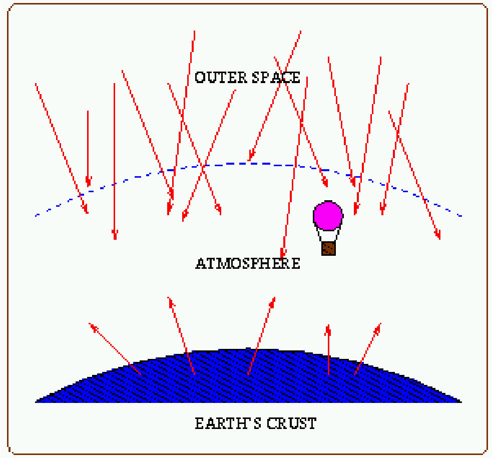
Direct Detection of Cosmic Positrons

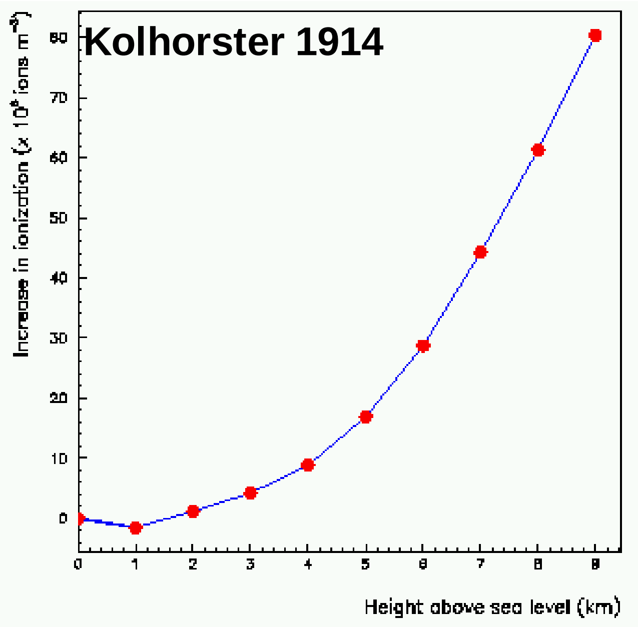
Mirko Boezio
INFN Trieste, Italy

International Workshop on Positrons in Astrophysics
March 20th 2012

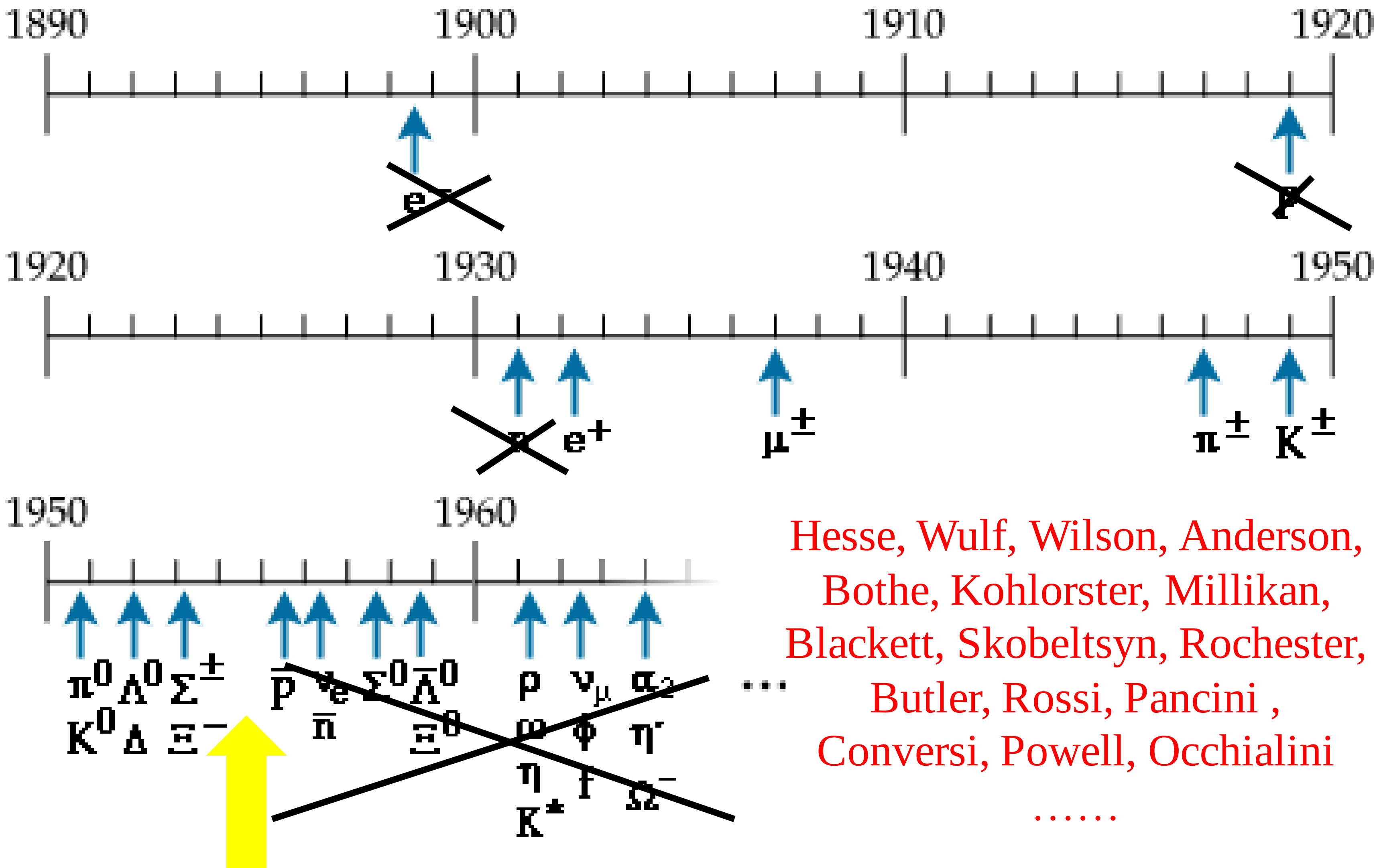
The discovery of cosmic rays

- Victor Hess ascended to 5000 m in a balloon in 1912
- ... and noticed that his electroscope discharged more rapidly as altitude increased
- Not expected, as background radiation was thought to be terrestrial. Extraterrestrial origin, confirming previous hints by Theodore Wulf and Domenico Pacini
- **e⁺ discovered by Carl Anderson, Nobel Prize winner with Hess in 1936**





PARTICLE PHYSICS BIRTH WAS DUE TO COSMIC RAYS



Hesse, Wulf, Wilson, Anderson,
Bothe, Kohlorster, Millikan,
Blackett, Skobeltsyn, Rochester,
Butler, Rossi, Pancini ,
Conversi, Powell, Occhialini
……

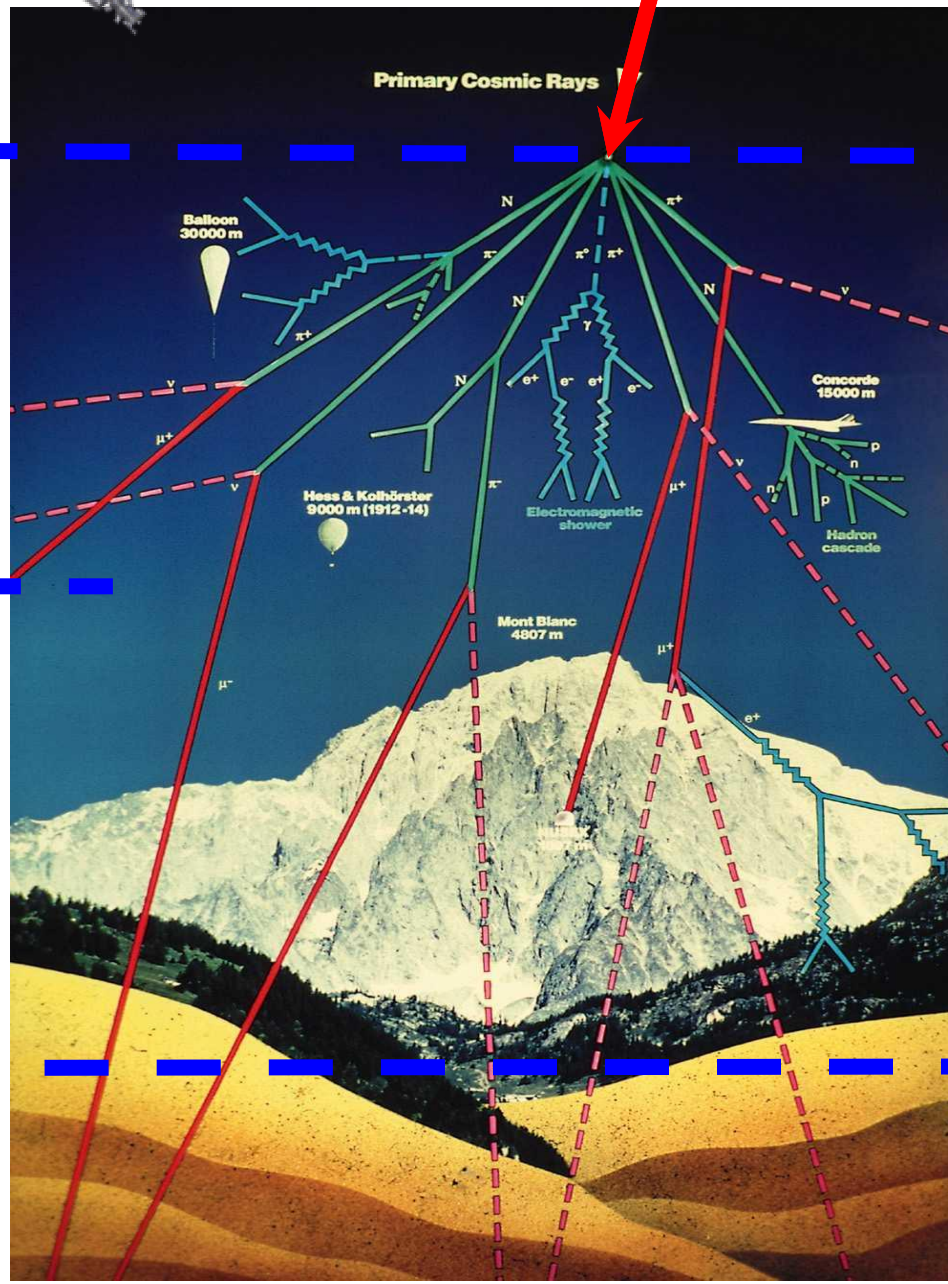
Advent of accelerators

~500 km

Smaller detectors but long duration.

Primary cosmic ray

Top of atmosphere



~40 km

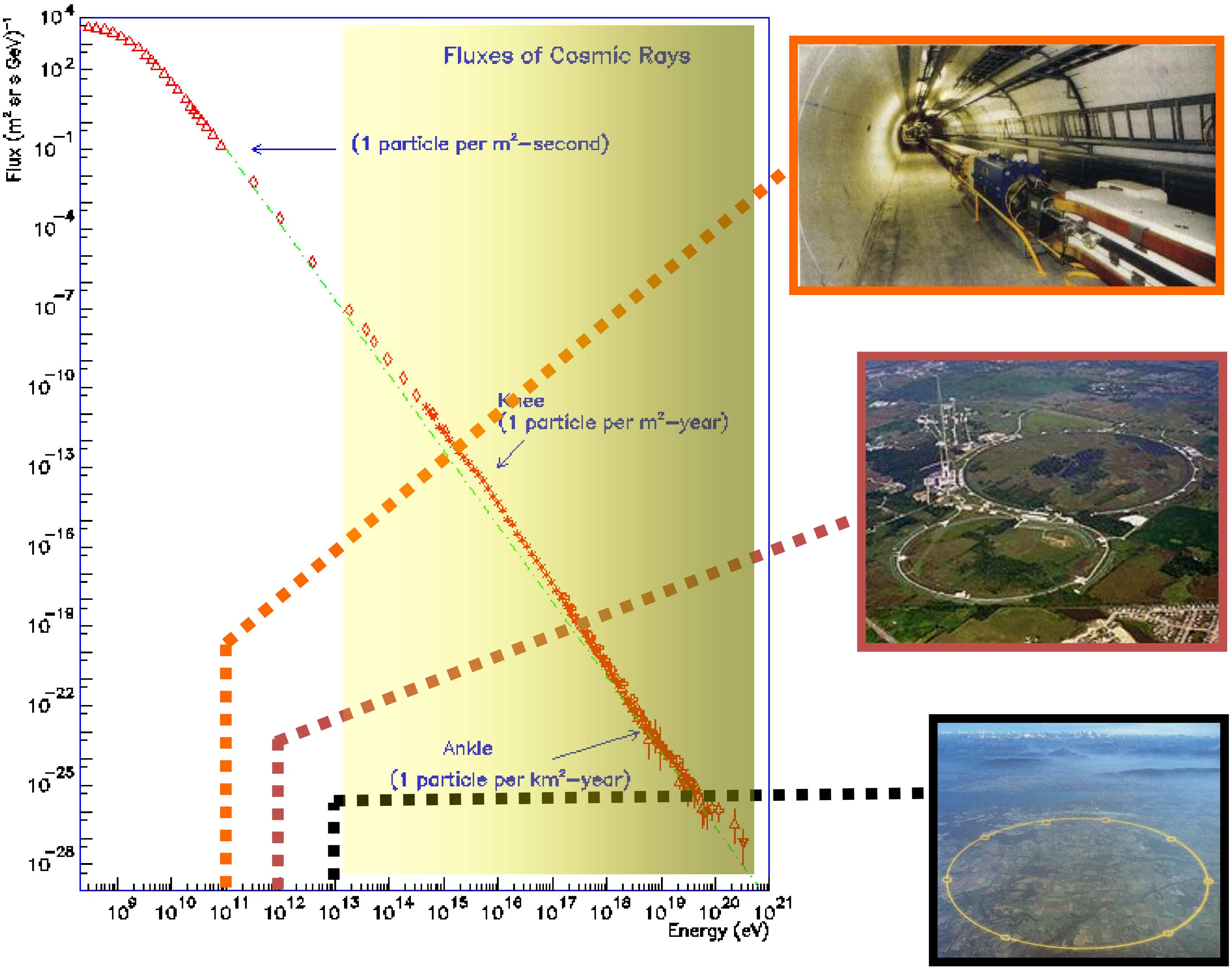
Large detectors but short duration. Atmospheric overburden ~5 g/cm^2.

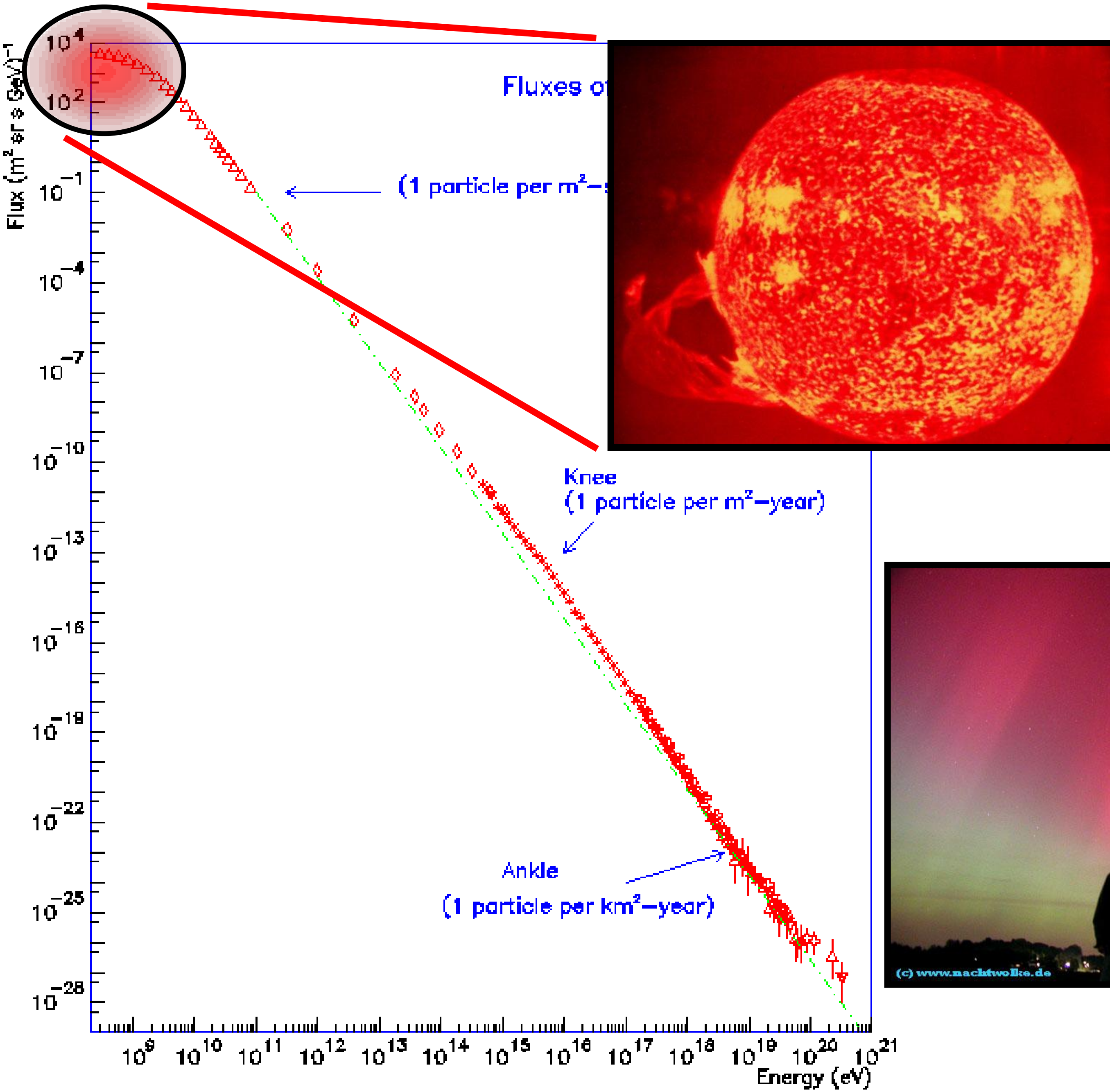
Till 2008 almost all data on cosmic antiparticles from these experiments.

~5 km

Ground

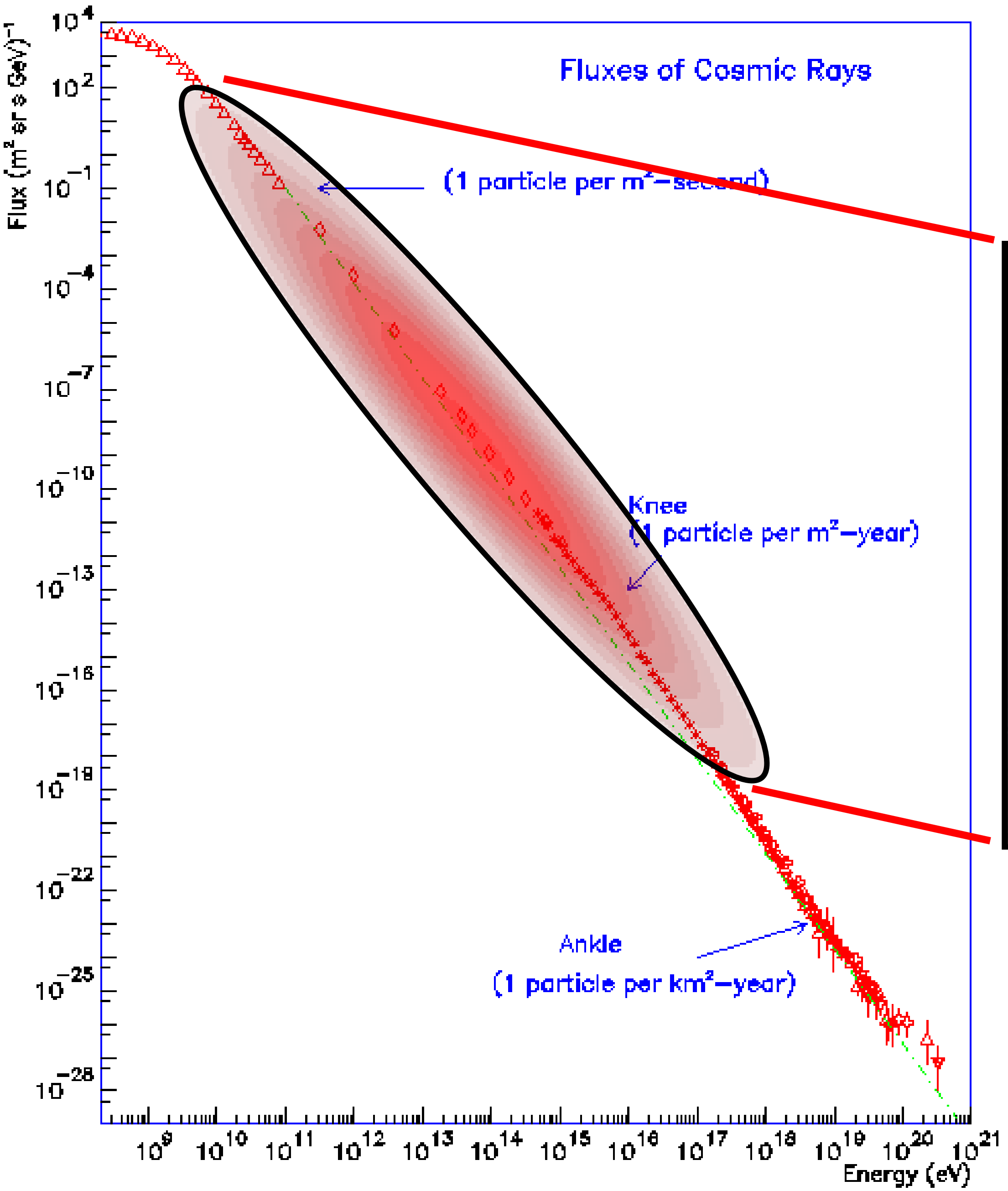
0 m


Fluxes of Cosmic Rays
Flux (m² sr s GeV)⁻¹
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Energy (eV)

