2.4 Cosmic ray Positrons

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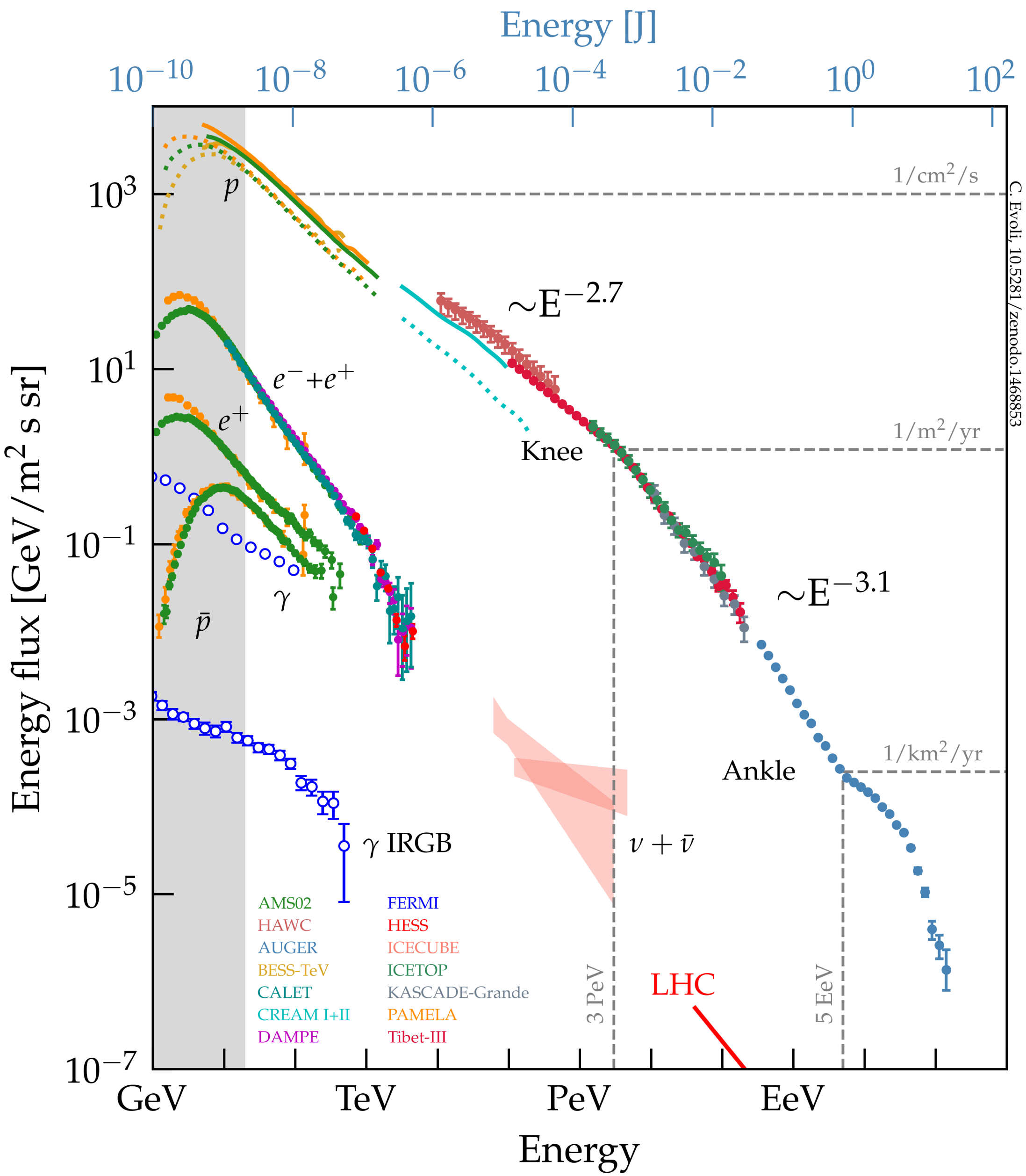
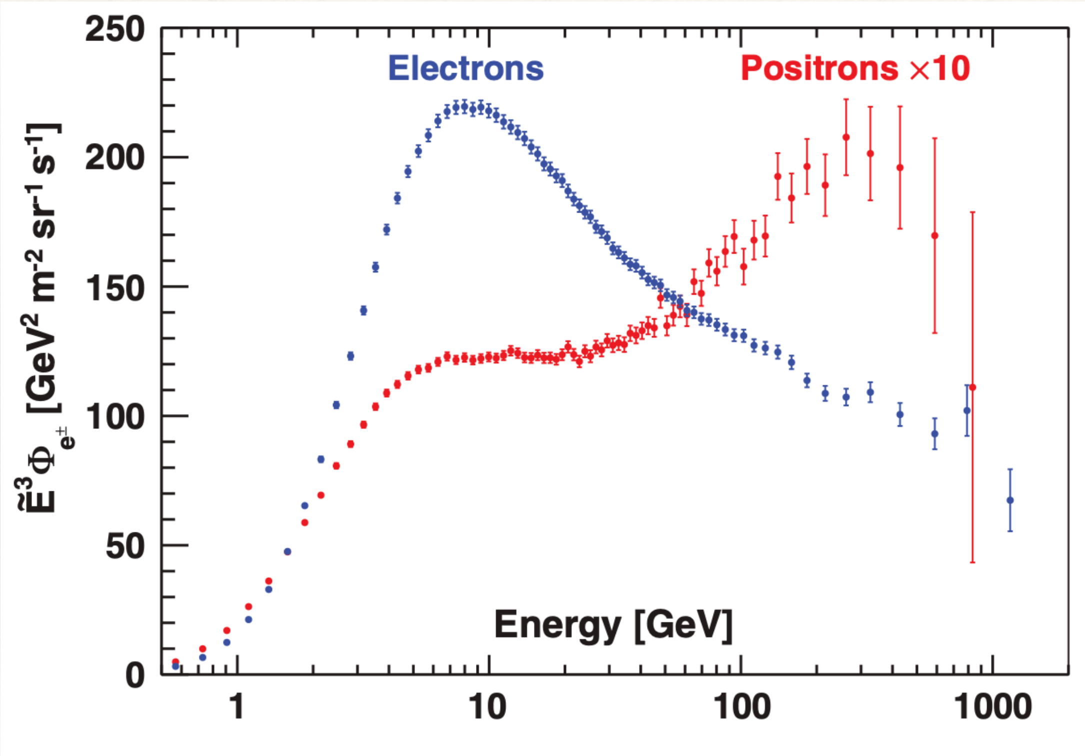
- Course webpage: https://blackboard.cuhk.edu.hk

