Indirect DM searches

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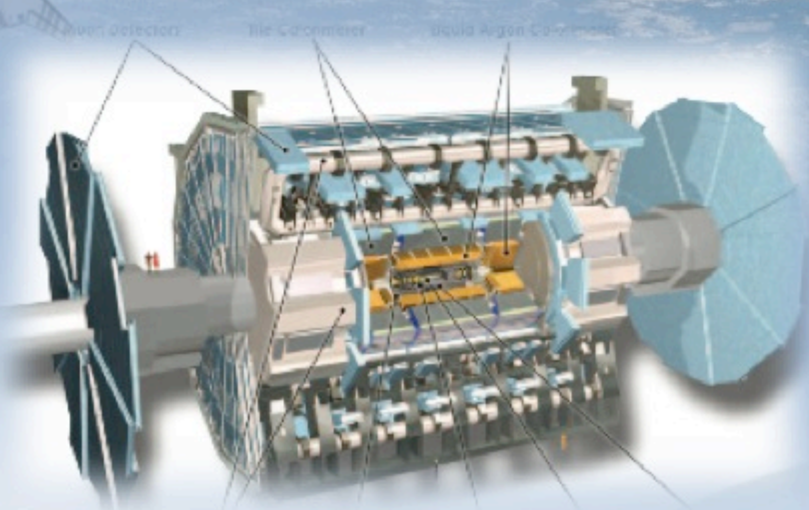
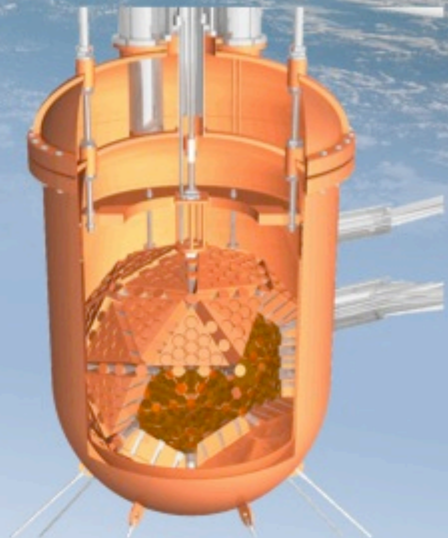
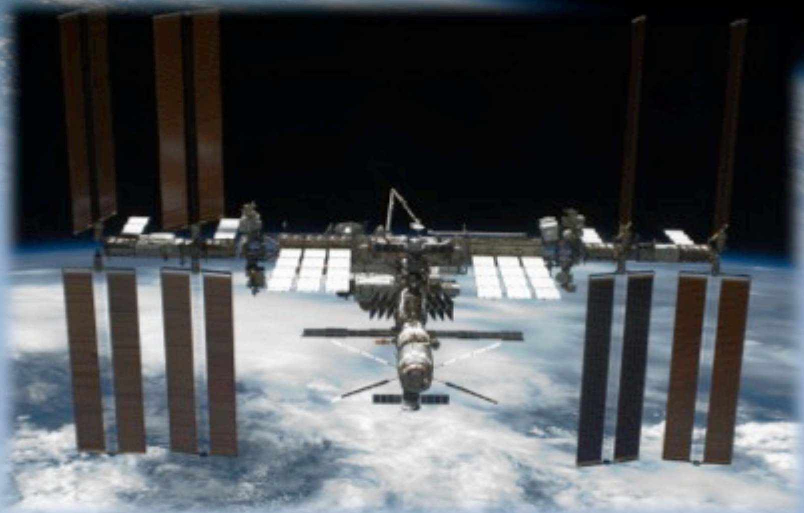
Academia Sinica /Taiwan

August/2014
KUBEC Workshop
on Dark Matter Searches

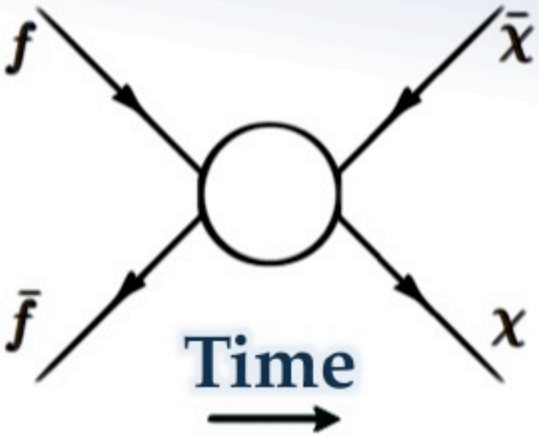
Dark Matter searches



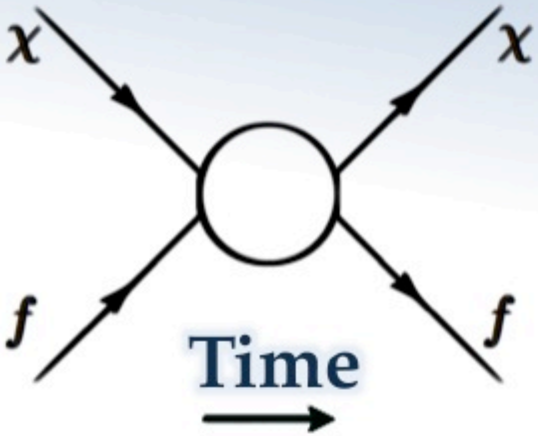




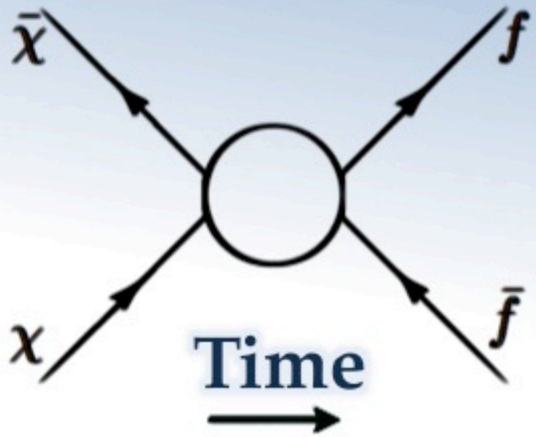
Colliders



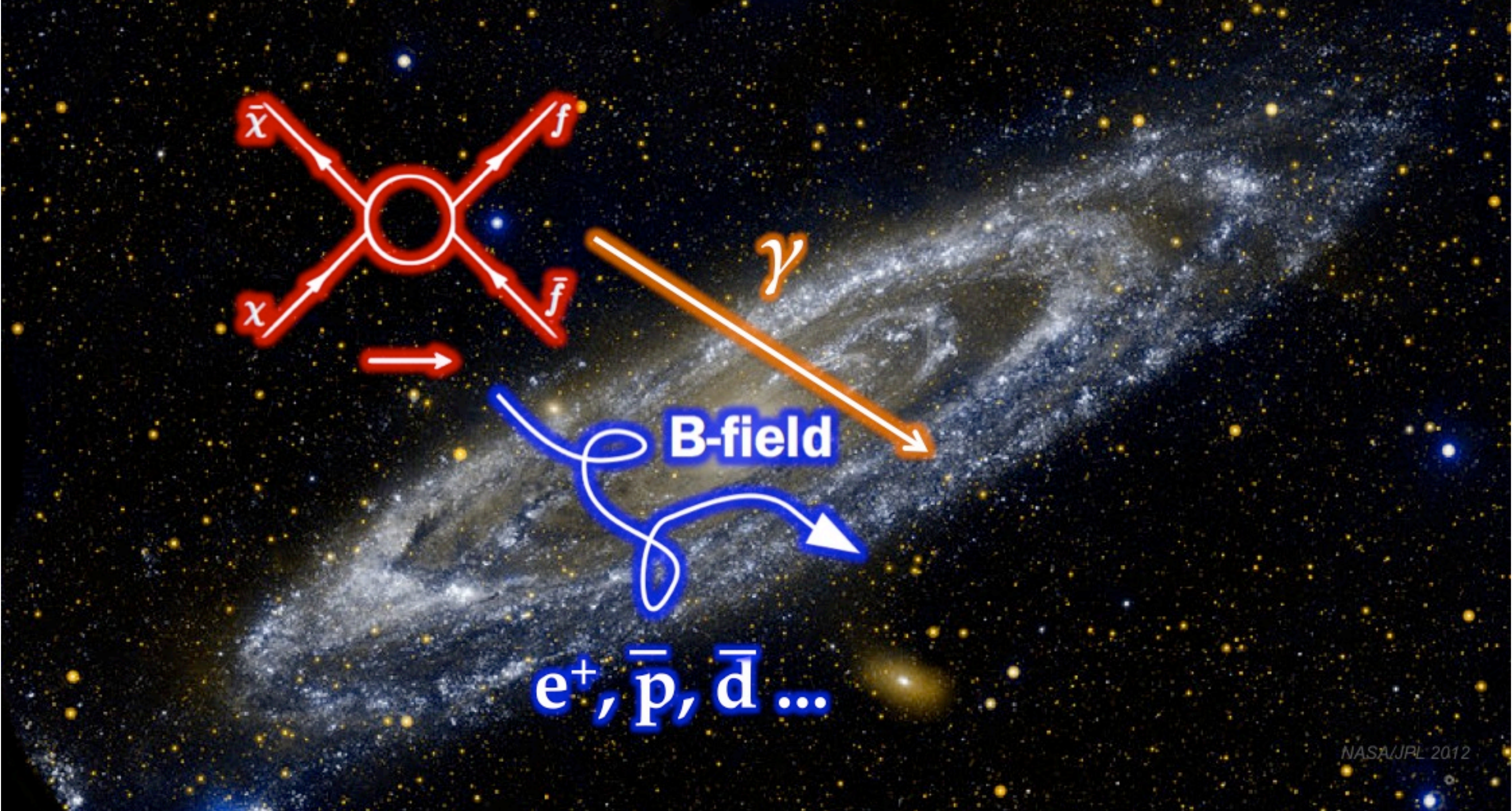
Direct search



Indirect search

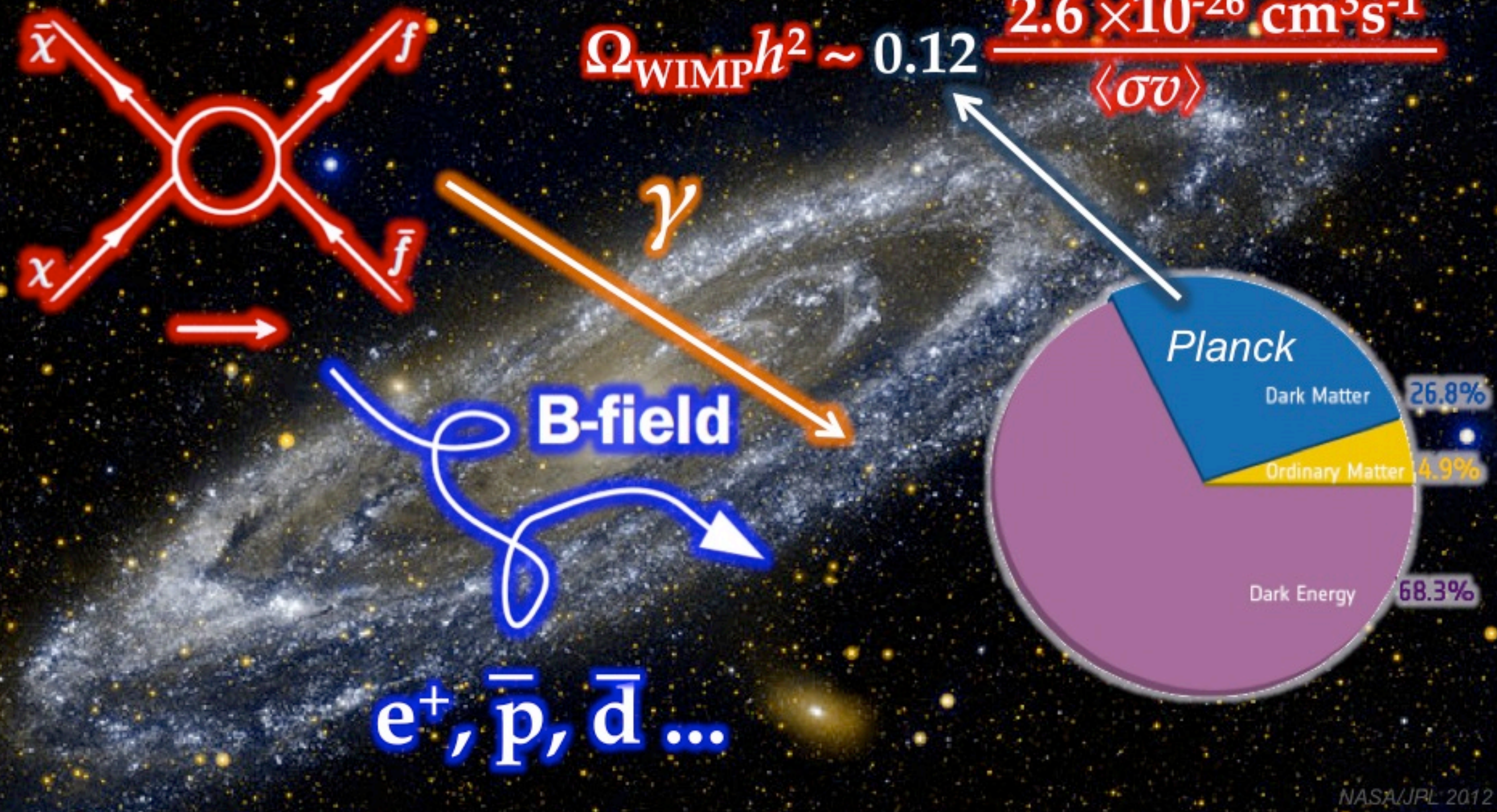


Indirect searches

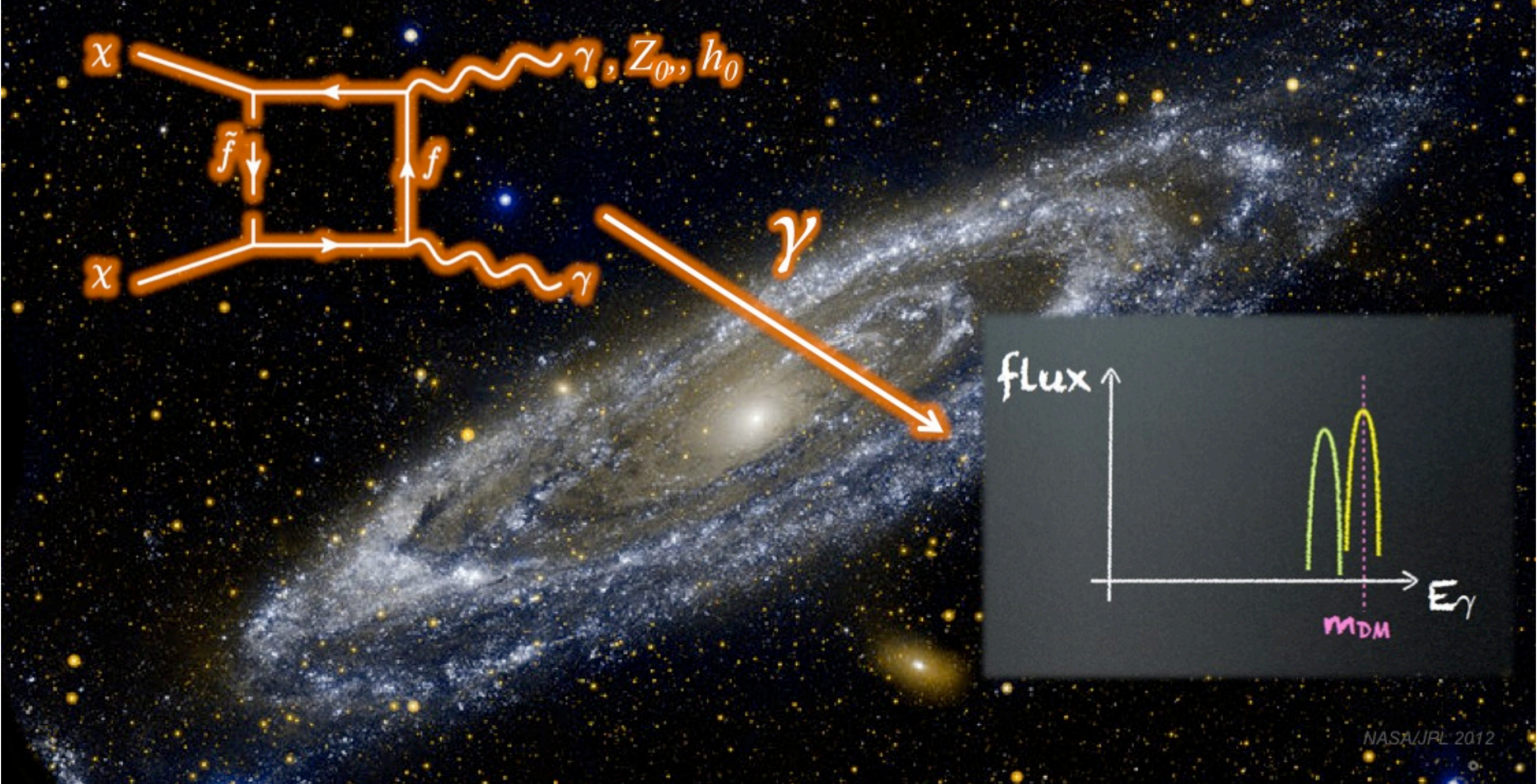


Two important parameters : m_χ, $\langle \sigma v \rangle$

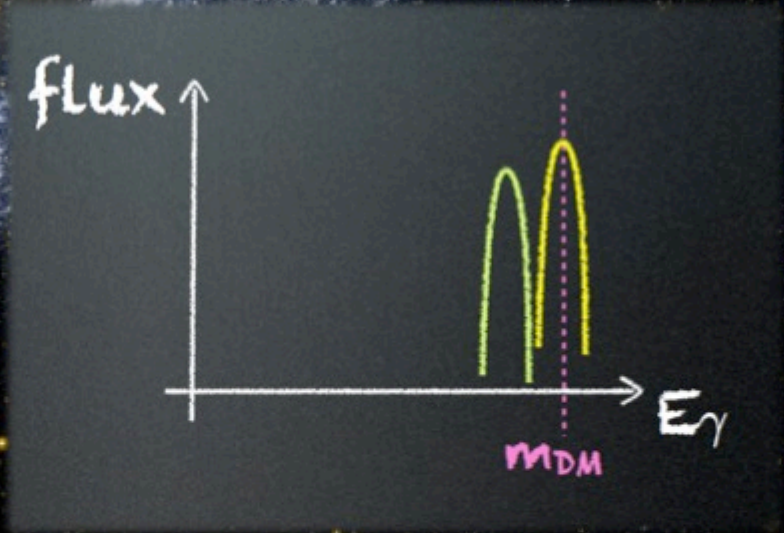
$$\Omega_{WIMP} h^2 \sim 0.12 \frac{2.6 \times 10^{-26}\ cm^3 s^{-1}}{\langle \sigma v \rangle}$$



Gamma-ray lines



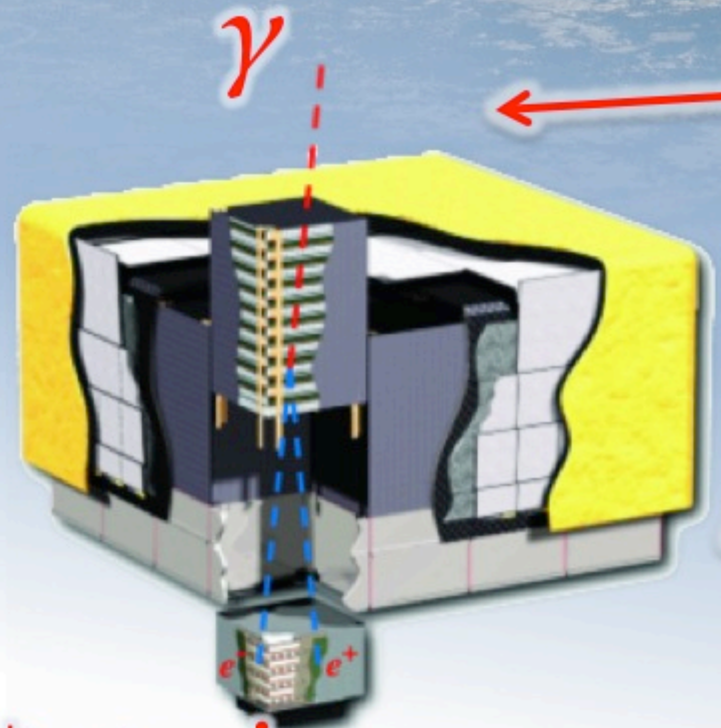
Gamma-ray lines

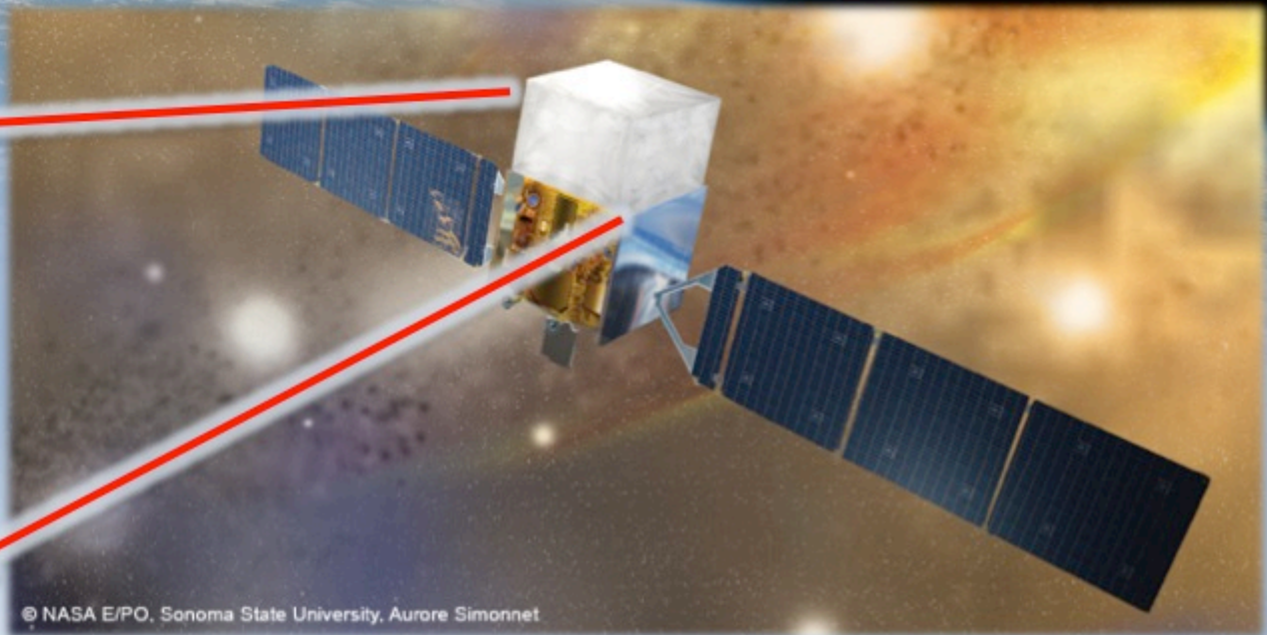


Loop-suppressed
→ small branching ratio
$\langle \sigma v \rangle_{\gamma\gamma} \sim 10^{-3} \langle \sigma v \rangle_{tot} \sim 10^{-29}$ cm^{3}s^{-1}

NASA/JPL 2012

Fermi-LAT





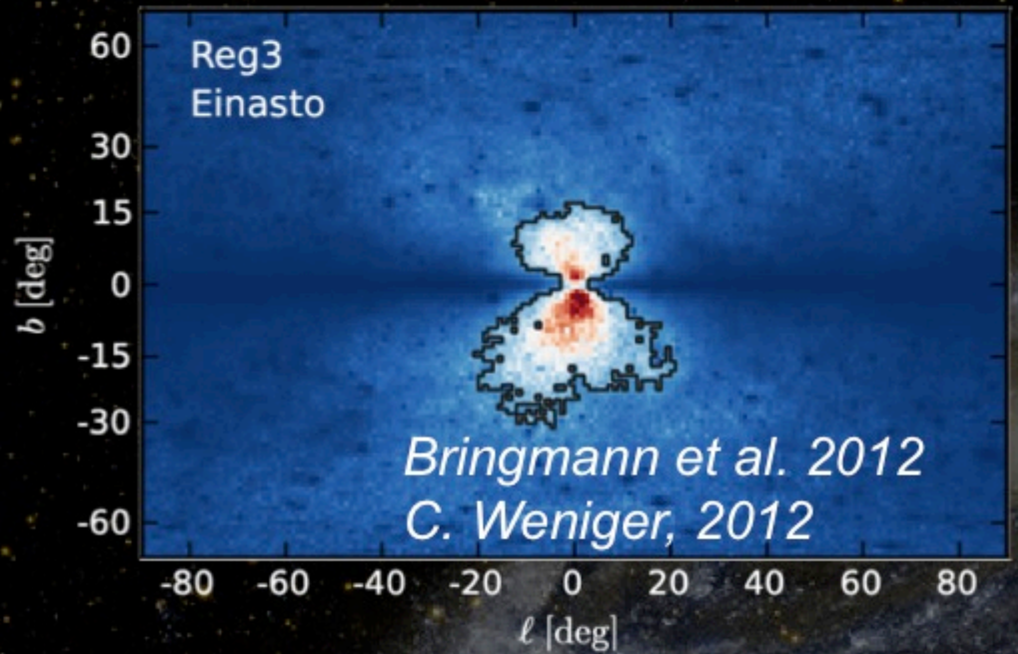
e^+, e^- pair

Launched
in June/2008

Energy range : 20 MeV – 300 GeV
Data available in public :
http://fermi.gsfc.nasa.gov/ssc/

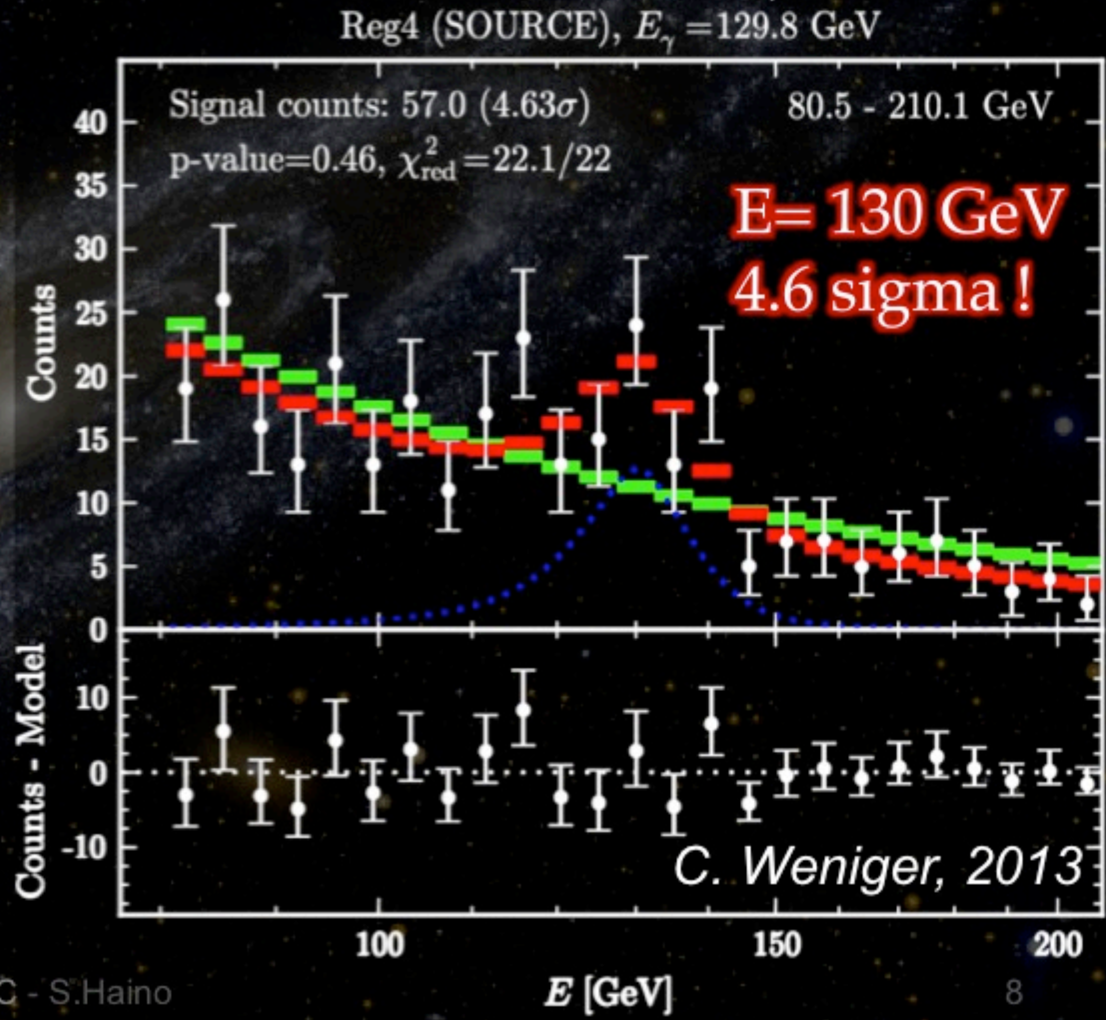
A line found ?

1, Identify best ROI



2, Fit : Power law BG + Line

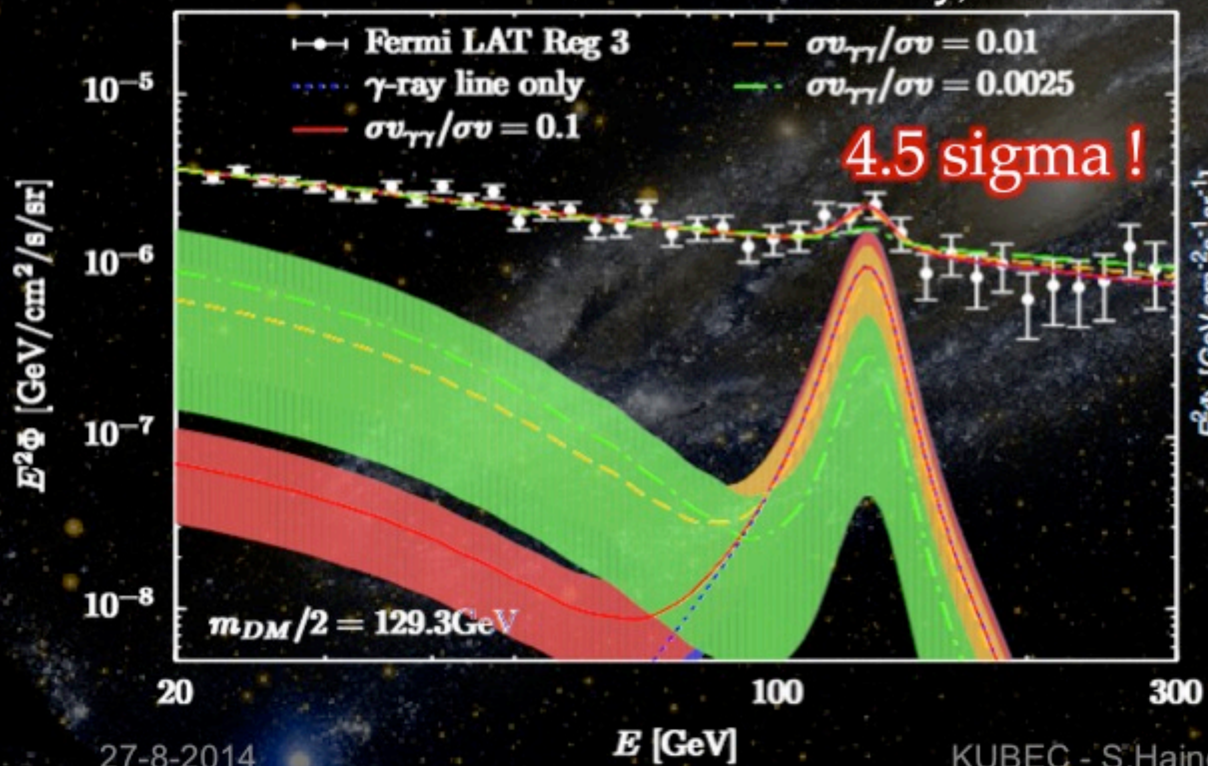
e.g. $dJ/dE = \mathbf{S}\,\delta(E-E_\gamma) + \boldsymbol{\beta} E^{-\gamma}$



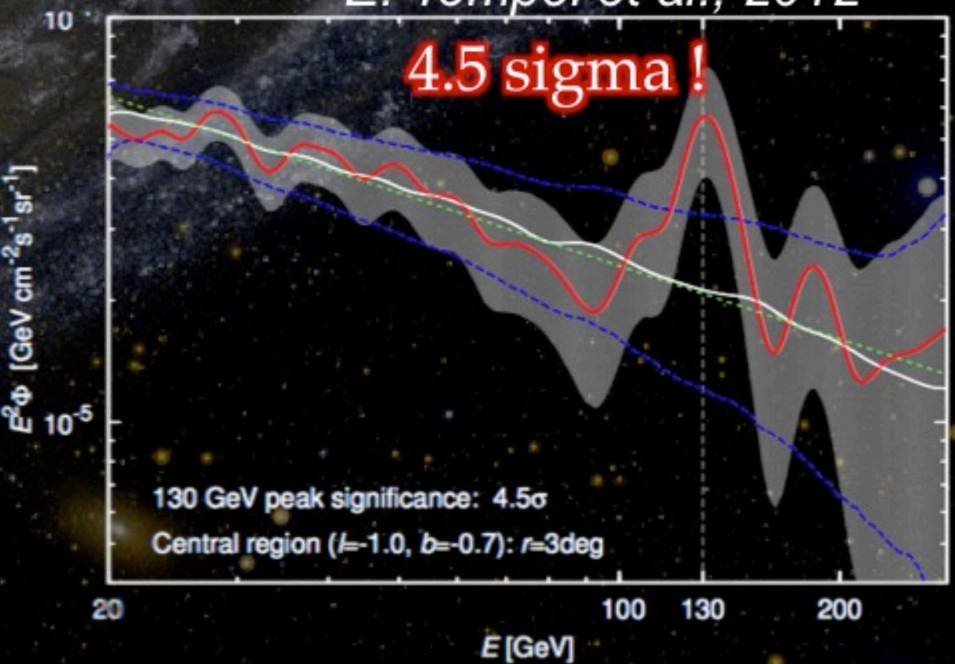
Follow up studies ...

