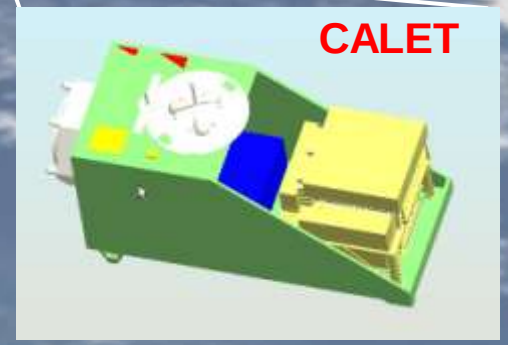
The CALET Mission to Search for Nearby Cosmic-Ray Sources and for Dark Matter



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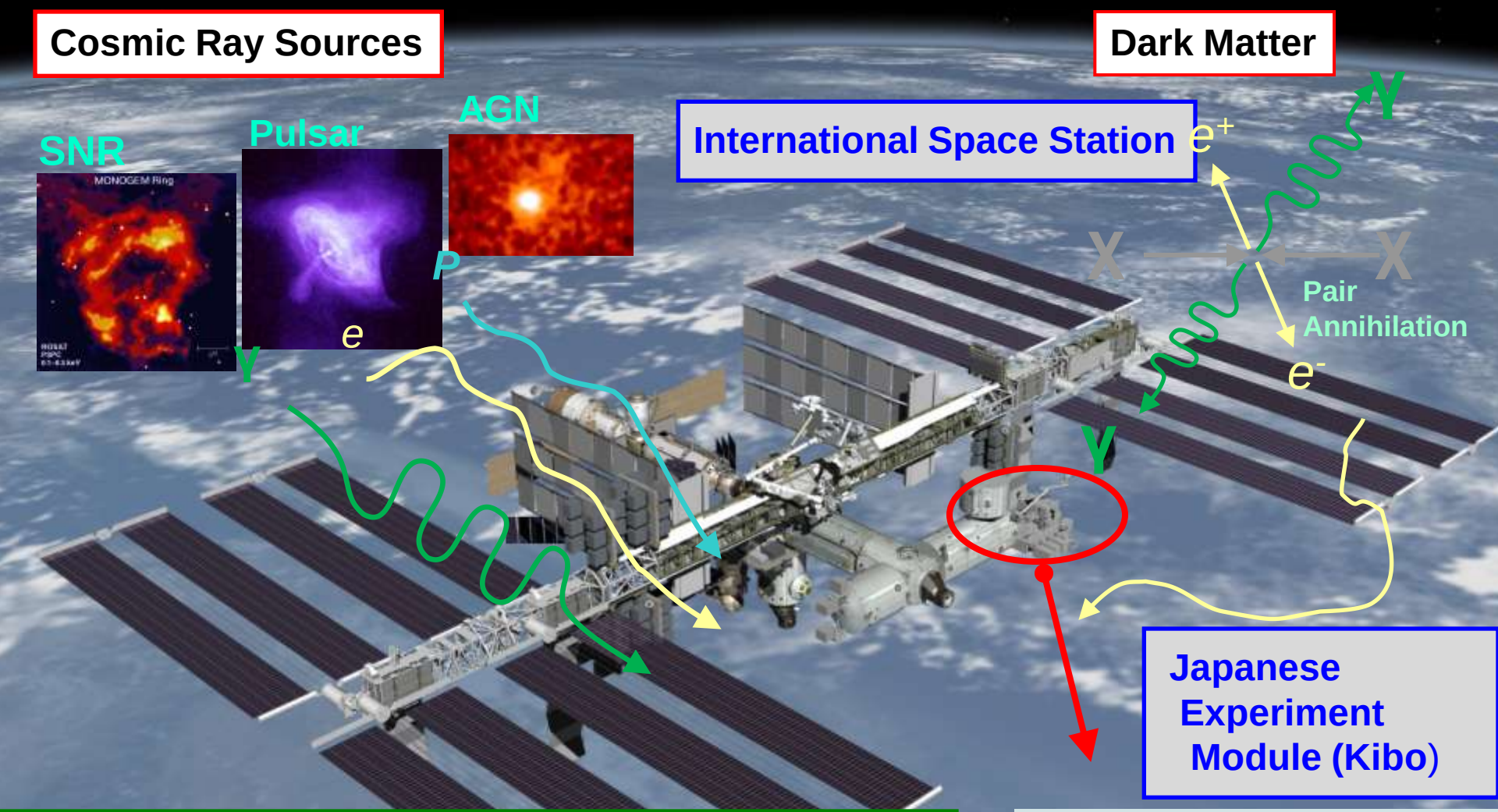
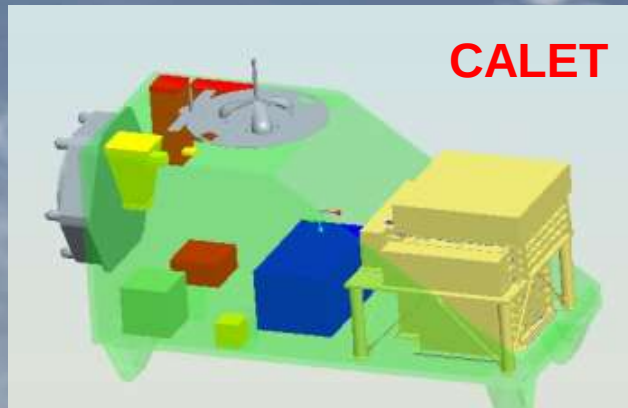
Waseda University



CALorimetric Electron Telescope

A Dedicated Detector for Electron Observation in 1GeV – 10,000 GeV



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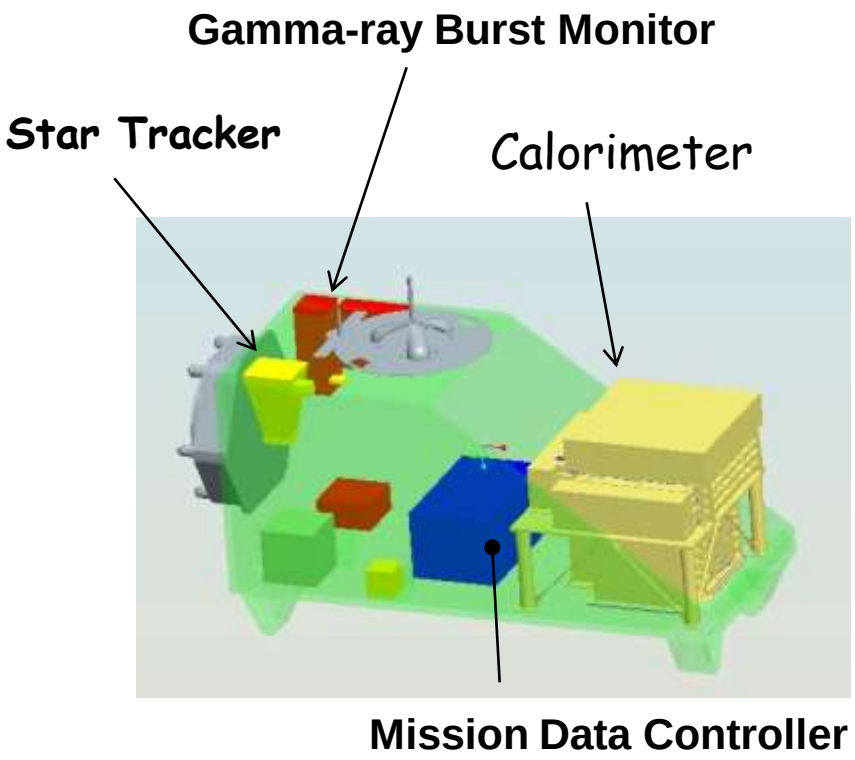
+ University & INFN Roma Tor Vergata , Trieste

CALET Overview



- **Observation:**
  - **Electrons : 1-10,000 GeV**
  - **Gamma-rays : 10-10,000 GeV**
    + Gamma-ray Bursts : 7 keV-20 MeV
  - **Protons, Heavy Nuclei:**
    several 10 GeV- 1000 TeV (per particle)
  - **Solar Particles and Modulated Particles in Solar System: 1-10 GeV (Electrons)**

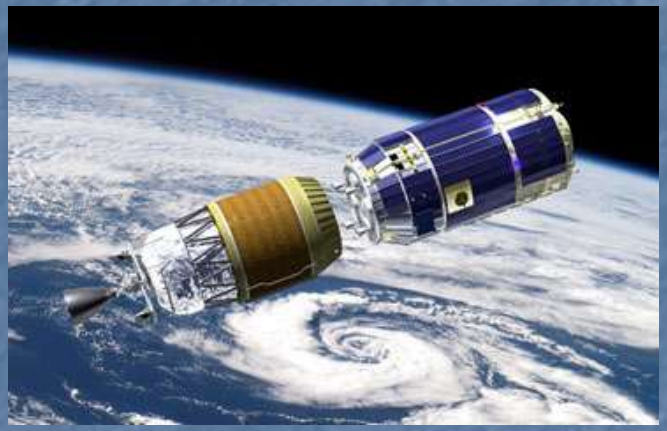
- **Instrument:**

High Energy Electron and Gamma- Ray Telescope Consisted of

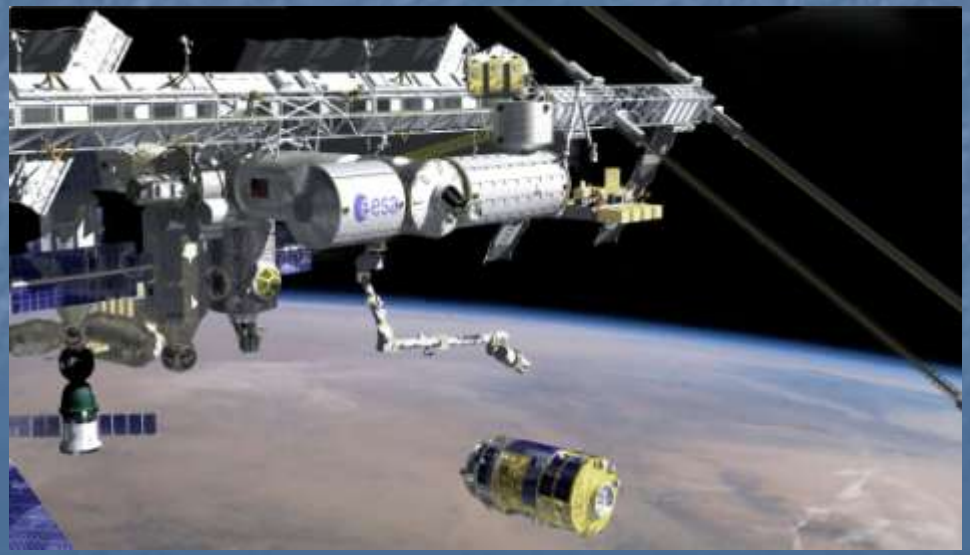
- **Imaging Calorimeter**
  Particle ID, Direction
- **Total Absorption Calorimeter**
  Energy Measurement, Particle ID
- **Silicon Pixel Array**
  (contributed from Italian Group)
  Charge Measurement up in Z=1-35

Launch of the H-IIB Launch Vehicle Test Flight

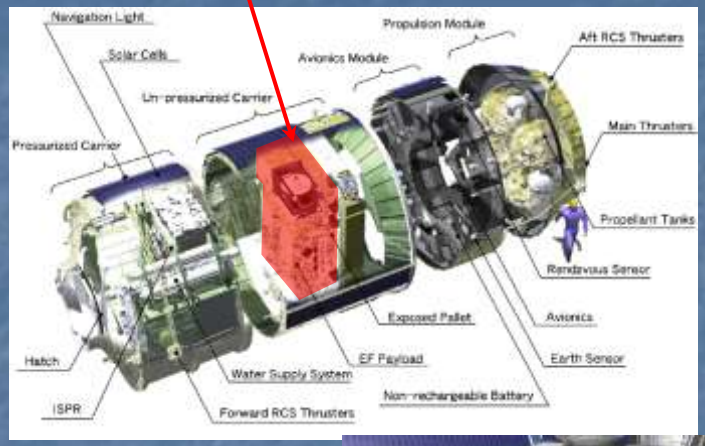
- Launched on Sep.11, 2009 at Yoshinobu Launch Complex at the Tanegashima Space Center in Japan
- Docked successfully to ISS on Sep. 18, 2009.



© JAXA



Launching Procedure of CALET



H-IIB Transfer Vehicle (HTV)

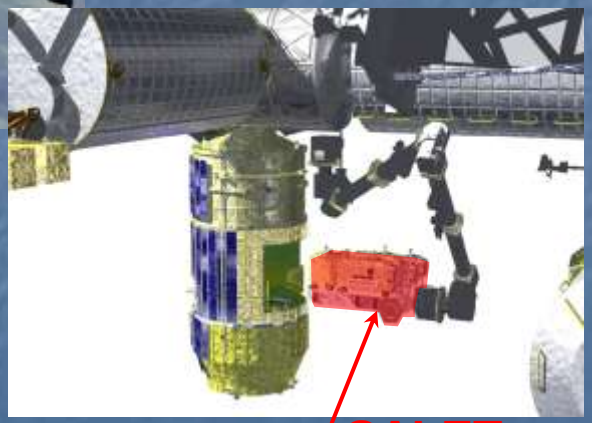
CALET launched by HTV

Launching of H-IIB Rocket

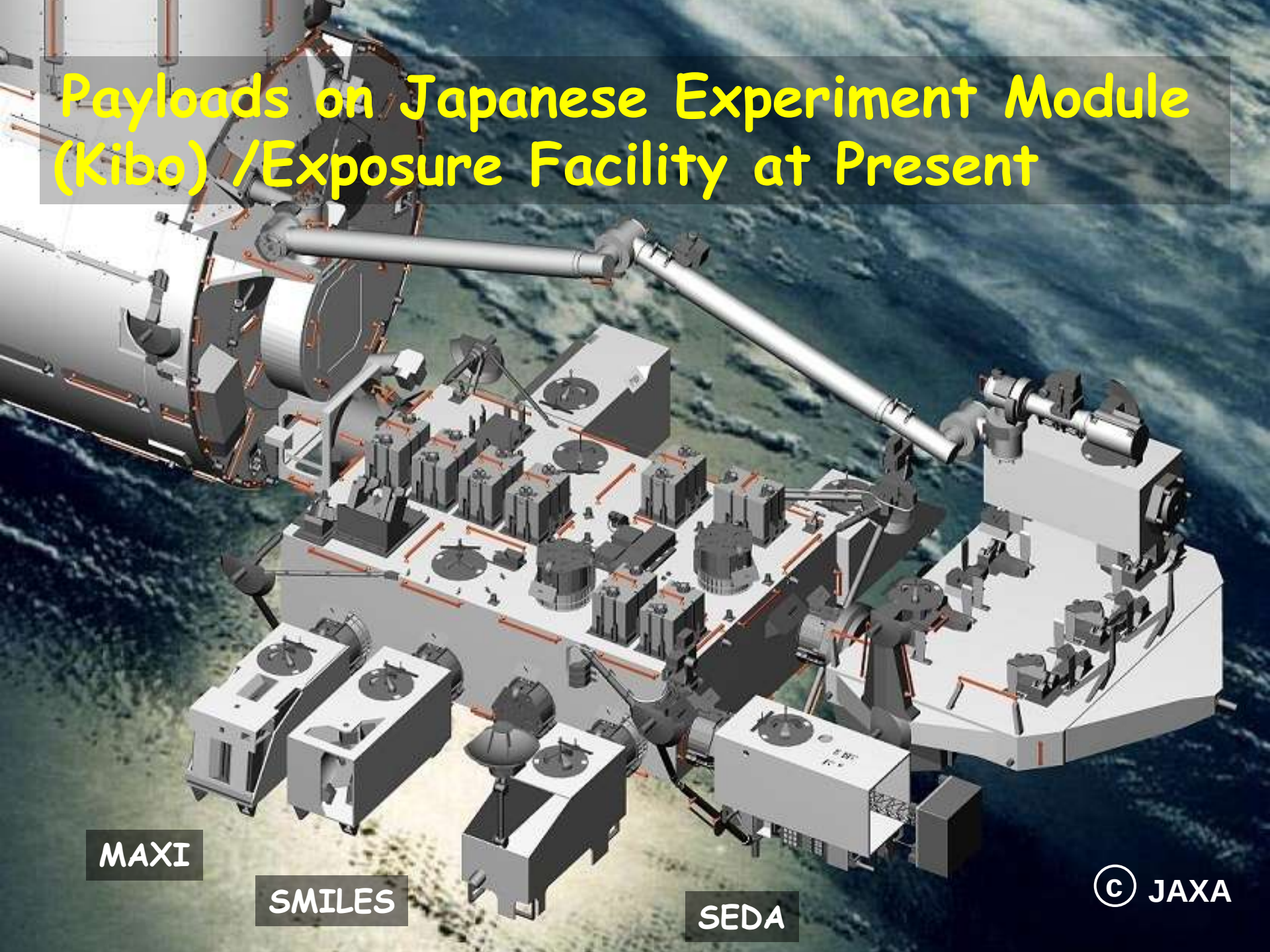
Separation from H-IIB

Approach to ISS

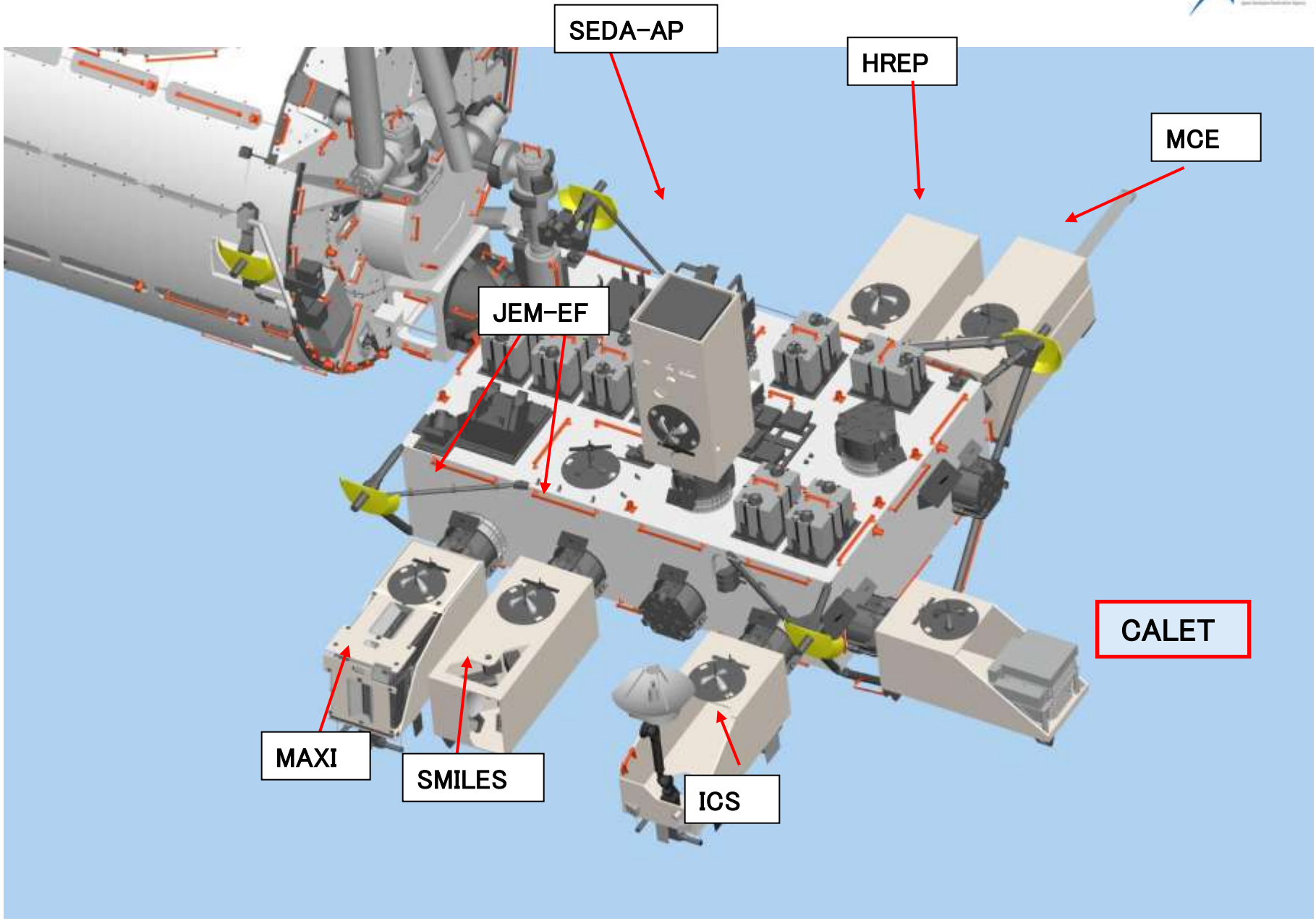
Pickup of CALET



Payloads on Japanese Experiment Module (Kibo) /Exposure Facility at Present



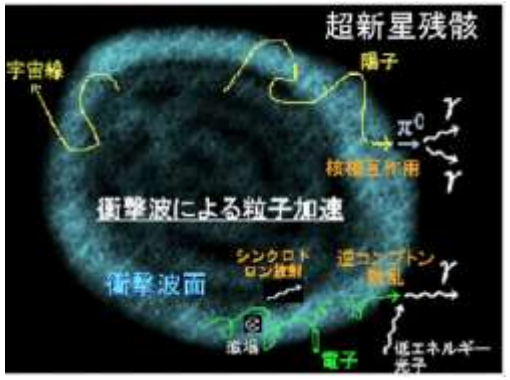
Future Plan of JEM/EF (~2013)