Positrons

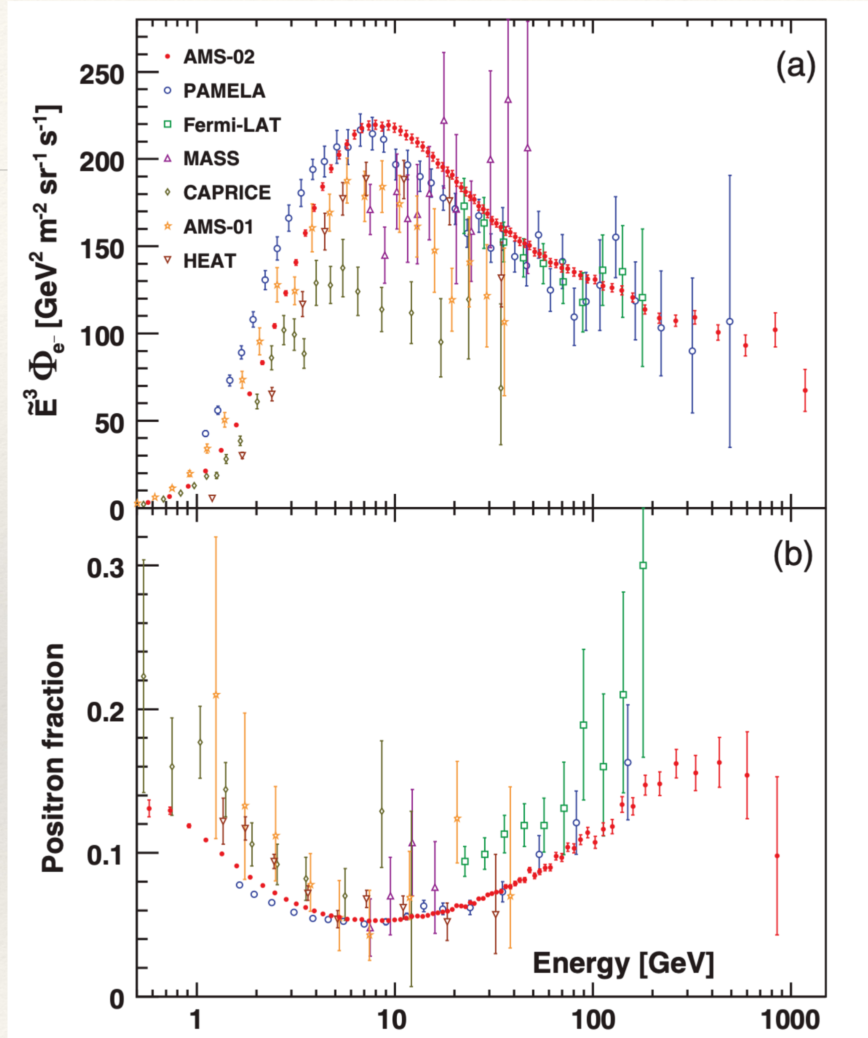


Energy [J]
10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2}
10^{3}
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
Energy flux [GeV/m^2 s sr]
p
e^-+e^+
e^+
γ
$\bar{p}$
γ IRGB
$\sim$E$^{-2.7}$
Knee
$\sim$E$^{-3.1}$
Ankle
$\nu + \bar{\nu}$
1/cm^2/s
1/m^2/yr
1/km^2/yr
3 PeV
5 EeV
LHC
AMS02
HAWC
AUGER
BESS-TeV
CALET
CREAM I+II
DAMPE
FERMI
HESS
ICECUBE
ICETOP
KASCADE-Grande
PAMELA
Tibet-III
GeV
TeV
PeV
EeV
Energy
C. Evoli, 10.5281/zenodo.1468853

Positrons



Electrons
Positrons ×10
$\tilde{E}^3 \Phi_{e^\pm}$ [GeV^2 m^{-2} sr^{-1} s^{-1}]
Energy [GeV]

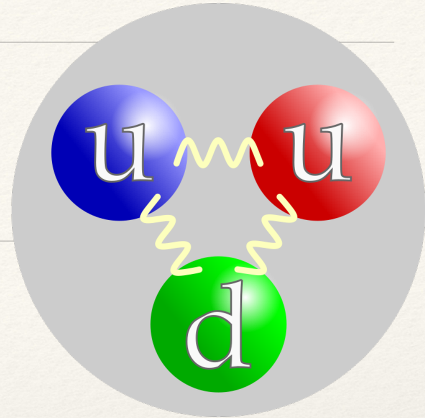


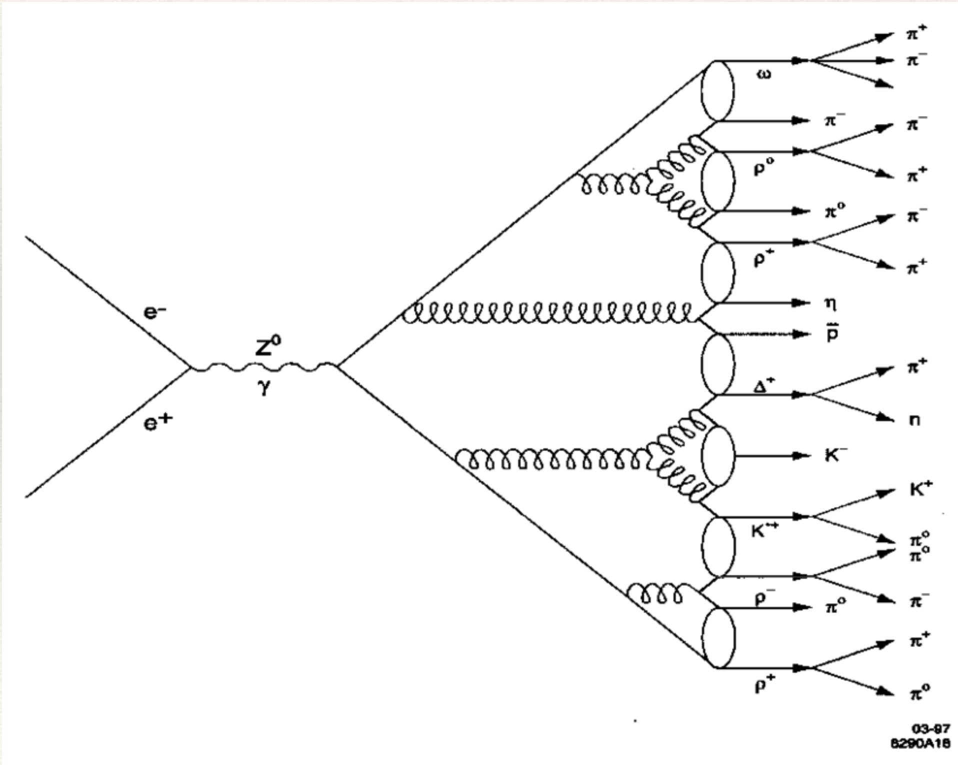
(a)
AMS-02
PAMELA
Fermi-LAT
MASS
CAPRICE
AMS-01
HEAT
$\tilde{E}^3 \Phi_{e^-}$ [GeV^2 m^{-2} sr^{-1} s^{-1}]
(b)
Positron fraction
Energy [GeV]

