# 7.5 Years of ISS-RAD

## WRMISS, 2023
## Rome, Italy

Cary Zeitlin

NASA JSC Space Radiation Analysis Group

On behalf of the ISS-RAD Science Teams Past and Present

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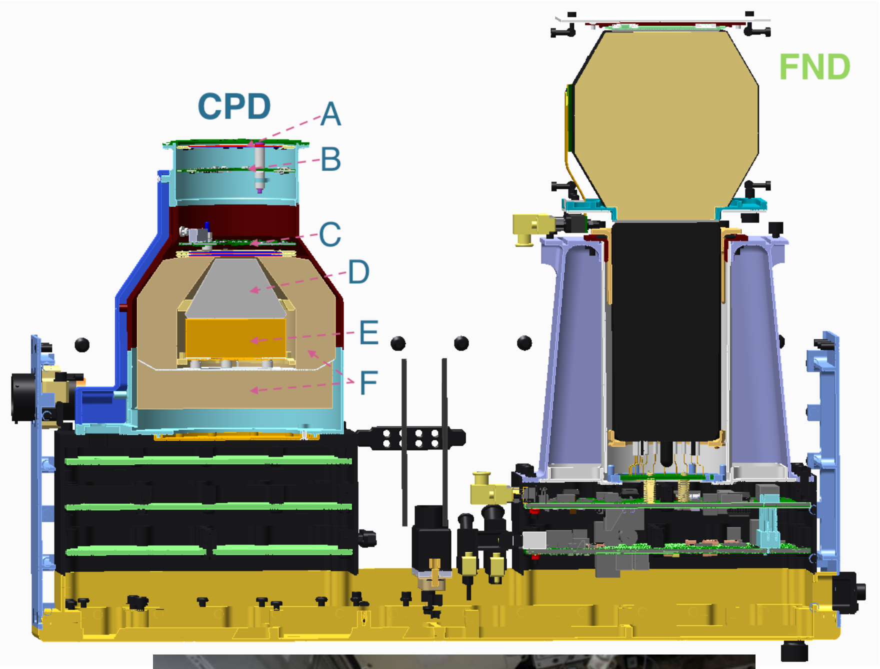
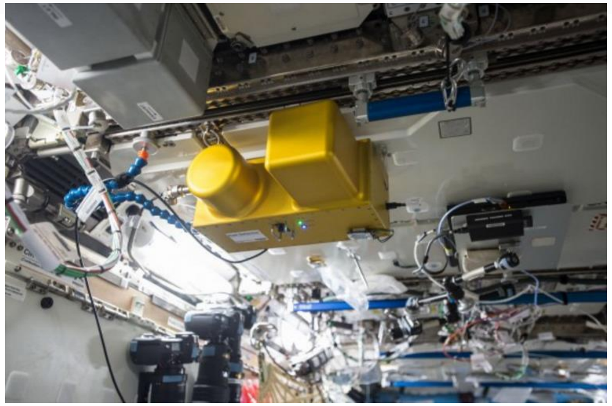
# Overview & Timeline Since Deployment

- ISS-RAD consists of 2 sensor heads:
  - CPD (charged particle detector)
  - FND (fast neutron detector)
  - Sensor heads are connected by the RIB (RAD interface board).
- Feb 2016 – March 2017: LAB1O3 for Activation & Checkout.
- March 2017 – May 2020: Survey.
- May 2020 – present: LAB1O6.
- FSW upgrade March 2021.



RAD at LAB1O3 Forward (+X)

# Survey Details & Charged Particle Absorbed Dose Rates

- Measurements in USLAB, JPM, COL, Node2, and Node3. Typical schedule:
  - Move every 3 months.
  - Rotate monthly.
- GCR results ~ consistent for given locations across deployments but SAA increased over survey period.
- Data from JPM, COL, Node 3 all show this.

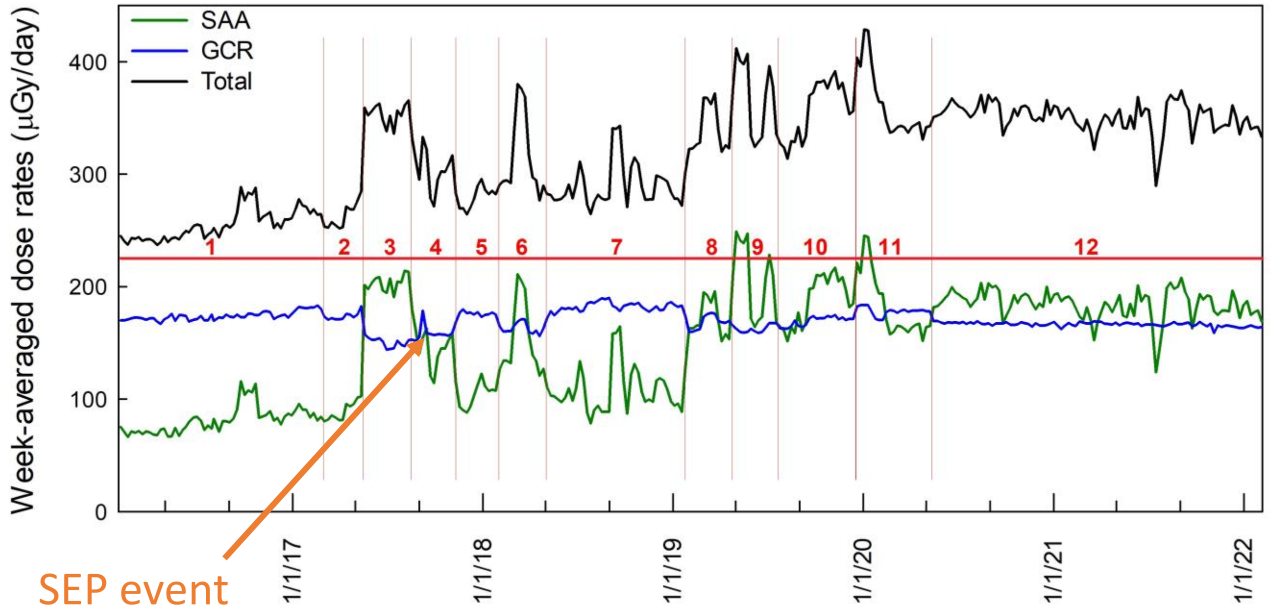
**Table 1**
Locations and orientations of RAD, along with average daily doses in units of μGy, for twelve distinct periods of operation.

| RAD location/orientation and average dose rates in μGy/d | | | | | | |
|---|---|---|---|---|---|---|
| Per. | Location | First date | Last date | Orientations | GCR | SAA |
| 1 | USLab, 1O3 | 02/01/2016 | 03/01/2017 | F, A | 174 | 81 |
| 2 | Node 3, A5 | 03/01/2017 | 05/16/2017 | Z, F, S | 174 | 90 |
| 3 | JPM, D5 | 05/16/2017 | 08/16/2017 | P, Z, S | 150 | 203 |
| 4 | COL, 1A2 | 08/16/2017 | 11/10/2017 | Z, P, S | 157 | 146 |
| 5 | USLab, 1O3 | 11/10/2017 | 02/01/2018 | P, S, A | 176 | 103 |
| 6 | COL, 1A2 | 02/01/2018 | 05/03/2018 | F, N, Z | 163 | 154 |
| 7 | USLab, 1O3 | 05/03/2018 | 01/25/2019 | F, P, S, N, A | 182 | 108 |
| 8 | Node 2, P3 | 01/25/2019 | 04/25/2019 | Z, N, F | 168 | 184 |
| 9 | JPM, D5 | 04/25/2019 | 07/22/2019 | A, F, N | 162 | 249 |
| 10 | COL, 1A2 | 07/22/2019 | 12/18/2019 | F, A, N | 170 | 211 |
| 11 | Node 3, A5 | 12/18/2019 | 05/12/2020 | N, A, P | 178 | 183 |
| 12 | USLab, 1O6 | 05/12/2020 | 02/01/2022[a] | Z | 167 | 185 |

The second column from the left shows both the ISS module and the panel location within the module; orientations are listed only by their first initial: F for forward (along the usual velocity vector), A for aft, Z for zenith, N for nadir, P for port, and S for starboard.
[a]ISS-RAD remains in the USLab module at the panel 1O6 position, pointing zenith, at the time of this writing.

