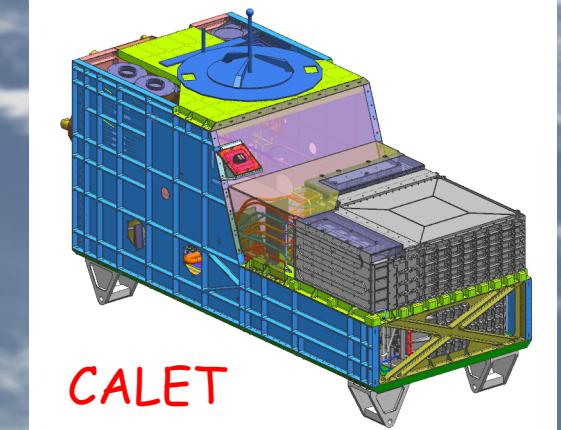


The Calorimetric Electron Telescope (CALET) for High Energy Astroparticle Physics on the International Space Station

Shoji Torii
for the CALET Collaboration

Waseda University &
Japan Aerospace Exploration Agency (JAXA)



CALET



CALET Collaboration Team



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7) Kanagawa University, Japan

8) KEK, Japan

9) Louisiana State University, USA

10) NASA/GSFC, USA

11) National Inst. of Radiological Sciences, Japan

12) Nihon University, Japan

13) Ritsumeikan University, Japan

14) Saitama University, Japan

15) Shibaura Institute of Technology, Japan

16) Shinshu University, Japan

17) Tokyo Technology Institute, Japan

18) University of Denver, USA

19) University of Florence, IFAC (CNR) and INFN, Italy

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21) University of Rome Tor Vergata and INFN, Italy

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23) Waseda University, Japan

24) Washington University-St. Louis, USA

25) Yokohama National University, Japan

26) University of Padova and INFN, Italy

27) Ibaraki University, Japan

28) Tokiwa University, Japan



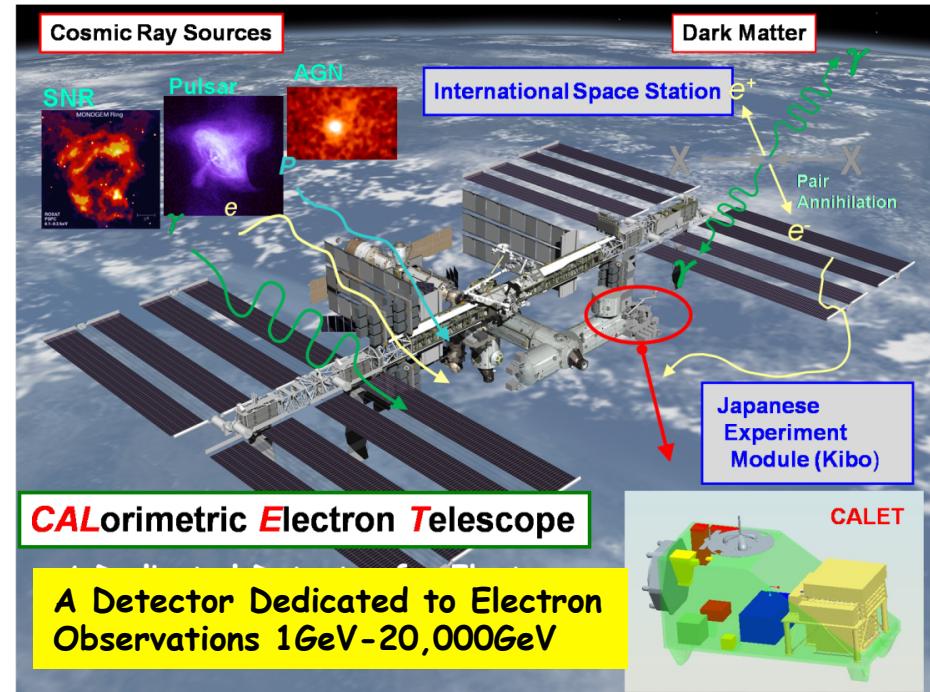
CALET Observation Targets

Calorimeter (CALET/CAL)

- Electrons: 1 GeV - 20 TeV
- Gamma-rays: 4 *GeV - 10 **TeV
(Gamma-ray Bursts: > 1 GeV)
- Protons and Heavy Ions:
10's of GeV - 1,000** TeV
- Ultra Heavy ($Z>28$) Nuclei:
 $E > 600$ MeV/nucleon
- (* 50% efficiency, ** statistical dependent)

Gamma-ray Burst Monitor (CGBM)

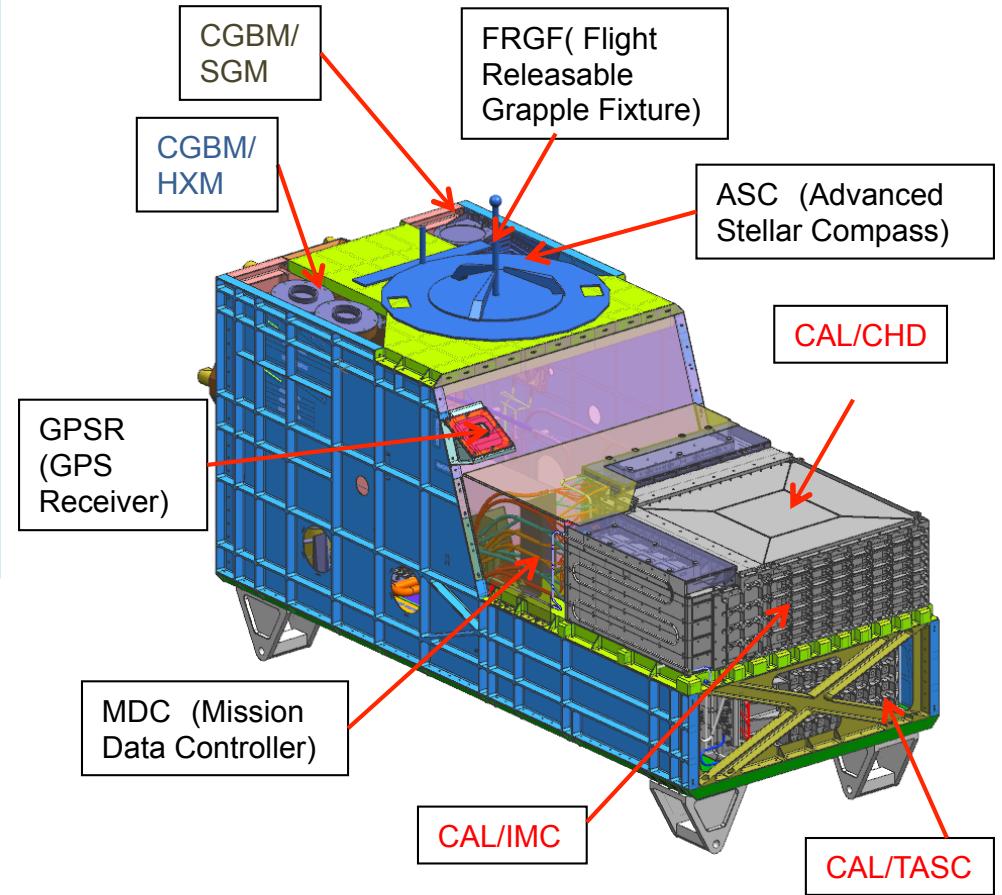
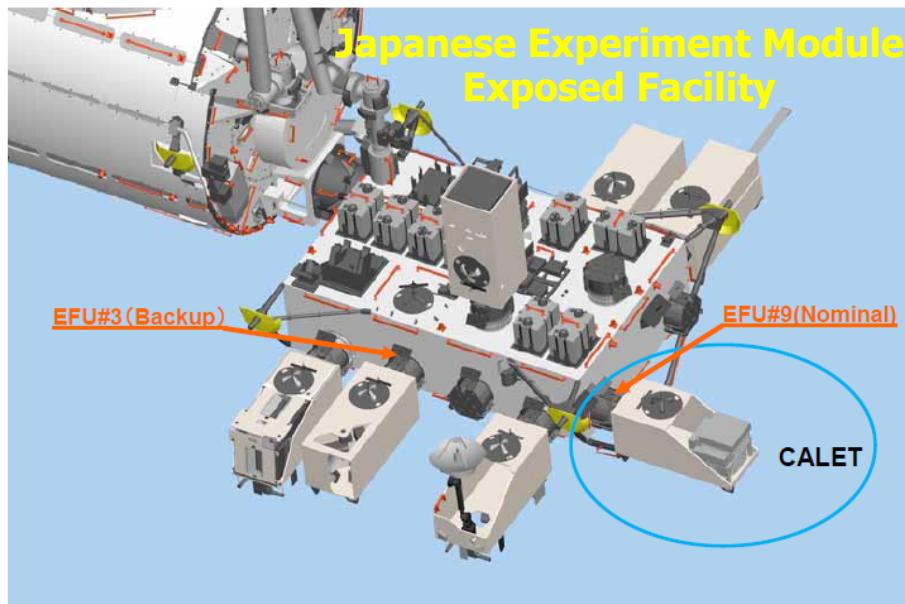
- X-rays/Soft Gamma-rays:
7keV - 20MeV



Science Objectives	Observation Targets
Nearby Cosmic-ray Sources	Electron spectrum into trans-TeV region
Dark Matter	Signatures in 10 GeV - 10 TeV electron and gamma energy spectra
Origin and Acceleration of Cosmic Rays	p-Fe above several tens of GeV, Ultra Heavy Nuclei
Cosmic-ray Propagation in the Galaxy	B/C ratio to several TeV /nucleon
Solar Physics	Electron flux below 10 GeV
Gamma-ray Transients	Gamma-rays and X-rays 7 keV - 20 MeV



CALET Payload Overview



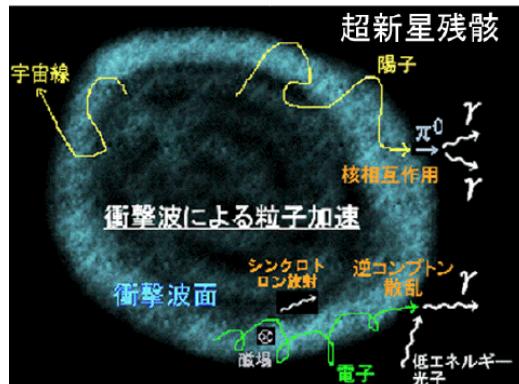
- Launch carrier: HTV-5
- Planned location: JEM Port 9
- Launch target date: FY 2014
- Mission period: More than 2 years
(5 years target)
- Data rate:
 - Medium data rate: 300 kbps
 - Low data rate: 35 kbps

- Mass: 650kg (Max)
- JEM/EF Standard Payload Size
(1850L×800W×1000H in mm)
- Power: 650W (Nominal)

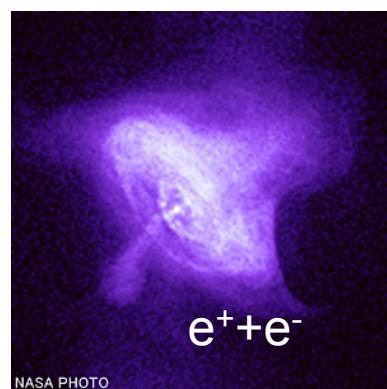
Electron & Positron Origins and Production Spectrum

Astrophysical Origin

Shock Wave Acceleration in SNR

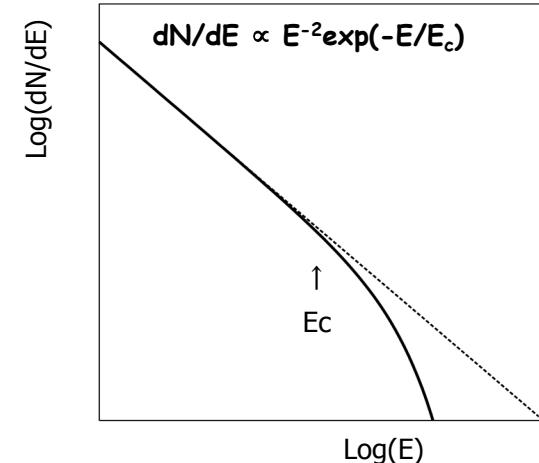


Acceleration in PWN

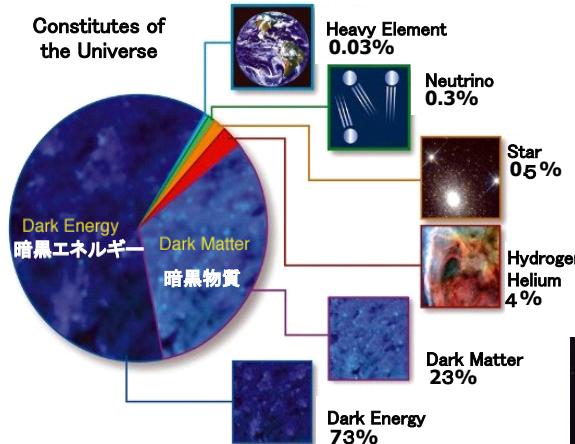


etc.

