Towards a precise measurement of the cosmic-ray positron fraction

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I. Physikalisches Institut B
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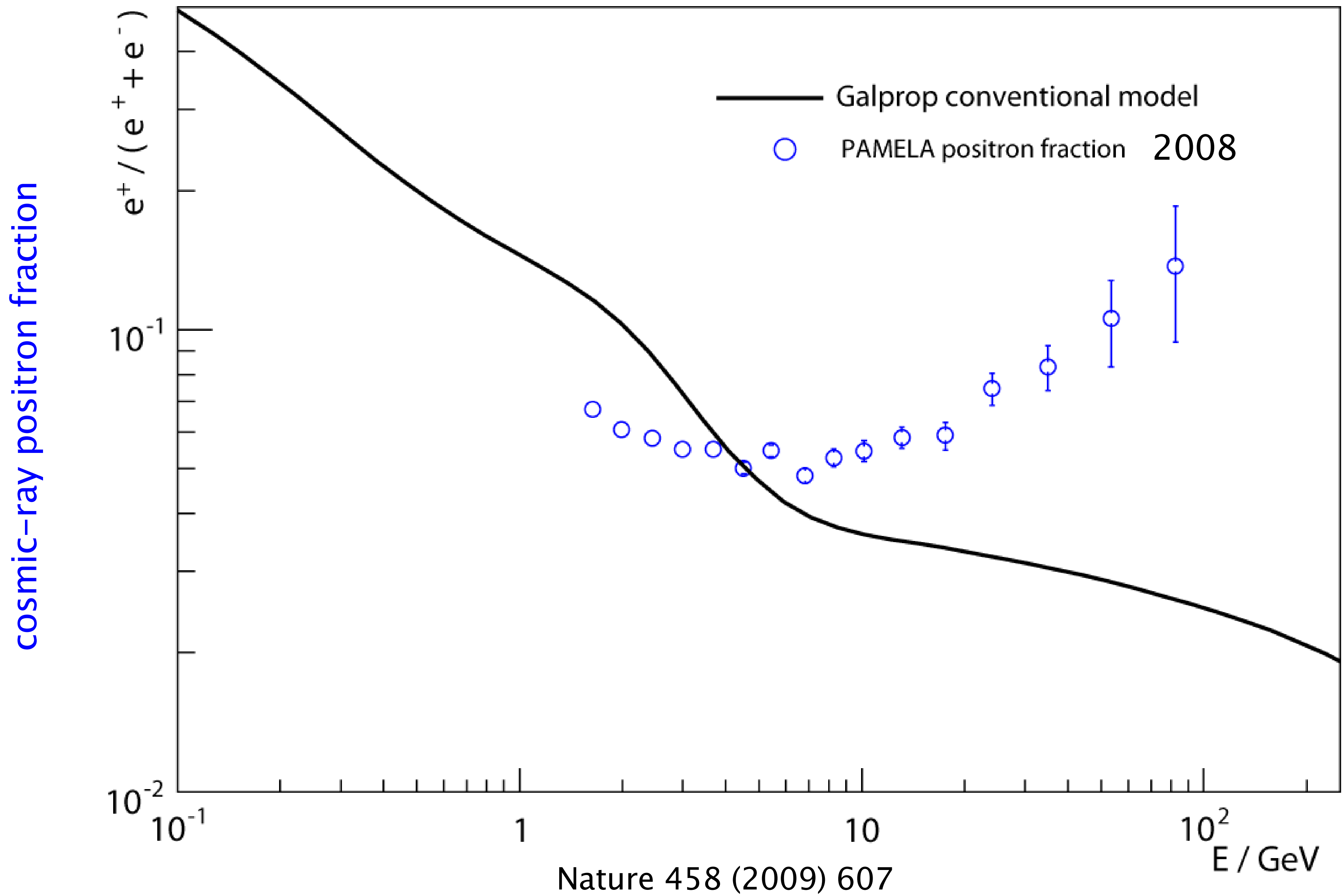
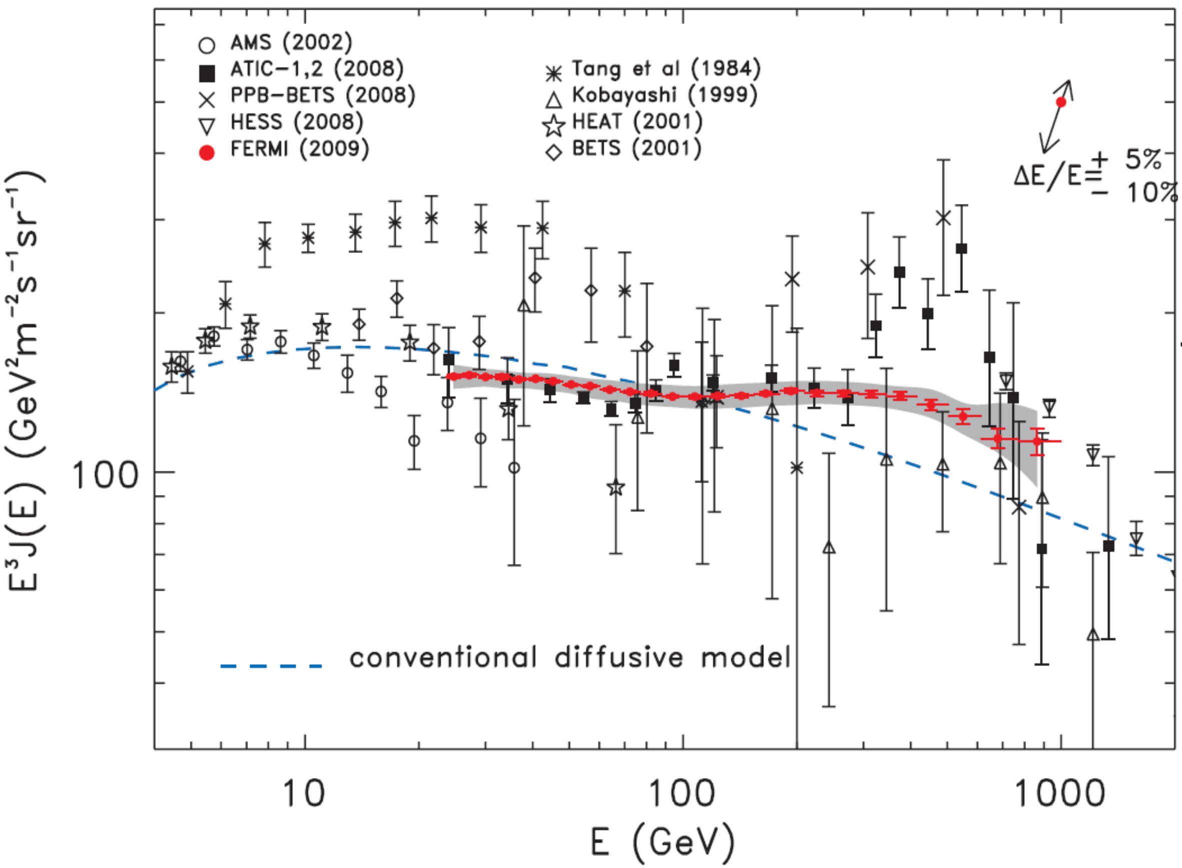
Dienstagsseminar – Aachen – 30 June 2009

Astrophysics or particle physics?



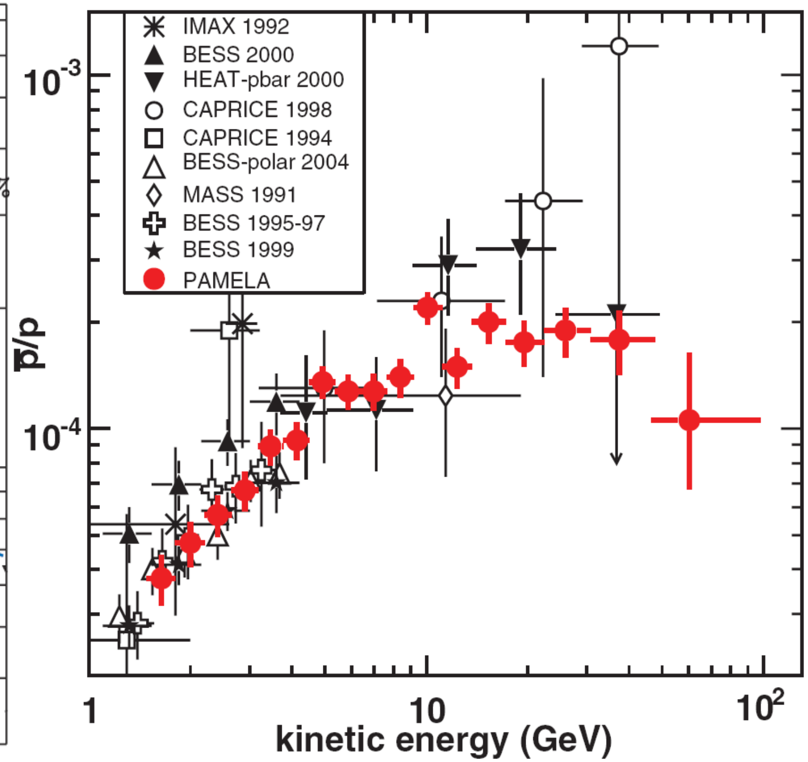
Astrophysics or particle physics?

cosmic-ray electron spectrum



PRL 102 (2009) 181101

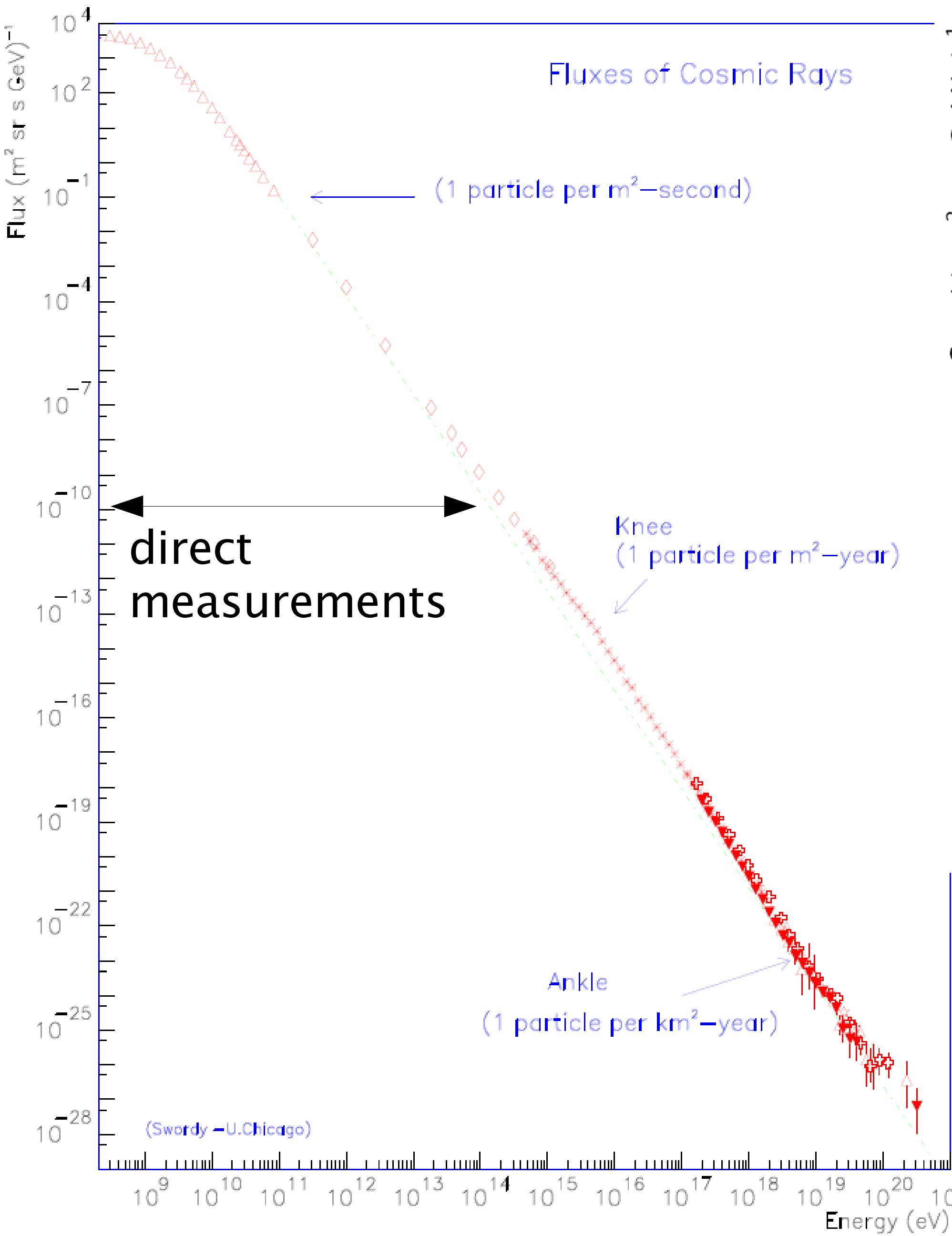
cosmic-ray antiproton ratio

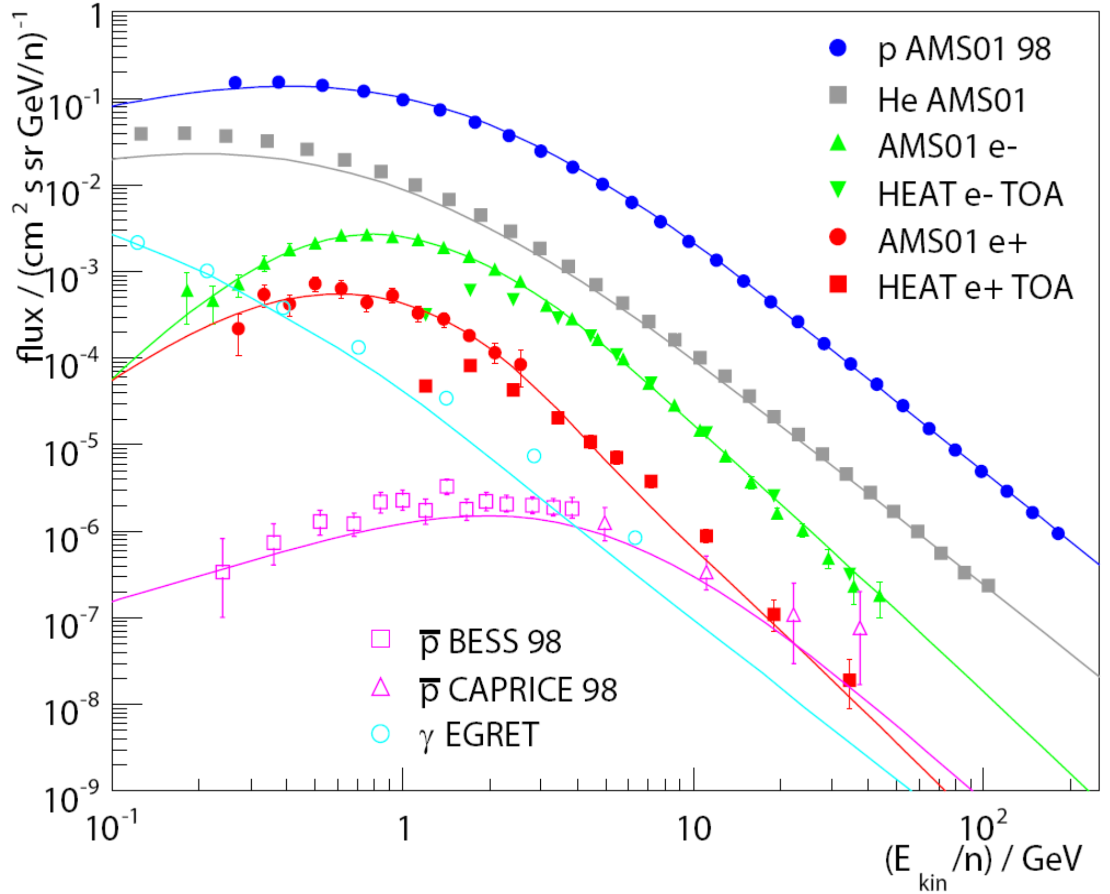


PRL 102 (2009) 051101

Outline

- Cosmic rays in the Galaxy
- A few recent developments: interpretation of positron/electron measurements
- A look at the PAMELA data: charge-sign dependent solar modulation
- PEBS (Positron-Electron-Balloon-Spectrometer): Taking the next step in positron-electron spectroscopy
- Performance study for the subdetectors of PEBS
- A look at mSUGRA parameter space in light of PAMELA and projections for PEBS





Figures of merit for positron measurement:

	exposure (m^2sr days)	proton suppression	energy reach
PAMELA	2	ECAL only	0.27 TeV
AMS	80	ECAL+TRD	0.8 TeV
PEBS	30/3 flights	ECAL+TRD	2 TeV

Cosmic-ray propagation

$$\frac{\partial \psi}{\partial t} = \underbrace{q(\vec{r},t)} + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left(\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right) - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

propagation equation:

source term, diffusion, convection, reacceleration, energy loss, fragmentation, decay

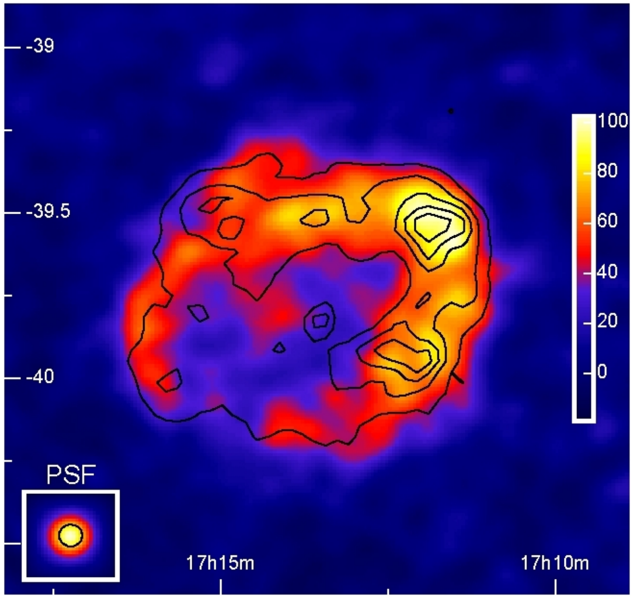
numerical solution: Galprop

primaries (protons, alphas, nuclei, electrons)

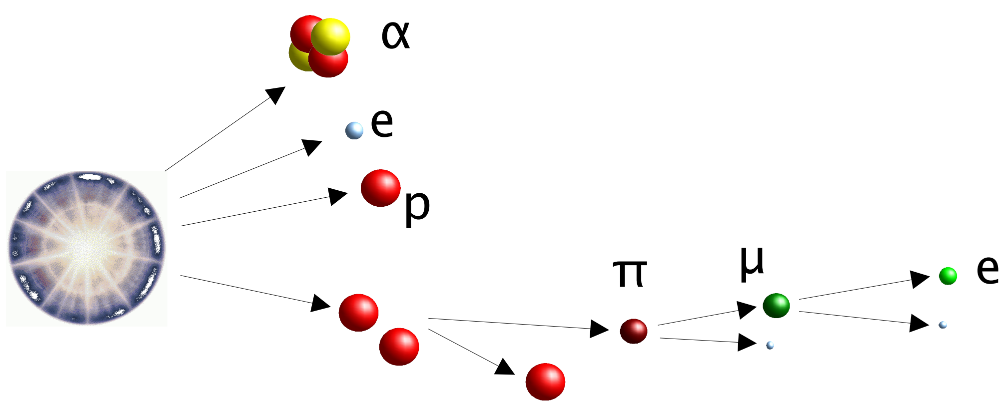
accelerated by first-order Fermi acceleration at supernova remnants? $\mathrm{d}q(p)/\mathrm{d}p \propto p^{-\gamma}$

secondaries (positrons, antiprotons, gammas, nuclei, ...)

produced in interactions of primaries with interstellar matter



Supernova remnant RX J1713.7−3946 H.E.S.S. observatory



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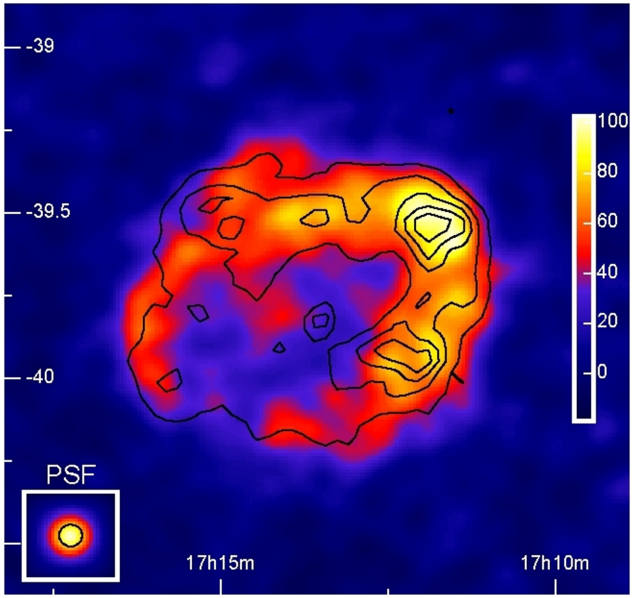

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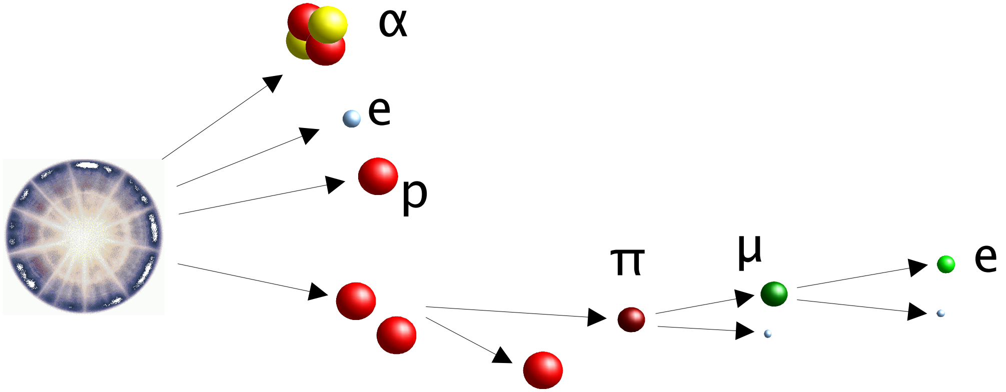

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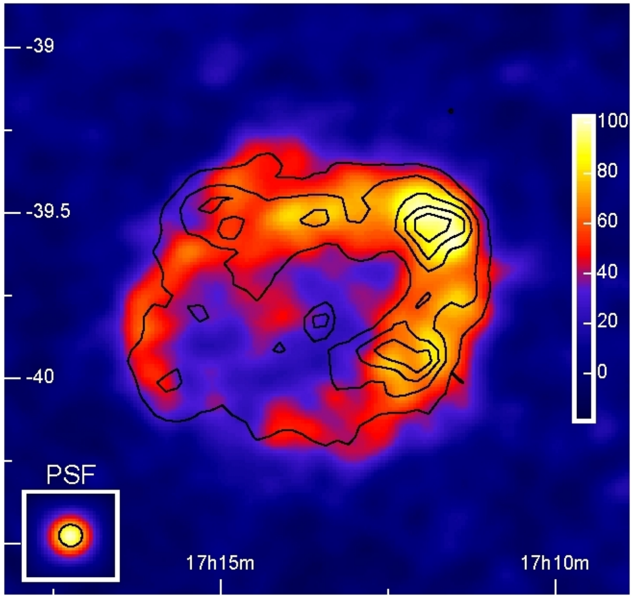

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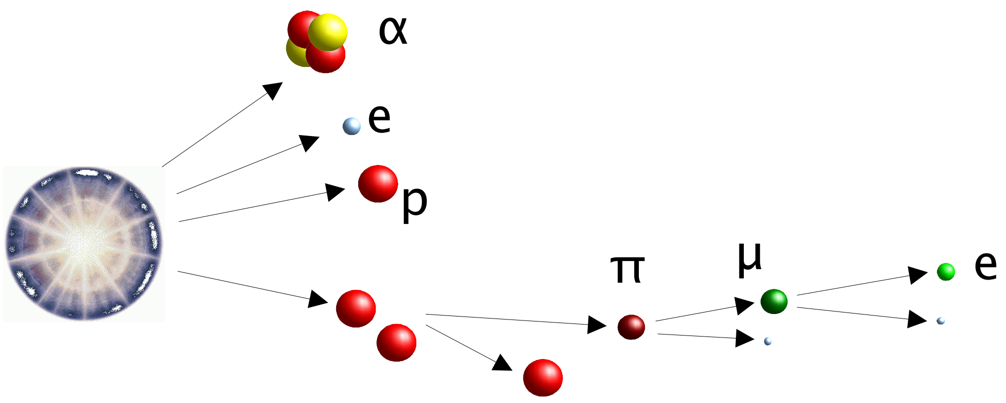

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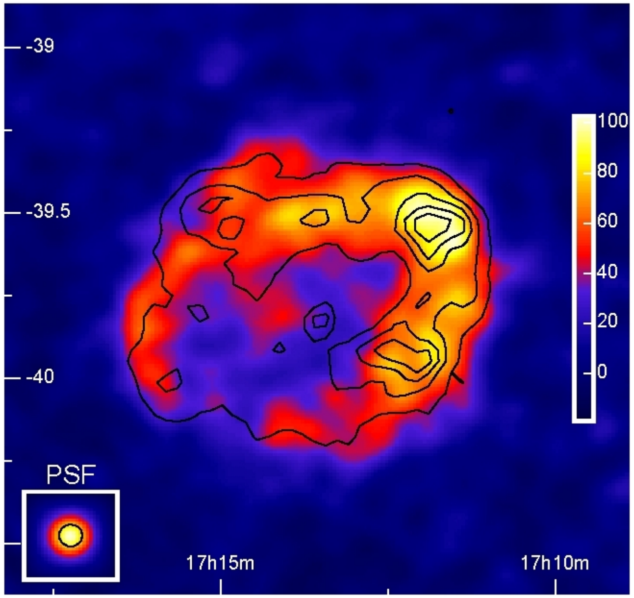

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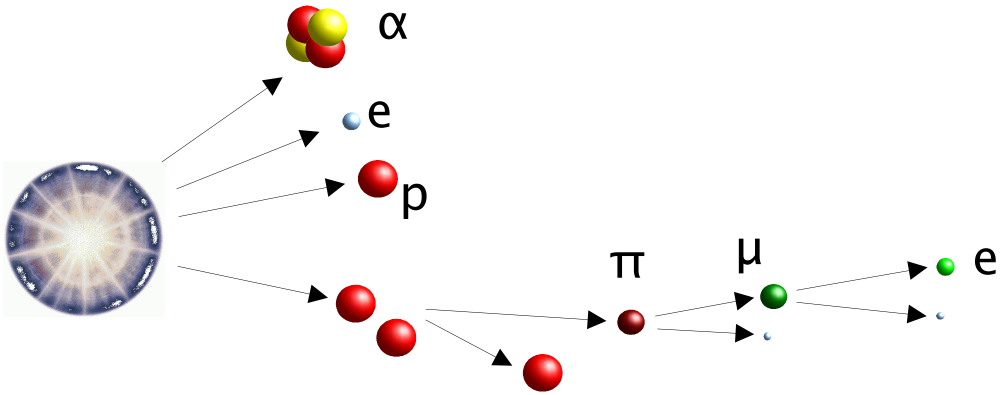

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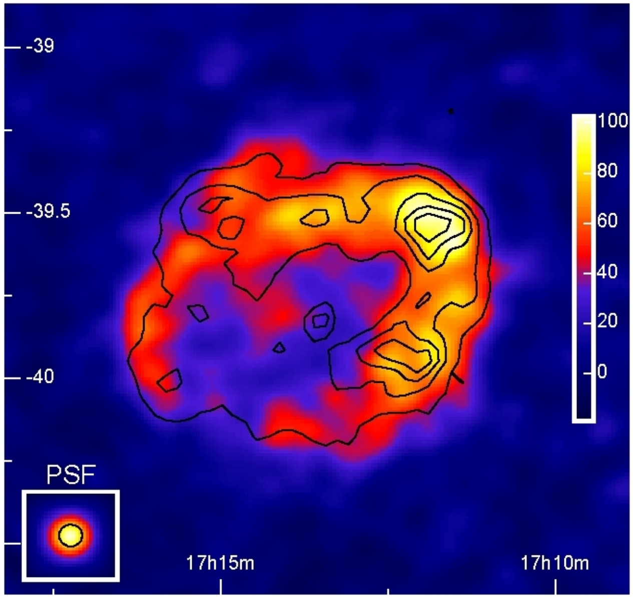

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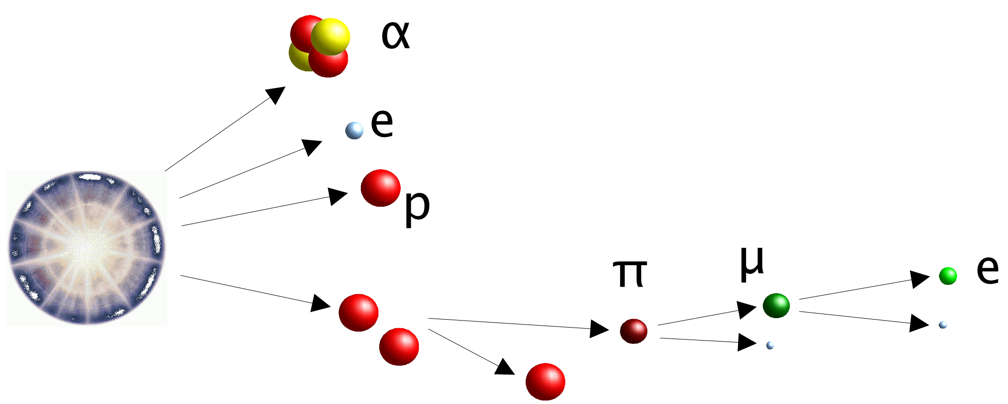

