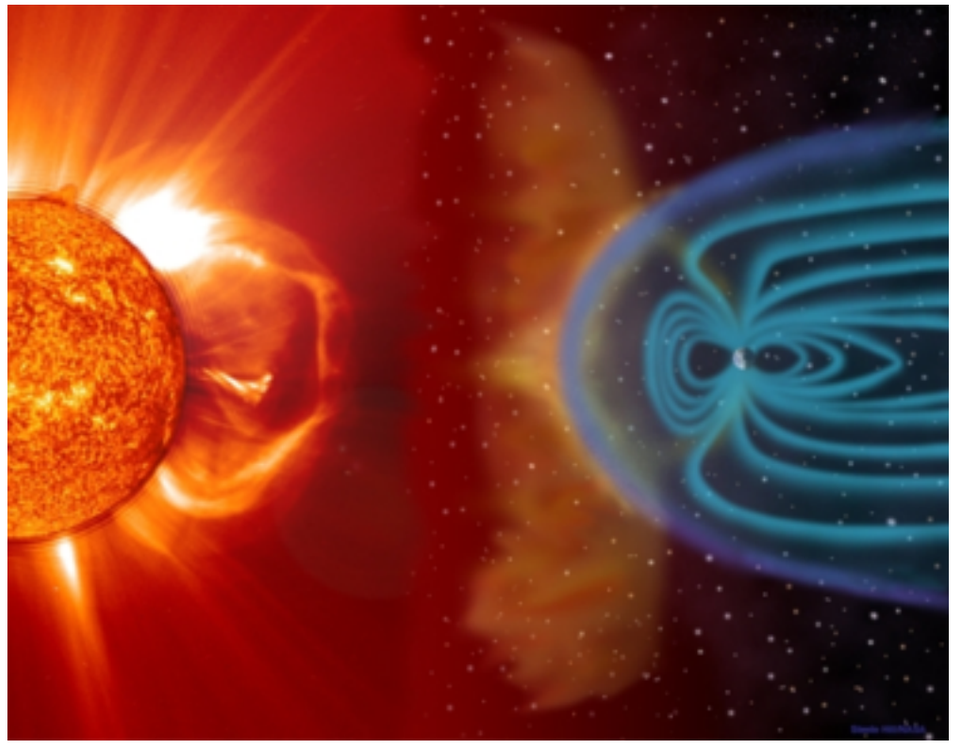
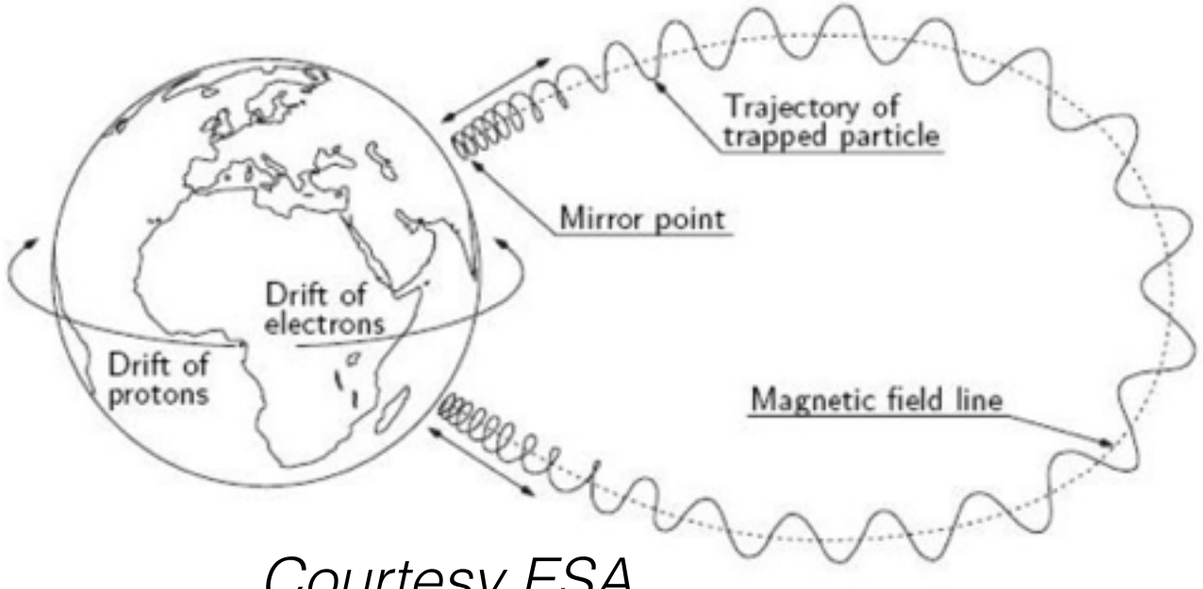
Charged Particle Dosimetry on the International Space Station with Silicon Hybrid Pixel Detectors