Dose rates are measured in B, converted from Si to $H_2O$ with factor of 1.23.

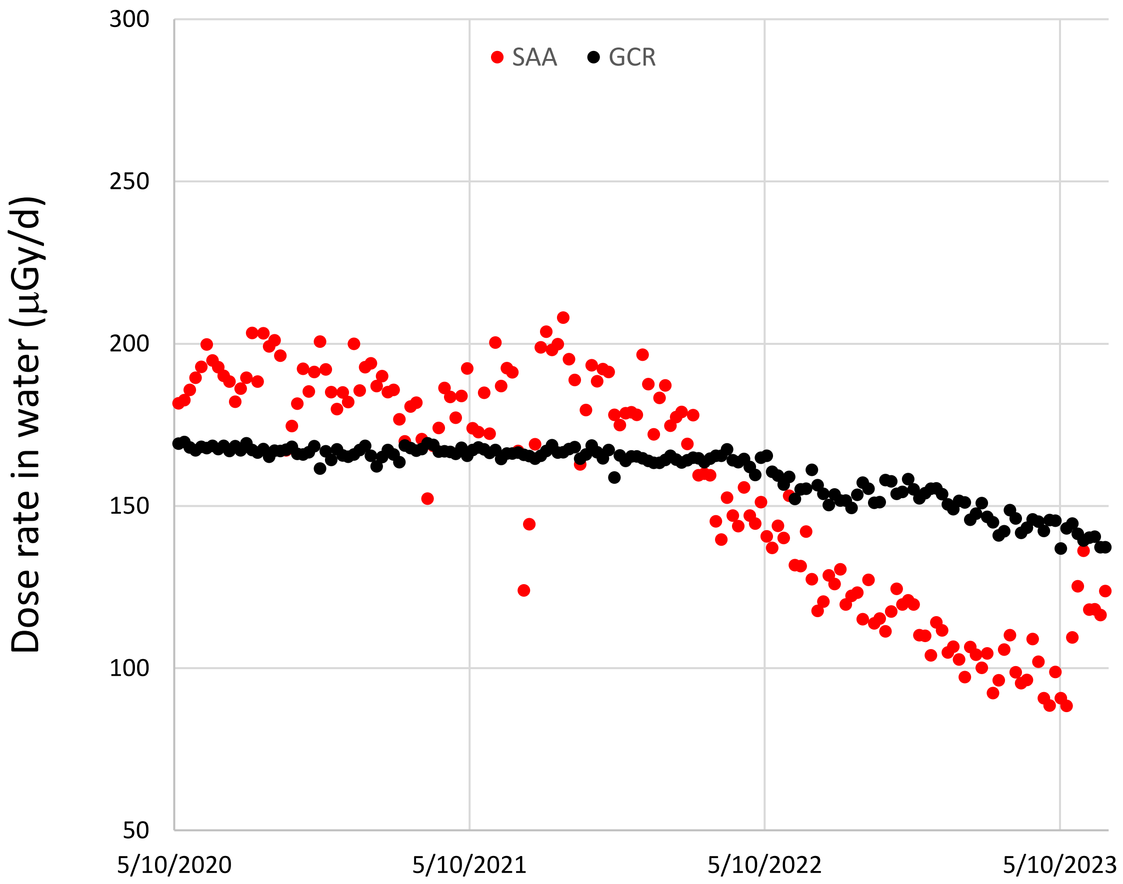
# Charged Particle Absorbed Dose Rates




1 = LAB1O3 2 = Node 3 3 = JPM 4 = COL
5 = LAB1O3 6 = COL 7 = LAB1O3 8 = Node 2
9 = JPM 10 = COL 11 = Node 3 12 = LAB1O6

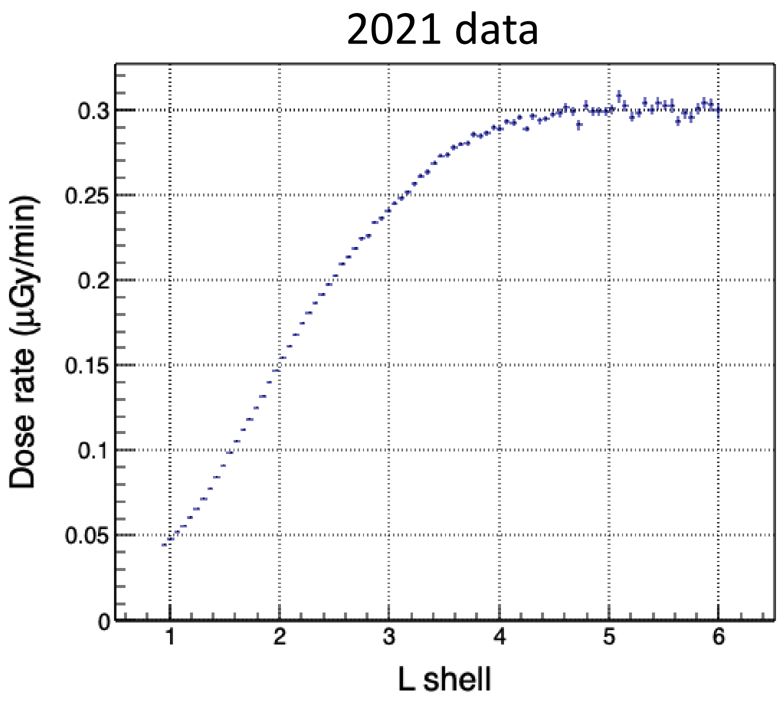
- Annotations in red denote different survey periods.
- GCR ~ insensitive to rotations & weakly dependent on variations between ISS modules.
- SAA sensitive to both.
- Solar modulation effects clear in period 12 (RAD @ LAB1O6).
- 2022-23 show further decreases.