Profumo, Linden, JCAP 1207 (2012) 011; Ibarra, Gehler, Pato, JCAP 1207 (2012) 043; Dudas et al., arXiv: 1205.1520; Cline, PRD86 (2012) 015016; Choi, Seto, PRD86 (2012) 043515; Kyae, Park, arXiv:1205.4151; Lee, Park, Park, arXiv:1205.4675; Boyarsky, Malyshev, Ruchayskiy, arXiv:1205.4700; Rajaraman, Tait, Whiteson, arXiv:1205.4723; Acharya et al., arXiv:1205.5789; Buckley, Hooper, PRD86 (2012) 043524; Geringer-Samet, Koushiappas, PRD86 (2012) 021302; Li, Yuan, PLB715 (2012) 35; Chu et al., arXiv:1206.2279; Das, Ellwanger, Mitropoulos, JCAP 1208 (2012) 003; Kang et al., arXiv:1206.2863; Weiner, Yavin, arXiv:1206.2910...

W. Buchmuller and M. Garny, 2012



E. Tempel et al., 2012



… and Fermi publication

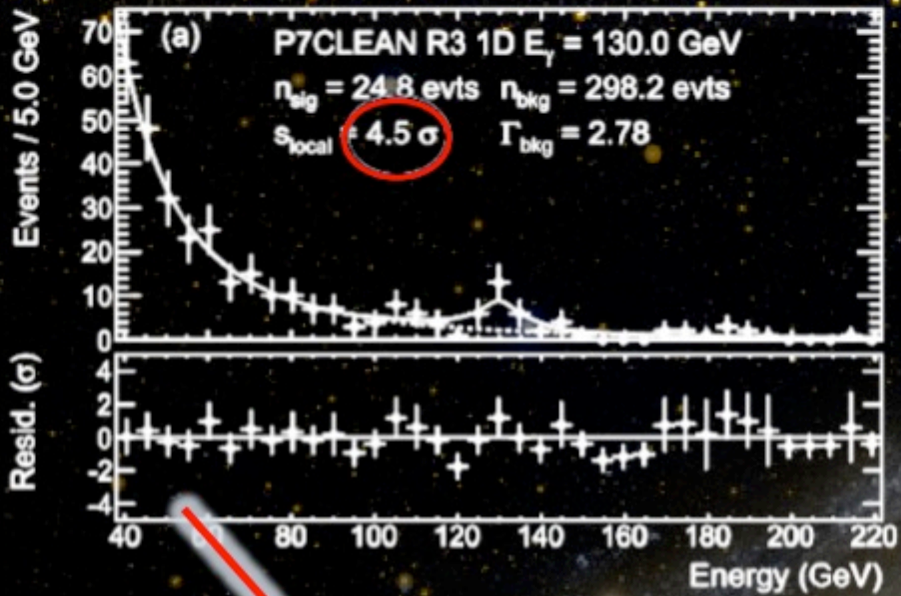
PRD 88, 082002 (2013)

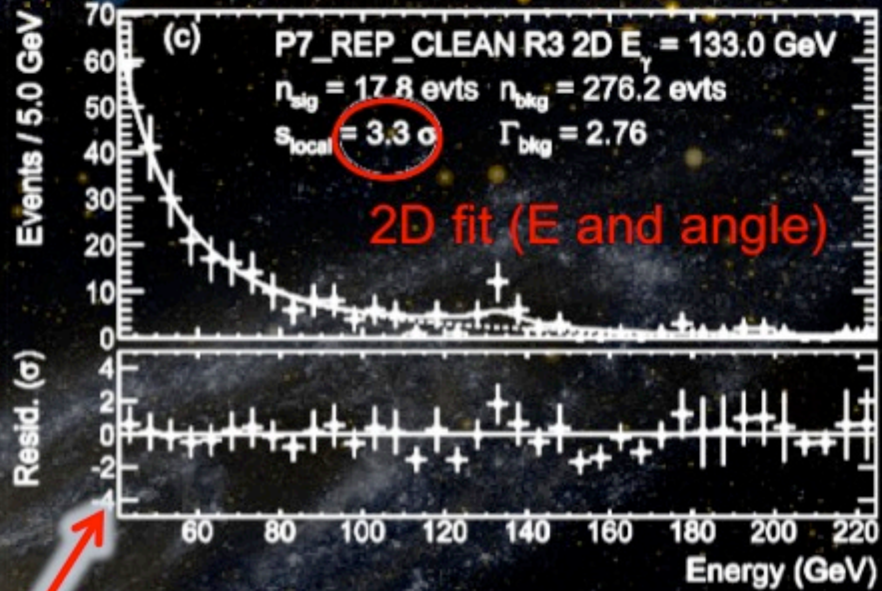
Search for Gamma-ray Spectral Lines with the *Fermi* Large Area Telescope and Dark Matter Implications

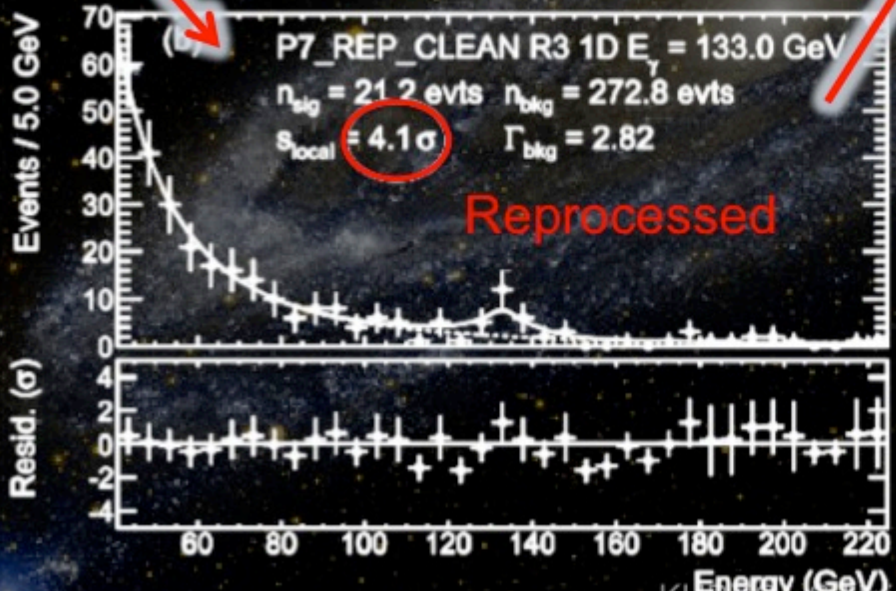
M. Ackermann,[1] M. Ajello,[2] A. Albert,[3,*] A. Allafort,[4] L. Baldini,[5] G. Barbiellini,[6,7] D. Bastieri,[8,9] K. Bechtol,[4] R. Bellazzini,[10] E. Bissaldi,[11] E. D. Bloom,[4,†] E. Bonamente,[12,13] E. Bottacini,[4] T. J. Brandt,[14] J. Bregeon,[10] M. Brigida,[15,16] P. Bruel,[17] R. Buehler,[1] S. Buson,[8,9] G. A. Caliandro,[18] R. A. Cameron,[4] P. A. Caraveo,[19] J. M. Casandjian,[20] C. Cecchi,[12,13] E. Charles,[4,‡] R.C.G. Chaves,[20] A. Chekhtman,[21] J. Chiang,[4] S. Ciprini,[22,23] R. Claus,[4] J. Cohen-Tanugi,[24] J. Conrad,[25,26,27,28] S. Cutini,[22,23] F. D'Ammando,[29] A. de Angelis,[30] F. de Palma,[15,16] C. D. Dermer,[31] S. W. Digel,[4] L. Di Venere,[4] P. S. Drell,[4] A. Drlica-Wagner,[4] R. Essig,[4] C. Favuzzi,[15,16] S. J. Fegan,[17] E. C. Ferrara,[14] W. B. Focke,[4] A. Franckowiak,[4] Y. Fukazawa,[32] S. Funk,[4] P. Fusco,[15,16] F. Gargano,[16] D. Gasparrini,[22,23] S. Germani,[12,13] N. Giglietto,[15,16] F. Giordano,[15,16] M. Giroletti,[29] T. Glanzman,[4] G. Godfrey,[4] G. A. Gomez-Vargas,[33,34,35] I. A. Grenier,[20] S. Guiriec,[14] M. Gustafsson,[36] D. Hadasch,[18] M. Hayashida,[4,37] A. B. Hill,[4,38,39] D. Horan,[17] X. Hou,[40] R. E. Hughes,[3] Y. Inoue,[4] E. Izaguirre,[4] T. Jogler,[4] T. Kamae,[4] J. Knödlseder,[41,42] M. Kuss,[10] J. Lande,[4] S. Larsson,[25,26,43] L. Latronico,[44] F. Longo,[6,7] F. Loparco,[15,16] M. N. Lovellette,[31] P. Lubrano,[12,13] D. Malyshev,[4] M. Mayer,[1] M. N. Mazziotta,[16] J. E. McEnery,[14,45] P. F. Michelson,[4] W. Mitthumsiri,[4] T. Mizuno,[46] A. A. Moiseev,[47,45] M. E. Monzani,[4] A. Morselli,[33] I. V. Moskalenko,[4] S. Murgia,[4] T. Nakamori,[48] R. Nemmen,[14] E. Nuss,[24] T. Ohsugi,[46] A. Okumura,[4,49] N. Omodei,[4] M. Orienti,[29] E. Orlando,[4] J. F. Ormes,[50] D. Paneque,[51,4] J. S. Perkins,[14,52,47] M. Pesce-Rollins,[10] F. Piron,[24] G. Pivato,[9] S. Rainò,[15,16] R. Rando,[8,9] M. Razzano,[10,53] S. Razzaque,[54] A. Reimer,[11,4] O. Reimer,[11,4] R. W. Romani,[4] M. Sánchez-Conde,[4] A. Schulz,[1] C. Sgrò,[10] J. Siegal-Gaskins,[55] E. J. Siskind,[56] A. Snyder,[4] G. Spandre,[10] P. Spinelli,[15,16] D. J. Suson,[57] H. Tajima,[4,49] H. Takahashi,[32] J. G. Thayer,[4] J. B. Thayer,[4] L. Tibaldo,[4] M. Tinivella,[10] G. Tosti,[12,13] E. Troja,[14,58] Y. Uchiyama,[59] T. L. Usher,[4] J. Vandenbroucke,[4] V. Vasileiou,[24] G. Vianello,[4,60] V. Vitale,[33,61] B. L. Winer,[3,§] K. S. Wood,[31] M. Wood,[4] Z. Yang,[25,26] G. Zaharijas,[6,62] and S. Zimmer[25,26]

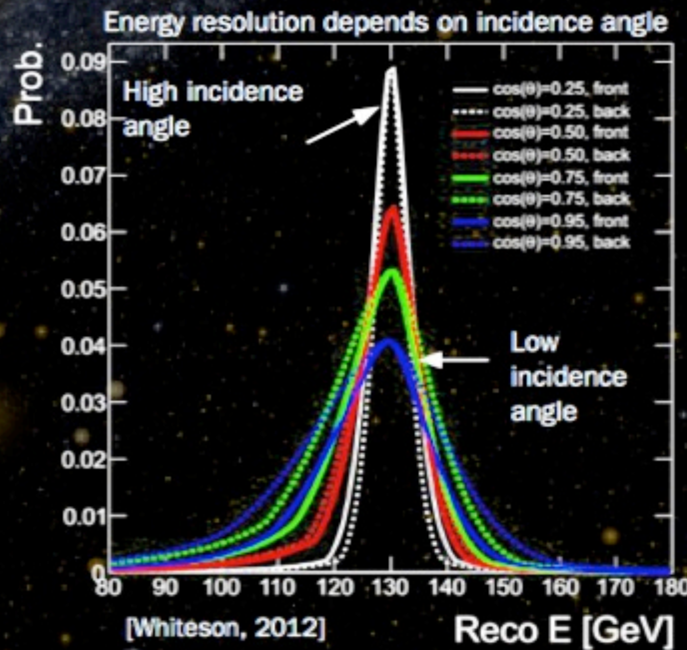
Fermi analysis

PRD 88, 082002 (2013)

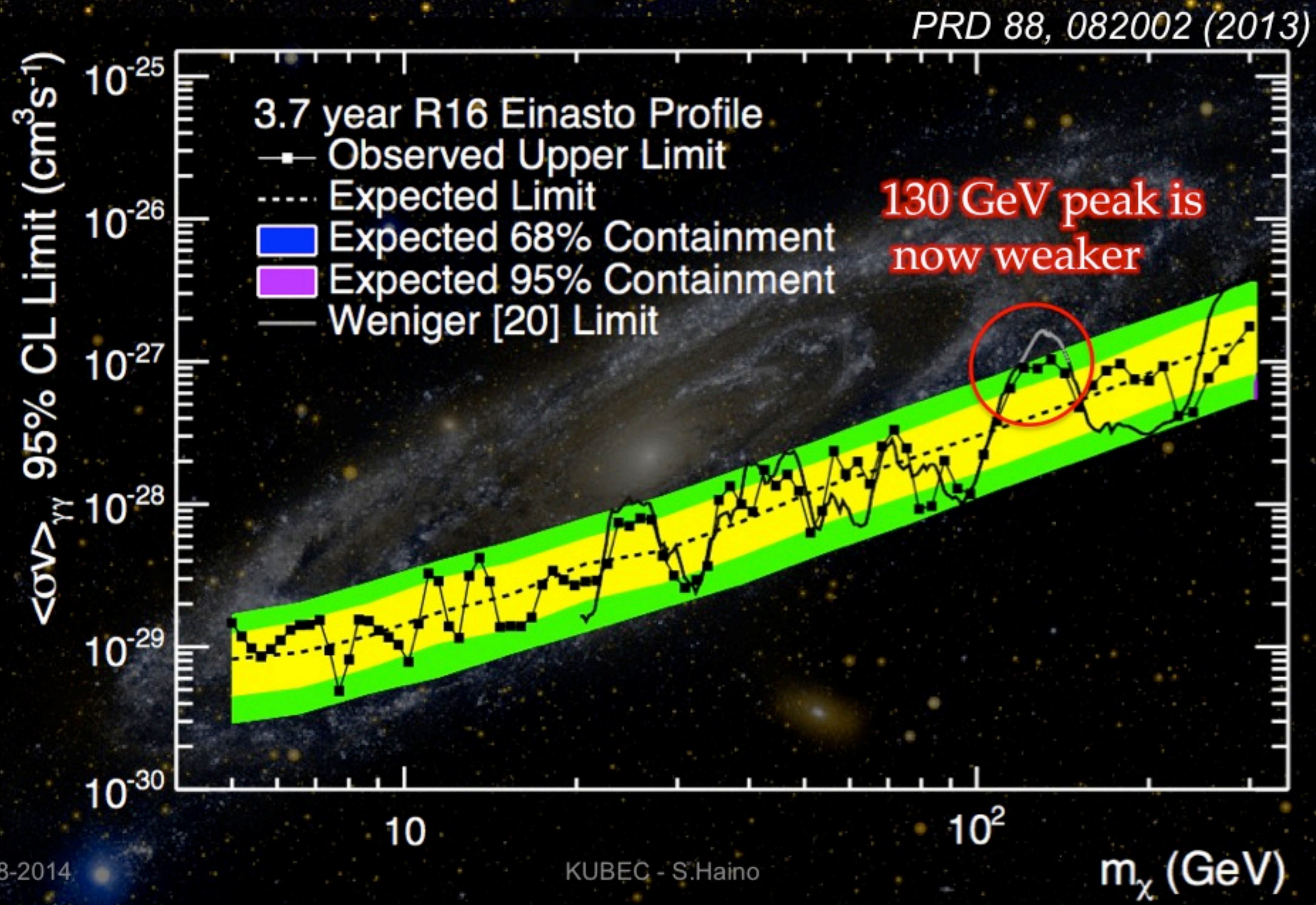




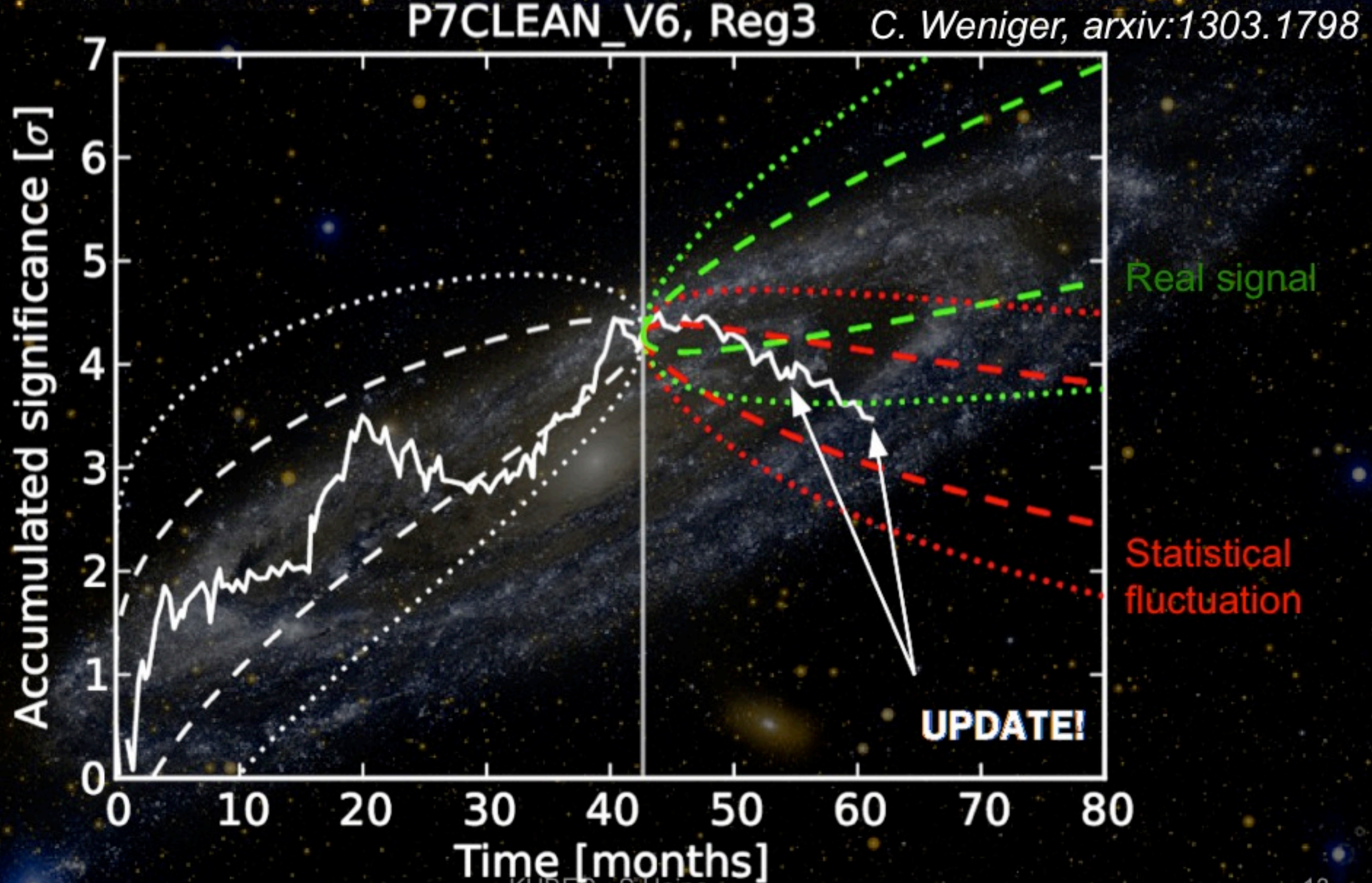




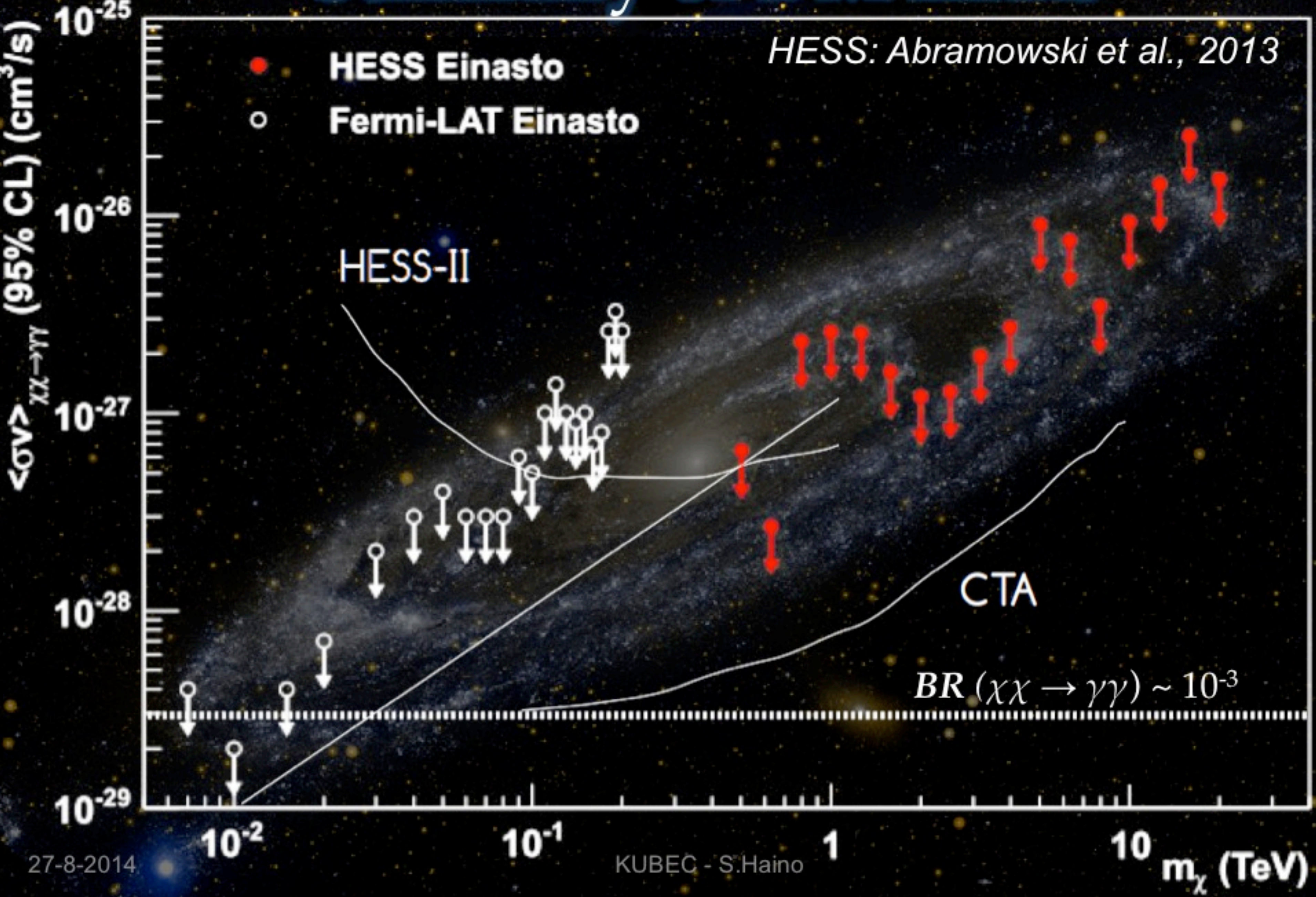
Fermi limits



Time evolution of significance

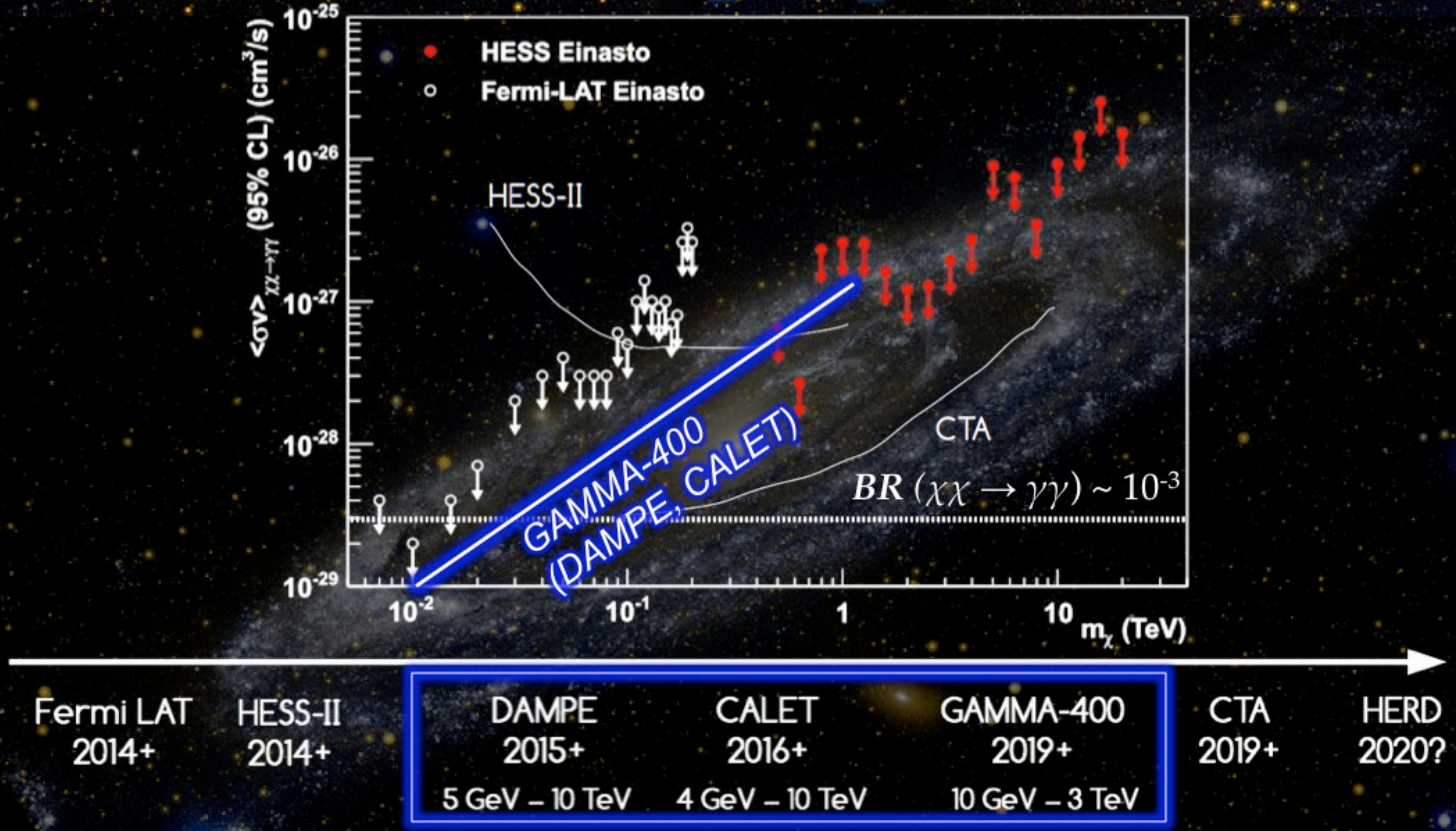


Summary of DM limits

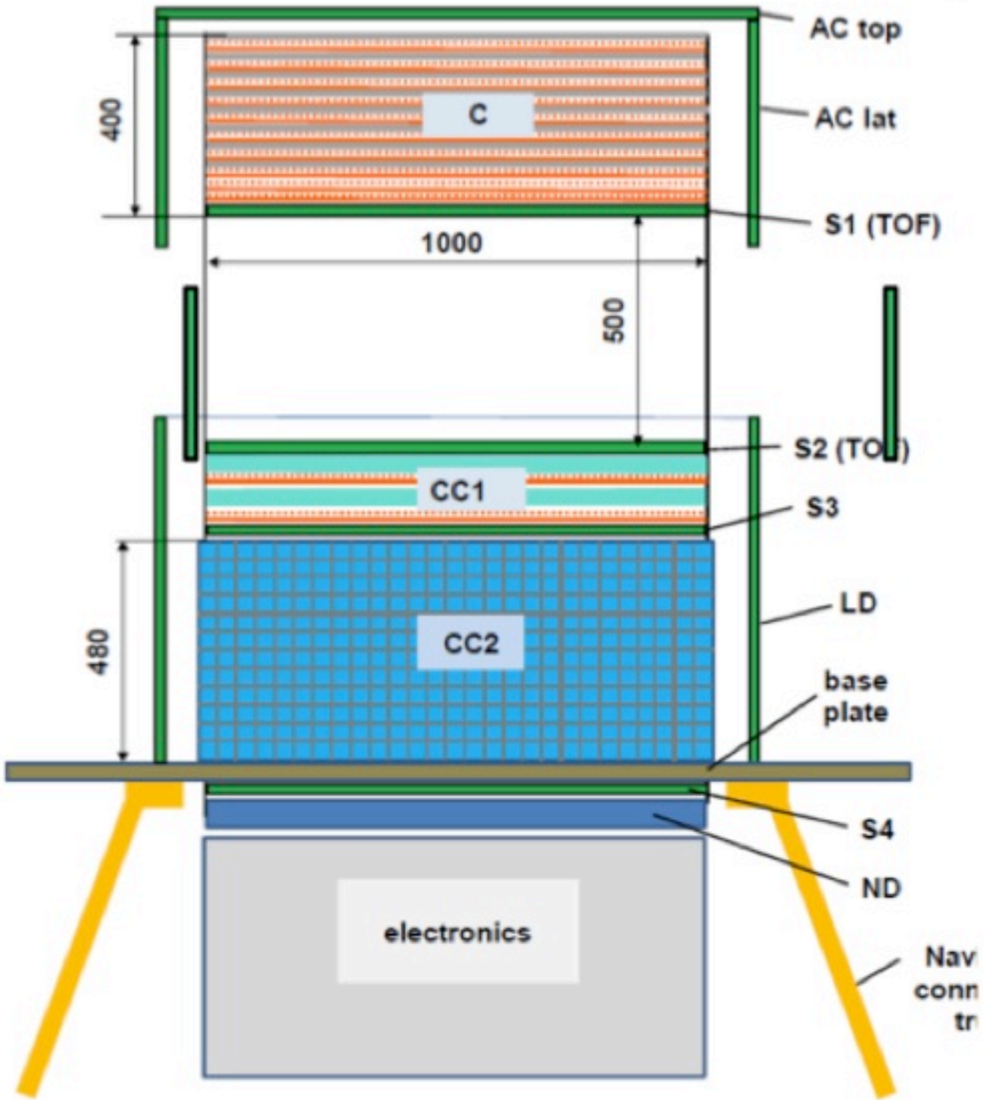


Future prospects

Bergstrom, 2012



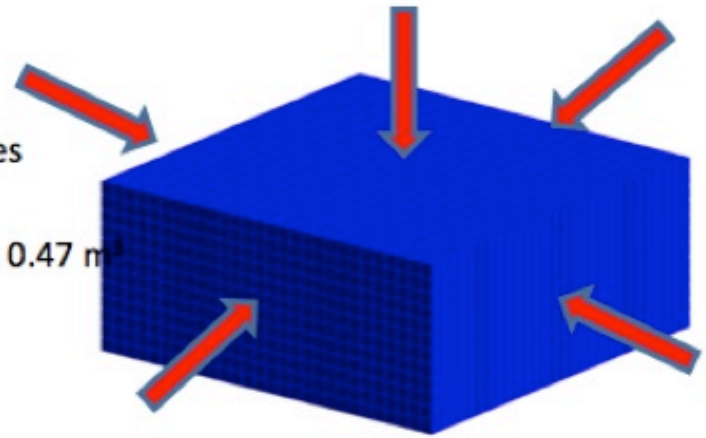
The GAMMA-400 apparatus



GAMMA-400 characteristics:

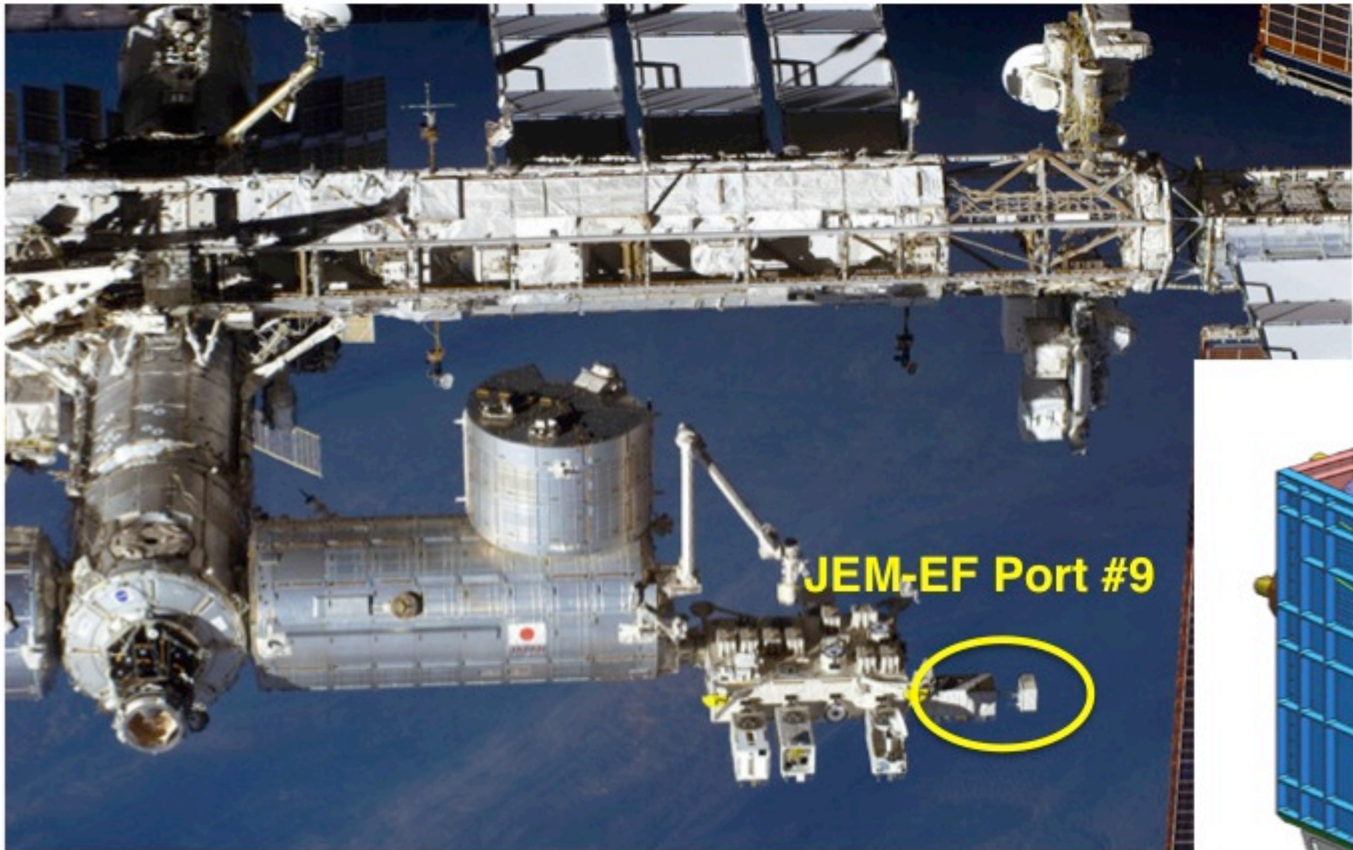
- **a dual instrument** for **photons** (100 MeV $\div$ 1 TeV) and **cosmic rays** (electrons ~ 10 TeV and high energy cosmic-ray nuclei, p and He spectra at the "knee" ($10^{14} - 10^{15}$ eV);
- **State of the art Si-W converter/tracker with analogue read-out;**
- **3-D, deep, homogeneous calorimeter with excellent resolution and large acceptance.**

- 28 x 28 x 12 CsI(Tl) cubes
- L_{cubes} = 3.6 cm
- CC2 dimensions: 1 x 1 x 0.47 m^3
- X_0: 54.6 x 54.6 x 23.4
- λ_I: 2.5 x 2.5 x 1.1
- Mass = 1980 kg
- Planar GF: 9.5 m^2sr
- $GF_{eff,\ el.}^{0.1\text{-}1\ TeV}$ ~ 3.4 m^2sr
- $GF_{eff,\ prot.}^{1\ TeV}$ ~ 3.9 m^2sr

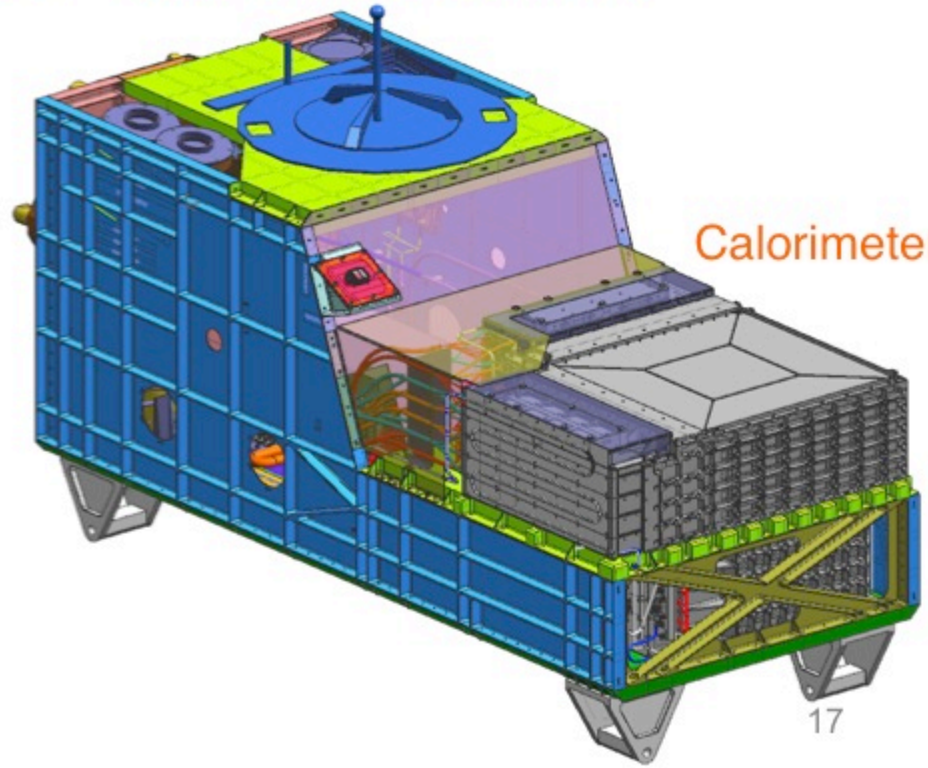


CALorimetric Electron Telescope overview

CALET, project is a Japan-led international mission for the International Space Station, in collaboration with Italy and the US.



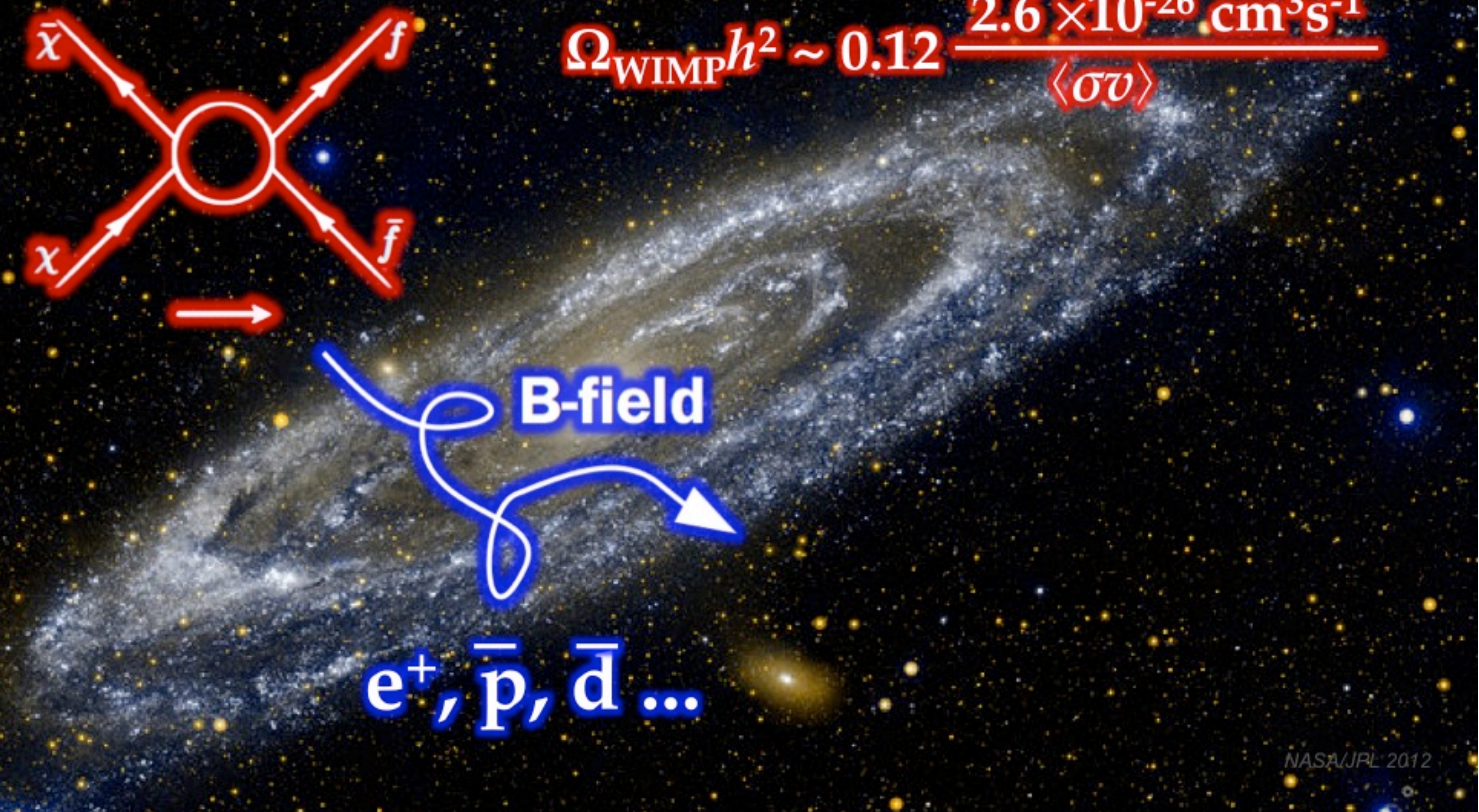
Weight: 650 kg
Mission Life: 5 years
Launch Target: by March, 2015
(Fiscal Year 2014)



The CALET payload will be launched by the Japanese carrie H-II Transfer Vehicle 5 (HTV5) and robotically attached to th port #9 of the Japanese Experiment Module – Exposed Facili (JEM-EF) on the International Space Station.

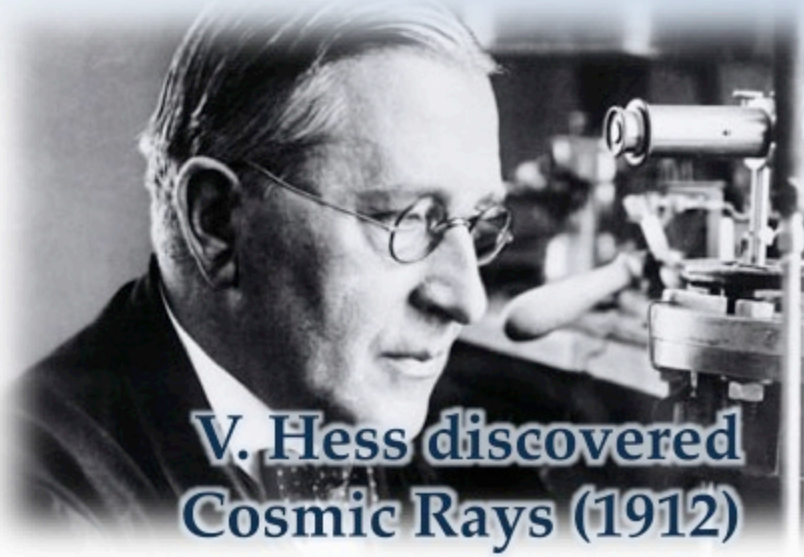
Cosmic-ray antiparticles

$$\Omega_{\mathrm{WIMP}} h^2 \sim 0.12 \frac{2.6 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}}{\langle \sigma v \rangle}$$



1912 – 2012 : A century of Cosmic Rays

- Until 1950's, new particles had been discovered in Cosmic Rays
- Even after accelerators took over, Cosmic Rays play important role in Particle Physics



V. Hess discovered Cosmic Rays (1912)

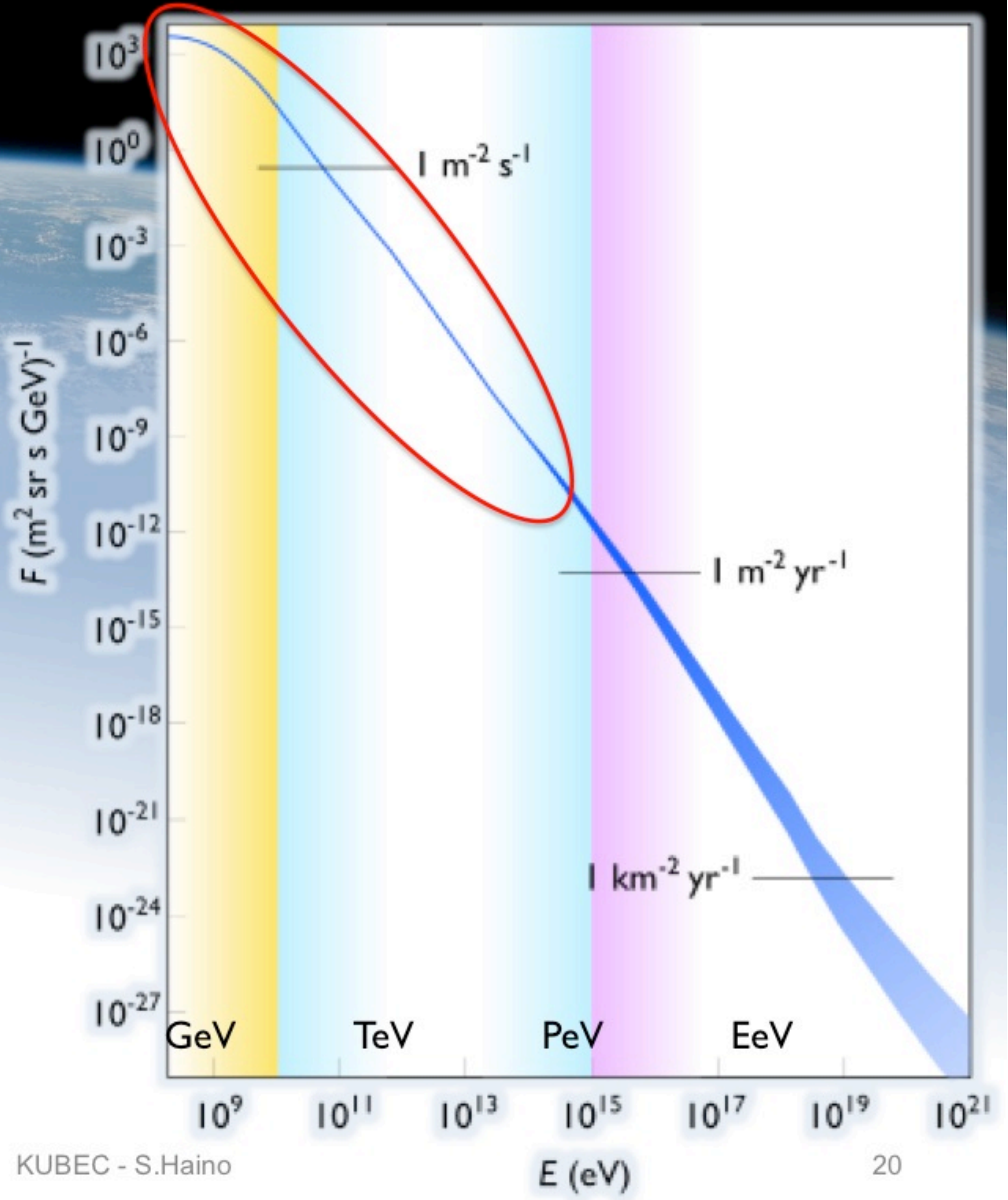
C.D. Anderson discovered positron and muon (1932 and 1936)

GeV-TeV :

Direct measurements with balloons and in space

GeV :

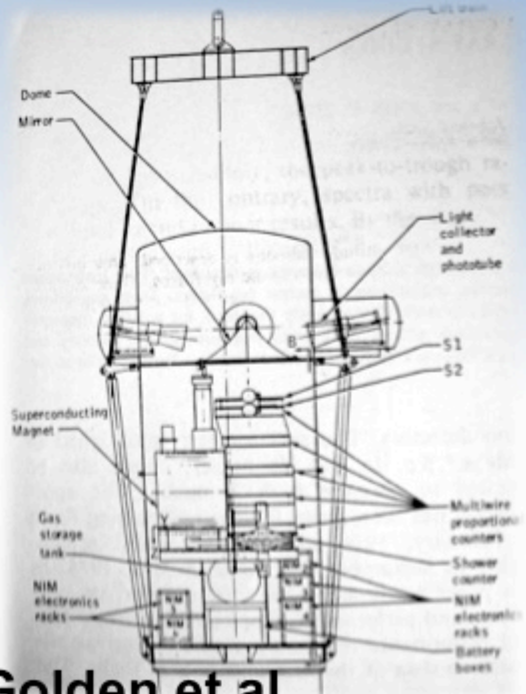
Fundamental physics with antiparticles



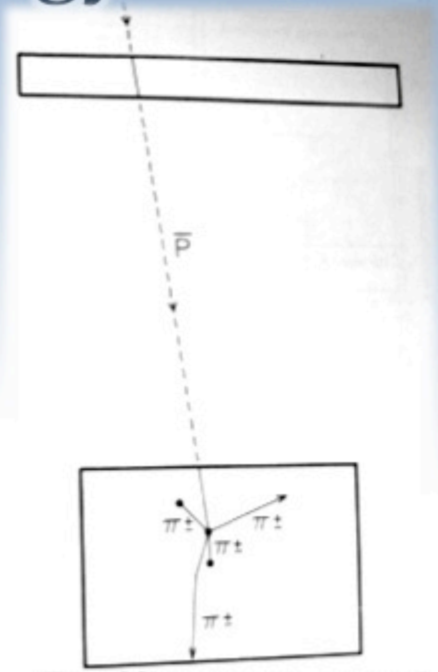
Cosmic Ray antiprotons in ~1980

First observation in 1979

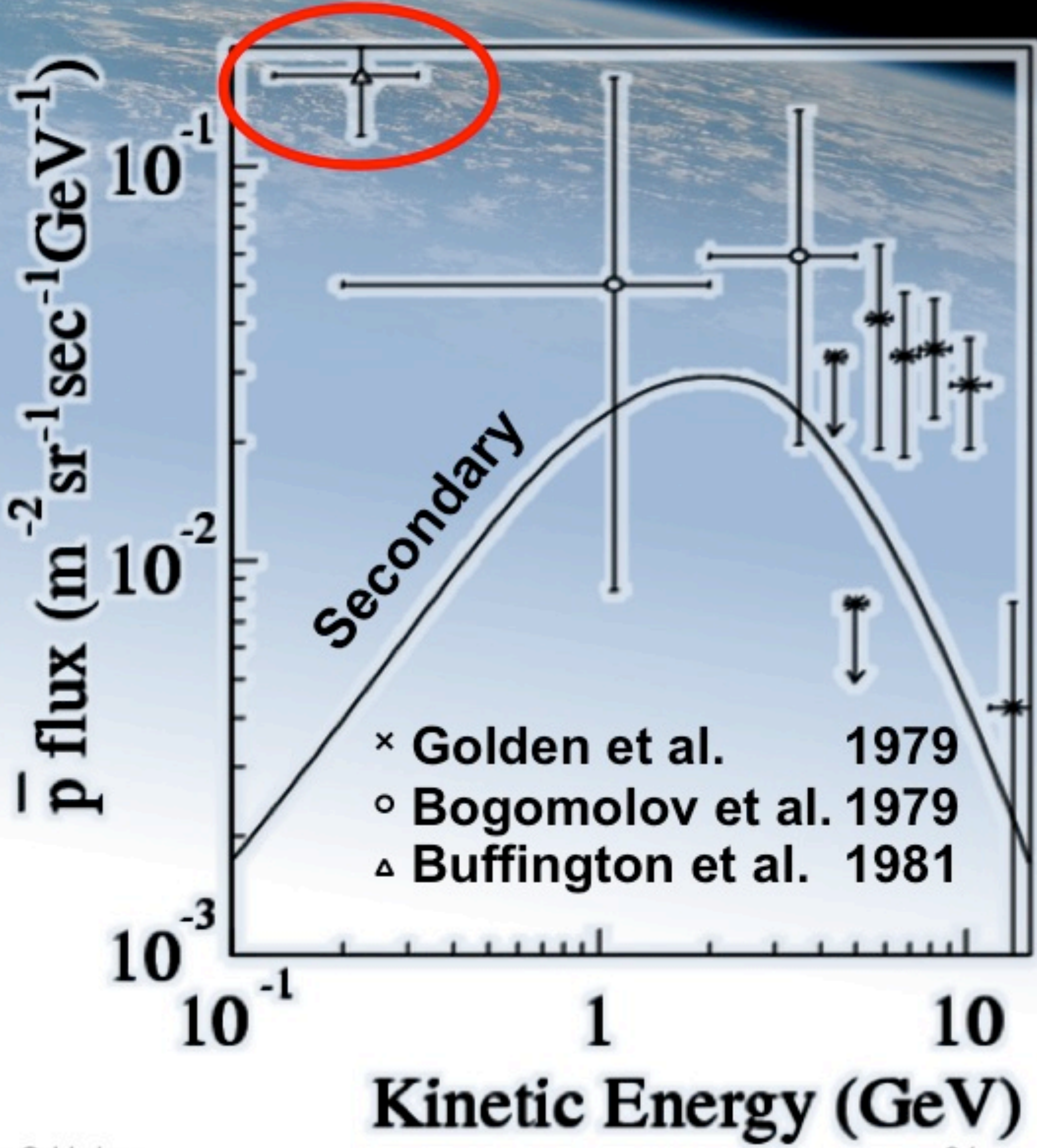
Significant excess in low energy



Golden et al.
Magnetic spectrometer



Buffington et al.
Spark chamber

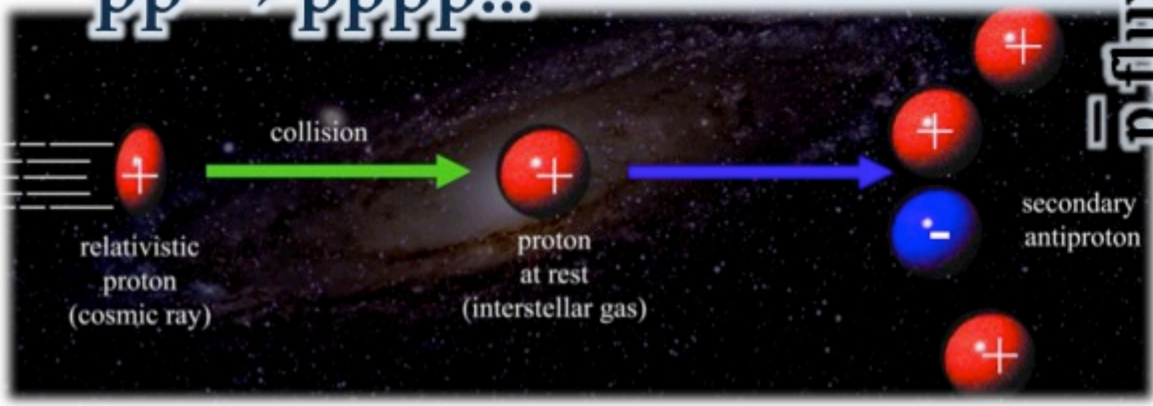


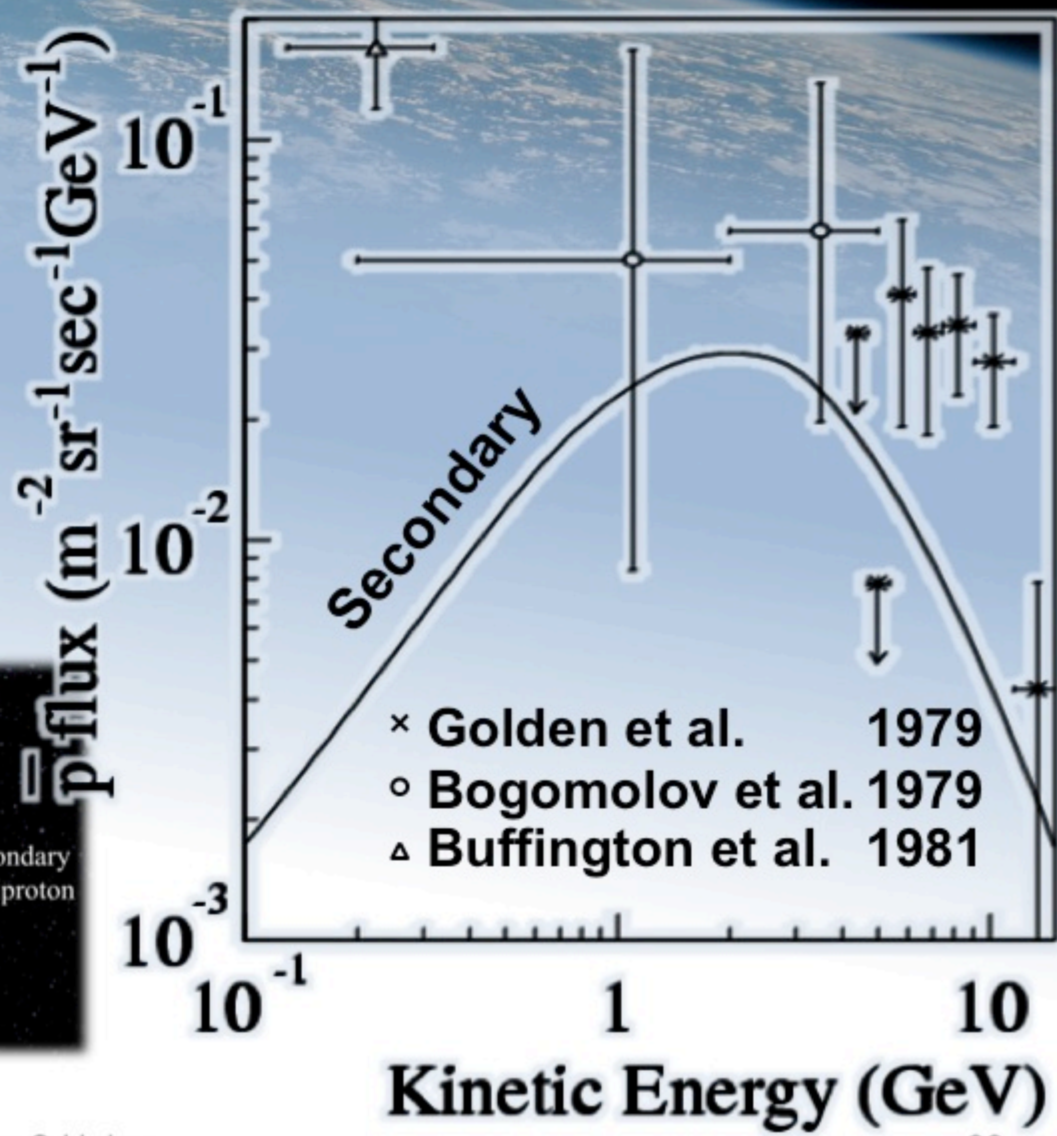
Antiproton production

- Kinematic constraints in low energy
- Spectrum has a peak at E_{kin}~2 GeV

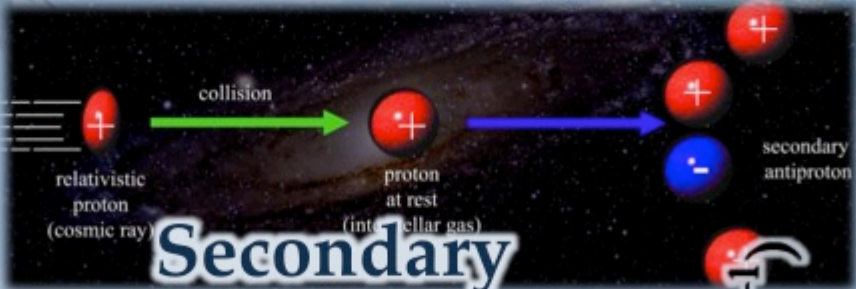
Secondary production

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





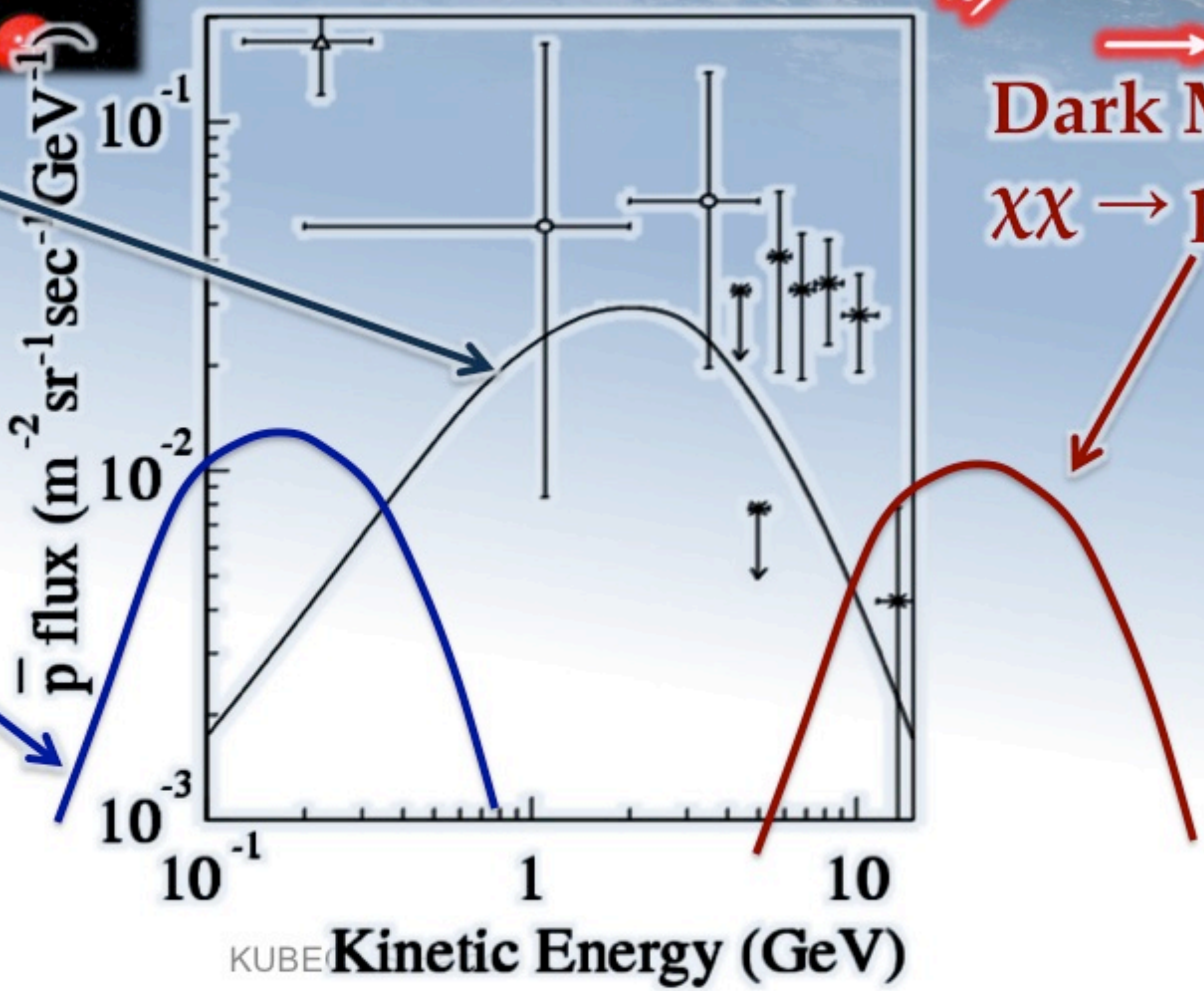
Possible signal windows



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

Dark Matter
$\chi\chi \rightarrow p\bar{p}...$

Primordial Black Holes (PBH) → $p\bar{p}$...



