Two Generations of CubeSat Missions (CSSWE and CIRBE) to Take on the Challenges of Measuring Relativistic Electrons in the Earth's Magnetosphere

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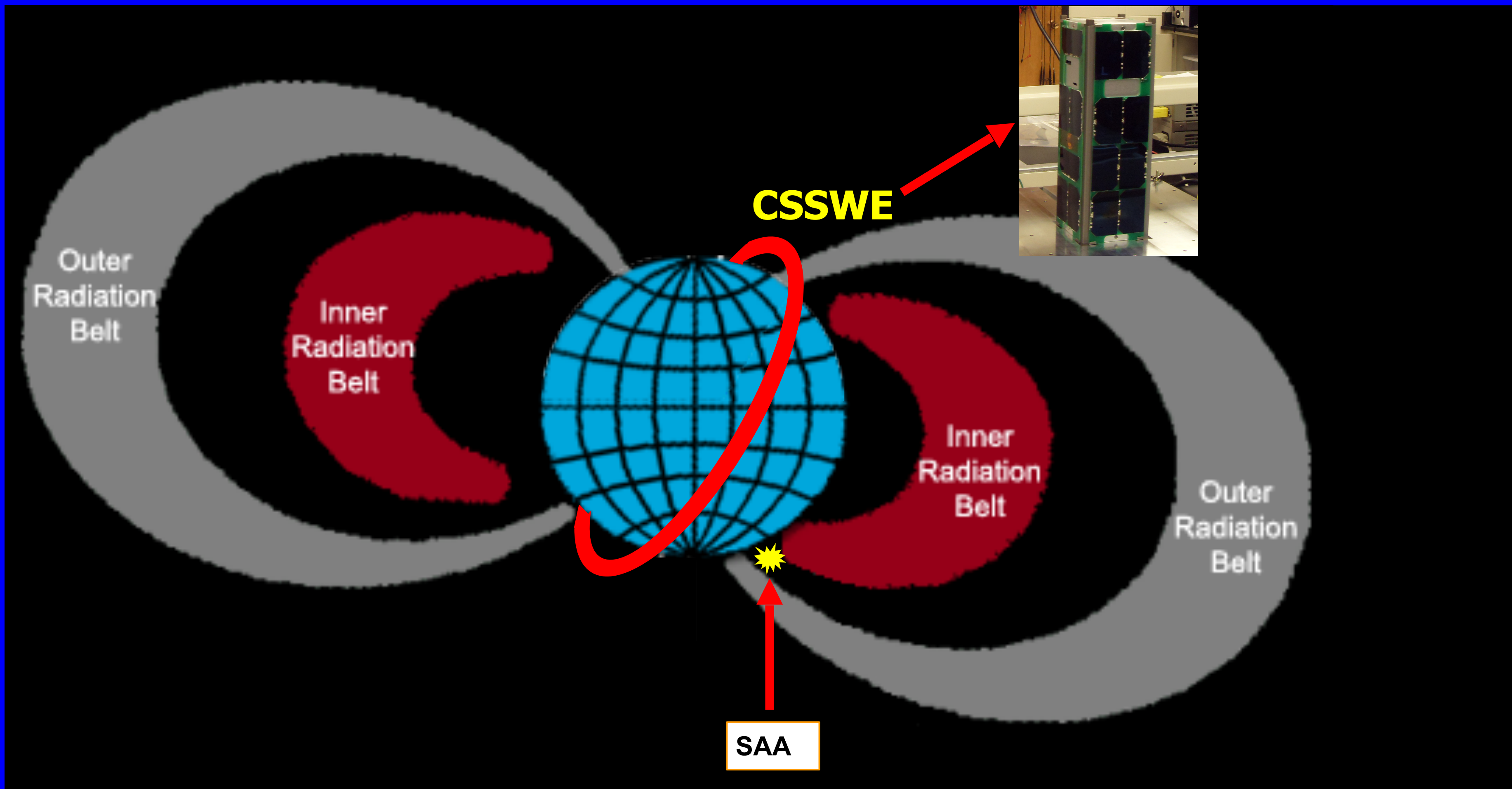
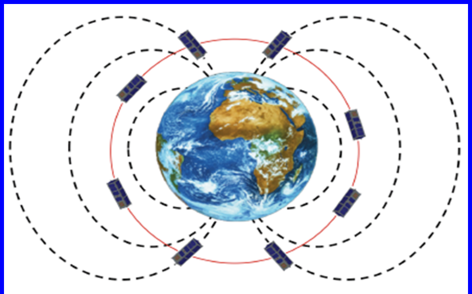
Acknowledgement:
CSSWE (Colorado Student Space Weather Experiment) Team https://lasp.colorado.edu/home/csswe/
CIRBE (Colorado Inner Radiation Belt Experiment) Team https://lasp.colorado.edu/home/cirbe/

- Good sciences can be done based on CubeSat measurements, e.g., CSSWE/REPTile
- Challenges of measuring energetic particles in the inner belt
- Advanced Design and Technologies for CIRBE/REPTile-2

Colorado Student Space Weather Experiment (CSSWE)
orbit: 480 km x 790 km, inclination 65^{0}

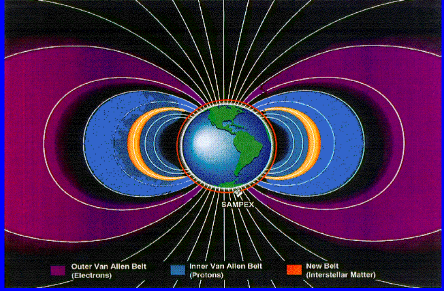
Measuring Energetic Particles in near Earth Space Environment
Operated: September 2012 – end of 2014

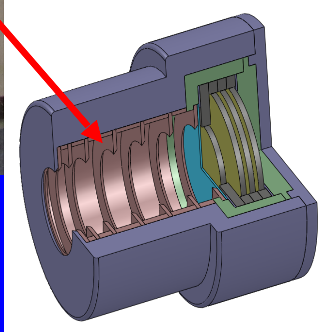




CSSWE: Colorado Student Space Weather Experiment

(Spring of 2010)





Relativistic Electron-Proton Telescope integrated little experiment (REPTile)

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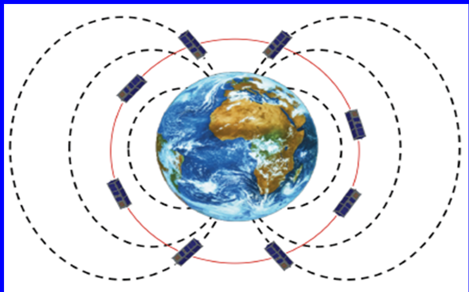
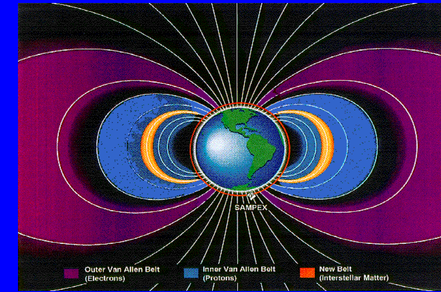


CSSWE: Colorado Student Space Weather Experiment

(Spring of 2011)



LASP
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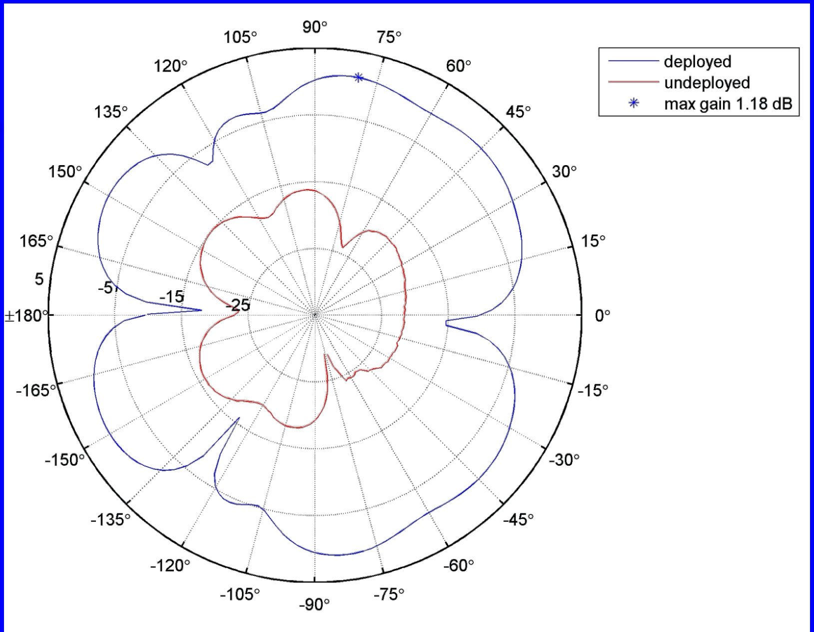
Aerospace Engineering

Testing in anechoic chamber of FirstRF Corp. to determine the antenna gain pattern →



1st Plugs-out Test (11/10-11/2011):