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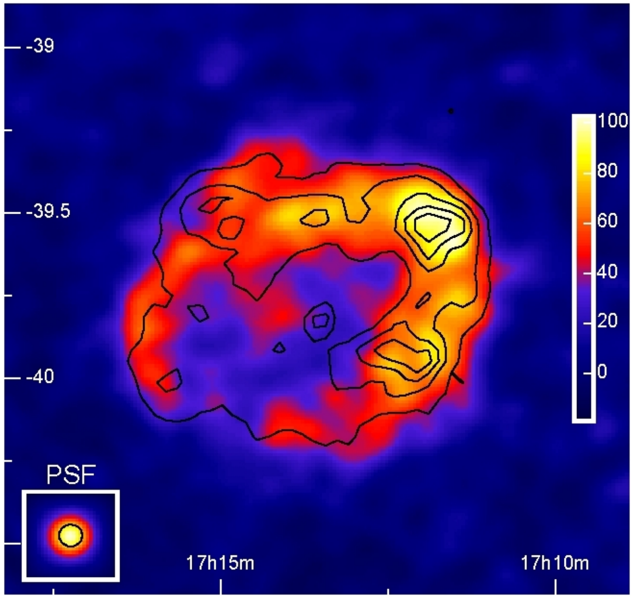

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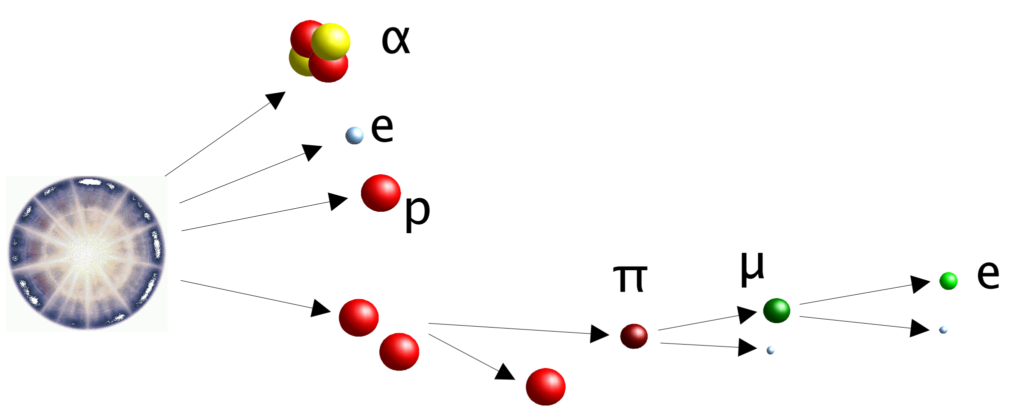

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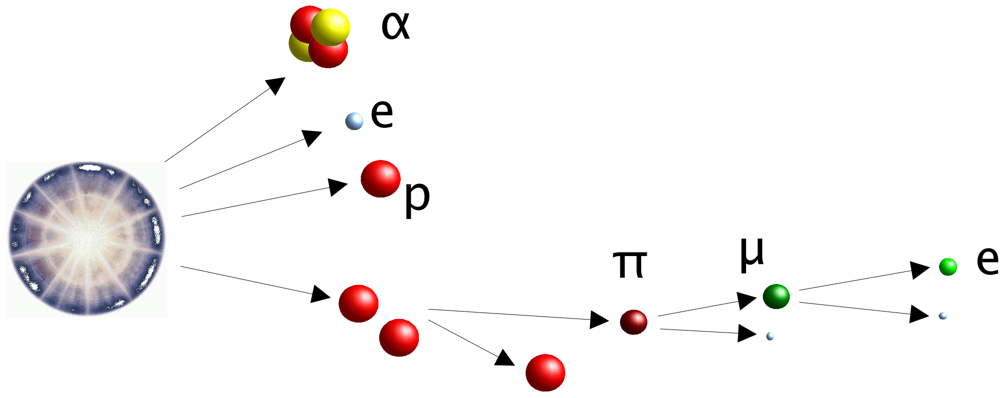

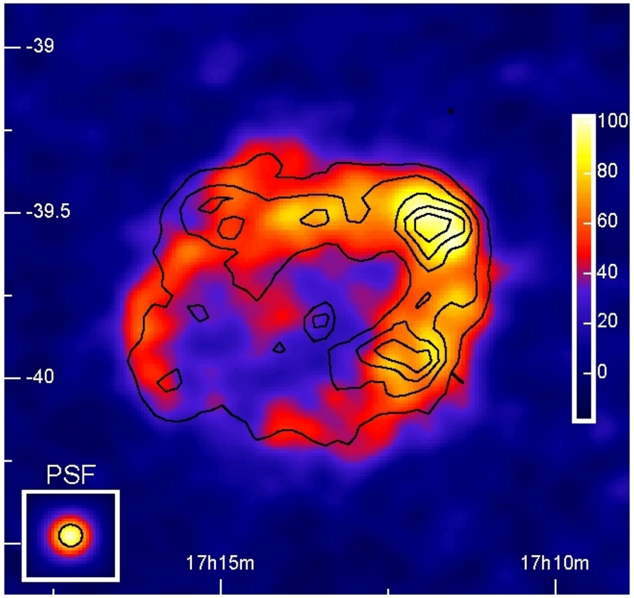

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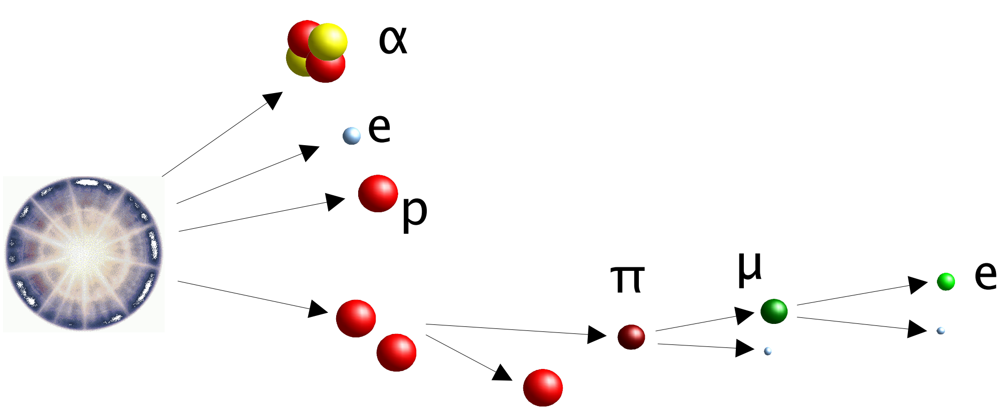

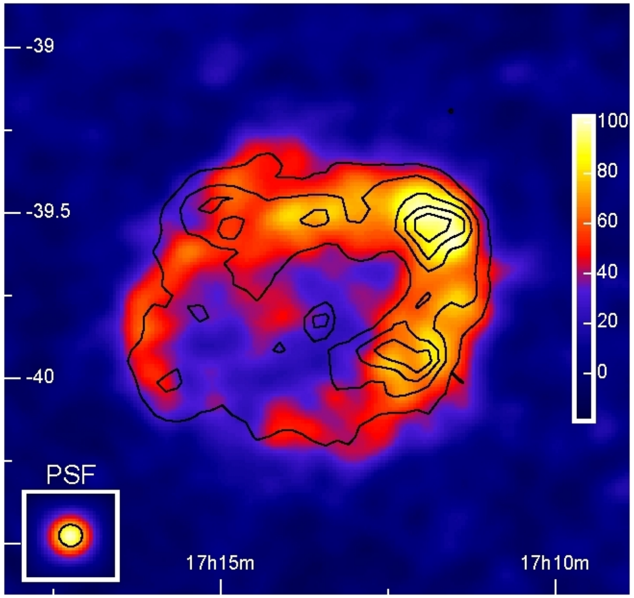

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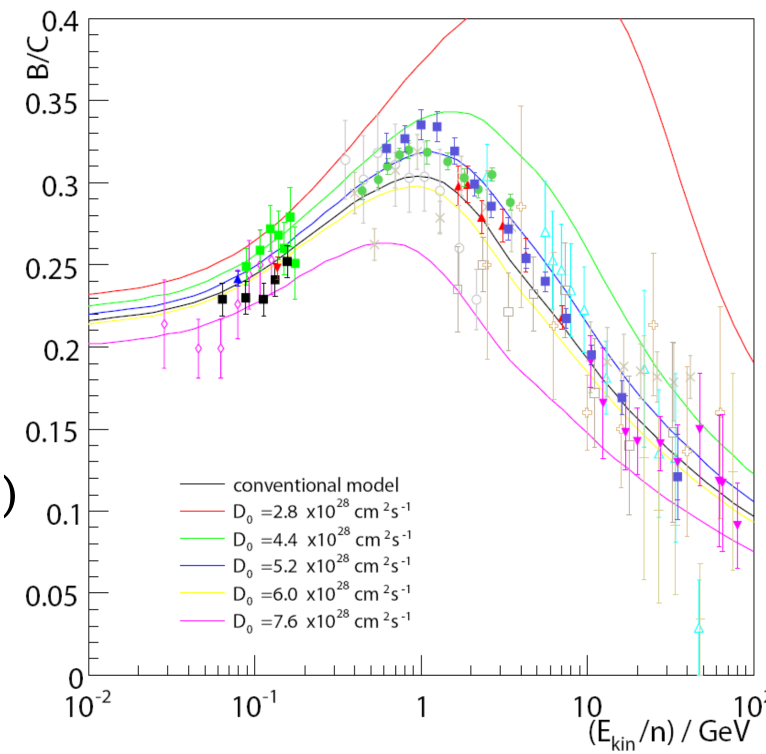
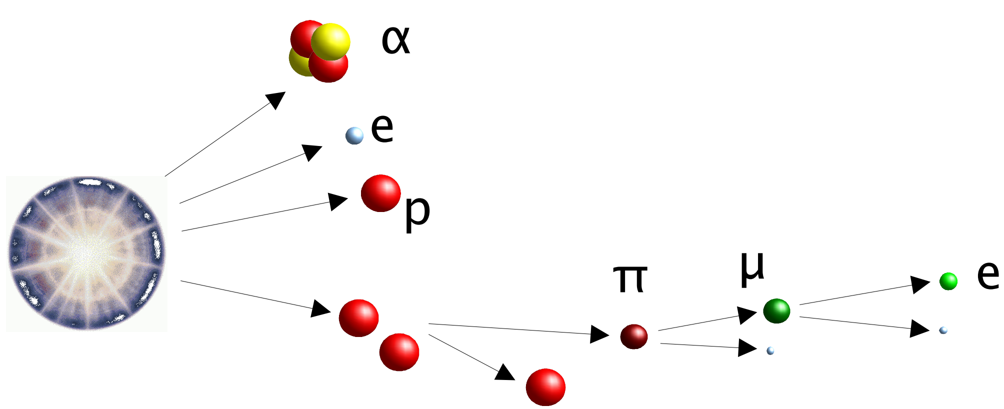
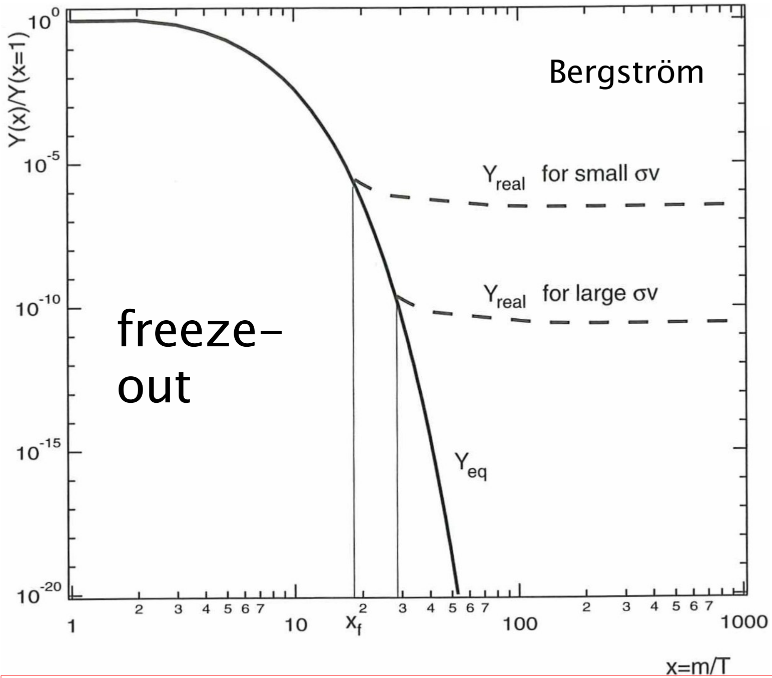


B/C ratio



Indirect search for dark matter: neutralino (SUSY)



$$\chi = N_{11}\tilde{B} + N_{12}\tilde{W}_3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

$$\Omega_\chi h^2 \approx \frac{3 \cdot 10^{-27}\,\mathrm{cm^3 s^{-1}}}{\langle \sigma v \rangle}$$

relic density

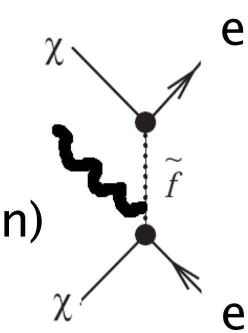
annihilation rate:

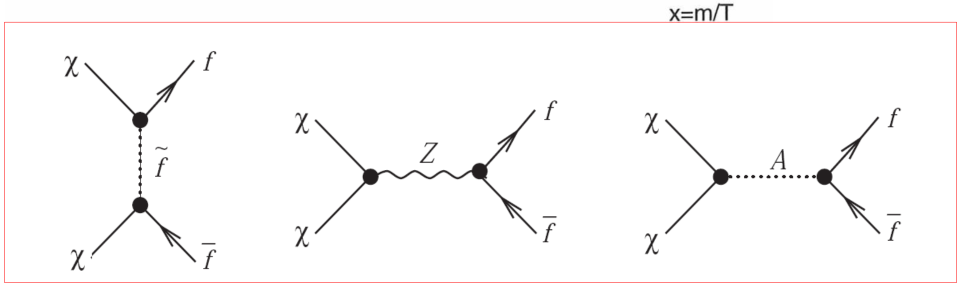
$$1/2(\rho_\chi(\vec{x})/m_\chi)^2 \sigma_{\rm ann} v$$

weak interaction:
typically σ~10^{-11} mb
freeze-out: v~0.3-0.4

Ω_{dm} = 0.228 ± 0.013

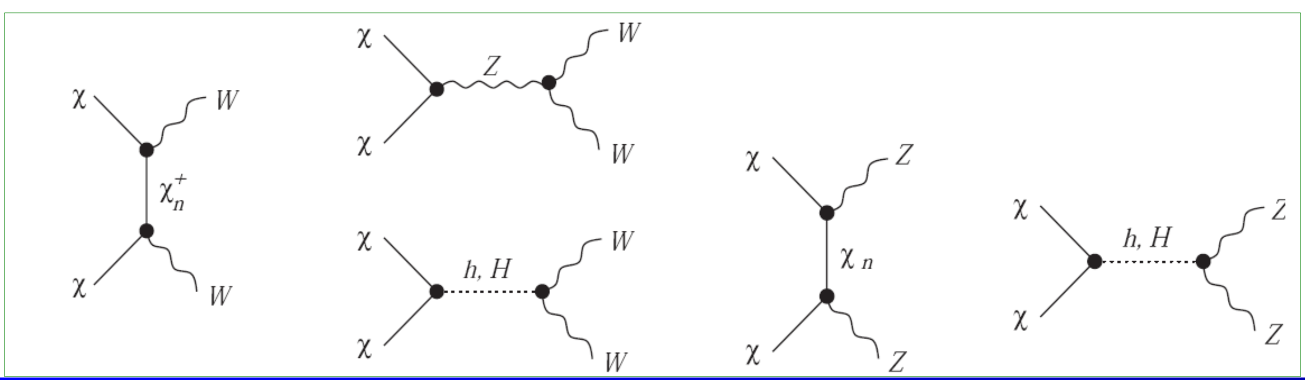
Internal Bremsstrahlung:
factor m_e (s-wave helicity suppression)
=> factor α/π

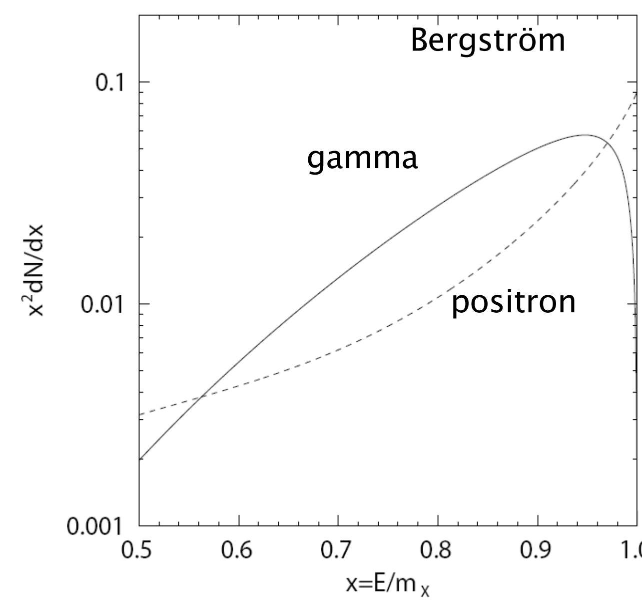




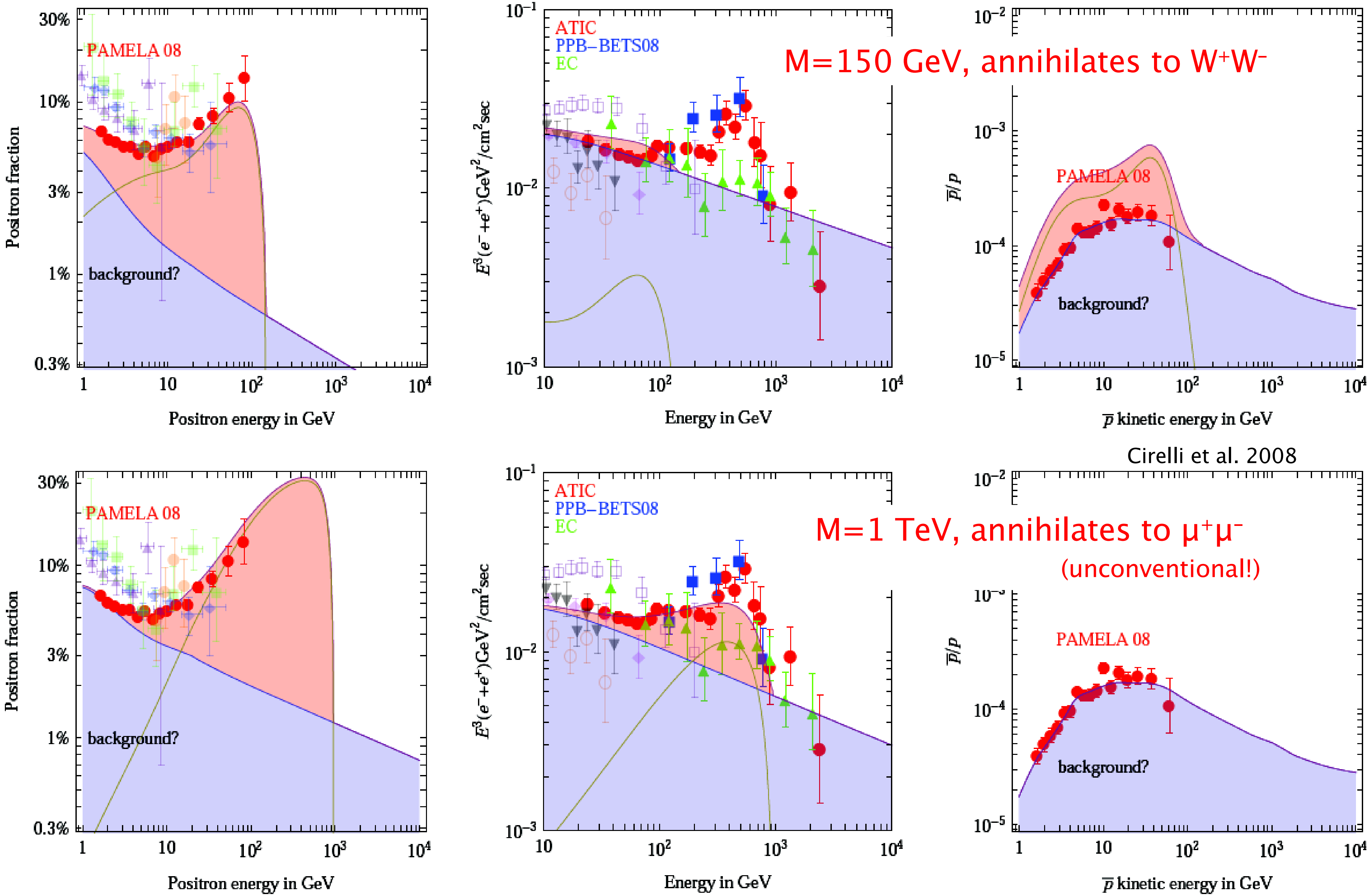
annihilation to fermions

annihilation to bosons



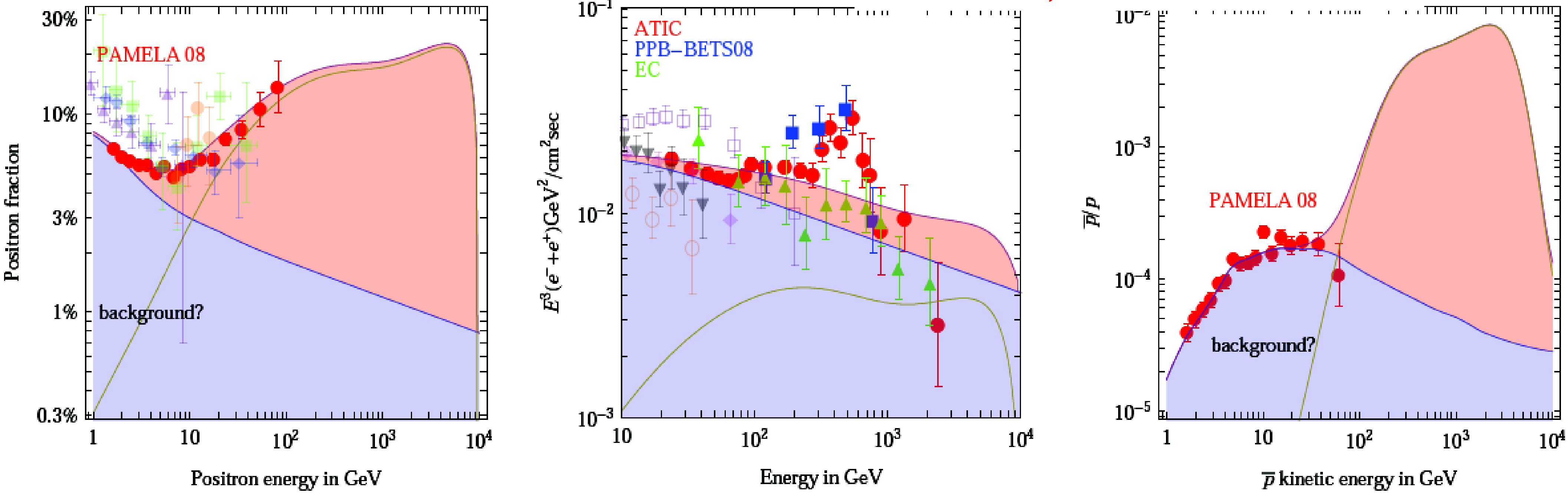


Exotic sources for positrons and electrons?



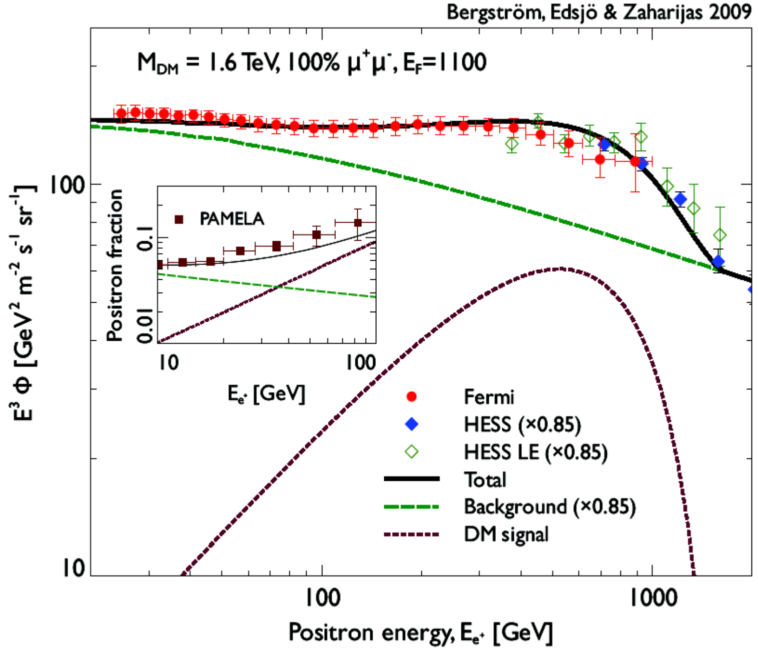
Explaining the positron and electron data

M=10 TeV, annihilates to W^+W^-



peak structure:
"smoking gun"
for exotic
contribution

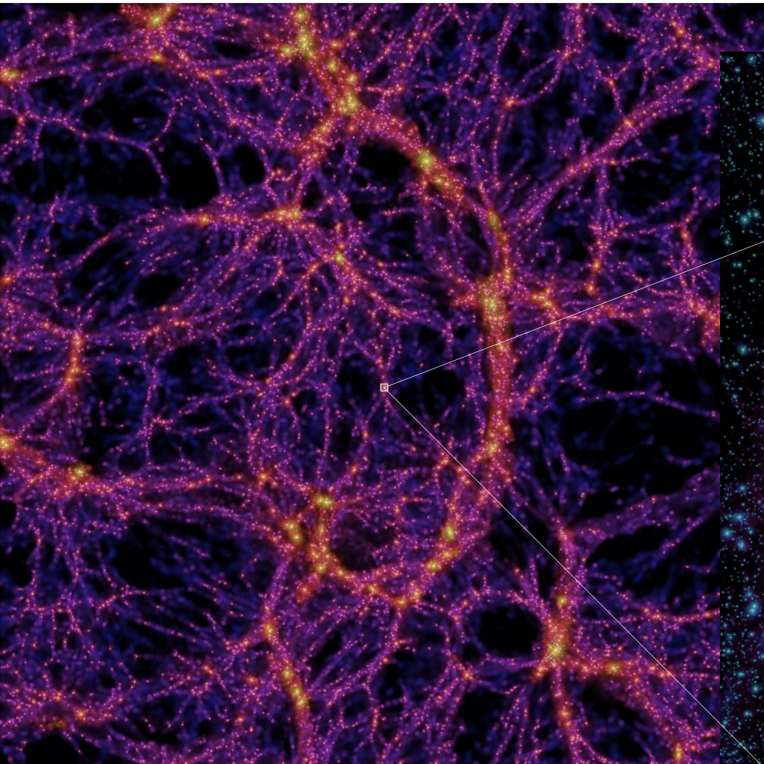
Bergström, Edsjö & Zaharijas 2009



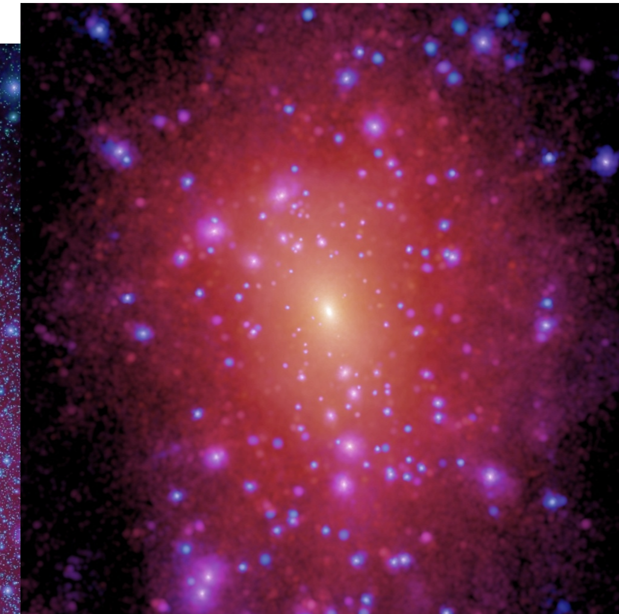
Cirelli et al. 2008

M_{DM}=10 TeV:
difficult to test at
the LHC

N-body simulations and boost factors



Aquarius simulation (2008)

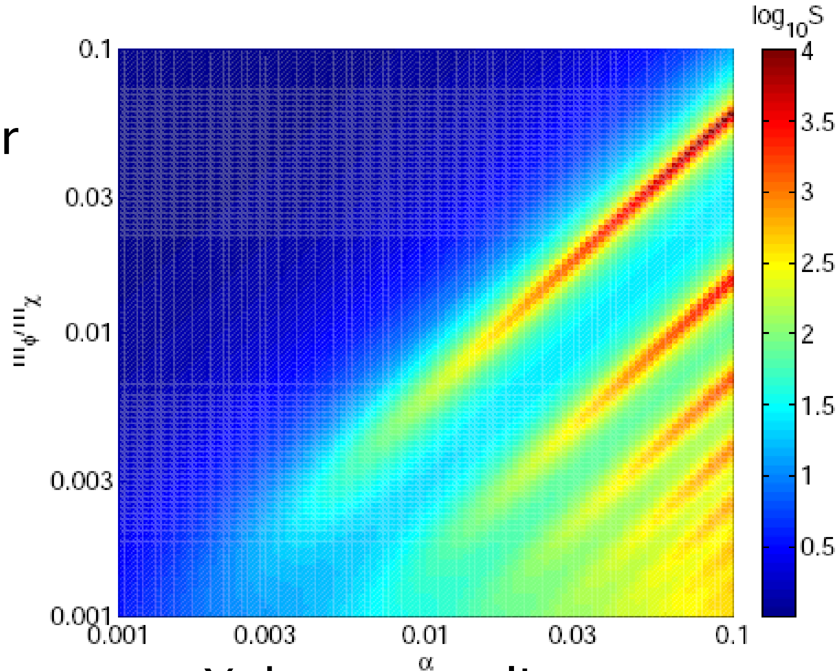


convergence test

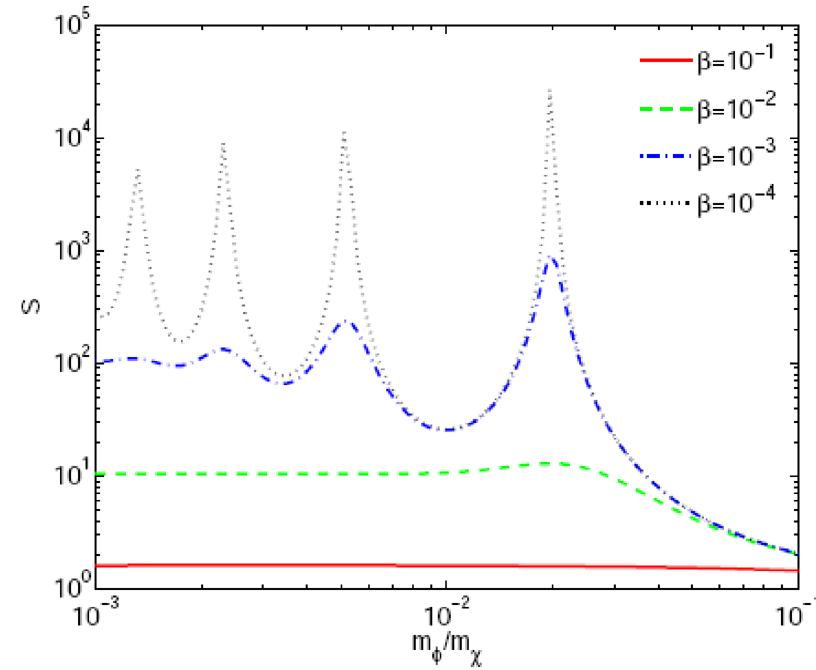
Enhancement factors to annihilation flux are attributed to clumpiness of dark matter distribution.
Generically: boost factors of O(1–10) from N–body simulations.

