Cosmic Antimatter

Stéphane Coutu

The Pennsylvania State University

3rd School on Cosmic Rays and Astrophysics

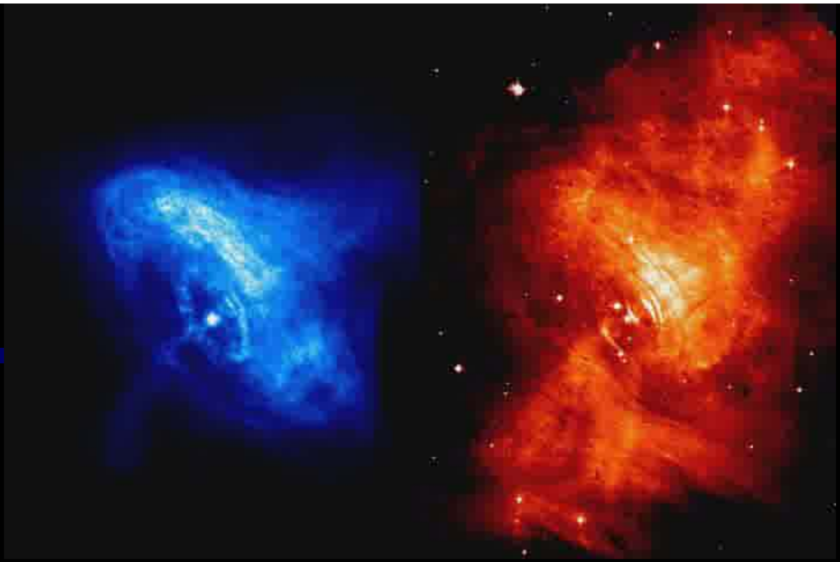
Arequipa, Peru

August 28-29, 2008

Outline

- Cosmic Rays
- Antimatter: Positrons, Antiprotons
  - Origins, secondary *vs.* primary *vs.* exotic
  - Early theory and data
  - New measurements (HEAT, others)
  - Current results and status
- Searches for heavy antimatter (e.g., Anti-Helium)
- Future Prospects

Cosmic Rays

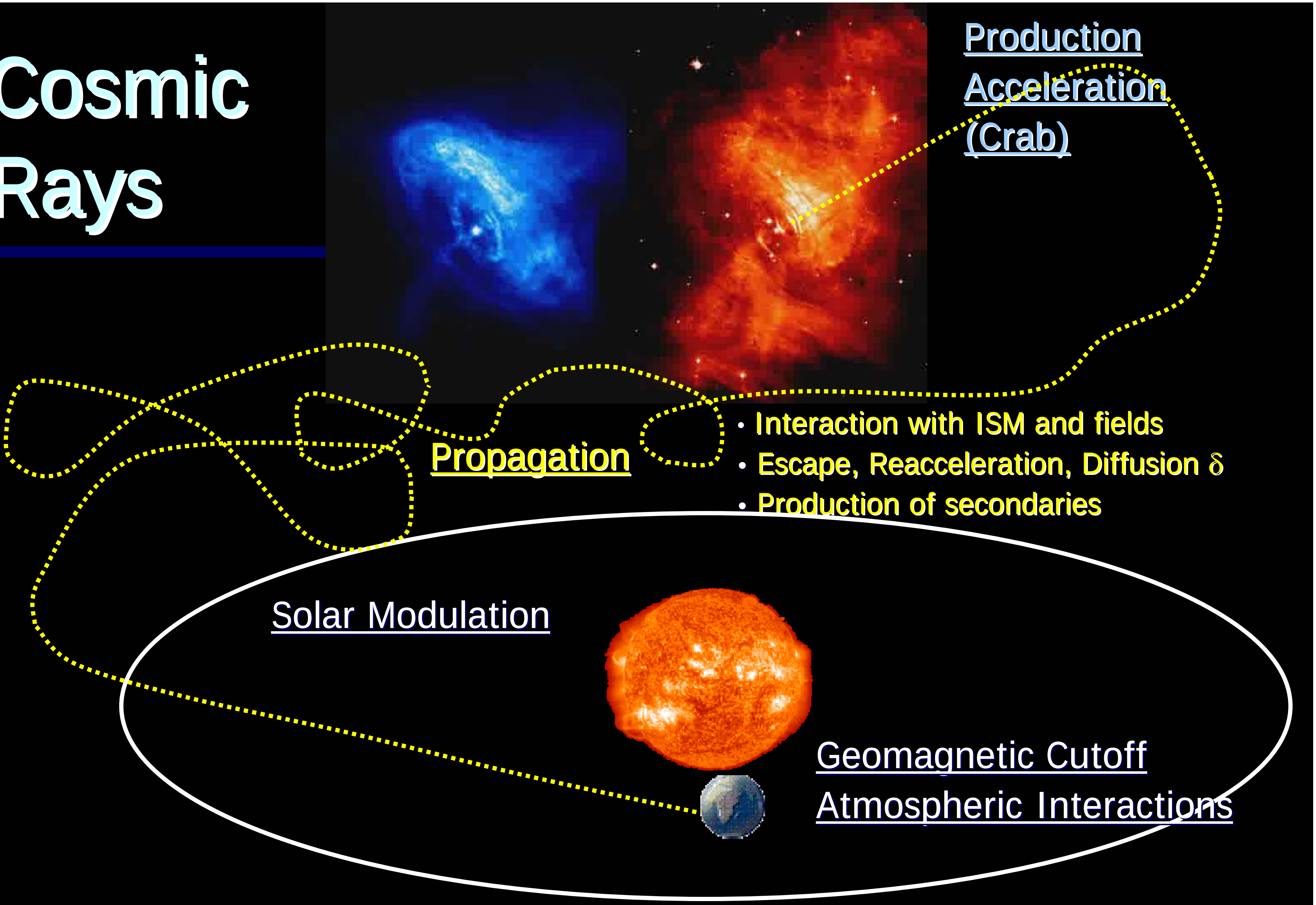


Production

Acceleration

(Crab)

Cosmic Rays



Production

Acceleration

(Crab)

Propagation

- Interaction with ISM and fields
- Escape, Reacceleration, Diffusion δ
- Production of secondaries

Solar Modulation

Geomagnetic Cutoff

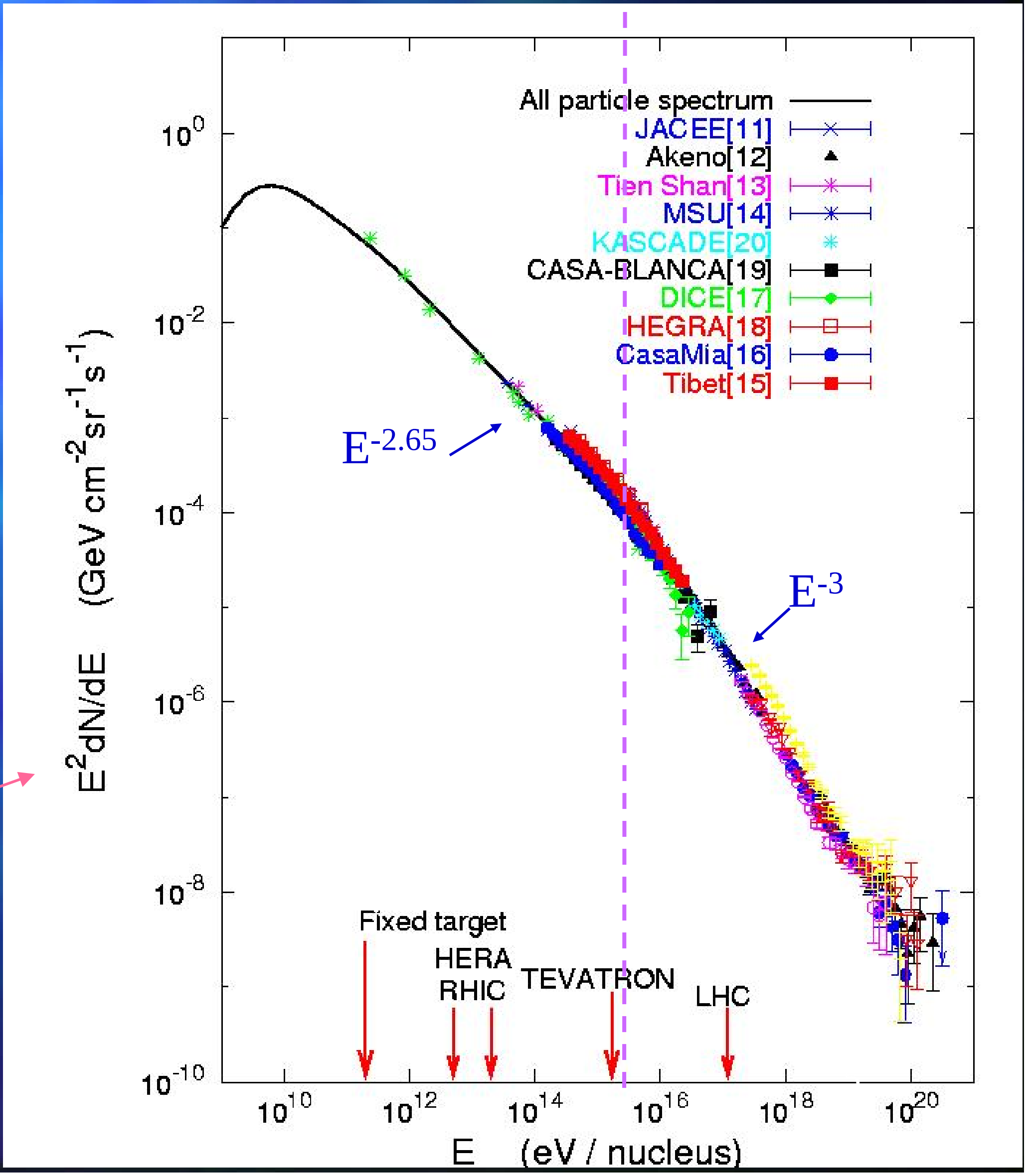
Atmospheric Interactions

Cosmic Rays

- Natural acceleration limit
- Practical limit to direct studies

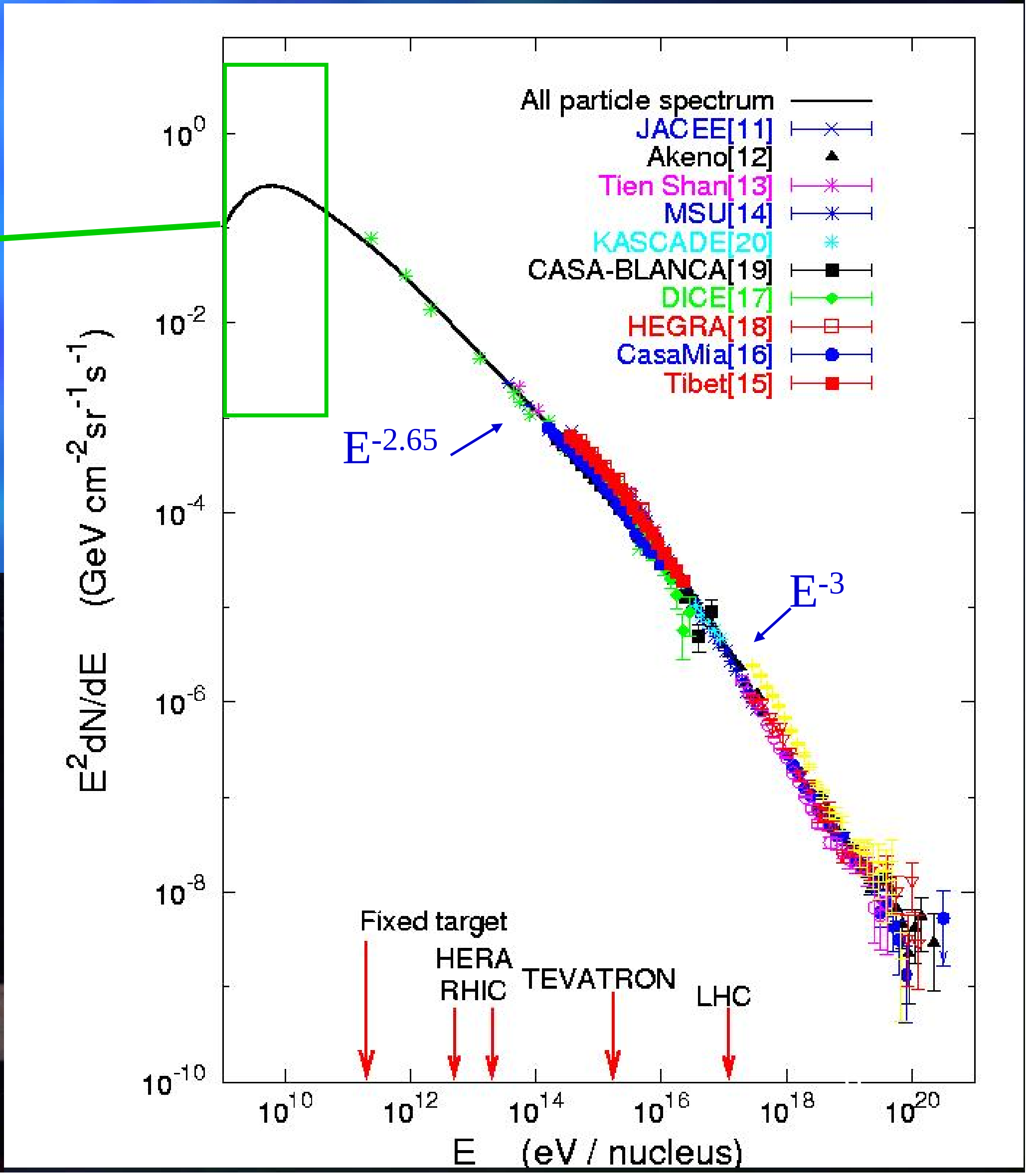
- Composition (at ~GeV):
  - 85% H (p)
  - 12% He (α)
  - 1% heavier nuclei
  - 2% $e^{\pm}$ ($\geq$90% e^{-})
  - 10^{-5}-10^{-4} antiprotons.
- Energy spectrum spans ≥ 13 orders of magnitude.

Fluxes rescaled by E^2



Cosmic Rays

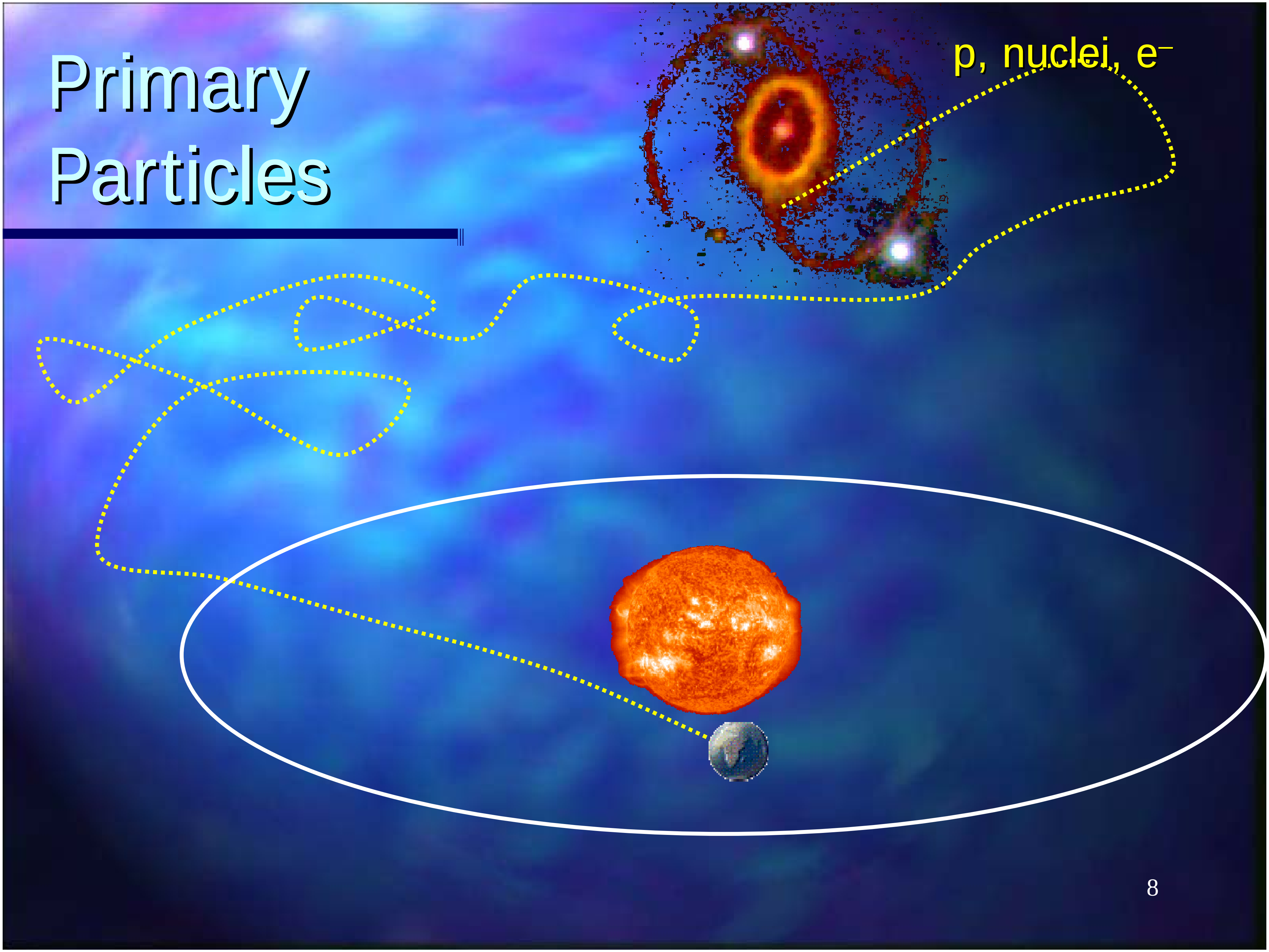
- HEAT Missions (NASA)
  - Antimatter measurements
  - Balloon missions
  - 1994 - 2002



p, pbar, $e^{\pm}$ in Cosmic Rays

- Primary p, nuclei, e^{-} produced at CR acceleration sites (e.g. supernova shocks);