2nd Plugs-out Test (after Vibe test): 11/29/2011

3rd Plugs-out Test (after T-V test): 12/21/2011

So far, 25 peer-reviewed papers published →

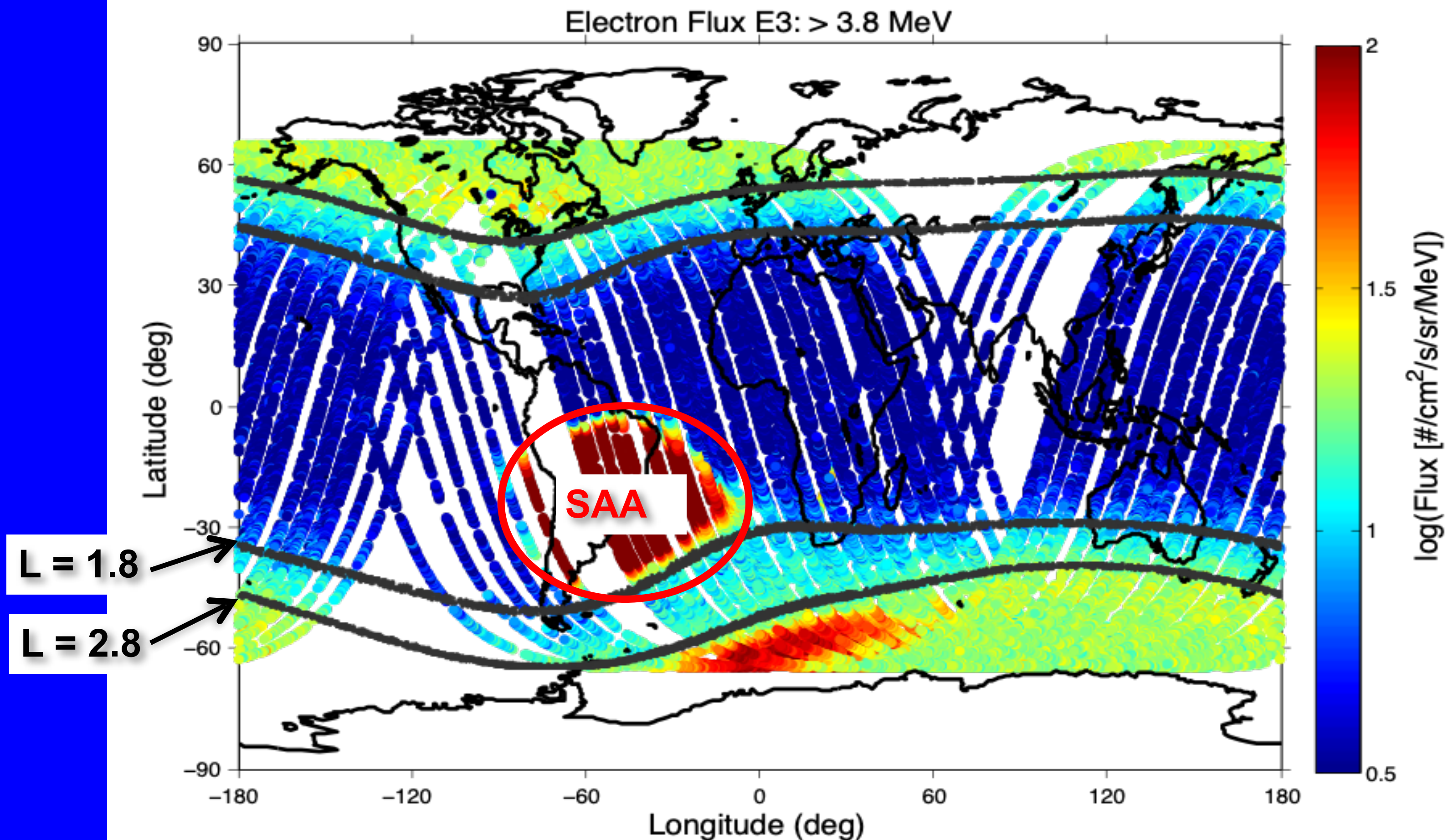
+ 5 Ph.D. Theses Completed (Drew Turner, David Gerhardt, Lauren Blum, Quintin Schiller, and Kun Zhang)

Directly involved >65 grad and undergrad students

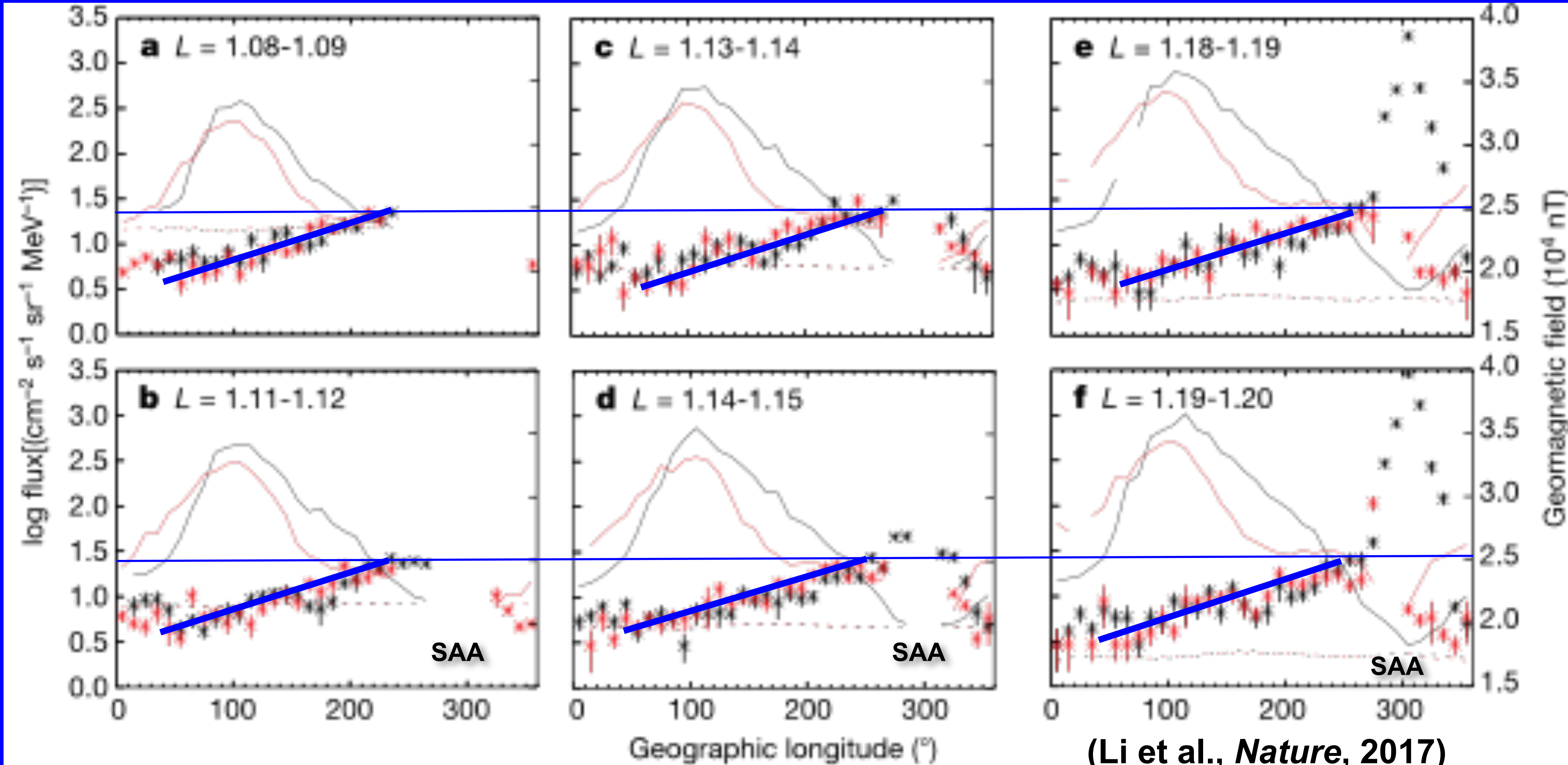
Peer-reviewed Publication List Associated with Colorado Student Space Weather Experiment (CSSWE) CubeSat Mission