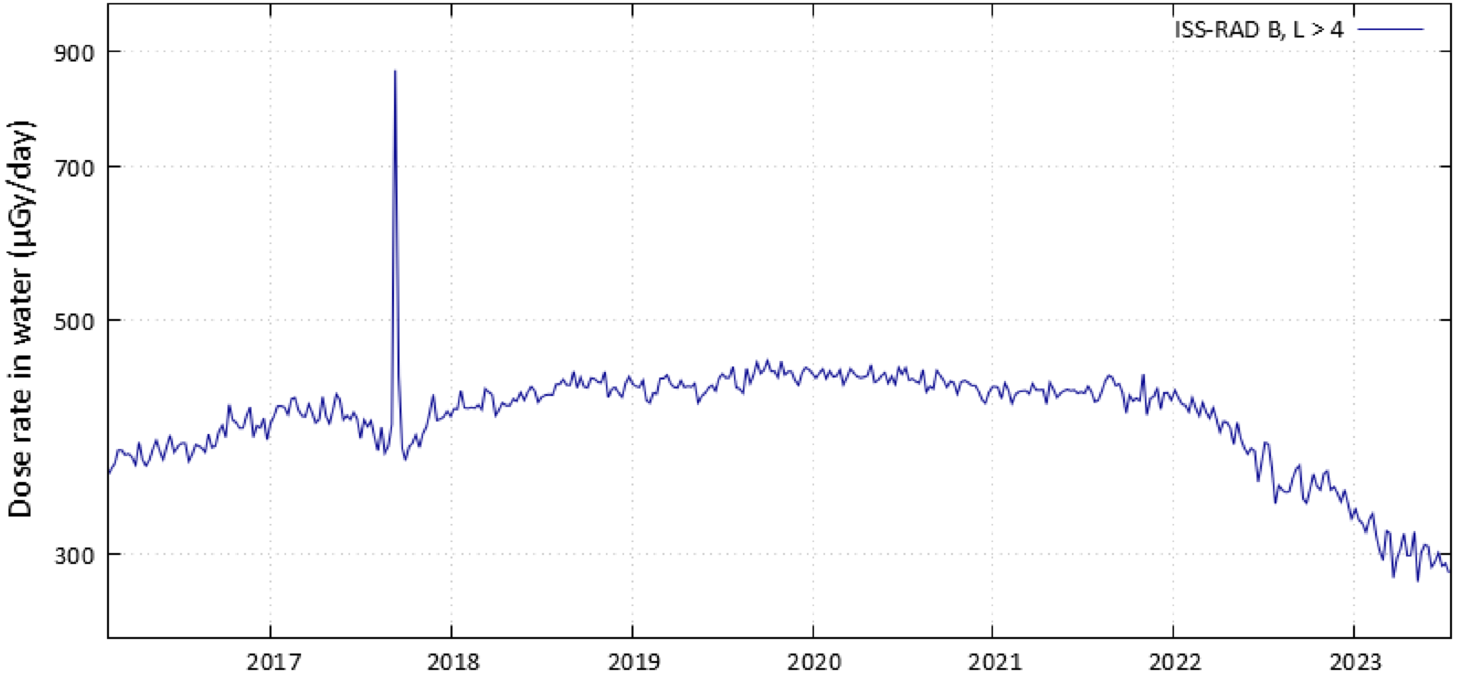
# Absorbed Dose Rates 2020-23




- RAD @ LAB1O6, weekly averages.
- Solar cycle affects SAA dose rates more than GCR in ISS orbit.
- SAA decrease due to expansion of Earth's atmosphere.
- Outlier SAA points in July 2021 from "flying backwards" periods.
- Recent increase in SAA may be from changing local shielding.

# Solar Cycle Effects in High-Latitude GCR Data



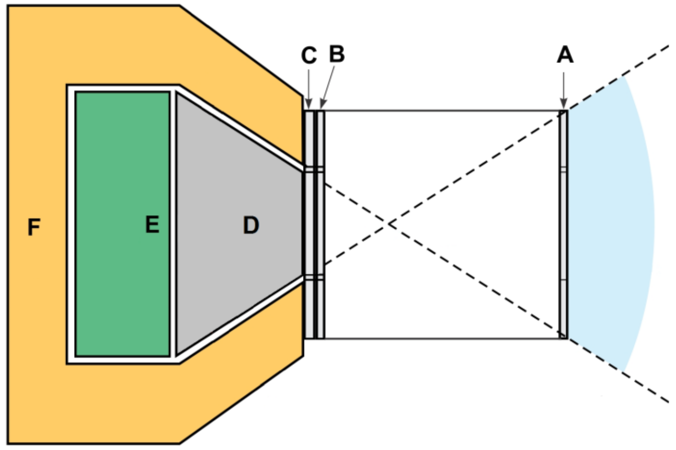

- Average dose rate vs. L-shell suggests L > 4 is a good definition of high latitude. (But only ~ 1 hour/day.)
- L > 4 dose rate time series clearly shows modulation.

# Charged Particle <Q> Measurements

**Table 2**
Locations and orientations of RAD, along with average quality factors using the ICRP 60 definition for 11 of the 12 time periods shown in Table 1.

| RAD location/orientation and average quality factors | | | | | | |
|---|---|---|---|---|---|---|
| Per. | Location | Orientations | GCR | SAA | orbit-av. | $H_{tot}$ μSv/d |
| 2 | Node 3, A5 | Z, F, S | 3.3 | 1.8 | 2.8 | 743 |
| 3 | JPM, D5 | P, Z, S | 3.1 | 1.6 | 2.2 | 795 |
| 4 | COL, 1A2 | Z, P, S | 2.9 | 1.5 | 2.2 | 677 |
| 5 | USLab, 1O3 | P, S, A | 2.5 | 1.4 | 2.1 | 577 |
| 6 | COL, 1A2 | N, Z | 2.9 | 1.4 | 2.2 | 692 |
| 7 | USLab, 1O3 | F,P,S,N,A | 2.6 | 1.6 | 2.2 | 634 |
| 8 | Node 2, P3 | Z, N, F | 2.6 | 1.6 | 2.1 | 706 |
| 9 | JPM, D5 | A, F, N | 2.9 | 1.3 | 2.0 | 740 |
| 10 | COL, 1A2 | F, A, N | 2.8 | 1.4 | 2.1 | 745 |
| 11 | Node 3, A5 | N, A, P | 2.6 | 1.5 | 2.1 | 745 |
| 12a | USLab, 1O6 | Z | 3.1 | 1.5 | 2.0 | 807 |
| 12b | USLab, 1O6 | Z | 3.2 | 1.6 | 2.4 | 820 |

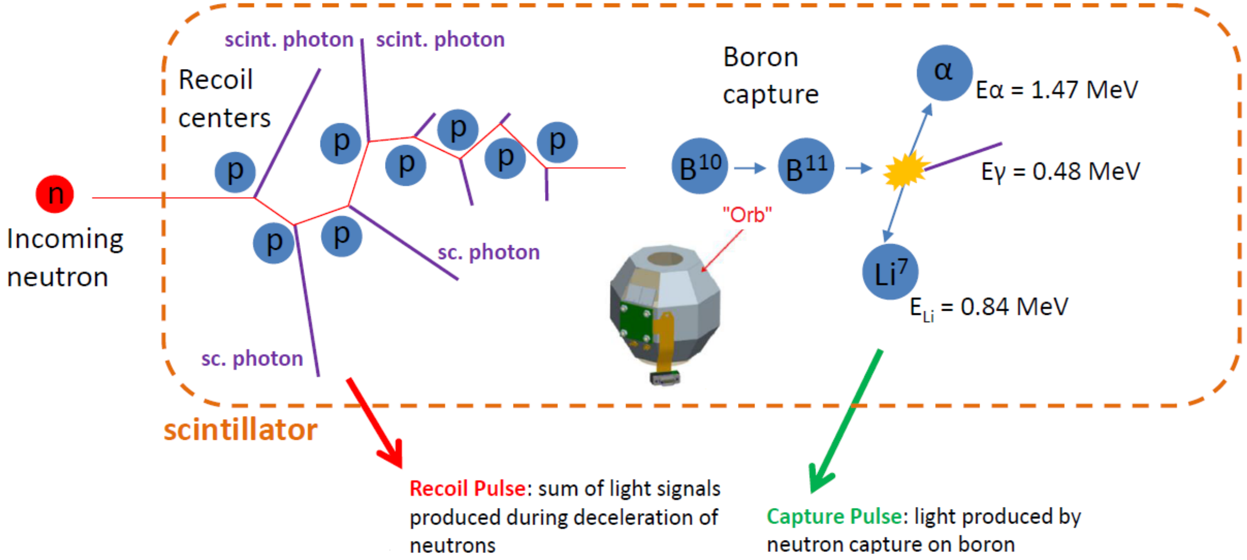
Data for the Lab1O6 location are shown in two parts to allow comparison of results obtained using the correction method for pre-software-upgrade data and post-upgrade data. For period 12a, corrected data from the 9 months prior to the software upgrade were used, and for 12b, uncorrected data from the 9 months after the upgrade were used.

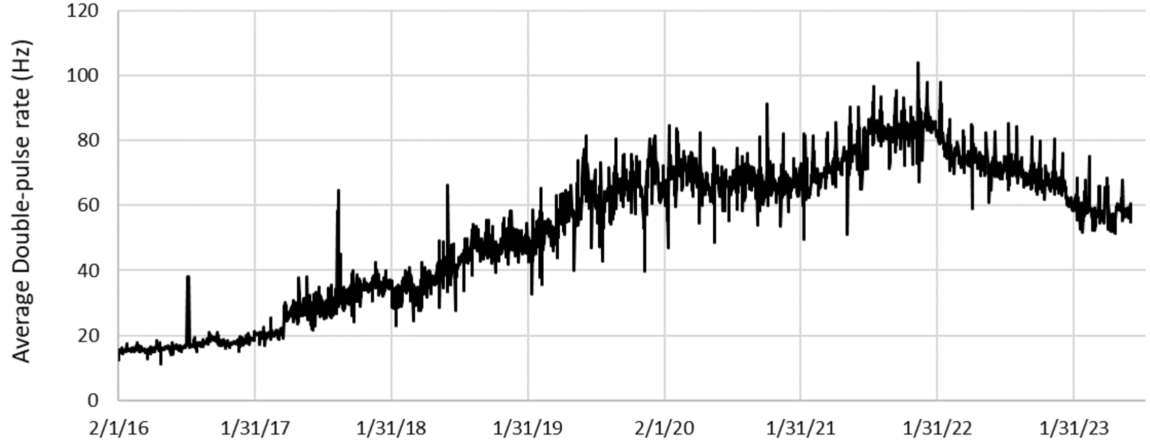



- <Q> measurement uses narrow FOV, sensitive to rotations.
- Complications due to partial failure of A detector in silicon stack – works for low LET but on high-LET events ~ 90% fails to record full energy deposition.
  - Grounding problem??
  - Modified triggering & onboard analysis in revised FSW to work around.
- Use B*C coincidences but require some energy deposited in A & D to eliminate (or at least reduce) the number of out-of-cone particles.