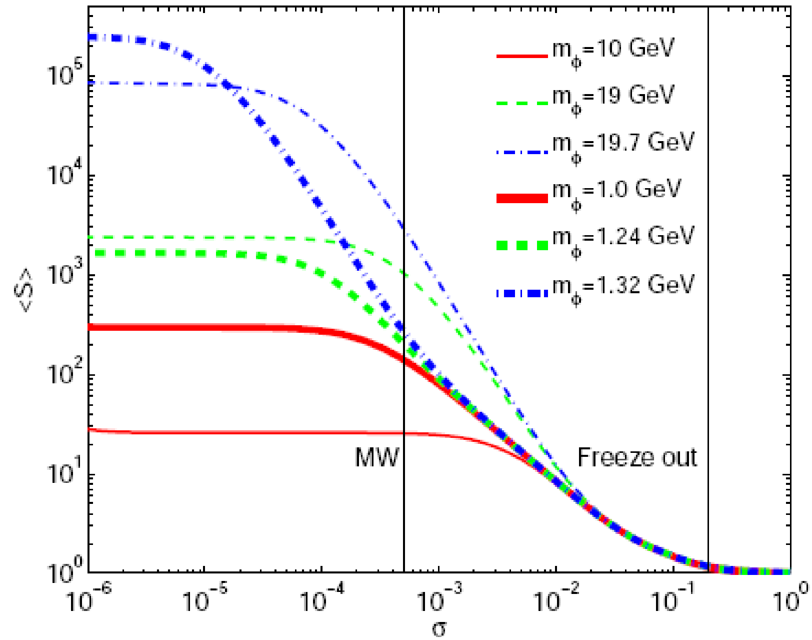
Sommerfeld enhancement

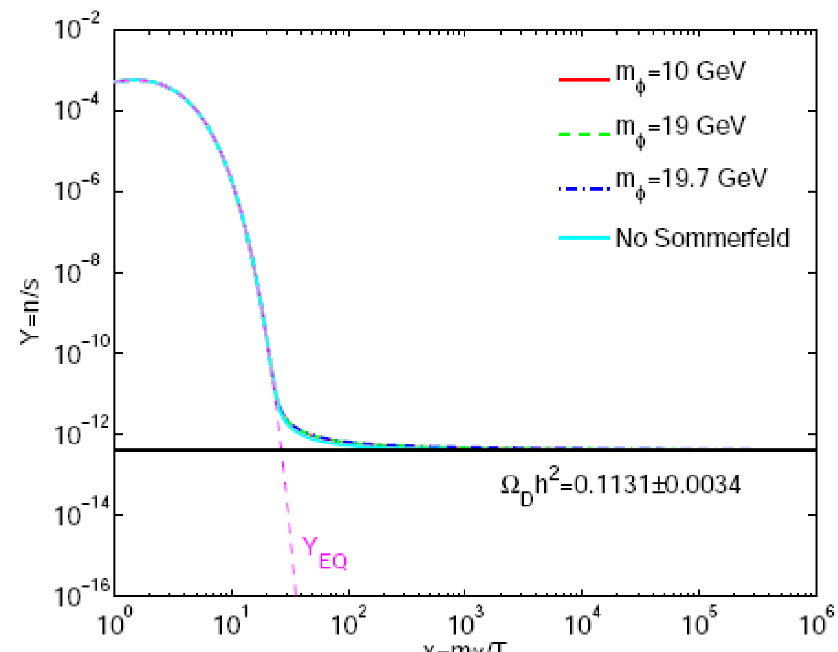
ϕ: force carrier exchanged by DM particles



Yukawa coupling constant



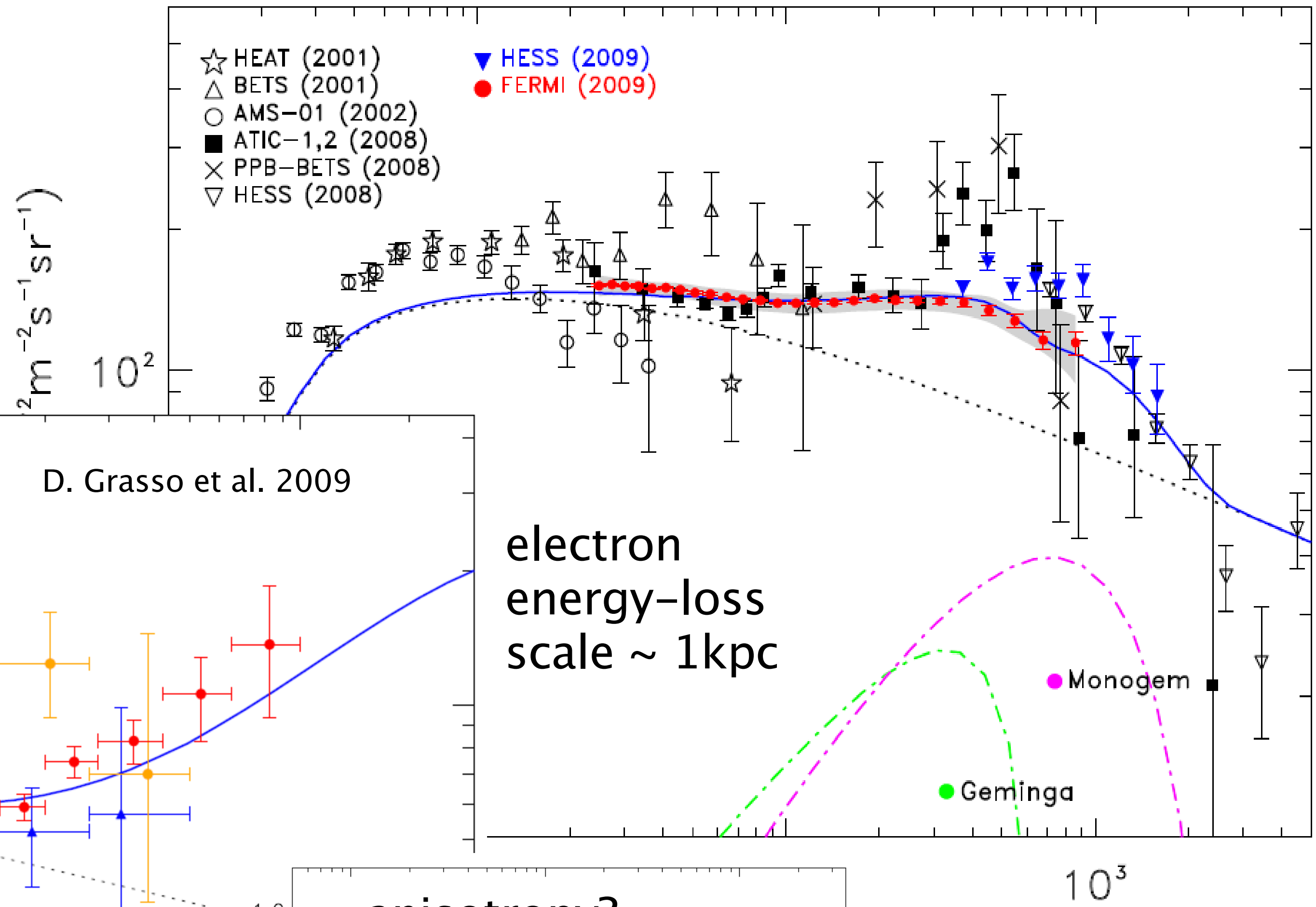


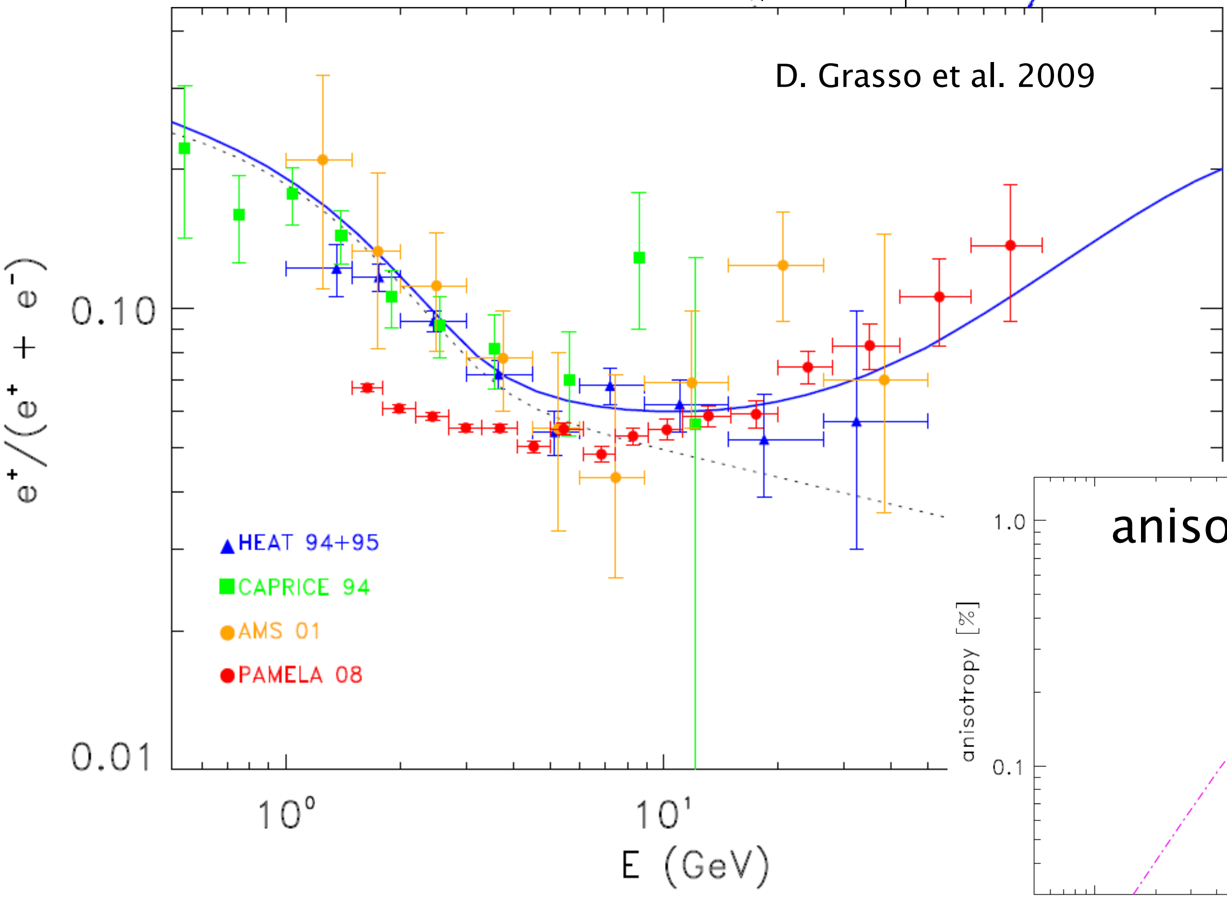


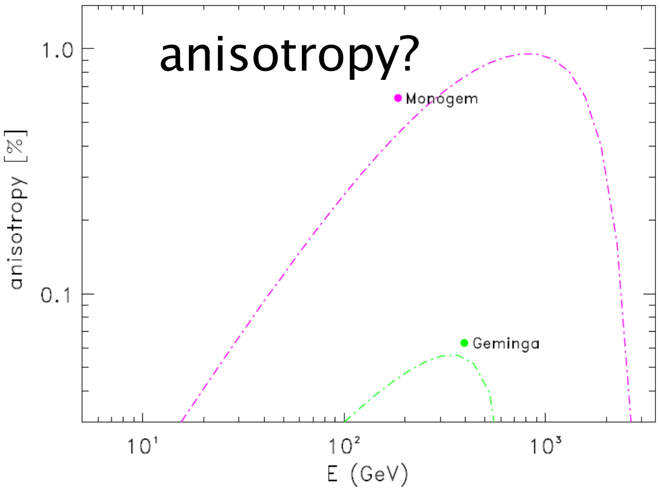
Yuan et al. (2009)

Astrophysical explanation

nearby young pulsars:
electrons are accelerated in quasi-static electric fields in the magnetosphere
→ synchrotron photons
→ $e^{\pm}$ pairs by pair production in the dense magnetic fields







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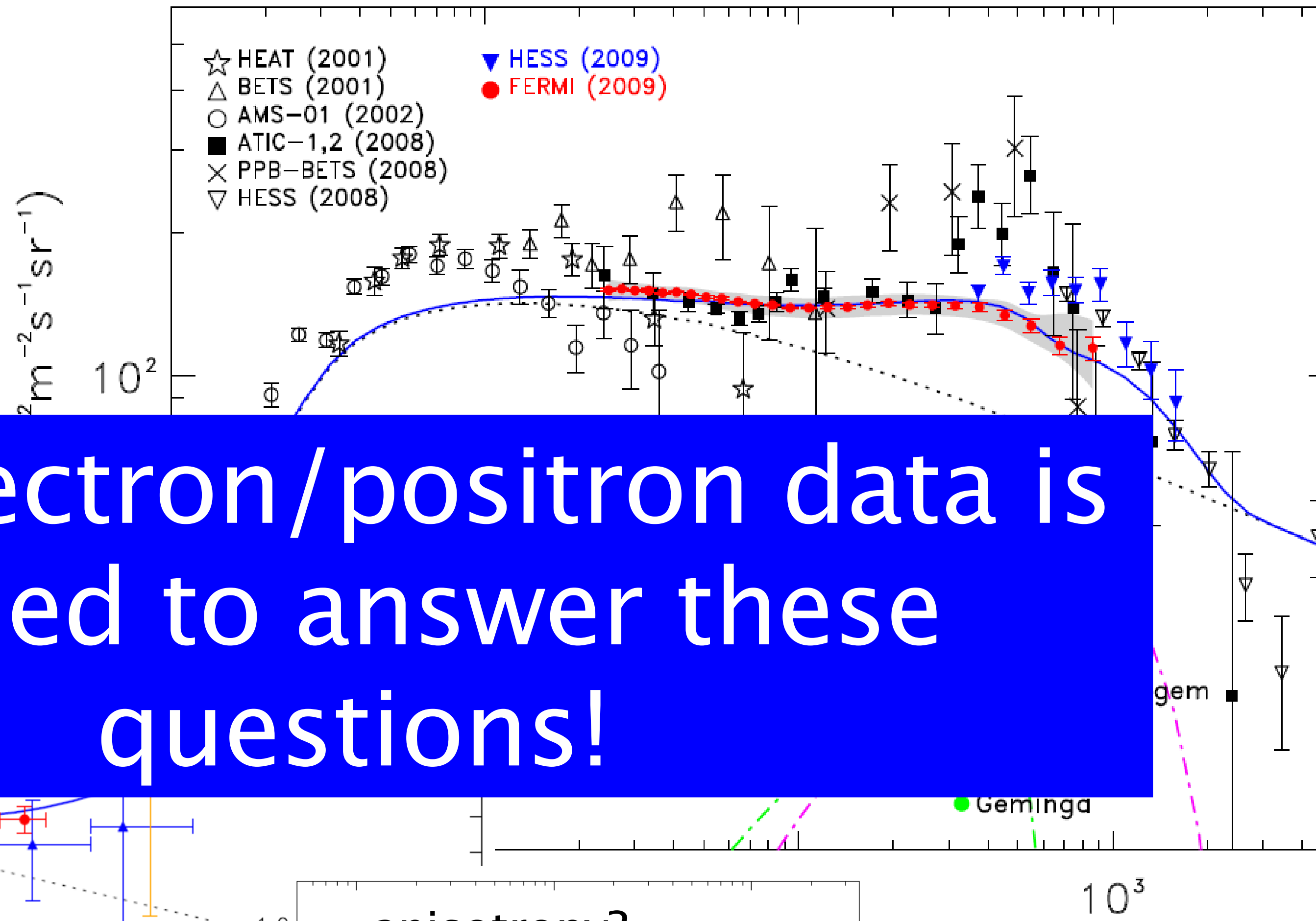
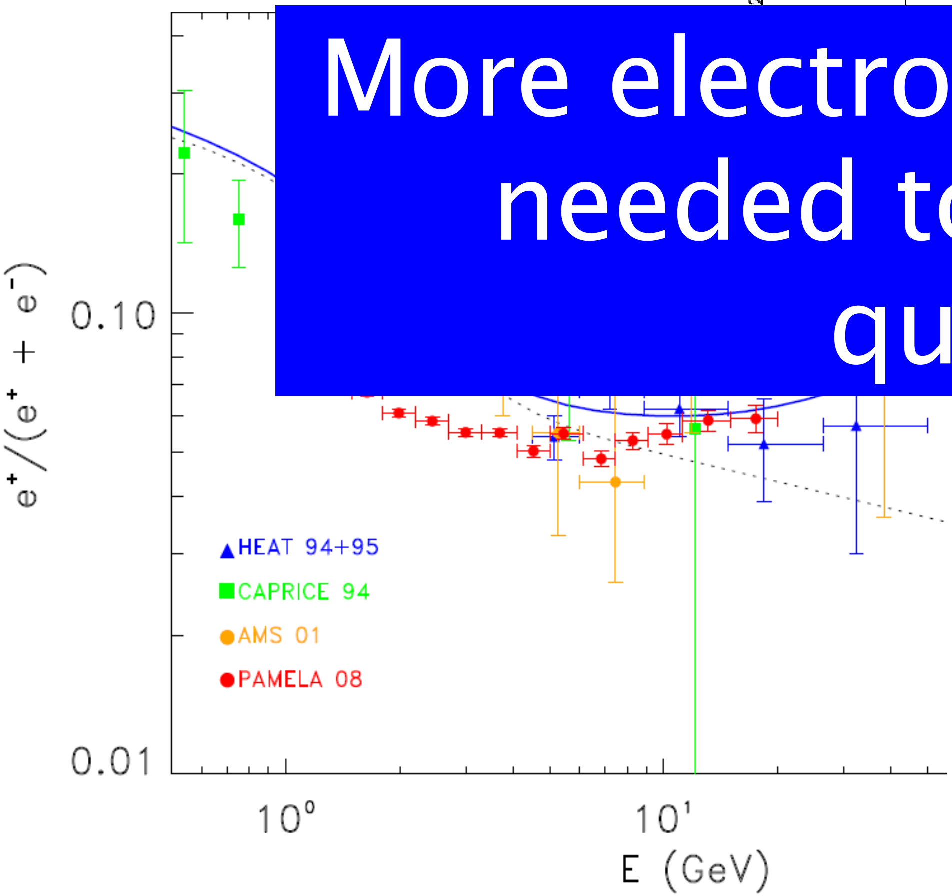
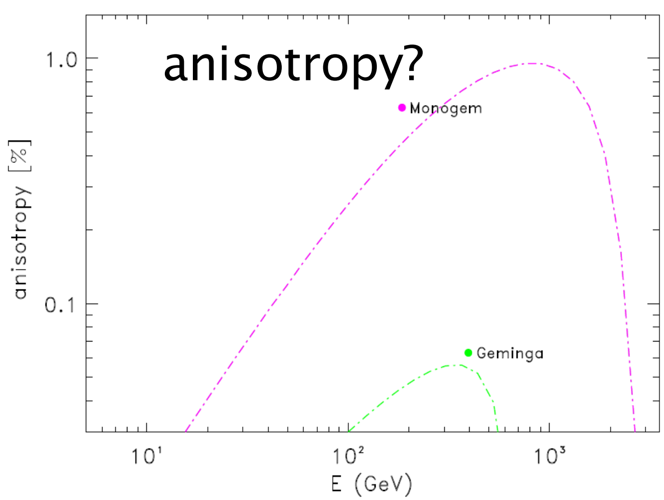
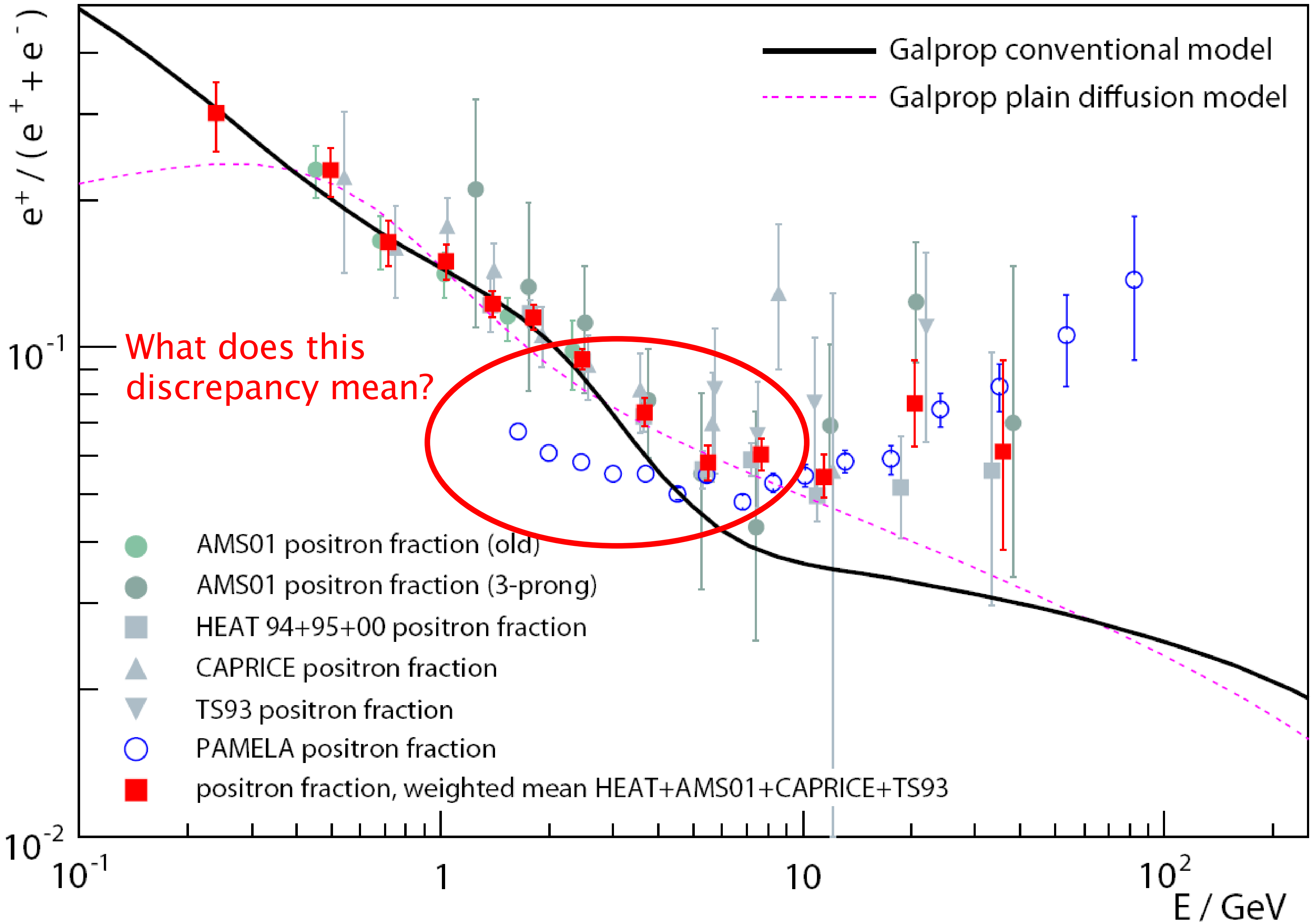




More electron/positron data is needed to answer these questions!

