EXPERIMENTAL ASTROPARTICLES 1

25 July 2016

Vincent Poireau, LAPP Annecy

PLAN

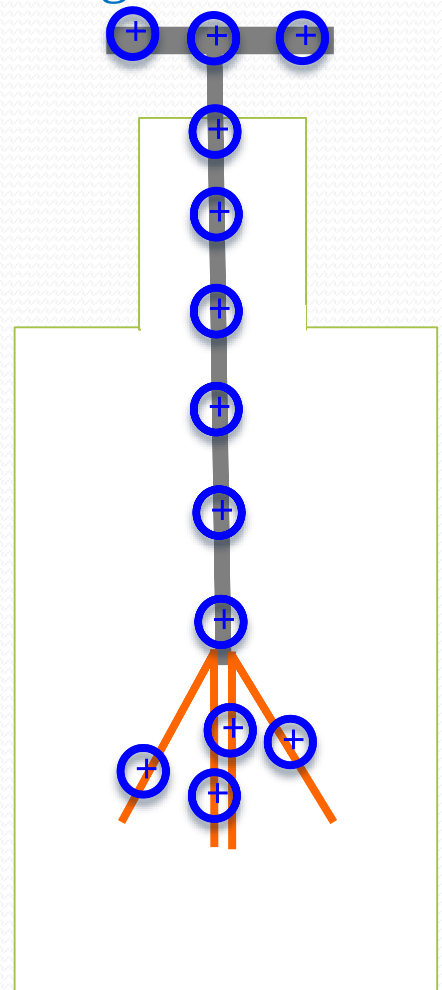
- Experimental astroparticles 1
  - Cosmic rays
  - Indirect search for dark matter
  - Some experiments
  - AMS-02: detailing a modern experiment
  - Recent results on cosmic rays and their implications

- Experimental astroparticles 2
  - This afternoon, presented by **Julien Masbou**
  - Cosmic rays with photons - γ astronomy
  - Cosmic rays at the highest energy

COSMIC RAYS

HISTORIC

- 1736 – 1806 : Charles Augustin de Coulomb observed that a sphere initially charged and isolated loses its electrical charge

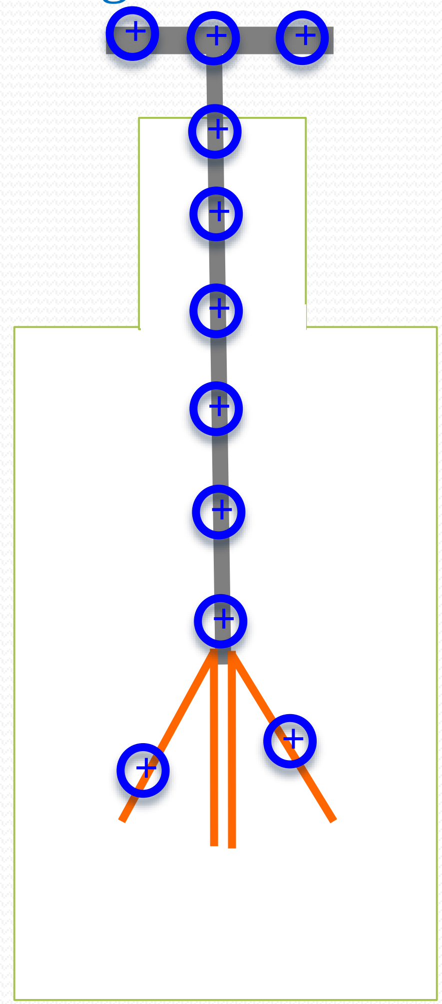


HISTORIC

- 1736 – 1806 : Charles Augustin de Coulomb observed that a sphere initially charged and isolated loses its electrical charge

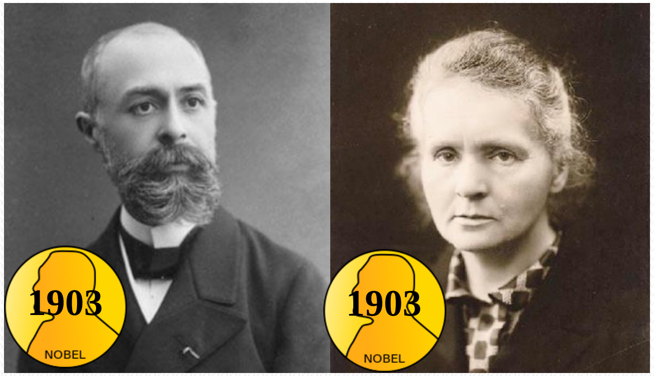
Electroscopes are spontaneously discharging ????

An electroscope



HISTORIC

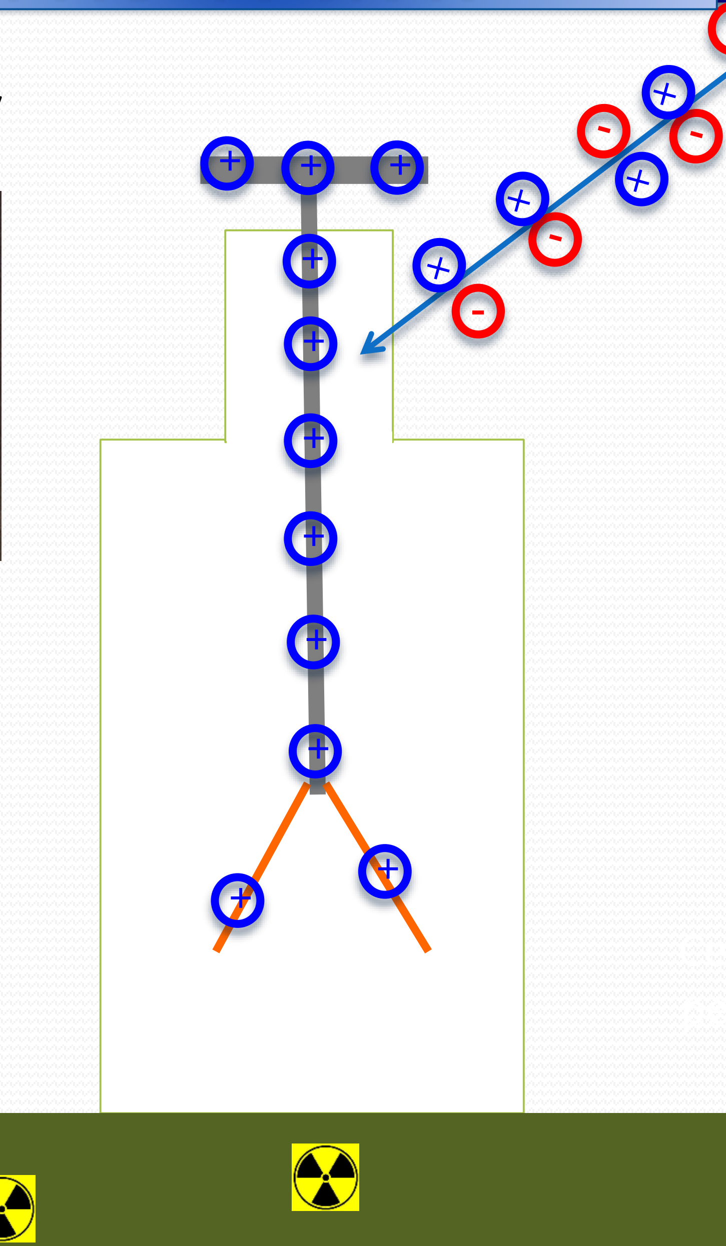
Beginning of 20th century



Henri Becquerel (1852-1908)

Marie Curie (1867-1934)

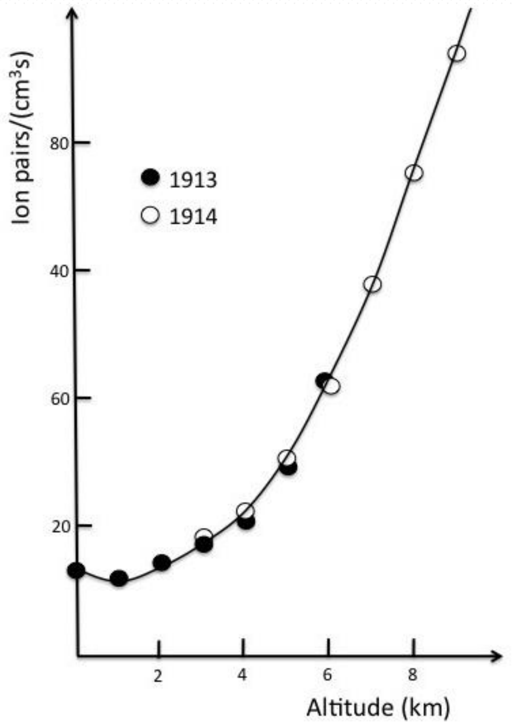
The radioactivity could explain the spontaneous discharge

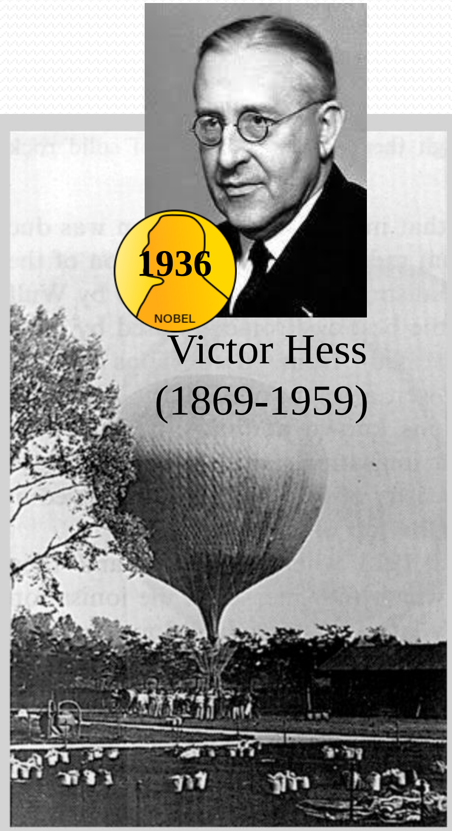


C.T.R. Wilson (1869-1959)

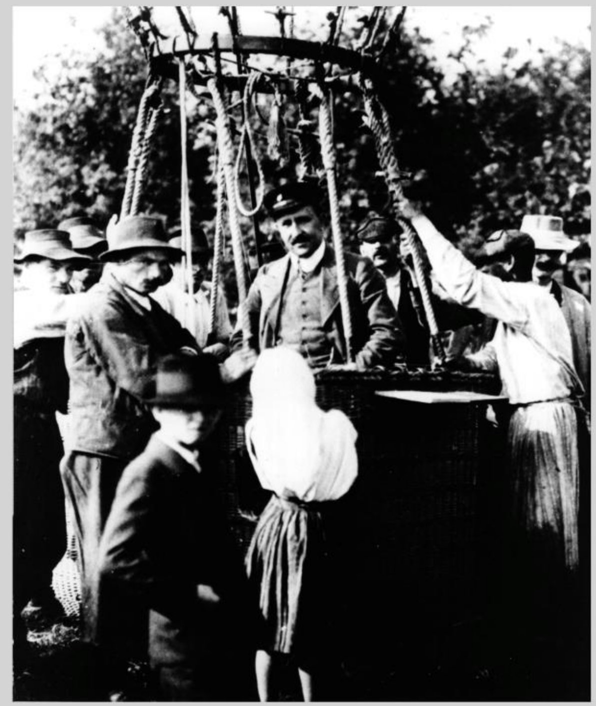
HISTORIC

- 1912: Victor Hess measures the atmospheric ionization with electroscopes during balloon flights at various altitudes: the ionization increases





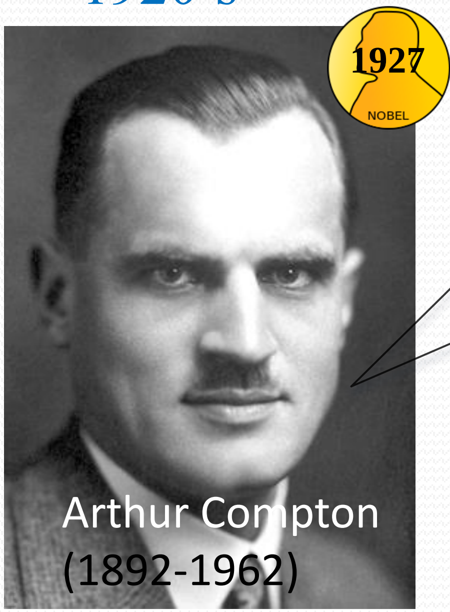
Victor Hess
(1869-1959)



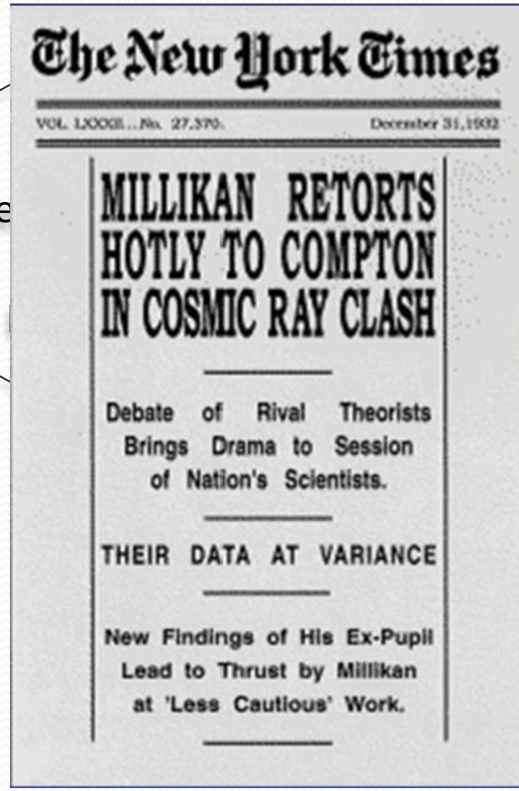
- This ionization comes from space!

HISTORIC

- From what are they composed? The debate is passionate in the 1920's



Arthur Compton (1892-1962)


The New York Times

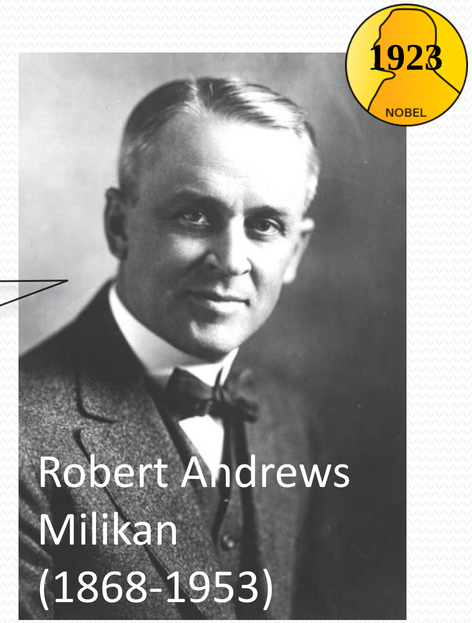
VOL. LXXXII...No. 27,370. December 31, 1932

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.



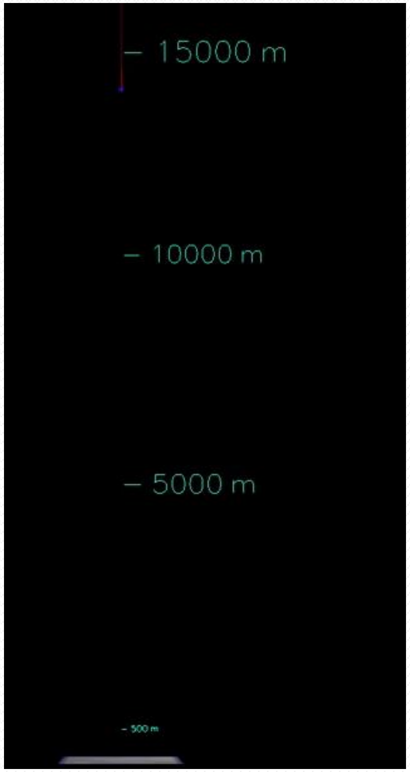
Robert Andrews Milikan (1868-1953)

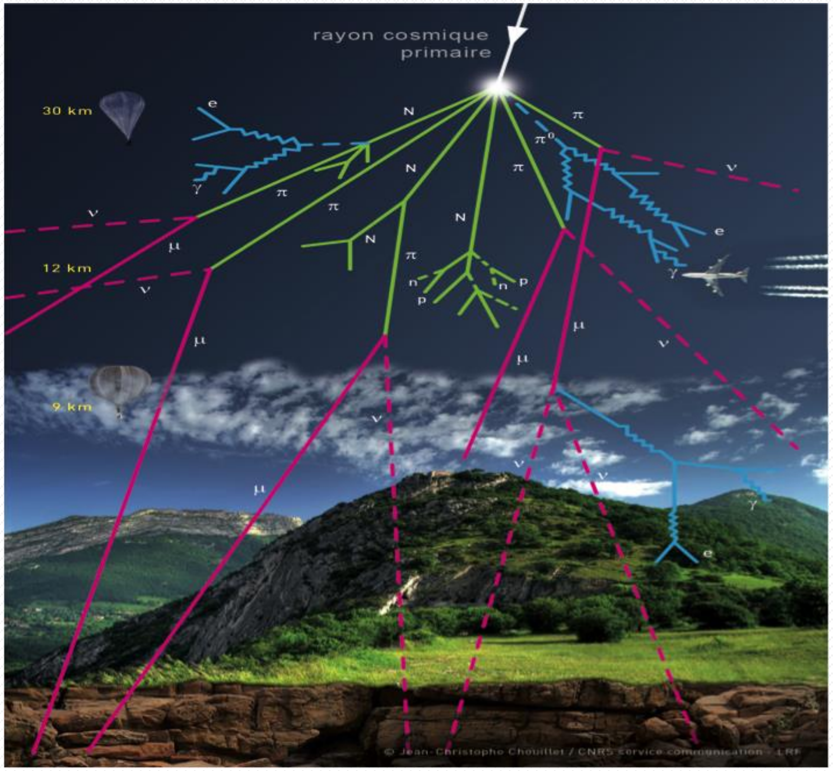
1925: very high energy gammas → « cosmic rays »

- Their intensity varies depending on where we are on Earth…
- Cosmic rays are charged particles!
    - More particle from the western direction: **positively charged**

HISTORIC

- 1937: Pierre Auger positions three Geiger counters separated of 70 m at le pic du midi
- Cosmic rays arrive in group: atmospheric shower

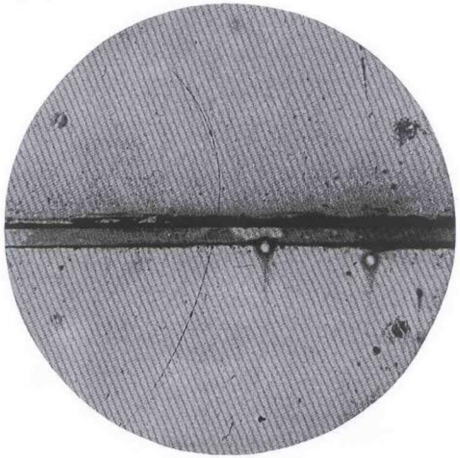


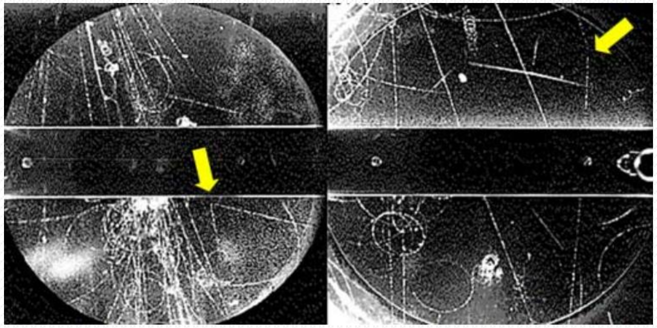


Pierre Victor Auger
(1899-1993)

HISTORIC

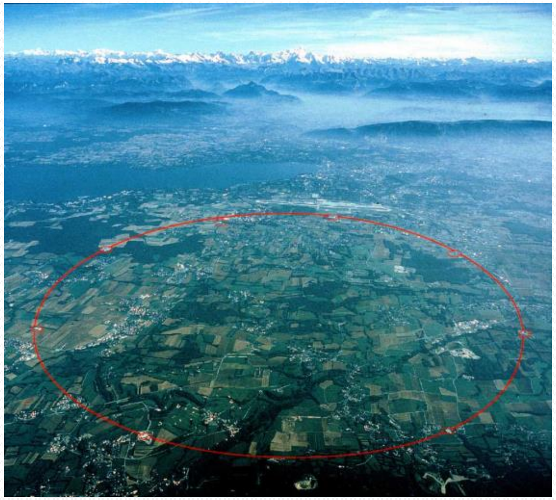
- Many new particles discovered in the cosmic rays
  - 1932: positron e^+ (first observation of antimatter)
  - 1936: muon μ
  - 1949: pion π
  - 1949: kaon K
  - 1949: lambda Λ
  - 1952: xi Ξ
  - 1953: sigma Σ





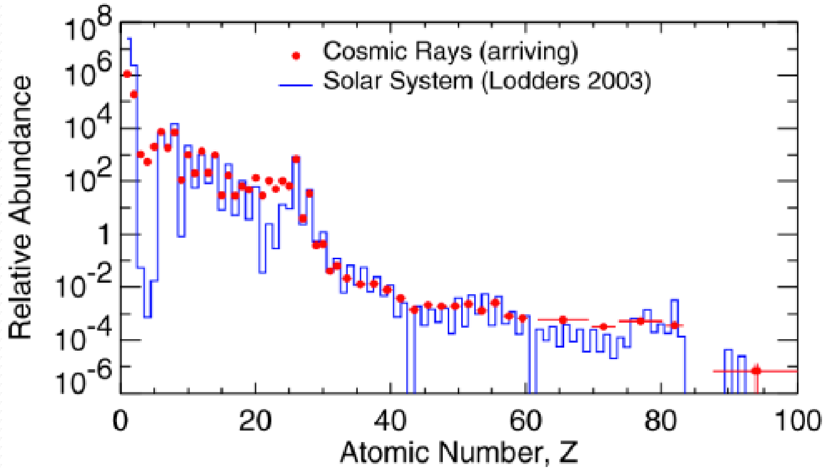
- Birth of a new science: particle physics!