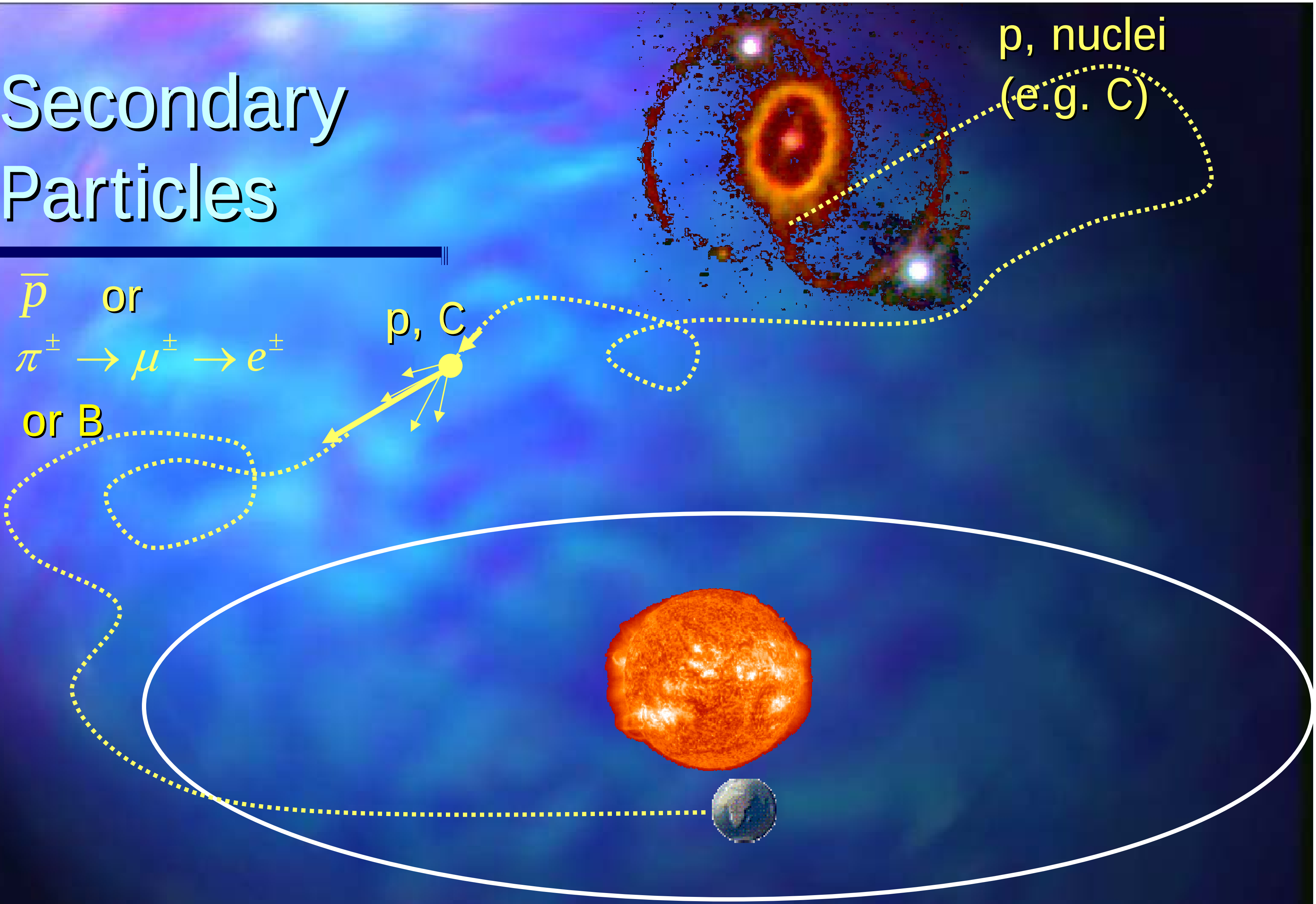
Primary Particles



p, pbar, $e^{\pm}$ in Cosmic Rays

- Primary p, nuclei, e^{-} produced at CR acceleration sites (e.g. supernova shocks);
- Secondary $e^{\pm}$ produced in equal numbers in the ISM: CR nuclei + ISM $\Rightarrow \pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$;
- Secondary pbars, rare nuclei also produced in the ISM;

Secondary Particles



$\bar{p}$ or

$\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$

or B

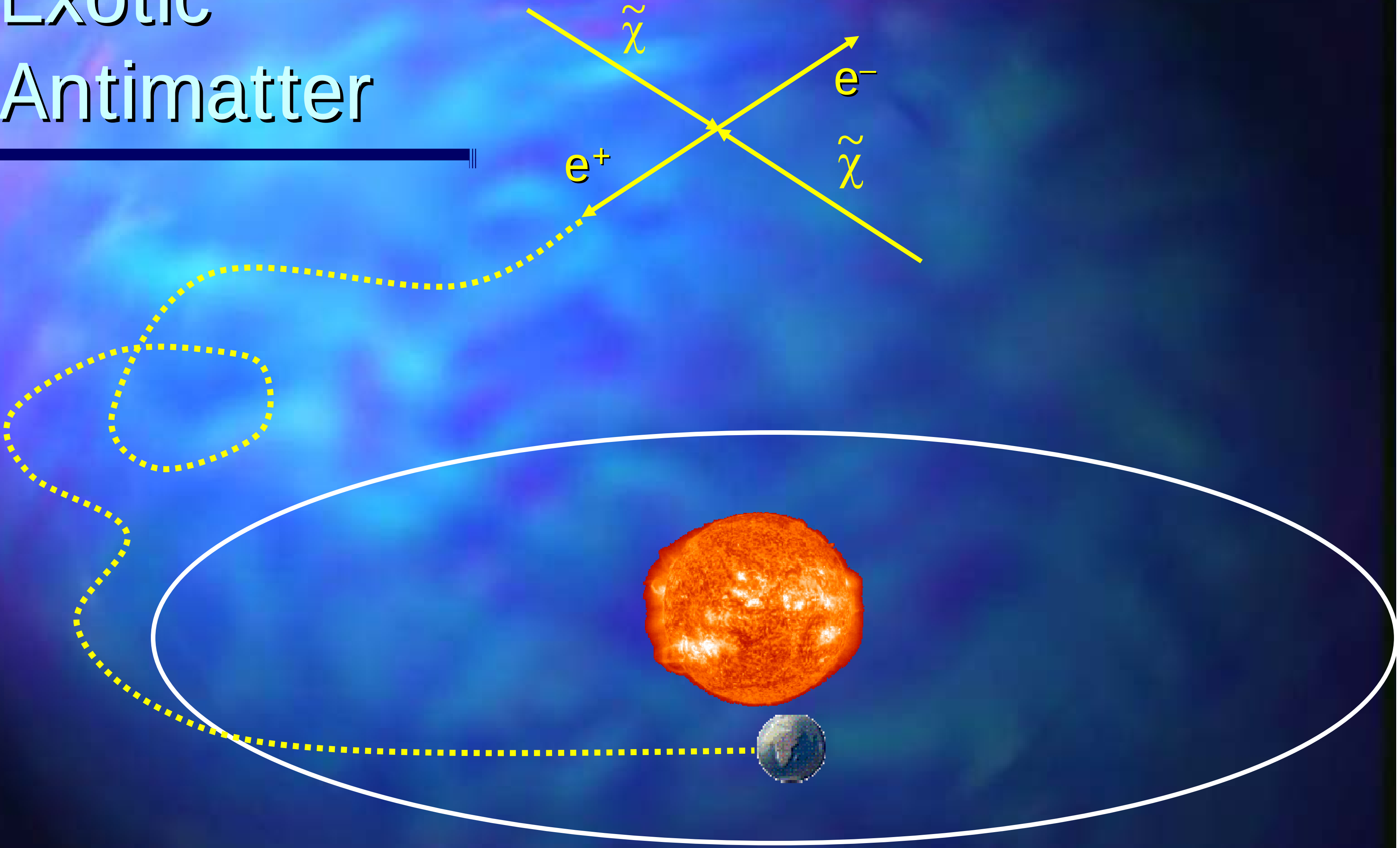
p, C

p, nuclei
(e.g. C)

p, pbar, $e^{\pm}$ in Cosmic Rays

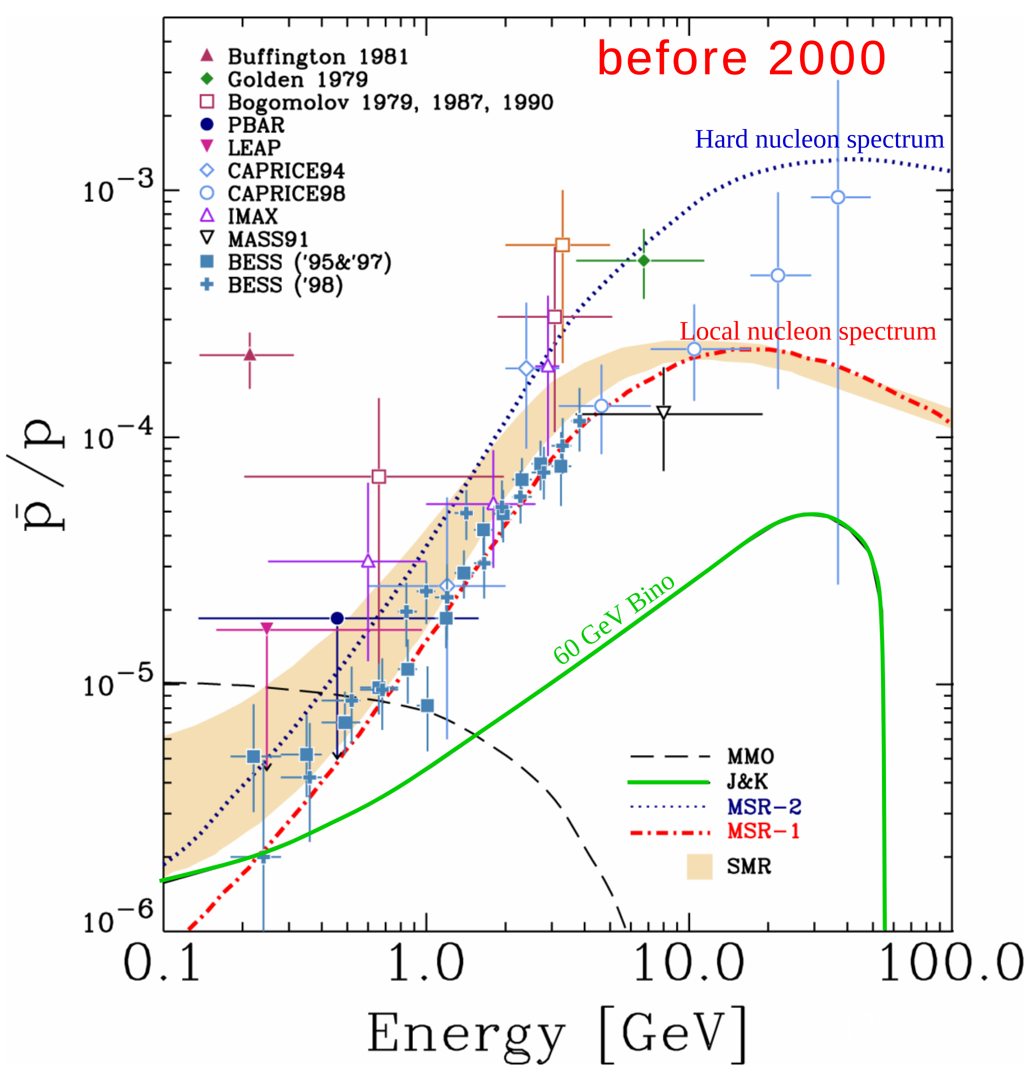
- Primary p, e^{-} produced at CR acceleration sites (e.g. supernova shocks);
- Secondary $e^{\pm}$ produced in equal numbers in the ISM: CR nuclei + ISM $\Rightarrow \pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$;
- Secondary pbars, rare nuclei also produced in the ISM;
- Antimatter, rare nuclei probe ISM structure and primary nucleon component; since antimatter is rare, look for:
- "Exotic" pbars, $e^{\pm}$?
  - Annihilating dark matter particles (e.g. neutralinos);
  - $\gamma \rightarrow e^{\pm}$ near pulsar magnetic poles;
  - CR nuclei + Giant Molecular Cloud $\rightarrow e^{\pm}$ + reacceleration;
  - Evaporating primordial black holes.

Exotic Antimatter



pbar Measurements as of 2000

- If pbars are secondary, expect:
    - E_{th}~7GeV, few pbars <1 GeV
    - Solar modulation below ~1GeV
    - Decrease in pbar/p at high E;
- Excellent BESS measurements below ~few GeV;
- Several secondary production models, *e.g.*: MSR-1: local nucleon spectrum, MSR-2: hard nucleon spectrum (explains EGRET data);
- Primary pbar predictions (WIMP annihilation, PBH evaporation) agree that the contribution is small at best;
- High statistics measurements needed at 5-50 GeV



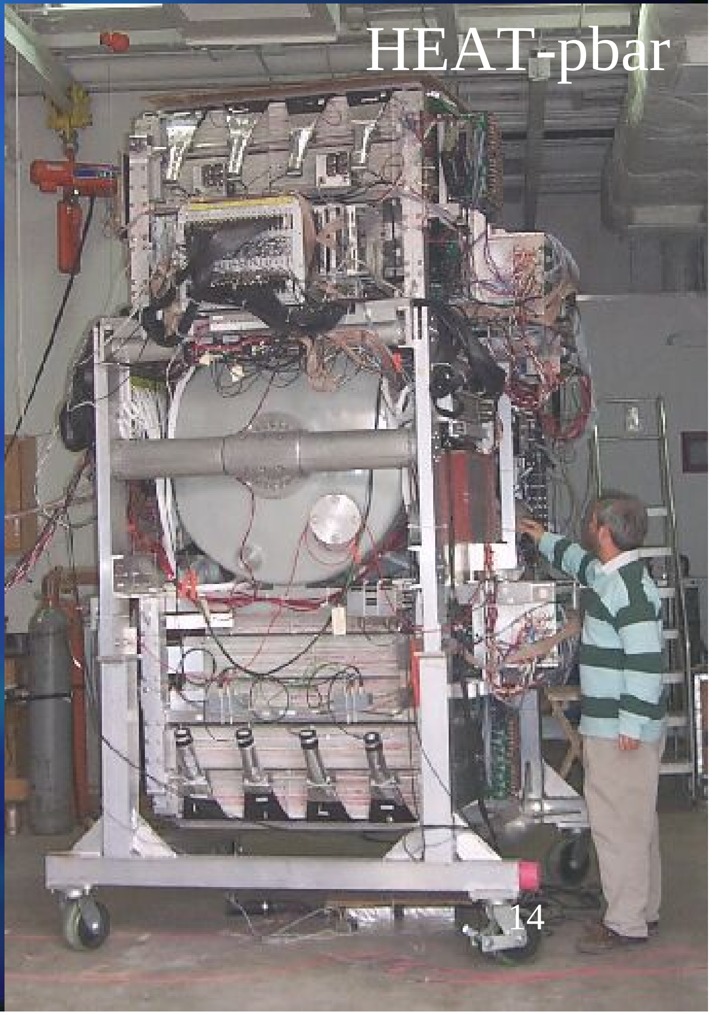
HEAT-pbar (High Energy Antimatter Telescope)