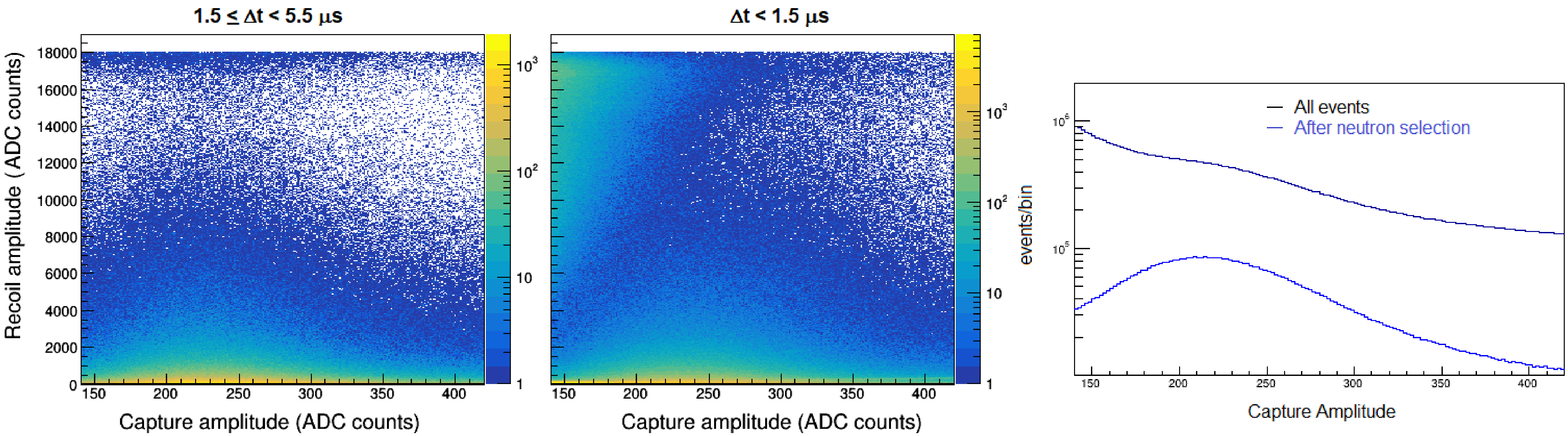
# FND Operation & Performance

- FND measures neutrons from 0.2 to 8 MeV using a boron-loaded plastic scintillator with capture-gating logic.
  - Neutron signature is a pulse pair within a narrow time window (< 10 μs).
  - 2nd pulse from $^{11}B$ fission has a characteristic amplitude range.
- Large increase in double-pulse rate over time, not due to neutrons.
  - Concentrated at low Δt, low capture amplitude, high recoil amplitude.
  - PMT after-pulsing?
  - PMT also tends to lose gain over time, compensated w/HV boosts & in analysis.



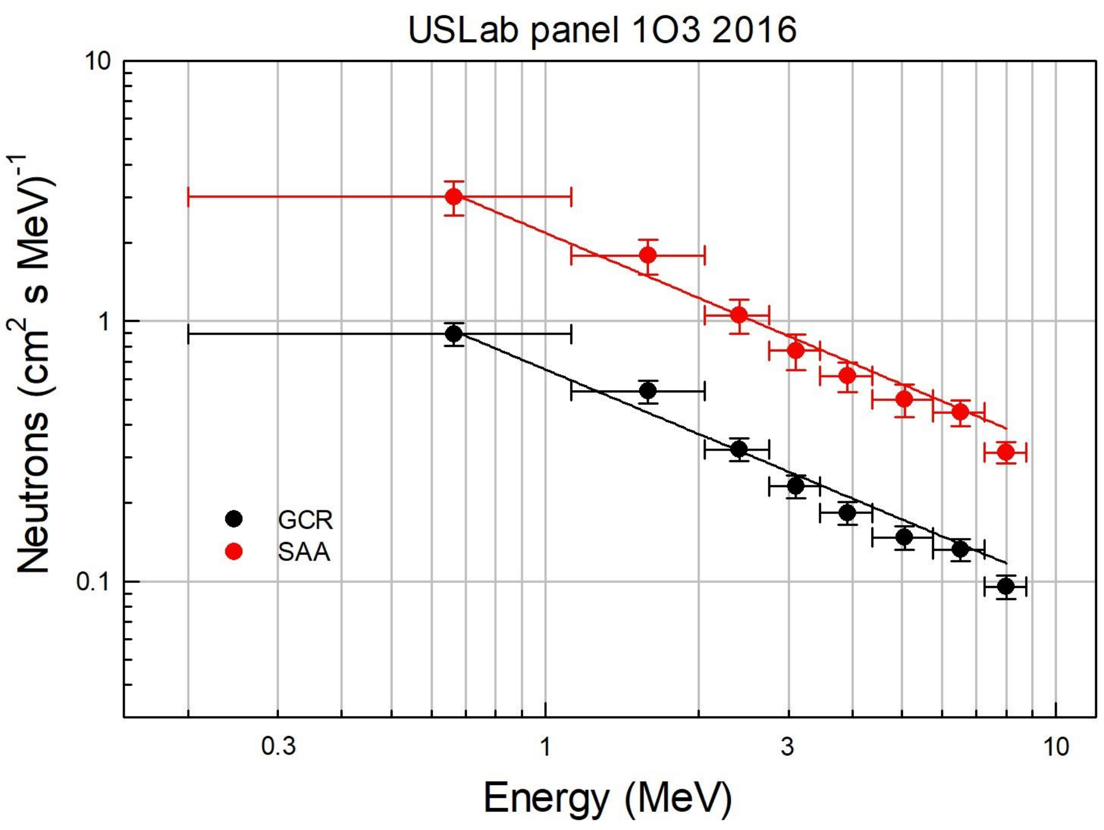
# FND Background Cleanup




- Capture amplitude window set to 140 – 420 ADC counts in onboard firmware.
- Distribution without selection cuts is dominated by background, falls monotonically.
  - True neutron events just a shoulder as ~ 85% of double-pulse triggers are now background.
- Eliminate background with Δt and recoil amplitude cuts → get expected capture distribution.

# Unfolded FND Neutron Spectra

- Differential fluence spectra look like power laws w/similar slopes for both GCR and SAA.
- Little variation in slope between locations, curves move up & down but retain shape.
- Fast neutrons are mostly from evaporation so ~ constant spectral shape makes sense.
- Power-law slopes ~ -0.7 to -0.9.