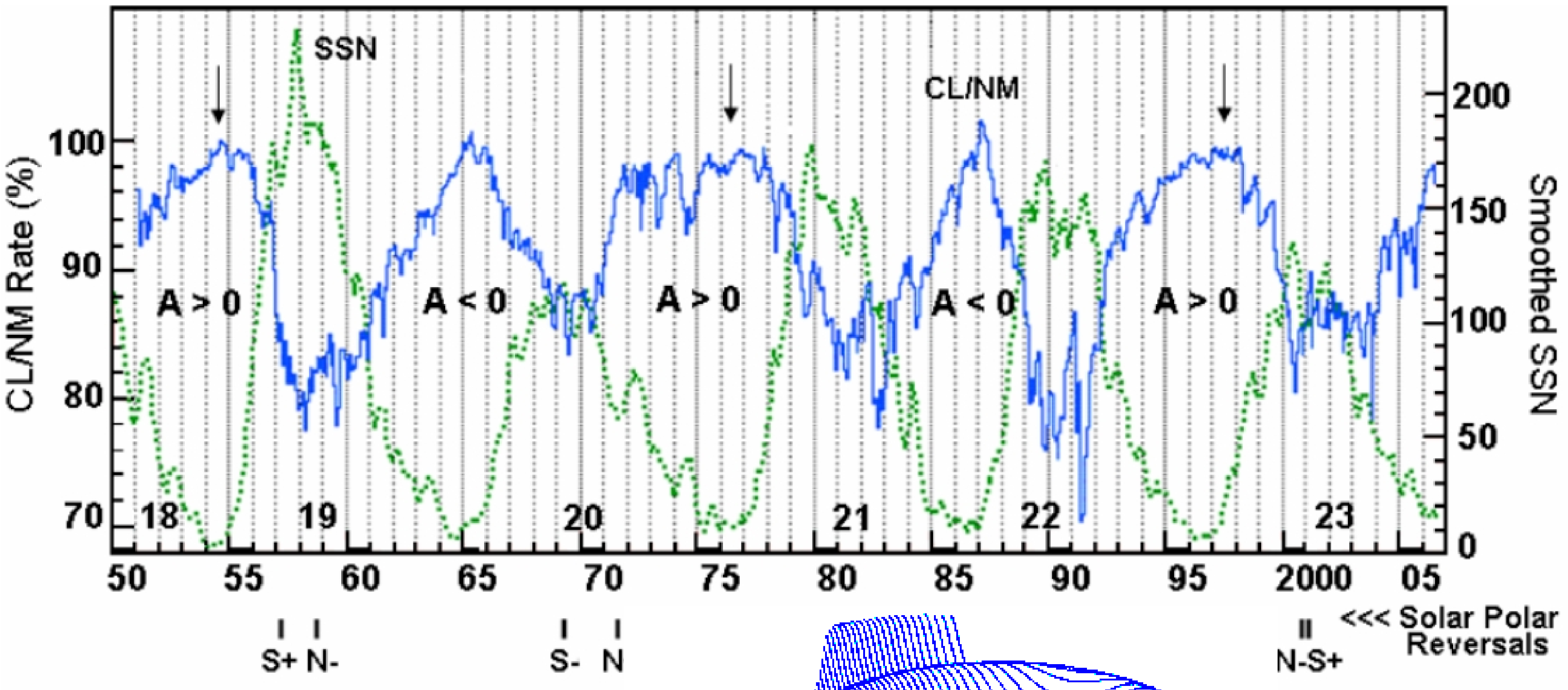


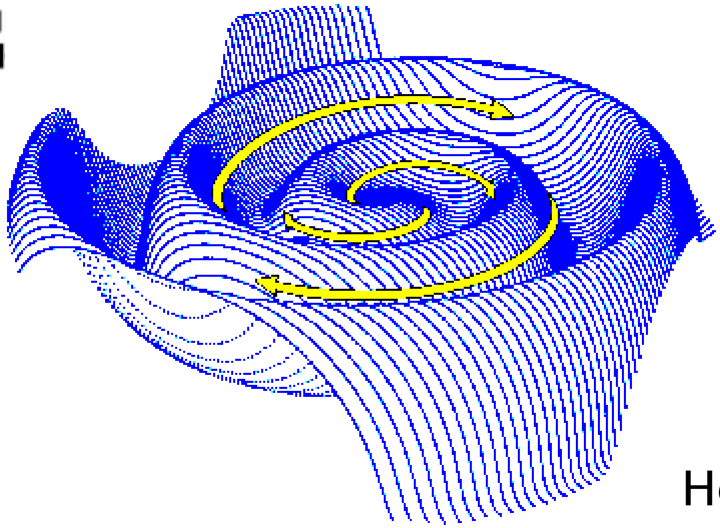
The anomaly in the positron fraction



Solar modulation

30th ICRC, 1, 493





Heliospheric current sheet

A simple model for charge-dependent solar modulation

general case: Parker equation (1965)

$$\frac{\partial f}{\partial t} = -(\boldsymbol{V} + \langle \boldsymbol{v_D} \rangle) \nabla f + \nabla (\boldsymbol{K}^{(S)} \nabla f) + \frac{1}{3} (\nabla \boldsymbol{V}) \frac{\partial f}{\partial \ln p}$$

$J = p^2 f$

- V solar wind velocity
- K diffusion tensor
- v_D related to antisymmetric part of diffusion tensor

force-field approximation (Gleeson and Axford, 1968):

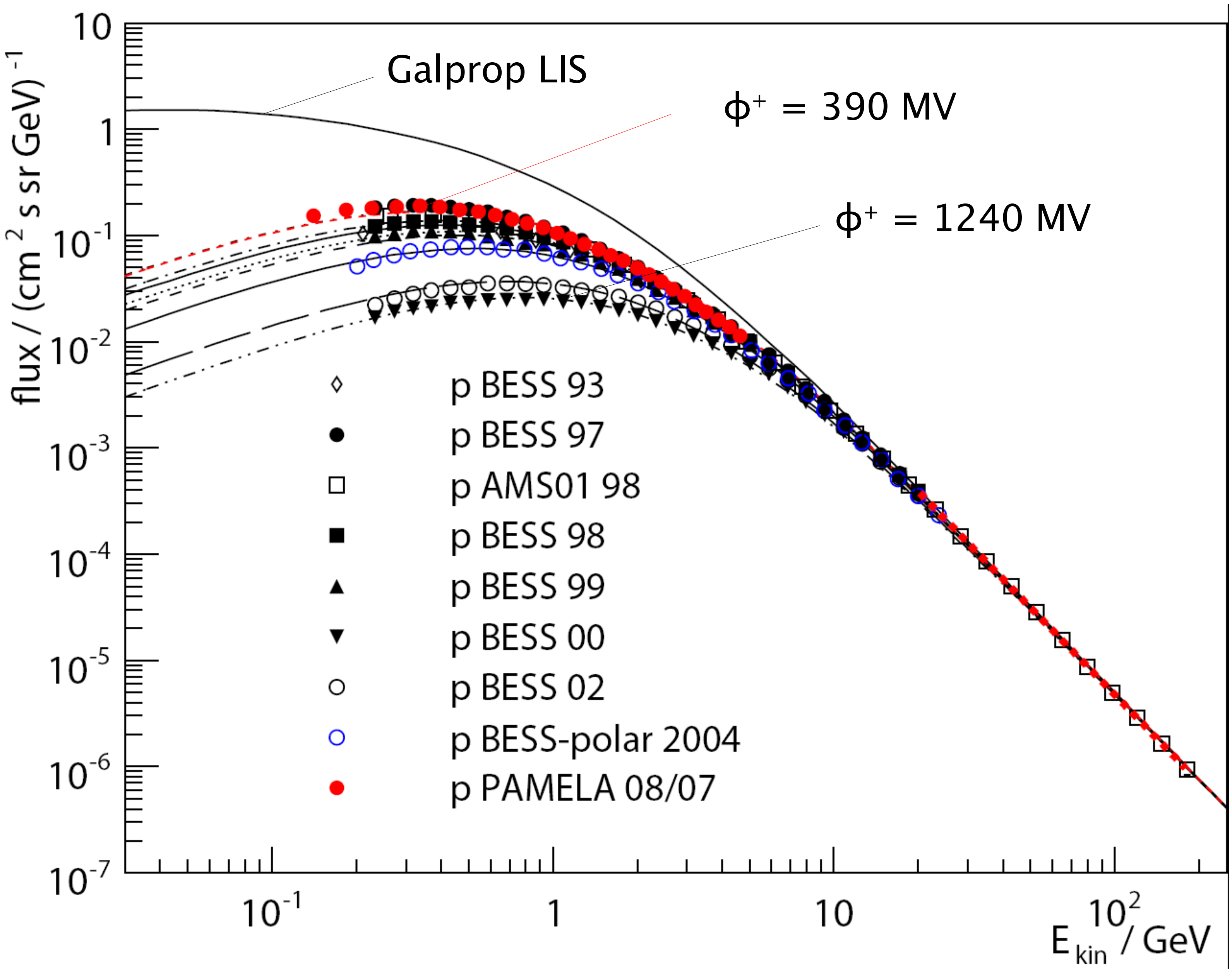
$$J(E) = \frac{E^2 - m^2}{(E + |z|\phi)^2 - m^2} \cdot J_{IS}(E + |z|\phi)$$

simple idea: allow different value of ϕ for positively and negatively charged particles

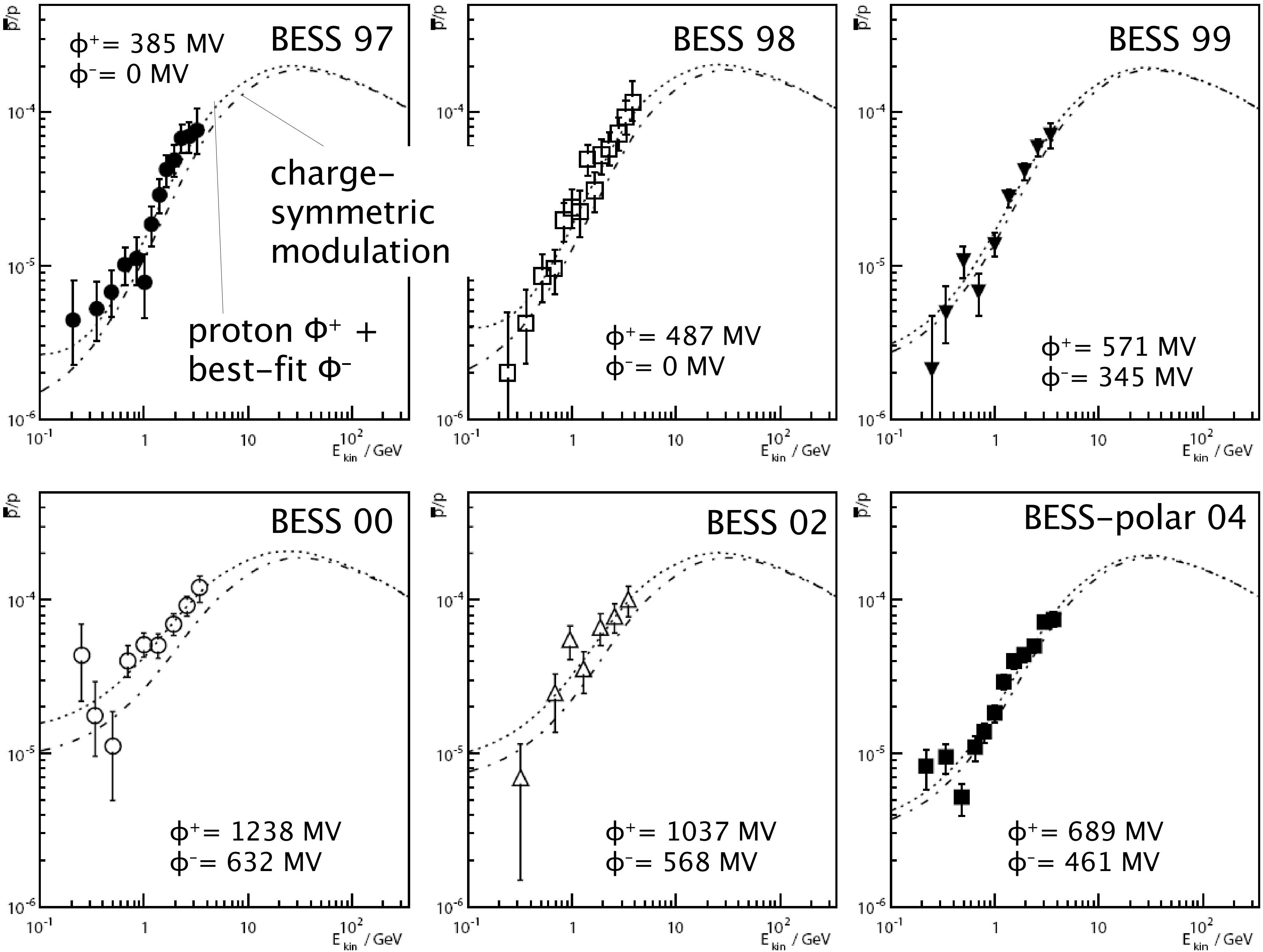
Galprop conventional model is used for the calculation of interstellar flux J_{IS} for all particle species

at low energies: geomagnetic cutoff effects complicate the picture

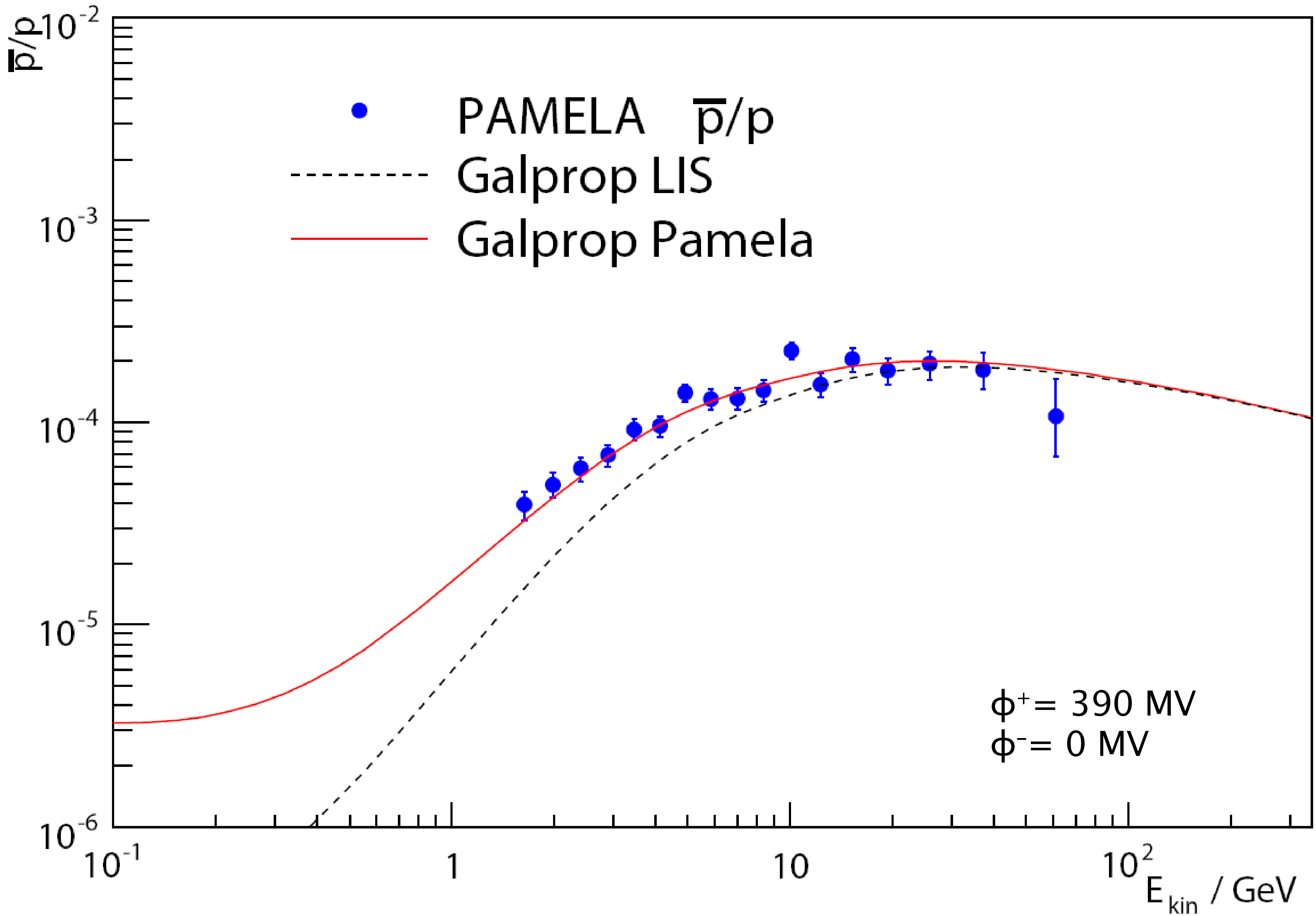
Modulated proton spectra



BESS antiproton/proton ratios

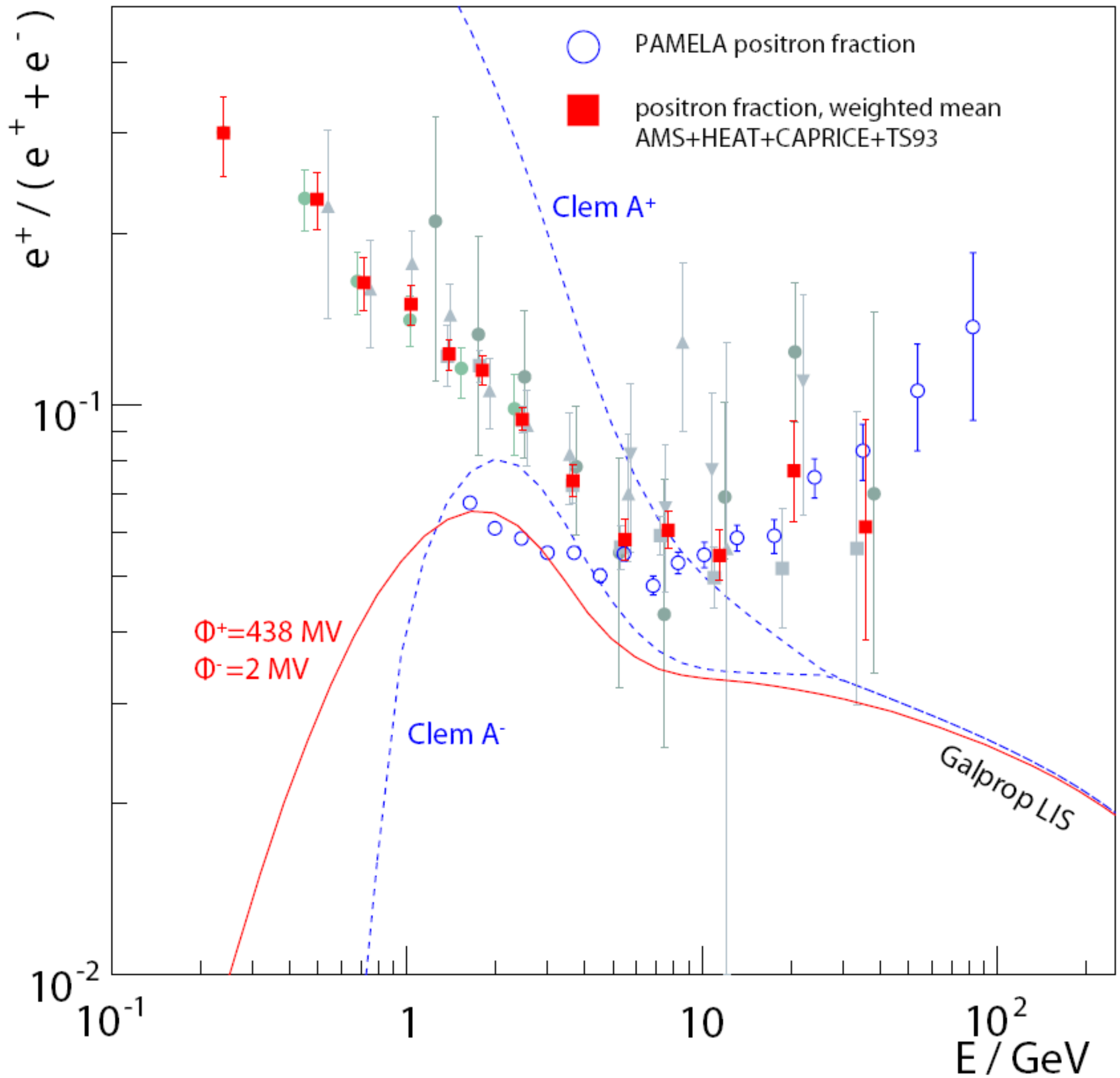


PAMELA pbar/p



Comparison to model by Clem et al.

$$f_E(P, \phi, qA) = C(qA, P) \times M(P, \phi) \times f(P)$$

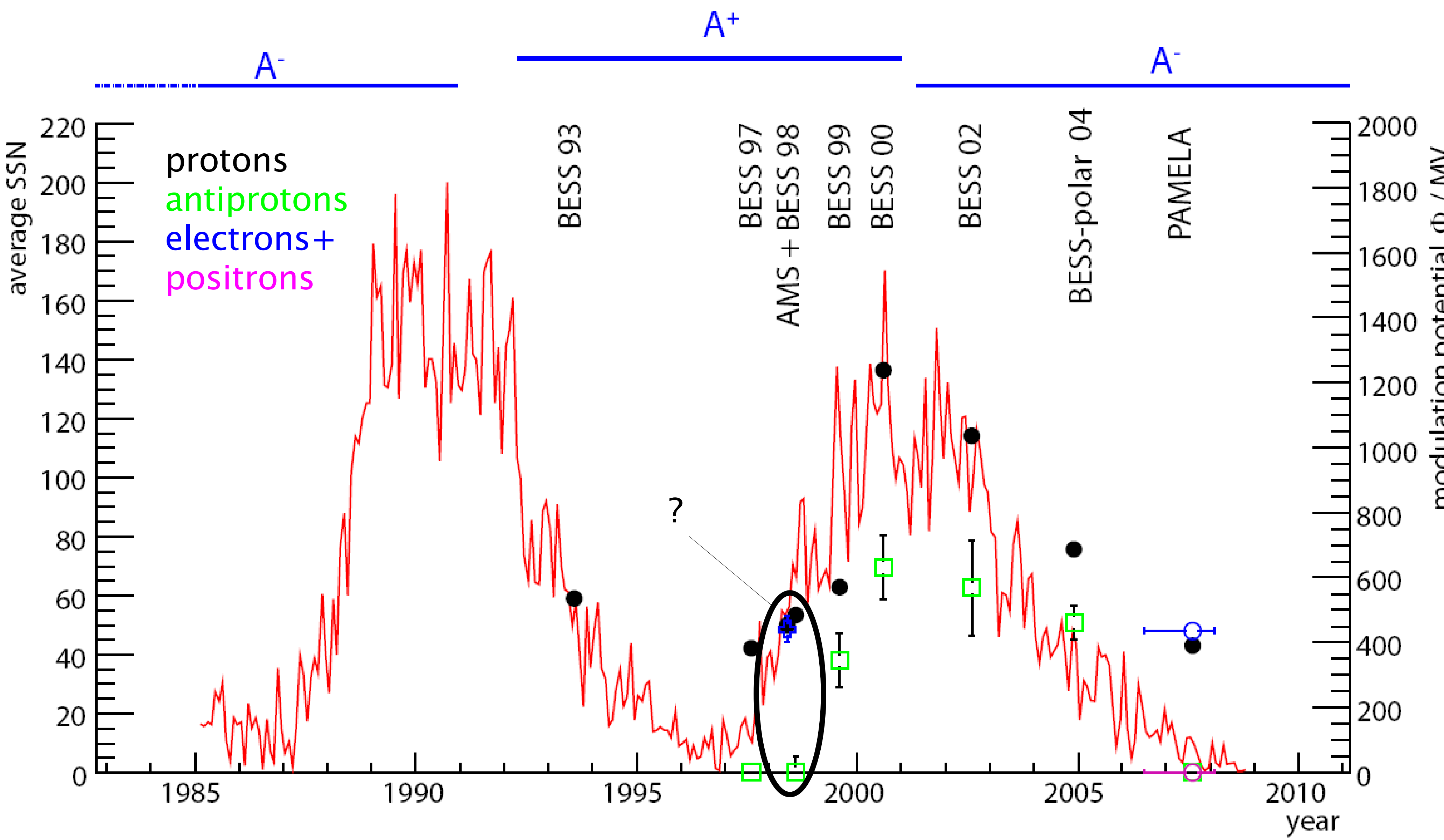


Clem et al.,
ApJ **464** (1996) 507

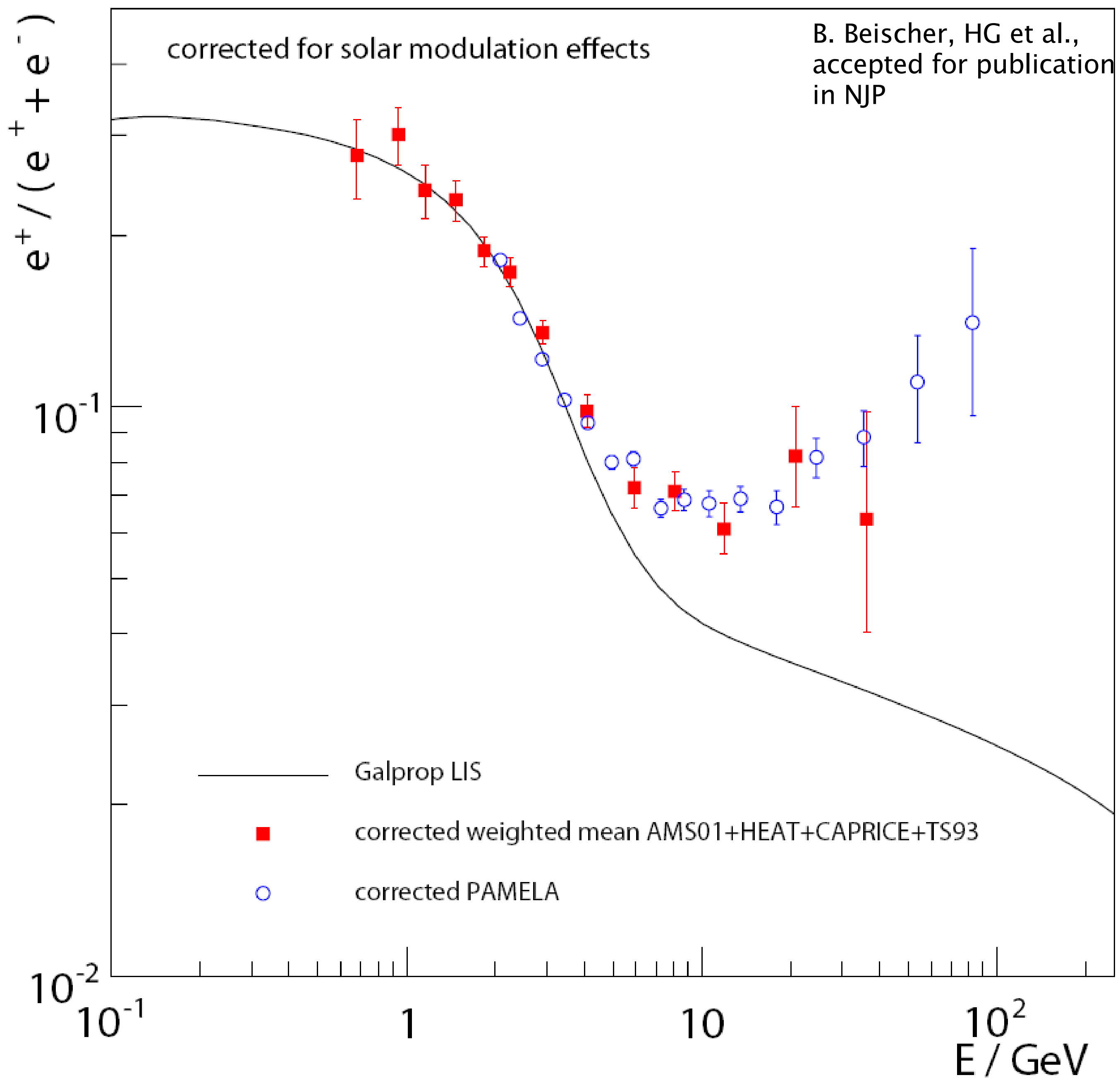
q: charge
A= ±1:
orientation of
solar dipole
Φ: generic phase
P: momentum

ϕ^+,ϕ^- from
p/pbar data
match!

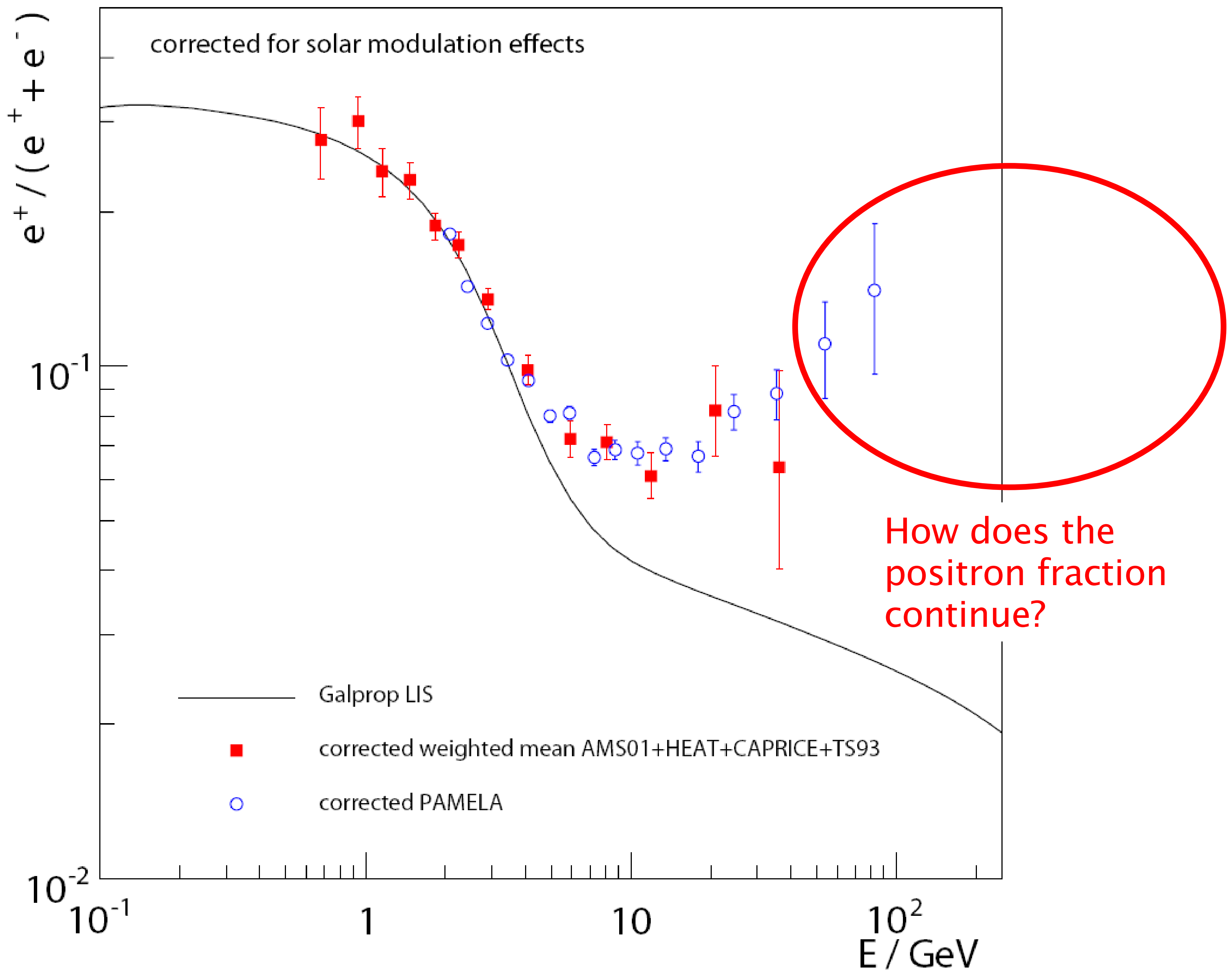
Correlation with sunspot number



positron fraction corrected



The anomaly in the positron fraction



AMS-02

S119E009662

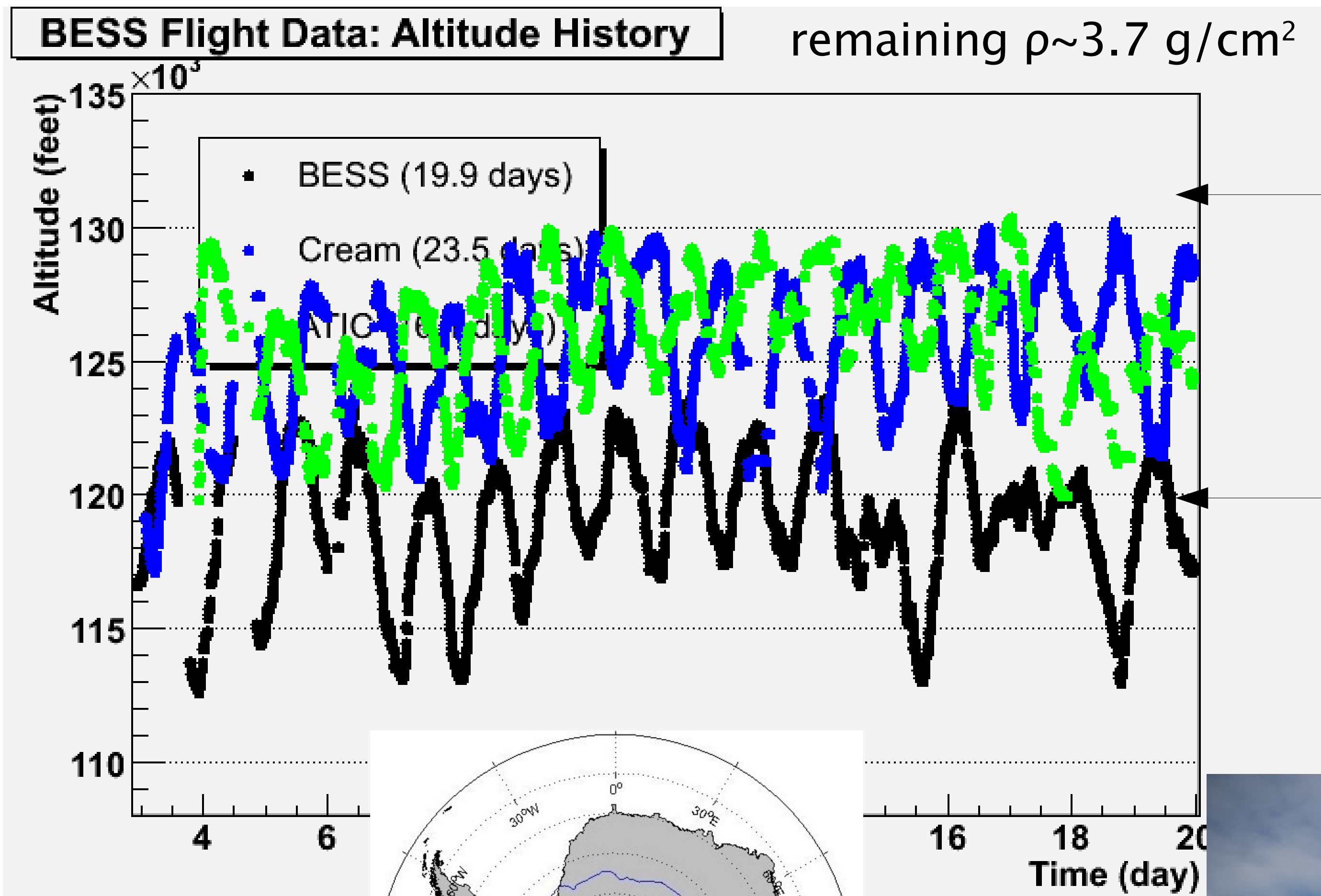
AMS on the International Space Station 2010–2013

Test assembly of AMS–02 at CERN

15 years construction time
USD 1,500,000,000 total cost

Physics program after AMS?