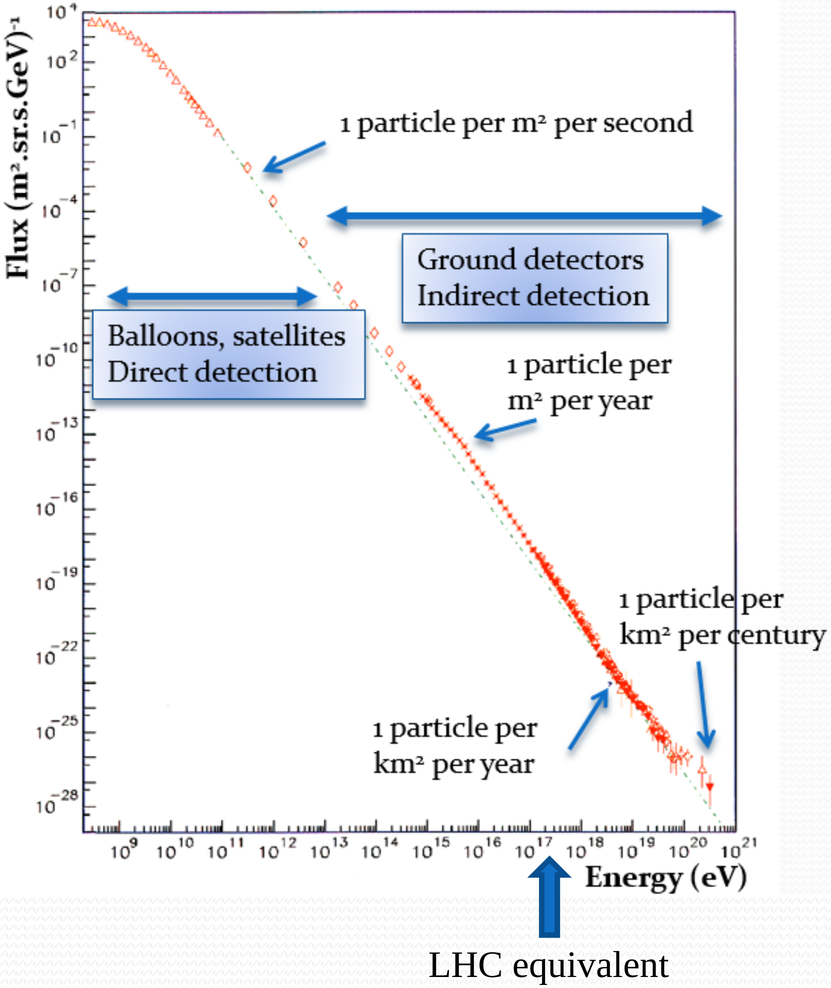
- Cosmic rays are replaced by accelerators where particles are artificially produced



COSMIC RAYS

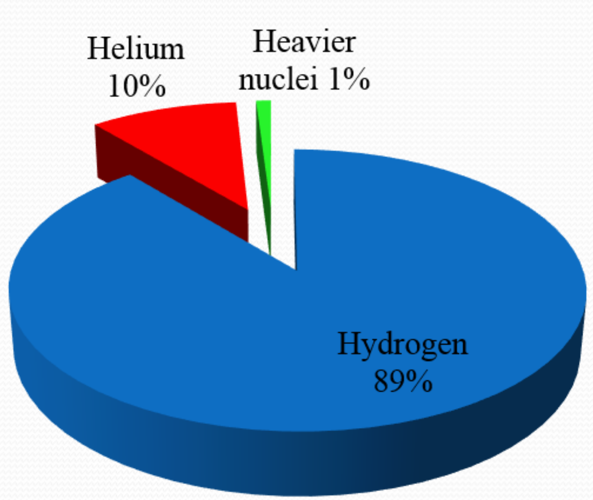
- Cosmic rays
  - 12 orders in **energy**
    - 100 MeV to 10^{20} eV
  - 30 orders in **flux**
  - Isotropic flux
- Abondance of nuclei in the cosmic rays similar to the one from the solar system

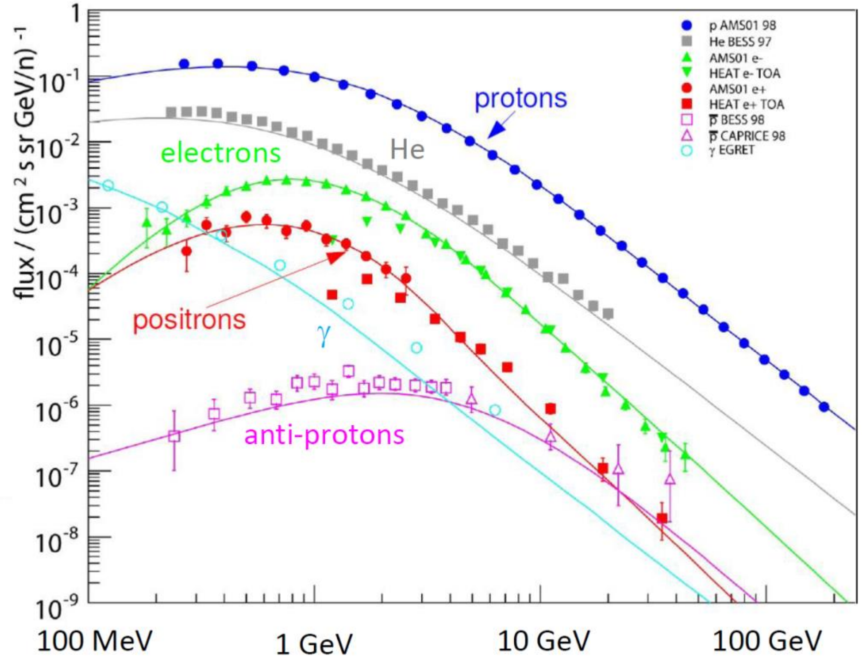




COSMIC RAYS

- Composition
  - **Charged** : electrons, protons, nuclei
  - **Neutral** : photons, neutrinos
- Charged cosmic rays

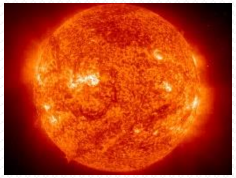




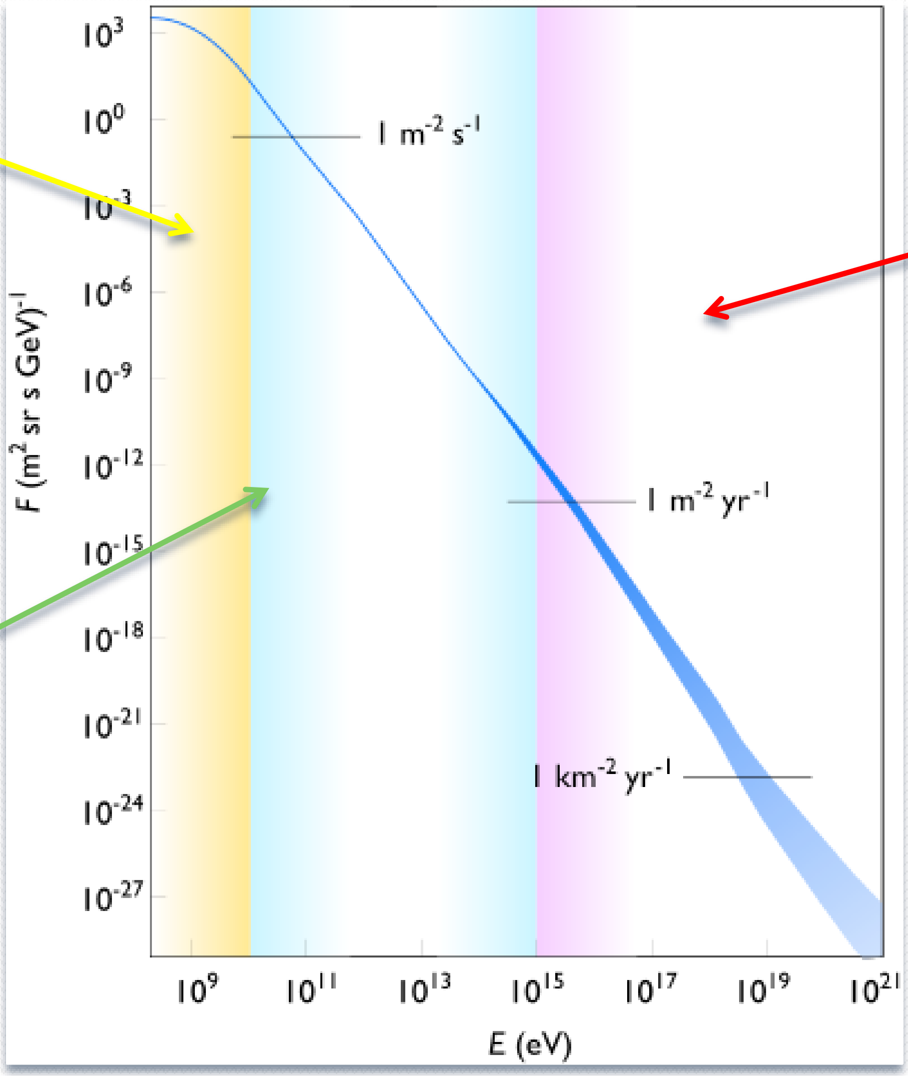
- Power law spectrum $1/E^{\gamma}$, $\gamma = 2.7\text{-}3.5$
  - The measured spectrum results
    - from the **production** and **acceleration** mechanisms ($1/E^{\alpha}$, $\alpha = 2.0\text{-}2.4$)
    - from the **diffusion** ($1/E^{\delta}$, $\delta = 0.3\text{-}0.7$)
  - $\gamma = \alpha + \delta$

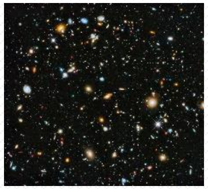
COSMIC RAYS

- Where are they coming from?



From
the sun



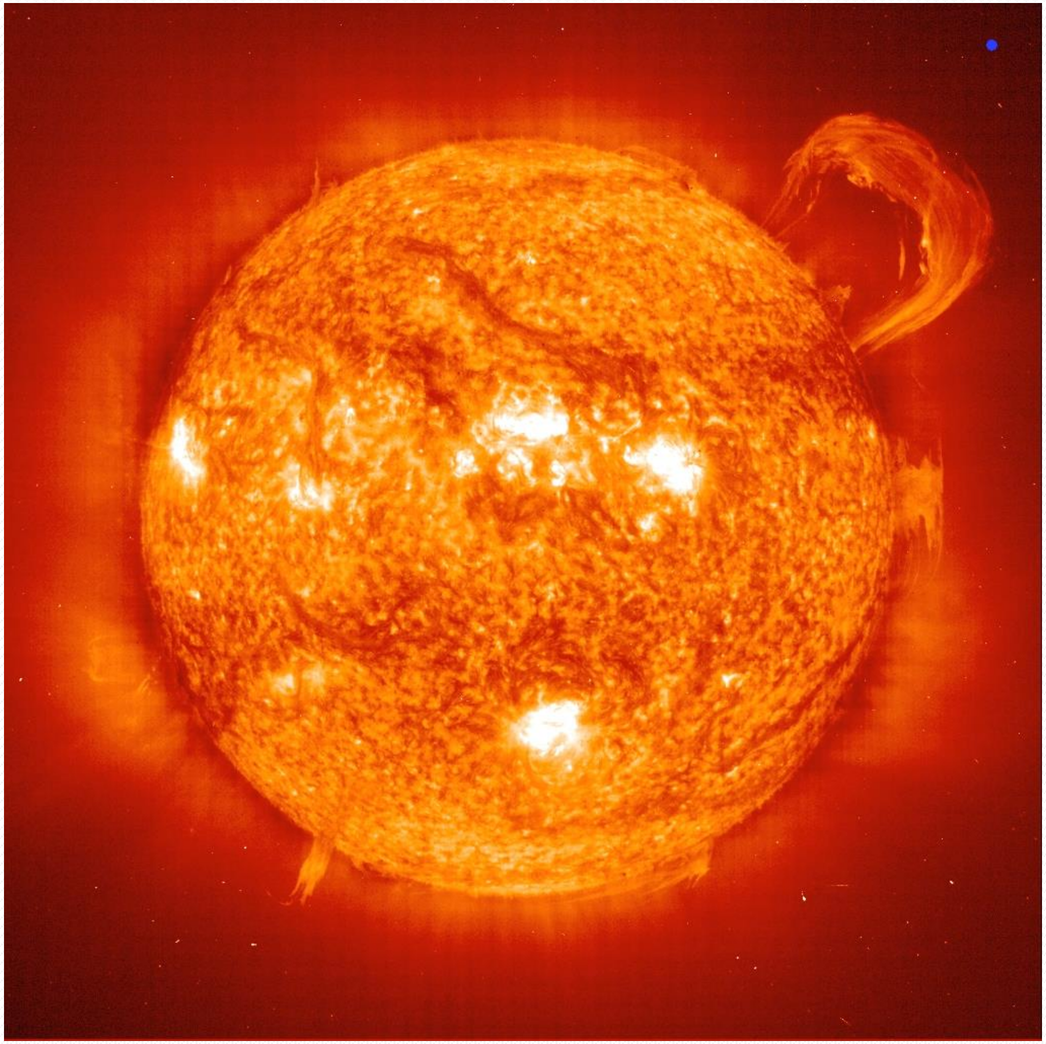


From outside
our Galaxy

From our
Galaxy

COSMIC RAYS

- Low energy cosmic rays are accelerated by the sun



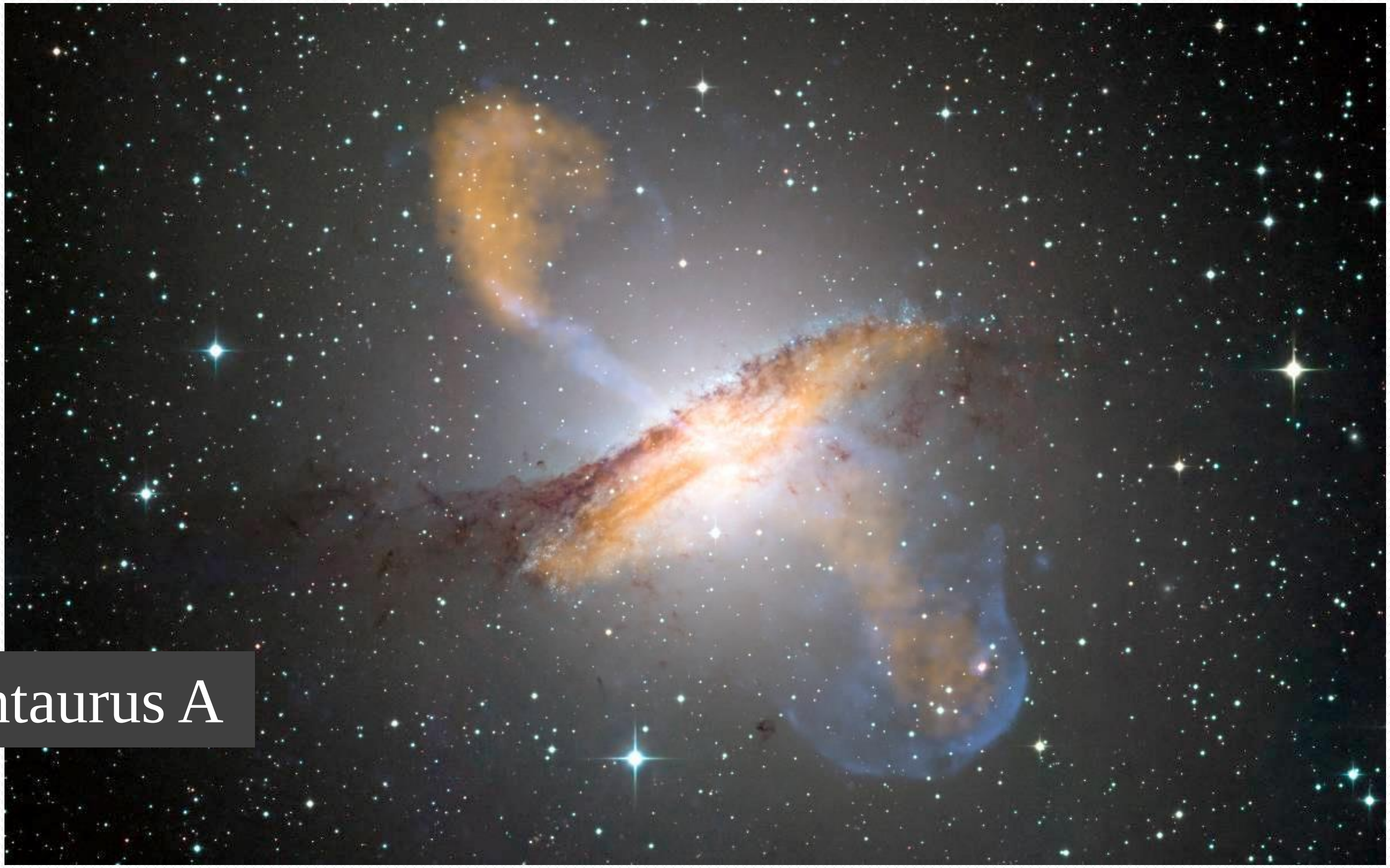
Aurora borealis

COSMIC RAYS

- At intermediate energies, supernovae remants produce cosmic rays

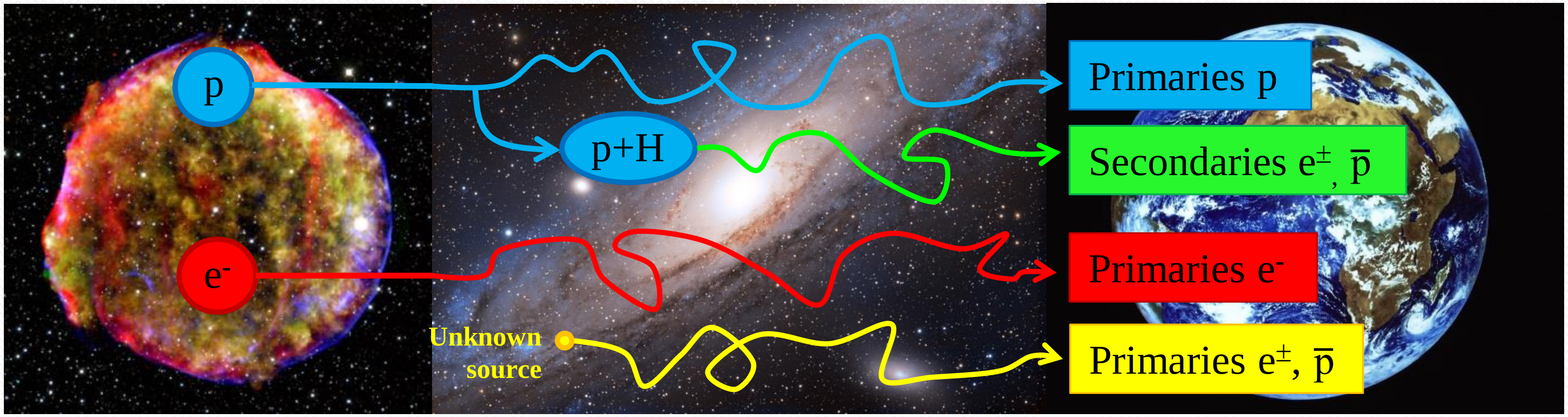
COSMIC RAYS

- At extreme energies, active galaxy nuclei, quasars, or gamma ray bursts are potential candidates



Centaurus A

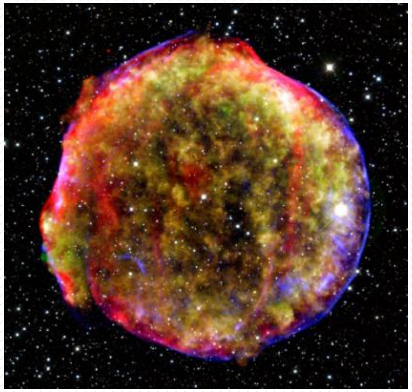
COSMIC RAYS



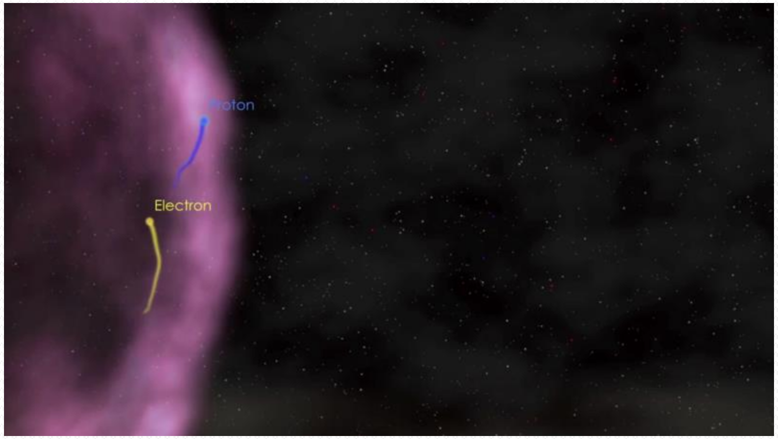
- Primary cosmic rays
  - Produced direcly **in the source**
  - Sources: **supernova remnants, pulsars**, **active galactic nuclei**, **quasars**
  - Primaries include
    - Electrons, protons, helium, carbon, …
- Secondary cosmic rays
  - Originate from the **interaction** of primaries on **interstellar medium**
  - Secondaries include
    - Positrons, antiprotons, bore, …
- Additional sources of electrons and positrons?