The HEAT-pbar Collaboration

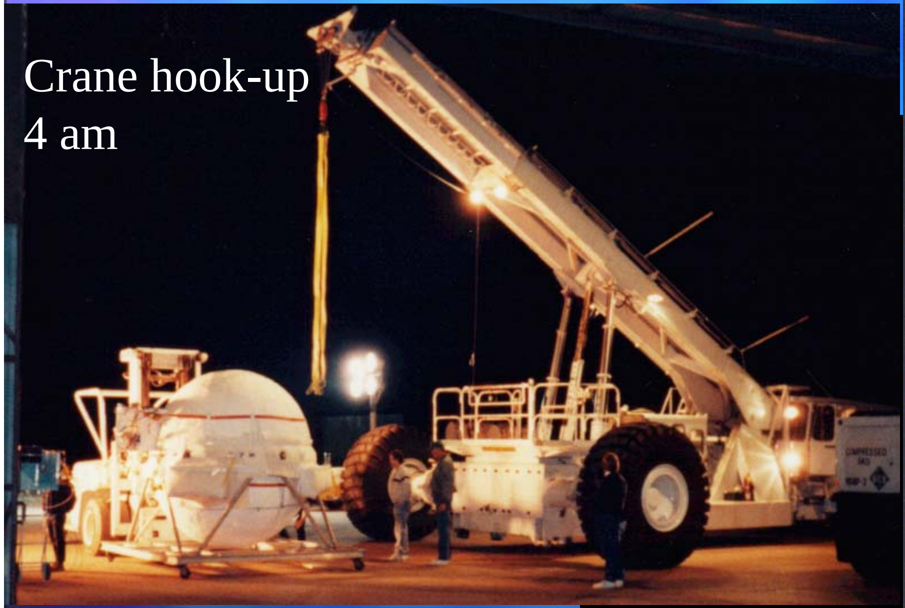
U of Chicago: A. Labrador, D. Müller, S.P. Swordy
Northern Kentucky U.: S.L. Nutter
Indiana U: A. Bhattacharyya, C. Bower, J.A. Musser
U of Michigan: S.P. McKee, M. Schubnell, G. Tarlé, A.D. Tomasch
Penn State U.: A.S. Beach, J.J. Beatty, S. Coutu, S. Minnick
U. Minnesota: M. DuVernois

- Superconducting Magnet Spectrometer with Drift Tube Hodoscope (DTH), Multiple Ionization (dE/dx) Detector and Time-of-Flight (TOF) system.
- 1) Jun. 2000 flight from Ft. Sumner, NM (22 hour flight)

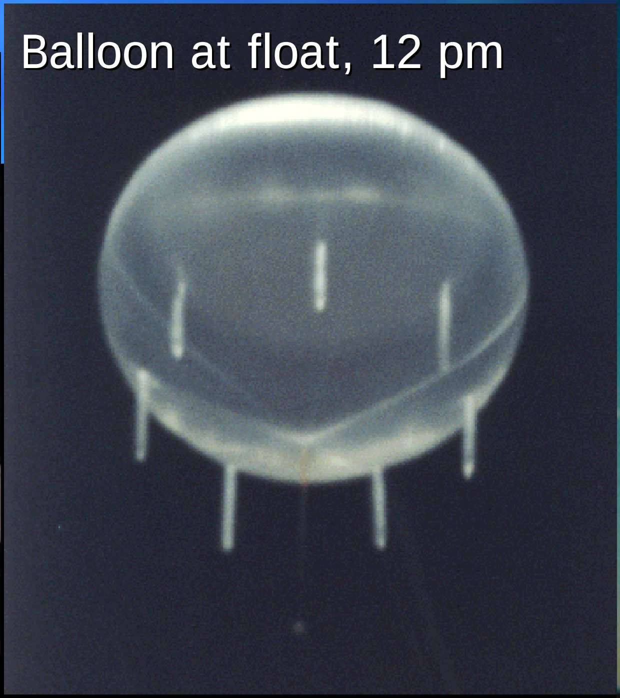
  2) May 2002 flight from Ft. Sumner, NM (6 hour flight; failed balloon)



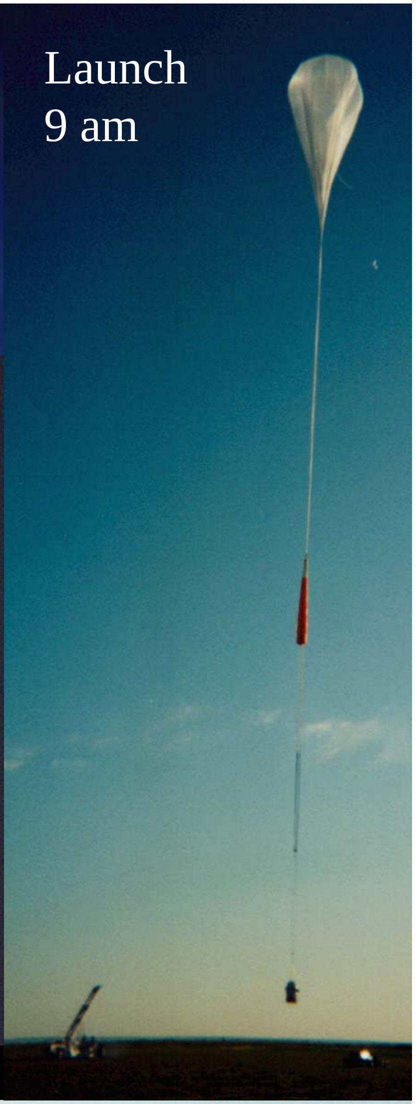
Scientific Ballooning



Crane hook-up
4 am



Balloon at float, 12 pm



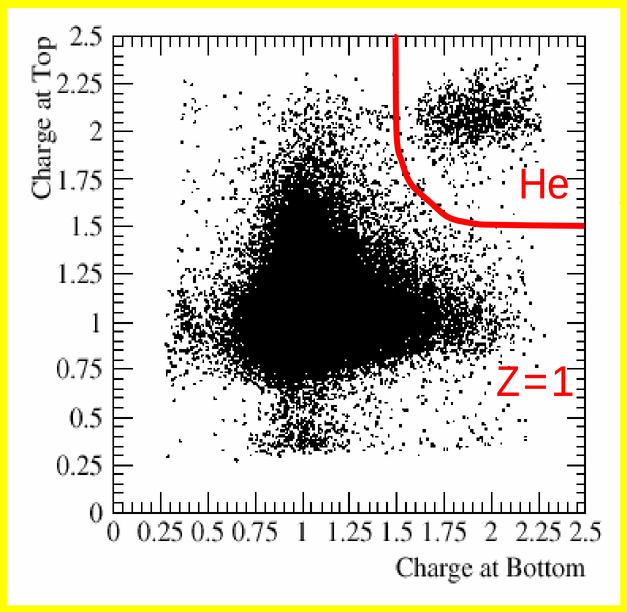
Launch
9 am

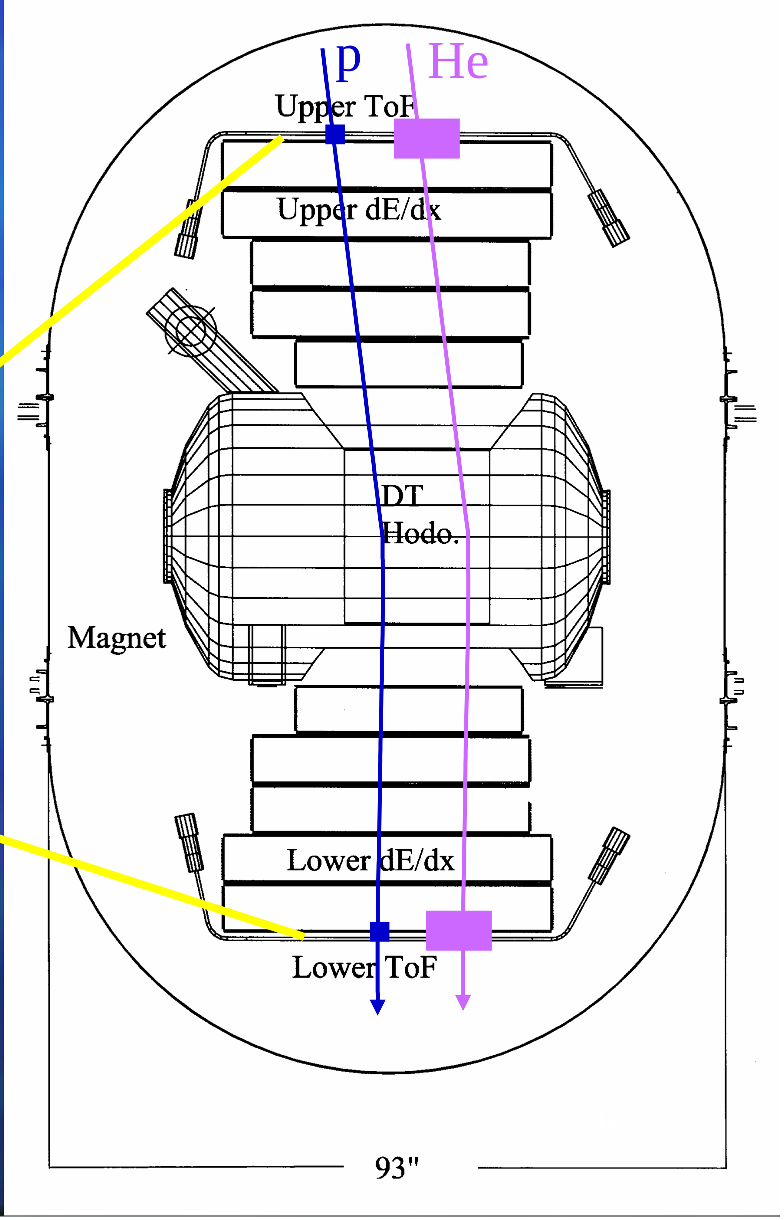
Balloon inflation 8 am

Identifying Antiprotons with HEAT-pbar

- TOF System:
  - Require Z=1
  - β>0 (downgoing)

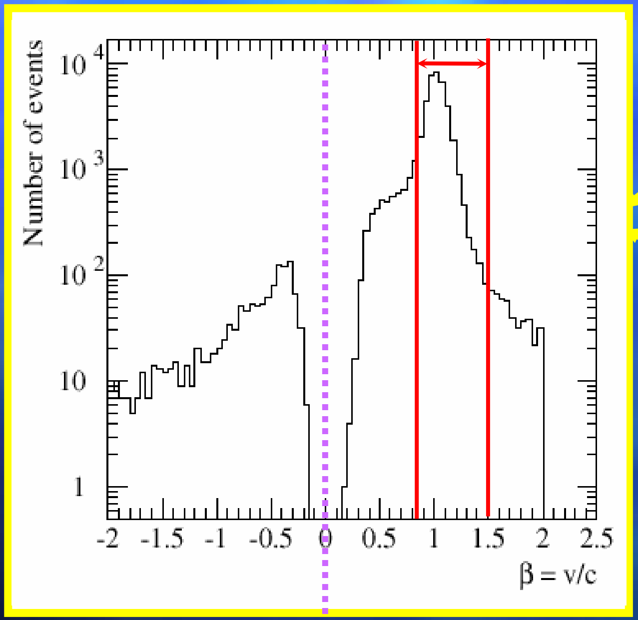
$$dE / dx \propto \frac{Z^2}{\beta^2 e^2}$$





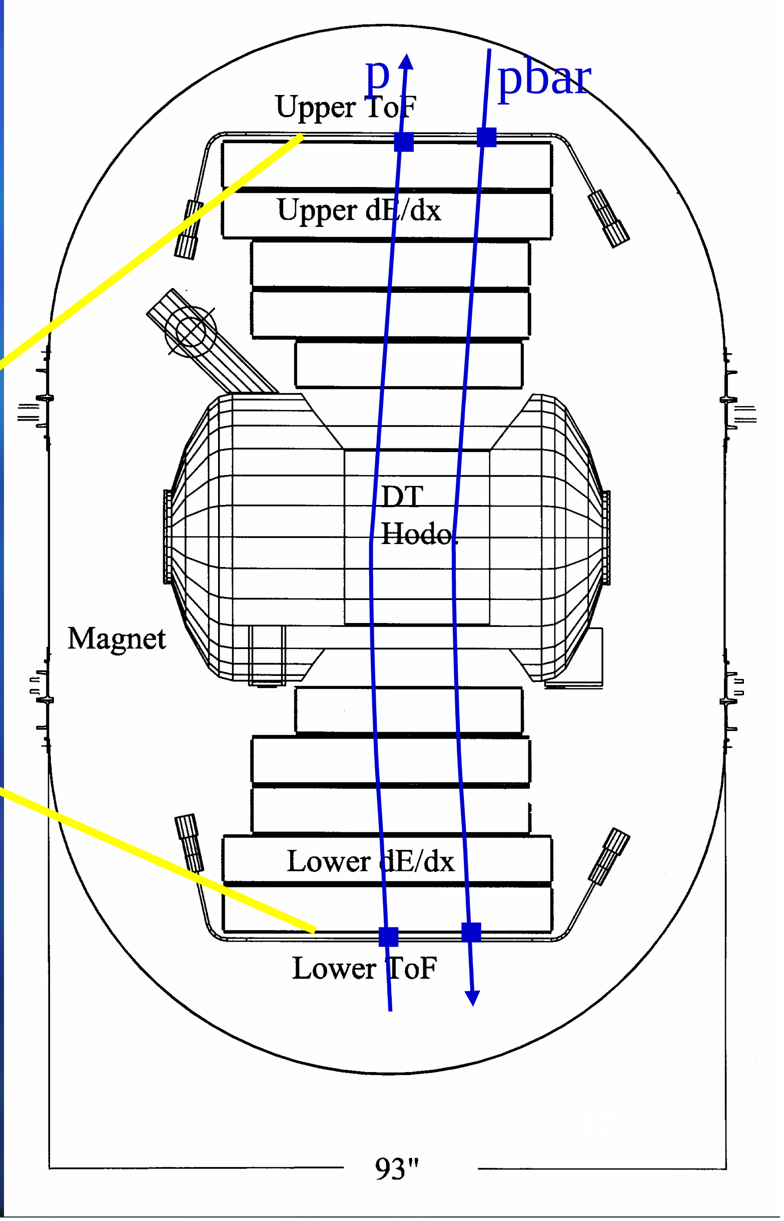
Identifying Antiprotons with HEAT-pbar

- TOF System:
  - Require Z=1
  - β>0 (downgoing)



Upgoing

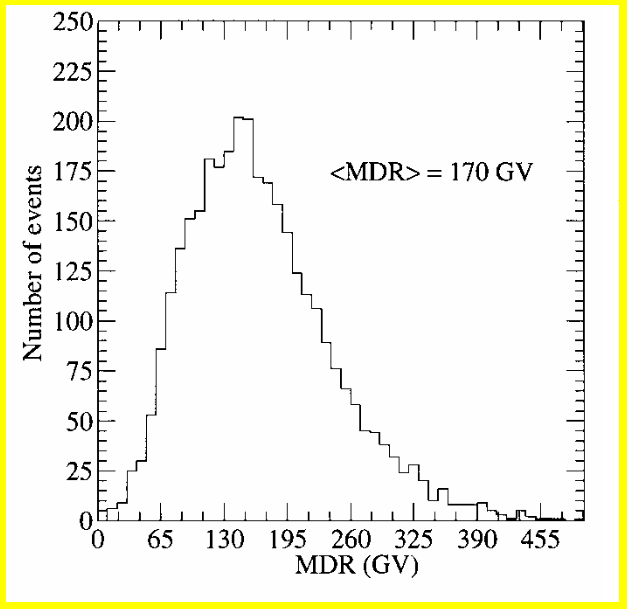
Downgoing



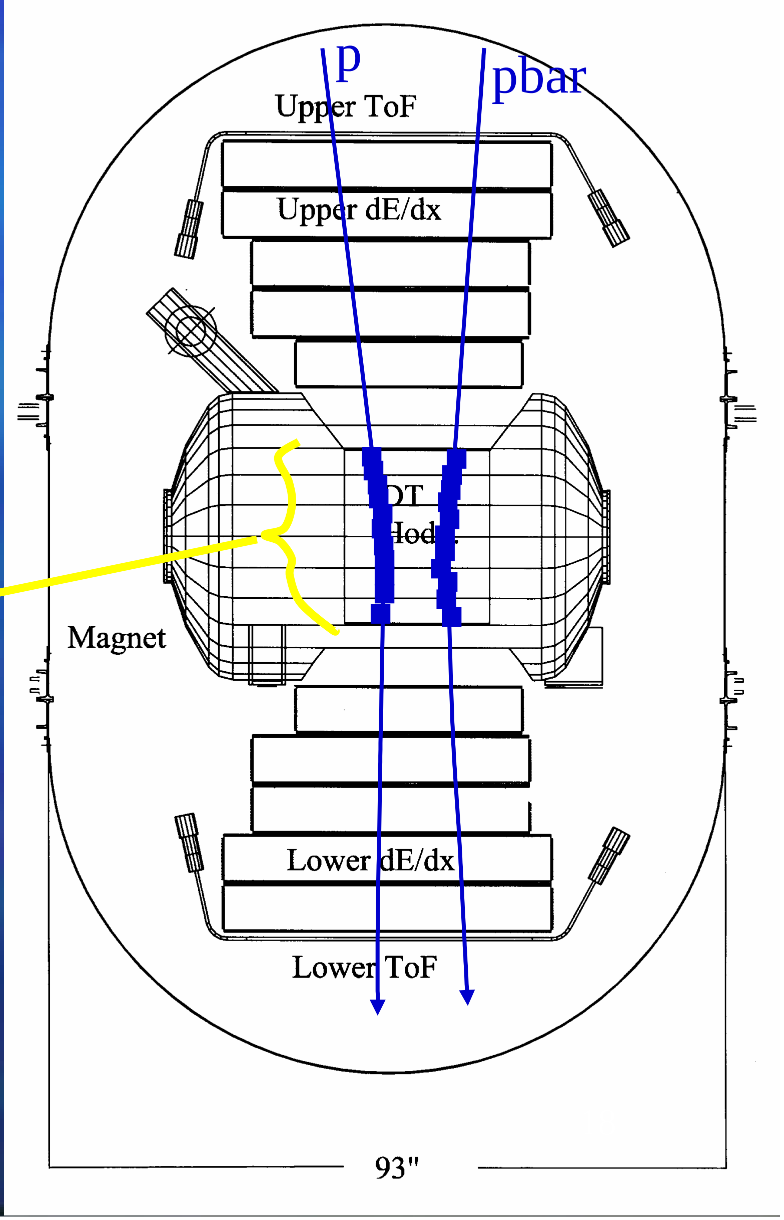
Identifying Antiprotons with HEAT-pbar

- DTH:
  - p from amount of bending in B=1T
  - Sign of Z from direction

$R=pc/Ze$, p_{max}~ 54GeV/c



$$\mathrm{MDR} = \frac{3\cdot d}{\sigma}\sqrt{(N+4)/720}\int \mathbf{B}\bullet \mathbf{dl}$$