Cosmic-ray Positrons

- Similar to anti-proton story
  - There must be secondary production of positrons
- The proton-proton interactions chain
- $p + p \to (\pi^{0,\pm}) \ + X$
-

- Some intuitions of hadronic physics
- It is extremely complicated
-





Cosmic-ray Positrons

- Similar to anti-proton story
  - There must be secondary production of positrons

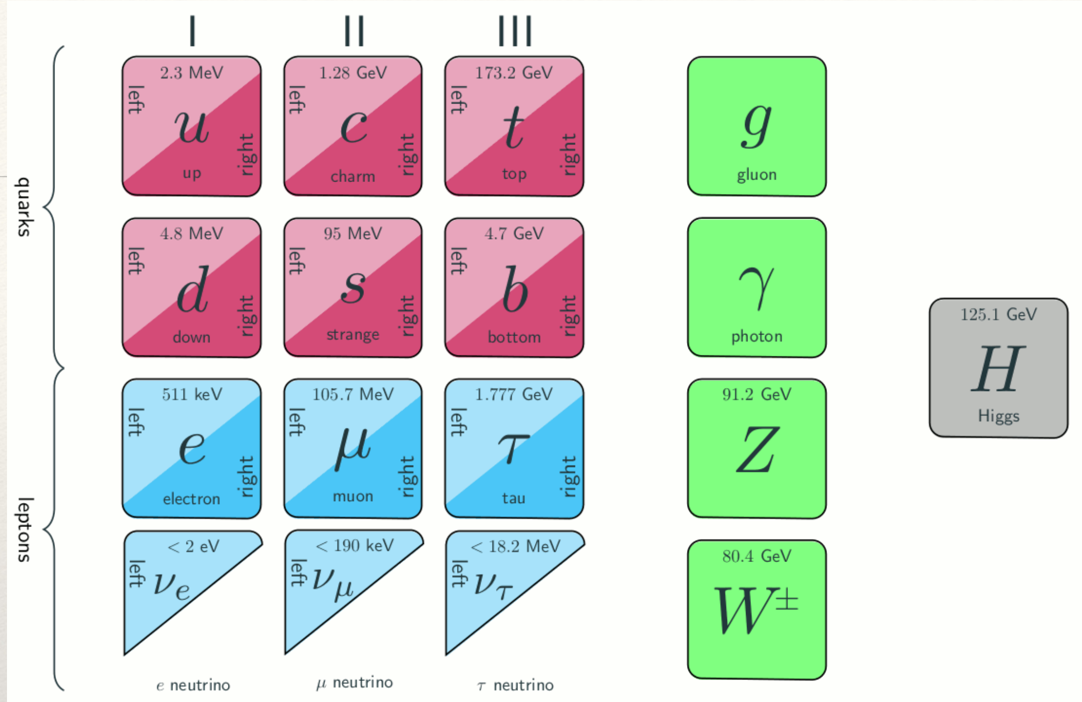
- Rule of thumbs for particle interactions
- Quantum number conservation
  - Baryon number
  - Lepton number
  - Charge

- The proton-proton interactions chain
- $p + p \rightarrow (\pi^{0,\pm}) \; + X$
- Pions are the lightest hadronic states
  - Charged pions decay into muson
  - Neutron pion decay into photons

Particle name	Particle symbol	Antiparticle symbol	Quark content[14]	Rest mass (MeV/c^2)	Mean lifetime (s)	Commonly decays to (>5% of decays)
Pion[1]	π^+	π^-	$u\bar{d}$	139.570 39 ± 0.000 18	$2.6033 \pm 0.0005 \times 10^{-8}$	$\mu^+ + \nu_\mu$
Pion[1]	π^0	Self	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$ [a]	134.976 8 ± 0.000 5	$8.5 \pm 0.2 \times 10^{-17}$	$\gamma + \gamma$

Cosmic-ray Positrons

- $\pi^+ \rightarrow$
- $\mu^+ \rightarrow$



Rule of thumbs for particle interactions

Quantum number conservation

- Baryon number
- Lepton number
- Charge

CR Secondary positron prediction

- $$\frac{\partial}{\partial t}n_i = D\nabla^2 n_i - \frac{\partial}{\partial E}\left(n_i\dot{E}\right) + Q_i^{pri} - n_i n_{ism}\sigma_{i\to\neq i}v - n_i\frac{1}{\tau_i} + \sum_j\left(n_j n_{ism}\sigma_{j\to i}v + n_j\frac{1}{\tau_j}Br_{j\to i}\right)$$

- The production term: (similar to antiprotons)
- $$n_{\bar{p}}(T_{\bar{p}}) = \left(\left(\int_{E_{th}} n_p(E_p)\frac{d\sigma_{pp->\bar{p}X}}{dT_{\bar{p}}}(E_p, T_{\bar{p}})dE_p - n_{\bar{p}}\sigma_{\bar{p}->X}\right)\frac{X}{m}\right.$$ ——— Leaky box solution
- In the diffusion equation
- $c n_{ism}\int_{E_{th}} n_p(E_p)\frac{d\sigma_{pp->\bar{p}X}}{dT_{\bar{p}}}(E_p, T_{\bar{p}})dE_p$: No. of antiprotons produced per volume per time, per energy