1) Spence, Harlan, et al. (2022) Achievements and Lessons Learned from Successful Small Satellite Missions for Space Weather-Oriented Research, *Space Weather* [Paper #2021SW003031], https://doi.org/10.1029/2021SW003031
2) Baker, D. N., et al. (2021) The Relativistic Electron-Proton Telescope (REPT) Investigation: Design, Operational Properties, and Science highlights, Space Science Reviews (2021) 217:68, https://doi.org/10.1007/s11214-021-00838-3
3) Zhang, K., X. Li, H. Zhao, Q. Schiller, L.-Y. Khoo, Z. Xiang, R. Selesnick, M. A. Temerin, and J. A. Sauvaud (2019) Cosmic Ray Albedo Neutron Decay (CRAND) as a source of inner belt electrons: Energy spectrum study, Geophys. Res. Lett., 46, https://doi.org/10.1029/2018GL080887
4) Li, X., R. Selesnick, Q. Schiller, K. Zhang, H. Zhao, D. N. Baker, and M. Temerin (2017), Measurement of electrons from albedo neutron decay and neutron density in near-Earth space, *Nature* 552, 382-385, doi:10.1038/nature24642.
5) Zhang, K., X. Li, Schiller, D. Gerhardt, H. Zhao, and R. Millan (2017), Detailed characteristics of radiation belt electrons revealed by CSSWE/REPTile measurements: Geomagnetic activity response and precipitation observation, *J. Geophys. Res. Space Physics*, 122, doi:10.1002/2017JA024309.
6) Li, X., D. N. Baker, H. Zhao, K. Zhang, A. N. Jaynes, Q. Schiller, S. G. Kanekal, J. B. Blake, and M. Temerin (2017), Radiation belt electron dynamics at low L (<4): Van Allen Probes era versus previous two solar cycles, *J. Geophys. Res. Space Physics*, 122, doi:10.1002/2017JA023924.
7) Q. Schiller, W. Tu, A. Ali, X. Li, H. Godinez, D. L. Turner, S. K. Morley, M. G. Henderson (2017), Simultaneous event specific estimates of transport, loss, and source rates for relativistic outer radiation belt electrons, *J. Geophys. Res. Space Physics*, 122, doi:10.1002/2016JA023093.
8) Clilverd, M. A. et al. (2017), Investigating energetic electron precipitation through combining ground-based and balloon observations, *J. Geophys. Res. Space Physics*, 122, doi:10.1002/2016JA022812.
9) Gerhardt, David T., Scott E. Palo (2016), Volume magnetization for system-level testing of magnetic materials within small satellites, *Acta Astronautica 127*, 1-12.
10) Xiang, Zheng et al. (2016), Multi-satellite simultaneous observations of magnetopause and atmospheric losses of radiation belt electrons during an intense solar wind dynamic pressure pulse, Ann. Geophys., 34, 493–509.
11) Li, X., R. S. Selesnick, D. N. Baker, A. N. Jaynes, S. G. Kanekal, Q. Schiller, L. Blum, J. F. Fennell, and J. B. Blake (2015), Upper limit on the inner radiation belt MeV electron intensity, *J. Geophys. Res. Space Physics, 120*, 1215-1228, doi:10.1002/2014JA020777.
12) Baker D. N. et al. (2014), An Impenetrable Barrier to Ultra-Relativistic Electrons in the Van Allen Radiation Belt, *Nature*, doi:10.1038/nature13956.
13) Jaynes, A. N., X. Li, Q. G. Schiller, L. W. Blum, W. Tu, D. L. Turner, B. Ni, J. Bortnik, D. N. Baker, S. G. Kanekal, J. B. Blake, and J. Wygant (2014), Evolution of relativistic outer belt electrons during an extended quiescent period, *J. Geophys. Res. Space Physics, 119*, doi:10.1002/2014JA020125.
14) Gerhardt D Scott E. Palo, Quintin Schiller, Lauren Blum, Xinlin Li, and Rick Kohnert (2014), The Colorado Student Space Weath Experiment (CSSWE) On-Orbit Performance, *J. of Small Satellites*, Vol. 03, No. 01 (Jul 2014) pp. 265-281.
15) Schiller, Q., D. Gerhardt, L. Blum, X. Li, and S. Palo (2014), Design and Scientific Return of a Miniaturized Particle Telescope Onboard the Colorado Student Space Weather Experiment (CSSWE) CubeSat, 35th IEEE Aerospace Conference, 8.1102, doi:10.1109/AERO.2014.6836372.
16) Schiller, Q., X. Li, L. Blum, W. Tu, D. L. Turner, and J. B. Blake (2014), A non-storm time enhancement of relativistic electrons in the outer radiation belt, *Geophys. Res. Lett.*, 41, doi:10.1002/2013GL058485.
17) Blum, L. W., Q. Schiller, X. Li, R. Millan, A. Halford, and L. Woodger (2013), New conjunctive CubeSat and balloon measurements to quantify rapid energetic electron precipitation, *Geophys. Res. Lett., 40*, 1-5, doi:10.1002/2013GL058546.
18) Li, X., et al. (2013a), First results from CSSWE CubeSat: Characteristics of relativistic electrons in the near-Earth environment during the October 2012 magnetic storms, *J. Geophys. Res. Space Physics, 118*, doi:10.1002/2013JA019342.
19) Li, X., S. Palo, R. Kohnert, L. Blum, D. Gerhardt, Q. Schiller, and S. Callif (2013b), Small Mission Accomplished by Students - Big Impact on Space Weather Research, *Space Weather Journal, 11*, doi:10.1002/swe.20025, 2013.
20) Li, X., S. Palo, R. Kohnert, D. Gerhardt, L. Blum, Q. Schiller, D. Turner, W. Tu, N. Sheiko, and C. S. Cooper (2012), Colorado Student Space Weather Experiment: Differential flux measurements of energetic particles in a highly inclined low Earth orbit, in Dynamics of the Earth's Radiation Belts and Inner Magnetosphere, Geophys. Monogr. Ser., vol. 199, edited by D. Summers et al., 385–404, AGU, Washington, D. C., doi:10.1029/2012GM001313.
21) Lauren Blum, Quintin Schiller, with advisor Xinlin Li (2012), Characterization and Testing of an Energetic Particle Telescope for a CubeSat Platform, *26th Annual AIAA/USU Conference on Small Satellites*
22) Li, X., S. Palo, and R. Kohnert (2011), Small Space Weather Research Mission Designed Fully by Students, *Space Weather Journal 9, S04006, doi:10.1029/2011SW000668*
23) Palo, S., Xinlin Li, David Gerhardt, Drew Turner, Rick Kohnert, Vaughn Hoxie and Susan Batiste (2010), Conducting Science with a CubeSat: The Colorado Student Space Weather Experiment, *24th Annual AIAA/USU Conference on Small Satellites.*
24) Schiller, Q., Abhishek Mahendrakumar, with advisor Xinlin Li (2010), REPTile: A Miniaturized Detector for a CubeSat Mission to Measure Relativistic Particles in Near-Earth Space, *24th Annual AIAA/USU Conference on Small Satellites.*
25) Gerhardt, D. T. with advisor Scott Palo (2010), Passive Magnetic Attitude Control for CubeSat Spacecraft, *24th Annual AIAA/USU Conference on Small Satellites.*

Nature-Extended Data Fig 2 (Baker et al., *Nature*, 2014)
CSSWE/REPTile Data – September 1-23, 2013



CSSWE/REPTile: 0.5 MeV Electrons for Oct 7-10, 2012

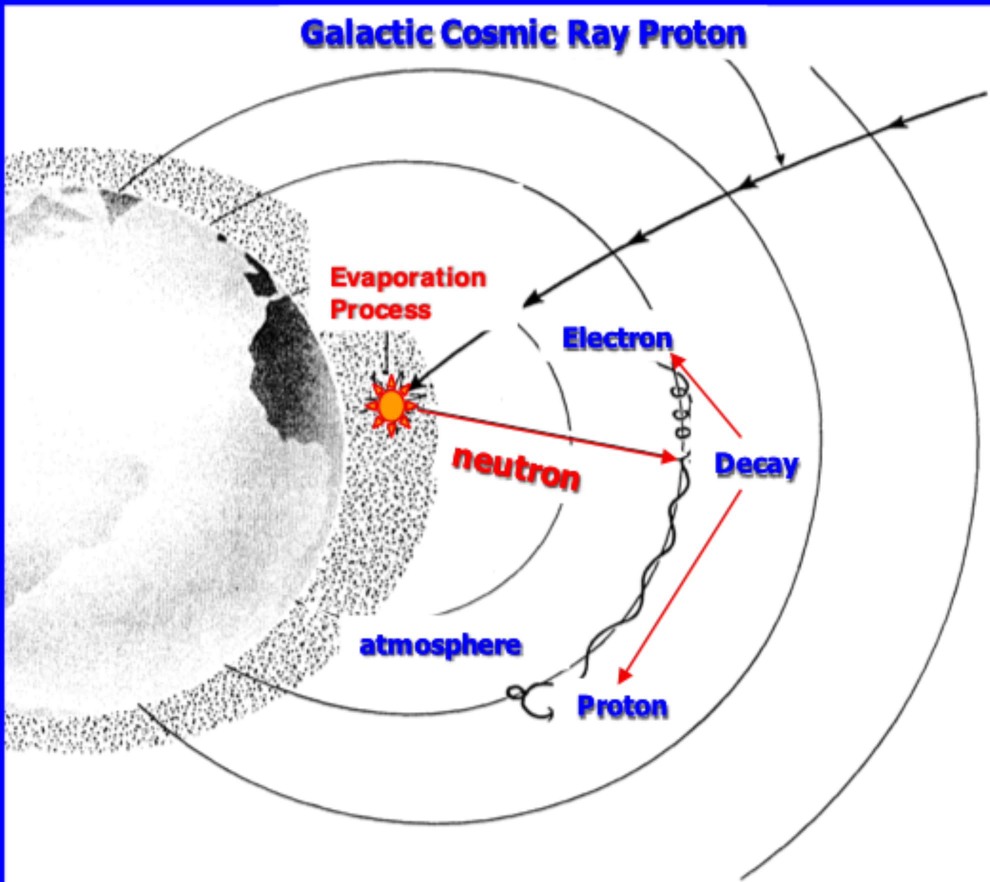


(Li et al., *Nature*, 2017)

<u>First direct detection</u> of CRAND electrons in near-Earth space

A 60-year mystery in space physics was resolved based on our CubeSat measurements

