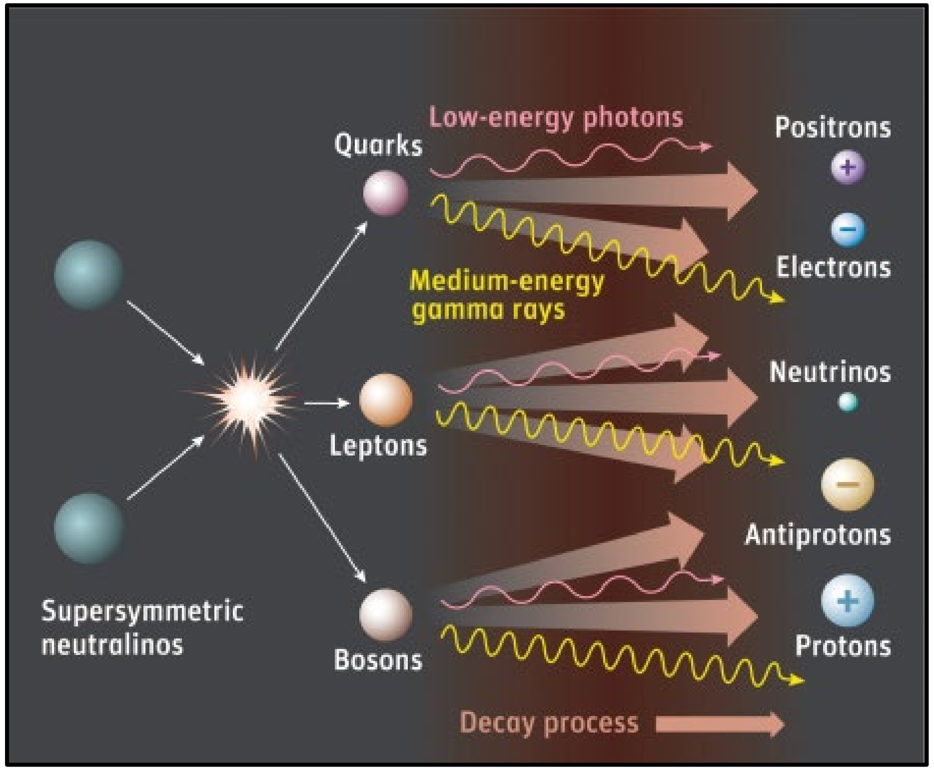


- Le particelle di materia oscura "urtano" gli atomi dei rivelatori.
- Questi atomi acquistano un'energia e rilasciano un segnale ben definito.
- Gli esperimenti vengono condotti sottoterra come nei laboratori del Gran Sasso per essere schermati dai raggi cosmici.



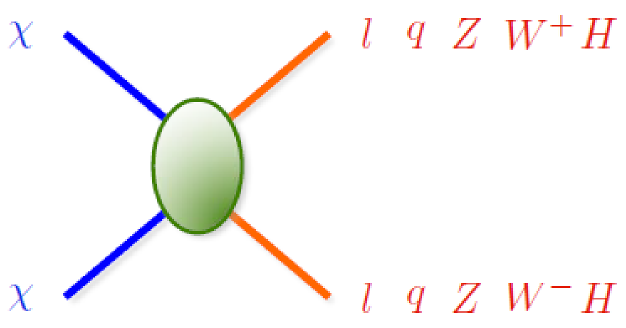
Come rivelarla? 3) Rivelazione indiretta





- Alcune particelle di materia oscura incontrandosi e interagendo potrebbero creare delle particelle di materia ordinaria tra cui anche anti-particelle: positroni, antiprotoni.
- L’antimateria nei raggi cosmici è rara, quindi se la materia oscura ne producesse una grande quantità (rispetto alle attese) si ricaverebbero informazioni sulla sua natura.

Features of the astrophysical signals



Non-relativistic annihilation (or decay)

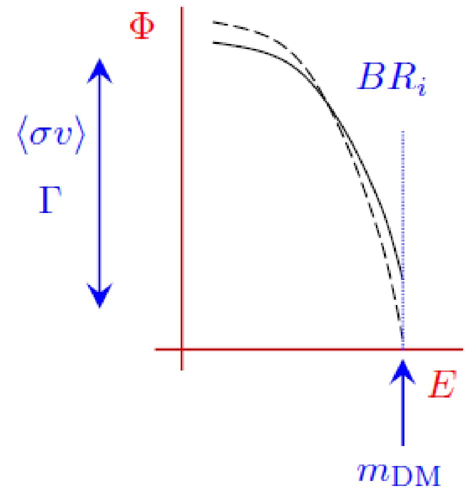
$$S \sim \left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right)^{2,1} \times \{\langle\sigma v\rangle \,,\, \Gamma\} \times [\text{energy spectrum}]$$

Relevant particle physics properties:

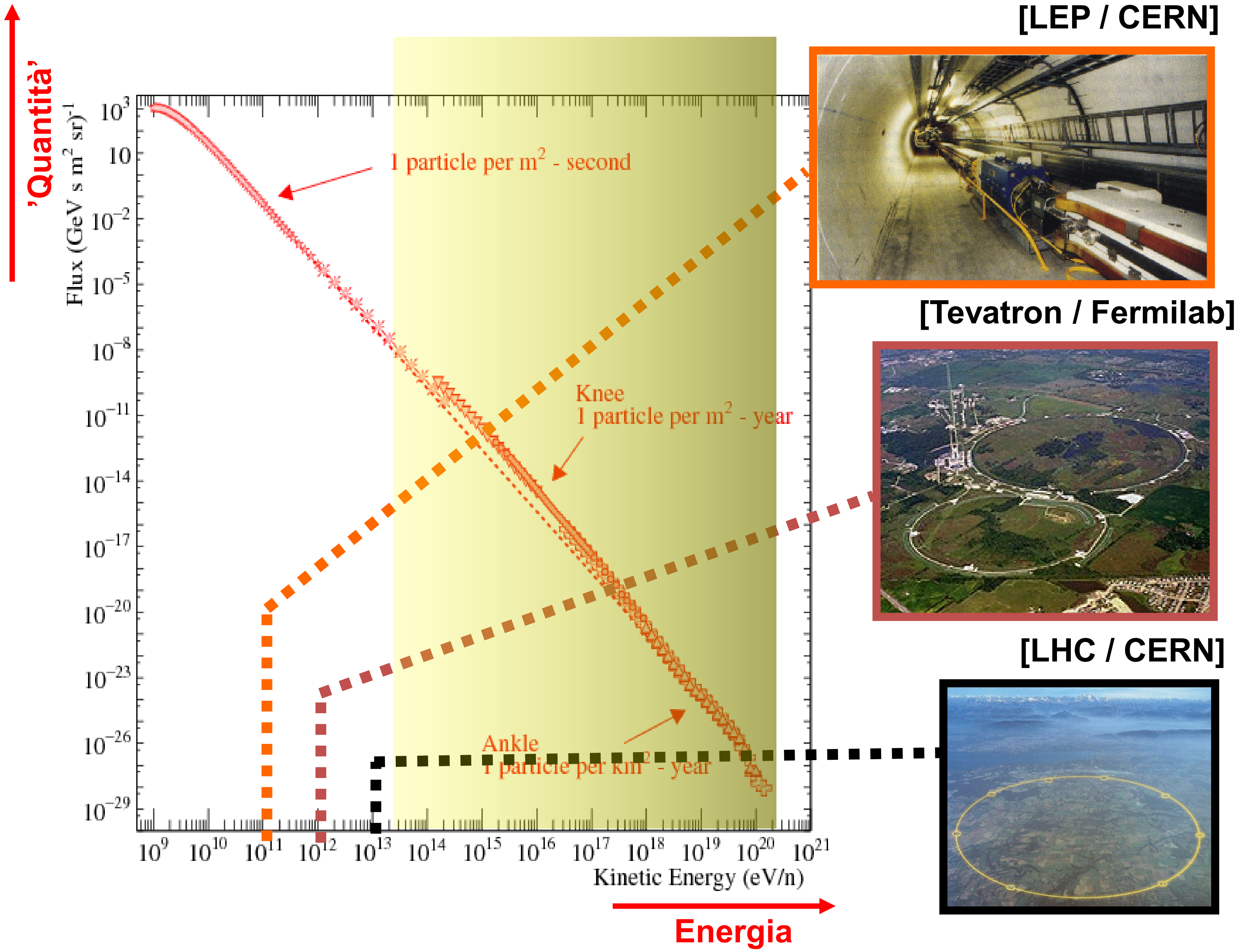
1. Annihilation cross section (or decay rate)
2. Mass of the DM particle
3. BR in the different final states

1 + 2 : Size of the signal

2 + 3 : Spectral features

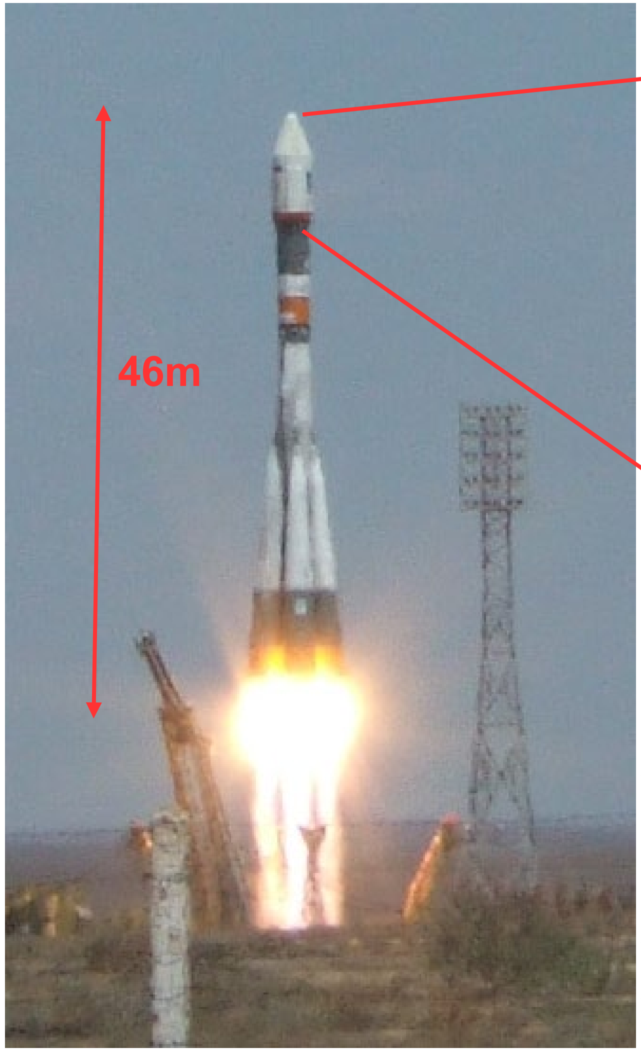


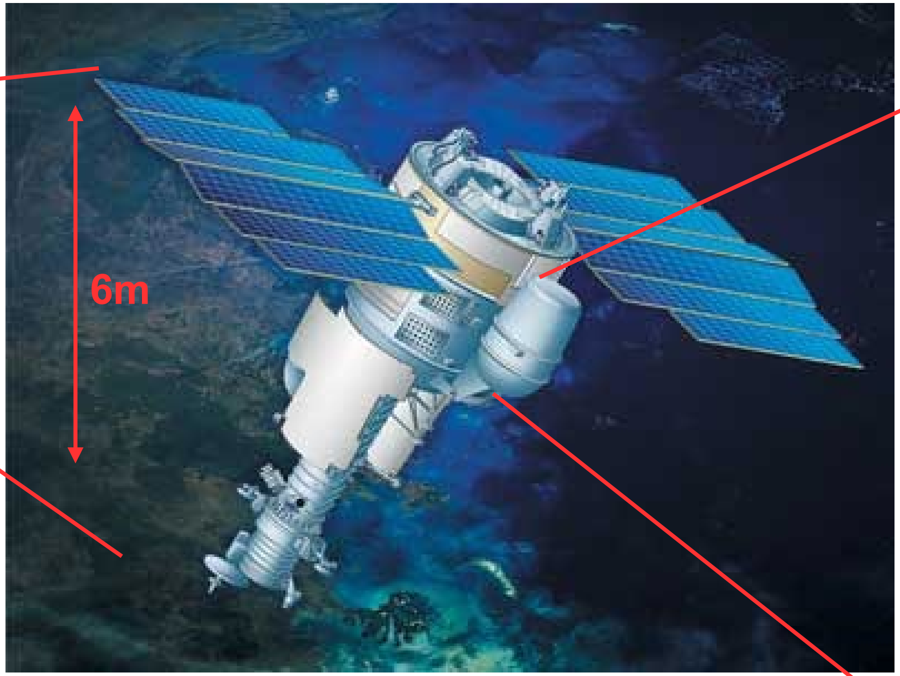
Courtesy by N. Fornengo

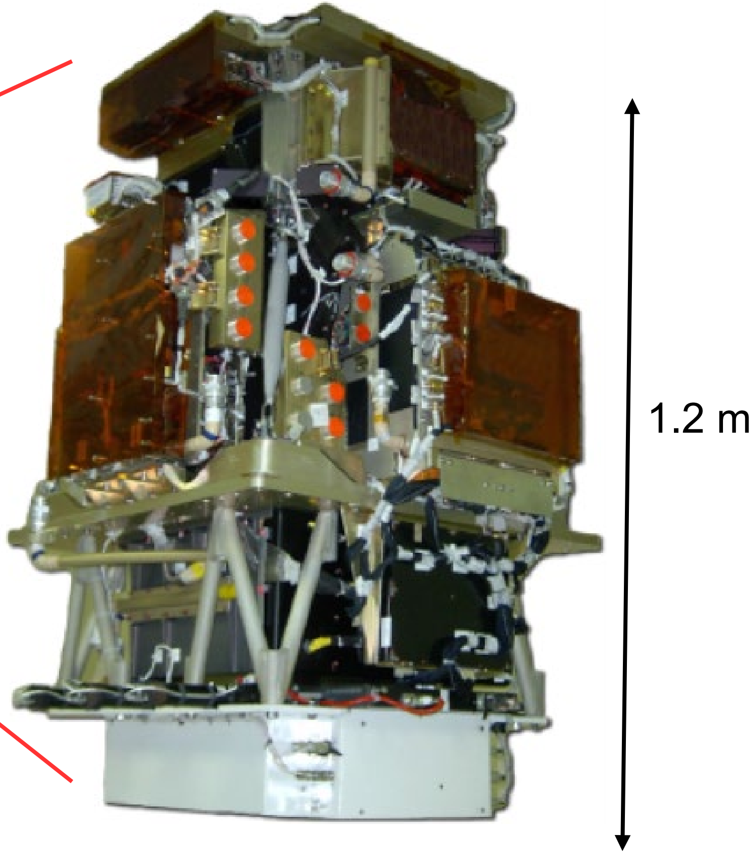


'Quantità'
Flux (GeV s m² sr)⁻¹
1 particle per m² - second
Knee
1 particle per m² - year
Ankle
1 particle per km² - year
Kinetic Energy (eV/n)
Energia
[LEP / CERN]
[Tevatron / Fermilab]
[LHC / CERN]