Electron & Positron Observation

Astrophysical Origin

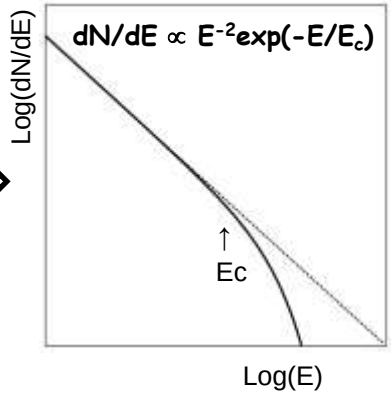
Shock Wave Acceleration in SNR



Acceleration in PWN

⇒

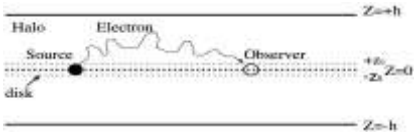
Production Spectrum
(Power Law Distribution + Cutoff)



⇒

Propagation in the Galaxy

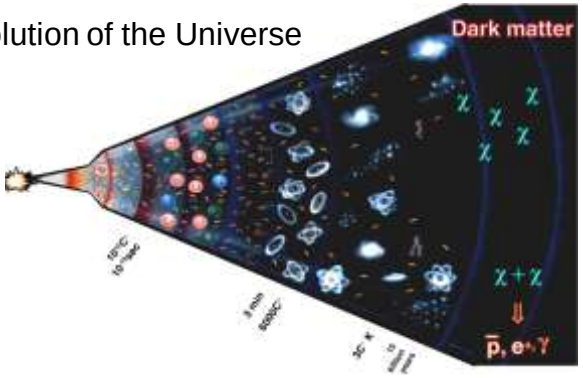
- **Diffusion Process**
- **Energy Loss**
  $dE/dt = -bE^2$
  (Syncrotron + Inverse Compton)
- **π+/- or K+/- → μ+/- → e+/-**



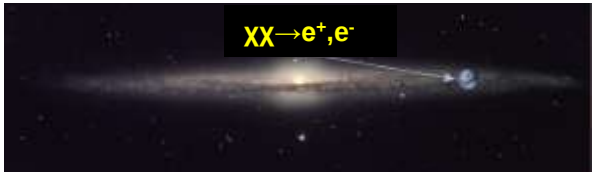
⇑

Dark Matter Origin

Evolution of the Universe



Annihilation of Dark Matter (WIMP)



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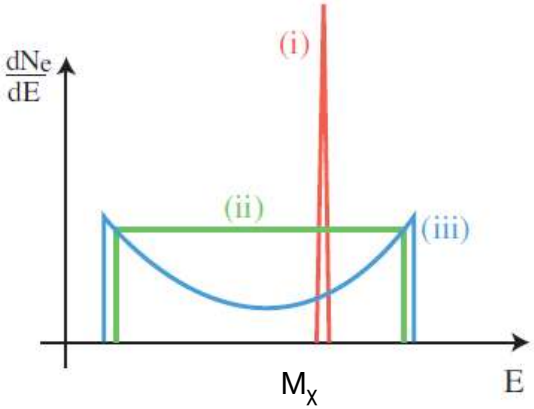


Production Spectrum

(i) Monoenergetic: Direct Production of e+e- pair
(ii) Uniform : Production via Intermediate Particles
(iii) Double Peak : Production by Dipole Distribution via Intermediate Particles

Astrophysical Source Candidates

- **Supernova Remnants**
  - Shock acceleration gives a $d\phi/dt \propto E^{-2}exp(-E/E_c)$ spectrum injected into the ISM, where $E_c \sim 10$ *TeV.*
- **Pulsar Wind Nebulae (PWNe)**
  - Electrons released from the stellar surface in the polar caps pair produce in the magnetic fields producing e^+/e^- pairs
  - The pairs are accelerated at the PWN termination shock, again giving a $d\phi/dt \propto E^{-2}exp(E/E_c)$ injection
- **Microquasars**
  - Relativistic jets sending out beams of mono-energetic electrons in to the ISM
- **Interactions of CR nuclei with interstellar gas**
  - producing π+/- or K+/- $\rightarrow$ μ+/- $\rightarrow$ e+/-

$e^{\pm}$ Propagation

© Ioka

$$\frac{\partial}{\partial t} f\left(t,\varepsilon_e,\vec{x}\right) = \boxed{D\left(\varepsilon_e\right)\nabla^2 f} + \boxed{\frac{\partial}{\partial \varepsilon_e}\left[b\varepsilon_e^2 f\right]} + \boxed{q\left(t,\varepsilon_e,\vec{x}\right)}$$

Diffusion

Energy loss by IC & synchro.

Injection

$$b \sim 10^{-16}\,\mathrm{GeV}^{-1}\,\mathrm{s}^{-1}$$

$$D\left(\varepsilon_e\right) \sim 5.8\times 10^{28}\,\mathrm{cm}^2\mathrm{s}^{-1}\left(1+\frac{\varepsilon_e}{4\mathrm{GeV}}\right)^{1/3}$$ ← B/C ratio

For a single burst with $q \propto \varepsilon_e^{-\alpha}$ Power law spectrum

$$f = \frac{q_0 \varepsilon_e^{-\alpha}}{\pi^{3/2} d_{diff}^3}\left(1-bt\varepsilon_e\right)^{\alpha-2} e^{-\left(d/d_{diff}\right)^2}$$

$$d_{diff}\left(t,\varepsilon_e\right) \sim 2\left[D\left(\varepsilon_e\right)t\right]^{1/2}$$

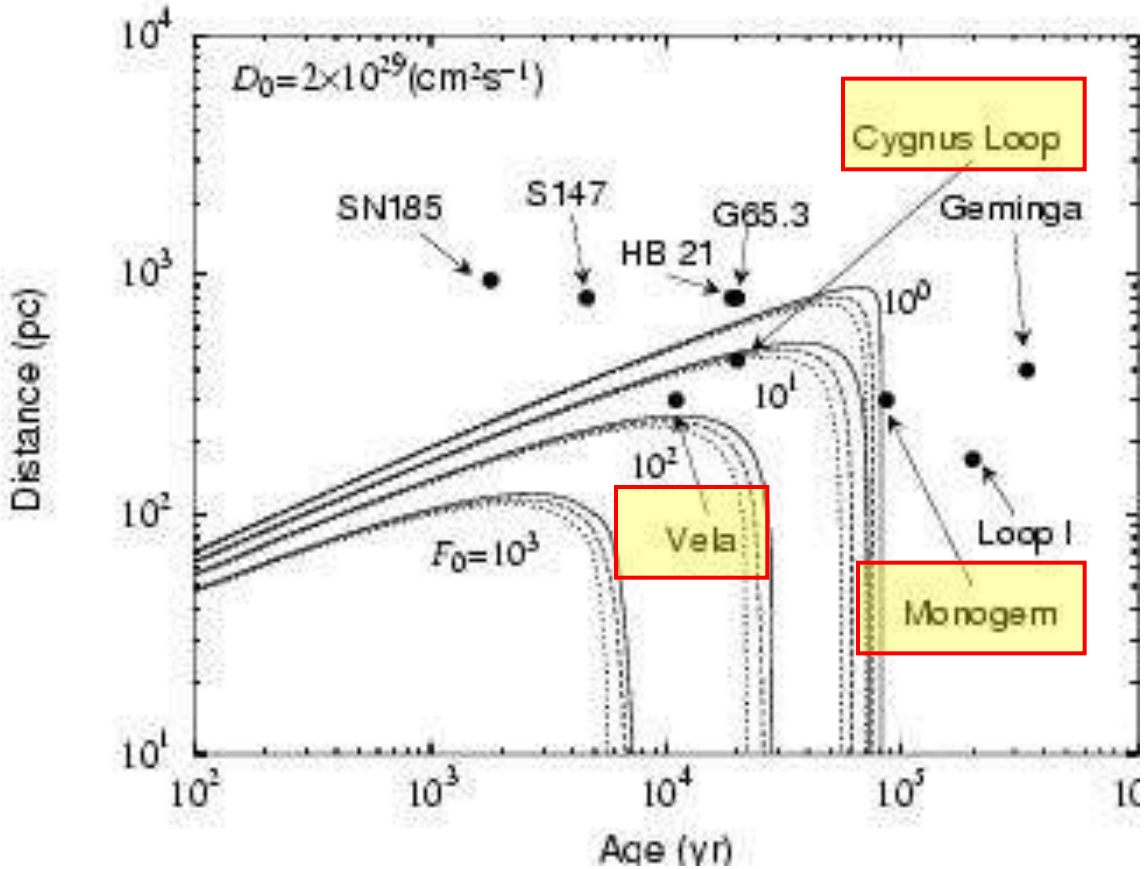
Atoyan 95, Shen 70
Kobayashi 03

$$\boxed{\varepsilon_{\mathrm{cut}} \sim \frac{1}{bt}}$$

A Naïve Result from Propagation

$$T\ (age) = 2.5X10^5X(1\ TeV/E)\ yr$$

$$R\ (distance) = 600X(1\ TeV/E)^{1/2}\ pc$$



1 TeV Electron Source:

- **Age < a few10^5 years very young comparing to ~10^7 year at low energies**
- **Distance < 1 kpc nearby source**

Source candidates limited:

Vela

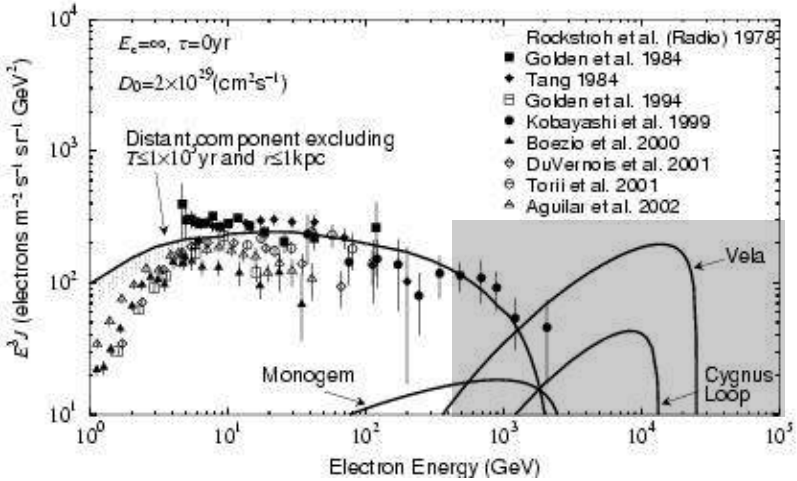
Cygnus Loop

Monogem

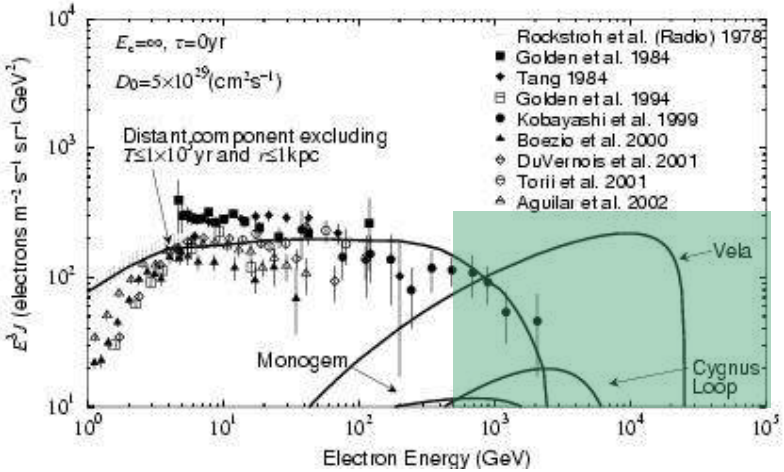
Unobserved Sources?

Model Dependence of Energy Spectrum and Nearby Source Effect

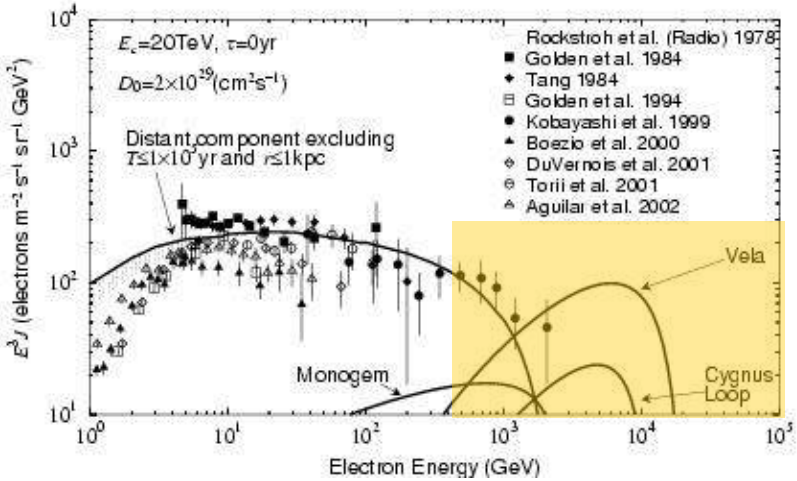
Ec=∞、ΔT=0 yr, Do=2x10^{29} cm^2/s



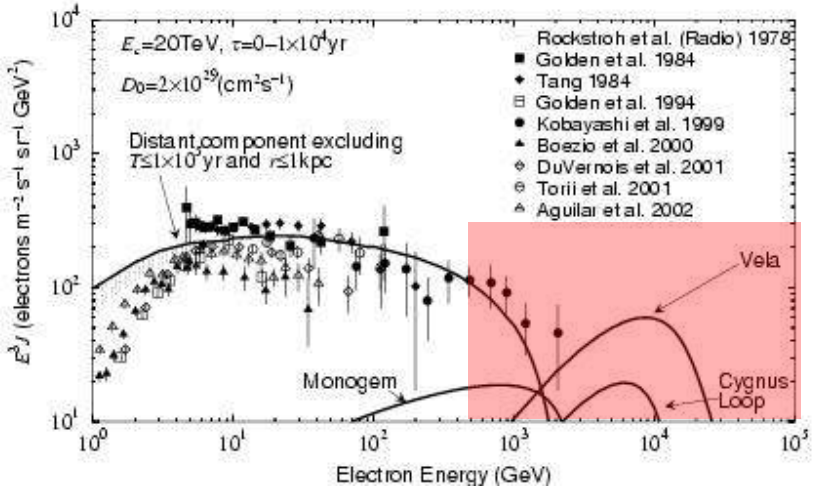
Do=5 x 10^{29} cm^2/s



Ec= 20 TeV



Ec=20 TeV、ΔT=1-10^4 yr



Kobayashi et al. 2003

New Calculation for SNR Origin

S.Profumo arXiv:0812.4457v2 28 Apr. 2009

fluxes shown in fig. 4 and 5 assuming the ST model.

Name	Distance [kpc]	Age [yr]	$\dot{E}$ [ergs/s]	E_{out} [ST]	E_{out} [CCY]	E_{out} [HR]	E_{out} [ZC]	$f_{e^\pm}$	g
Geminga [J0633+1746]	0.16	3.42×10^5	3.2×10^{34}	0.360	0.344	0.013	0.053	0.005	0.70
Monogem [B0656+14]	0.29	1.11×10^5	3.8×10^{34}	0.044	0.133	0.006	0.020	0.020	0.70
Vela [B0833-45]	0.29	1.13×10^4	6.9×10^{36}	0.084	0.456	0.006	0.372	0.0015	0.14
B0355+54	1.10	5.64×10^5	4.5×10^{34}	1.366	0.677	0.022	0.121	0.2	0.61
Loop I [SNR]	0.17	2×10^5		*0.3*				0.006	
Cygnus Loop [SNR]	0.44	2×10^4		*0.03*				0.01	

Source Candidates

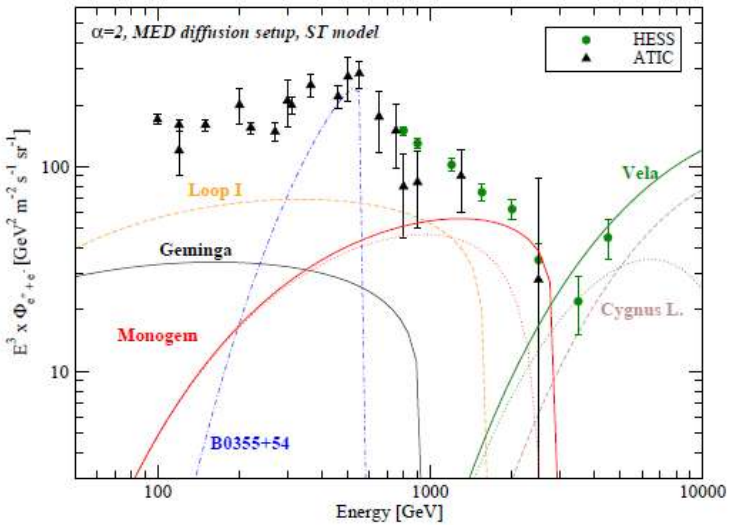


FIG. 4: The spectrum of selected nearby pulsars and SNR's (for the parameters employed to calculate the fluxes see tab. II). We assume an $e^\pm$ injection spectral index $\alpha = 2$, and a median diffusion setup (MED). The dotted lines correspond to injection spectra featuring an exponential cutoff at $E_{e^\pm} = 10$ TeV.

