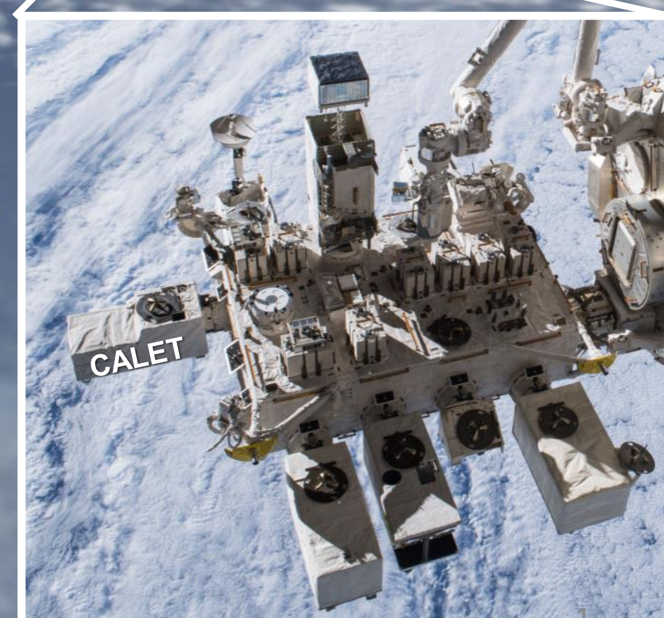
Recent Results and Dark Matter Search with CALET on the ISS

<u>Yoichi Asaoka</u>
for the CALET collaboration
WISE, Waseda University



CALET Collaboration Team

O. Adriani[25], Y. Akaike[2], K. Asano[7], Y. Asaoka[9,31], M.G. Bagliesi[29], E. Berti[25], G. Bigongiari[29], W.R. Binns[32], S. Bonechi[29], M. Bongi[25], P. Brogi[29], A. Bruno[15], J.H. Buckley[32], N. Cannady[13], G. Castellini[25], C. Checchia[26],M.L. Cherry[13], G. Collazuol[26], V. Di Felice[28], K. Ebisawa[8], H. Fuke[8], T.G. Guzik[13], T. Hams[3], N. Hasebe[31], K. Hibino[10], M. Ichimura[4], K. Ioka[34], W. Ishizaki[7], M.H. Israel[32], K. Kasahara[31], J. Kataoka[31], R. Kataoka[17], Y. Katayose[33], C. Kato[23], Y.Kawakubo[13], N. Kawanaka[30], K. Kohri [12], H.S. Krawczynski[32], J.F. Krizmanic[2], T. Lomtadze[27], P. Maestro[29], P.S. Marrocchesi[29], A.M. Messineo[27], J.W. Mitchell[15], S. Miyake[5], A.A. Moiseev[3], K. Mori[9,31], M. Mori[20], N. Mori[25], H.M. Motz[31], K. Munakata[23], H. Murakami[31], S. Nakahira[9], J. Nishimura[8], G.A De Nolfo[15], S. Okuno[10], J.F. Ormes[25], S. Ozawa[31], L. Pacini[25], F. Palma[28], V. Pal'shin[1], P. Papini[25], A.V. Penacchioni[29], B.F. Rauch[32], S.B. Ricciarini[25], K. Sakai[3], T. Sakamoto[1], M. Sasaki[3], Y. Shimizu[10], A. Shiomi[18], R. Sparvoli[28], P. Spillantini[25], F. Stolzi[29], S. Sugita[1], J.E. Suh[29], A. Sulaj[29], I. Takahashi[11], M. Takayanagi[8], M. Takita[7], T. Tamura[10], N. Tateyama[10], T. Terasawa[7], H. Tomida[8], S. Torii[31], Y. Tunesada[19], Y. Uchihori[16], S. Ueno[8], E. Vannuccini[25], J.P. Wefel[13], K. Yamaoka[14], S. Yanagita[6], A. Yoshida[1], and K. Yoshida[22]

1) Aoyama Gakuin University, Japan
2) CRESST/NASA/GSFC and Universities Space Research Association, USA
3) CRESST/NASA/GSFC and University of Maryland, USA
4) Hirosaki University, Japan
5) Ibaraki National College of Technology, Japan
6) Ibaraki University, Japan
7) ICRR, University of Tokyo, Japan
8) ISAS/JAXA Japan
9) JAXA, Japan
10) Kanagawa University, Japan
11) Kavli IPMU, University of Tokyo, Japan
12) KEK, Japan
13) Louisiana State University, USA
14) Nagoya University, Japan
15) NASA/GSFC, USA
16) National Inst. of Radiological Sciences, Japan
17) National Institute of Polar Research, Japan
18) Nihon University, Japan
19) Osaka City University, Japan
20) Ritsumeikan University, Japan
21) Saitama University, Japan
22) Shibaura Institute of Technology, Japan
23) Shinshu University, Japan
24) University of Denver, USA
25) University of Florence, IFAC (CNR) and INFN, Italy
26) University of Padova and INFN, Italy
27) University of Pisa and INFN, Italy
28) University of Rome Tor Vergata and INFN, Italy
29) University of Siena and INFN, Italy
30) University of Tokyo, Japan
31) Waseda University, Japan
32) Washington University-St. Louis, USA
33) Yokohama National University, Japan
34) Yukawa Institute for Theoretical Physics, Kyoto University, Japan

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Outline

1. Introduction
   - Objectives
   - Instrument
   - Calibration
   - Operations
2. Results
   - Electrons
   - (Protons)
3. Indirect Dark Matter Searches with CALET
   - H.Motz et al. PoS (ICRC2019) 533 (as an example)
   - **not a collaboration work, just uses published spectra**
4. Summary

Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al. (CALET Collaboration), Astropart. Phys. 91 (2017) 1.

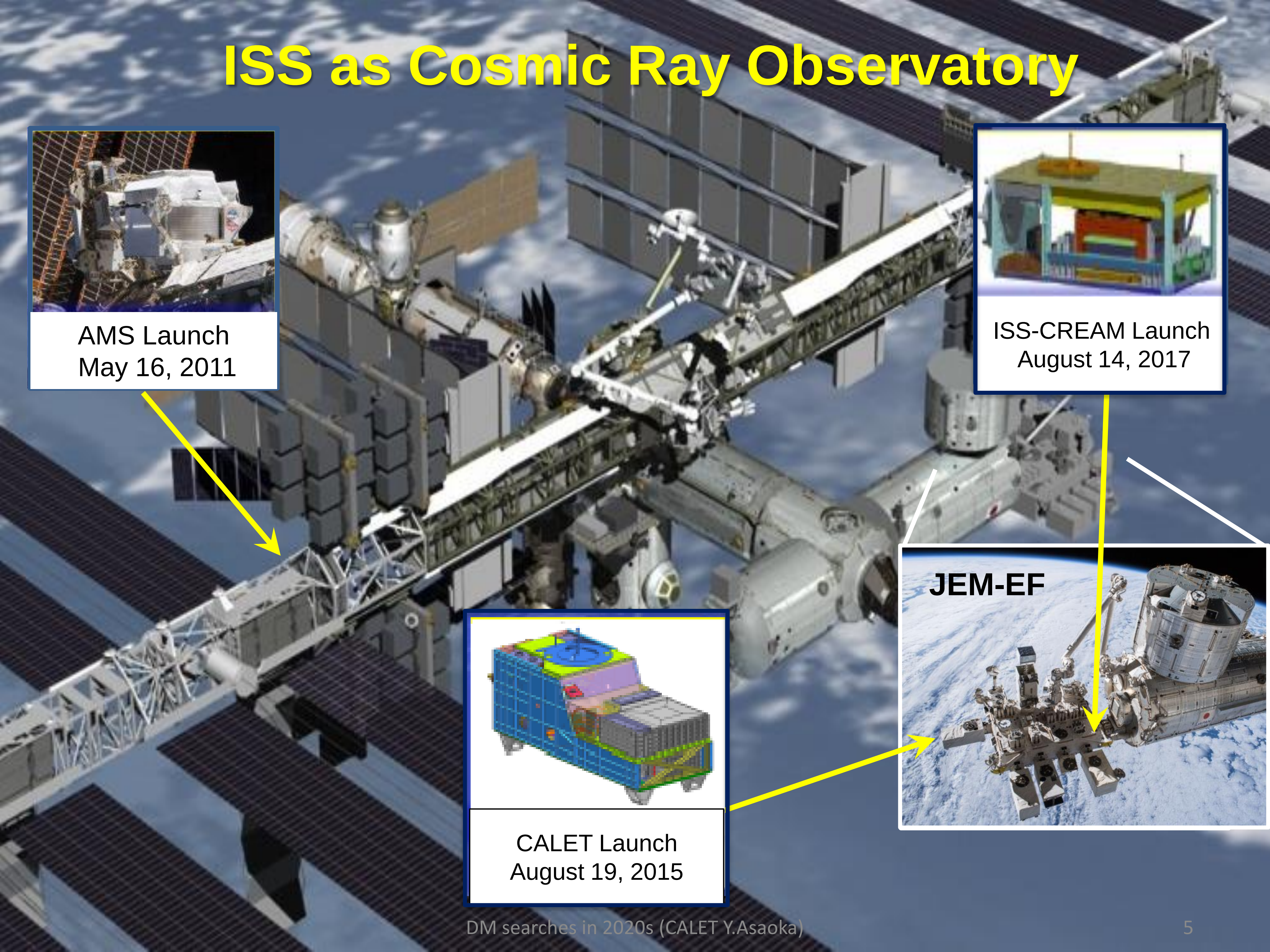
Y.Asaoka, S.Ozawa, S.Torii et al. (CALET Collaboration), Astropart. Phys. 100 (2018) 29.

O.Adriani et al. (CALET Collaboration), Phys.Rev.Lett. 119 (2017) 181101.

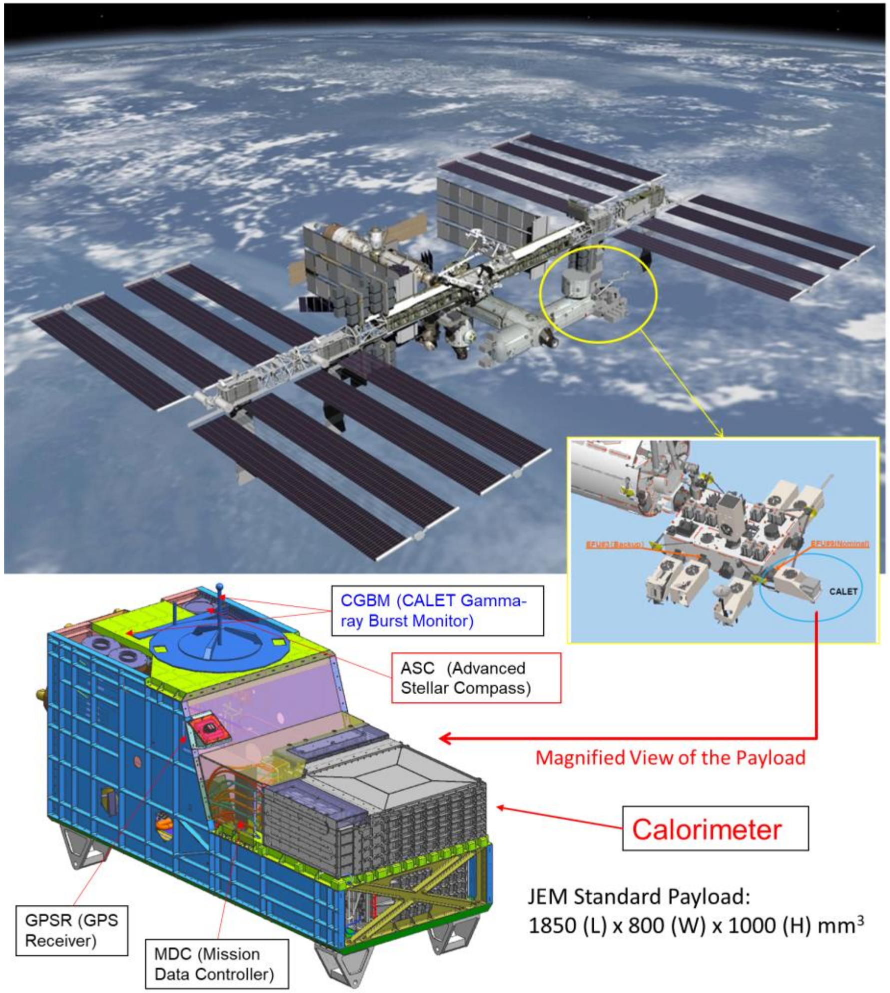
O.Adriani et al. (CALET Collaboration), Phys.Rev.Lett. 120 (2018) 261102.

O.Adriani et al. (CALET Collaboration), Phys.Rev.Lett. 120 (2018) 261102.

ISS as Cosmic Ray Observatory



CALET: Cosmic Ray Detector onboard the ISS

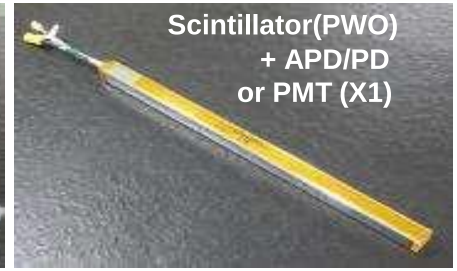


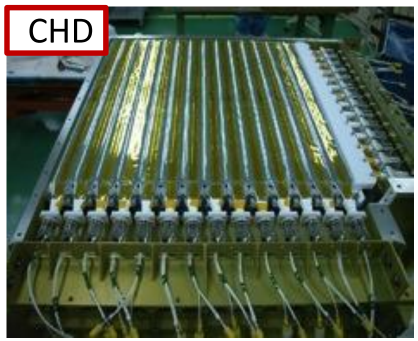
Continues stable observation since Oct. 13, 2015 and collected ~1.8 billion events so far.

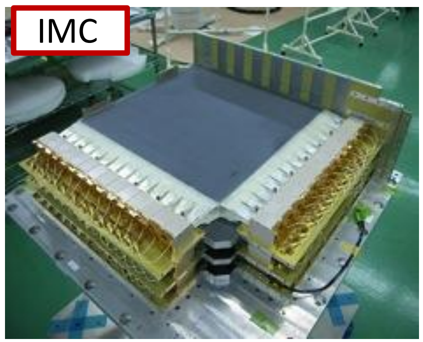
Overview of CALET Observations

- Direct cosmic ray observations in space at the highest energy region by combining:
  - ✓ A large-size detector
  - ✓ Long-term observation onboard the ISS (5 years or more is expected)
- Electron observation in the 1 GeV - 20 TeV energy range, with high energy resolution owing to optimization for electron detection
  ⇨ Search for Dark Matter and Nearby Sources
- Observation of cosmic-ray nuclei in the 10 GeV - 1 PeV energy range.
  ⇨ Unravelling the CR acceleration and propagation mechanism
- Detection of transients in space by long-term stable observations
  ⇨ EM radiation from GW sources, Gamma-ray burst, Solar flare, etc.