PAMELA: rivelatore di raggi cosmici



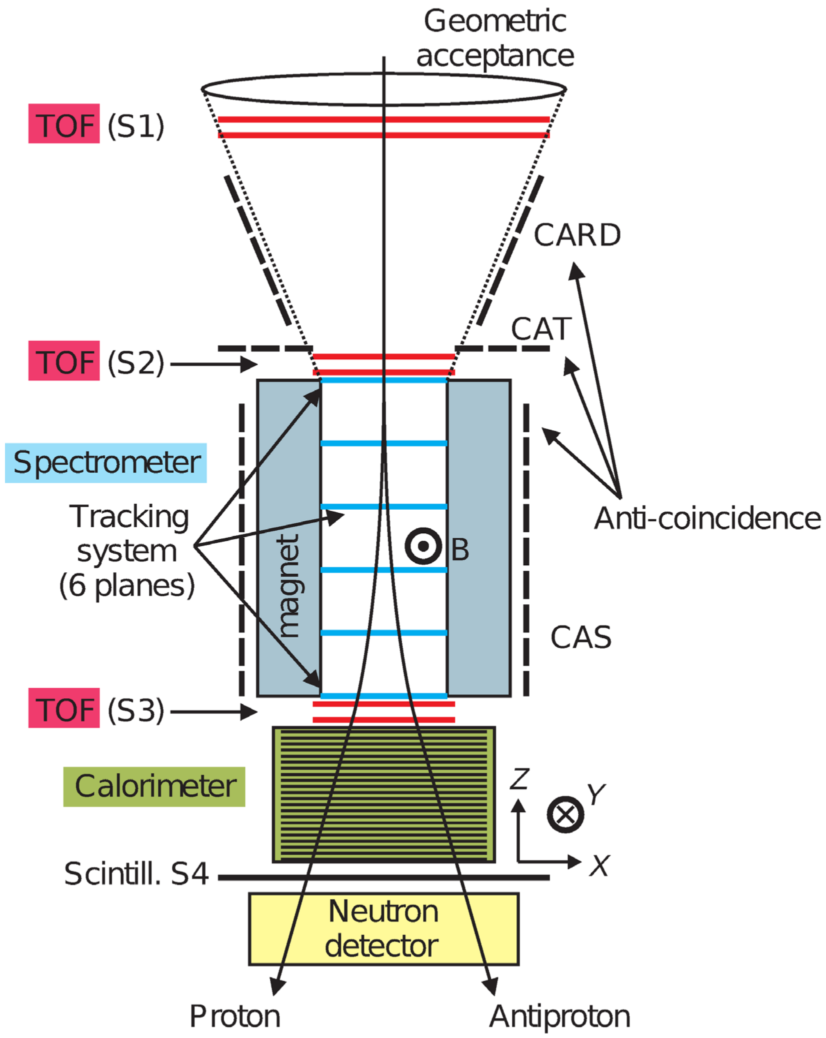




- **Rivelatore di raggi cosmici in orbita attorno alla terra.**

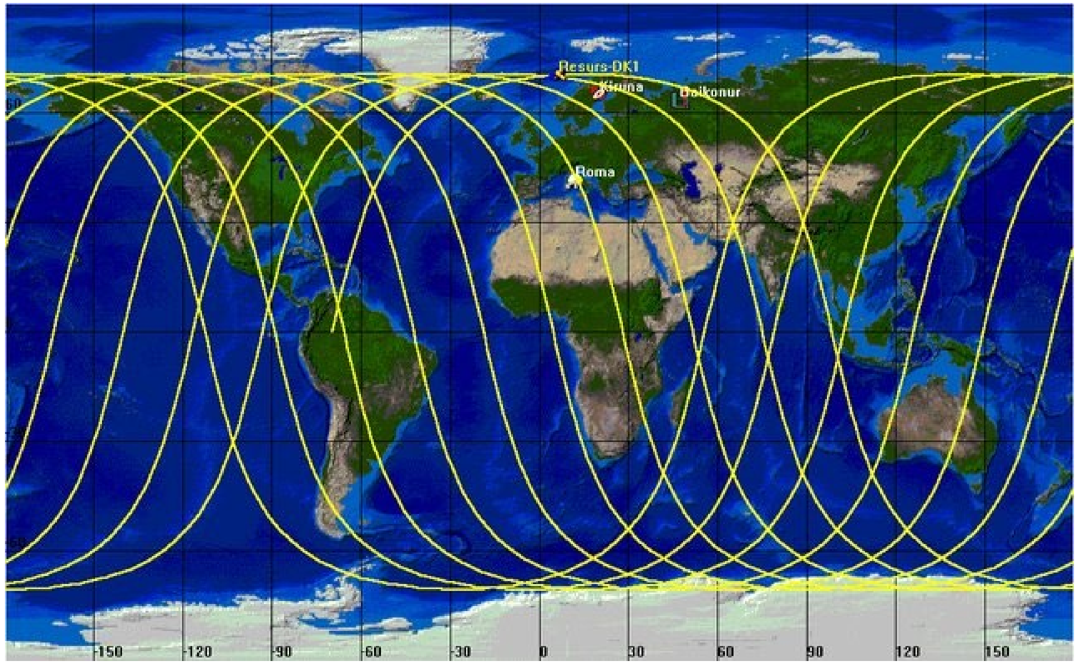
- **Lanciato il 15 giugno 2006.**
- **Ha operato fino al gennaio 2016.**

L'esperimento PAMELA: l'apparato



L'apparato misura le particelle cariche sfruttando la proprietà dei campi magnetici di curvare le particelle (Forza di Lorentz).

Le particelle di materia curvano nel verso opposto a quelle di materia. In questo modo si può misurare l'abbondanza di antimateria nei raggi cosmici.

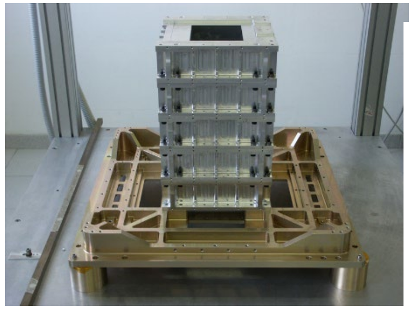


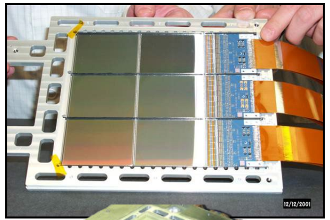
L'orbita di PAMELA. Il satellite ha volato ad un'altezza tra i 350 e i 600 km.

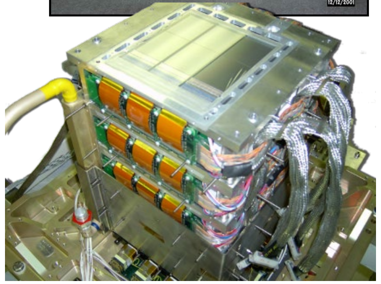
Compie un'orbita attorno alla terra ogni 90 minuti.

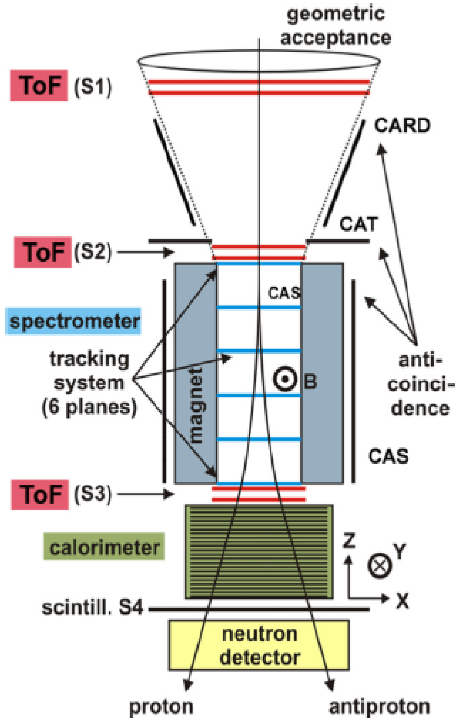
L'Apparato PAMELA

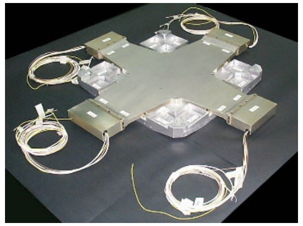
Italy: Bari, Florence, Frascati, Naples, Rome, Trieste, CNR, Florence

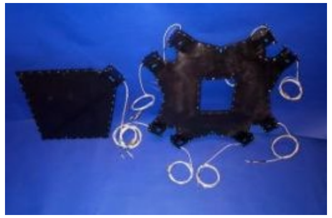


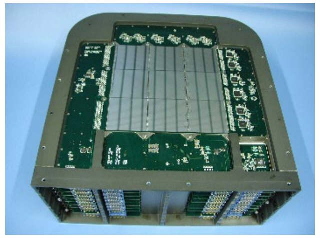


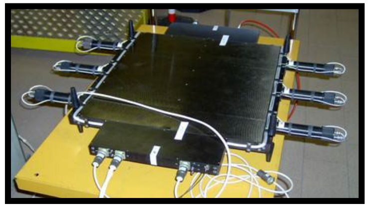


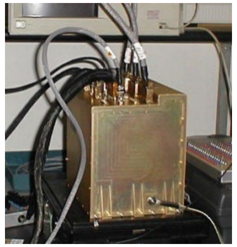










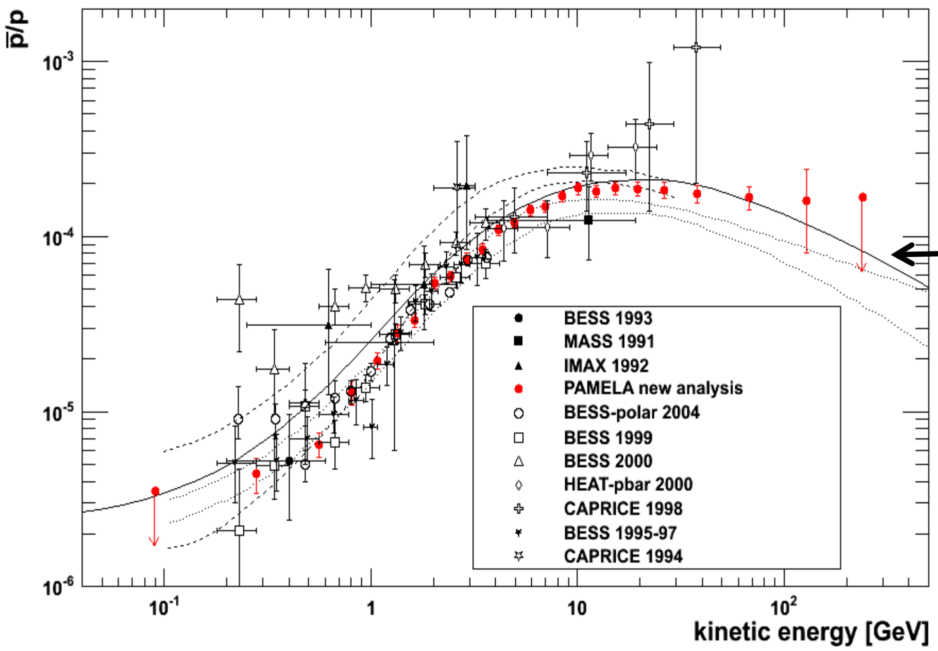


Russia: Moscow, St. Petersburg

Germany: Universität Gesamthochschule Siegen — Siegen

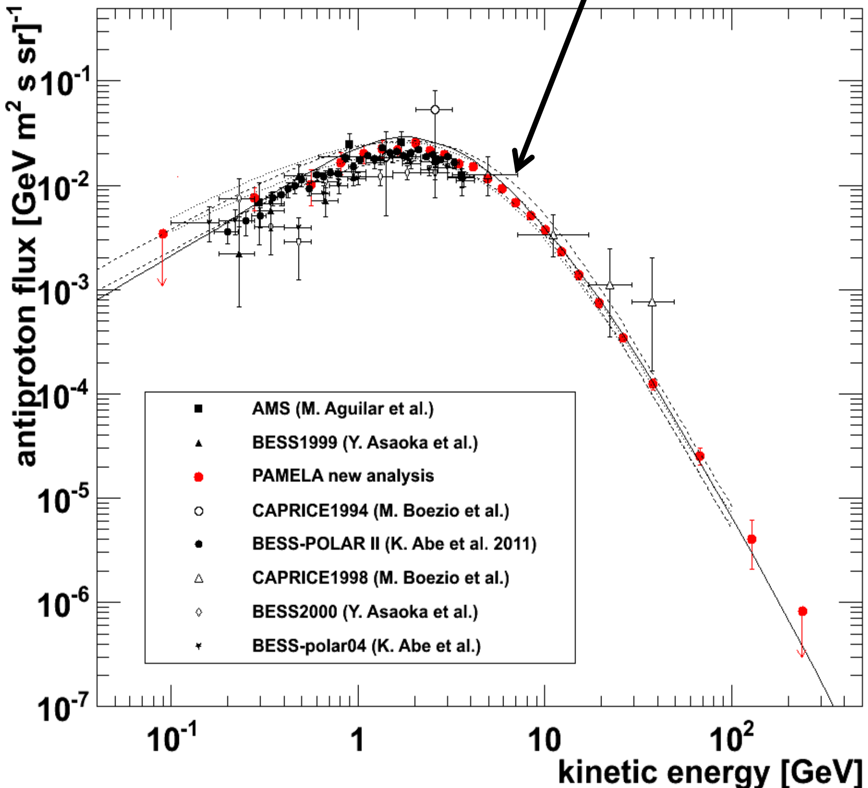
Sweden: Kungl Tekniska Högskolan — KTH, Stockholm