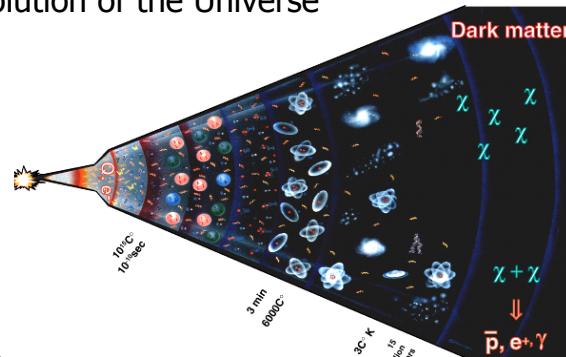
Power Law Distribution with a Cutoff



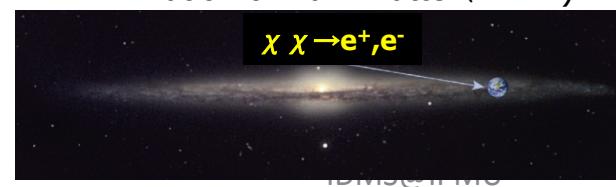
Dark Matter Origin



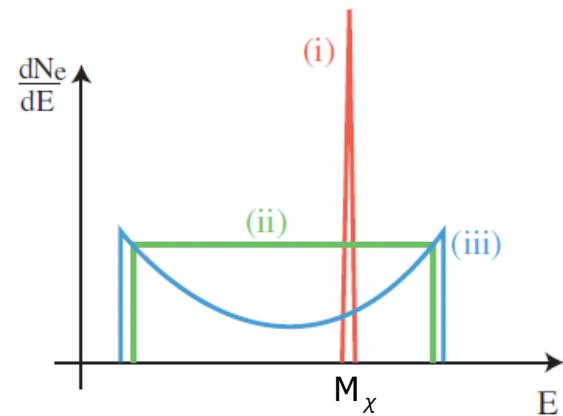
Evolution of the Universe



Annihilation of Dark Matter (WIMP)



Typical Distribution Depending on the Mass and Type of DM



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

e^\pm Propagation in the Galaxy

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

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

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

$$d_{diff}(t, \varepsilon_e) \sim 2 \left[D(\varepsilon_e) t \right]^{1/2} \text{Atoyan 95, Shen 70, Kobayashi 03}$$

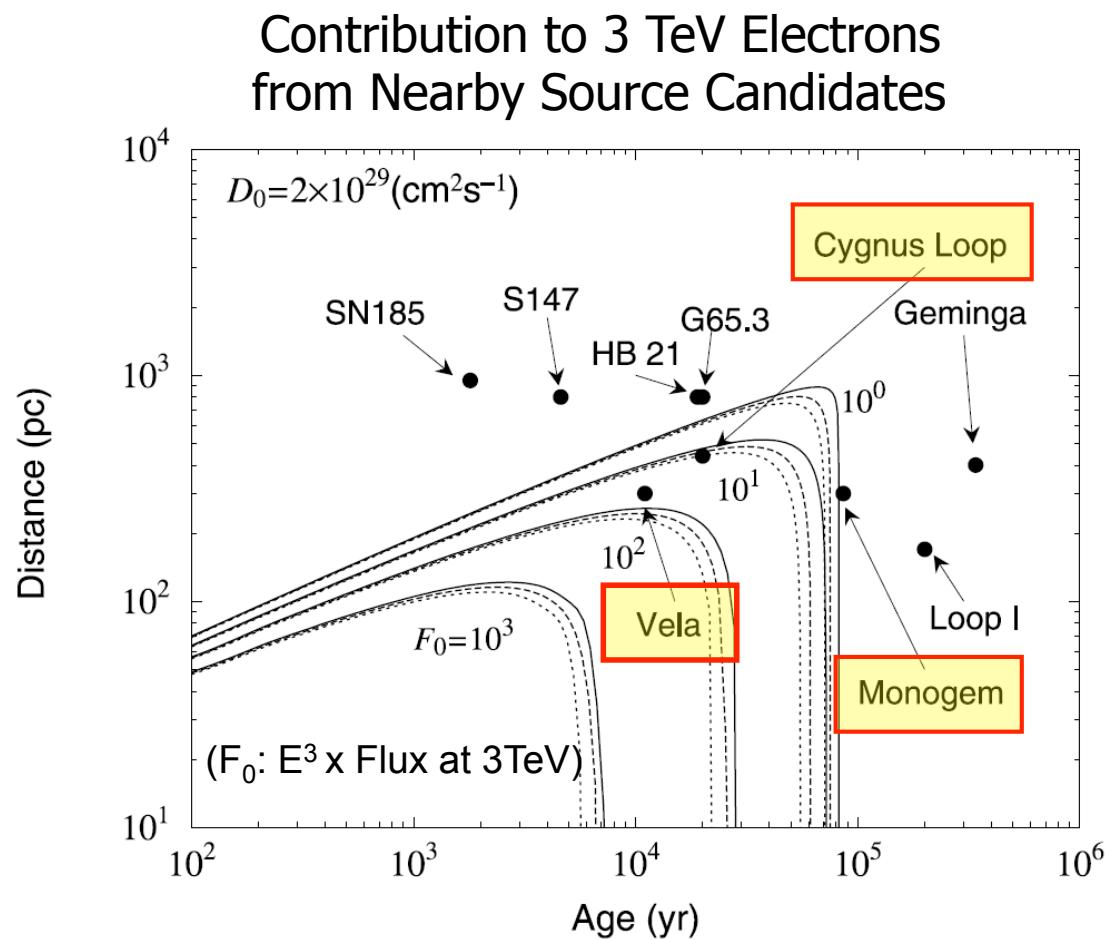
$$\mathcal{E}_{\text{cut}} \sim \frac{1}{bt}$$



CALET Main Target: Nearby Sources of Electrons in TeV region

$$T (\text{age}) = 2.5 \times 10^5 \times (1 \text{ TeV}/E) \text{ yr}$$

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

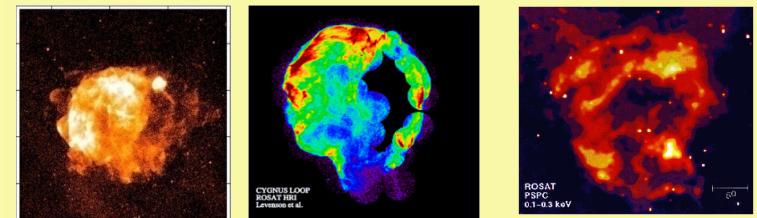


> 1 TeV Electron Source:

- Age < a few 10^5 years
very young comparing to $\sim 10^7$ year at low energies
- Distance < 1 kpc
nearby source

Source (SNR) Candidates :

Vela Cygnus Loop Monogem



Unobserved Sources?



CALET Capability for Electron (+ Positron) Observation : Nearby Sources

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
> 1000		827
> 1000		644

Conditions applied:

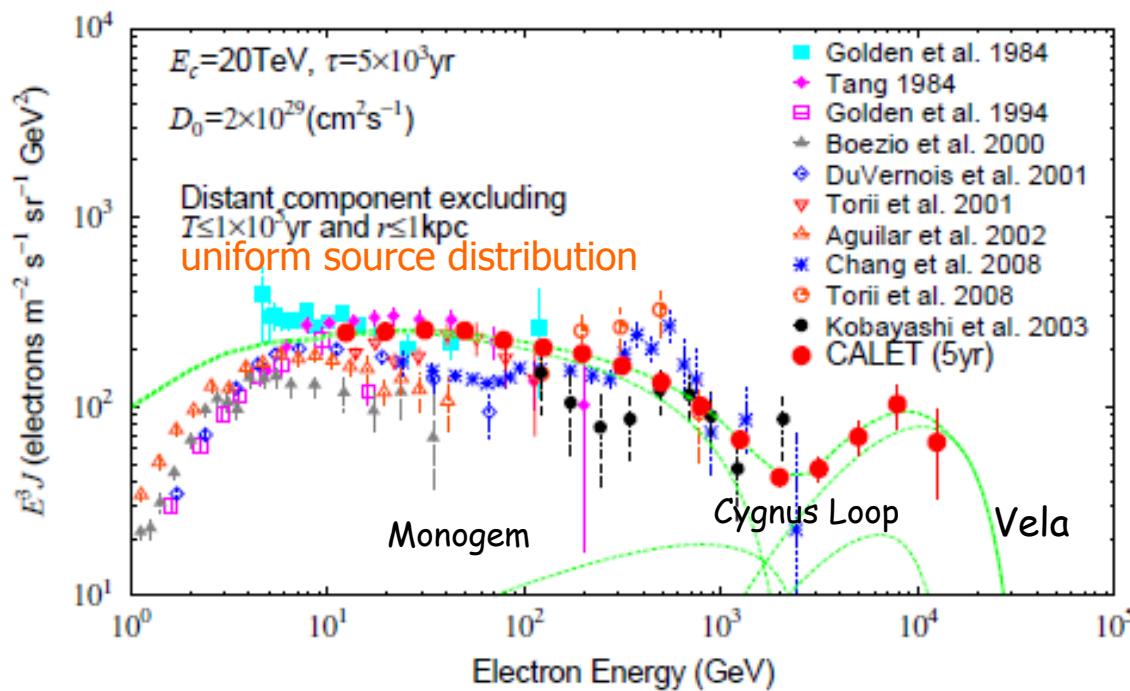
Electron efficiency = 70%
 Proton rejection factor = 10^5
 Geometrical factor = $0.12 \text{ m}^2 \text{sr}$
 Exposure time = 5 years

Primary electron spectrum from Fermi data with Hess cutoff:

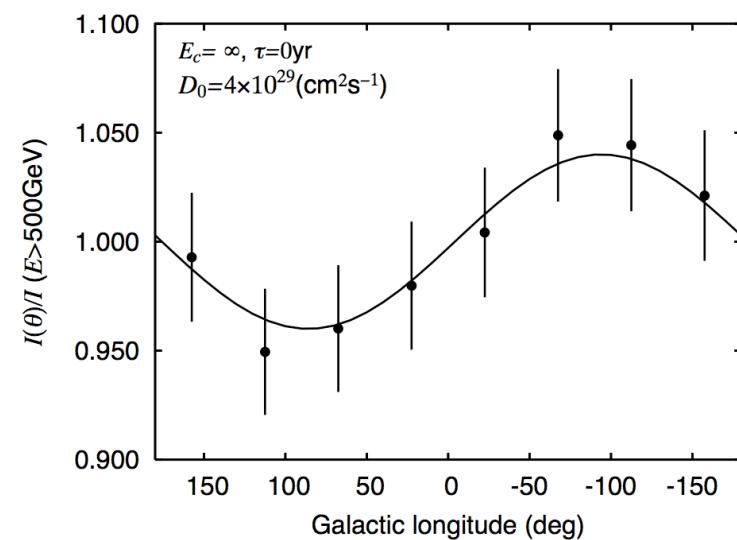
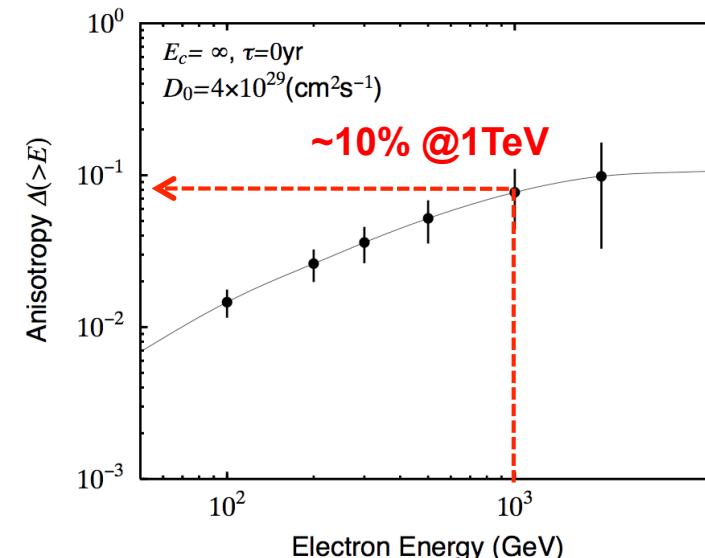
$$J(E) = 185^* (E/1 \text{ GeV})^{-3.045} e^{-E/3.4 \text{ TeV}} \text{ GeV}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-2}$$

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

Expected Flux



Expected Anisotropy from Vela SNR

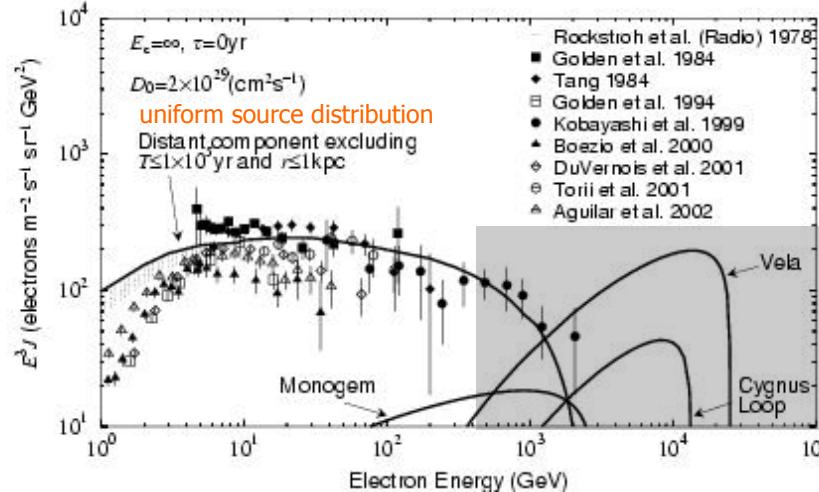




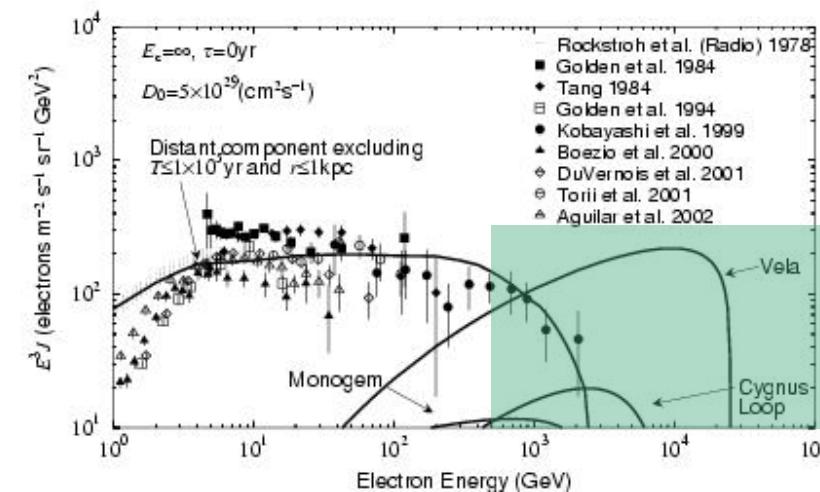
Model Dependence of Energy Spectrum and Nearby Source Effect

E_c : Cutoff Energy ΔT : Acceleration Period D : Diffusion Constant at 1 TeV ($\propto E^{0.6}$)

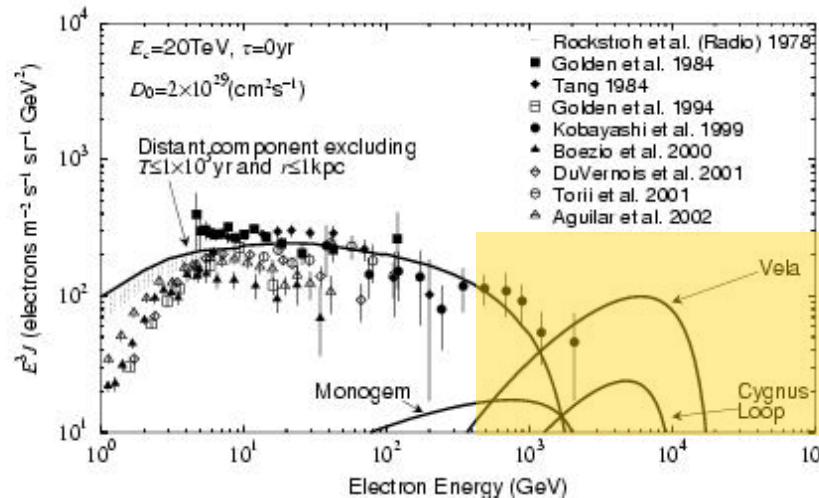
$E_c = \infty, \Delta T = 0$ yr, $D_0 = 2 \times 10^{29} \text{ cm}^2/\text{s}$



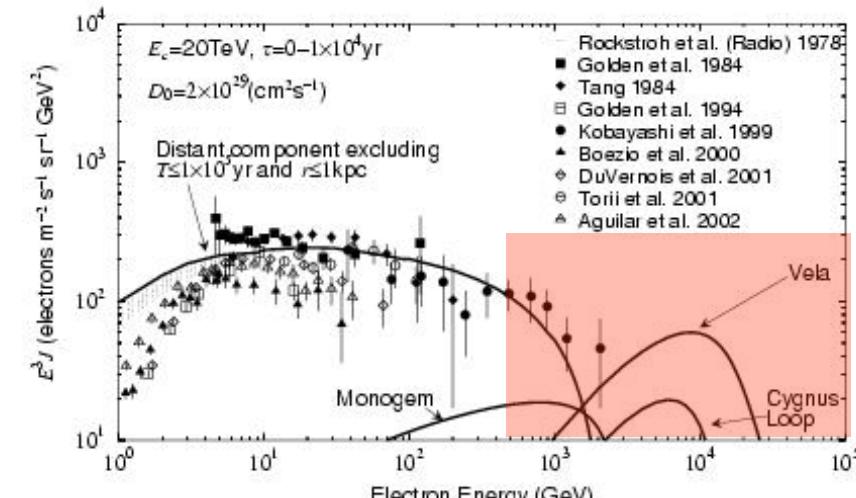
$D_0 = 5 \times 10^{29} \text{ cm}^2/\text{s}$



$E_c = 20 \text{ TeV}$



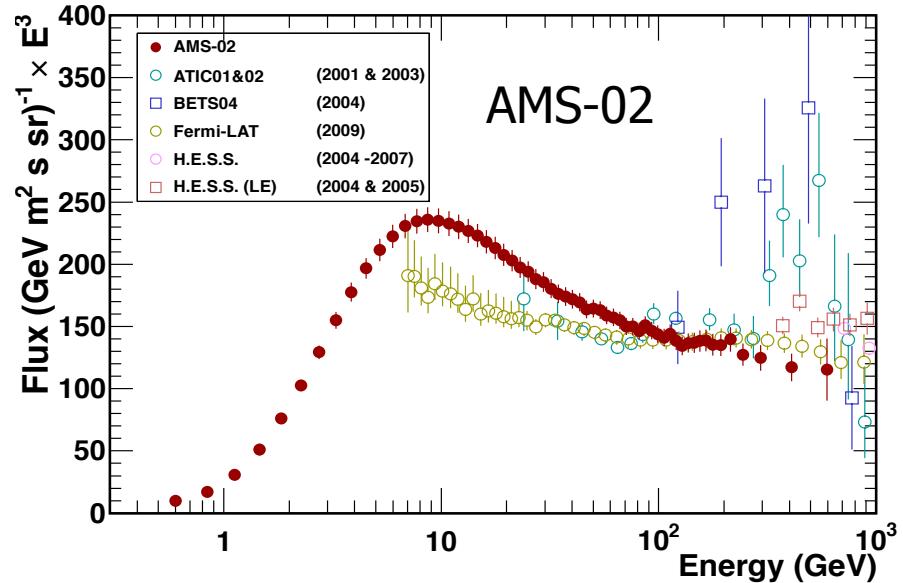
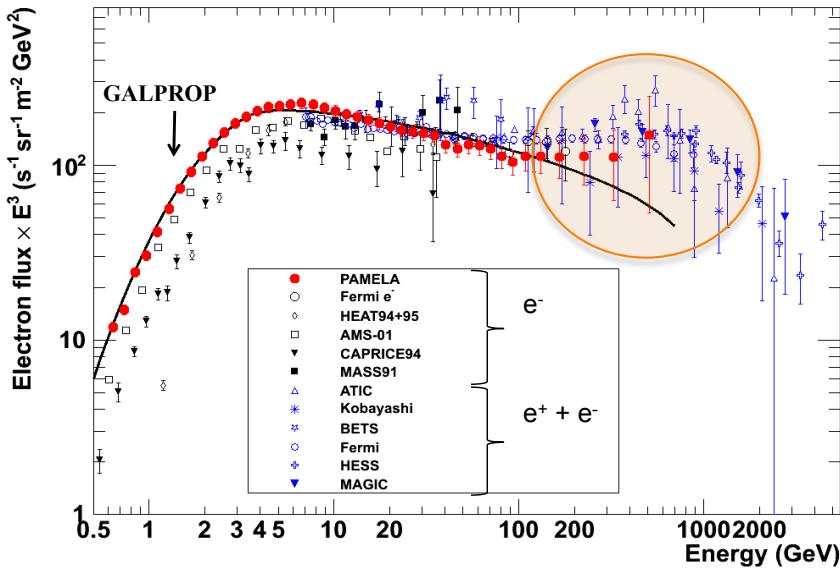
$E_c = 20 \text{ TeV}, \Delta T = 10^4 \text{ yr}$