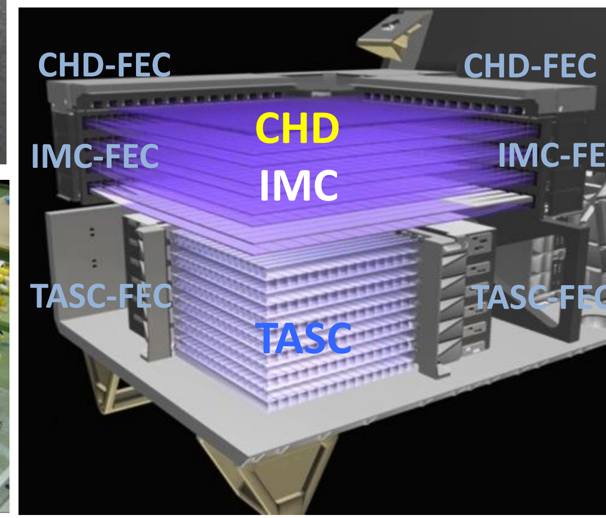
CALET Instrument







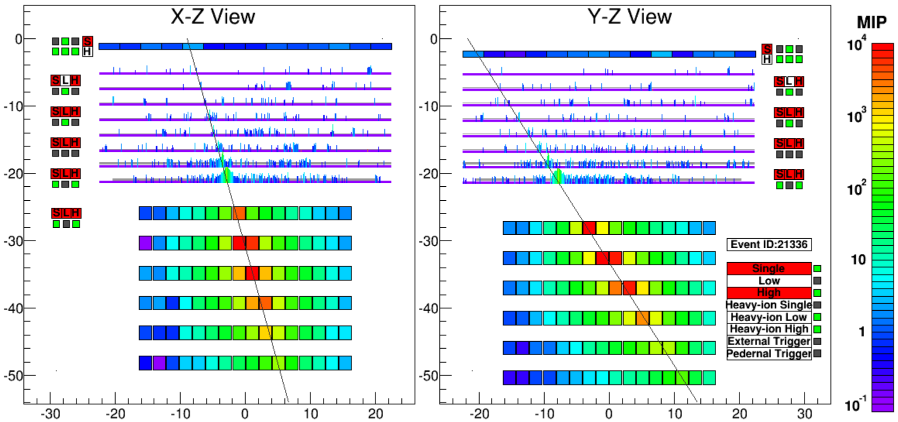
CALORIMETER



	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	Charge (Z=1-40)	Tracking , Particle ID	Energy, e/p Separation
Geometry (Material)	Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3	448 Scifi x 16 layers (X,Y) : 7168 Scifi 7 W layers ($3X_0$): $0.2X_0$ x 5 + $1X_0$ x2 Scifi size : 1 x 1 x 448 mm^3	16 PWO logs x 12 layers (x,y): 192 logs log size: 19 x 20 x 326 mm^3 Total Thickness : 27 X_0 , ~1.2 λ_I
Readout	PMT+CSA	64-anode PMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger)@top layer

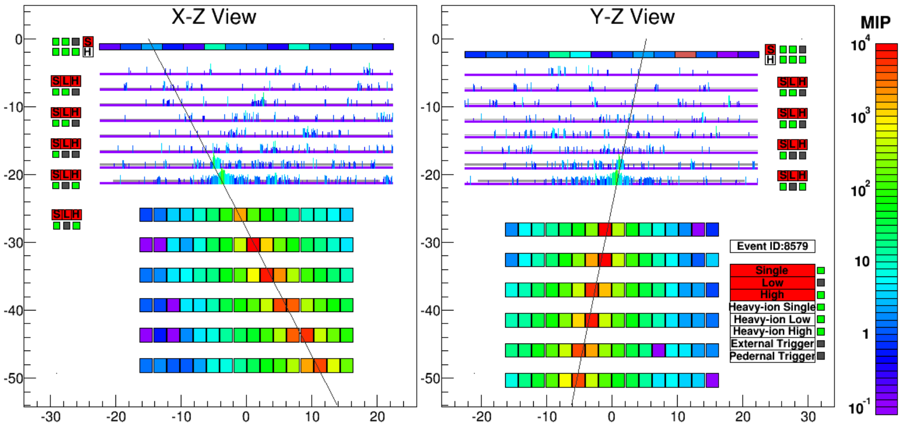
Event Examples of High-Energy Showers

Electron, E=3.05 TeV



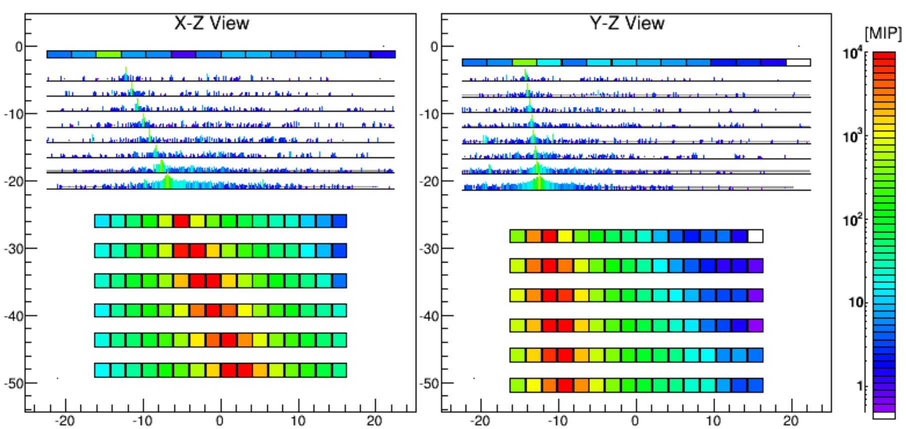
fully contained even at 3TeV

Proton, ΔE=2.89 TeV



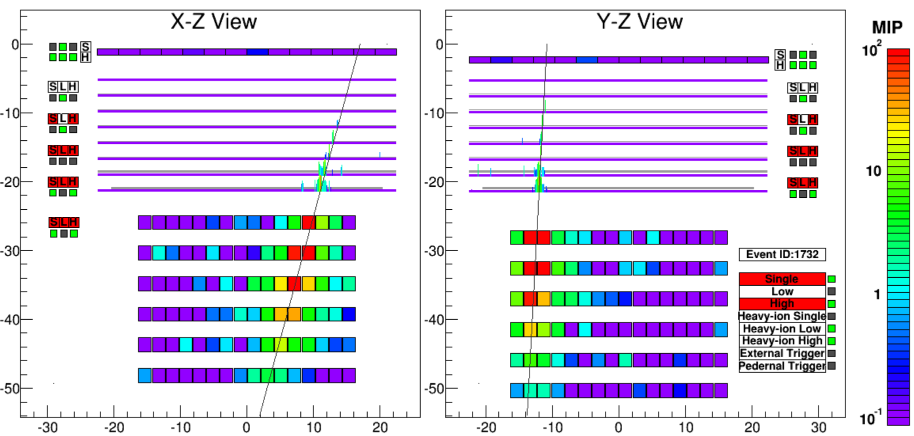
clear difference from electron shower

Fe(Z=26), ΔE=9.3 TeV



energy deposit in CHD consistent with Fe

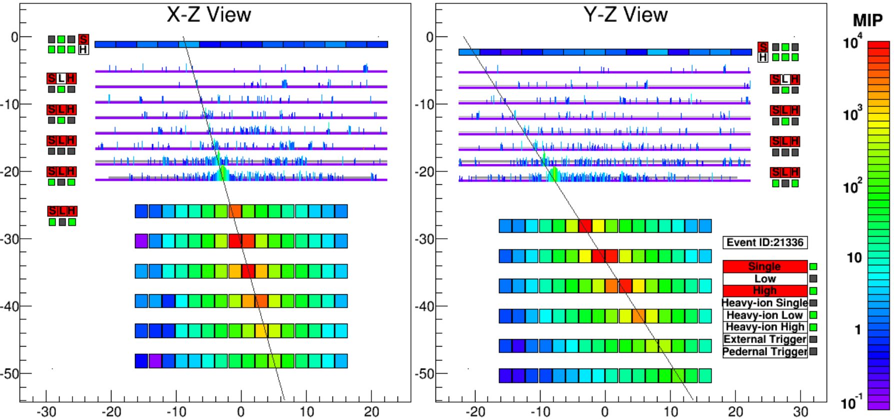
Gamma-ray, E=44.3 GeV



no energy deposit before pair production

Event Examples of High-Energy Showers

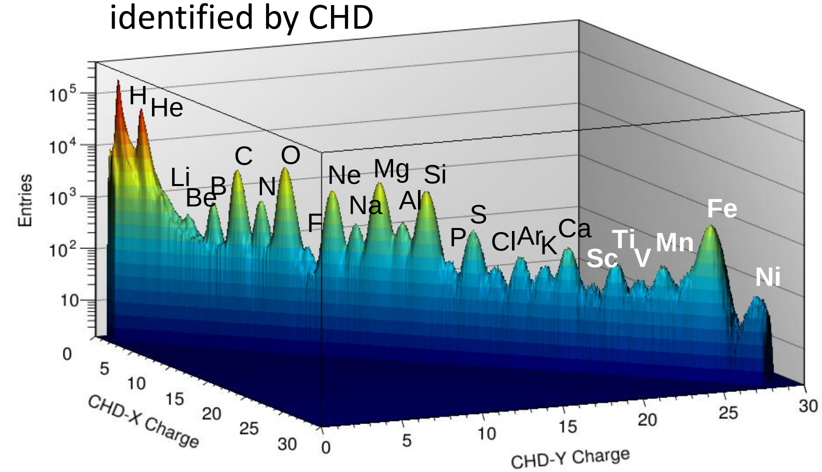
Electron, E=3.05 TeV



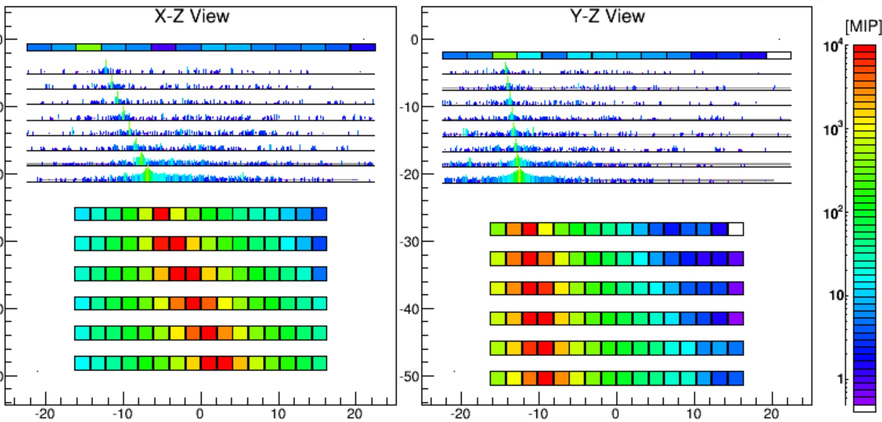
fully contained even at 3TeV

Proton, ΔE=2.89 TeV

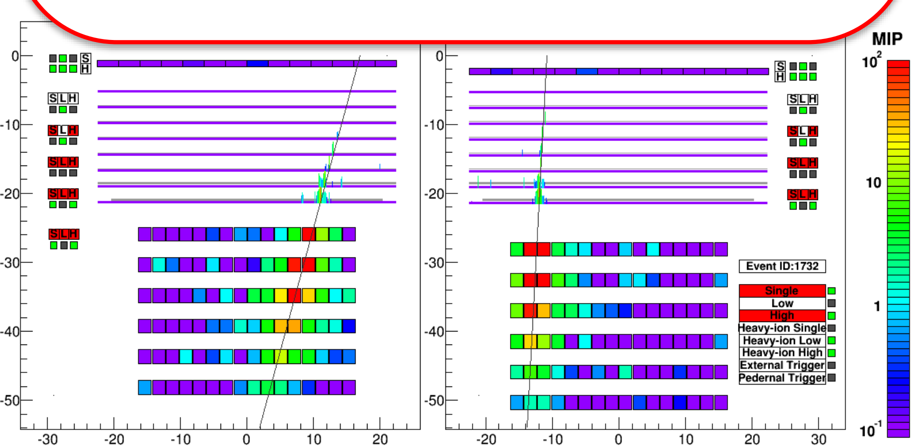
Individual elements up to Z=28 are clearly identified by CHD



Fe(Z=26), ΔE=9.3 TeV

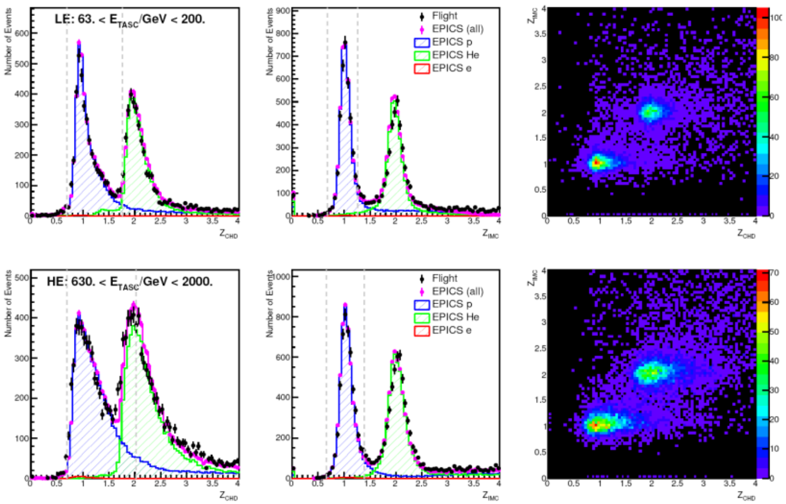


energy deposit in CHD consistent with Fe



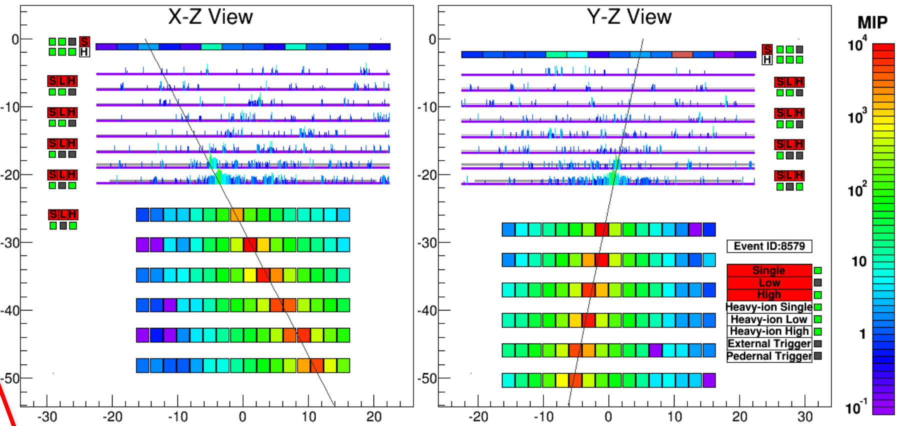
no energy deposit before pair production

Event Examples of High-Energy Showers



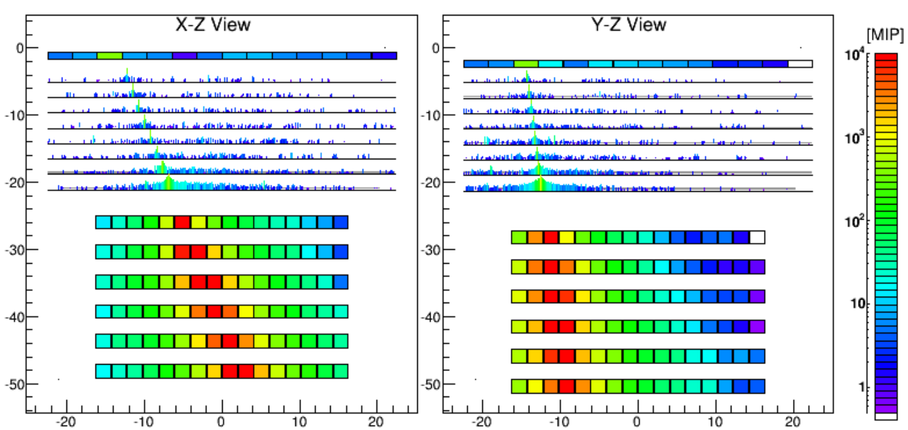
Proton/helium separation using CHD/IMC charge