CR Secondary positron prediction

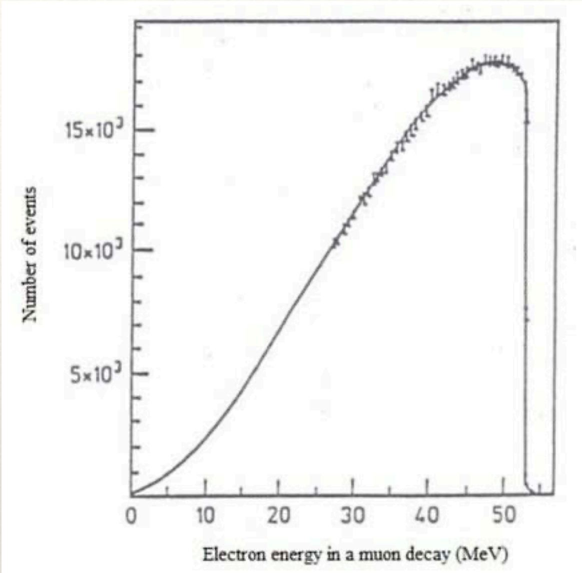
- Steps for secondary positron production

- Proton-proton interaction -> pions
- Pion decay -> muons
- Muon decay -> electron positrons

Cosmic-ray Positrons

- $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_e$
  - Plus the anti-version
- Charged pion mass: 140 MeV
  - $\Gamma \sim 2.6 \times 10^{-8}$ s
- Muon mass: 106 MeV
  - $\Gamma \sim 2.2 \times 10^{-6}$ s

Electron spectrum from muon decay at rest



It is continuous => not two body decays

CR Secondary positron prediction

- $pp \to \pi/K \to \mu \to e^{\pm}$, how to model this ??

- Pion energy density distribution obtained from proton-proton interaction

$$\frac{dn_\pi}{dE_\pi} = \int_{E_{p,min}} \frac{dn_p}{dE_p} \frac{d\sigma_{pp\to\pi}}{dE_\pi} n_{ISM} c\, dE_p$$

- Muon energy density from the pion spectrum,

- $$\frac{dn_\mu}{dE_\mu} = \int_{E_{min}} \frac{dn_\pi}{dE_\pi} \frac{dN_{\pi\to\mu}}{dE_\mu} dE_\pi$$

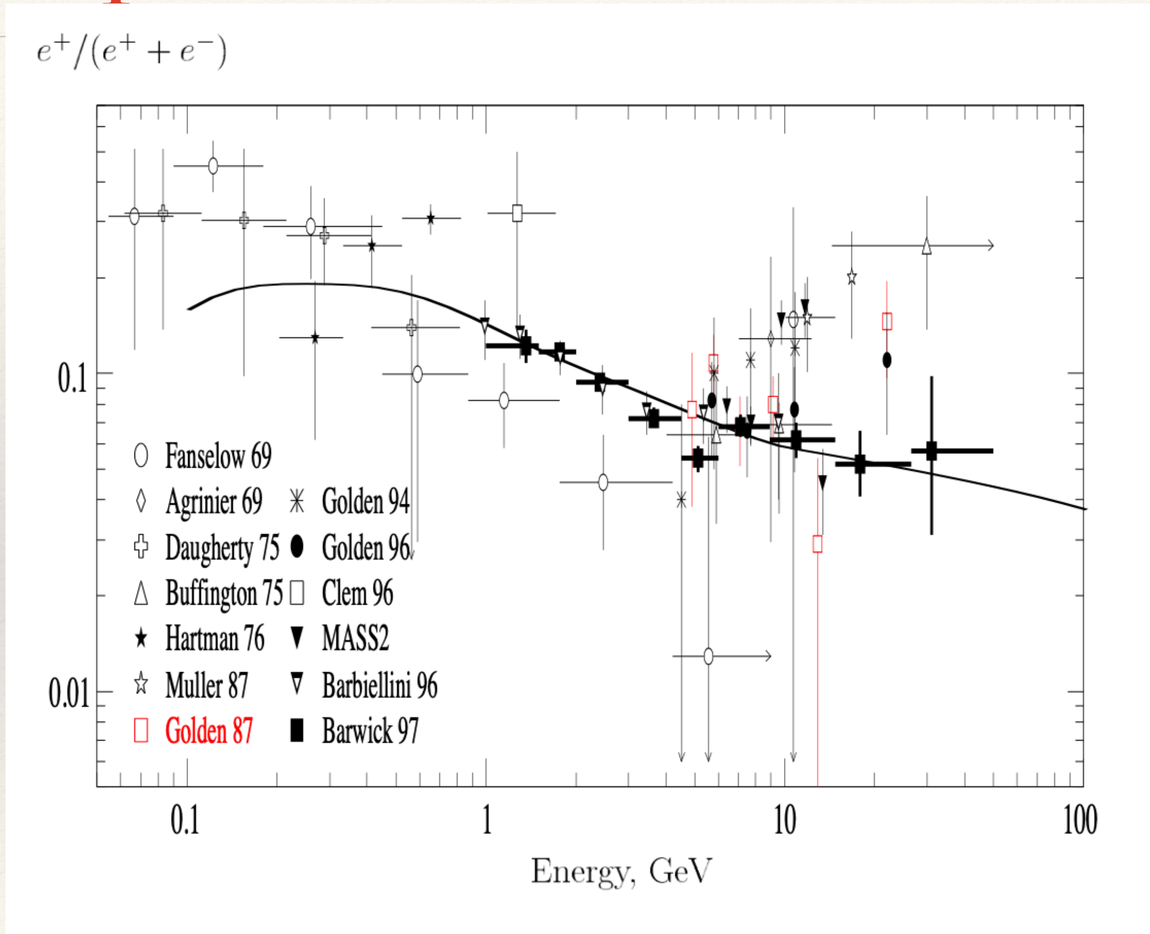
- Electron energy density from the muon spectrum,

- $$\frac{dn_e}{dE_e} = \int_{E_{min}} \frac{dn_\mu}{dE_\mu} \frac{dN_{\mu\to e}}{dE_e} dE_\mu$$