Stuart P. George

The Space Radiation Problem

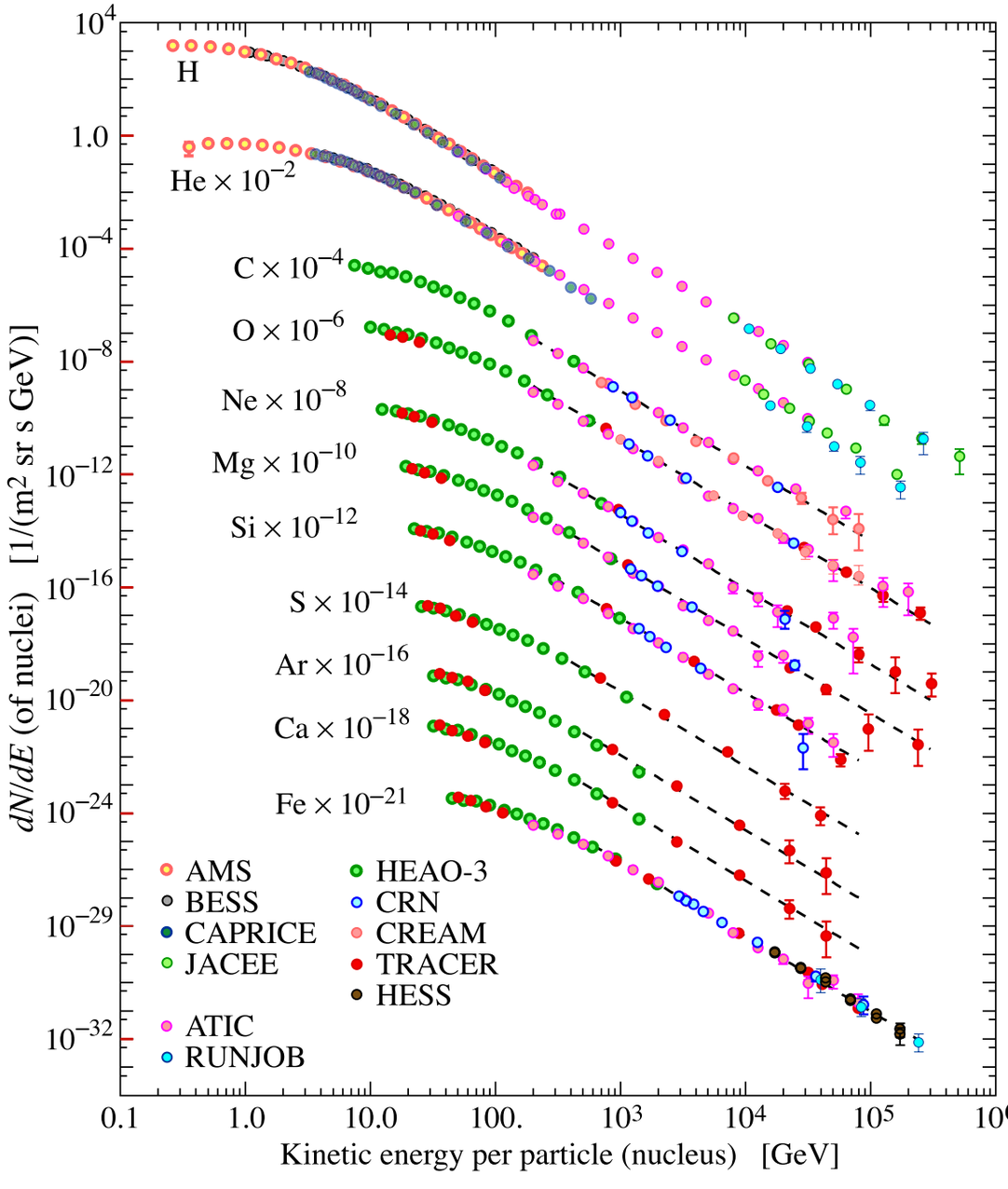
- The space radiation field in low earth orbit consists of galactic cosmic rays (SAA) and ions trapped by the geomagnetic field (GCR)
- These contribute approximately the same dose per day (~125 uSv/ day)
- Most of these are protons
- Also some heavier particles…