PAMELA Antiparticle Results: Antiprotons



O. Adriani et al,
PRL 102 (2009) 051101;
PRL 105 (2010) 121101;
Phys. Rep. 544 (2014) 323.

Secondary production calculations

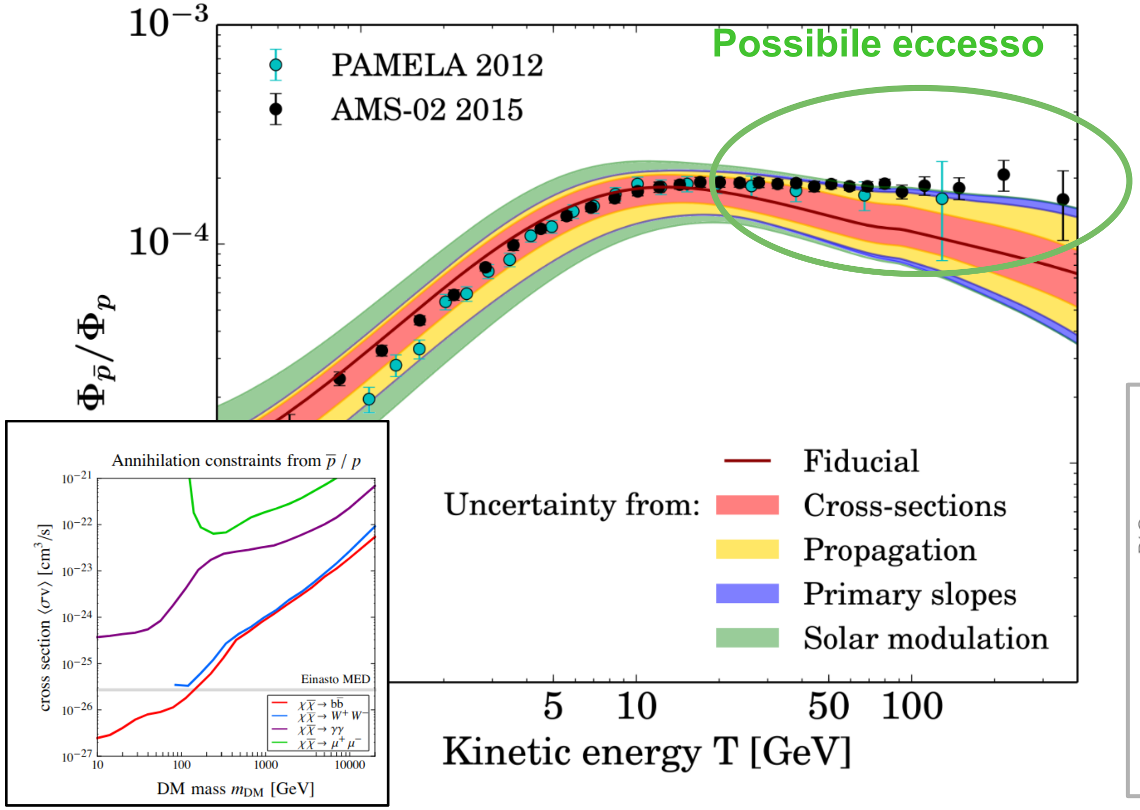


Antiprotoni e materia oscura

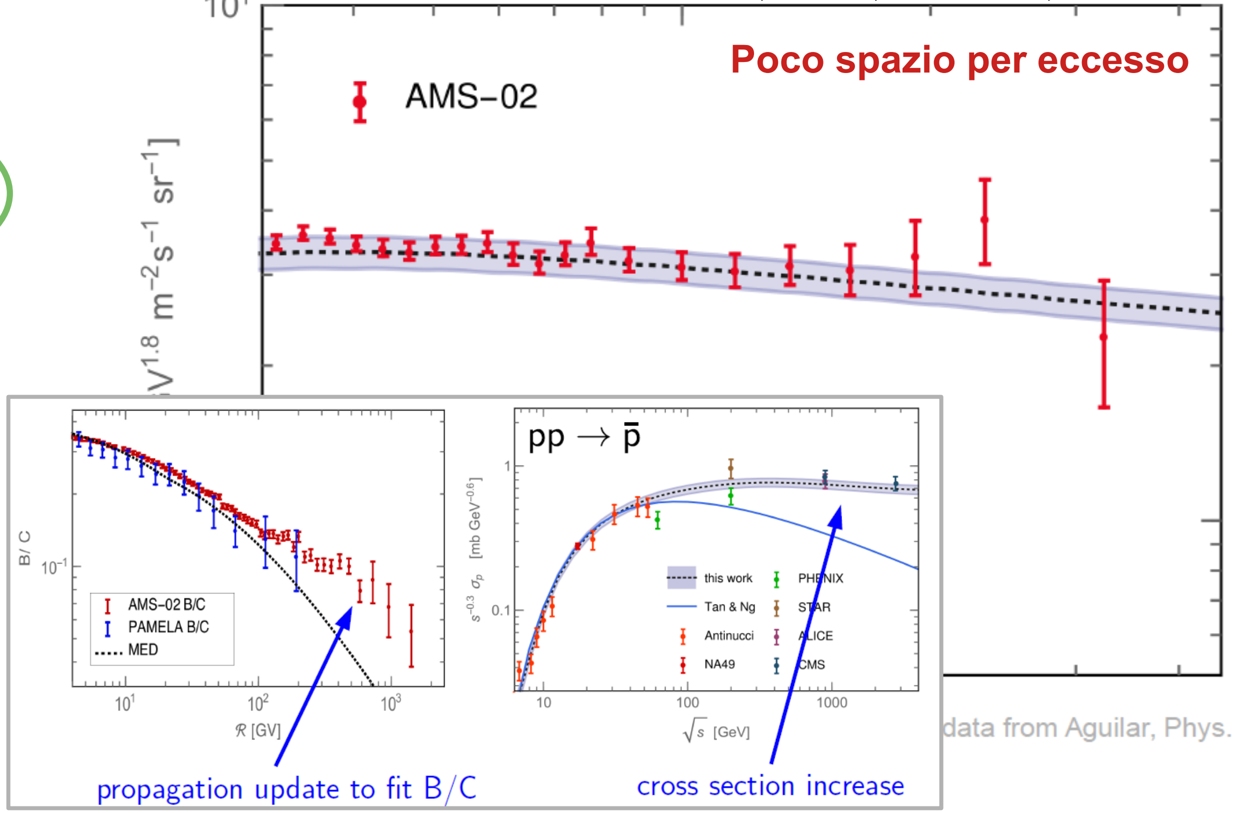
Alcune modellizzazioni della componente secondaria lasciavano spazio ad un possibile eccesso > 50 GeV

Misure aggiornate delle sezioni d'urto e dei modelli di propagazione riducono significativamente lo spazio per un eccesso…

Giesen G. et al., JCAP09(2015)023

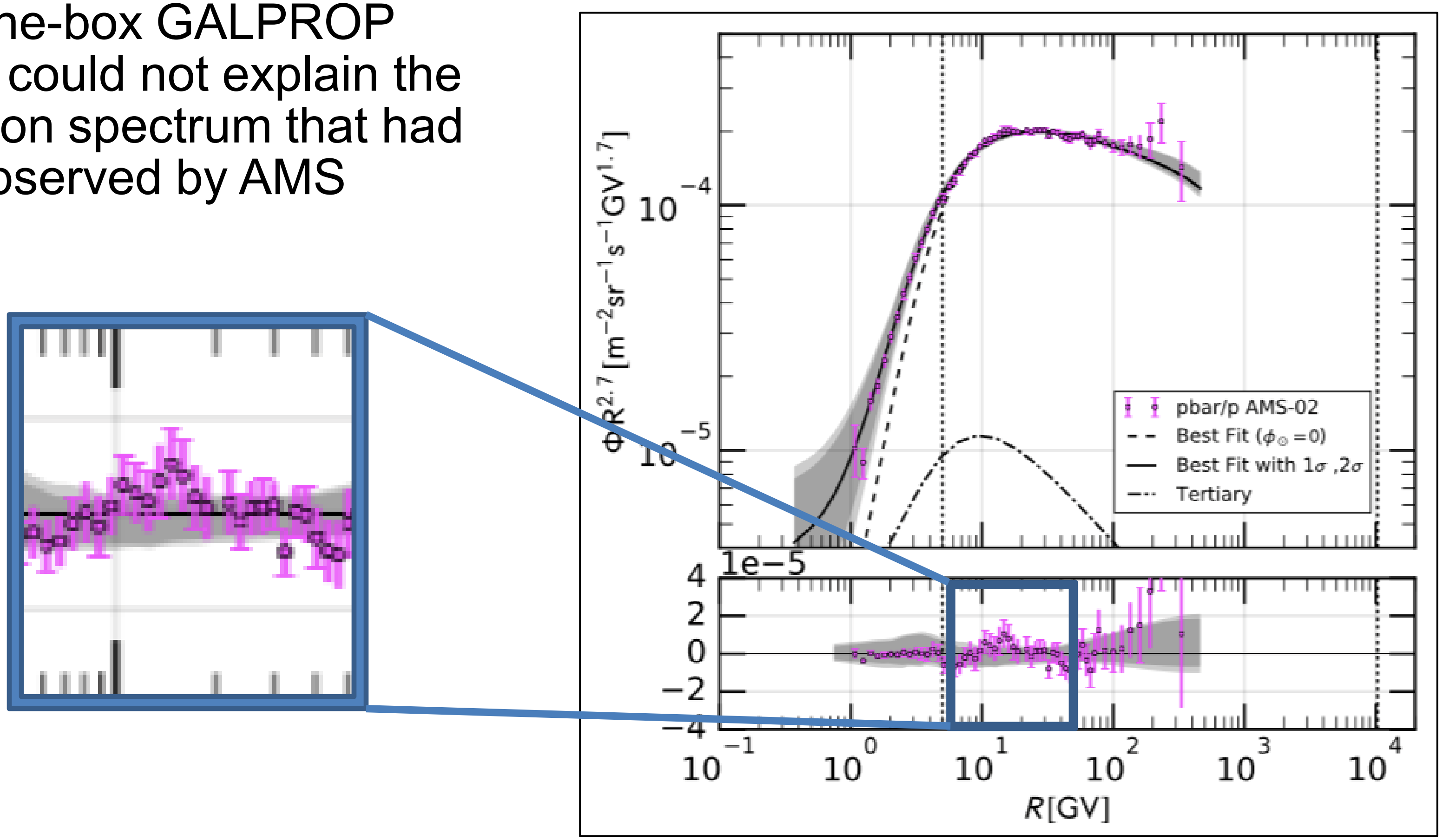


M. Winkler, Dbar19, March 2019, UCLA



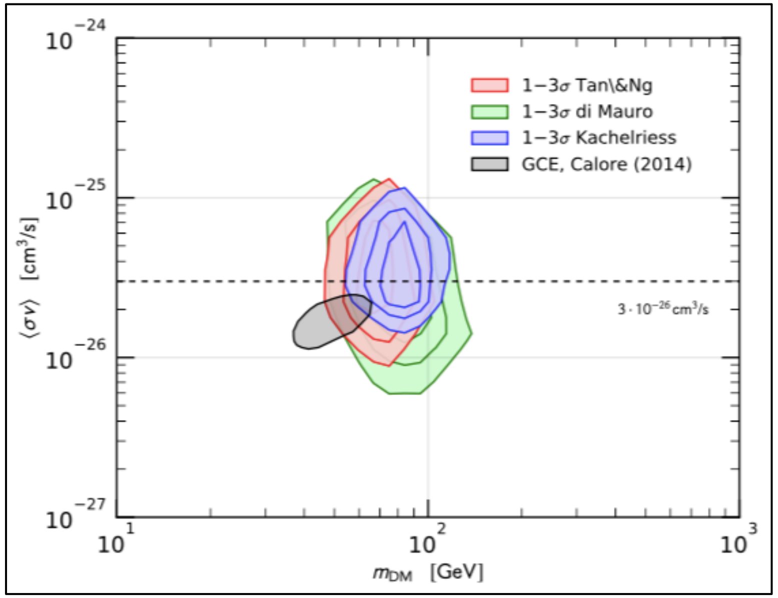
The Antiproton Excess

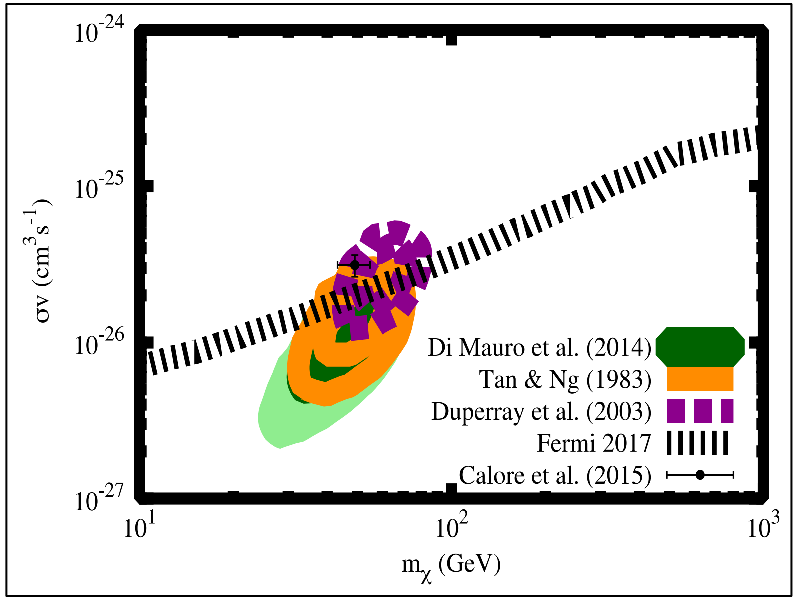
- The AMS antiproton excess was pointed out in 2016 by two independent groups (Cuoco, Krämer, Korsmeier and Cui, Yuan, Tsai, Fan)
- Both papers identified a small, but statistically significant excess (~4.5**σ**)
- These papers made it clear that out-of-the-box GALPROP models could not explain the antiproton spectrum that had been observed by AMS