Kobayashi et al. ApJ (2004)

Recent results of electron and positron observations 1-1000 GeV

Something interesting in the electron energy spectrum below 1 TeV
is revealed by accurate measurements with high statistics

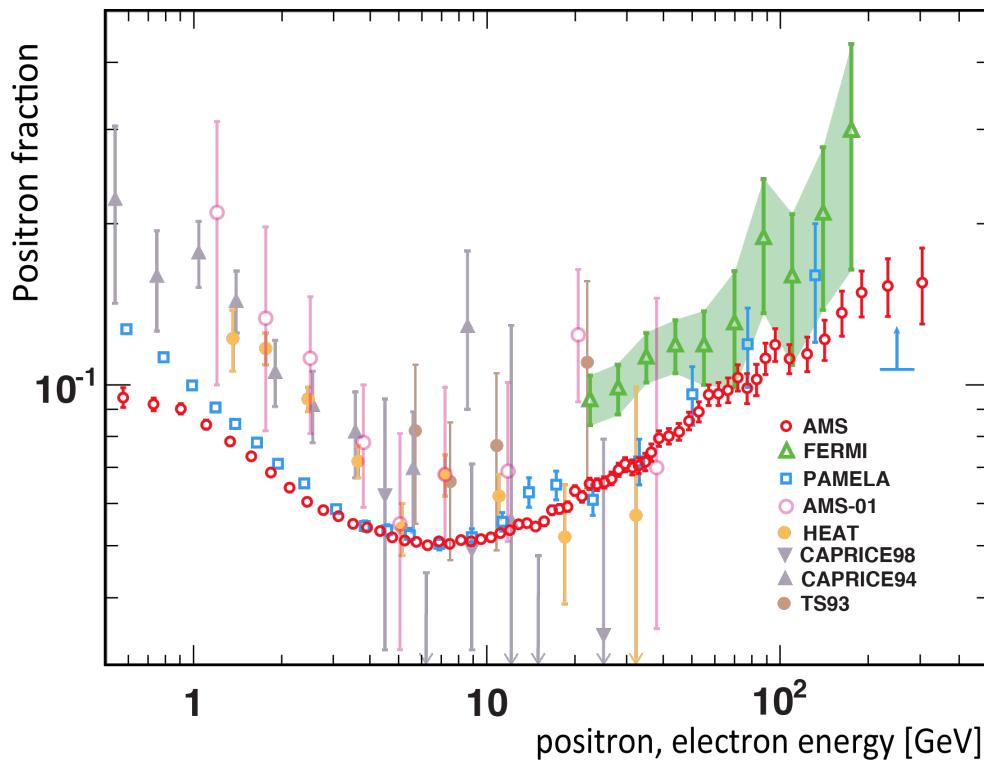


- It is now relatively well established that there is an enhancement in the electron energy spectrum in the $200 \sim 1000$ GeV energy range, which is not expected for a uniform distribution of sources in Galaxy. Source candidates are suggested to be nearby pulsars or dark matter.
- ATIC, Fermi-LAT and HESS all see an enhancement, but experiment limitations preclude a complete characterization of the feature.
- Recent AMS-02 observations are consistent with Fermi-LAT above 100 GeV, but a systematic discrepancy exists in the 10-100 GeV range .
- The exact shape of the spectral feature needs to be refined and details of this shape may help identify the source of the energetic electrons.

Positron fraction from AMS-02

AMS-02 observed:

- Steady increase from 10 to ~ 250 GeV with slope decreasing by an order of magnitude
- No fine structure, consistent with sum of diffuse spectrum and a single common power law source.



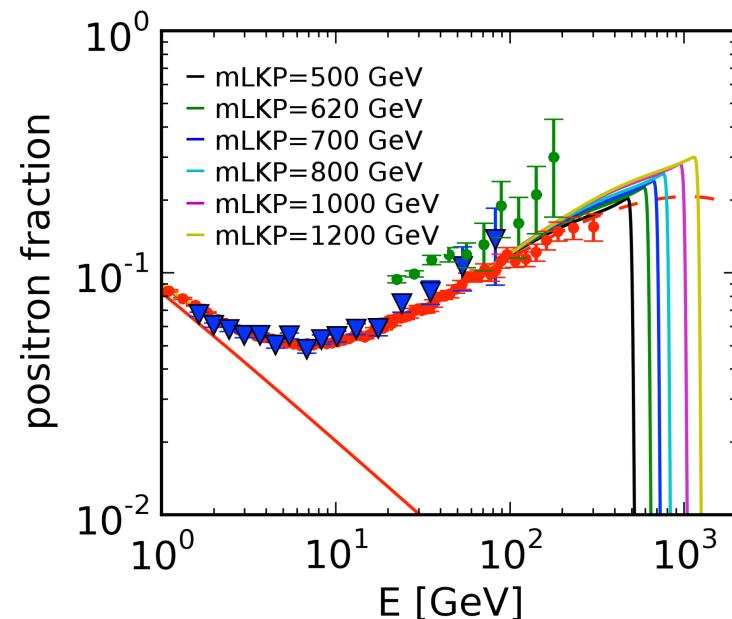
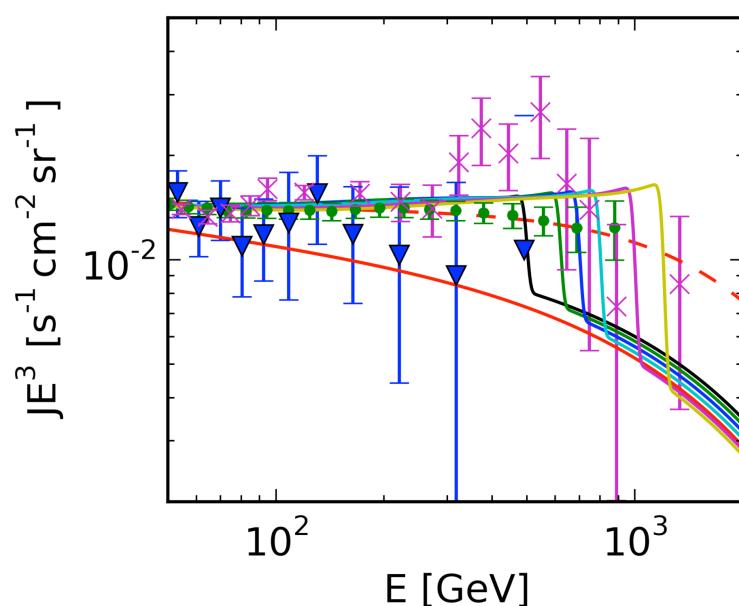
The positron fraction is higher by about one-order of magnitude at 100 GeV than predicted for secondary positrons by a widely used CR propagation model.

Possible solutions:

1. New primary sources of positrons
 - Annihilation of dark matter
 - Positron production and acceleration by pulsars
2. Modifications of Galactic cosmic-ray propagation model

Consistent understanding of the e^+e^- spectrum with the positron fraction

Background: power law (different for electron and positron) with exp. cutoff
+ **case A) Dark Matter:** Kaluza Klein Dark Matter (LKP) in the mUED scenario
+ **case B) GSS:** Generic Source Spectrum (power law with cutoff)



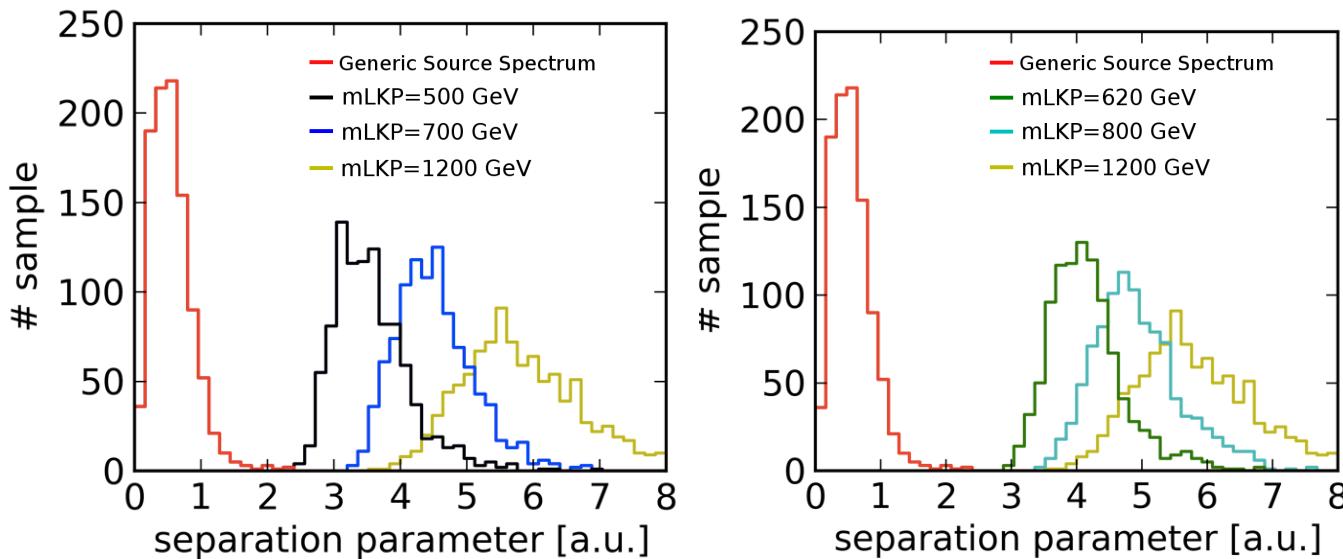
Fits of the **Generic Source Spectrum** (dashed red line, background flux solid red line) and Kaluza Klein Dark Matter of different masses, calculated using the annihilation and propagation routines of DarkSUSY, to positron fraction (right plot) data from **AMS-02** (red) and total flux (left plot) measured by Fermi, including systematic error (green).

χ^2 is below 95% CL exclusion for all cases except $m(\text{LKP})=500 \text{ GeV}$, thus proving that both Dark Matter annihilation and local accelerators are valid hypotheses within the constraints of current experiments.

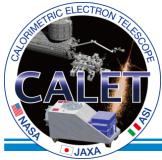
CALET capability to separate the generic source spectrum and Dark Matter cases

The expected 2yr-signal in CALET was calculated for each case, based on the detector's simulated properties. An unbinned analysis by least square fit based on the event distribution in energy was developed, which is able to separate the Generic Source Spectrum (GSS) and Dark Matter cases. Specifically it identifies the drop in the spectrum at the mass of the Dark Matter particle, allowing reconstruction of the mass with high precision.

*Distribution of a fit parameter used for separation
between Dark Matter and GSS for 1000 simulated samples of each case.*



- Clear Separation between local accelerators (Generic Source Spectrum - GSS) and Kaluza Klein Dark Matter Annihilation possible with 2-yr CALET data.
- Mass of Lightest Kaluza Klein Particle can be reconstructed with high resolution ($\sigma \sim 11.6 \text{ GeV}$).