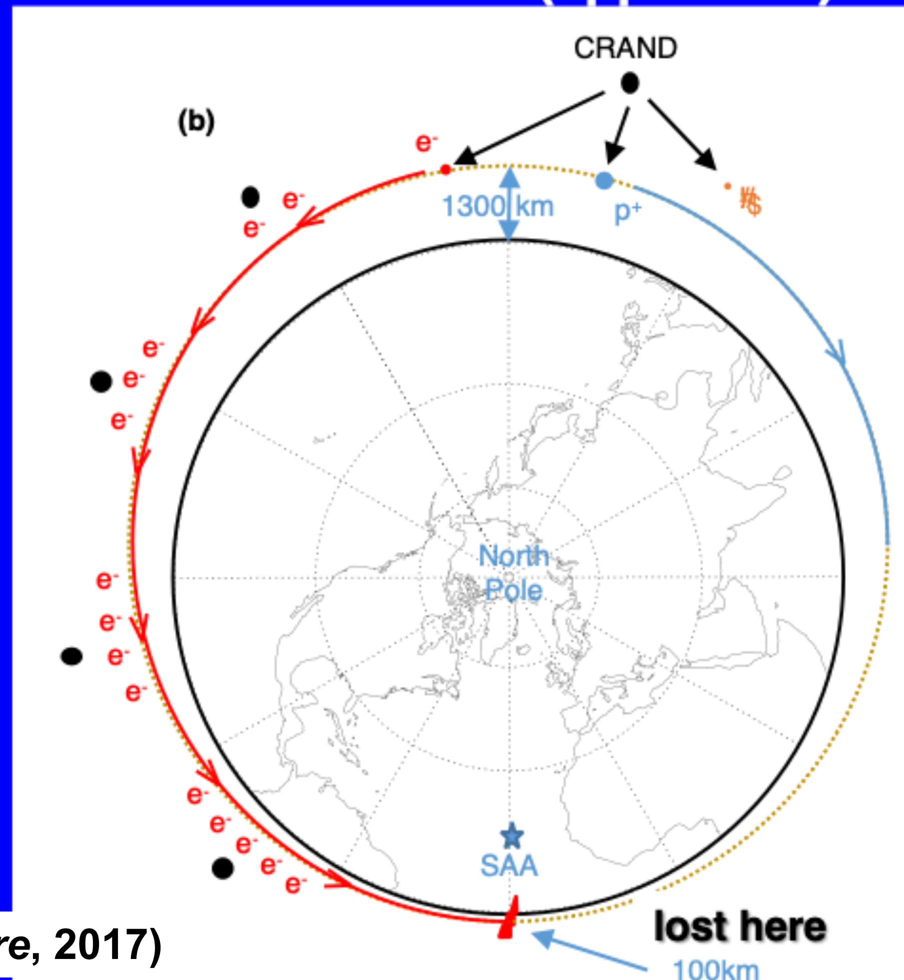
The only feasible explanation: Cosmic Ray Albedo Neutron Decay (CRAND) via evaporation process



CRAND electrons are mostly from the β-decay of thermal neutrons:

$(m_n - m_p - m_e)c^2 \approx 782$ keV

(upper limit)



(Li et al., *Nature*, 2017)

What is next after CSSWE?

Colorado Inner Radiation Belt Experiment (CIRBE)

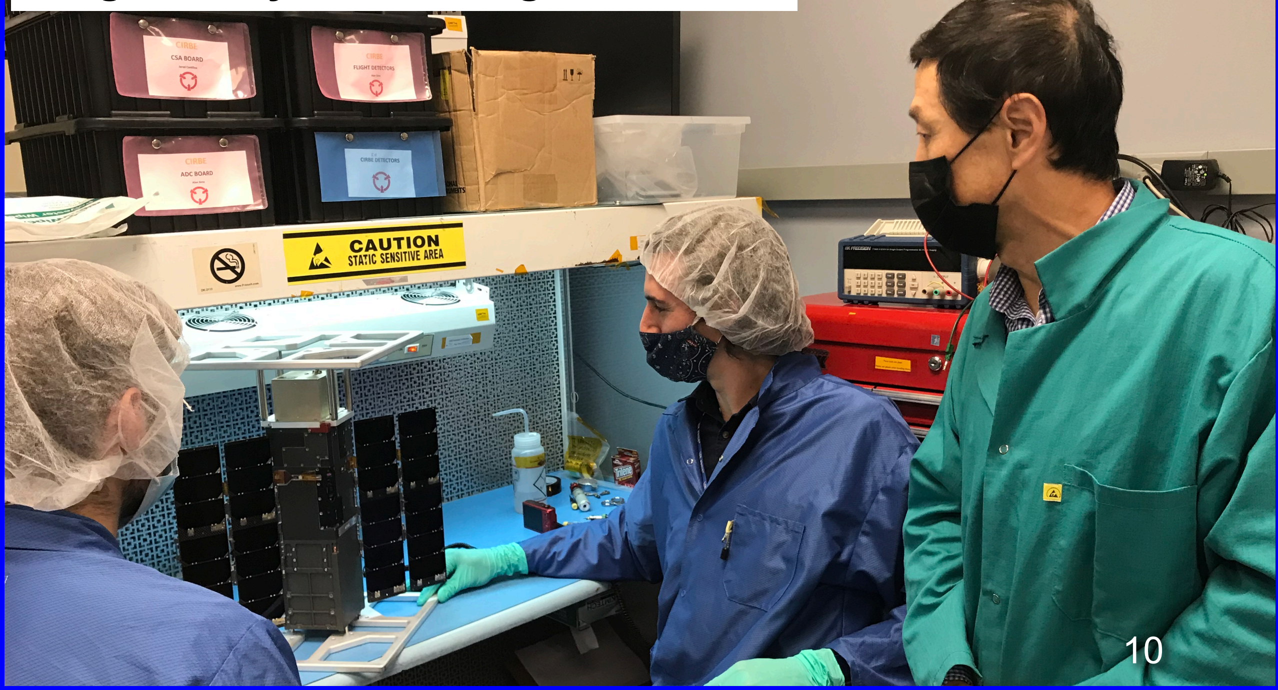
PI: Xinlin Li (LASP and Dept. of Aerospace Engineering Sciences, CU Boulder)
Co-Is: Richard Selesnick, Rick Kohnert, and Scott Palo
Collaborator: Quintin Schiller

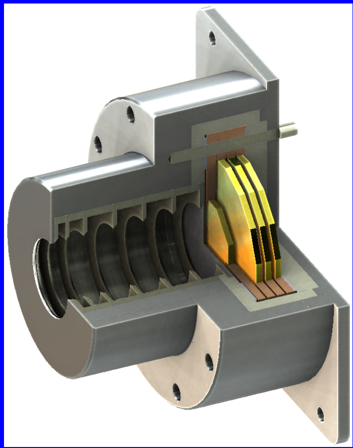
CIRBE
Colorado Inner Radiation Belt Experiment

Funded by NASA/H-TIDeS 2017
$4M total

Launch was manifested for early 2023

Integrated System testing on 9/29/21





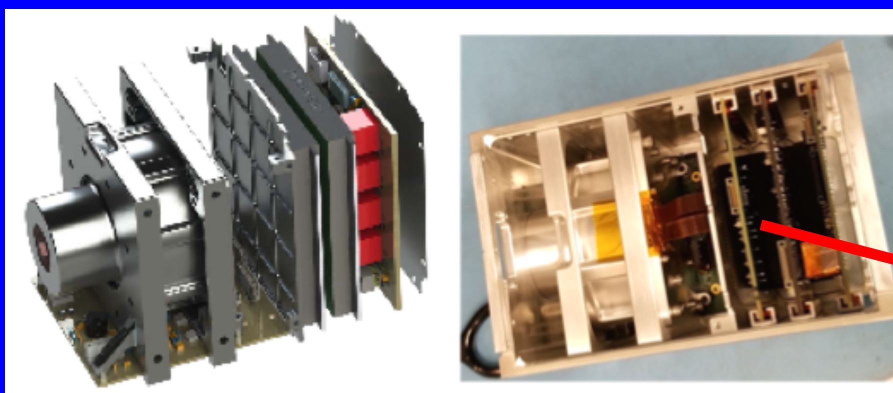
REPTile (Relativistic Electron and Proton integrated little experiment)