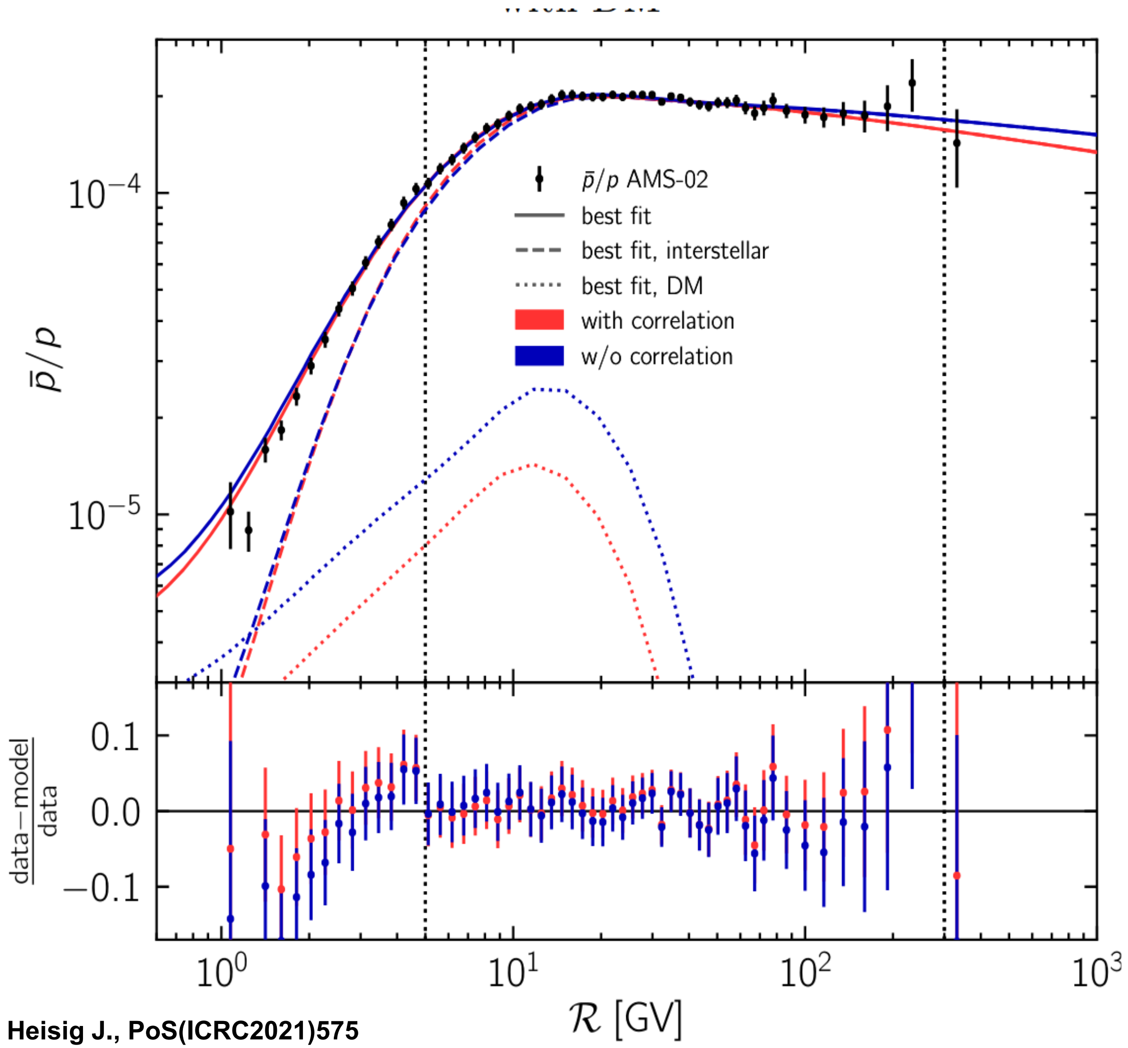
Concordance With The Galactic Center Gamma-Ray Excess

- The range of dark matter models that could potentially account for the antiproton excess are similar to those that are required to generate the excess of GeV-scale gamma rays observed from the Galactic Center
- A ~40-70 GeV dark matter candidate with a thermal annihilation cross section (**σ**v ~2x10^{-26} cm^3/s) could account for both of these signals





Antiprotoni AMS02: basse energie



Heisig J., PoS(ICRC2021)575

Includento la correlazione tra le sorgenti di errore sistematico (assunzioni fatte dagli autori e non dalla collaborazione AMS02) e usando i dati di AMS02 dopo 7 anni di presa dati la significanza dell'eccesso diminuisce significativamente.

"Here, we have considered another source of uncertainties, namely correlations in the AMS-02 systematic errors... The most relevant of these stem from cross sections for cosmic-ray absorption in the detector… Their inclusion reveals that the excess is not robust."

A Worldwide Success

Top 10, 2008

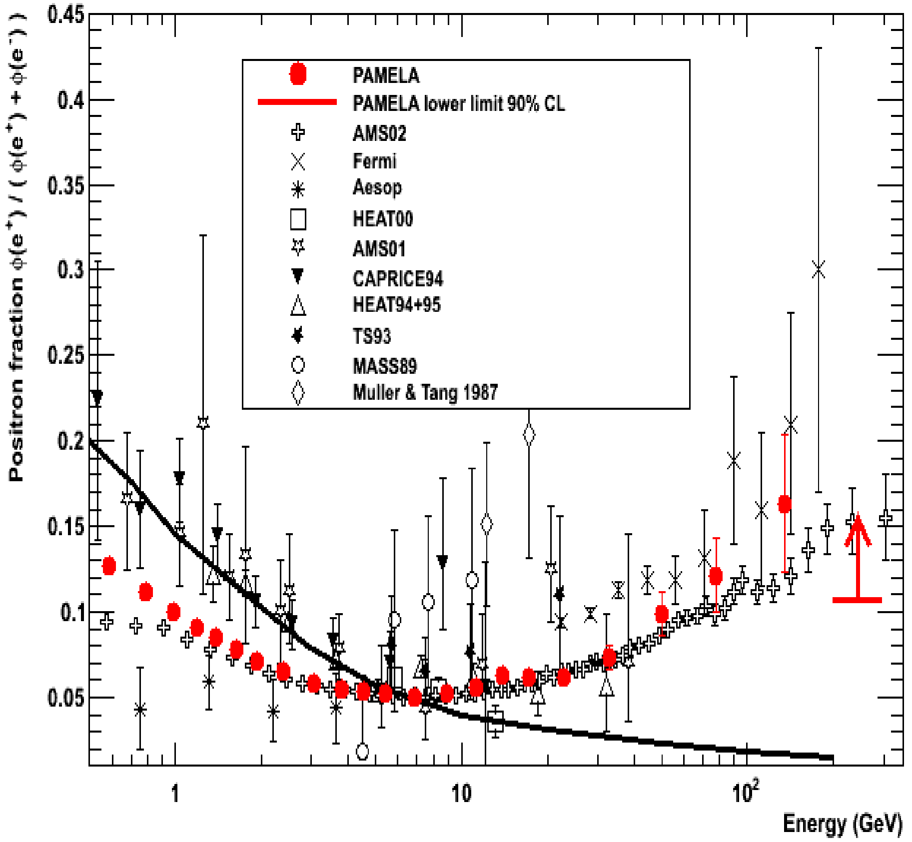
Vol 458|2 April 2009|doi:10.1038/nature07942 nature

LETTERS

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bonvicini[8], S. Bottai[2], A. Bruno[6,7], F. Cafagna[7], D. Campana[4], P. Carlson[10], M. Casolino[11], G. Castellini[12], M. P. De Pascale[11,13], G. De Rosa[4], N. De Simone[11,13], V. Di Felice[11,13], A. M. Galper[14], L. Grishantseva[14], P. Hofverberg[10], S. V. Koldashov[14], S. Y. Krutkov[9], A. N. Kvashnin[5], A. Leonov[14], V. Malvezzi[11], L. Marcelli[11], W. Menn[15], V. V. Mikhailov[14], E. Mocchiutti[8], S. Orsi[10,11], G. Osteria[4], P. Papini[2], M. Pearce[16], P. Picozza[11,13], M. Ricci[17], S. B. Ricciarini[2], M. Simon[15], R. Sparvoli[11,13], P. Spillantini[1,2], Y. I. Stozhkov[5], A. Vacchi[8], E. Vannuccini[2], G. Vasilyev[9], S. A. Voronov[14], Y. T. Yurkin[14], G. Zampa[8], N. Zampa[8] & V. G. Zverev[14]

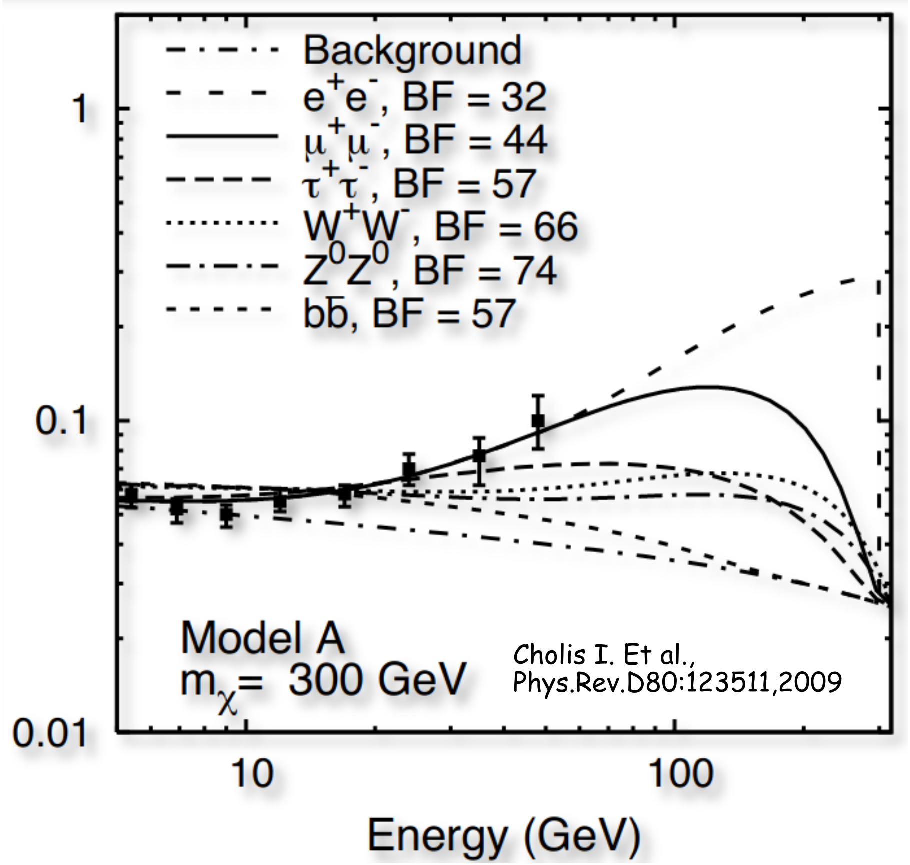
1921 citations and counting (source Scopus)

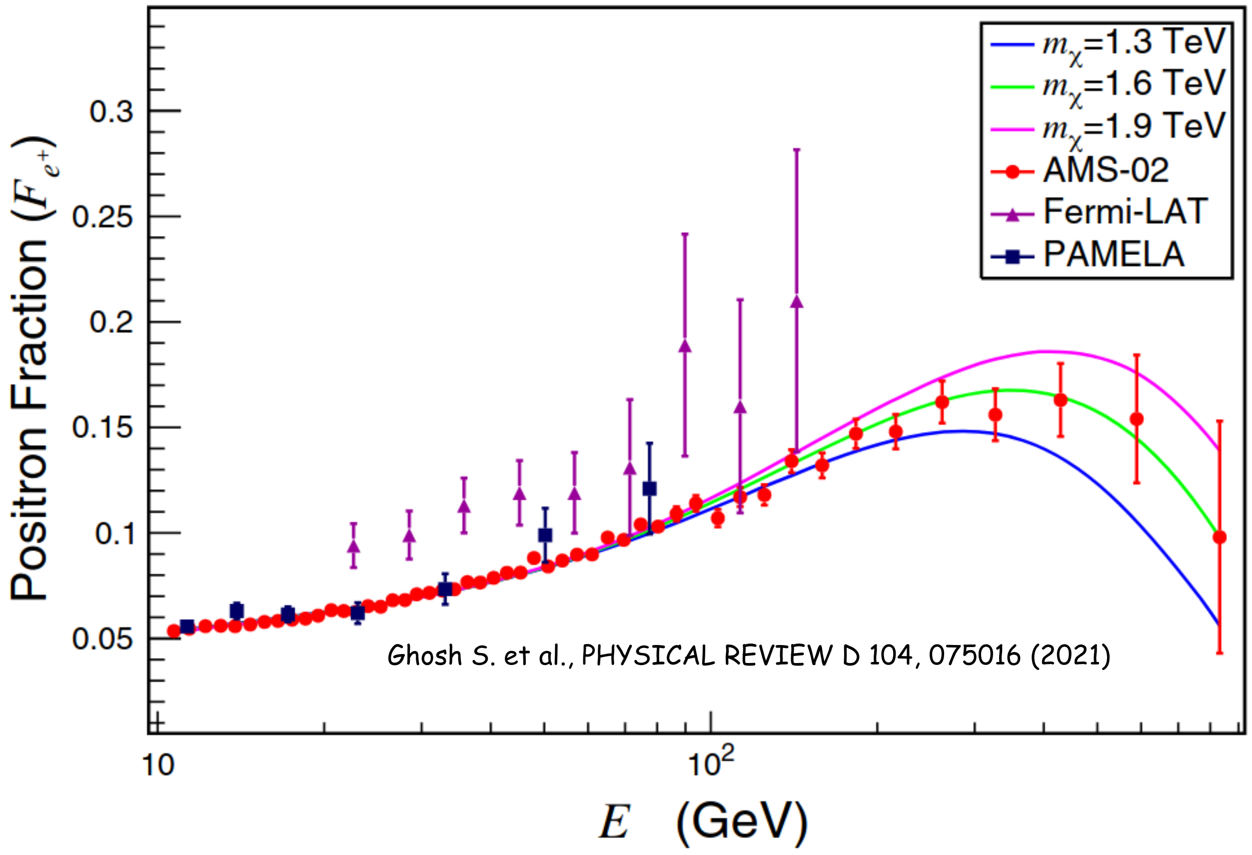


Eccesso di positroni e materia oscura

Annichilazione di materia oscura → grande sezione d'urto, boost factor richiesto, leptophilic models

Dopo le misure di AMS02 i modelli che accomodano la materia oscura vedono masse piu` grandi 1-3 TeV