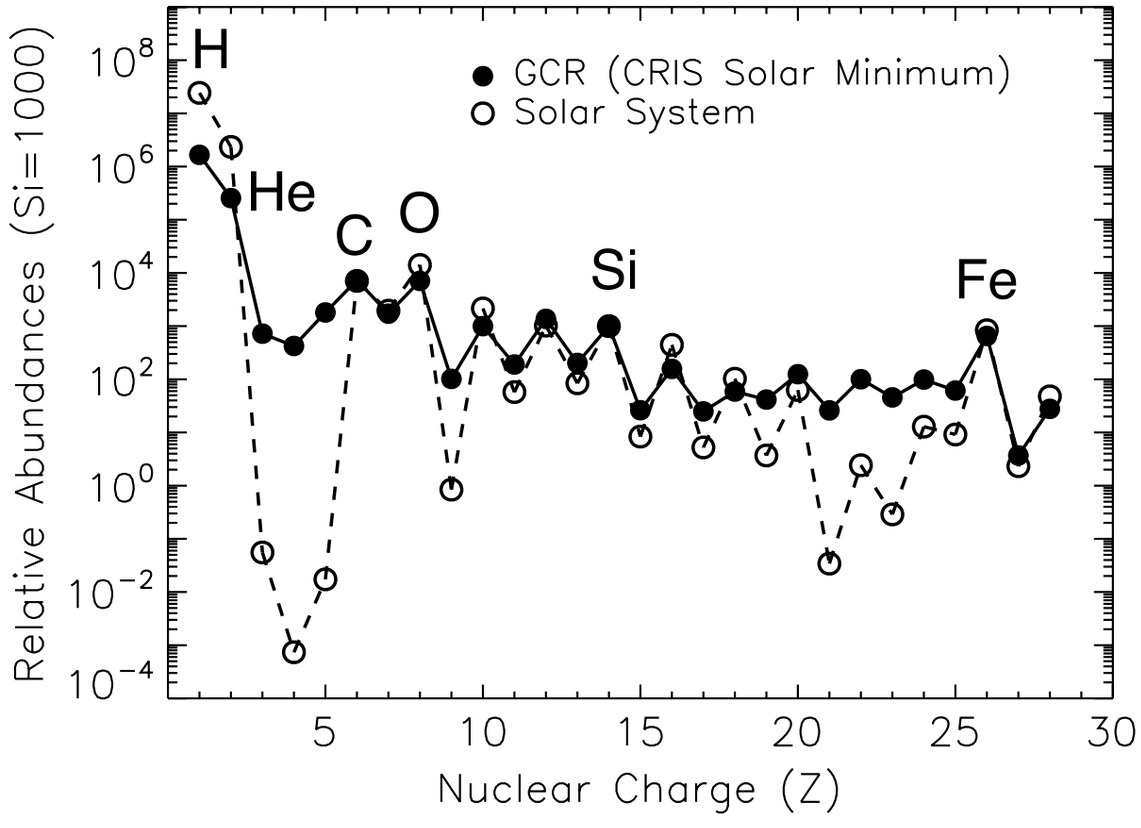




Courtesy ESA

Galactic Cosmic Rays





Six REM (Timepix) are flying on the ISS

Courtesy NASA

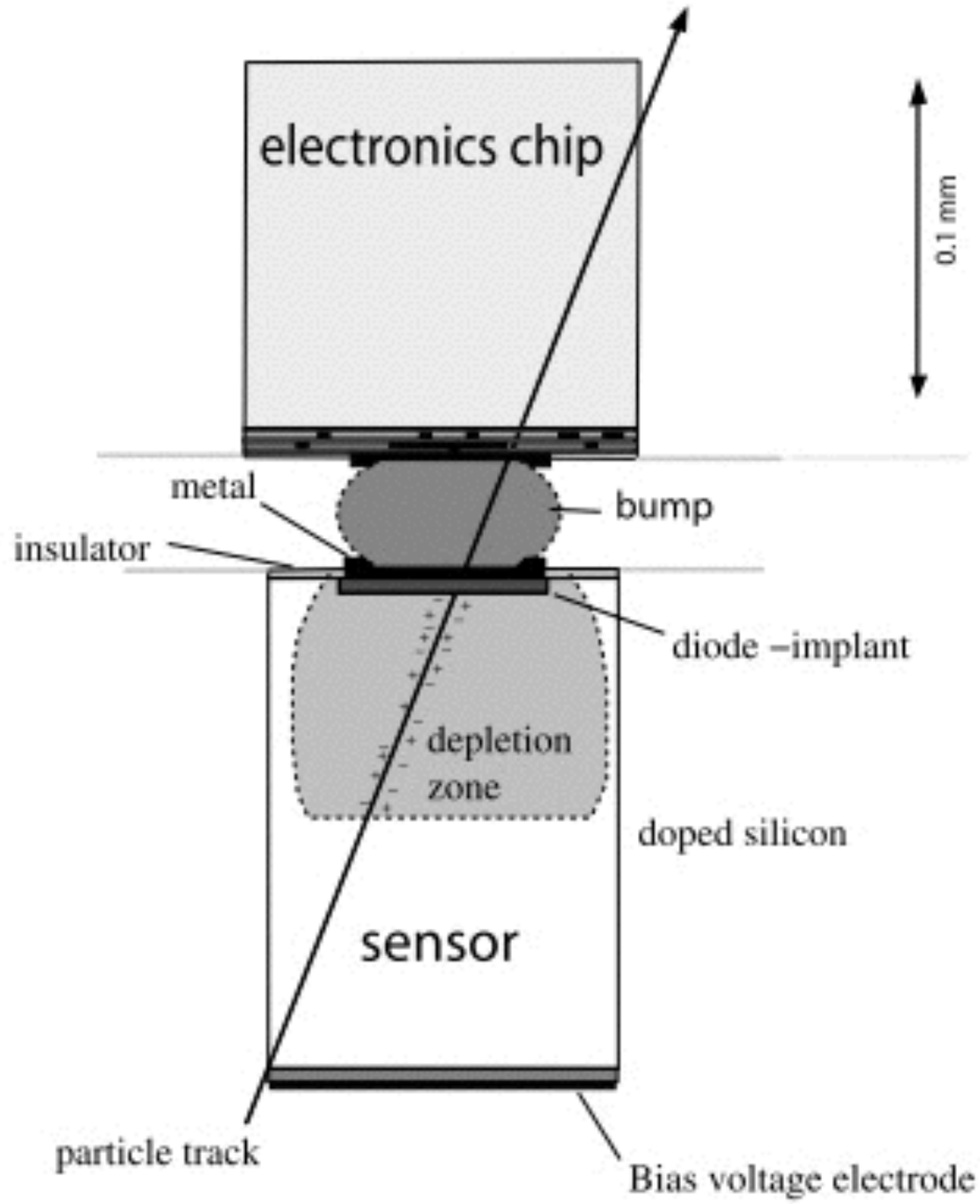
Timepix is compact, light and low power - all significant advantages for space flight applications ($25,000/kg)

What is a Hybrid Pixel Detector

- Hybrid pixel detectors mean that the semiconductor sensor and the readout chip are made separately and joined together later

- Allows use of different sensor materials for different applications (Si, CdZnTe, GaAs)

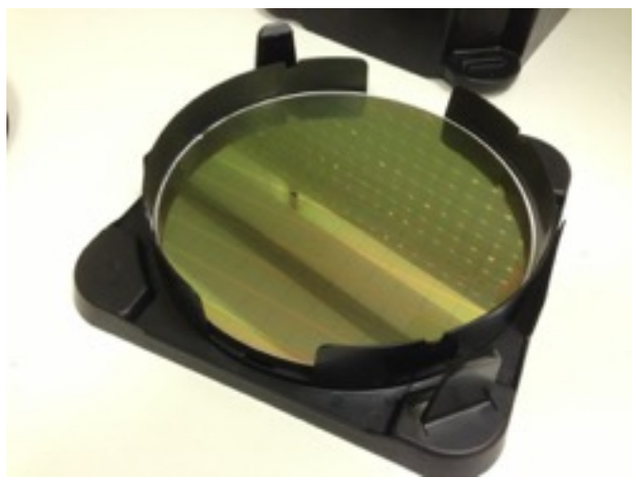
- Necessitated out of desire to use different Si processes for sensor and readout



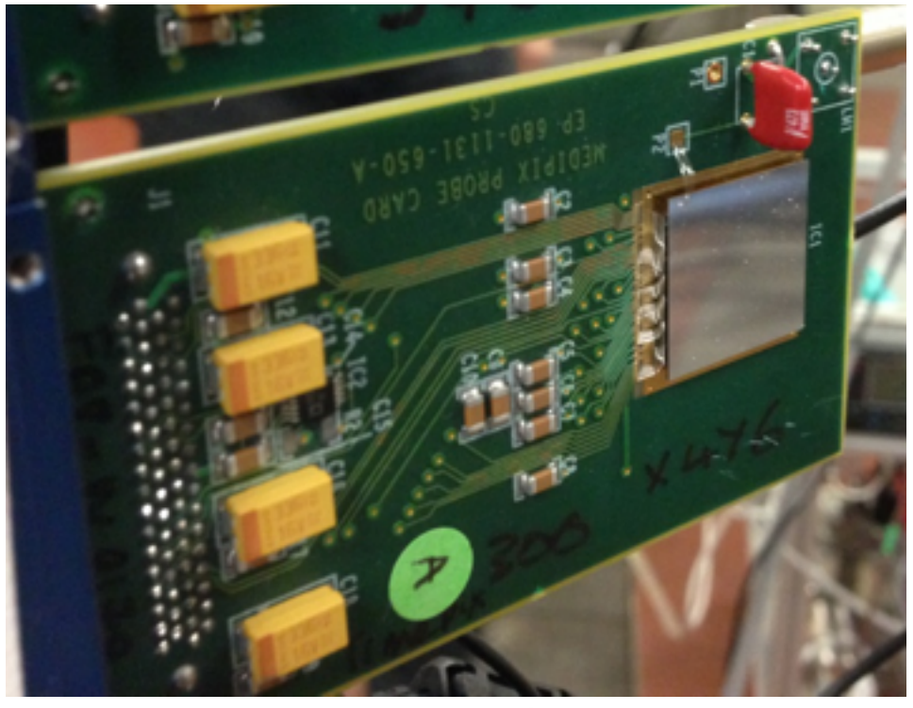
The Timepix - a quick intro

- The timepix asic consists of 256 x 256 CMOS pixels each measuring 55 x 55 um.