# Unfolded FND H*(10) Results

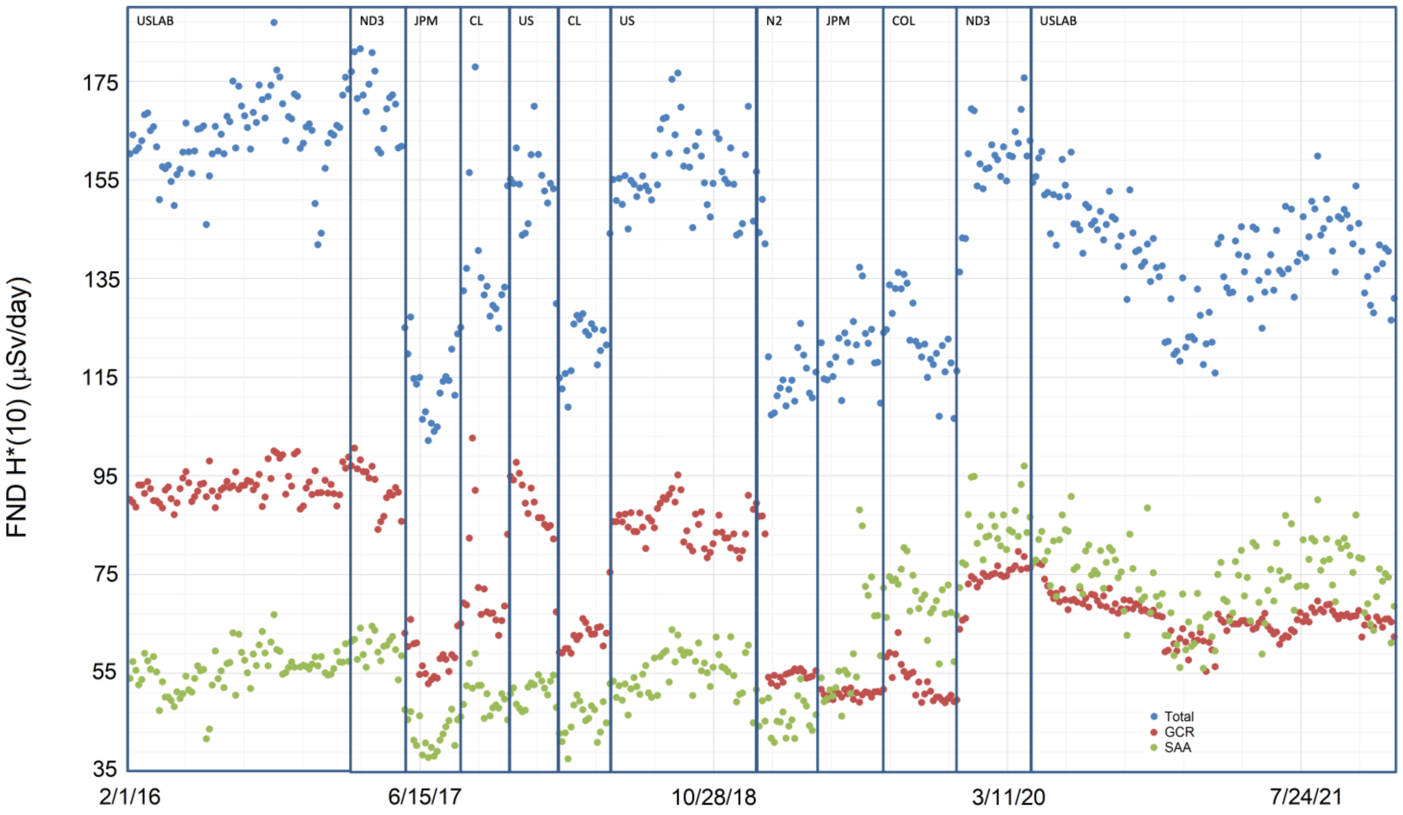


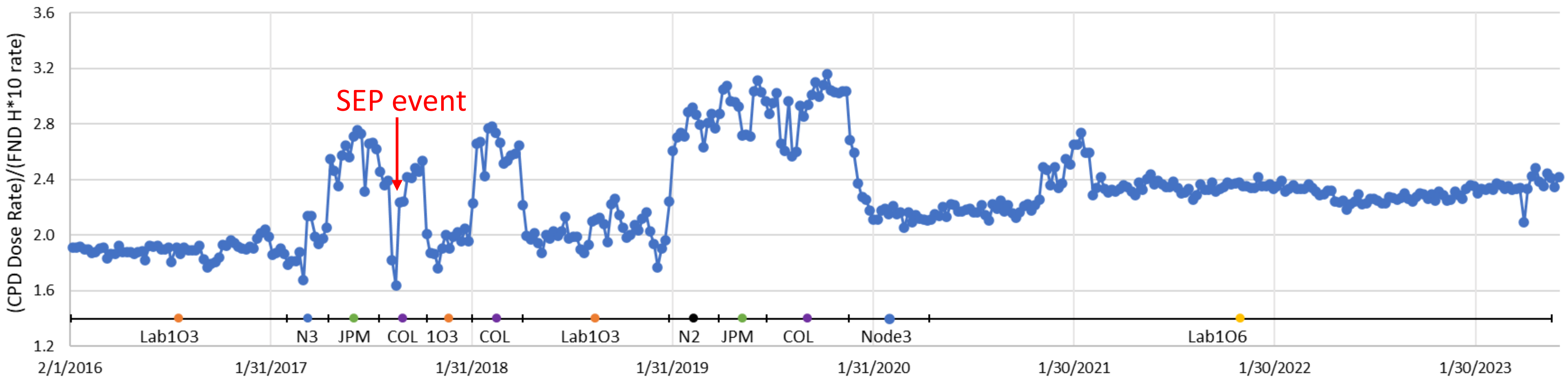

**Table 1**

Locations and average daily H*(10) results derived from FND data, in units of $\mu$Sv. *ISS-RAD remains in the USLAB module at the panel LAB1O6 position, at the time of this writing. It is expected to stay there indefinitely. The annotations N2 and N3 stand for Node 2 and Node 3, respectively. The GCR H*(10) rates should be considered to have ±7% uncertainties, the SAA rates ±13%, and the totals ±15% from propagation of errors. A few values in the "Total" column differ from the sums of GCR and SAA due to rounding.

| RAD Location and Average H*(10) Rates in $\mu$Sv/d | | | | | |
|---|---|---|---|---|---|
| Location | First Date | Last Date | GCR | SAA | Total |
| USLAB, 1O3 | 2/1/2016 | 3/1/2017 | 90 | 51 | 141 |
| Node 3, A5 | 3/1/2017 | 5/16/2017 | 90 | 56 | 146 |
| JPM, D5 | 5/16/2017 | 8/16/2017 | 58 | 54 | 112 |
| COL, 1A2 | 8/16/2017 | 11/10/2017 | 73 | 55 | 127 |
| USLAB, 1O3 | 11/10/2017 | 2/1/2018 | 90 | 60 | 151 |
| COL, 1A2 | 2/1/2018 | 5/3/2018 | 62 | 56 | 118 |
| USLAB, 1O3 | 5/3/2018 | 1/25/2019 | 88 | 66 | 154 |
| Node 2, P3 | 1/25/2019 | 4/25/2019 | 56 | 61 | 117 |
| JPM, D5 | 4/25/2019 | 7/22/2019 | 52 | 72 | 123 |
| COL, 1A2 | 7/22/2019 | 12/18/2019 | 54 | 71 | 125 |
| Node 3, A5 | 12/18/2019 | 5/12/2020 | 71 | 85 | 155 |
| USLAB, 1O6 | 5/12/2021 | 2/1/2022 | 66 | 81 | 147 |

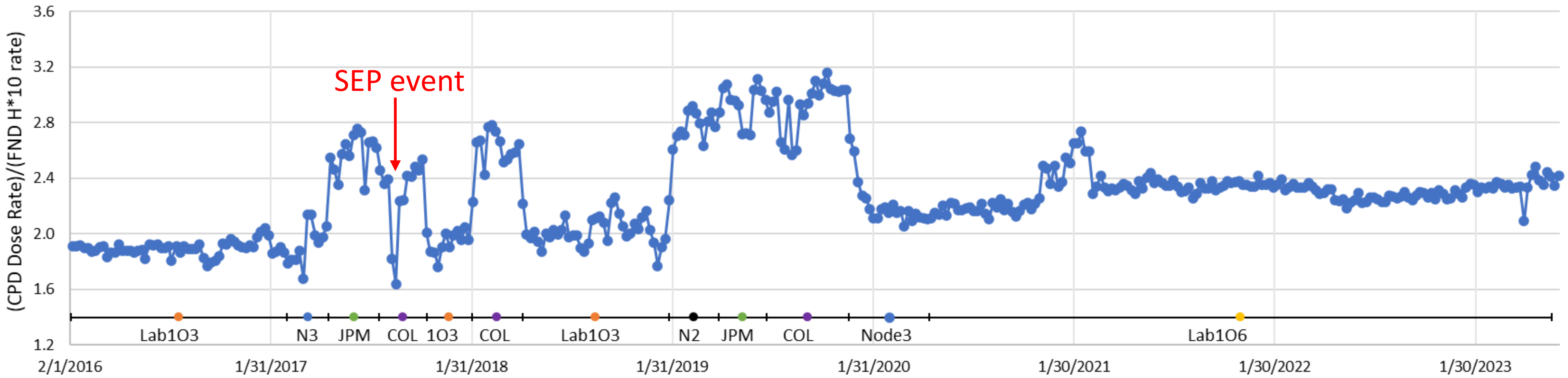
- GCR varies by factor of ~ 2 unlike GCR charged particle dose rate.
- See SAA increasing over time in this data as well as charged particle data.