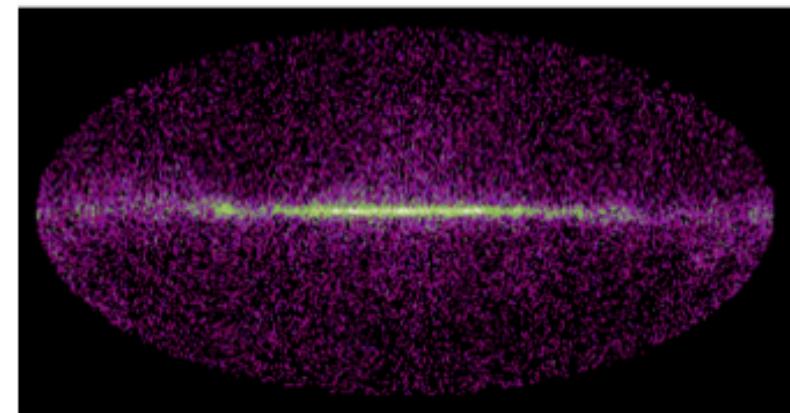


Detection of High Energy Gamma-rays

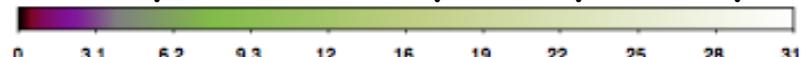
Performance for Gamma-ray Detection

Energy Range	4 GeV-10 TeV
Effective Area	600 cm ² (10GeV)
Field-of-View	2 sr
Geometrical Factor	1100 cm ² sr
Energy Resolution	3% (10 GeV)
Angular Resolution	0.35 ° (10GeV)
Pointing Accuracy	6'
Point Source Sensitivity	8 × 10 ⁻⁹ cm ⁻² s ⁻¹
Observation Period (planned)	2014-2019 (5 years)

Simulation of Galactic Diffuse Radiation

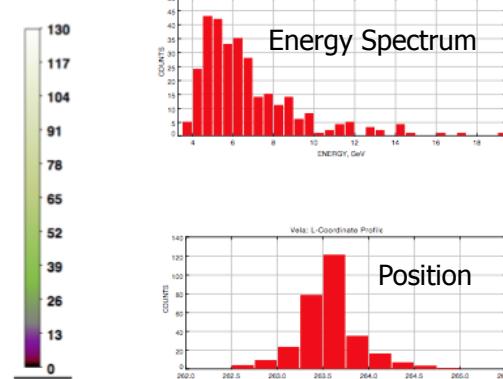
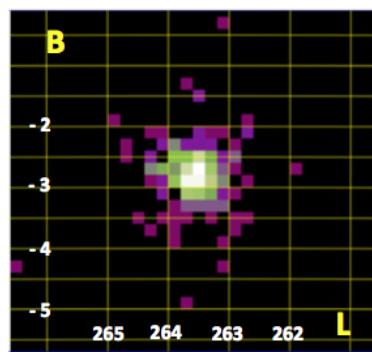


~25,000 photons are expected per one year

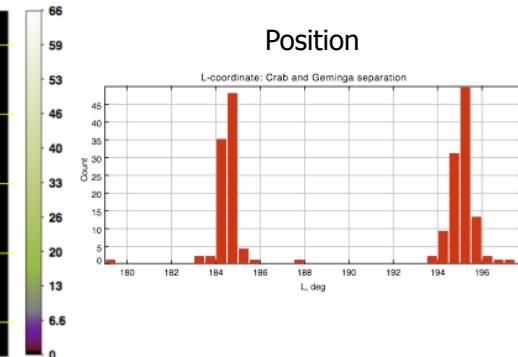
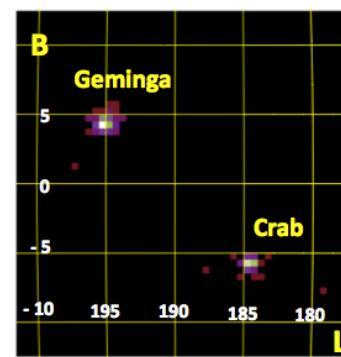


*) ~7,000 photons from extragalactic γ-background (EGB) each year

Simulation of point source observations in one year



Vela: ~ 300 photons above 5 GeV

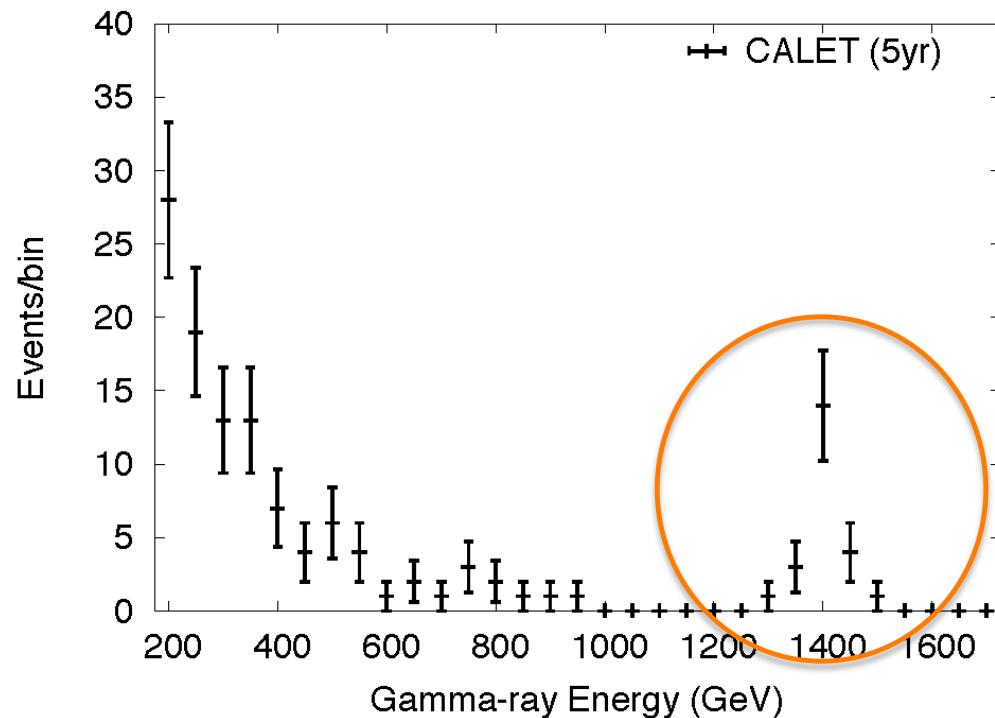


Geminga: ~150 photons above 5 GeV
Crab: ~ 100 photons above 5 GeV



CALET Capability for Detection of Gamma-ray Lines from Dark Matter

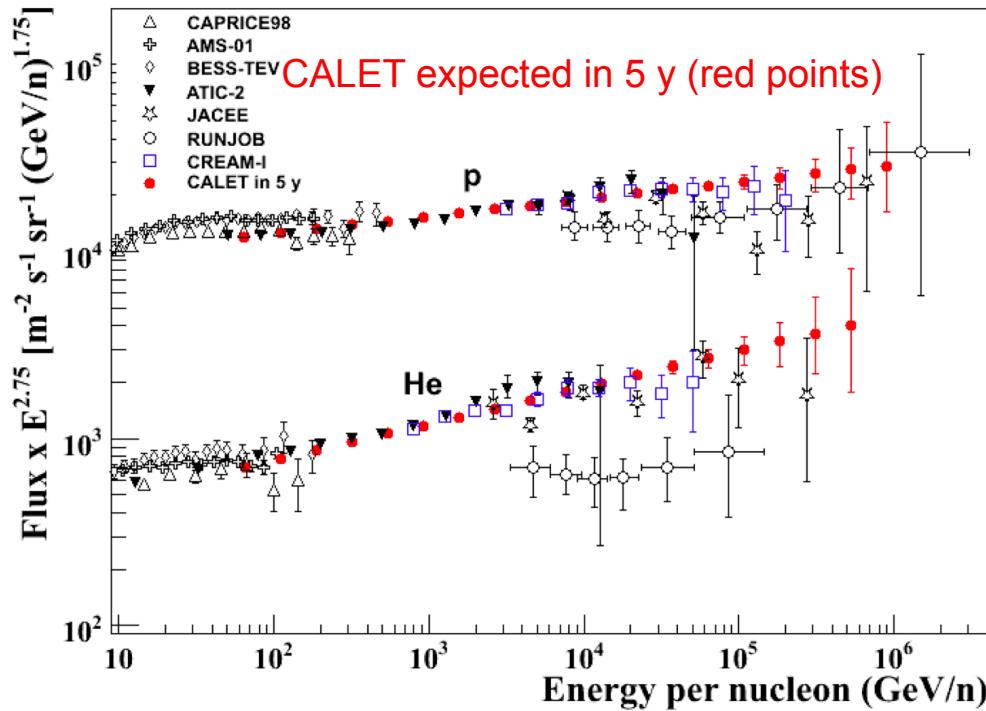
Monochromatic gamma-ray signals from WIMP dark matter annihilation would provide a distinctive signature of dark matter, if detected. Since **gamma-ray line signatures are expected in the sub-TeV to TeV region**, due to annihilation or decay of dark matter particles, **CALET**, with an **excellent energy resolution of 1 - 3 % above 100 GeV**, is a suitable instrument to detect these signatures .



- Simulated 1.4 TeV gamma-ray line from dark matter toward the Galactic center ($300^\circ < |l| < 60^\circ$, $|b| < 10^\circ$) including the Galactic diffuse background for CALET 5 year observations.
- The annihilation cross-section is taken as $\langle\sigma v\rangle_{\gamma\gamma} = 1 \times 10^{-25} \text{ cm}^3 \text{s}^{-1}$ with a NFW halo profile. The distinctive line signature is clearly seen in the gamma-ray spectrum.



P and He Observation



Energy reach in 5 years:

- Proton spectrum to ≈ 900 TeV
- He spectrum to ≈ 400 TeV/n

Multi -TeV Region

- Proton and He **slopes** are different ?
- Single power law or **curvature**.
- Is there a **proton cutoff** below 1 PeV ?

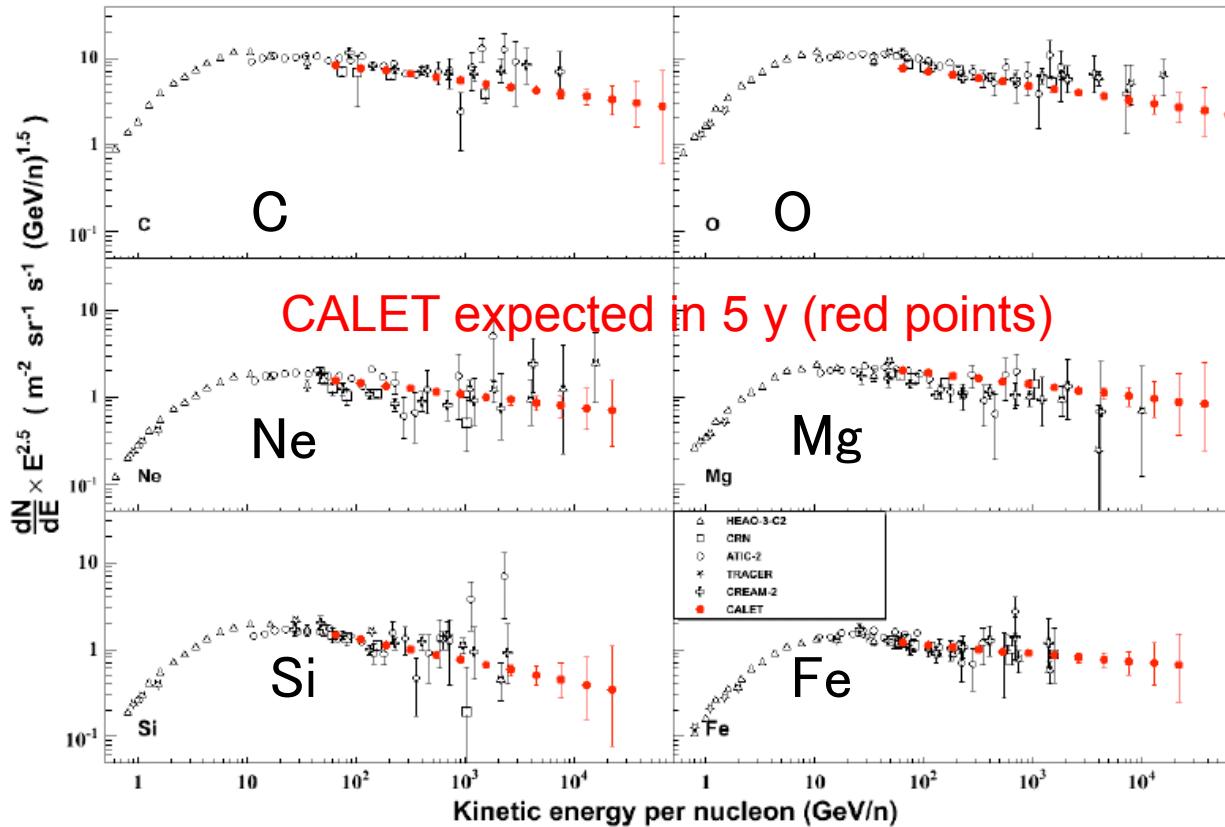
Requirements for calorimetry:

- **Proton** interaction requires $> 0.5 \lambda_{\text{INT}}$
- Energy Measurement at 100 TeV scale requires confinement of the e.m. core of the shower, i.e. $> 20 X_0$

	λ_{INT}	X_0 (nominal incidence)
CALET	1.5	30
CREAM	0.5+0.7	20
AMS-02	0.5	17

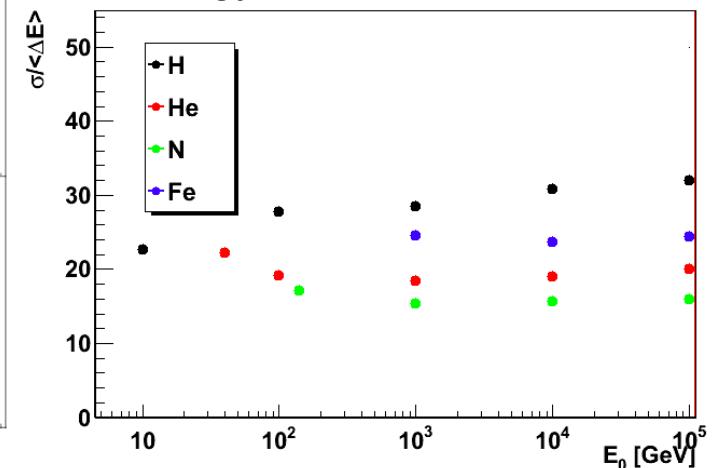


Intermediate nuclei to Fe Observation



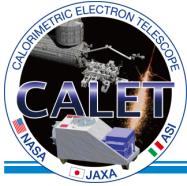
- Is there a **spectral cutoff** below 1 PeV ?
- single power law or **spectrum concavity** ?

Energy resolution for nuclei



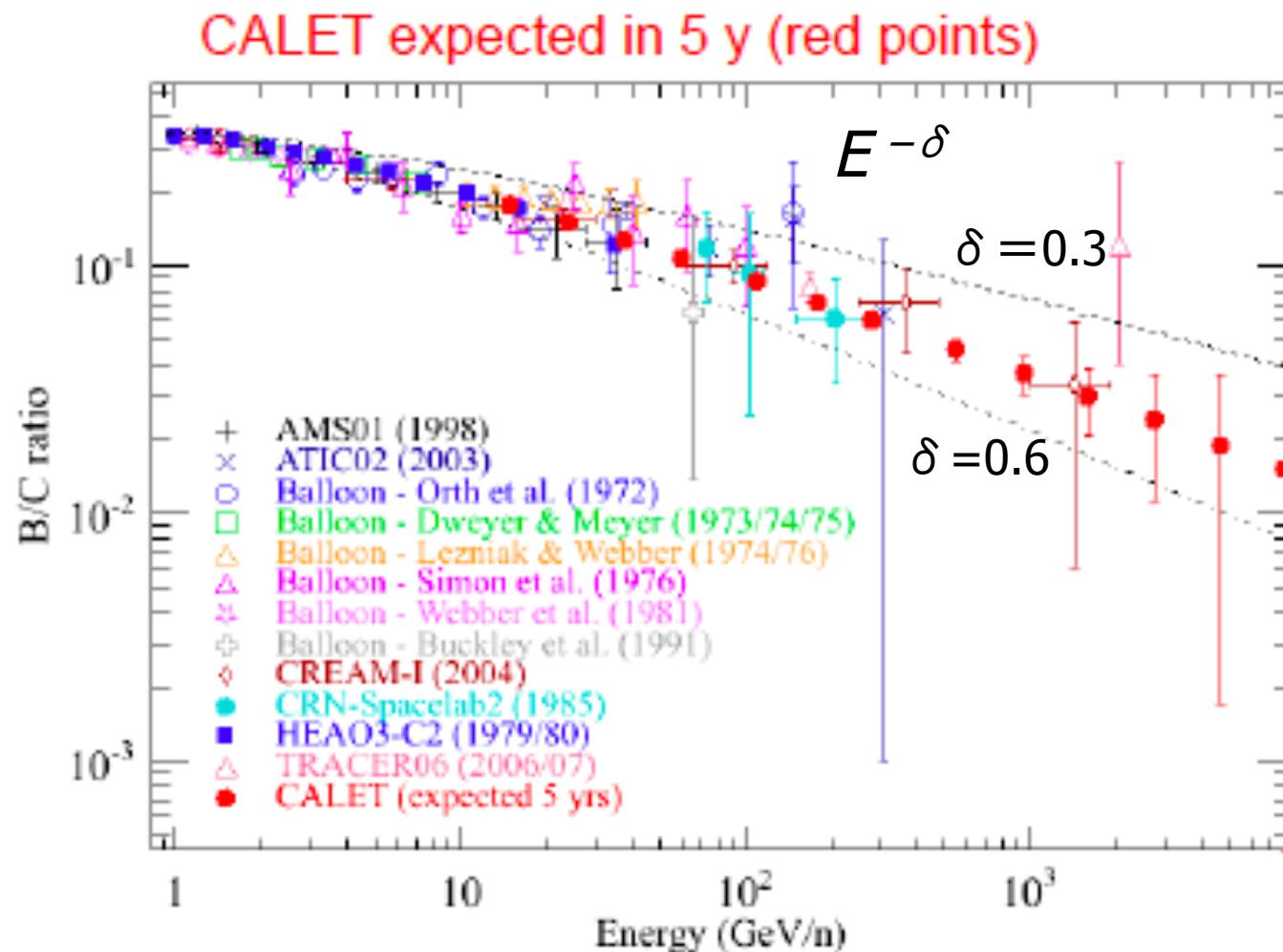
Spectra of C, O, Ne, Mg, Si to ≈ 20 TeV/n
 B/C ratio to $\approx 4\text{-}6$ TeV/n
 Fe spectrum to ≈ 10 TeV/n

CALET energy reach
 (5 years)



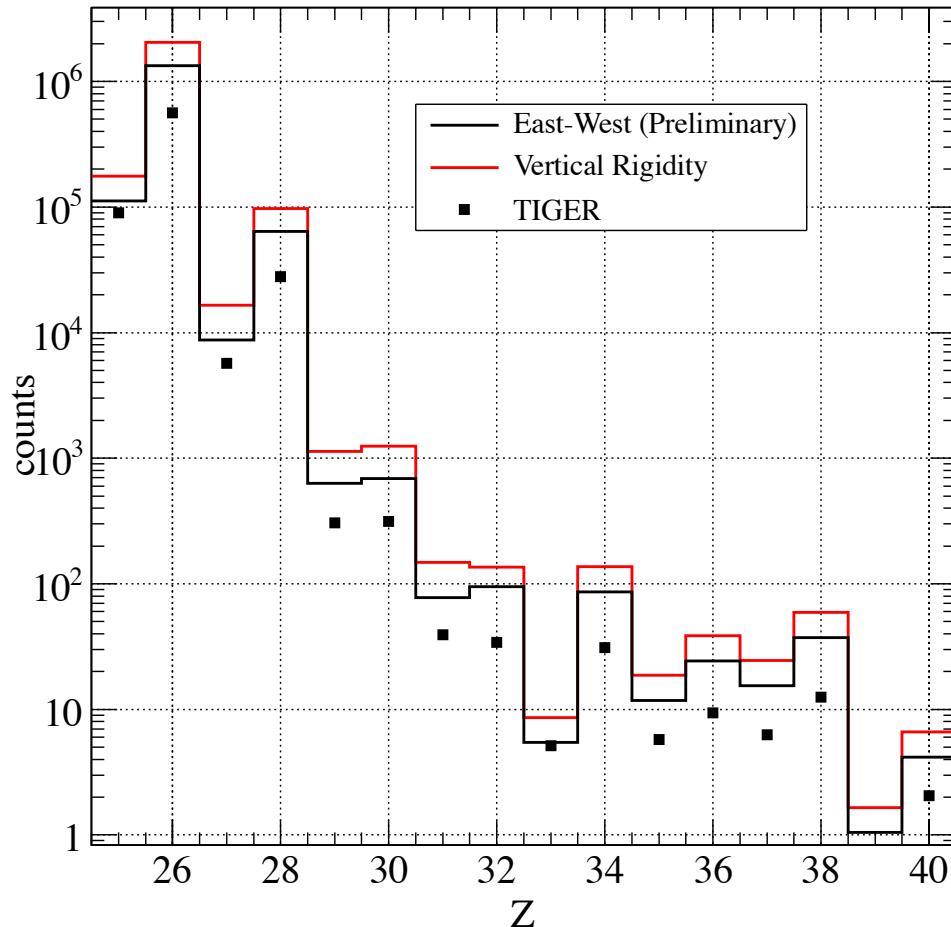
B/C ratio measurements by CALET

CALET will measure the B/C ratio to over 1 Tev/nucleon and provide an exact value of the energy exponent δ within an accuracy of 0.05





