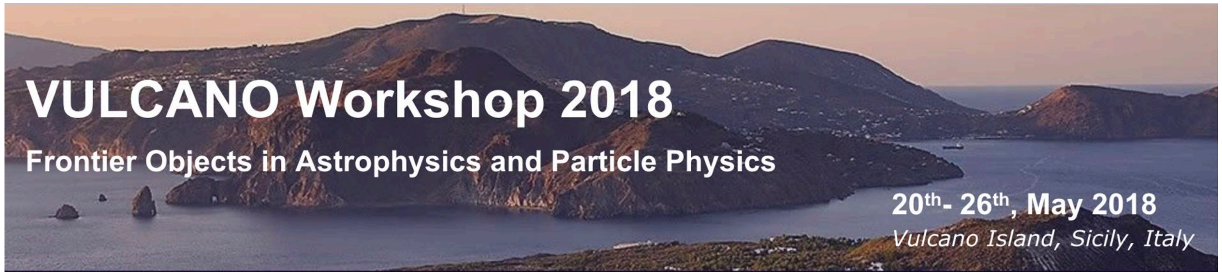


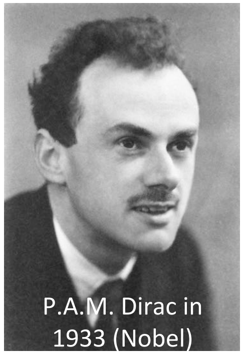

# Antimatter in CRs

… 90 years later

Roberto Iuppa
Università di Trento e TIFPA

# Family album

Roberto Iuppa

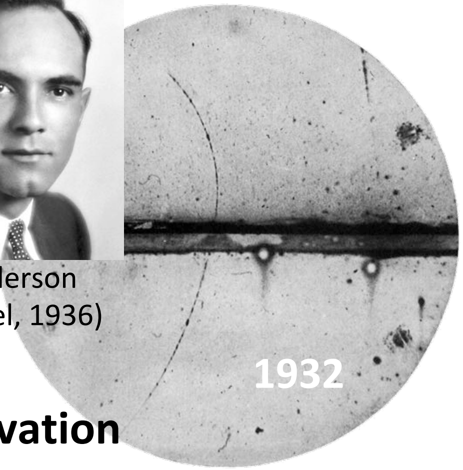

P.A.M. Dirac in 1933 (Nobel)

## Prediction

$$\left(\beta mc^2 + c\left(\sum_{n=1}^{3}\alpha_n p_n\right)\right)\psi(x,t) = i\hbar\frac{\partial\psi(x,t)}{\partial t}$$

**1928**


Anderson (Nobel, 1936)



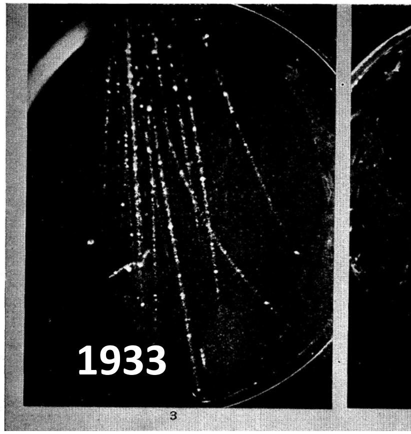

## Observation

*Phys. Rev. 43, 491 (1933)*

## Pair production

*Blackett and Occhialini.* *Proc. Roy. Soc., A, vol. 139, Pl. 22.*

cloud chamber+Rossi coincidence circuit: sort of CR selfie





Occhialini and Blackett (Blackett Nobel in 1948)

**Annihilation** observed by Mr. O. Klemperer, communicated by Dr. J. Chadwick (**1934**) to the Cambridge Philosophical Society

# Anti-worlds

Roberto Iuppa

THEORY OF ELECTRONS AND POSITIONS 325

of particle. The negative protons would of course be much harder to produce experimentally, since a much larger energy would be required, corresponding to the larger mass.

If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.

P.A.M. Dirac, Nobel lecture 1933.

# Anti-worlds

Roberto Iuppa



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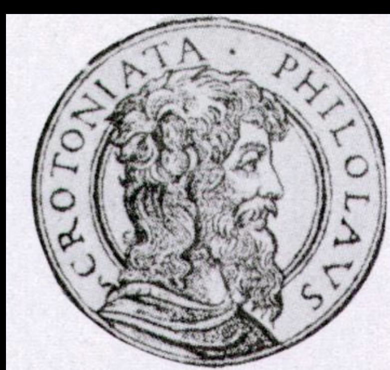


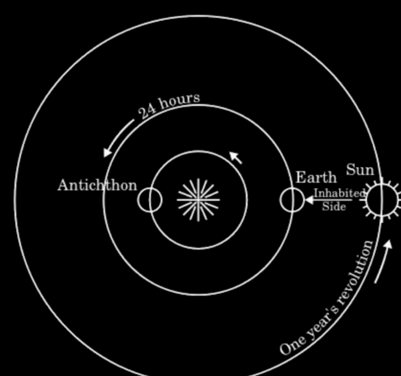

# Anti-worlds

Roberto Iuppa

THEORY OF ELECTRONS AND POSITIONS 325

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P.A.M. Dirac, Nobel lecture 1933.

# Sakharov conditions – CPT theorem

Roberto Iuppa

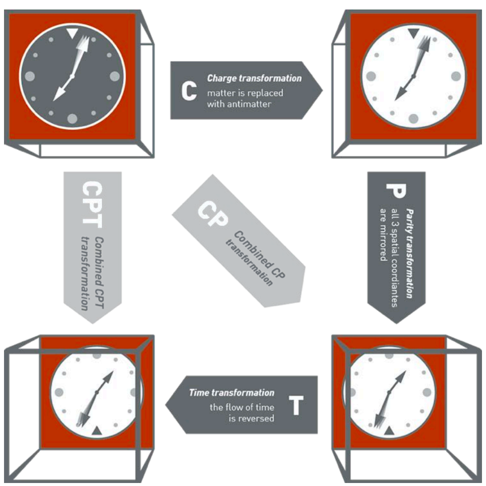
VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from anti-matter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

*JETP 5, 24-27 (1966)*

1. Baryon number B violation.
2. C-symmetry and CP-symmetry violation.
3. Interactions out of thermal equilibrium.




*from https://antimatter.at/*

CPT theorem: any Lorentz invariant local Quantum Field Theory whose Hamiltonian is hermitian must have CPT symmetry.

*(Schwinger 1951 up to Jost 1957)*

Roberto Iuppa

# antimatter at CERN

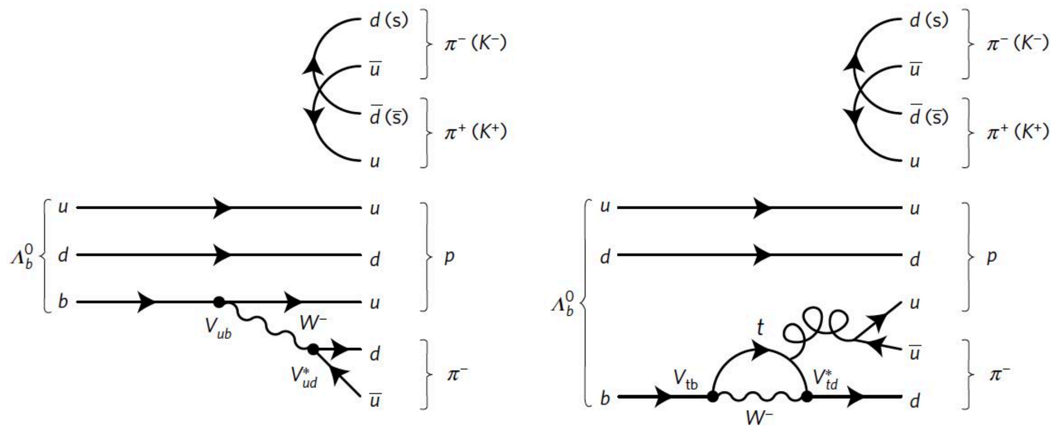
(my favourite list)

# Evidence for CP violation in the baryon sector

Roberto Iuppa

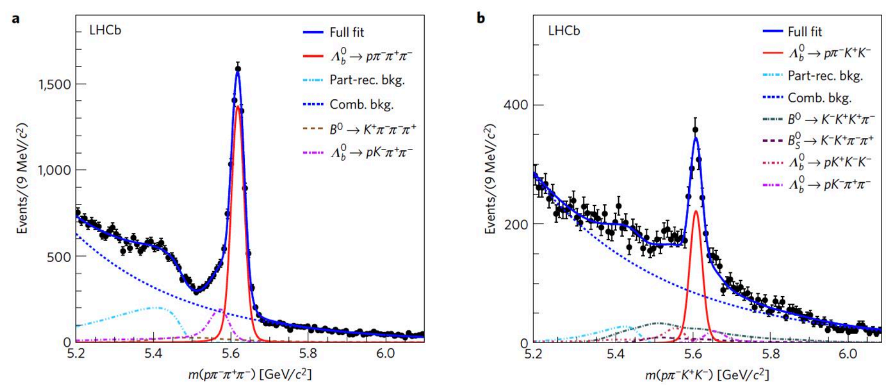
*Nature Physics 13, 391–396 (2017)*

Few months ago, **the LHCb collaboration reported the first evidence of CP violation in the baryon sector**, indicating an asymmetry between baryonic matter and antimatter




$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \quad for\ \Lambda_b^0$$

$$\bar{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \quad for\ \bar{\Lambda}_b^0$$




$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$

$$\bar{A}_{\hat{T}}(\bar{C}_{\hat{T}}) = \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_{\hat{T}} < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)}$$

P-violating observable $\quad a_P^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}})$

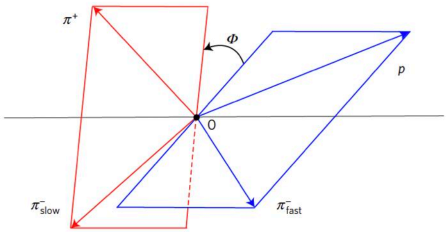
CP-violating observable $\quad a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}})$

# The LHCb result

Roberto Iuppa

*Nature Physics 13, 391–396 (2017)*

Scheme A designed to isolate regions of phase space according to their dominant resonant contributions.