Magnetic Rigidity

Curvature → Rigidity

$p \;\; = q e \rho B$ [eV/c]

$R \;\; = c \rho B \quad (R = pc/qe$ [V]$)$

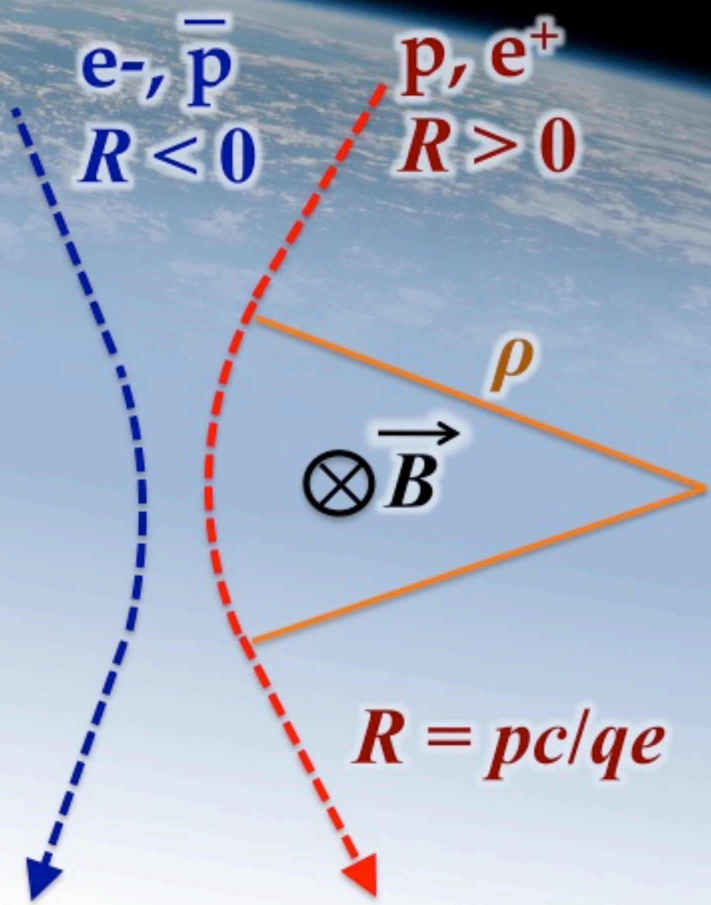
R/GV ≈ 0.3 (ρ/m) (B/Testa)

$q < 0 \;\rightarrow\; R < 0$

e.g.

$p = 1$ GeV/c, $q = 1$ ($R = 1$ GV),

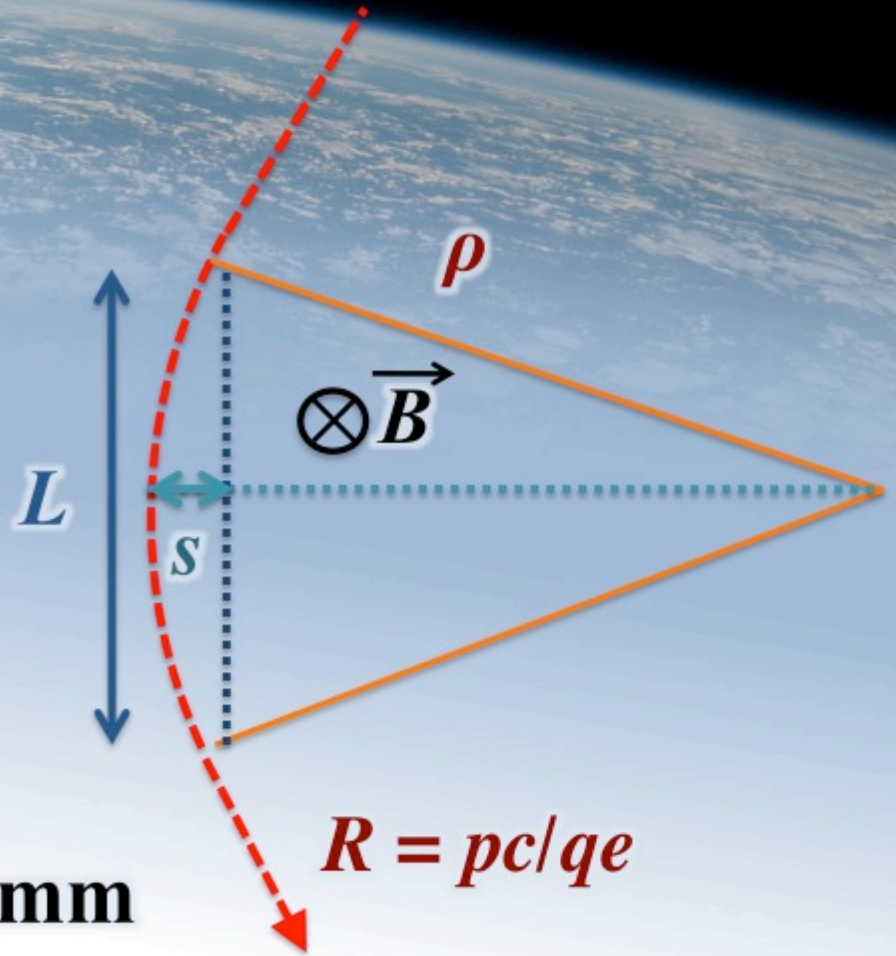
$B = 1$ Tesla $\rightarrow\; \rho \approx 3.3$ m



Rigidity resolution

$$s \approx \frac{0.3BL^2}{8R}$$

$$\Delta(1/R) = \frac{\Delta R}{R^2} \approx \frac{8\Delta s}{0.3BL^2}$$



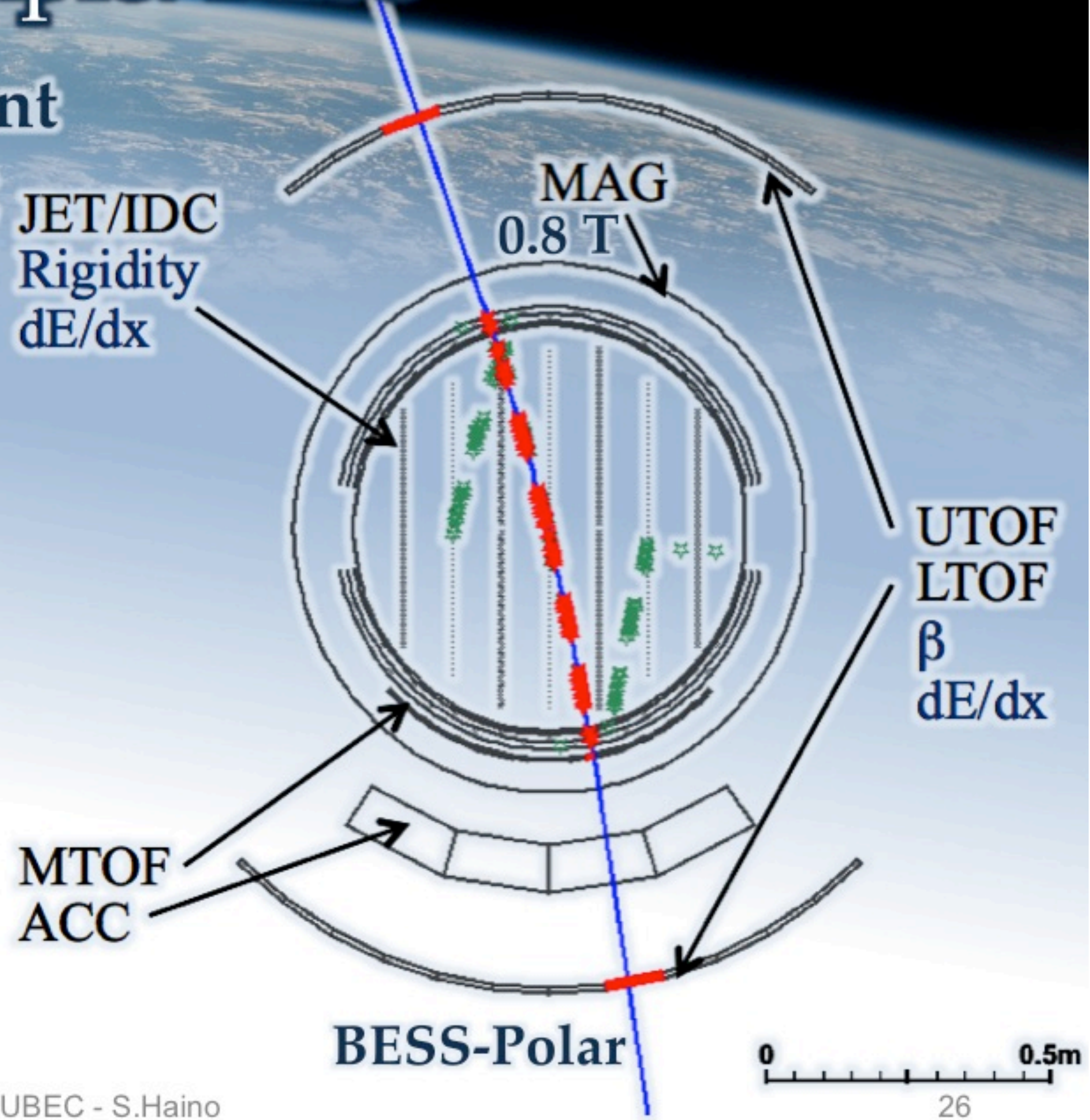
e.g.

$B = 1$ Tesla, $L = 1$ m, $\Delta s = 0.1$ mm

$\rightarrow \Delta R/R \approx 2.7$ % ($R = 10$ GV)

Example: BESS

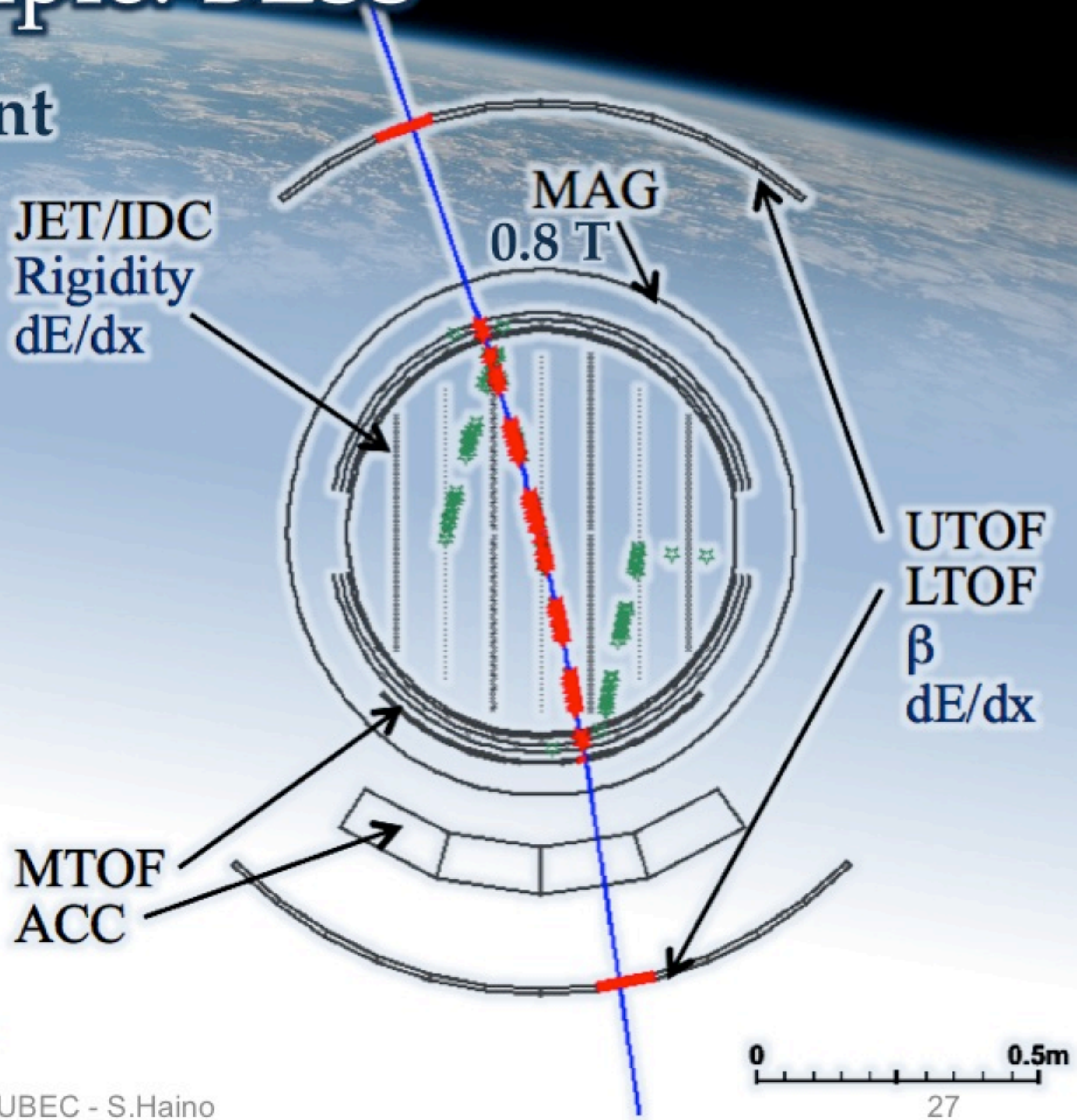
Balloon-borne Experiment with a Superconducting Spectrometer
(Japan-US collaboration)



Example: BESS

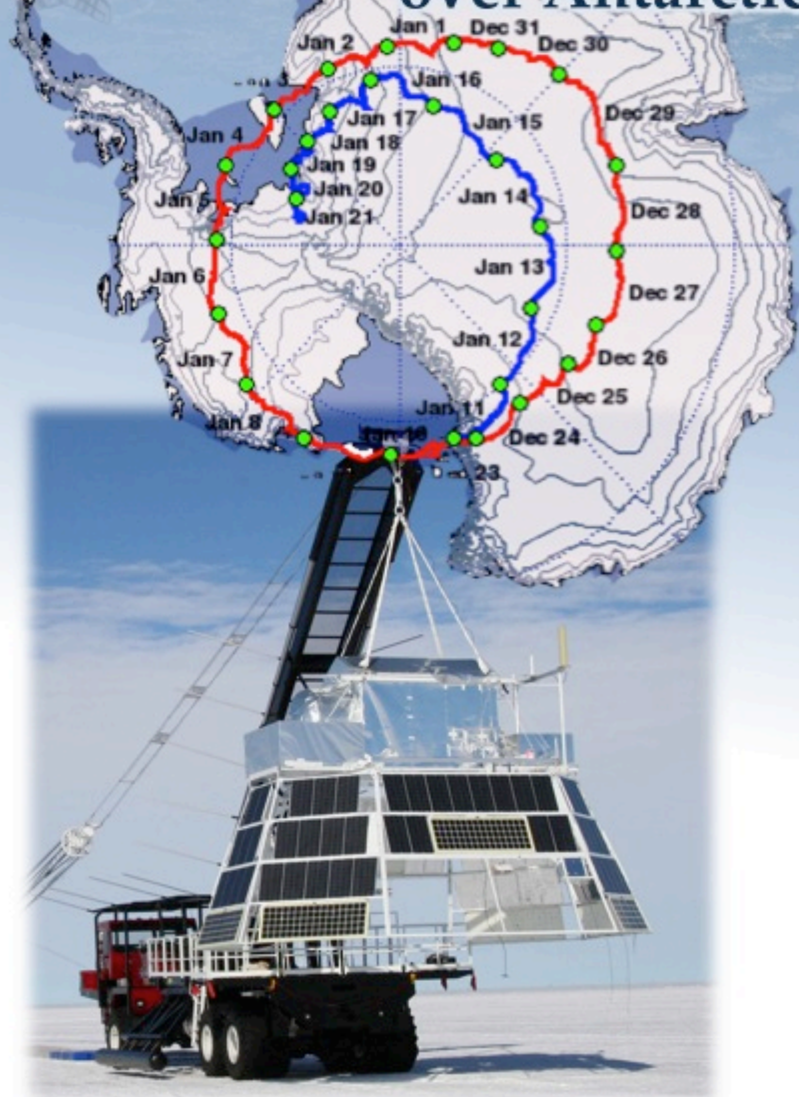
Balloon-borne Experiment with a Superconducting Spectrometer
(Japan-US collaboration)

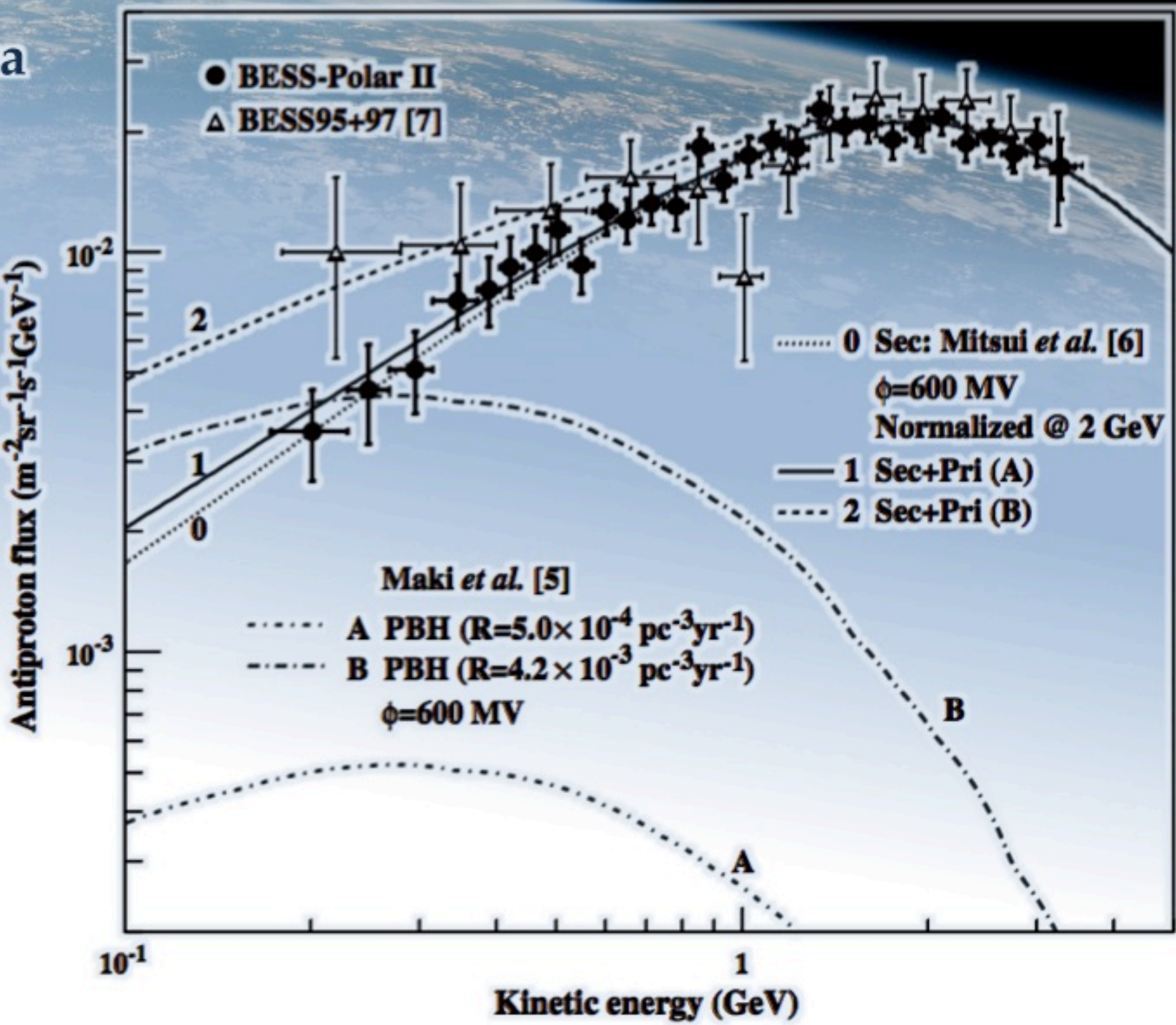
BESS-Polar in Antarctica



BESS-Polar

25 days flight over Antarctica

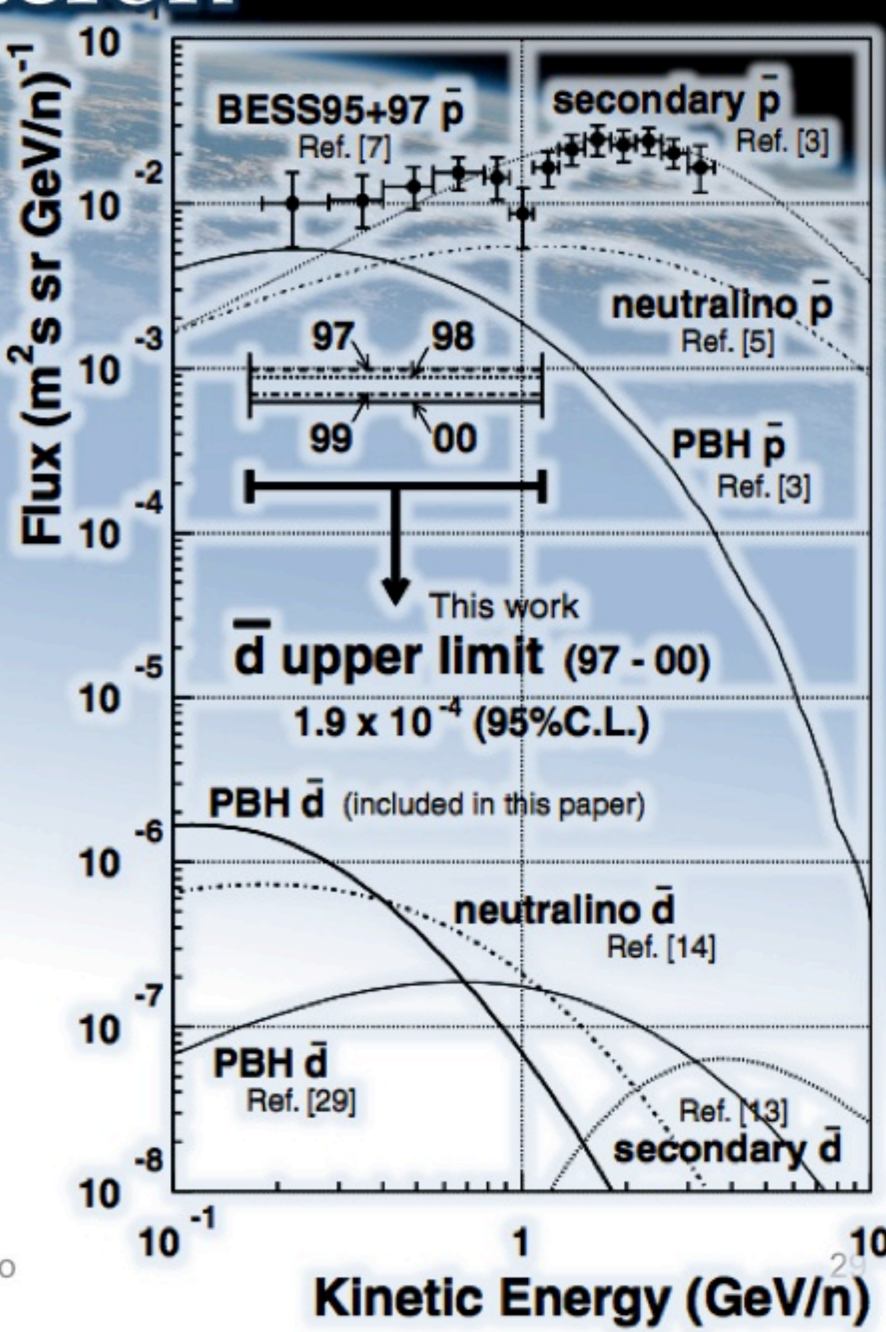




Anti-deuteron

- **Secondary BG is much more suppressed than antiprotons**
- **The first upper limit published by BESS**

H.Fuke et al., PRL 95 (2005) 081101



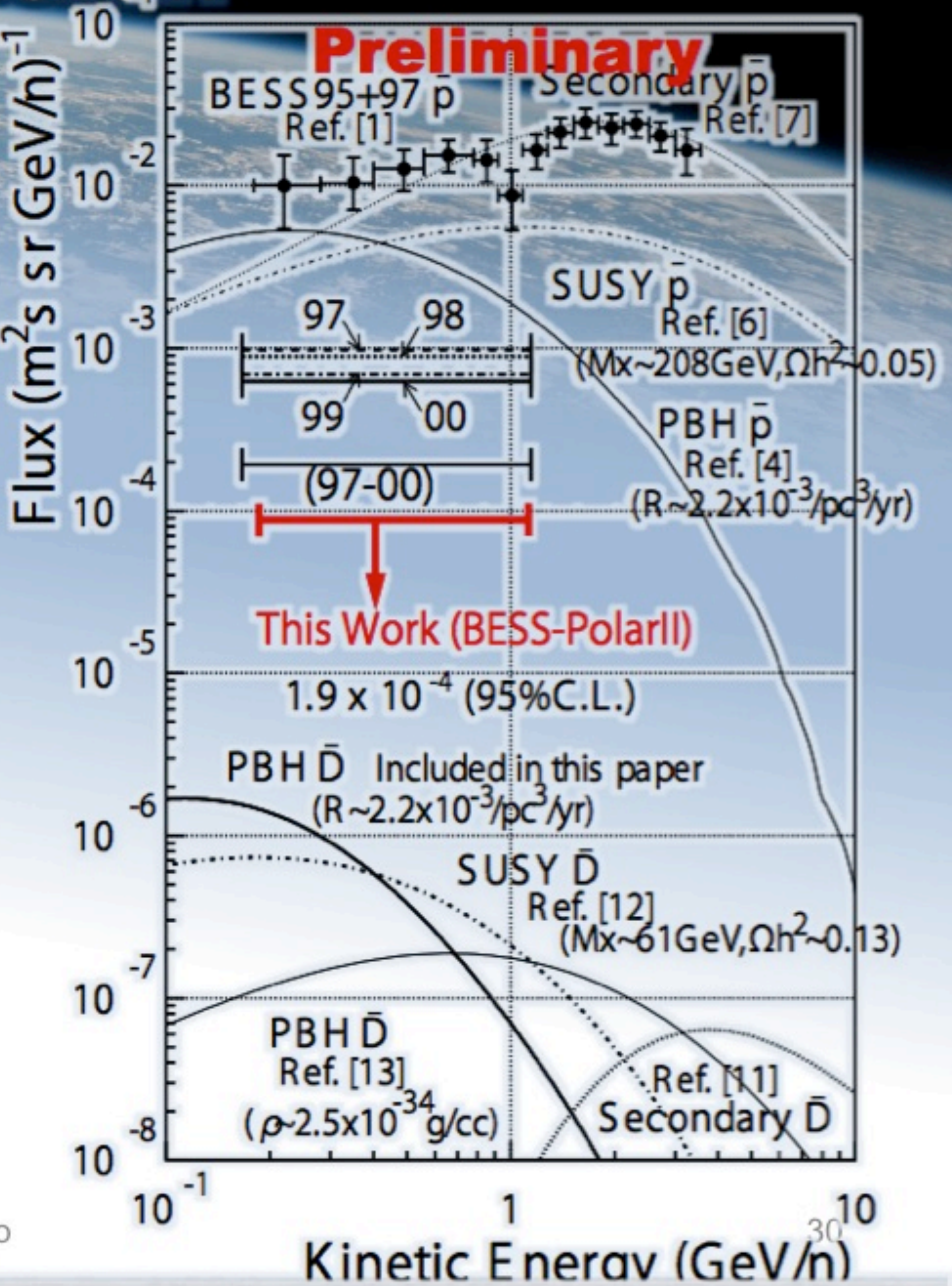
Anti-deuteron

- **Secondary BG is much more suppressed than antiprotons**
- **The first upper limit published by BESS**

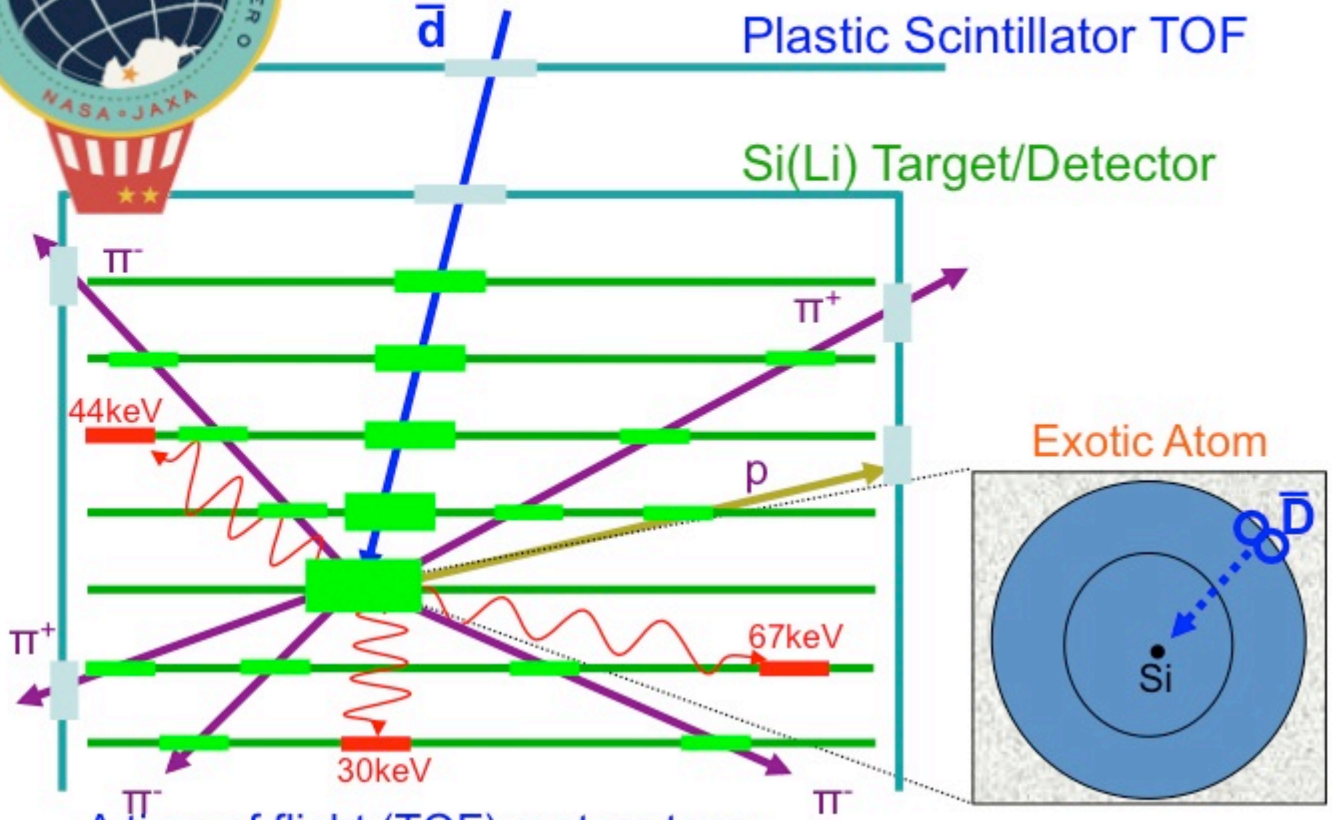
  H.Fuke et al., PRL 95 (2005) 081101
- **The new limit with BESS-Polar II**