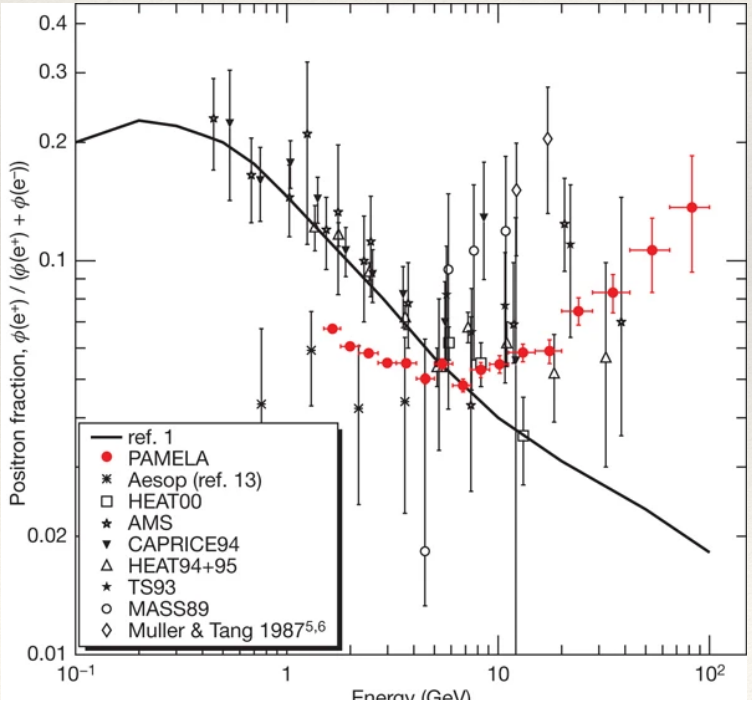
$$\frac{dn_e}{dE_e} = n_{ISM} c \iiint \frac{dn_p}{dE_p} \frac{d\sigma_{pp\to\pi}}{dE_\pi} \frac{dN_{\pi\to\mu}}{dE_\mu} \frac{dN_{\mu\to e}}{dE_e} dE_\mu dE_\pi dE_p$$

CR Secondary positron prediction

- In principle, you know how to do
- Positron fraction (1997):



The positron anomaly

- The positron fraction is rising
- It was predicted to be falling from CR secondary production
- 

Published: 02 April 2009

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, R. Bellotti, M. Boezio, E. A. Bogomolov, L. Bonechi, M. Bongi, V. Bonvicini, S. Bottai, A. Bruno, F. Cafagna, D. Campana, P. Carlson, M. Casolino, G. Castellini, M. P. De Pascale, G. De Rosa, N. De Simone, V. Di Felice, A. M. Galper, L. Grishantseva, P. Hofverberg, S. V. Koldashov, … V. G. Zverev + Show authors

Nature **458**, 607–609 (2009) | Cite this article

An anomalous positron abundance in cosmic rays with energies 1.5-100 GeV

PAMELA Collaboration • Oscar Adriani (Florence U. and INFN, Florence) Show All(51)

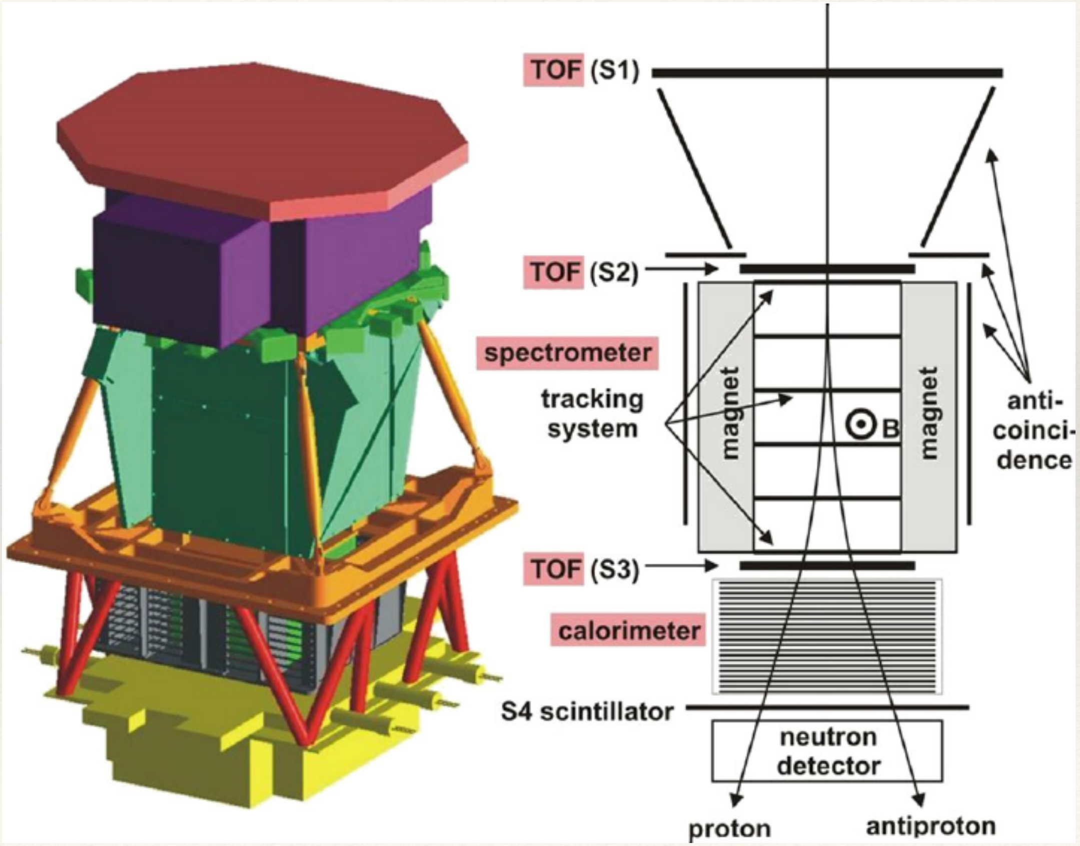
Oct, 2008

20 pages
Published in: *Nature* 458 (2009) 607-609
e-Print: 0810.4995 [astro-ph]
DOI: 10.1038/nature07942
Experiments: PAMELA
View in: ADS Abstract Service