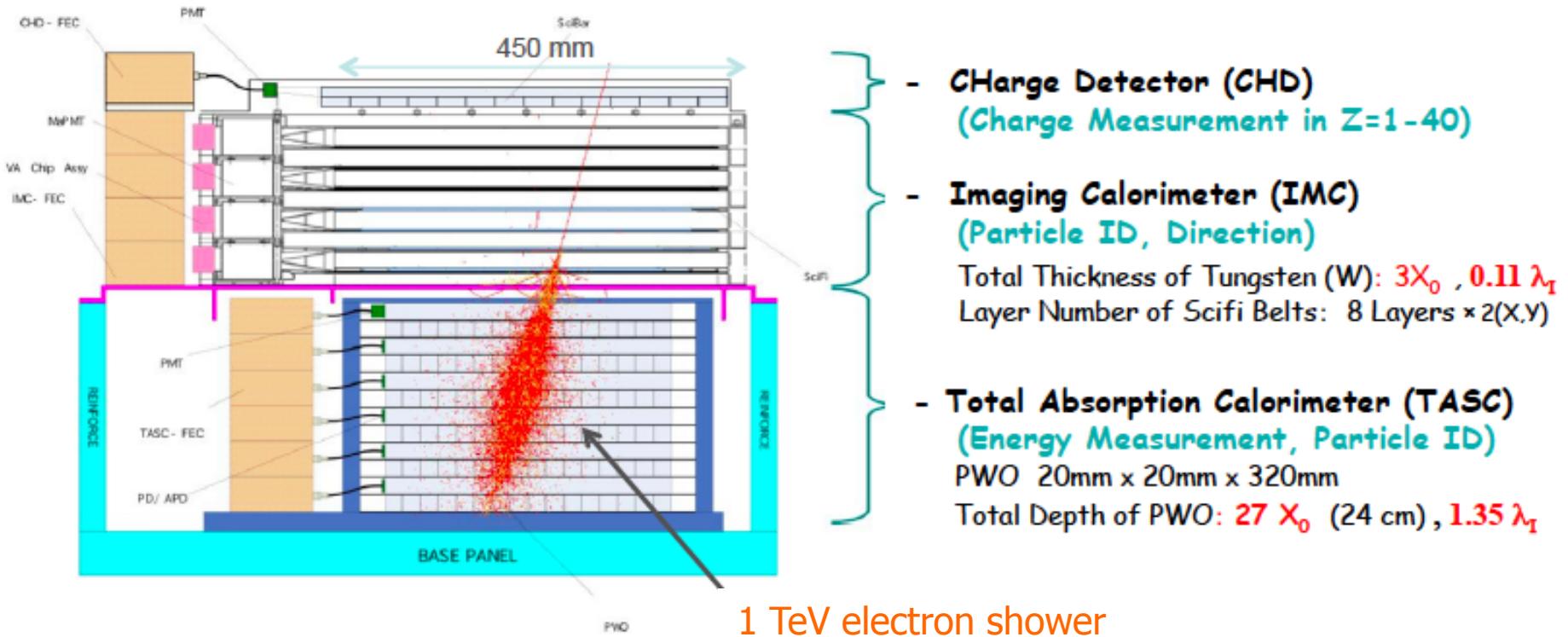
Expected CALET UH-GCR Measurement



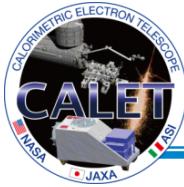
- CALET should obtain 2-4× the statistics of TIGER in expected 5 year mission.
- Assumption that results for vertical cutoff rigidities represent average of East-West effect is not valid.
- CALET measurements in orbit will require less correction for nuclear interactions.



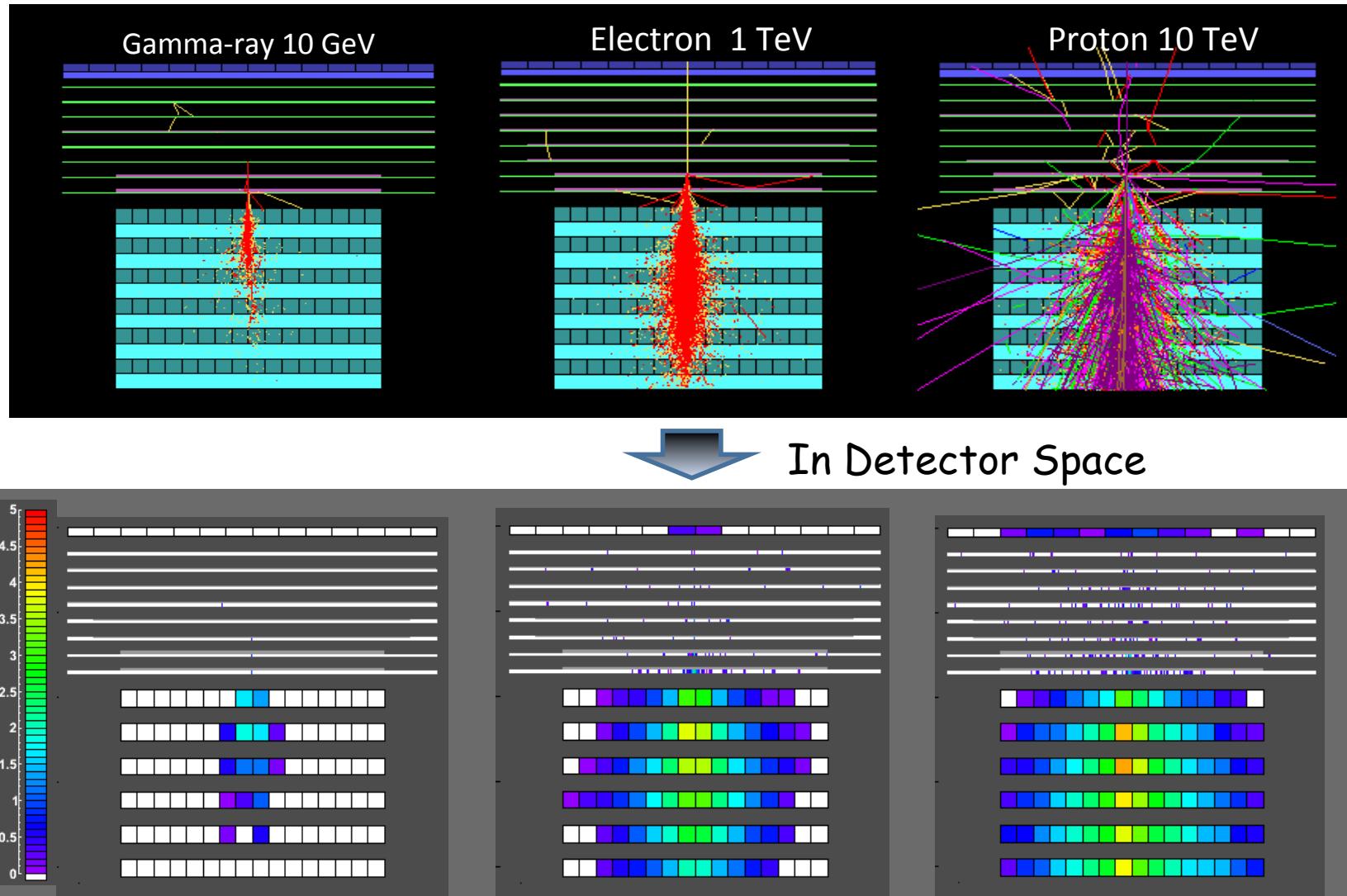
Overview of the CALET Instrument



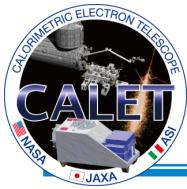
	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Function	Charge Measurement ($Z=1-40$)	Arrival Direction, Particle ID	Energy Measurement, Particle ID
Sensor (+ Absorber)	Plastic Scintillator : 2 layers Unit Size: 32mm \times 10mm \times 450mm	SciFi : 16 layers Unit size: 1mm ² \times 448 mm Total thickness of Tungsten: $3 X_0$	PWO log: 12 layers Unit size: 19mm \times 20mm \times 326mm Total Thickness of PWO: $27 X_0$
Readout	PMT+CSA	64 -anode PMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger) - 2 -



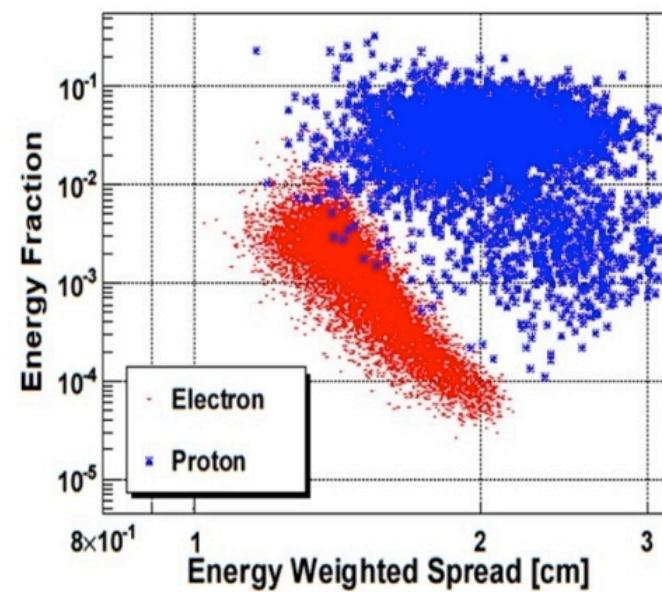
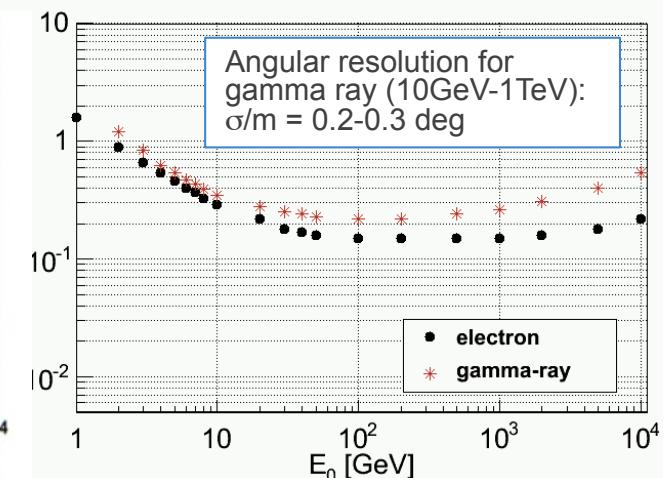
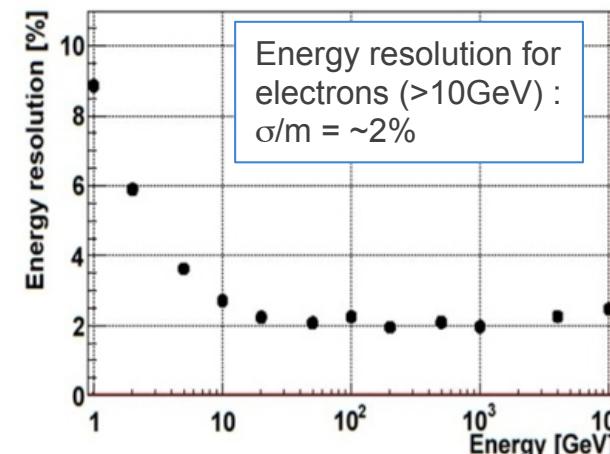
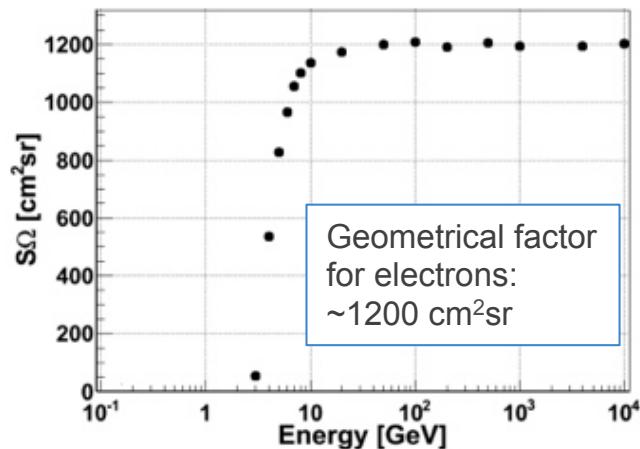
CALET/CAL Shower Imaging Capability (Simulation)



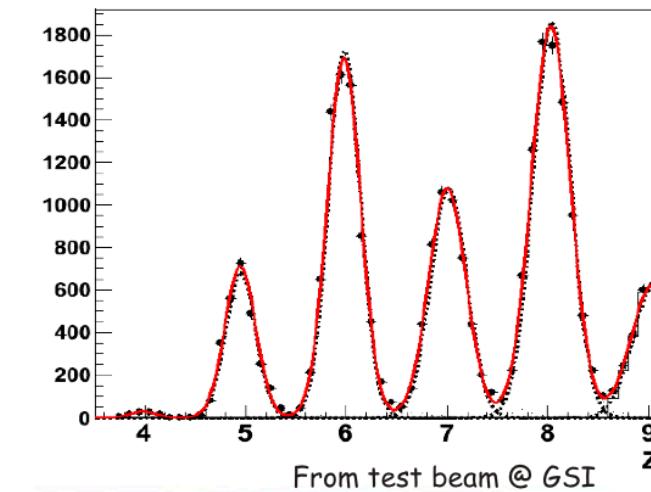
- Proton rejection power of 10^5 can be achieved with IMC and TASC shower imaging capability.
- Charge of incident particle is determined to $\sigma_z=0.15-0.3$ with the CHD.