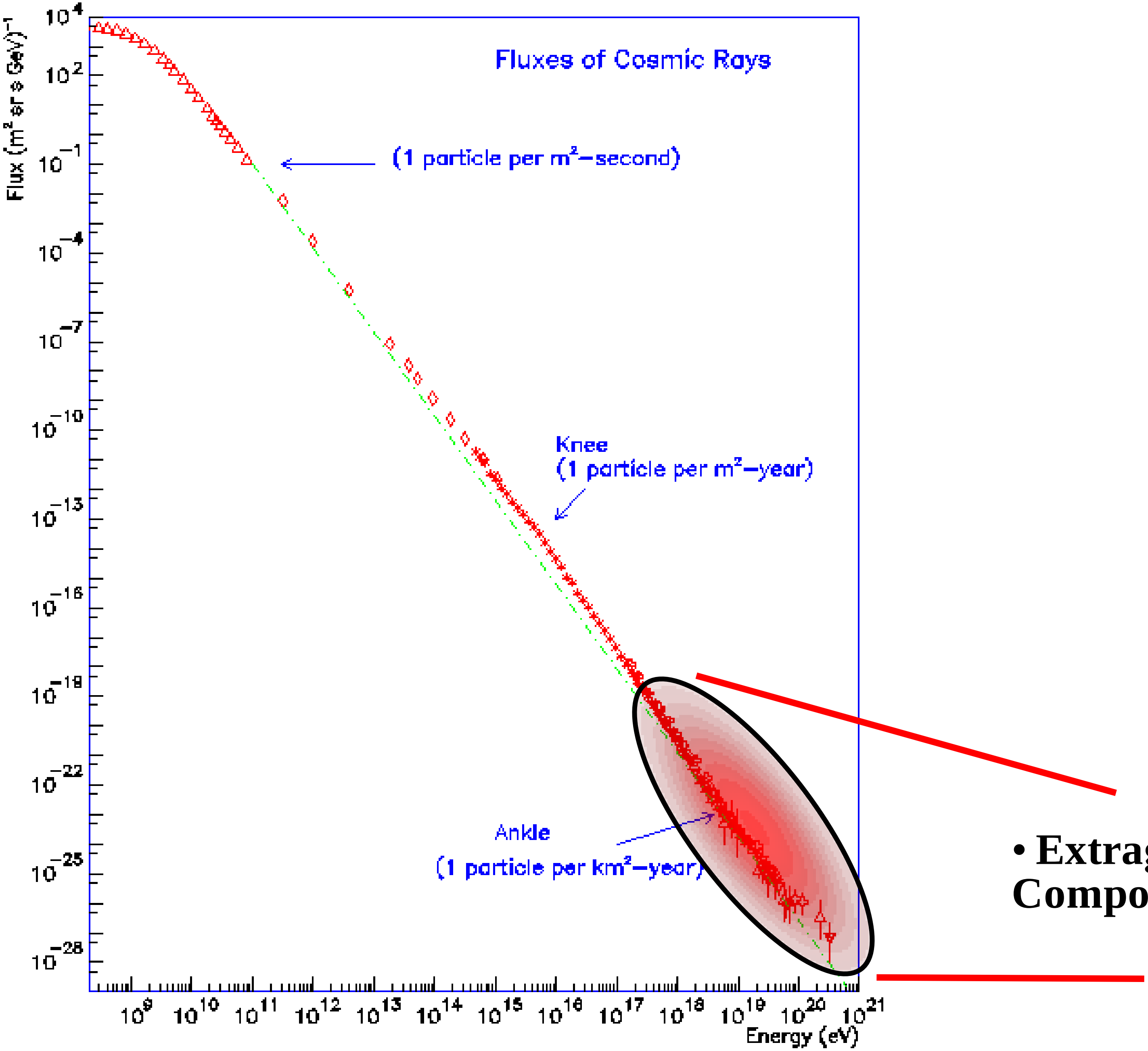


Solar Flare

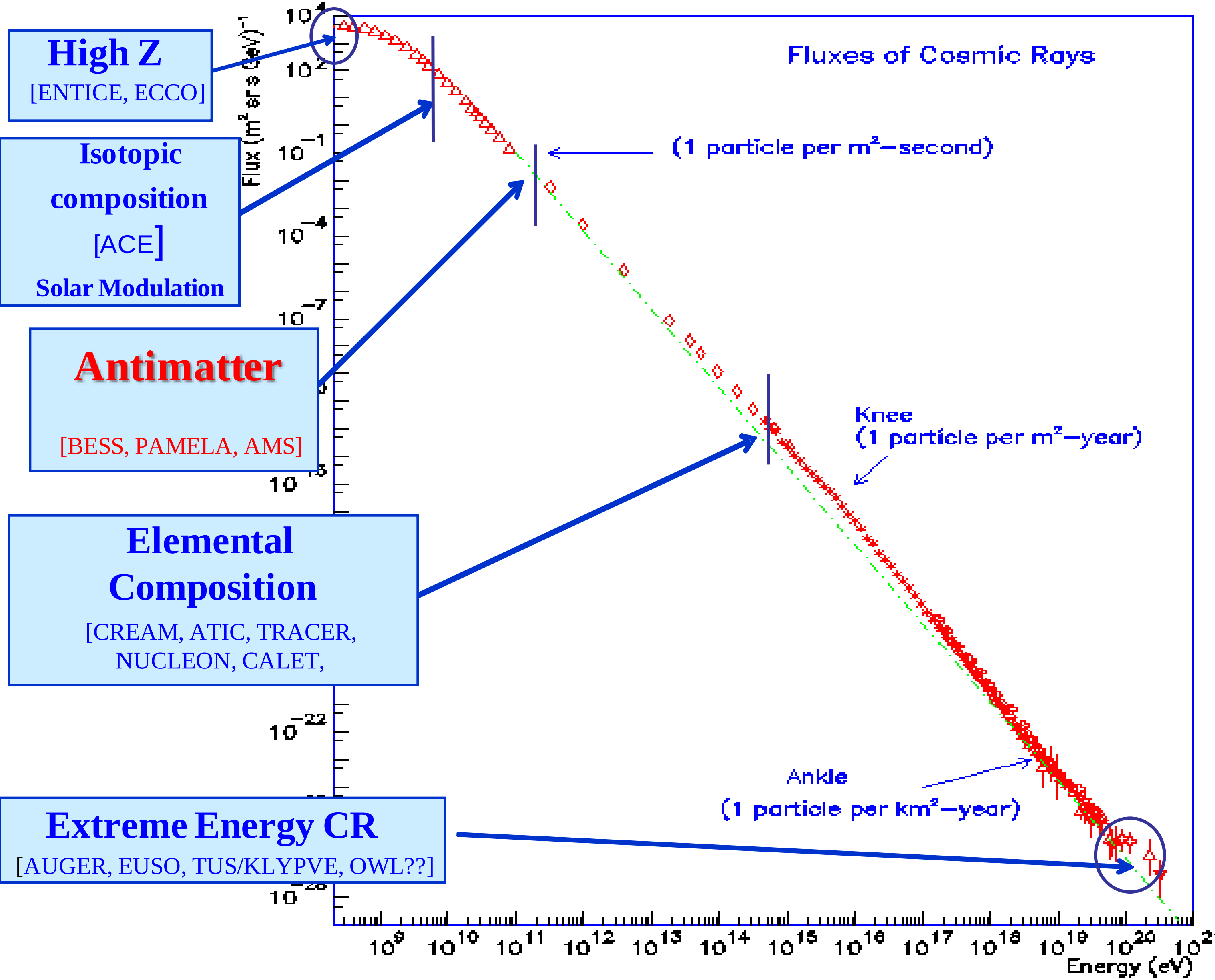
Northern Ligths



- **SuperNova Explosion**

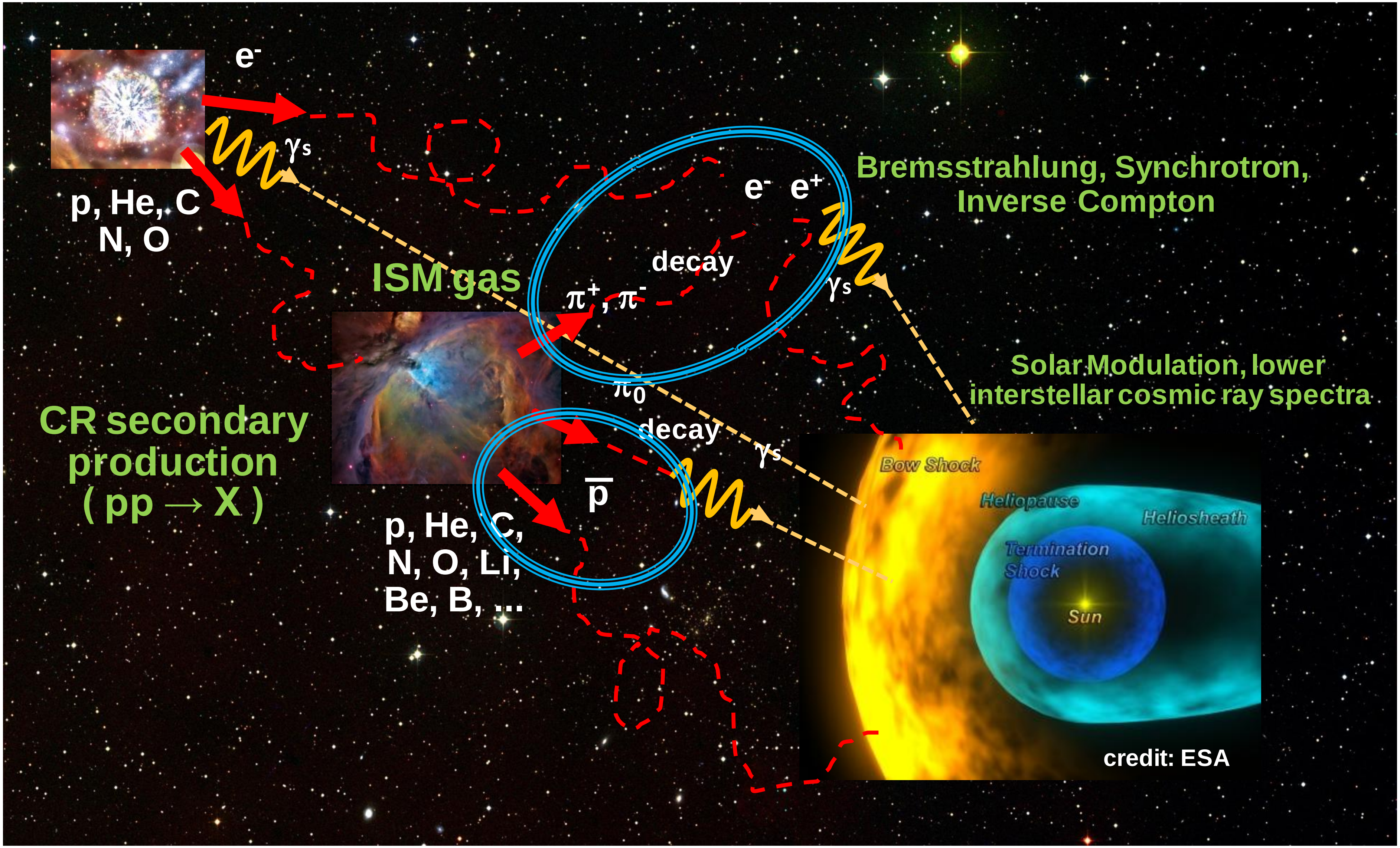


- **Extragalactic Component: AGNs?**



High Z
[ENTICE, ECCO]
Isotopic composition
[ACE]
Solar Modulation
Antimatter
[BESS, PAMELA, AMS]
Elemental Composition
[CREAM, ATIC, TRACER, NUCLEON, CALET,
Extreme Energy CR
[AUGER, EUSO, TUS/KLYPVE, OWL??]
Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Flux (m² sr s GeV)⁻¹
Energy (eV)

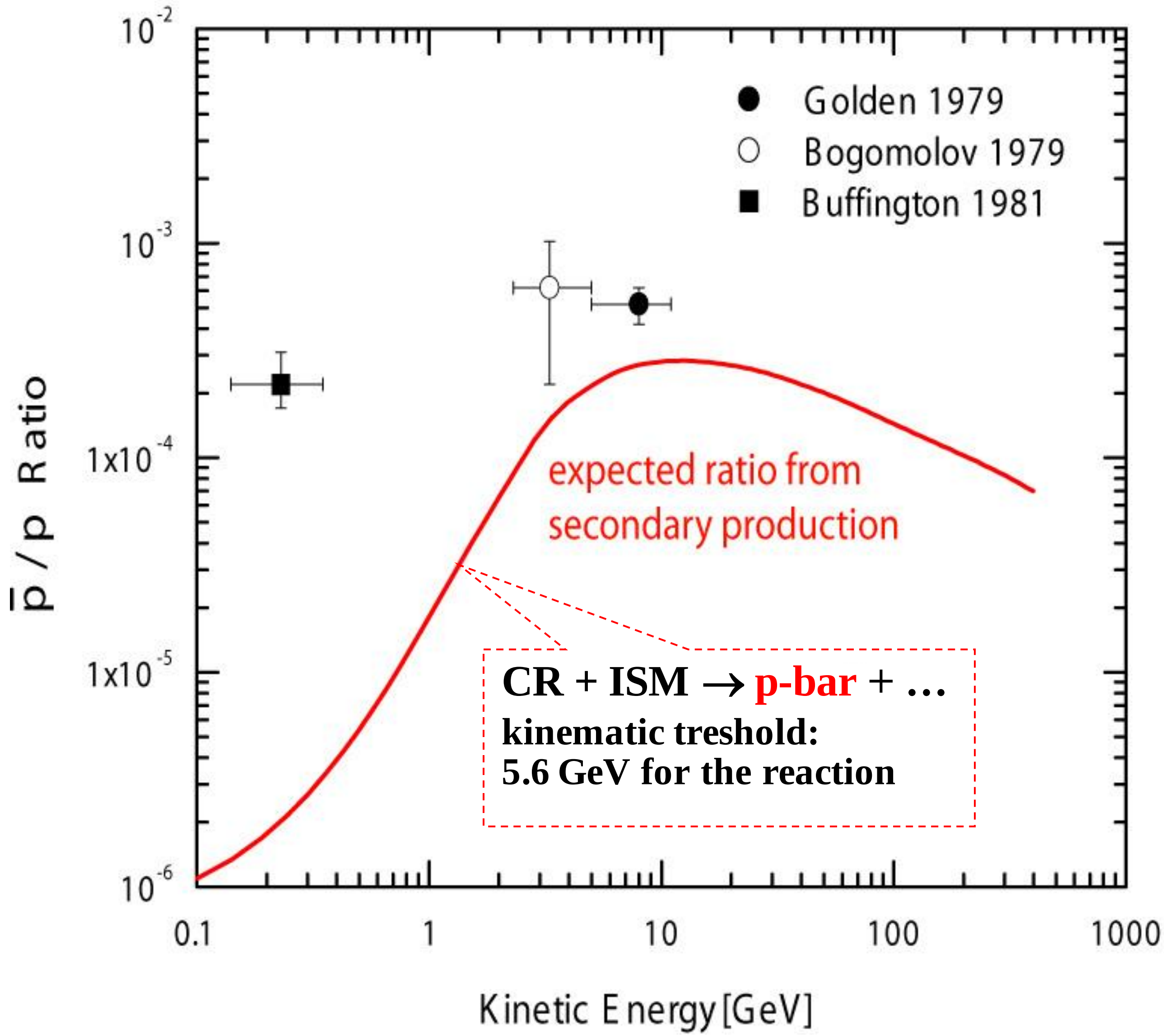
Cosmic Rays and Anti-Particles



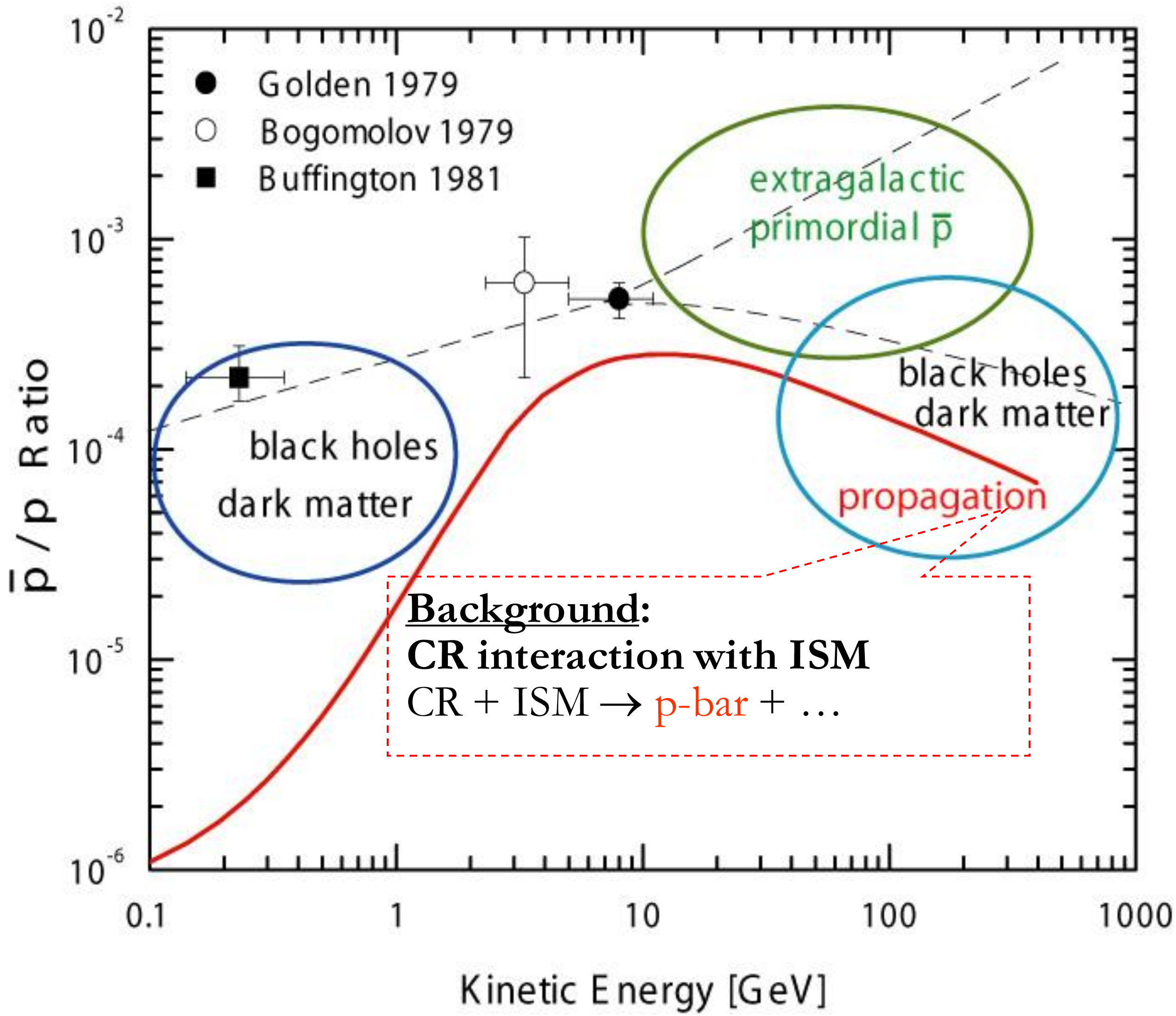
Astrophysics and Cosmology compelling Issues

- ***Origin and propagation of Cosmic Rays***
- ***Nature of the Dark Matter that pervades the Universe***
- ***Apparent absence of cosmological Antimatter*** (see R. Battiston's talk on 21st)

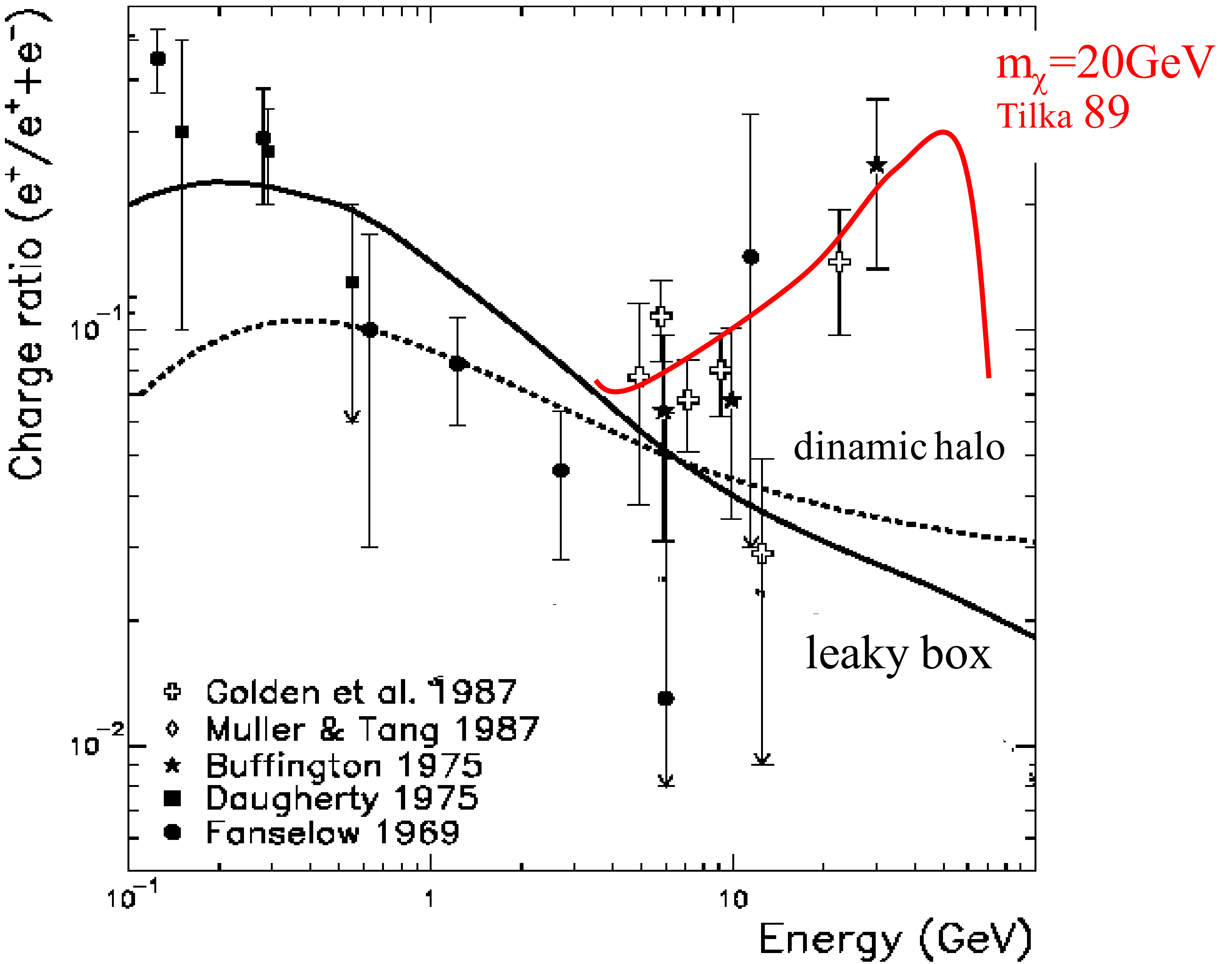
The first historical measurements on galactic antiprotons

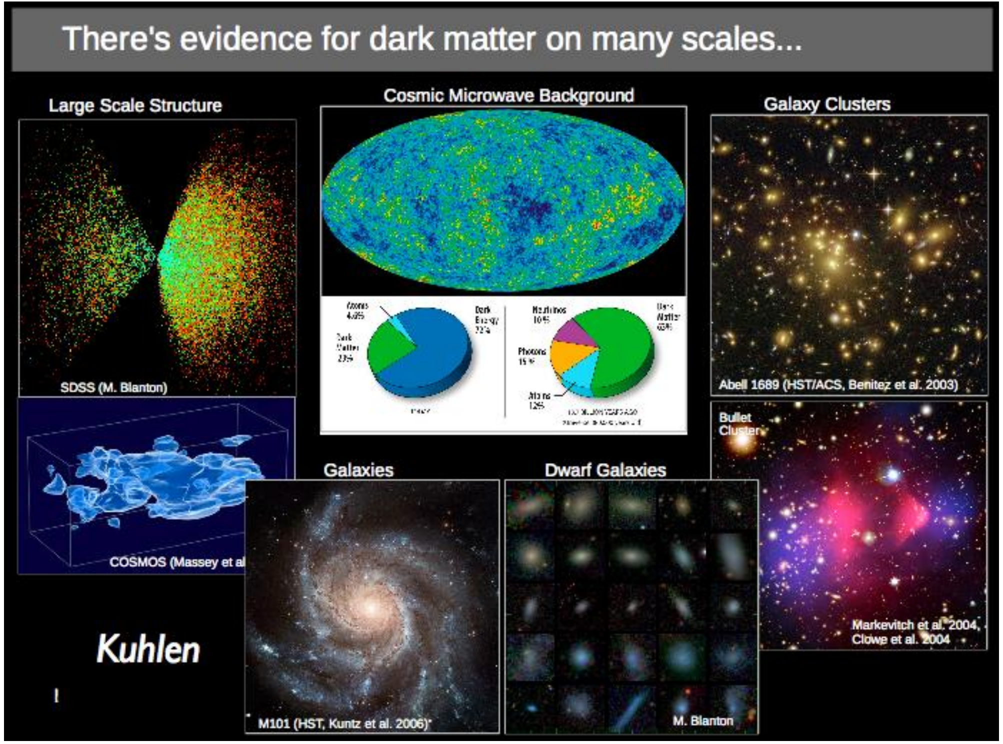


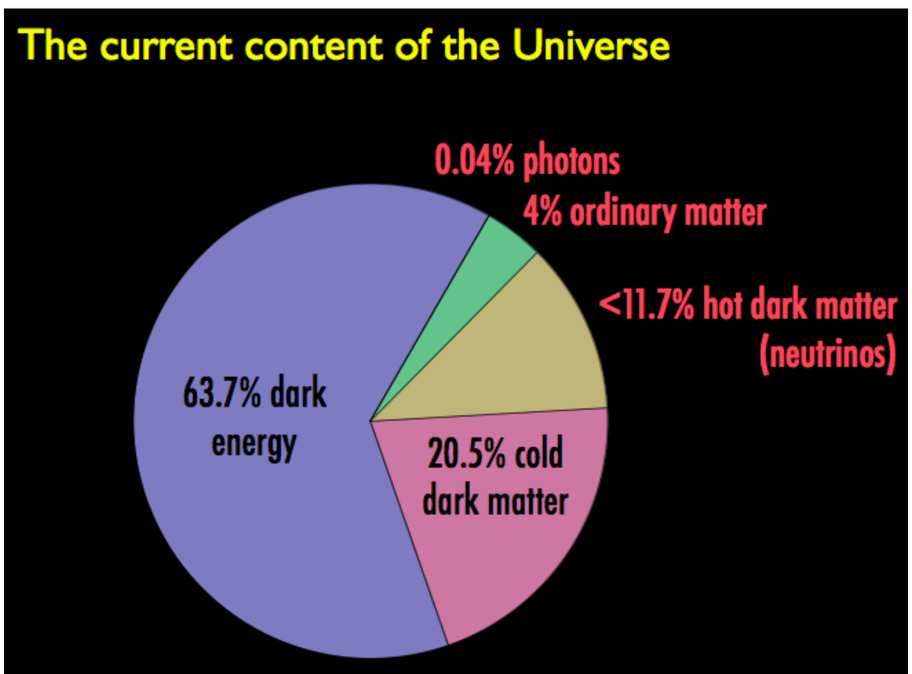
The first historical measurements of the $\bar{p}/p$ - ratio and various Ideas of theoretical Interpretations



Balloon data : Positron fraction before 1990



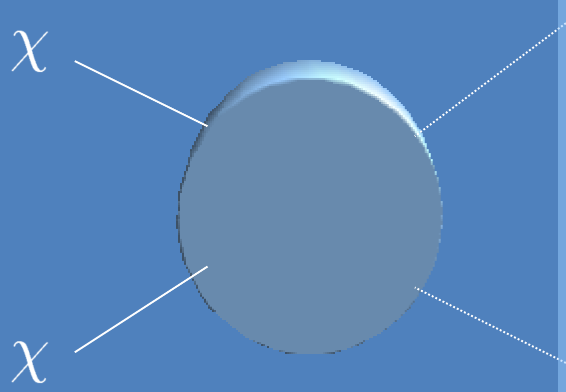




P. Gondolo, IDM 2008

DM annihilations

DM particles are stable. They can annihilate in pairs.