Electron + Positron

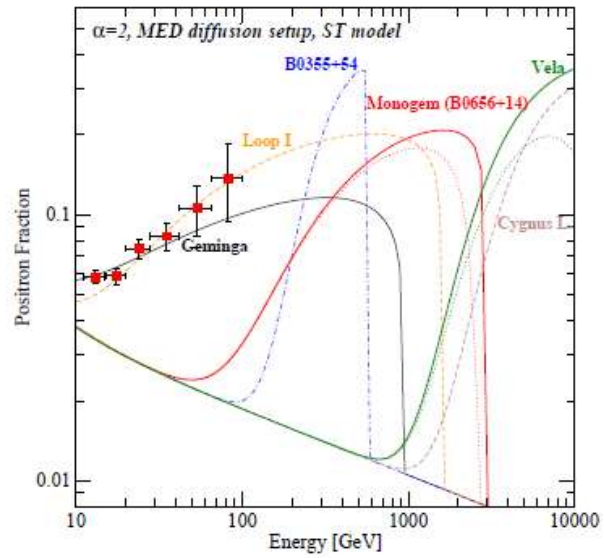
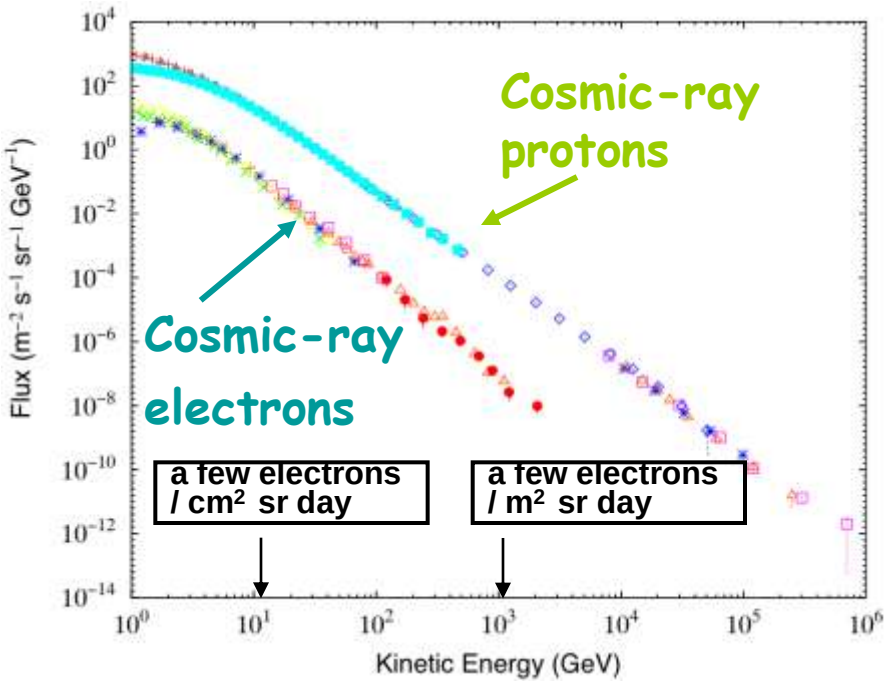


FIG. 5: The positron fraction for the same sources as in fig. 4 and tab. II.

Positron Ratio

Electron and Positron Observation

Cosmic-ray Energy Spectra



- Flux of electrons and positrons:
  ~1% of protons @10GeV
  ~0.1 % @ 1000GeV
  ~0.1%@ 10 GeV
- Spectrum of electrons:
  steeper than protons
  power-law index:
  e:~-3.0, p:-2.7

=> As higher energies,
Lower electron flux
Lager proton backgrounds

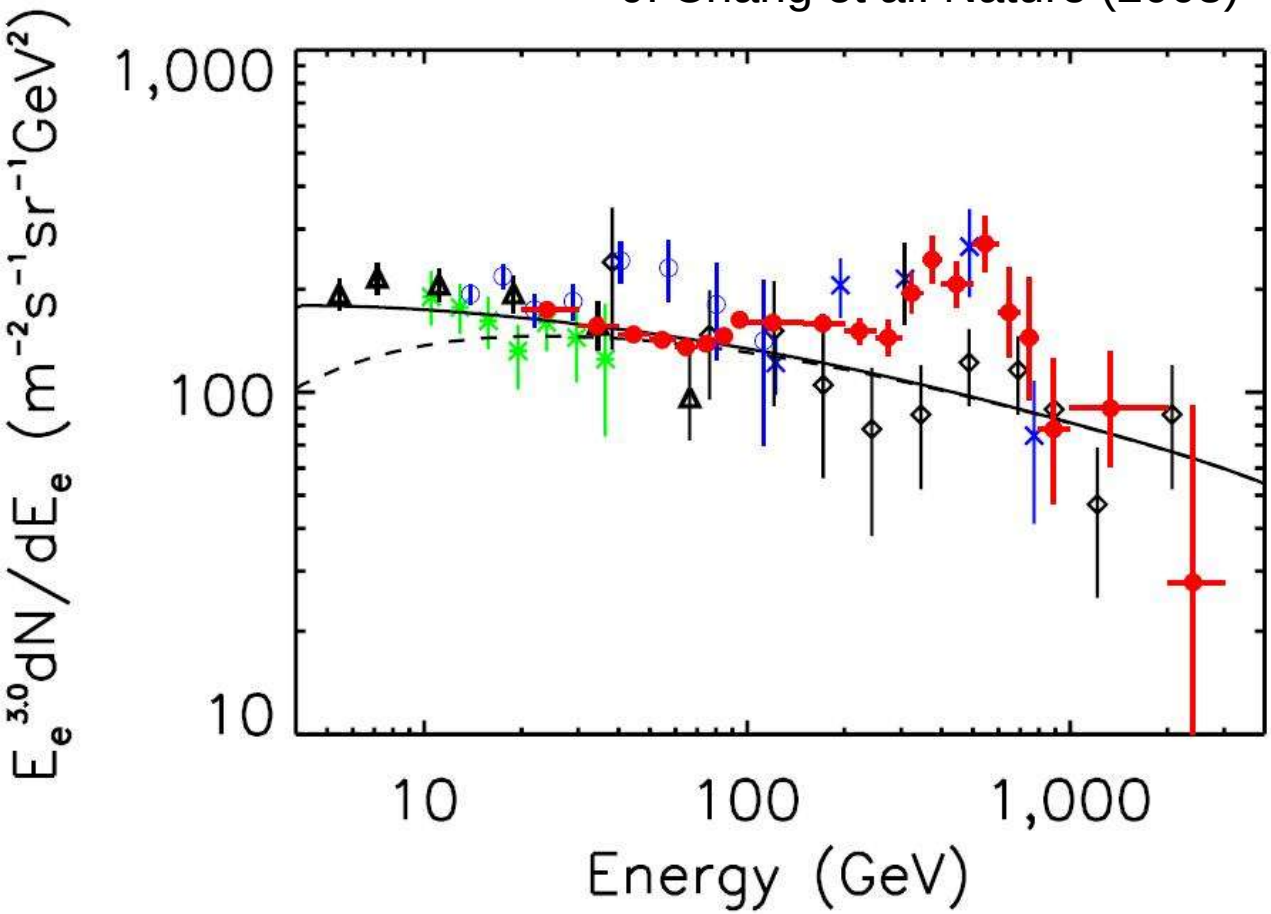
Large amount of exposures
with a detector of high proton rejection power + charge separation

⇒ Long duration balloon flight in 10~1000 GeV
Observation in space for years over 1000 GeV

Observed Spectra by ATIC

If we assume the power law spectrum (with γ=-3.3) calculated by GALPROP, an excess of electrons might be seen in 300-800 GeV. The excess is considered as a contribution from exotic sources: Nearby pulsars or WIMPs.

J. Chang et al. Nature (2008)



AMS (stars)

HEAT (triangles)

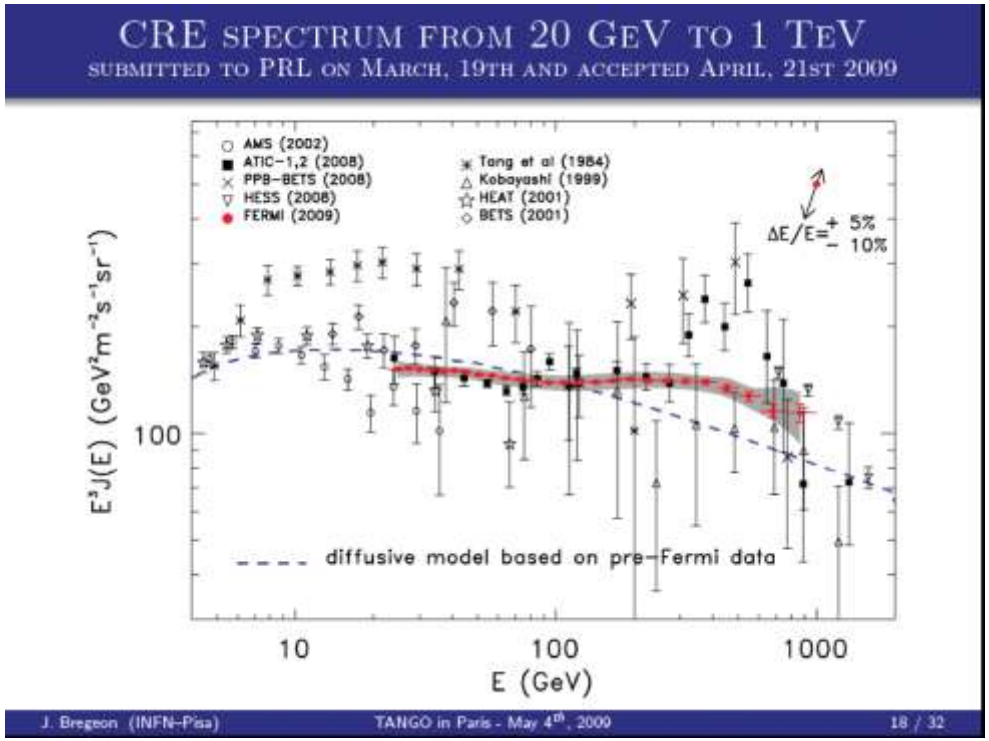
BETS (circles)

PPB-BETS (crosses)

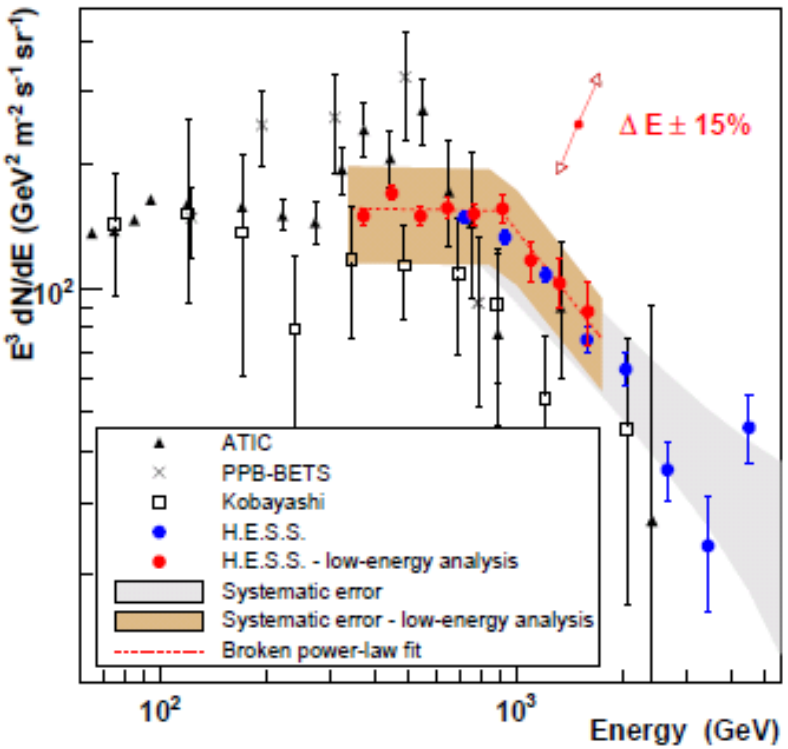
Emulsions (diamonds)

ATIC (red circles)

Then, excellent observations in statistics are carried out by FERMI-LAT and HESS, and a new era of electron observation is opened probably by indicating a flattening of energy spectrum and a sharp cut-off over 1 TeV, respectively.



F.Aharanian et al. arXiv:0905:0105

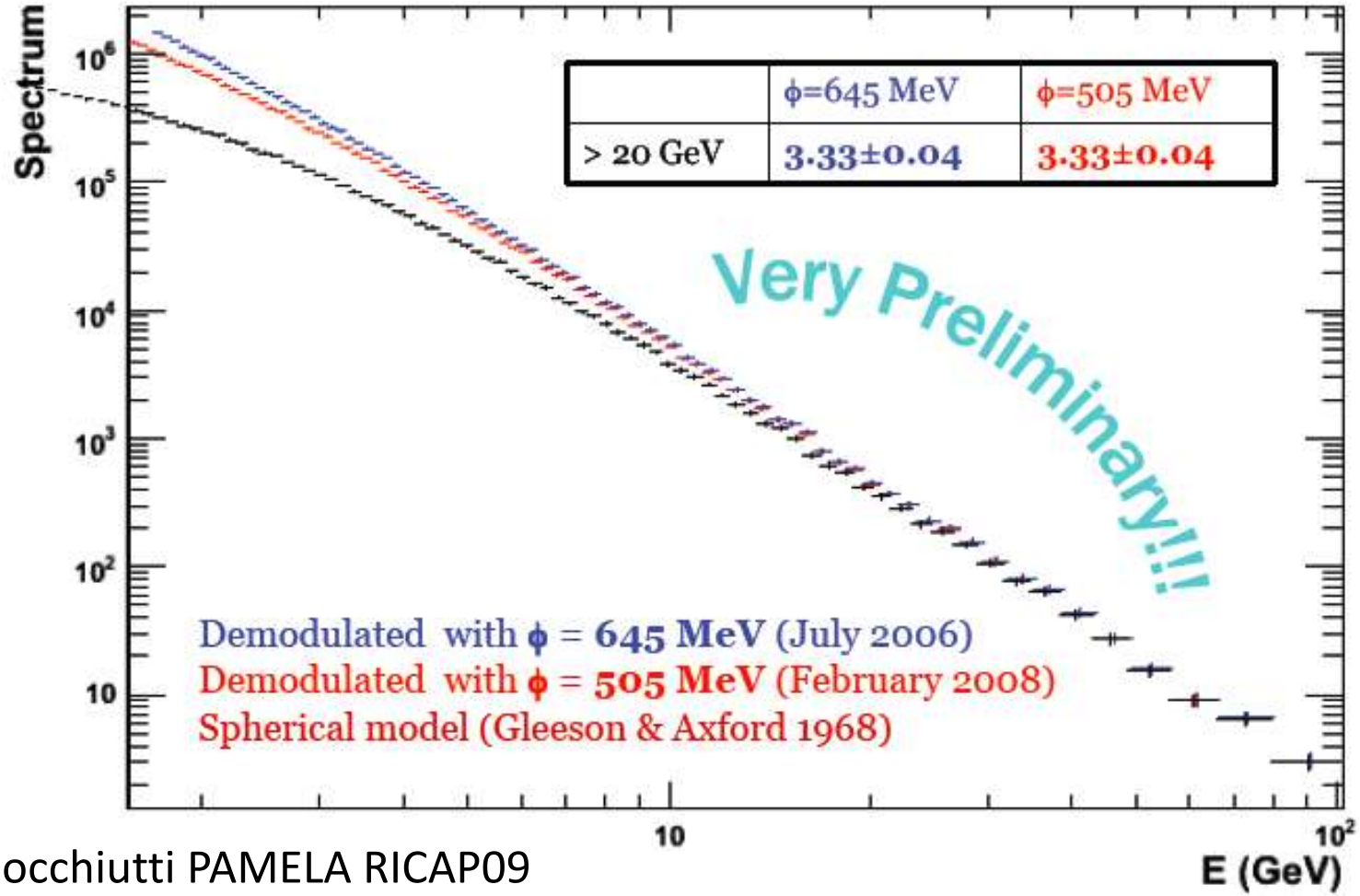


I really appreciate their efforts to derive the electron spectrum in unexploded region.

PAMELA electron (e^-) flux

Demodulated spectrum

Power-law fit -- spectral index



	ϕ=645 MeV	ϕ=505 MeV
> 20 GeV	3.33±0.04	3.33±0.04

Mocchiutti PAMELA RICAP09

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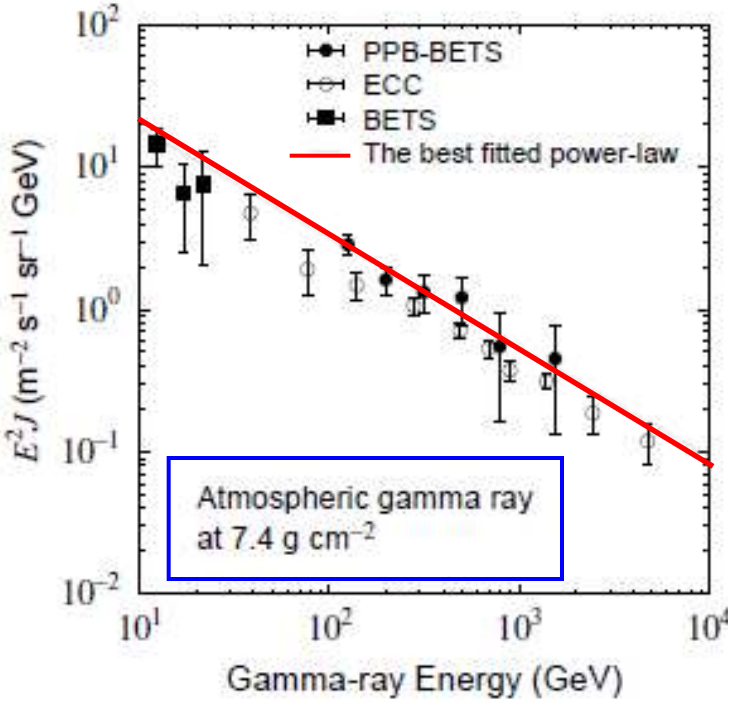
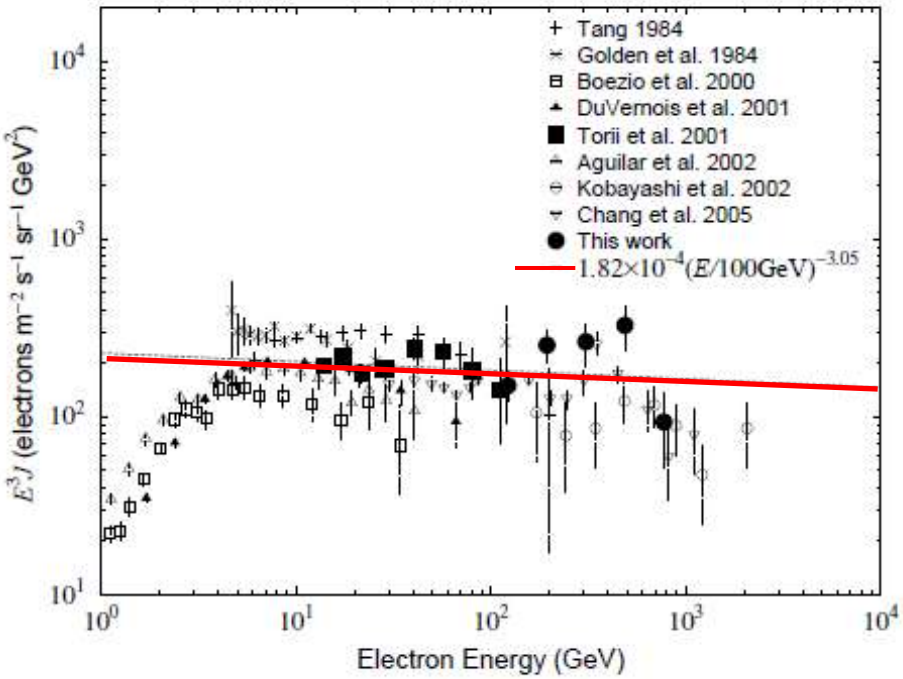
BETS+ PPB-BETS results can be presented by a single power law spectrum with a flatter shape of γ=-3.05 within statistical errors.

$$J_e = (1.82 \pm 0.13) \times 10^{-4} \left(\frac{E}{100\mathrm{GeV}}\right)^{-3.05 \pm 0.05} (\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{-1}) \qquad (5)$$

in the energy range of 10 GeV to 800 GeV. The reduced chi-square value is 1.605 for 11 degrees of freedom. A power-law spectrum is acceptable at the 95 % confidence level of statistical errors.