Proton, ΔE=2.89 TeV



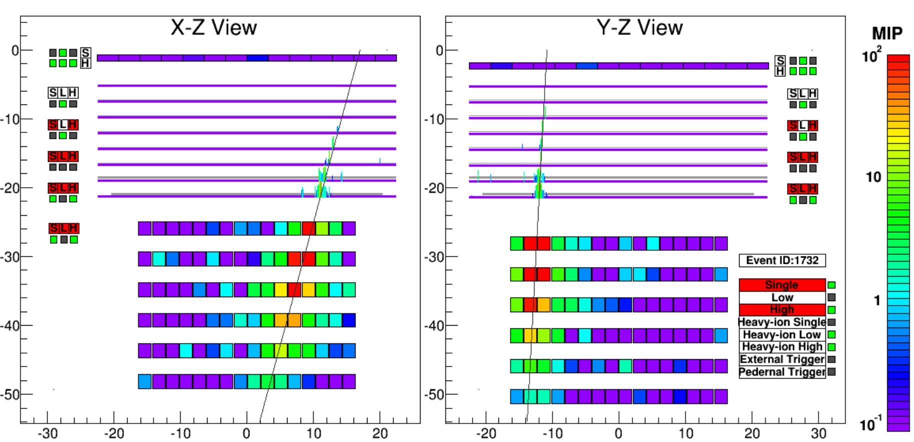
clear difference from electron shower

Fe(Z=26), ΔE=9.3 TeV



energy deposit in CHD consistent with Fe

Gamma-ray, E=44.3 GeV

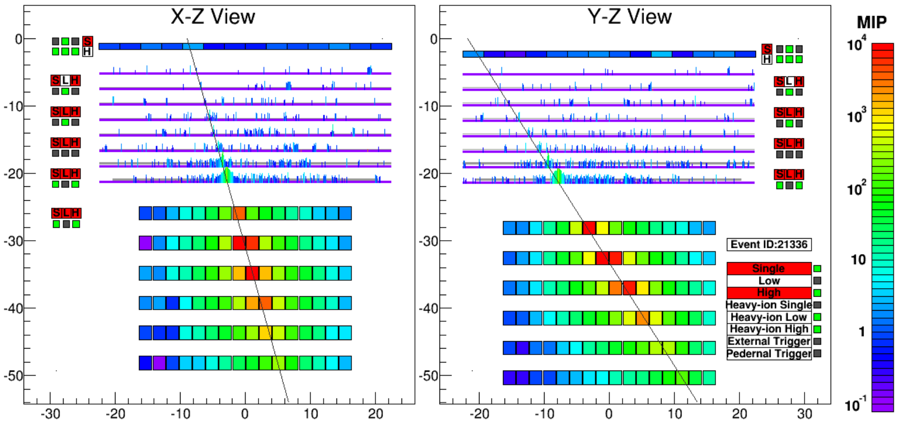


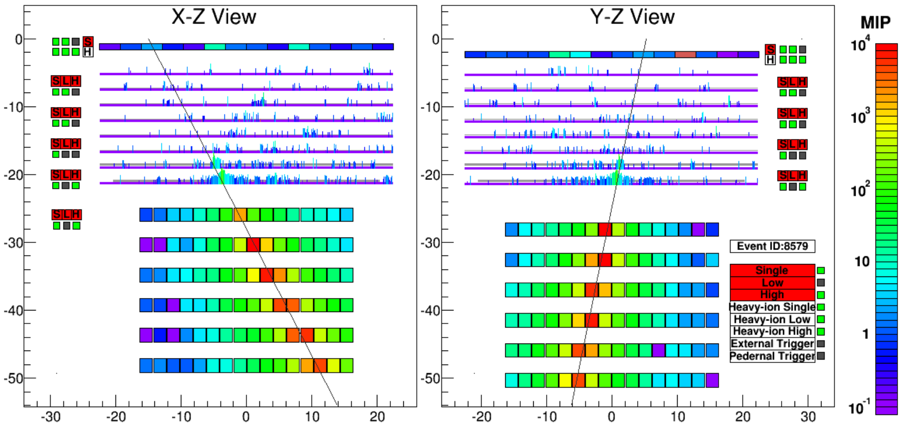
no energy deposit before pair production

Event Examples of High-Energy Showers

Electron, E=3.05 TeV

Proton, ΔE=2.89 TeV

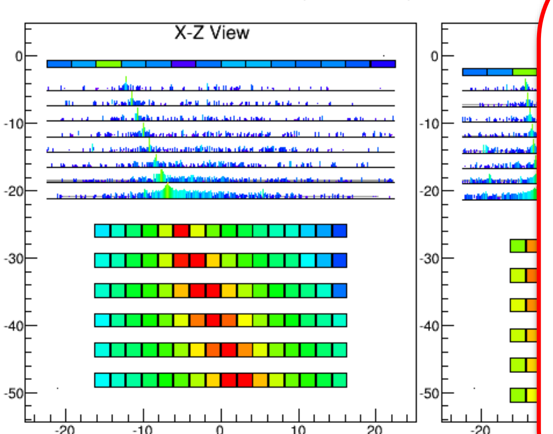




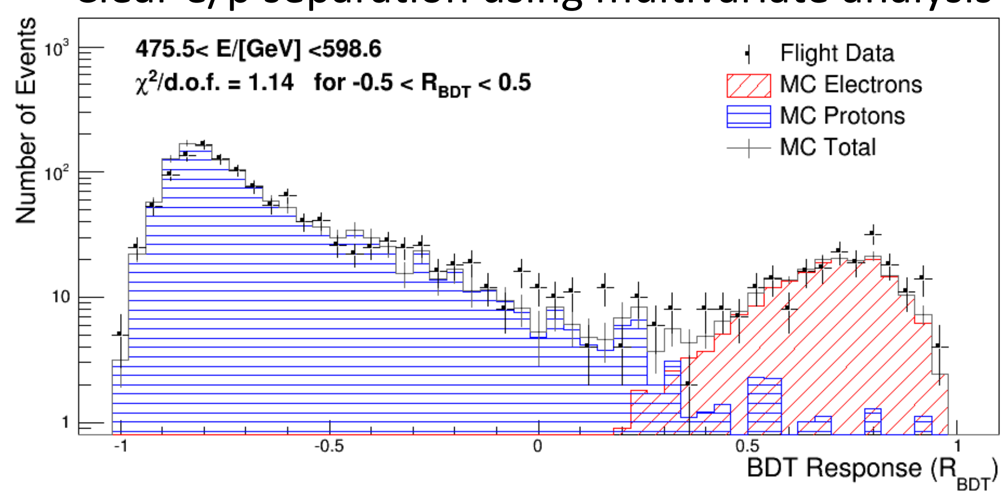
fully contained even at 3TeV

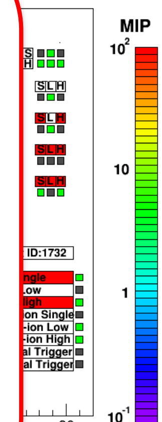
clear difference from electron shower

Fe(Z=26), ΔE=9.



Clear e/p separation using multivariate analysis





energy deposit in CHD cons

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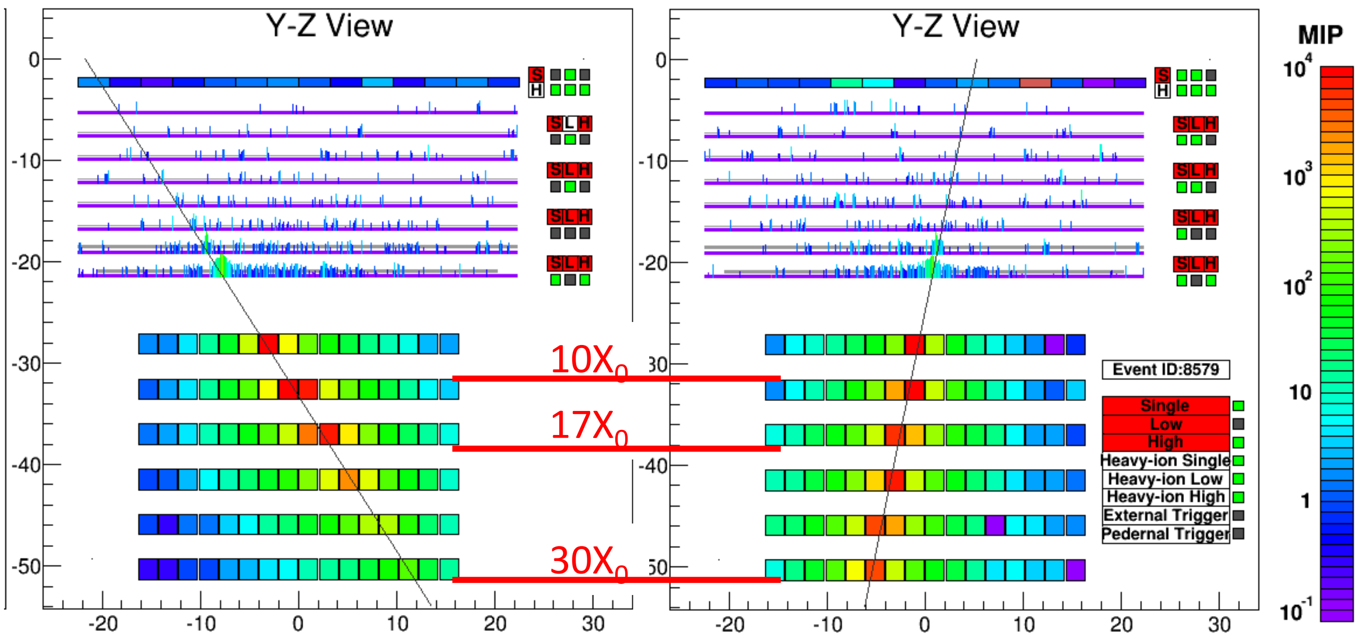
All-Electron Measurement with CALET

3TeV Electron Candidate

Corresponding Proton Background



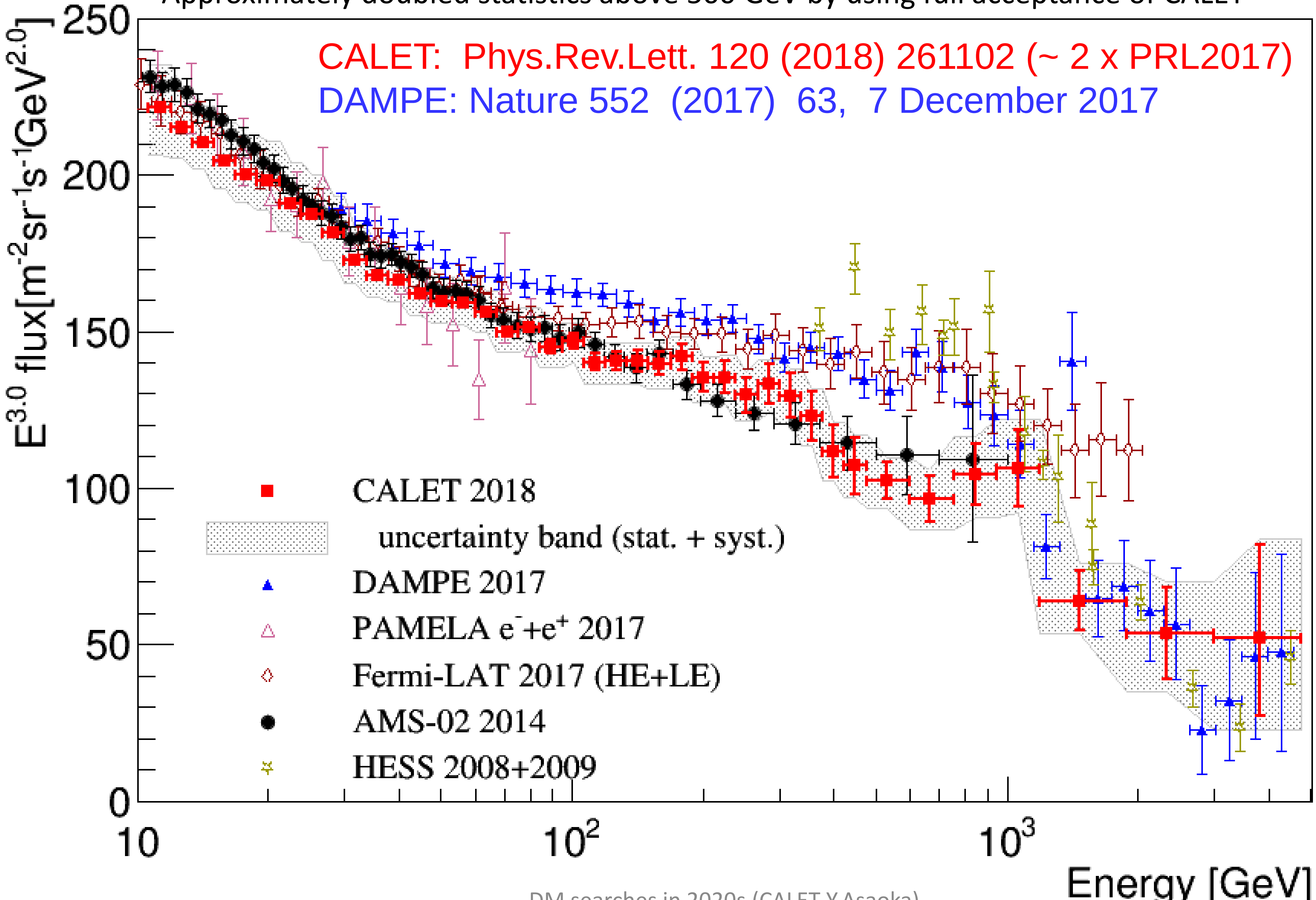
(Flight data; detector size in cm)

1. **Reliable tracking**
   well-developed shower core
2. **Fine energy resolution**
   full containment of TeV showers
3. **High-efficiency electron ID**
   $30X_0$ thickness, closely packed logs

⇒ CALET is best suited for observation of possible fine structures in the all-electron spectrum up to the trans-TeV region.