$W^-, Z^0, b, \tau^-, t, h^0, \ldots$ ⇒ $e^\mp, p^{(-)}, D^{(-)}, \ldots$

$W^+, Z^0, \bar{b}, \tau^+, \bar{t}, h^0, \ldots$ ⇒ $e^\pm, p^{(-)}, D^{(-)}, \ldots$

Primary annihilation channels

Decay

Final states

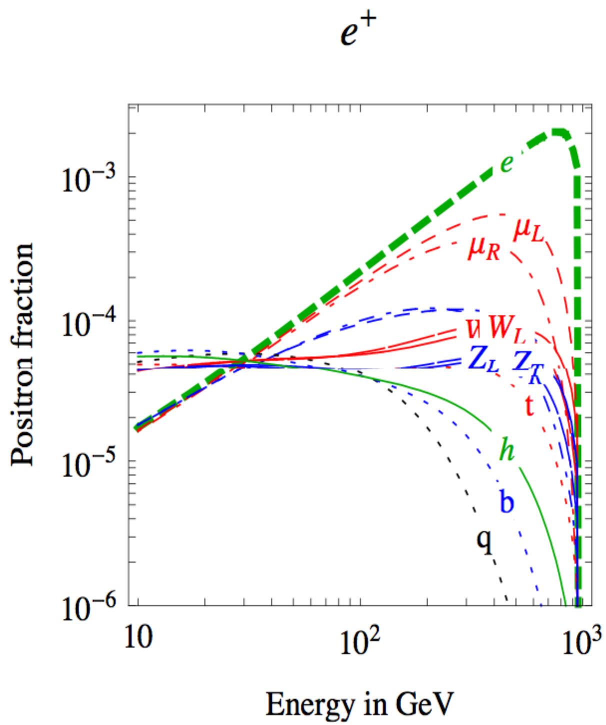
$\sigma_a = \langle\sigma v\rangle$

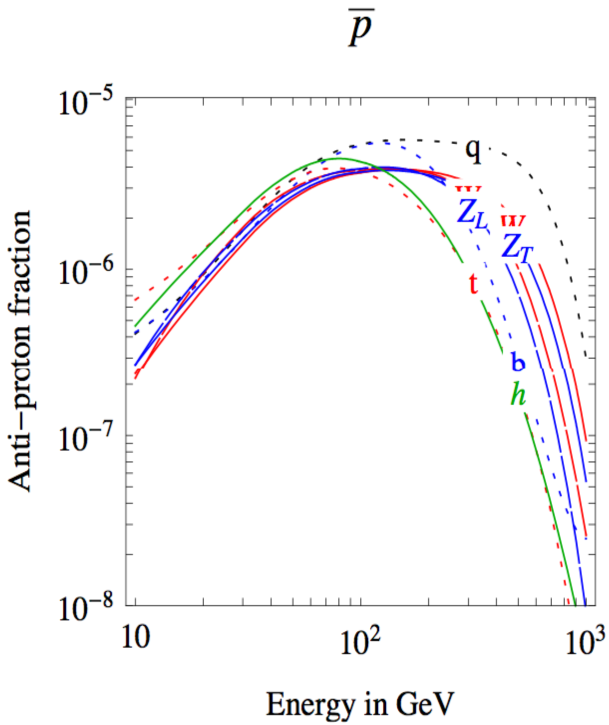
DM annihilations

Resulting spectrum for positrons and antiprotons
M_{WIMP}= 1 TeV

The flux shape is completely determined by:

1) WIMP mass
2) Annihilations channels





Antiparticle Experiments
(old and new)

Antimatter and Dark Matter Research

Wizard Collaboration

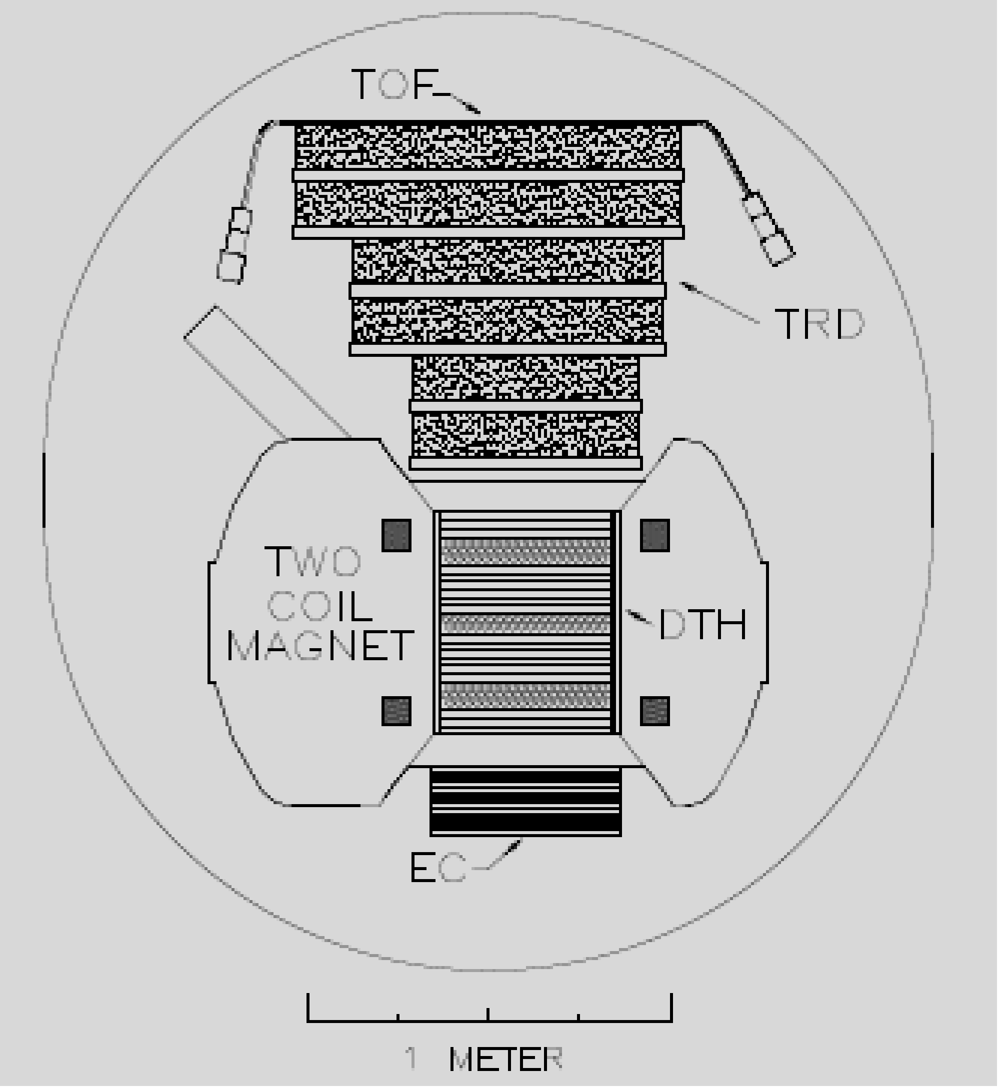
- ✓ MASS - 1,2 (89,91)
- ✓ TrampSI (93)
- ✓ CAPRICE (94, 97, 98)
- ✓ PAMELA (2006-)

- ✓ BESS (93, 95, 97, 98, 2000 2004,2007)
- ✓ Heat (94, 95, 2000)
- ✓ IMAX (96)
- ✓ BESS LDF (2004, 2007)
- ✓ AMS-01 (1998)
- ✓ AMS-02 (2011-)

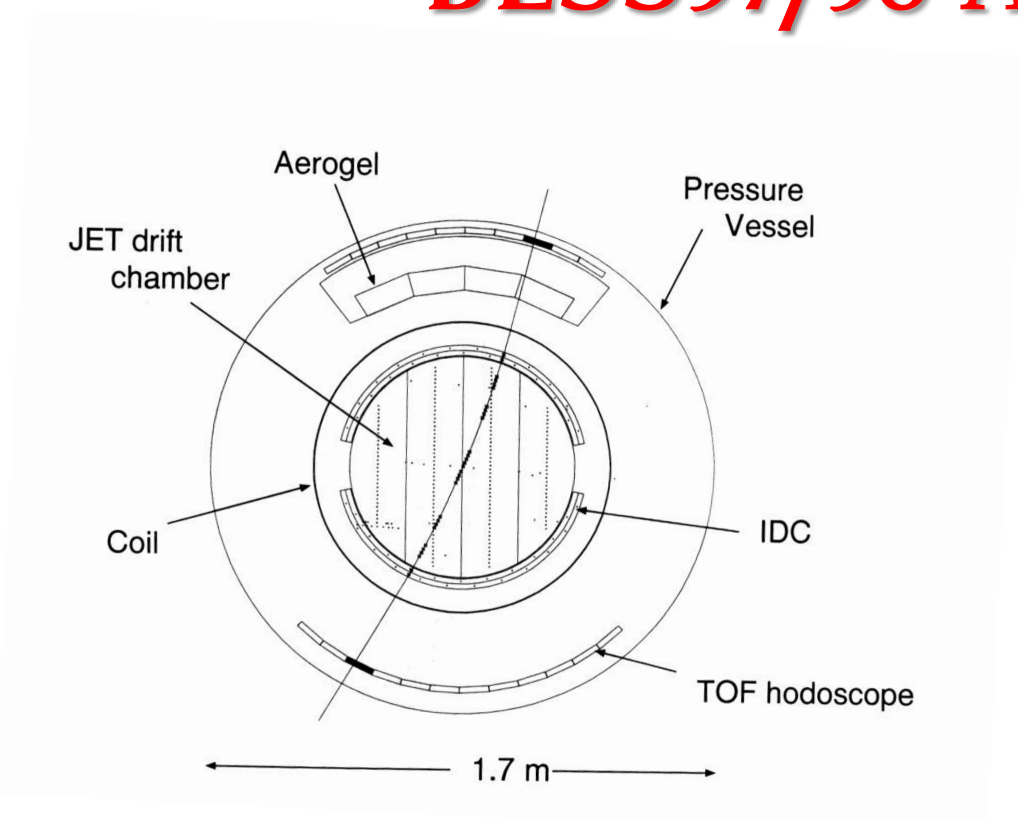
HEAT 94-95

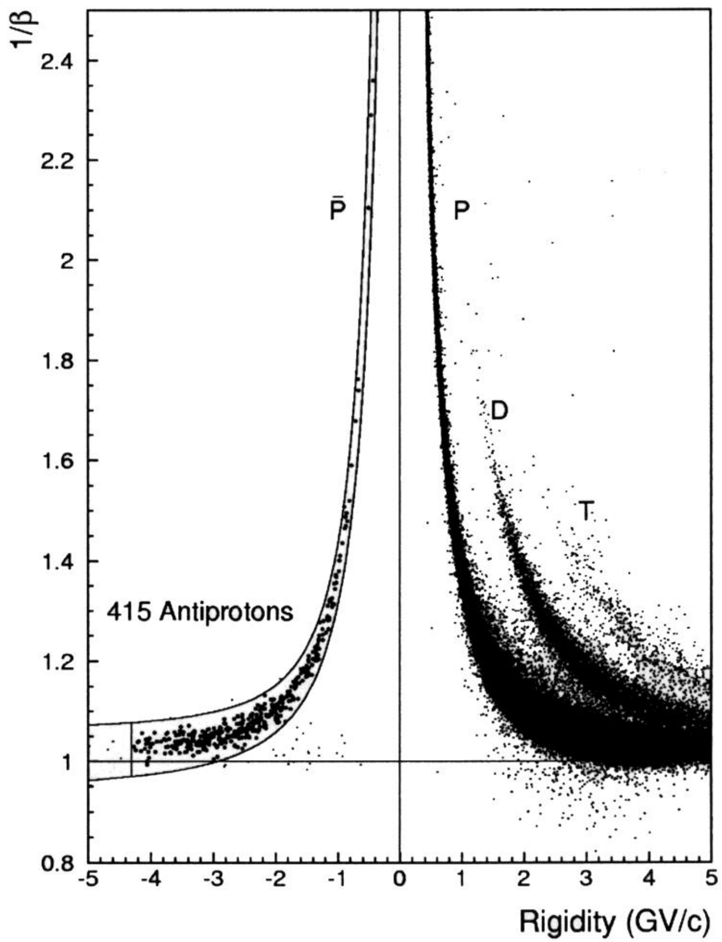
Subnuclear Physics Techniques in Space Experiments

- Charge sign and momentum
- Beta selection
- Z selection
- hadron – electron discrimination

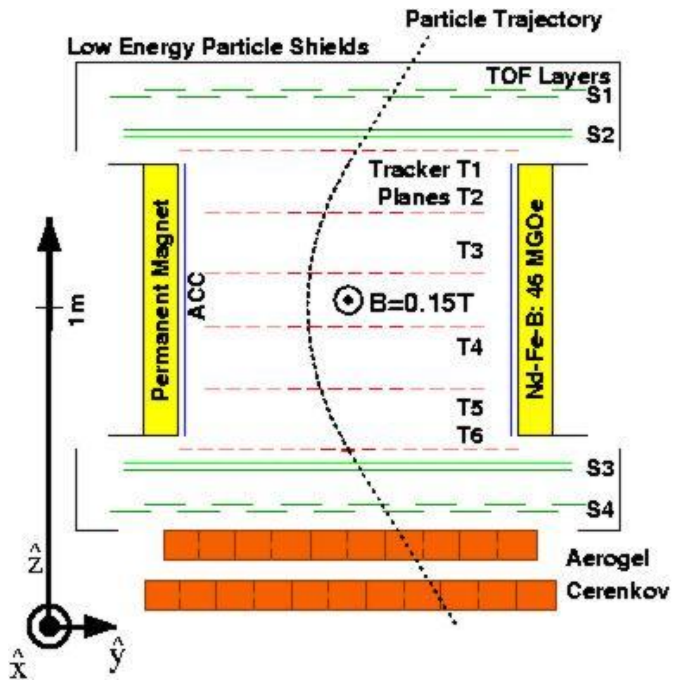


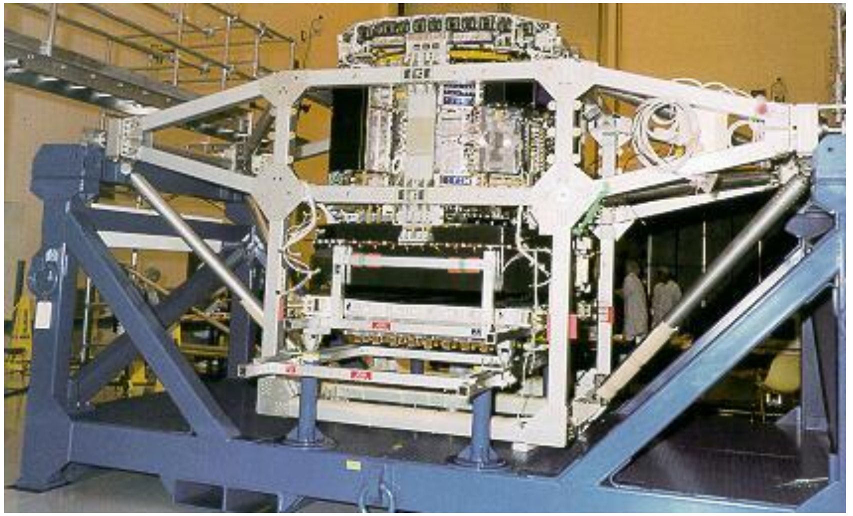
BESS97/98 Apparatus

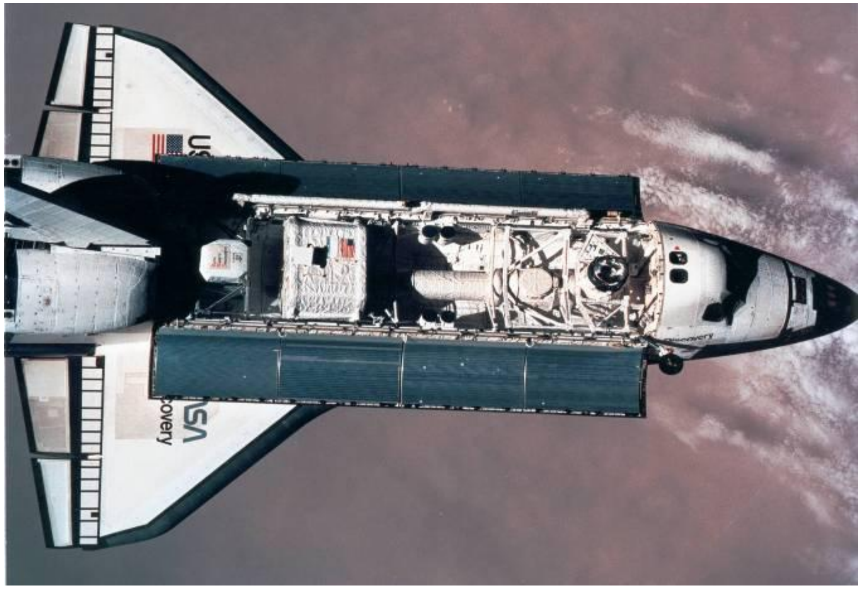




AMS-01 : the Detector



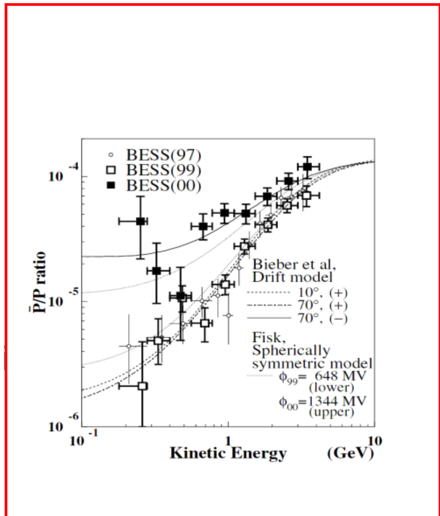




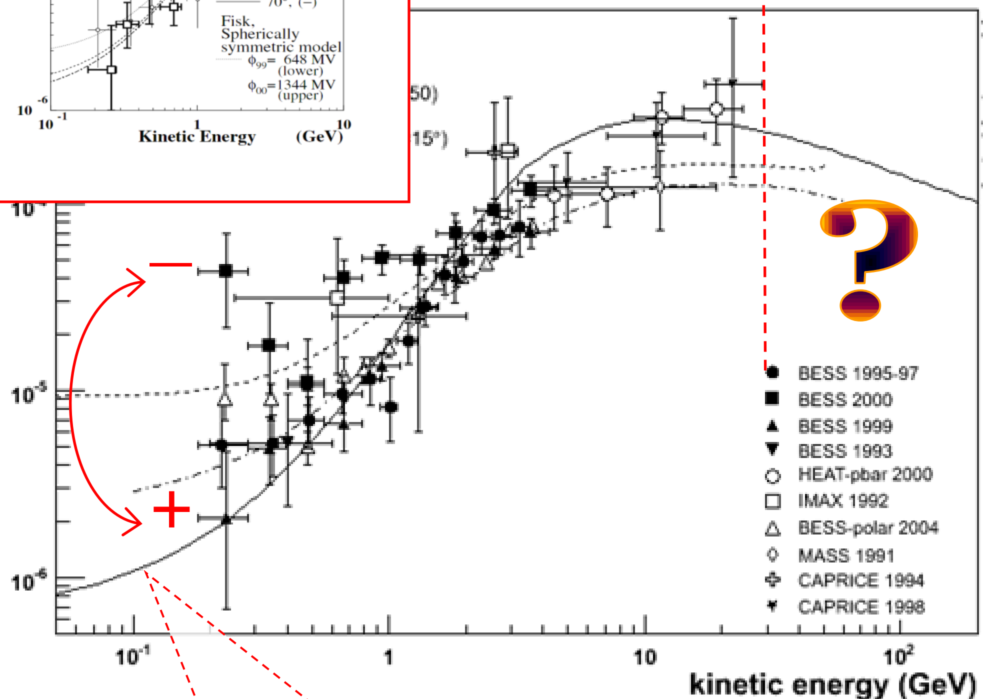
- Acceptance: Ω » 0.15 m^2sr
- Bending power » 0.14 Tm^2
- TOF : trigger + β and dE/dx meas.
- Tracker: sign Z + Rigidity + dE/dx meas.
- Cherenkov: e/p separation up to ~ 3 GeV.

CR antimatter

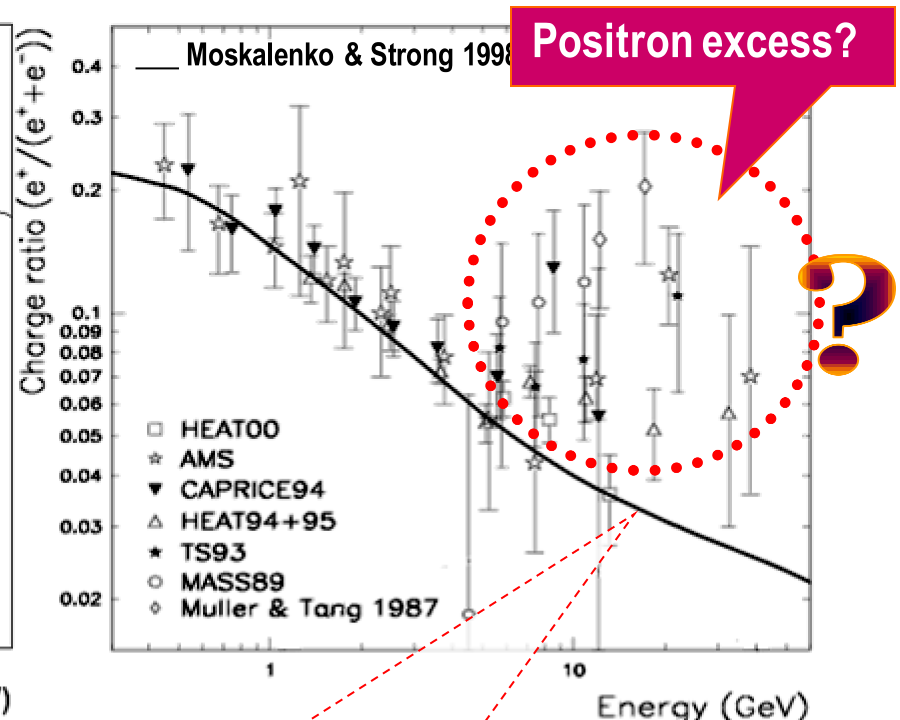
Status in 2006



Antiprotons



Positrons

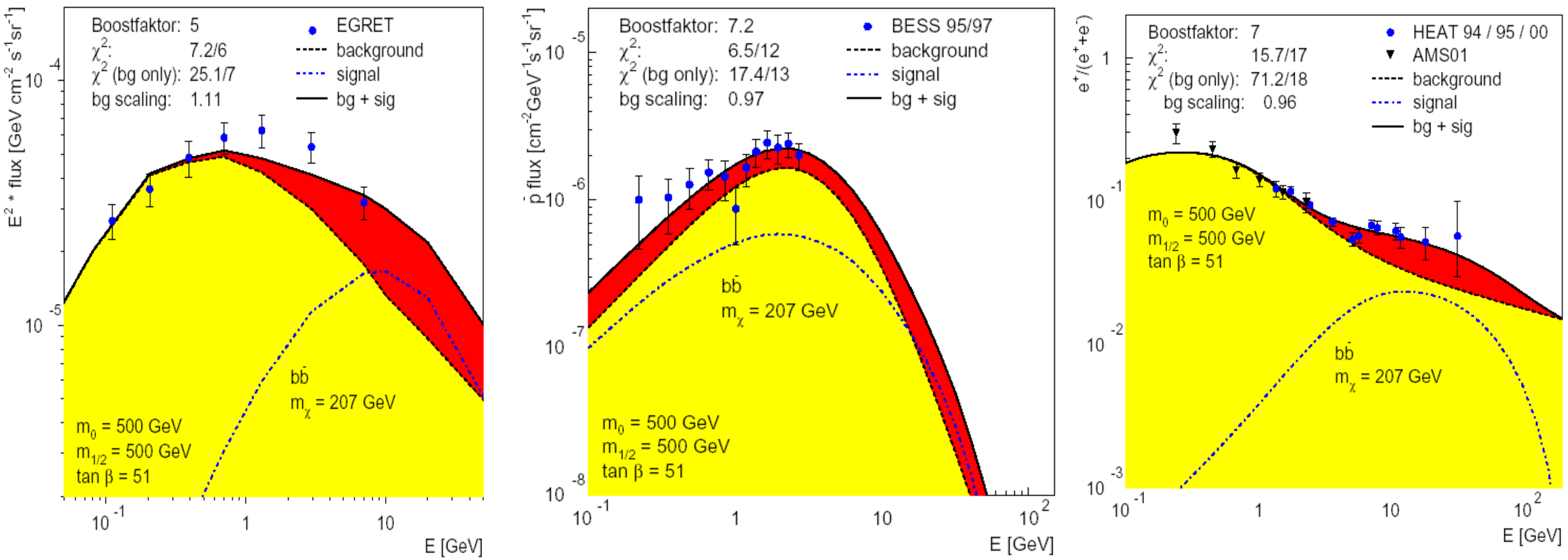


CR + ISM → **p-bar** + …
kinematic treshold:
5.6 GeV for the reaction

$$pp \rightarrow \bar{p}ppp$$

$$CR + ISM \rightarrow \pi^{\pm} + x \rightarrow \mu^{\pm} + x \rightarrow e^{\pm} + x$$
$$CR + ISM \rightarrow \pi^{0} + x \rightarrow \gamma\gamma \rightarrow e^{\pm}$$

-



Gobal Fit of experimental data on gamma-rays from the Galactic Centre, on antiprotons and positrons. Same model for cosmic-ray propagation and Dark Matter annihilation.

W. De Boer et al., Eur. Phys. J. C33(2004)S981.

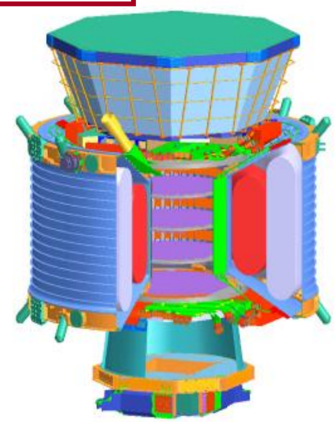
Neutralino Mass 207 GeV.

Antimatter Missions in "Space"

BESS LDBF
2004, 2007

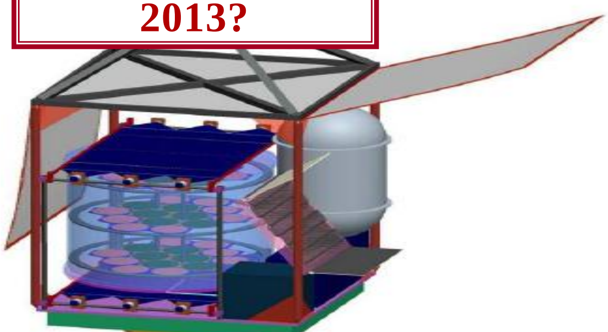
PAMELA
2006-

AMS-02
2011-



PEBS
2014?

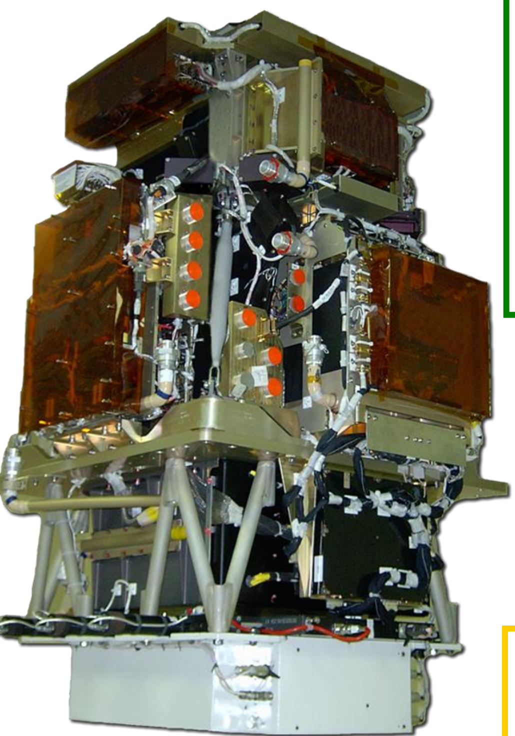
GAPS
2013?