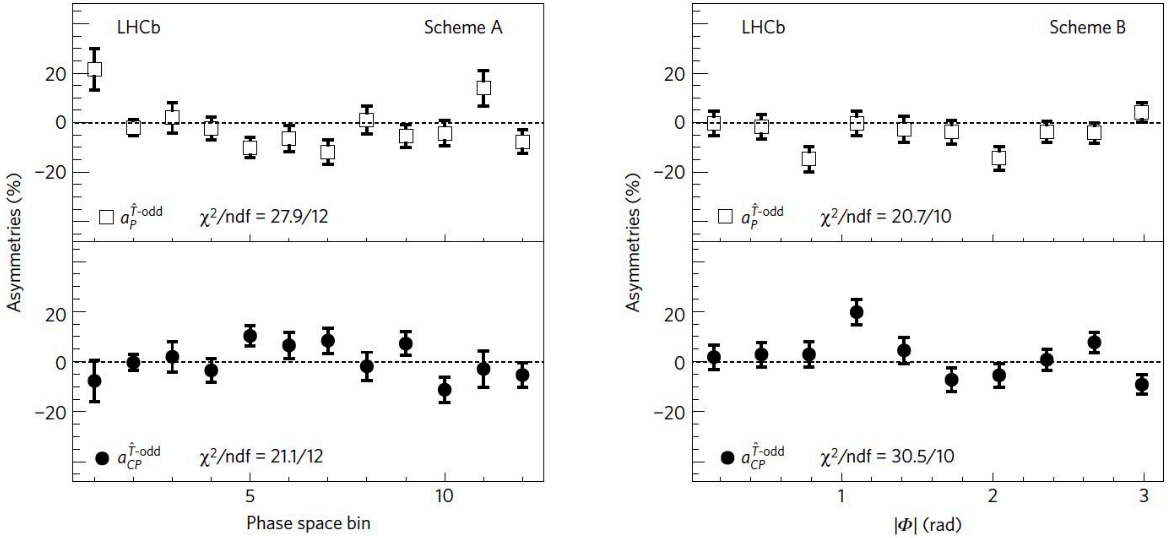




**Figure 4 | Distributions of the asymmetries.** The results of the fit in each region of binning schemes A and B are shown. The asymmetries $a_P^{\hat{T}\text{-odd}}$ and $a_{CP}^{\hat{T}\text{-odd}}$ for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays are represented by open boxes and filled circles, respectively. The error bars represent one standard deviation, calculated as the sum in quadrature of the statistical uncertainty resulting from the fit to the invariant mass distribution and the systematic uncertainties estimated as described in the main text. The values of the $\chi^2$/ndf are quoted for the *P*- and *CP*-conserving hypotheses for each binning scheme, where ndf indicates the number of degrees of freedom.

The results are consistent with CP symmetry for the Λ->pπKK case (1030±56 events), but evidence for ***CP violation at the 3.3σ level is found for the Λ->pπππ case (6646±105)*** . No significant P violation is found.

# The 1S-2S transition

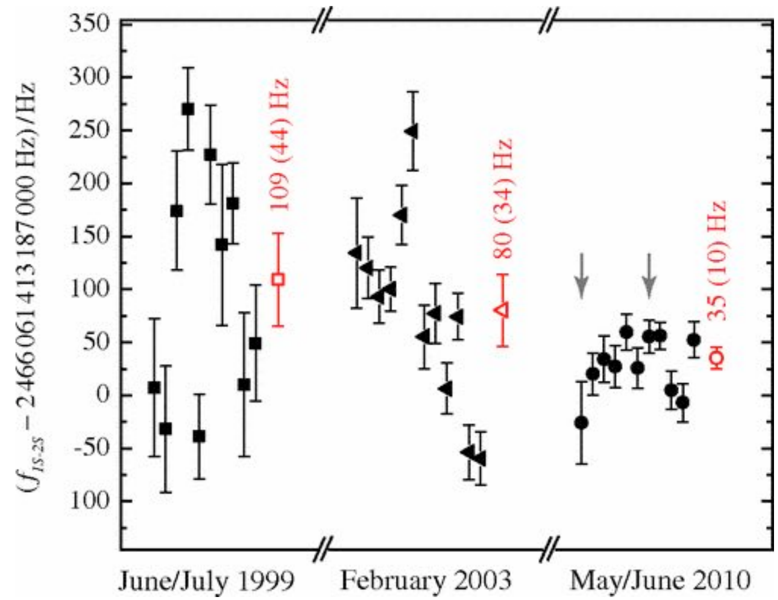
Roberto Iuppa

## Improved Measurement of the Hydrogen $1S-2S$ Transition Frequency

Christian G. Parthey, Arthur Matveev, Janis Alnis, Birgitta Bernhardt, Axel Beyer, Ronald Holzwarth, Aliaksei Maistrou, Randolf Pohl, Katharina Predehl, Thomas Udem, Tobias Wilken, Nikolai Kolachevsky, Michel Abgrall, Daniele Rovera, Christophe Salomon, Philippe Laurent, and Theodor W. Hänsch

Phys. Rev. Lett. **107**, 203001 (2011) – Published 11 November 2011

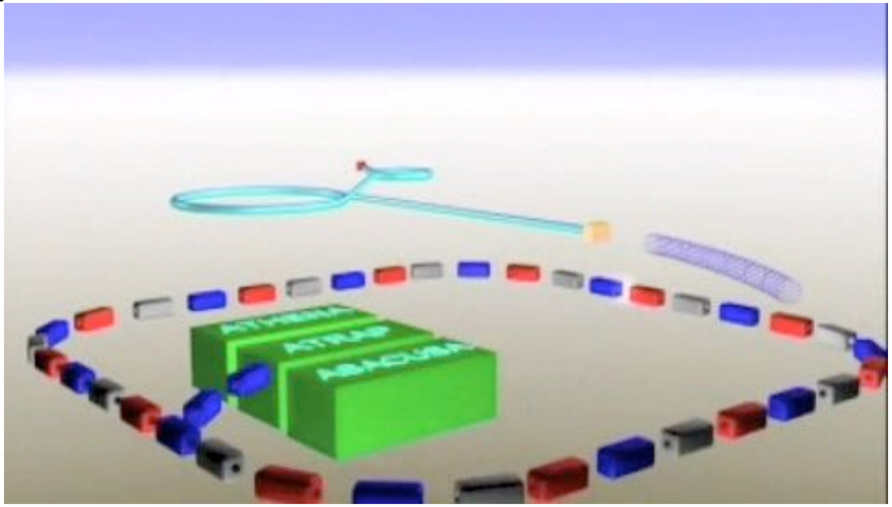
We have measured the $1S-2S$ transition frequency in atomic hydrogen via two-photon spectroscopy on a 5.8 K atomic beam. We obtain $f_{1S-2S} = 2\,466\,061\,413\,187\,035\,(10)$ Hz for the hyperfine centroid, in agreement with, but 3.3 times better than the previous result [M. Fischer *et al.*, Phys. Rev. Lett. **92**, 230802 (2004)]. The improvement to a fractional frequency uncertainty of $4.2 \times 10^{-15}$ arises mainly from an improved stability of the spectroscopy laser, and a better determination of the main systematic uncertainties, namely, the second order Doppler and ac and dc Stark shifts. The probe laser frequency was phase coherently linked to the mobile cesium fountain clock FOM via a frequency comb.