PAMELA

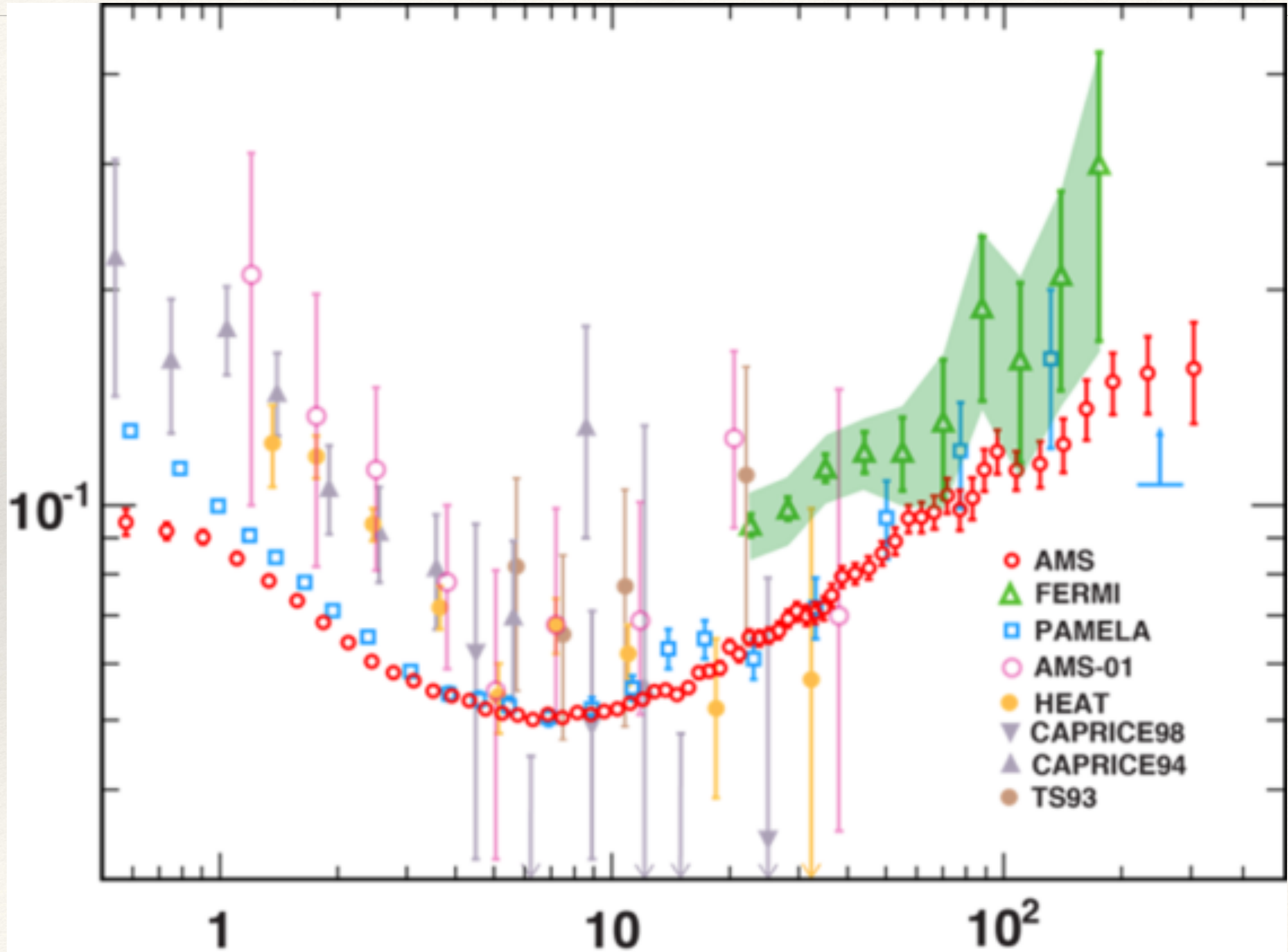
- PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics)

Organization	PAMELA group
Mission Type	Cosmic Ray
Host Satellite	Resurs DK1
Launch	15 June 2006
Launch vehicle	Soyuz-FG
Launch site	Baikonur Cosmodrome
Mission duration	3 years (planned), 9 years, 7 months and 23 days (achieved)
Mission end	7 February 2016
Mass	470 kg