All Electron Spectrum: Extended Measurement by CALET

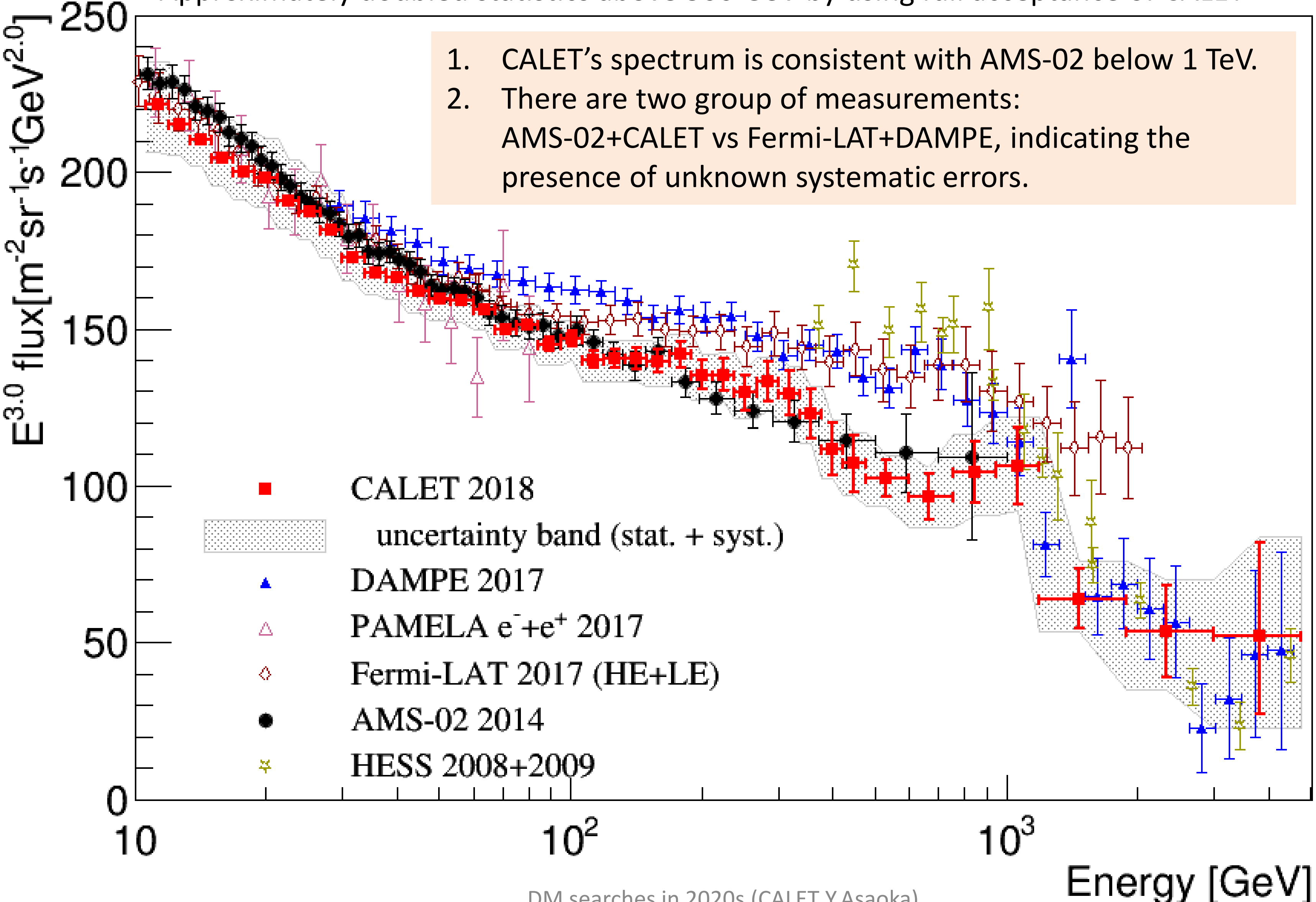
Approximately doubled statistics above 500 GeV by using full acceptance of CALET



All Electron Spectrum: Extended Measurement by CALET

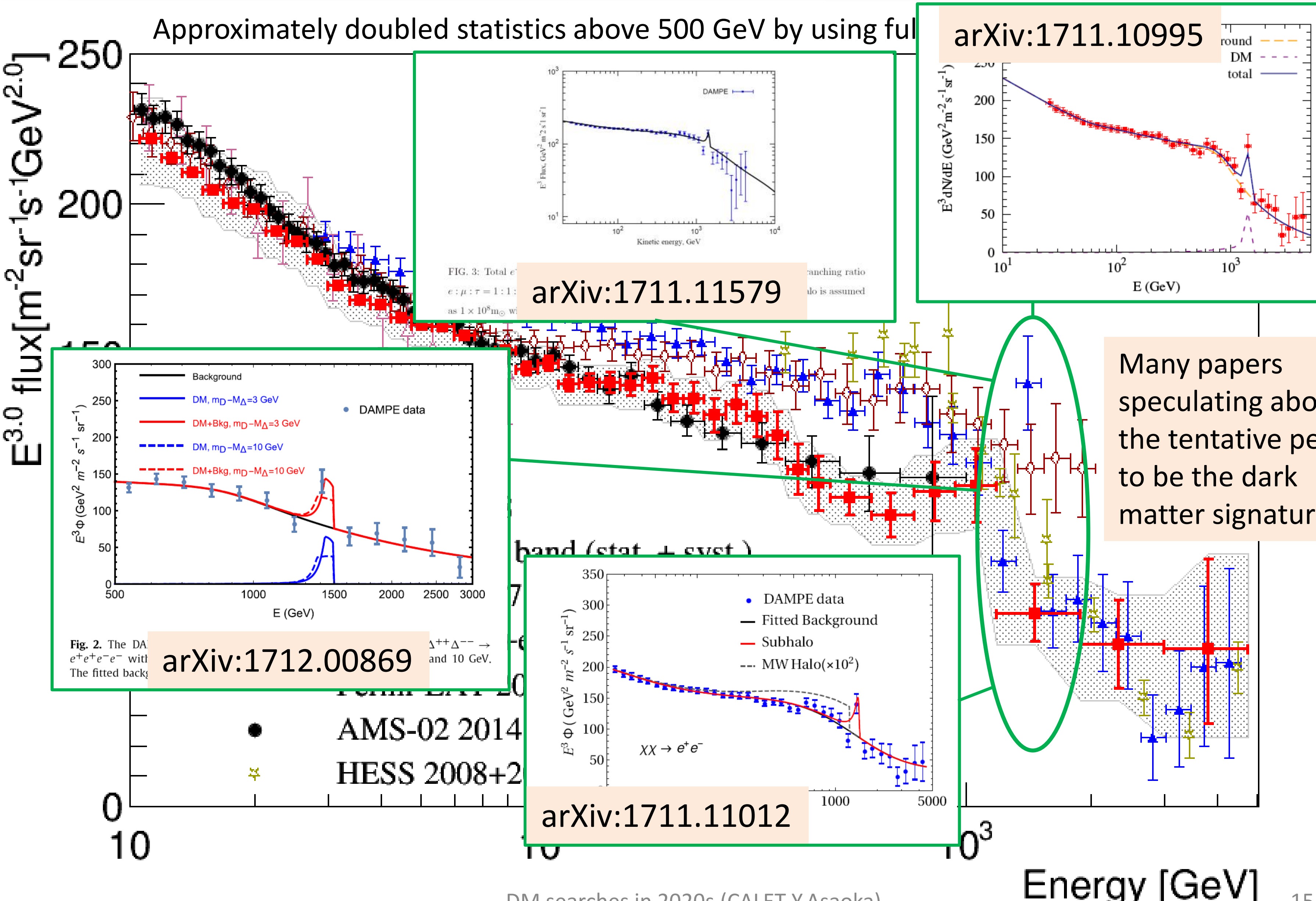
Approximately doubled statistics above 500 GeV by using full acceptance of CALET

1. CALET's spectrum is consistent with AMS-02 below 1 TeV.
2. There are two group of measurements: AMS-02+CALET vs Fermi-LAT+DAMPE, indicating the presence of unknown systematic errors.



All Electron Spectrum: Extended Measurement by CALET

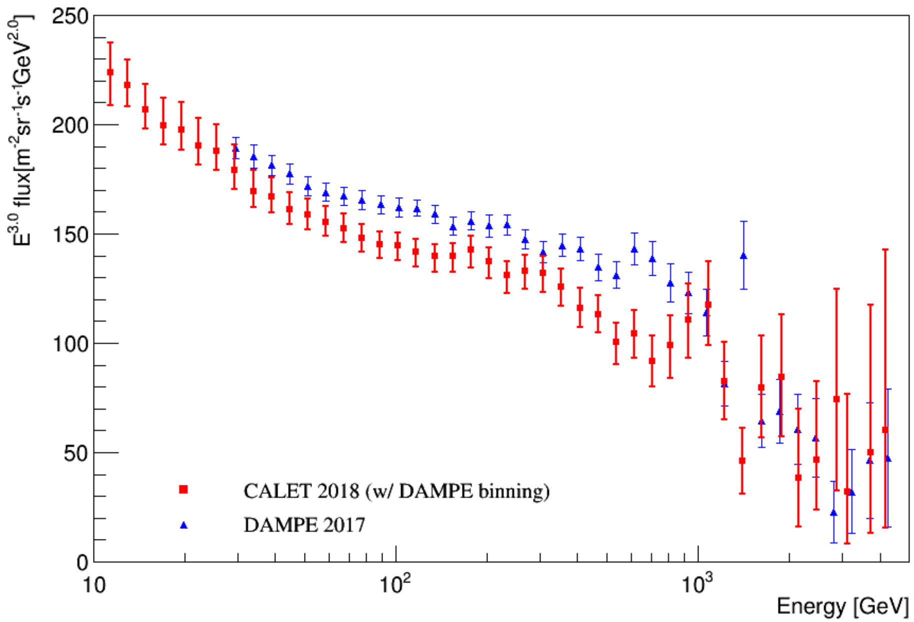
Approximately doubled statistics above 500 GeV by using ful



Many papers speculating about the tentative peak to be the dark matter signature

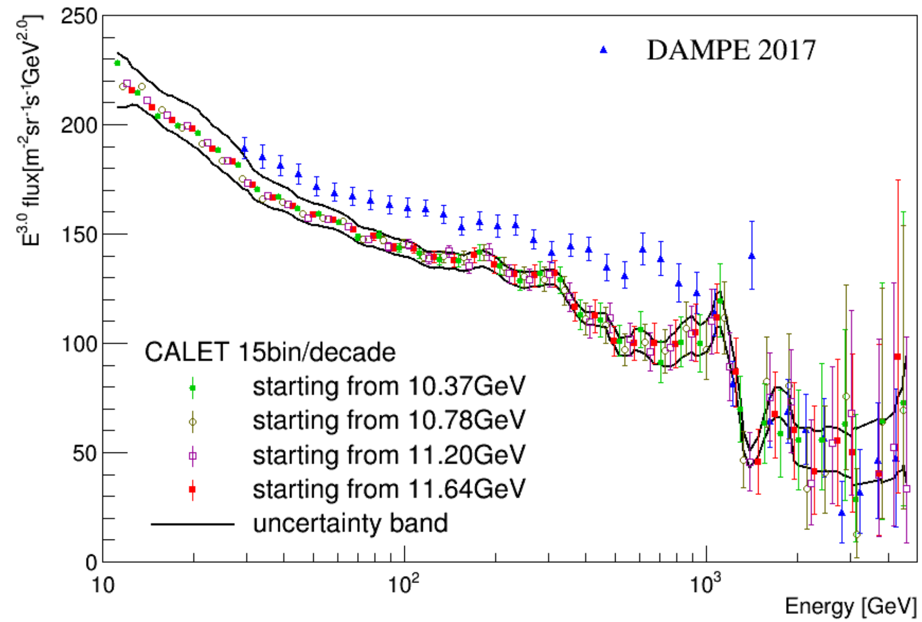
Testing the Tentative Peak at 1.4 TeV with CALET

Here, we have adopted the same energy binning as DAMPE.



1.4 TeV peak is disfavored with 4σ significance

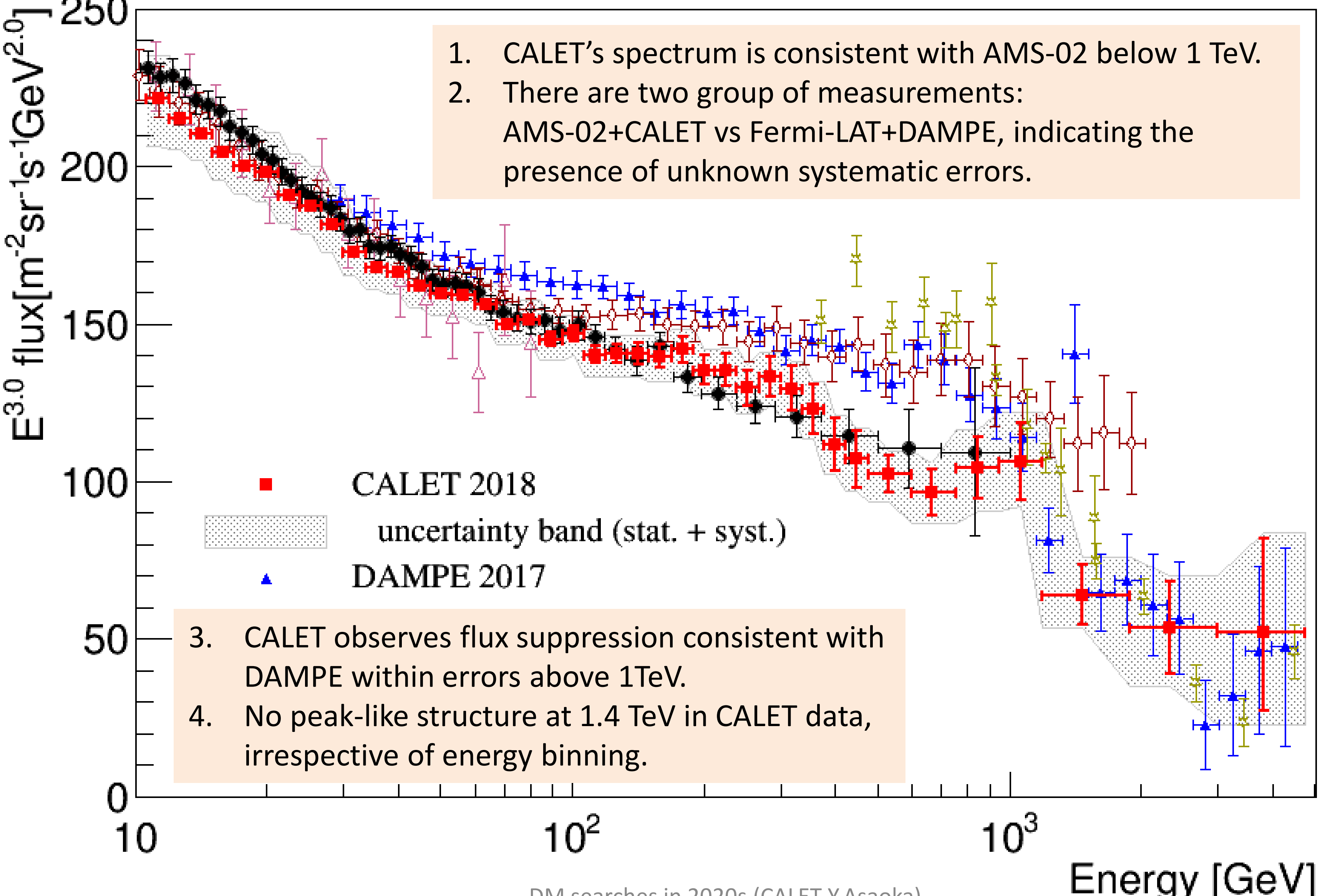
What happens if we shifted our energy binning…



We don't see any peak-like structure at around 1.4TeV even in the shifted energy binning.