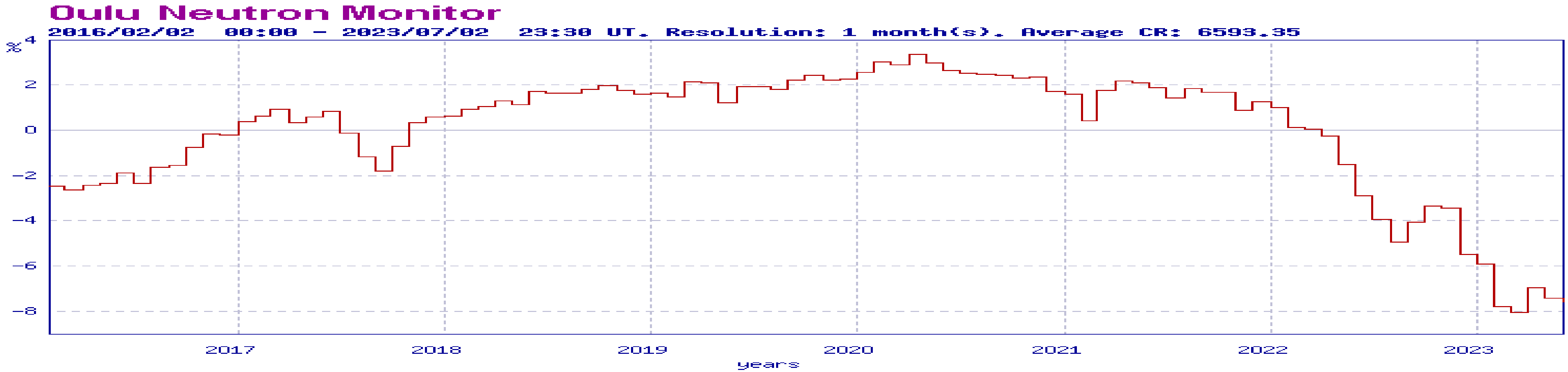
# GCR Charged Dose Rate & FND H*(10)




- Ratio of charged-particle dose to FND H*(10) illustrates shielding variations between modules.
- Going from more shielding to less shielding → charged particle dose rate ~ stable, but neutron H*(10) rate decreases → ratio increases.
- Gradual increase in ratio since 2022 could be environment changing or PMT gain drop not fully compensated in ground analysis (or both).

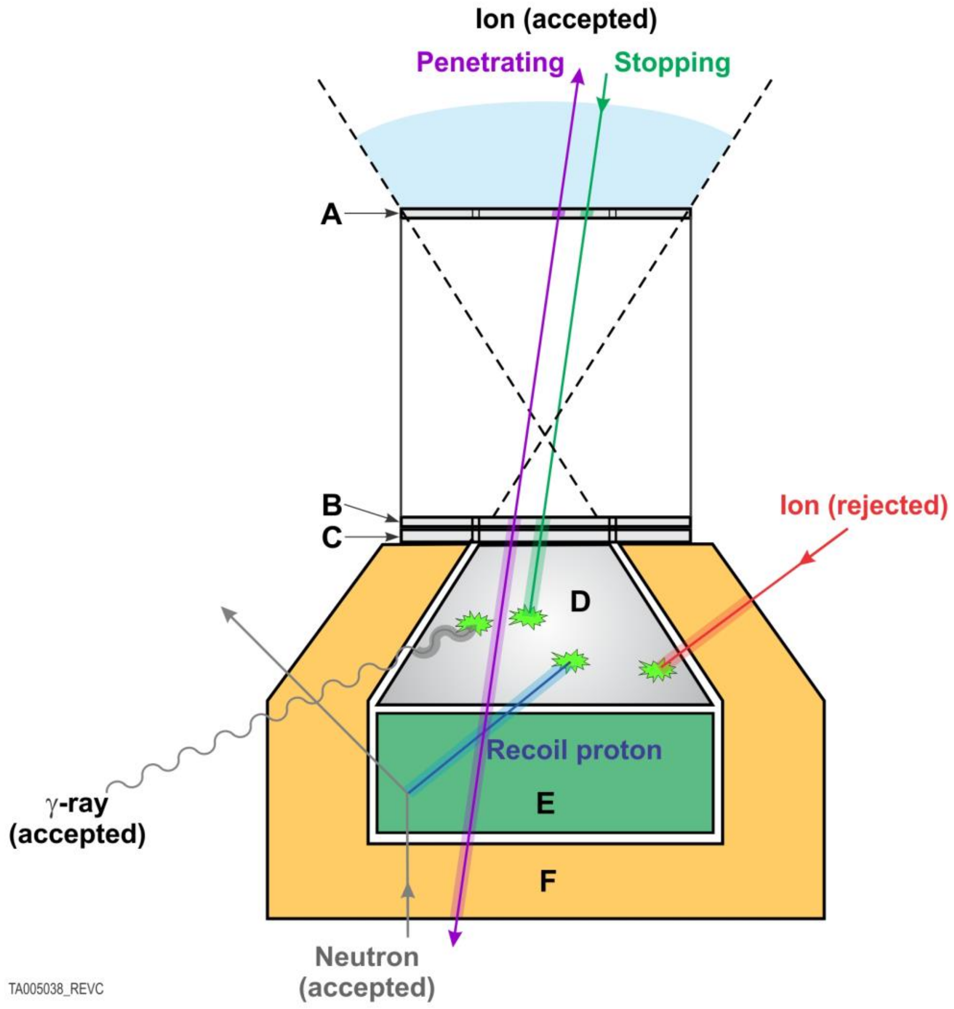
# GCR Charged Dose Rate & FND H*(10)