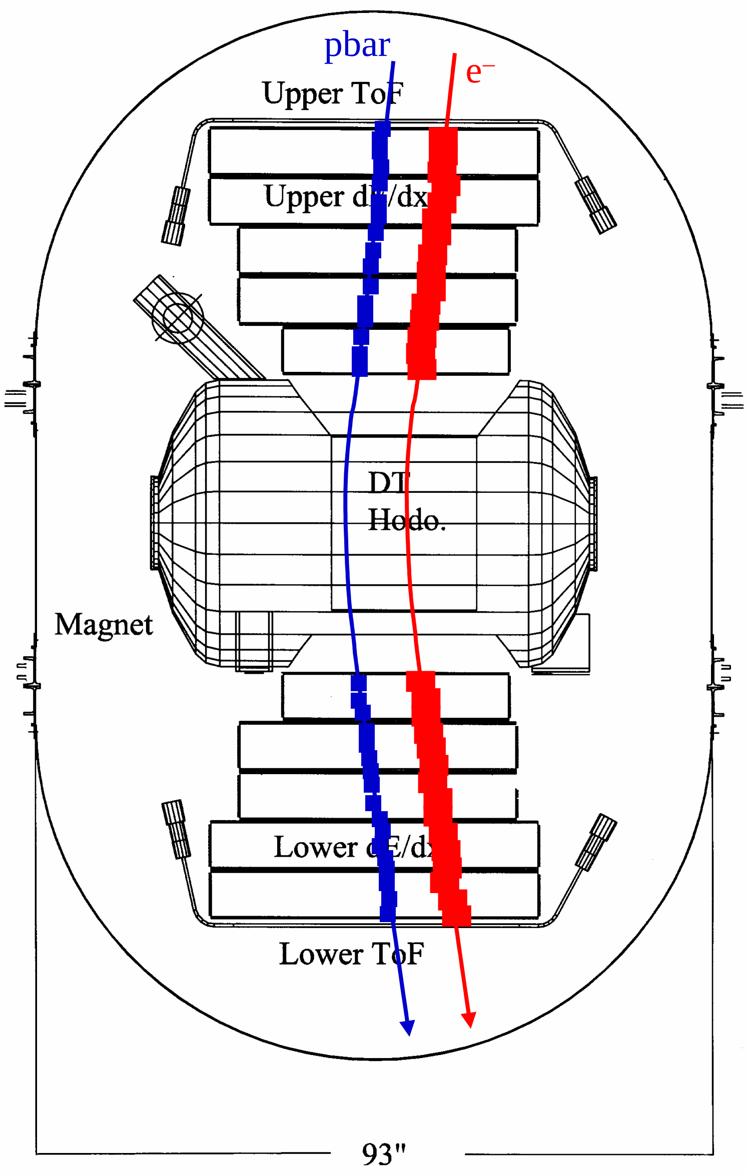


Identifying Antiprotons with HEAT-pbar

- Multiple dE/dx: p / π-μ / e separation

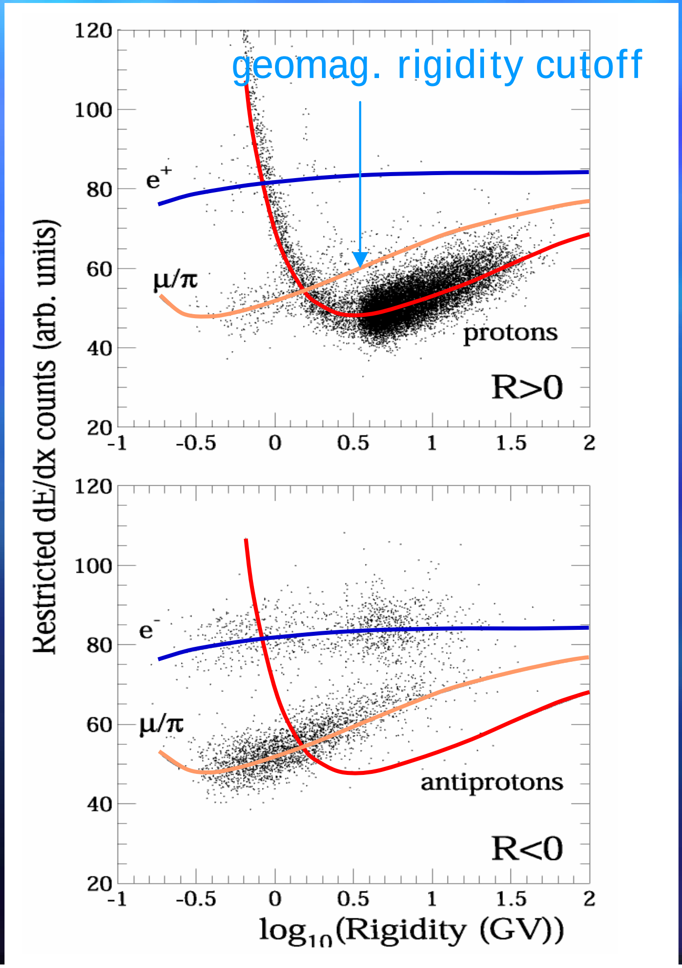
Technique exploits the logarithmic rise in the mean rate of energy loss (Bethe-Bloch):

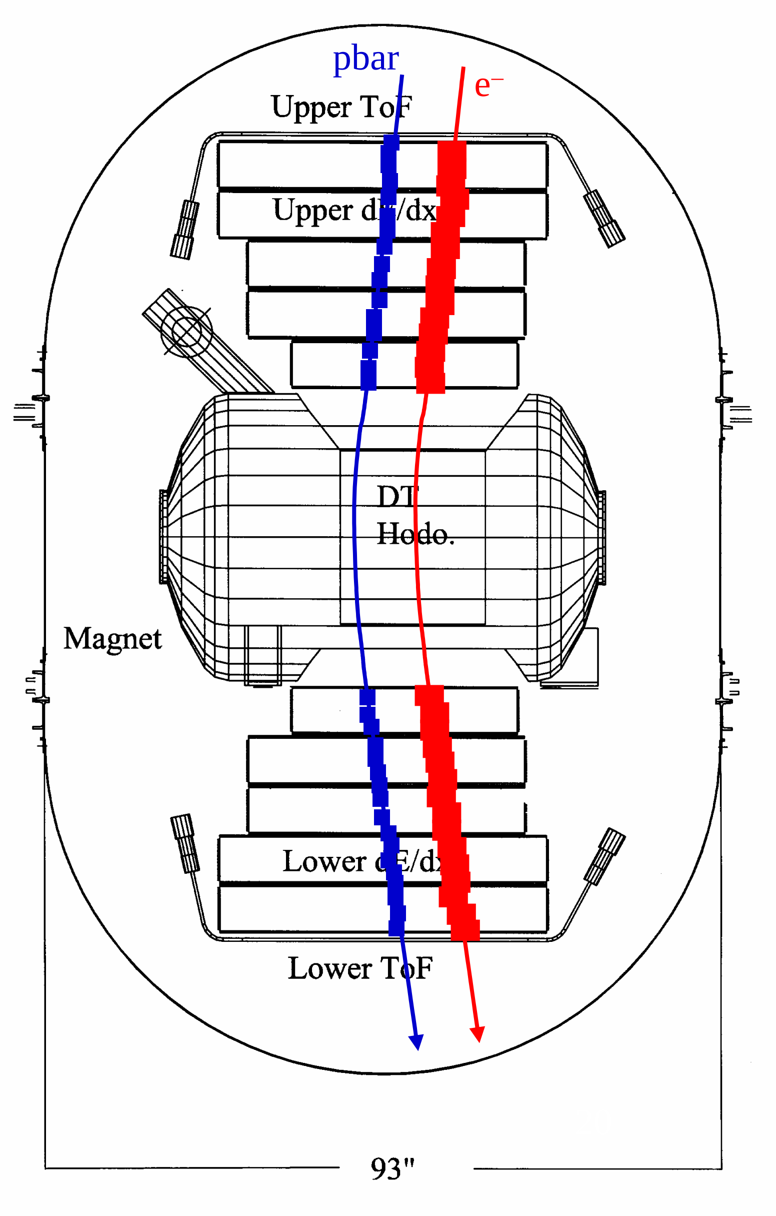
$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$



Identifying Antiprotons with HEAT-pbar

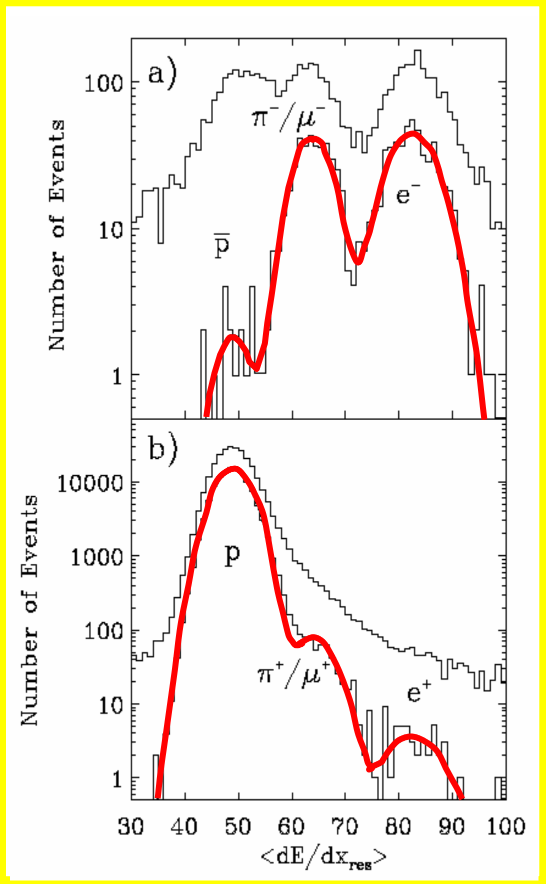
- Multiple dE/dx: p / π-μ / e separation

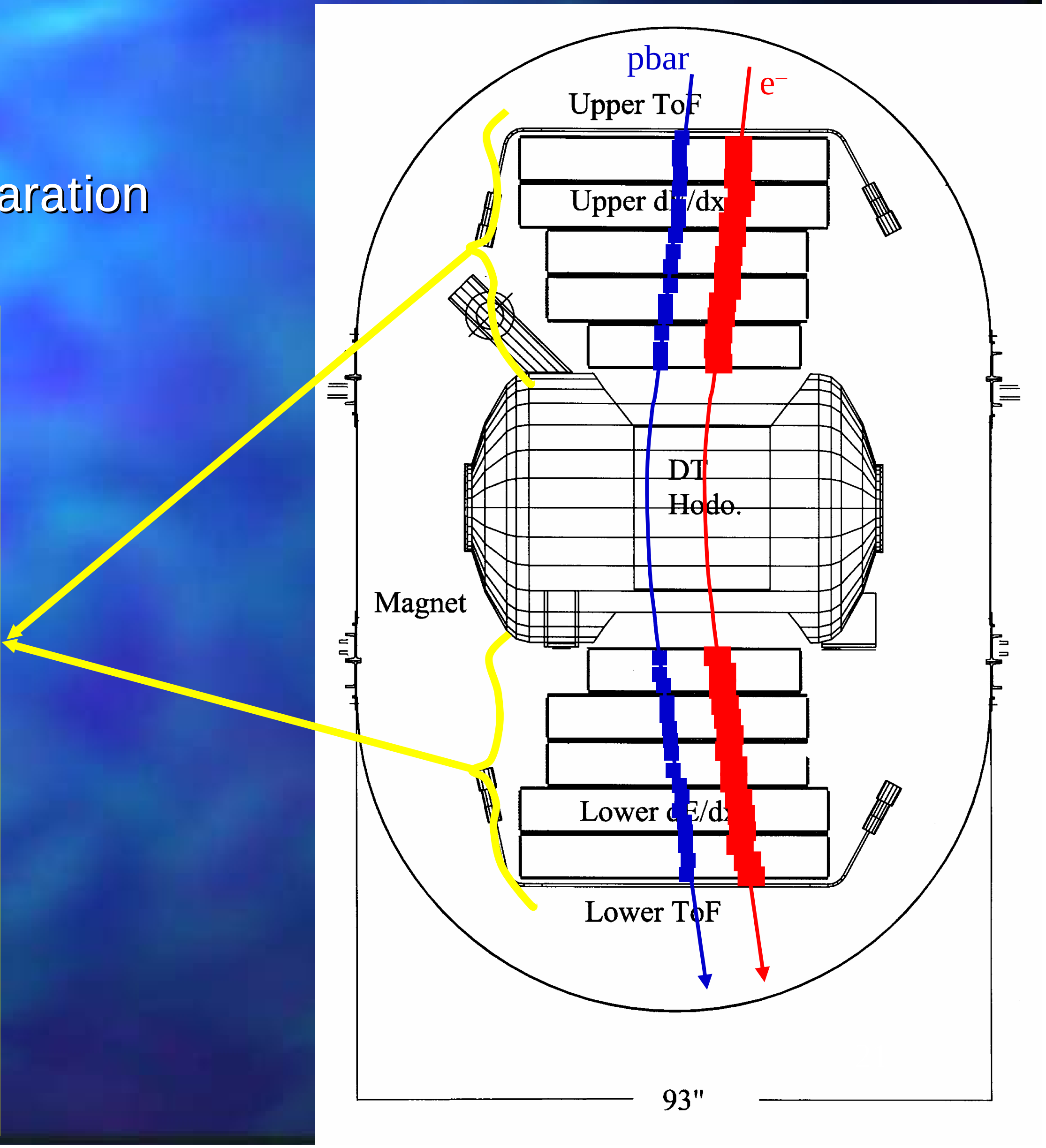




Identifying Antiprotons with HEAT-pbar

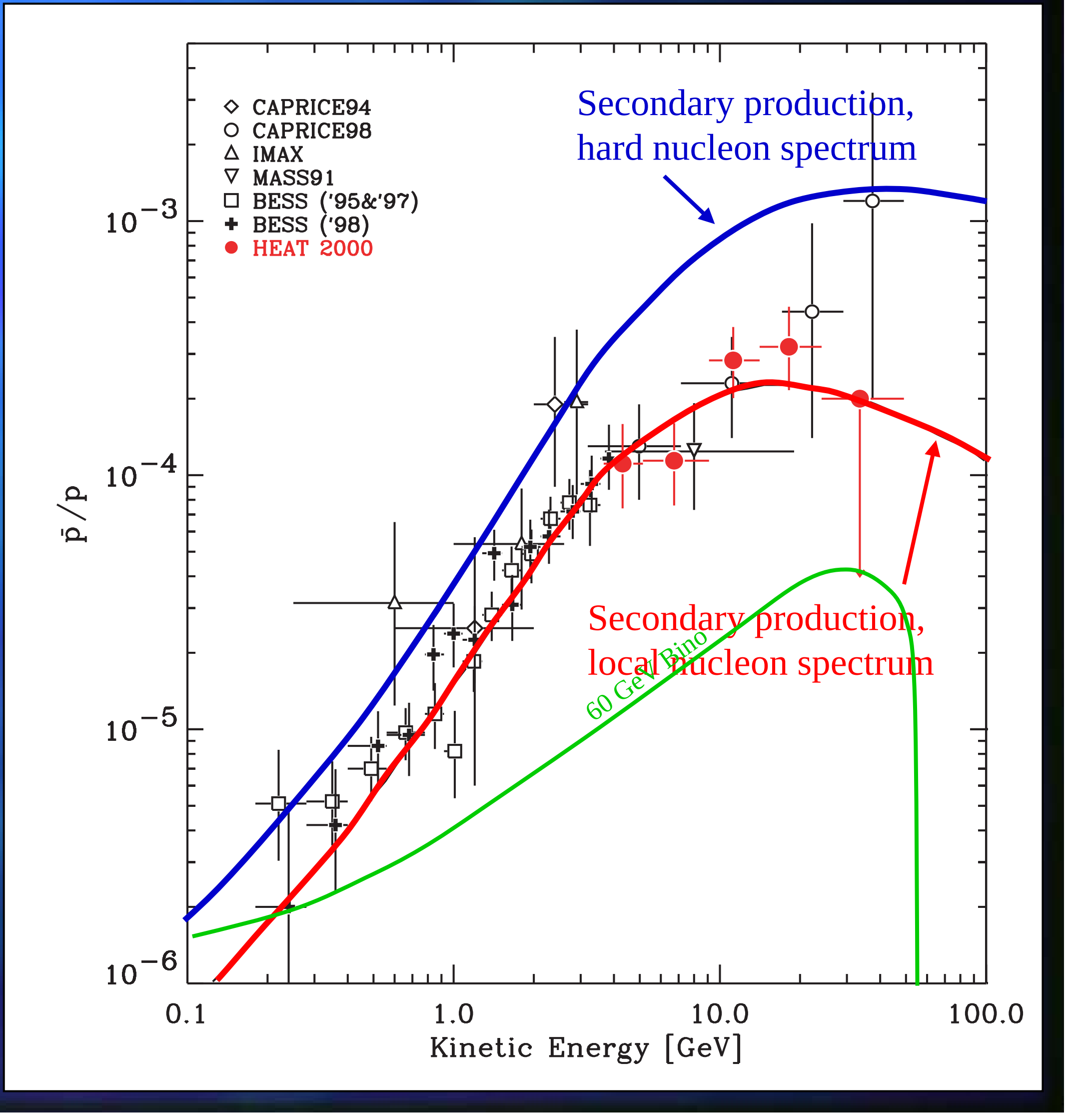
- Multiple dE/dx: p / π-μ / e separation





New Antiproton Results

- BESS, IMAX, MASS, CAPRICE and HEAT data in agreement with secondary production expectations;
- No support for 'hard nucleon injection spectrum' models;
- Prospects for primary pbar detection (e.g. from WIMP annihilation) not good;
- Good agreement with model indicates mature understanding of secondary antimatter production and propagation.