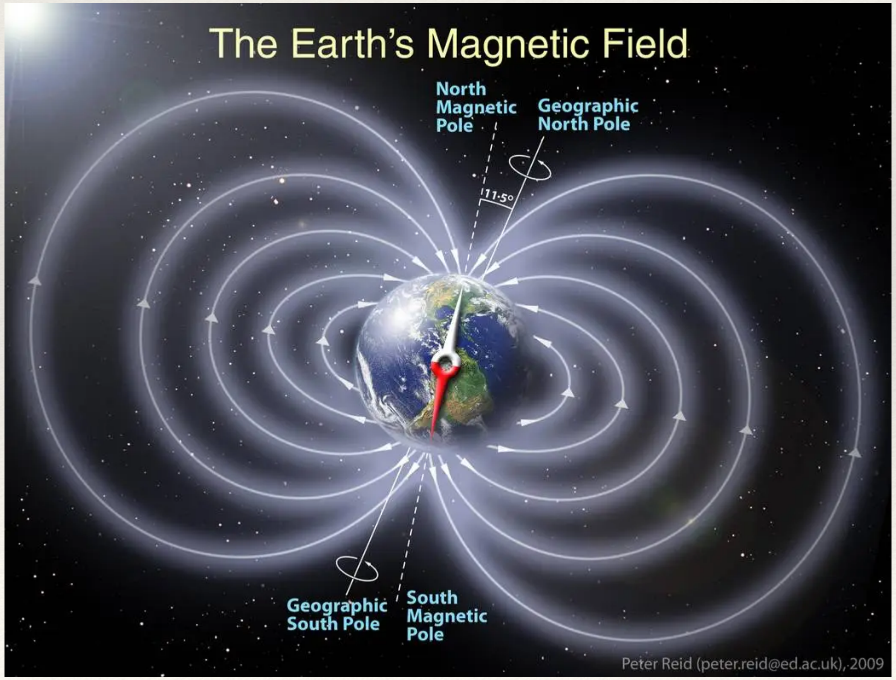
AMS and Fermi results confirms this

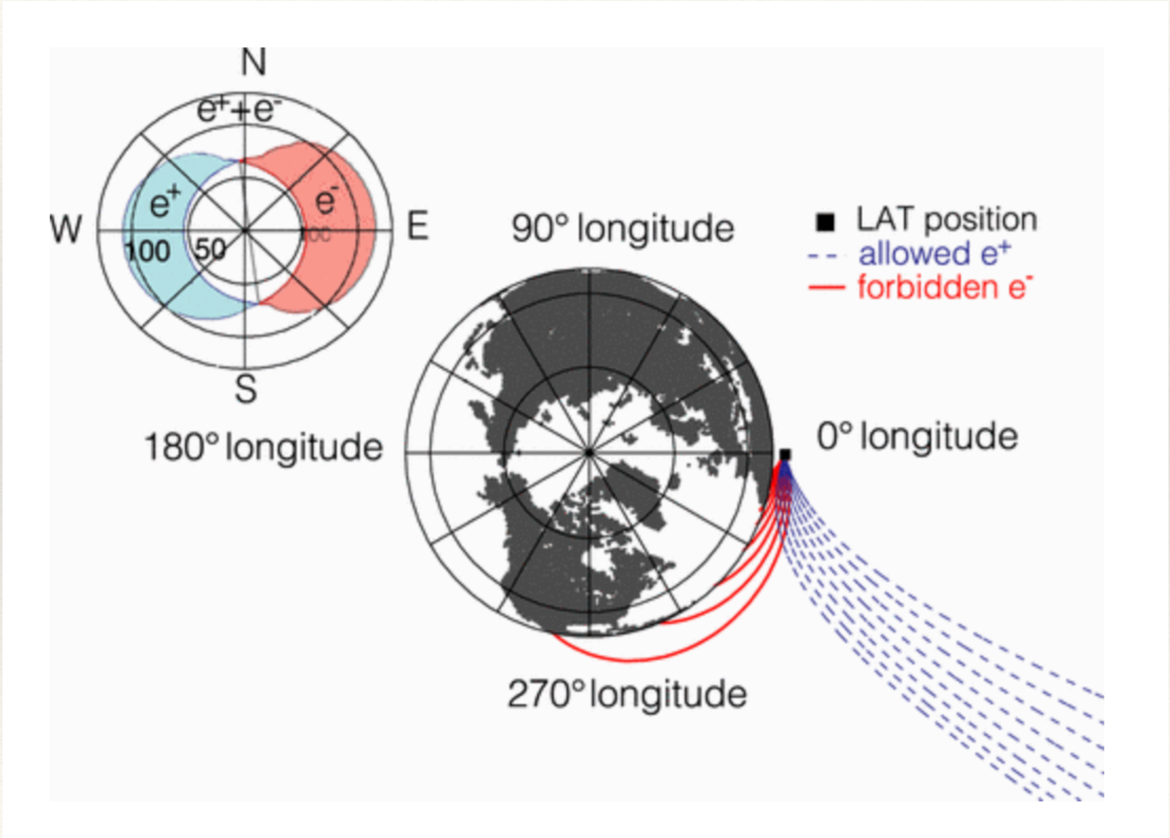
- New source?



Fermi positron detection

- Fermi doesn't have a magnetic
- How to detect positrons?





Multi-messenger Observations of a Binary Neutron Star Merger #1

LIGO Scientific and Virgo and Fermi GBM and INTEGRAL and IceCube and IPN and Insight-Hxmt and ANTARES and Swift and Dark Energy Camera GW-EM and DES and DLT40 and GRAWITA and Fermi-LAT and ATCA and ASKAP and OzGrav and DWF (Deeper Wider Faster Program) and AST3 and CAASTRO and VINROUGE and MASTER and J-GEM and GROWTH and JAGWAR and CaltechNRAO and TTU-NRAO and NuSTAR and Pan-STARRS and KU and Nordic Optical Telescope and ePESSTO and GROND and Texas Tech University and TOROS and BOOTES and MWA and CALET and IKI-GW Follow-up and H.E.S.S. and LOFAR and LWA and HAWC and Pierre Auger and ALMA and Pi of Sky and Chandra Team at McGill University and DFN and ATLAS Telescopes and High Time Resolution Universe Survey and RIMAS and RATIR and SKA South Africa/MeerKAT Collaborations and AstroSat Cadmium Zinc Telluride Imager Team and AGILE Team and 1M2H Team and Las Cumbres Observatory Group and MAXI Team and TZAC Consortium and SALT Group and Euro VLBI Team • B.P. Abbott (LIGO Lab., Caltech) et al. (Oct 16, 2017)

Published in: *Astrophys.J.Lett.* 848 (2017) 2, L12 • e-Print: 1710.05833 [astro-ph.HE]

pdf links DOI cite claim reference search 4,125 citations

The Large Area Telescope on the Fermi Gamma-ray Space Telescope Mission #2

Fermi-LAT Collaboration • W.B. Atwood (UC, Santa Cruz) et al. (Feb, 2009)

Published in: *Astrophys.J.* 697 (2009) 1071-1102 • e-Print: 0902.1089 [astro-ph.IM]

pdf links DOI cite claim reference search 4,115 citations

Fermi Large Area Telescope Third Source Catalog #3

Fermi-LAT Collaboration • F. Acero (AIM, Saclay) et al. (Jan 8, 2015)

Published in: *Astrophys.J.Suppl.* 218 (2015) 2, 23 • e-Print: 1501.02003 [astro-ph.HE]

pdf DOI cite claim reference search 1,539 citations

Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data #4

Fermi-LAT Collaboration • M. Ackermann (DESY) et al. (Mar 9, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 23, 231301 • e-Print: 1503.02641 [astro-ph.HE]

pdf links DOI cite claim reference search 1,517 citations

$Fermi$ Large Area Telescope Fourth Source Catalog #5

Fermi-LAT Collaboration • S. Abdollahi (Hiroshima U.) et al. (Feb 26, 2019)

Published in: *Astrophys.J.Suppl.* 247 (2020) 1, 33 • e-Print: 1902.10045 [astro-ph.HE]

pdf DOI cite claim reference search 1,423 citations

Fermi Large Area Telescope Second Source Catalog #6

Fermi-LAT Collaboration (Aug, 2011)

Published in: *Astrophys.J.Suppl.* 199 (2012) 31 • e-Print: 1108.1435 [astro-ph.HE]

pdf DOI cite claim reference search 1,356 citations

Measurement of the Cosmic Ray e+ plus e- spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope #7