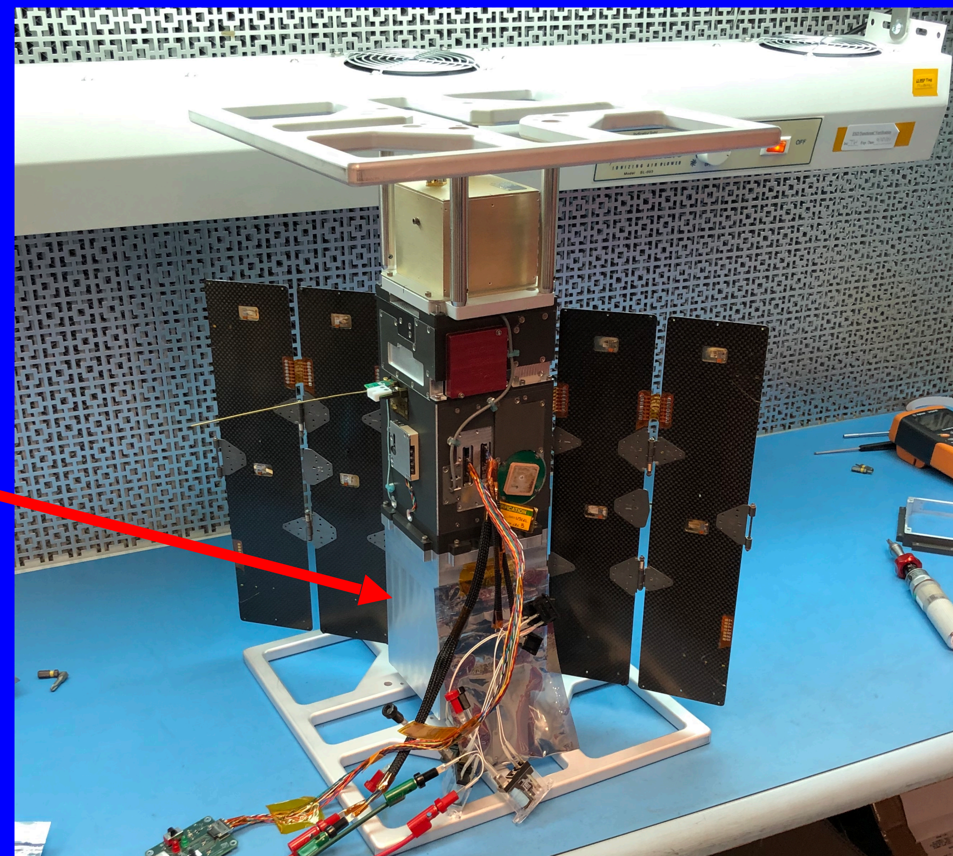
CIRBE
Colorado Inner Radiation Belt Experiment

Operated in space 2012-2014 on CSSWE

Next generation of REPTile

REPTile-2





REPTile-2 fully integrated and tested (plus a spare copy – for post flight calibration)

1st Plugs-out test of CIRBE on 11/18/2021

2nd Plugs-out test 4/11/2022

3rd Plugs-out & End-to-End test on 7/21/2022

…….

What is the difference between CIRBE and CSSWE?

Refined measurements of <u>electrons (0.3–4 MeV)</u> and protons (6.5–40 MeV):

(1) **Pulse Height Analysis (PHA) → high energy resolution (129 channels), requiring more power for onboard processing → deployed solar panels**

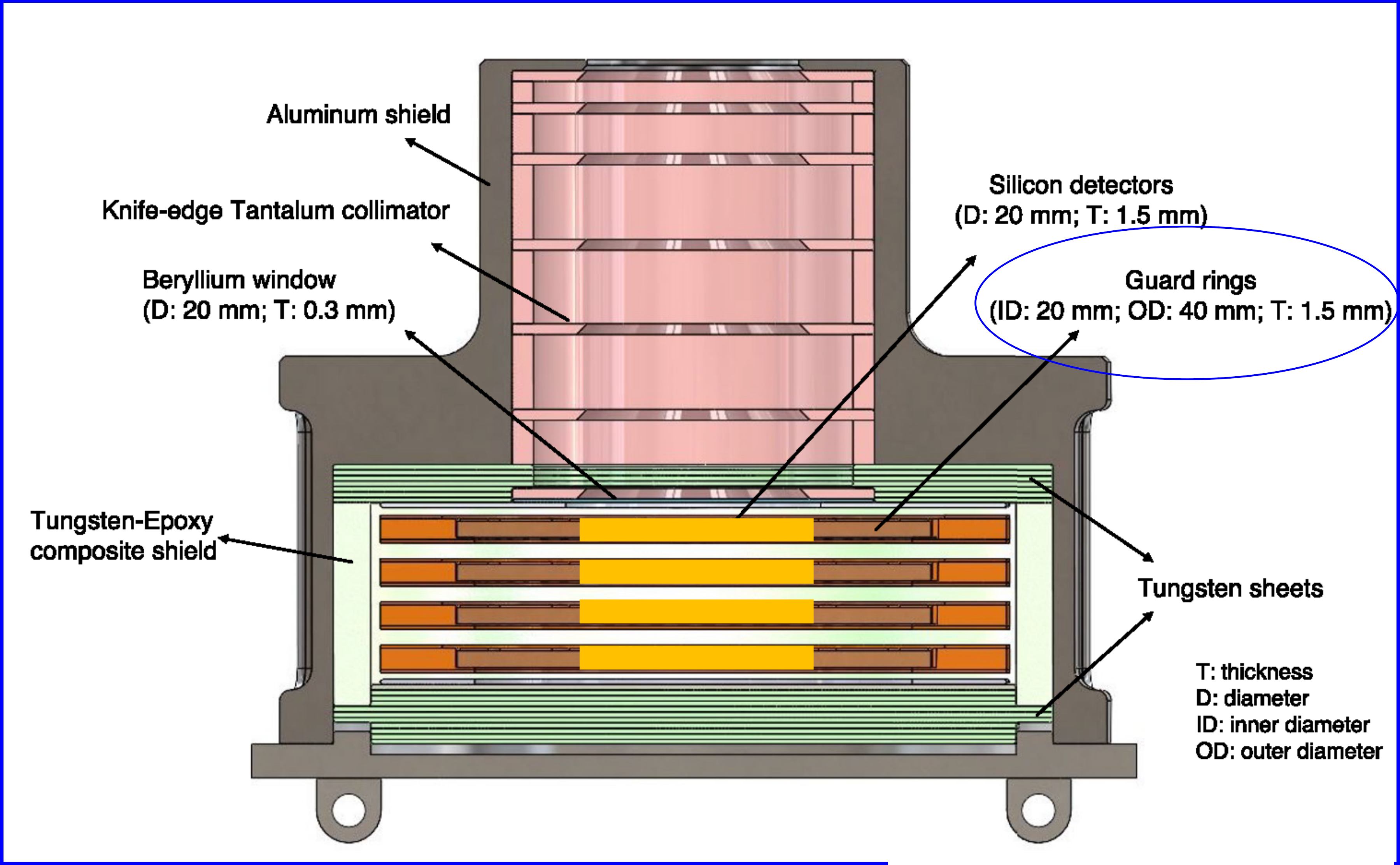
(2) **Anti-coincidence technique → veto the contamination by side and back penetrating protons (cleaner measurements)**

(3) **Active ADCS vs. passive ADCS on CSSWE**

(4) **UHF and S-band vs. UHF only on CSSWE**

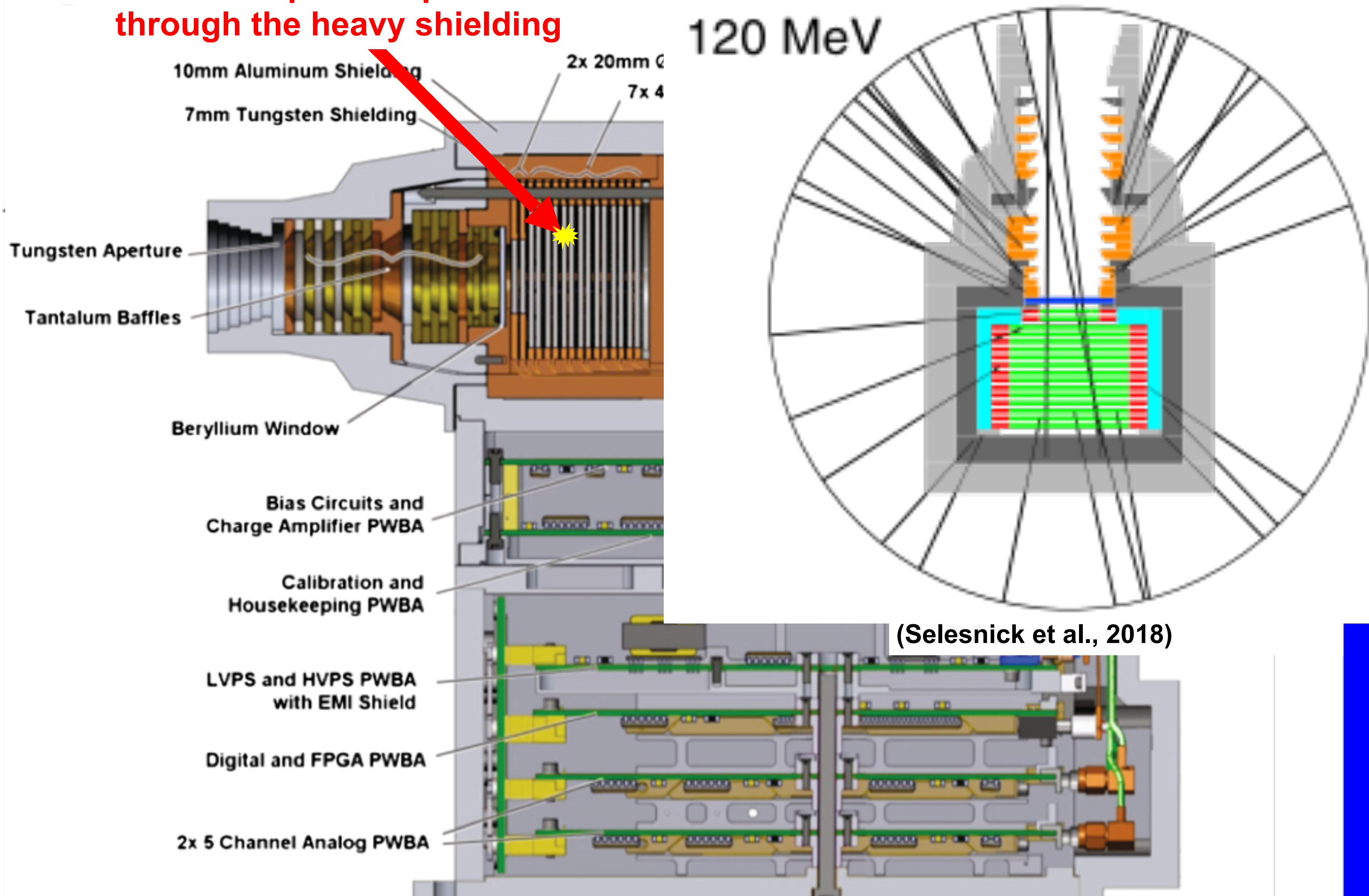
A screen shot of a CIRBE team meeting (Spring of 2020)