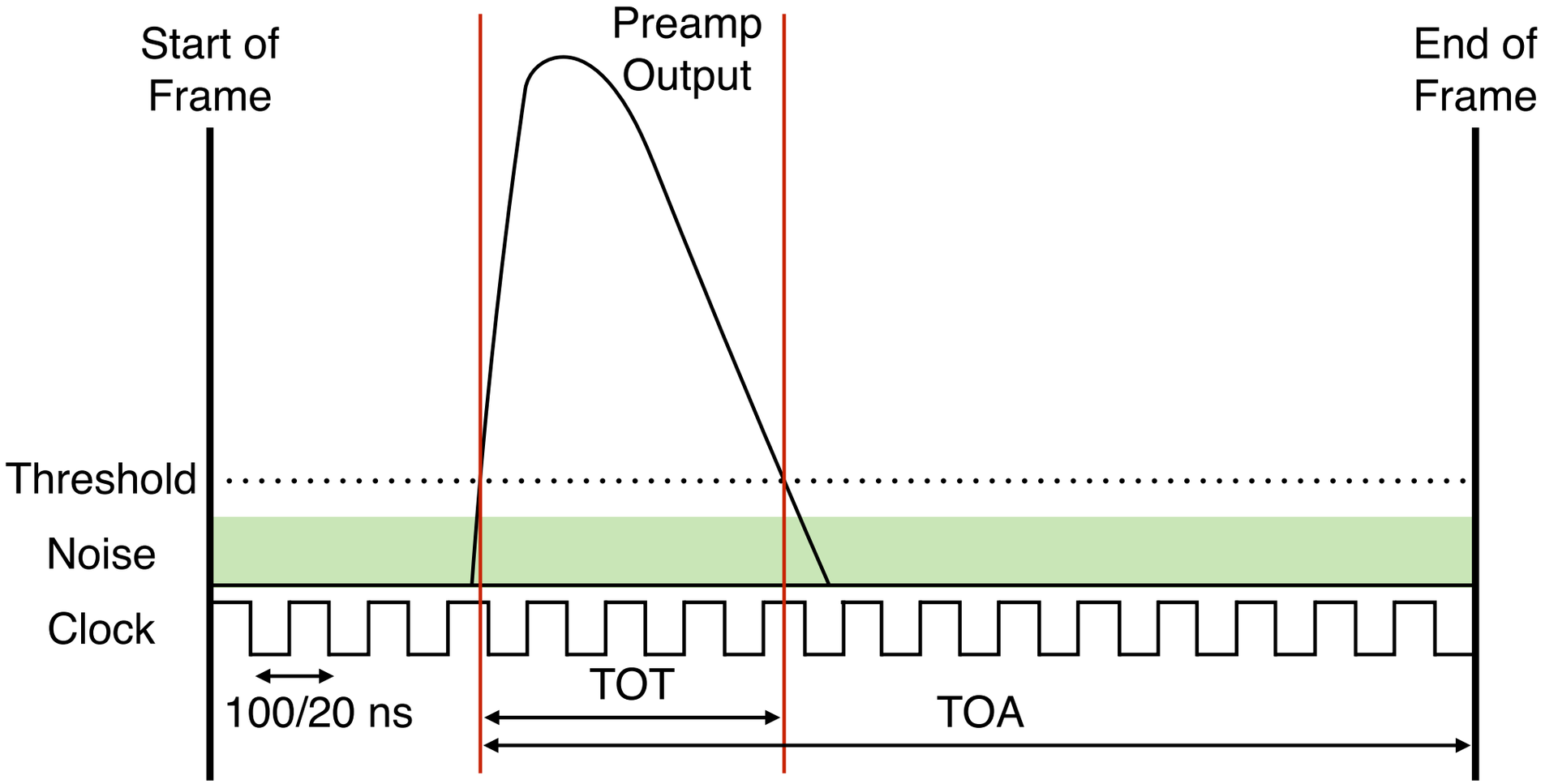
- Typically used with a high resistivity silicon sensor at 300 - 500 um thickness (other materials also used, CdZeTe, gas…)