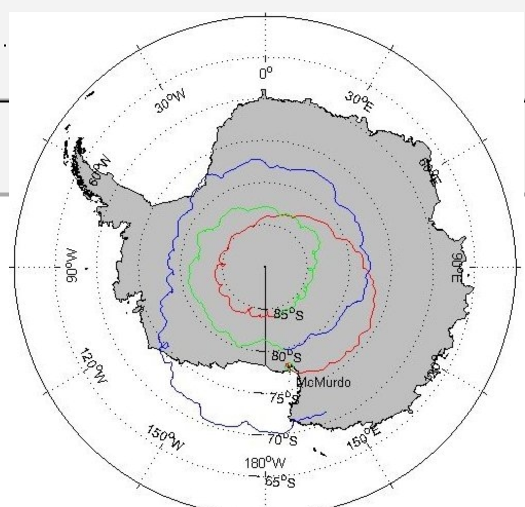
Balloons



remaining ρ~3.7 g/cm^2

40 km

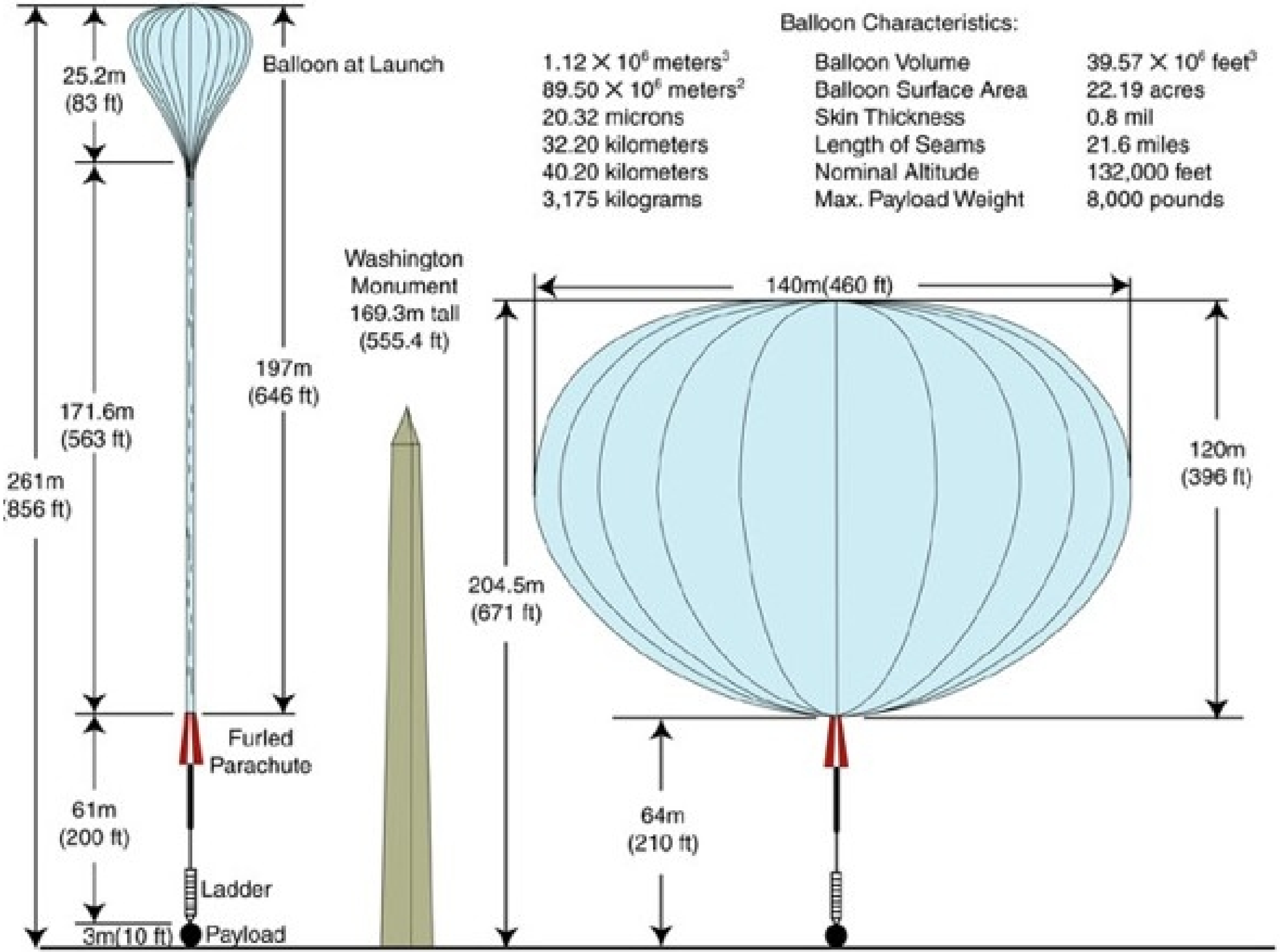
36.5 km



record-breaking CREAM I flight: 42d

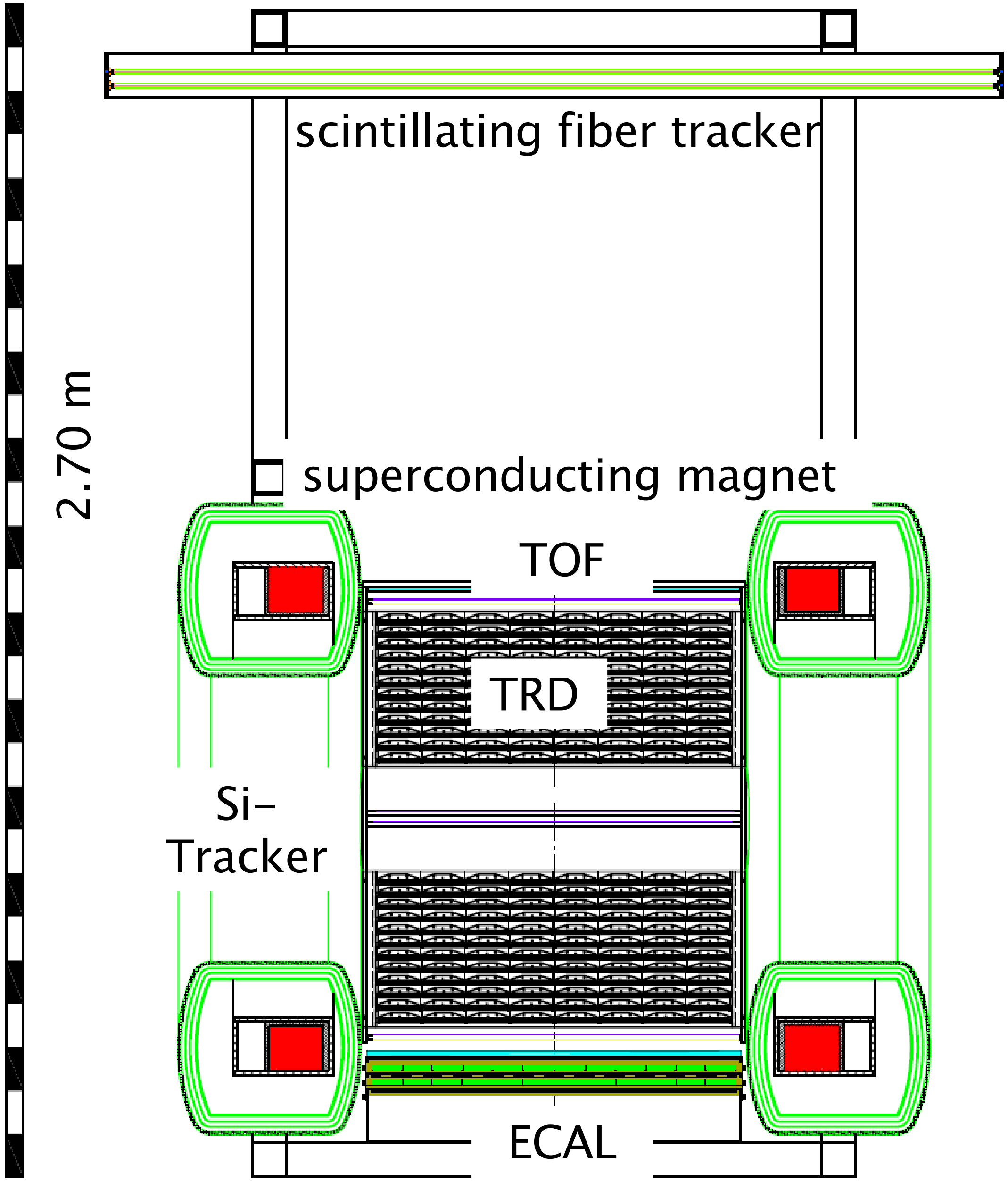
BESS-polar 2007

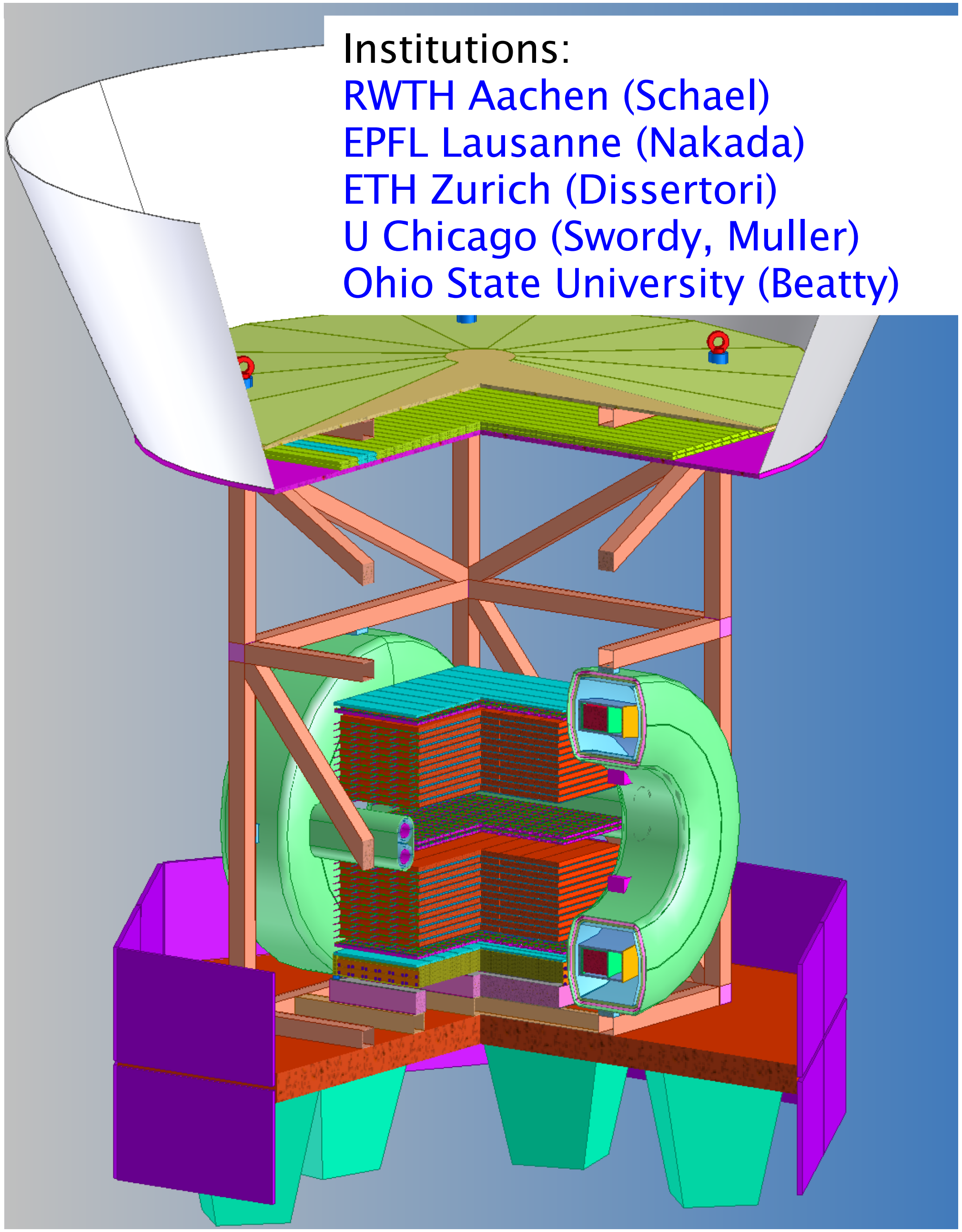
Balloons



25.2m
(83 ft)
Balloon at Launch
171.6m
(563 ft)
197m
(646 ft)
261m
(856 ft)
Furled
Parachute
61m
(200 ft)
Ladder
3m(10 ft)
Payload
Washington
Monument
169.3m tall
(555.4 ft)
Balloon Characteristics:
1.12 × 10⁶ meters³ Balloon Volume 39.57 × 10⁶ feet³
89.50 × 10⁶ meters² Balloon Surface Area 22.19 acres
20.32 microns Skin Thickness 0.8 mil
32.20 kilometers Length of Seams 21.6 miles
40.20 kilometers Nominal Altitude 132,000 feet
3,175 kilograms Max. Payload Weight 8,000 pounds
140m(460 ft)
204.5m
(671 ft)
120m
(396 ft)
64m
(210 ft)

PEBS: design



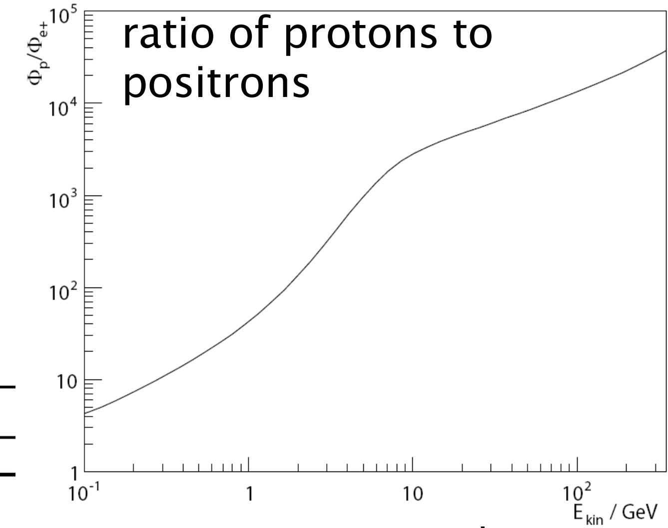


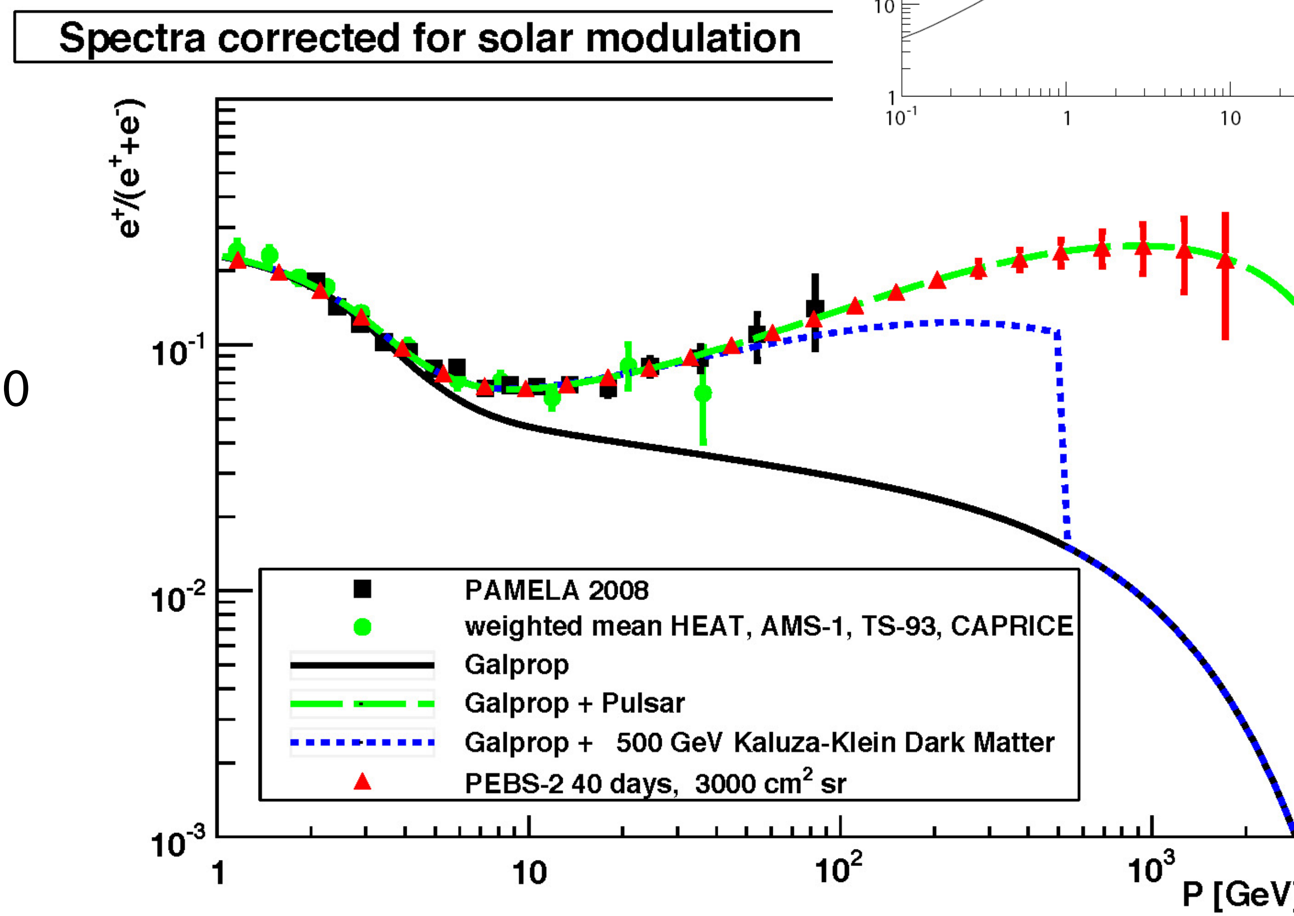
Institutions:

RWTH Aachen (Schael)
EPFL Lausanne (Nakada)
ETH Zurich (Dissertori)
U Chicago (Swordy, Muller)
Ohio State University (Beatty)

PEBS: physics program

primary targets:
- positron fraction up to 2TeV
(→indirect dark matter search)
- low-energy positron fraction
(→solar modulation and geomagnetic effects)



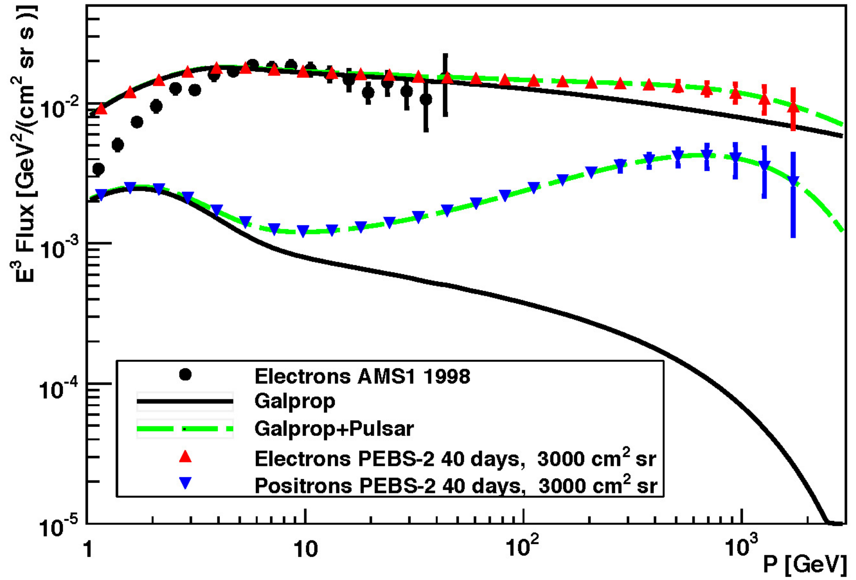


acceptance: 3000 cm² sr
design: flights of up to 40 days

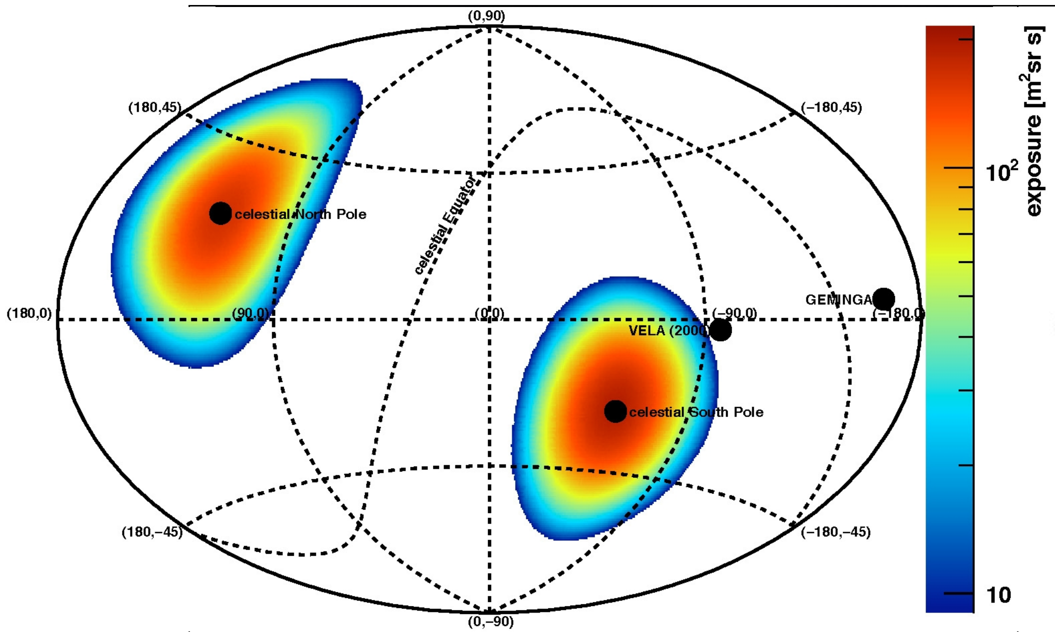
PEBS: physics program

primary targets:

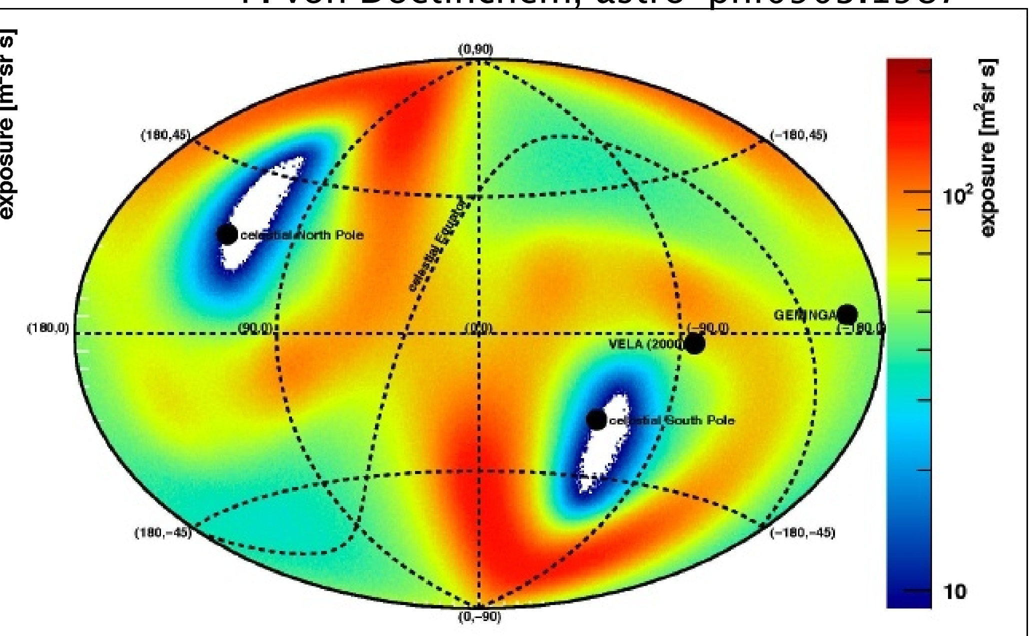
- positron fraction up to 2TeV
(→indirect dark matter search)
- low-energy positron fraction
(→solar modulation and geomagnetic effects)
- total electron spectrum up to several TeV
(→ verify HESS/ATIC
(hadronic backgrounds!?); nearby sources?)