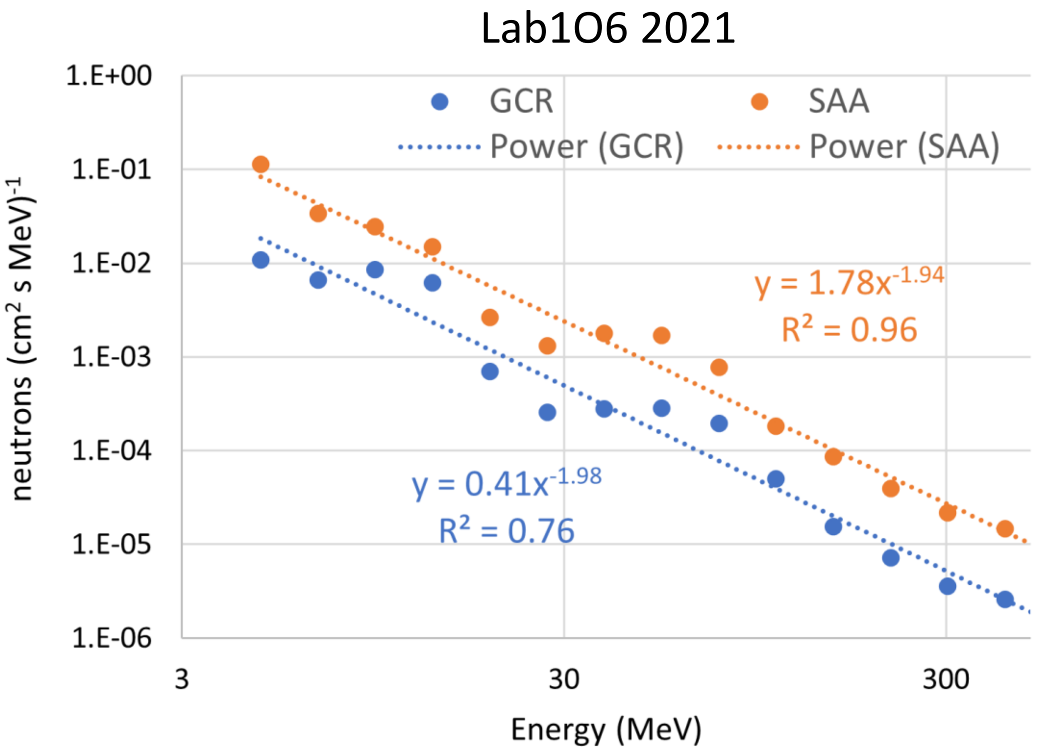



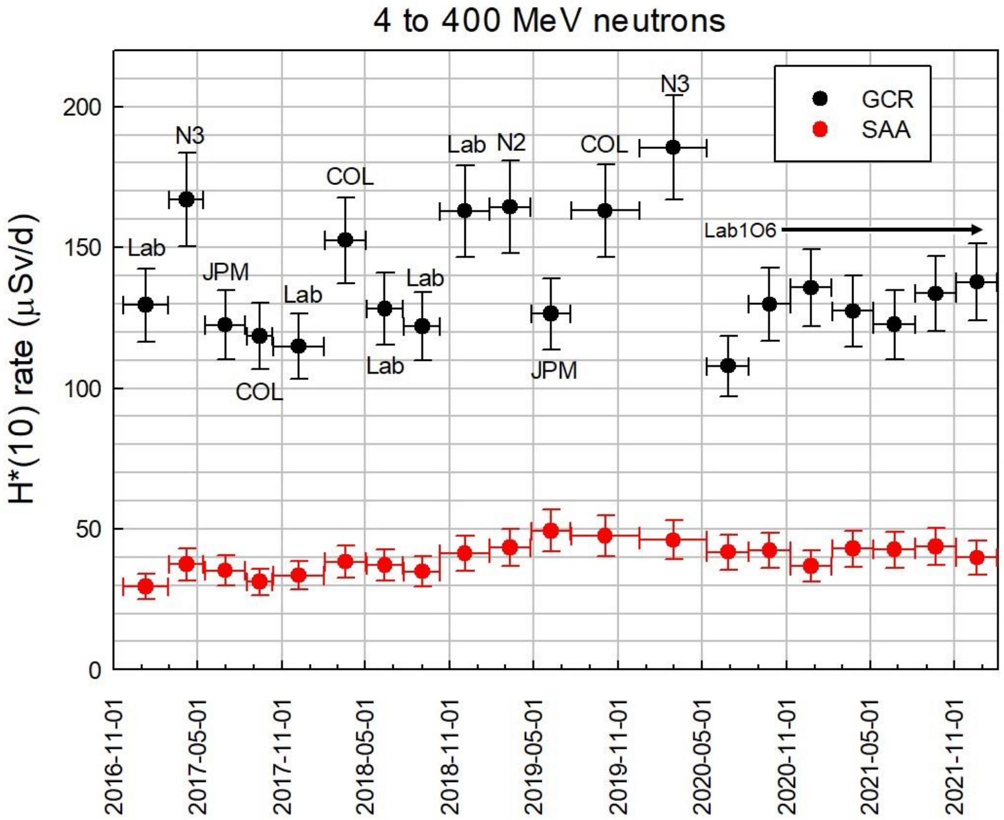
# CPD Also Measures Neutrons

- Same detectors & analysis concept as MSL-RAD neutron/$\gamma$ detection.
- $\gamma$'s & higher-energy neutrons tend to interact in D, lower-energy neutrons in E.
  - B, C, and F used as anticoincidence.
  - Neutral trigger = D and/or E hit, others not.
- GEANT4 used to determine detector response functions (DRFs).
  - DRFs modified for ISS-RAD by Jan Koehler (Kiel).
- Updated DRFs and modified inversion algorithm by Sven Löffler (also Kiel).



# CPD Neutron H*(10) Results




- Power-law fits → similar slopes for GCR & SAA.
- Overall, GCR variations ~ SAA variations, std/mean ~ 0.16 for both.
- Contrast with charged particle absorbed dose rates: std/mean ~ 0.06 GCR, ~ 0.36 SAA

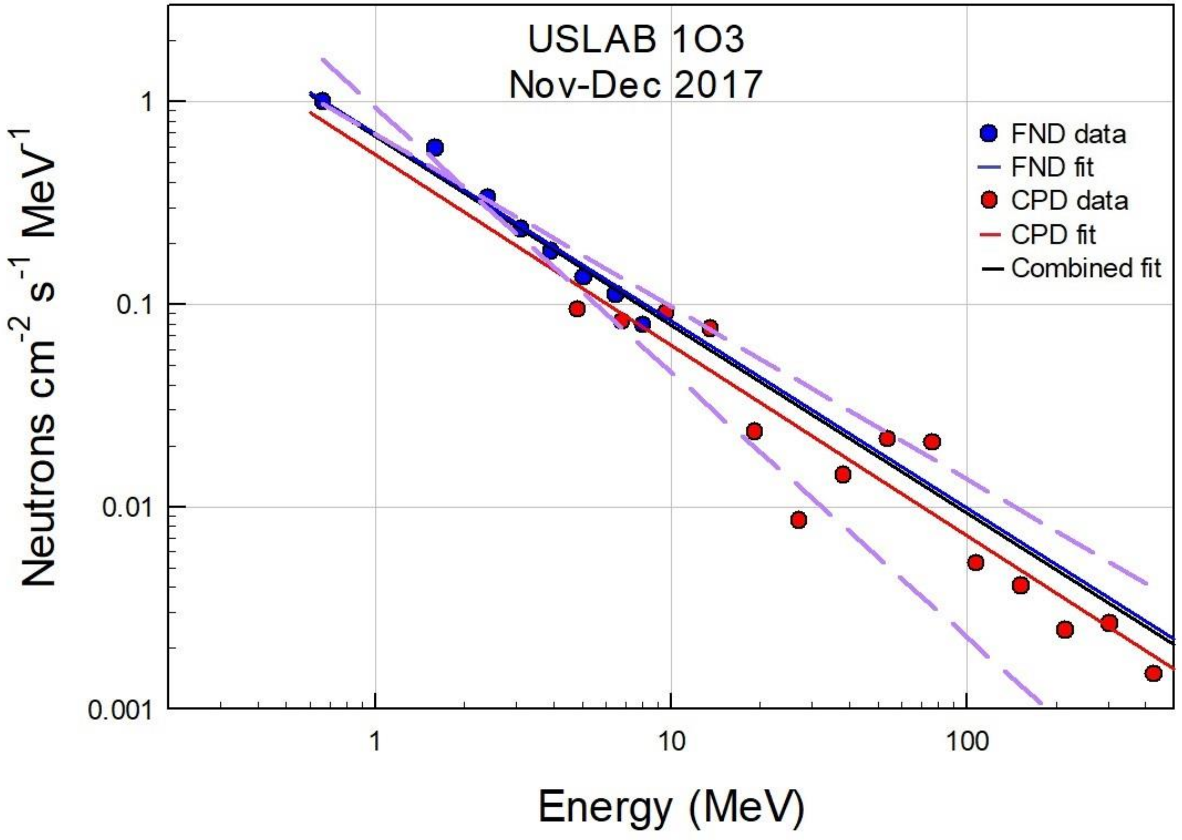
# CPD Neutron H*(10) Internal Consistency

| Locations with multiple measurements | H*(10) rate µSv/d | Std. Dev. µSv/d |
|---|---|---|
| LAB1O3 | 167 | 22 |
| JPM | 167 | 13 |
| COL | 184 | 31 |
| Node 3 | 218 | 19 |
| LAB1O6 | 170 | 8 |

- Full orbit results ~ consistent when measurements repeated.
- All measurements, full orbit:
  - <H*(10)> = 177 µSv/d
  - Standard deviation = 19 µSv/d