  K.Yoshimura et al.,

  COSPAR (2014) Moscow



GAPS detects atomic X-rays and annihilation products from exotic atoms

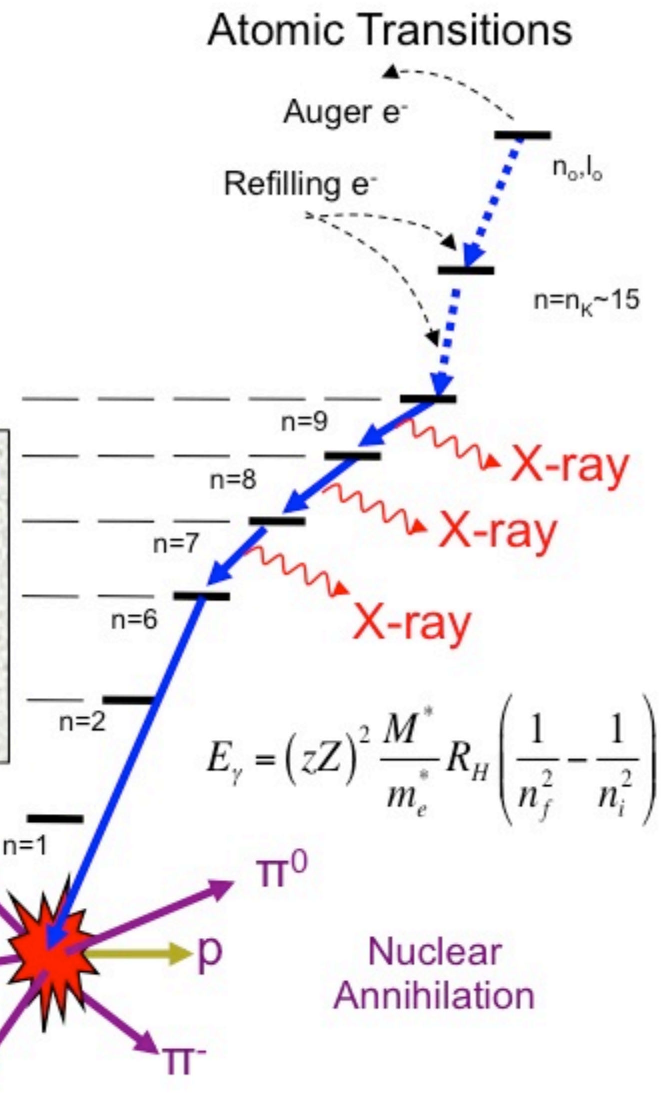


A time of flight (TOF) system tags candidate events and records velocity

The antiparticle slows down & stops in a target material, forming an excited exotic atom

Deexcitation X-rays provide signature

Annihilation products provide added background suppression



$$E_\gamma = (zZ)^2 \frac{M^*}{m_e^*} R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

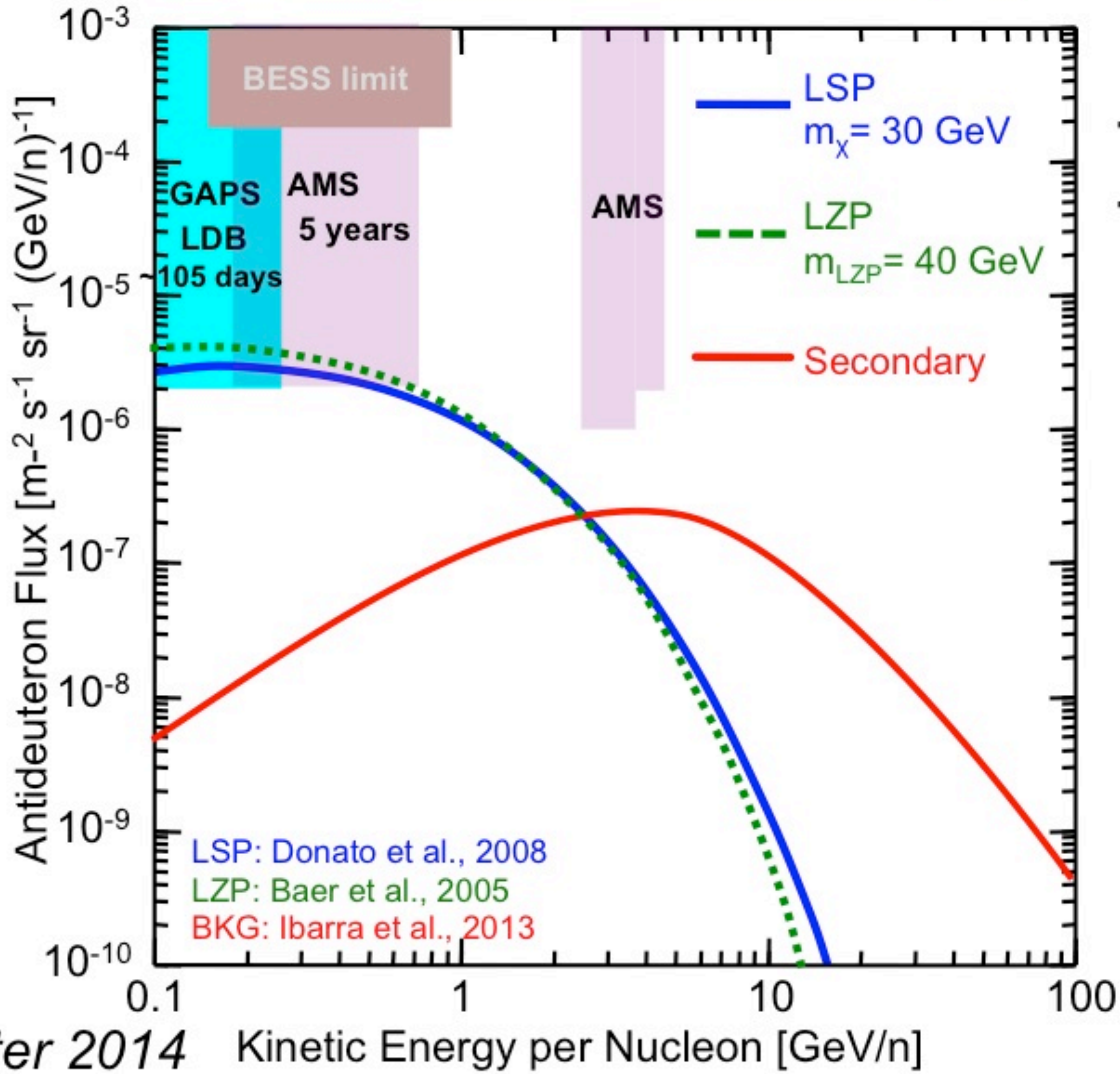
X-ray yields were measured at KEK in 2004 and 2005

C.J. Hailey Dark Matter 2014

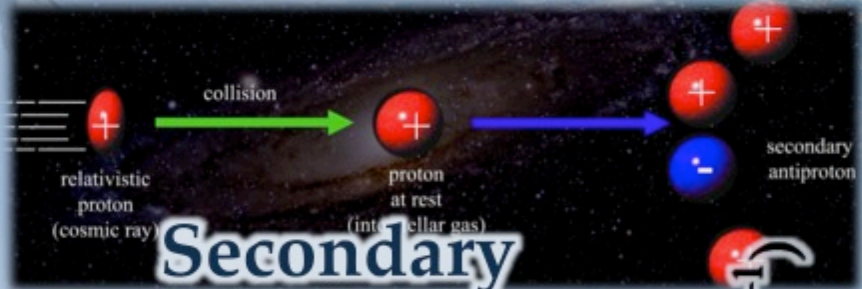
Antideuterons provide clean DM signatures

Background free at low energy!

GAPS Target :
Antarctic flight
in 2018-2019



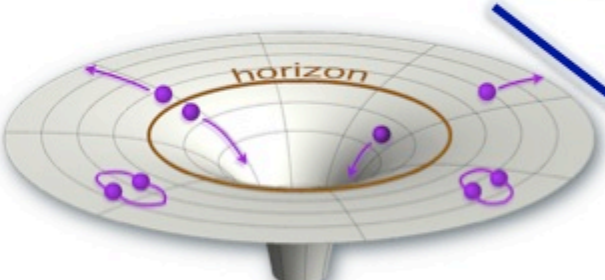
Possible signal windows

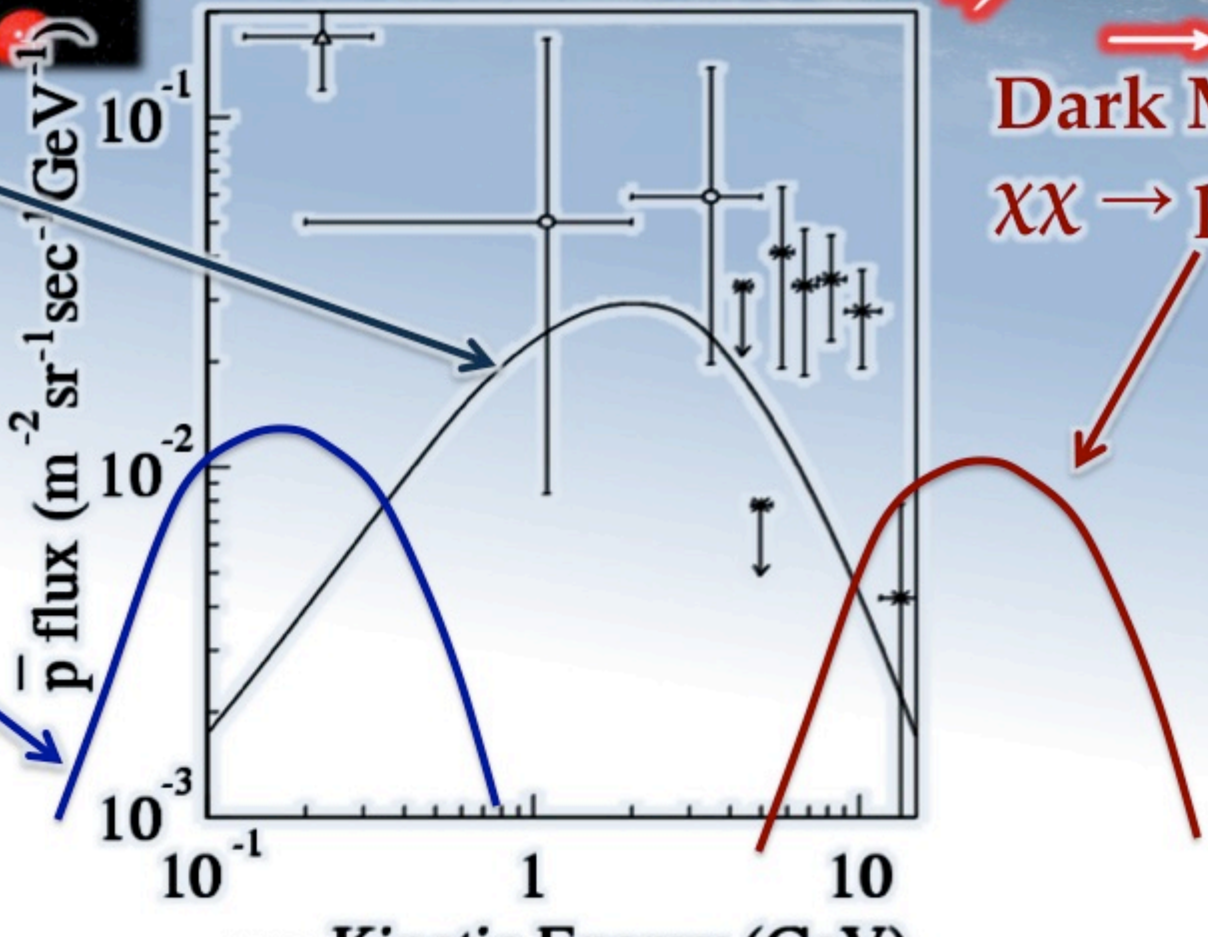


Secondary
$pp \rightarrow ppp\bar{p}...$

Dark Matter
$\chi\chi \rightarrow p\bar{p}...$

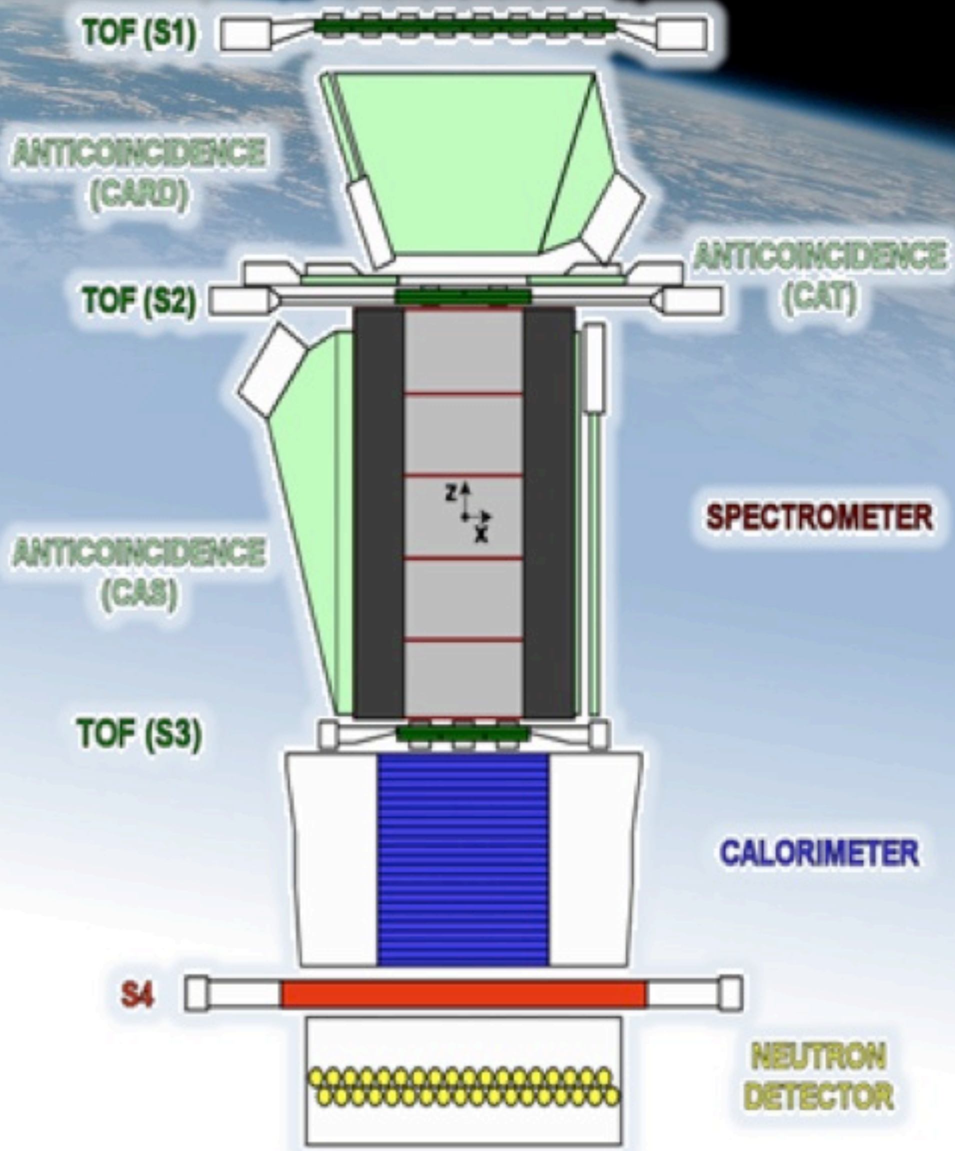
Primordial Black Holes (PBH) → $p\bar{p}$...





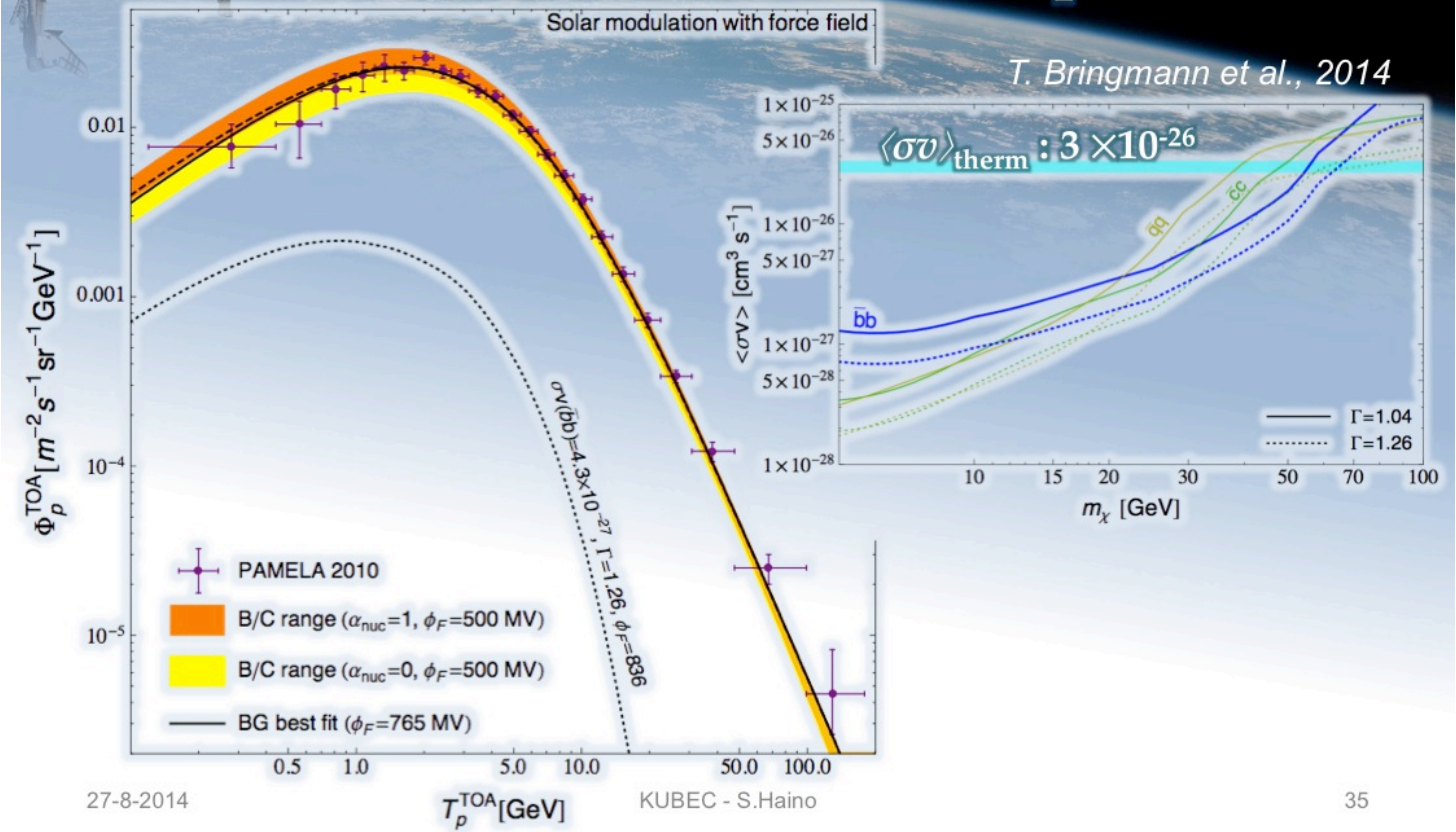
PAMELA

Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

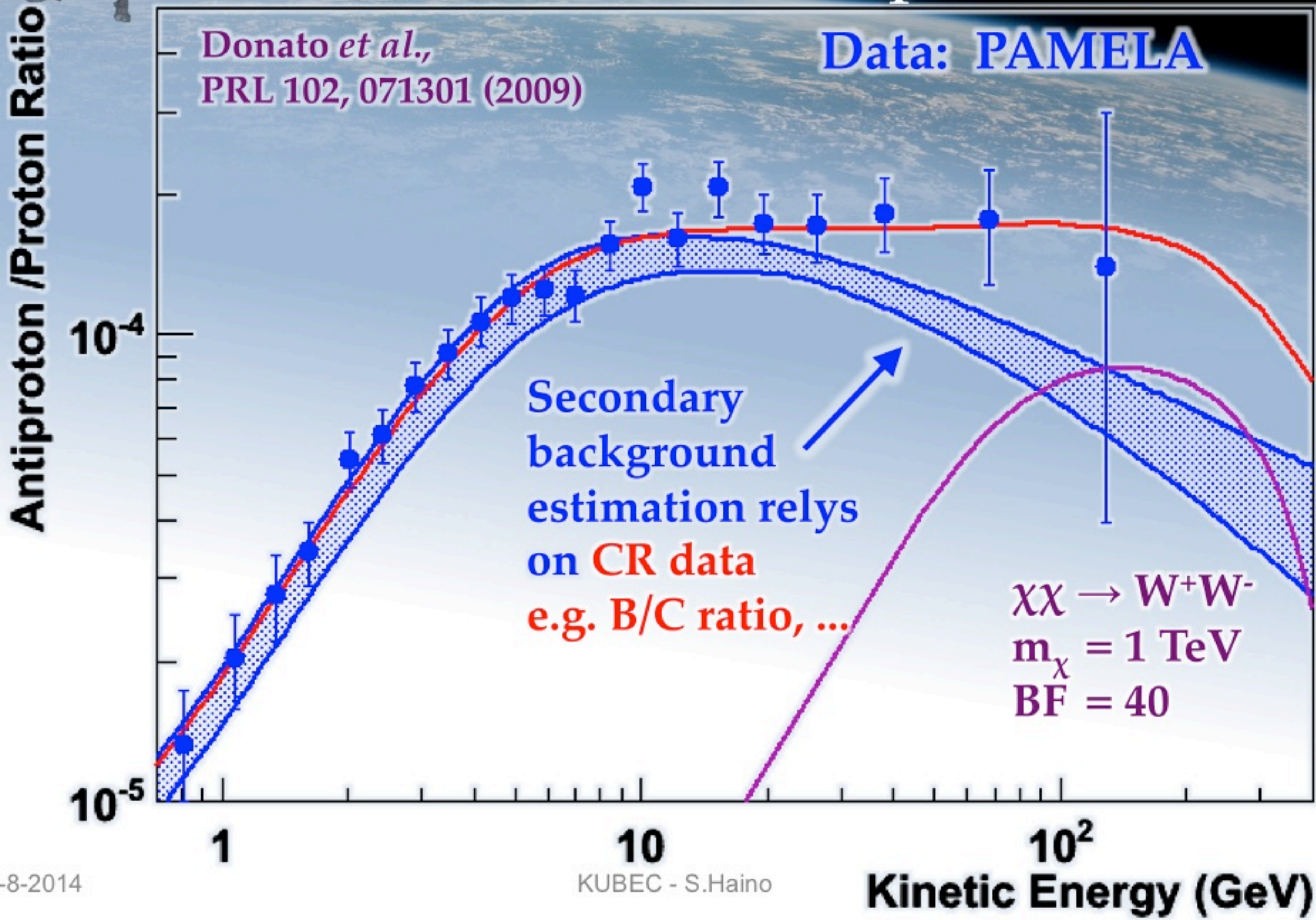


Launched in June/2006 by Soyuz-U rocket

DM limit from PAMELA antiprotons



DM search with antiprotons

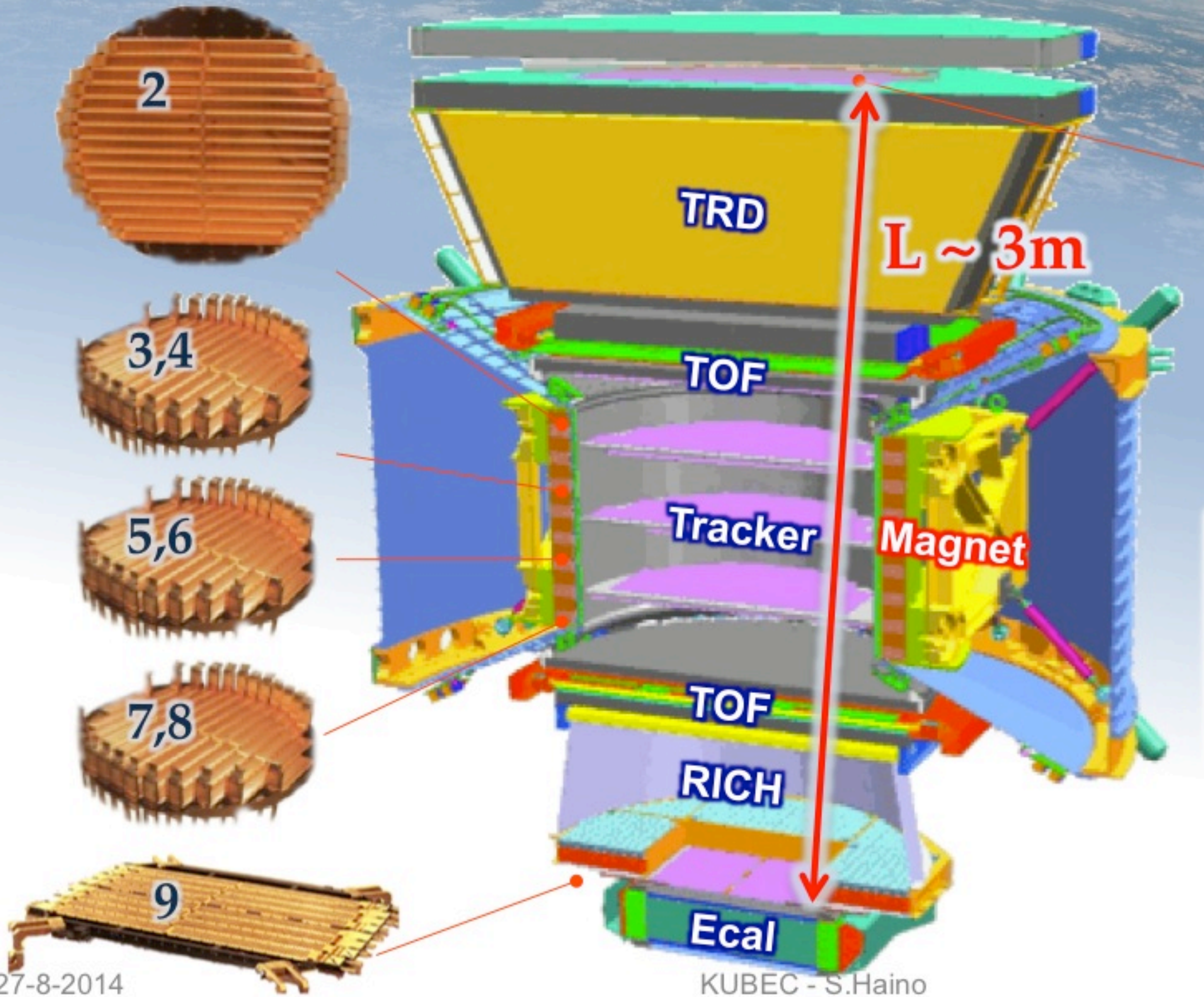


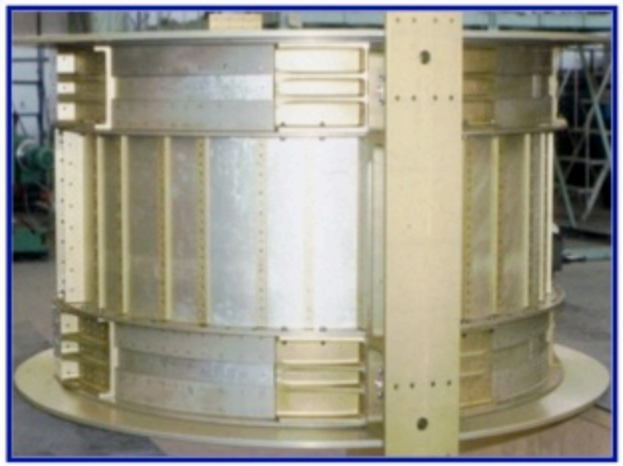
Alpha Magnetic Spectrometer (AMS-02) on the ISS

Installed on 19/May/2011

AMS is continuously recording ~16 billion Cosmic-Ray events every year...

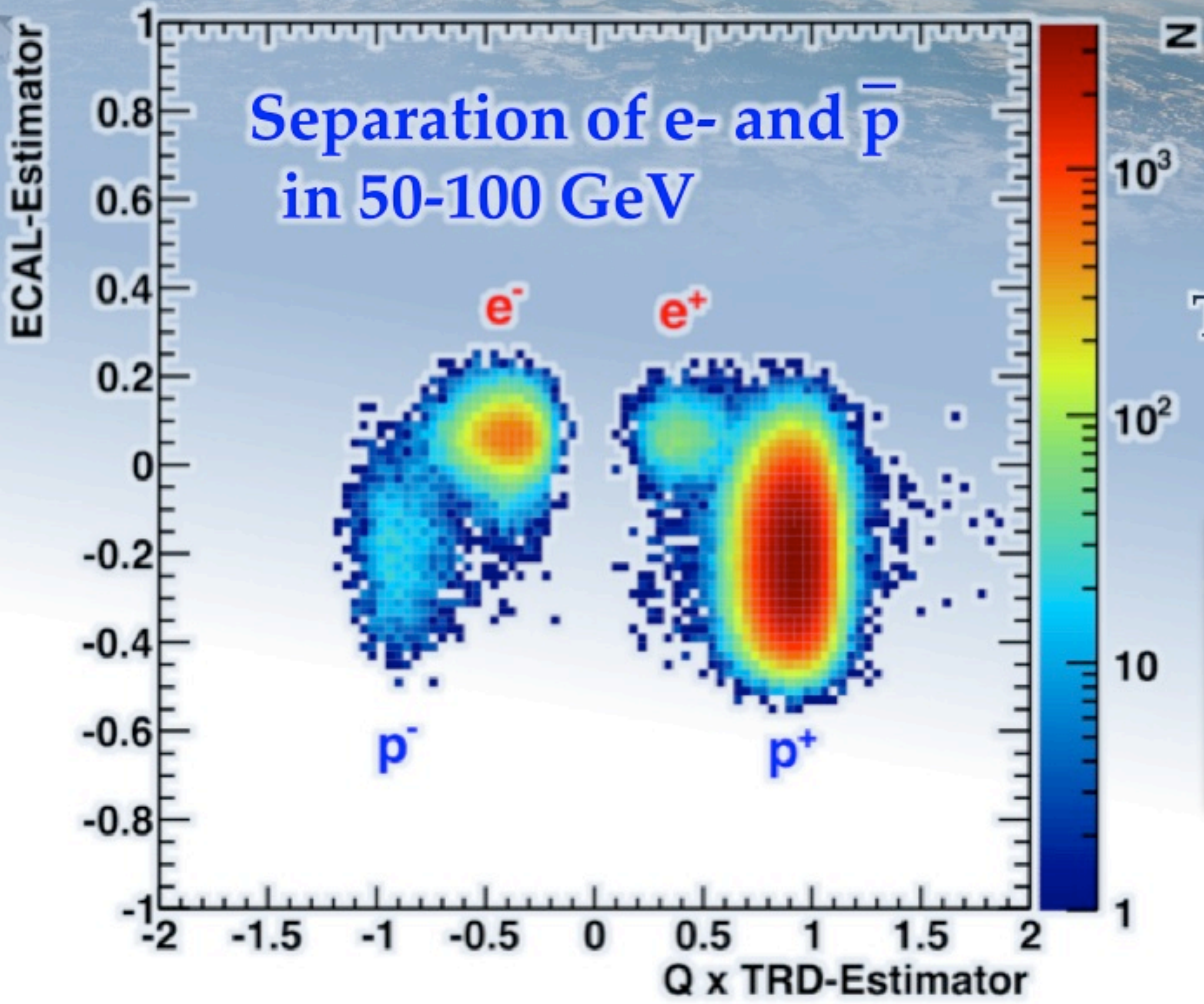
AMS – 9 layers of silicon tracker

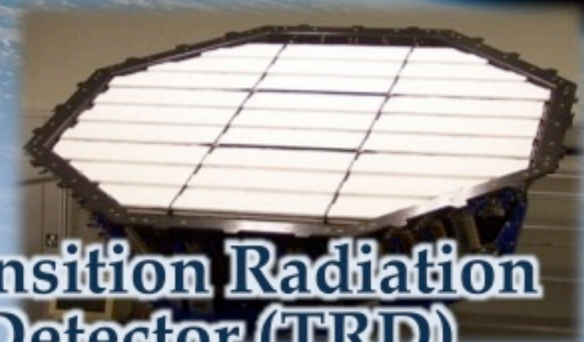




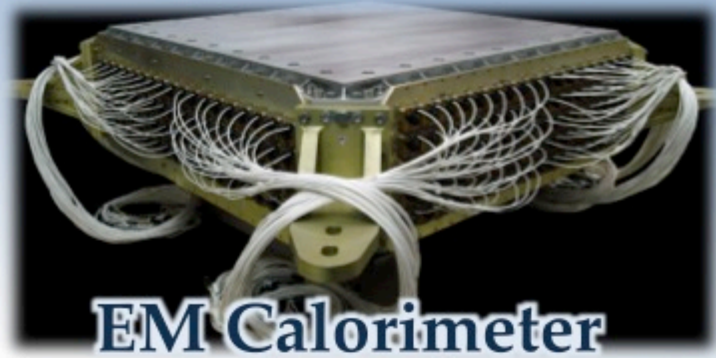
Magnet

Antiproton identification in AMS





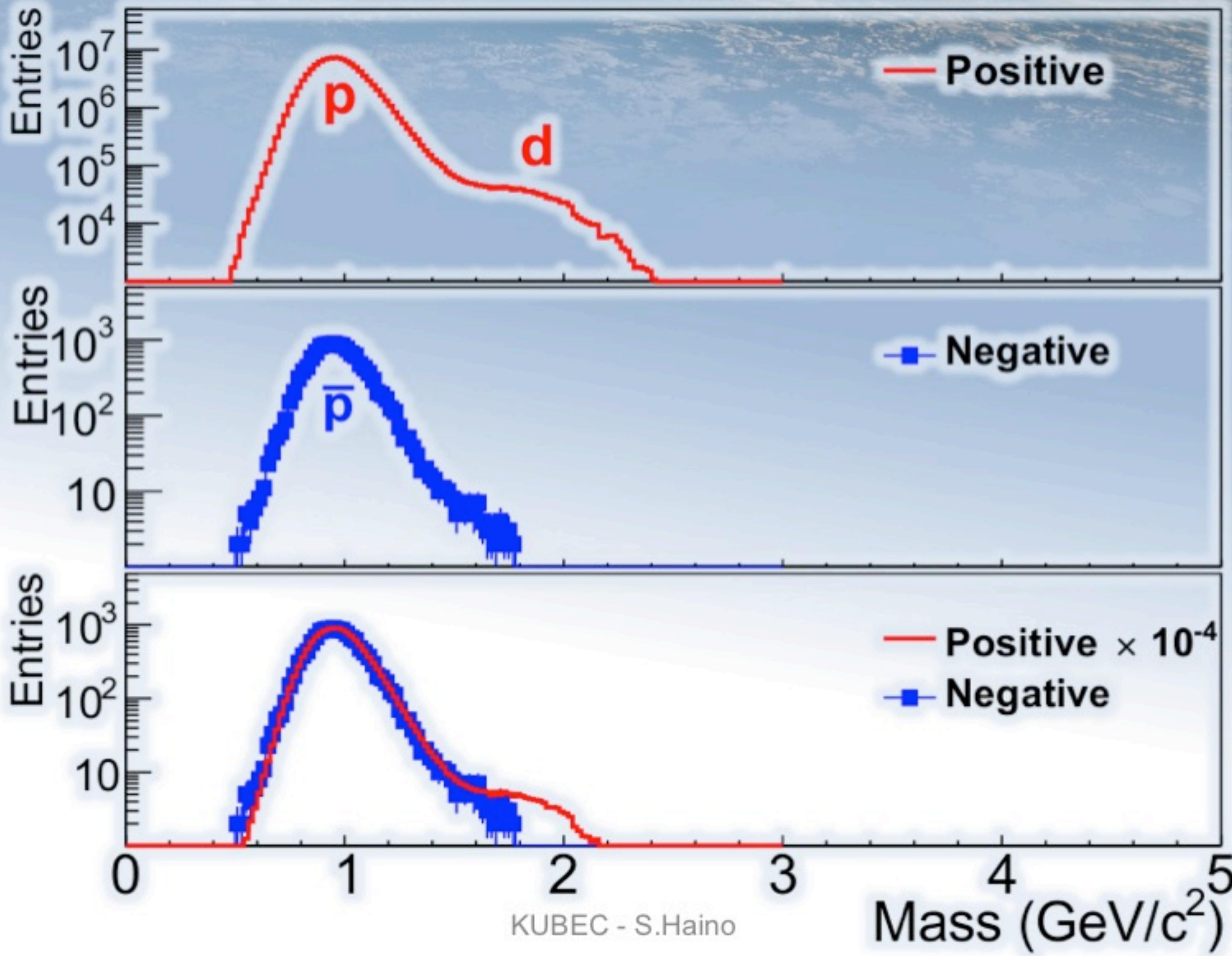
Transition Radiation Detector (TRD)