Positrons and Antiprotons with PAMELA
(and FERMI)

PAMELA detectors

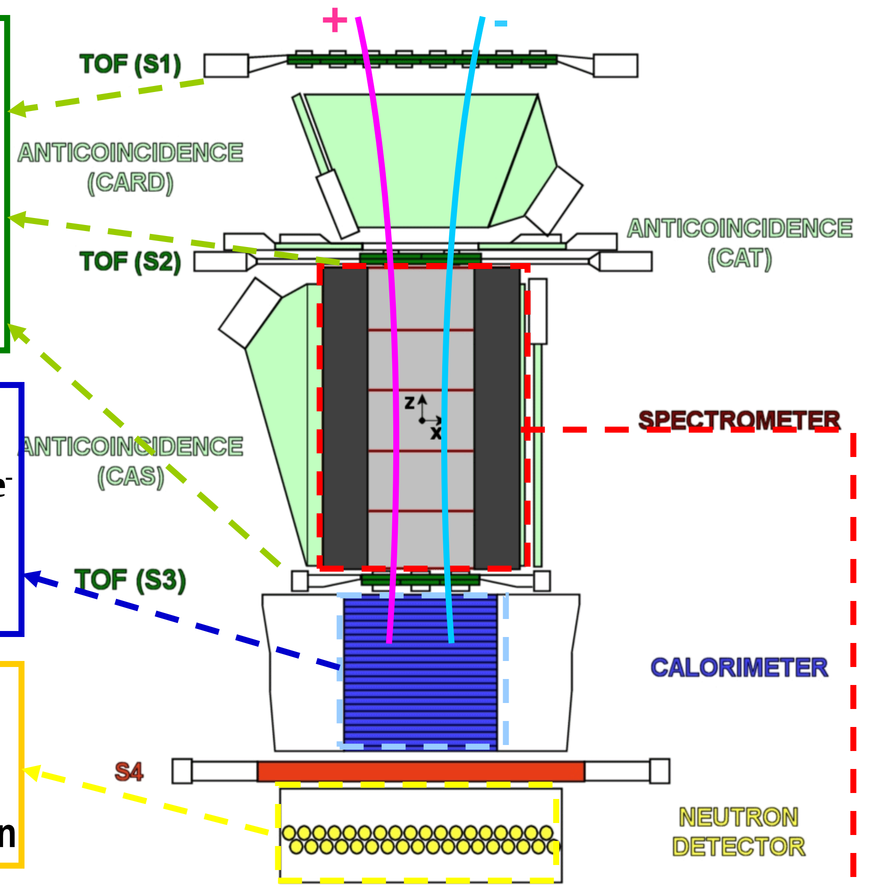
Main requirements → high-sensitivity antiparticle identification and precise momentum measure



Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Electromagnetic calorimeter
W/Si sampling (16.3 X_0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

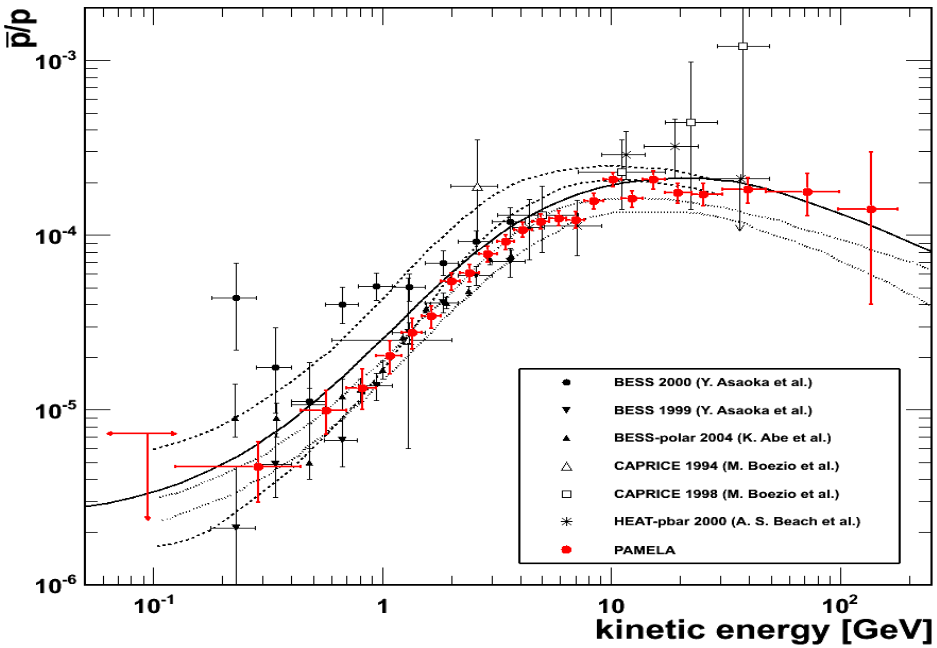
Neutron detector
^{3}He tubes + polyethylene moderator:
- High-energy e/h discrimination



GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

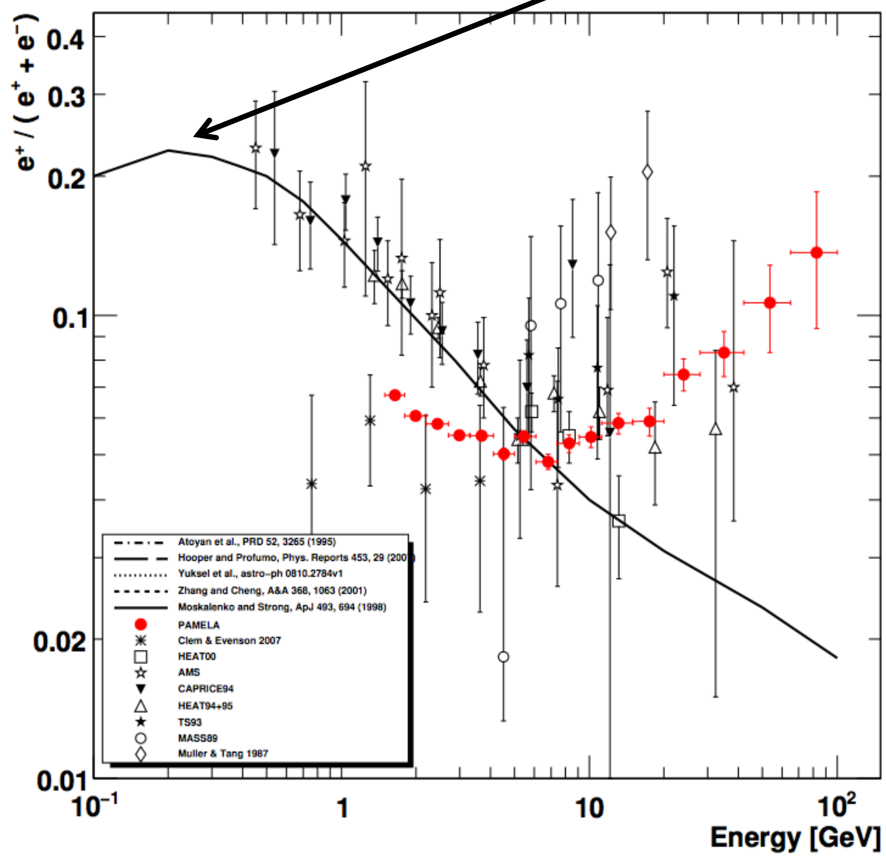
Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

Antiparticle Results



PRL 102 (2009) 051101,
PRL 105 (2010) 121101.

Secondary production calculations



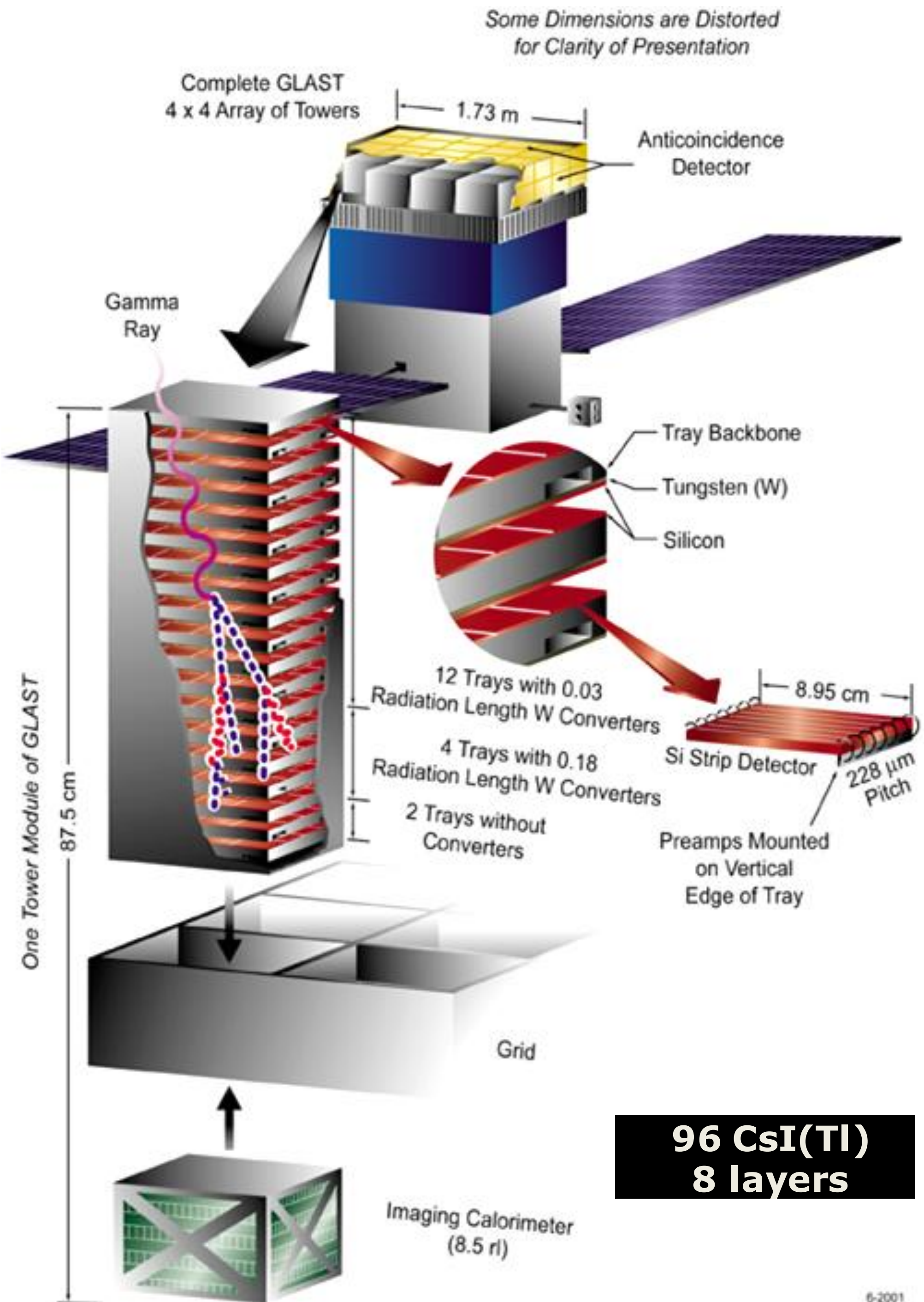
Nature 458 (2009) 607,
Astropart. Phys. 34 (2010) 1

More details and new results in subsequent talks by E. Mocchiutti and U. Giaccari

GLAST/ FERMI

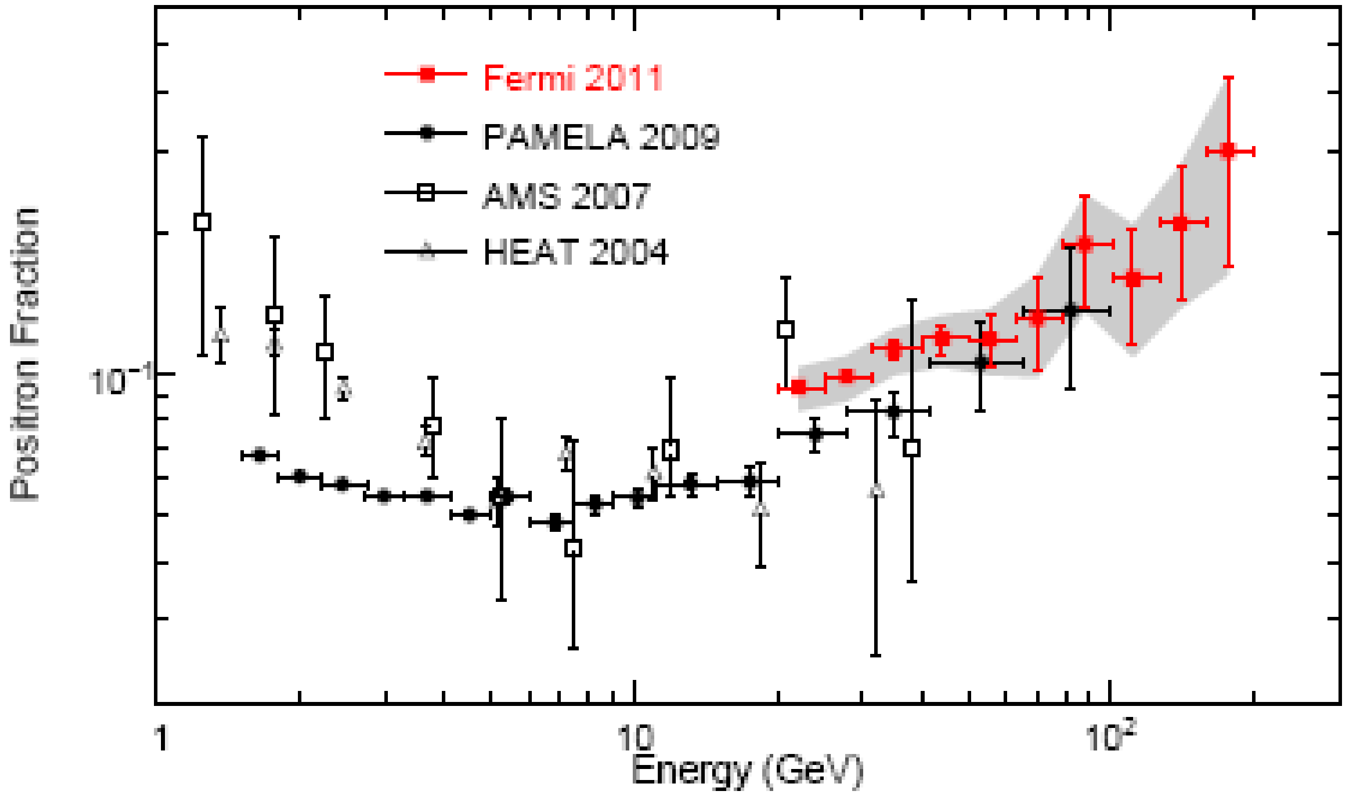
Gamma-Ray Large Area Space Telescope

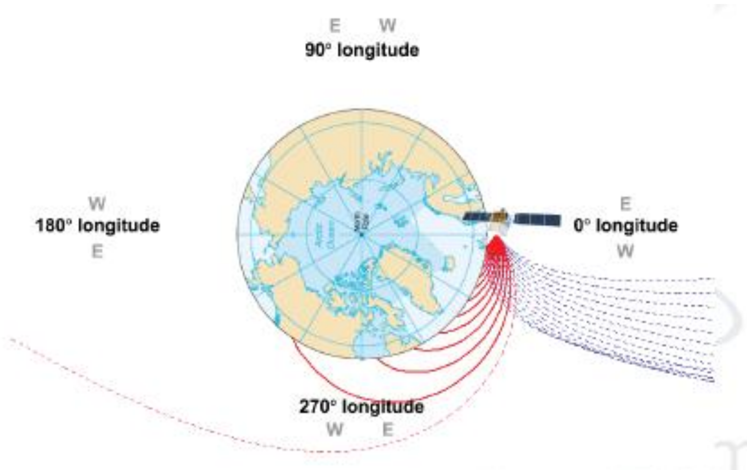
3000 kg, 650 W
1.8 m x 1.8 m x 1 m
20 MeV – 300 GeV



96 CsI(Tl)
8 layers

Fermi Positron Fraction

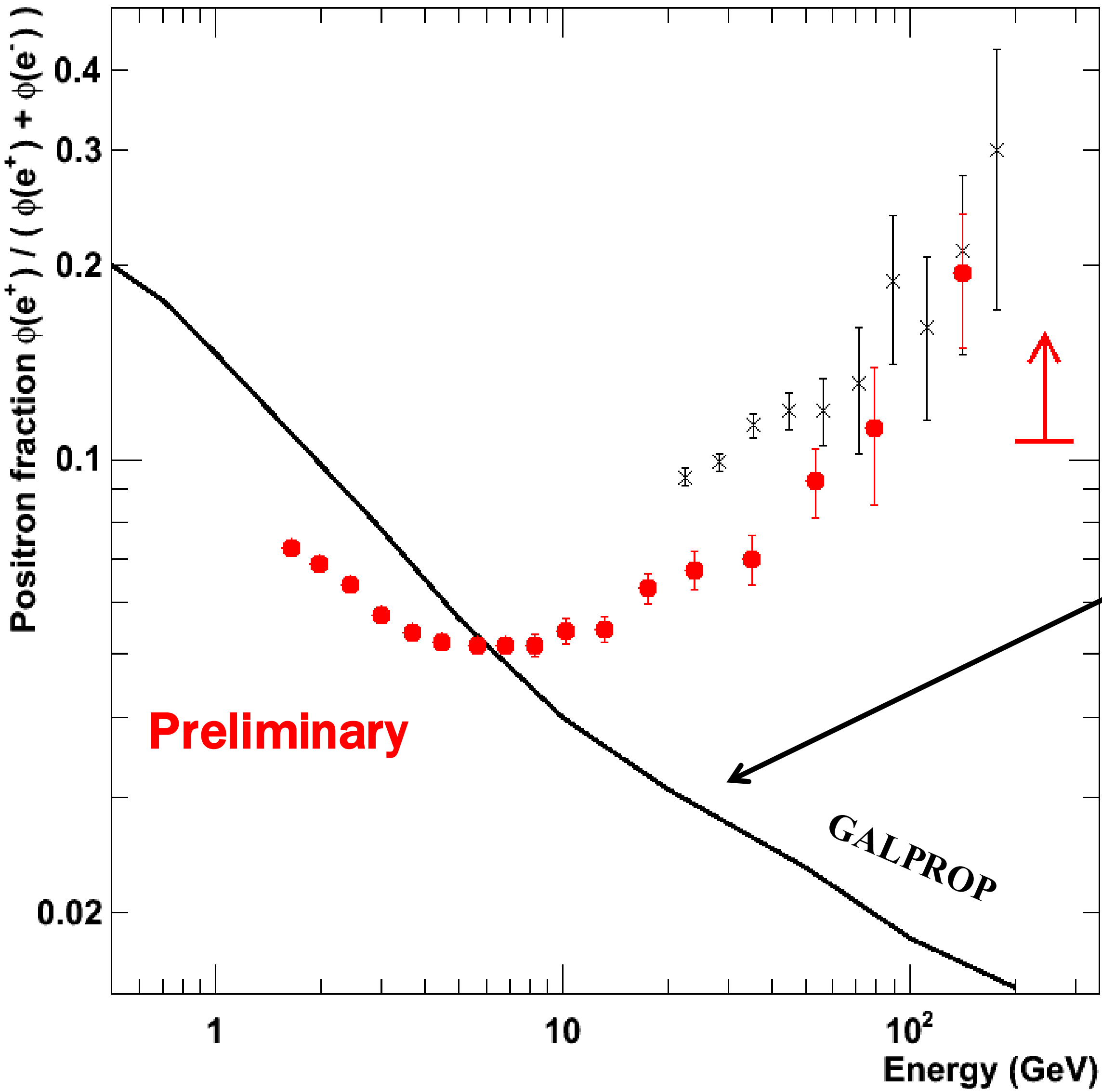




M. Ackermann, Phys.Rev.Lett. 108 (2012) 011103; astro-ph: 1109.0521

More details in subsequent talk by W. Mitthumsire

PAMELA Positron Fraction



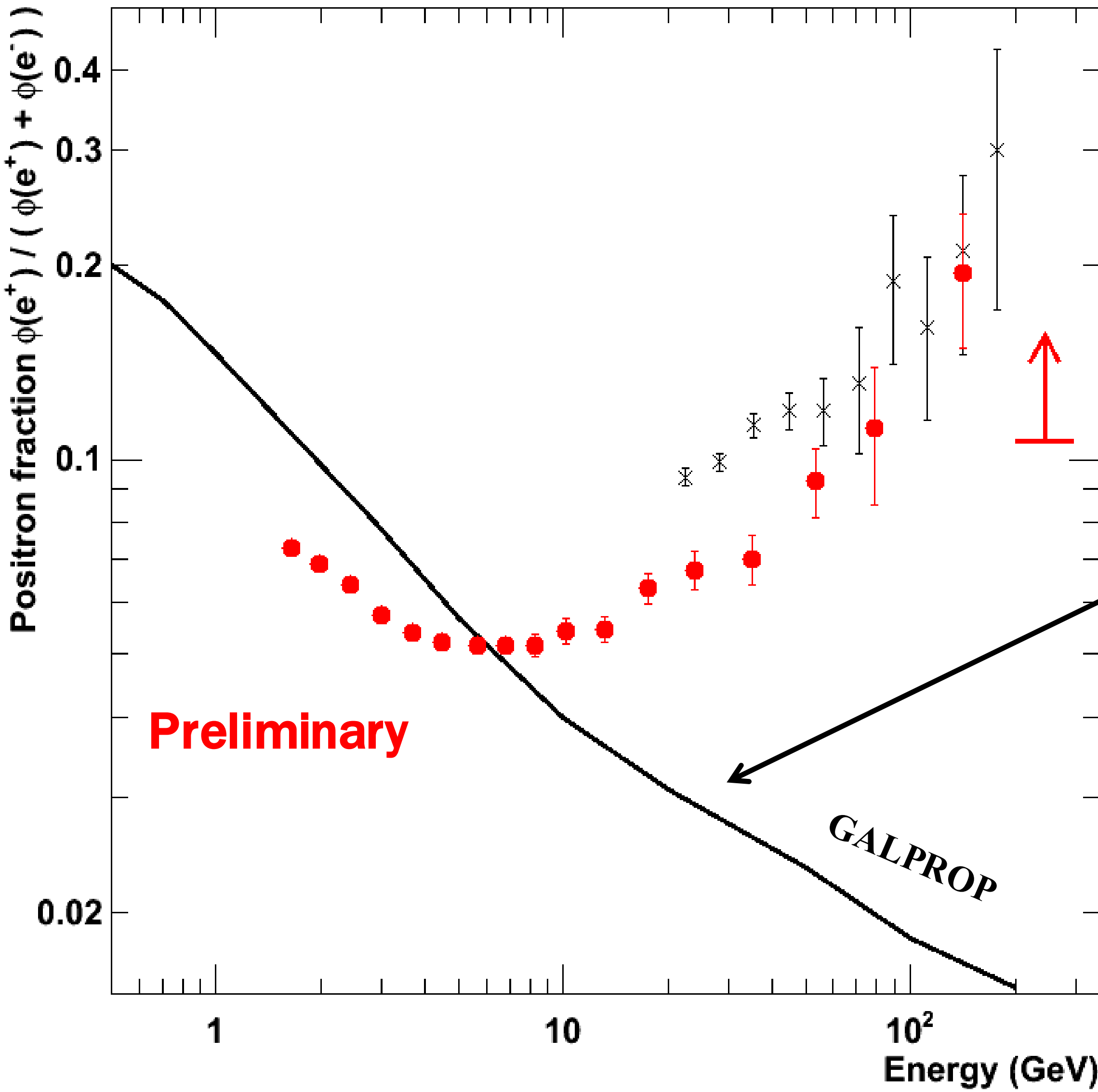
Secondary production
Moskalenko & Strong 98

But how reliable is this curve?