ACCELERATION

- In our Galaxy, main source of primary cosmic rays: supernova remnants
  - Very strong magnetic field in the **shell** of supernovas



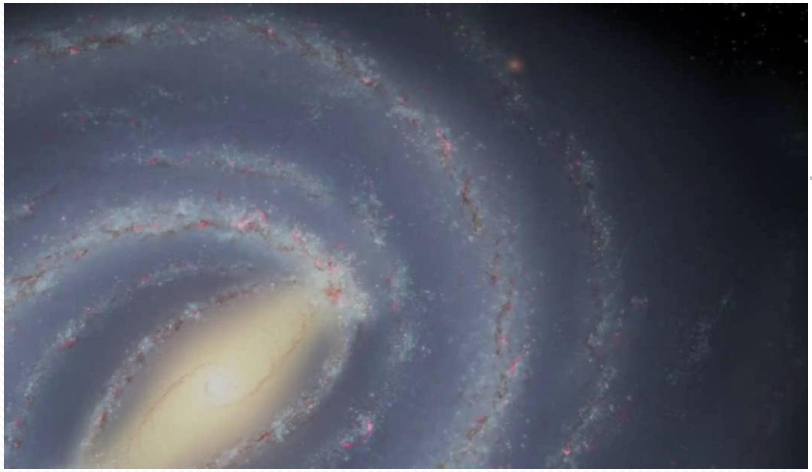
- Acceleration
  - Due to the **shock wave**
  - First order **Fermi mechanism**
  - Naturally produce a **power law** spectrum

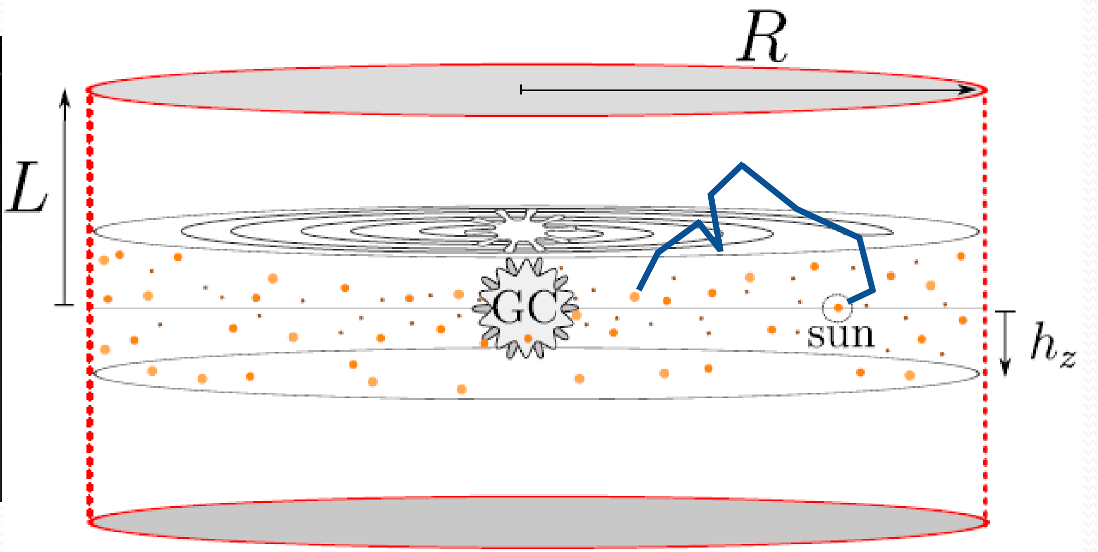


- This process explains why the cosmic ray composition is similar to the one from the solar system

PROPAGATION

- Charged cosmic rays: propagation equivalent to a diffusion in the Galactic medium
  - **Irregular magnetic field** of the diffusive halo = random walk
  - **Diffusion** coefficient $K(E) = K_0 \beta R^{\delta}$ $(R=p/Z)$
    - Free parameters: K_0, δ, L, V_c, V_a
  - **Large uncertainties** on these parameters

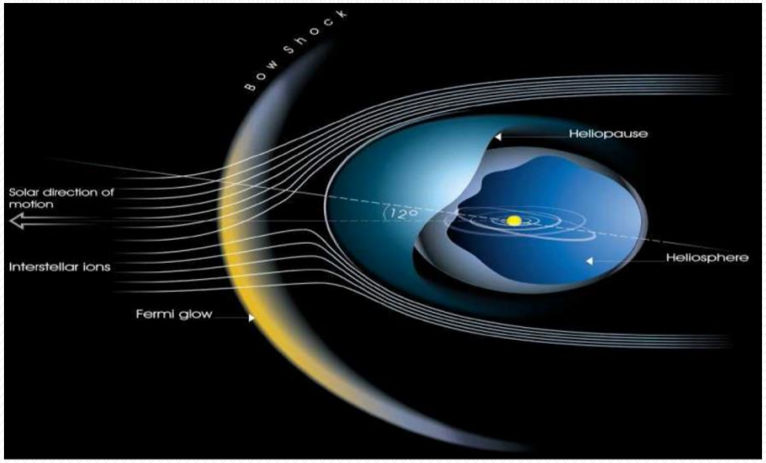


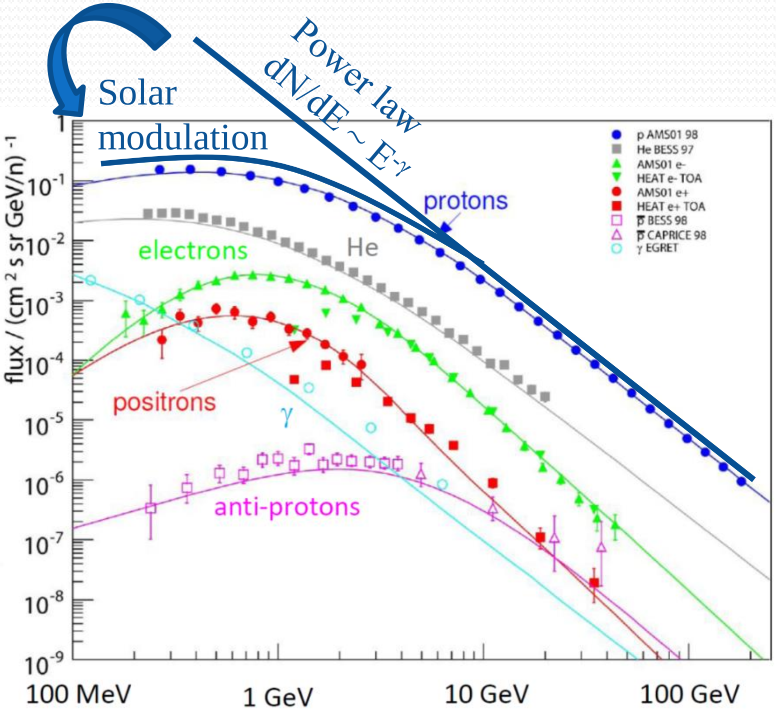


h_z=200 pc, L=1-15 kpc, R=25 kpc

SOLAR MODULATION

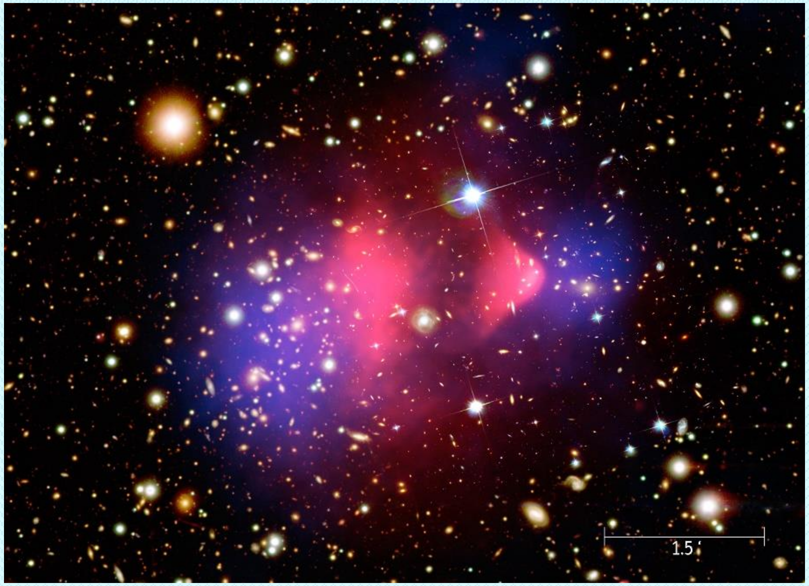
- Heliosphere: a region of space influenced by the sun (solar wind)
  - **Size**: 150 AU
- Solar wind: a continous flow of charged particles from sun
  - **e**$^-$ and **p**
  - Carries the **sun magnetic field** to the interplanetary space
- Solar cycles
  - **Reversal** of the sun magnetic field polarity
  - Every **11 years**
  - Solar activity going from a minimum to a maximal intensity
- Solar modulation affects cosmic rays below 20 GeV
  - **Deviation** from the power law





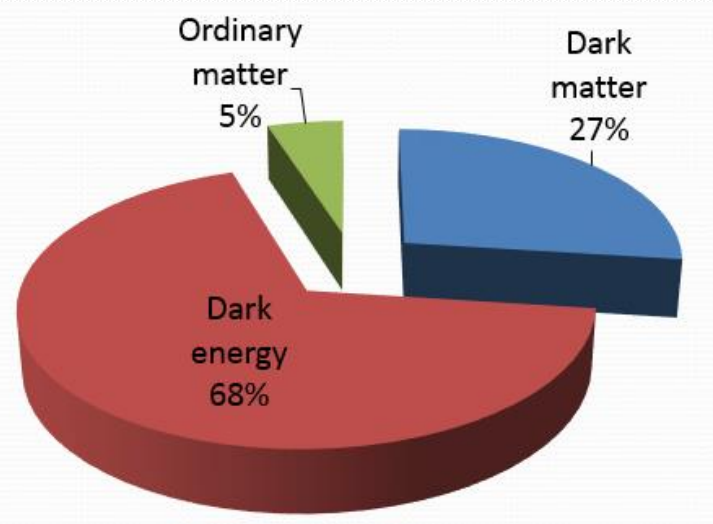
Vincent Poireau

INDIRECT SEARCH FOR DARK MATTER



DARK MATTER

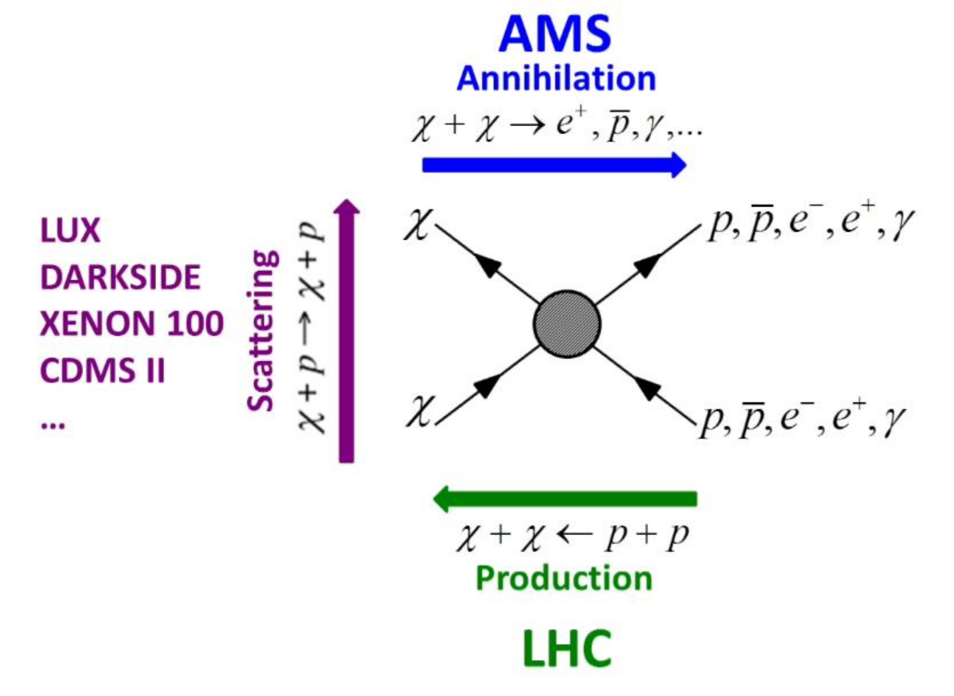
- A very large fraction of the Universe content remains mysterious



- Dark matter: 27% of our Universe is made of unknown matter (other than electrons, quarks, …)
- « Observation »: galaxy rotation curves, X-ray emission, gravitational lensing, cosmic microwave background

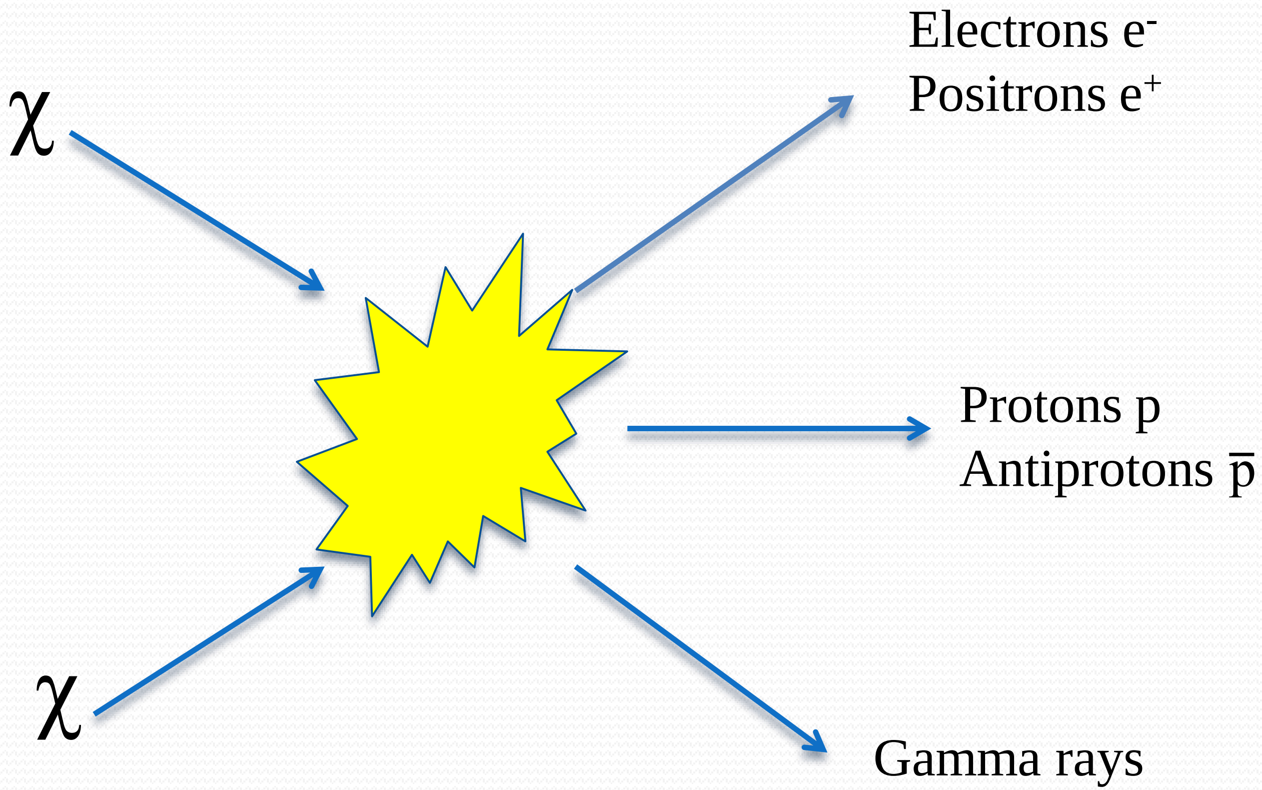
DARK MATTER

- Best candidate: weakly interacting massive particle ⇒ WIMP
  - **Massive particles**: 100 GeV – several TeV
  - **Weakly** interacting with the ordinary matter
- Several ways to see its effect



DARK MATTER

- Annihilation of the WIMPs
  - Natural cross-section from relic density: **$\langle\sigma v\rangle \approx 3.10^{-26}$ cm^{3}s^{-1}**



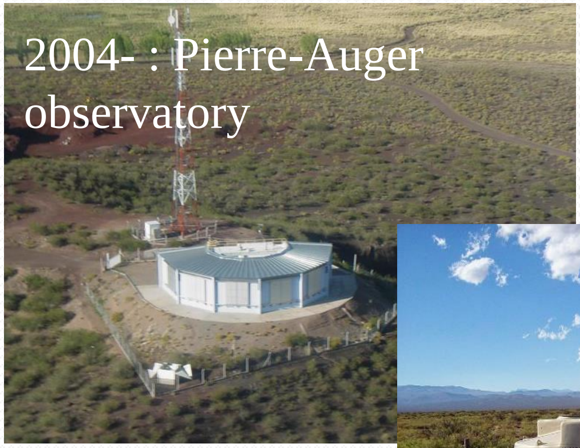
COSMIC RAY EXPERIMENTS

EXPERIMENTS

1959-1974: Vulcano Ranch (USA)
8km^2

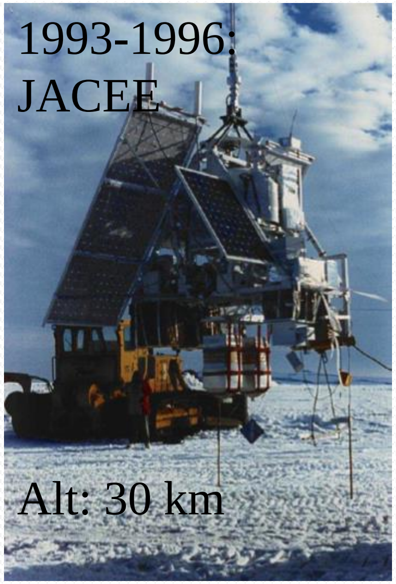
1998-2004: AGASA (Japon)
100 km^2

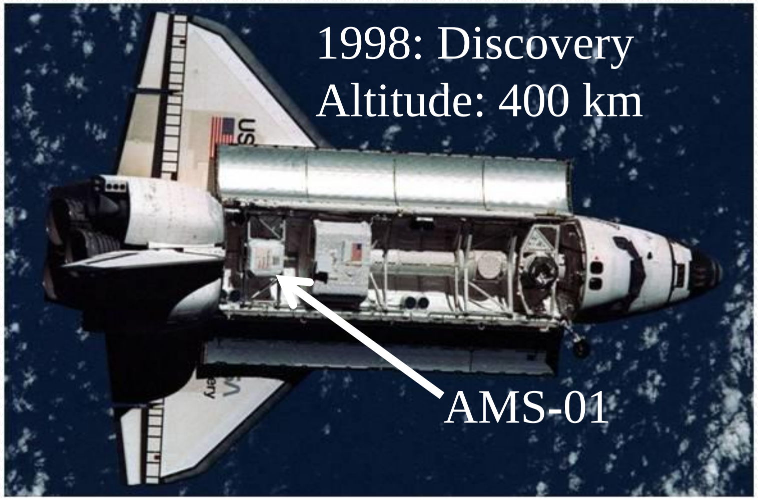
1980-1993: Fly eye (Utah)