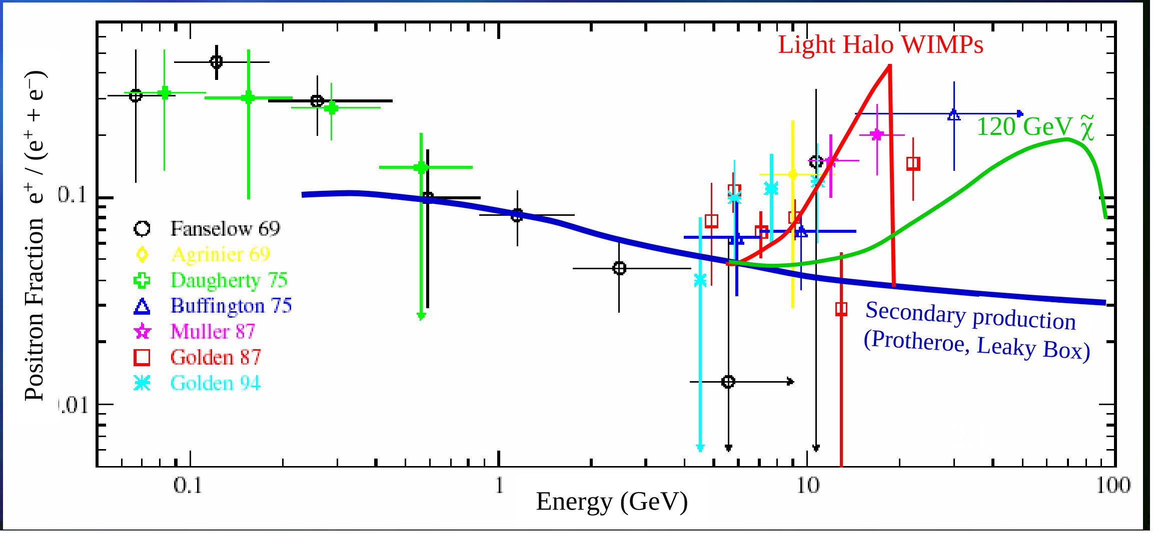
HEAT: 71 pbars above 4.2 GeV
CAPRICE: 31 pbars

Positron Fraction as of 1995

- Positron fraction $e^+/(e^+ + e^-)$ is small (≈ 10%) ⇒ substantial primary e^- component.
- Below ~7 GeV: data in agreement with secondary predictions (large solar modulation effects below 1 GeV);
- Above ~7 GeV: more antimatter than expected!

⇒ additional (“exotic”) antimatter component?

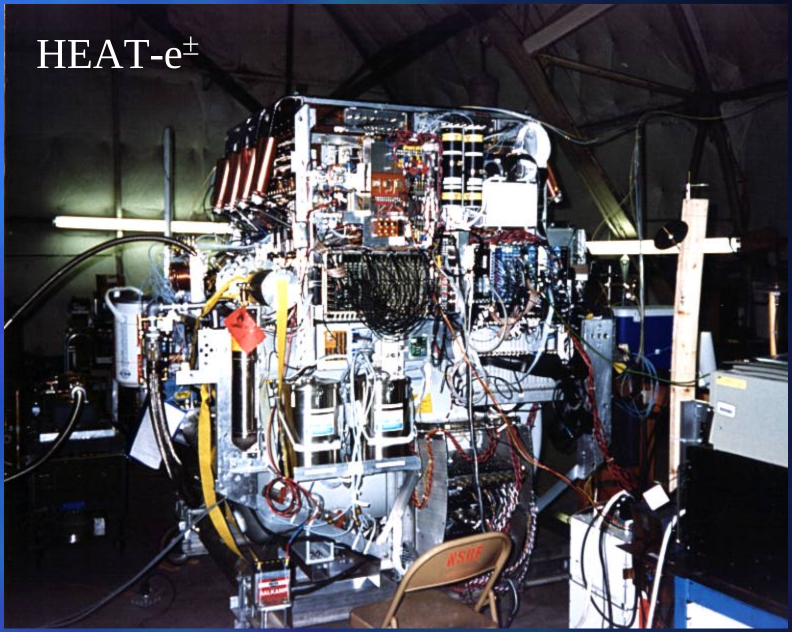
  - Turner/Wilczek light WIMP annihilation (×20);
  - Kamionkowski/Turner heavy WIMP annihilation (×10).
- Positron line is a “smoking gun” for WIMPs.



HEAT-e± (High Energy Antimatter Telescope)

<u>The HEAT-e± Collaboration</u>

U of Chicago: J. Knapp, D. Müller, S.P. Swordy, E. Torbet
Eastern New Mexico U: S.L. Nutter
Indiana U: C. Bower, J.A. Musser
UC Irvine: S.W. Barwick, E. Schneider
U of Michigan: C. Chaput, S.P. McKee, G. Tarlé, A.D. Tomasch
Penn State U: J.J. Beatty, S. Coutu, M. DuVernois
Washington U St. Louis: G. de Nolfo, D. Ficenec

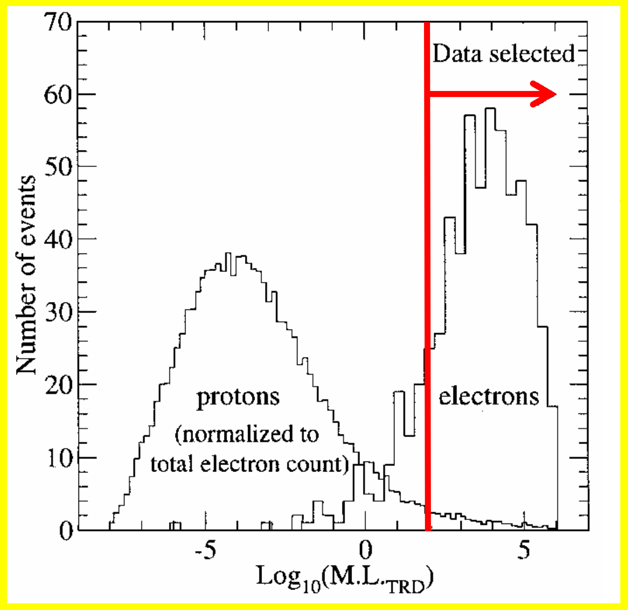


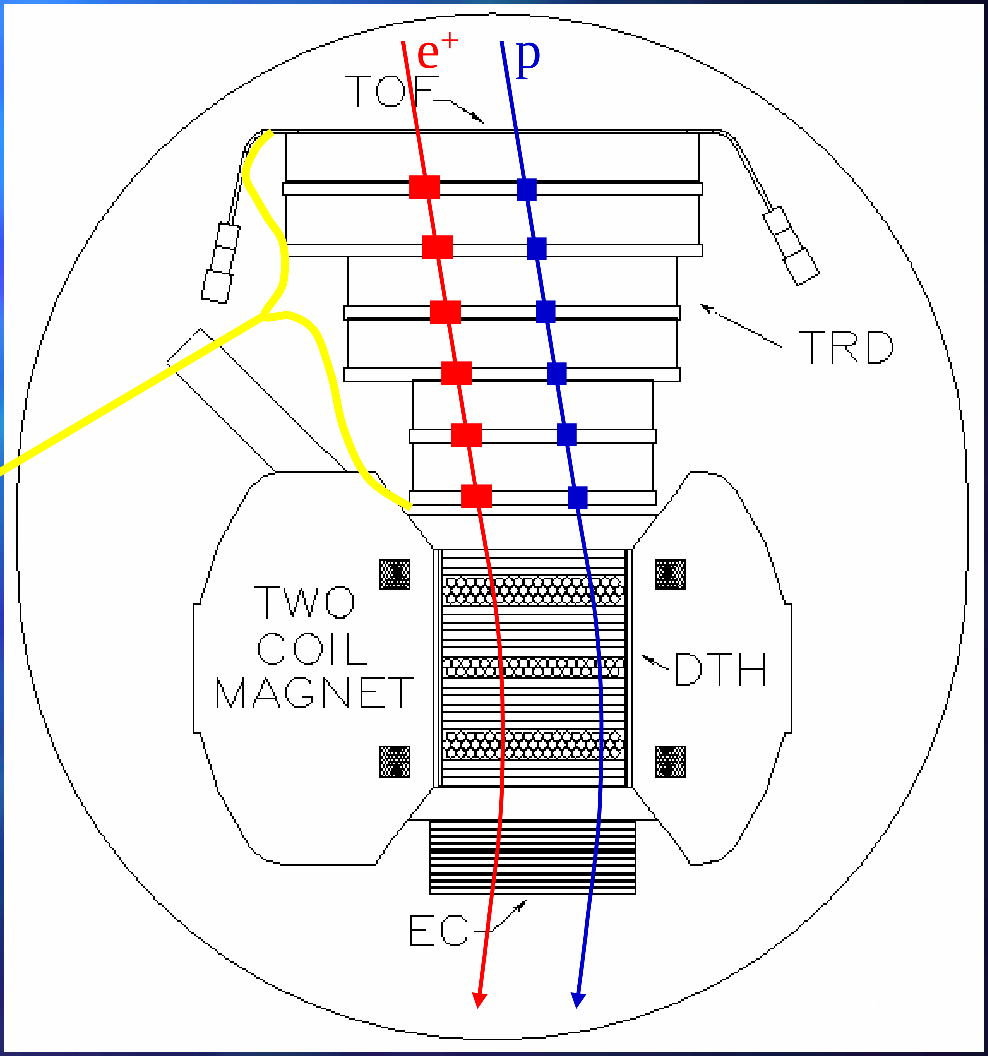
- Superconducting Magnet Spectrometer with Drift Tube Hodoscope (DTH), Electromagnetic Calorimeter (EC), Transition Radiation Detector (TRD) and Time-of-Flight (TOF) system.
- 1) May 1994 flight from Ft. Sumner, NM (29.5 hour flight)

  2) Aug. 1995 flight from Lynn Lake, Manitoba (26 hour flight)

Identifying Positrons with HEAT-$e^{\pm}$

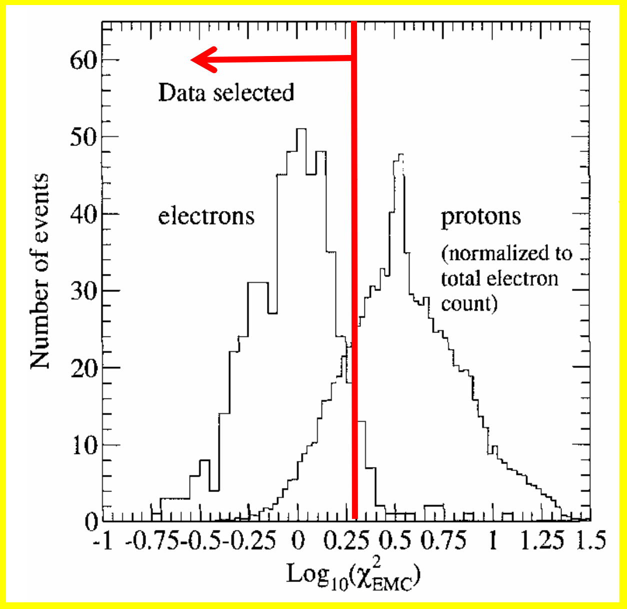
- TOF, DTH: same as HEAT-pbar
- TRD:
  - dE/dx losses in MWPC
  - TR for $e^{\pm}$ ($\gamma = E/mc^2 > 4\times10^3$)

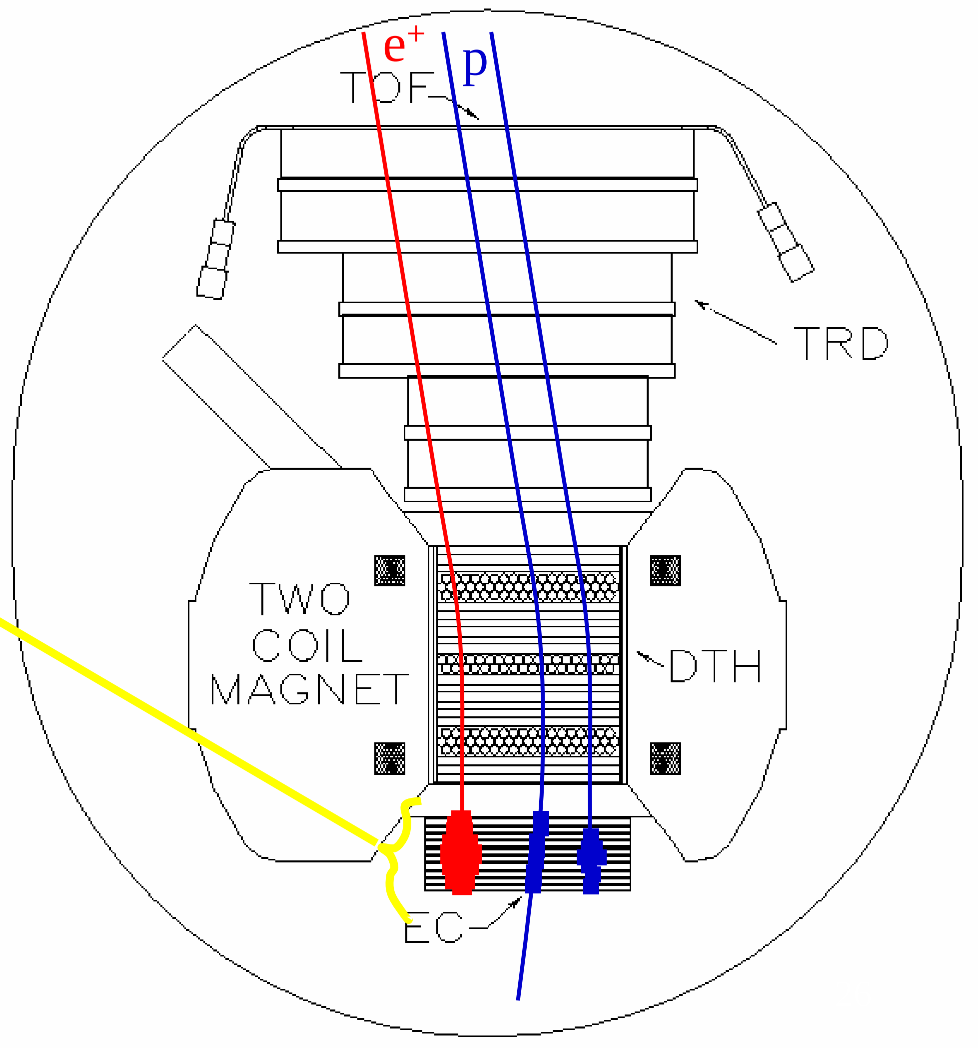




Identifying Positrons with HEAT-$e^{\pm}$

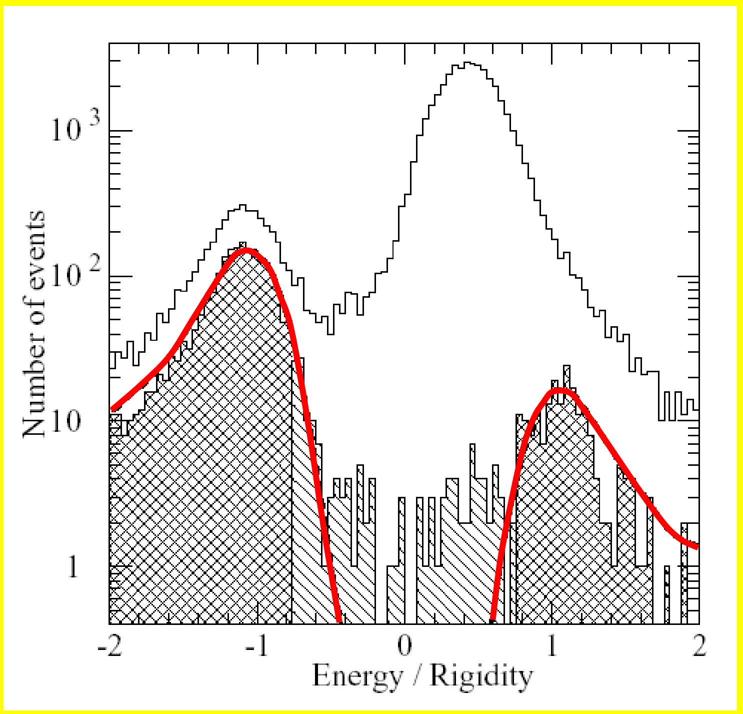
- EC:
  - EM showers for $e^{\pm}$
  - Hadronic or no showers for p