Mirko Boezio, Positrons in Astrophysics, 2012/03/20

See also P. Salati's talk on the 22nd

PAMELA Positron Fraction

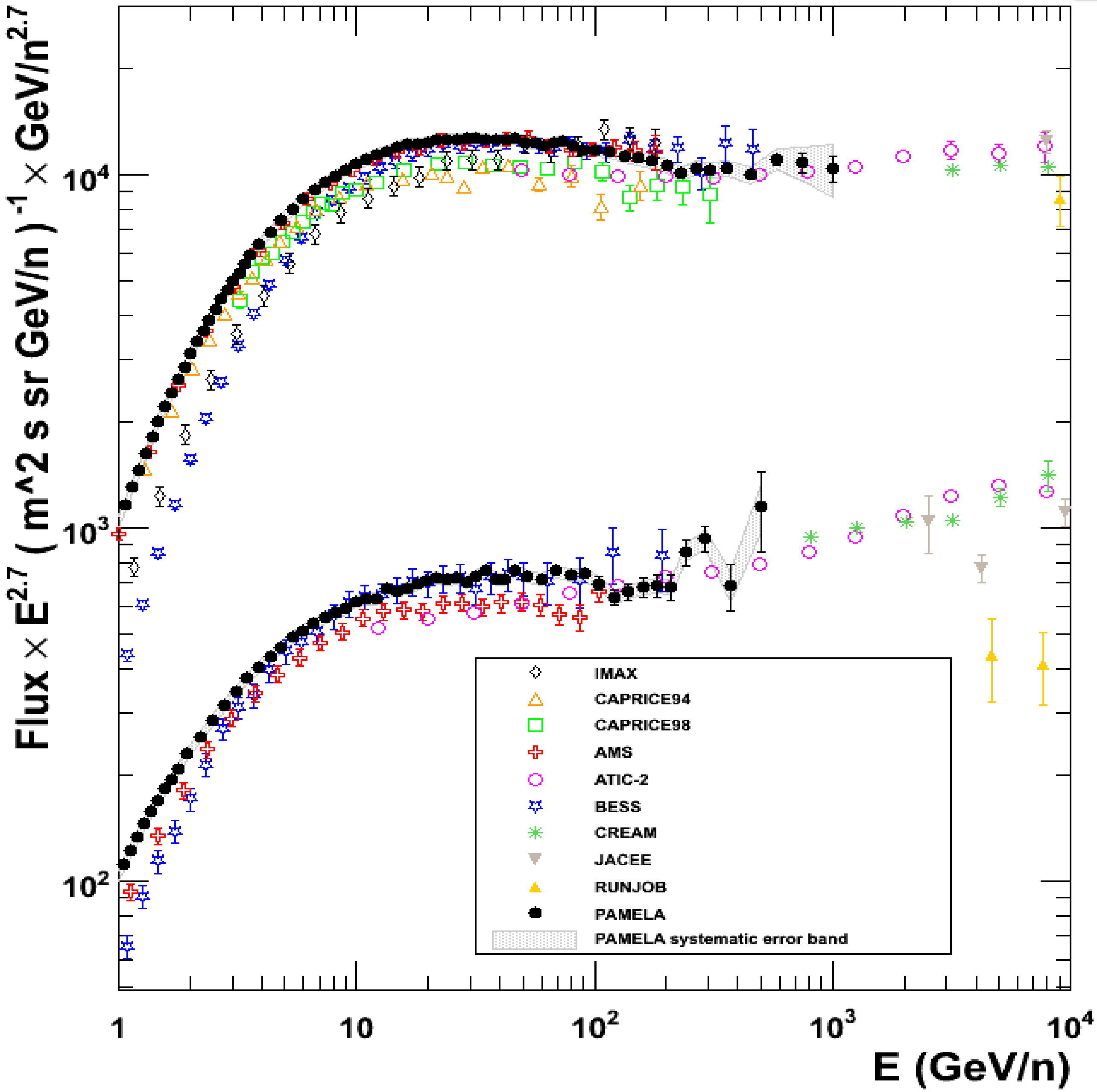


Secondary production
Moskalenko & Strong 98

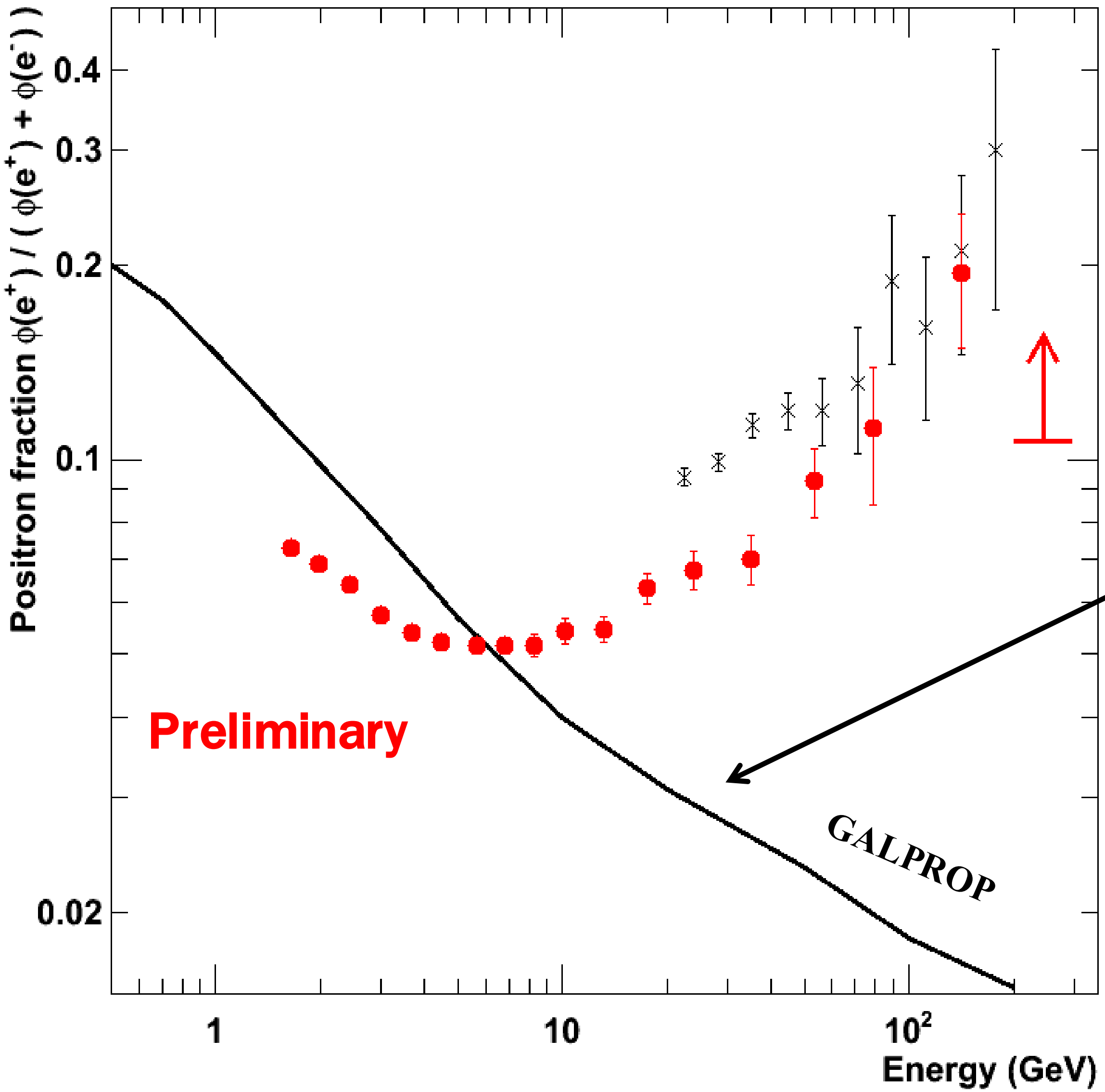
Uncertainties on:
- **Secondary production (primary fluxes, cross section)**

Mirko Boezio, Positrons in Astrophysics, 2012/03/20

Proton and Helium Nuclei Spectra



PAMELA Positron Fraction

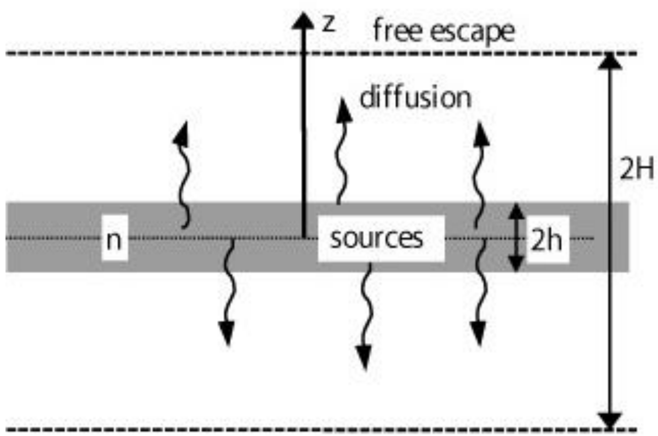


Secondary production
Moskalenko & Strong 98

Uncertainties on:
- **Secondary production (primary fluxes, cross section)**
- **Propagation models**

Mirko Boezio, Positrons in Astrophysics, 2012/03/20

Diffusion Halo Model



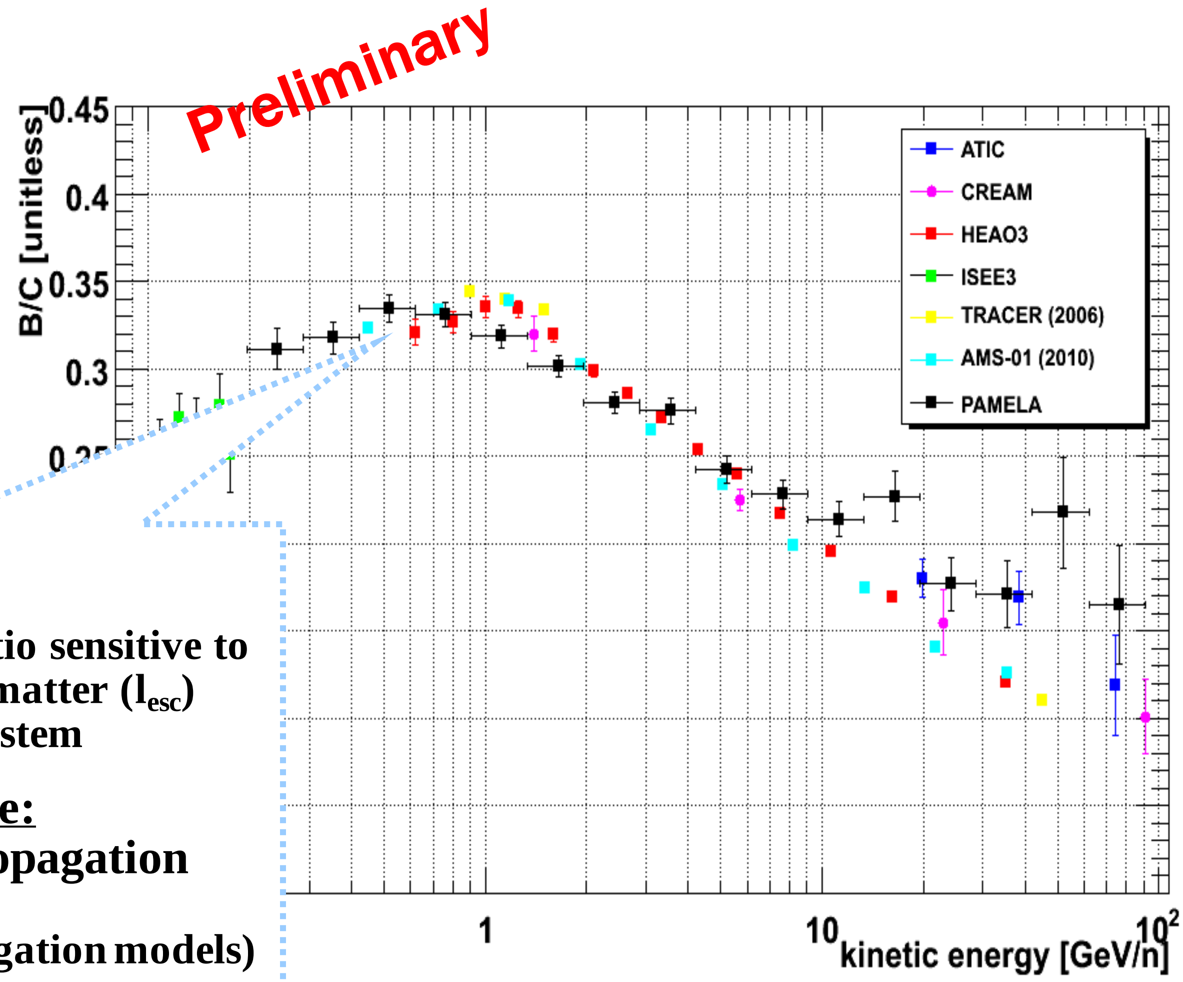
$$\frac{\partial N_i(E,z,t)}{\partial t} = \underbrace{D(E)\cdot\frac{\partial^2}{\partial z^2}N_i(E,z,t)}_{\text{diffusion}} \underbrace{- N_i(E,z,t)\left\{\frac{1}{\tau_i^{\text{int}}(E,z)}+\frac{1}{\gamma(E)\tau_i^{dec}}\right\}}_{\text{interaction and decay}}$$

$$+ \underbrace{\sum_{k>i}\frac{N_k(E,z,t)}{\tau_{\text{int}}^{k\to i}(E,z)}}_{\text{secondary production}} + \underbrace{Q_i(E,z)}_{\text{primary sources}}$$

$$\underbrace{-\frac{\partial}{\partial E}\left\{\left\langle\frac{\partial E}{\partial t}\right\rangle\cdot N_i(E,z,t)\right\}+\frac{1}{2}\frac{\partial^2}{\partial E^2}\left\{\left\langle\frac{\Delta E^2}{\Delta t}\right\rangle\cdot N_i(E,z,t)\right\}}_{\text{energy changing processes (ionisation, reacceleration)}}$$

Secondary nuclei

$$\frac{N_S}{N_P} \propto \lambda_{esc} \cdot \sigma_{P \to S}$$

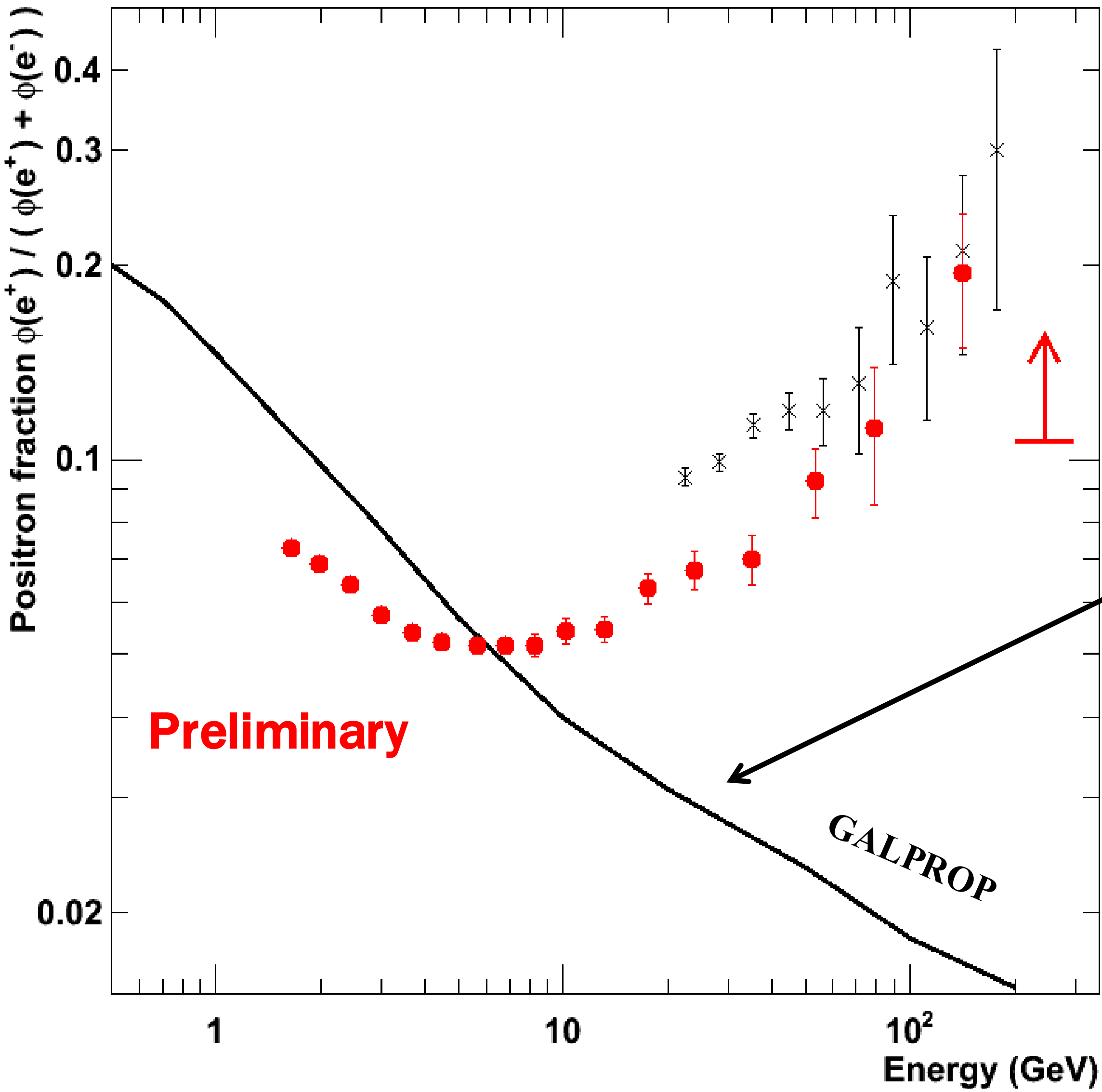


- **B nuclei of secondary origin:**
  CNO + ISM → B + …
- **Local secondary/primary ratio sensitive to average amount of traversed matter (l_{esc}) from the source to the solar system**

Local secondary abundance:
⇒ study of galactic CR propagation

(B/C used for tuning of propagation models)

PAMELA Positron Fraction

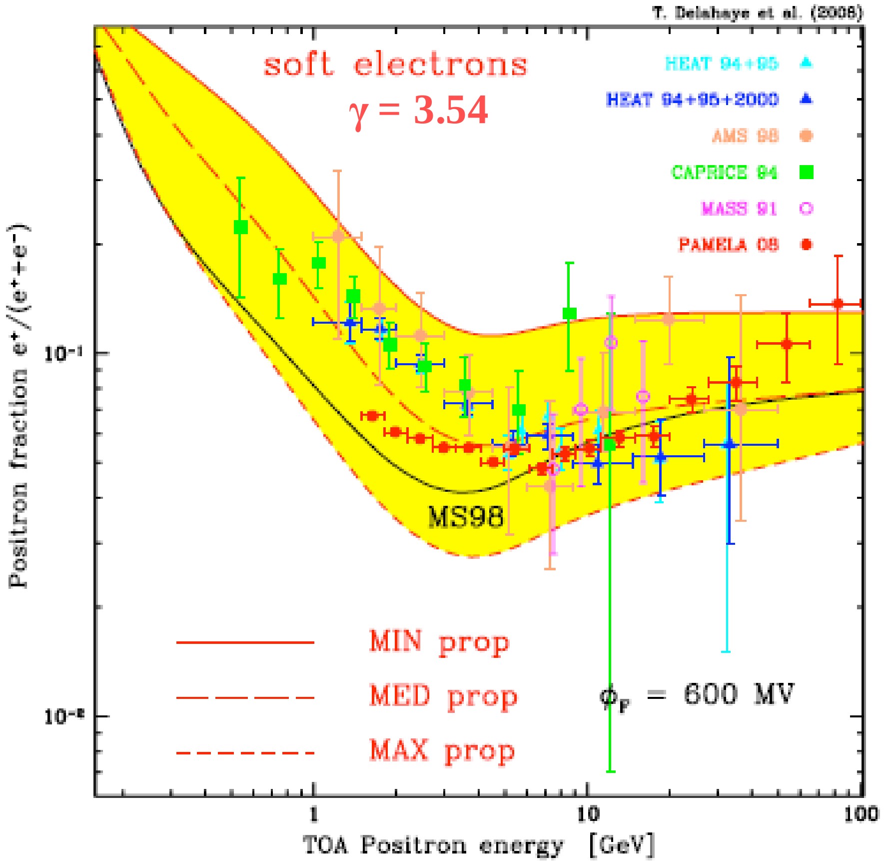


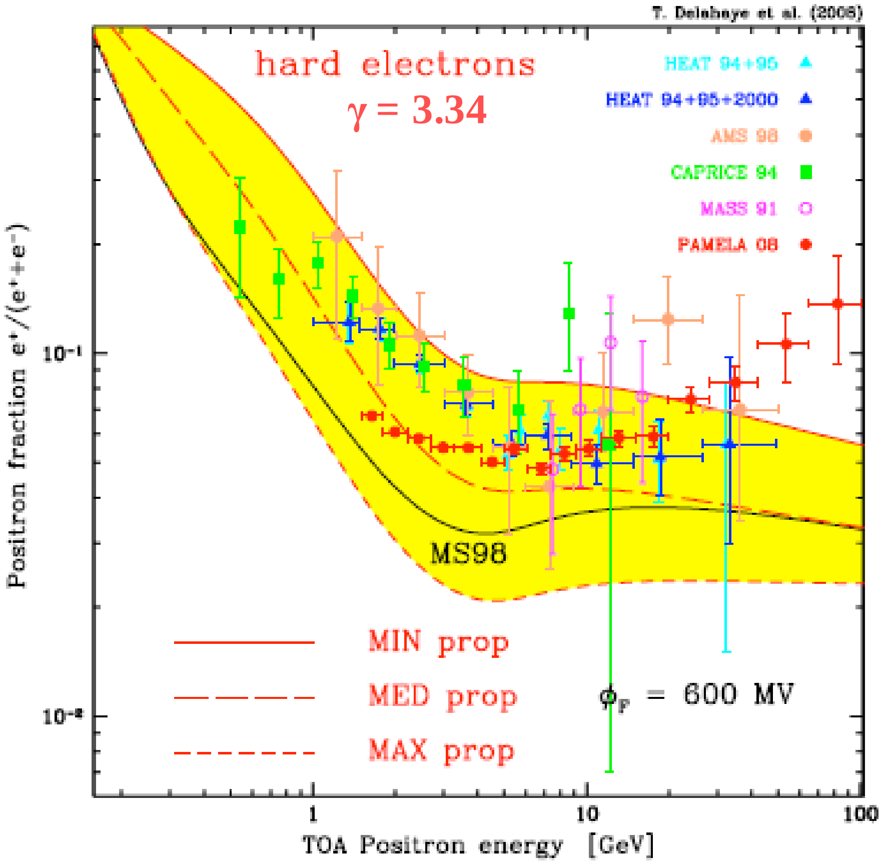
Secondary production
Moskalenko & Strong 98

Uncertainties on:
- **Secondary production (primary fluxes, cross section)**
- **Propagation models**
- **Electron spectrum**

Mirko Boezio, Positrons in Astrophysics, 2012/03/20

Theoretical uncertainties on "standard" positron fraction

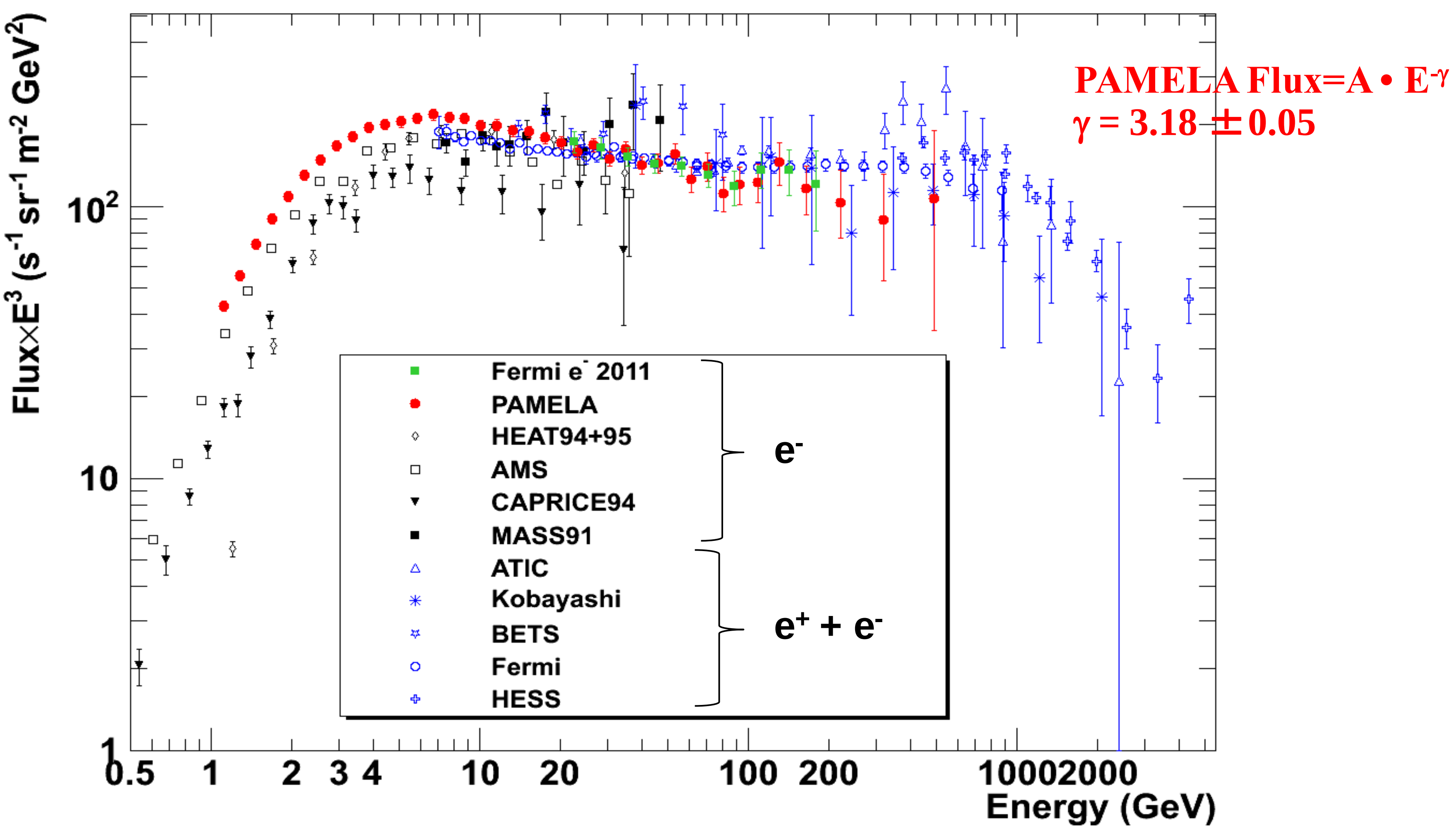




Flux=A • E$^{-\gamma}$

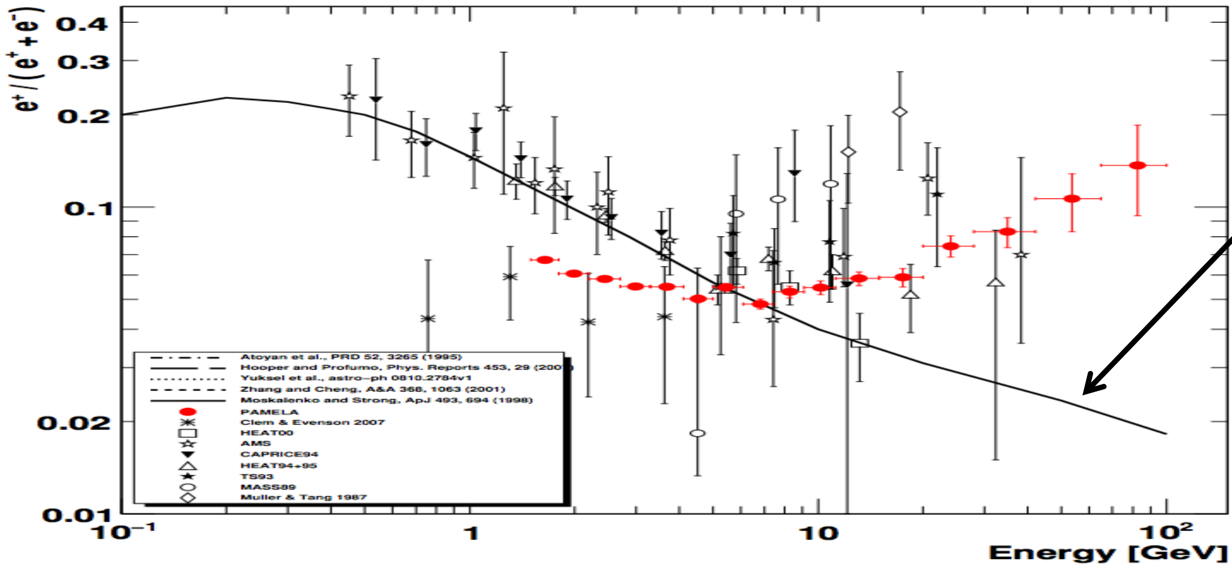
T. Delahaye et al., Astron.Astrophys. 501 (2009) 821; arXiv: 0809.5268v3