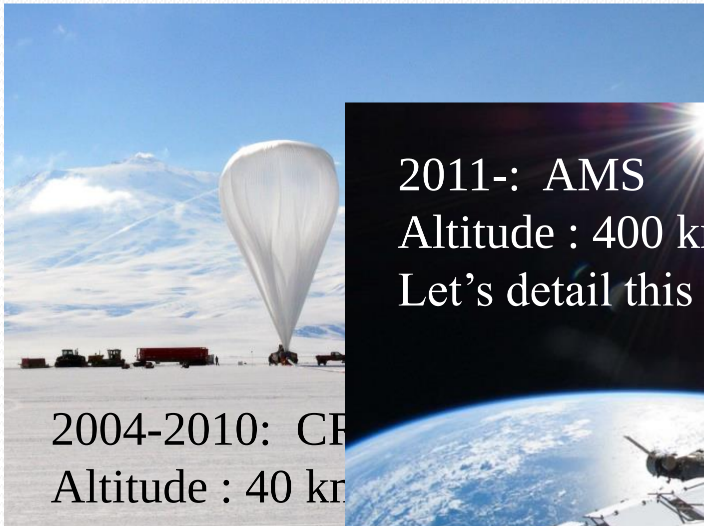
2004- : Pierre-Auger observatory

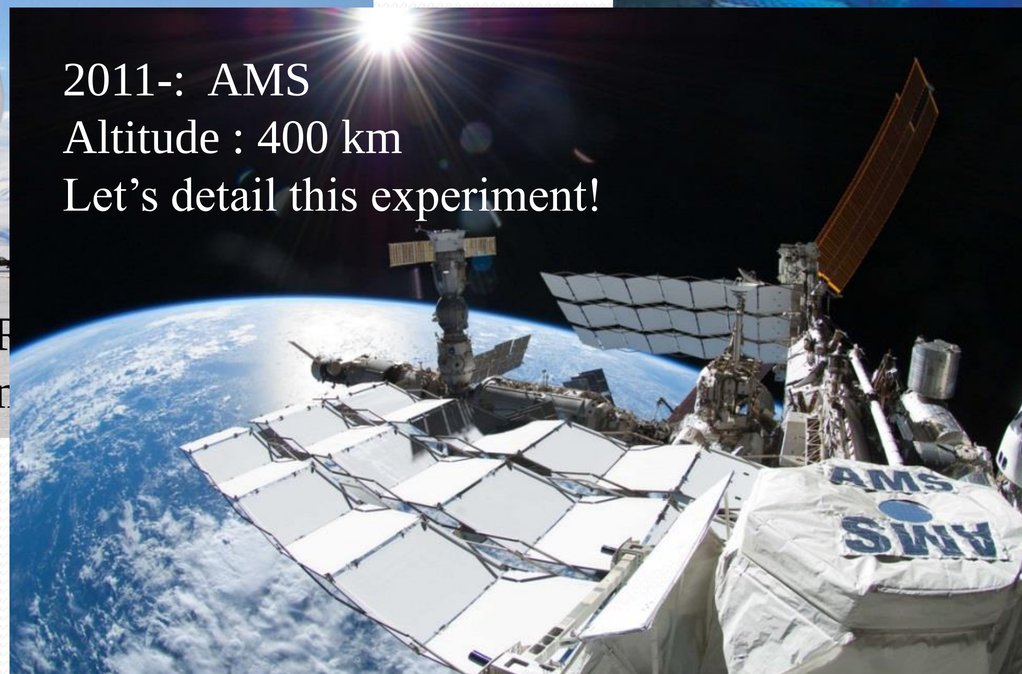
EXPERIMENTS

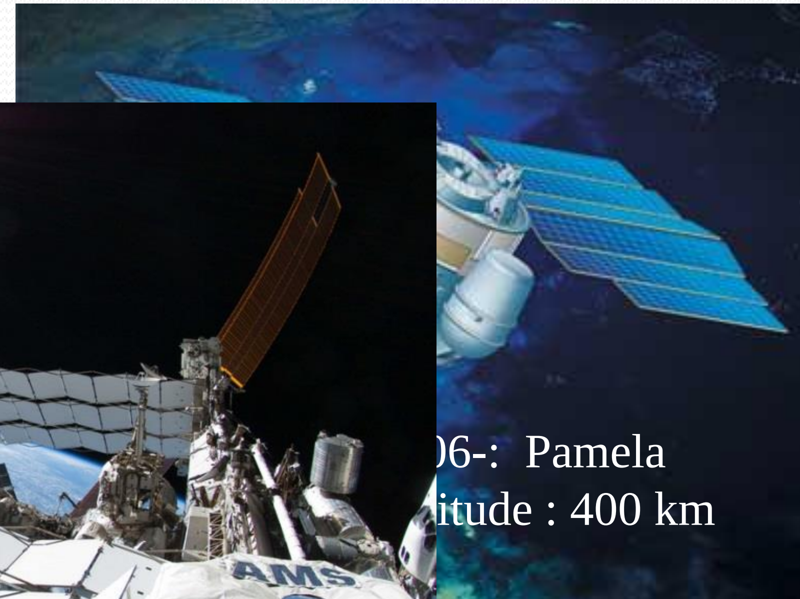




EXPERIMENTS







THE AMS-02 EXPERIMENT

AMS-02

- A particle detector in space
  - Detect **charged** particles and **gamma** rays
  - From **100 MeV** to **a few TeV**

5m x 4m x 3m
7.5 tons

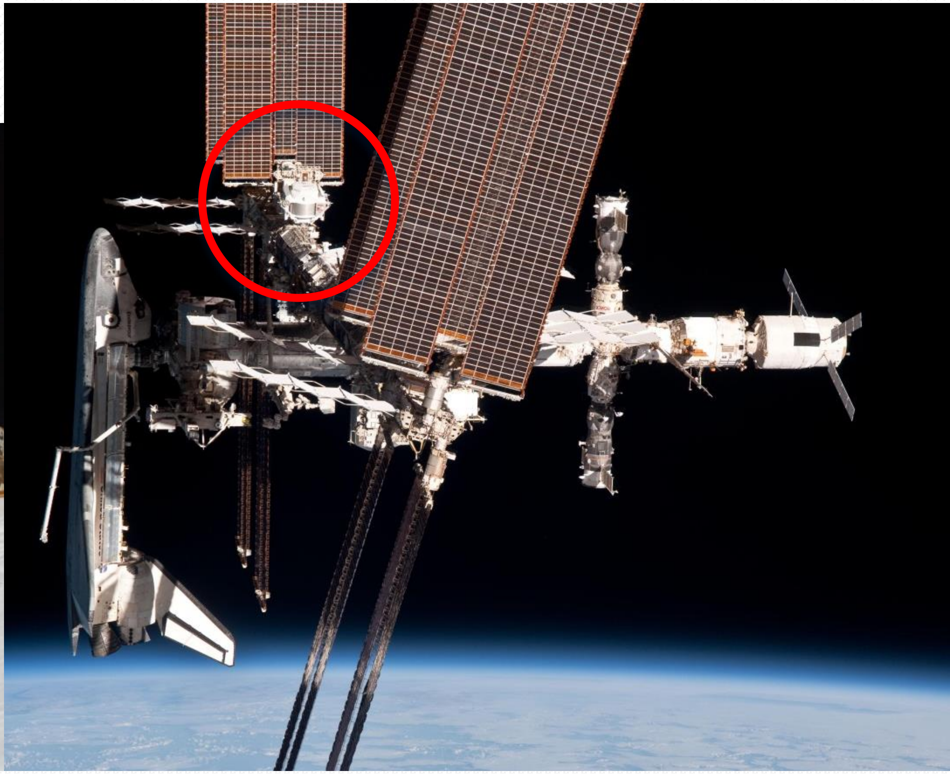
AMS-02

- Launched from Cap Canaveral on the 16^{th} of May 2011
  - **Penultimate** American shuttle!


NASA HD
Spacevidcast Live
STS-134 Mission Coverage
T -00:00:12
Official Clock
SSME Thrust: 0.0%
Altitude (ft): -23
Speed (mph): 0
Range (nm): 0.0
Mach: 0.00
G: 0.0

AMS-02

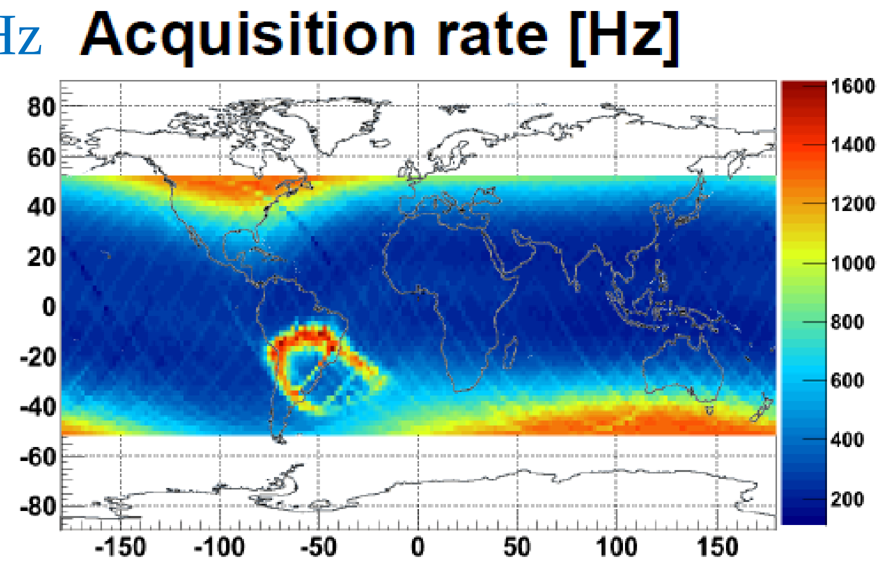
- Installation on the ISS on the 19th of May 2011
  - Orbit at **400 km** altitude
  - One orbit every **90 minutes**



- Detect the cosmic rays before they interact in the atmosphere

FLIGHT OPERATION

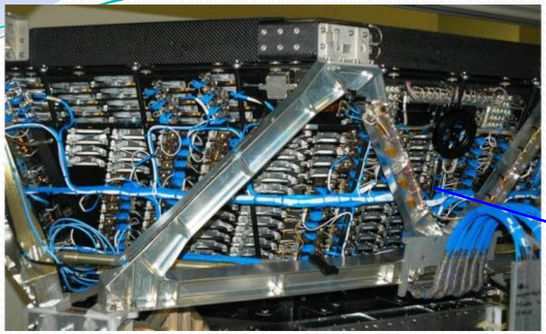
- Acquisition rate from 200 to 2000 Hz
- Continuous operation 7d/7 24h/24
- Acquisition
  - ~**40 millions** events a day
  - ~**100 GB** transferred every day
  - **35 TB** of data every year
  - **200 TB** of reconstructed data every year



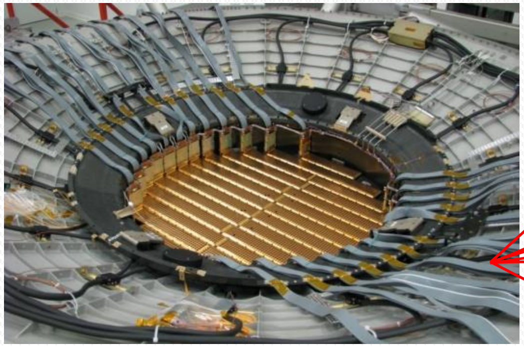
- 85 billions of events recorded since May 2011
  - Much more than all the cosmic rays collected **in the last 100 years**
- Will operate at least until 2024

DETECTOR

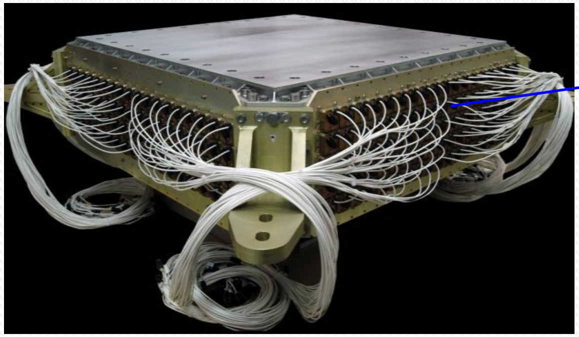
Transition radiation detector
Identifies e^+, e^-

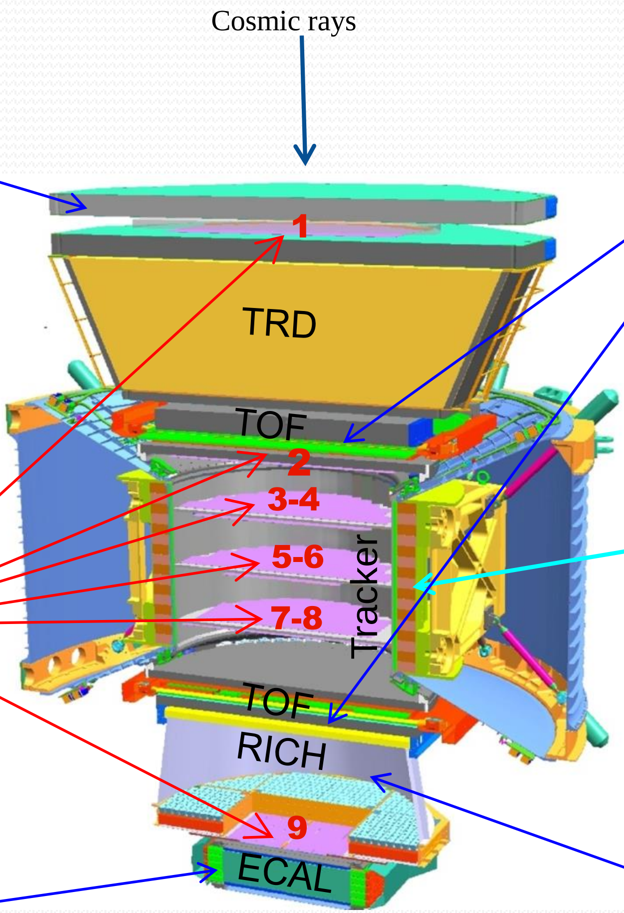


Silicium tracker
Z, P



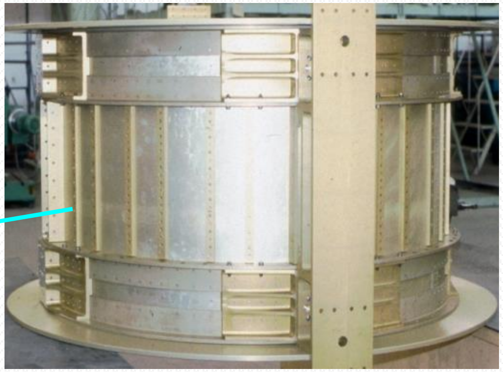
Electromagnetic calorimeter
E of e^+, e^-, γ



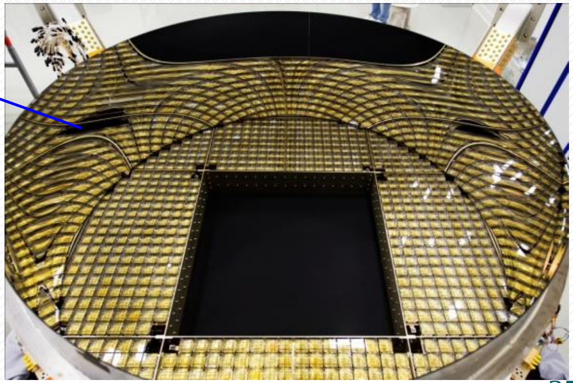


Time of flight
Z, E

Magnet 0,14 T
±Z

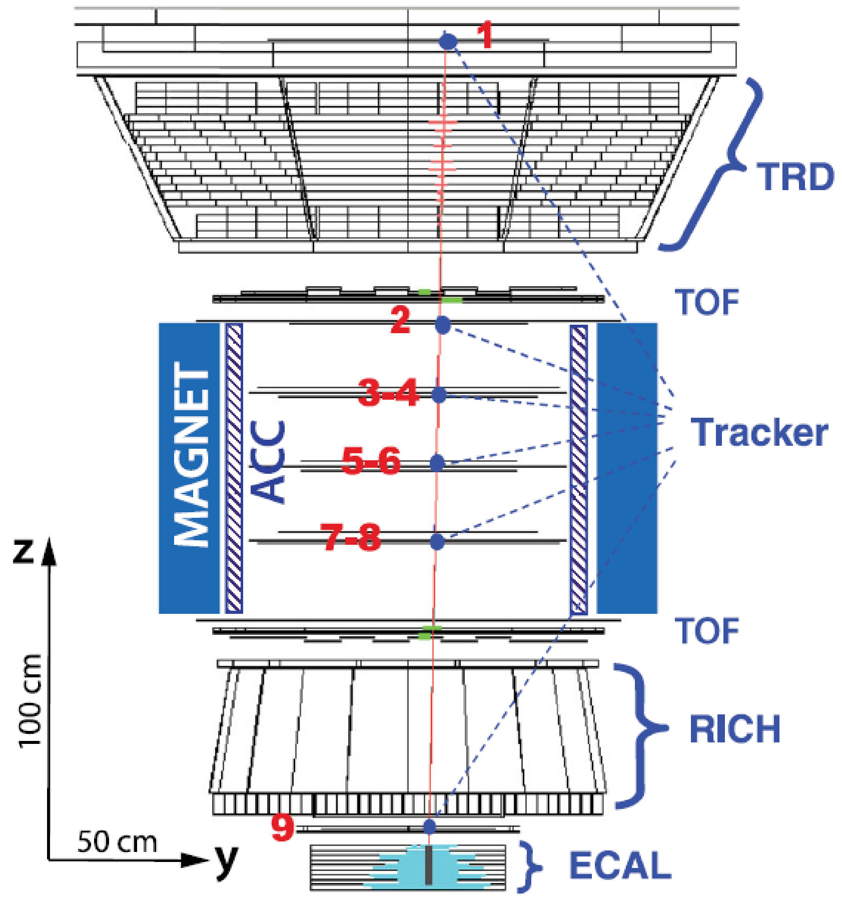


Cherenkov detector
Z, E



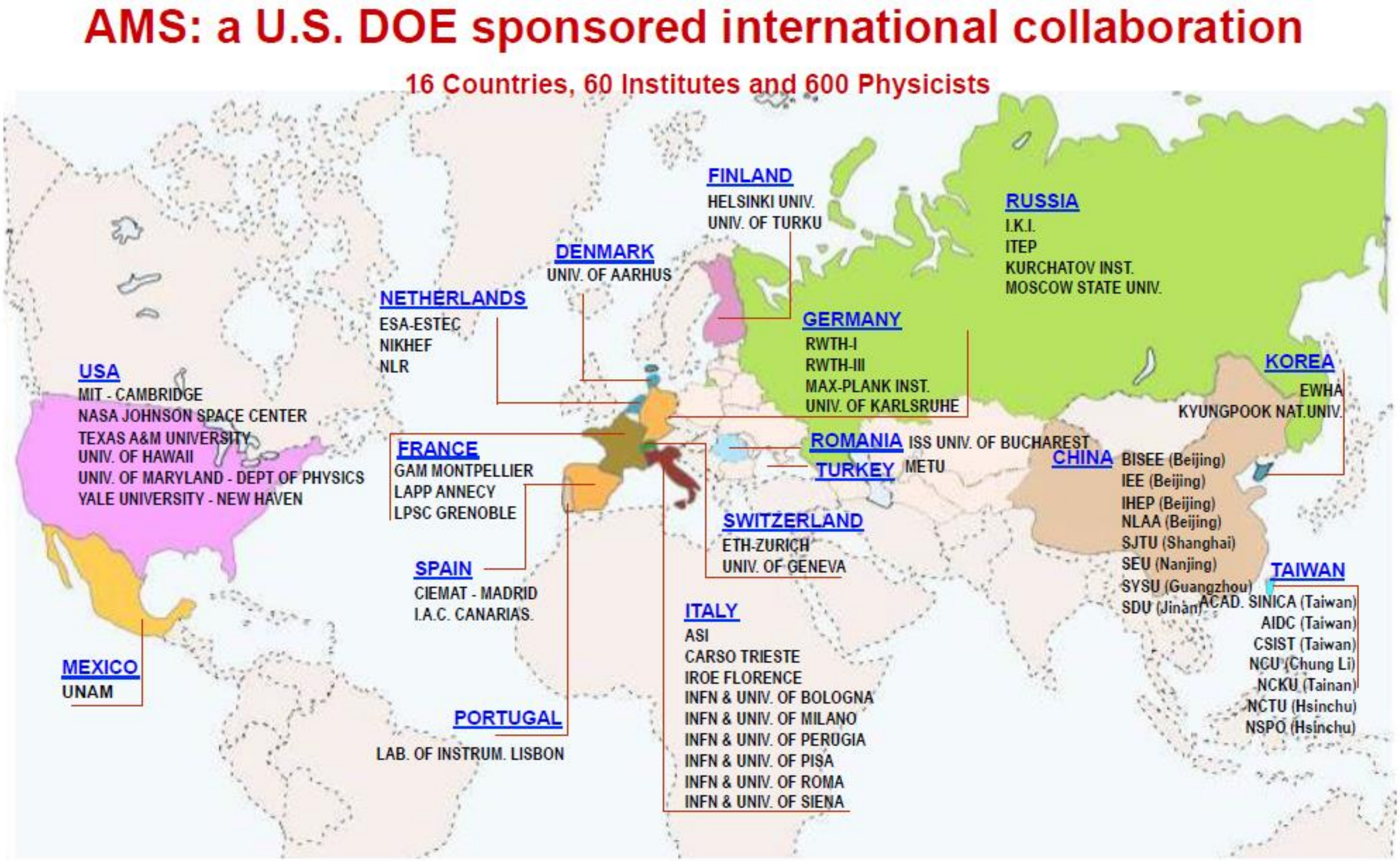
DETECTOR

- Rigidity
  - R = p/Z
  - Expressed in GV



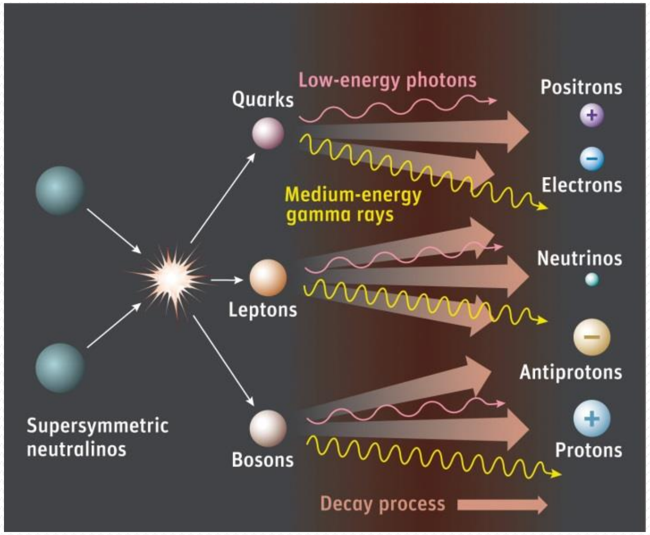
A 369 GeV positron event

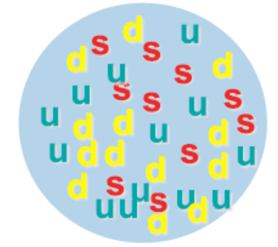
COLLABORATION



AMS TOPICS

- Measurement of cosmic ray fluxes
  - Understand the cosmic ray **propagation** in our Galaxy
- Indirect search of dark matter
  - **Positrons** and **antiprotons** produced during its annihilation
- Search for primordial antimatter
  - **Anti-helium** relic of the Big-Bang or **anti-carbon** from anti-stars
- Surprises? Strangelets?