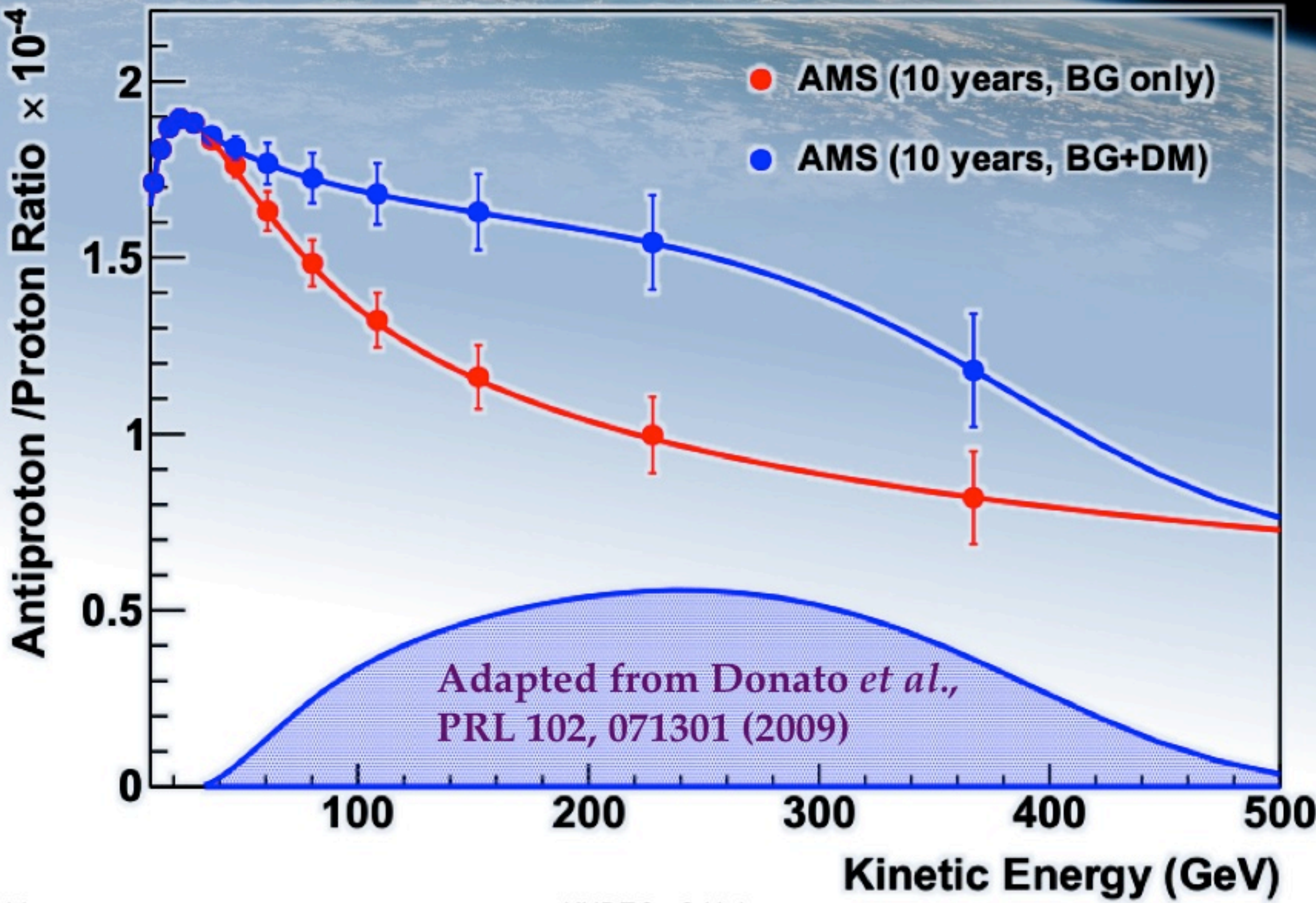
EM Calorimeter
(17 X_0)

Antiproton identification in AMS

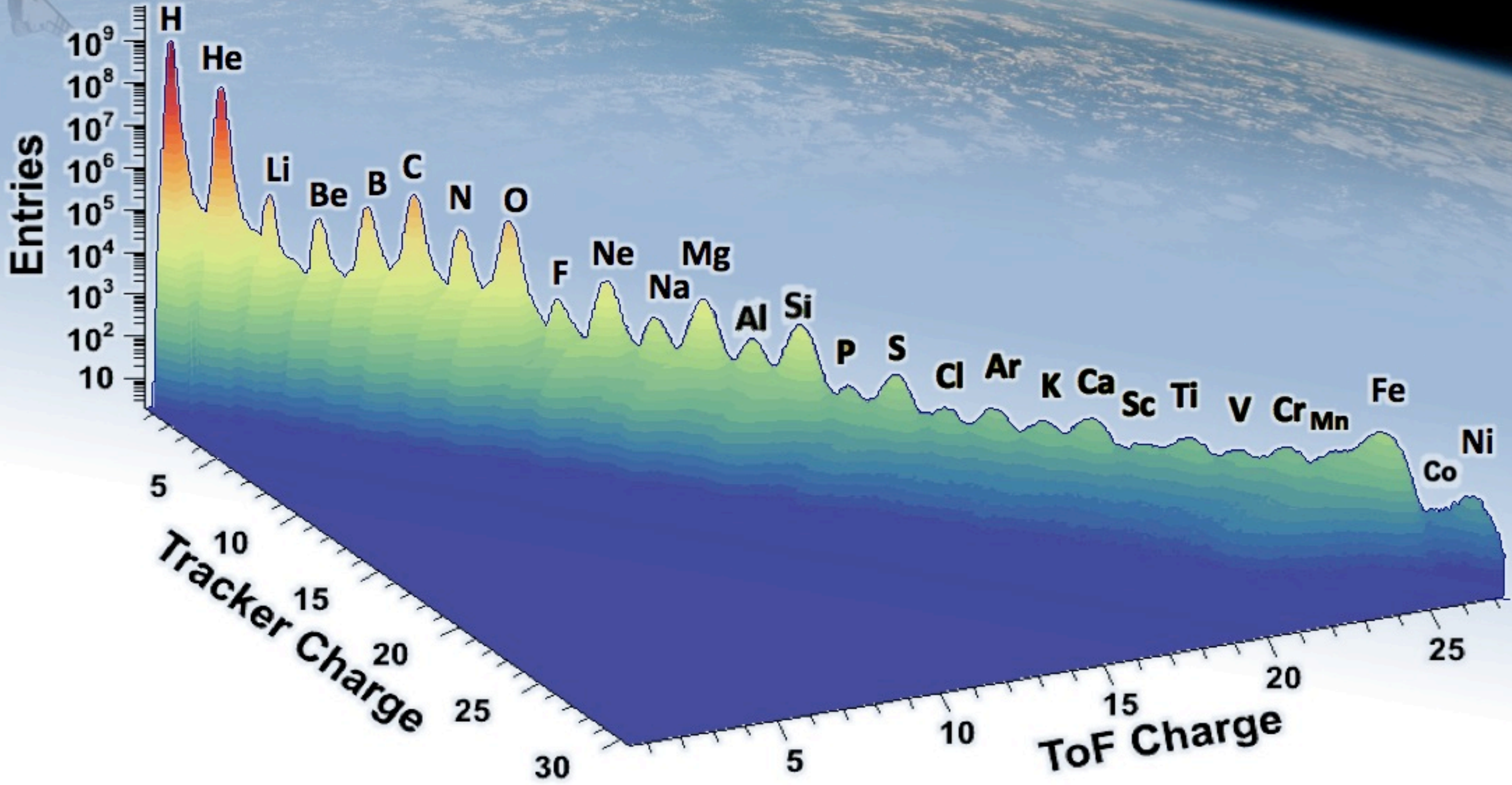
Mass reconstruction with RICH and Tracker at E~ 10 GeV



AMS Potential of DM search



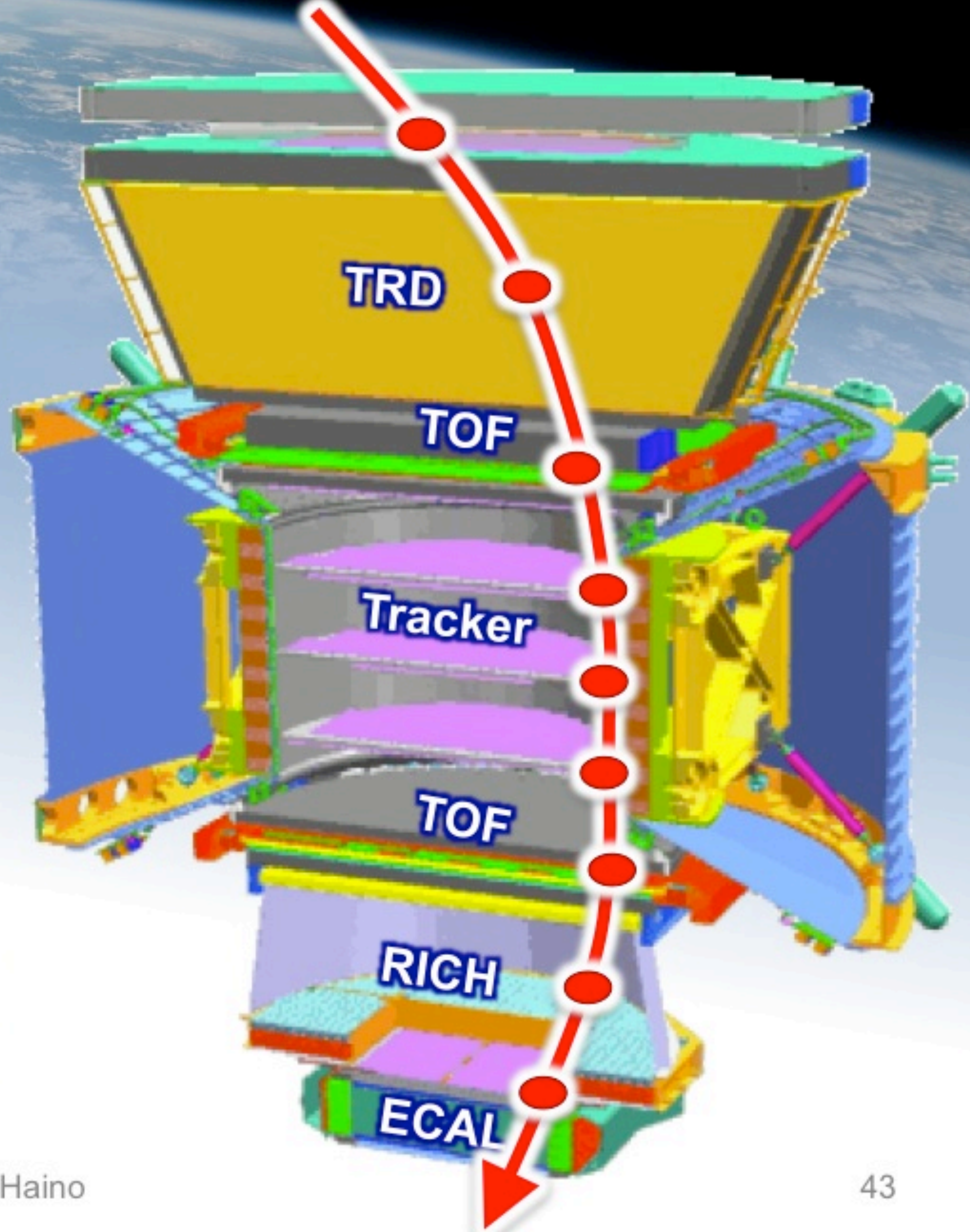
Nuclei identification in AMS



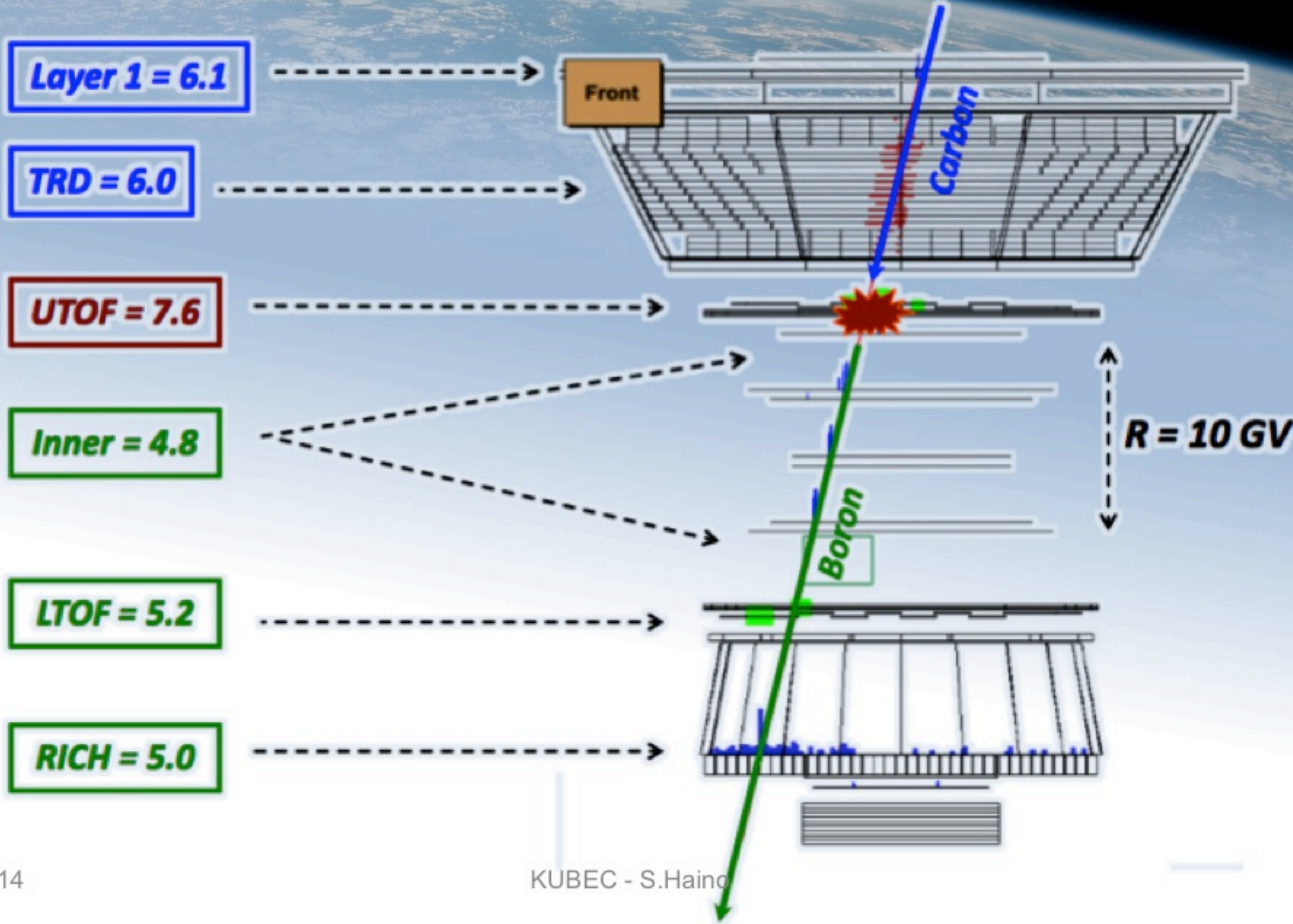
Multiple charge measurements

Charge resolution ΔZ (au) for Carbon (Z=6)

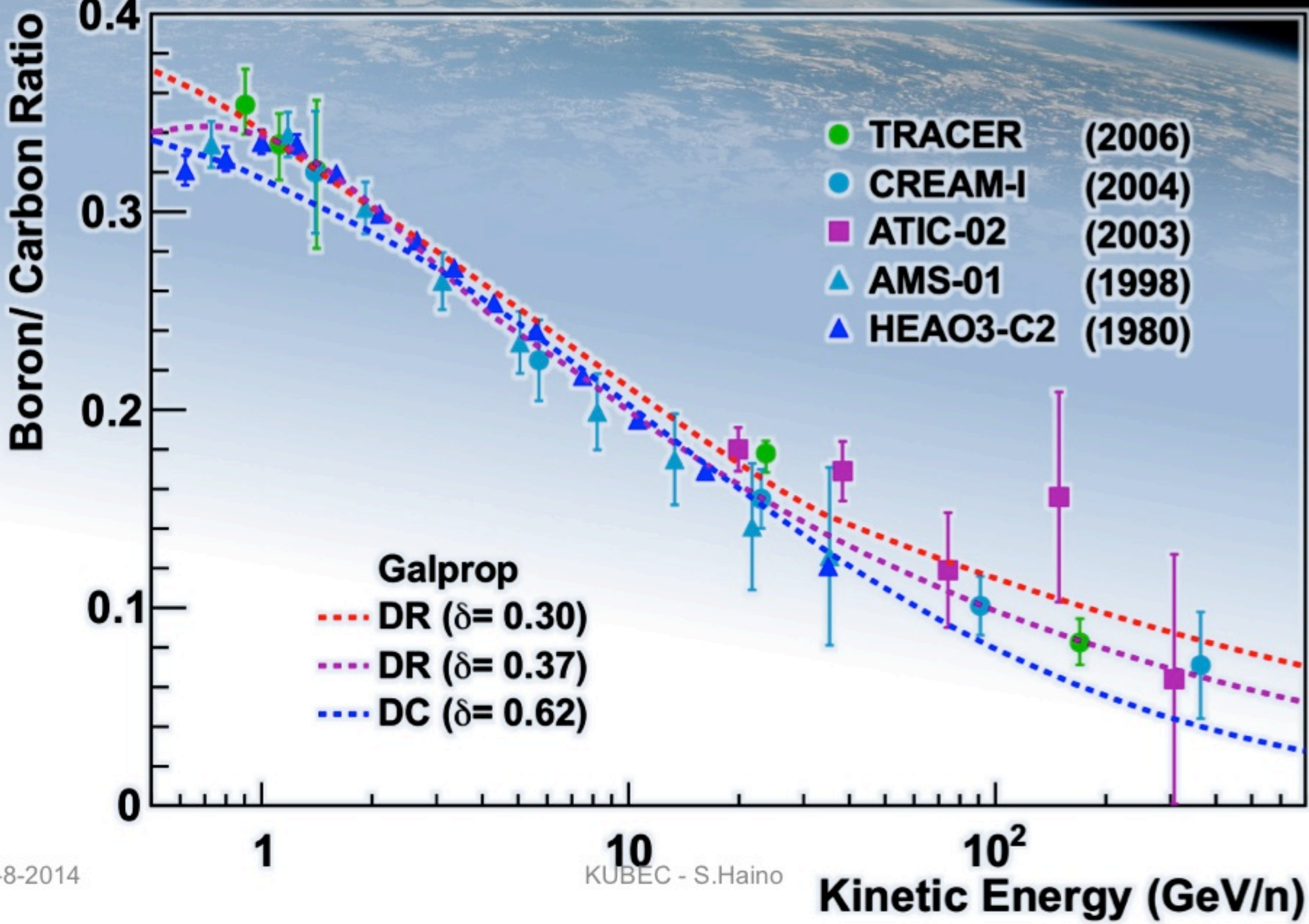
- Tracker plane 1 : 0.30
- TRD : 0.33
- Upper TOF : 0.17
- Inner plane 2-8 : 0.15
- Lower TOF : 0.20
- RICH : 0.32
- Tracker plane 9 : 0.30



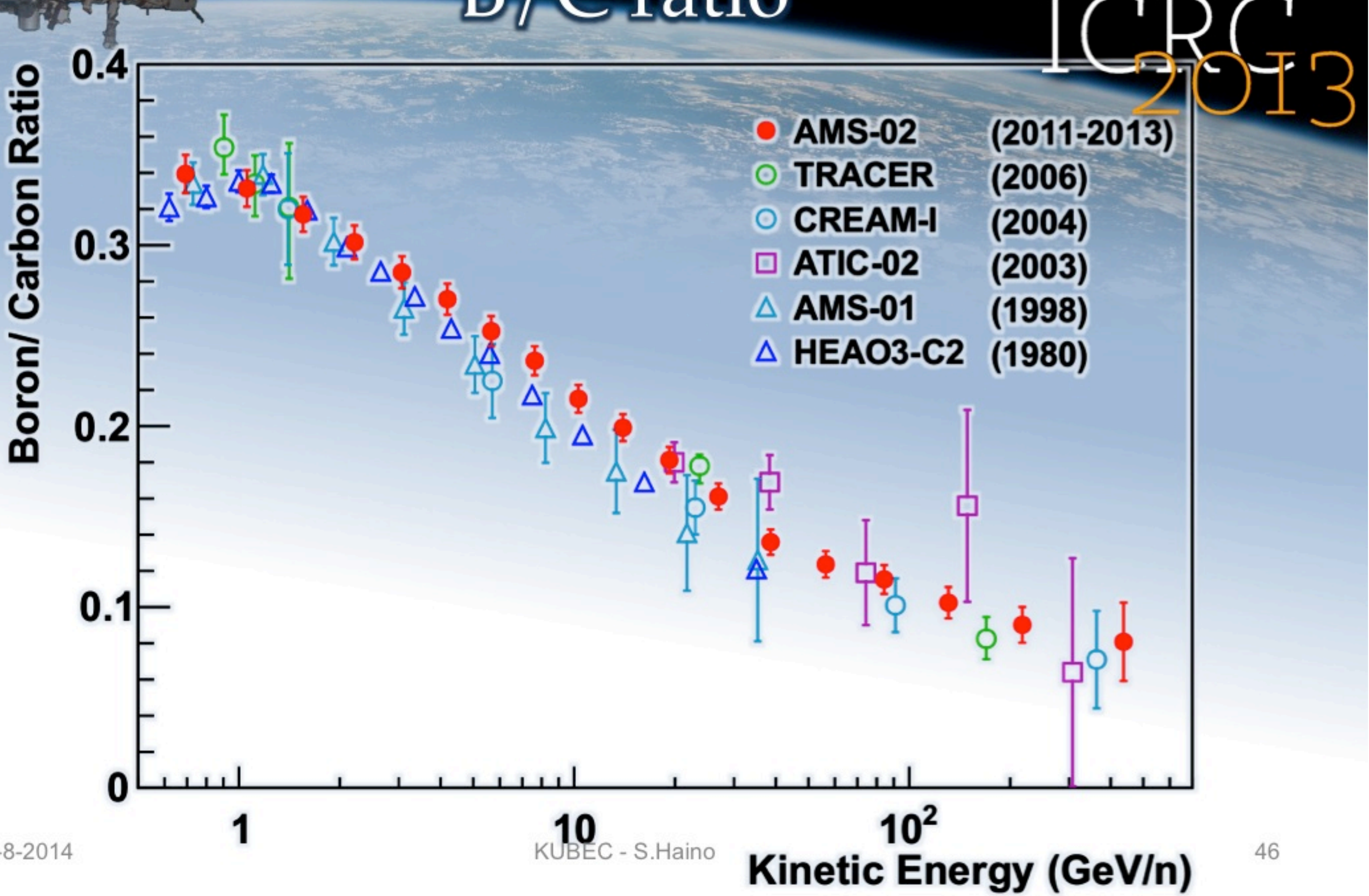
Detection of fragmentation



B/C ratio – before AMS



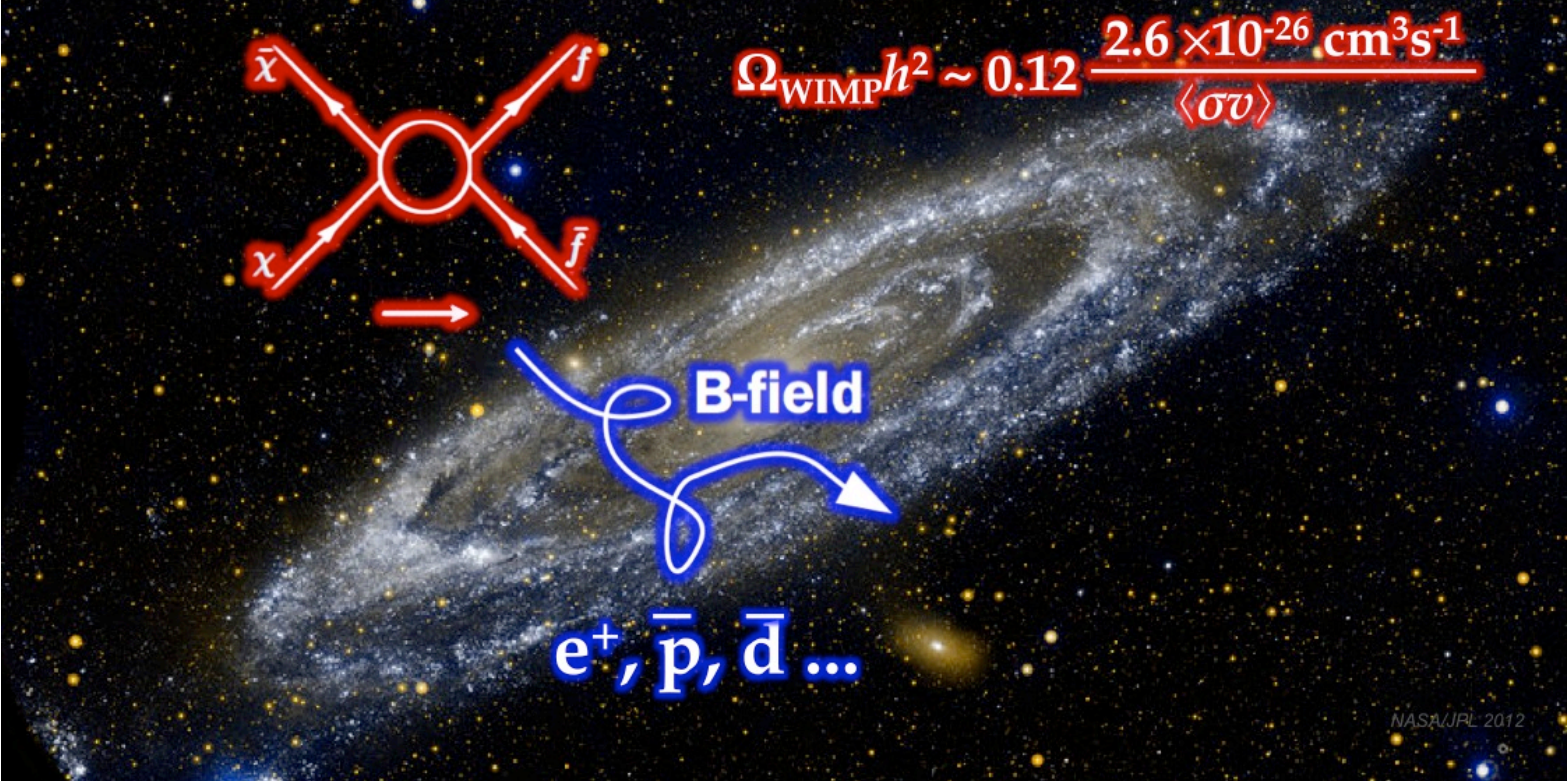
B/C ratio



ICRC 2013
Boron/ Carbon Ratio
0.4
0.3
0.2
0.1
0
AMS-02 (2011-2013)
TRACER (2006)
CREAM-I (2004)
ATIC-02 (2003)
AMS-01 (1998)
HEAO3-C2 (1980)
1
10
10^2
Kinetic Energy (GeV/n)

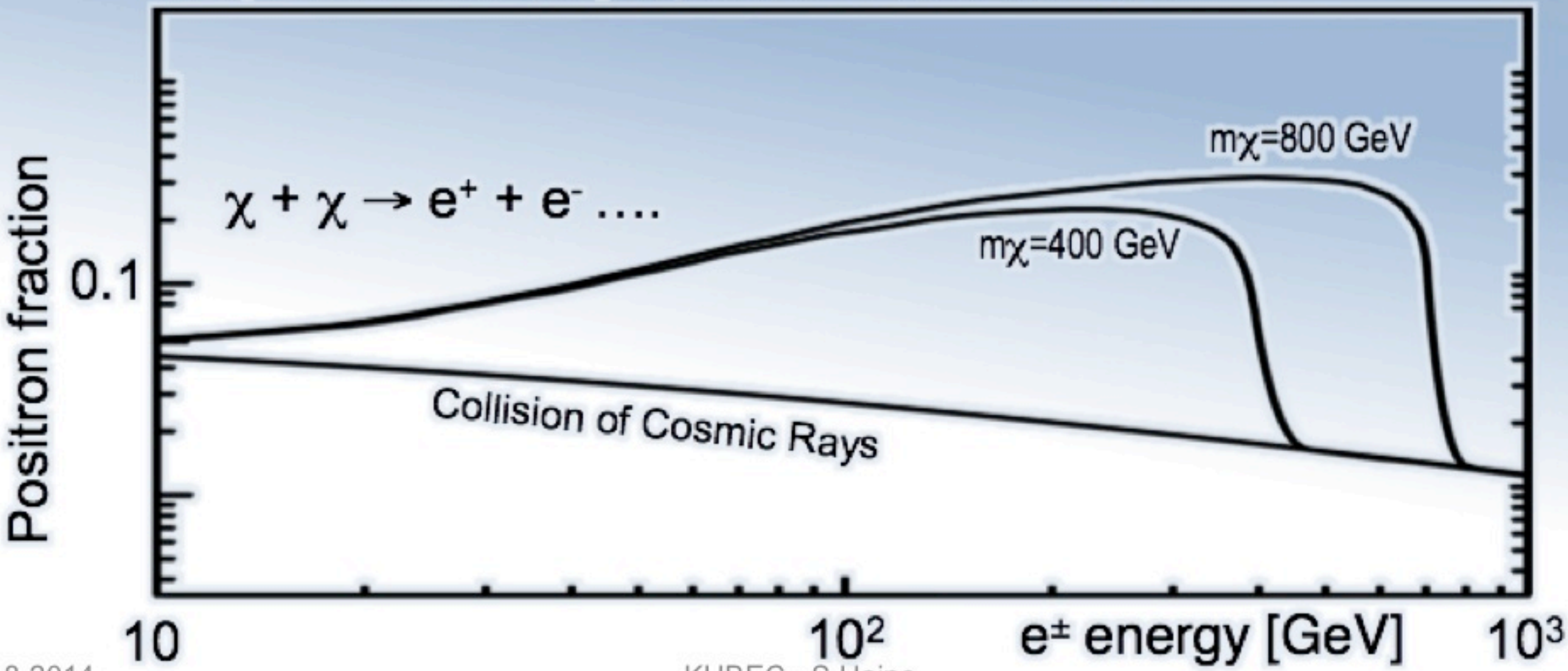
Cosmic-ray positrons

$$\Omega_{WIMP}h^2 \sim 0.12 \frac{2.6 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}}{\langle \sigma v \rangle}$$