Electron Spectrum

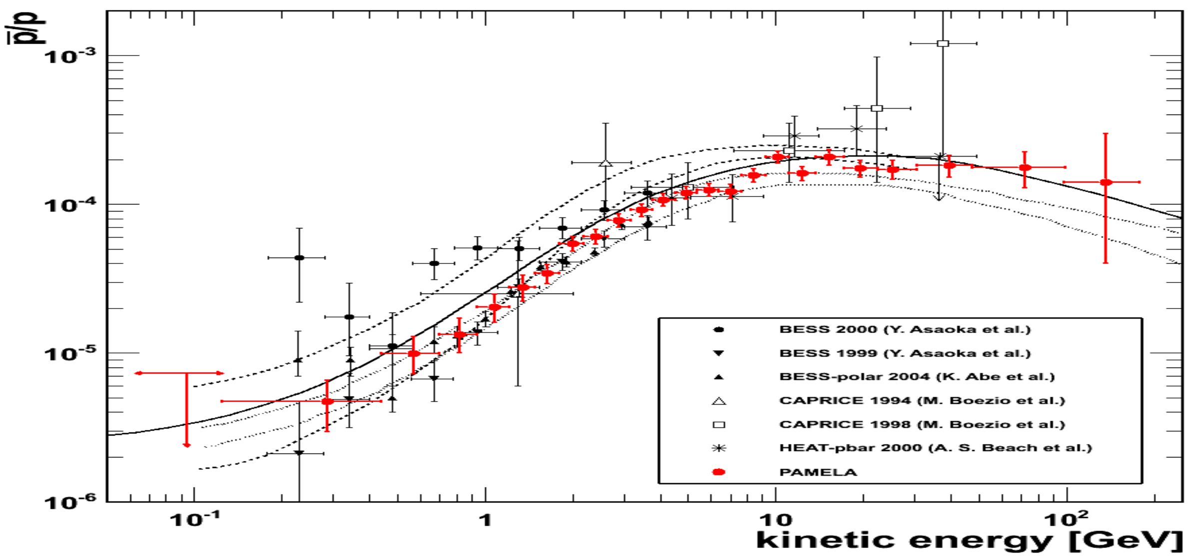


Mirko Boezio, Positrons in Astrophysics, 2012/03/20

A Challenging Puzzle for CR Physics



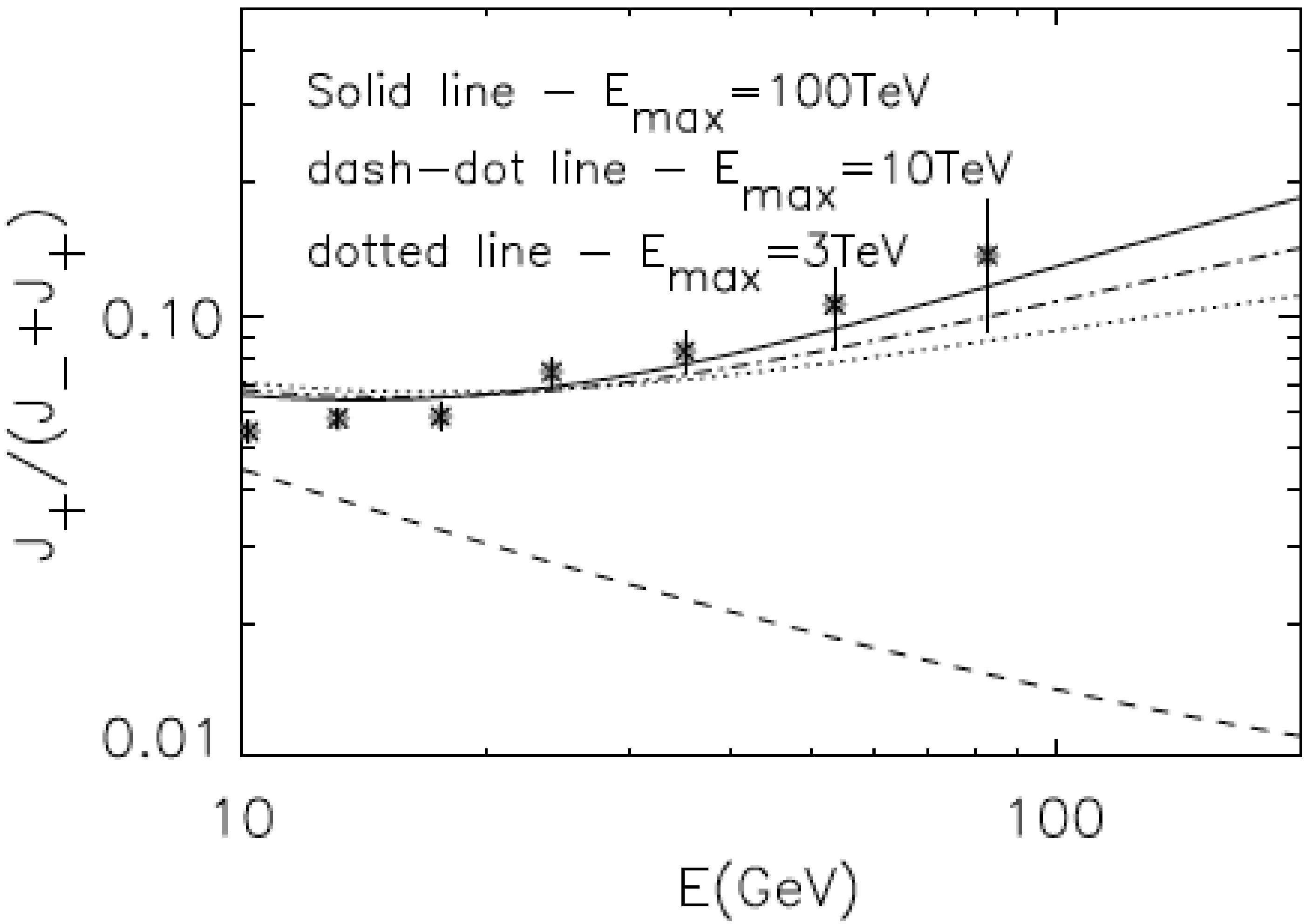
CR Positron spectrum significantly harder than expectations from secondary production



But antiprotons in CRs are in agreement with secondary production

Astrophysical Explanation: SNR

Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated.
But also other secondaries are produced: significant increase expected in the $\bar{p}$/p and B/C ratios.



P.Blasi et al., PRL 103 (2009) 051104 arXiv:0903.2794 [astro-ph]

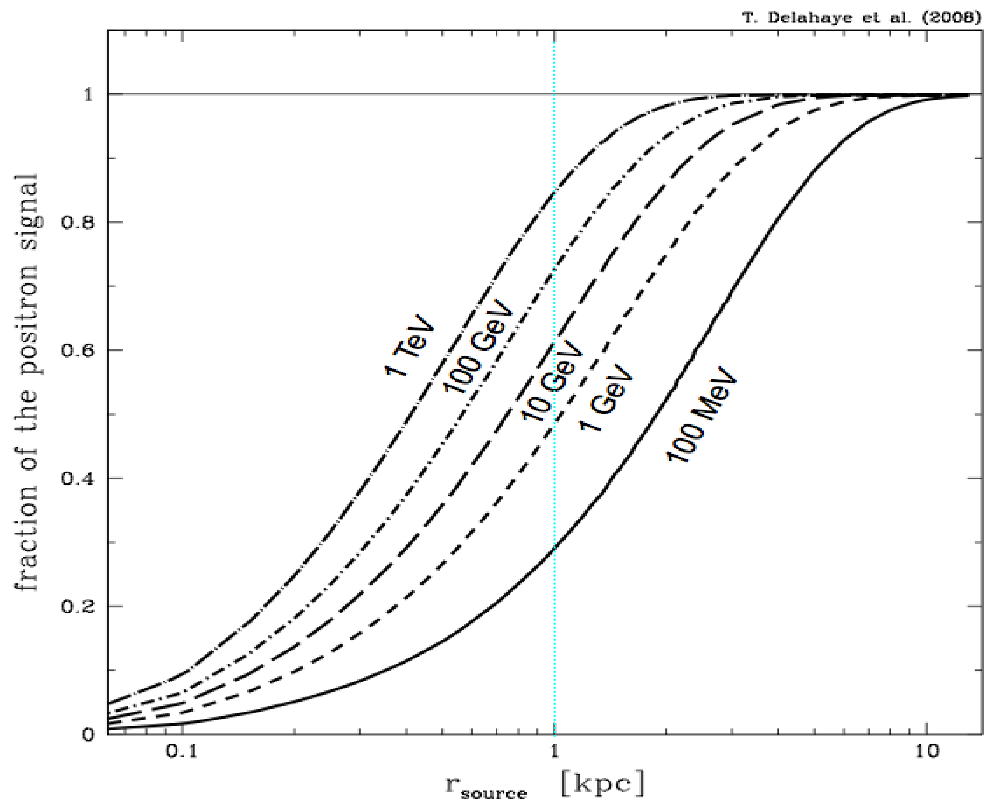
Positrons detection

Where do positrons come from?

Mostly locally within 1 Kpc, due to the energy losses by Synchrotron Radiation and Inverse Compton

Typical lifetime

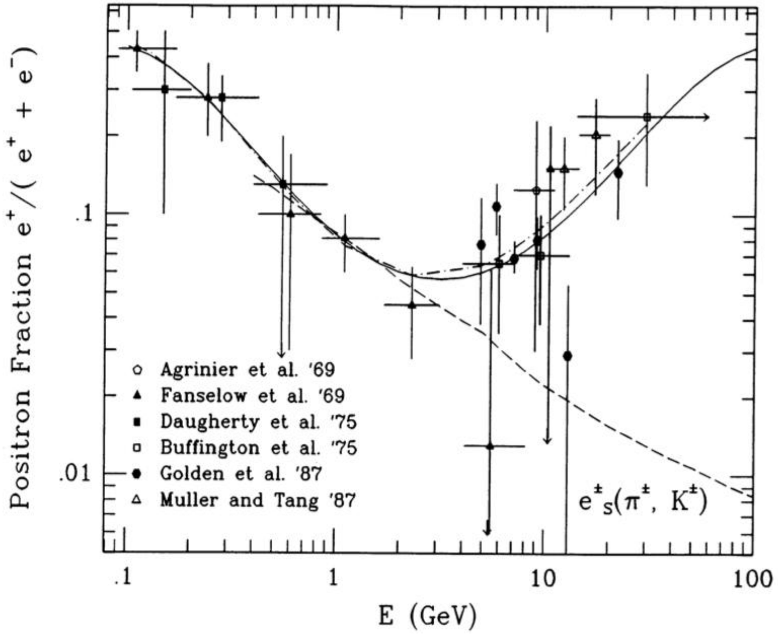
$$\tau \simeq 5 \cdot 10^5 \mathrm{yr} \left(\frac{1\,\mathrm{TeV}}{E} \right)$$



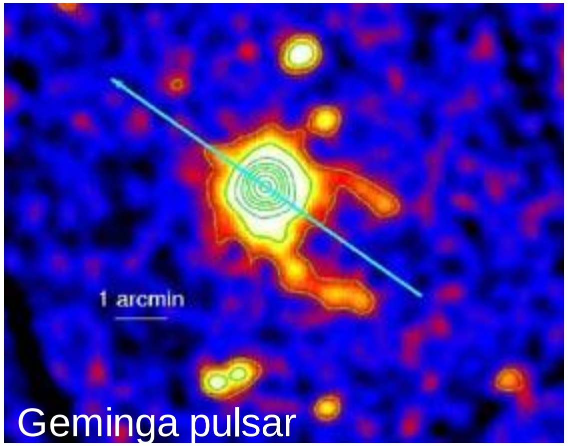
Astrophysical Explanation: Pulsars

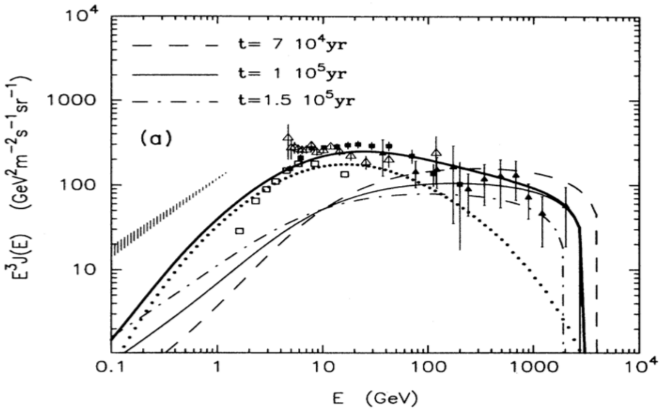
Are there "standard" astrophysical explanations of the high energy positron data?

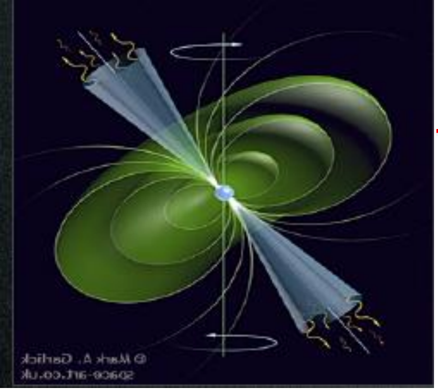
Young, nearby pulsars



Not a new idea: Boulares, ApJ 342 (1989), Atoyan et al (1995)







Astrophysical Explanation: Pulsars

- **Mechanism: the spinning B of the pulsar strips e^- that accelerated at the polar cap or at the outer gap emit γ that make production of $e^\pm$ that are trapped in the cloud, further accelerated and later released at $\tau \sim 10^5$ years.**

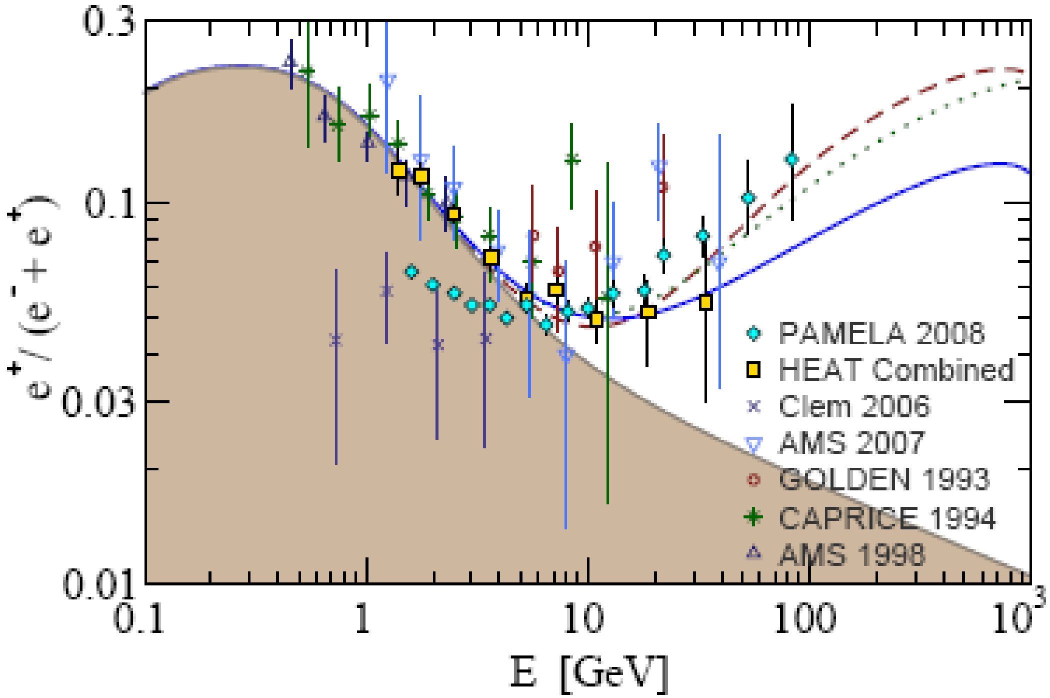
- **Young ($T < 10^5$ years) and nearby (< 1kpc)**
- **If not: too much diffusion, low energy, too low flux.**

- **Geminga: 157 parsecs from Earth and 370,000 years old**
- **B0656+14: 290 parsecs from Earth and 110,000 years old.**

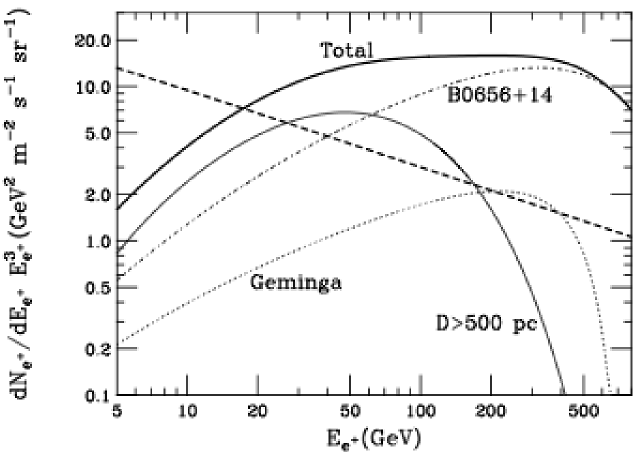
- **Diffuse mature pulsars**

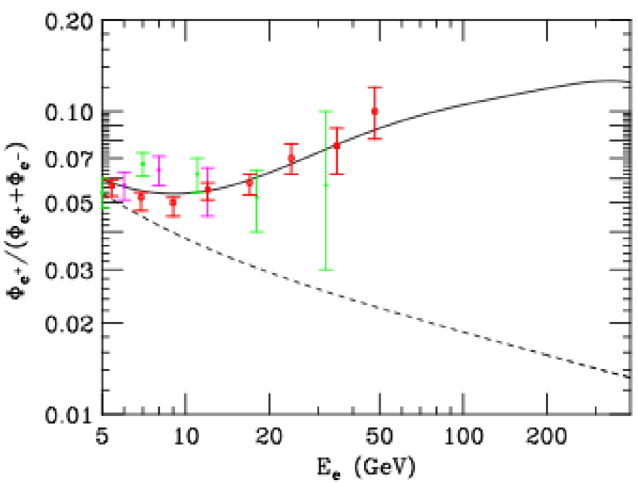
See P. Salati's talk on the 22^{nd}

Astrophysical Explanation: Pulsars



H. Yüksak et al., arXiv:0810.2784v2
Contributions of e- & e+ from Geminga assuming different distance, age and energetic of the pulsar





diffuse mature & nearby young pulsars
Hooper, Blasi, and Serpico
arXiv:0810.1527

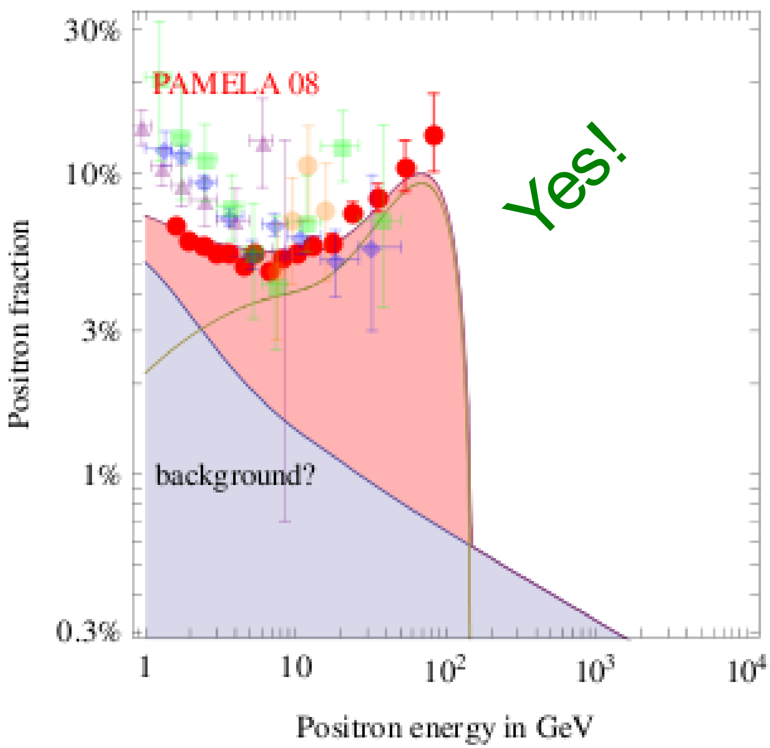
M. Cirelli et al., Nucl. Phys. B 813 (2009) 1; arXiv: 0809.2409v3

Interpretation: DM

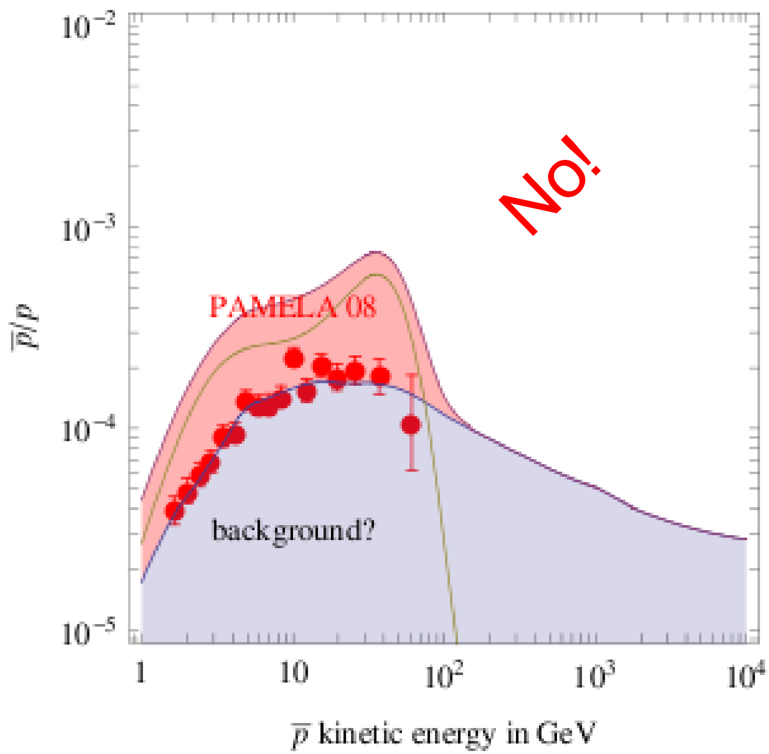
Which DM spectra can fit the data?

DM with $m_\chi \simeq 150\,\mathrm{GeV}$ and W^+W^- dominant annihilation channel (possible candidate: Wino)

positrons



antiprotons



Interpretation: DM

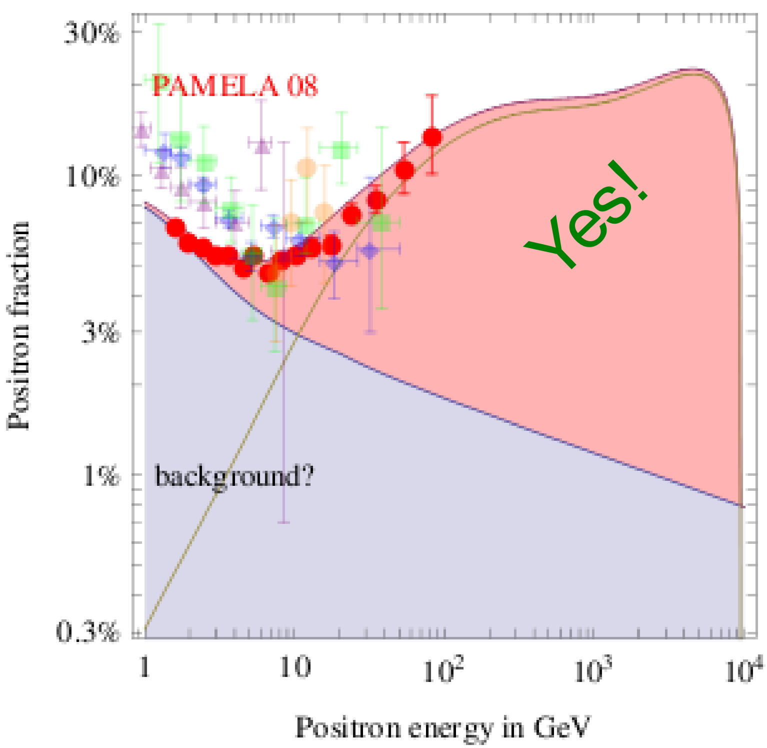
M. Cirelli et al., Nucl. Phys. B 813 (2009) 1; arXiv: 0809.2409v3

Which DM spectra can fit the data?