ELECTRONS AND POSITRONS IN COSMIC RAYS

POSITRON FRACTION

- Positrons : expected only as secondary
- Positron excess with respect to the secondary prediction = source of primary positrons

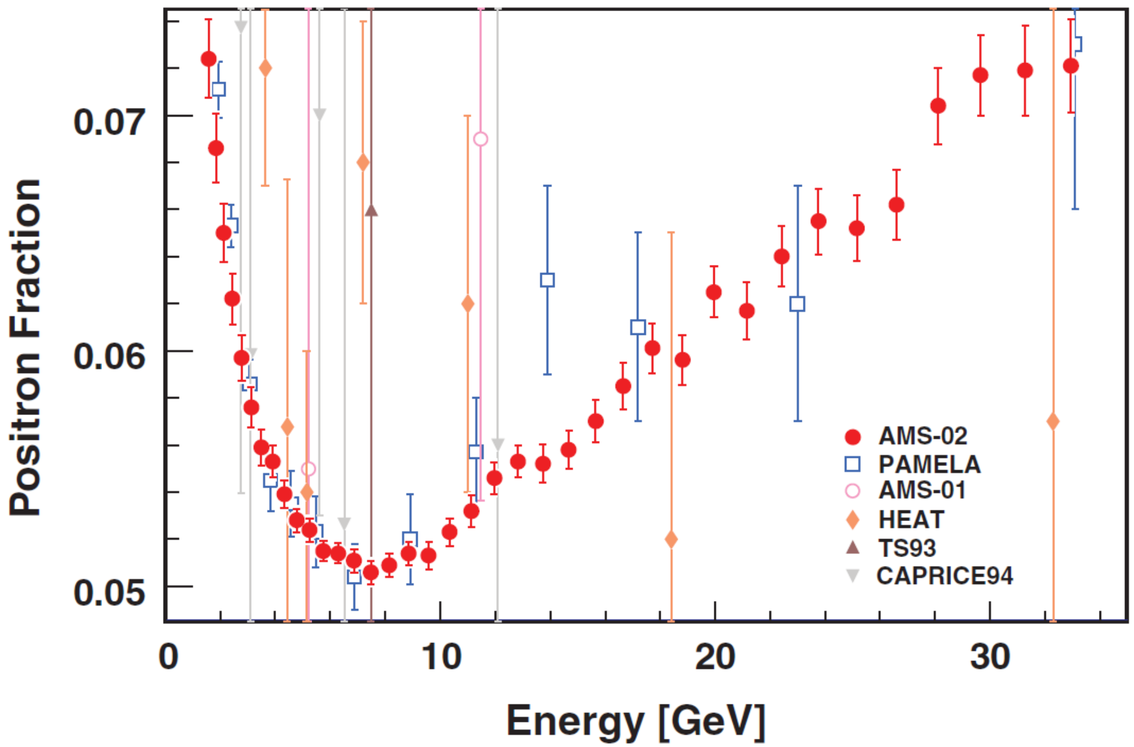
- Positron fraction $$F = \frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}} = \frac{N_{e^+}}{N_{e^+} + N_{e^-}}$$
  - Allows to factorize the **acceptance** and efficiencies
  - **Simplify** the computation of systematic uncertainties

- Challenges
  - **100 times** more protons than electrons
  - **2000 times** more protons than positrons

  $\Rightarrow$ Need to divide number of protons by **10^6**

POSITRON FRACTION

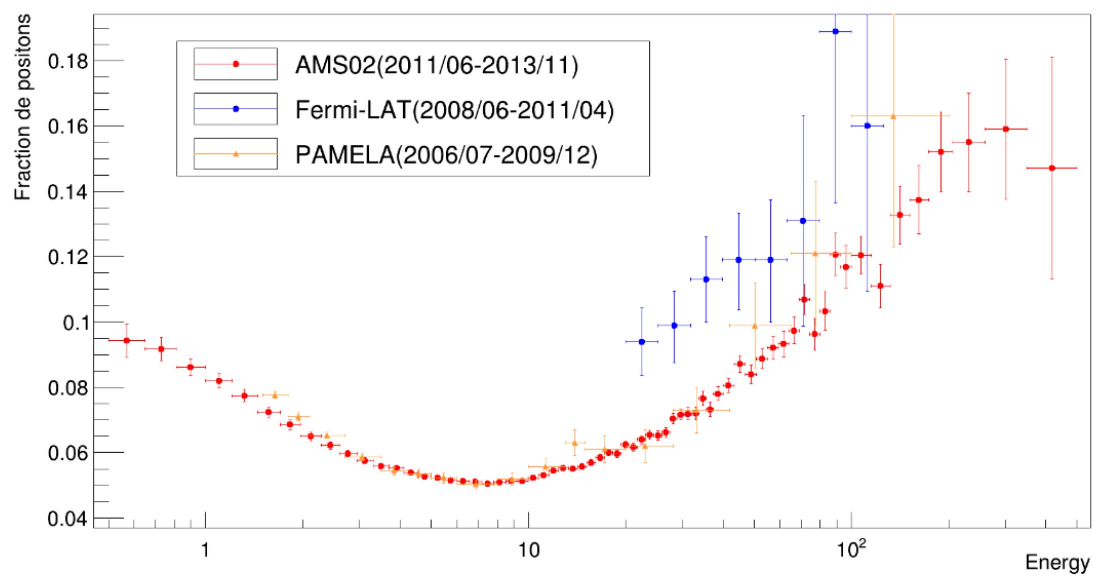
- Result for the positron fraction below 35 GeV
  - Fraction begins to increase **above 10 GeV**
  - **Incompatible** with secondary positrons only
  - A **source of primary positrons** is needed!
    - **Nearby** source since positrons do not propagate more than a **few kpc**



POSITRON FRACTION

- Fraction at high energy

Phys. Rev. Lett. 113, 121101 (2014)



- AMS: precision and energy never reached before
- No sharp structure
- Fit of the slope
  - Cease to increase at **275 ± 32 GeV**
- With the current sensitivity, the flux is isotropic

FLUX MEASUREMENT

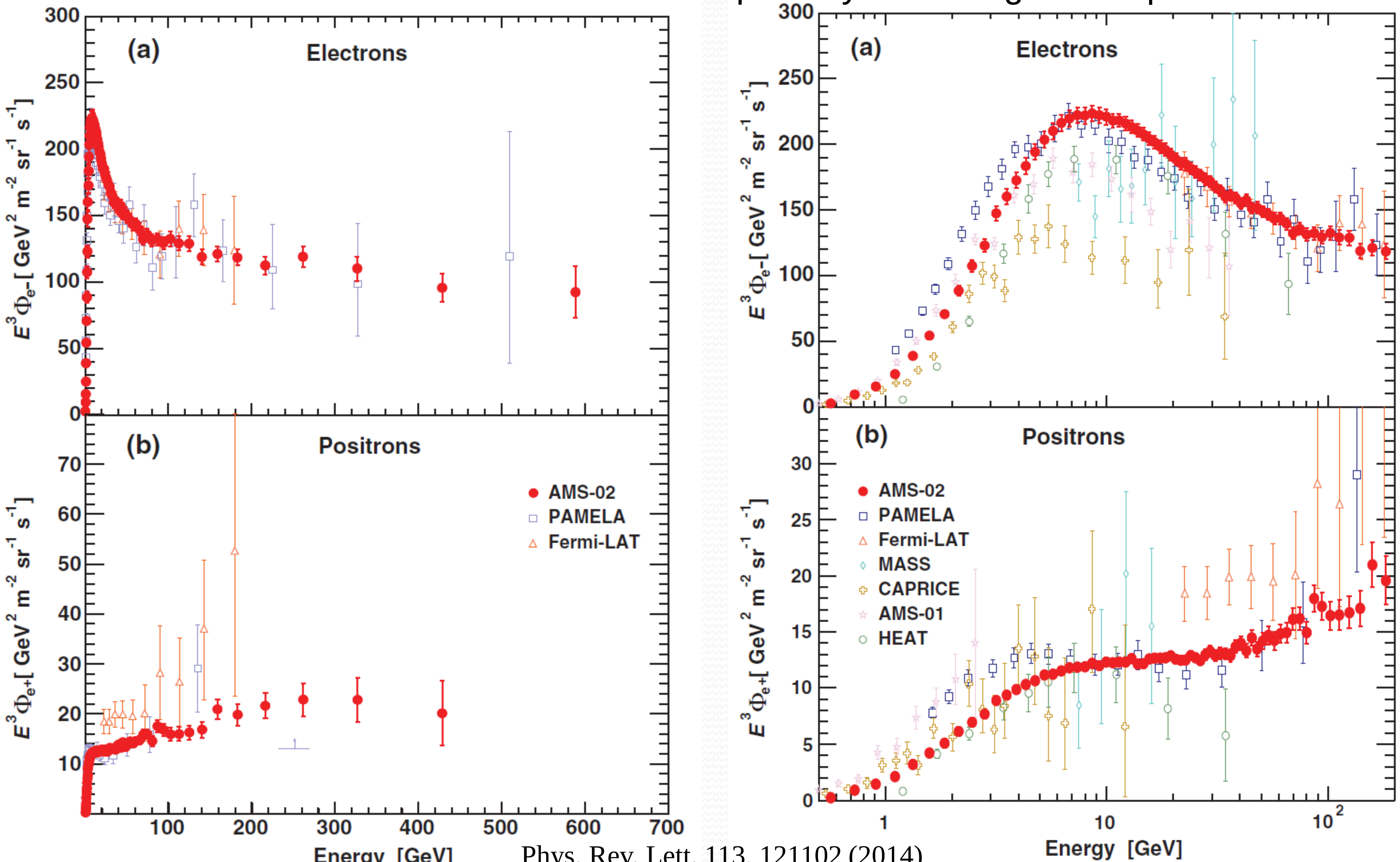
- Fluxes bring more information for the models than the fraction

- Obtaining the flux via $$\frac{N}{A \times \varepsilon_{Trig.} \times \varepsilon_{sel.} \times T \times dE}$$

  - N **number** of positrons or electrons
  - A **acceptance**
  - ε_{Trig} and ε_{sel} **trigger** and **selection efficiencies**
  - T exposure **time**
  - dE energy **bin size**

FLUX MEASUREMENT

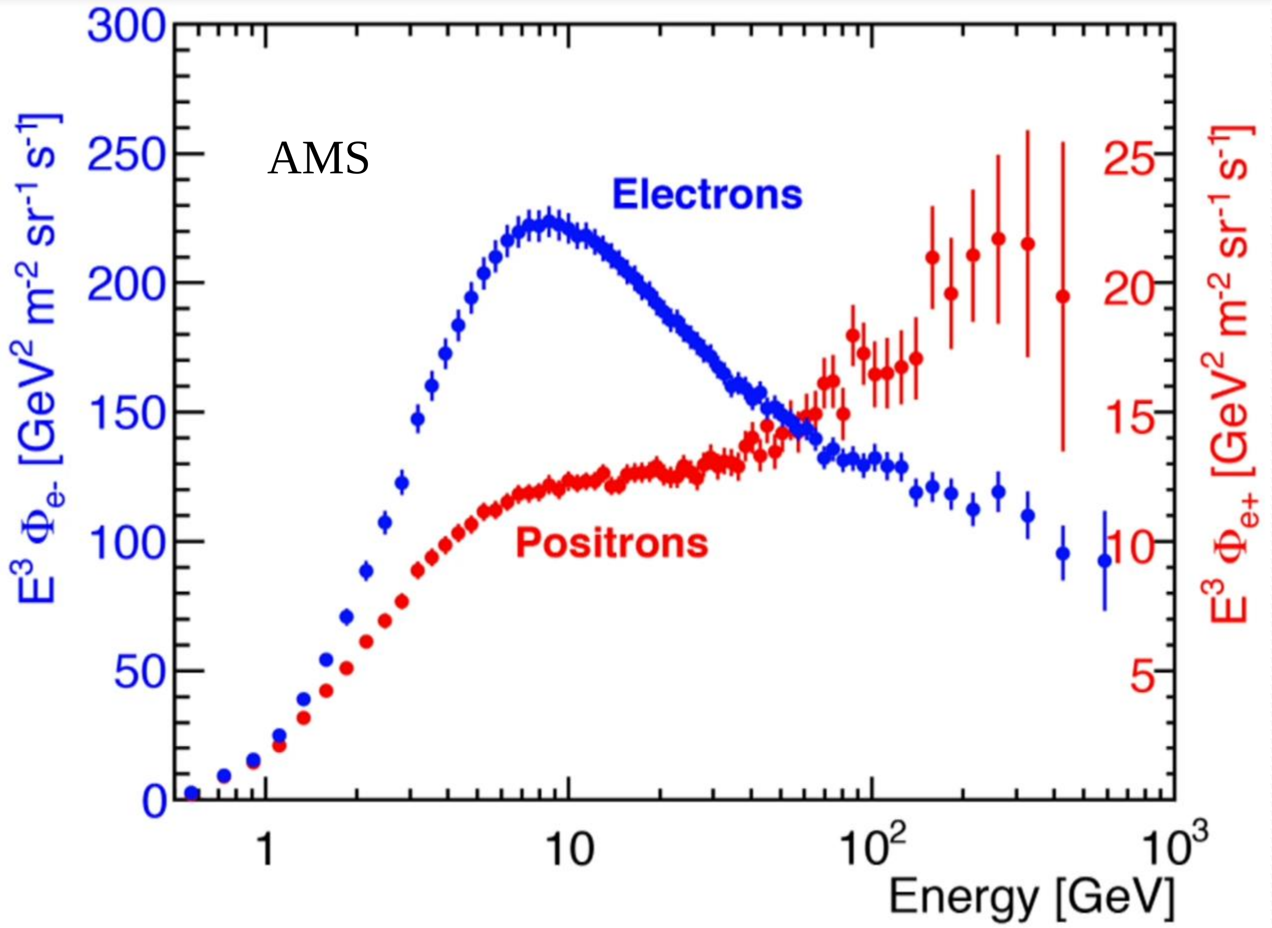
Linear scale | Flux multiplied by E^3 | Log scale up to 200 GeV



Phys. Rev. Lett. 113, 121102 (2014)

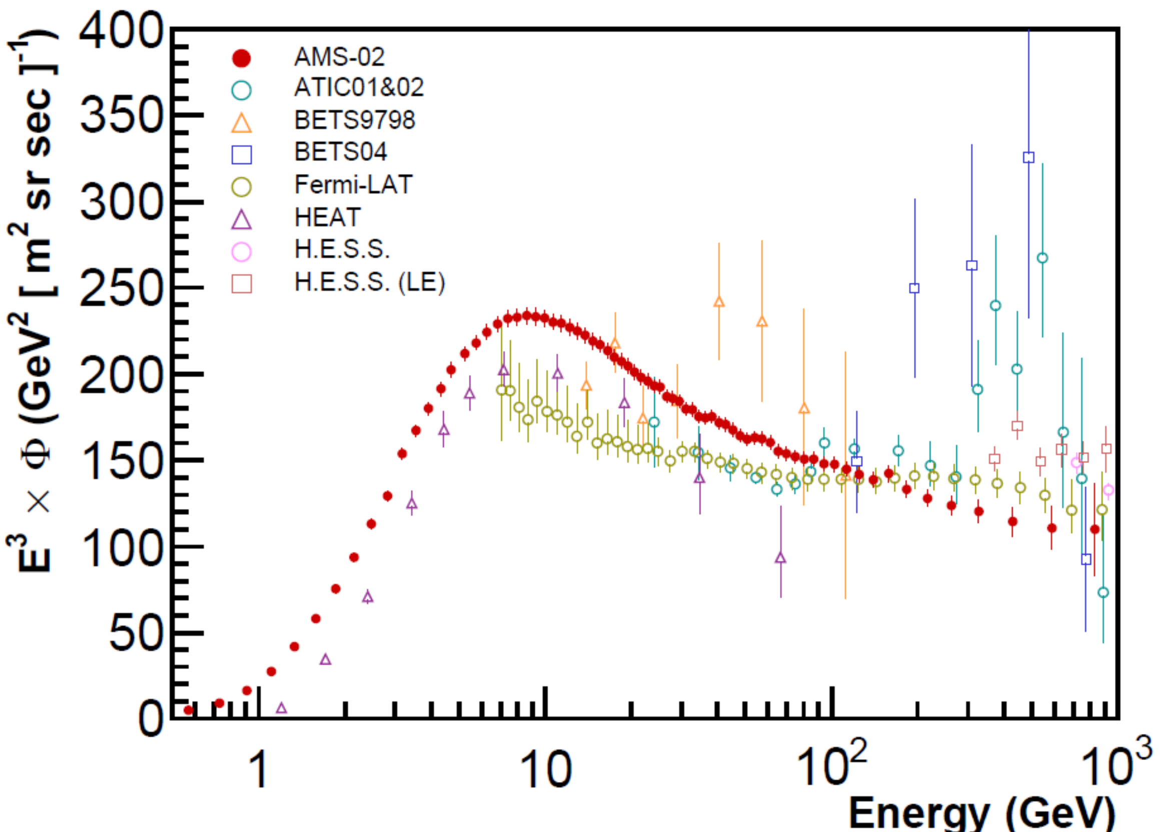
FLUX MEASUREMENT

- The electron and positron fluxes are different in their magnitude and energy dependence