Configuration of REPTile-2
(Relativistic Electron and Proton integrated little experiment-2)



(Khoo et al., JGR, 2022)

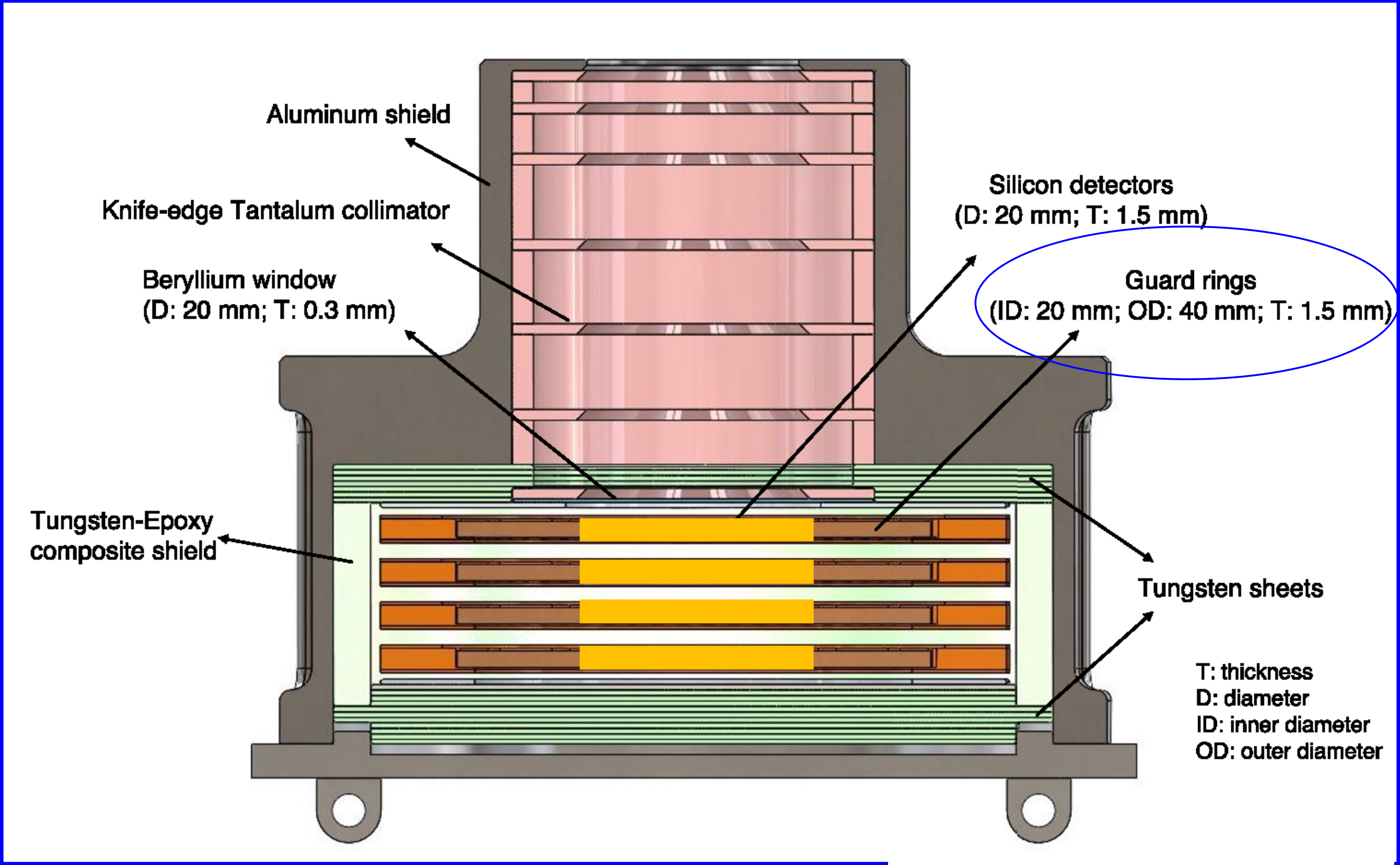
> 120 MeV protons penetrate through the heavy shielding



(Baker et al., 2012)

(Selesnick et al., 2018)

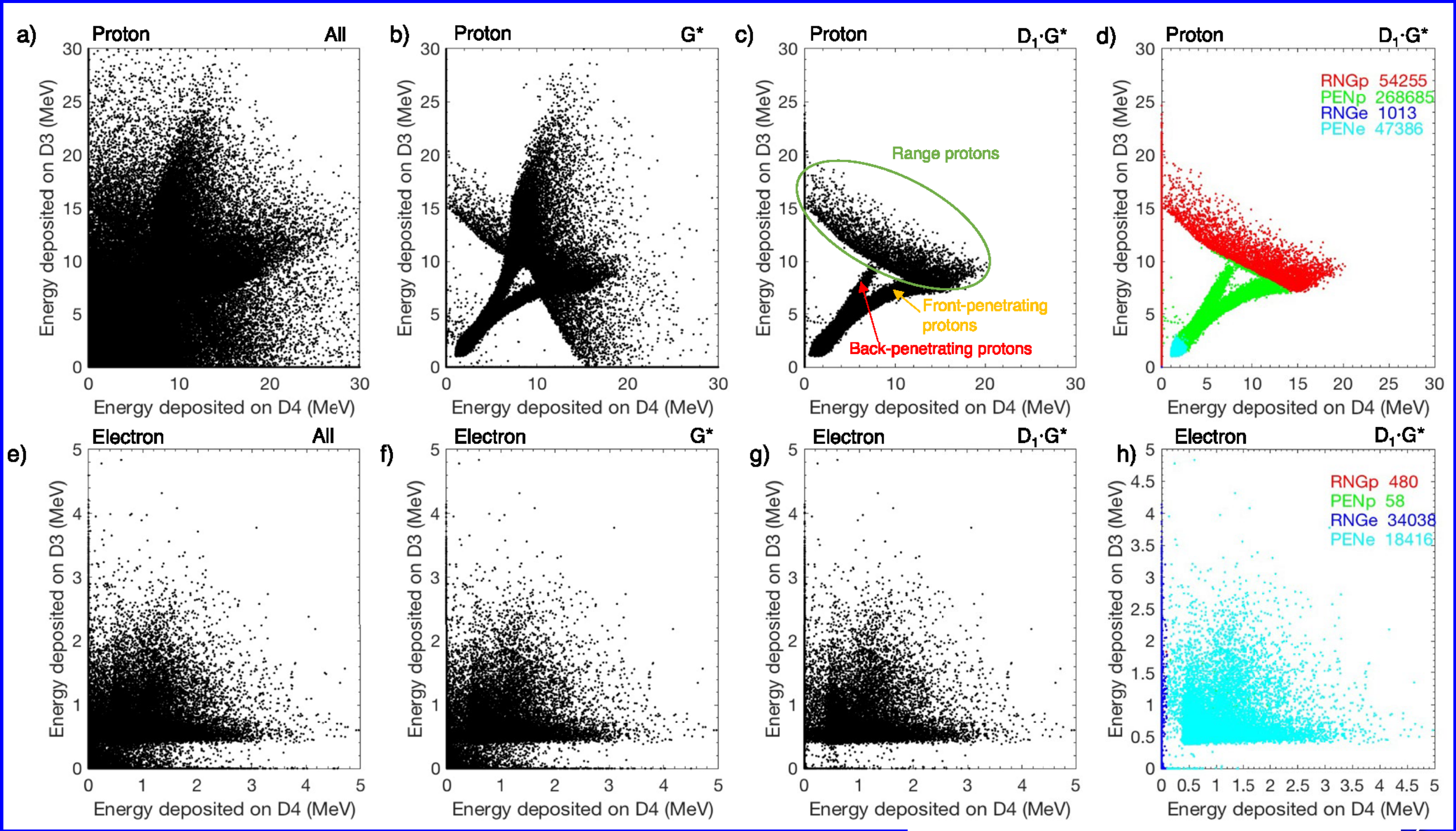
Configuration of REPTile-2
(Relativistic Electron and Proton integrated little experiment-2)