All Electron Spectrum: Extended Measurement by CALET

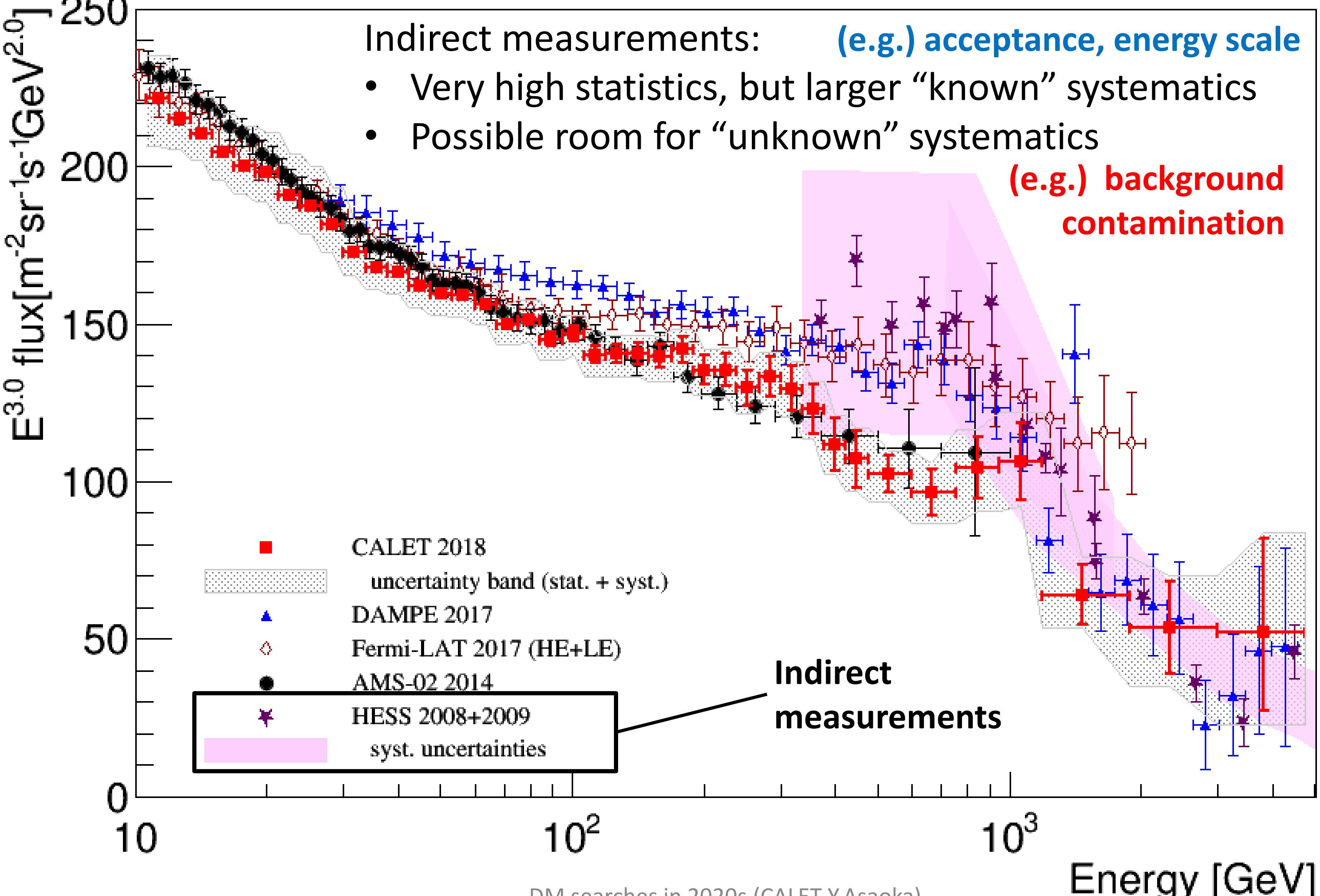
Approximately doubled statistics above 500 GeV by using full acceptance of CALET



1. CALET's spectrum is consistent with AMS-02 below 1 TeV.
2. There are two group of measurements: AMS-02+CALET vs Fermi-LAT+DAMPE, indicating the presence of unknown systematic errors.
3. CALET observes flux suppression consistent with DAMPE within errors above 1TeV.
4. No peak-like structure at 1.4 TeV in CALET data, irrespective of energy binning.

All Electron Spectrum: Comparison with Indirect Measurements

Published results only (note: not included the HESS data presented at ICRC2017)

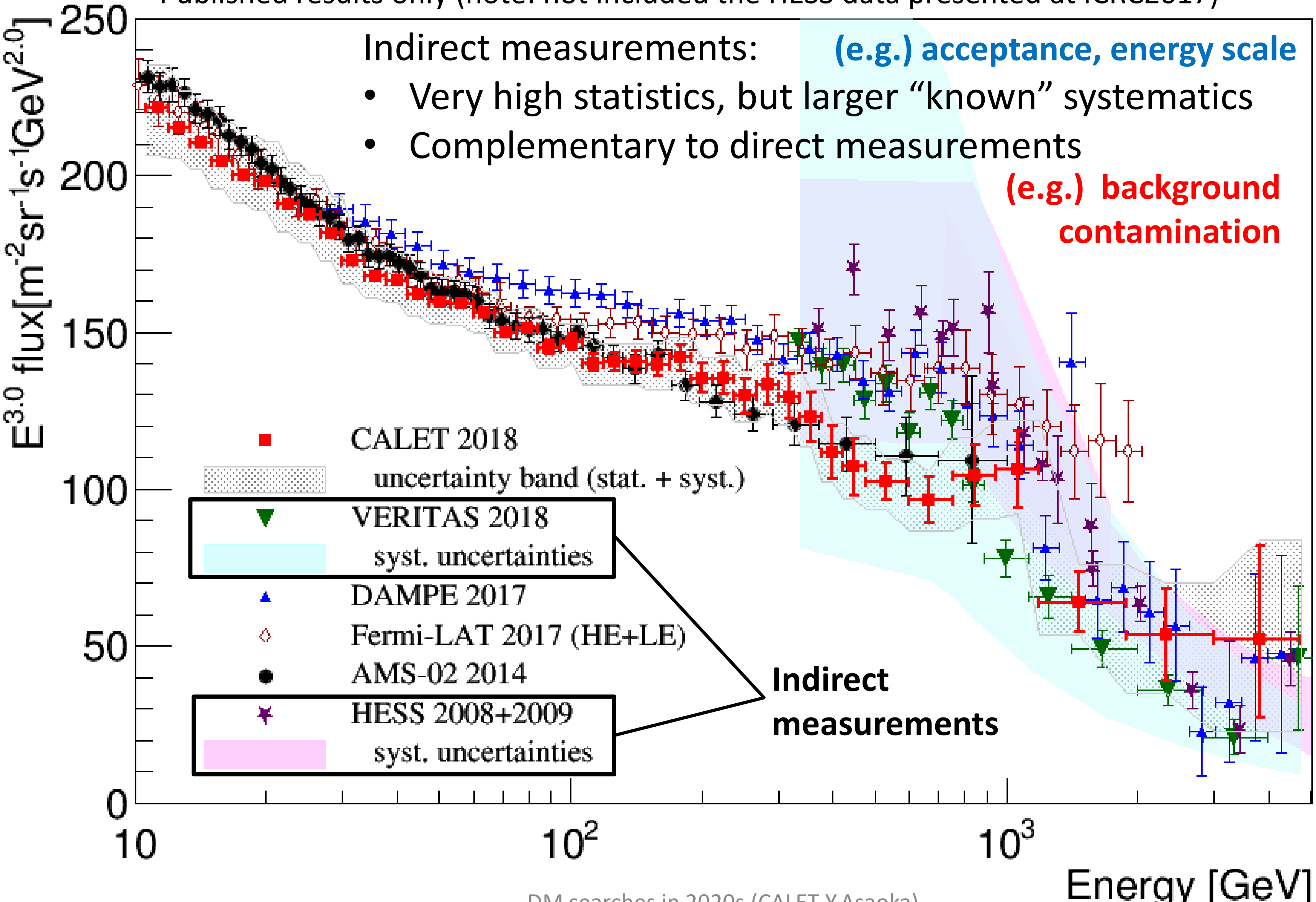


All Electron Spectrum: Comparison with Indirect Measurements

Published results only (note: not included the HESS data presented at ICRC2017)

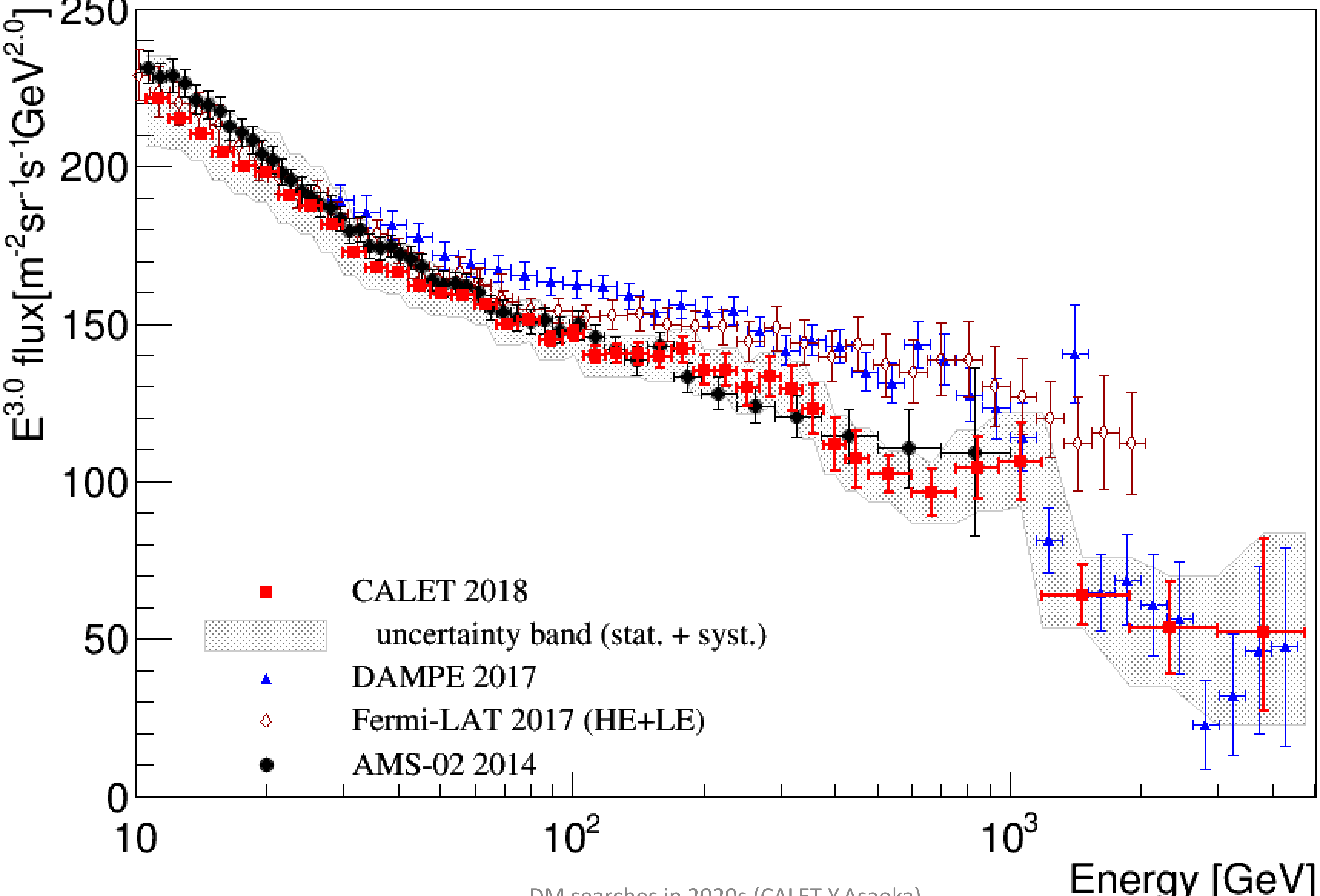
Indirect measurements:

- Very high statistics, but larger “known” systematics
- Complementary to direct measurements



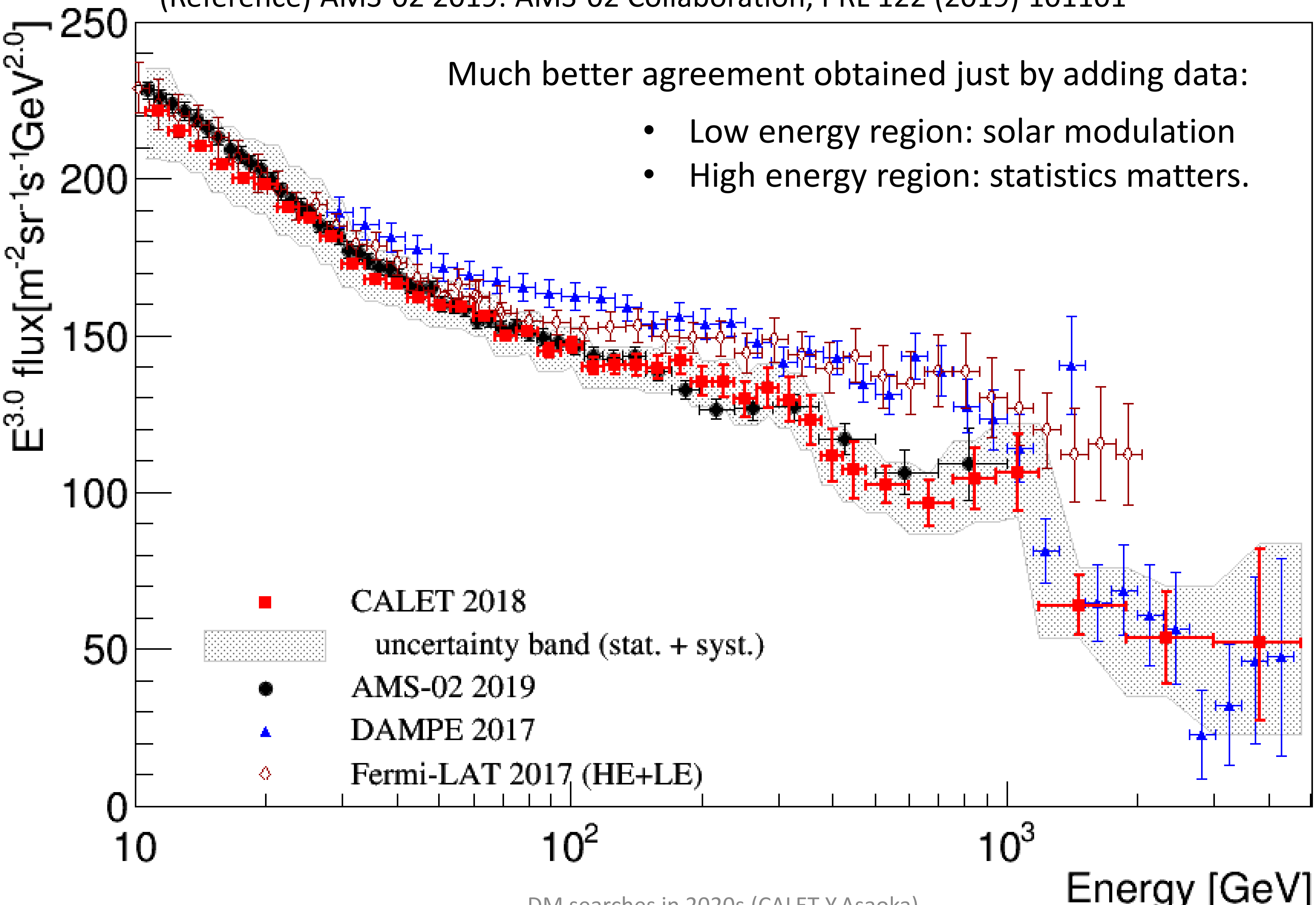
All Electron Spectrum: Comparison between Recent Direct Measurements

Recent direct measurements are compared.