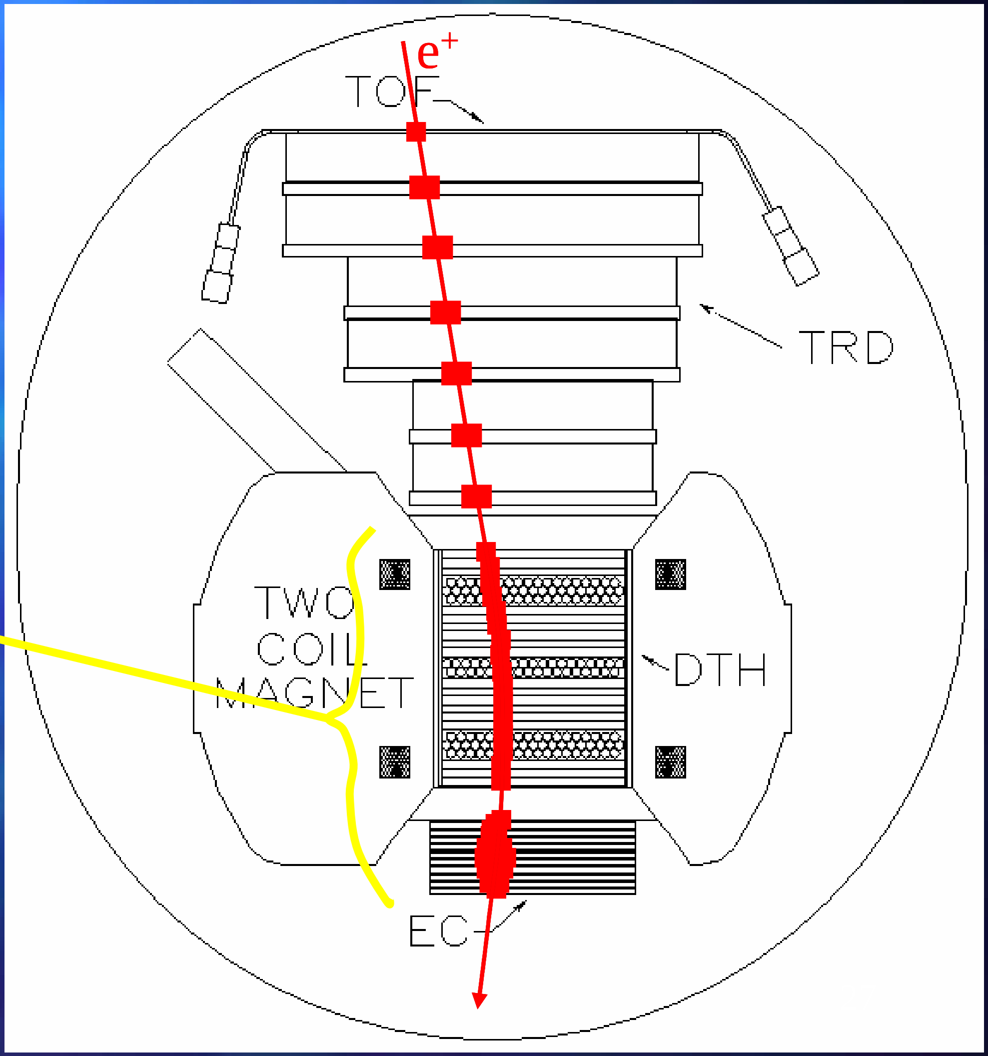




Identifying Positrons with HEAT-e$^{\pm}$

- DTH & EC:
  - E/p agrees with expectations
  - Overall 10^5 p rejection, 33% electron efficiency





Correcting for Background

Atmospheric secondaries contribution estimated by GEANT-based Monte Carlo:

- electron correction: 5-6%; positron correction: 44-52%
- proton correction: 5-6%; antiproton correction: 14-26%
- systematic uncertainty: ~30% => $e^+/(e^++e^-)$ systematics: ~ 1%

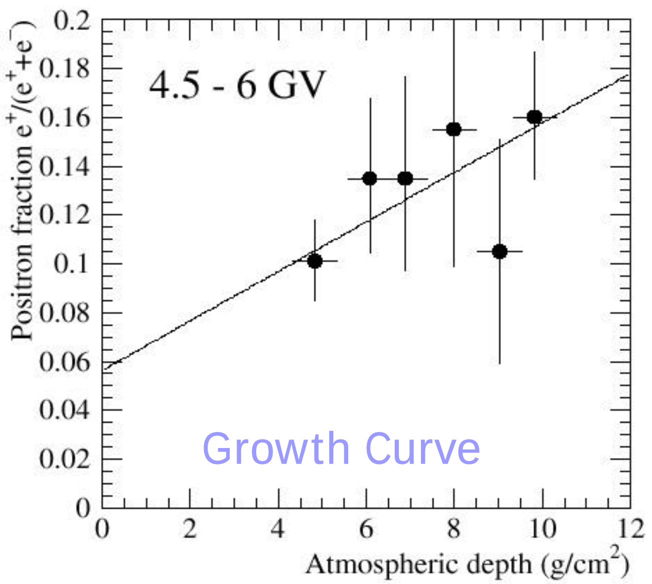
  pbar / p systematics: ~ 4%

e.g., positron fraction:

- from growth curve:

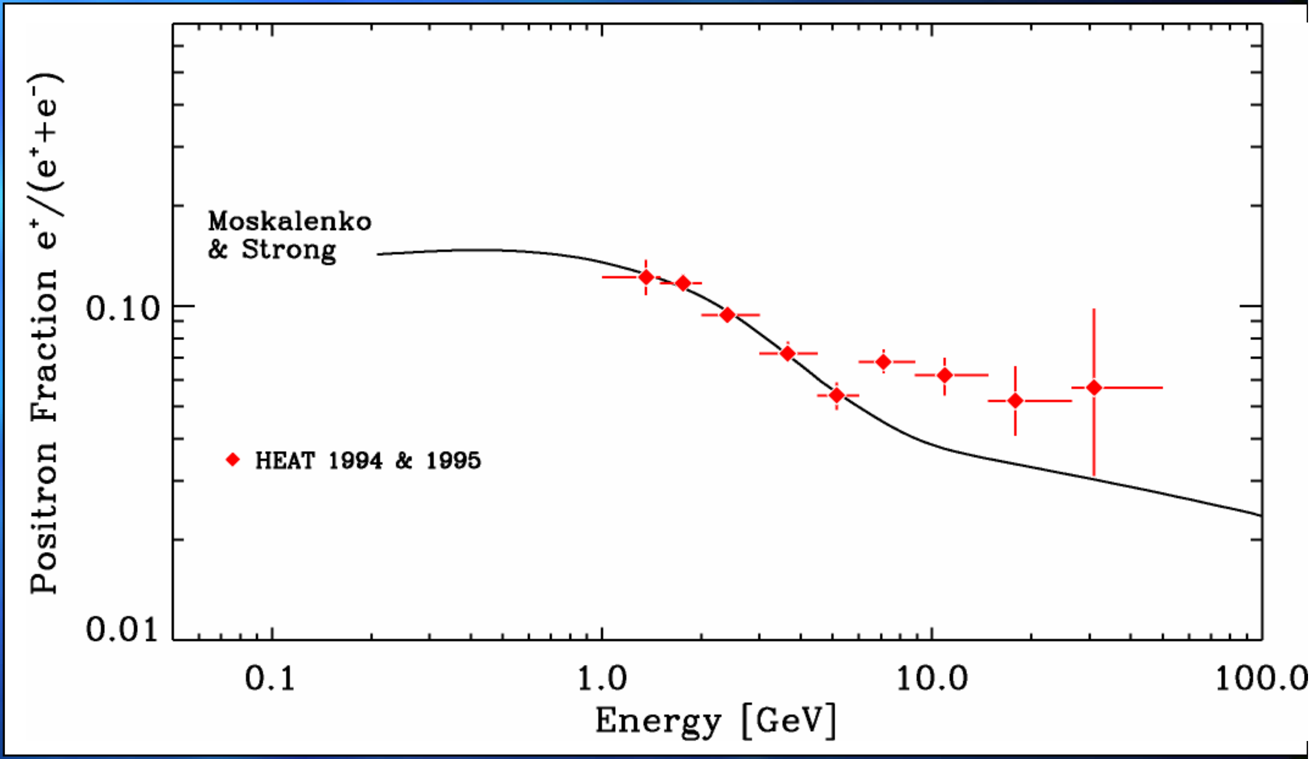
  0.056 ± 0.038
- from data with MC corrections:

  0.057 ± 0.006



Positron Fraction since 1995

- New positron fraction measurements are more statistically significant, with much improved hadron rejection power;
- Rise beyond about 10 GeV *not* confirmed!
- New detailed model predictions of e^+, pbar, γ production and propagation;
- Results much closer to secondary production expectations.

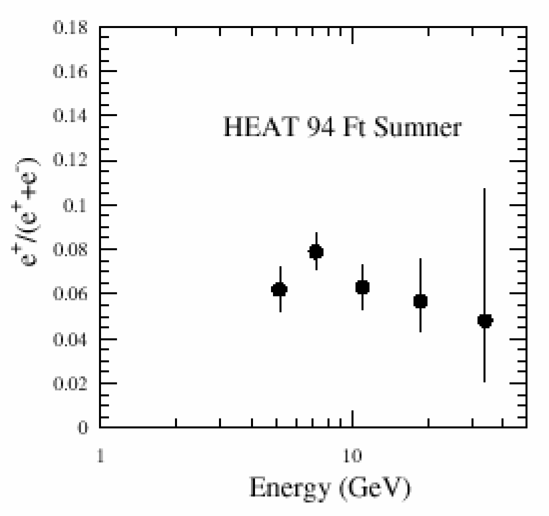


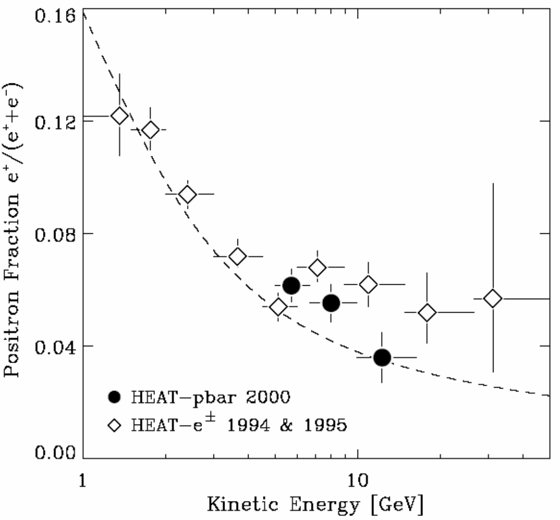
But …?

HEAT: 1200 e^+ above 1 GeV
CAPRICE: 730 e^+

HEAT Positron Fraction $e^+/(e^++e^-)$

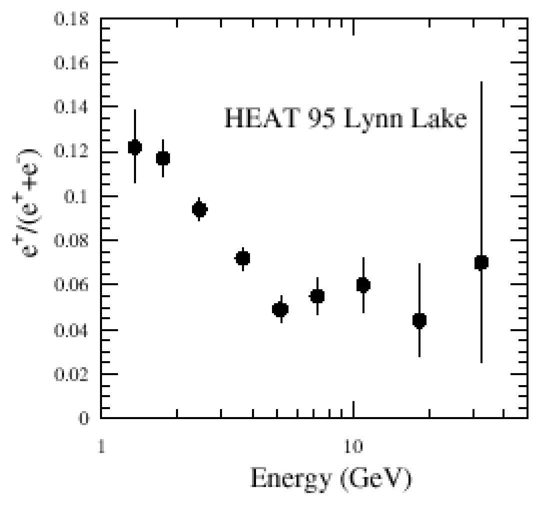
May 1994
New Mexico
(4GV cutoff)
HEAT-$e^\pm$
Solar min

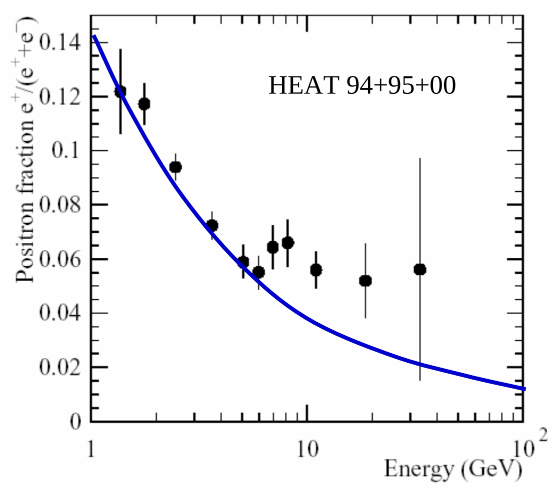




June 2000
New Mexico
(4GV cutoff)
HEAT-pbar
Solar max

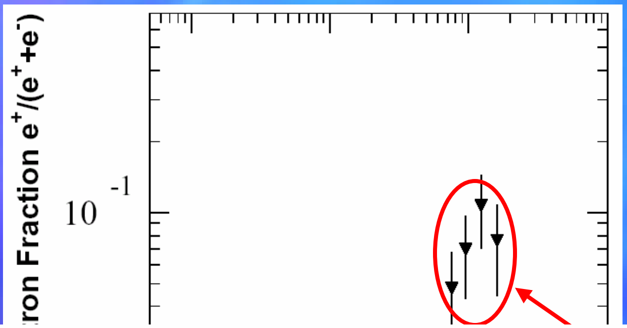
August 1995
Manitoba
(<1GV cutoff)
HEAT-$e^\pm$
Solar min

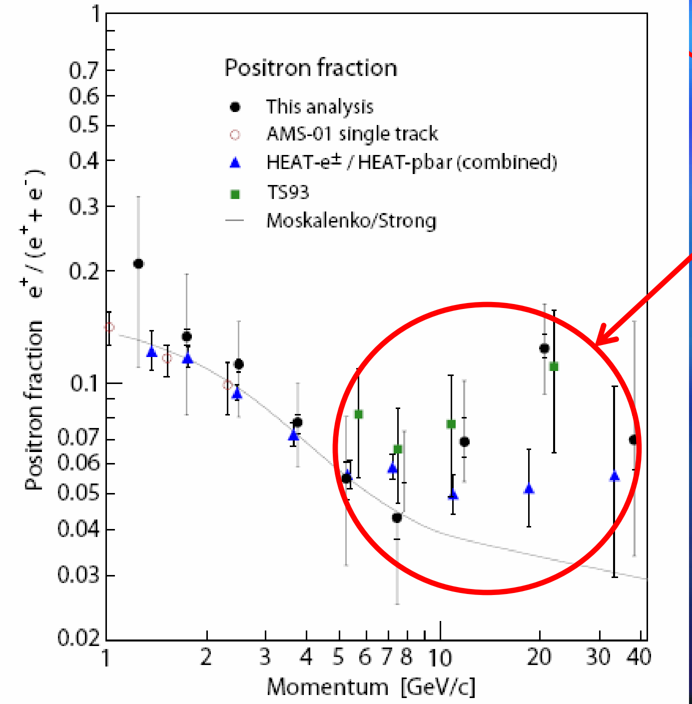




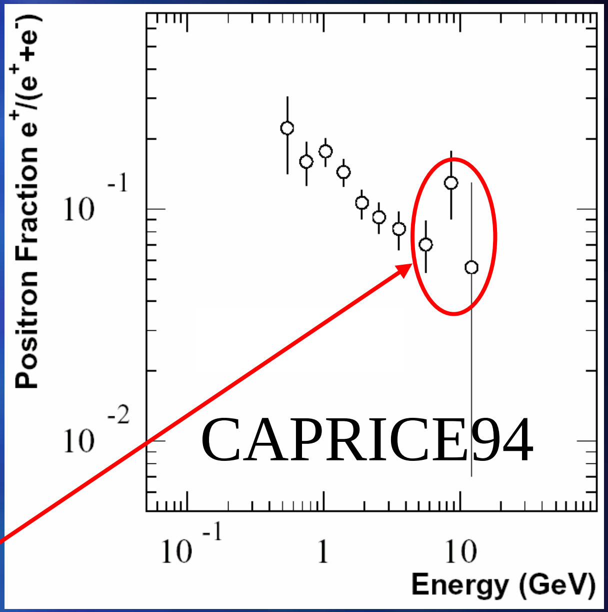
Moskalenko & Strong,
ApJ **493,** 694(98)
Galactic diffusion calculation

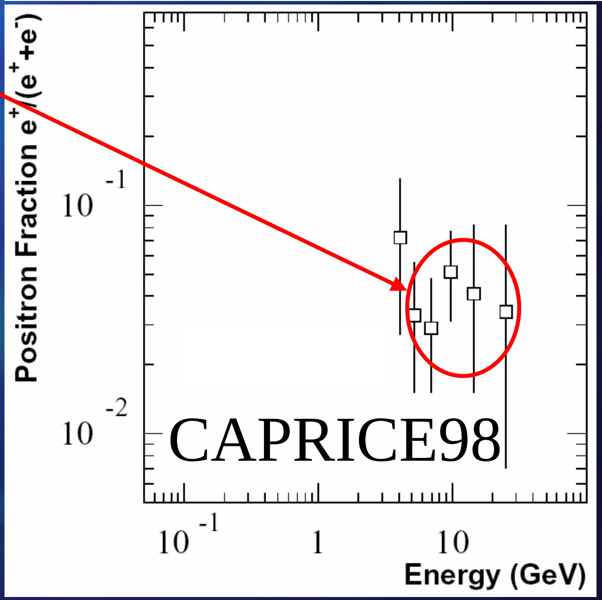
Other Recent Positron Fractions $e^+/(e^++e^-)$





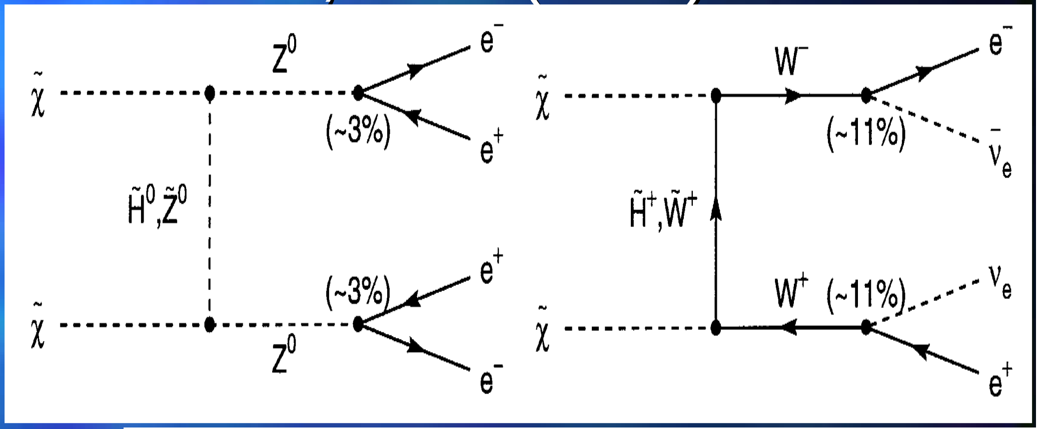
Structure?