COMBINED FLUX

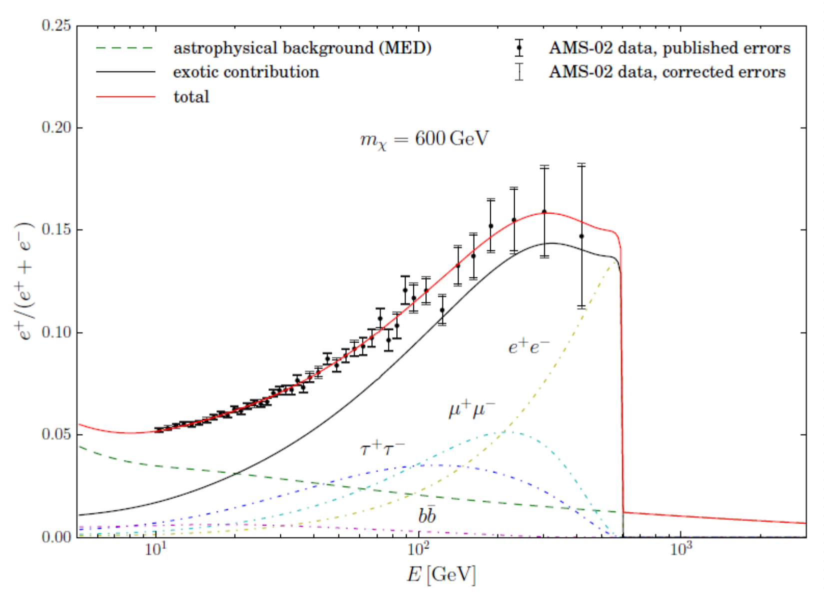
- electron + positron flux measurement
  - Independent from **charge sign** measurement
  - **High selection efficiency** (70% at 1 TeV)



Phys. Rev. Lett. 113, 221102 (2014)

INTERPRETATION: DARK MATTER

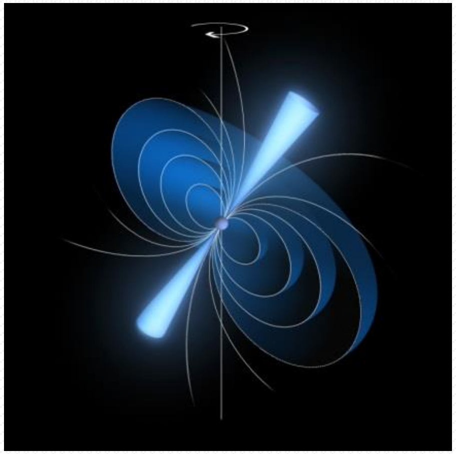
- Fitting the positron fraction using the best combination of annihilation channels



A&A 575, A67 (2015)

- Dark matter may explain the fraction, but unnatural annihilation cross-section
  - **×1000** compared to the one expected from the relic density
- Not likely that we have observed an indirect observation of dark matter
  - **In tension** with other observables (antiprotons, gamma rays, …)

INTERPRETATION: PULSARS



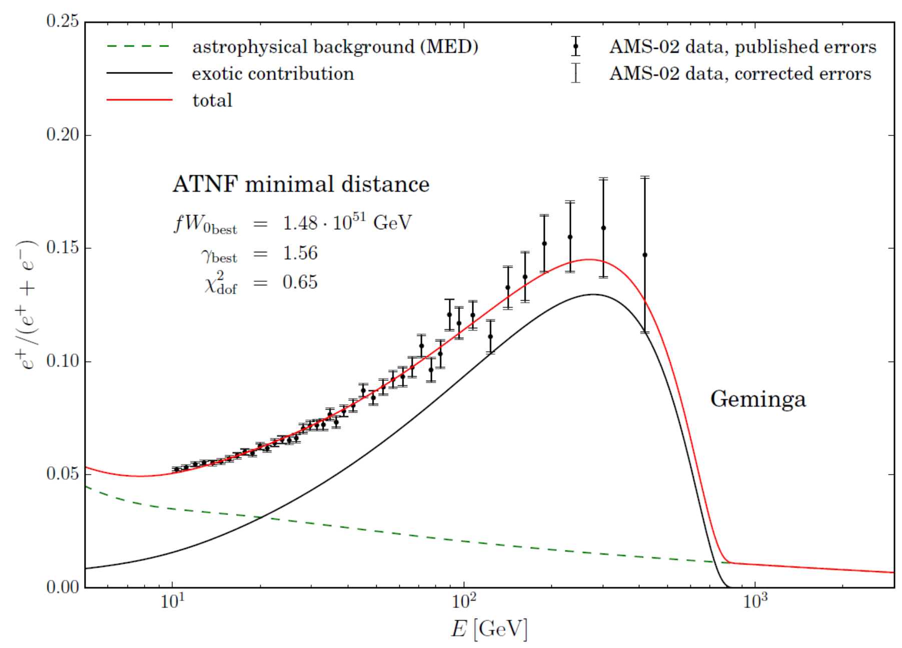
- Neutron stars spinning at high rate with a strong magnetic field
- 200 pulsars at less than 2 kpc from Earth
  - Only a **small fraction** able to emit positrons
- Mechanism
  - **Electrons extracted** from the surface by the high fields

    $\Rightarrow$ electrons produce **synchrotron photons**

    $\Rightarrow$ photons produce **e^+-e^- pairs**

    $\Rightarrow$ Some **escape** from the pulsar
- Precise prediction very difficult

- Five closeby pulsars able to explain the fraction

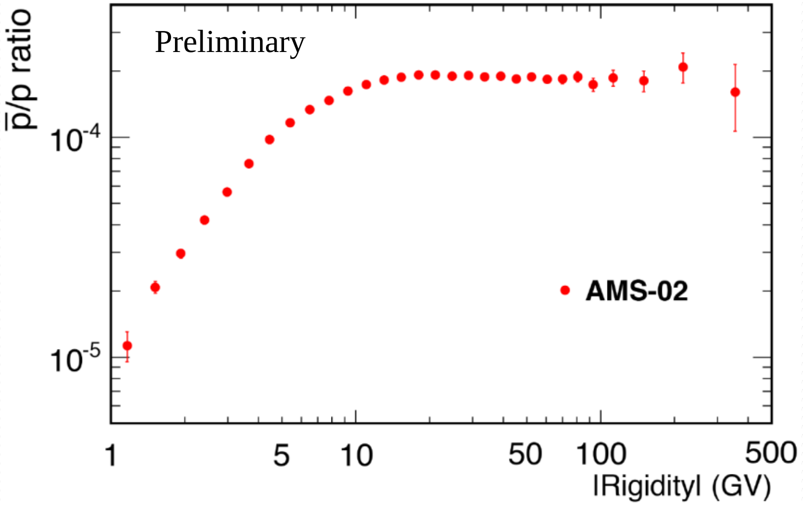


A&A 575, A67 (2015)

ANTIPROTONS IN COSMIC RAYS

ANTIPROTONS

- Dark matter could create an excess of antiprotons with respect to the expectations
  - Pulsars **do NOT** produce antiprotons

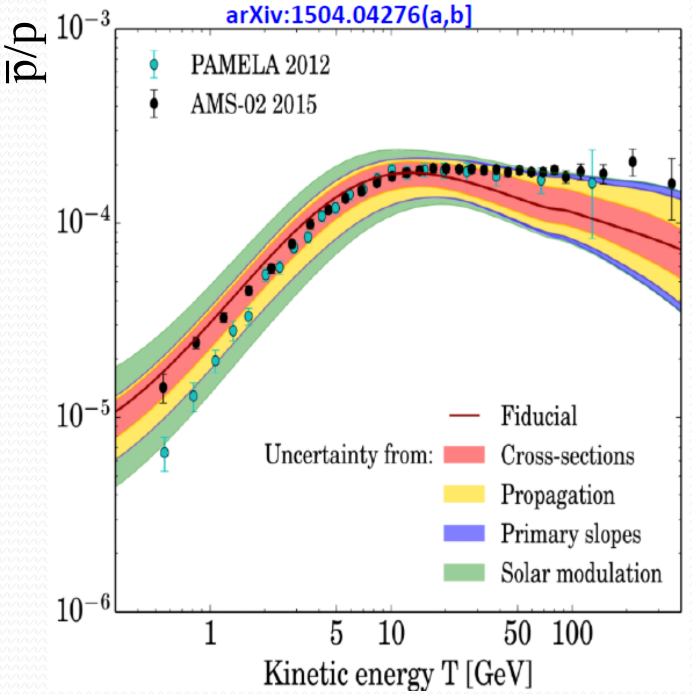


- AMS presented recently the measurement of $\bar{p}/p$
  - 290 000 antiprotons

- Is dark matter necessary to explain this measurement?
  - Controversial topic!
  - Need to compute what is expected from **secondary antiprotons**

ANTIPROTONS

- Adding the contribution of the secondary antiprotons with its uncertainty
  - **Comparison** of data and expectations for $\bar{p}/p$

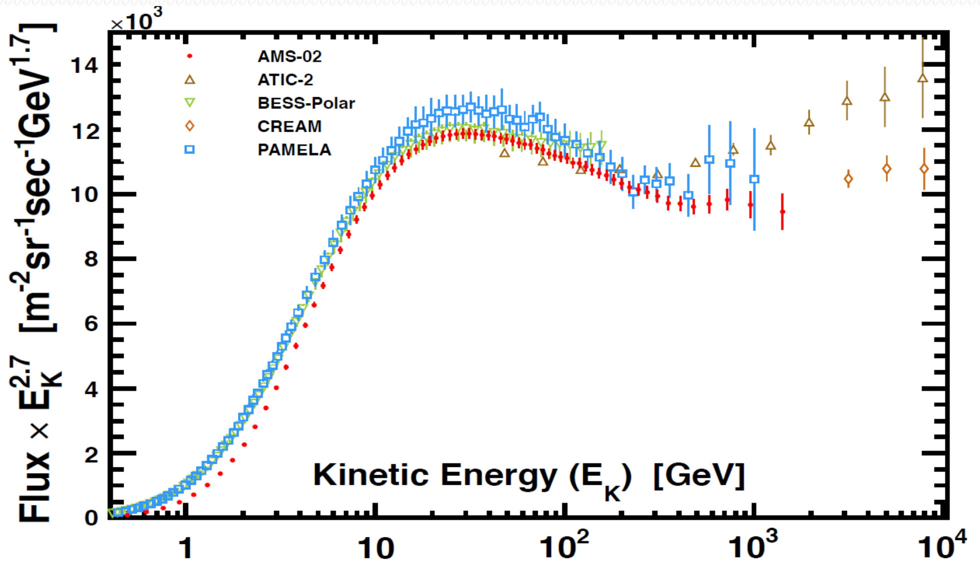


- The ratio $\bar{p}/p$ is not in discrepancy with the expectations
  - **No dark matter** needed here (yet)

OTHER RESULTS ON COSMIC RAYS

PROTONS

- Protons are the most abundant charged particles in cosmic rays
  - Knowledge of the proton spectrum is important in understanding the **origin**, **acceleration**, and **propagation** of cosmic rays
- ATIC–2, CREAM, and PAMELA experiments showed deviations of the proton flux from a single power law
- Fresh result from AMS



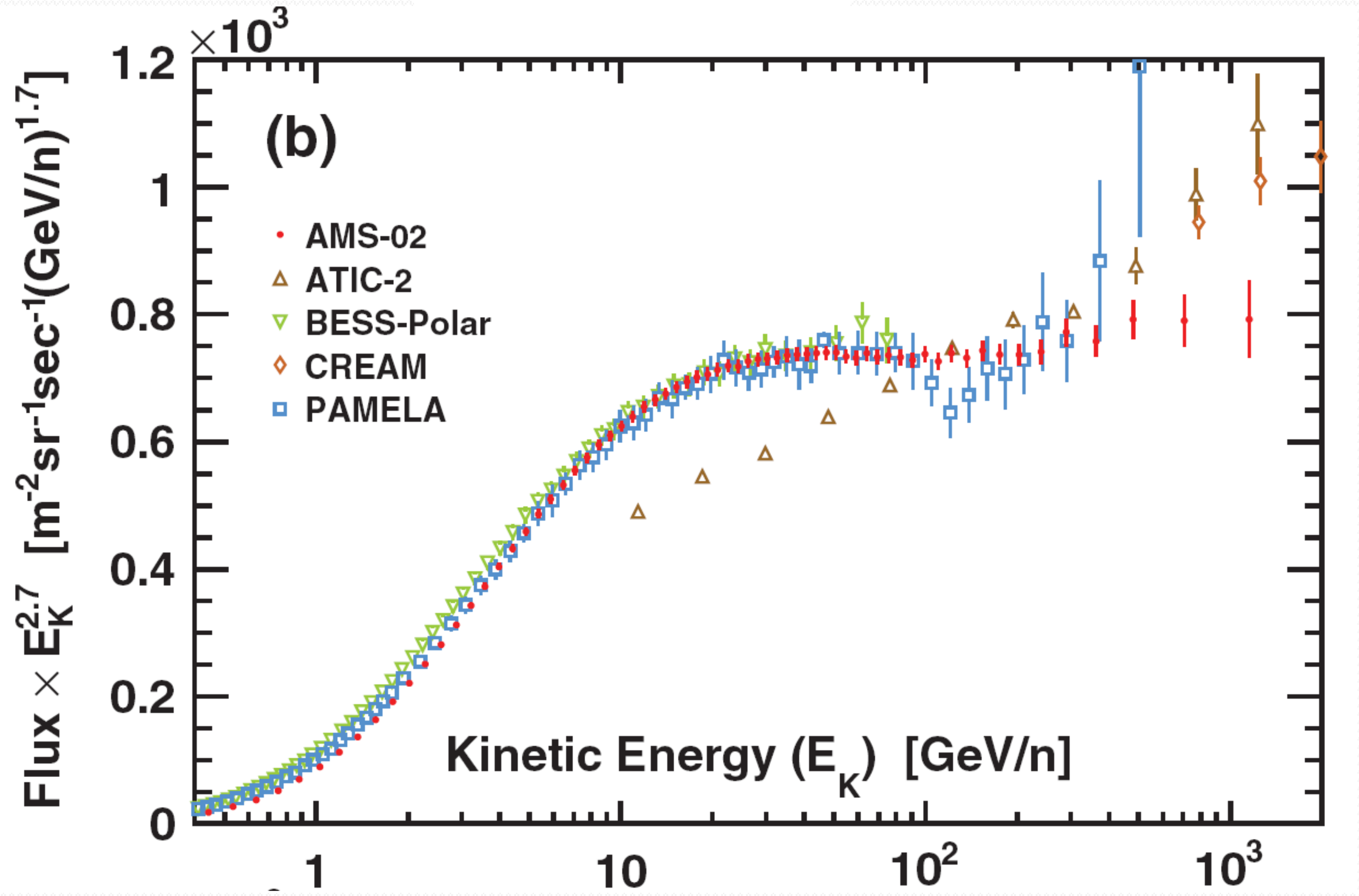
PRL 114, 171103 (2015)

- The spectral index is progressively hardening at high rigidities

HELIUM

- AMS compared with recent data

PRL 115, 211101 (2015)

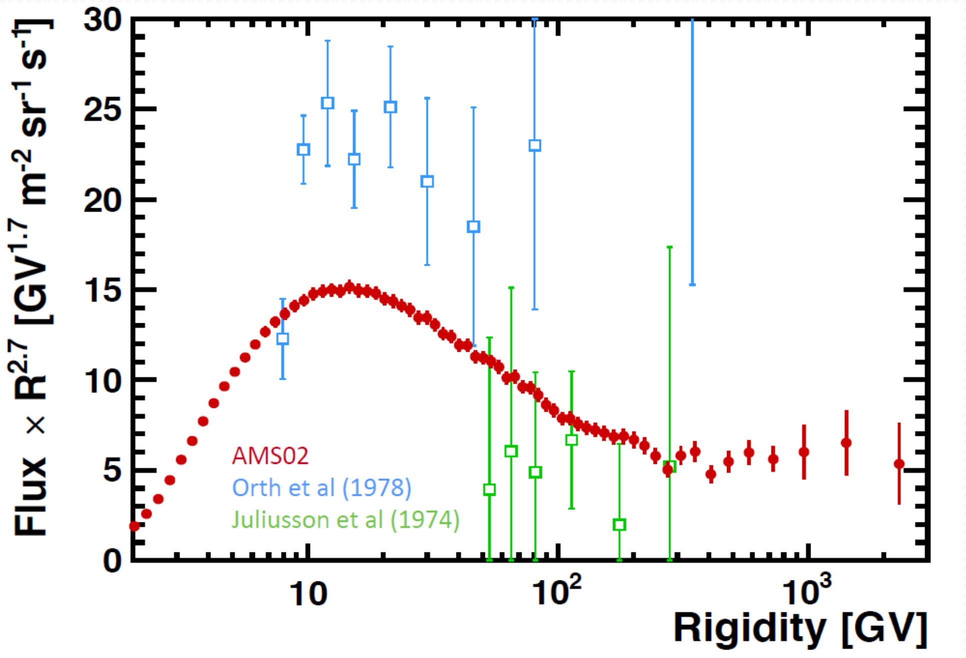


LITHIUM

- Like B and Be, lithium is produced by spallation processes

CNO…Fe + ISM → Li
→ B, Be + ISM → Li

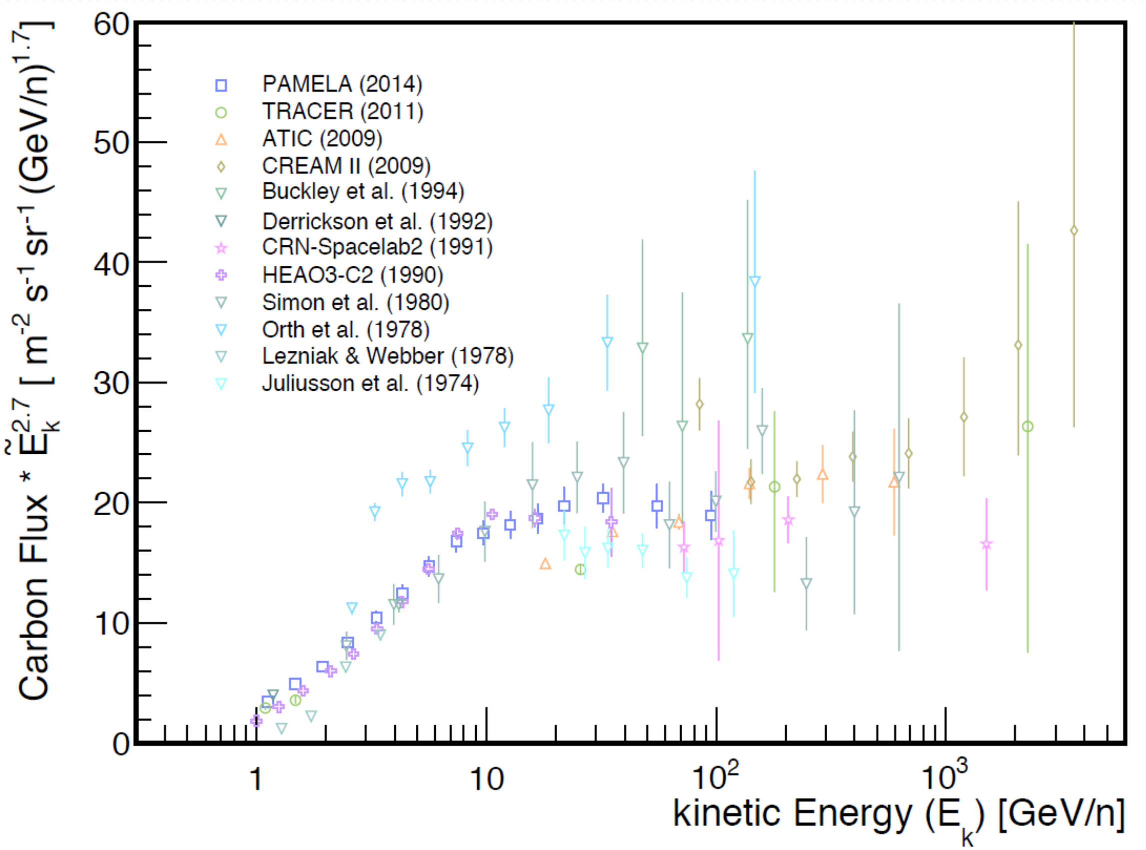
- Sensitive to propagation parameters (diffusion, convection, reacceleration, …)



Deviation from single power law and **hardening** of the lithium flux above 300 GV

CARBON

- Carbon is the nuclei with the 3rd highest abundance (after H and He) and is produced and accelerated by cosmic ray sources
  - Allows to test **production and propagation** mechanism