All Electron Spectrum: Comparison with the Updated AMS-02 Result

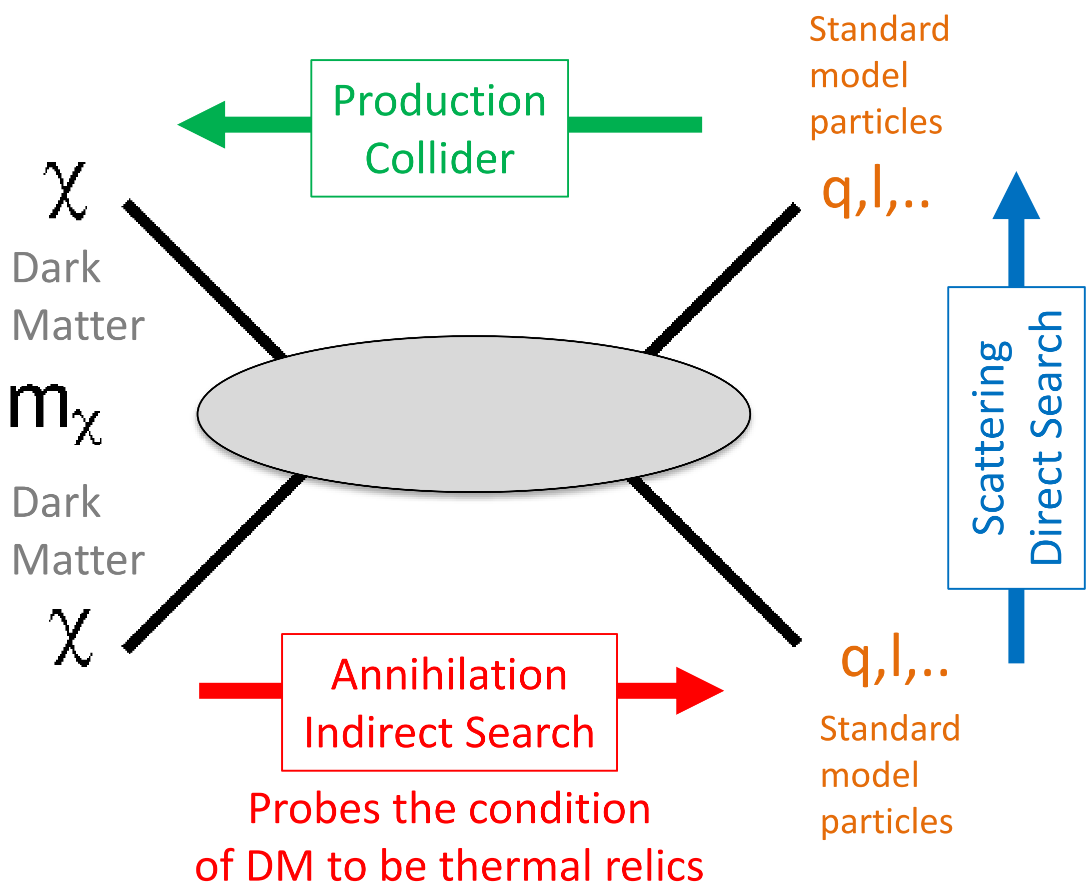
(Reference) AMS-02 2019: AMS-02 Collaboration, PRL 122 (2019) 101101



Search for "Particle" Dark Matter

Dark Matter (DM): The solid evidence for new physics
WIMP = Weakly Interacting Massive Particles

- Thermal relics (basic processes in the early universe)
- Candidate "new" particles as a byproduct of new physics frameworks



- Three complementary approaches
- Direct search made a significant progress to approach "neutrino floor"
  - Many underground detectors
- Production experiment in collider must identify dark matter as missing mass.
  - Large model dependence
- Indirect searches directly probe the condition of dark matter to be thermal relics.
  - (downside) existence of astrophysical background

Indirect Dark Matter Search：
Gamma-rays ＋Charged Particles (Antiparticles)

Advantage: Directly constrain the condition to be thermal relic

- Canonical cross section which matches the observed DM density: $\langle\sigma v\rangle \sim 3 \times 10^{-26}\ cm^3/s$

Challenges: To know the background of galactic cosmic rays (including secondaries)

- Relatively large uncertainties

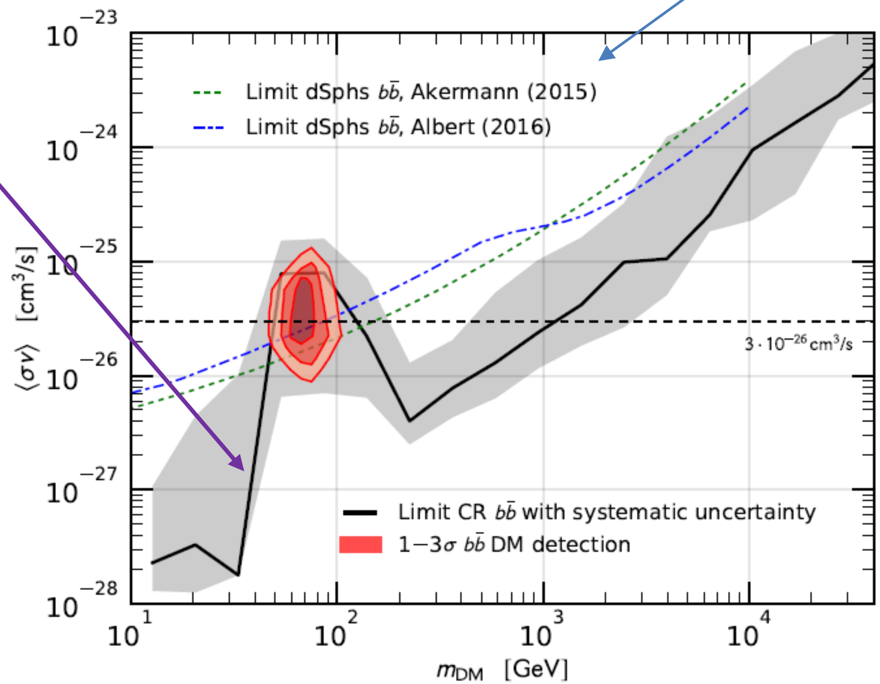
Examples: Gamma-rays, positrons, antiprotons, other cosmic rays

- Gamma-rays: can observe high density region like galactic center
- Antiprotons: only background from secondary production
- Complementary channels: hadrons and leptons

Constraints from AMS-02 antiprotons

Cuoco, Kramer, Korsmeier PRL 118(2017)191102

Constraints are obtained by using the predicted antiproton flux due to hadronization of quark pairs produced by DM annihilation.



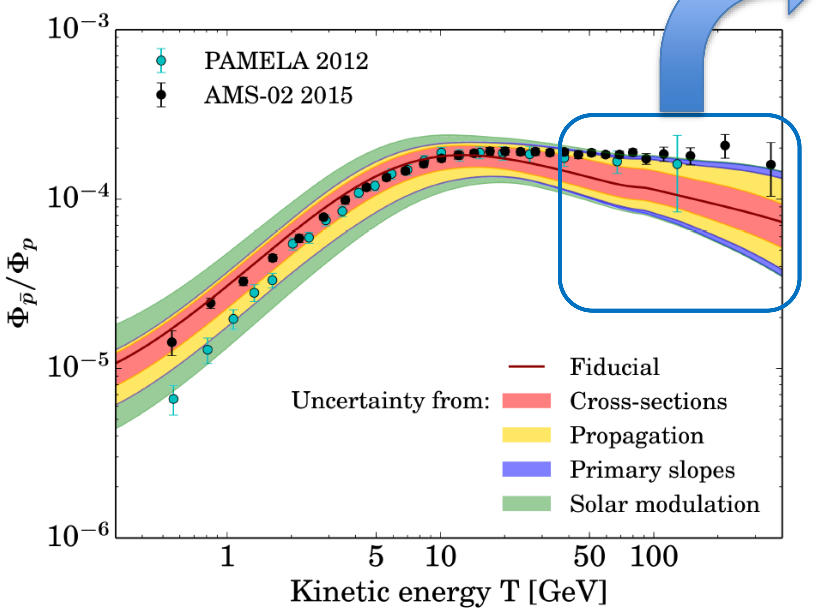
Constrains from Fermi-LAT

PRL 115 (2015) 231301

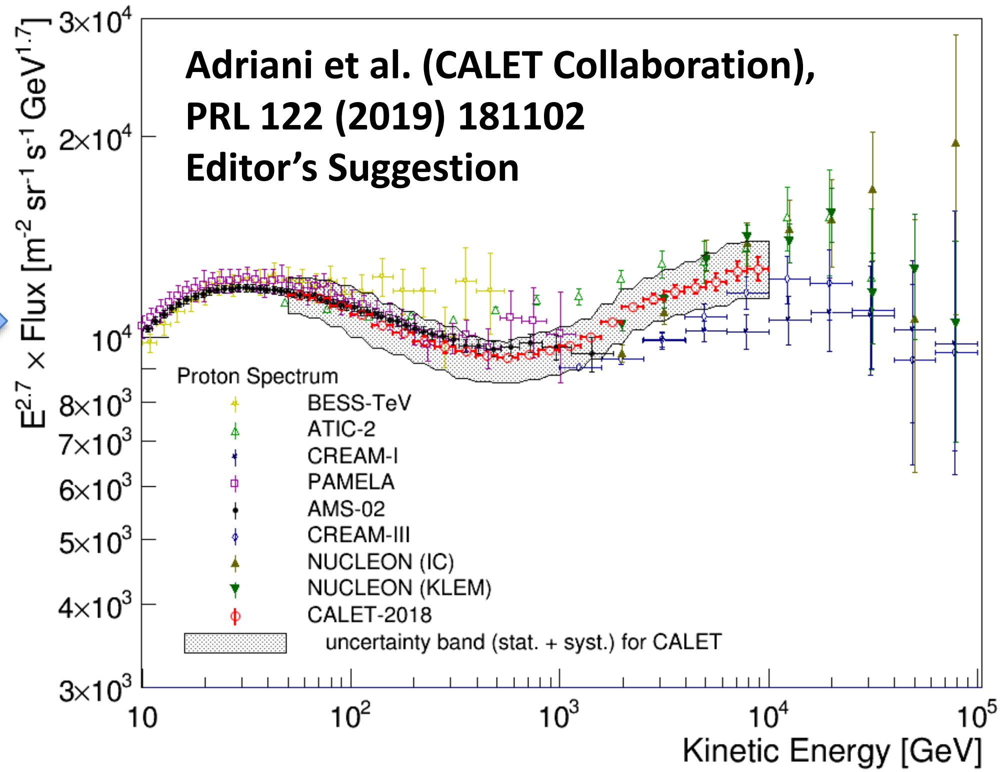
Constraints are obtained using the gamma-ray continuum produced during hadronization. Stacking the dwarf spheroidal galaxies to achieve huge target mass.
(*) uncertainties in J-factor

Importance of Proton Spectrum
in the Indirect DM Searches using Antiparticles

- In the high energy region, the major uncertainty in antiproton flux comes from primary spectrum.
- The antiproton energy is about one order of magnitude smaller than primary protons.



Giesen et al. JCAP(2015)023



<u>CALET proton spectrum:</u>

- Progressive hardening up to the TeV region revealed with a single instrument in space.
- Consistent with accurate magnet spectrometers in the low energy region but extends to nearly an order of magnitude higher energy.

Indirect Dark Matter Search：
Gamma-rays ＋Charged Particles (Antiparticles)

Advantage: Directly constrain the condition to be thermal relic

- Canonical cross section which matches the observed DM density: $\langle\sigma v\rangle \sim 3 \times 10^{-26}\ cm^3/s$

Challenges: To know the background of galactic cosmic rays (including secondaries)

- Relatively large uncertainties

Examples: Gamma-rays, positrons, antiprotons, other cosmic rays

- Gamma-rays: can observe high density region like galactic center
- Antiprotons: only background from secondary production
- **Complementary channels: hadrons and leptons**

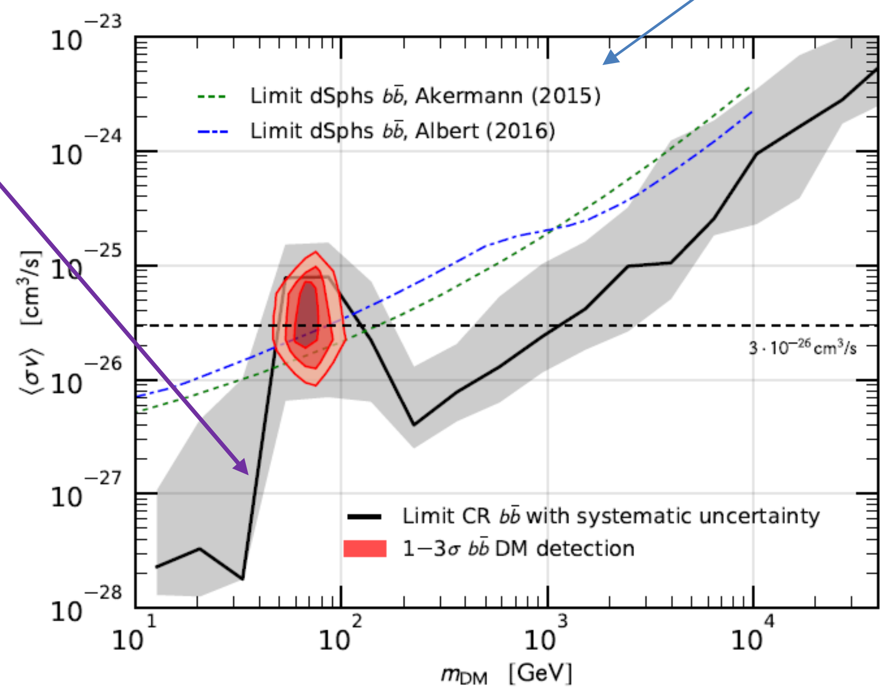
Constrains from Fermi-LAT

PRL 115 (2015) 231301

Constraints from AMS-02 antiprotons

Cuoco, Kramer, Korsmeier PRL 118(2017)191102

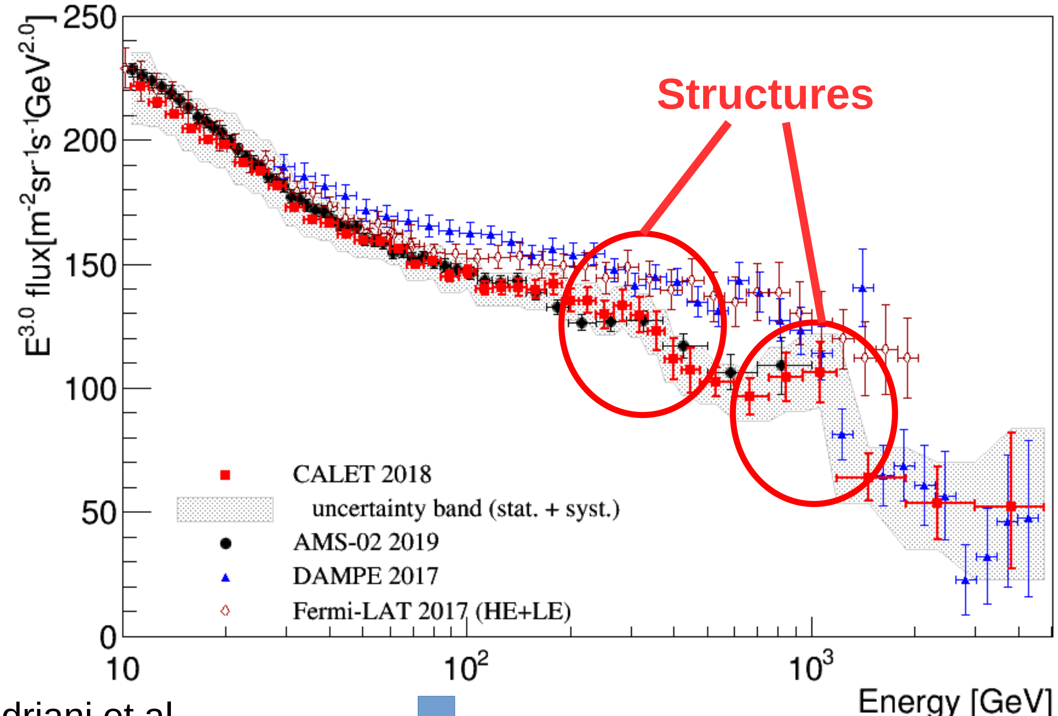
Constraints are obtained by using the predicted antiproton flux due to hadronization of quark pairs produced by DM annihilation.