P. von Doetinchem, astro-ph:0903.1987



sky coverage of PEBS

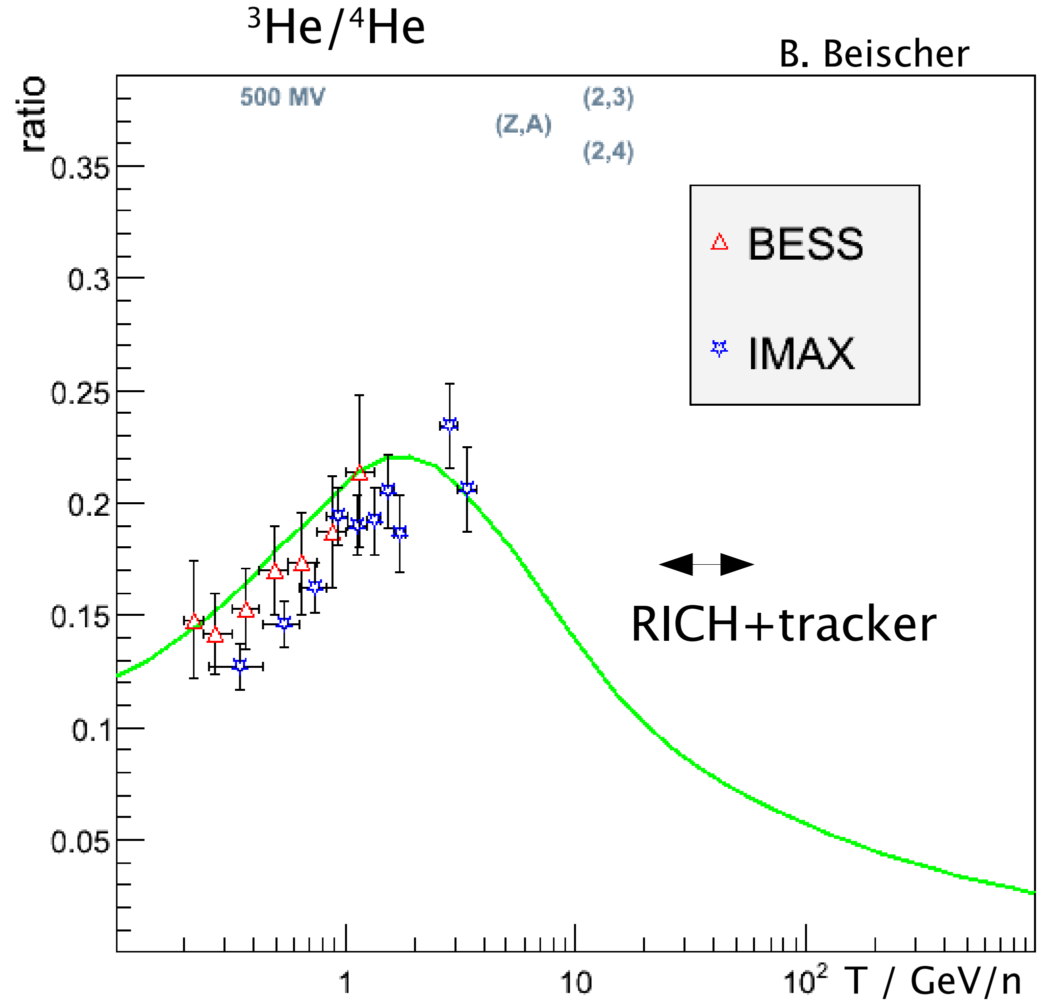


sky coverage of AMS-2

PEBS: physics program

primary targets:
• positron fraction up to 2TeV (→indirect dark matter search)
• low-energy positron fraction (→solar modulation and geomagnetic effects)
• total electron spectrum up to several TeV (→ verify HESS/ATIC (hadronic backgrounds!?); nearby sources?)

and maybe:
• antiprotons
• B/C
• $^3He/^4He$ (with RICH)



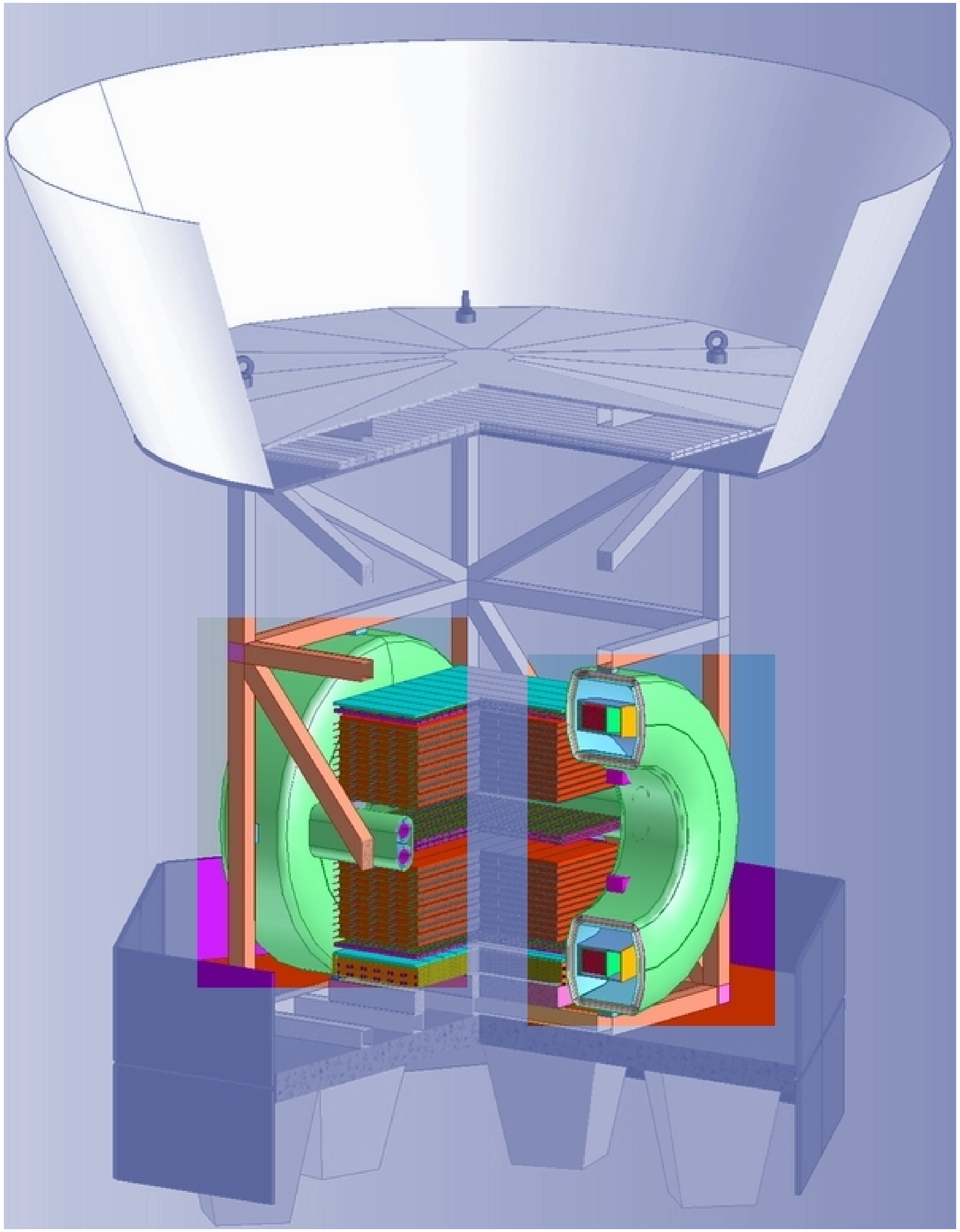
Extensive design study for PEBS:
Geant4 simulation – reconstruction – analysis – testbeam measurements
=>
Proposal submitted to NASA

PEBS: design

Magnet:

Pair of superconducting Helmholtz coils inside Helium cryostat,
mean B = 0.8T,
weight: 850kg,
design life time: 20-40 days

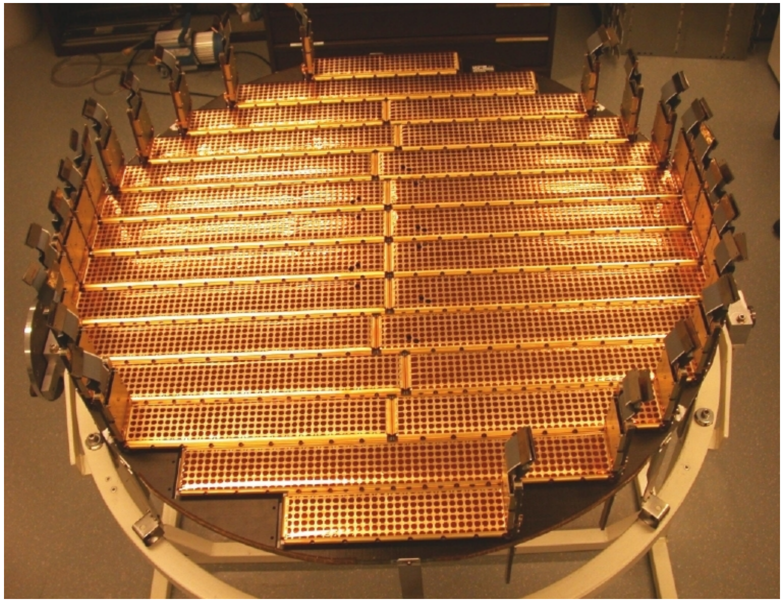
ISOMAX magnet



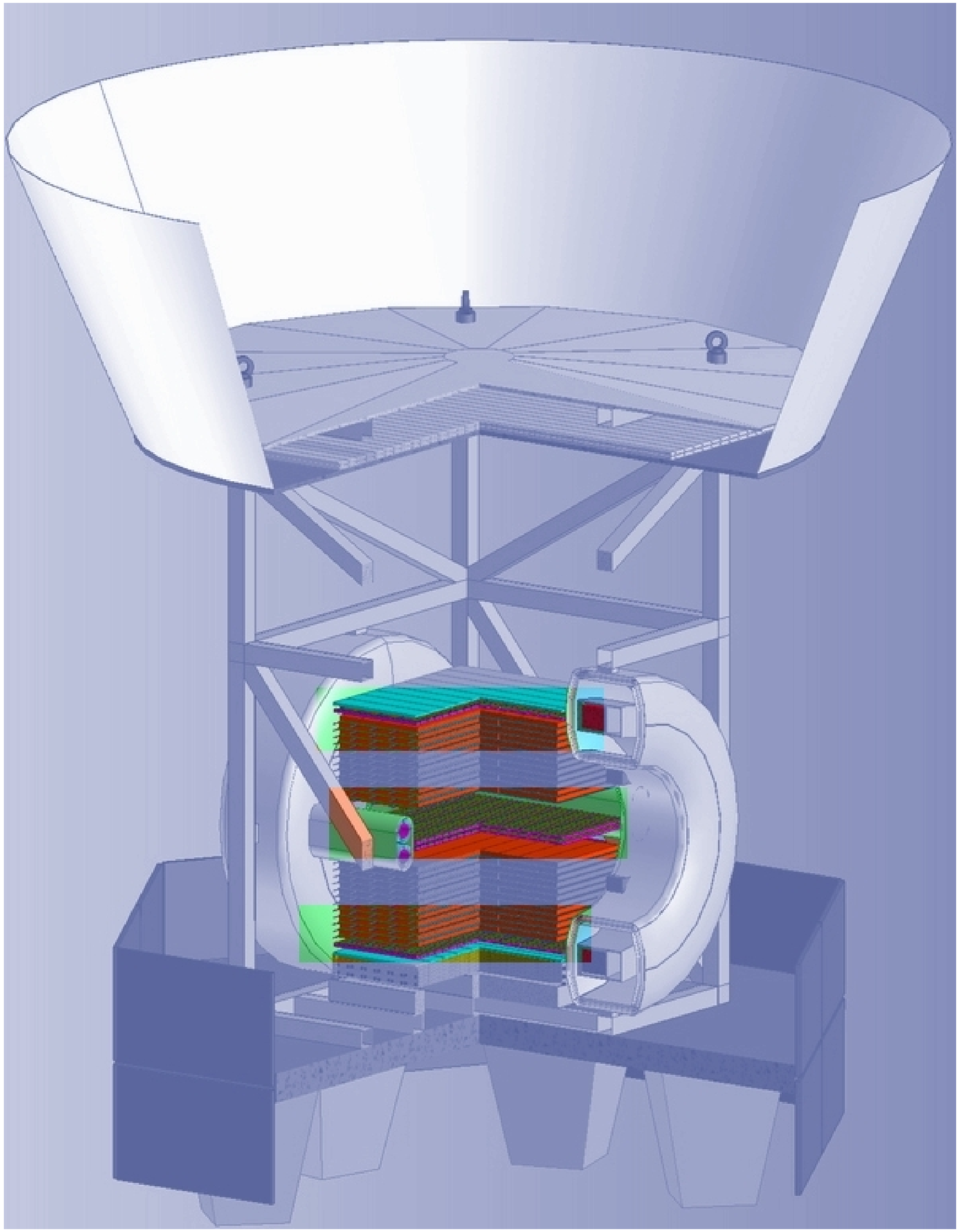
PEBS: design

Silicon Strip Tracker:

high-precision tracking inside magnetic field,
2+2+2 layers inside magnet,
design similar to AMS Si tracker,
aim at resolution of 0.01 mm



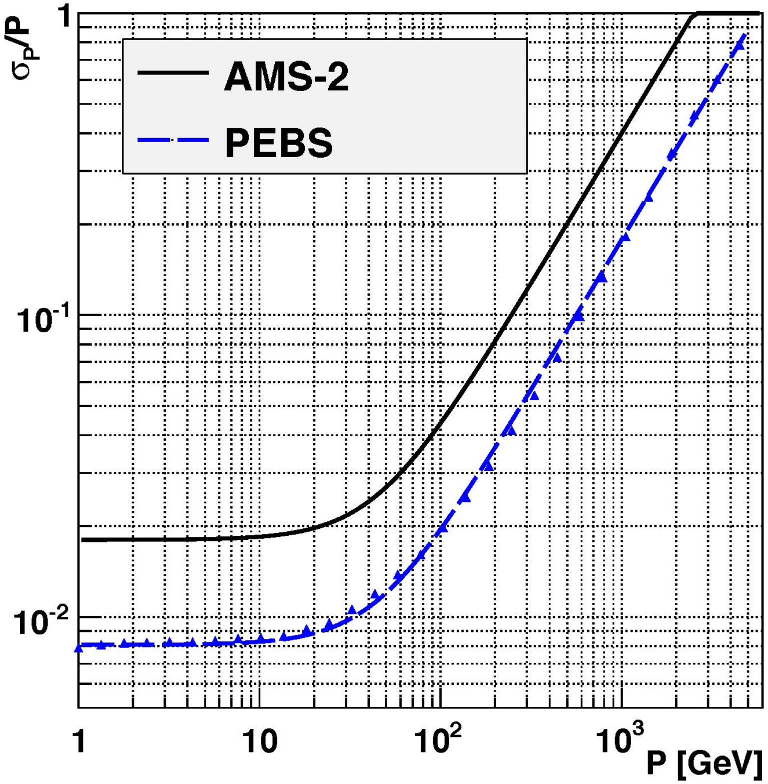
AMS02 tracker plane
(P. Azzarello)

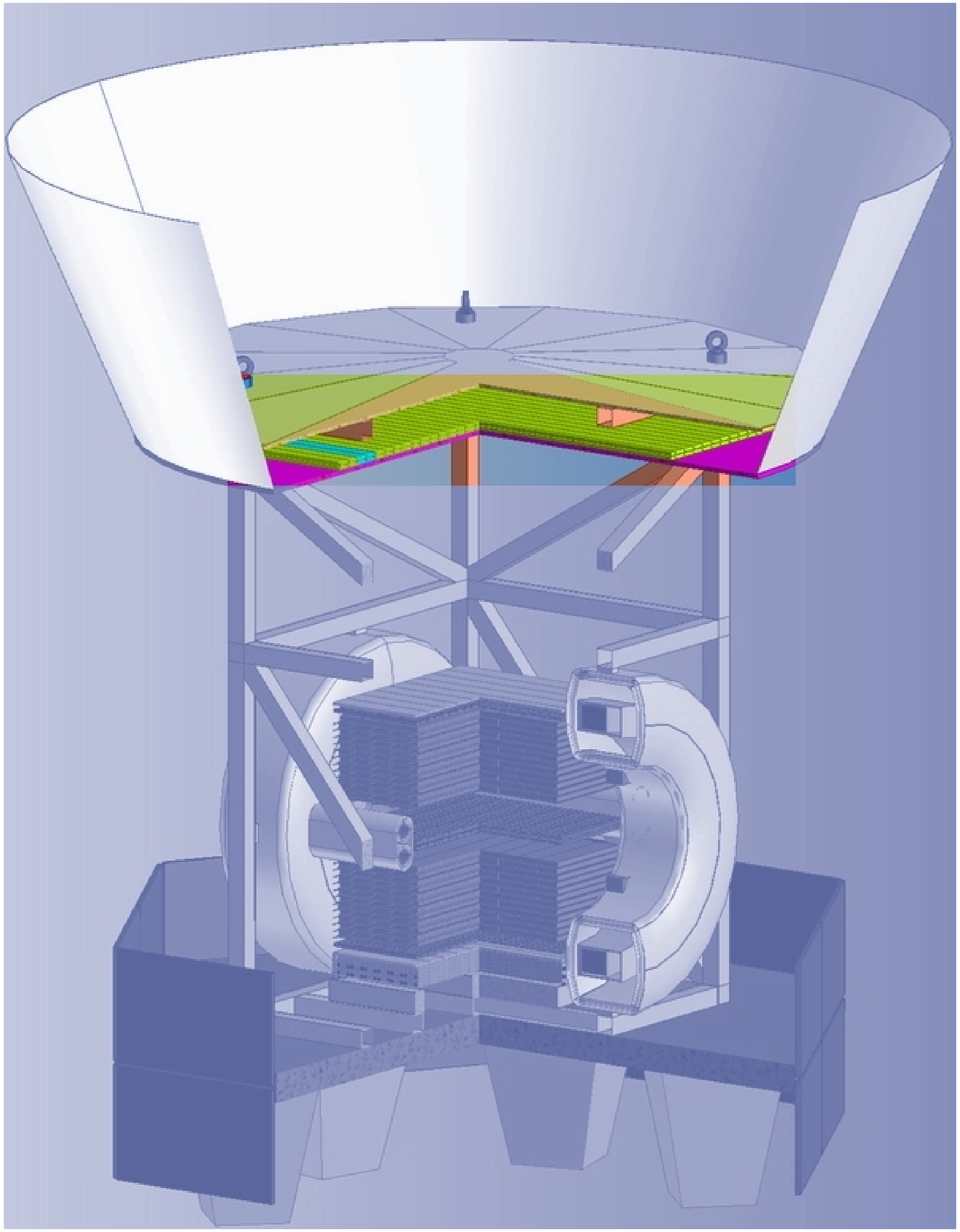


PEBS: design

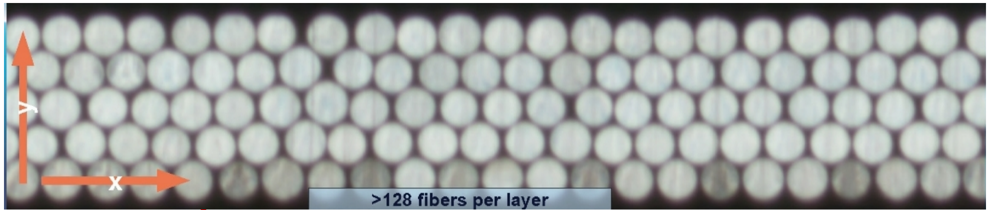
Tracker:

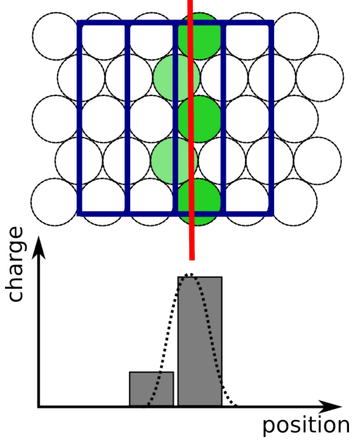
Scintillating fibres (d=250 μm), with Silicon Photo-Multiplier (SiPM) readout, design spatial resolution: 0.05 mm

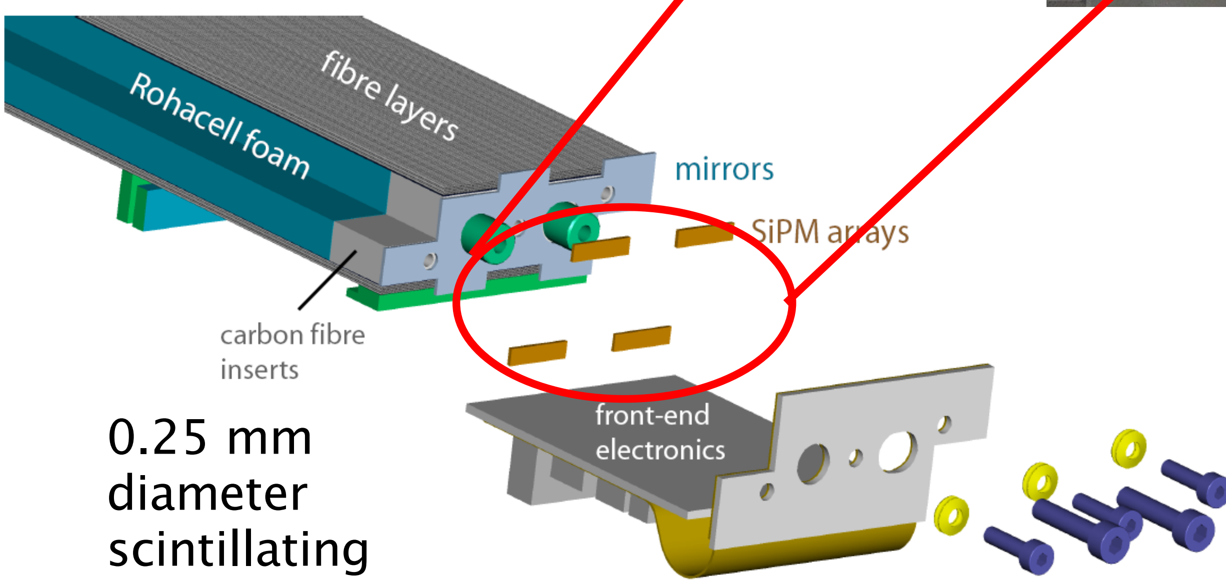




PEBS tracker module design



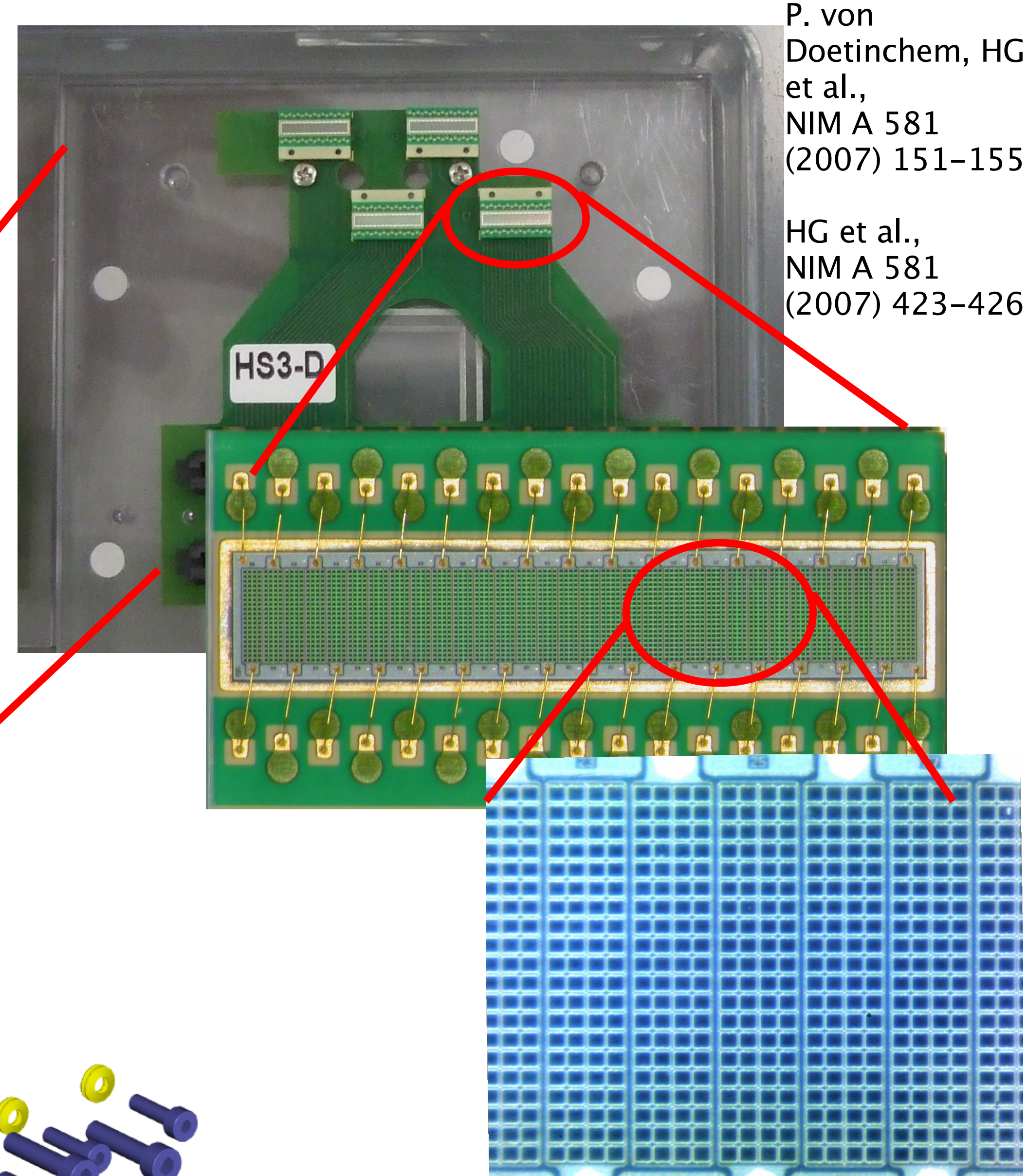




0.25 mm diameter scintillating fibers

P. von Doetinchem, HG et al., NIM A 581 (2007) 151-155

HG et al., NIM A 581 (2007) 423-426

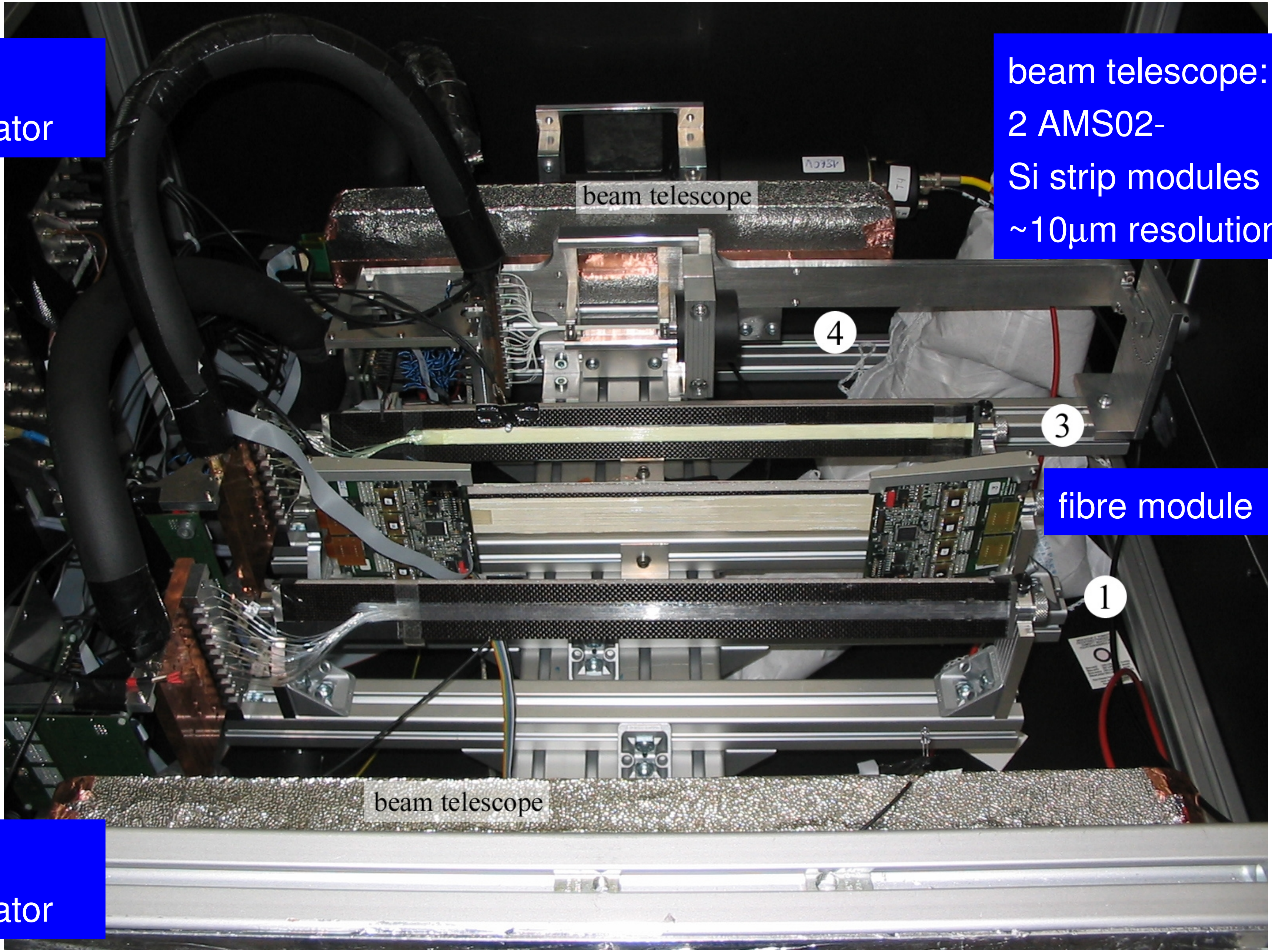


32 channel SiPM, 80 pixels per channel, 0.25x1 mm^2 each

PEBS testbeam 2006-2008 setup

trigger scintillator

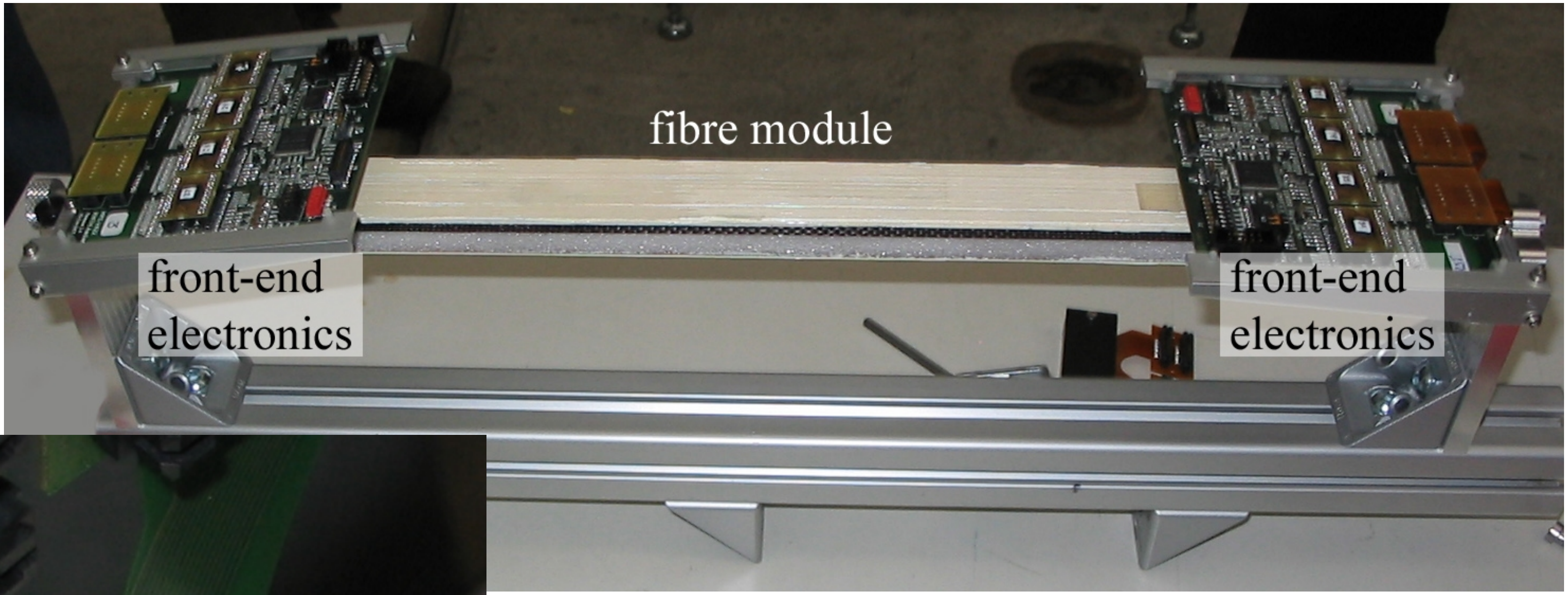
beam telescope:
2 AMS02-
Si strip modules
~10µm resolution