Timepix ASIC Wafer

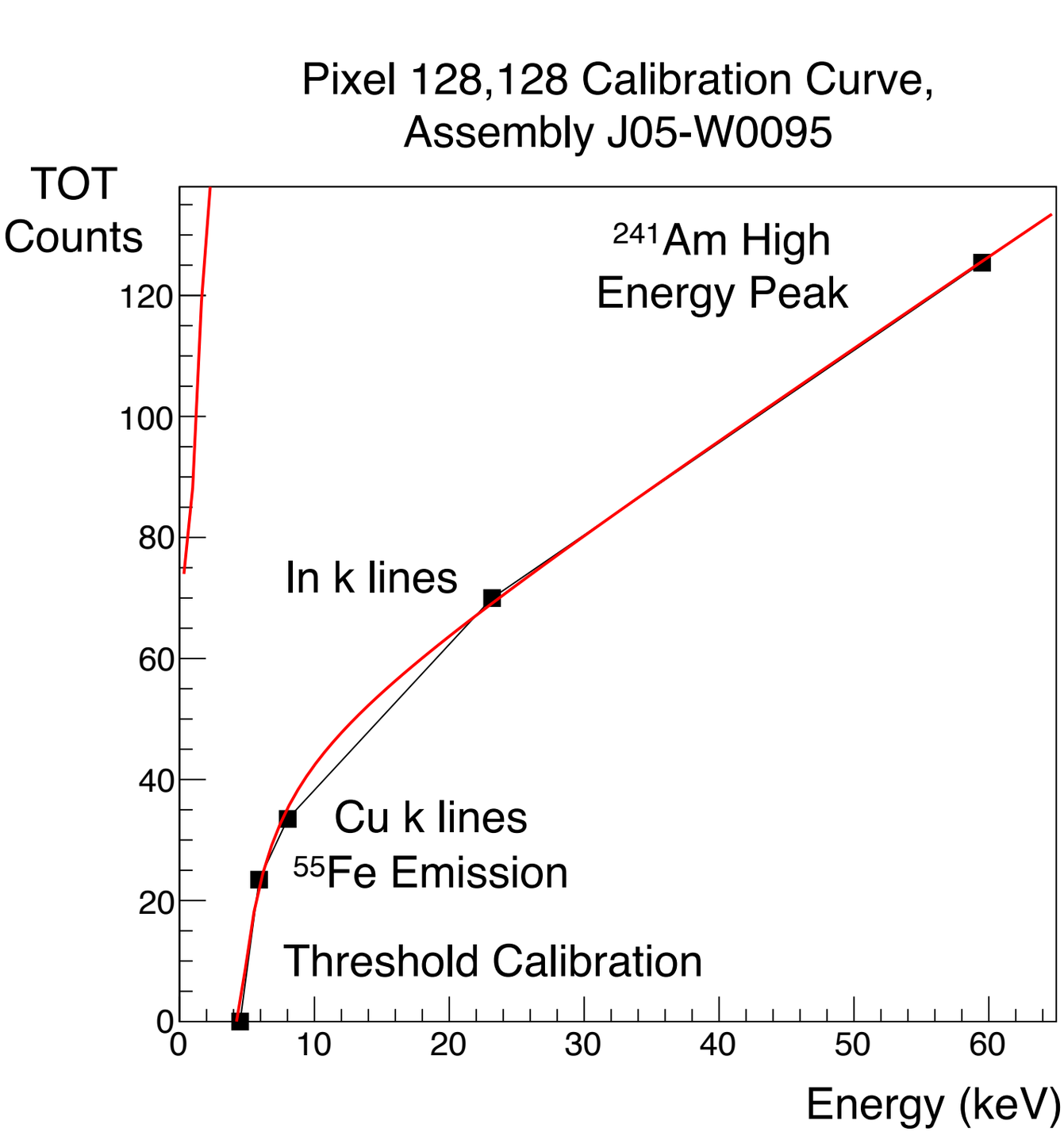


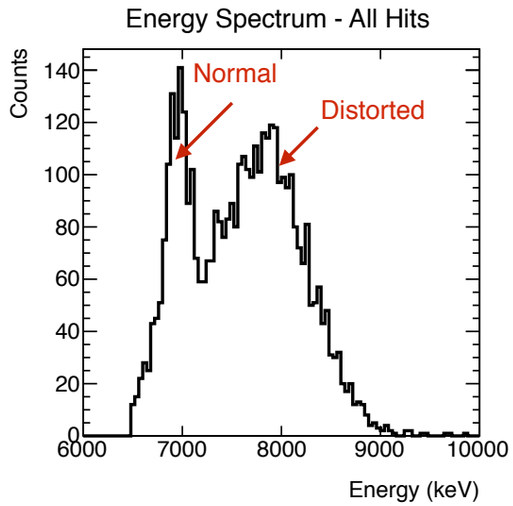
Timepix mounted on CERN probe card

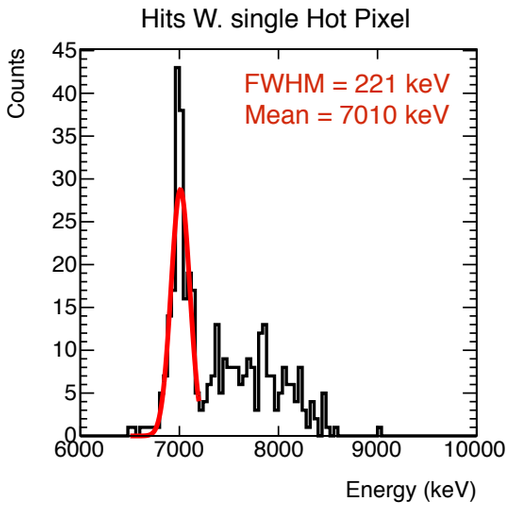


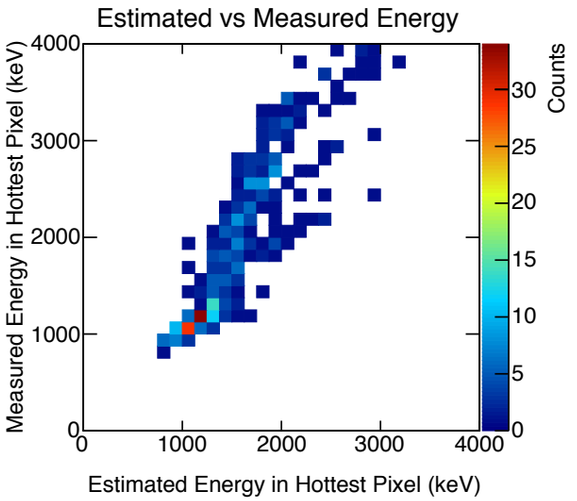
- Medipix (pulse counting)
- TOA (Time of arrival)
- TOT (Charge surrogate measurement as a Wilkinson ADC)
- TOA/TOT achieved with an on chip clock synchronised to all pixels (up to 100 Mhz, but 50 stable)