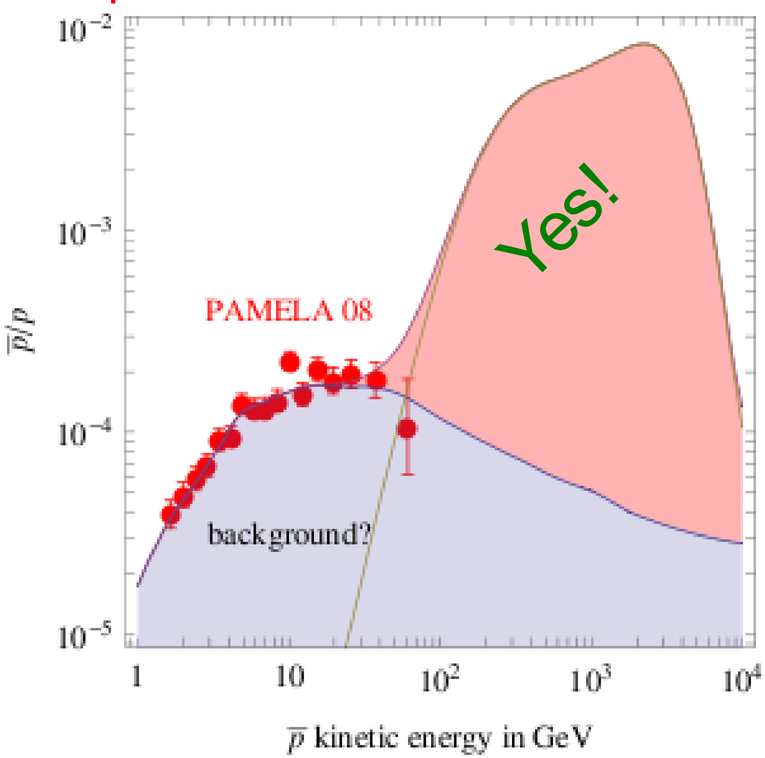
DM with $m_\chi \simeq 10\,\mathrm{TeV}$ and W^+W^- dominant annihilation channel (no "natural" SUSY candidate)

But B≈10^4

positrons



antiprotons

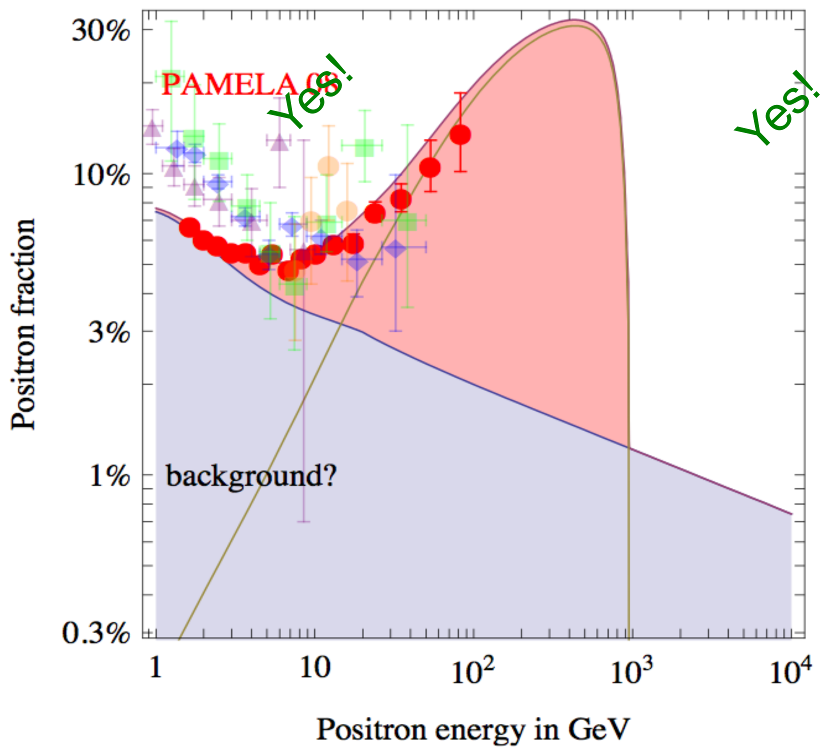


M. Cirelli et al., Nucl. Phys. B 813 (2009) 1; arXiv: 0809.2409v3

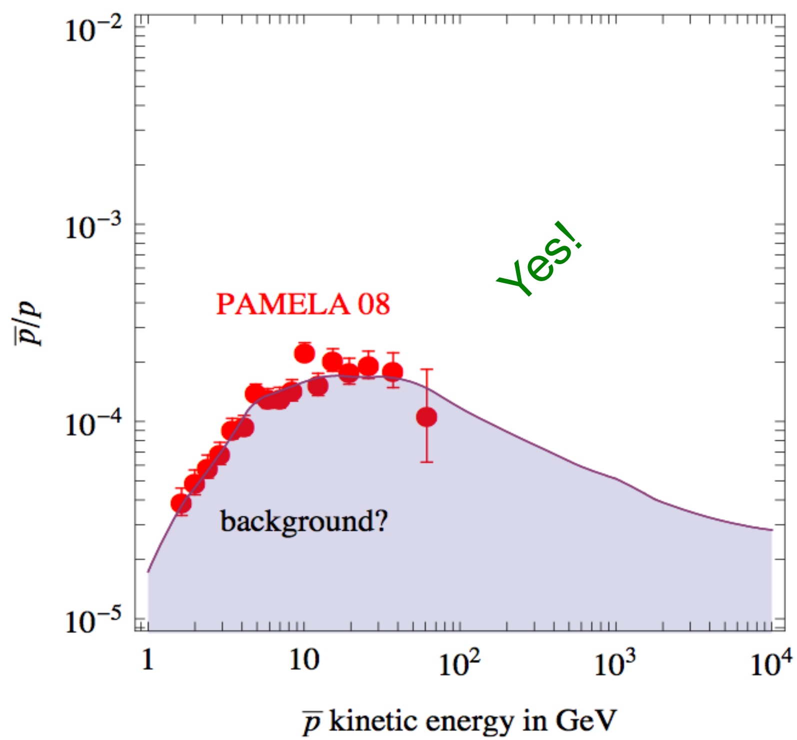
Interpretation: DM

DM with $m_\chi \simeq 1\,\mathrm{TeV}$ and $\mu^+\mu^-$ dominant annihilation channel

positrons

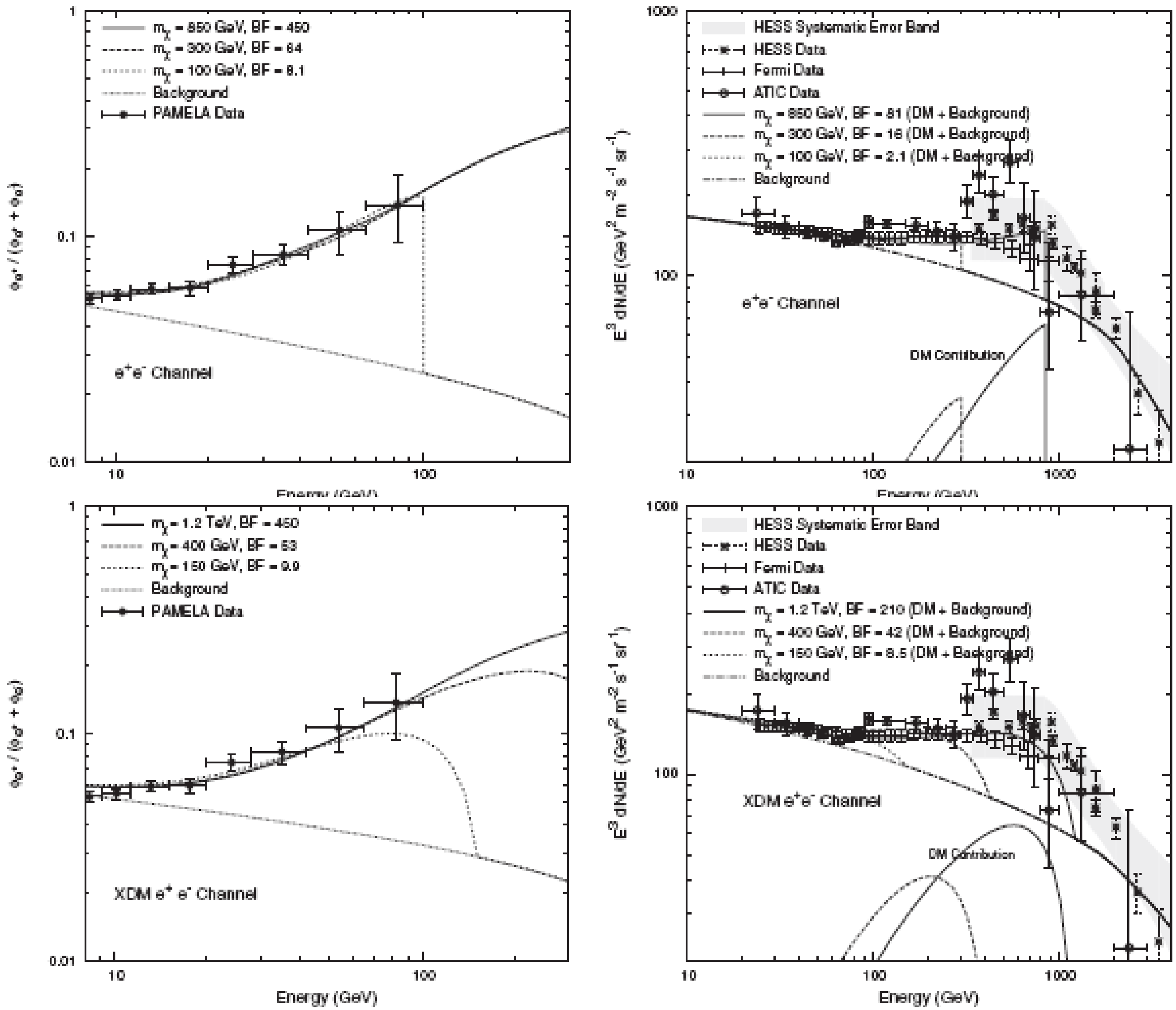


antiprotons



Interpretation: DM

I. Cholis et al. Phys. Rev. D 80 (2009) 123518; arXiv:0811.3641v1



- Propose a new light boson ($m_\Phi \leq$ GeV), such that $\chi\chi \to \Phi\Phi$; $\Phi \to e^+e^-$, $\mu^+\mu^-$, ...
- Light boson, so decays to antiprotons are kinematically suppressed

Electrons

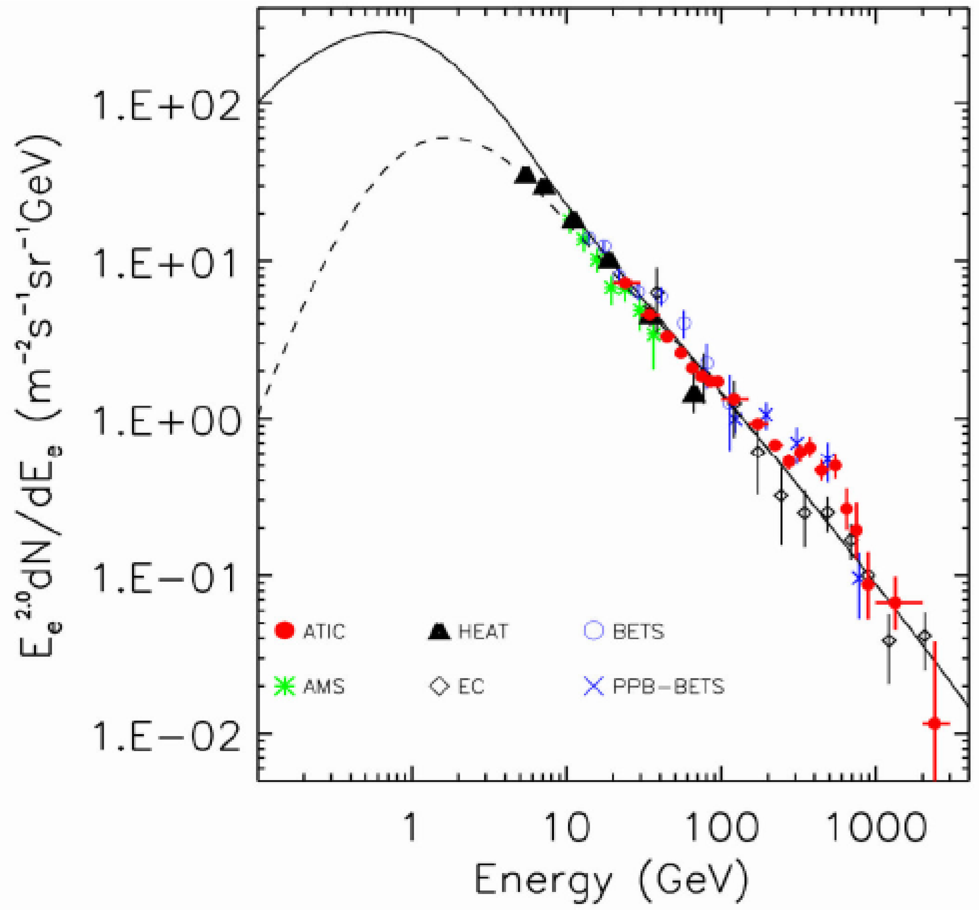
The ATIC electron results exhibits a feature

Curves are from GALPROP diffusion propagation simulation code

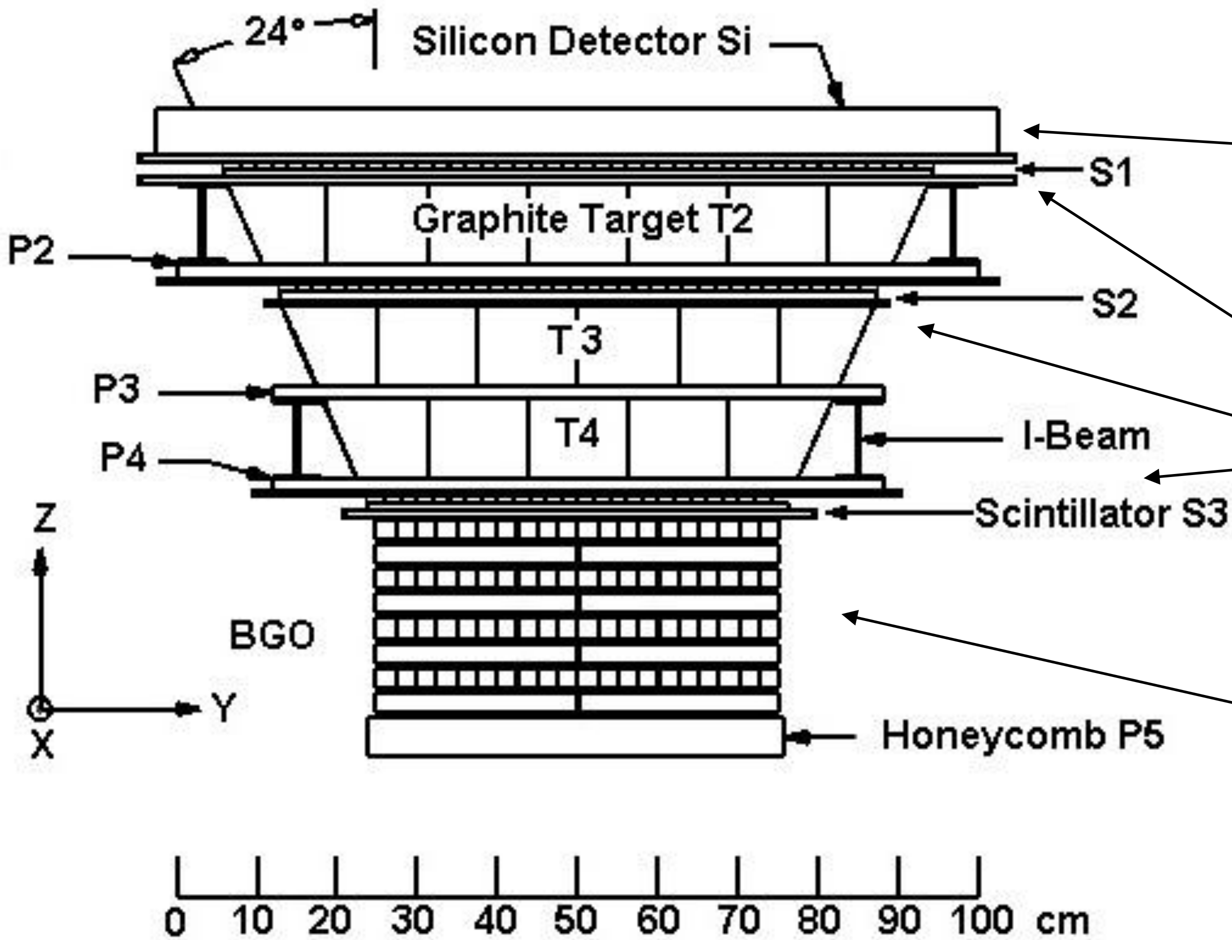
– Solid curve is local interstellar space
– Dashed curve is with solar modulation (500 MV)

"Excess" at about 300 – 600 GeV

Also seen by recent PPB-BETS



ATIC Instrument Details



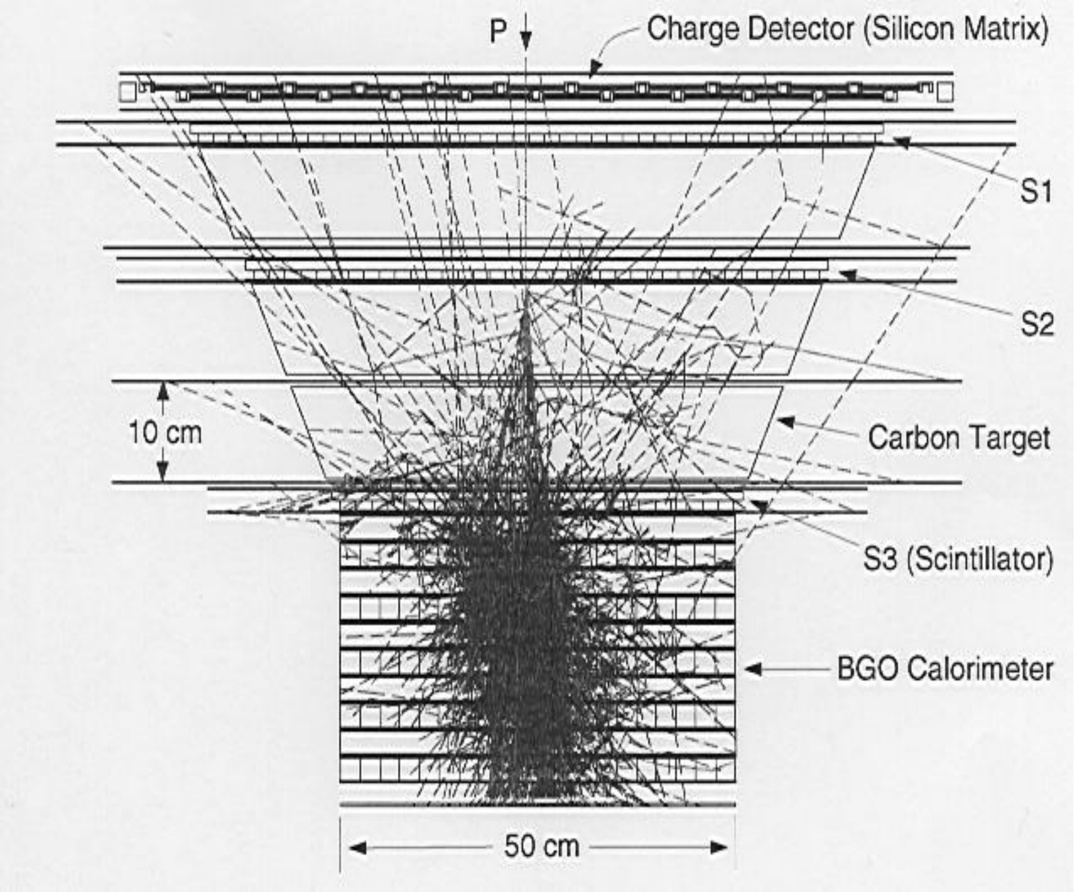
silicon matrix charge detector

plastic scintillator strip hodoscopes interleaved with graphite interaction targets

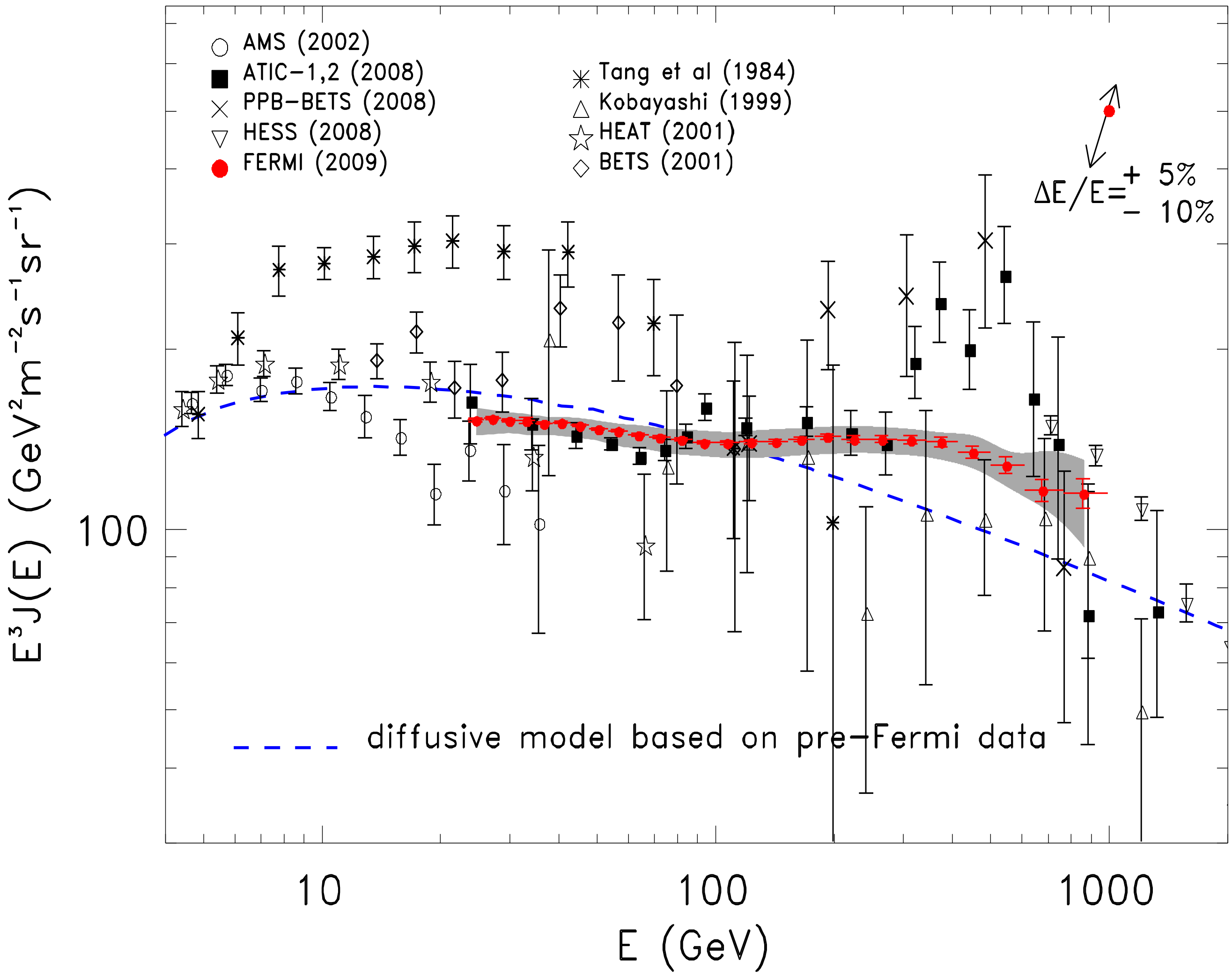
18 radiation length deep, fully active bismuth germanate (BGO) calorimeter.

Geometry Factors: S1-S3: 0.42 m2sr; S1-S3-BGO 6: 0.24 m2sr;

ATIC Detection Method

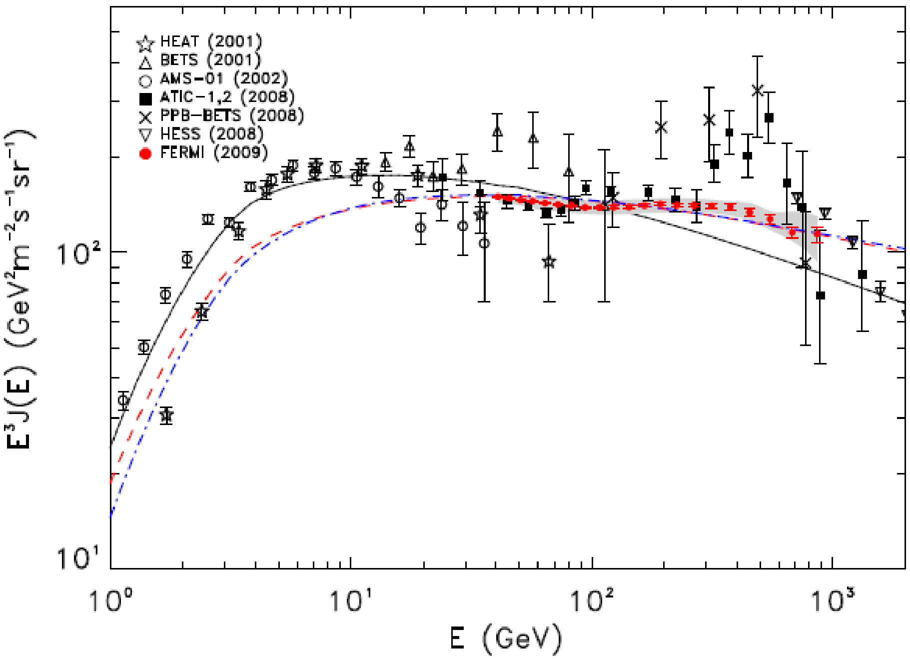


FERMI all Electron Spectrum



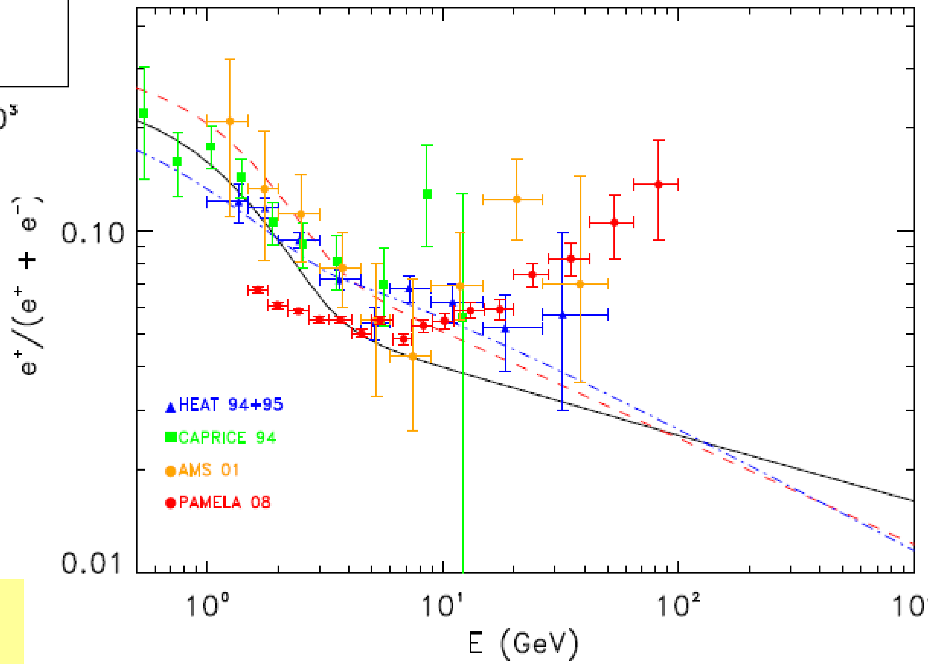
A. Abdo, Phys.Rev.Lett. 102 (2009) 181101

Theoretical uncertainties on "standard" positron fraction



Modify the injection indices of GALPROP?