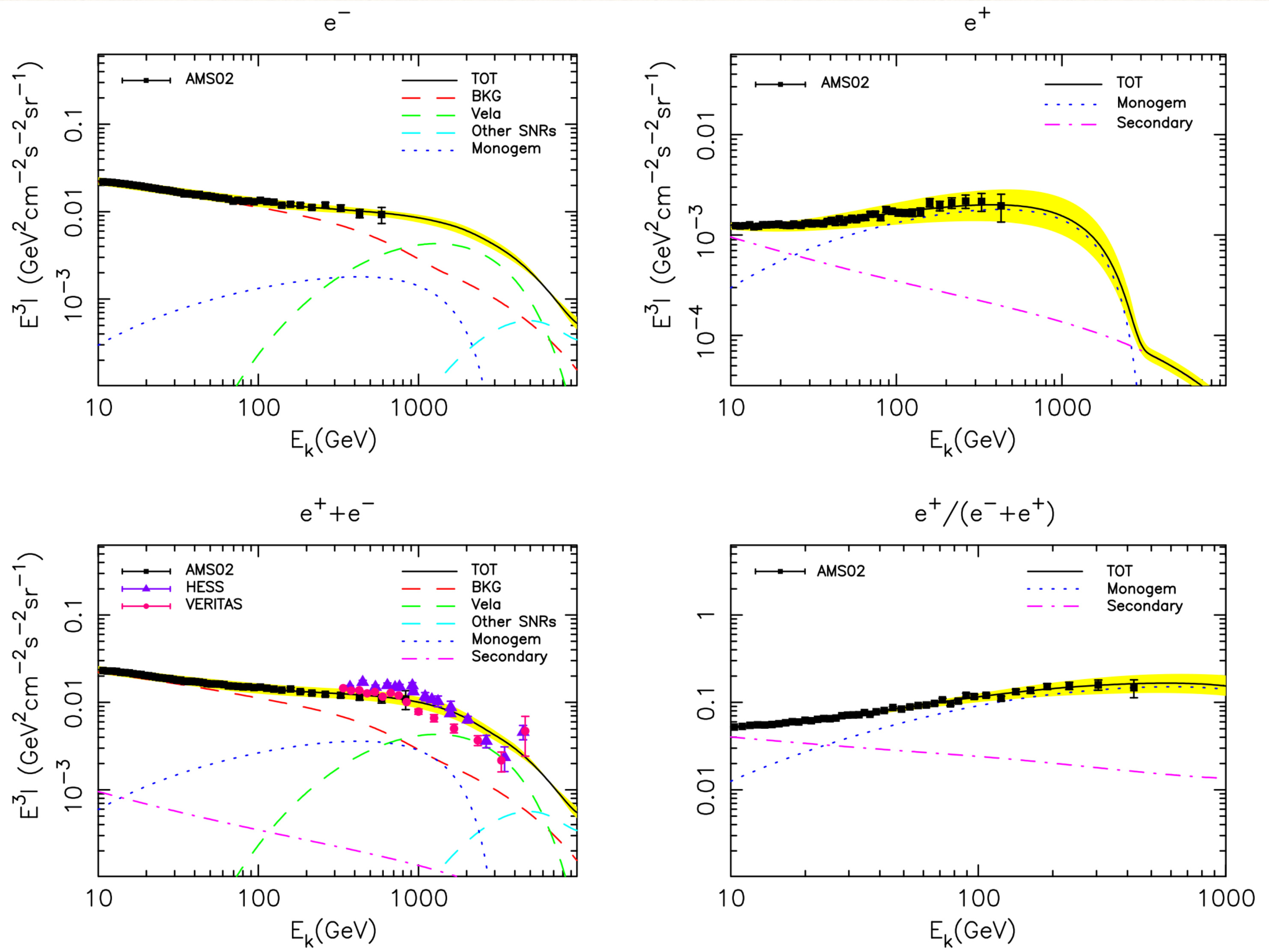
Fermi-LAT Collaboration • Aous A. Abdo (Naval Research Lab, Wash., D.C.) et al. (May, 2009)

Published in: *Phys.Rev.Lett.* 102 (2009) 181101 • e-Print: 0905.0025 [astro-ph.HE]

pdf links DOI cite claim reference search 1,141 citations

Possible interpretation

- Supernova remnants as electron source
- Pulsar Wind Nebula as electron and positron source
- Other primaries?



Perspective on the Cosmic-ray Electron Spectrum above TeV

Kun Fang, Bing-Bing Wang, Xiao-Jun Bi, Su-Jie Lin, and Peng-Fei Yin
Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

Received 2016 December 25; revised 2017 January 19; accepted 2017 January 19; published 2017 February 17

An anomalous positron abundance in cosmic rays with energies 1.5-100 GeV

PAMELA Collaboration • Oscar Adriani (Florence U. and INFN, Florence) et al. (Oct, 2008)

Published in: *Nature* 458 (2009) 607-609 • e-Print: 0810.4995 [astro-ph]

pdf DOI cite claim reference search 2,629 citation

A Model of Leptons

Steven Weinberg (MIT, LNS)

Nov, 1967

3 pages

Published in: *Phys.Rev.Lett.* 19 (1967) 1264-1266

DOI: 10.1103/PhysRevLett.19.1264

View in: OSTI Information Bridge Server, ADS Abstract Service

links cite claim reference search 15,067 citations

Planck 2015 results. XIII. Cosmological parameters #1

Planck Collaboration • P.A.R. Ade (Cardiff U.) et al. (Feb 5, 2015)

Published in: *Astron.Astrophys.* 594 (2016) A13 • e-Print: 1502.01589 [astro-ph.CO]

pdf DOI cite claim reference search 13,595 citations

Review of Particle Physics #2

Particle Data Group • K.A. Olive (Minnesota U.) et al. (2014)

Published in: *Chin.Phys.C* 38 (2014) 090001

links DOI cite claim reference search 9,384 citations

Review of Particle Physics #3

Particle Data Group • M. Tanabashi (Nagoya U. and KMI, Nagoya) et al. (Aug 17, 2018)

Published in: *Phys.Rev.D* 98 (2018) 3, 030001

links DOI cite claim reference search 9,352 citations

Review of Particle Physics #4

Particle Data Group • C. Patrignani (Bologna U. and INFN, Bologna) et al. (Oct 3, 2016)

Published in: *Chin.Phys.C* 40 (2016) 10, 100001

pdf links DOI cite claim reference search 7,184 citations

Review of particle physics #5

Particle Data Group • K. Nakamura (Tokyo U., IPMU and KEK, Tsukuba) et al. (2010)

Published in: *J.Phys.G* 37 (2010) 075021

links DOI cite claim reference search 6,880 citations

Review of Particle Physics #6

Particle Data Group • R.L. Workman (George Washington U.) et al. (Aug 8, 2022)

Published in: *PTEP* 2022 (2022) 083C01

pdf links DOI cite claim reference search 5,200 citations

Review of particle physics #7

Particle Data Group • S. Navas (Granada U., Theor. Phys. Astrophys. and CAFPE, Granada) et al. (Aug 1, 2024)

Published in: *Phys.Rev.D* 110 (2024) 3, 030001

DOI cite claim reference search 2,709 citations

A Theory of Dark Matter #8

Nima Arkani-Hamed (Princeton, Inst. Advanced Study), Douglas P. Finkbeiner (Harvard-Smithsonian Ctr. Astrophys.), Tracy R. Slatyer (Harvard U., Phys. Dept.), Neal Weiner (New York U., CCPP) (Oct, 2008)

Published in: *Phys.Rev.D* 79 (2009) 015014 • e-Print: 0810.0713 [hep-ph]

pdf DOI cite claim reference search 1,991 citations