S.Torii et al. :arXiv0809:0760 (2008)

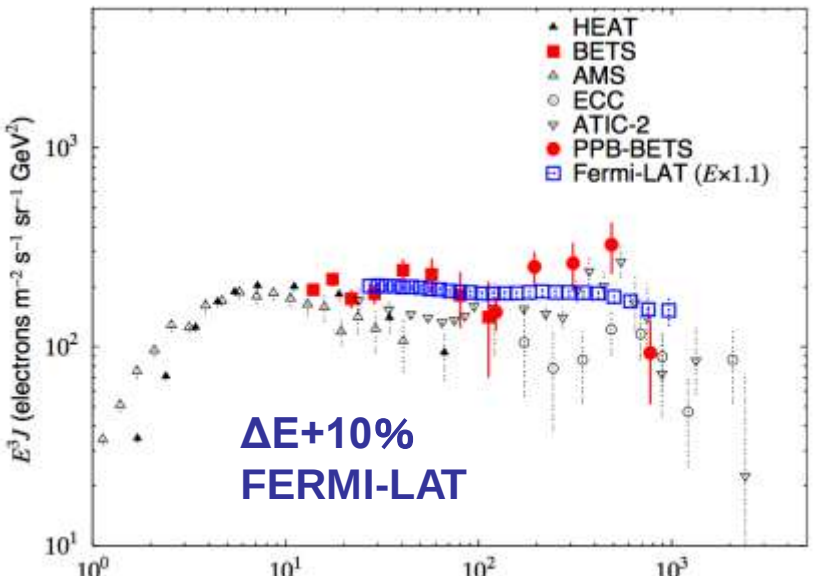




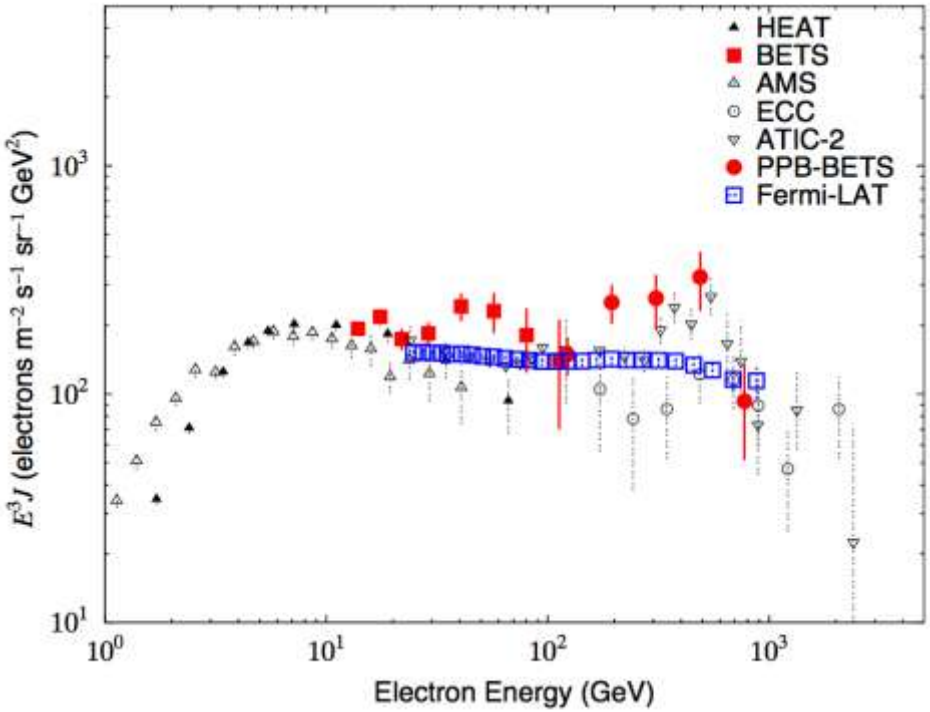
A "Mild" Solution:

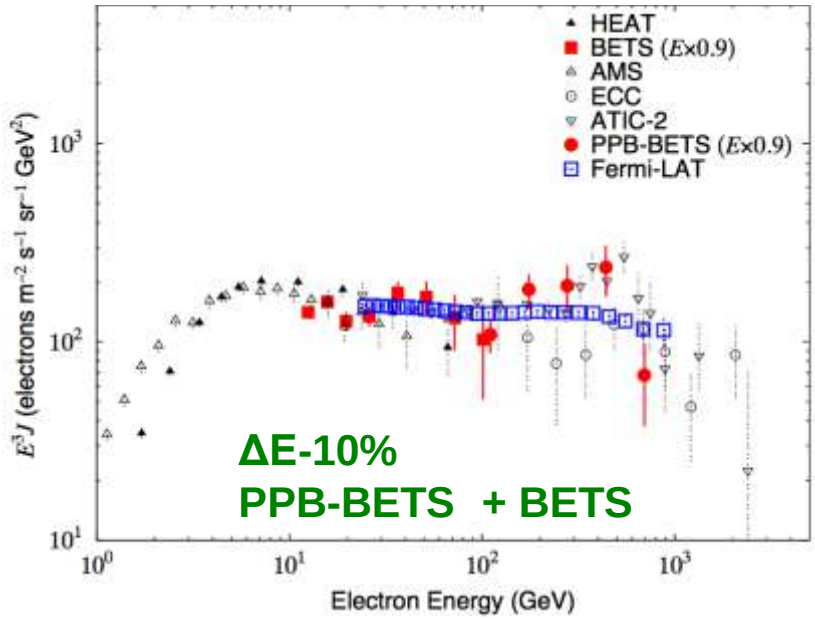
- The 10 % shift of energy can bring a consistent flux between FERMI-LAT and PPB-BETS due to poor statistics of PPB-BETS.

- Moreover, when the spectrum is flatter than expected, as a power law of -3.05 corresponding to the source spectrum of -2.2, the excess is not so prominent as to be excluded.



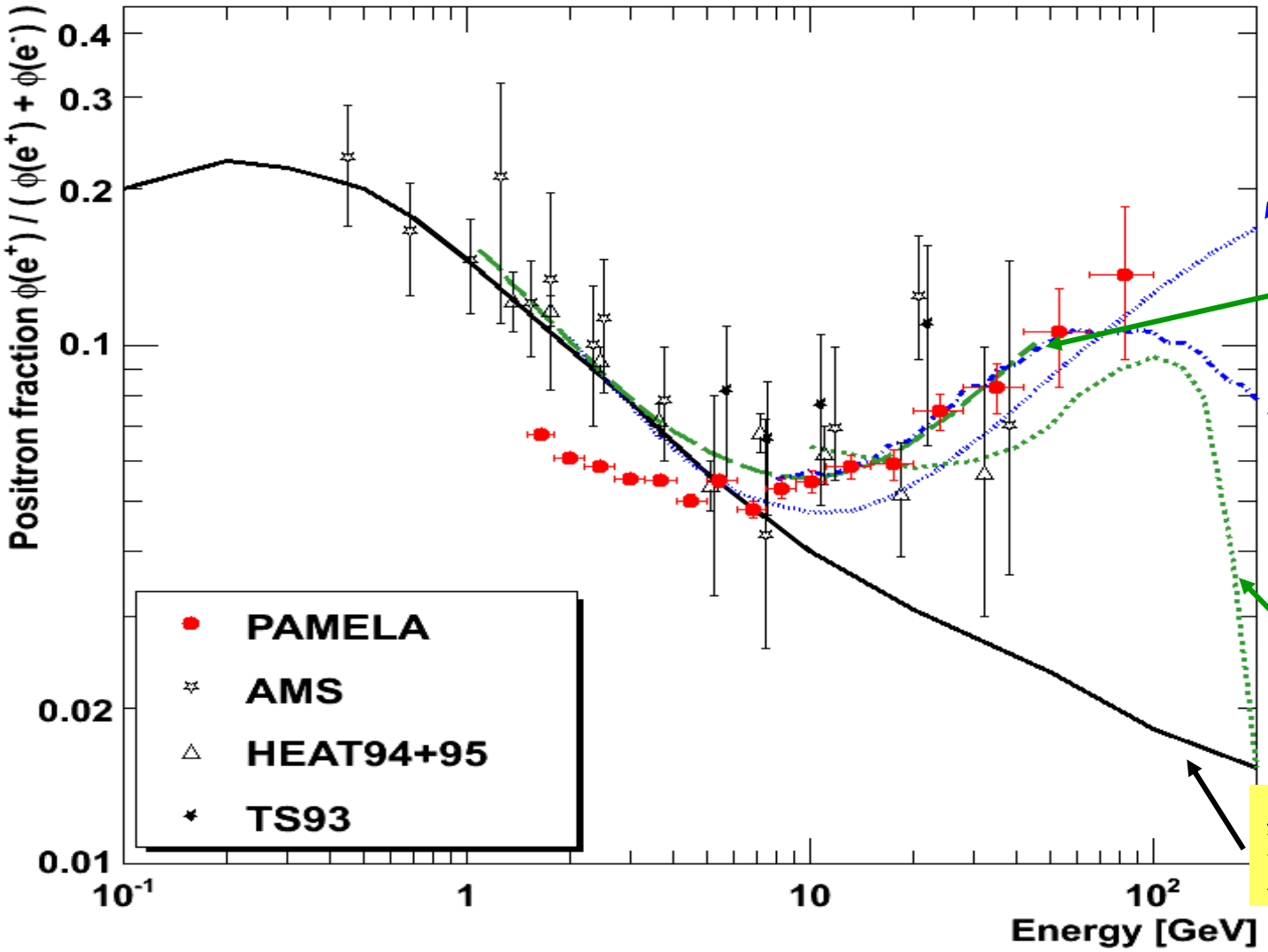
Or, +5% FERMI-LAT & -5% PPB-BETS





PAMELA Positron Fraction

Nature 458, 607 (2009)



Pulsar Component
Yüksel et al. 2008
astro-ph 0810.2784

KKDM (mass 300 GeV)
Hooper & Profumo 2007
Phys. Reports 453, 29

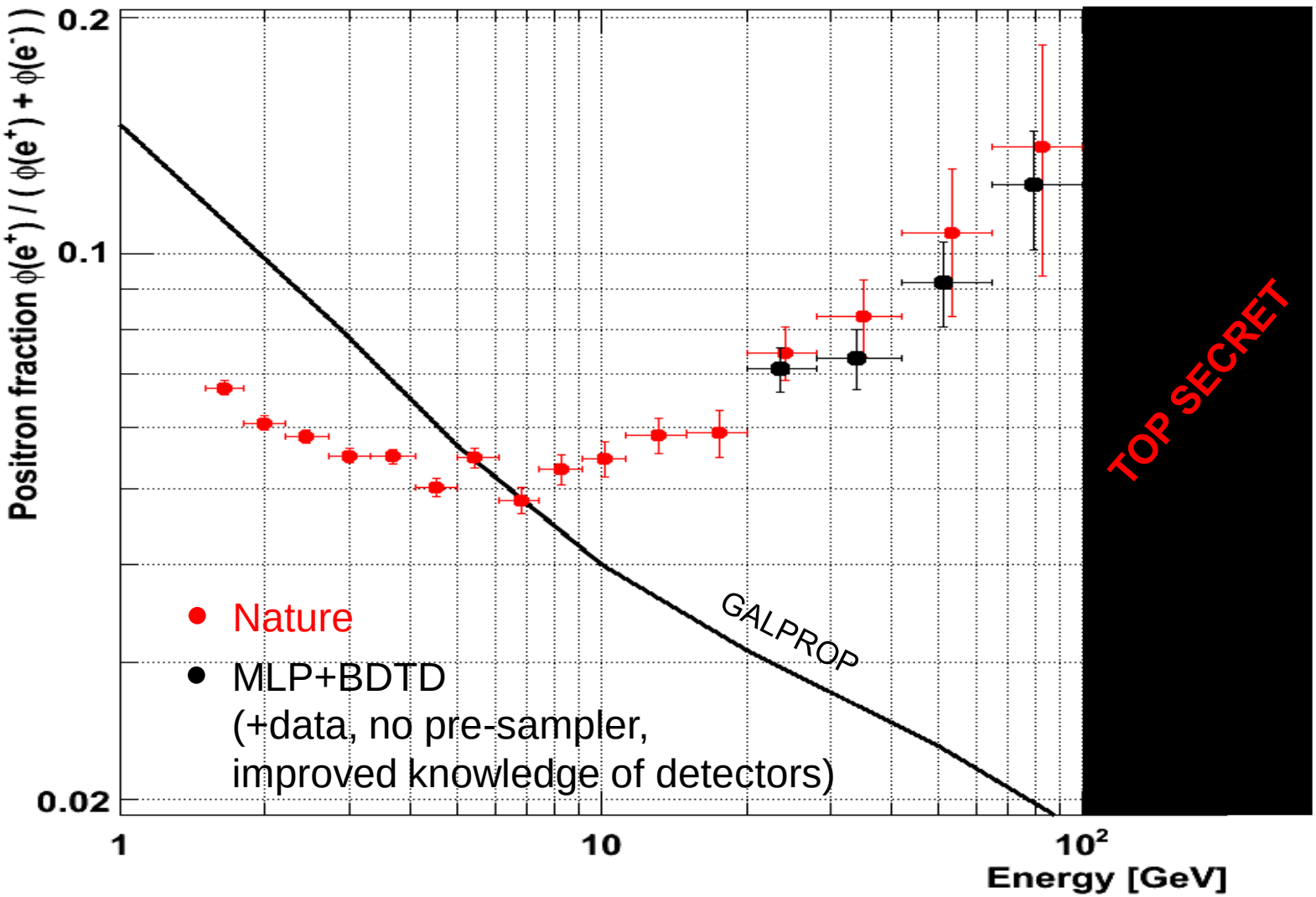
Supernovae Component
Shaviv et al. 2009
astro-ph 0902.0376

Wino (mass 200 GeV)
Grajek et al. 2008
astro-ph 0812.4555

Secondary production
Moskalenko & Strong 1998
ApJ 493, 694

Positron fraction, MLP+BDTD

statistics improved by ~2.5 ÷ 3



Efforts by the new experiments for deriving the positron and electron spectra are really appreciated to open a door to new era in astroparticle physics.

We are waiting for much more study by ATIC, PAMELA, Fermi-LAT, HESS and a forthcoming experiment in space, AMS-02.

Moreover,

We need an accurate and very-high-statistics observation for searching Dark Matter and/or Nearby Pulsars in the sub-TeV to the trans-TeV region with a detector which has following performance:

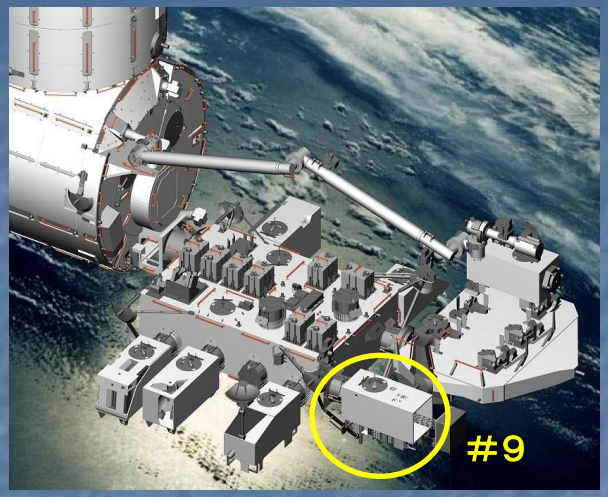
- The systematic errors including GF is less than a few %.
- The absolute energy resolution is as small as a few % (~ATIC).
- The exposure factor is as large as more than 100 m^2srday (~ FERMI-LAT).
- The proton rejection power is comparable to 10^5 , and does not depend largely on energies .

It should be a dedicated detector for electron observation in space.

⇨ **Calorimetric Electron Telescope (CALET) is proposed.**

CALET System Design

The CALET mission instrument can satisfy the requirements as a standard payload in size, weight, power, telemetry etc. for launching by HTV and observation at JEM/EF.



Gamma-ray Burst Monitor

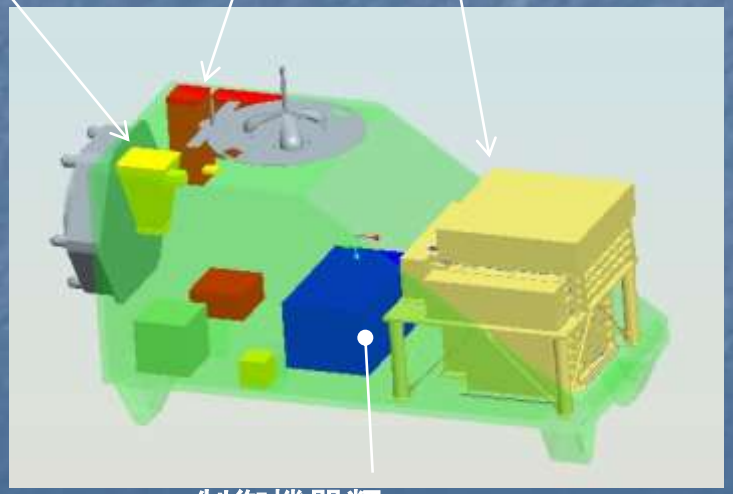
ガンマ線バーストモニタ（赤）
視野範囲半角45度

Star Tracker

スタートラッカ（黄）
視野範囲半角30度

Calorimeter

カロリーメータ（黄土）
視野範囲半角45度



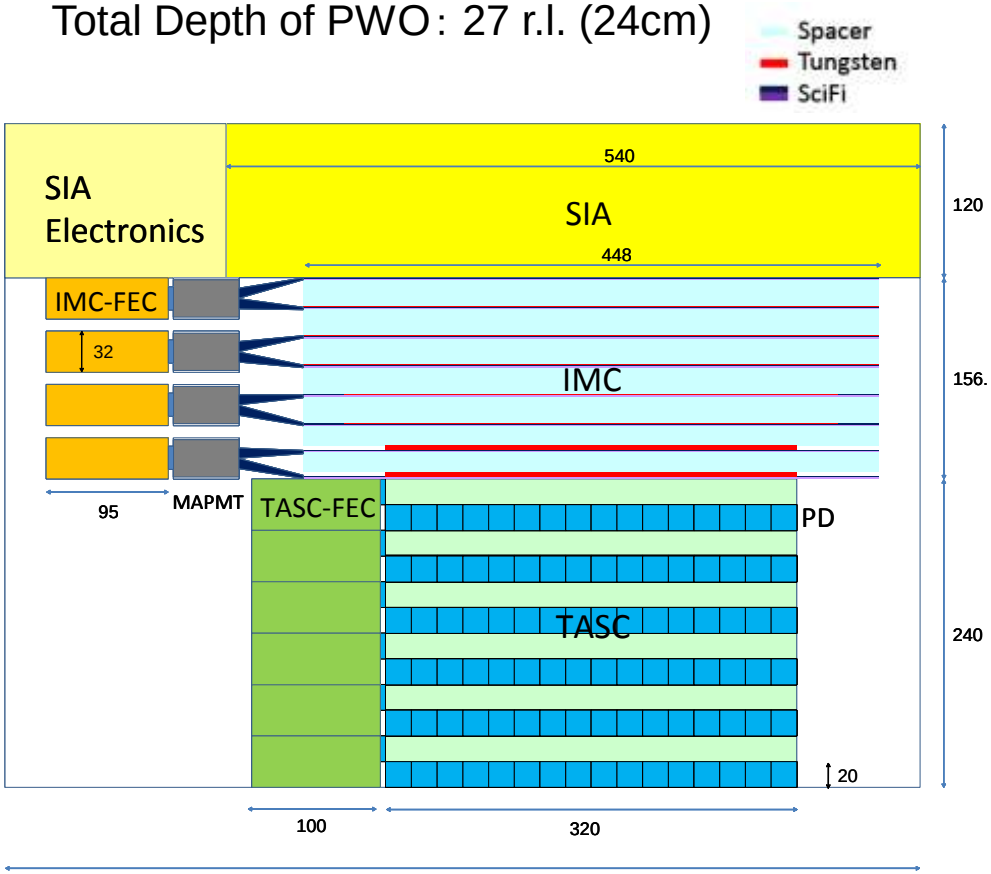
制御機器類
（視野は不要）

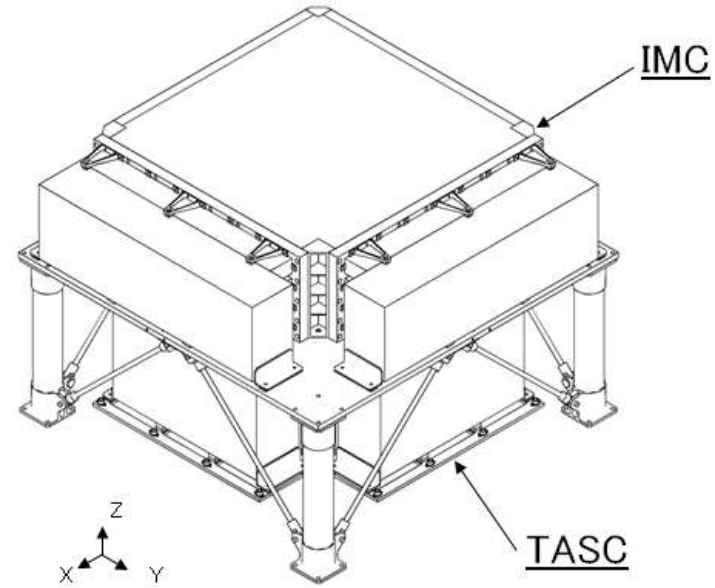
Mission Data Controller

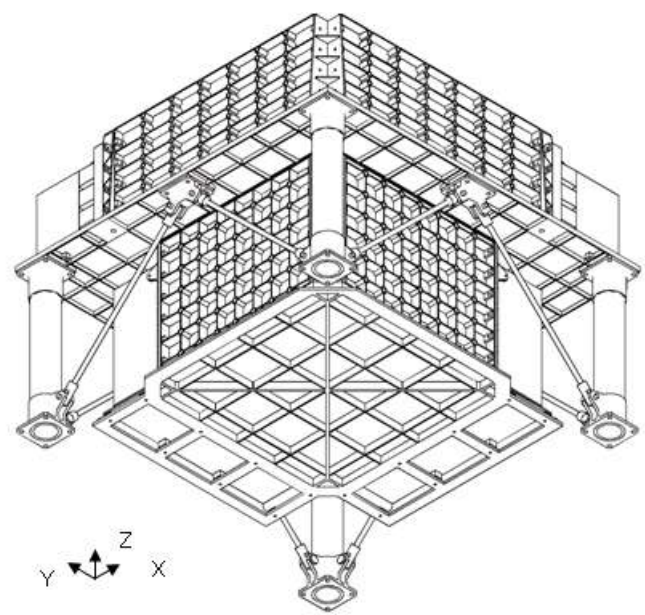
Field of View
(45 degrees from the zenith)