# The ALPHA experiment

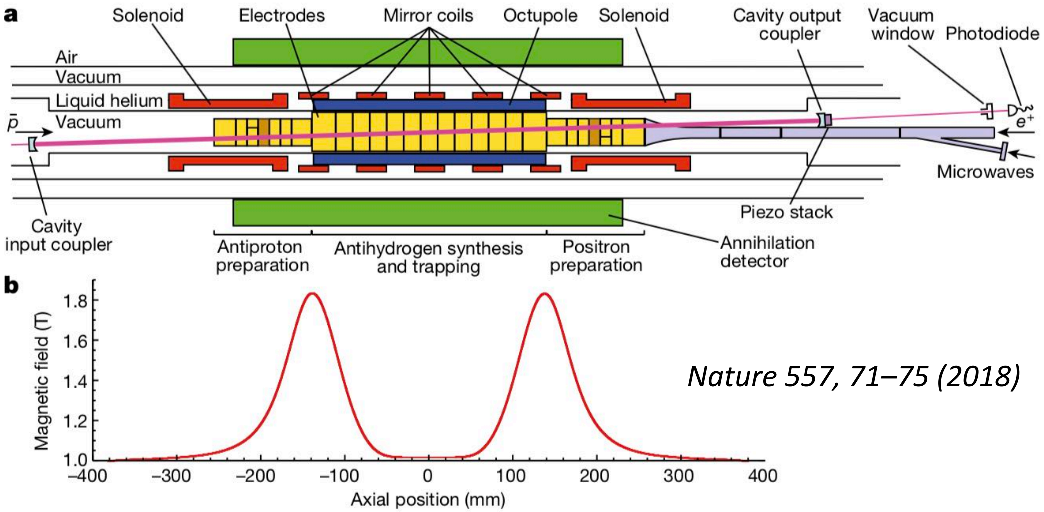
Roberto Iuppa

*from CERN*



**Antihydrogen** can be trapped in ALPHA-2's magnetic multipole trap if it is produced with a **kinetic energy of less than 0.54 K** in temperature units.

In round numbers, a typical trapping trial in ALPHA-2 involves mixing **90,000 antiprotons with 3,000,000 positrons** to produce 50,000 **antihydrogen atoms, about 20** of which will be trapped.




*Nature 557, 71–75 (2018)*

**Anti-atoms have a storage lifetime of at least 60 h in the trap**.

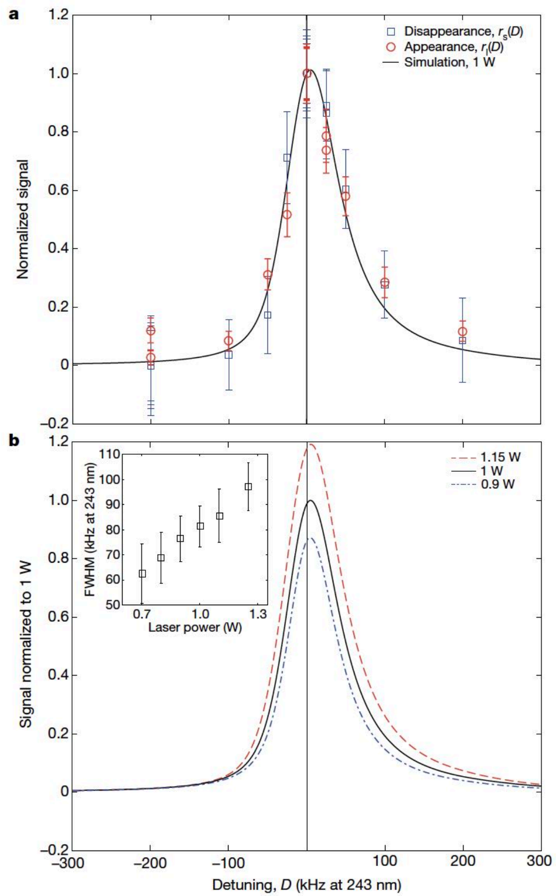
# ALPHA result

Roberto Iuppa

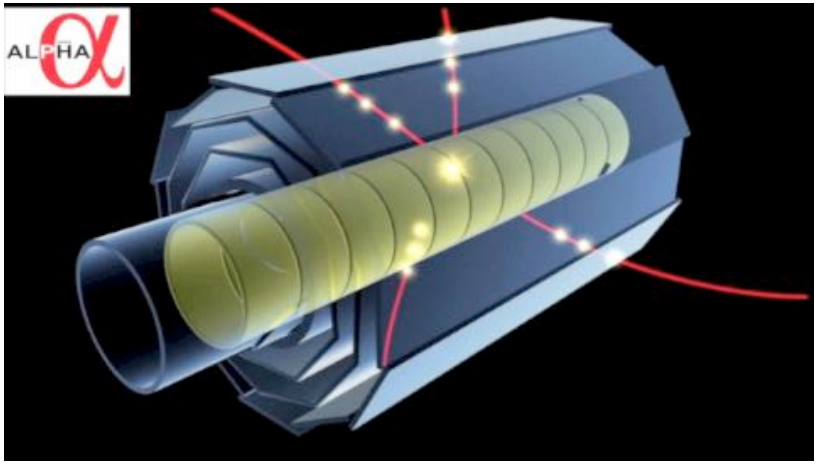
To excite the 1S–2S transition, ALPHA-2 uses a cryogenic, in vacuo enhancement cavity for continuous-wave light from a 243-nm laser system to boost the intensity in the trapping volume.

Two counter-propagating photons resonantly excite 1S-2S. A third photon absorbed and ionizes the atom -> LOSS.

Signature: pbar+X->4π .




*Nature 557, 71–75 (2018)*




Including all of the statistical and systematic uncertainties that we have identified (Table 3, for 121 nm), our fit of the experimental data to the hydrogen model yields

$$f_{d-d} = 2{,}466{,}061{,}103{,}079.4(5.4)\ \text{kHz}$$

The value (Methods) for hydrogen calculated at the minimum field in our system (1.03285(63) T) is

$$f_{d-d} = 2{,}466{,}061{,}103{,}080.3(0.6)\ \text{kHz}$$

where the uncertainty is determined by the experimental error in measuring the field.

**CPT invariance tested down to 2x10$^{-12}$.**

Sensitivity 10x improvement expected soon.

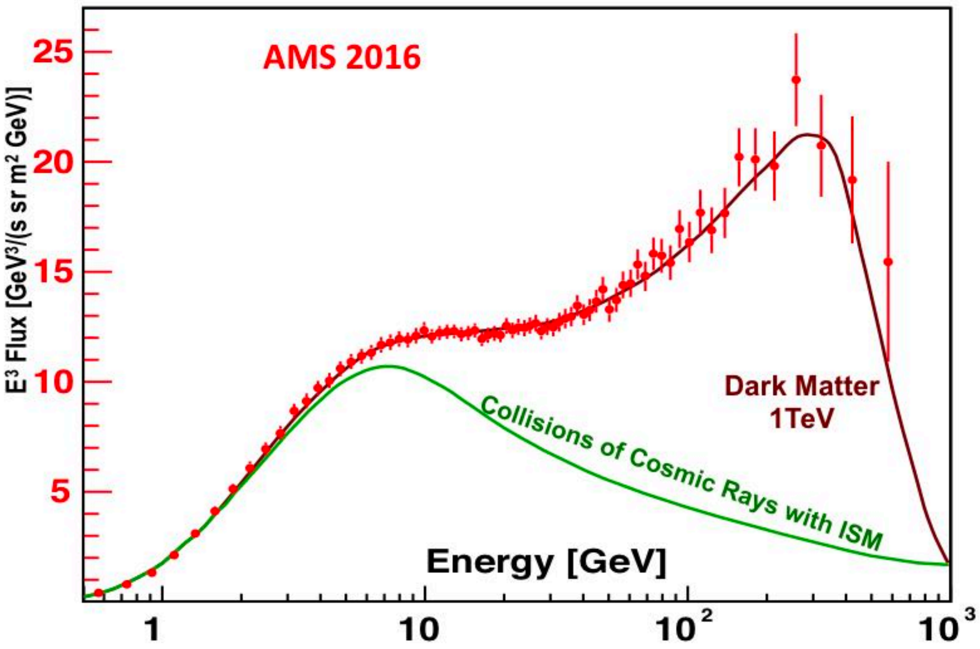
The measured resonance frequency for this transition in antihydrogen is consistent with the expected hydrogen frequency to a precision of about **2 x 10$^{-12}$**.