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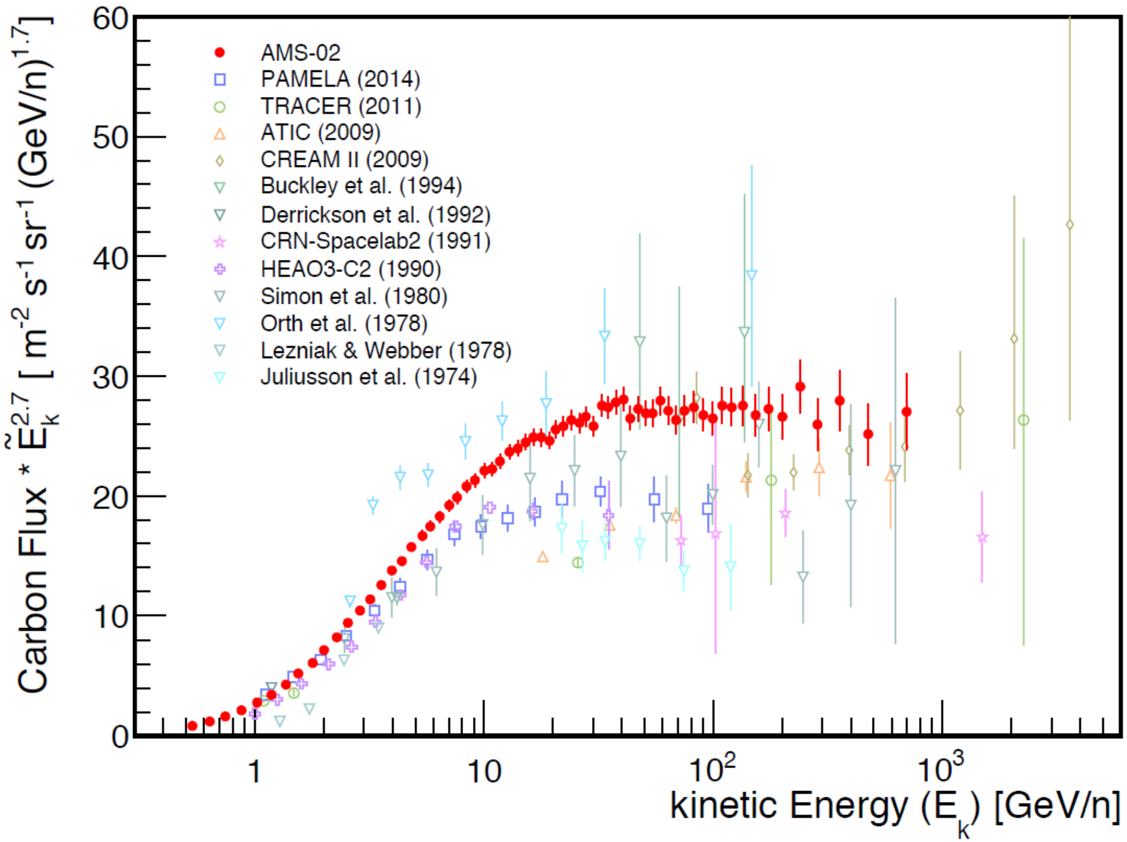
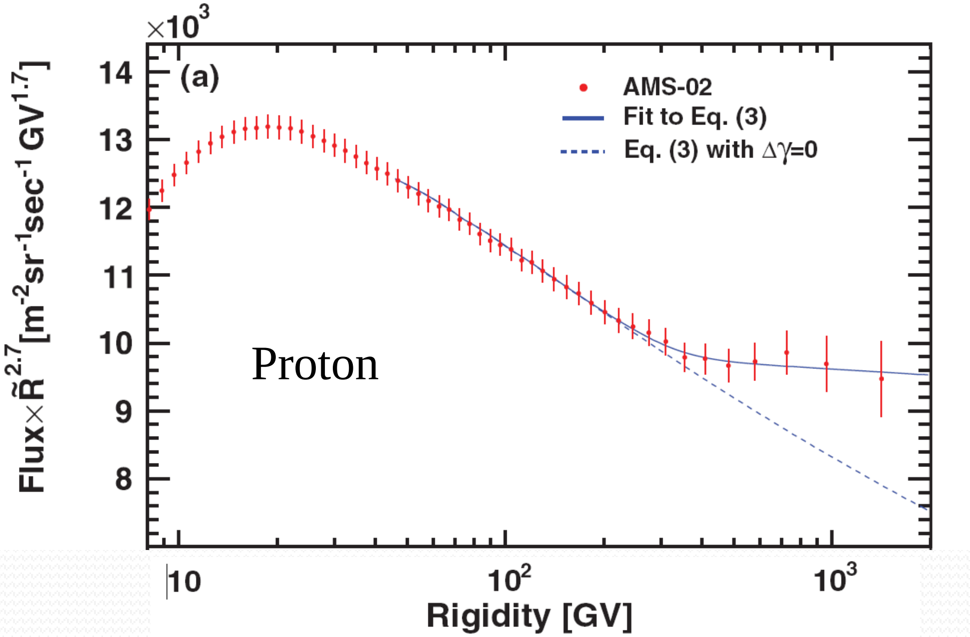
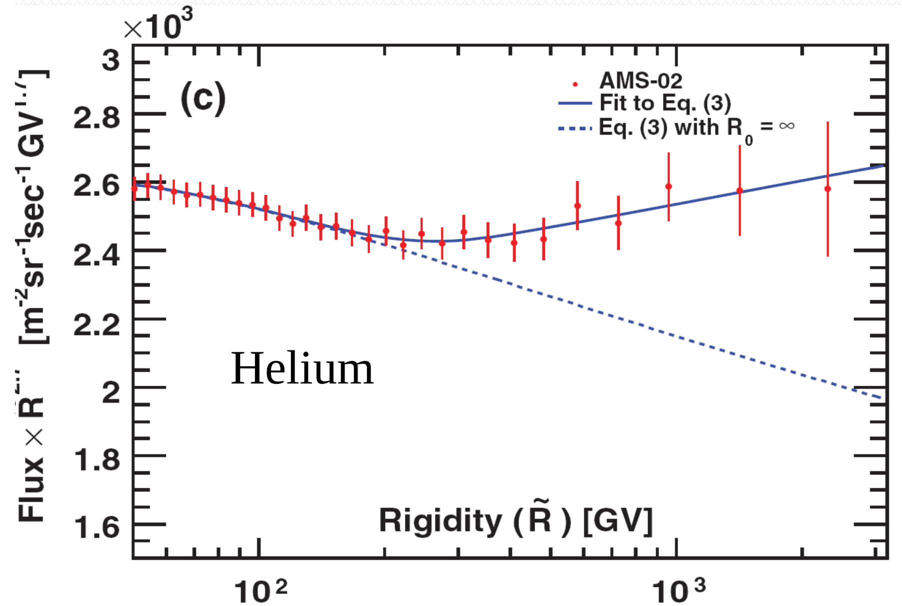


NUCLEUS ANOMALY

- Recent and unexpected observation: the power law is broken at high energy

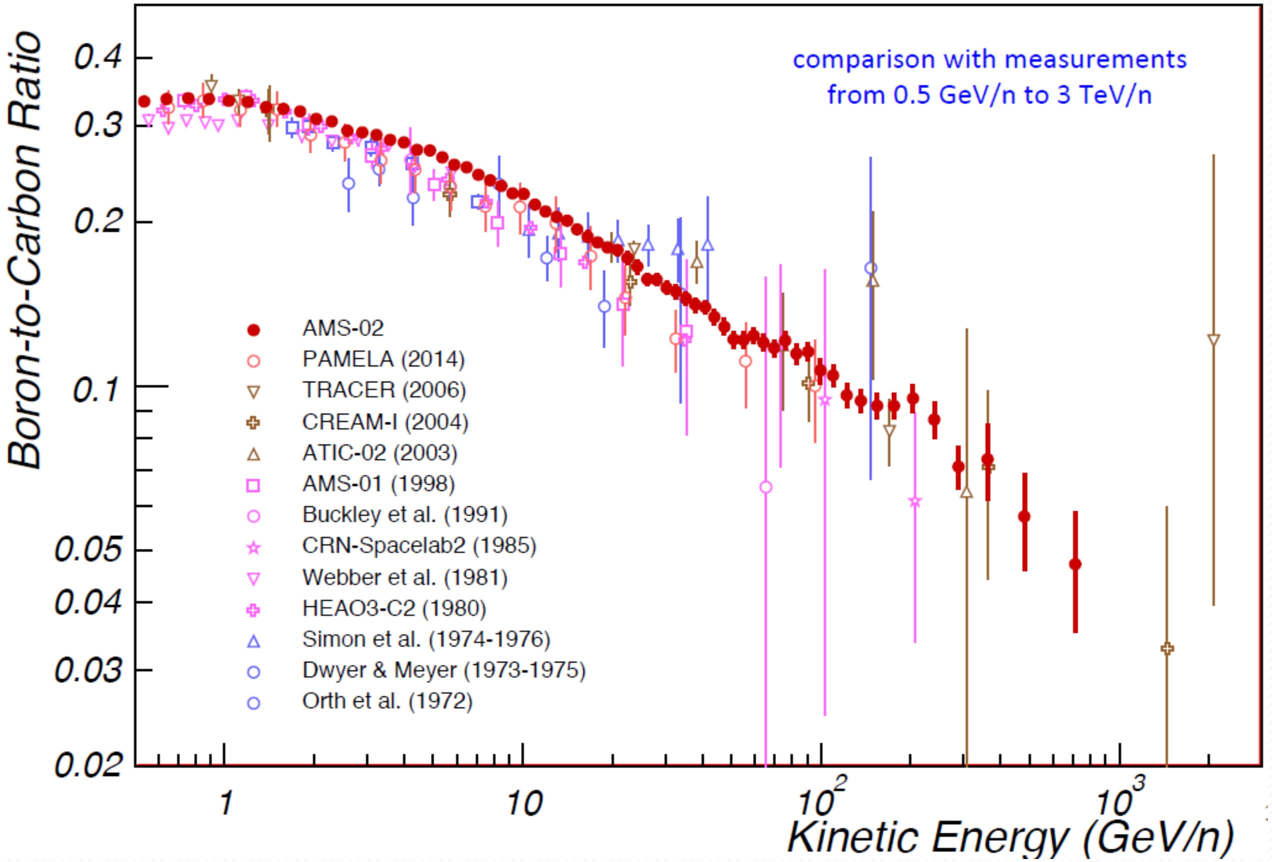




- What can cause these anomalies?
  - Sources?
  - Acceleration?
  - Propagation?
- Still an open question!

B/C RATIO

- Allows to understand the propagation of cosmic rays
  - **Strong constraints** on propagation model, especially on the δ **parameter**



IN SUMMARY

- Cosmic rays are charged and neutral particles coming from space
  - From **a few MeV to 10^{20} eV**
  - Mainly **protons**, **helium**, **electrons**, …
- Sources
  - At intermediate energies, they come from **supernova remnant** in our Galaxy
  - Protons, electrons, … come directly **from the source**
  - Positrons, antiprotons, … are created by **collision** with the interstellar medium, with a rate that **can be predicted**
- Propagation
  - Charged cosmic ray propagation is equivalent to a **diffusion**

- Positrons in cosmic rays
  - There is **more positrons** at high energy compared to the expectations
  - **New source**: dark matter? pulsars?
  - AMS will extend its **energy range**, and will be able to **discriminate** between the dark matter and pulsar hypotheses
- Antiprotons in cosmic rays
  - Antiprotons could be produced by dark matter
  - After the recent AMS measurement, **no need (yet) for dark matter**
- Other measurements
  - Many other measurement are **yet to come**, with on-going experiments or **promising future experiments**

TO BE CONTINUED…
(Julien Masbou)

ADDITIONAL SLIDES

WIMP “miracle”

- Start with **heavy, stable dark matter** (DM) particle X in thermal equilibrium.
- **Early universe** T > M_X: $X\bar{X} \leftrightarrow f\bar{f}$
- **Universe cools** T< M_X : $X\bar{X} \rightarrow f\bar{f}$
- **Freeze out:** Hubble expansion eventually prevents $X\bar{X} \rightarrow f\bar{f}$
- Solving Boltzmann equation

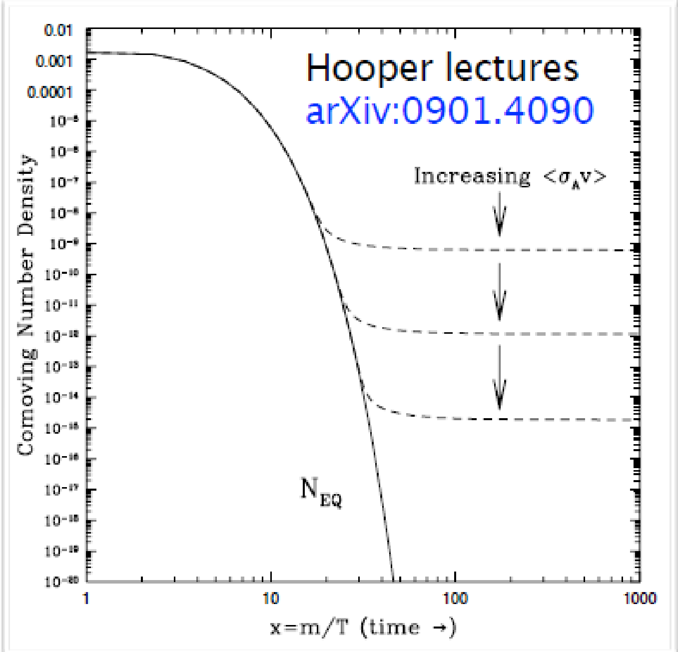
$$\frac{dn}{dt} = -\frac{3\dot{R}}{R}n - \langle\sigma v\rangle n^2 + \langle\sigma v\rangle n_0^2 \quad *$$

assuming measured DM density results in:

$$\frac{\Omega_{\mathrm{DM}}h^2}{0.1} \approx \left(\frac{\langle\sigma v\rangle}{3\ \mathrm{pb}\cdot\mathrm{cm/s}}\right)^{-1}$$

and for m_{DM} =100 GeV and weak g:

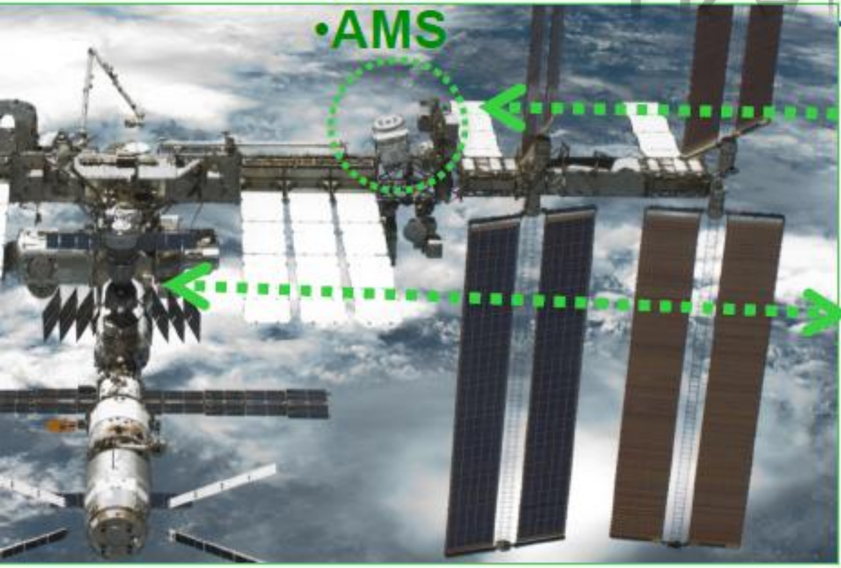
$$\sigma \sim g^4/m_{\mathrm{DM}}^2 \sim 3\mathrm{pb}\cdot\mathrm{cm/s}$$



* Lee, Weinberg (1977)
FERMILAB-PUB-77/41-THY

n (n_0)	DM number density (at equilibrium)
$\dot{R}/R$	expansion rate
⟨σv⟩	DM annihilation cross section x velocity
$\Omega_X h^2$	physical X density

TRANSMISSION



Astronaut at ISS AMS Laptop

Ku-Band
High Rate (down):
Events <10Mbit/s>

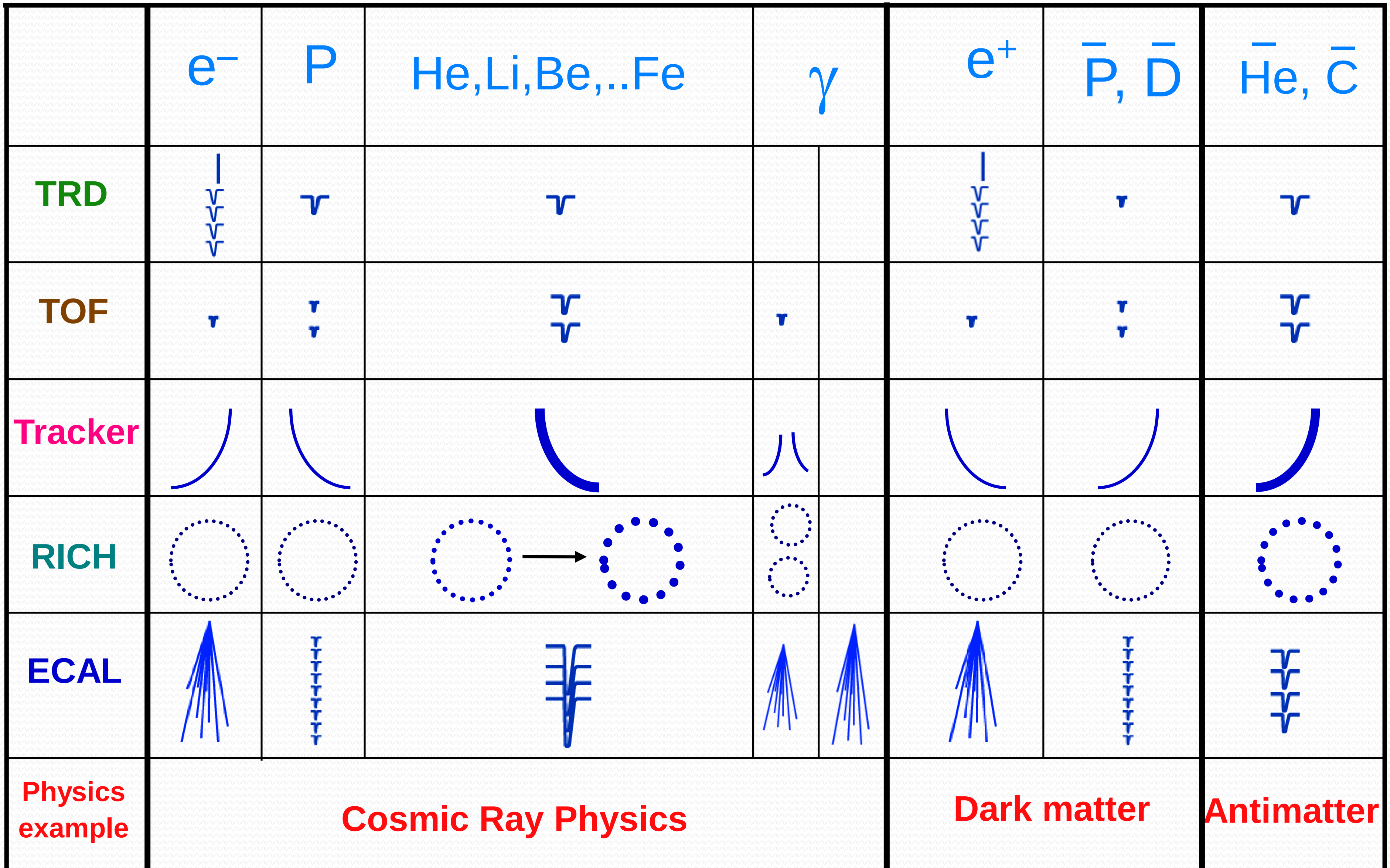
S-Band
Low Rate (up & down):
Commanding: 1 Kbit/s
Monitoring: 30 Kbit/s

White Sands Ground Terminal, NM

AMS Payload Operations Control and Science Operations Centers (POCC, SOC) at CERN since June 2011

AMS Computers at MSFC, AL

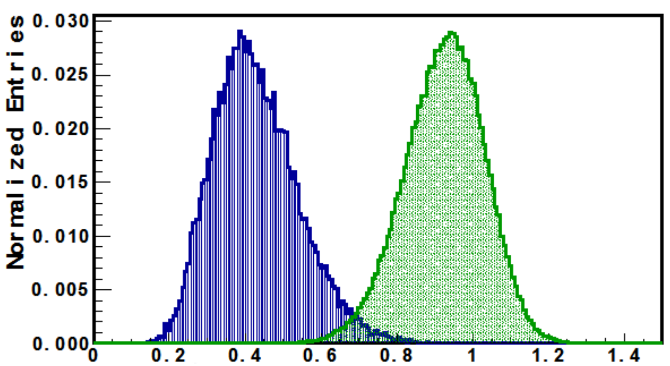
DÉTECTEUR

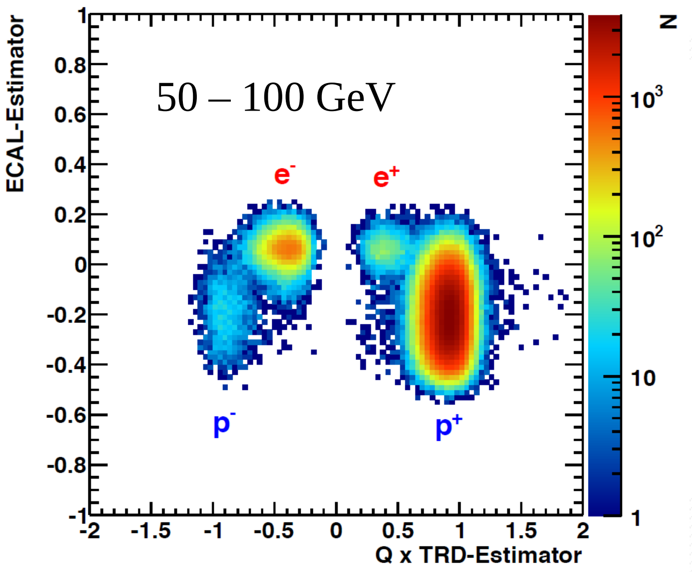

e⁻
P
He,Li,Be,..Fe
γ
e⁺
P̄, D̄
H̄e, C̄
TRD
TOF
Tracker
RICH
ECAL
Physics example
Cosmic Ray Physics
Dark matter
Antimatter