CALET Calorimeter

- Imaging Calorimeter
  Total Thickness of Tungsten (W) : 3 r.l.
  Layer Number of Scifi Belts :
  8 Layers ×2(X,Y)
- Total Absorption Calorimeter
  PWO 20mmx20mmx320mm
  Total Depth of PWO : 27 r.l. (24cm)







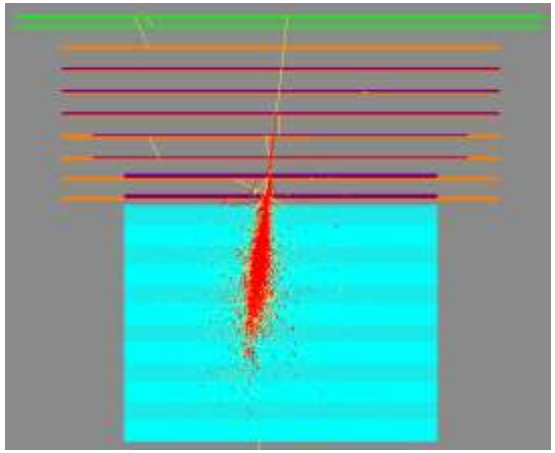
CALET Performance for Electron Observation

Electron 100 GeV

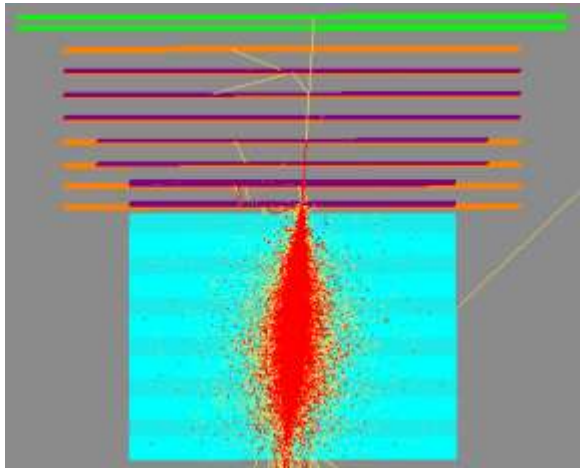
SIA

IMC

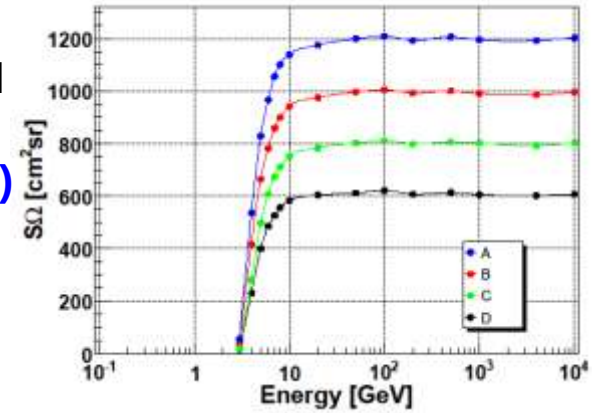
TASC



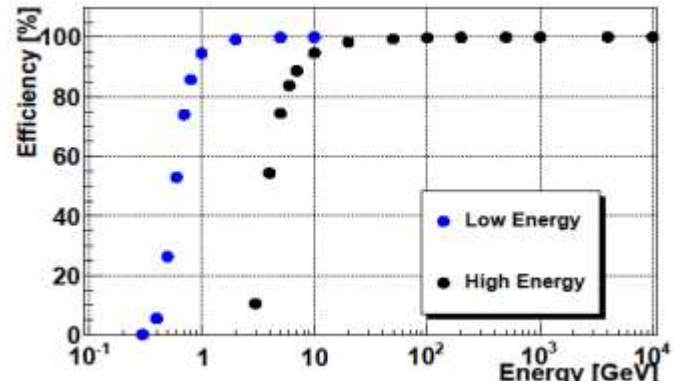
Electron 1 TeV



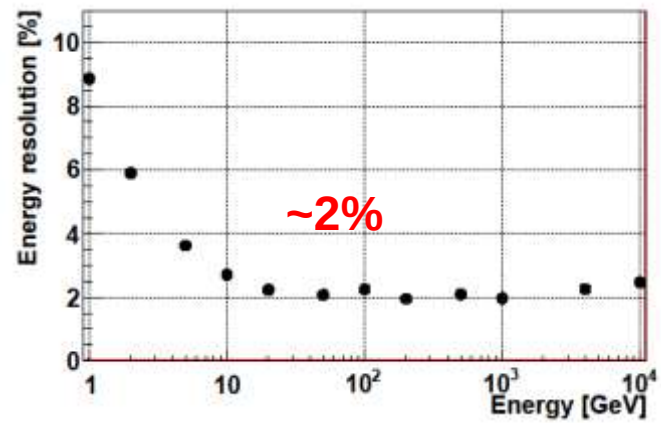
Geometrical Factor (Blue Marks)



Detection Efficiency

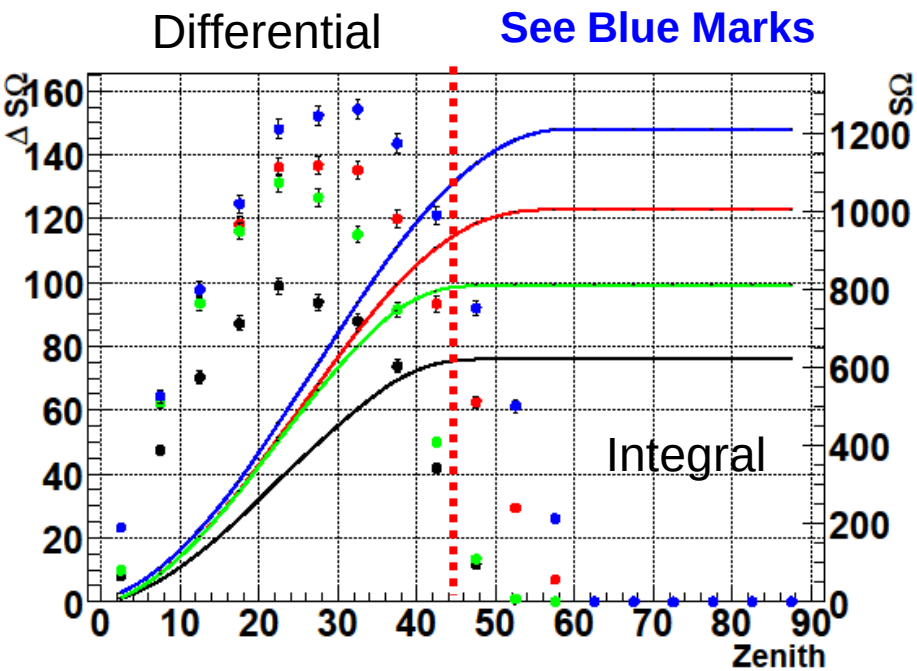


Energy Resolution

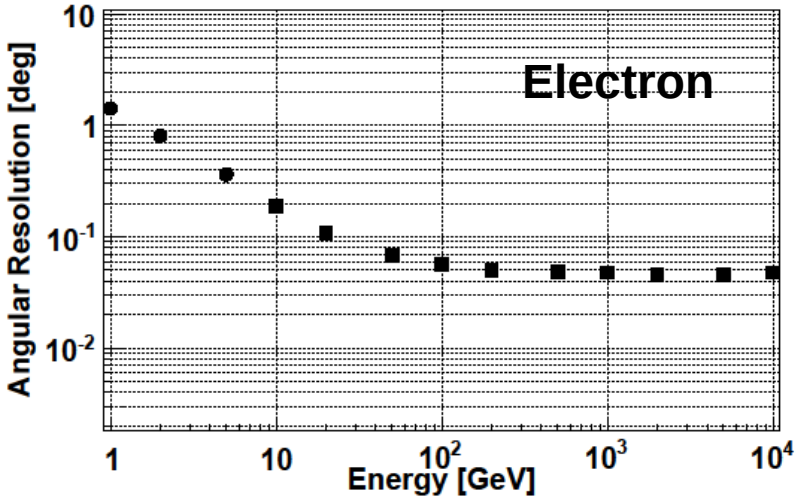


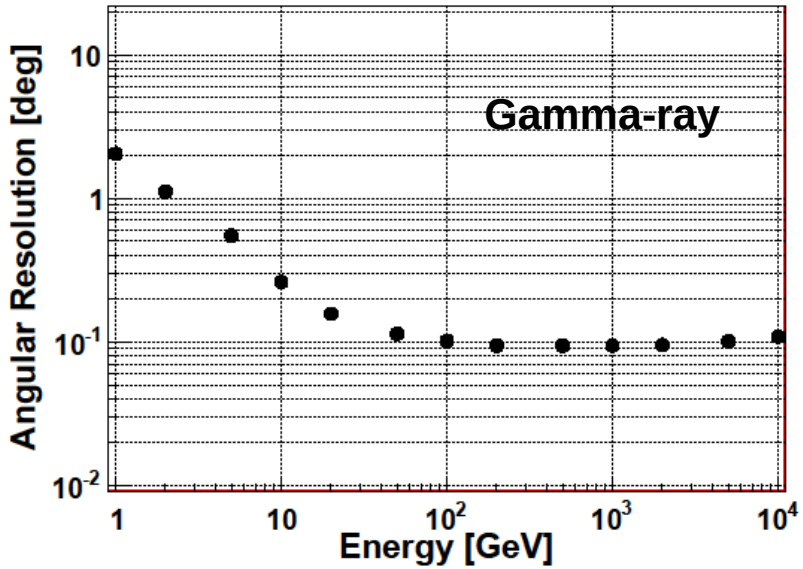
CALET Performance for Electron Observation (2)

SΩ (for electrons) vs Incident Angle



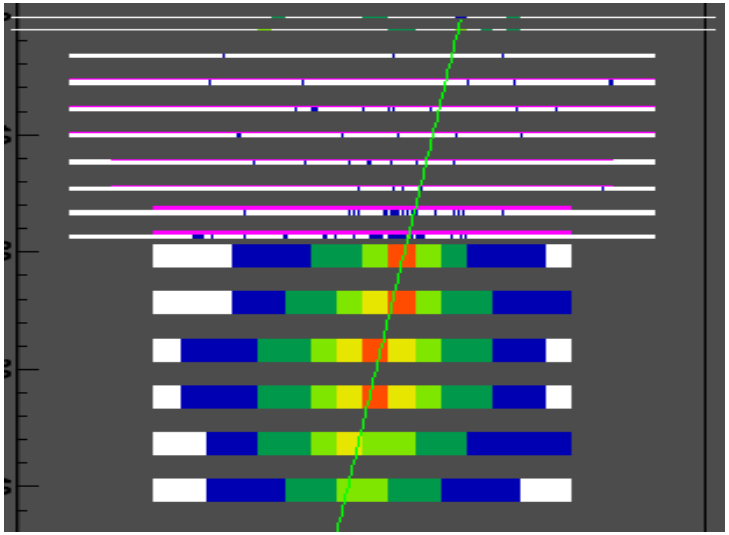
Angular Resolution



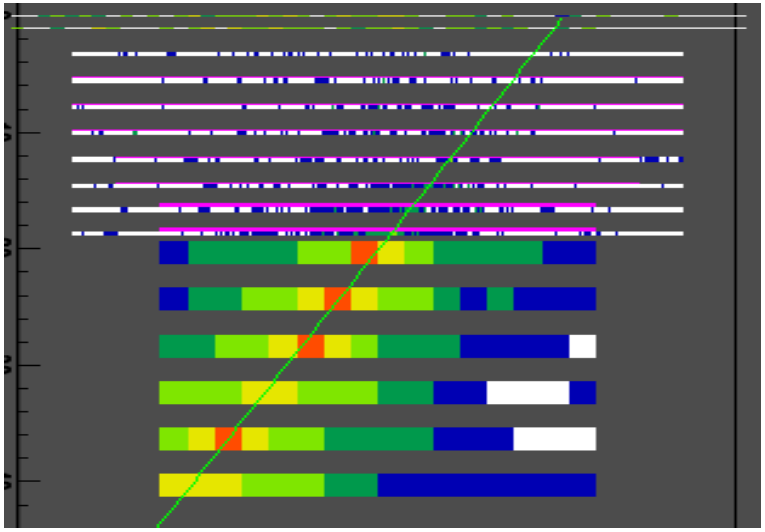


Proton Rejection Power for 1 TeV Electron

Electron 1 TeV



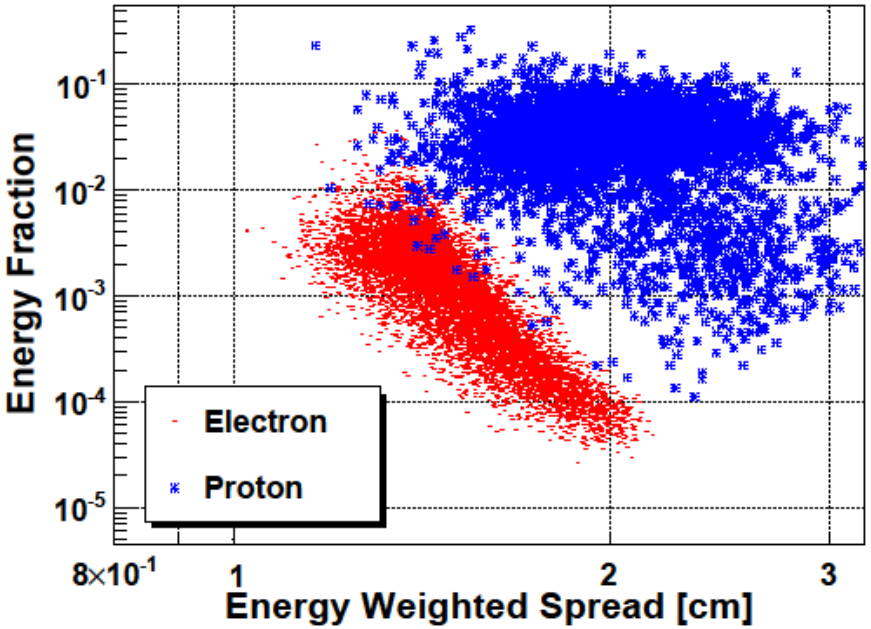
Proton 2.9 TeV



Generated Events

Protons: 1.6×10^{6} events with energy spectrum $E^{-2.7}$ in 1-1000TeV

Electrons: 1 TeV



4 proton events are contaminated in electron region (95 % electron retained)

⇒ Proton rejection power: ~2×10^{5} (90% C.L.)

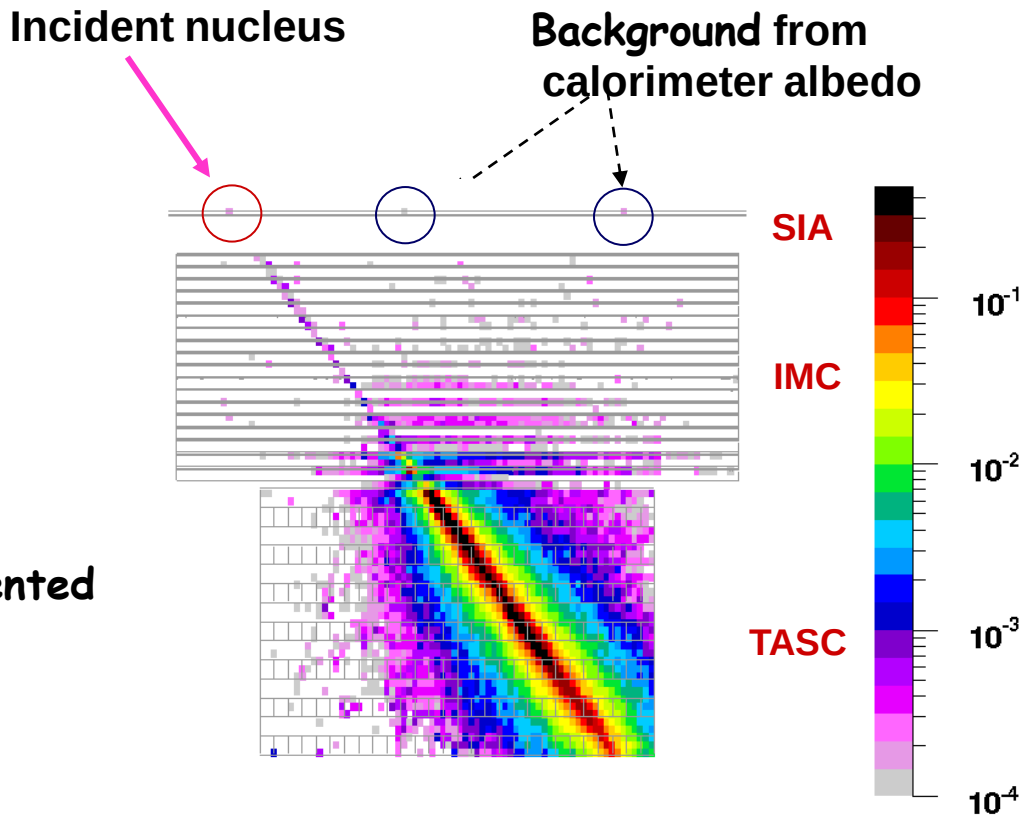
Charge Identification of cosmic nuclei in CALET

Silicon Array (SIA)

2 independent charge-measurements per incident nucleus

- Back-extrapolation of track reconstructed in the finely segmented Imaging Calorimeter (IMC)

- Impact point reconstruction and identification of the pixel hit by the incident cosmic nucleus



Example of simulation with Fluka:

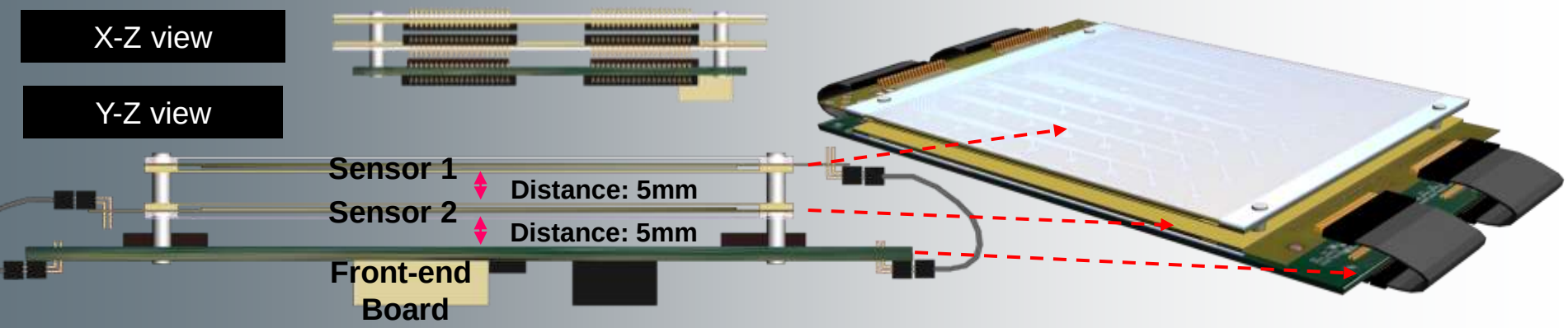
1 TeV/n Carbon interacting in the IMC

Building block: 2 Silicon Sensors + Front-end Electronics board

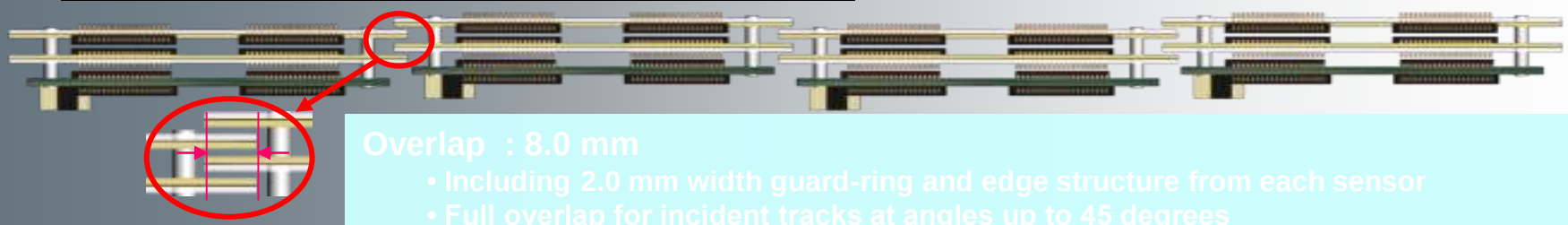
Basic module: one pair of aligned sensors + front-end (VAB) board

X-Z view

Y-Z view

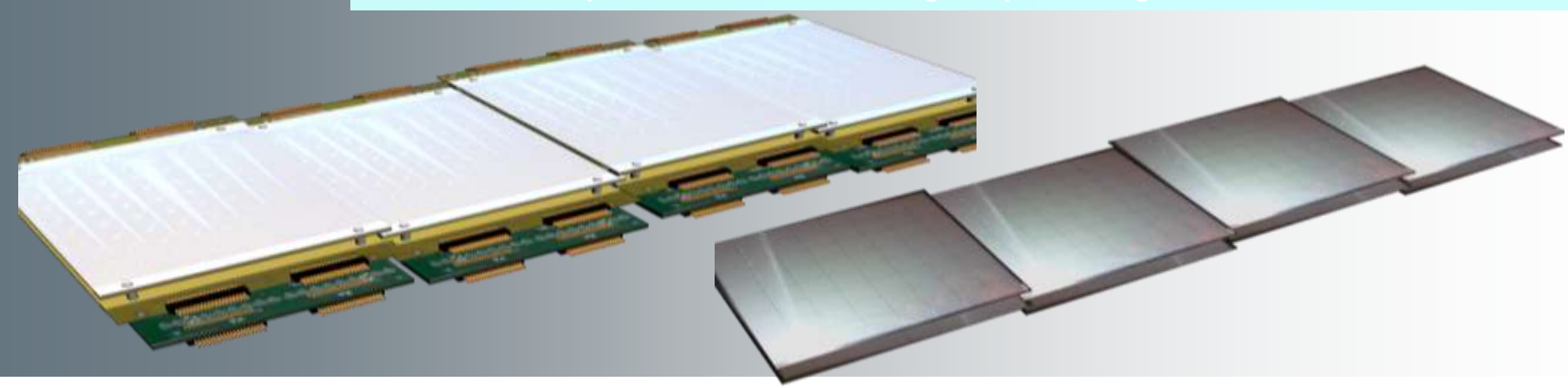


Ladder : with 12 sensors (Active length 104.44 cm)



Overlap : 8.0 mm

- Including 2.0 mm width guard-ring and edge structure from each sensor
- Full overlap for incident tracks at angles up to 45 degrees



Large dynamic range of electronics: charge measurement up to Z = 35

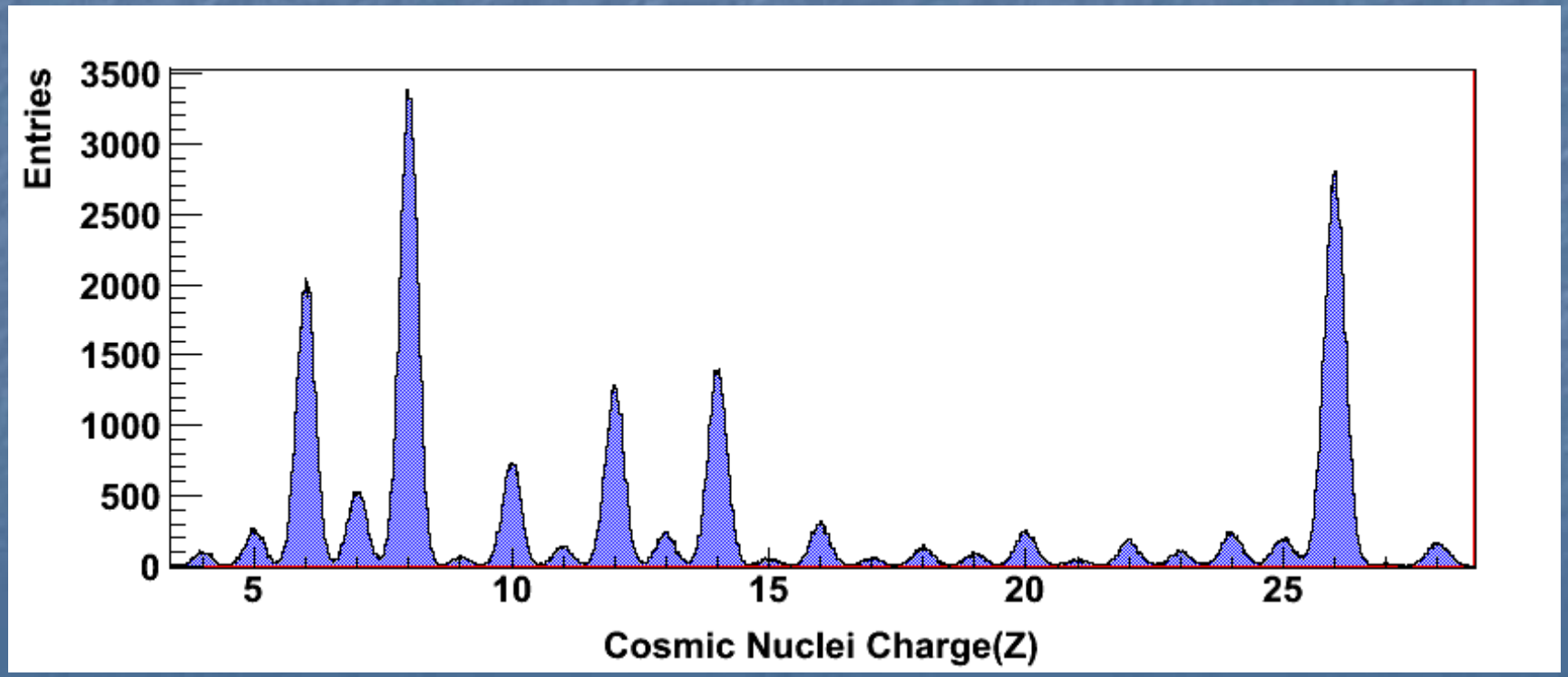
Expected charge resolution of SIA (2 indep. dE/dx measurements):

~ 0.1 at p, He

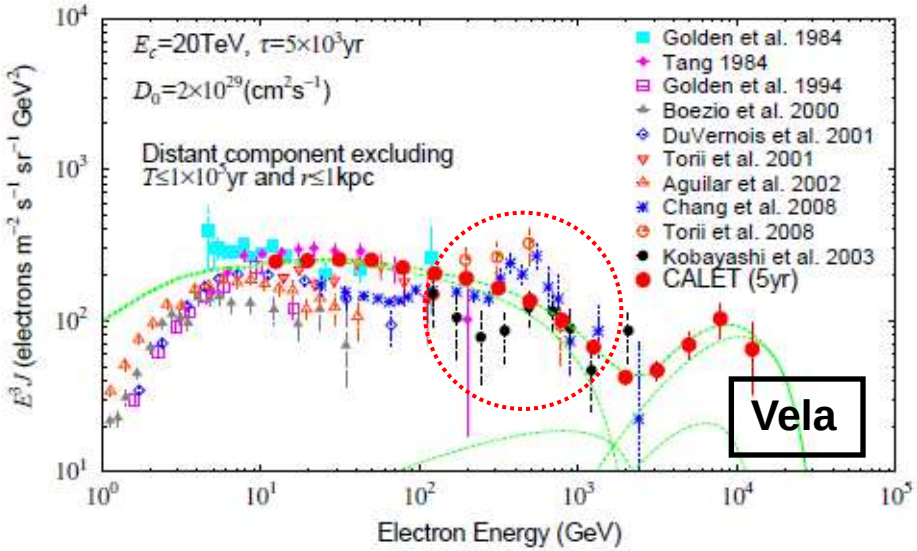
~ 0.16 at B-C-N-O

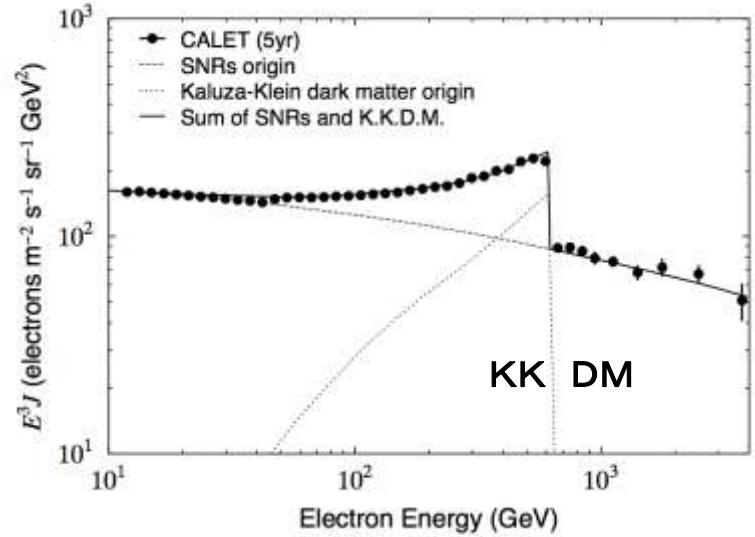
~ 0.21 at sub-Fe, Fe

individual elements can be resolved



Electron Observation (5 years)
-Nearby Sources and KK Dark Matter-





Energy (GeV)	Primary e⁻	e⁻ from Vela
500-600	1168	154
600-800	1235	239
800-1000	501	168
1000-1500	546	270
1500-2000	146	134
2000-3000	99	134
3000-4000	23	51
4000-5000	7	23
5000-7000	5	22
7000-9000	1	7
>9000	0	3

Conditions applied:

Electron efficiency = 70%
Proton rejection factor = 10^5
Geometrical factor = 0.12 m^{2}sr
Exposure time = 5 years

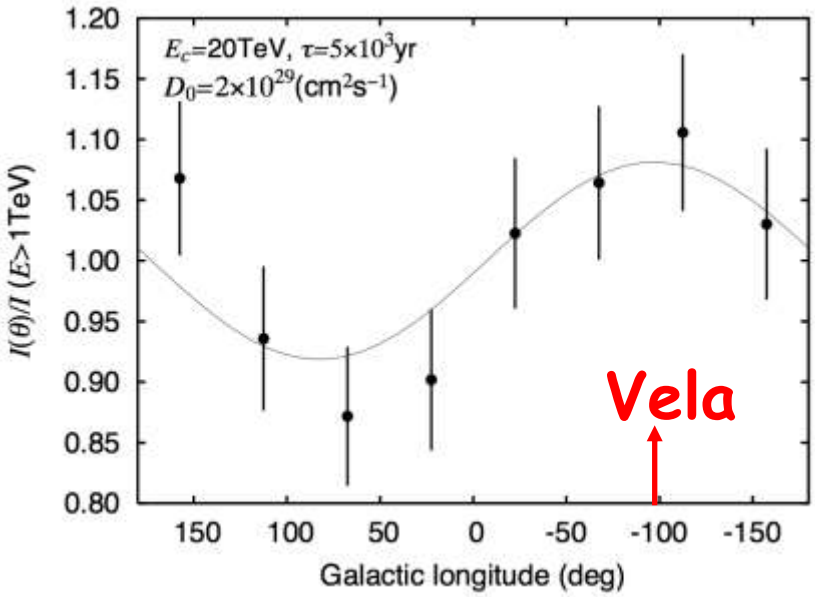
Primary electron spectrum from Fermi data with Hess cutoff:

$J(E) = 185 * (E/1\ \mathrm{GeV})^{-3.045}\ e^{-E/3.4\ \mathrm{TeV}}\ \mathrm{GeV}^{-1}\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-2}$

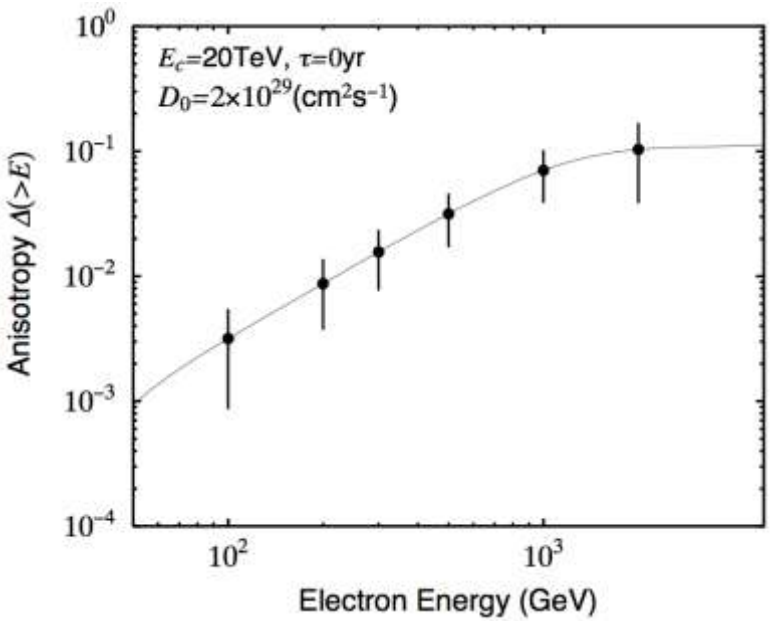
Vela spectrum from Astro-ph/0308470v1, Kobayashi et al., Figure 4 Top

Search for Cosmic-Ray Sources
- Anisotropy of Electrons -

Anisotropy toward nearby sources such as Vela



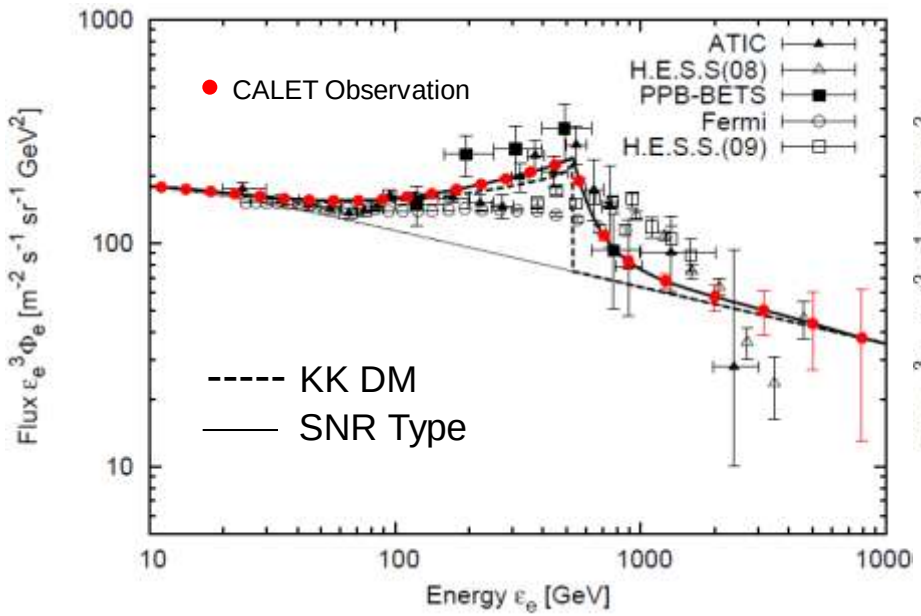
Expected electron intensity distribution (>1TeV)



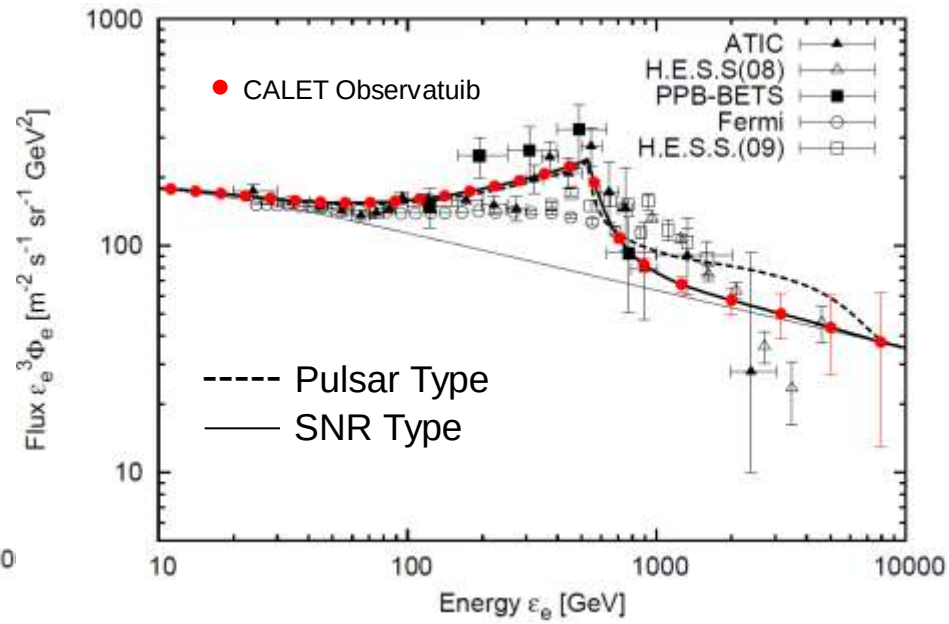
Expected anisotropy with electron energy

Electron Observation (5 years) – Astrophysical Model-

KK DM($\Delta t=0$) vs SNR type ($\Delta t=10^5$ year)



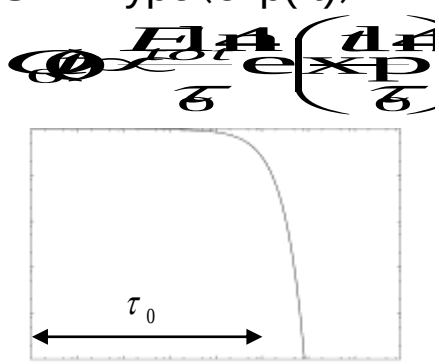
SNR Type vs Pulsar ($\Delta t=3\times10^5$ year)