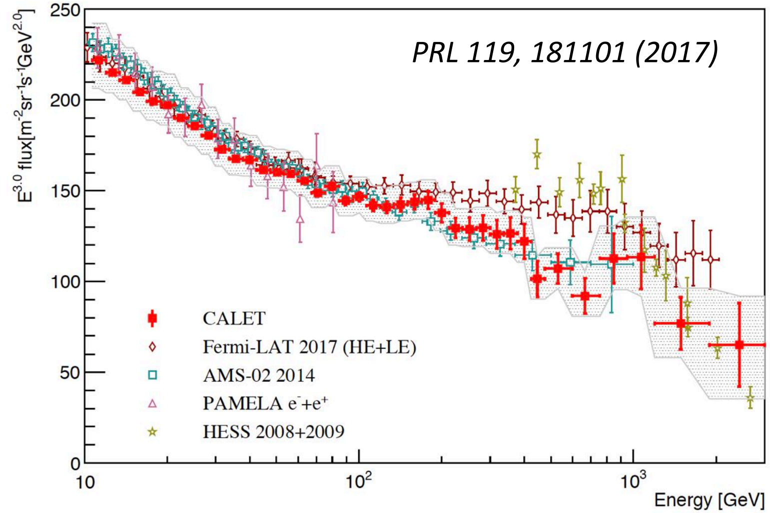
# antimatter in cosmic rays

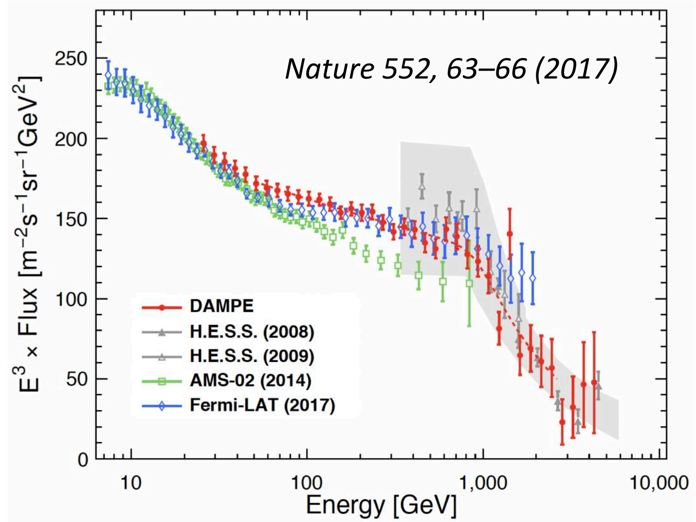
# AMS-02 positrons

Roberto Iuppa

*http://www.ams02.org/*



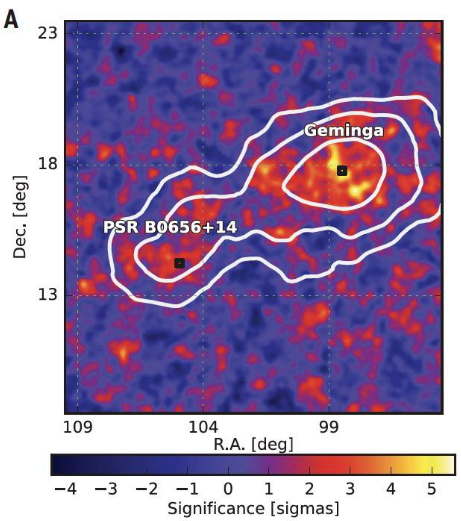




On the AMS-02 official website, a “Dark Matter 1 TeV” model is fit to the positron spectrum up to 800 GeV.

Exotic scenarios continued being proposed even after the publication of the electron break at ~1 TeV by CALET and DAMPE (confirming HESS)

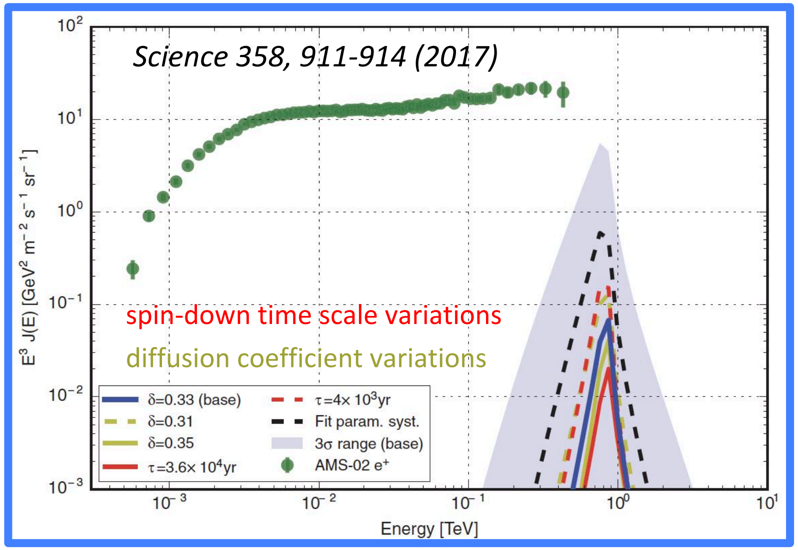
# Positrons and pulsar wind nebulae

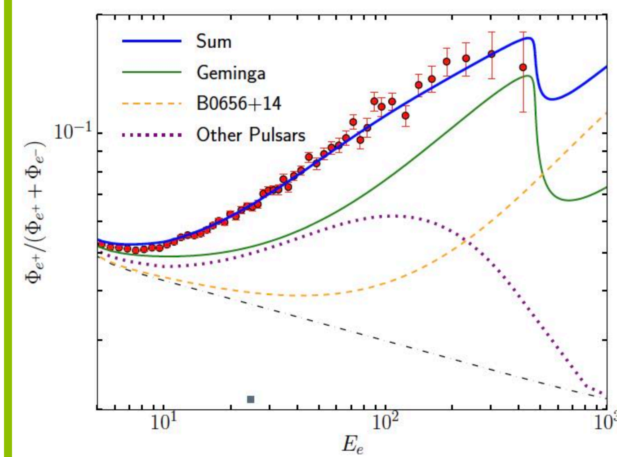
Roberto Iuppa



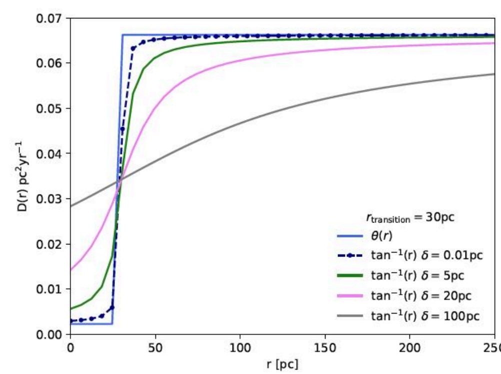

*Science 358, 911-914 (2017)*

HAWC measurement of Geminga and B0656+14 diffuse emission had huge impact on debate the positron anomaly.




*PRD96 (2017) 10, 103013*




*arXiv:1803.09731*

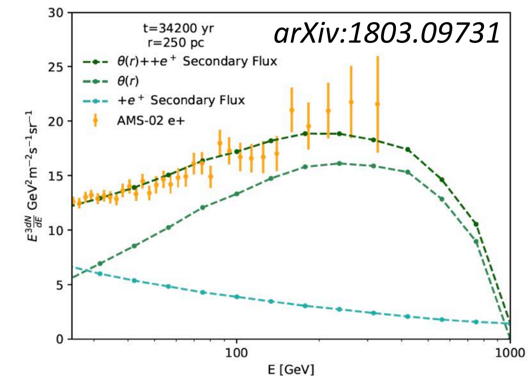
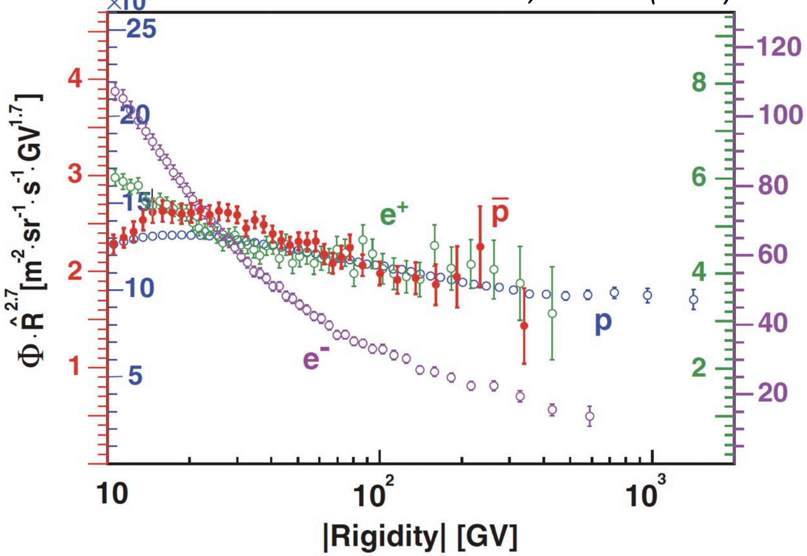



FIG. 5: The positron flux with the contributions of Geminga and secondary production, compared to AMS-02 data. The transition for this case is set to 35 pc with ∼ 40% $e^{\pm}$ energy injection efficiency.