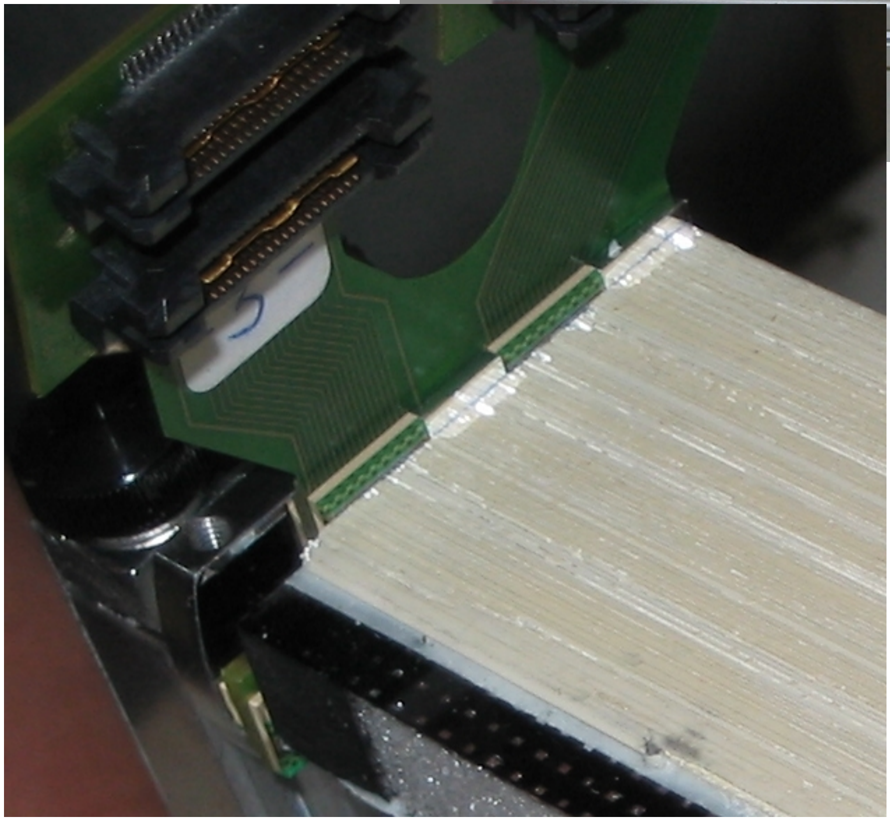


fibre module

trigger scintillator

PEBS testbeam 2006-2008 fiber module

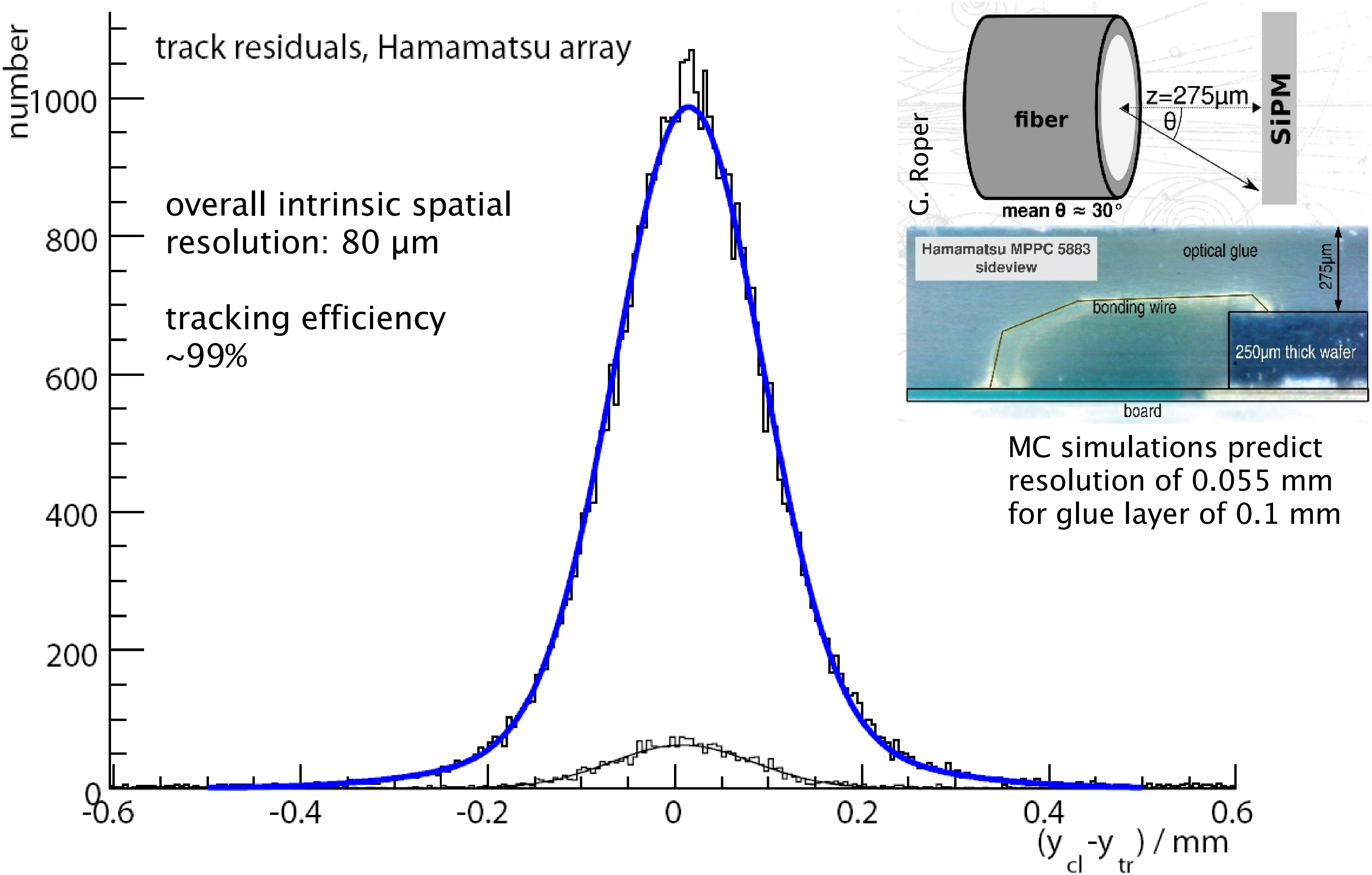




Kuraray fibers, 0.25 mm diameter.

Readout by VA chips, AMS electronics used for digitization, unified readout with beam telescope.

Spatial resolution



overall intrinsic spatial resolution: 80 μm

tracking efficiency ~99%

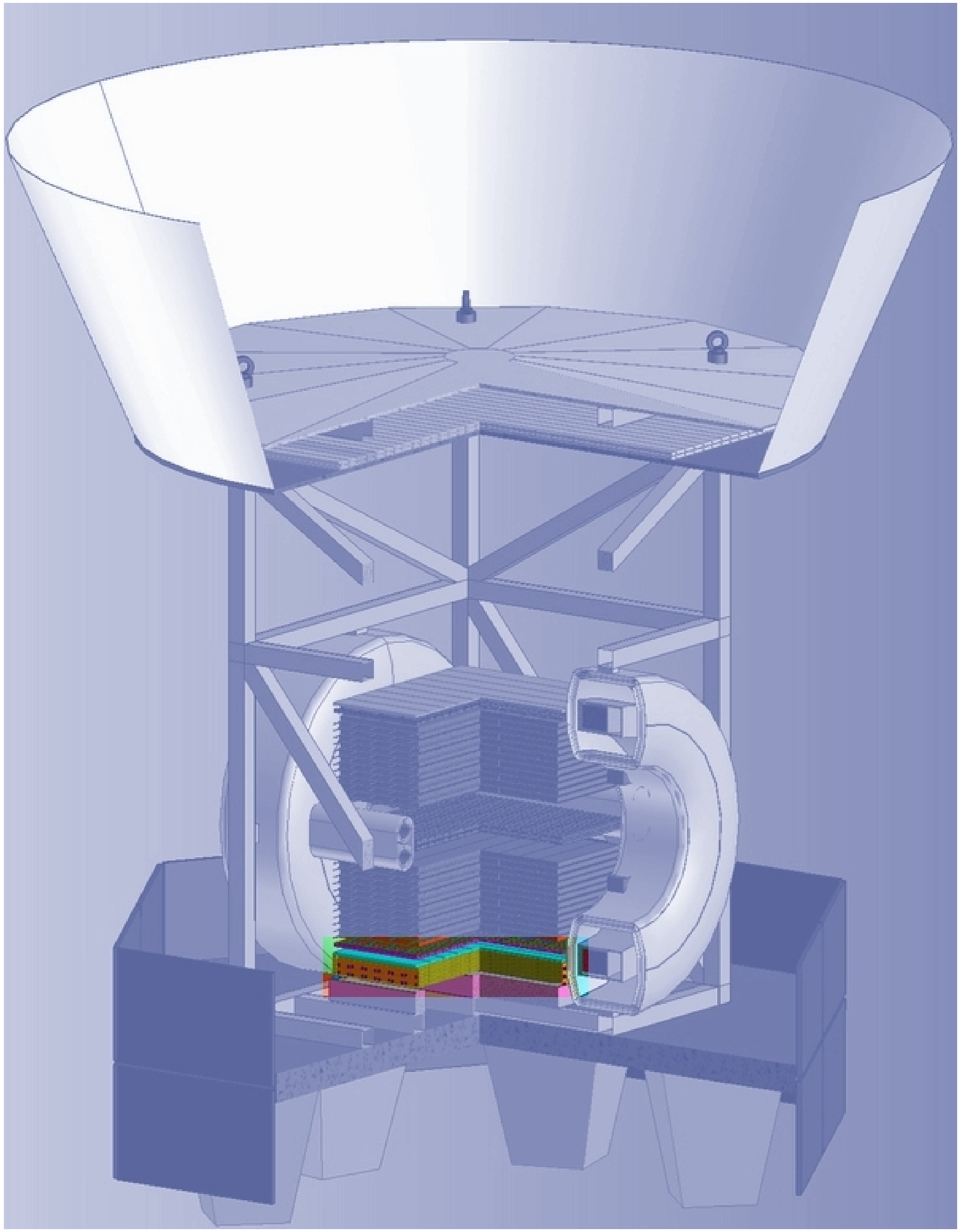
MC simulations predict resolution of 0.055 mm for glue layer of 0.1 mm

PEBS: design

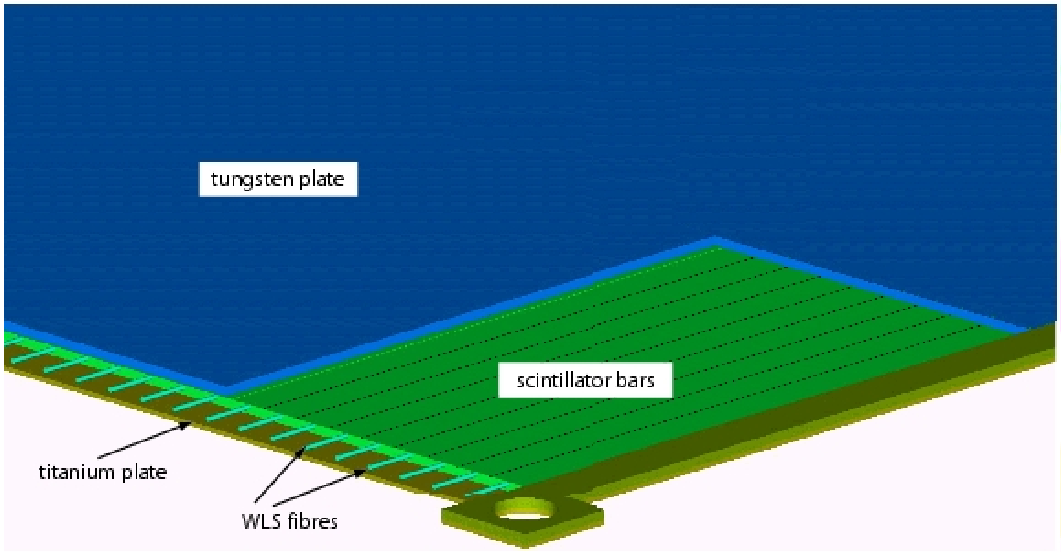
Electromagnetic calorimeter:

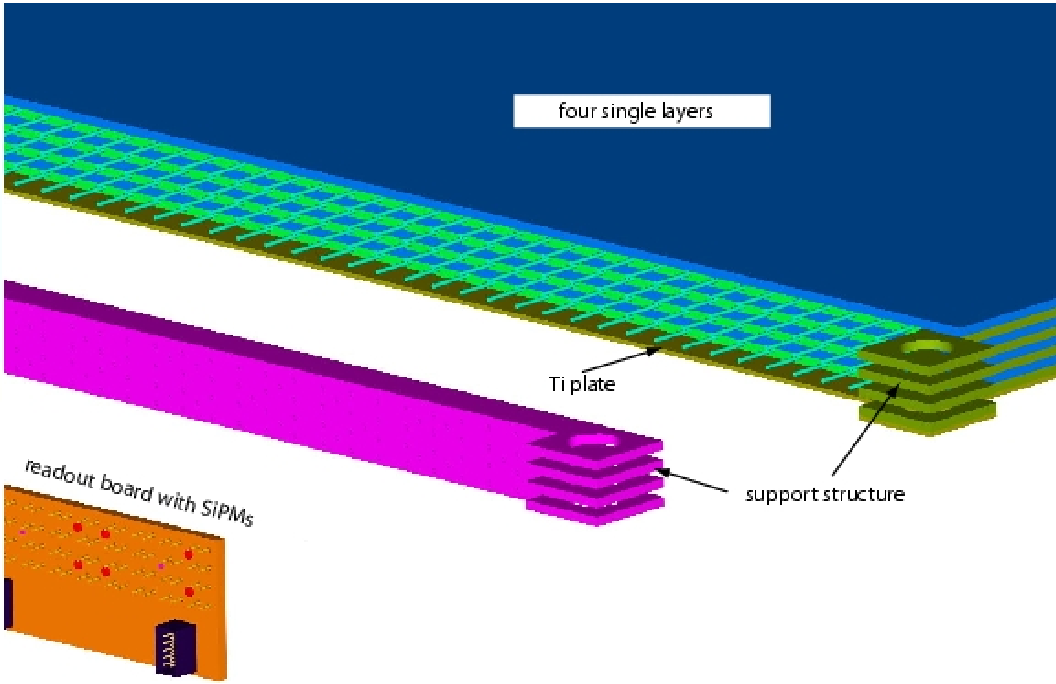
20 x (2mm W + 7.75 x 2 mm^2
scintillator bar + SiPM) = 11.4 X_0,
weight: 600kg,

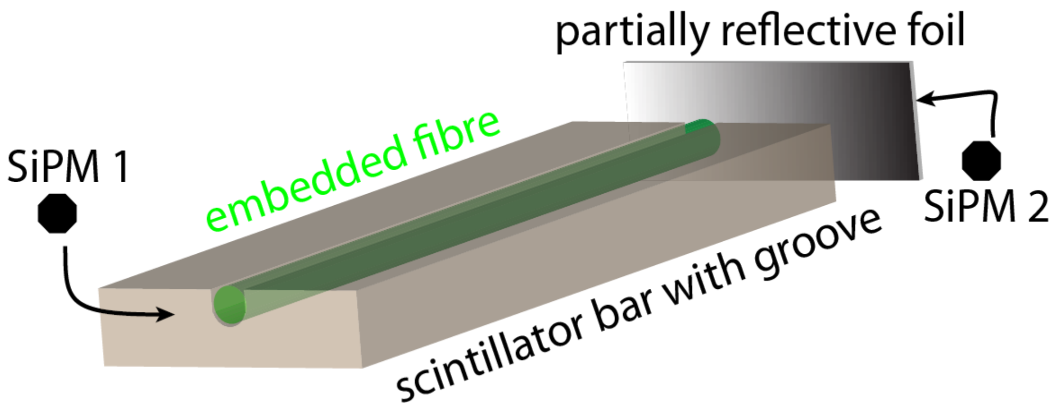
task: positron/electron identification,
proton rejection of $O(10^3)$

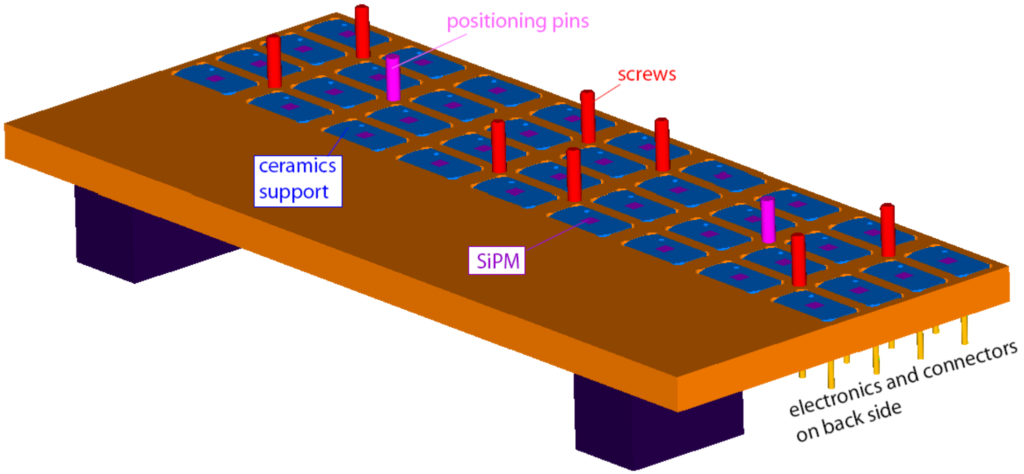


PEBS ECAL design

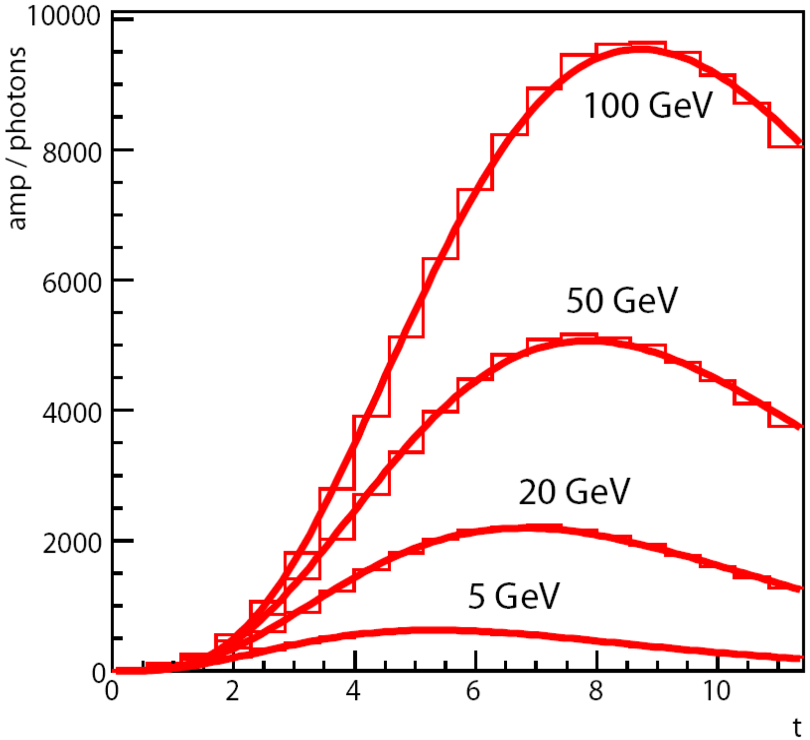


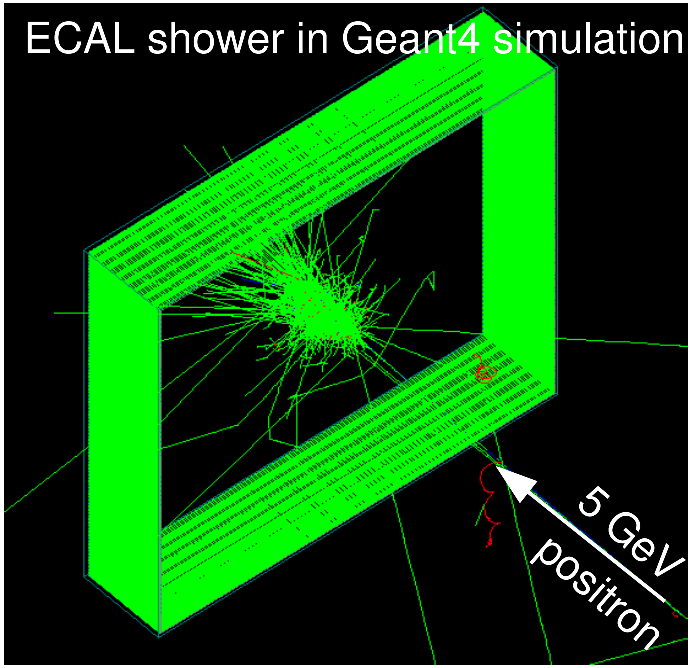






PEBS ECAL energy resolution





$$\frac{\mathrm{d}E}{\mathrm{d}t} = E_0 b \frac{(bt)^{a-1}\mathrm{e}^{-bt}}{\Gamma(a)}$$

20 layers in total:

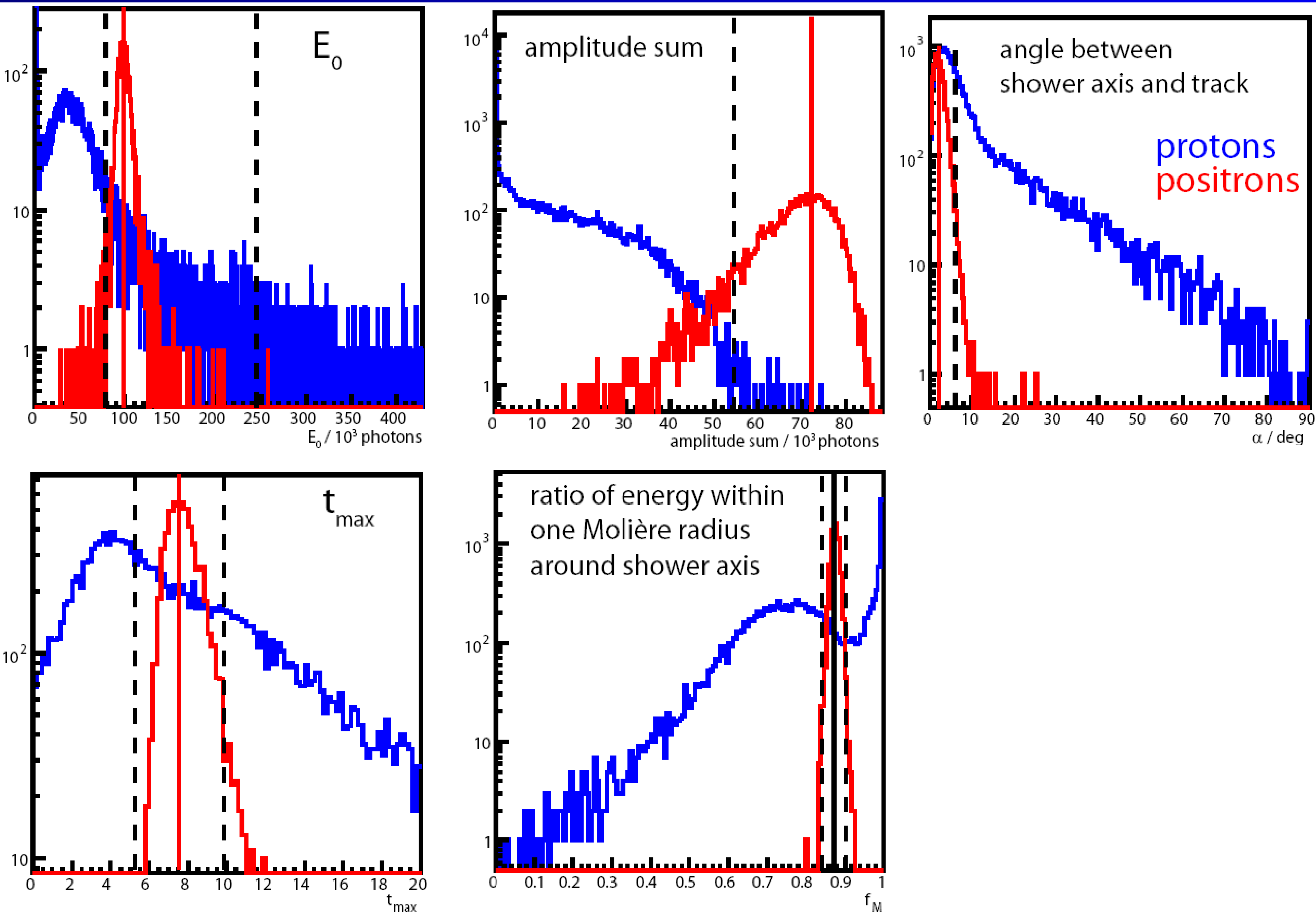
2 mm tungsten +

2 mm scintillator bar +WLS fiber +

2 SiPMs

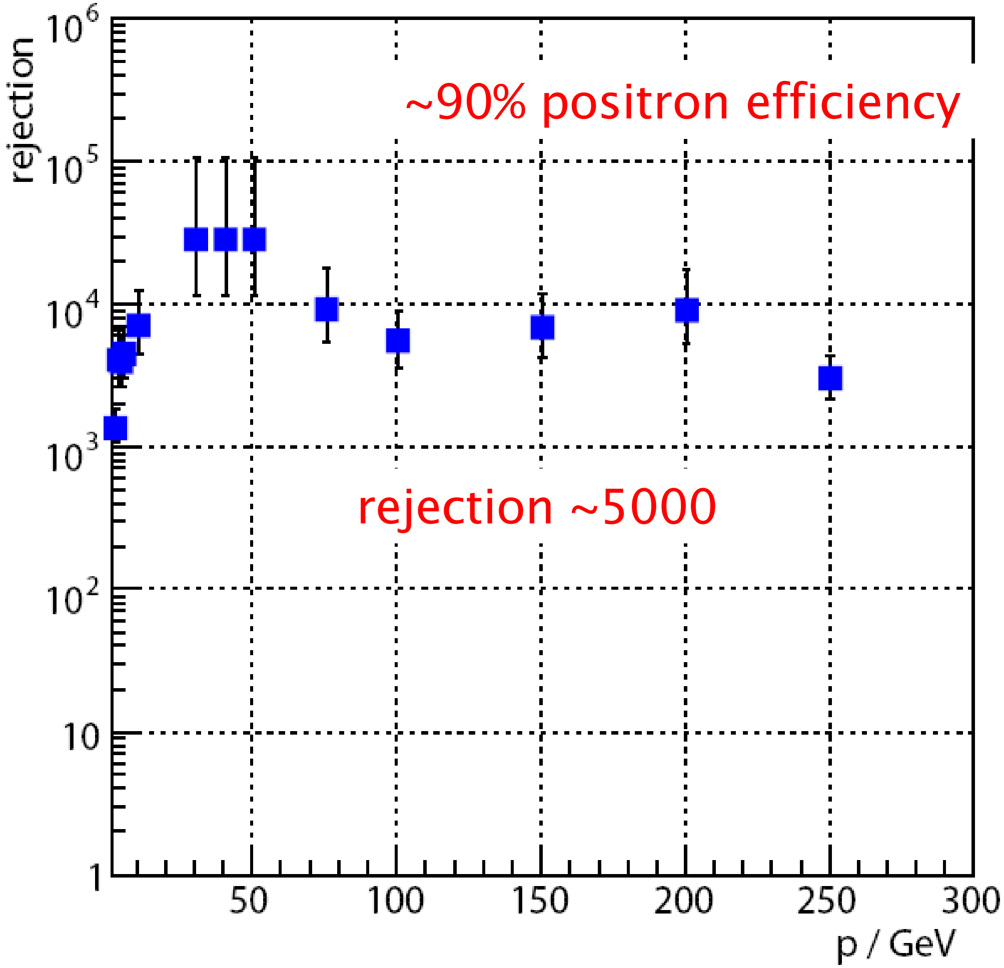
11.4 X_0 in total

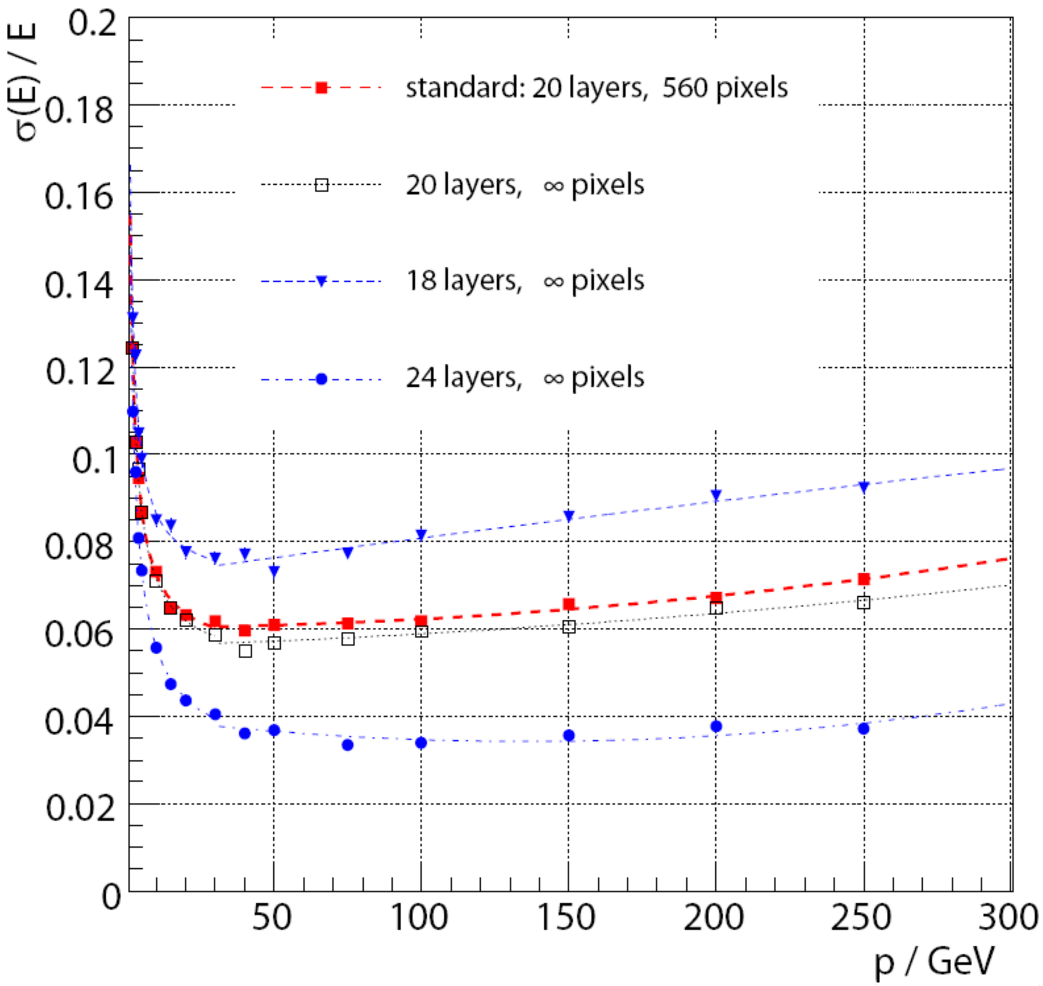
ECAL shower shape analysis based on Geant4