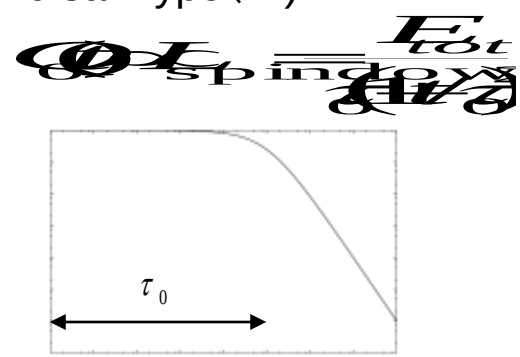
Source

age=5.6x10^5 yr,
E_e=1.7x10^{50} erg,
spectral index=1.7

SNR Type（exp(-t)）

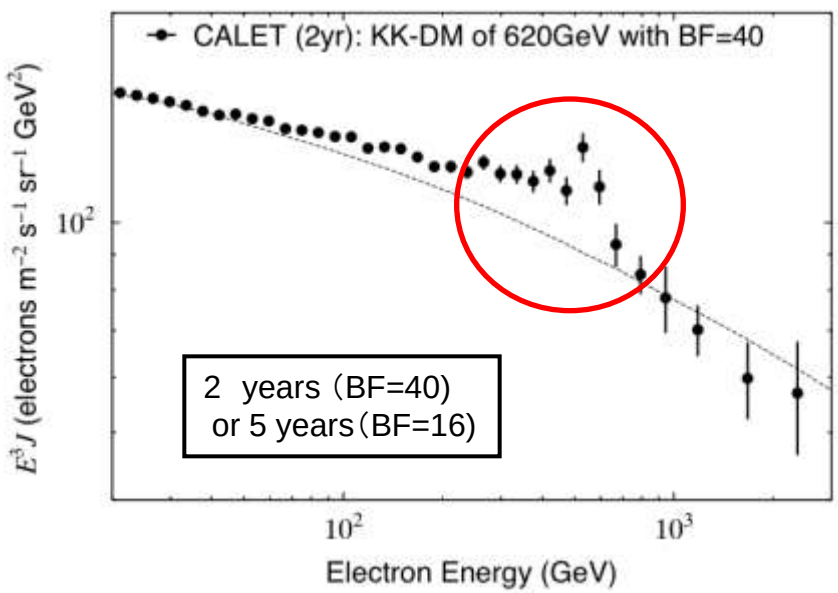


Pulsar Type（t^{-2}）

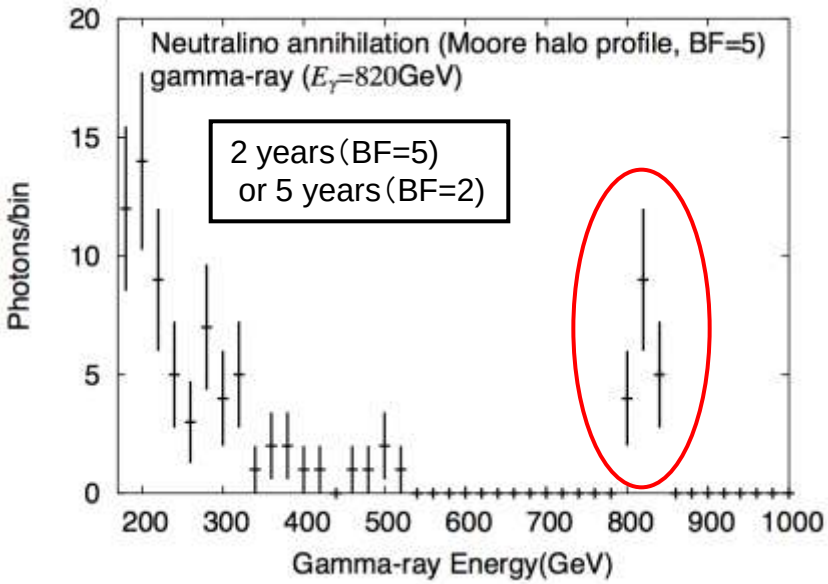


Dark Matter Search Efficiency

Expected electron + positron excess by KK dark matter (Mass 620 GeV) by the CALET observation



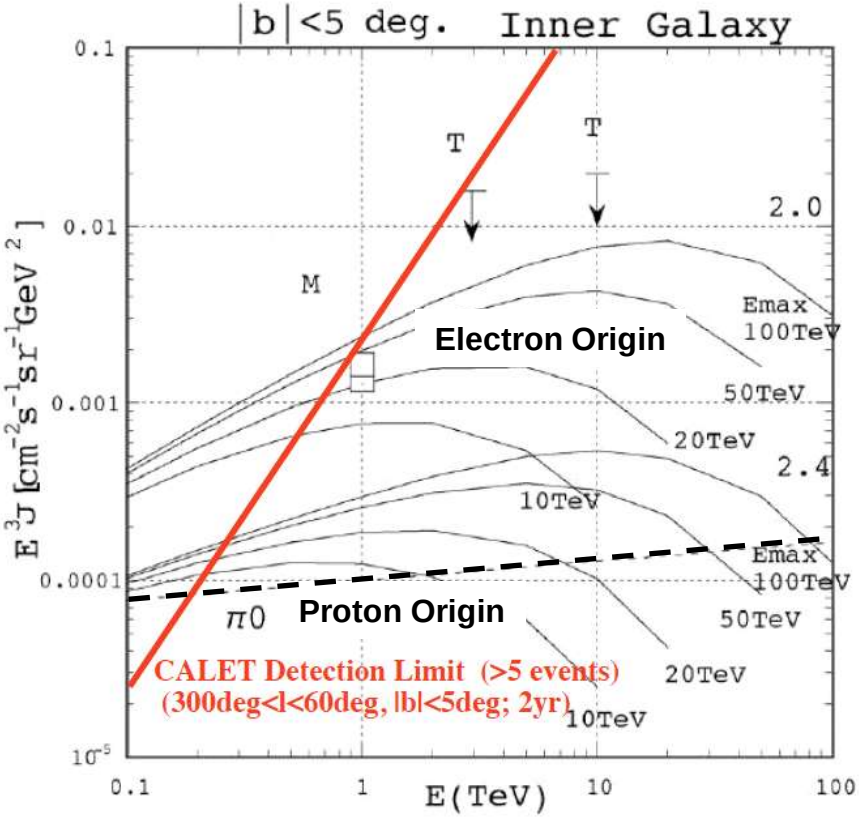
Expected gamma-ray excess by SUSY DM (Mass = 820GeV) by the CALET observation



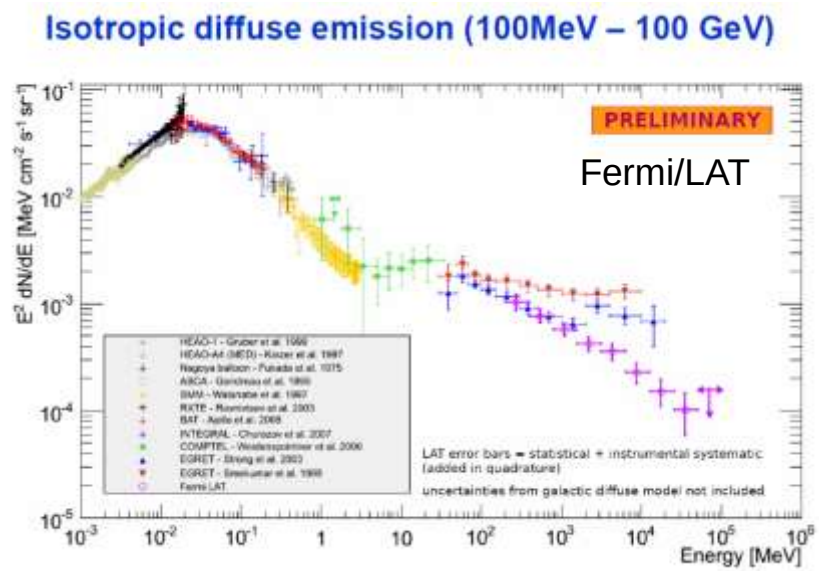
Gamma-ray Diffuse Component

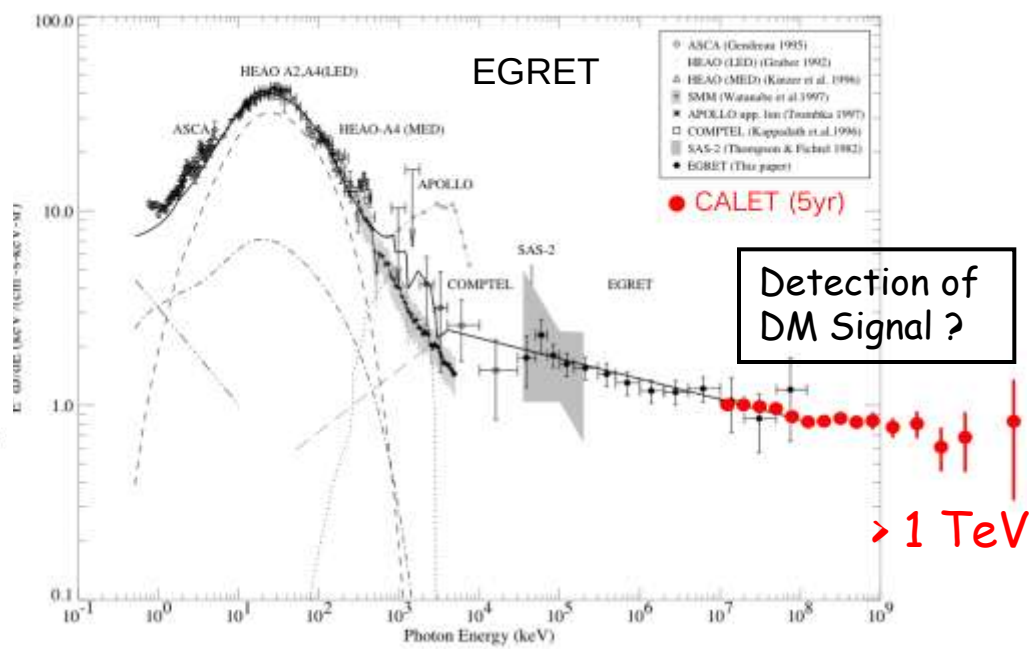
Extragalactic Component

Galactic Component



N.Tateyama (Ph.D Thesis)

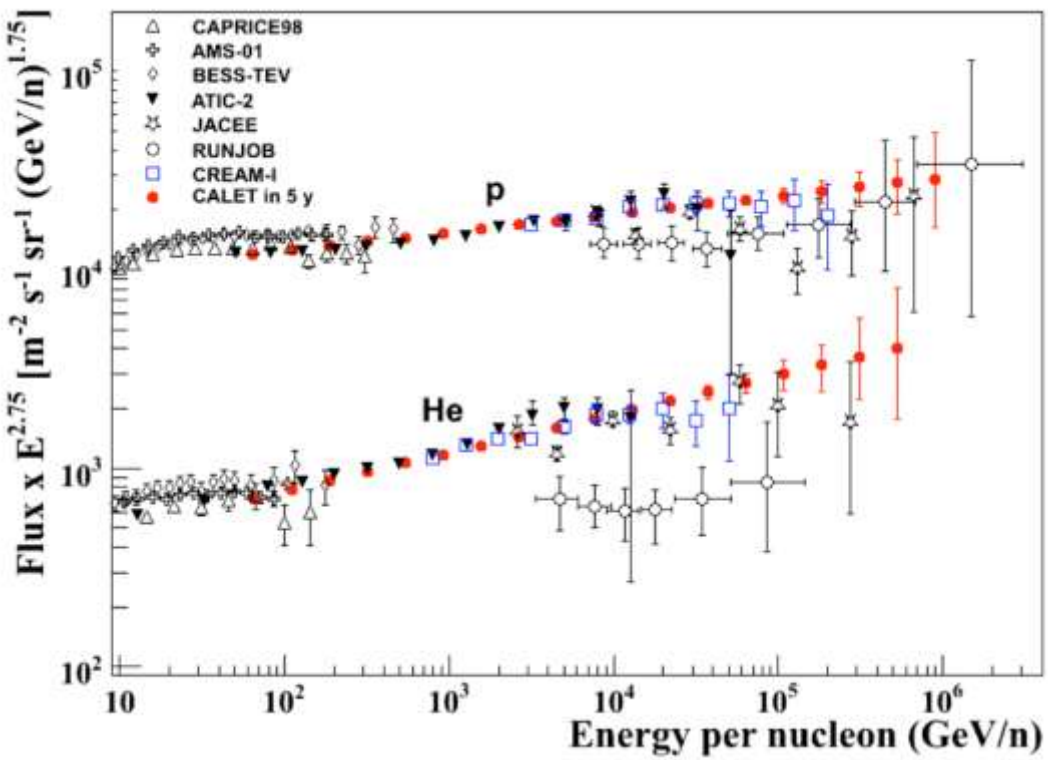




Detection of DM Signal ?

Proton and Nucleus Observation (1)
- Acceleration by Shock Wave ? -

CALET observation (red dots) and present data

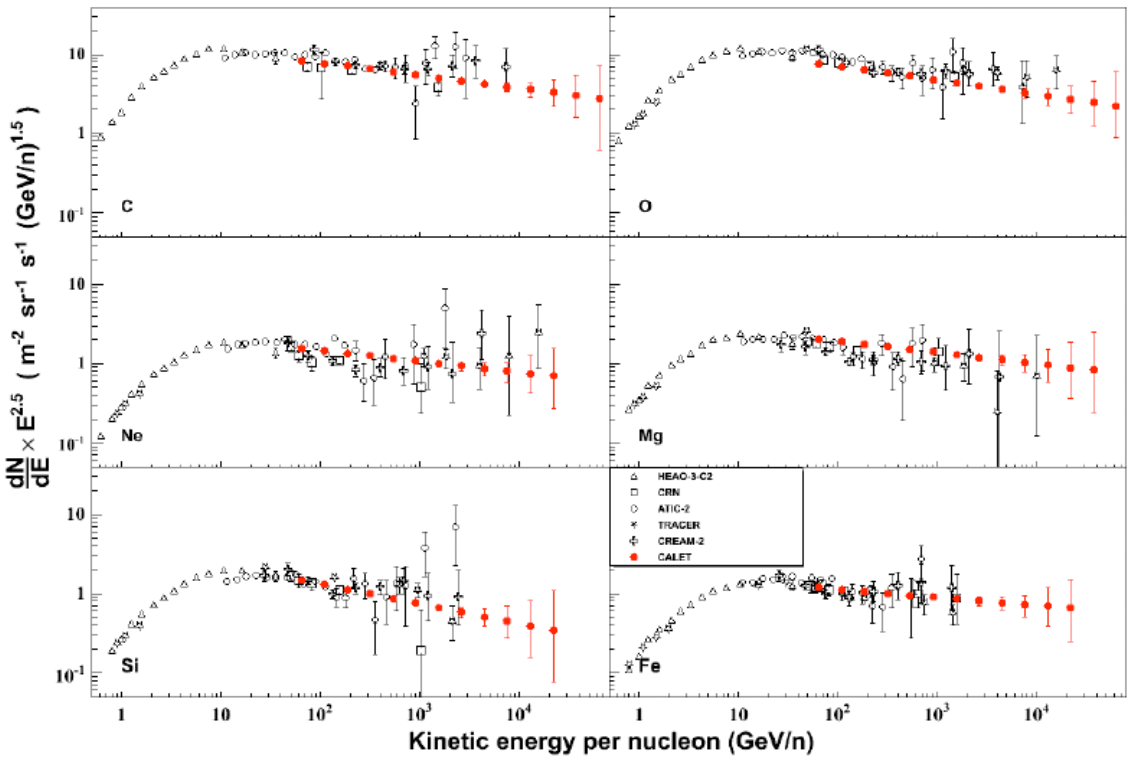


Expected numbers in each energy bin

E range (TeV/n)	Proton	He
0.4-0.7	967734	128408
0.7-1.2	402176	56356
1.2-2.0	167138	24733
2.0-3.5	69460	10855
3.5-5.9	28866	4764
5.9-10.0	11996	2091
10.0-16.9	4986	918
16.9-28.8	2072	403
28.8-48.9	861	177
48.9-83.0	358	78
83.0-140.9	149	34
140.9-239.3	62	15
239.9-406.4	26	6.6
406.4-690-2	10.7	2.9
690.2-1172.1	4.4	1.3
>1172.1	1.8	0

Proton and Nucleus Observation (2)

Expected flux by the CALET observation (red dots)



Expected number of heavy nuclei in each energy bin

E range (TeV/n)	C	O	Ne	Mg	Si	Fe
0.4-0.7	4544	4135	931	1213	701	781
0.7-1.2	1887	1699	390	509	278	335
1.2-2.0	783	698	164	214	110	144
2.0-3.5	325	287	69	90	44	62
3.5-5.9	135	118	29	38	17	26
5.9-10.0	56	48	12	16	6.8	11
10.0-16.9	23	20	5.1	6.6	2.7	4.8
16.9-28.8	10	8	2.1	2.8	1.1	2.1
28.8-48.9	4.0	3.4	0	1.2	0	0
48.9-83.0	1.7	1.4	0	0	0	0

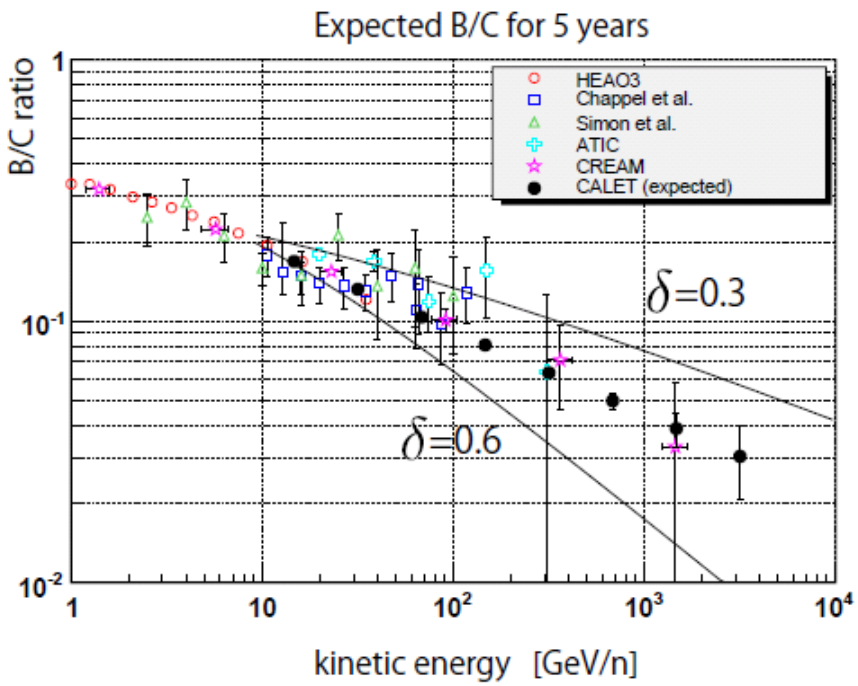
Maximum observable energy

Nucleus	10 events with E (TeV/n) >	5 events with E (TeV/n) >
H	586	893
He	265	416
C	22.9	34.6
O	20.6	30.9
Ne	9.2	14
Mg	10.8	16.4
Si	6.3	9.3
Fe	9	13.8

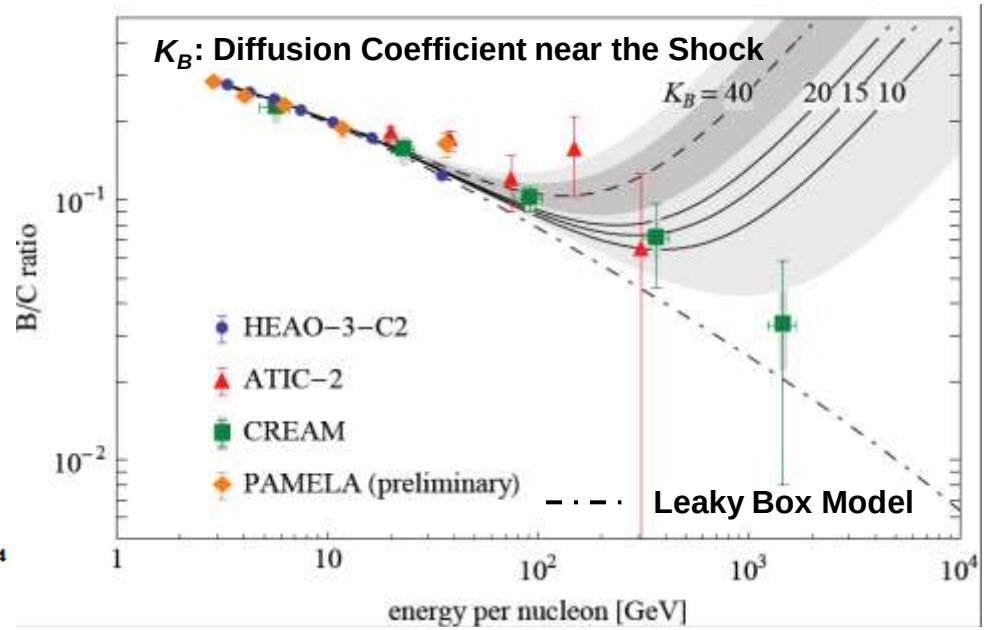
Measurement of 2ry/ 1ry ratio (B/C)
- Propagation in Galaxy-

- Energy dependence of diffusion constant: $D \sim E^{\delta}$
- Observation free from the atmospheric effects up to several TeV/n

CALET expectation for the 5-year observation (black dots) comparing with the present balloon data and the



The B/C ratio in a model where the positrons come from a nearby SNR where the secondary particles are also accelerated by the shock, which is consistent with the PAMELA positron excess. (Ahlers, Mertsch, Sarkar, 0909.4060)

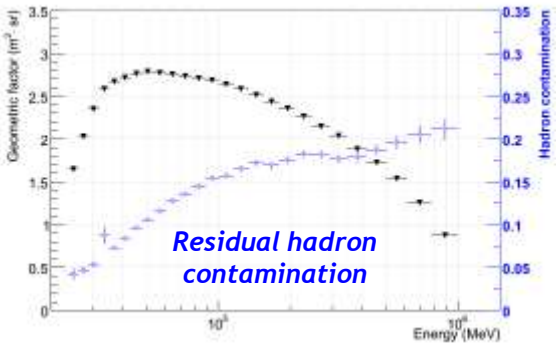


Why we need CALET ?