Physics of CR Positron Fraction

M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001;
J. Ellis, 26th ICRC Salt Lake City (1999) astro-ph/9911440;
H. Cheng, J. Feng and K. Matchev, Phys. Rev. Lett. 89 (2002) 211301;
S. Profumo and P. Ullio, J. Cosmology Astroparticle Phys. JCAP07 (2004) 006;
D. Hooper and J. Silk, Phys. Rev. D 71 (2005) 083503;
E. Ponton and L. Randall, JHEP 0904 (2009) 080;
G. Kane, R. Lu and S. Watson, Phys. Lett. B681 (2009) 151;
D. Hooper, P. Blasi and P. D. Serpico, JCAP 0901 025 (2009) 0810.1527; B2

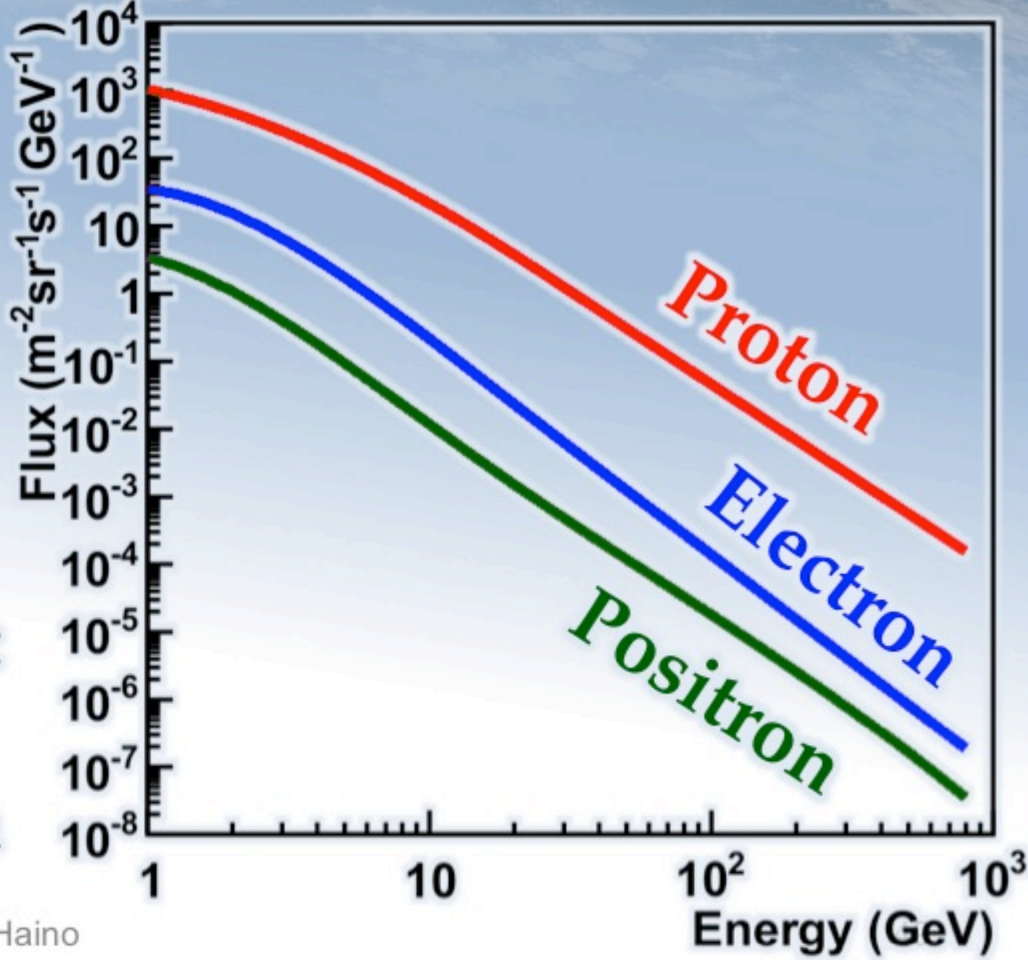


Difficulties – CR positron measurement

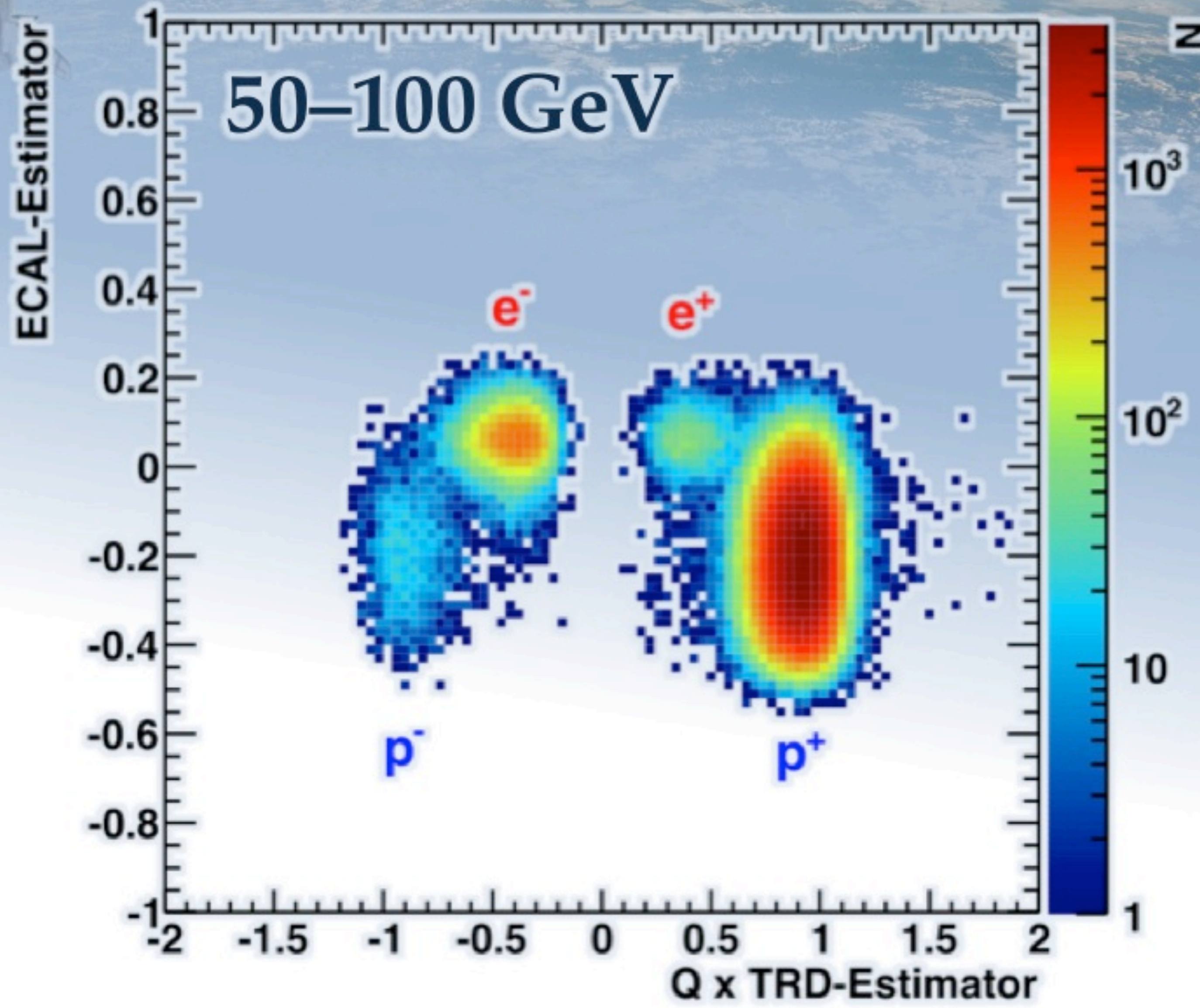
- Low abundance : 0.01~0.1 % of Cosmic Rays
  ➔ Large acceptance and long duration needed
- Large backgrounds

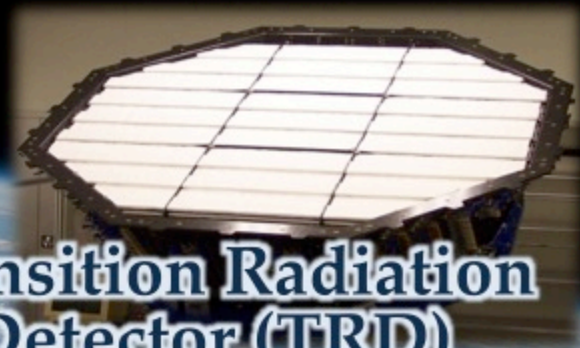
(1) Protons $\times 10^3$~10^4
➔ Redundant e^+/p separation capability

(2) Electrons $\times$ 10~100
➔ Deflection measurement in a magnetic field to determine charge sign



Positron identification





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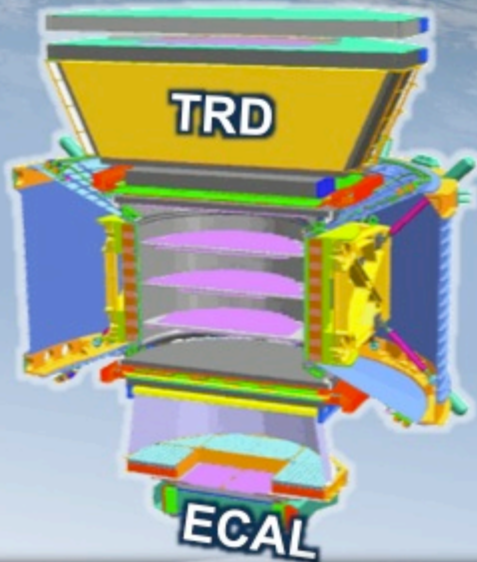
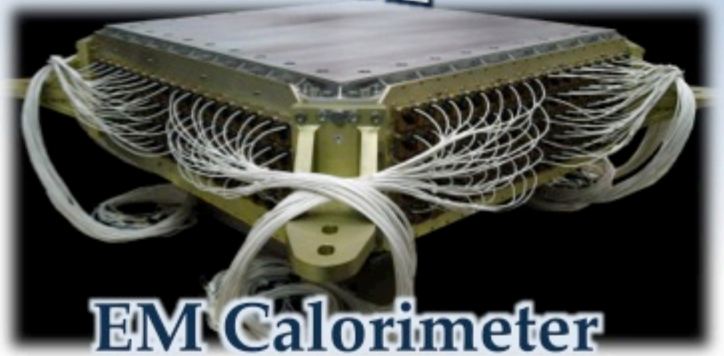
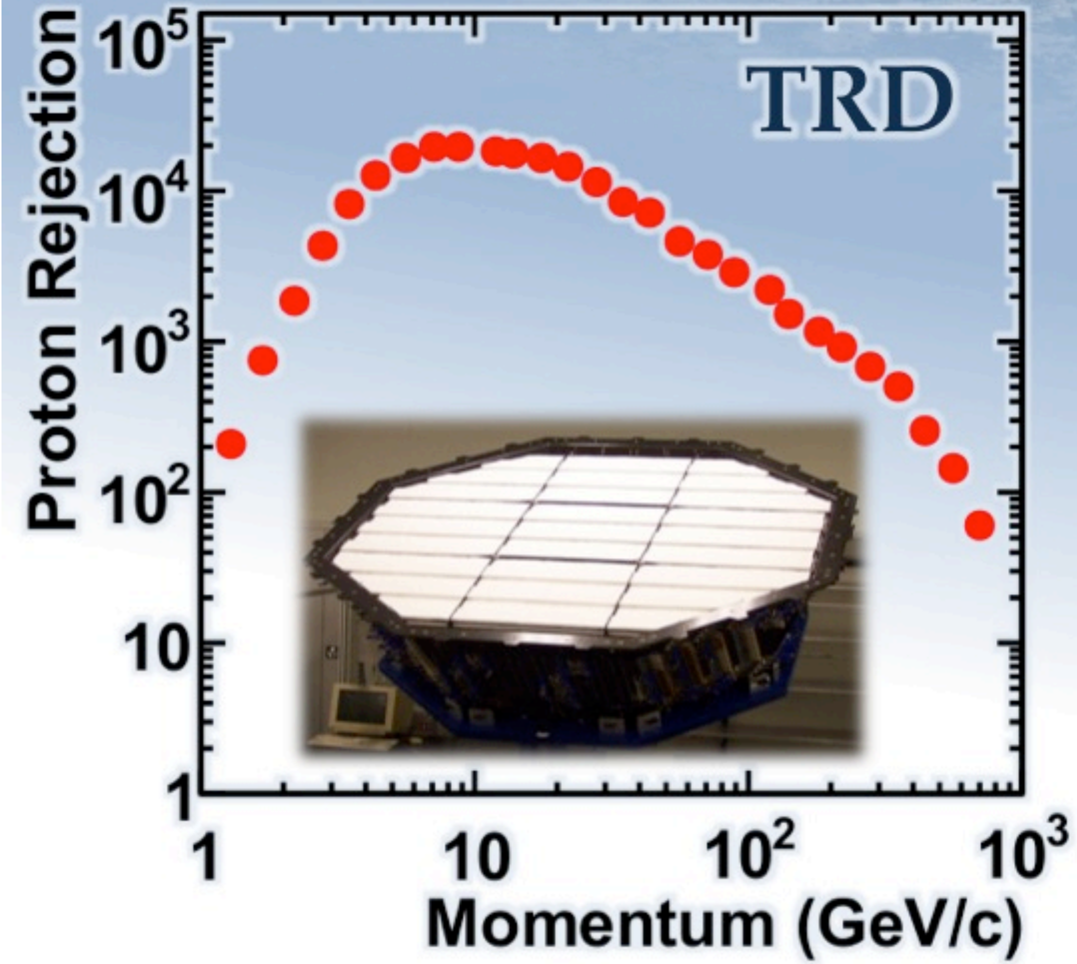


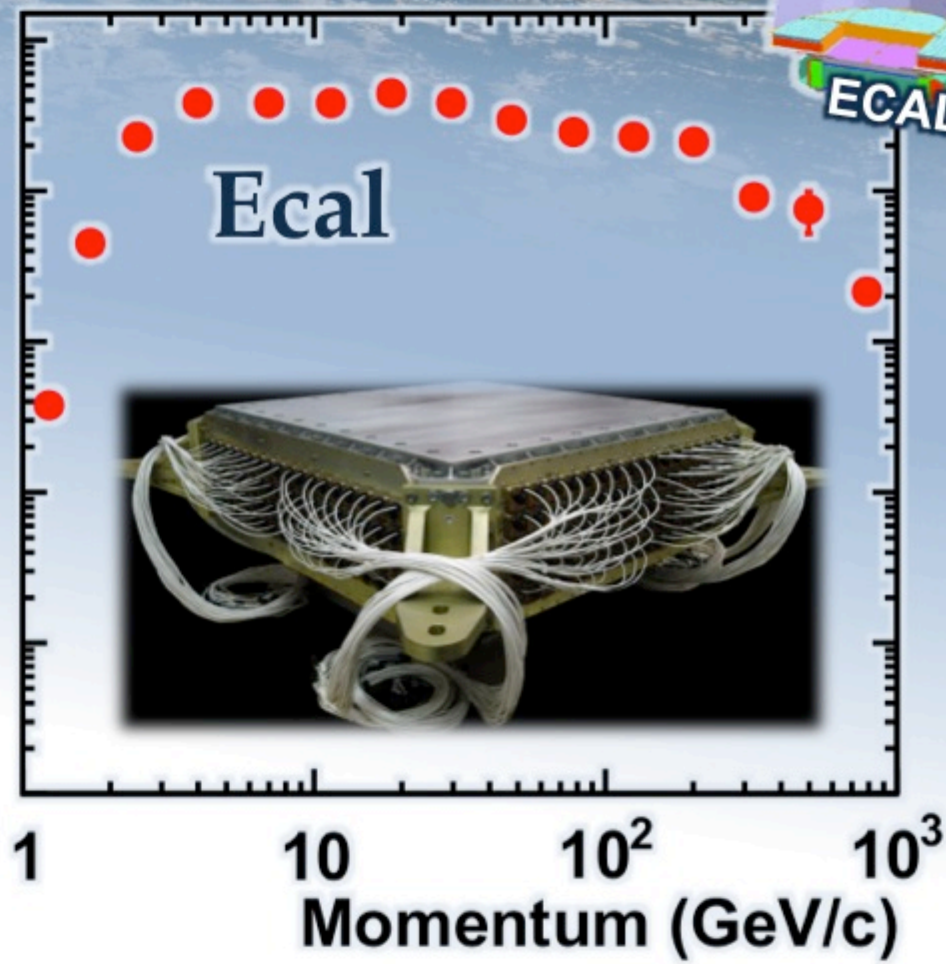


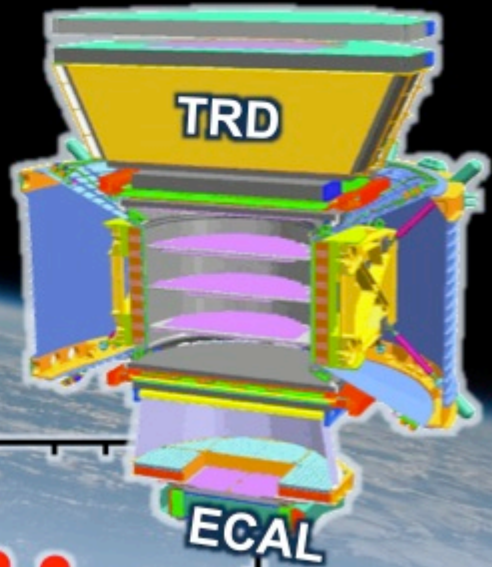
EM Calorimeter
(17 X_0)

Proton rejection

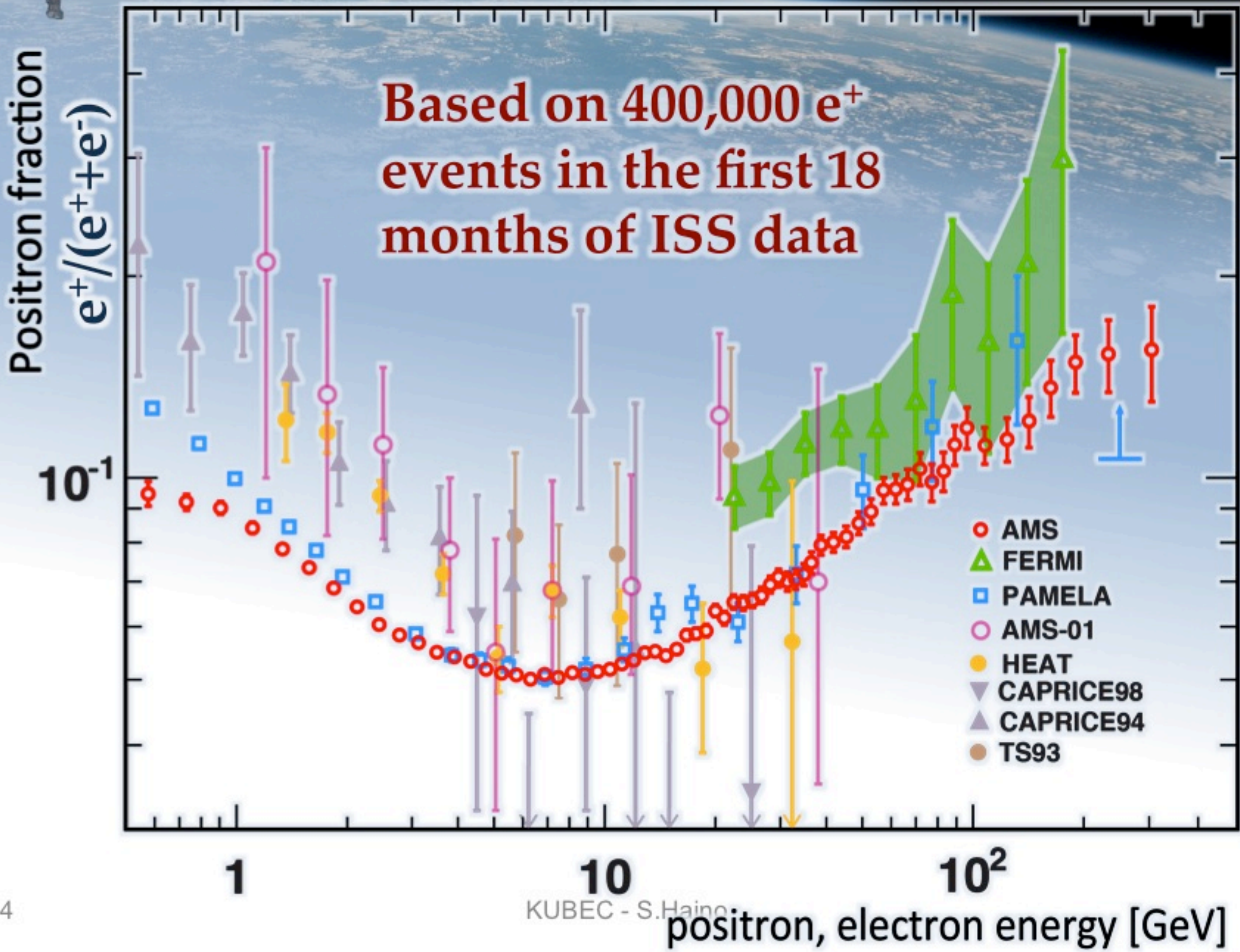
With 90 % e^+ efficiency



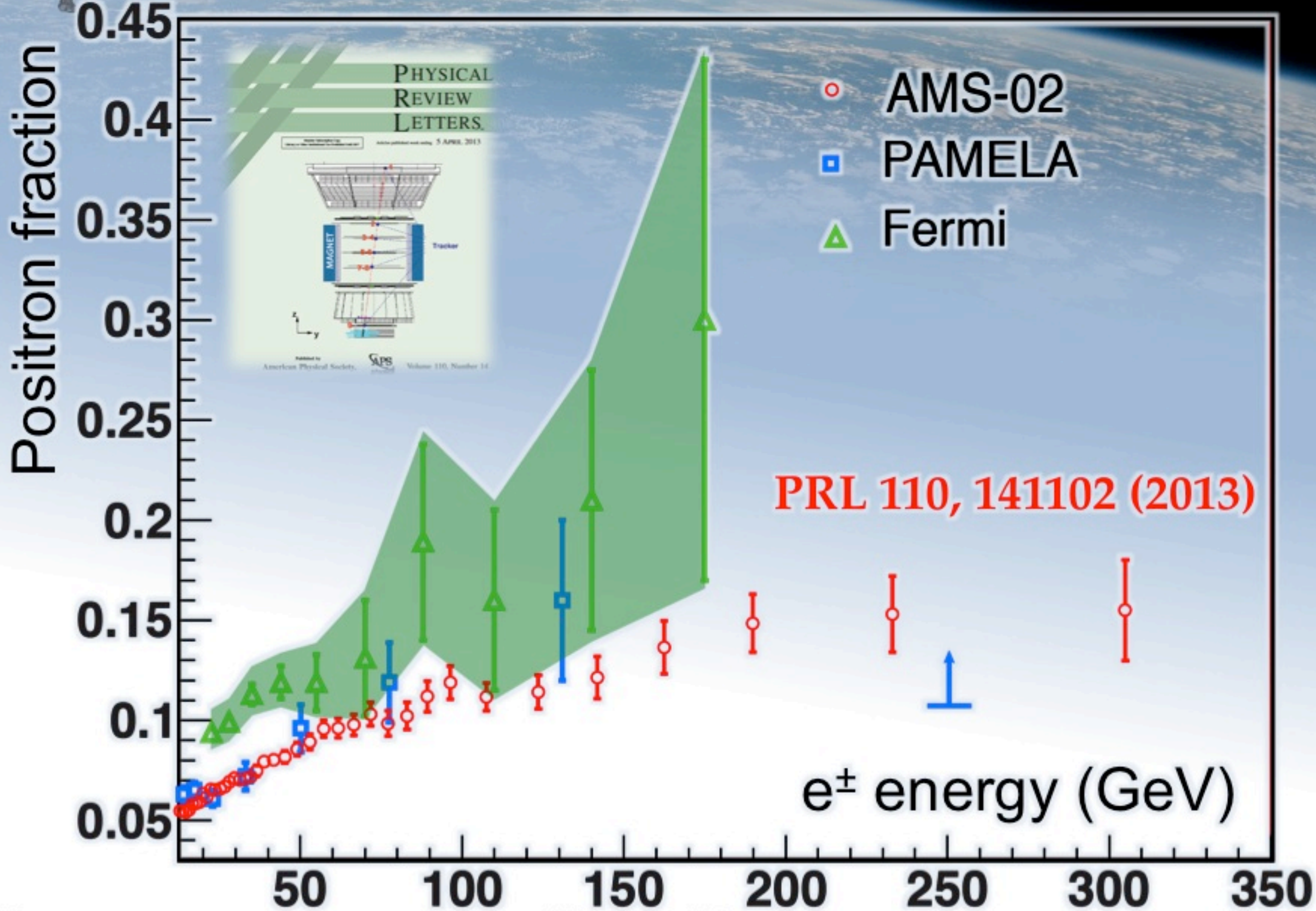




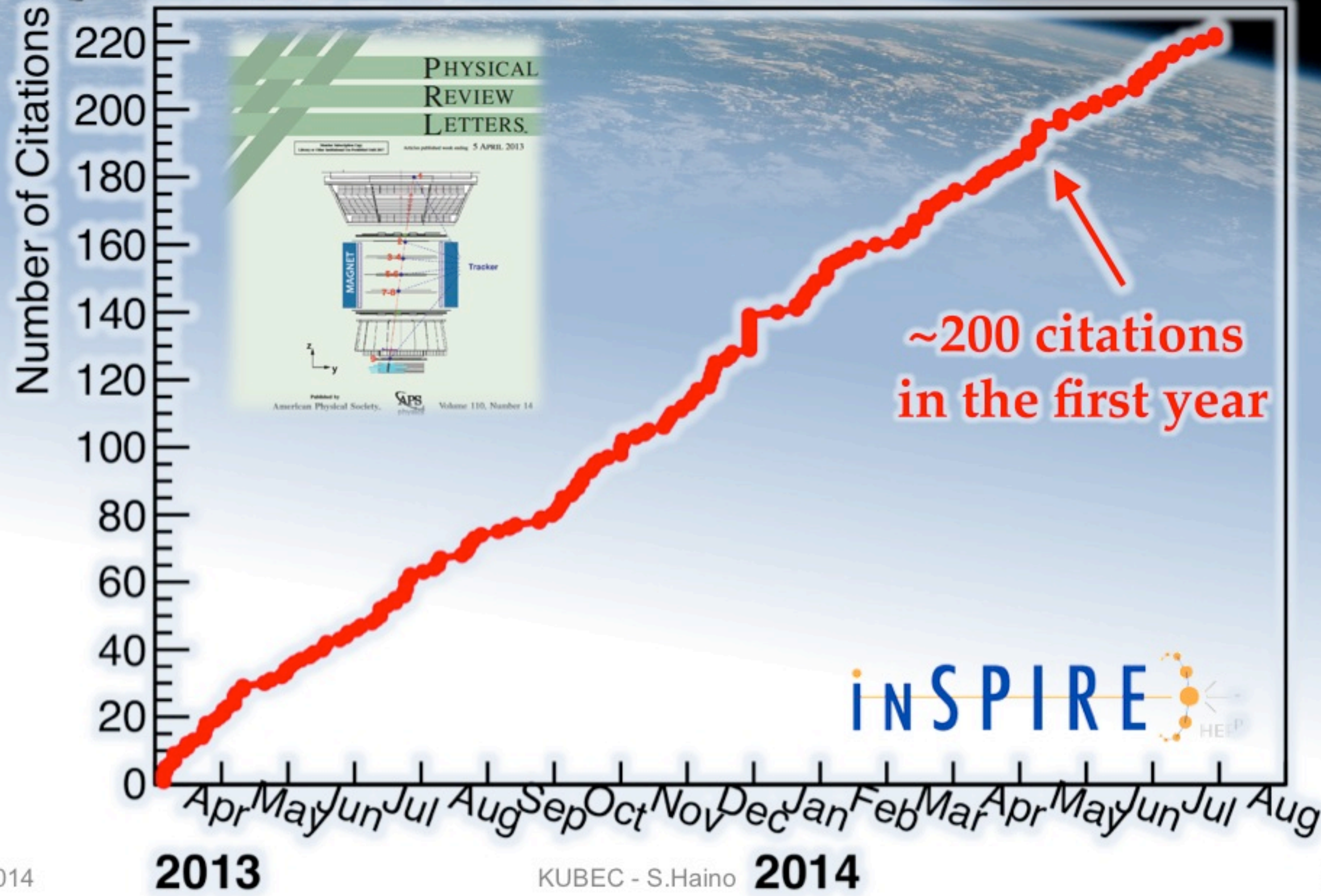
First results of AMS – e⁺ fraction



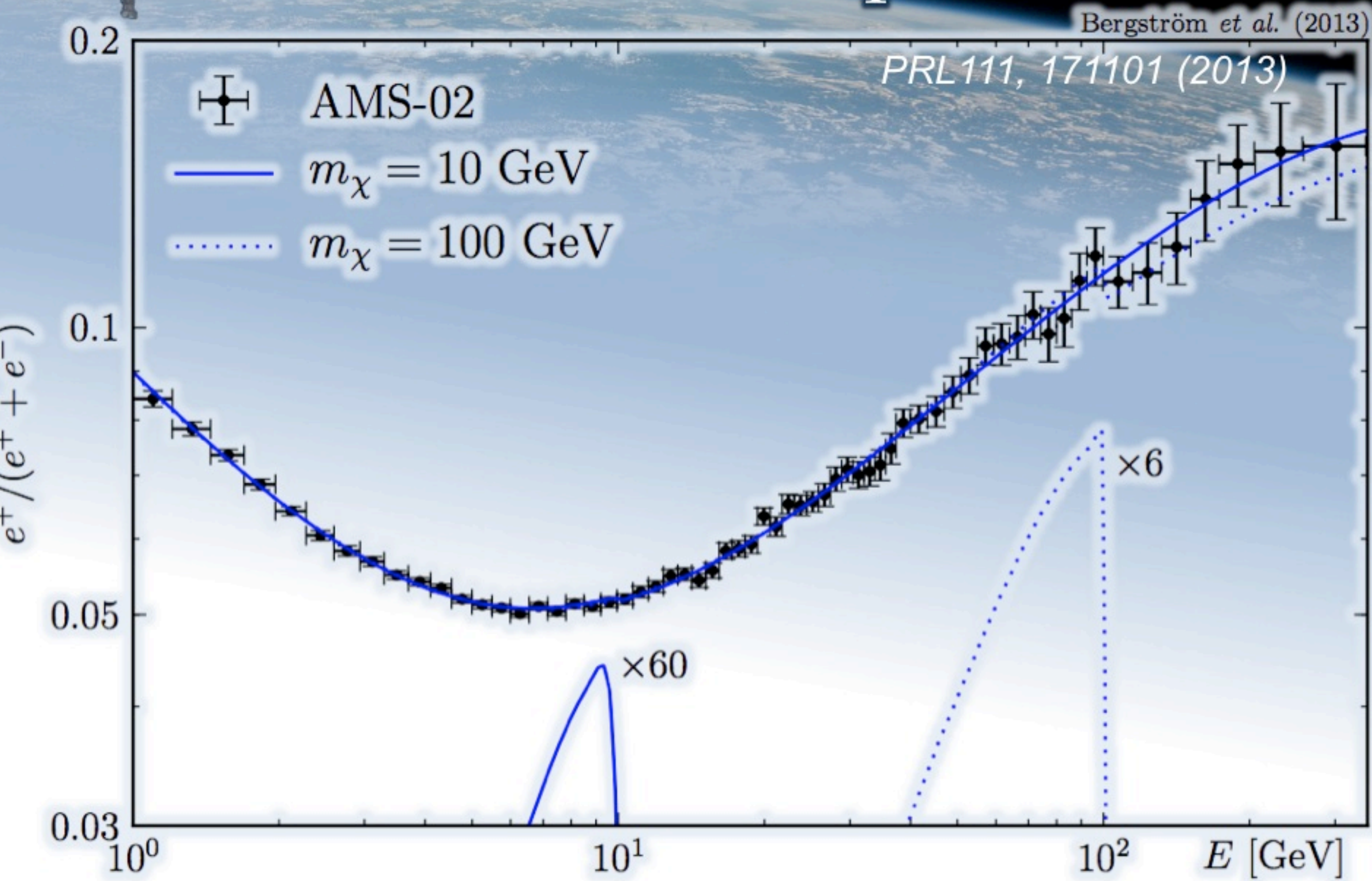
First results of AMS – e$^+$ fraction



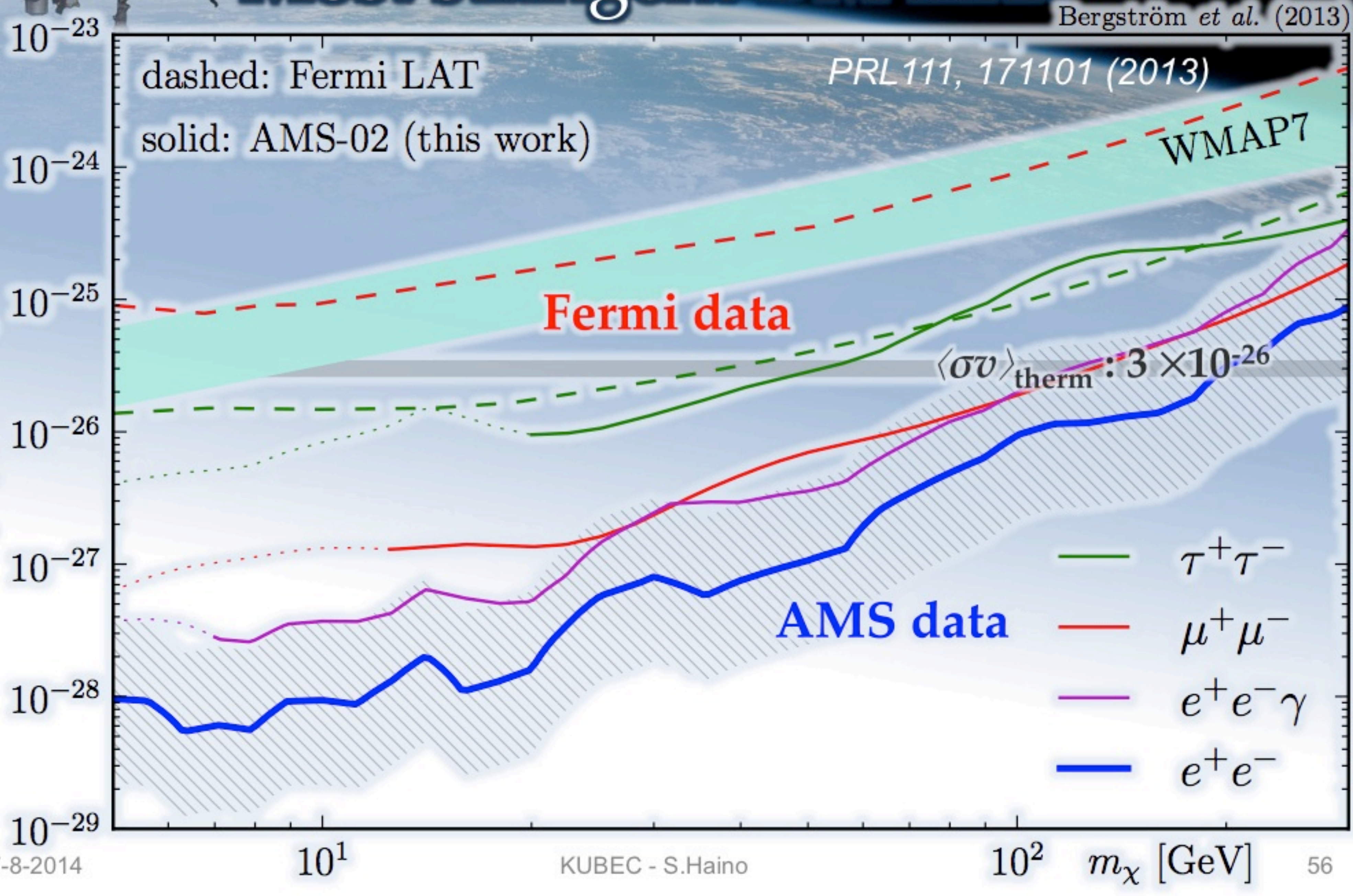
Citations increasing ...