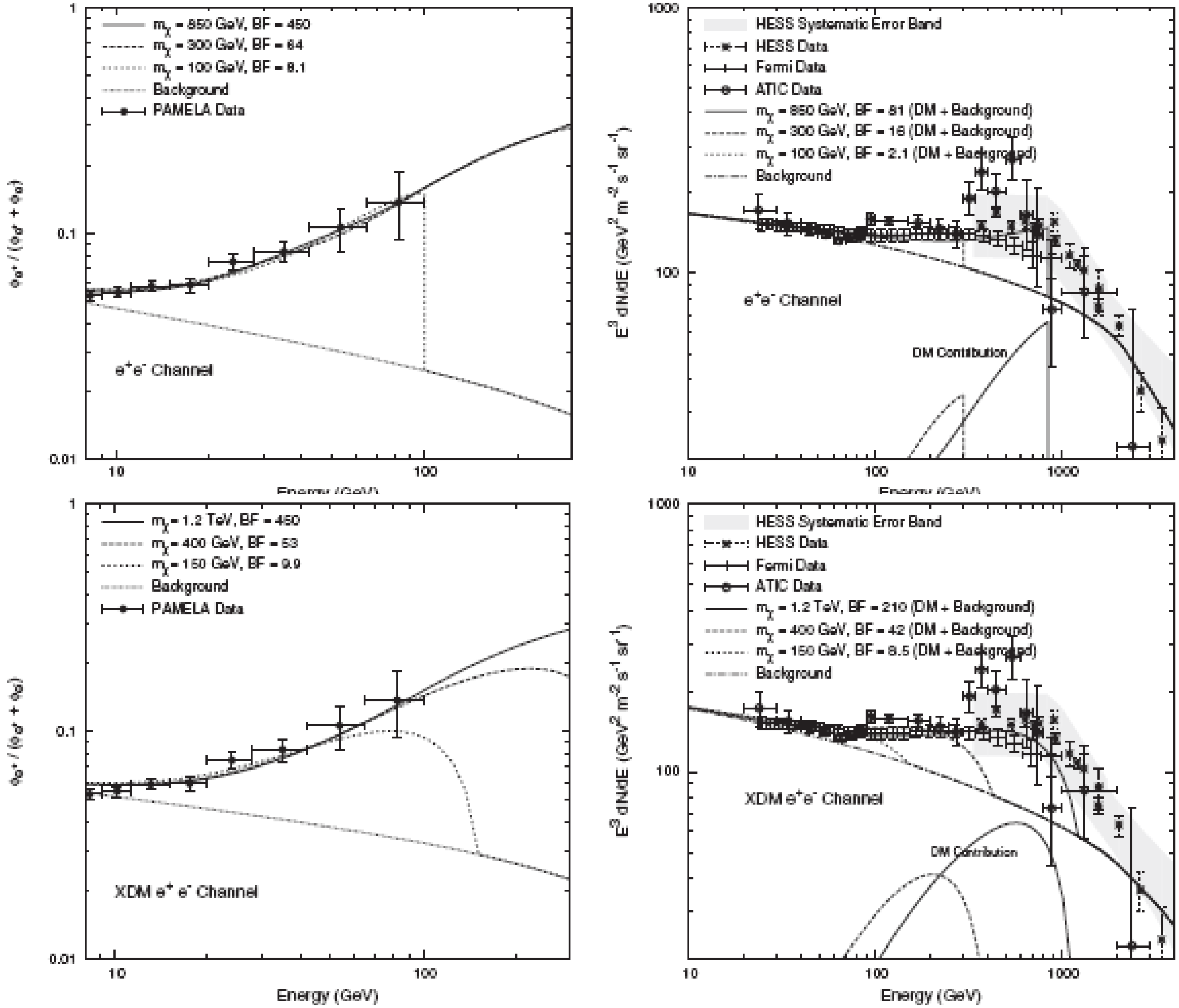
Does not fit at all the PAMELA ratio:



D. Grasso et al., Astropart.Phys. 32 (2009) 140; arXiv:0905.0636

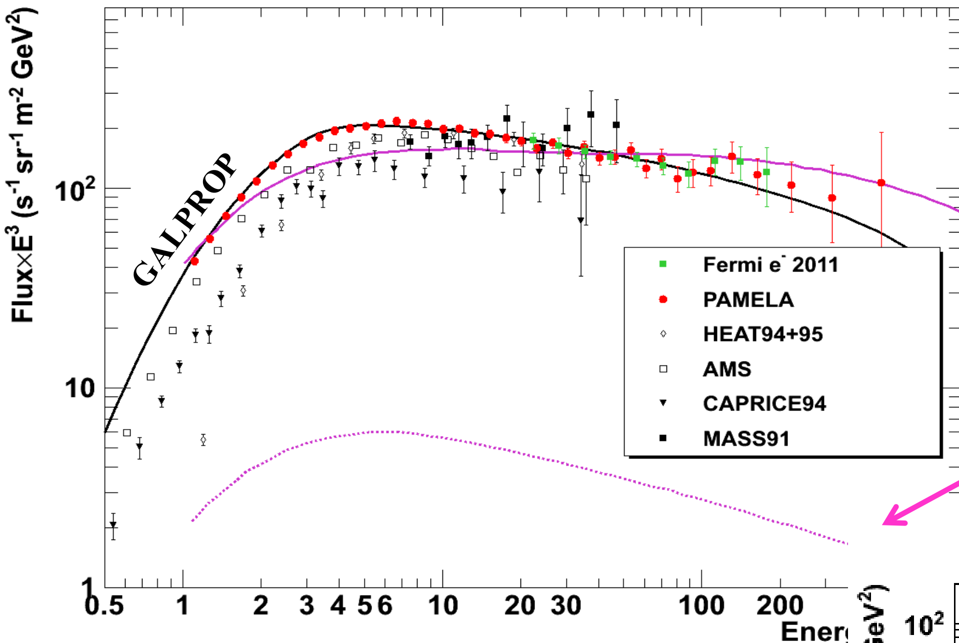
Interpretation: DM

I. Cholis et al. Phys. Rev. D 80 (2009) 123518; arXiv:0811.3641v1

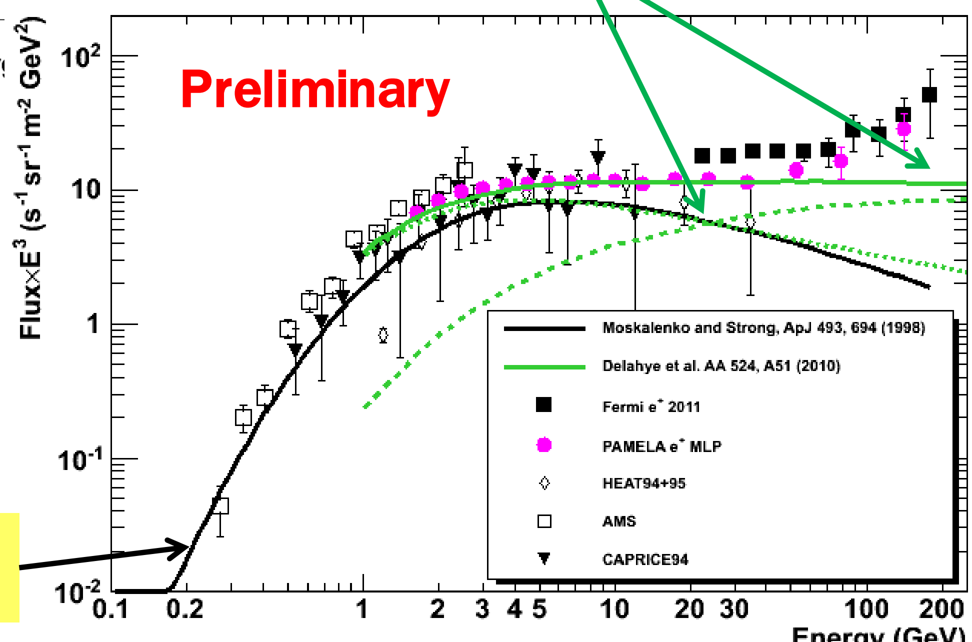


- Propose a new light boson ($m_\Phi \leq$ GeV), such that $\chi\chi \rightarrow \Phi\Phi$; $\Phi \rightarrow e^+e^-$, $\mu^+\mu^-$, ...
- Light boson, so decays to antiprotons are kinematically suppressed

e^- and e^+ Spectra

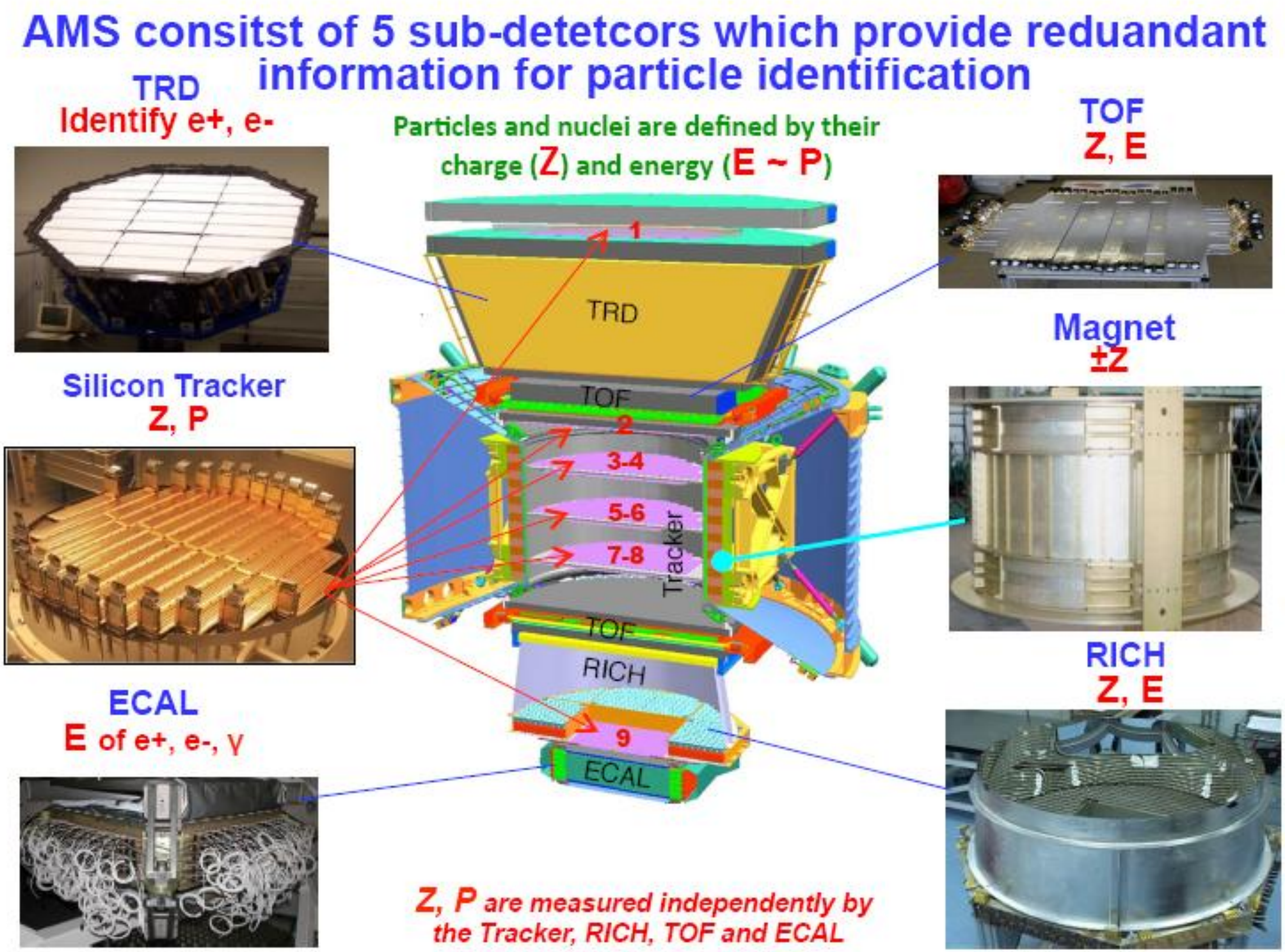


T. Delahaye et al., A&A 524 (2010) A51 Secondary & <u>Primary productions (from Astrophysical Sources)</u>



<u>Secondary production</u>
Moskalenko & Strong 98

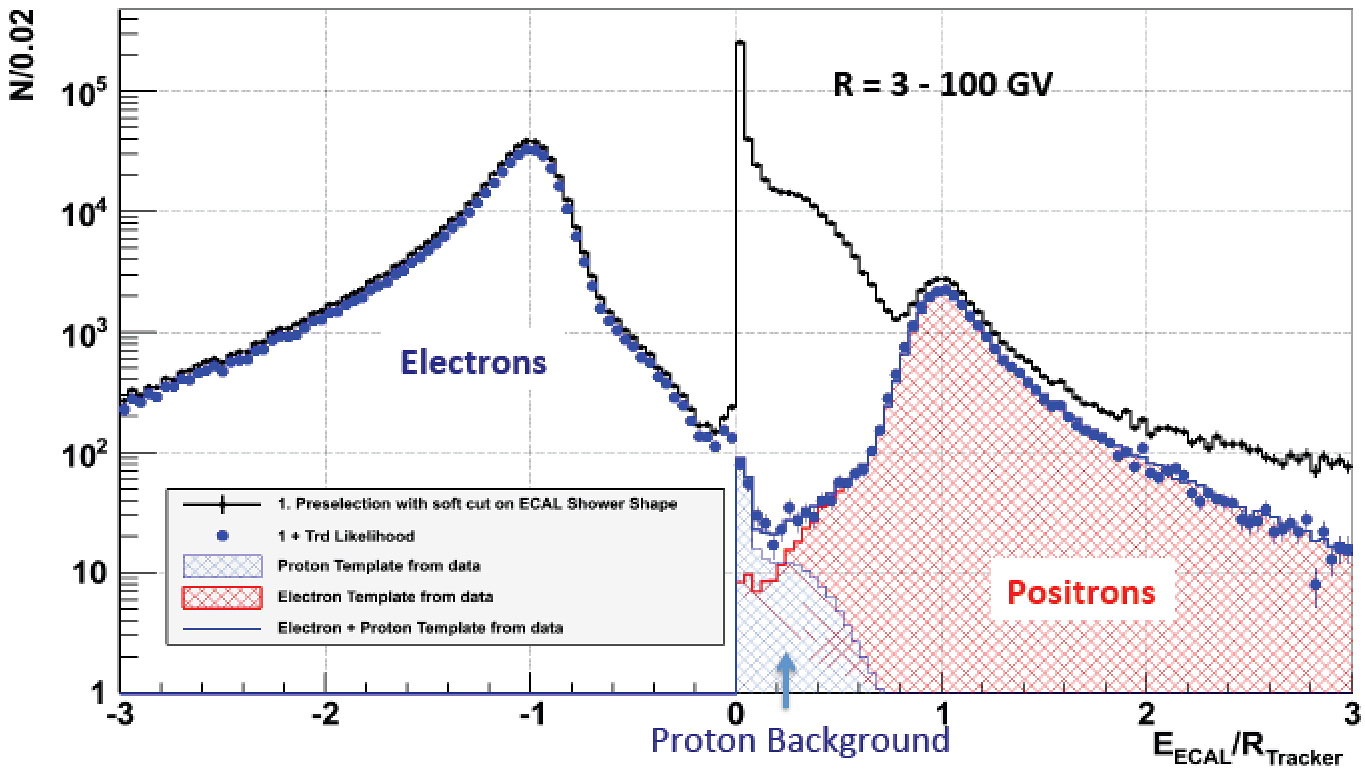
The Completed AMS Detector on ISS



AMS Particle Identification

- Example that demonstrates the particle identification capabilities of AMS
  1. Use the first 200 days of data from AMS-02 (5% of the expected data volume)
  2. Preselection with a very soft cut on ECAL Shower Shape
  3. Cut on TRD Electron Likelihood at 90% Electron Efficiency
     Positron Purity 98.89% for R= 3 – 100 GV

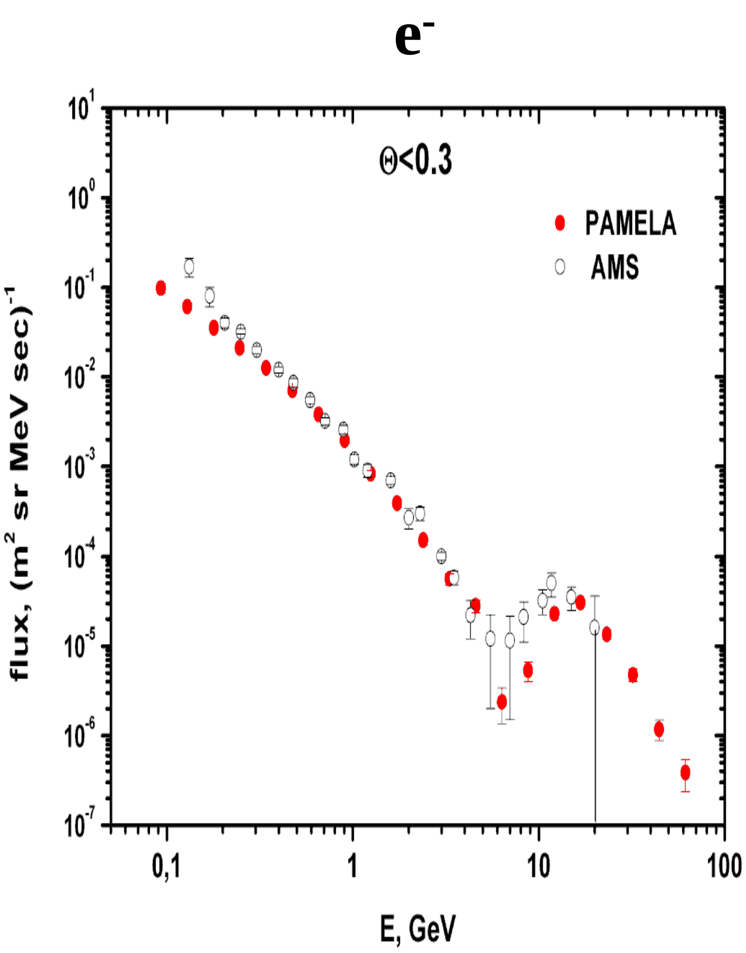
- We are working now on an optimal strategy to combine the information's from all AMS sub-detector and to estimate systematic errors

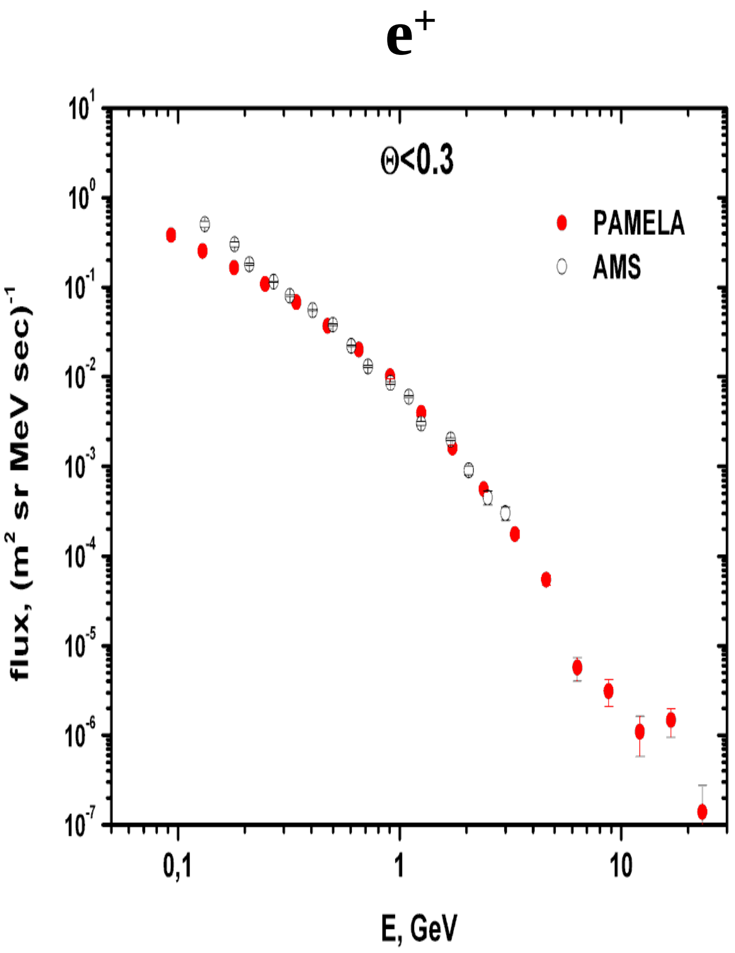


S. Schael, UCLA Dark Matter Conference 2012,

Trapped Antiparticles

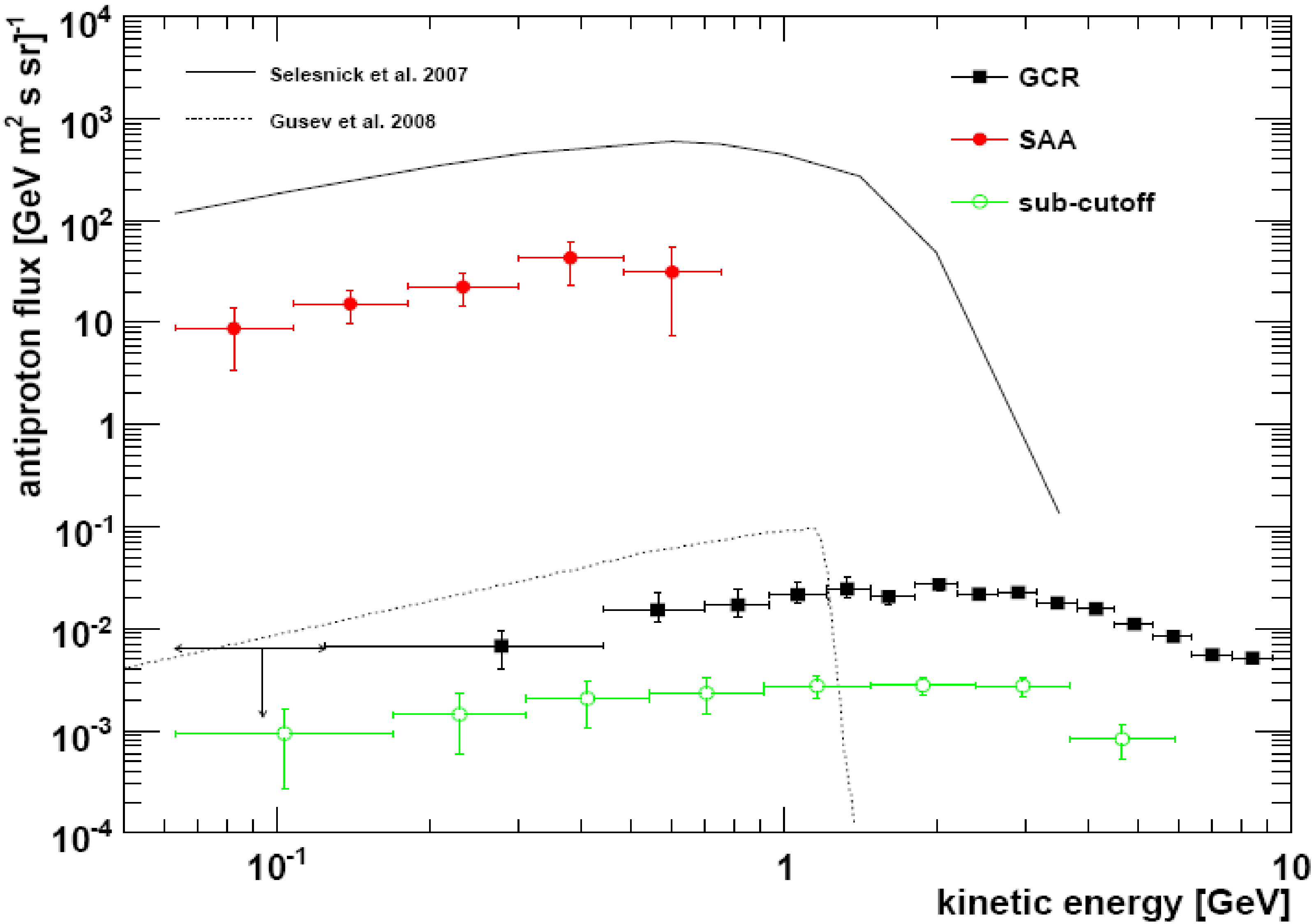
Subcutoff particles spectra





Mirko Boezio, Positrons in Astrophysics, 2012/03/20

PAMELA trapped antiprotons



O. Adriani et al., APJL 737 L29 (2011); arXiv:1107.4882

Conclusions

- **Astroparticle physics from space is a fascinating field, fertile and rich of scientific potentials.**
- **Several important esperiments are, or going to, directly measuring cosmic rays and their antimatter component: PAMELA, AMS-2011...**
- **Important results have already been published and soon more will come.**
- **Stay tuned, interesting times ahead!**

Thanks!