Constraints are obtained using the gamma-ray continuum produced during hadronization. Stacking the dwarf spheroidal galaxies to achieve huge target mass.
(*) uncertainties in J-factor

DM Search with CALET All-Electron Spectrum

Leptons are complementary probes of DM.
Using excellent energy resolution and high statistics combined with positron spectrum obtained by AMS-02, CALET results can be used to search for a DM signature in the all-electron spectrum.



Adriani et al.
(CALET Collaboration)
PRL 120 (2018) 261102

Interpretation of structures as Dark Matter signatures

- Interesting but just a speculation
- Allows to compare model with hints from other search methods
- to be taken more seriously if finding agreement

Explanation of structures by astrophysical origin

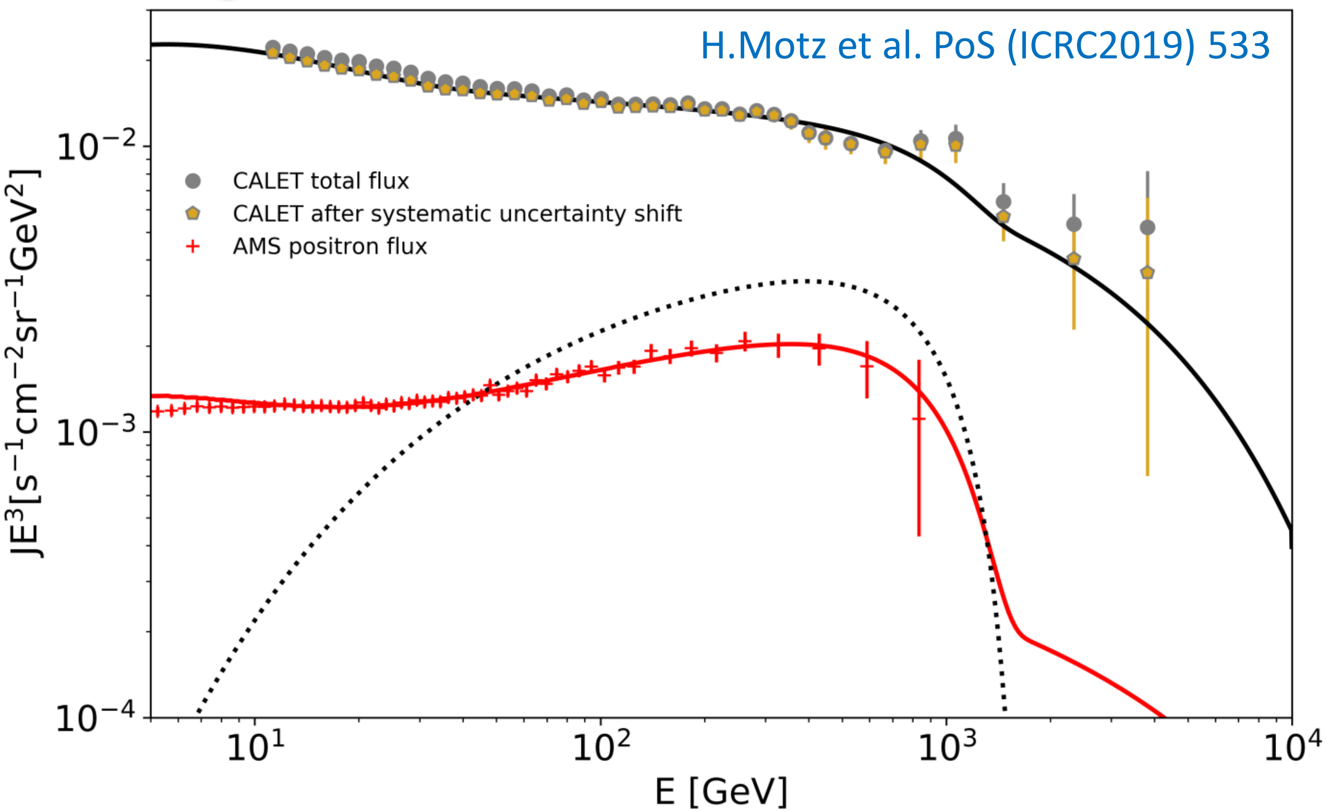
- constrains the Dark Matter properties (limits) by estimating the allowed contribution from Dark Matter as a function of Dark Matter mass.

Modeling the Electron and Positron Spectra

H.Motz et al. PoS (ICRC2019) 533 (not a collaboration work, just uses published spectra)

- The model must reproduce the observed spectra of all-electron (CALET) and positron (AMS-02), and be compatible with numerical calculation (e.g. GALPROP).
- The variation of parameters reflects the uncertain input in numerical calculation.

$$\begin{cases} \Phi_{\rm ele}(E) = C_p\phi_p(E) + C_s\phi_s(E) + C_{\rm ex}\phi_{\rm ex}(E) \\ \Phi_{\rm pos}(E) = C_s\phi_s(E) + C_{\rm ex}\phi_{\rm ex}(E) \\ \Phi_{\rm tot}(E) = \Phi_{\rm ele}(E) + \Phi_{\rm pos}(E) \end{cases}$$



$\phi_p(E)$: Primary electron

Broken power law plus exponential cutoff*
(* to reflect discrete source distribution)

$\phi_s(E)$: Secondary

Taken from numerical calculation.

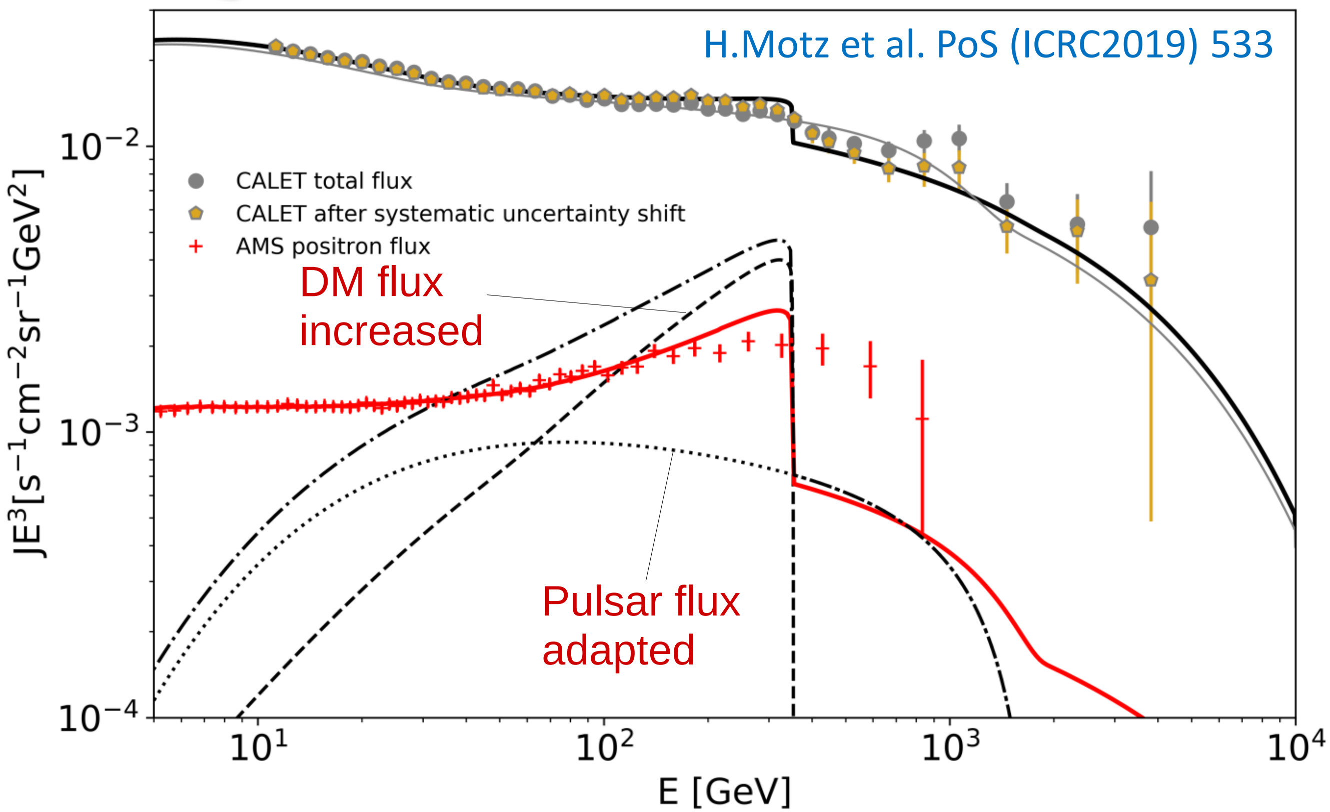
$\phi_{\rm ex}(E)$: Extra source

Common source (same amount of e^+&e^-), Pulsar spectrum is parameterized.

Modeling the Electron and Positron Spectra

- The model must reproduce the observed spectra of all-electron (CALET) and positron (AMS-02), and be compatible with numerical calculation (e.g. GALPROP).
- The variation of parameters reflects the uncertain input in numerical calculation.

$$\begin{cases} \Phi_{\rm ele}(E) = C_p\phi_p(E) + C_s\phi_s(E) + C_{\rm ex}\phi_{\rm ex}(E) + \phi_{\rm DM}(E, m_{\rm DM}) \\ \Phi_{\rm pos}(E) = C_s\phi_s(E) + C_{\rm ex}\phi_{\rm ex}(E) + \phi_{\rm DM}(E, m_{\rm DM}) \\ \Phi_{\rm tot}(E) = \Phi_{\rm ele}(E) + \Phi_{\rm pos}(E) \end{cases}$$



$\phi_p(E)$: Primary electron

Broken power law plus exponential cutoff*
(* to reflect discrete source distribution)

$\phi_s(E)$: Secondary

Taken from numerical calculation.

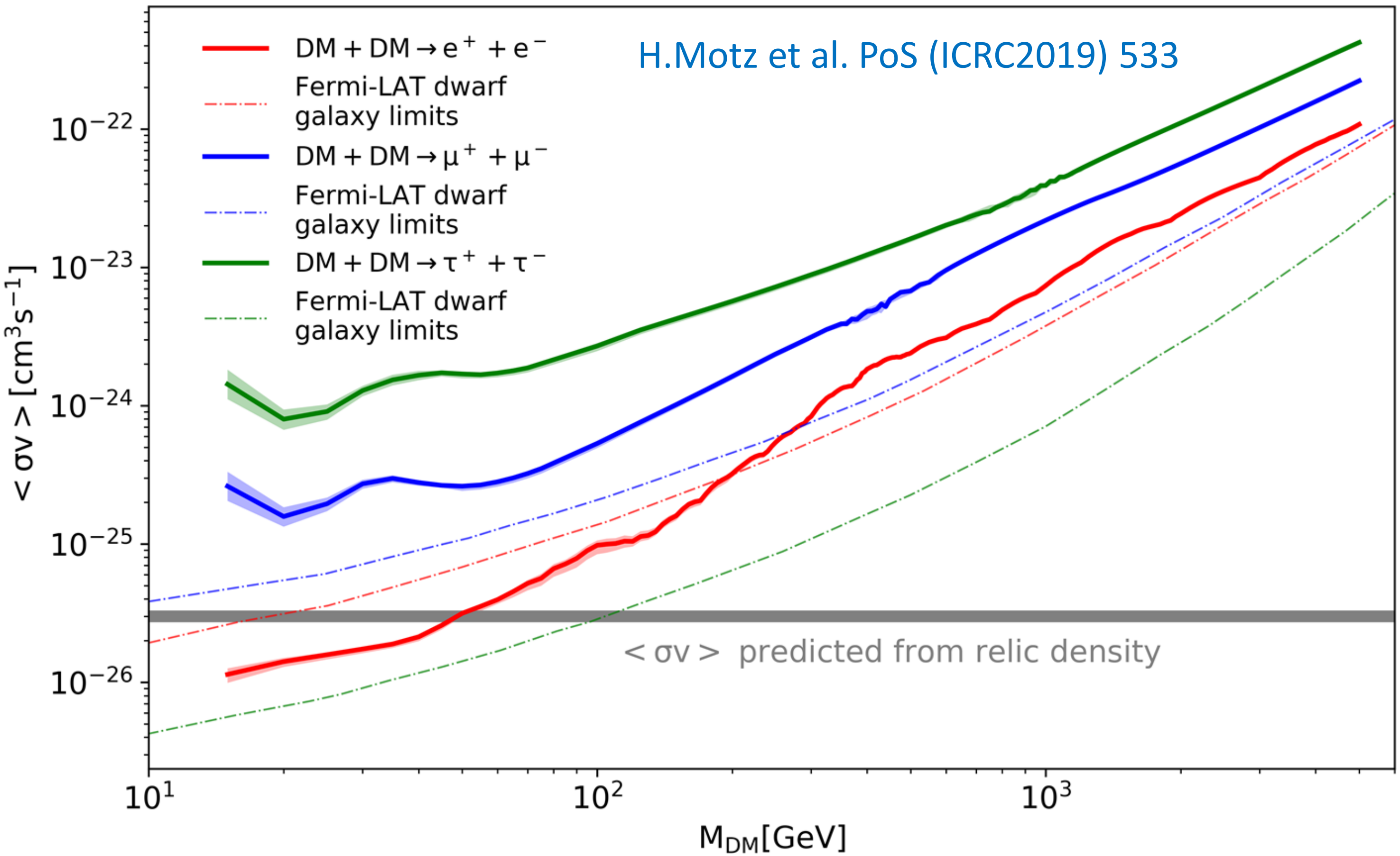
$\phi_{\rm ex}(E)$: Extra source

Pulsar spectrum (common).