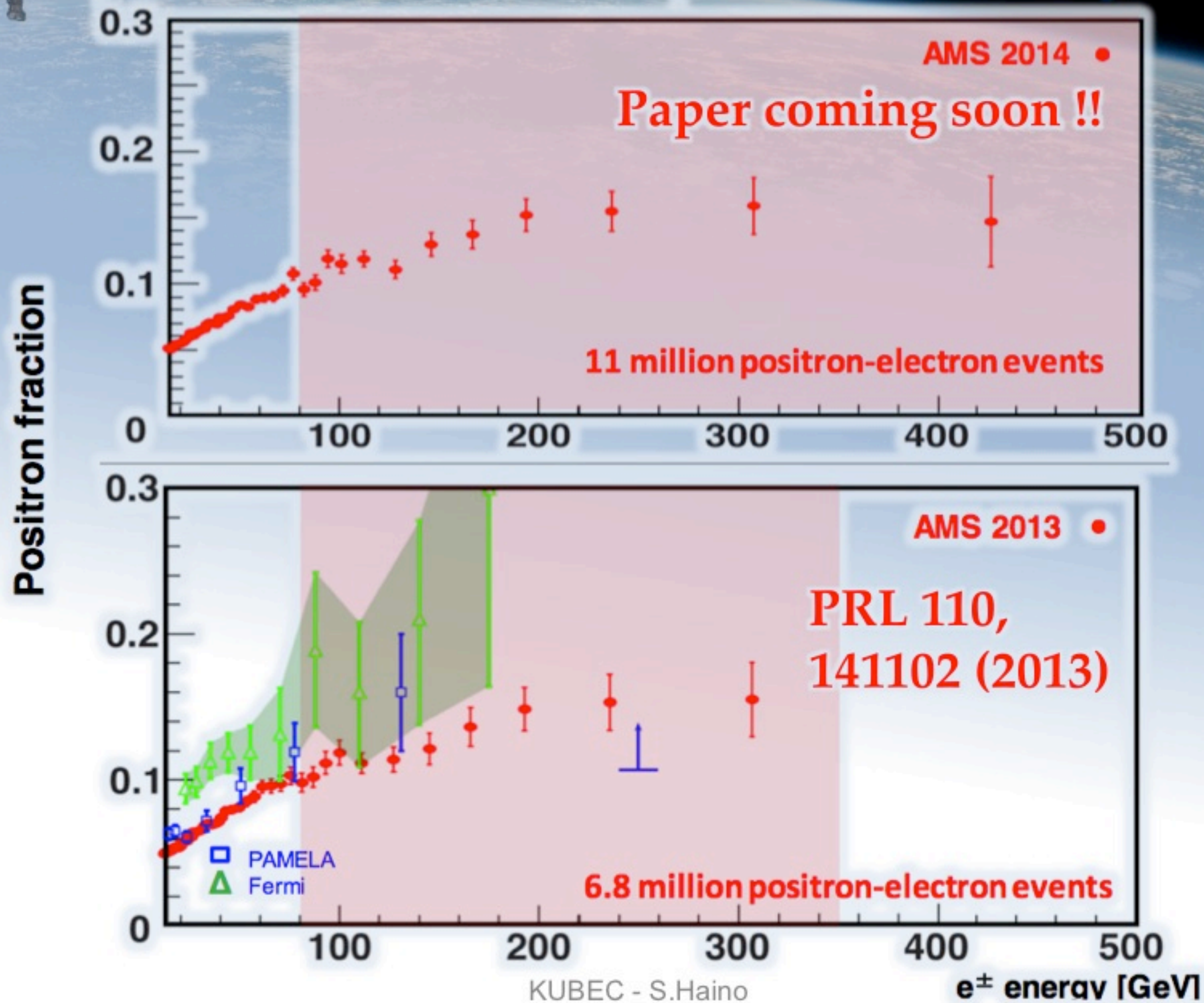
Search for DM peaks



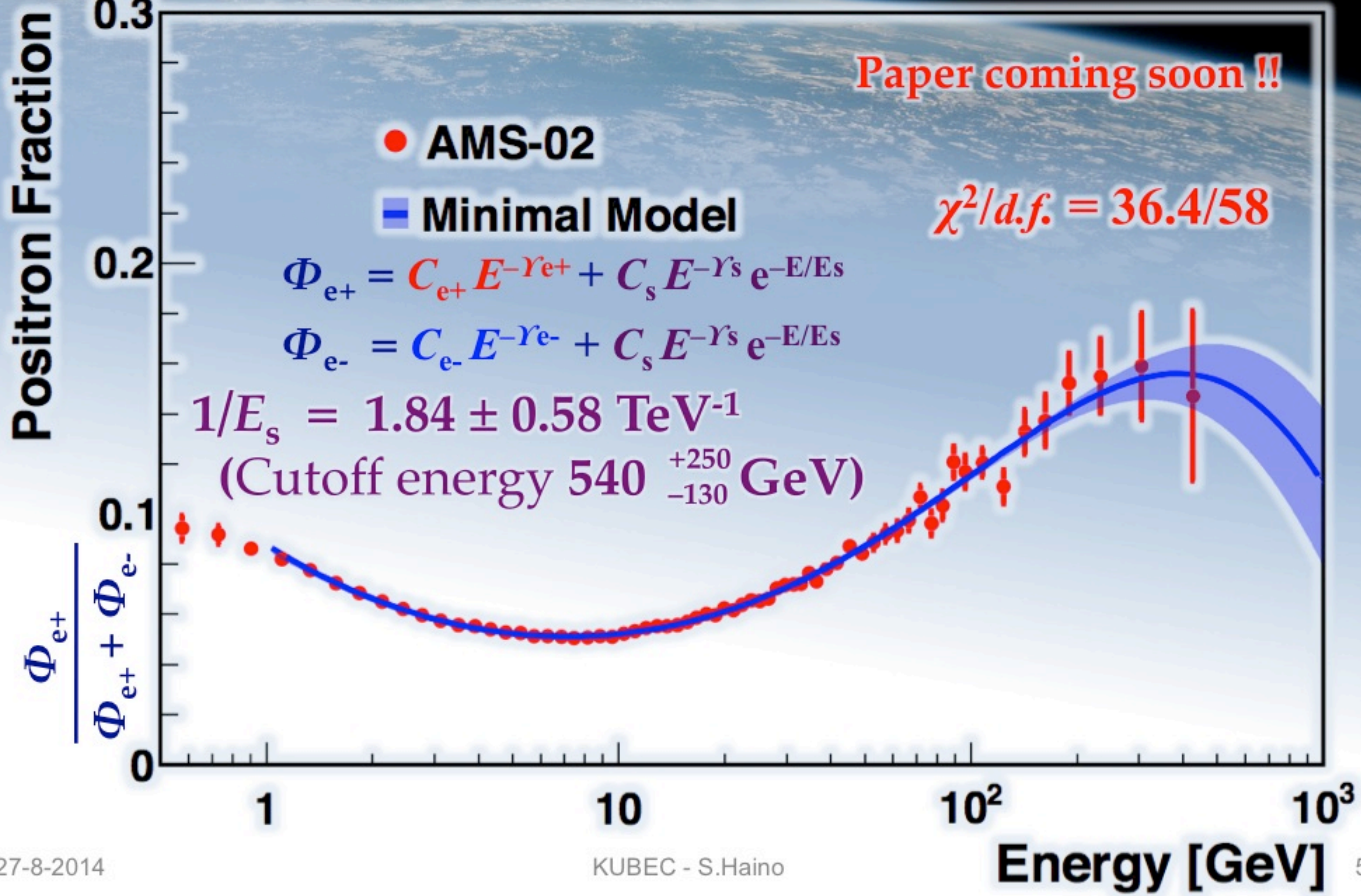
Most stringent DM limit



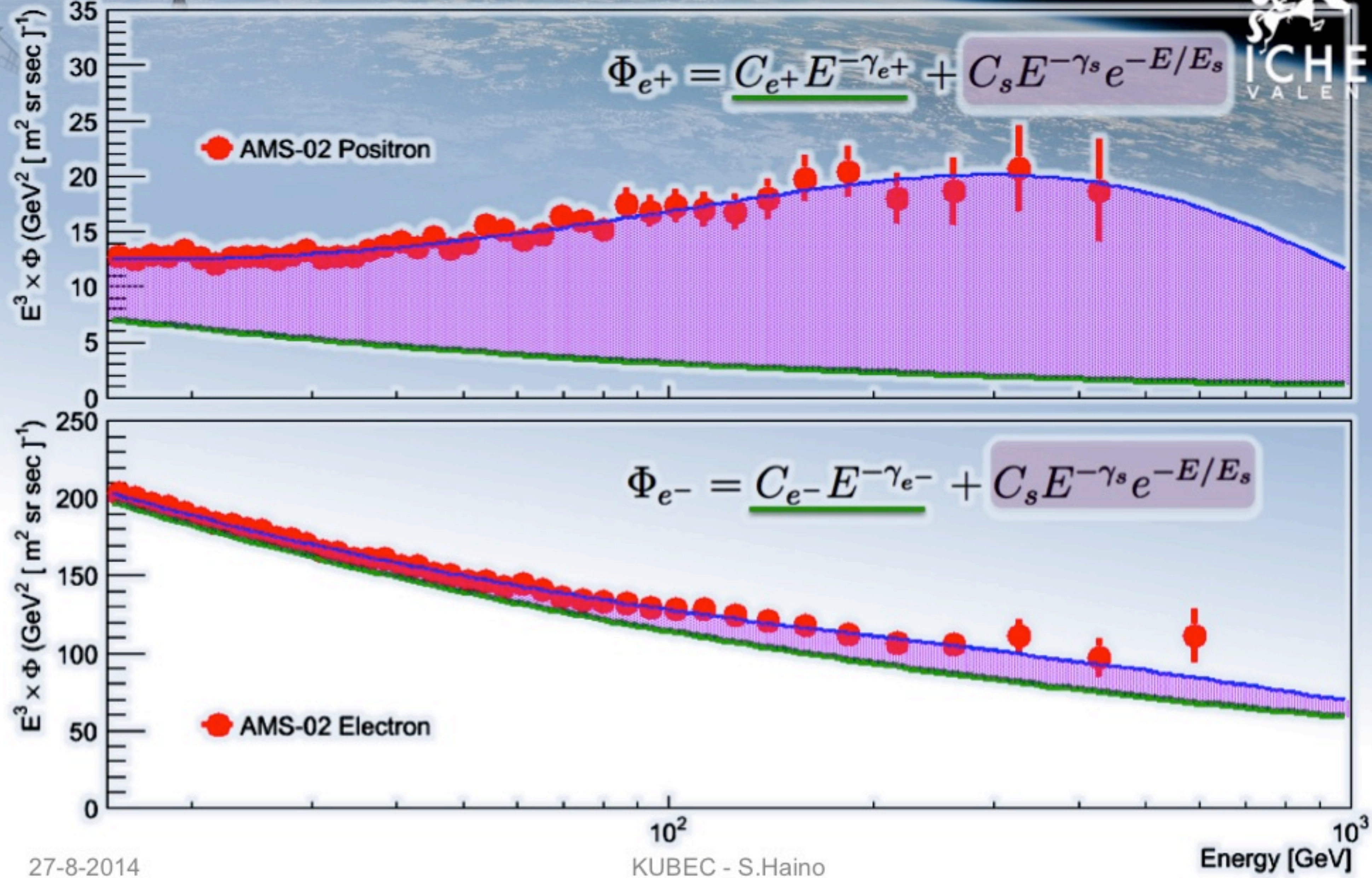
New AMS results (2014)



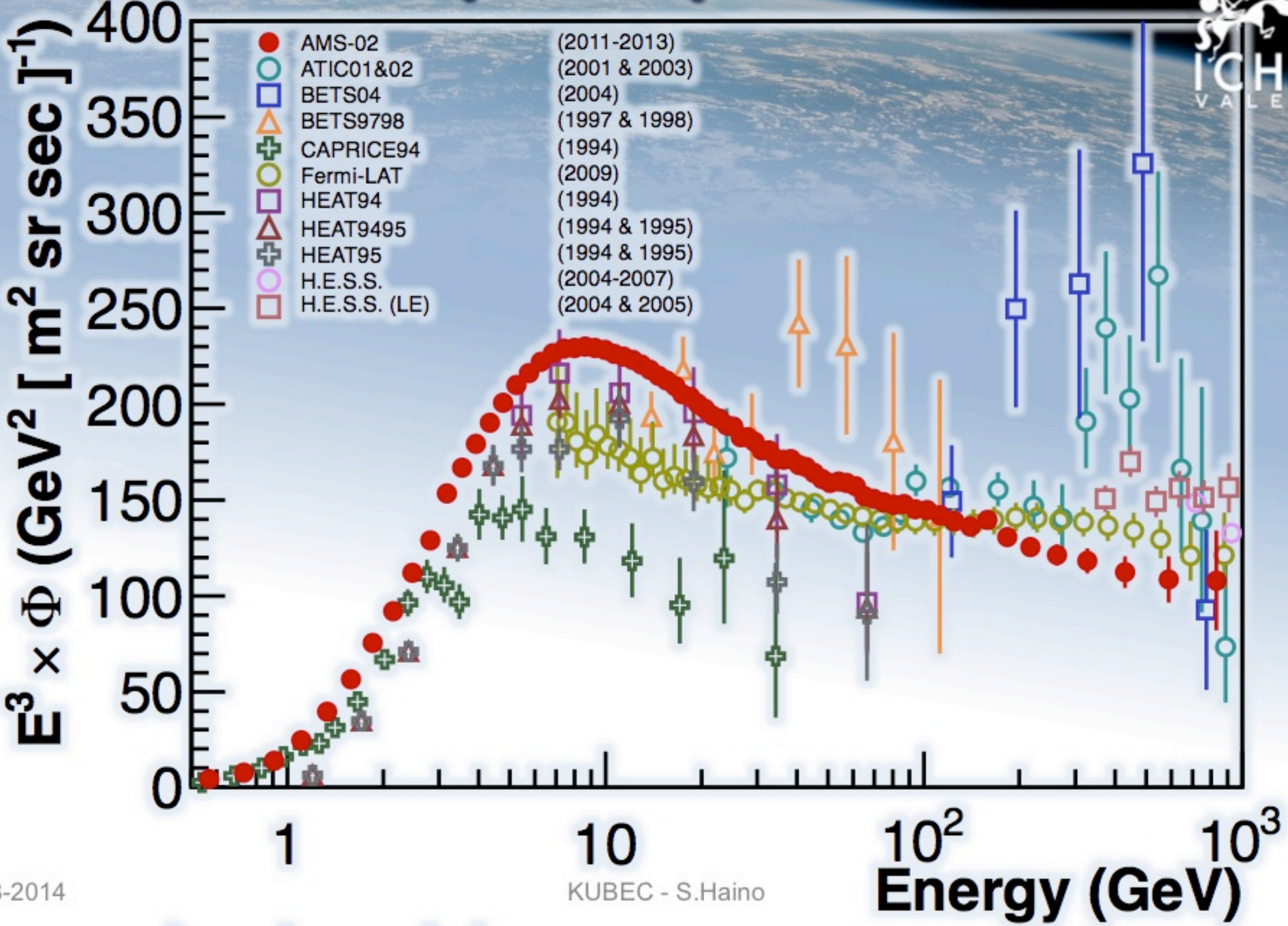
Fit to new AMS data



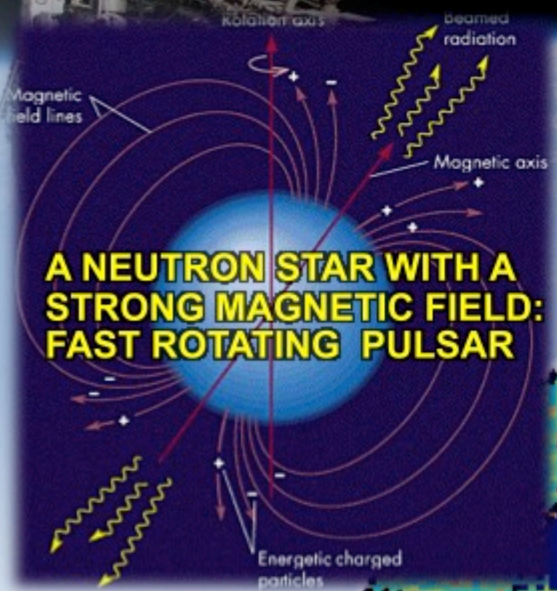
Fit to AMS e⁺ and e⁻ flux

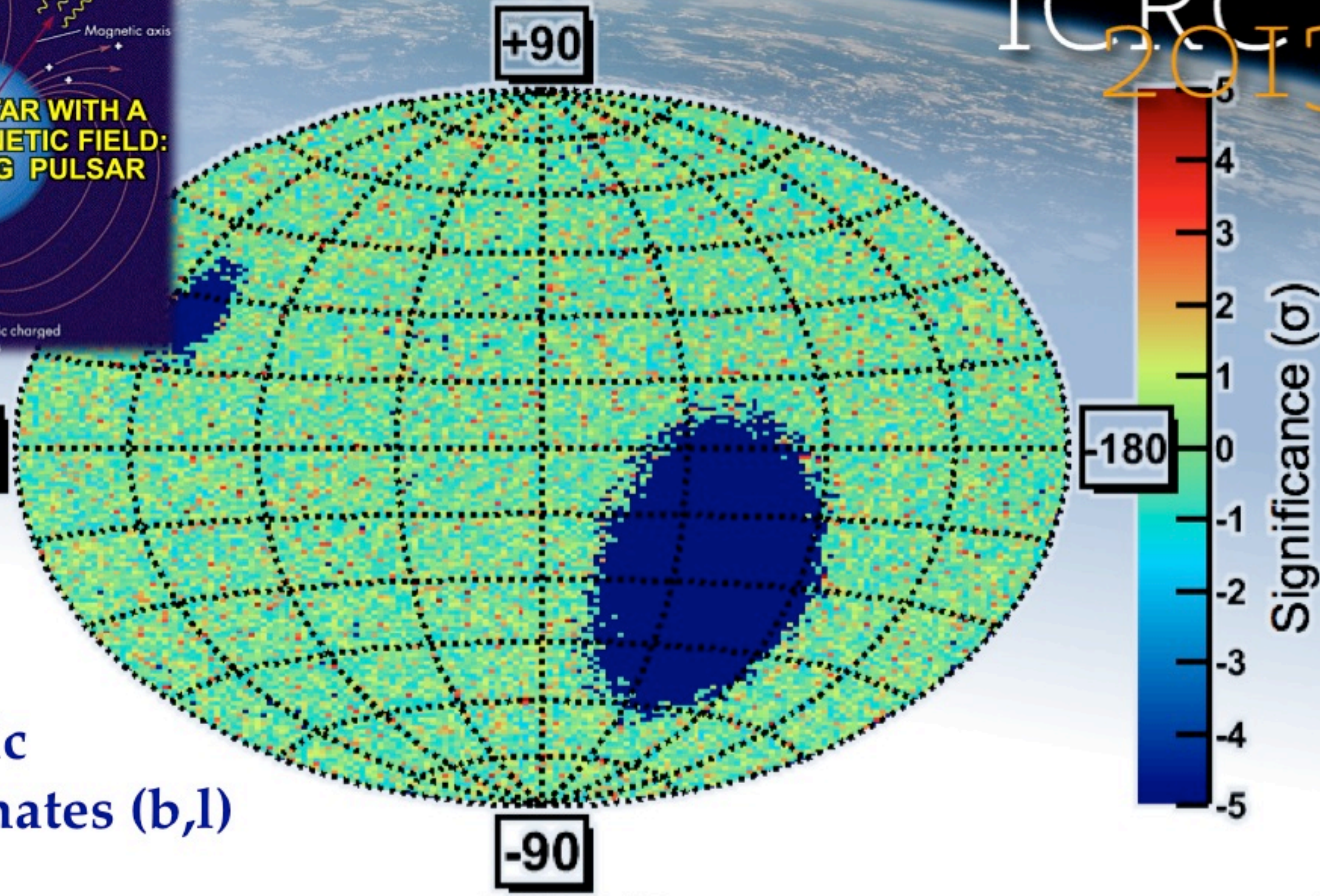


$(e^+ + e^-)$ flux


AMS-02 (2011-2013)
ATIC01&02 (2001 & 2003)
BETS04 (2004)
BETS9798 (1997 & 1998)
CAPRICE94 (1994)
Fermi-LAT (2009)
HEAT94 (1994)
HEAT9495 (1994 & 1995)
HEAT95 (1994 & 1995)
H.E.S.S. (2004-2007)
H.E.S.S. (LE) (2004 & 2005)
$E^3 \times \Phi$ (GeV^2 [m^2 sr sec]$^{-1}$)
0
50
100
150
200
250
300
350
400
1
10
10^2
10^3
Energy (GeV)

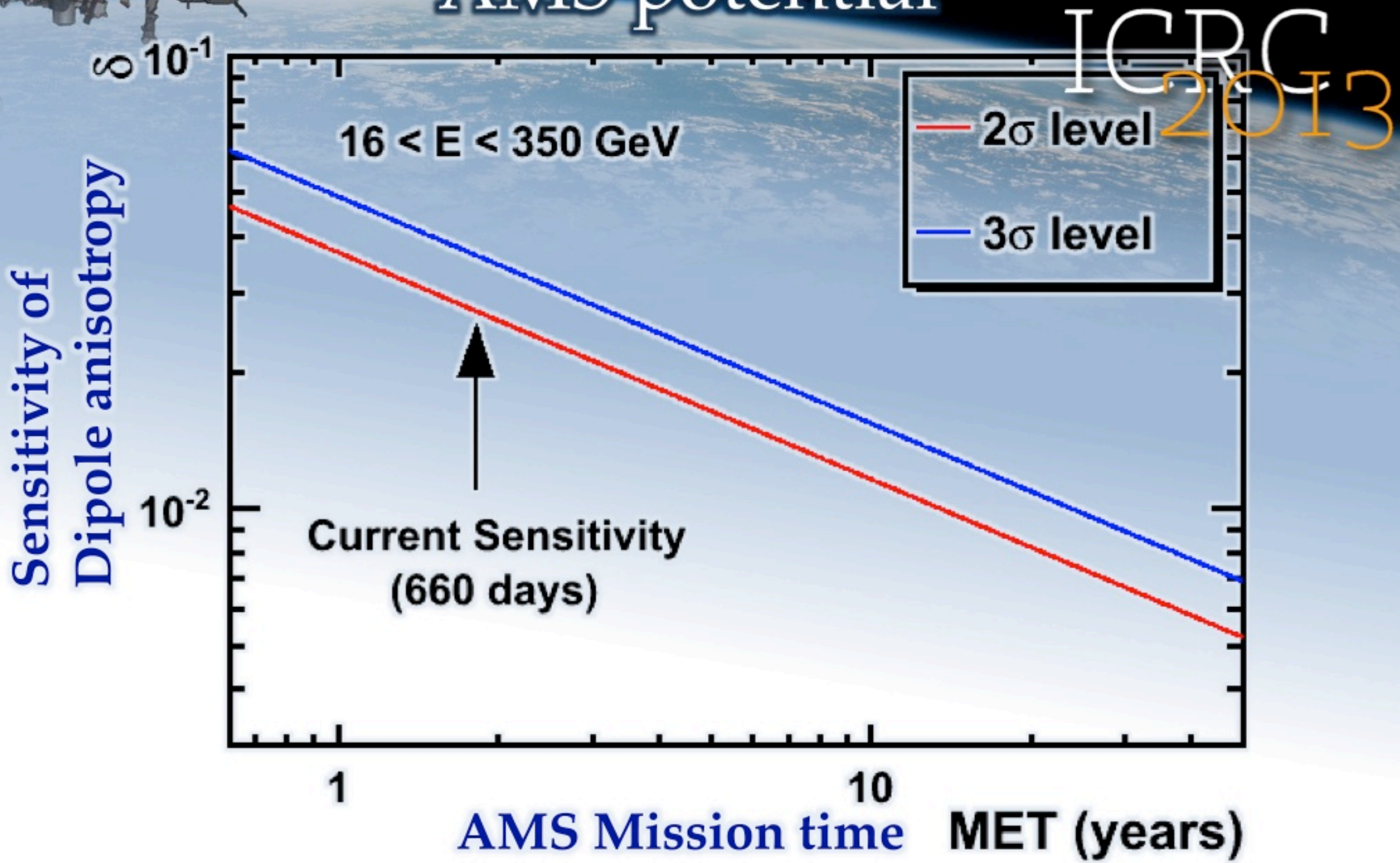
Positron anisotropy



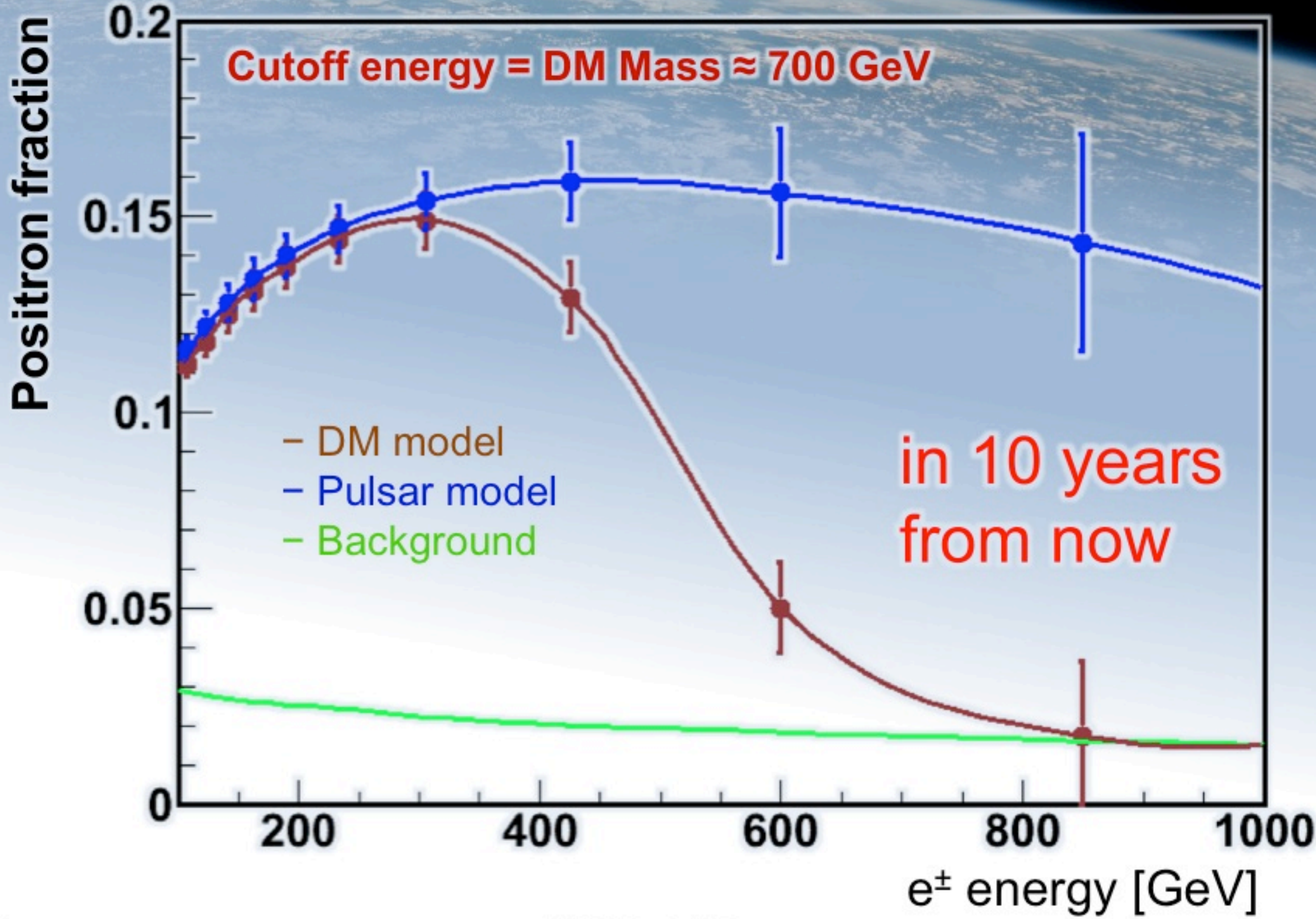


Galactic coordinates (b,l)

AMS potential



AMS Potential of DM search



Indirect DM searches – Conclusions

- **Indirect dark matter searches have entered a precision era after Fermi-LAT and AMS-02**
- **A striking DM signal seems now unexpected : we have to search for tiny effects VS important astrophysical contributions.**
- **A multi-channel approach should be important and powerful**