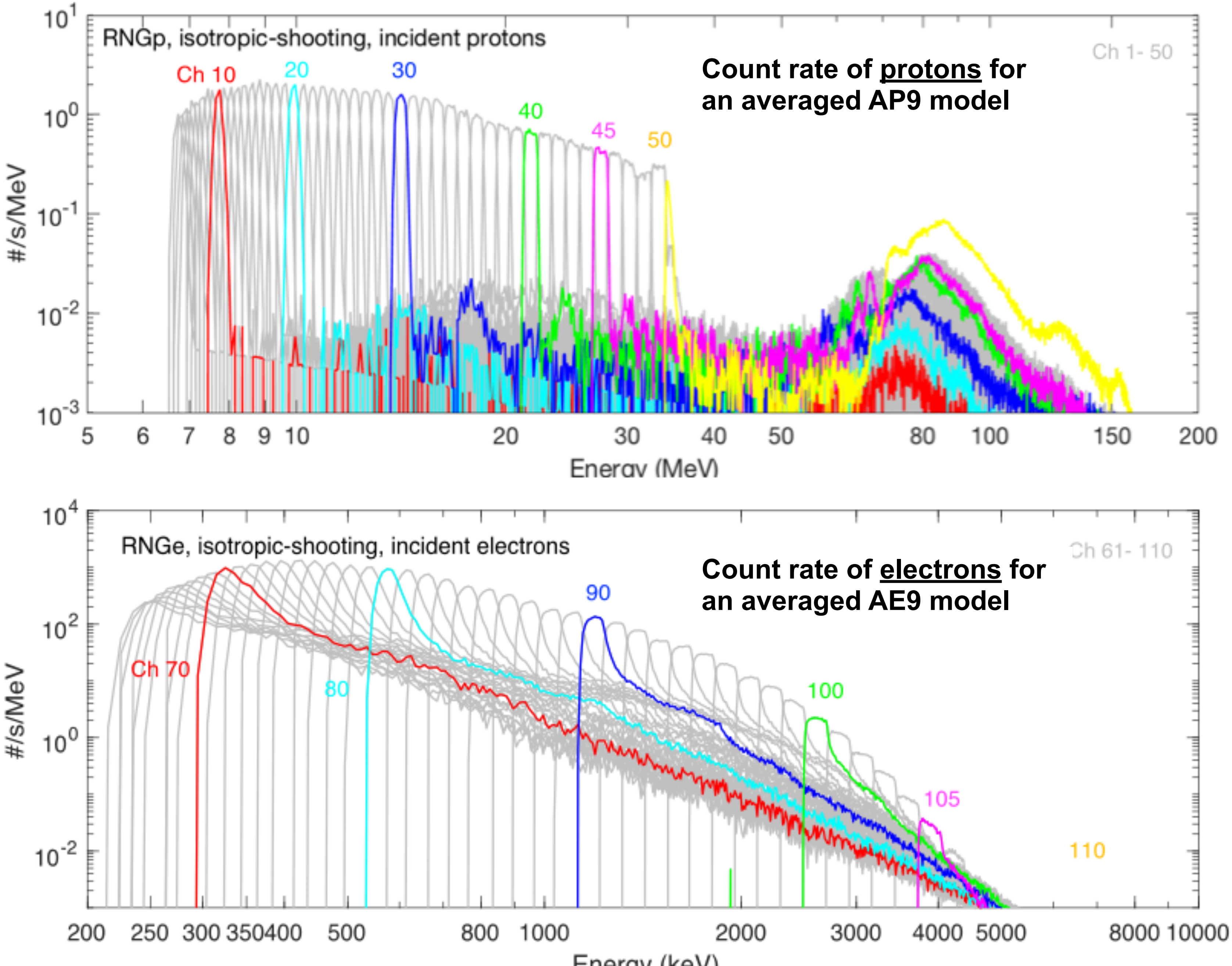
(Khoo et al., JGR, 2022)

Detailed Geant4 Simulations Guided the Design of REPTile-2

Energy deposition on D3 and D4 for a flat incident flux spectrum of electrons and protons in the energy range of 0.1-10 MeV and 1-200 MeV, respectively

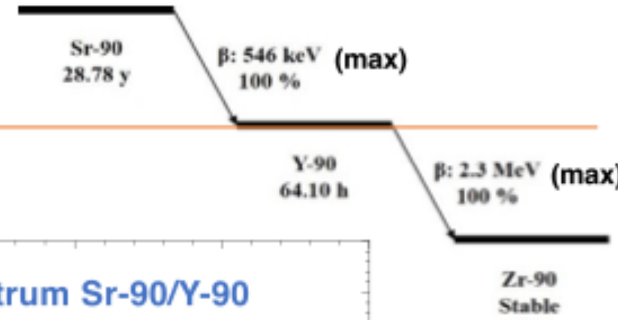


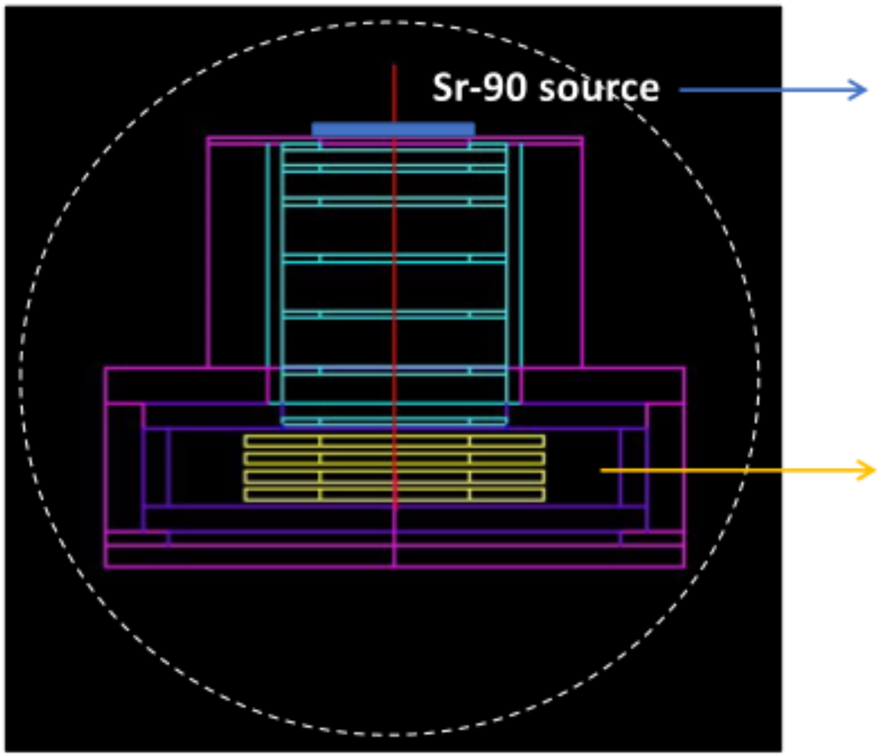
(Khoo et al., JGR, 2022)

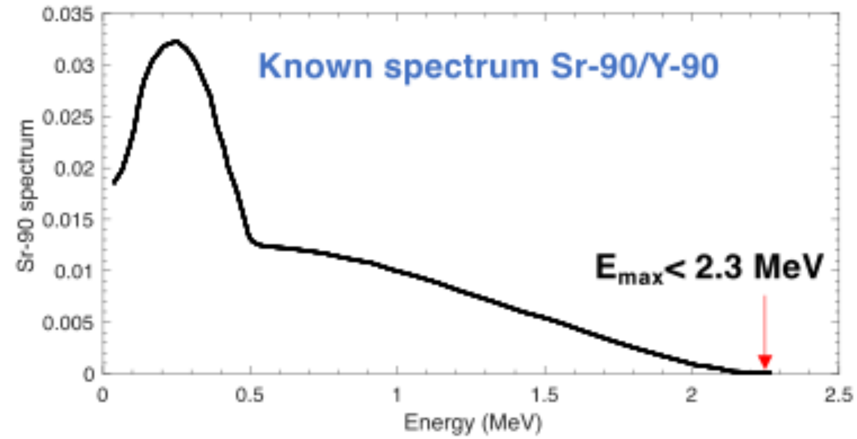

RNGp, isotropic-shooting, incident protons
Ch 1- 50
Ch 10
20
30
40
45
50
Count rate of protons for an averaged AP9 model
#/s/MeV
Energy (MeV)
RNGe, isotropic-shooting, incident electrons
Ch 61- 110
Count rate of electrons for an averaged AE9 model
Ch 70
80
90
100
105
110
#/s/MeV
Energy (keV)