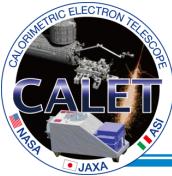
CALET Expected Performance by Simulations



Proton rejection power at 1TeV $\approx 10^5$ with 95% efficiency for electrons

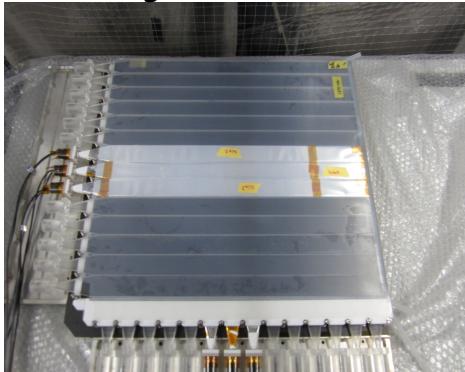


Experiment CHD
Charge resolution:
 $\sigma_Z = 0.15 - 0.3$

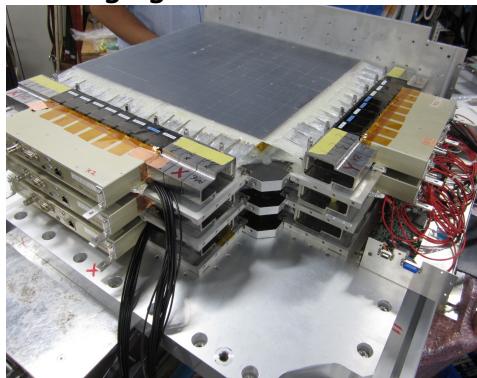


CERN Beam Test using the Structure & Thermal Model (STM)

Charge Detector: CHD



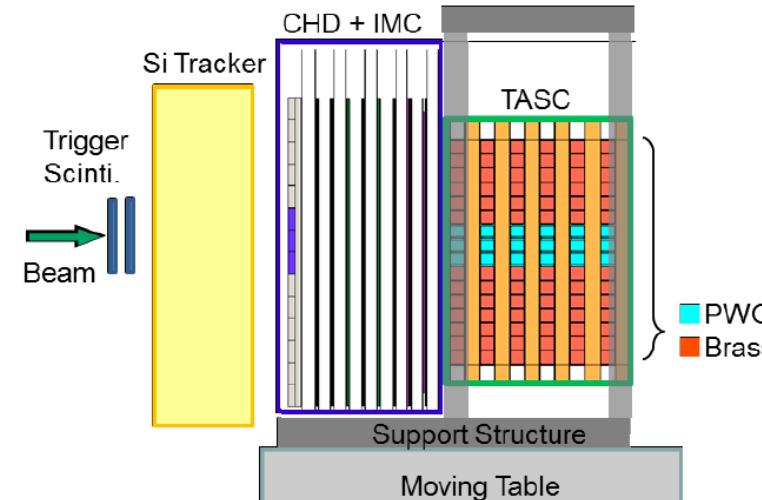
Imaging Calorimeter: IMC



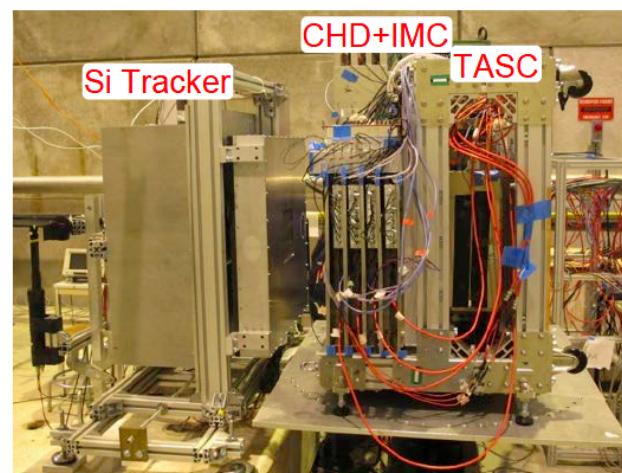
Total Absorption Calorimeter: TASC



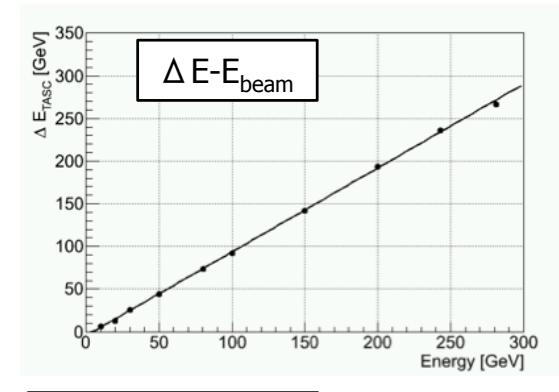
Schematic Side View of the Beam Test Model



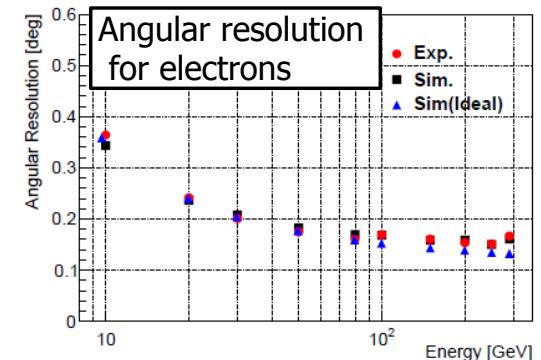
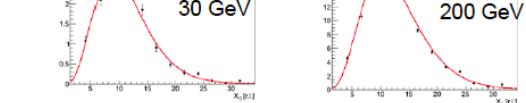
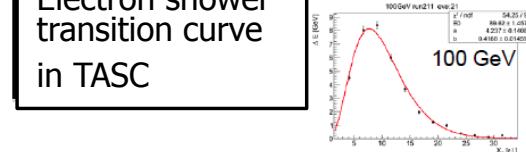
The Beam Test Model at CERN SPS H8 Beam Line

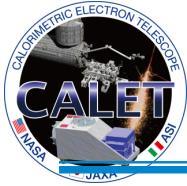


Beam Test Results



Electron shower transition curve in TASC



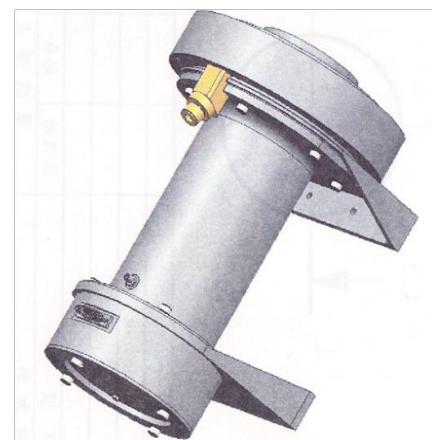
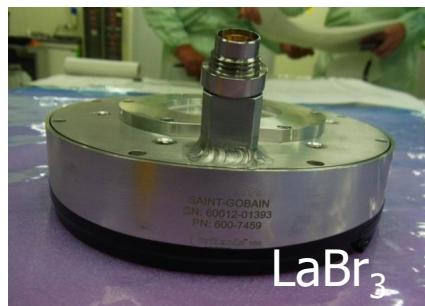


Characteristics of HXM and SGM in CGBM

	HXM	SGM
Detector (Crystal)	LaBr ₃ (Ce)	BGO
Number of Detector	2	1
Diameter (mm)	66(front), 79(rear)	102
Thickness(mm)	12.7	76
Geometrical Area (cm ²)	68(front),97(rear)*	82
Energy Range (keV)	7–1000	100–20000
Energy Resolution@662 keV	~4%	~15%
Field of View (FOV)	~ π str.	~4 π str.

* two detectors are combined.

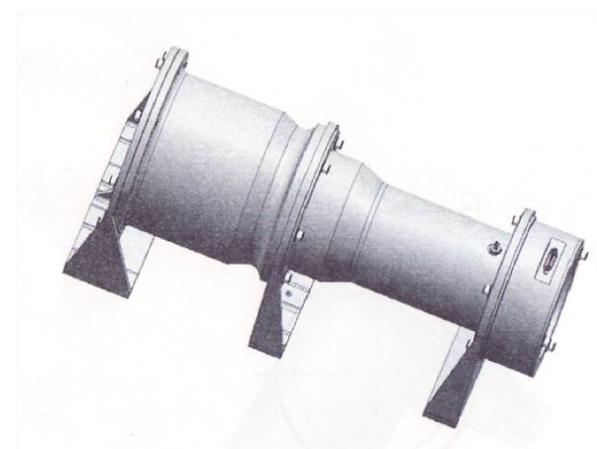
HXM

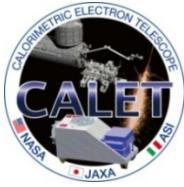


SGM



BGO





CALET GRB performance

Broad energy range (from few keV X-rays to GeV-TeV gamma-rays):
long-duration GRBs, short-duration GRBs, X-ray flashes and GeV GRBs.
Sensitivity of CGBM: $\sim 10^{-8}$ ergs cm $^{-2}$ s $^{-1}$ (1-1000 keV) for 50 s long bursts.

Parameters	CAL	CGBM
Energy range	1 GeV - 10 TeV (GRB trigger)	HXM: 7 keV - 1 MeV (goal 3 keV - 3 MeV) SGM: 100 keV - 20 MeV (goal 30 keV - 30 MeV)
Energy resolution	3% (10 GeV)	HXM: ~3% (662 keV) SGM: ~15% (662 keV)
Effective area	~600 cm 2 (10 GeV)	68 cm 2 (2 HXMs), 82 cm 2 (SGM)
Angular resolution	2.5° (1 GeV) 0.35° (10 GeV)	-
Field of view	~45° (~2 sr)	~3 sr (HXM), ~4π sr (SGM)
Dead time	2 ms	40 μs
Time resolution	62.5 μs	GRB trigger: 62.5 μs (event-by-event data) Normal mode: 125 ms with 8 ch, 4 s with 512 ch (histogram data)

Summary and Future Prospects

- ✧ CALET is primarily dedicated to observing electrons into the trans-TeV region to provide crucial information on nearby astrophysical sources and dark matter.
 - Electrons from 1 GeV to 20,000 GeV
 - Gamma-rays from 10 GeV to 10,000 GeV
 - Protons and heavy ions ($Z < \sim 28$) from 10's of GeV to $\sim 1,000$ TeV
 - Ultra Heavy ion ($28 < Z < \sim 40$) for energy greater than ~ 600 MeV/n
 - Gamma ray bursts 7keV to 20 MeV with HXM & SGM and ~ 1 GeV to 10 TeV with Calorimeter
- ✧ The CALET detectors are based on designs proven during balloon flights (BETS, bCALET) and accelerator beam tests.
- ✧ Development of the CALET flight hardware is now well underway.
- ✧ The CALET project has been approved for launch in FY2014 by HTV-5 to the Japanese Experiment Module (Kibo).
- ✧ The target mission is 5 years -> electron exposure = $220 \text{ m}^2 \text{ sr days}$