Positrons from Annihilating Galactic Halo WIMPs

- Kamionkowski/Turner, Phys. Rev. D **43**, 1774 (1991):

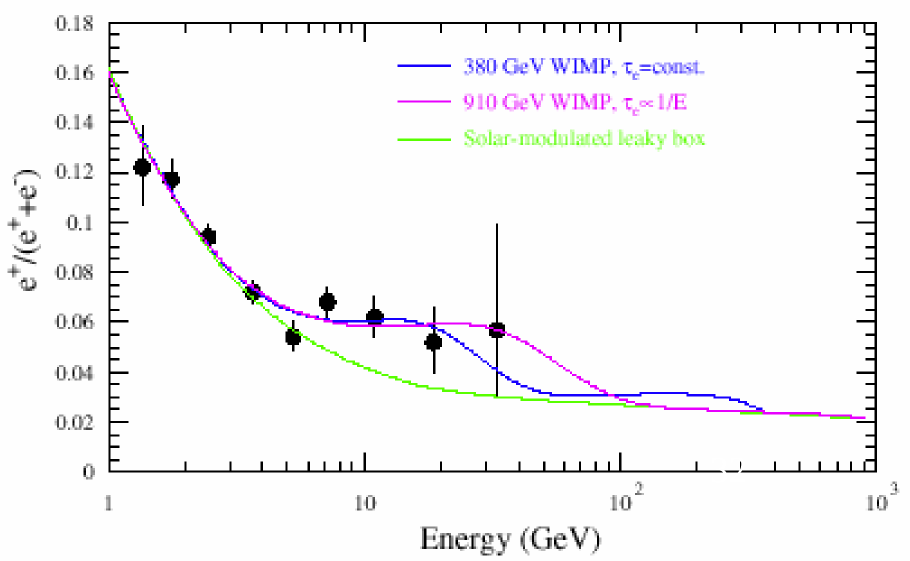


- Heavy WIMP

⇒ Z or W production

⇒ Direct decay into $e^{\pm}$

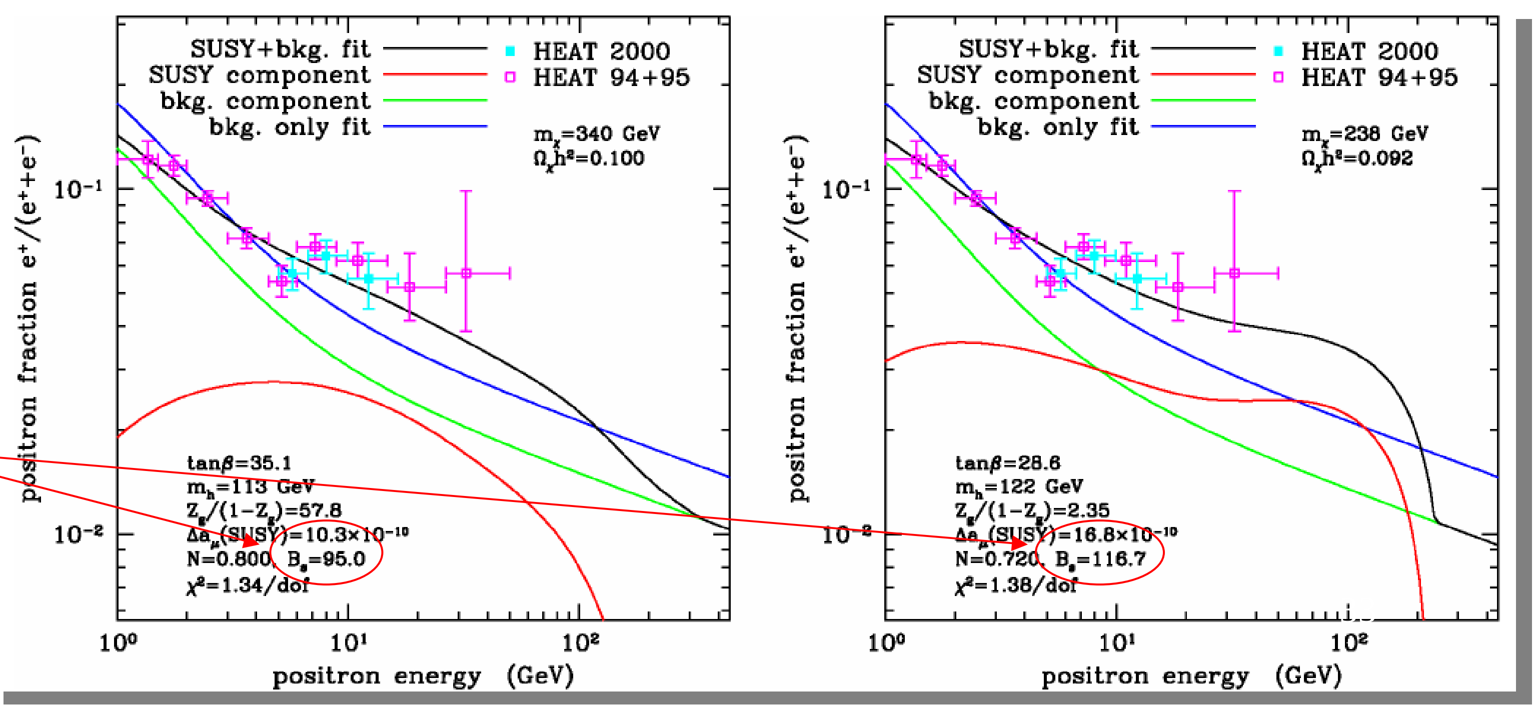
⇒ Other decay modes of the Z,W: $\pi^+ \rightarrow \mu^+ \rightarrow e^+$



Positrons from Annihilating Galactic Halo WIMPs

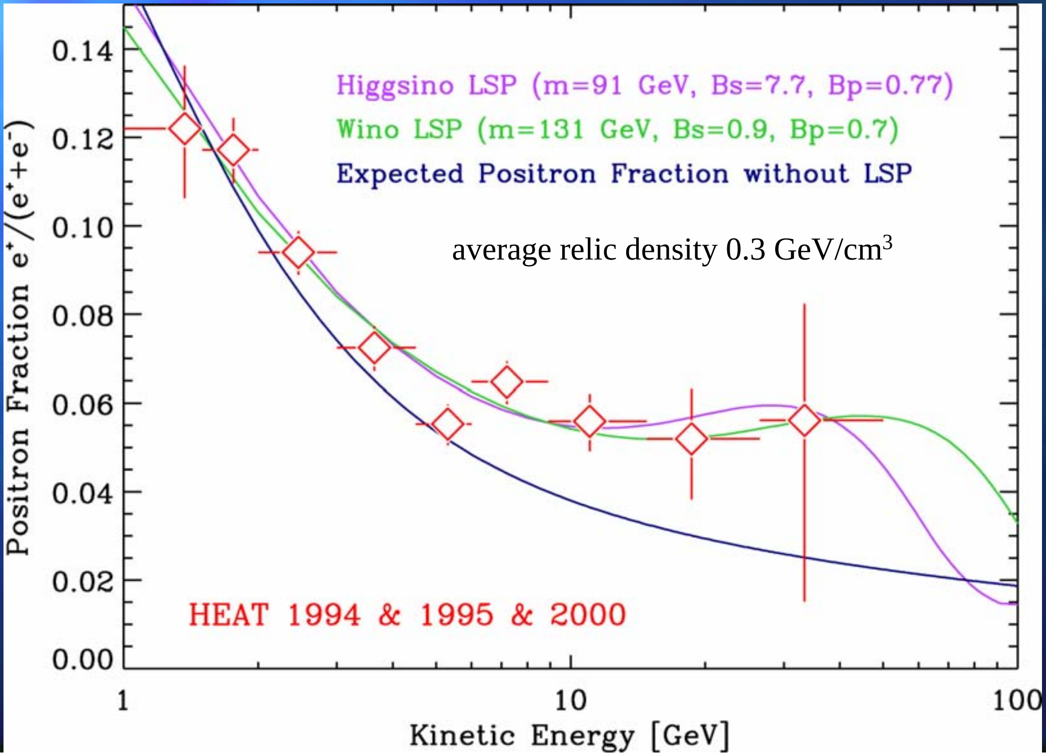
- Large region of MSSM space explored (Baltz/Edsjö, Phys. Rev. D **59**, 023511 (1999); Baltz, Edsjö, Freese & Gondolo, Phys. Rev. D **65**, 063511 (2002);
- **Heavy WIMPs required** (few hundred GeV);
- e^+ enhancement not as good a fit as KT, but helps.

Substantial boost factors required (e.g. clumpy halo)



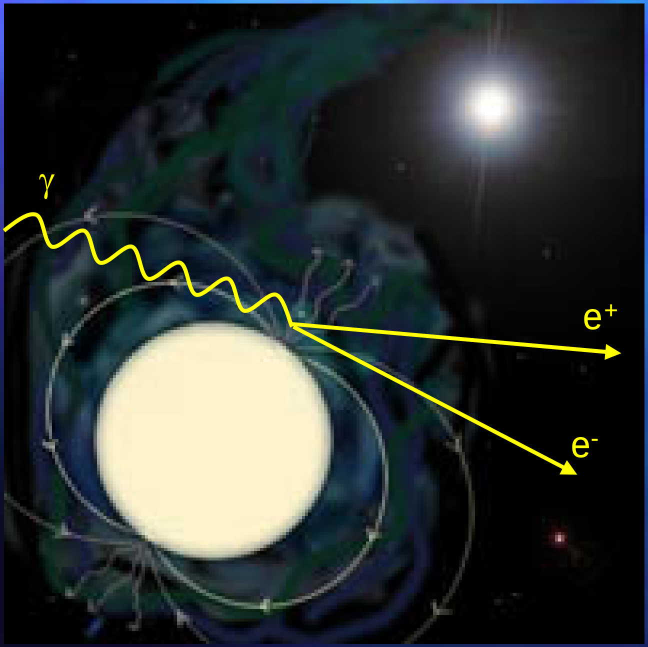
Positron Excess and Other SUSY Models

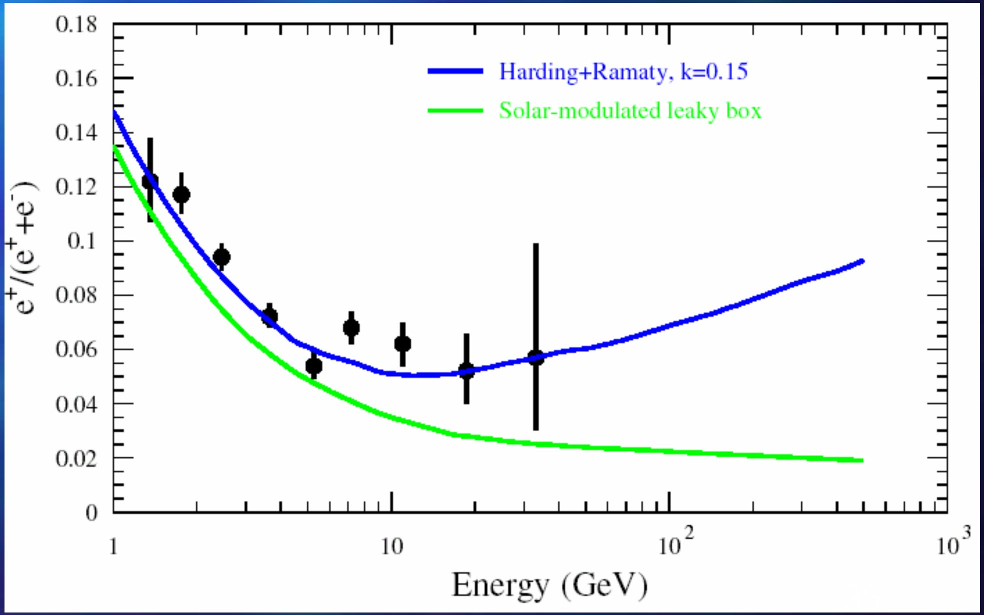
- Kane, Wang and Wells, astro-ph/0108138 (2001), hep-ph/0202156 (2002);
- $\chi\chi \rightarrow$ WW annihilation, W decays, Galactic propagation; $e^+/(e^+ + e^-)$ enhancement at ~10 GeV (insensitive to WIMP mass!);
- **Non thermal processes** in the early universe.



Positrons from γ Rays Near Compact Objects

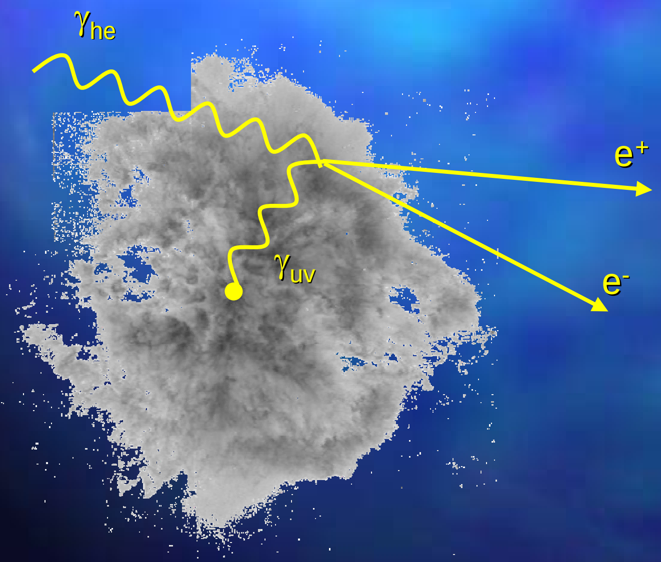
- Harding/Ramaty, 20th ICRC **2**, 92 (1987): $\gamma \to e^+e^-$ near pulsar magnetic pole.
- Positron fraction: monotonic rise with energy to ~0.5

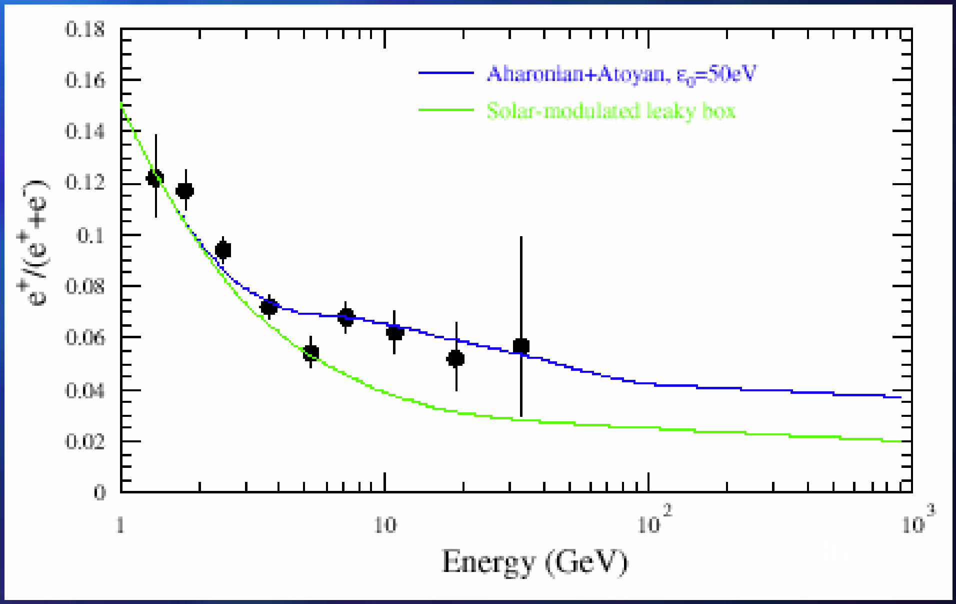




Positrons from $\gamma\gamma$ Interactions Near Discrete Sources

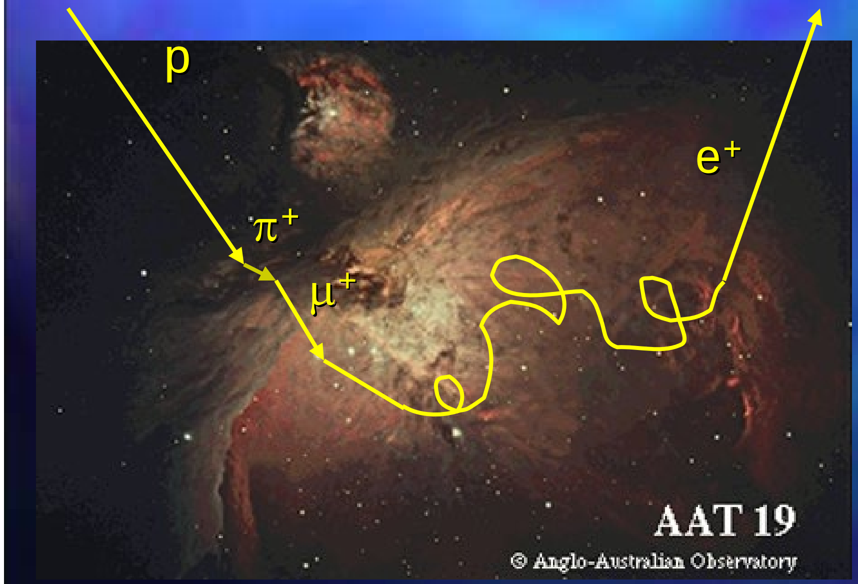
- Aharonian/Atoyan, J. Phys. G **17**, 1769 (1991):
  $\gamma_{he}\gamma_{uv} \rightarrow e^+e^-$ near high-intensity γ_{uv} source (e.g., OB star):
- Energy threshold for mechanism of $m_e c^2 / 4\varepsilon_0$, where ε_0 is the mean energy of γ_{uv}.