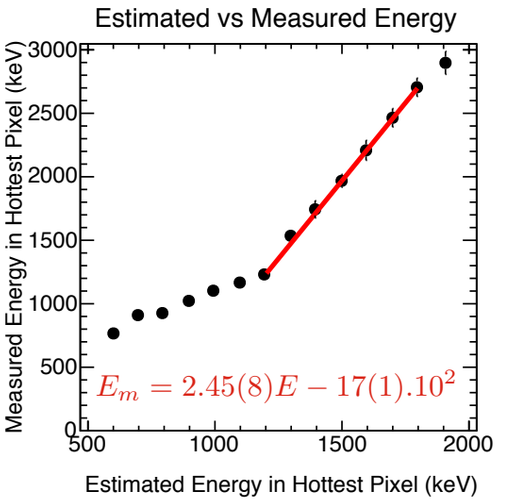
Timepix Calibration

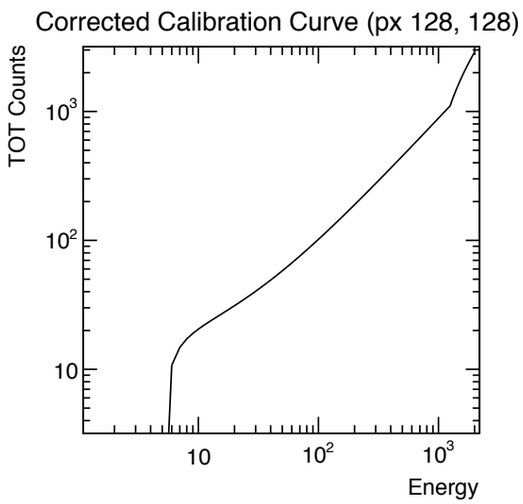


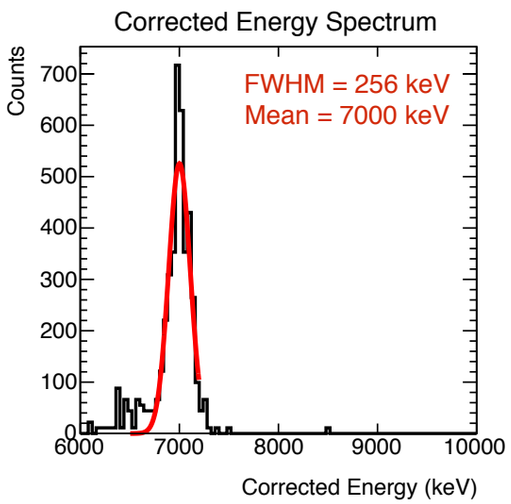




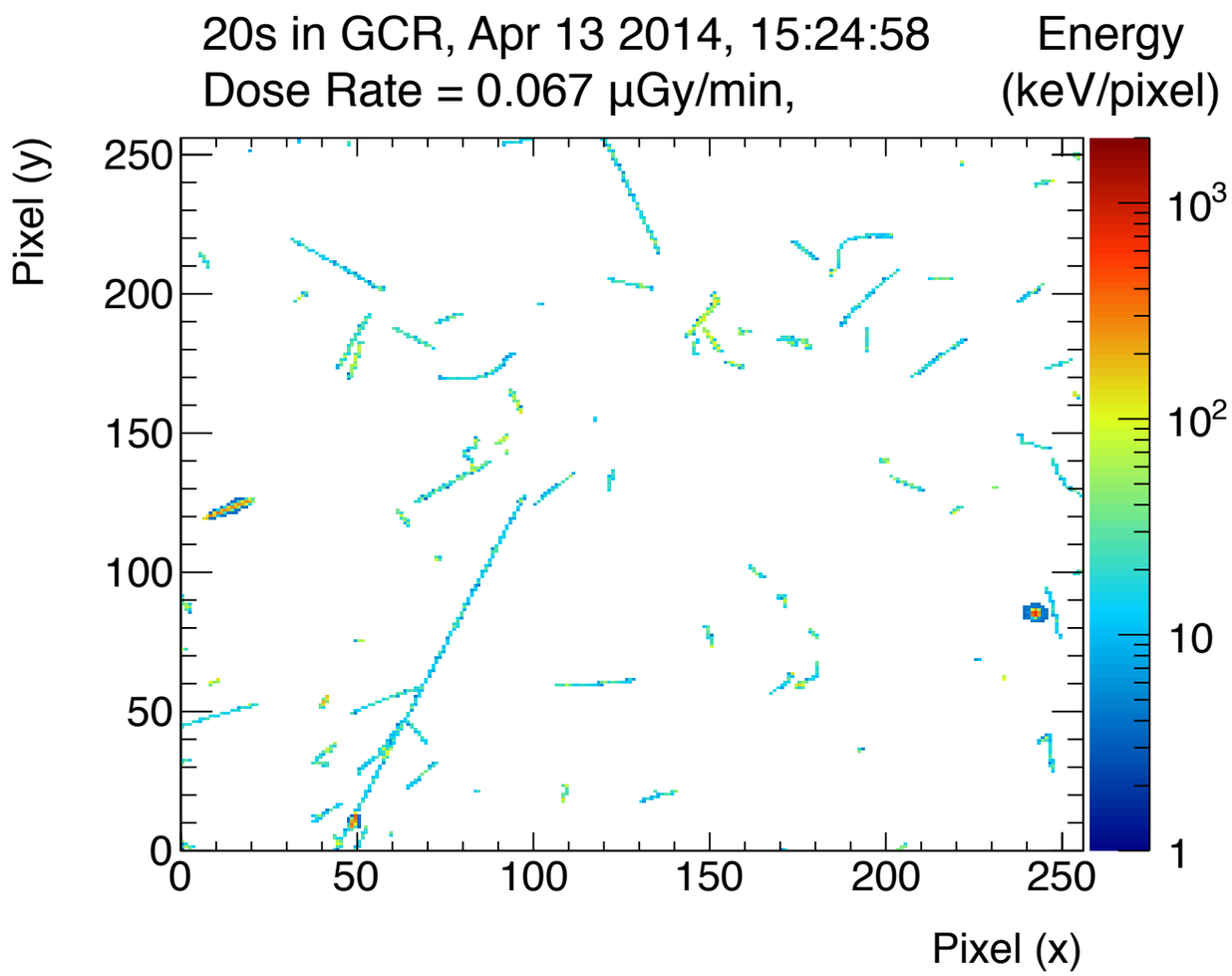


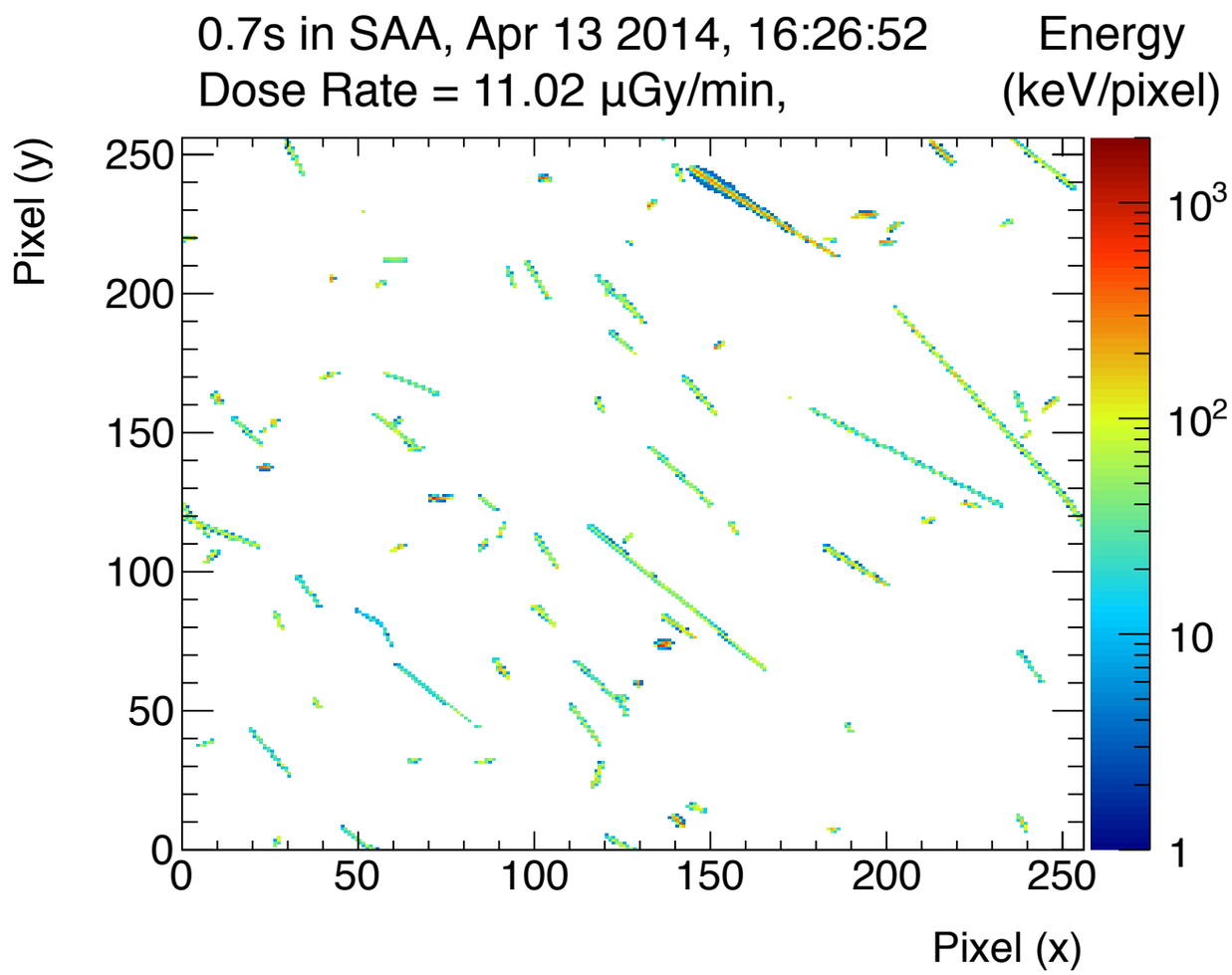






What do you measure with a Timepix





- Each track is left by a single charged particle, the