Produzione di positroni da Pulsar

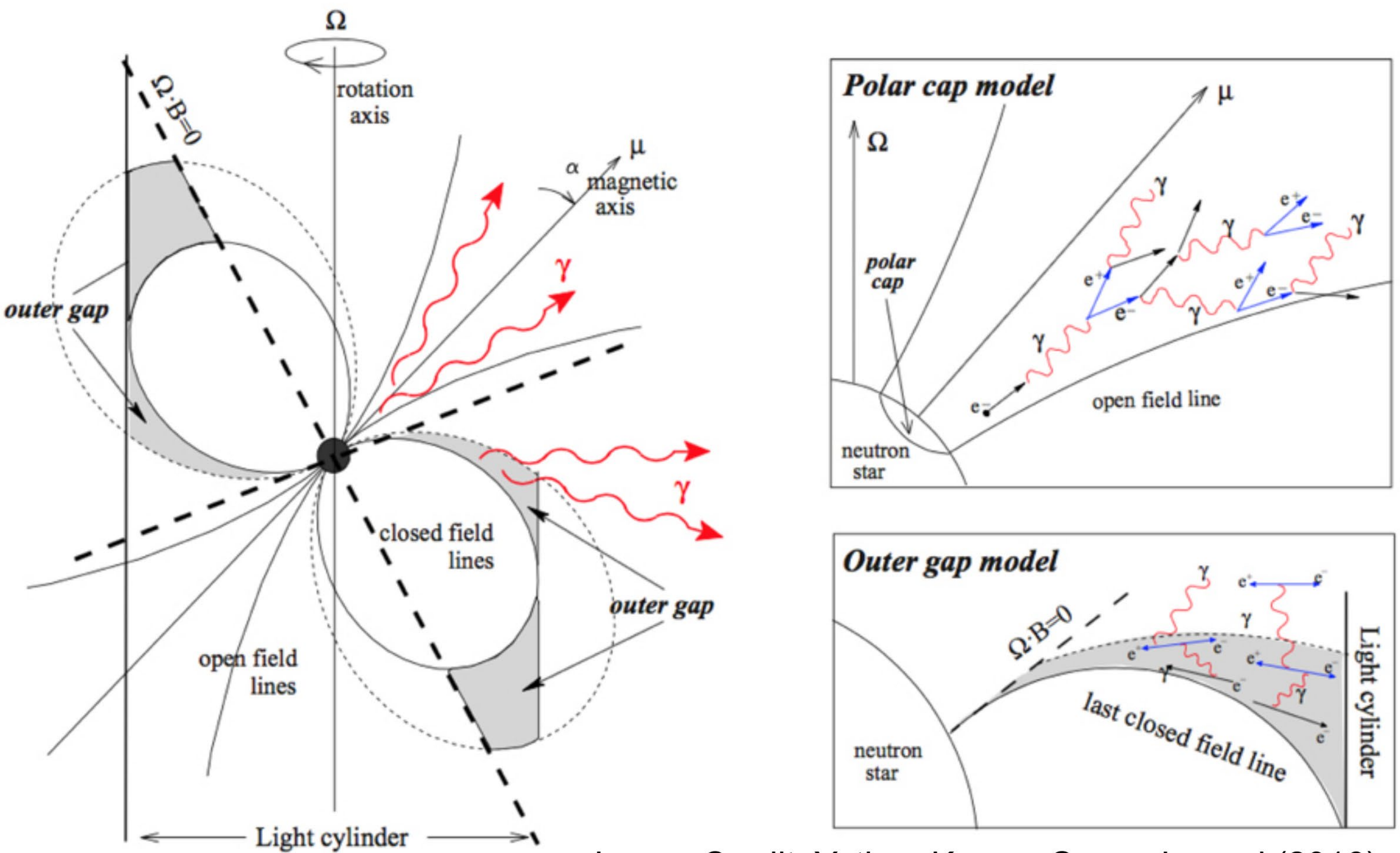
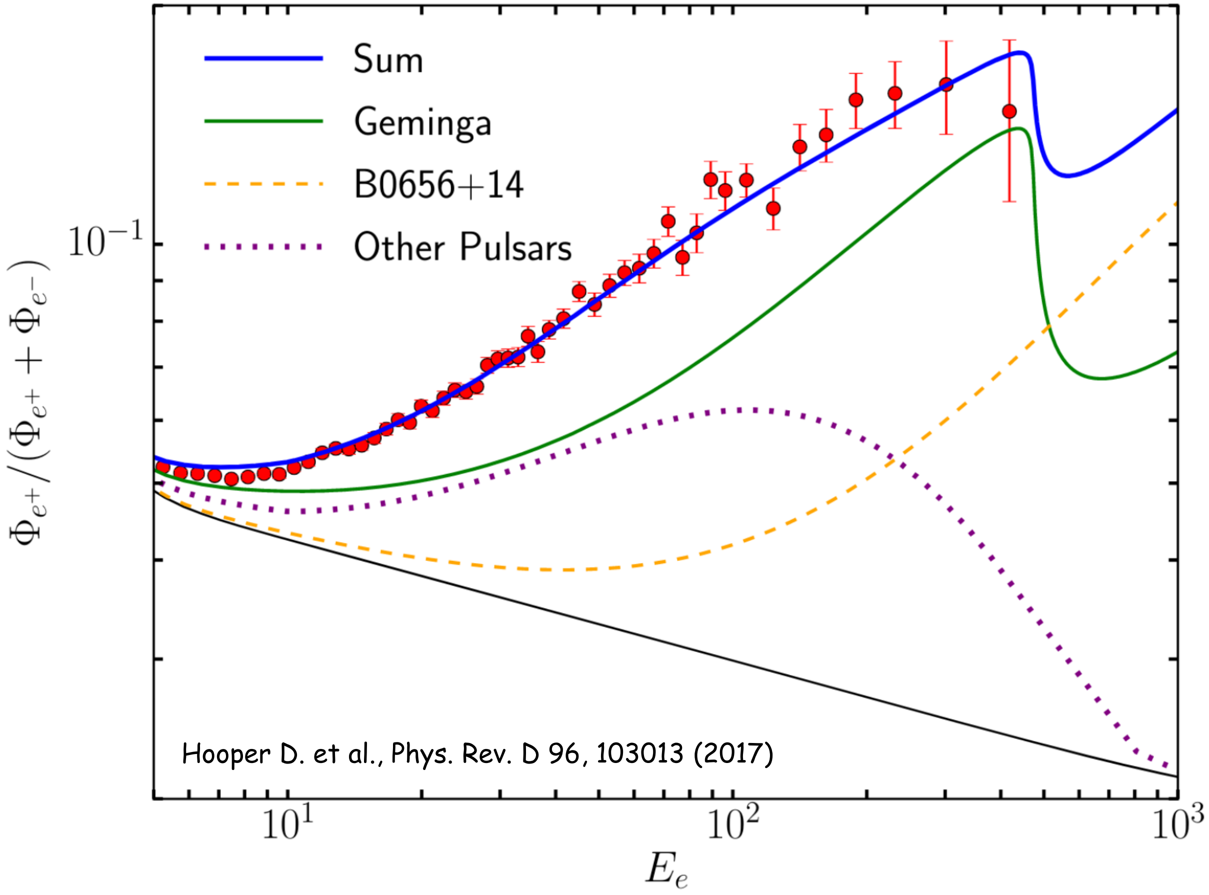
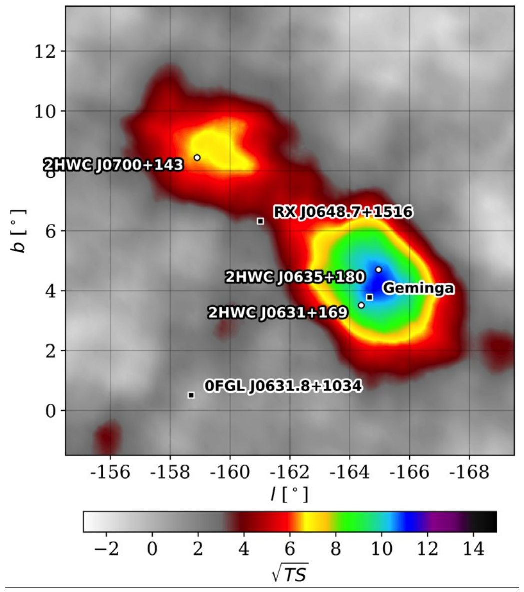


Image Credit: Yating, Kwong-Sang, Jumpei (2016)

-Electrons are accelerated by the strong magnetic fields, somewhere in the magnetosphere (the location is model dependent)
-These electrons then induce electromagnetic cascades through the emission of curvature radiation
-This results in the production of photons with energies above the threshold for pair production in the strong magnetic field
-These electrons and positrons then escape the magnetosphere through open field lines, or after reaching the pulsar wind

Produzione di positroni da Pulsar





Emissione gamma (HAWC) da GEMINGA da Inverse Compton. Usato per modellizzare il meccanismo di emissione dei positroni ed elettroni.

"What the HAWC data tell us is that below ~10 TeV or so, electrons leave the region surrounding Geminga before they lose the majority of their energy"

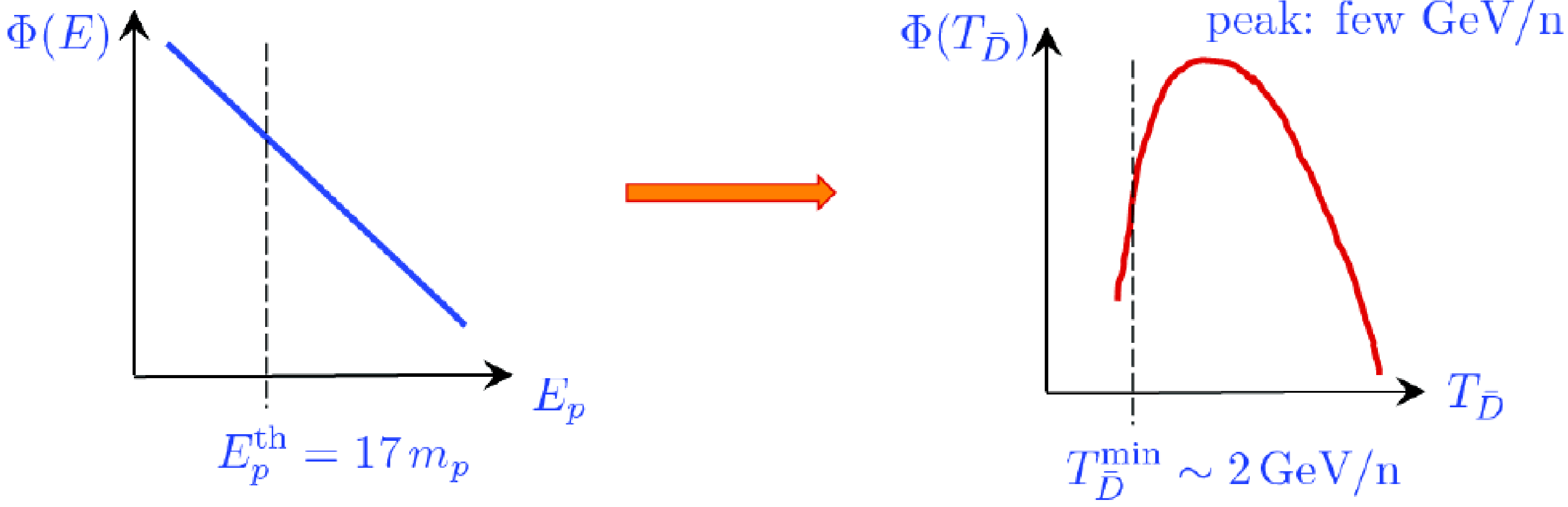
"In light of this result, we conclude that it is very likely that pulsars provide the dominant contribution to the long perplexing cosmic-ray positron excess"

Background “free” Signals?

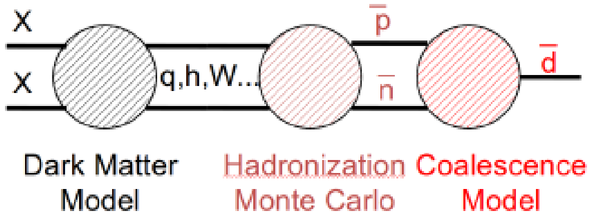
Antinuclei

Why Anti-Deuterium? Background

$$\underbrace{p_{CR}} + \overbrace{p_{ISM}}^{\text{at rest}} \longrightarrow \bar{p}\bar{n} + pn + pp$$



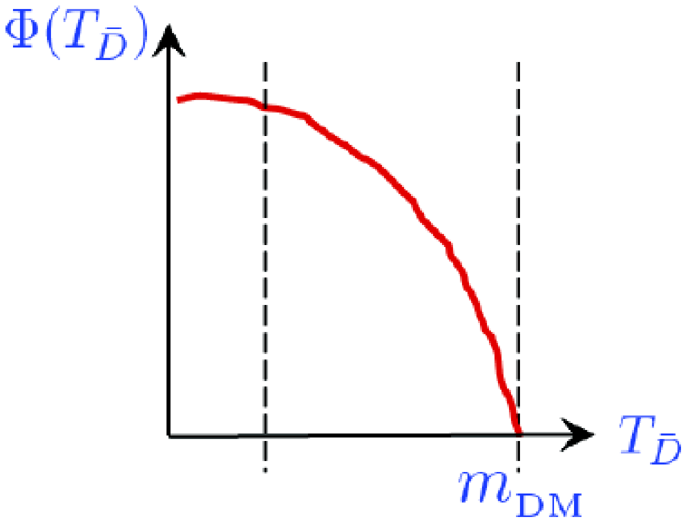
Why Anti-Deuterium? Signal



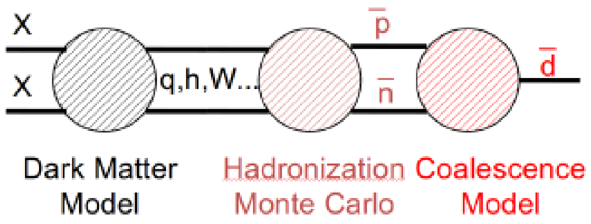
AntiDeuteron Flux

$$\phi(\bar{D}) \propto <\sigma v>_{\text{annihilitaion}} \left(\frac{\rho_{DM}}{M_{DM}}\right)^2 \otimes (\text{cohalescence } p_0)^3 \otimes \text{propagation}$$

$$\underbrace{\chi}_{\text{at rest}} + \overbrace{\chi}^{\text{at rest}} \longrightarrow \bar{p}\bar{n} + pn$$



Why Anti-Deuterium? Signal



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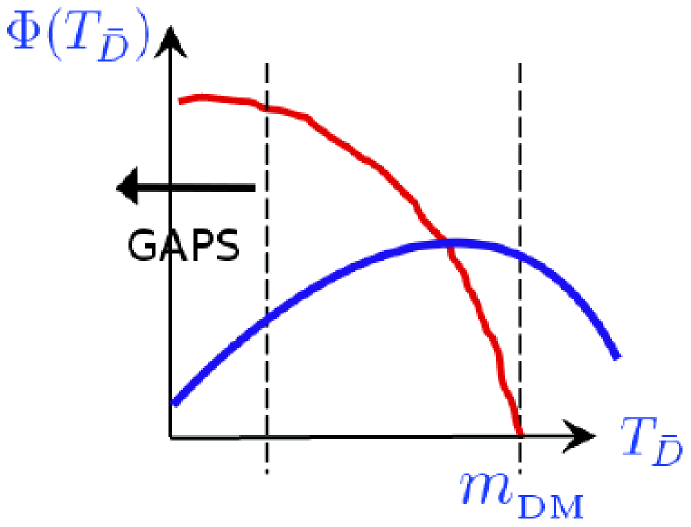