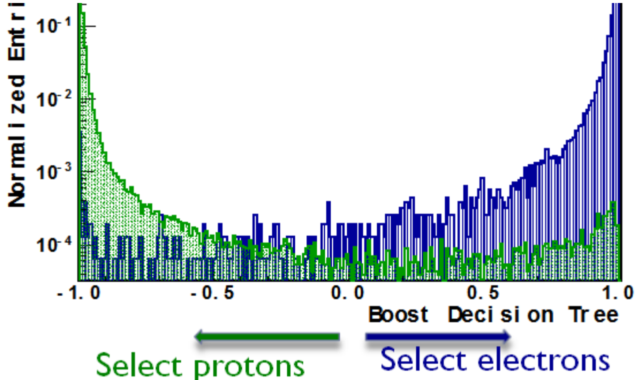
POSITRON FRACTION

- Key detectors for this measurement
  - **TRD**
  - **Tracker**
    - E/p close to 1 for electrons/positrons
  - **Calorimeter**
    - Based on 3D shower shape

- Methodology
  - **Selection** using the calorimeter variable
  - **Count** of e^+ (Z>0) and e^- (Z<0) from a 2D fit on the TRD and tracker variables
  - Count for each **energy range**

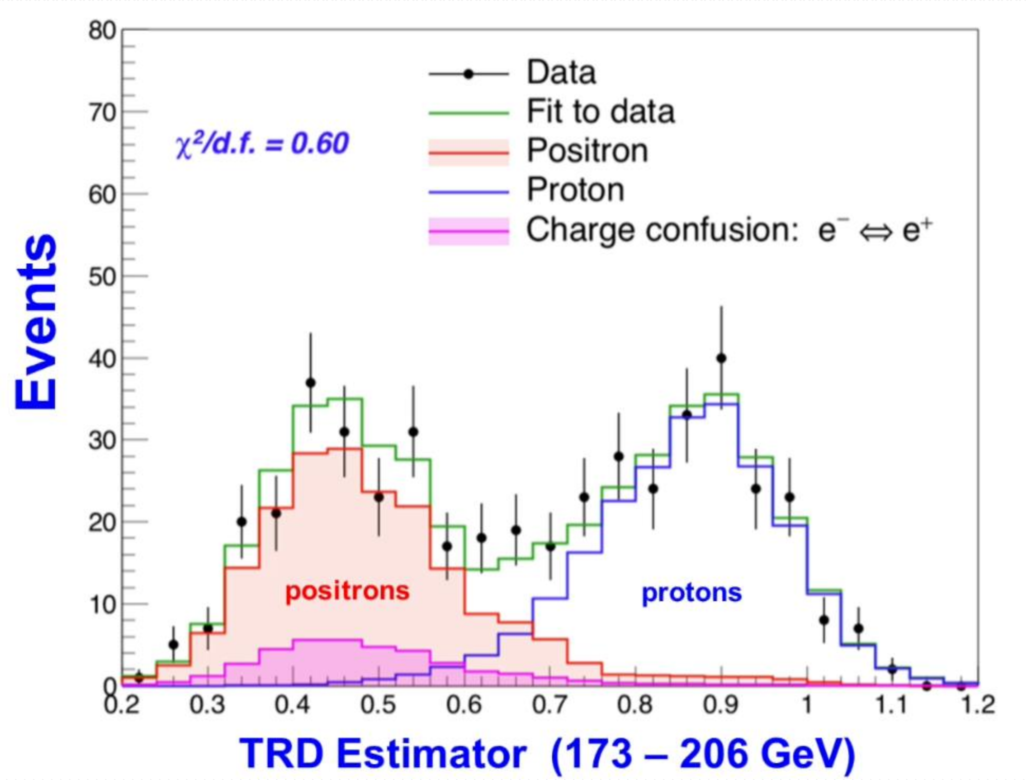






POSITRON FRACTION

- Counts of leptons after the selection
  - **Z > 0** : count of **positrons**



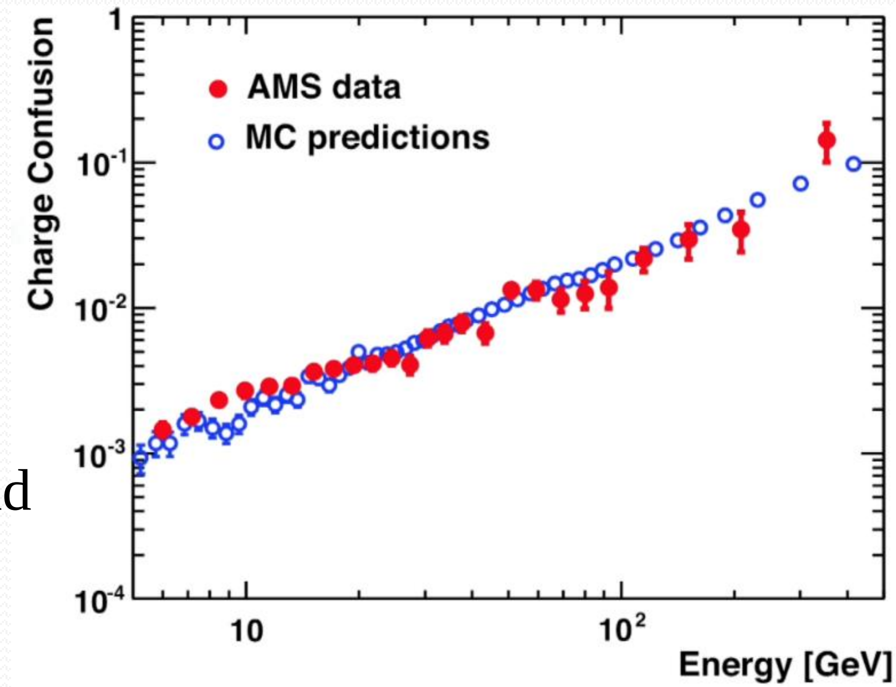
  - **Z < 0** : count of **electrons**

CHARGE CONFUSION

- For some energy range, difficulty to measure the sign of the charge

  $\Rightarrow$ confusion

- Two sources
  - Finite resolution of the tracker and multiple scattering
  - Production of secondary tracks along the path of the primary track



MINIMAL MODEL

- Fit of the AMS data using a minimal model
- Positrons
  - Secondary production
  - \+ source

$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

- Electrons
  - Primary and secondary production
  - \+ same source

$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

- Simultaneous fit to
  - Positron fraction from 2 GeV
  - Combined flux from 2 GeV

PROPAGATION

$$\frac{\partial\psi}{\partial t} - \nabla\cdot\{K(E)\nabla\psi\} - \frac{\partial}{\partial E}\{b(E)\,\psi\} = q(\mathbf{x}, t, E)$$

$$\psi = dn/dE$$

$$K(E) = K_0\,\beta\,(\mathcal{R}/1\ \mathrm{GV})^{\delta}$$

$$b(E) = \frac{E_0}{\tau_E}\,\epsilon^2$$

$$\epsilon = E/E_0$$

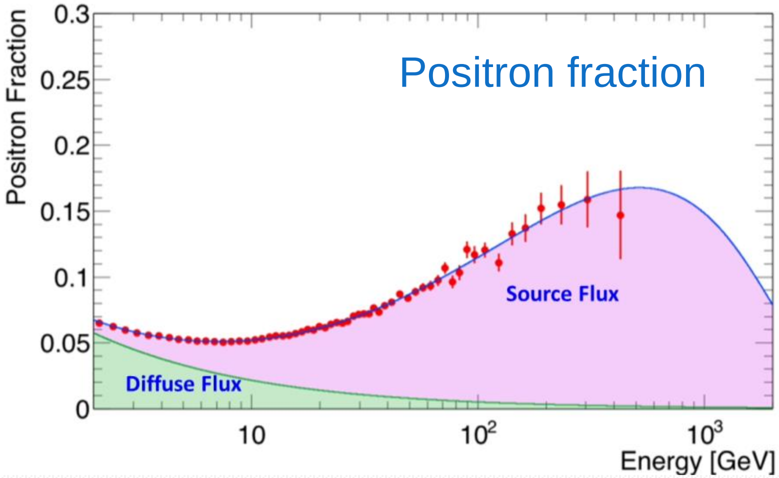
$$q_{e^+}^{\mathrm{DM}}(\mathbf{x}_S, E_S) = \frac{1}{2}\,\langle\sigma v\rangle\left\{\frac{\rho_\chi(\mathbf{x}_S)}{m_\chi}\right\}^2\left\{g(E_S) \equiv \sum_i B_i\,\frac{dN_{e^+}}{dE_S}\bigg|_i\right\}$$

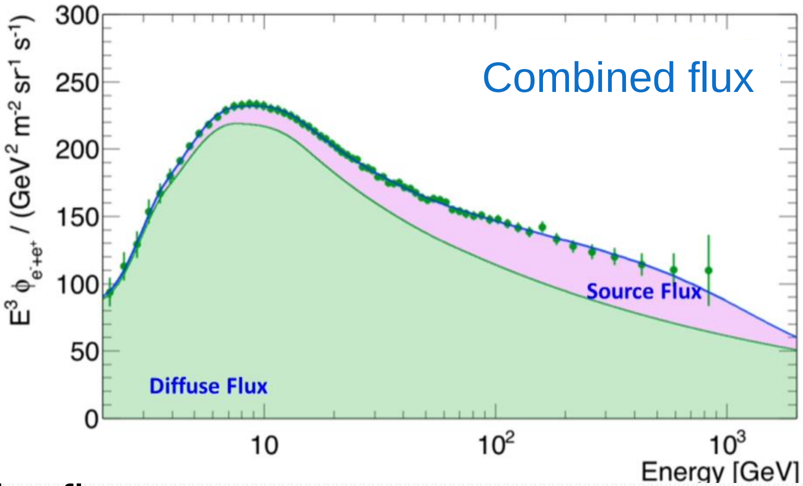
$$g(E) = Q_0\left(\frac{E_0}{E}\right)^{\gamma}\exp(-E/E_C)$$

$$\int_{E_{\min}}^{+\infty} E_S\,g(E_S)\,\mathrm{d}E_S = f W_0.$$

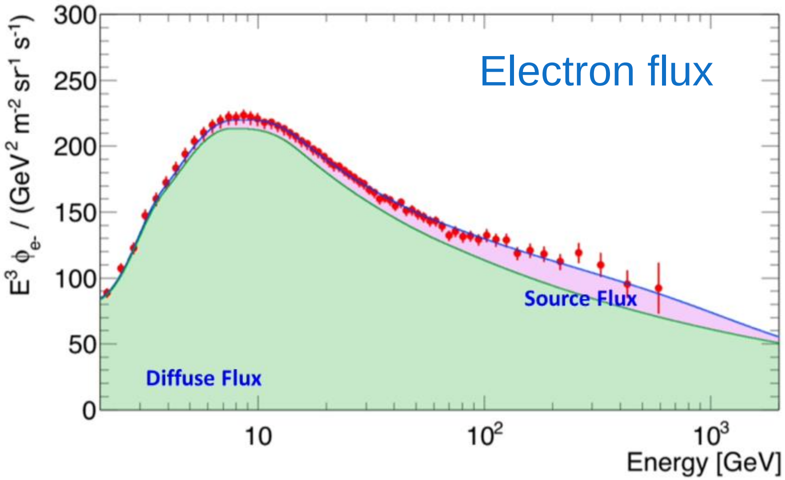
MINIMAL MODEL

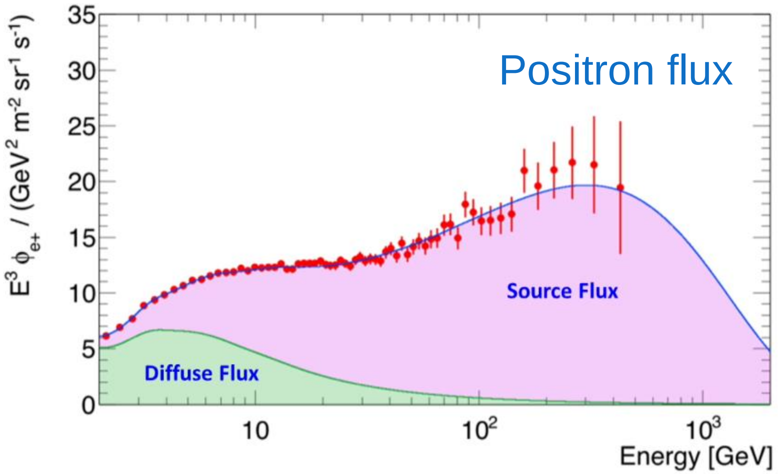
Result from the fits



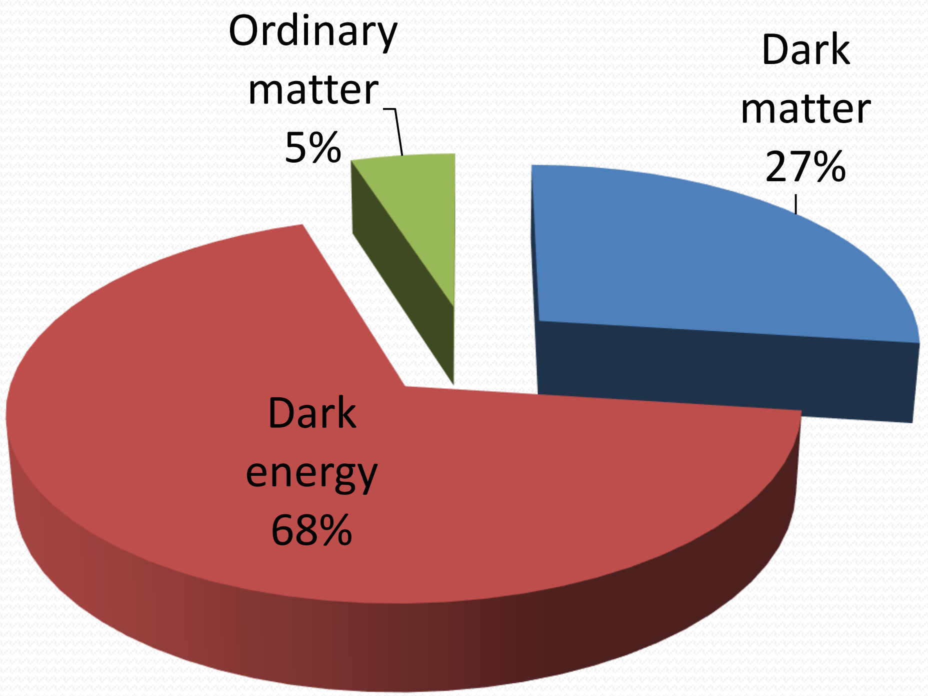


Prediction from the fits





Fits are satisfactory, which shows that the data can be described by a common e^+/e^- source


Ordinary matter 5%
Dark matter 27%
Dark energy 68%

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: EPS 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.4 - 22.9)\ \text{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Mass limit		Conditions	Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm \to qqW^\pm\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 e, μ (SS)	3 jets	Yes	20.7	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$<650 GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\tau}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	$\tan\beta$>18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$	1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	0	Yes	4.8	$\tilde{g}$	619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.14 TeV	$m(\tilde{\chi}_1^0)$ <200 GeV	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-630 GeV	$m(\tilde{\chi}_1^0)$<100 GeV	ATLAS-CONF-2013-053
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	430 GeV	$m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$	167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$	225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	200 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$	500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$	520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	0	Yes	20.7	$\tilde{\chi}_1^\pm$	180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	600 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W^*\tilde{\chi}_1^0 Z^*\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	315 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	857 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	0	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	0	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ	0	Yes	4.4	$\tilde{q}$	700 GeV	1 mm<$c\tau$<1 m, $\tilde{g}$ decoupled	1210.7451
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e, μ	0	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e, \mu + \tau$	0	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$	1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	0	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6 jets	-	4.6	$\tilde{g}$	666 GeV		1210.4813
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

10^{-1} 1 Mass scale [TeV]

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Current limits: neutralino/chargino

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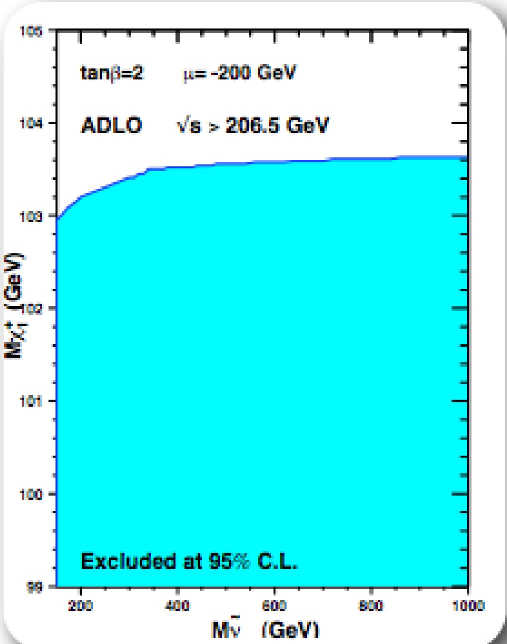
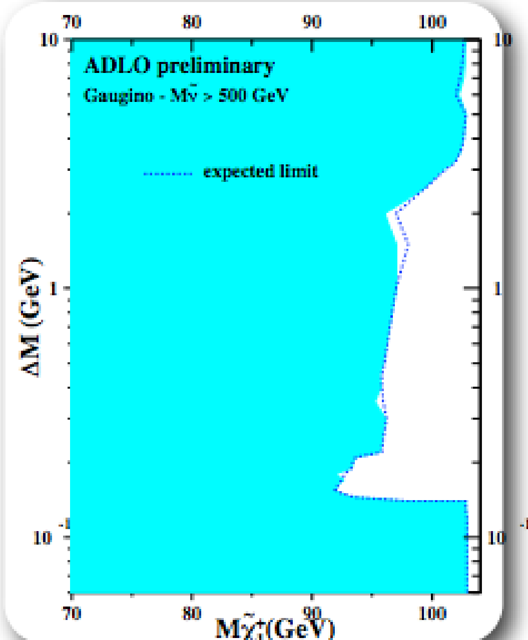
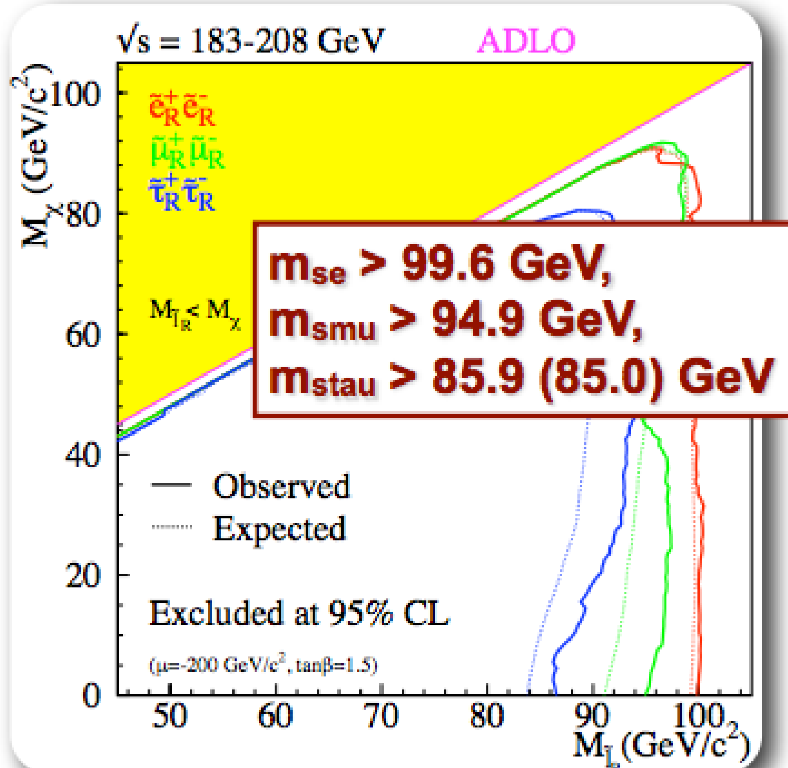
canonical case

degenerate case

$m\chi_1^0$ > 47/50 GeV
(CMSSM, mSUGRA)
No mass limit in general







m_{se} > 99.6 GeV,
m_{smu} > 94.9 GeV,
m_{stau} > 85.9 (85.0) GeV

$m\chi_1^\pm$ > 103.5 GeV
for m_{snue} > 300 GeV

$m\chi_1^\pm$ > 91.9 /92.4 GeV

LEPSUSYWG/01-03.1

LEPSUSYWG/02-04.1

LEPSUSYWG/04-01.1

S. Su

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