morphology is representative of the physics of the particle

How to Do Charged Particle Dosimetry in Space

- As ever… You need to know something about your field before you start…

Equivalent Dose in muscle

Silicon->Muscle Conversion Factor

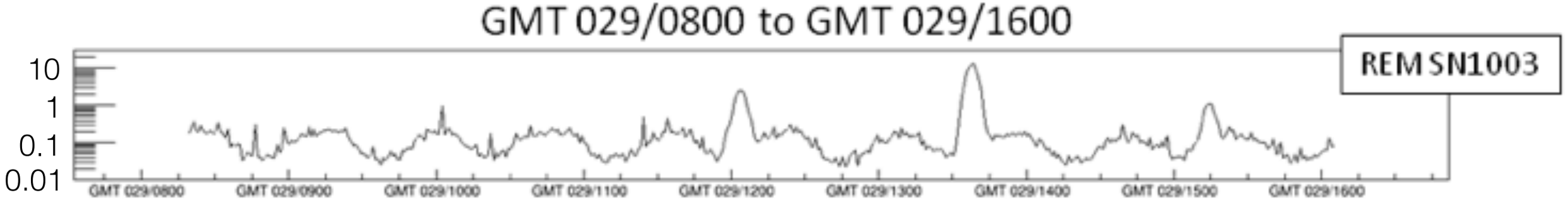
$$E_{D(m)} = D_{Si}.C_{Si\rightarrow m}.Q(\mathrm{LET}_m)$$