The GAPS experiment

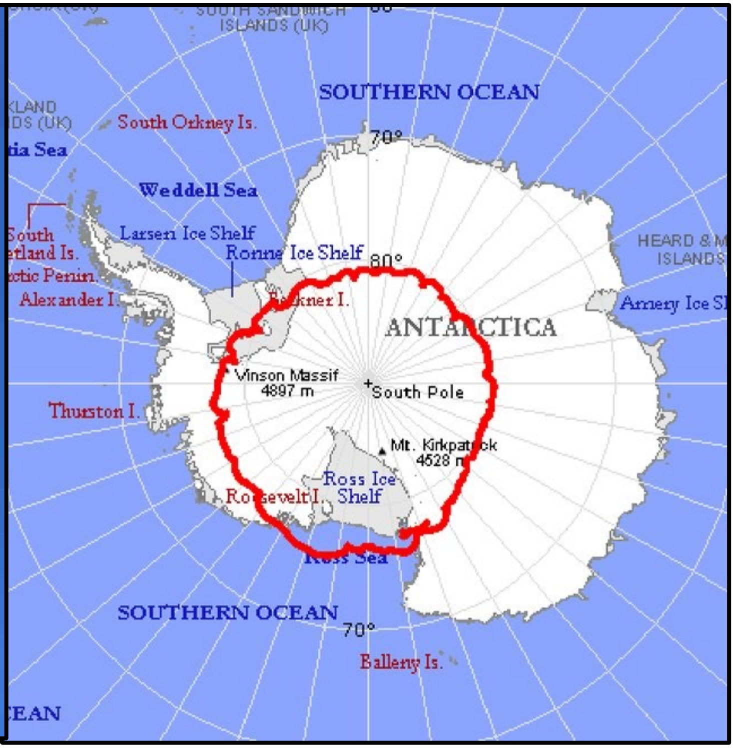
- International collaboration between US, Japanese, and Italian institutes

NASA
NSF
Alfred P. Sloan FOUNDATION
HEISING-SIMONS FOUNDATION
COLUMBIA UNIVERSITY
MIT Massachusetts Institute of Technology
UNIVERSITY of HAWAI'I MĀNOA
UCLA
Berkeley UNIVERSITY OF CALIFORNIA
SLAC
Lawrence Livermore National Laboratory
UC San Diego
PennState
OAK RIDGE National Laboratory

JAXA
科研費 KAKENHI
公益財団法人 住友財団
公益財団法人 三菱財団 THE MITSUBISHI FOUNDATION
AOYAMA GAKUIN UNIVERSITY
TOKAI UNIVERSITY
KU
SHINSHU UNIVERSITY

INFN Istituto Nazionale di Fisica Nucleare
asi agenzia spaziale italiana

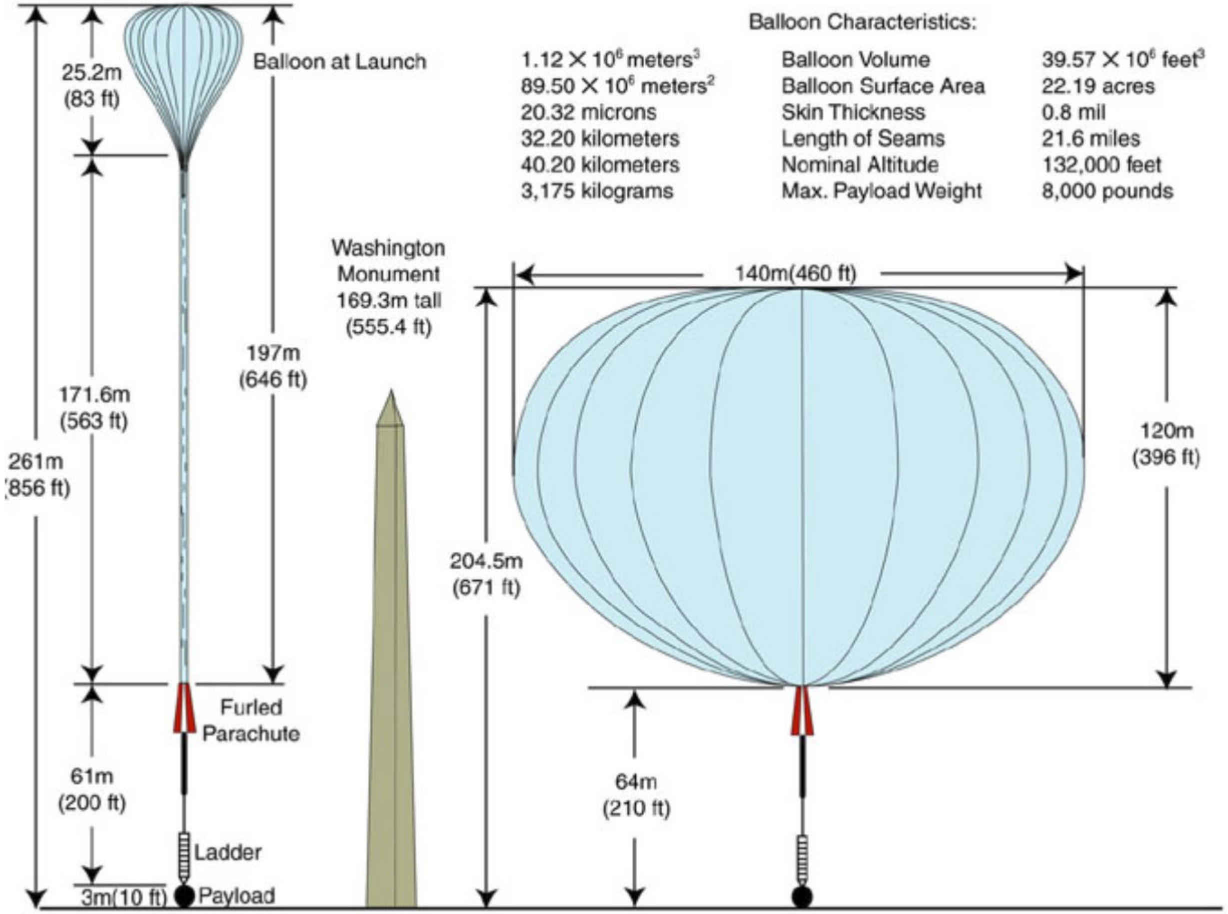
L’esperimento GAPS: il volo

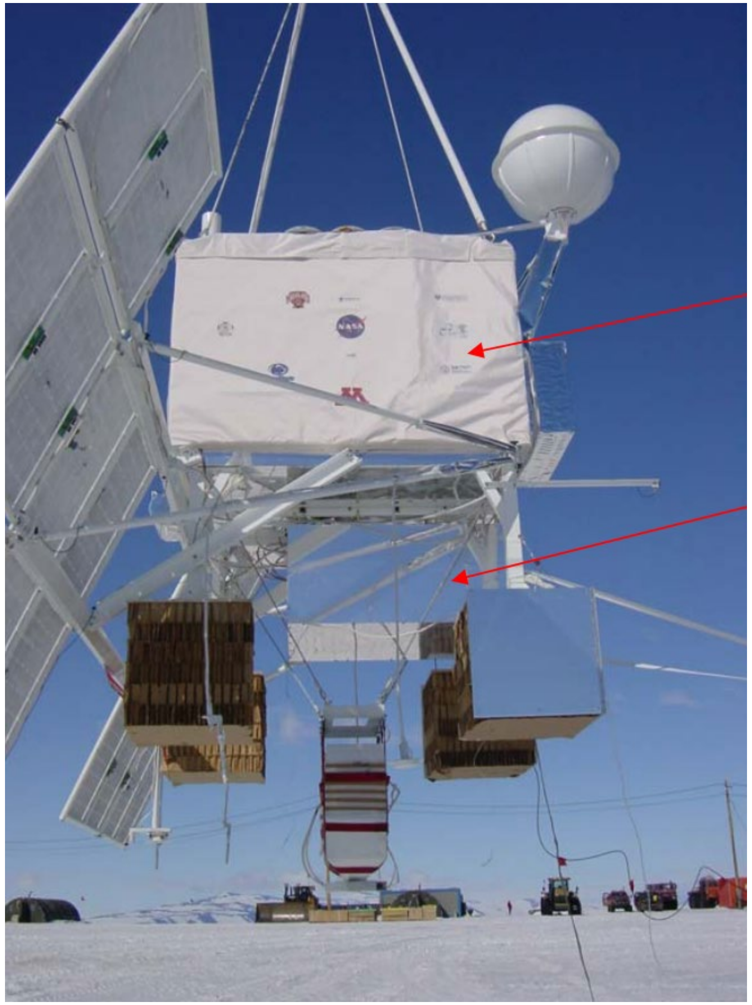


L’esperimento GAPS è un rivelatore di antinuclei nella radiazione cosmica.

Un esperimento NASA con la collaborazione italiana, anche dell’INFN di Trieste, e giapponese.
Attualmente in costruzione, il lancio avverrà con un pallone aerostatico nel 2023 dall’Antartide.
Il volo durerà circa 40 giorni dopodiché` lo strumento verrà recuperato per futuri lanci.