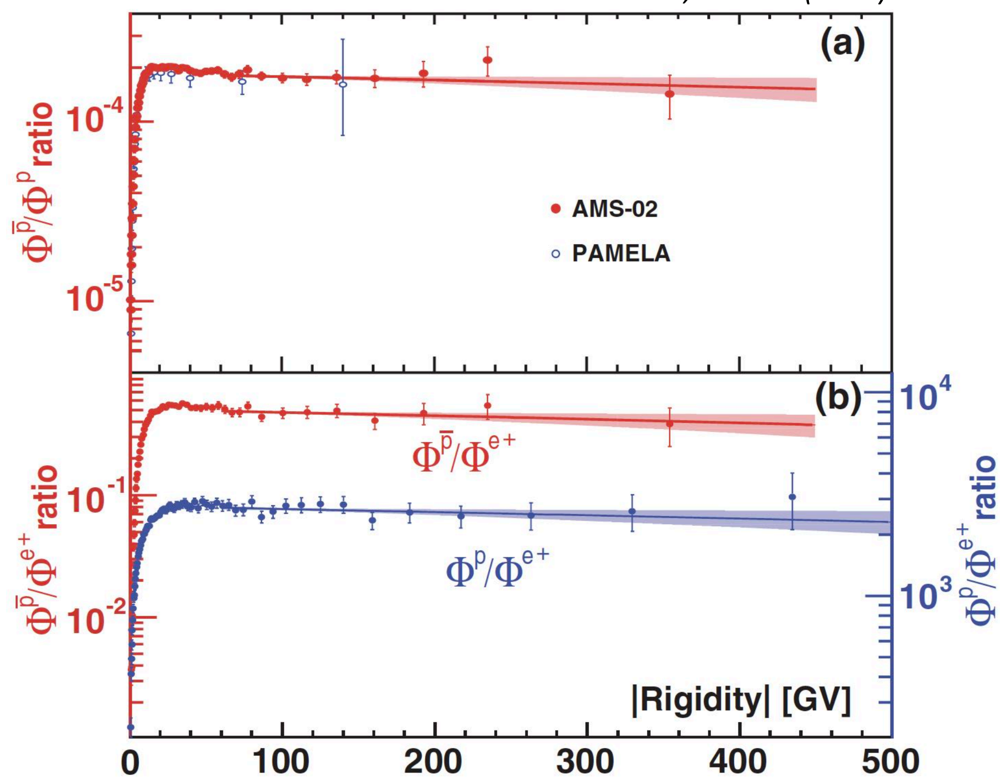
# AMS-02 antiprotons

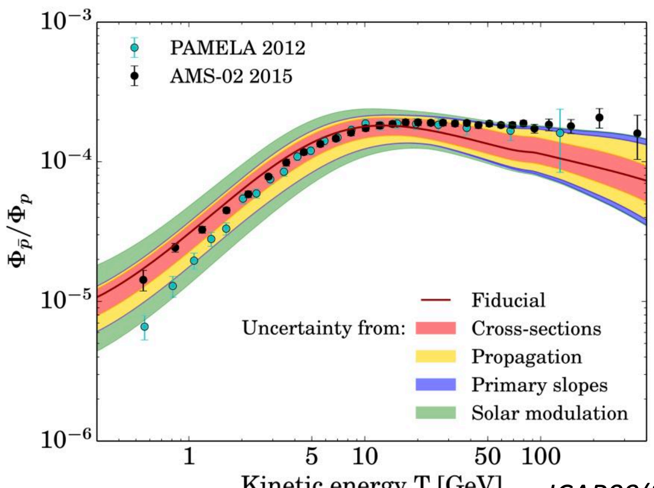
Roberto Iuppa

*PRL 117, 091103 (2016)*




*PRL 117, 091103 (2016)*




*JCAP09(2015)023*

# B/C → pbar/p uncertainty

Roberto Iuppa

*Res. Notes AAS 1 35 (2017)*

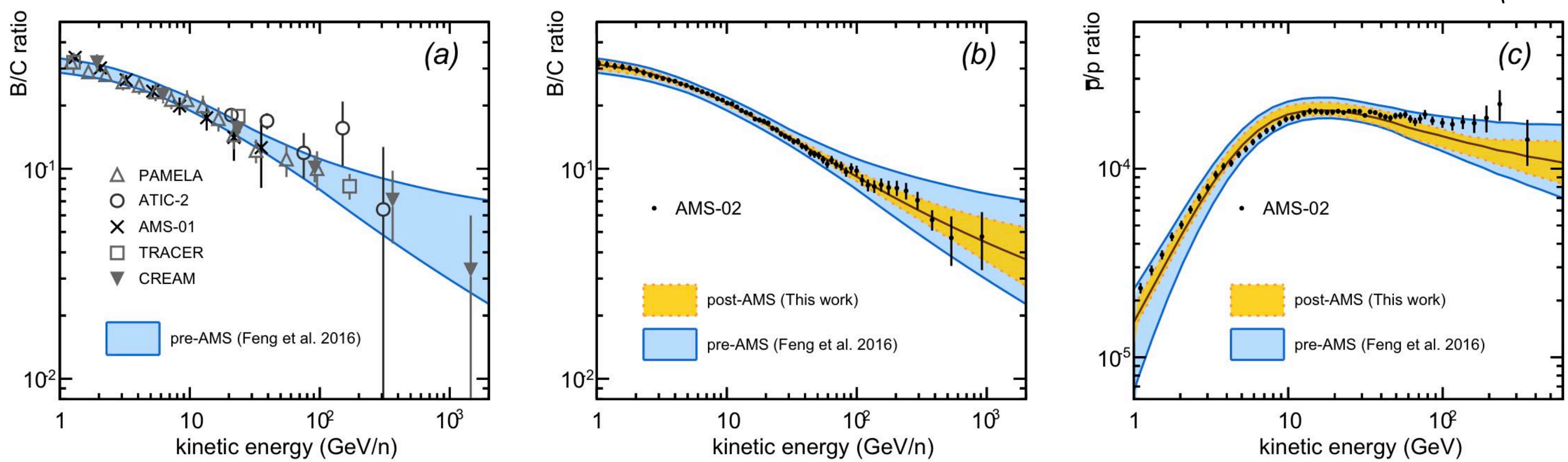
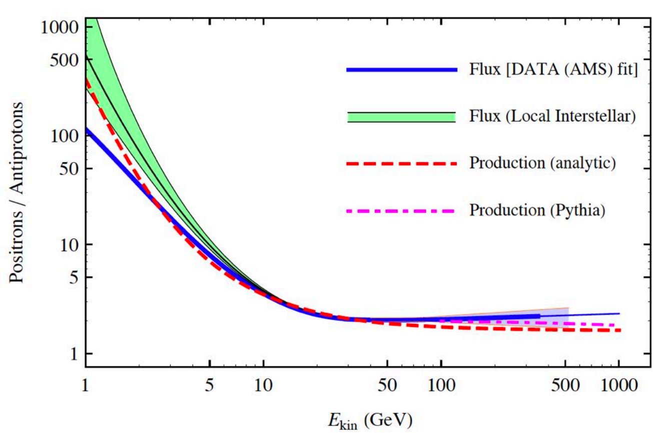



FIG. 1.— Calculations for the B/C (a, b) and $\bar{p}/p$ (c) ratios in comparison with the AMS data. The blue shaded bands are the uncertainties obtained from our pre-AMS data (a) analysis (Feng et al. 2016). The orange band is from this work, *i.e.*, using the AMS data only.

## What about the conventional mechanism?

"[…] in the entire energy range 1-350 GeV, the e+/p- ratio is consistent with being equal to ratio of the production rates in the conventional mechanism, as the production of low energy antiprotons is kinematically suppressed in collisions with a target at rest. These results strongly suggest that cosmic ray positrons and antiprotons have a common origin as secondaries in hadronic interactions."