PEBS ECAL performance from MC simulation

proton rejection





ECAL energy resolution: constant term ~7% @ 250 GeV due to leakage effects

AMS-2: 16.7 X_0, constant term of 2.3%

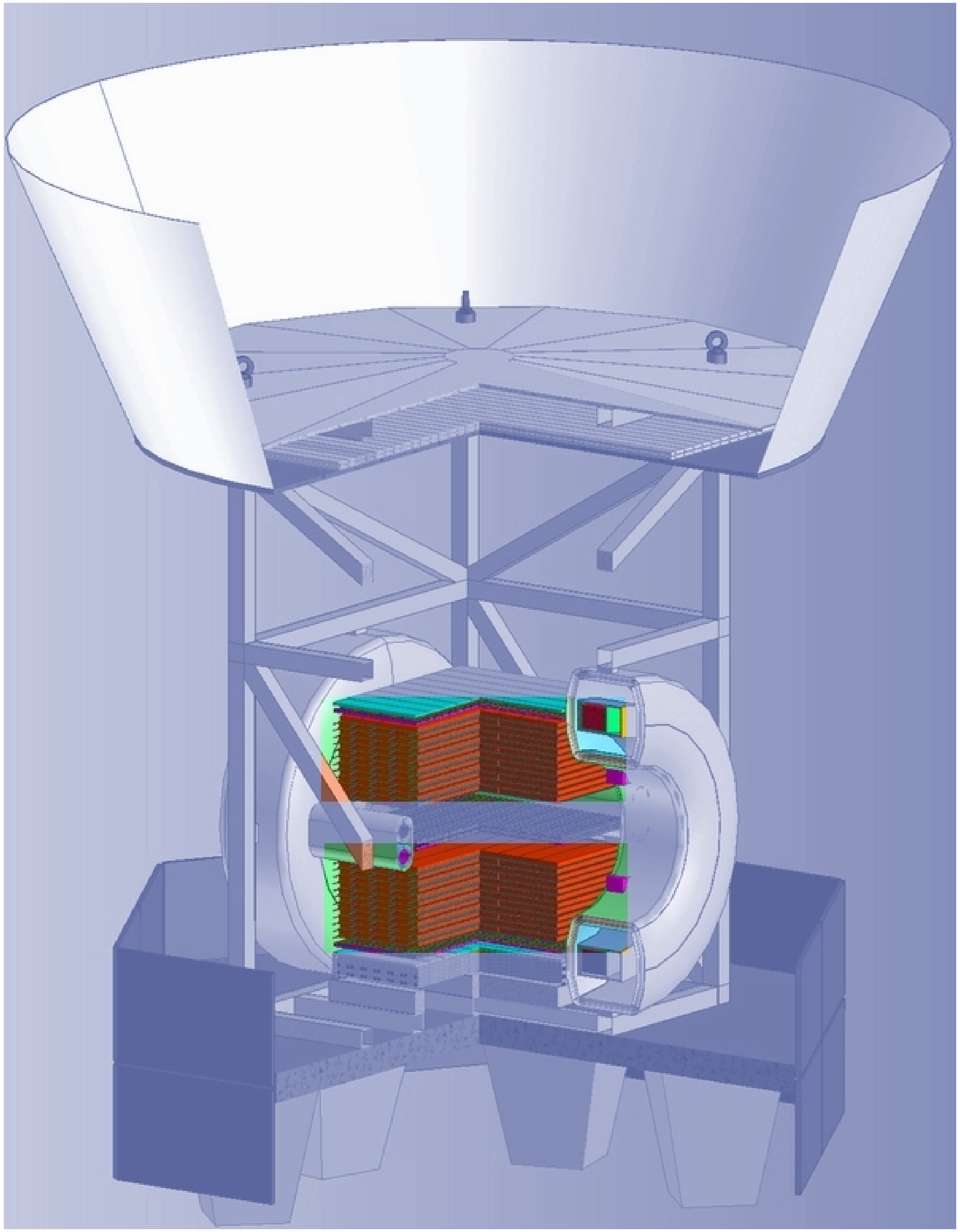
ECAL now under development at EPFL
prototype this fall

PEBS: design

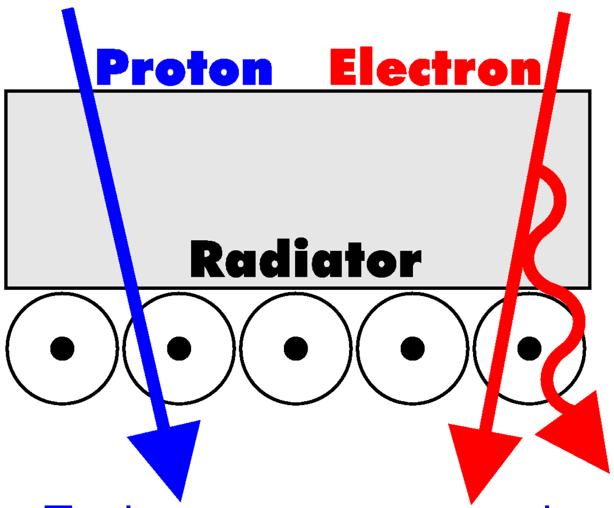
Transition radiation detector:

2 x 12 layers
(2cm fleece radiator + 6mm straw tube Xe/CO_2 80:20)

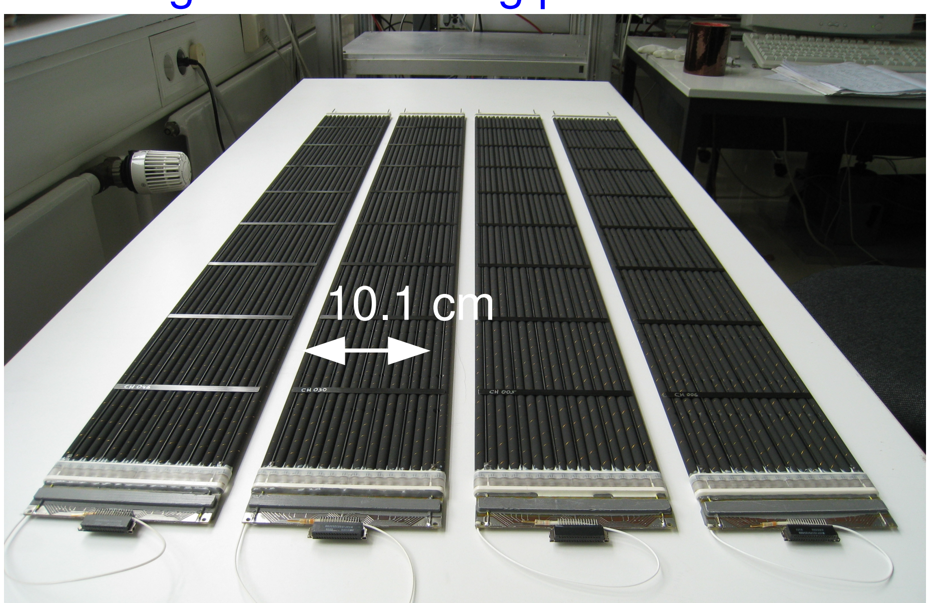
task: positron/electron identification,
proton rejection of $O(10^3)$



PEBS TRD design



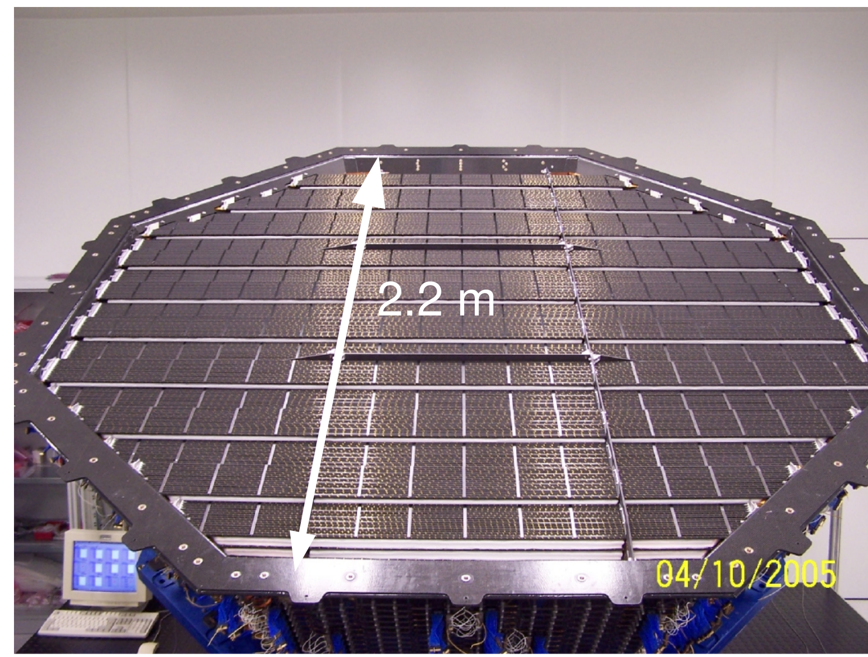
Tasks: proton suppression and tracking in non-bending plane



new TRD modules produced for PEBS

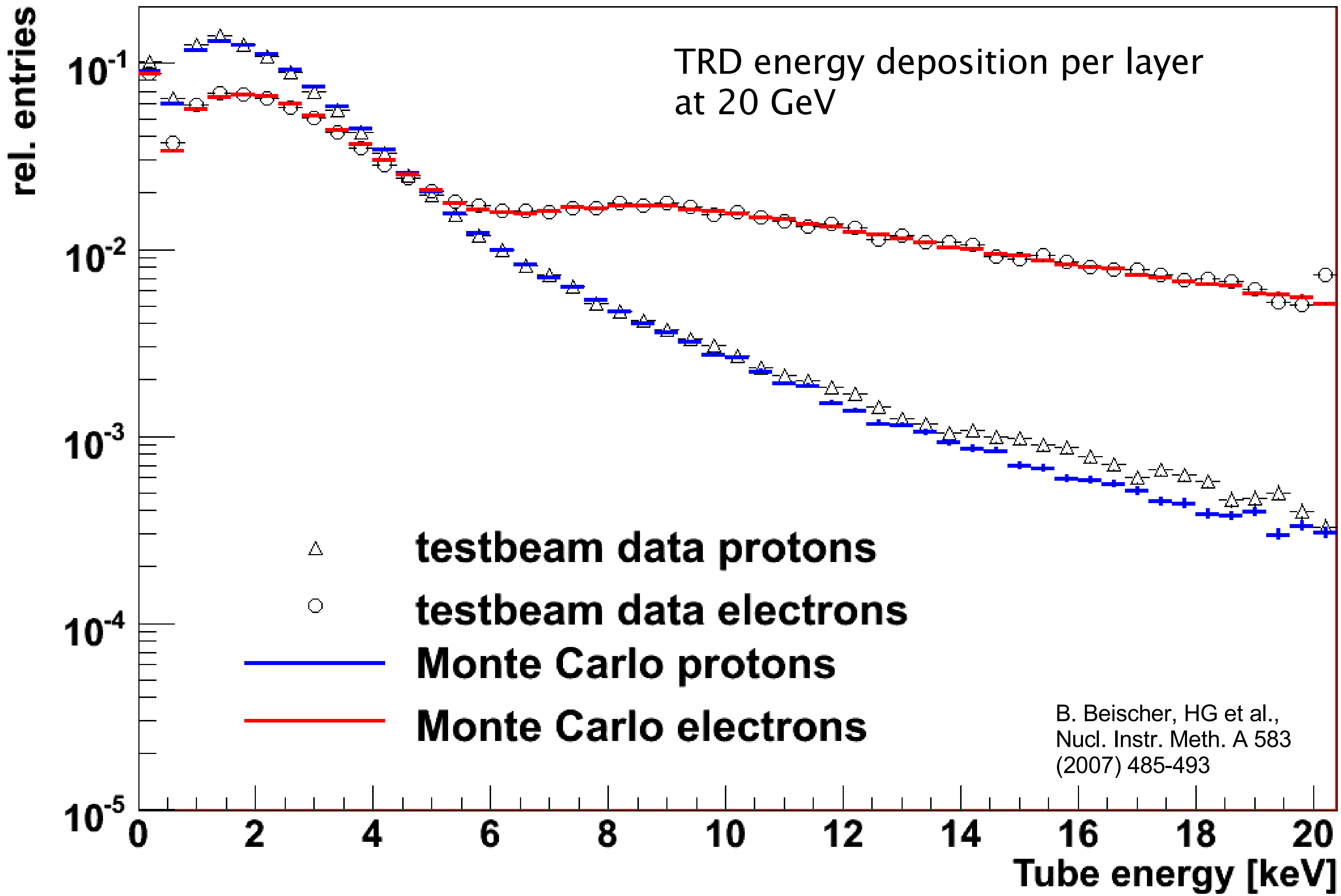
2 x 12 layers of fleece radiator, TR x-ray photons absorbed by Xe/CO_2 mixture (80:20), in 6mm straw tubes with 30 μm tungsten wire

Design equivalent to AMS02 space experiment

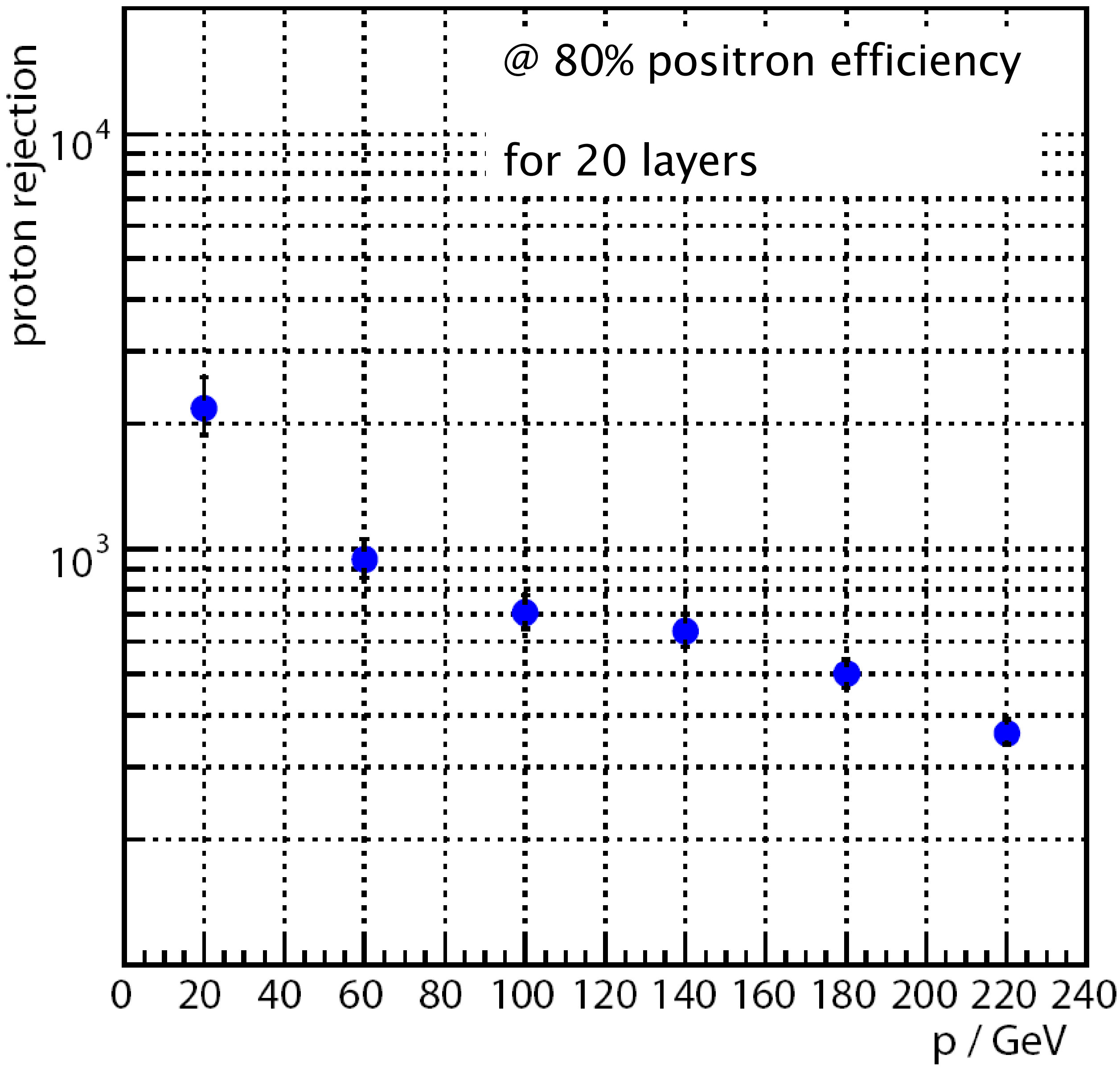


AMS02 TRD octagon integrated at RWTH Aachen workshop

Geant4 TR simulation compared to testbeam data

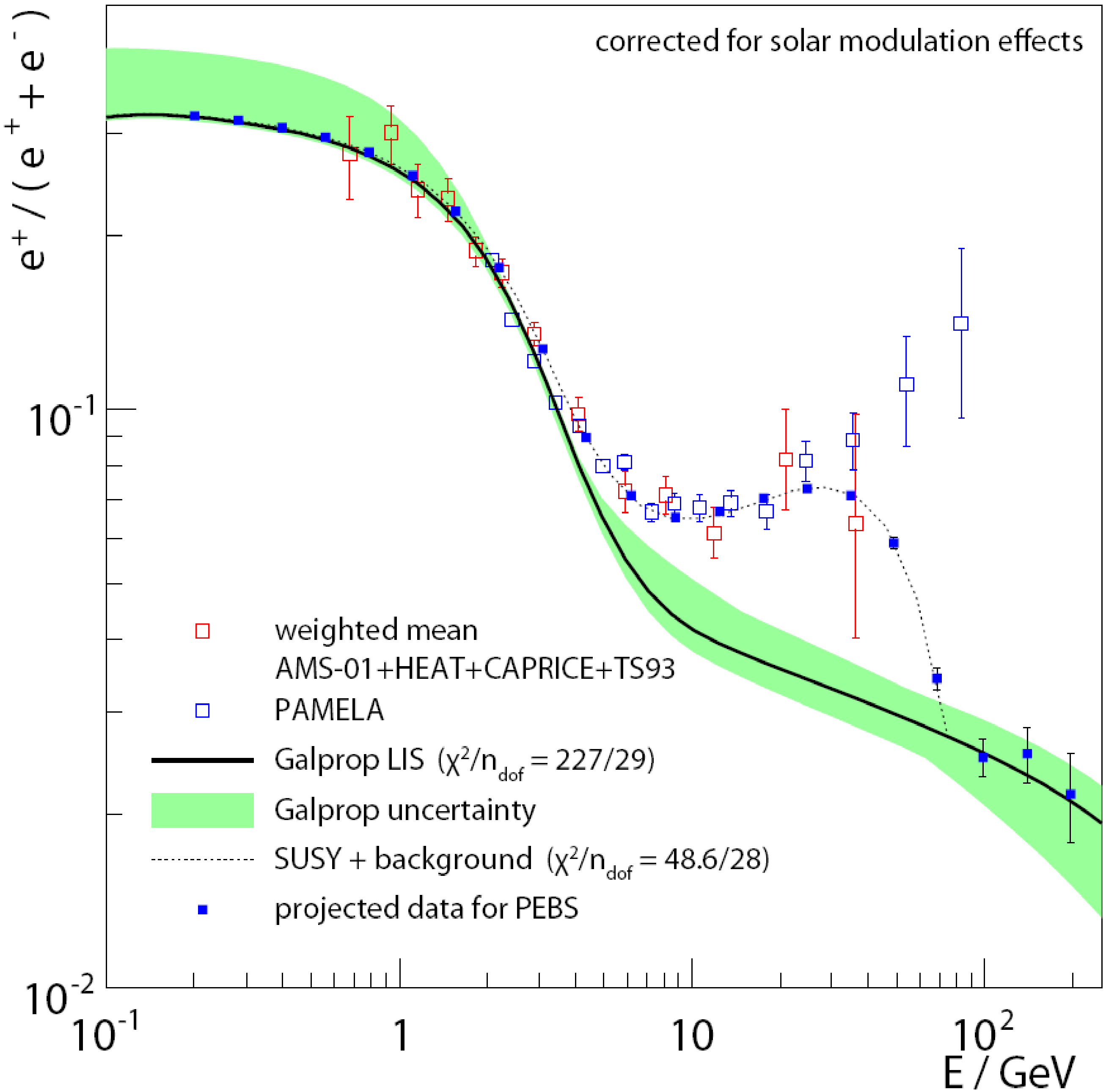


TRD rejection and efficiency from Geant4 study



combined ECAL+TRD rejection ~10^6

mSUGRA and PAMELA positron fraction



best fit mSUGRA model for PAMELA data:

m_0=2040 GeV

$m_{1/2}$=390 GeV

tan β = 40

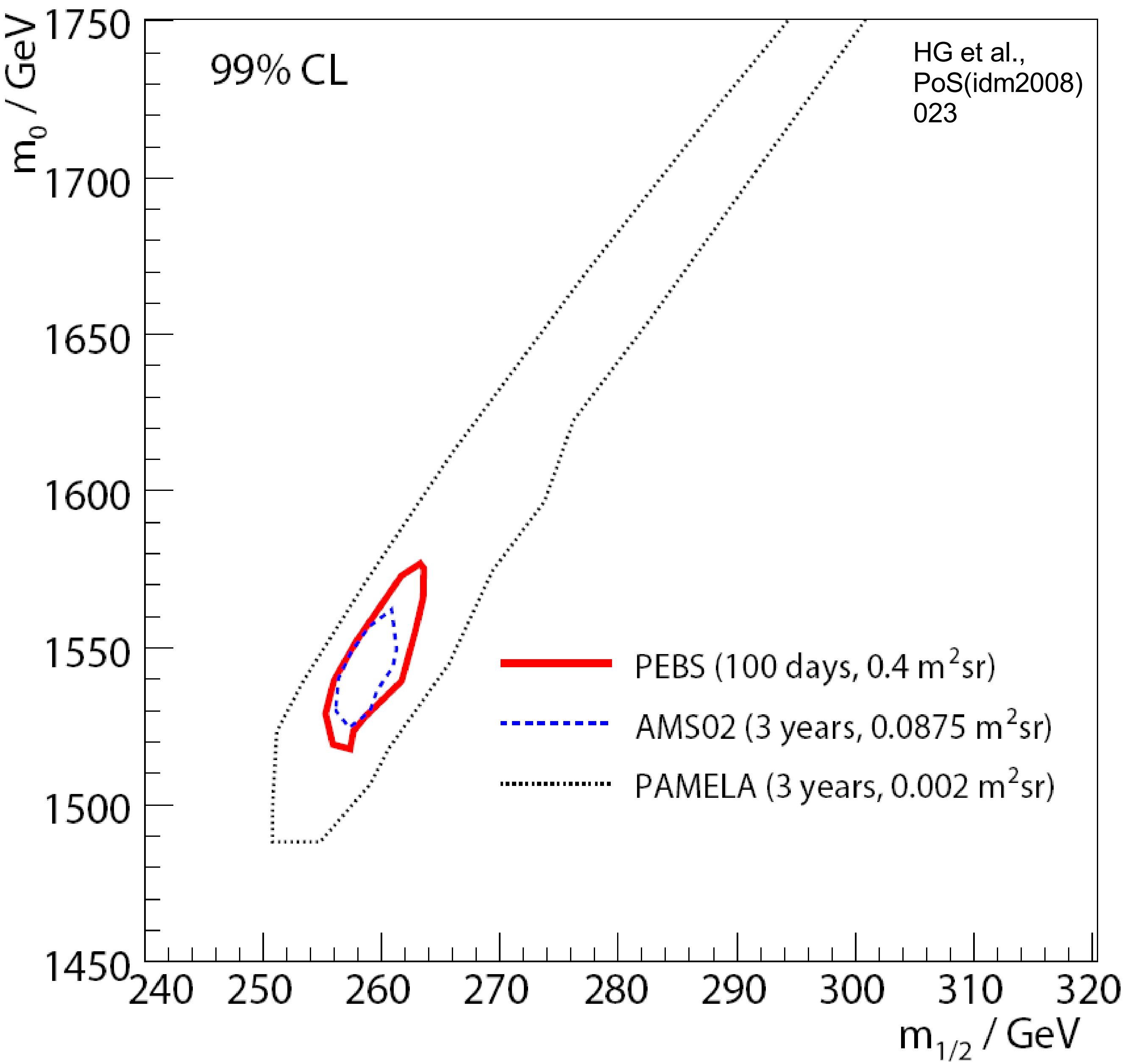
m_t=172.3 GeV

BF=1510

m_χ=93 GeV

statistical uncertainty in parameters of Galprop conventional model, taking B/C-data and low-energy PAMELA data into account

Comparison to AMS-02 and PAMELA



compare physics potential of detectors, based on acceptance and mission duration

Conclusions

Exciting times in astroparticle physics:

- New results from PAMELA, Fermi, HESS (among others).
- Theoretical developments (Internal bremsstrahlung, N-body simulations, Sommerfeld enhancement). AMS-2 will be launched in 2010.

Dark matter remains elusive and is a very active field of research

- But SUSY-DM explanation is becoming less favorable for electron/positron/antiproton data. Exotic DM models?

Simple model for charge-sign dependent solar modulation can explain low-energy PAMELA positron data.

The Positron Electron Balloon Spectrometer (PEBS) is being designed to take the next steps in cosmic-ray physics.

- Construction of TRD in progress, extensive prototyping for tracker.
- Fibre tracker employs ultra-thin scintillating fibers and revolutionary SiPMs.

Timeline according to proposal:

March 2009	Proposal to NASA
Fall 2009	Decision
2010-2011	Construction
Summer 2012	Flight from Kiruna
Winter 2013/14	Flight from Antarctica

Backup transparencies