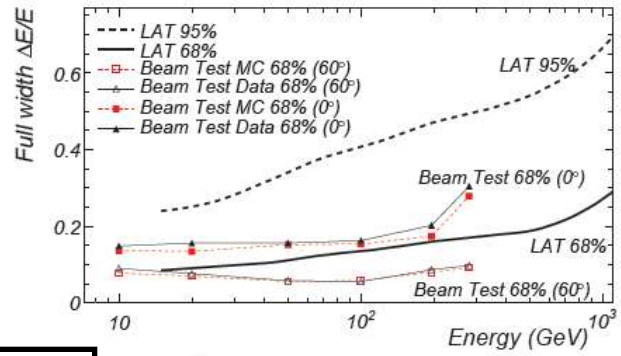
CALET is a dedicated detector for electrons and has a superior performance in the trans-TeV region as well as at the lower energies

FERMI Electron Analysis

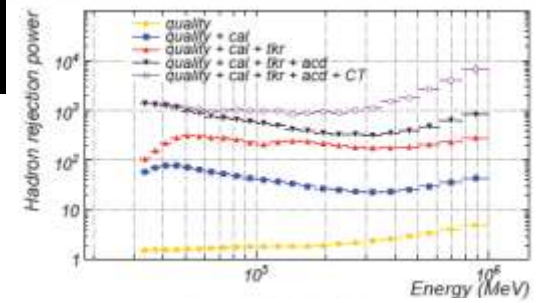
Geometric Factor depends strongly on energy



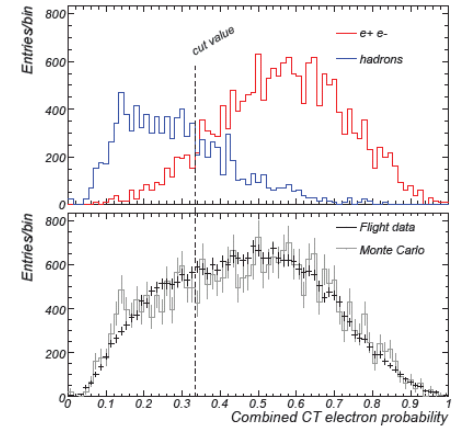
Energy resolution becomes worse at high energies (~30 %@ 1 TeV)



Proton rejection power depends fully on simulation by using different parameters

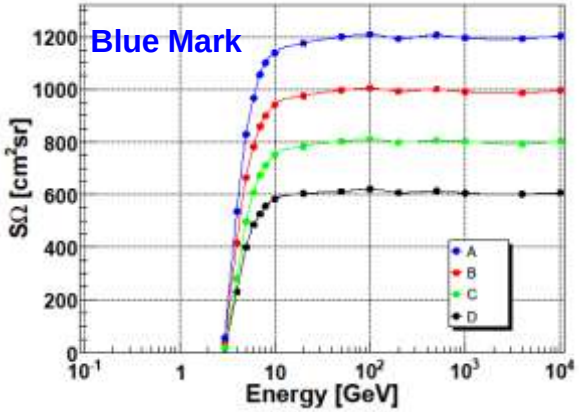


10^4

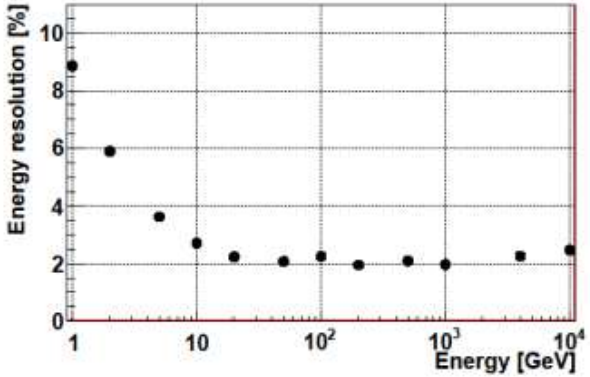


Expected CALET Performance

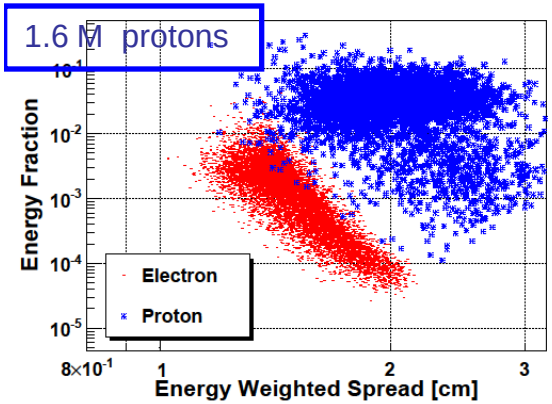
Geometric Factor is constant up to 10 TeV



Energy resolution is nearly 2 %, and constant over 100 GeV



Proton rejection power at 4 TeV is better than 10^5 with 95 % electron retained



Comparison of Detector Performance for Electrons

CALET is optimized for the electron observation in the tran-TeV region, and the performance is best also in 10-1000 GeV.

Detector	Energy Range (GeV)	Energy Resolution	e/p Selection Power	Key Instrument (Thickness of CAL)	SΩT (m²srday)
PPB-BETS (+BETS)	10 -1000	13% @100 GeV	4000 (> 10 GeV)	IMC : (Lead: 9 X_0)	~0.42
ATIC1+2 (+ ATIC4)	10 - a few 1000	<3% (>100 GeV)	~10,000	Thick Seg. CAL (BGO: 22 X_0) + **C Targets**	3.08
PAMELA	1-700	5% @200 GeV	10^5	Magnet+IMC (W:16 X_0)	~1.4 (2 years)
FERMI-LAT	20-1,000	5-20 % (20-1000 GeV)	10^3-10^4 (20-1000GeV) Energy dep. GF	Tracker+ACD + **Thin Seg. CAL** (W:1.5X_0+CsI:8.6X_0)	300@TeV (1 year)
AMS	1-1,000 (Due to Magnet)	~2.5% @100 GeV	10^4 (x 10^2 by TRD)	Magnet+IMC +TRD+RICH (Lead: 17X_o)	~100(?) (1year)
CALET	**1-10,000**	**~2% (>100 GeV)**	**~10^5**	**IMC+Thick Seg. CAL (W: 3 X_o+ PWO : 27 X_o)**	**220 (5 years)**

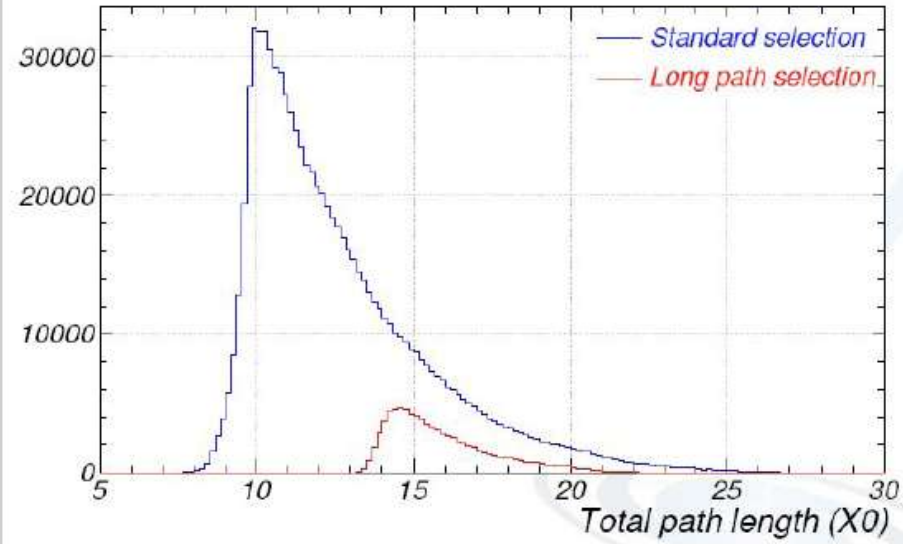
Summary and Future Prospect

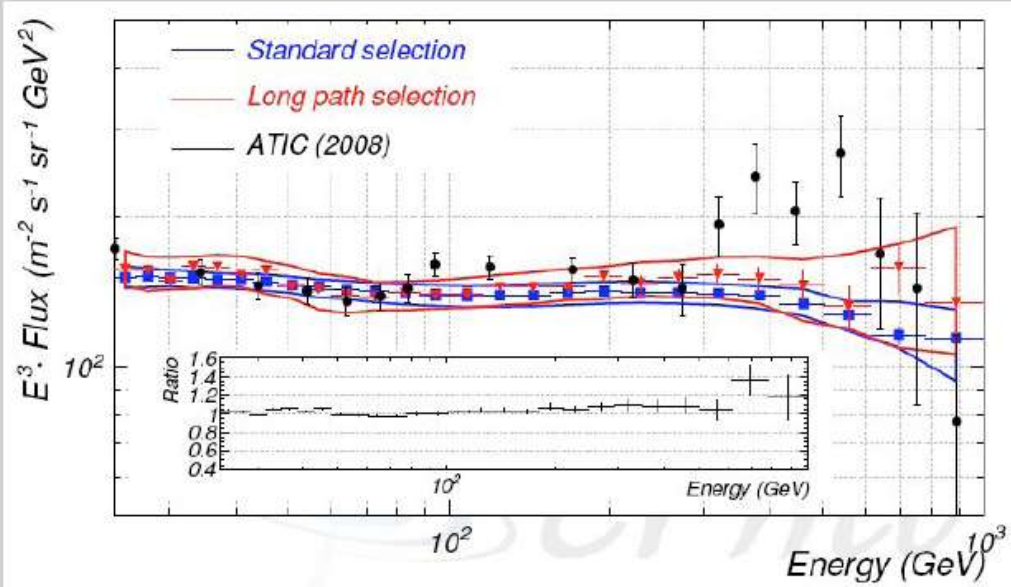
- ✓ We have successfully been developing the CALET instrument for JEM/EF facility from the experience of balloon experiments.
- ✓ The CALET has capabilities to observe the electrons up to 10 TeV , gamma-rays in 10GeV- 10TeV , proton and heavy ions in several 10 GeV - 1000 TeV, for investigation of high energy phenomena in the Universe.
- ✓ We have already completed a pre-phase A study within last 6 years.
- ✓ CALET was selected as only candidate of the exclusive port occupation utilization mission (2013 launch [targeted]), and the system requirement review (SRR) was successfully concluded for the transition to the planning decision phase in Oct. 2009.
- ✓ CALET will proceed to the construction phase after the system definition review (SDR) in March, 2010, and will be launched in plan around the mid of 2013.

Fermi/LAT New Electron Analysis J.F.Ormes

Checking the electron result

- Select events passing through only one calorimeter module
- Select events passing through at least 13 X_o
- Track starts in thin target or upper part of tracker

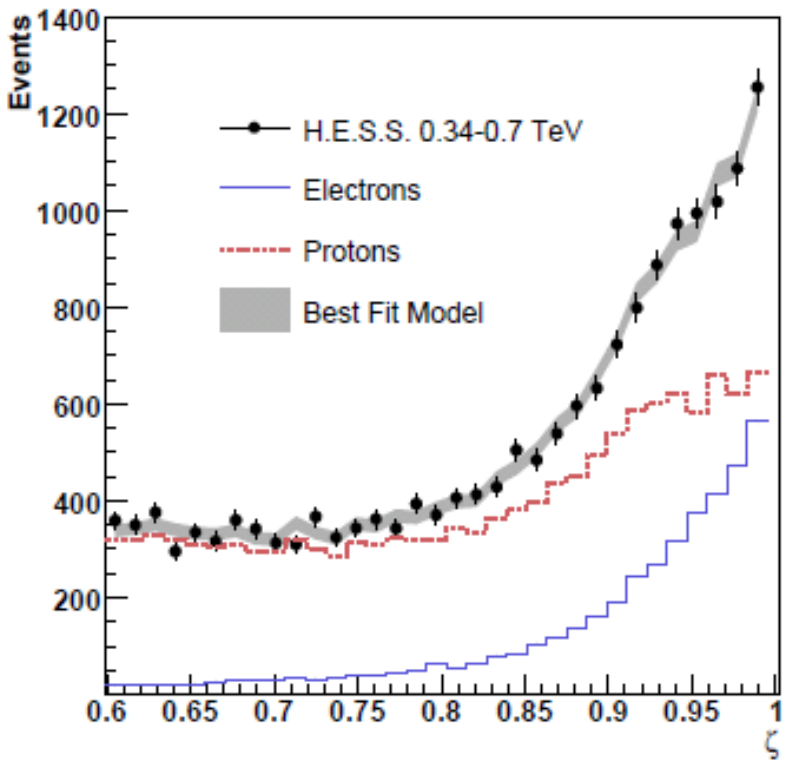




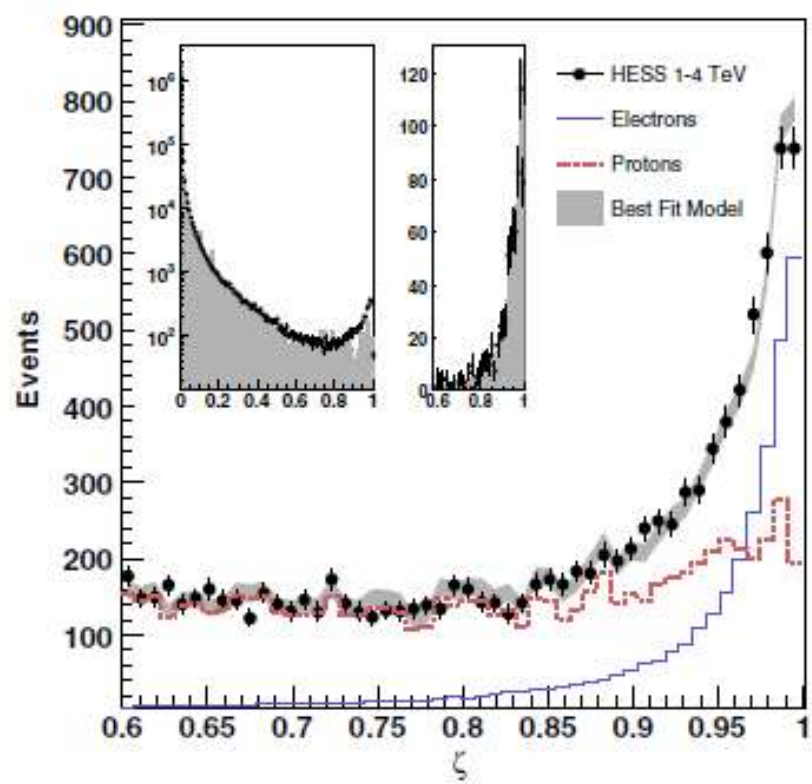
J. F. Ormes Fermi LAT

The H.E.S.S. analysis depends on simulation, and the residual protons are as dominant as similar with an amount of the electrons, or more at lower energies.

F.Aharanian et al. arXiv:0905:0105

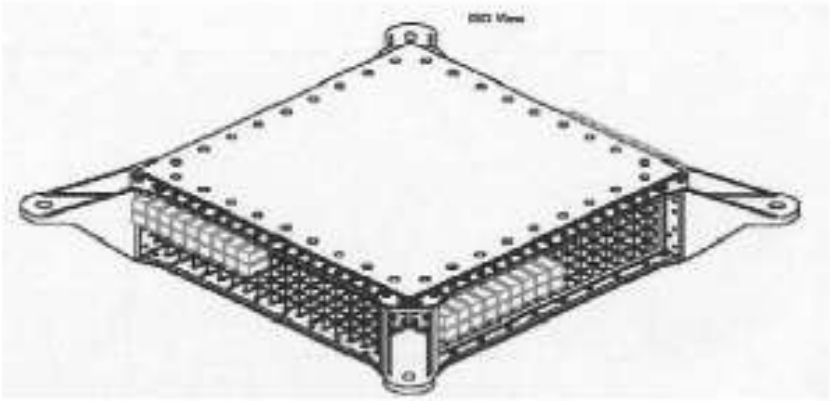


PRL ,201, 261104 (2008)

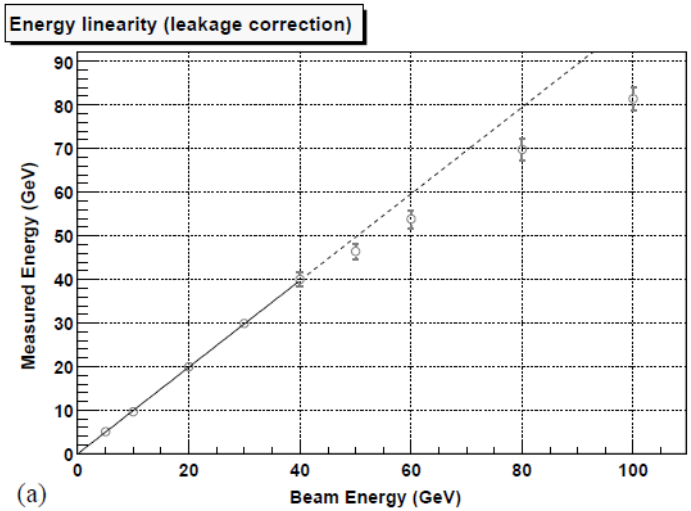
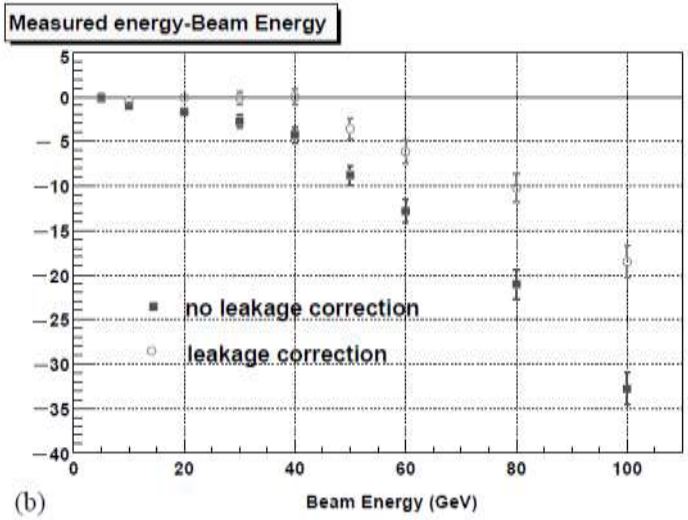


AMS-Cal Capability for Energy Resolution

NIM 490 (2002) 132



Lead + Scintillating fibers
Segmentation: 9mm
Area: 65.8cm x 65.8 cm
Weight: 492 kg

Calorimeter Thickness: 17 X_0

=> Energy Leakage over 50 GeV