*P. Lipari arXiv:1608.02018*



# TeV antiprotons: the Moon shadow

Roberto Iuppa

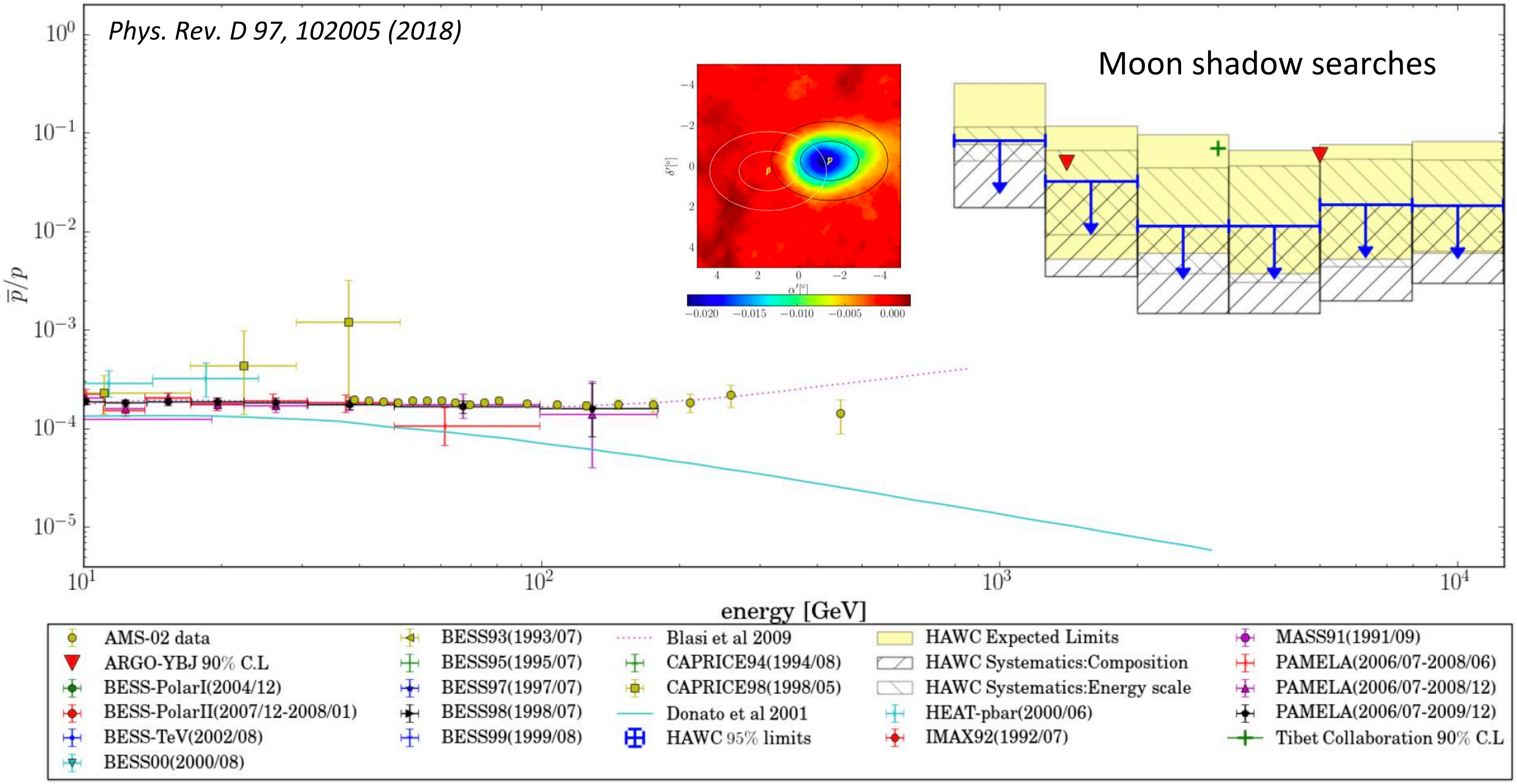


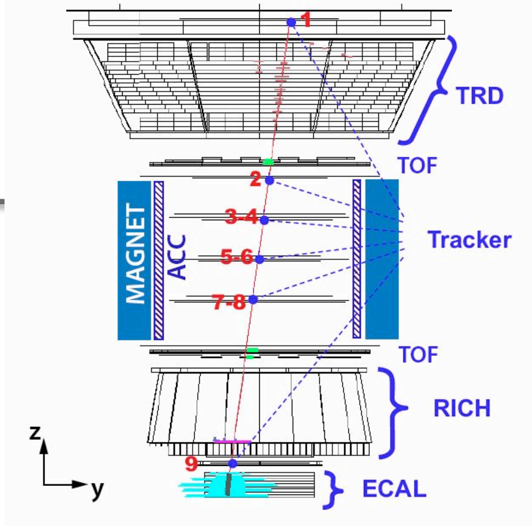

FIG. 5. Measurements of $\bar{p}/p$ in the GeV range and upper limits at the TeV scale. The yellow and shaded bands show HAWC sensitivity and systematic uncertainties respectively. The solid line shows the expected ratio from a purely secondary production of antiprotons [47]. The dotted line postulates primary antiproton production in supernovae [21]. Note that the other upper limits published above 1 TeV by ARGO-YBJ, L3 and Tibet AS-$\gamma$ are 90% intervals while the HAWC limits are at the 95% C.L.

# what future
# for CR antimatter searches?

(going to talk about new techniques
NO sensitivity curves)

# “Detector studies for AMS-03”

What are the limitations of AMS-02 above 1 TV?

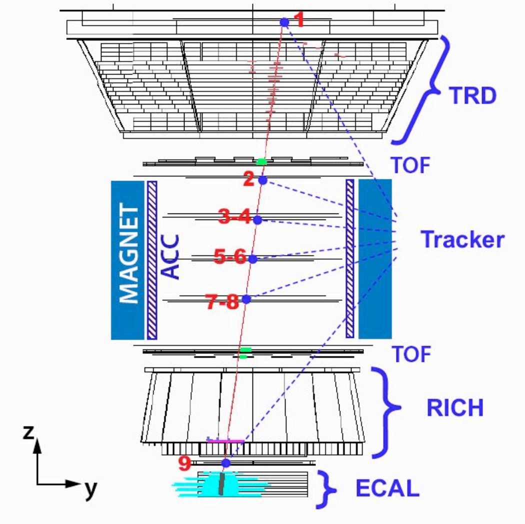



## PROTON and HELIUM PHYSICS @ AMS-02

From “Detector studies for AMS-03”, R. Battiston and N. Masi

| | 0,3 m2 sr | | 3,14E+07 s/y | | | EXCLUDED | EXCLUDED | EXCLUDED |
|---|---|---|---|---|---|---|---|---|
| | 10^8 100MeV | 10^9 GV | 10^10 | 10^11 | 10^12 TV | 10^13 | 10^14 | 10^15 PV |
| Integral . 1/y | .@ 0,1-1 | .@ 1-10 | .@ 10-100 | .@ 100-1000 | .@ 1.000 -> | .@ 10.000 -> | .@ 100.000 -> | .@ 1.000.000 -> |
| p | 3,00E+09 | 5,98E+09 | 1,19E+09 | 2,38E+07 | 4,32E+05 | 8,61E+03 | 1,72E+02 | 3,43E+00 |
| He | 1,08E+08 | 1,08E+09 | 2,15E+08 | 4,28E+06 | 7,77E+04 | 1,55E+03 | 3,09E+01 | 6,17E-01 |
| Detectors | tracker, TOF, RICH | Tracker, (RICH) | Tracker | Tracker | Tracker | TRD +ECAL ? | | |
| Variables | R, beta | R | R | R | R, gamma | gamma | | |
| Physics | Van Allen, solar, subcutoff | solar, geomagnetic, galactic | galactic | galactic | galactic, moon shadow, sun shadow | galactic, moon shadow, sun shadow | galactic | extragalactic, knee |
| Tools | acceptance vs R, live time, efficiency, MC, inner tracker, alignement, TOF calibration, RICH calibration, backtracing(near Earth) | acceptance vs R, live time, efficiency, MC, inner tracker, alignement, , RICH calibration, backtracing (near Earth) | acceptance vs R, live time, efficiency, MC, inner tracker, alignement, TOF calibration, RICH calibration, backtracing near Earth) | acceptance vs R, live time, efficiency, MC, inner/outer tracker, alignement, backtracing Earth-Moon, Earth- Sun) | acceptance vs R, live time, efficiency, MC, outer tracker, alignement, , ECAL calibration, backtracing Earth-Moon, Earth-Sun | acceptance vs R, live time, efficiency, MC, outer tracker, alignement, TRD calibration, ECAL calibration, backtracing Earth-Moon, Earth- Sun) | acceptance vs R, live time, efficiency, MC, outer tracker, alignement, TRD calibration, ECAL calibration, backtracing Earth-Moon, Earth- Sun) | |
| Background p | - | - | - | - | e- | e- | e- | |
| Background He | He3/He4 | He3/He4 | He3/He4 | He3/He4 | | | | |
| Limitations | multiple, scattering, acceptance,AMS02 magnetic field | - | - | different tracker acceptances, alignement | momentum resolution runs out, TRD comes in ?, if ECAL is used loss of factor 10 acceptance | only TRD has limited gamma resolution, if ECAL is used we lose a factor 50 | only TRD has limited gamma resolution, if ECAL is used we lose a factor 50 | no statistics |

# “Detector studies for AMS-03”




What are the limitations of AMS-02 above 1 TV? **The tracking system.**

$$Q = \bar{B}[\mathrm{T}]\, L[\mathrm{m}]\, \frac{d[\mathrm{m}]}{\sigma_p[\mathrm{m}]}$$

Q: maximum momentum estimator
BL: bending power
d: tracker lever arm
$\sigma_p$: single point resolution

**PROTON and HELIUM PHYSICS @ AMS-02**

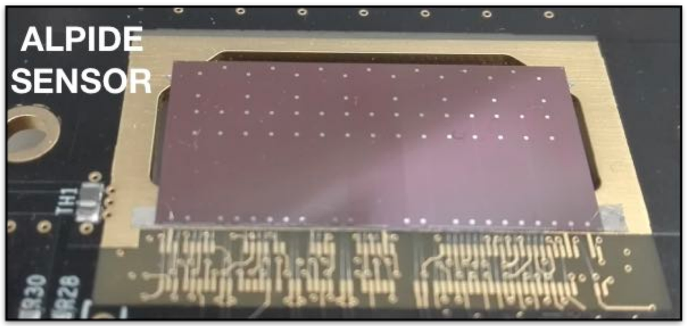
From “Detector studies for AMS-03”, R. Battiston and N. Masi