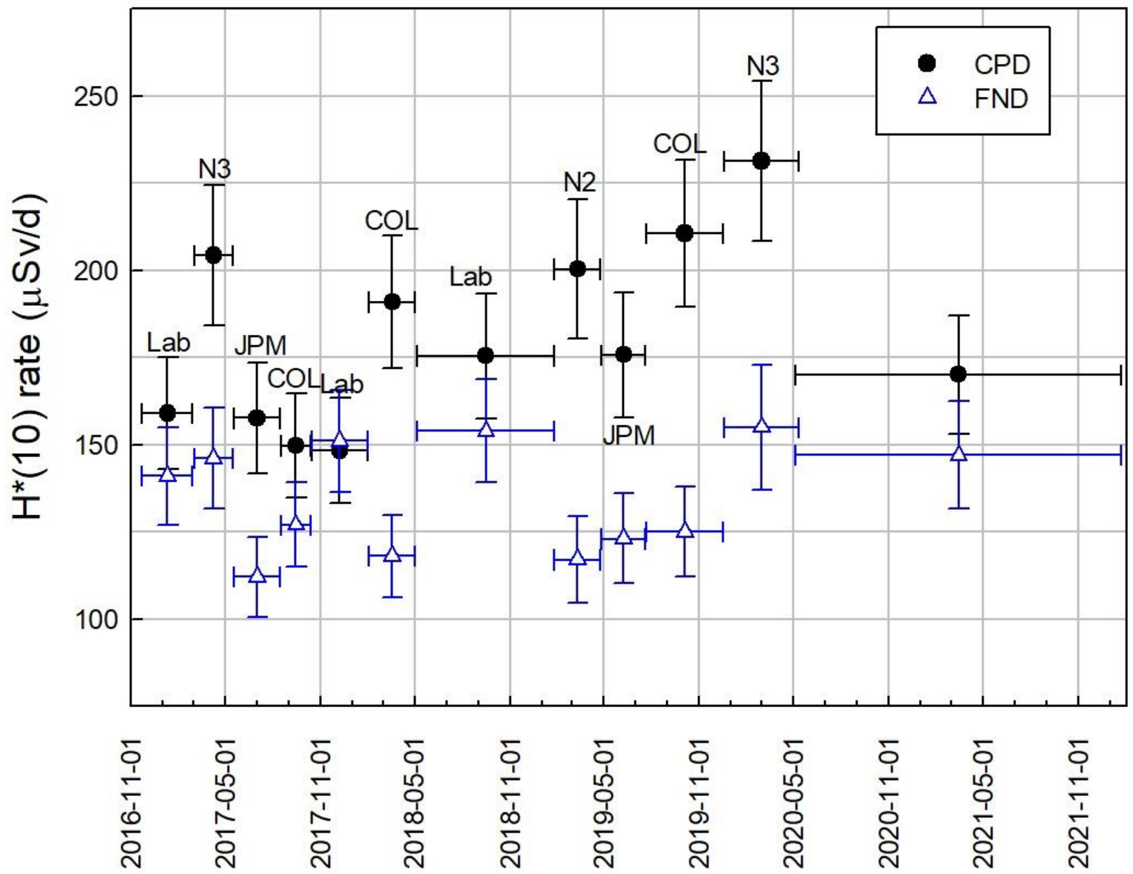
# CPD & FND Combined Neutron Spectra

- CPD neutral detection thresholds in D & E lower than MSL-RAD (no RTG).
- Neutrons measured ~ 4 to 400 MeV.
  - In this energy range, neutrons are more from spallation & fragmentation, less from evaporation than in FND range.
- Combine with FND fluence results, power-law fits are ~ consistent.
  - Slopes –(1 +- 0.25) depending on fit details. Similar in other data sets.
  - CPD data alone have steeper slopes.
- Different fits yield similar integrals: from 0.1 MeV to 1 GeV, find fluences of (8 +- 1) neutrons $cm^{-2}\ s^{-1}$.

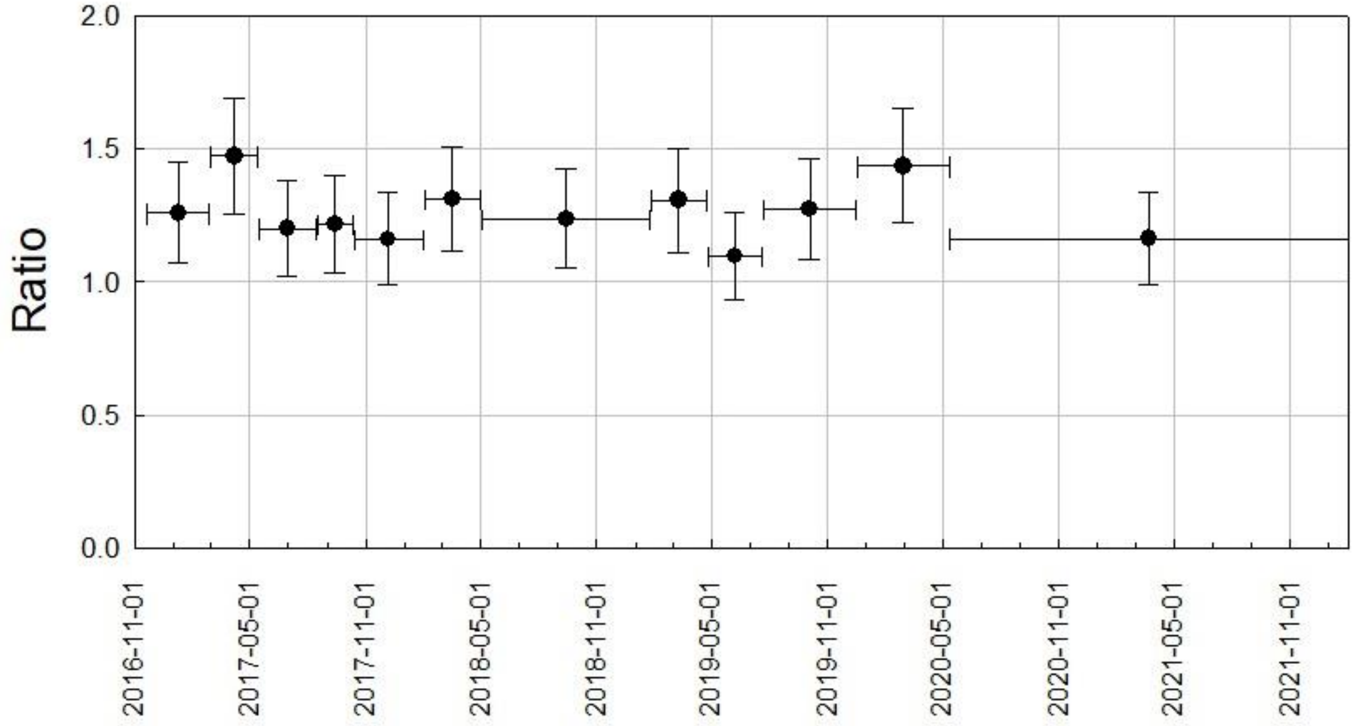


# Neutron H*(10) from FND & CPD Compared

- Full orbit data (no GCR/SAA split).
  - +-15% errors on CPD points.
- CPD $n^0$ H*(10) is the larger share, consistent with model predictions from HZETRN & PHITS.
- In less-shielded modules, CPD/FND difference is larger.
  - More shielding shifts neutron spectrum to lower energies.
- (CPD share + FND share) ≈ 85% of H*(10) from neutrons of all energies from same model calculations.



# GCR Neutron H*(10) Rate and Charged Particle Absorbed Dose Rate




- [CPD+FND neutron H*(10) rate] / [CPD B absorbed dose rate] stays in a narrow range from ~ 1 to ~ 1.5 regardless of location. Do models agree with this?
- Contrast with [B absorbed]/[FND H*(10)] ratio which is sensitive to location.

# Conclusions

- Despite some challenges in operations, ISS-RAD has provided a wealth of data on the energetic charged particle and neutron radiation environments in USLAB, Columbus, JPM, Nodes 2 & 3.
- Behavior of charged particle GCR and SAA absorbed dose rates with varying shielding is ~ as expected: GCR increases slightly with increased shielding & SAA is much more variable.
- Neutron H*(10) results not as easy to interpret.
- Solar cycle effects clearly visible, especially in SAA data & GCR data at high geomagnetic latitudes.

# THANKS FOR YOUR ATTENTION!

Special thanks to Livio & Thomas for putting together the LSSR Special Issue