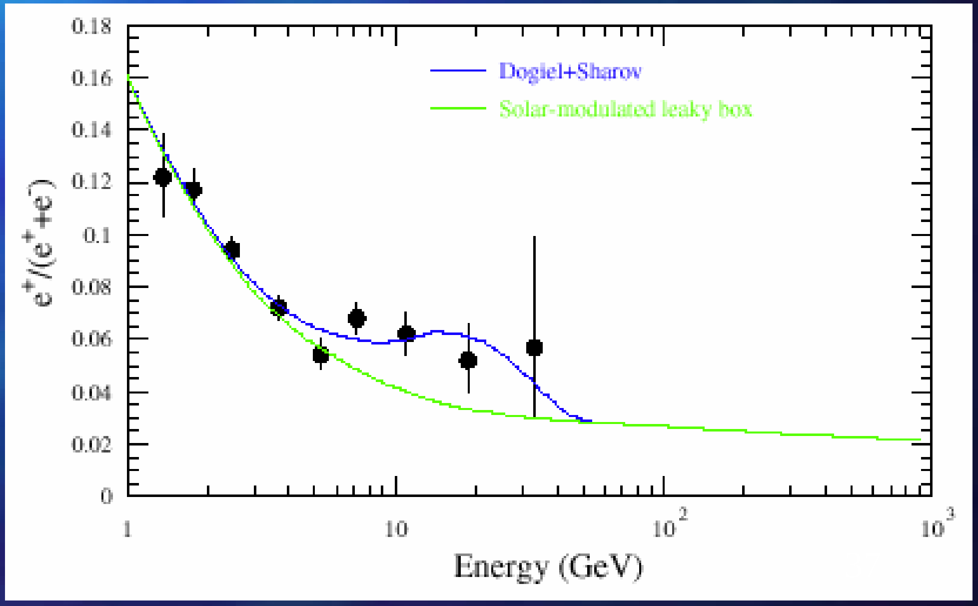




Positrons from Giant Molecular Clouds

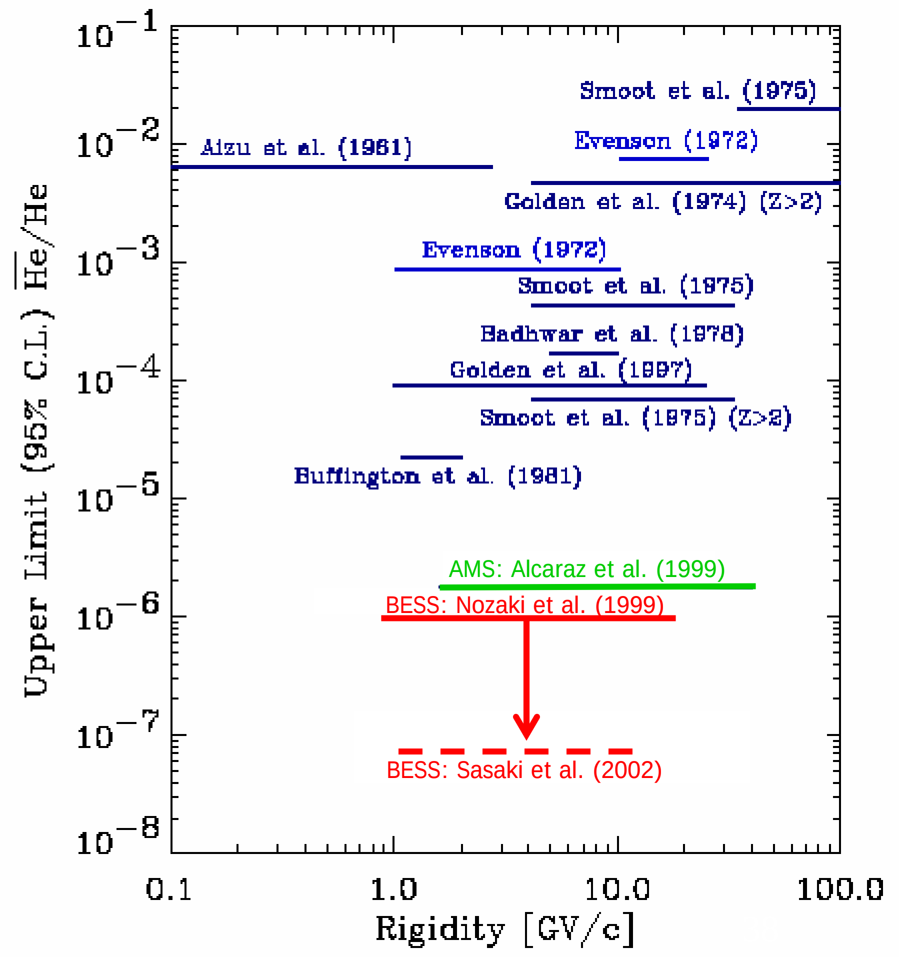
- Dogiel/Sharov, A&A **229**, 259 (1990):
- p-stuff → π^+ → μ^+ → e^+ in large molecular clouds; Fermi acceleration by gas turbulence.
- Rather contrived...





Heavy Antimatter

- Anti-Helium searches unsuccessful so far; best limit by BESS balloon spectrometer (Orito, S. *et al.*, PRL **84**, 1078 (2000)).
- ~ GeV extragalactic antimatter horizon only *at best* 60 Mpc due to magnetic fields (Adams, F.C. *et al.*, Ap.J. **491**, 6 (1997)).
- Any relic antimatter is not likely to be detected in cosmic rays.



Conclusions

Antiprotons

- Measurements consistent with purely secondary production of antiprotons.
- Data are in good agreement with 'standard spectrum' model.
- HEAT-pbar antiproton data confirm reliability of secondary production model.

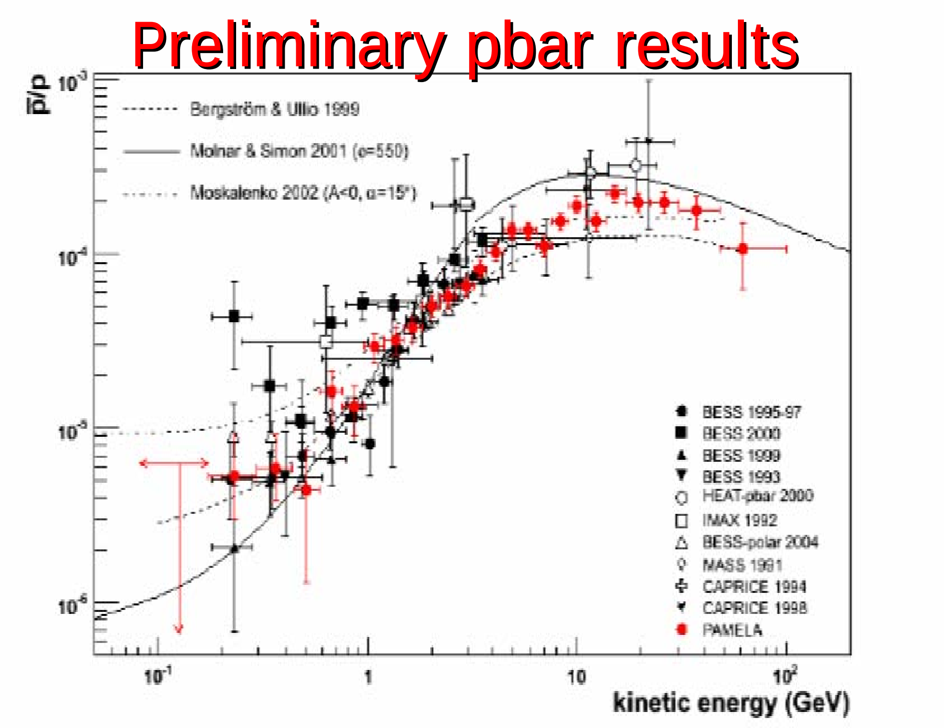
Positrons

- Positrons appear to be mainly from CR interactions in ISM but slight feature exists above ~7 GeV.
- New positron fraction measurements with HEAT-pbar confirm HEAT-$e^{\pm}$ results. Feature seen in experiments:
  - With two independent techniques.
  - At solar maximum and minimum.
  - At two different geomagnetic cutoff rigidities.
- Existing primary astrophysical e^{+} models do not explain the structure well.
- Feature (amplitude, location and shape) can be naturally reproduced with some SUSY models that are still allowed by current accelerator limits.

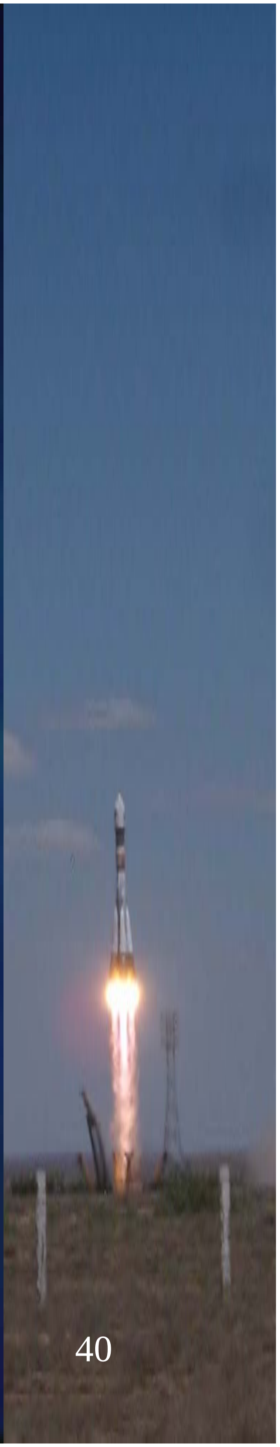
Most Recent Antimatter Measurements

PAMELA (Satellite, launched June 15th 2006 from Baikonur, 3 year mission, 0.05 – 280 GeV for positrons?);

Expect ~ 30 times balloon exposure



Preliminary pbar results

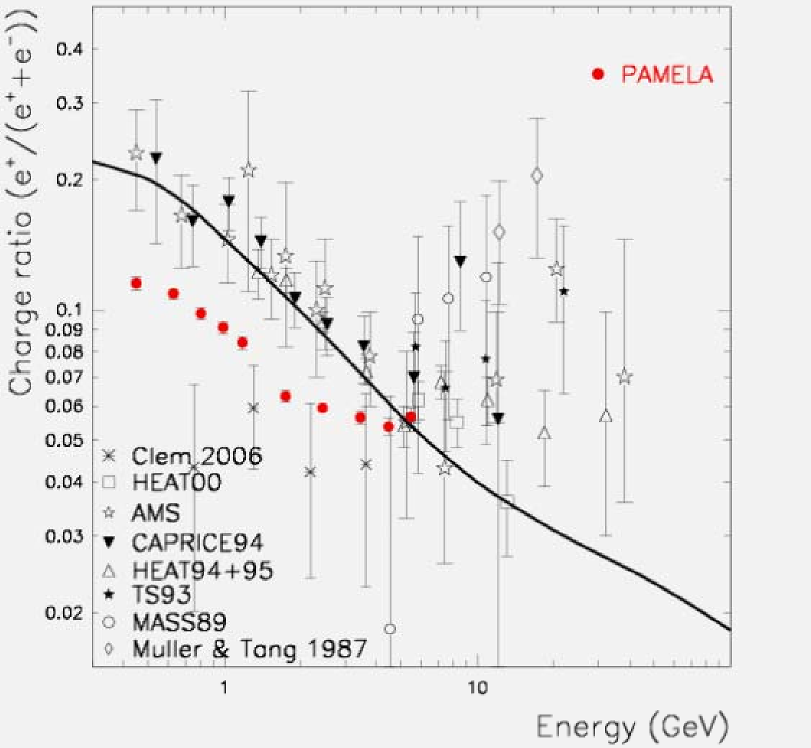


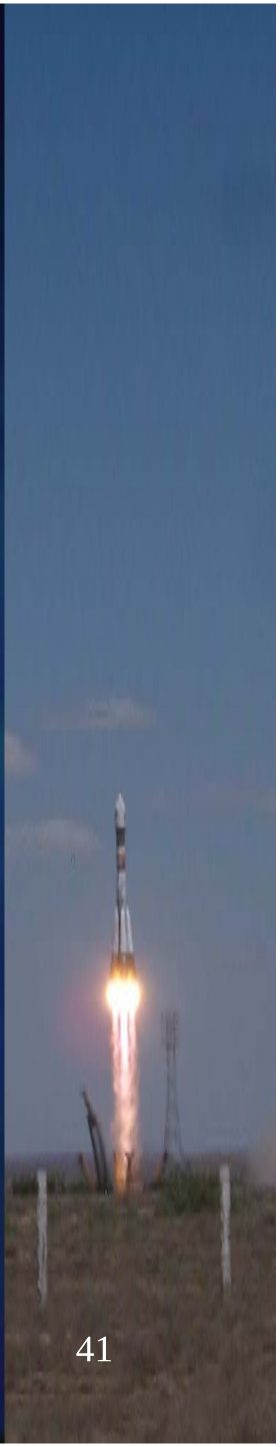
Most Recent Antimatter Measurements

PAMELA (Satellite, launched June 15th 2006 from Baikonur, 3 year mission, 0.05 – 280 GeV for positrons?);

Expect ~ 30 times balloon exposure (~15 times so far).

Preliminary e+ results

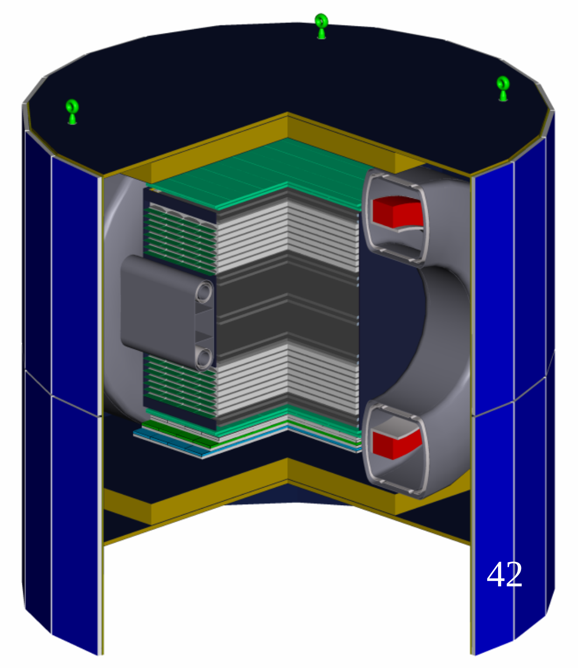




Outlook

Alpha Magnetic Spectrometer (AMS);

- ISS, launch on STS ?? 2010 or 2011 if funding approved by U.S. Congress for one last Space Shuttle mission;
- 3 year mission, 0.1 – 200 GeV?
- Possibly ~ 900 × balloon exposure.



Positron Electron Balloon Spectrometer (PEBS);

- Long-Duration balloon flights in Antarctica;
- 2010 – 2012?
- 20-30 day flights × 3, 1 – 100 GeV?