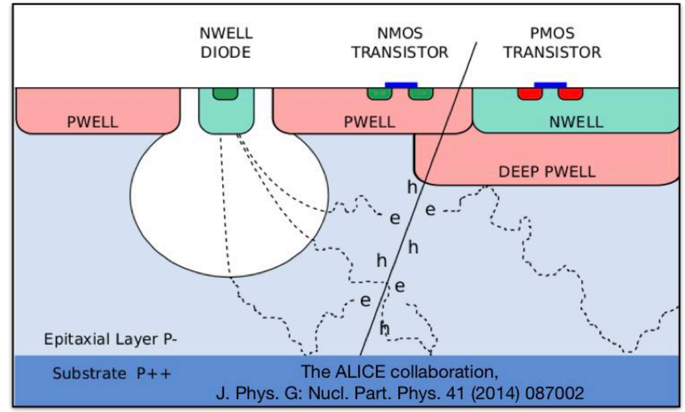
| | 0,3m2 sr | 3,14E+07s/y | | | | EXCLUDED | EXCLUDED | EXCLUDED |
|---|---|---|---|---|---|---|---|---|
| | **10^8** **100MeV** | **10^9** **GV** | **10^10** | **10^11** | **10^12** **TV** | **10^13** | **10^14** | **10^15** **PV** |
| **Integral . 1/y** | **.@ 0,1-1** | **.@ 1-10** | **.@ 10-100** | **.@ 100-1000** | **.@ 1.000 ->** | **.@ 10.000 ->** | **.@ 100.000 ->** | **.@ 1.000.000 ->** |
| p | 3,00E+09 | 5,98E+09 | 1,19E+09 | 2,38E+07 | 4,32E+05 | 8,61E+03 | 1,72E+02 | 3,43E+00 |
| He | 1,08E+08 | 1,08E+09 | 2,15E+08 | 4,28E+06 | 7,77E+04 | 1,55E+03 | 3,09E+01 | 6,17E-01 |
| **Detectors** | tracker, TOF, RICH | Tracker, (RICH) | Tracker | Tracker | Tracker | TRD +ECAL ? | | |
| **Variables** | R, beta | R | R | R | R, gamma | gamma | | |
| **Physics** | Van Allen, solar, subcutoff | solar, geomagnetic, galactic | galactic | galactic | galactic, moon shadow, sun shadow | galactic, moon shadow, sun shadow | galactic | extragalactic, knee |
| **Tools** | acceptance vs R, live time, efficiency, MC, inner tracker, alignement, TOF calibration, RICH calibration, backtracing(near Earth) | acceptance vs R, live time, efficiency, MC, inner tracker, alignement, , RICH calibration, backtracing (near Earth) | acceptance vs R, live time, efficiency, MC, inner tracker, alignement, TOF calibration, RICH calibration, backtracing near Earth) | acceptance vs R, live time, efficiency, MC, inner/outer tracker, alignement, backtracing Earth-Moon, Earth- Sun) | acceptance vs R, live time, efficiency, MC, outer tracker, alignement, , ECAL calibration, backtracing Earth-Moon, Earth-Sun | acceptance vs R, live time, efficiency, MC, outer tracker, alignement, TRD calibration, ECAL calibration, backtracing Earth-Moon, Earth- Sun) | acceptance vs R, live time, efficiency, MC, outer tracker, alignement, TRD calibration, ECAL calibration, backtracing Earth-Moon, Earth- Sun) | |
| **Background p** | - | - | - | - | e- | e- | e- | |
| **Background He** | He3/He4 | He3/He4 | He3/He4 | He3/He4 | | | | |
| **Limitations** | multiple, scattering, acceptance,AMS02 magnetic field | - | - | different tracker acceptances, alignement | momentum resolution runs out, TRD comes in ?, if ECAL is used loss of factor 10 acceptance | only TRD has limited gamma resolution, if ECAL is used we lose a factor 50 | only TRD has limited gamma resolution, if ECAL is used we lose a factor 50 | no statistics |

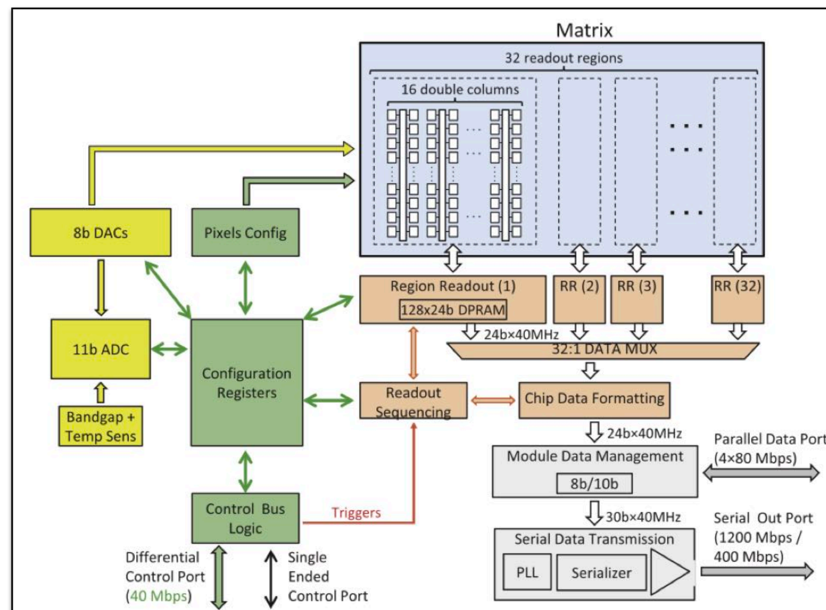
# New trackers

Roberto Iuppa

Monolithic Active Pixel Sensors (**MAPS**) are silicon detectors developed in CMOS technology. State-of-the-art of particle tracking in High Energy Physics.
Readout electronics, including signal detection, shaping and thresholding is embedded on the chip.




- Extremely low noise (fake hit rate $10^{-8}$)
- Need less charge to collect -> thinner
- Pixel size as low as 4 µm -> resolution down to 1 µm
- Also a lot of intelligence on chip: zero suppression and clustering
- Digital output -> no dE/dx
- Pixel tracker never used in space
- High power consumption (w.r.t. standard microstrip)
- MAPS design and development takes 5 years and 2 M€

# The case of ALPIDE

Roberto Iuppa

- Extremely low noise (fake hit rate $10^{-8}$)
- Need less charge to collect -> thinner
- Pixel size 28 µm -> **resolution of about 5 µm**
- Zero suppression and clustering
- Digital output -> no dE/dx: **cluster size sensitive**
- **Going to be used for HEPD-2 (launch 2020)**
- **Power consumption manageable** if slow control line used
- **Developed by the ALPIDE Collaboration**

*NIMA 824, 434-438 (2016)*

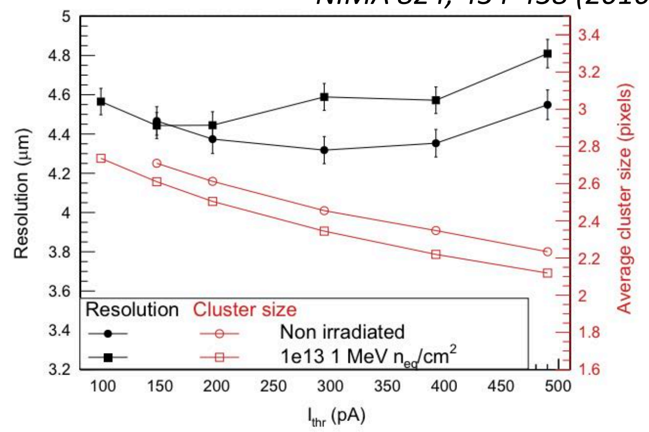
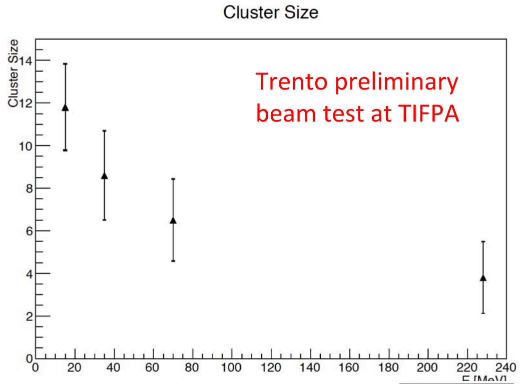
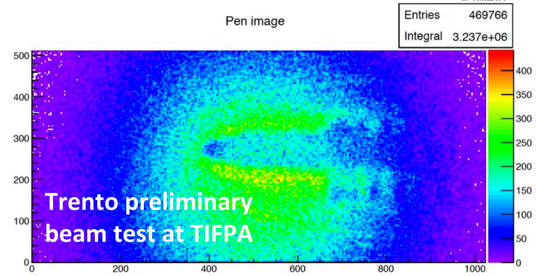
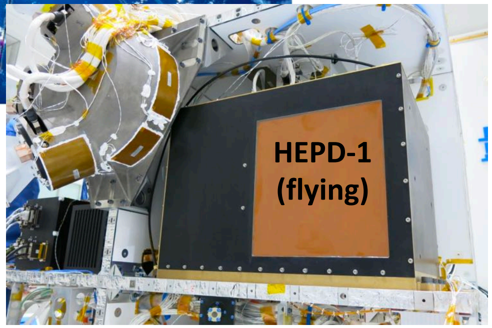


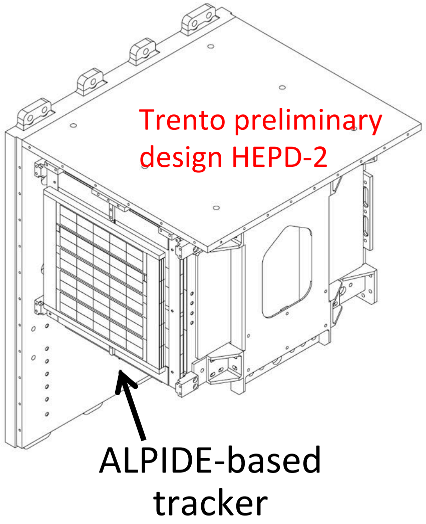

**Fig. 8.** Cluster sizes and spatial resolution of pALPIDE-1 shown for different dies as well as before and after neutron irradiation. Data is for sector 2 with a reverse bias voltage of −3 V.