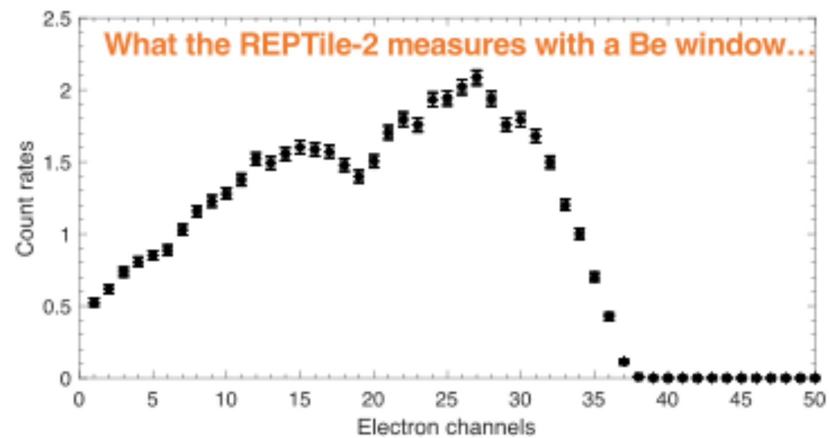
(Li et al., 2022)

Instrument calibration: Sr-90/Y-90 test



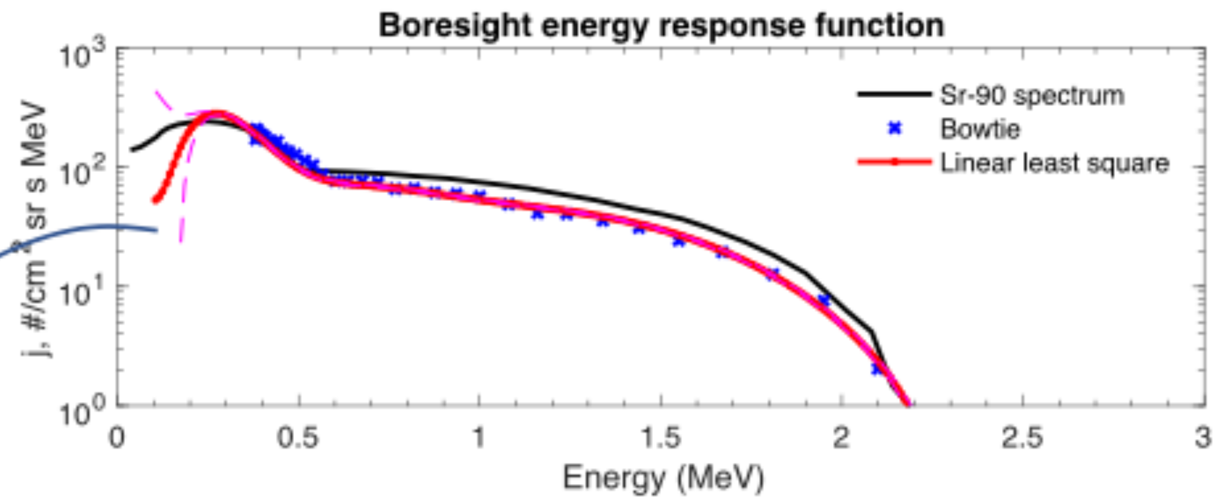




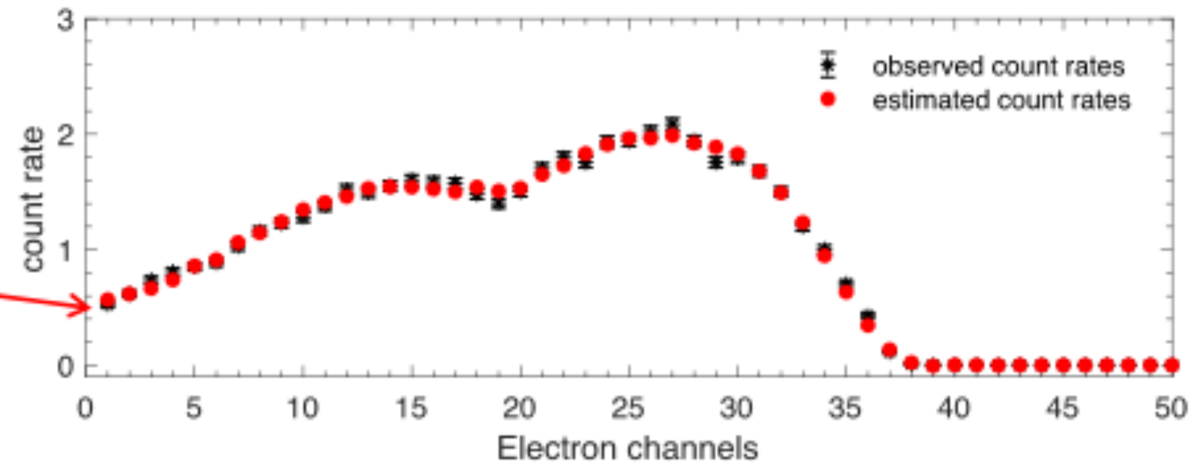


(Khoo et al., JGR, 2022)

Estimated flux and count rate comparion



$$r_i = \int G_i(E) j(E) dE$$



Based on our least square model, we determined the count rate (red) from the estimated flux and compare with the observed count rate

(Khoo et al., JGR, 2022)

Summary

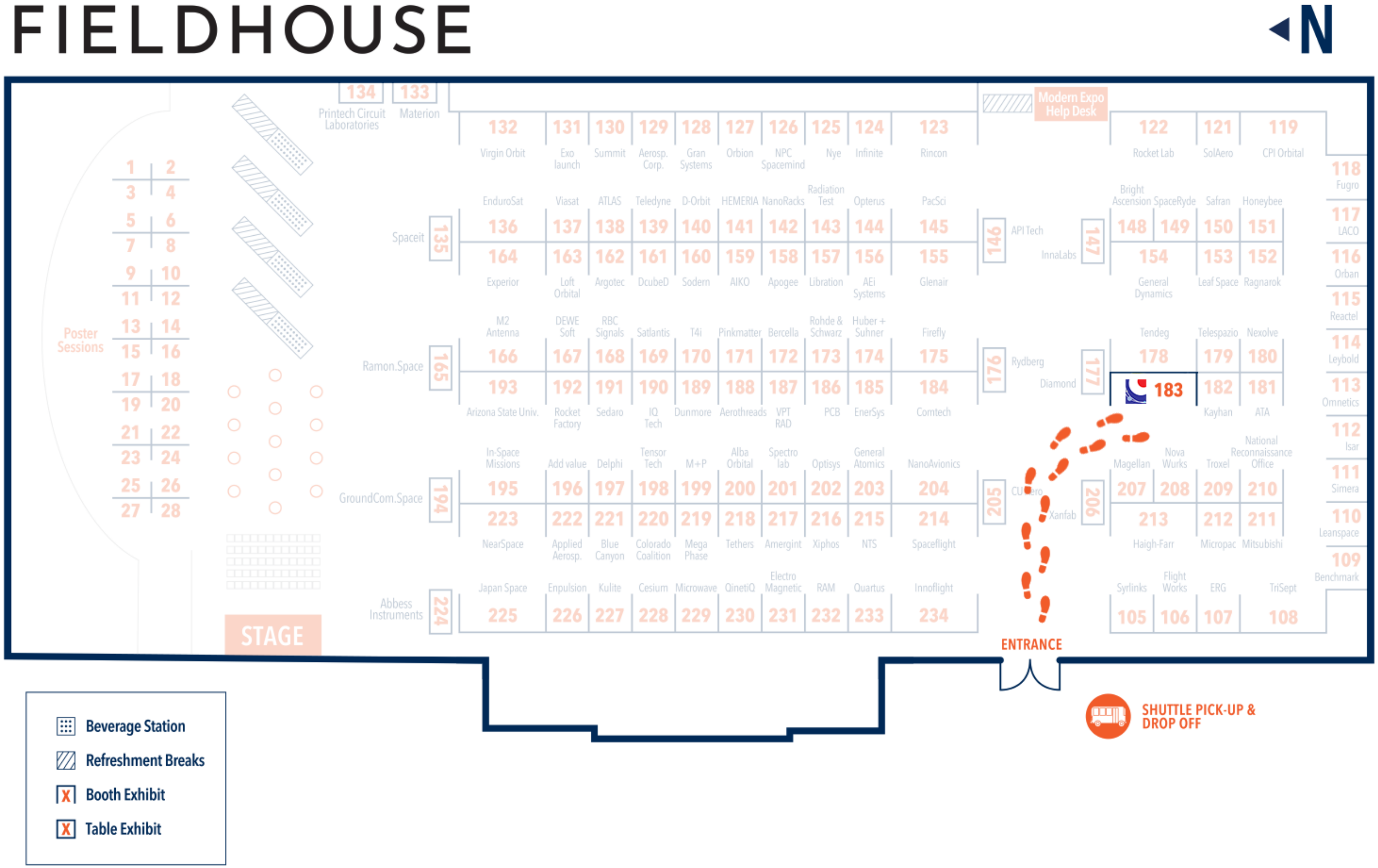
CSSWE/REPTile has been a great success in education, engineering, and sciences. It has demonstrated that CubeSat can be a useful tool to achieve high quality sciences

CIRBE/REPTile-2, vastly improved in the following:

(1) pulse height analysis (PHA), which enables measurements with high energy and time resolution
(2) anti-coincidence technique and logic, which reduce contamination by side and back penetrating protons, leading to cleaner measurements
(3) active attitude control systems (ADS) vs. passive ADS;
(4) addition of a S-band radio transmitter to increase science data throughput to the ground by 100x.

CIRBE is manifested for a LEO launch in early 2023

FIELDHOUSE



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