$\phi_{\rm DM}(E, m_{\rm DM})$: DM

DM spectrum (common)

Limits on Dark Matter Annihilation as a Function of Dark Matter Mass



Fermi-LAT limits from Phys. Rev. Lett. 115, 231301 (2015) (SM)

electron+positron complementary to gamma-ray search

→ different sensitivity to annihilation channels

→ different target region (galactic neighborhood vs. dwarf galaxies)

Shaded regions show dependence on nuisance parameters:

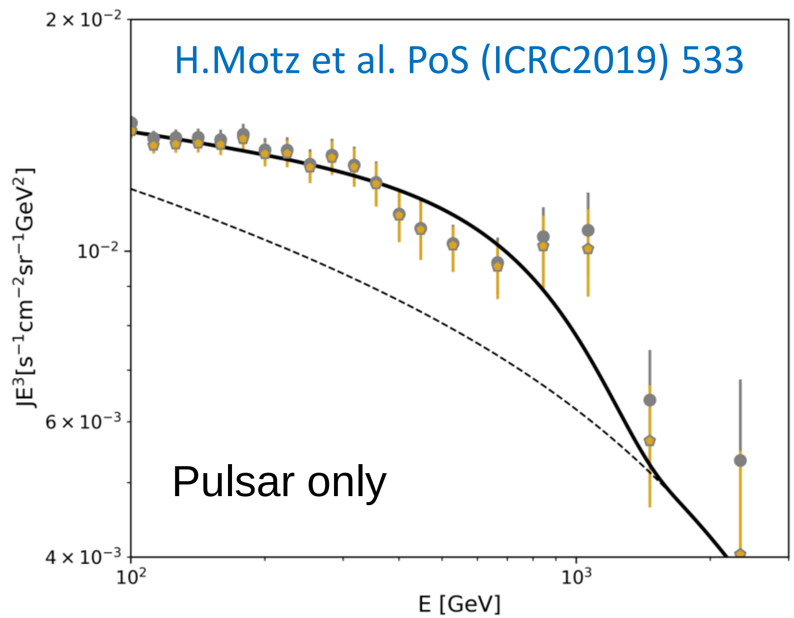
$E_{cut(d)}$ [2TeV,**4TeV**,10TeV]

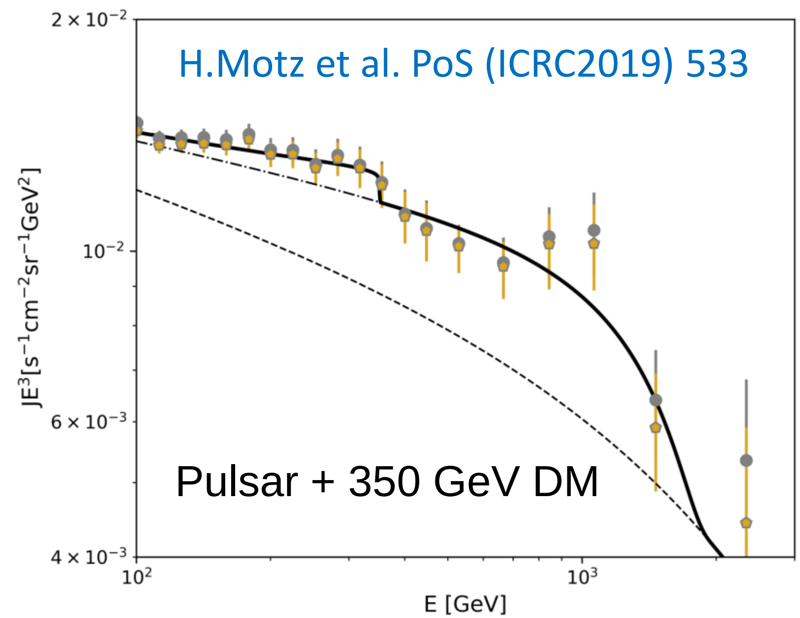
Φ [0.3GV,**0.5GV**,0.7GV]

s [0.03,**0.05**,0.1]

- We still have plenty room to be explored in lepton channel!
- CALET results better constrain annihilation to $e^+ + e^-$ pair.

Fit Improvement by Modeling 350 GeV Step-like Structure with Dark Matter Signature





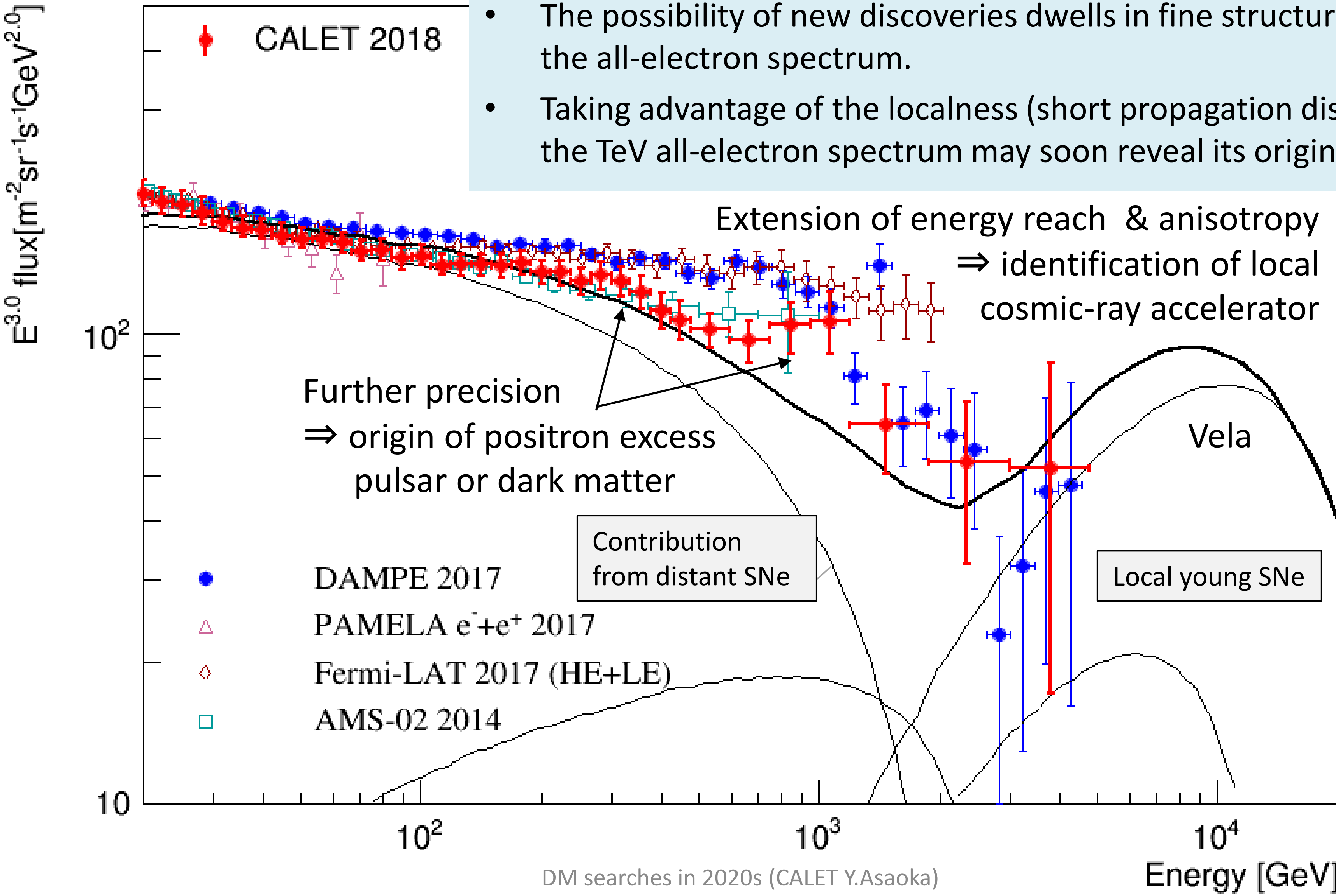
- χ^2 improvement compared to single pulsar case:

Full energy range (CALET & AMS-02 data) : $\Delta\chi^2 = 6.6$ ($33.9 \rightarrow 27.3$)
100 GeV – 3 TeV (CALET data only) : $\Delta\chi^2 = 7.0$ ($13.3 \rightarrow 6.3$)

Prospects for the CALET All-Electron Spectrum

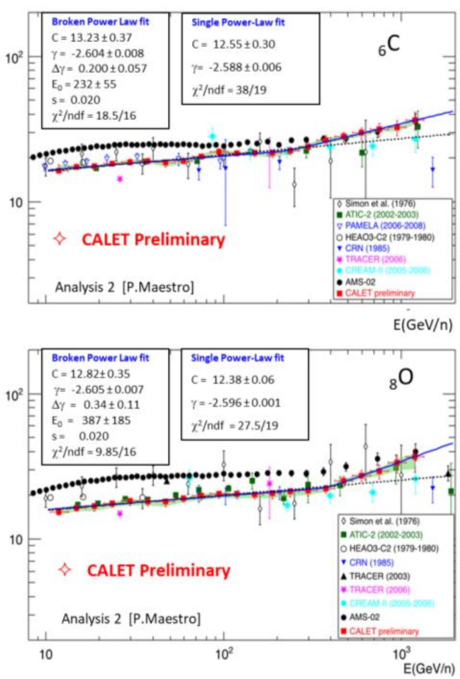
Five years or more observations ⇒ 3 times more statistics, reduction of systematic errors

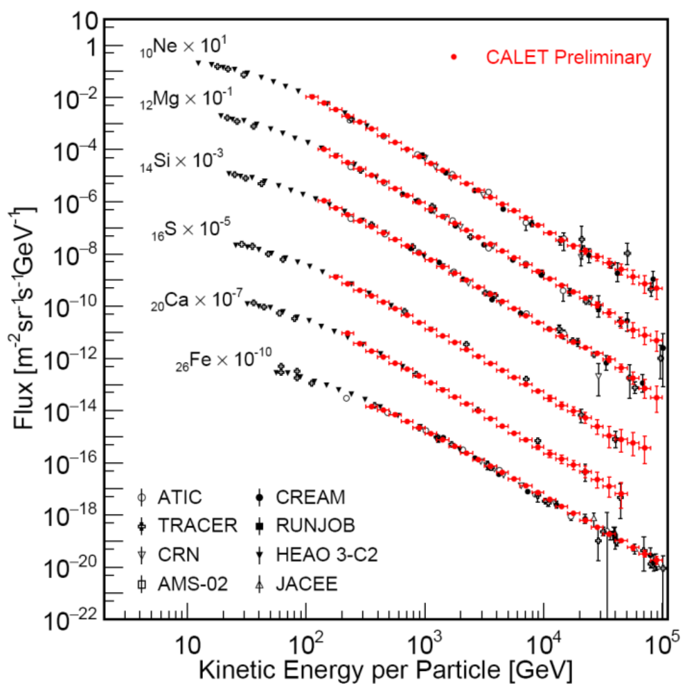
- The possibility of new discoveries dwells in fine structures of the all-electron spectrum.
- Taking advantage of the localness (short propagation distance), the TeV all-electron spectrum may soon reveal its origin.

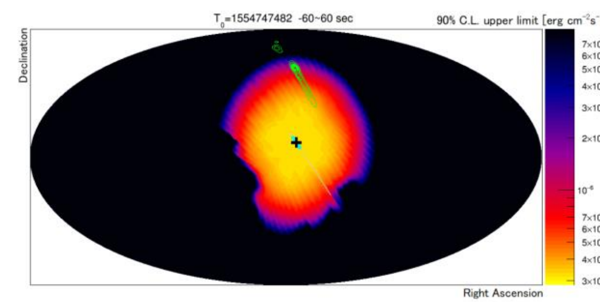


Summary and Prospects

- **CALET continues very stable observation since Oct. 2015, for more than 3.5 years.**
- **We have published all-electron spectrum (11 GeV – 4.8 TeV) and proton spectrum (50 GeV –10 TeV) including the detailed assessment of systematic errors.**
- **There are many more results such as heavy nuclei spectra, gamma-ray observations including GW counterpart searches, and space weather.**
- **The so far excellent performance of CALET and the outstanding quality of the data suggest that a 5-year (or more) observation period is likely to provide a wealth of new interesting results.**







GCN No.	LIGO/Virgo trigger	Trigger time T_0 (2019)	Events $T_0 \pm 60$ s	90% C.L. U.L.	Summed probability	CAL α (°)	CAL δ (°)
24088	S190408an	04-08 18:18:02.288 UTC	0	2.3×10^{-6}†	80%	352.9	8.3
24218	S190425z	04-25 08:18:05.017 UTC	0	1.0×10^{-4}	5%	131.3	-43.6
24276	S190426c	04-26 15:21:55.337 UTC	0	2.5×10^{-5}	10%	183	-50.9
24403	S190503bf	05-03 18:54:04.294 UTC	0	4.2×10^{-5}	10%	169	-45.5
24495	S190510g	05-10 02:59:39.292 UT	0	–	No	295.7	50.8
24531	S190512at	05-12 18:07:14.422 UT	0	1.9×10^{-5}	10%	214.9	37.7
24548	S190513bm	05-13 20:54:28.747 UT	0	6.0×10^{-5}†	5%	348	4.4
24593	S190517h	05-17 05:51:01.831 UT	0	–	No	126.2	-31.9
24617	S190519bj	05-19 15:35:44.398 UT	0	–	No	243.1	51.1
24648	S190521g	05-21 03:02:29.447 UT	0	6.0×10^{-6}	30%	205.7	49.2
24649	S190521r	05-21 07:43:59.463 UT	0	–	No	225.3	51.4
24735	S190602aq	06-02 17:59:27.089 UT	0	2.9×10^{-4}	5%	127.5	45.1

CALET Publication

1. ``Direct Measurement of the Cosmic-Ray Proton Spectrum from 50~GeV to 10~TeV with the Calorimetric Electron Telescope on the International Space Station“, O.Adriani, *Y.Asaoka, *P.S.Marrocchesi, *S.Torii et al. (CALET collaboration), Phys.Rev.Lett., 122, 181102 (2019).
2. ``CHARACTERISTICS AND PERFORMANCE OF THE CALORIMETRIC ELECTRON TELESCOPE (CALET) CALORIMETER FOR GAMMA-RAY OBSERVATIONS'', *N.Cannady, *Y.Asaoka, F.Satoh, M.Tanaka, S.Torii, M.L.Cherry, M.Mori, et al. (CALET collaboration), ApJS 238, 5 (2018).
3. ``Search for GeV gamma-ray counterparts of gravitational wave events by CALET“, O.Adriani, *Y.Asaoka, *M.Mori et al. (CALET collaboration), ApJ 863, 160 (2018).
4. ``Extended Measurement of the Cosmic-Ray Electron and Positron Spectrum from 11 GeV to 4.8 TeV with the Calorimetric Electron Telescope on the International Space Station“, O.Adriani, *Y.Asaoka, *S.Torii et al. (CALET collaboration), Phys.Rev.Lett. 120, 261102 (2018)
5. ``On-orbit operations and offline data processing of CALET onboard the ISS“, *Y.Asaoka, S.Ozawa, S.Torii et al. (CALET collaboration), Astropart. Phys., 100, 29 (2018).
6. ``Energy Spectrum of Cosmic-ray Electron and Positron from 10 GeV to 3 TeV Observed with the Calorimetric Electron Telescope on the International Space Station“, O.Adriani, *Y.Asaoka, *S.Torii et al. (CALET collaboration), Phys.Rev.Lett. 119, 181101 (2017).
7. ``Energy Calibration of CALET Onboard the International Space Station“, *Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al. (CALET collaboration), Astropart.Phys., 91, 1 (2017).
8. ``CALET UPPER LIMITS ON X-RAY AND GAMMA-RAY COUNTERPARTS OF GW151226“, O.Adriani, *Y.Asaoka, *S.Nakahira, *T.Sakamoto et al. (CALET collaboration) ApJL 829, L20 (2016).

*** indicates corresponding author(s)**

Red: electrons, Blue: protons, Green: gamma-rays, Brown: calibration/operations