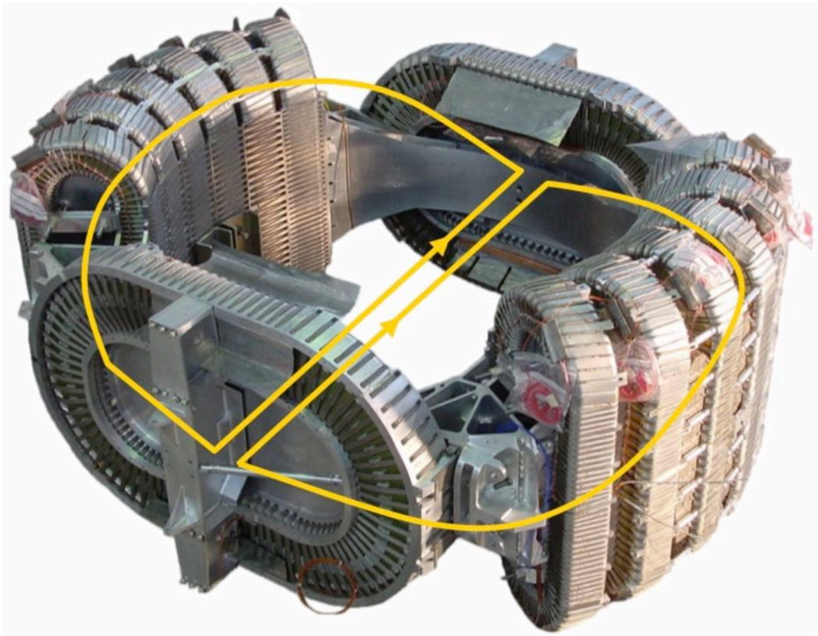




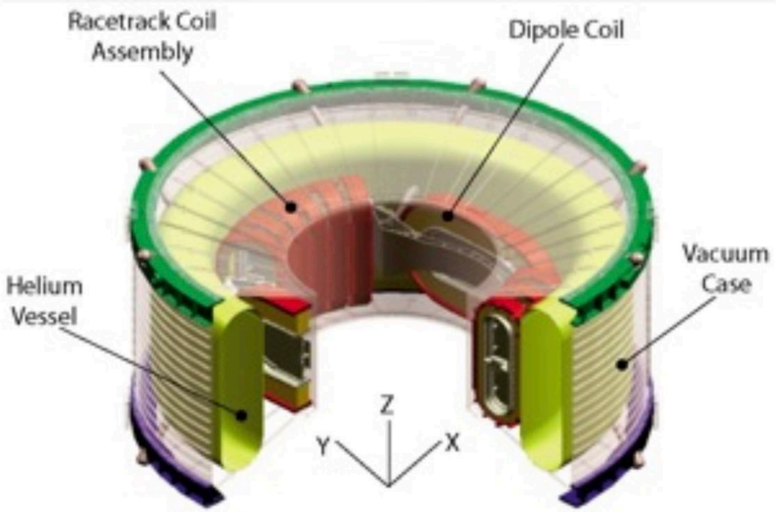
# Magnets – the AMS-02 case

Roberto Iuppa



The AMS-02 Superconducting Magnet is composed of 14 coils. Despite the toroidal shape the magnet develops a dipolar field along the direction of the two biggest coils. The intensity of the field is approximately 0.87 T in the center.

*from http://www.ams02.org/*



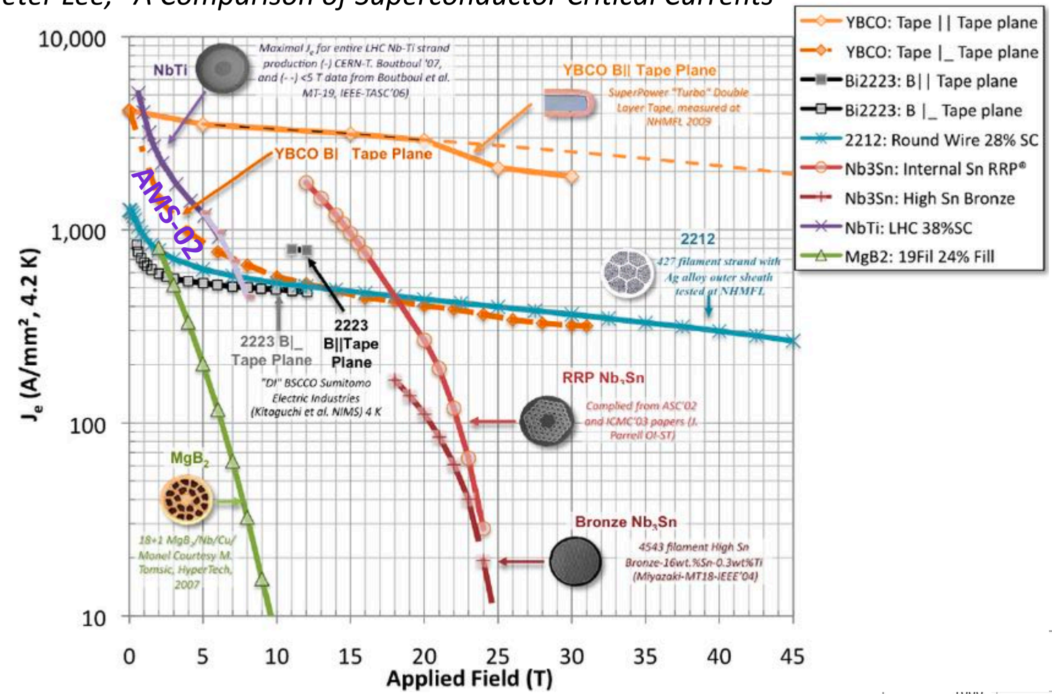

The Superconducting Magnet, the Helium Vessel and the Vacuum Case CAD Design.

The Magnet operates at a temperature of 1.8 K, using the cryogenic power provided by 2,500 L of superfluid Helium stored in a toroidal vessel. **Because of parasitic heat loads, the Helium will gradually boil off throughout the lifetime of the experiment, expected to be around three years.** After this time the SCM will warm up and it will no longer be operational.

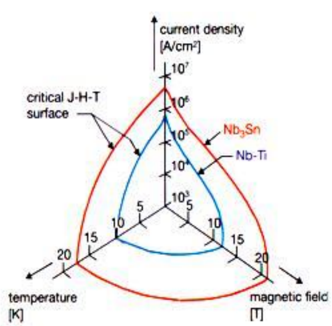
# High temperature superconducting magnets

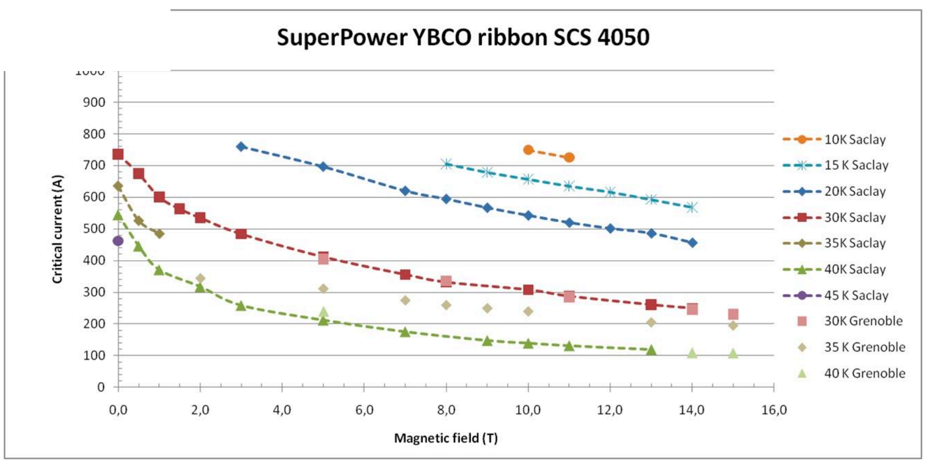
Roberto Iuppa

*Peter Lee, "A Comparison of Superconductor Critical Currents"*




Operating a superconducting magnet at **20K, instead of 1.9K** takes you to another world. Cooling manageable with a cryocooler: **simpler, less expensive, more robust, longer experiment lifetime**.



# Closing remarks

Roberto Iuppa

How they met themselves
*Dante Gabriel Rossetti (1860-1864)*

- 90 years after its prediction, antimatter remains one of the deepest mysteries to solve
- we have an idea of how baryogenesis occurred and which symmetries must have been conserved all through Universe history
- Standard Model CP violation just observed in the baryon sector, but too small to solve the problem
- CPT symmetry for H-Hbar systems experimentally verified up to $2x10^{-12}$
- CR antiprotons show some tension with purely secondary prediction
- CR positrons puzzled the community in the last decade (PAMELA…). Recent HAWC observations of PWNs crucial to revitalize the discussion
- Extending CR antimatter measurements up to 30 TV is of great importance. A new generation of magnetic spectrometers is under development