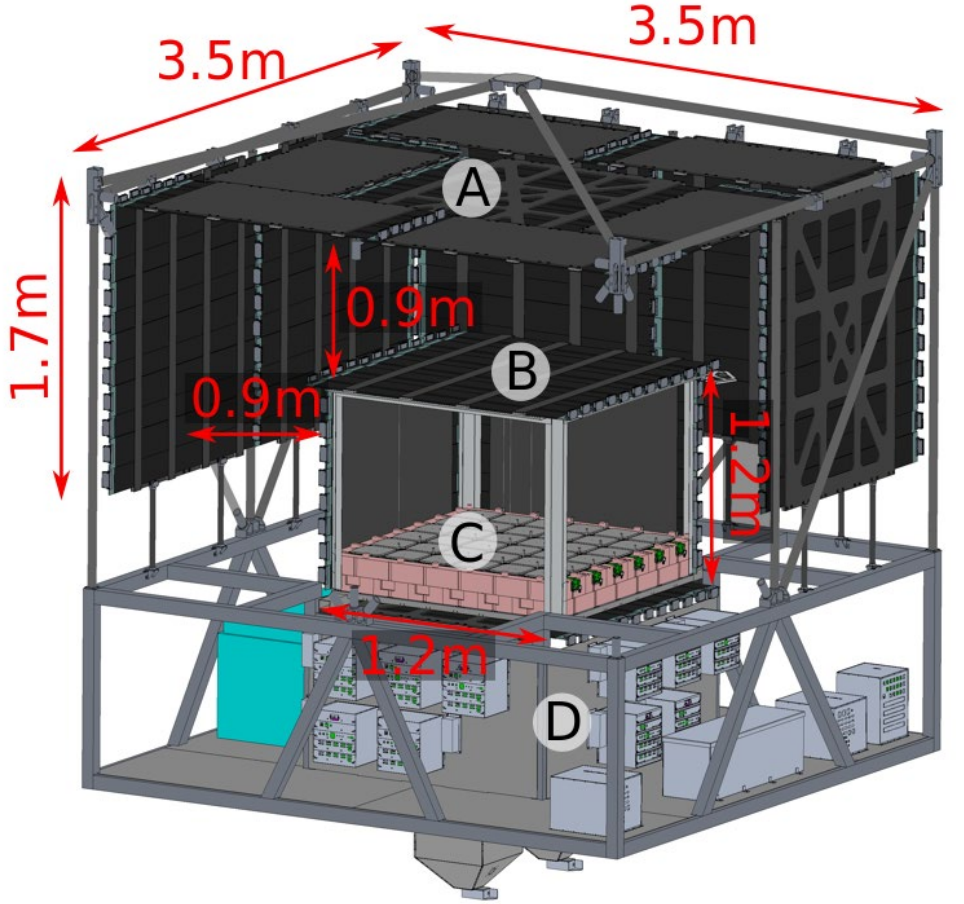
L'esperimento GAPS: il lancio

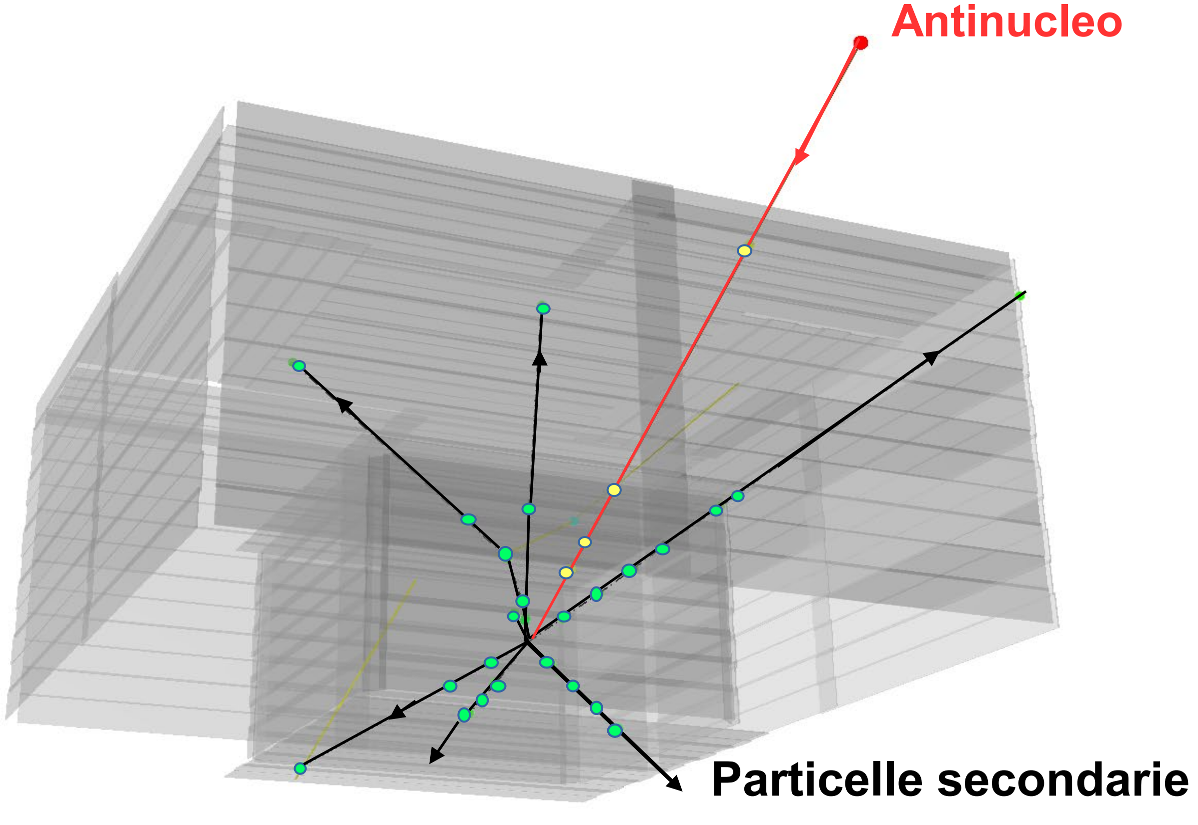




L'esperimento GAPS: l'apparato

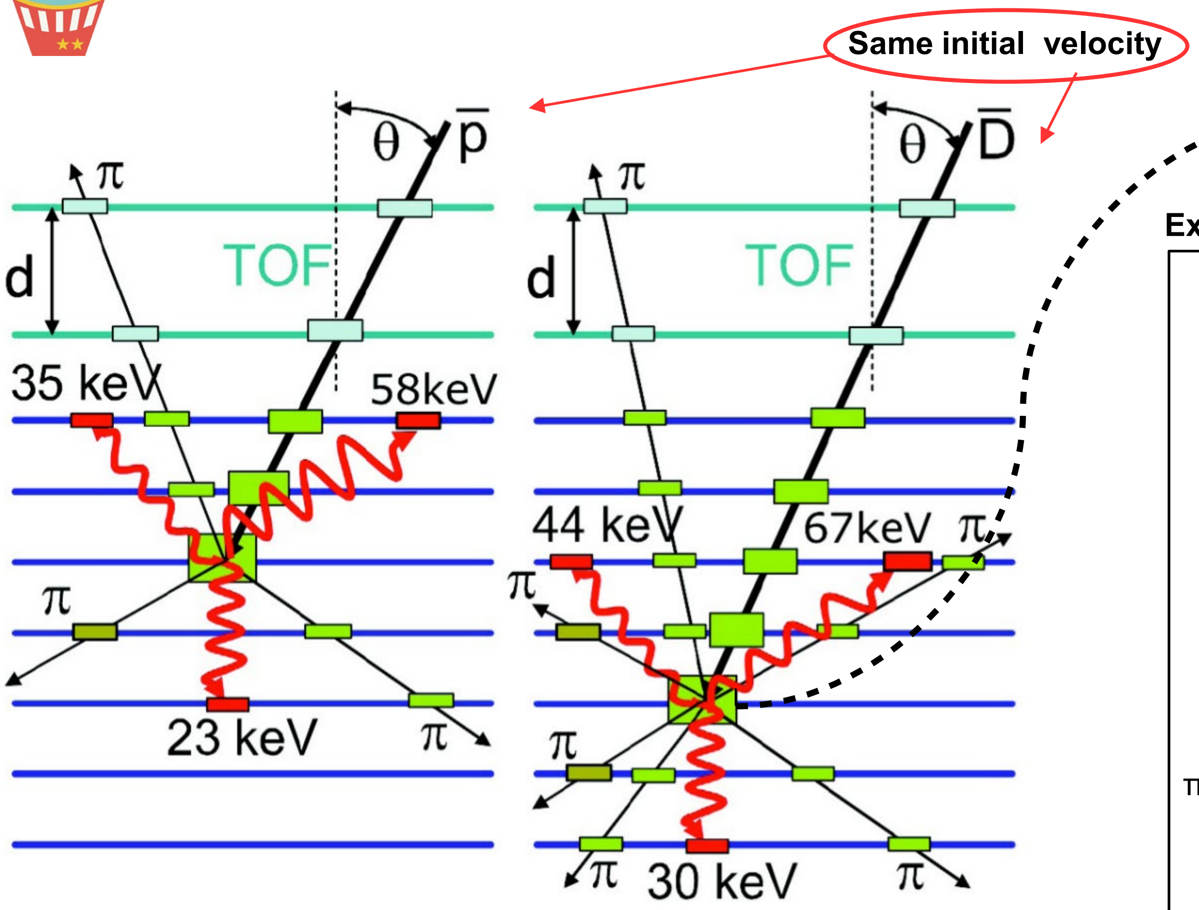
Visione schematica dell'apparato GAPS

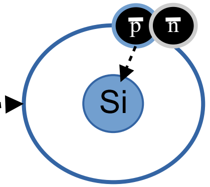




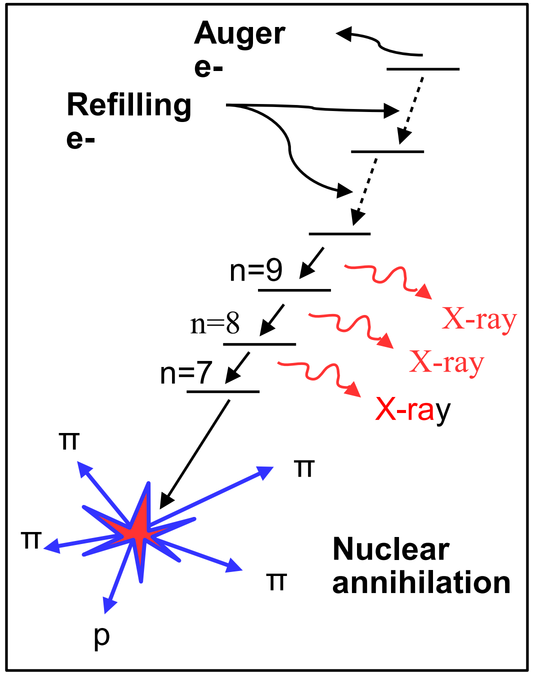
Cerchiamo degli eventi con una struttura a "stella"

GAPS detection technique





Exotic nucleus – atomic transitions

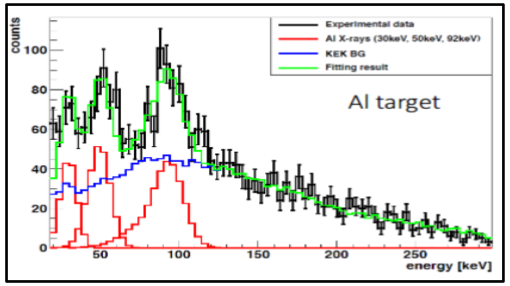


Stopping particles inside tracker volume

AntiD - antiP identification

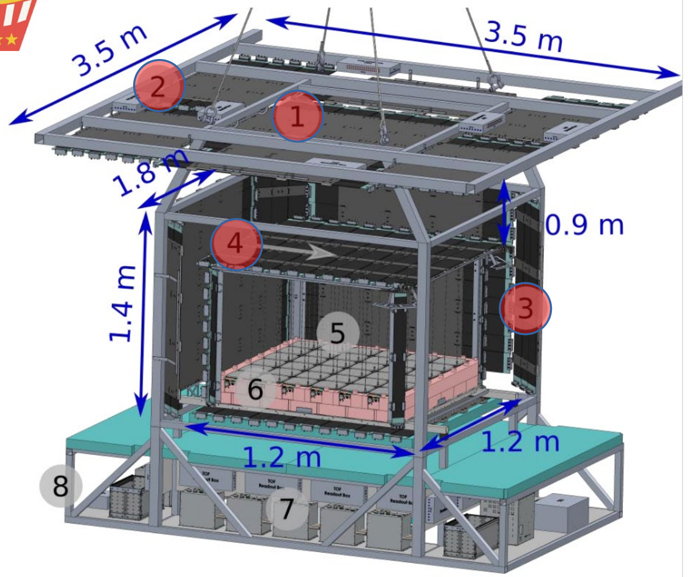
- Time of flight
- Depth - multiple dEdx
- X-rays emission
- Pion multiplicity

Aramaki et al. Astro.Ph. 49 (2013) 52

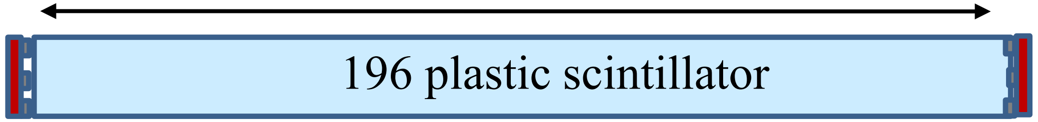


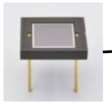
X-raymeasured at KEK in 2004/2005

TOF system



- Velocity measurements
- High speed trigger and veto
- dE/dx measurements





Si-PMs (x6)
Better performance
Save mass, power, cost

Trigger based on:

- **Beta**: rejects high beta particles.
- **Charge**: rejects high Z particles.
- **Hit**: count the number of paddles hit.

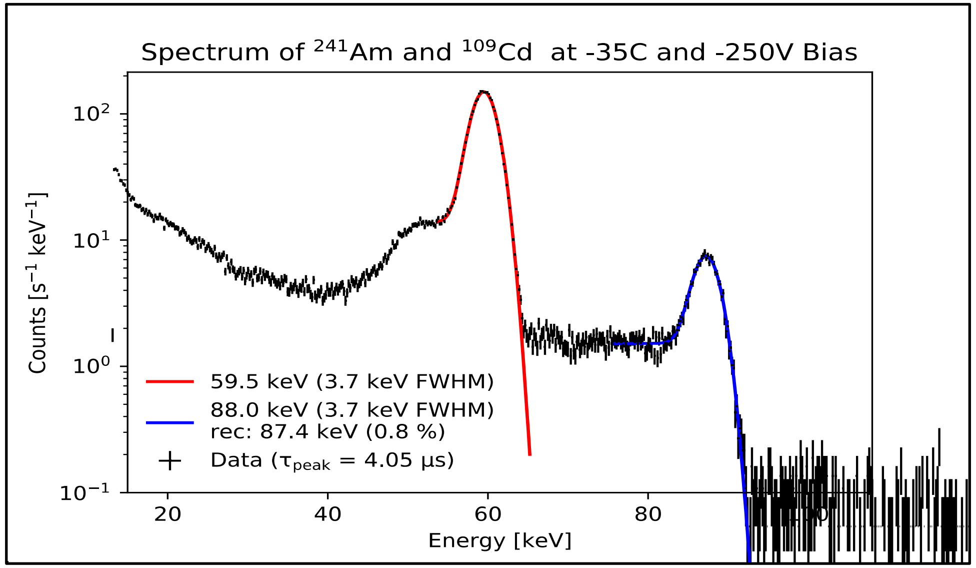
Expected Trigger Rates (H, He, C)
Raw : 82,000 Hz → After cuts : 550 Hz

Antiprotons Trigger		60%
Antideuterons Trigger		76%
Proton Rejection Factor		>2500

1.8m SiPM paddles

Tracker system

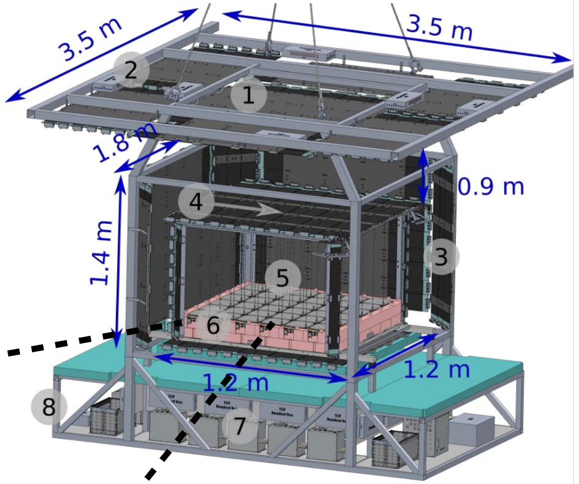
- 4 keV FWHM (at ~60 keV)
- Large area, relatively high temperature
- Leakage current < 5 nA/strip
- Large dynamical range (~keV→100 MeV)
- >1000 mass production with high-yield
- Novel heat-pipe system with low-power and lightweight is used for the thermal control

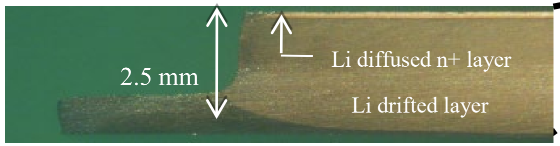


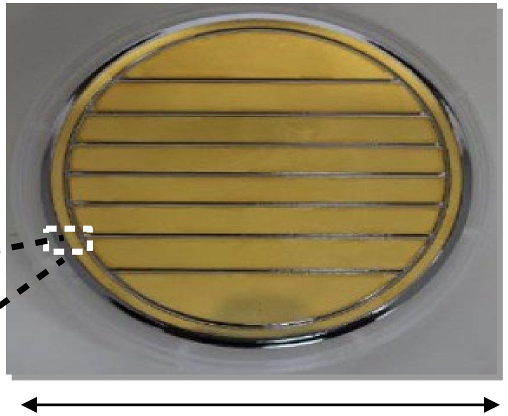
Li ions compensate impurities in boron-doped Si, creating extended thick depleted layer

Lithium-drifted Silicon

- Cylindrical detector
- -43C operational T
- 1100 SiLi detectors
- 10 planes



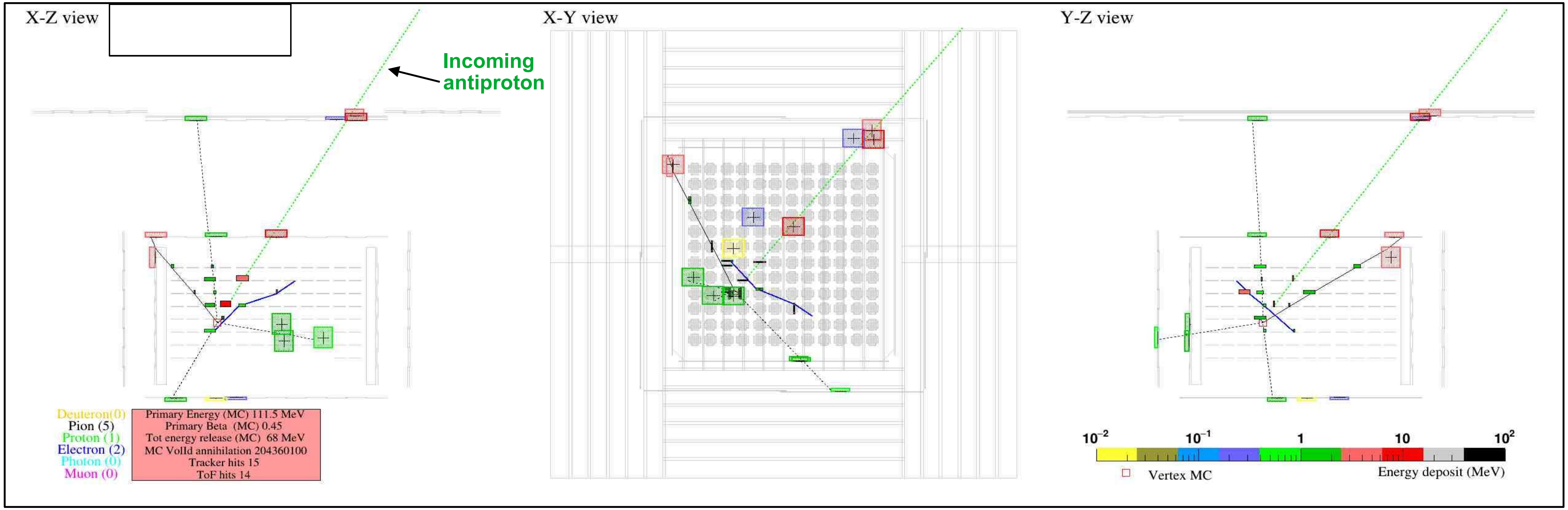




Simulated event

Fully detector simulation with (GEANT4)

Vertex reconstruction based on:
- Kalman-like filter for primary reconstruction
- Custom algorithm for secondaries
- Vertex reconstruction with minimization

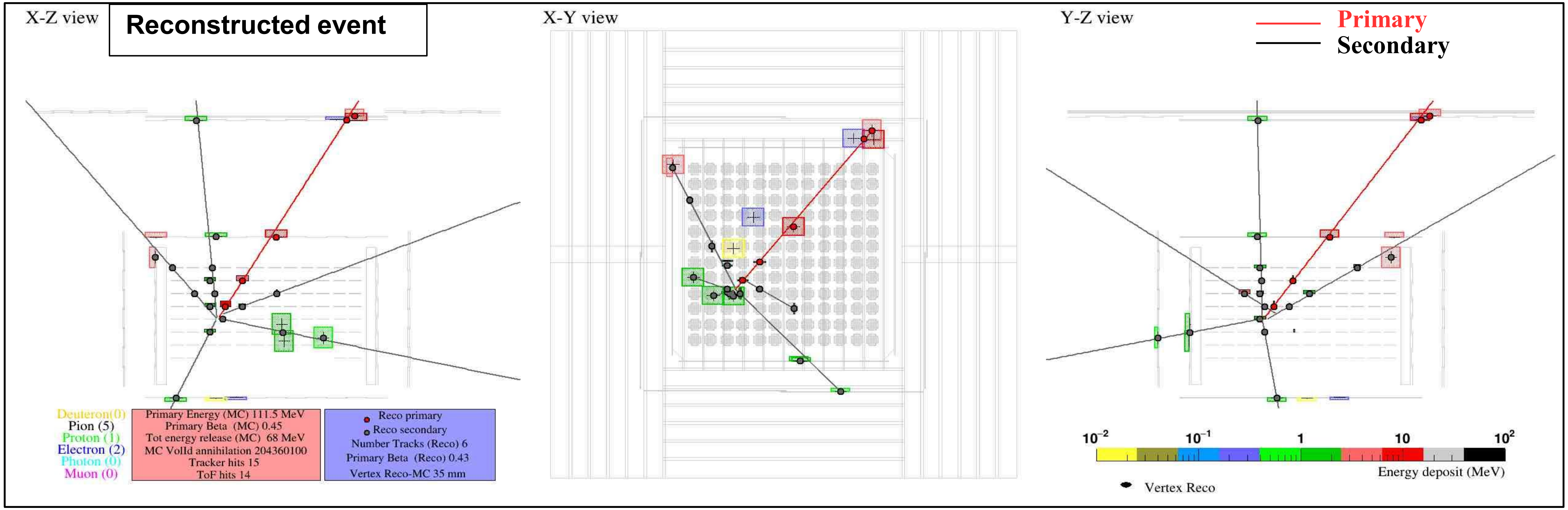


Reconstructed event

Vertex reconstruction based on:

- Kalman-like filter for primary reconstruction
- Custom algorithm for secondaries
- Vertex reconstruction with minimization

Fully detector simulation with (GEANT4)

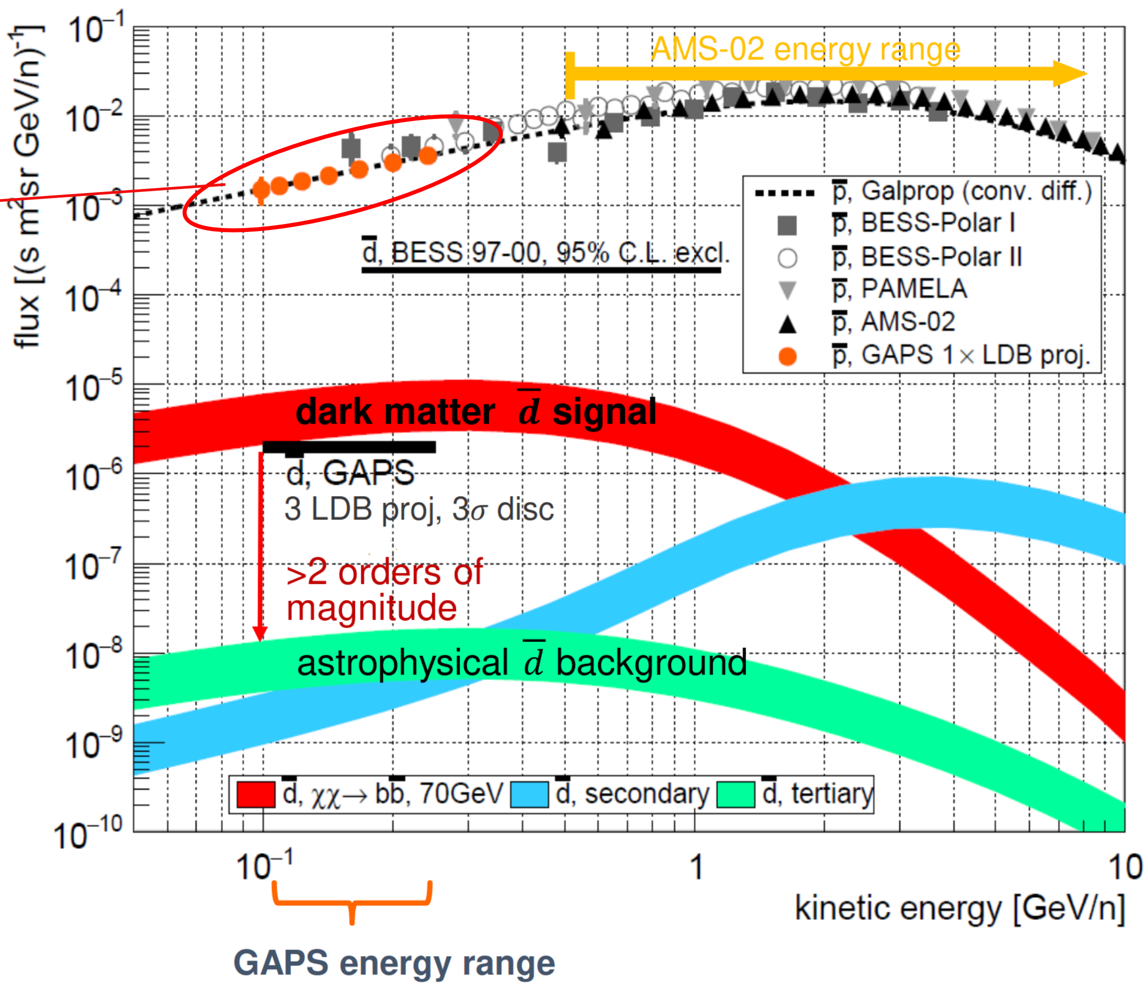


Antiproton measurement

Precision antiproton spectrum in unexplored low-energy range (<0.25 GeV/n).

• >600 antiprotons for each long-duration balloon flight.

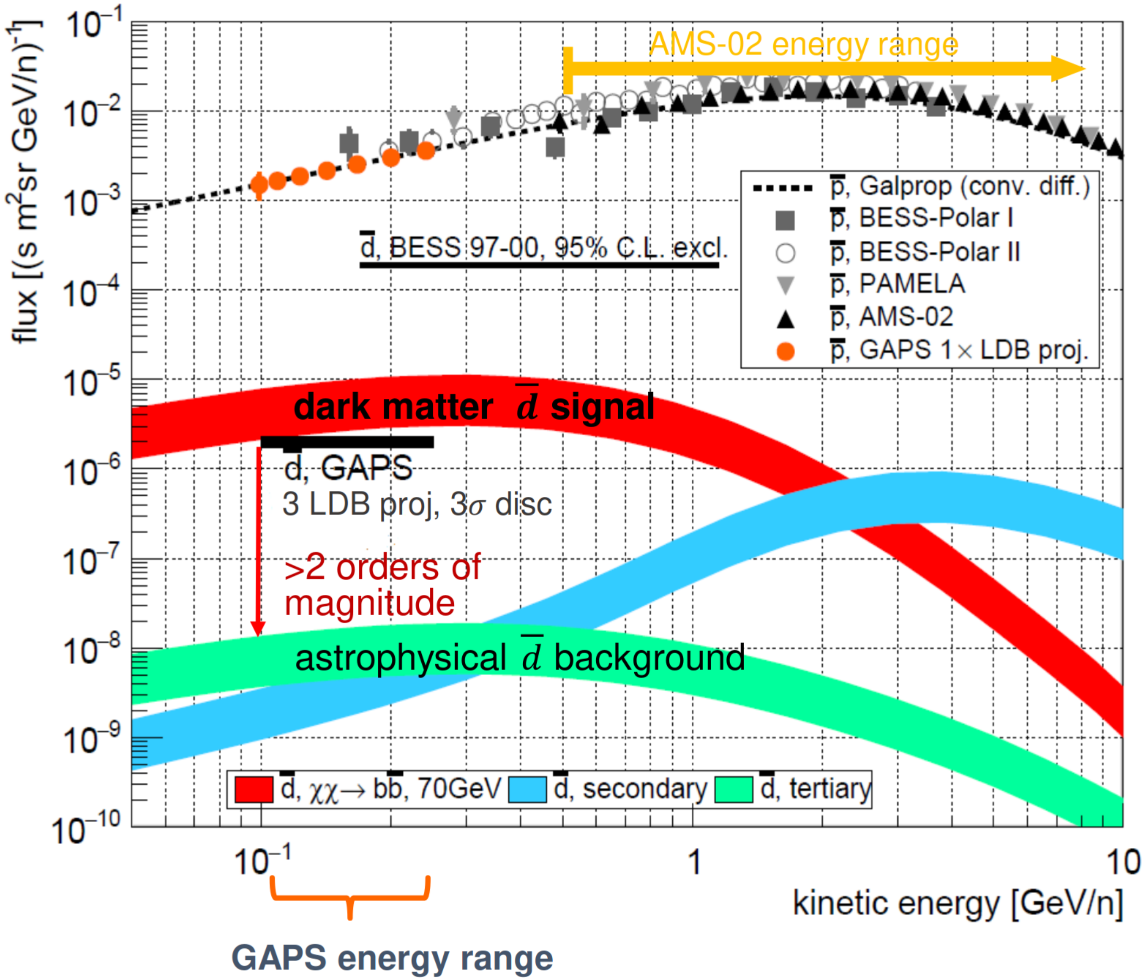
- BESS : 29 at ~0.2 GeV
- PAMELA: 7 at ~0.25 GeV
- AMS-02: E>0.25 GeV



Antideuteron sensitivity

GAPS antideuterons: A generic new physics signature with essentially zero conventional astrophysical background!

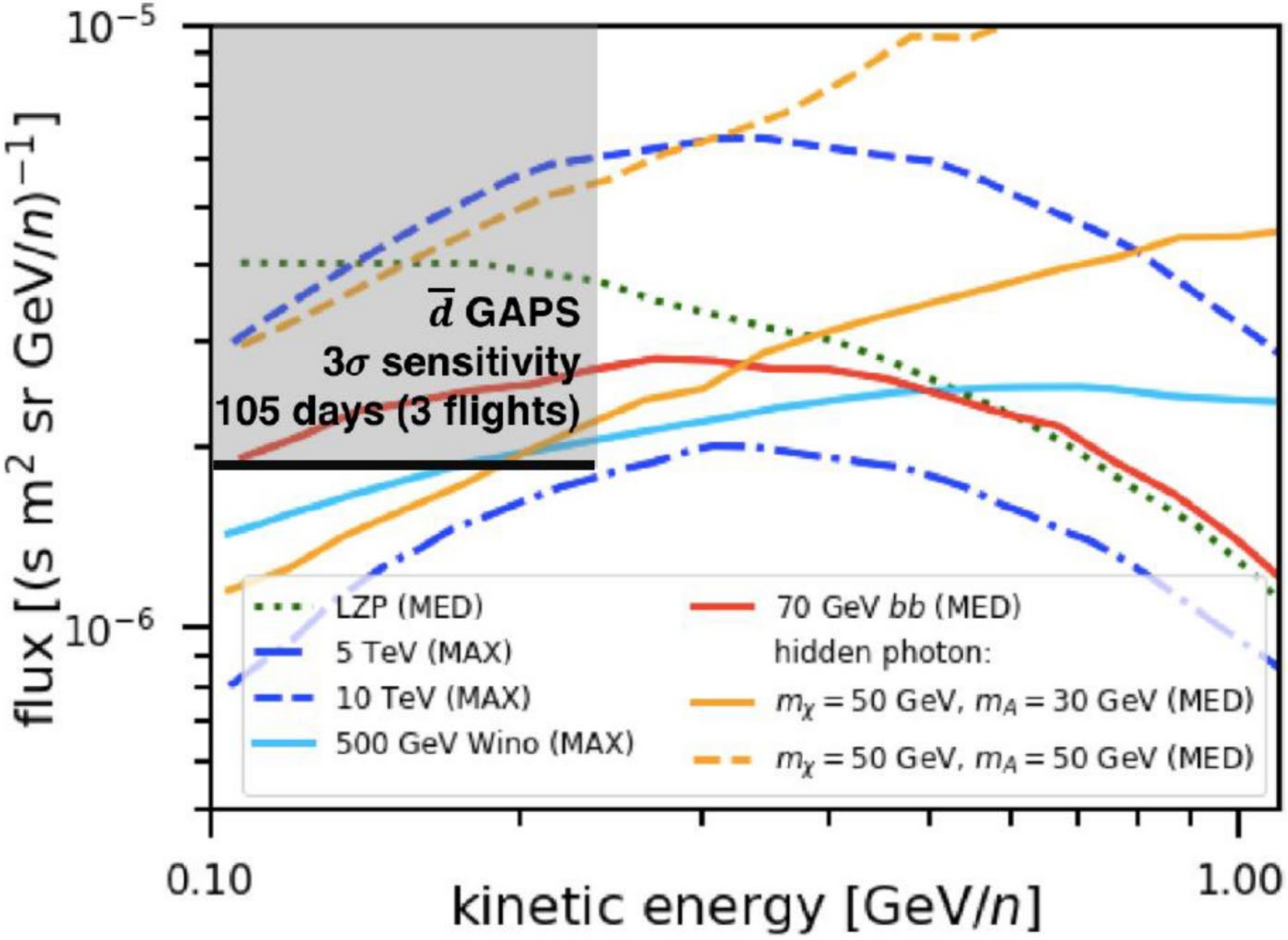
Sensitivity will be 1-2 orders of magnitude below the current best limits.



Antideuteron sensitivity

The GAPS antideuteron search is sensitive to a wide range of dark matter models, e.g.:

- Generic 70-GeV WIMP annihilation model that explains antiproton excess and -rays from the Galactic Center
- Dark matter gravitino decay
- Extra dimensions
- Dark photons
- Heavy DM models with Sommerfeld enhancement



AntiHelium sensitivity

GAPS flux sensitivity to antihelium-3 (three 35-day long duration flights).

GAPS extends to lower energies (0.11-0.3 GeV/n), complementary to AMS-02.
・Capable of confirming signal, orthogonal detection technique, uniquely low bkg.

2018: "To date, we have observed eight events...with Z = -2. All eight events are in the helium mass region." – S. Ting (La Palma, AMS overview)

AMS Candidate Anti-He4 event (p = 32.6 GeV/c)