Dose to Silicon

ICRU Quality Factor

$$D_{Si}$$

$$E_{D(m)} = D_{Si}.C_{Si \to m}.Q(\mathrm{LET}_m)$$

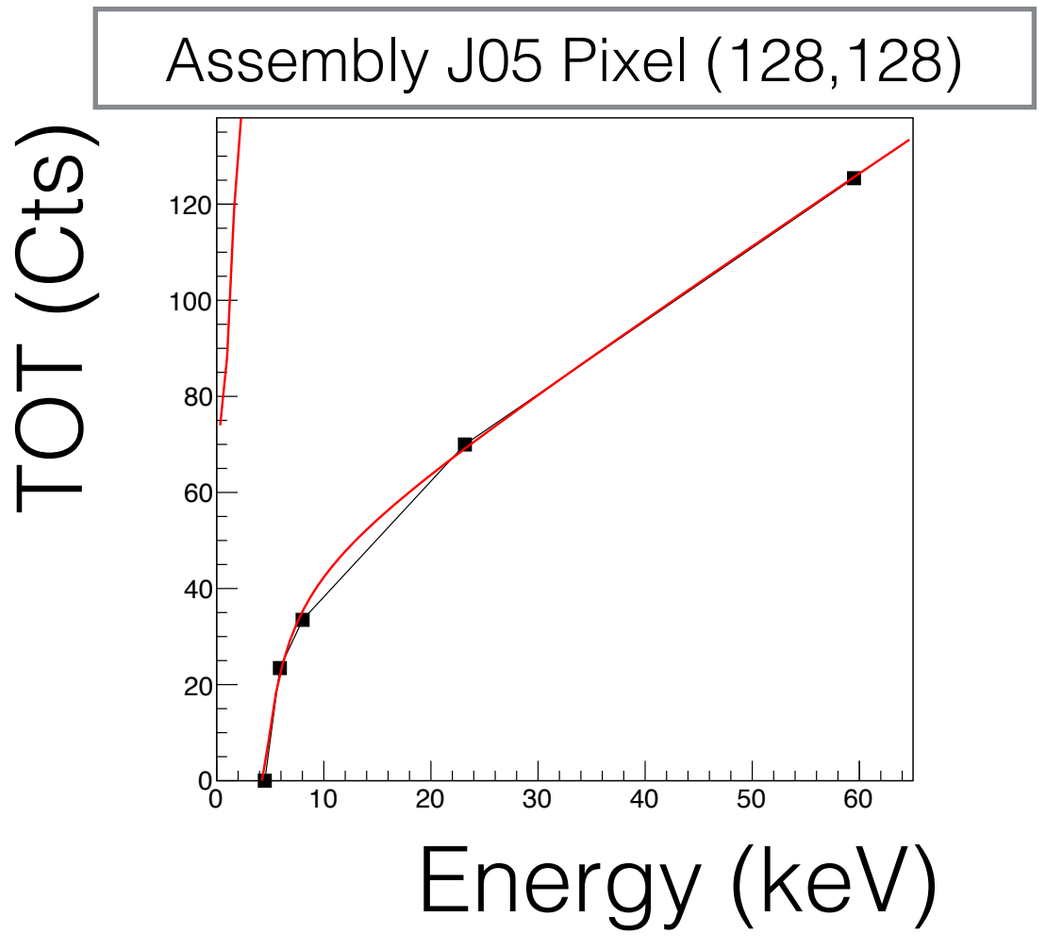


- Dose to silicon is just the energy deposited/unit sensor mass

- Measure energy via TOT

- TOT Calibrated to energy via low energy photons

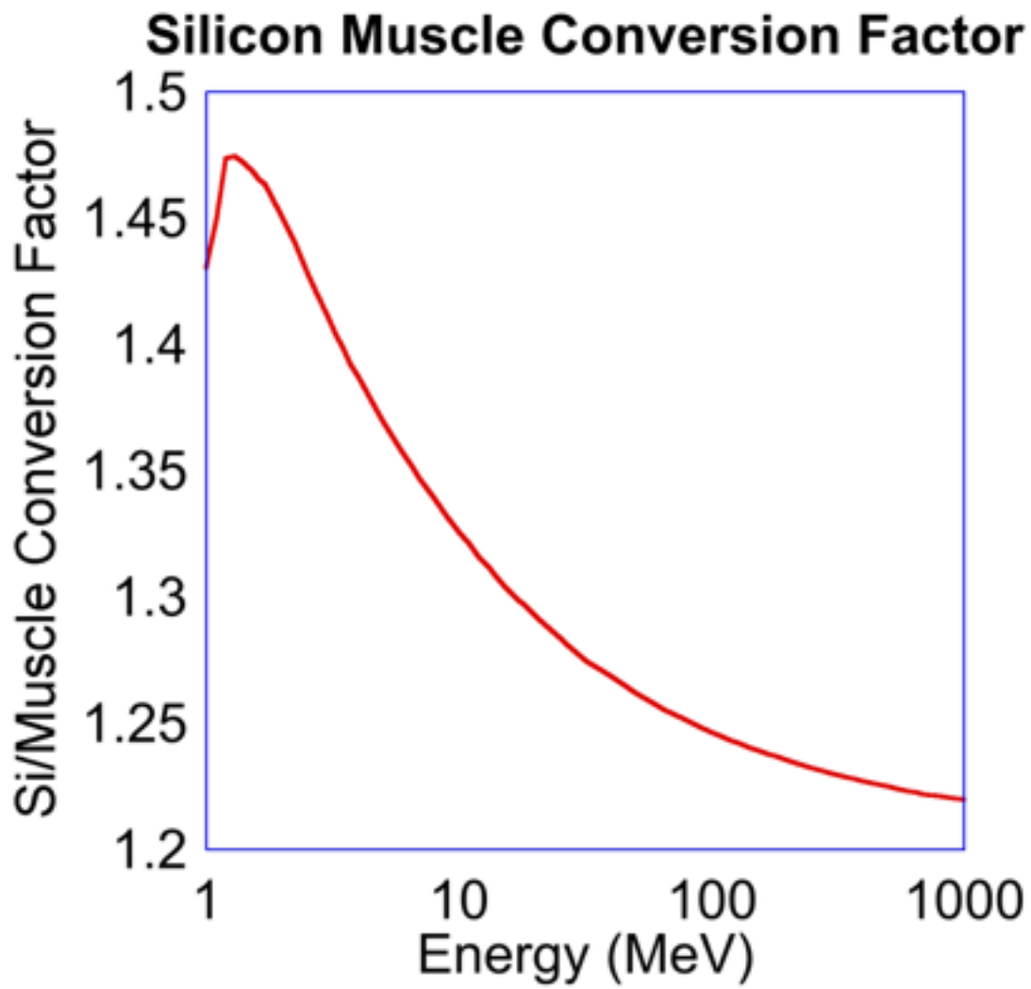
- First assumption - everything penetrates the sensor



$C_{Si \rightarrow m}$

Silicon->Muscle Conversion Factor

- Tissue conversion factor is a function of particle energy
- Varies ~20% over energy range
- However most of this variation is for slow particles -> stoppers
- Many people use a flat conversion factor based on MC or similar

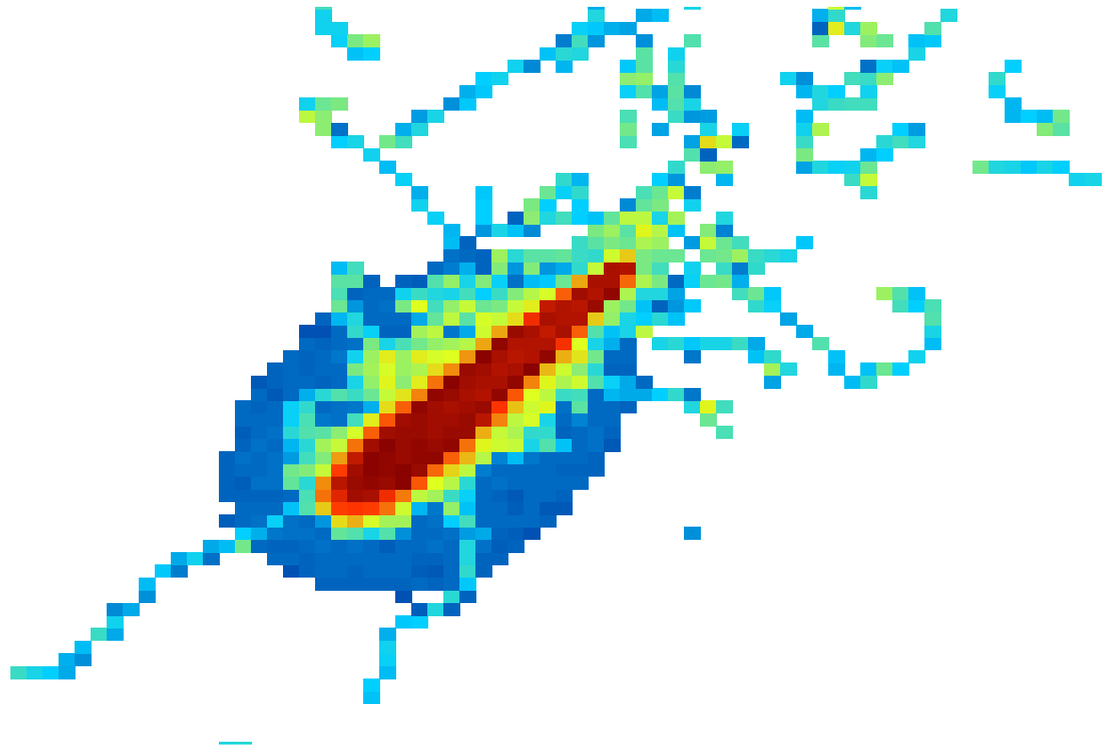


$$C_{Si \rightarrow m}$$

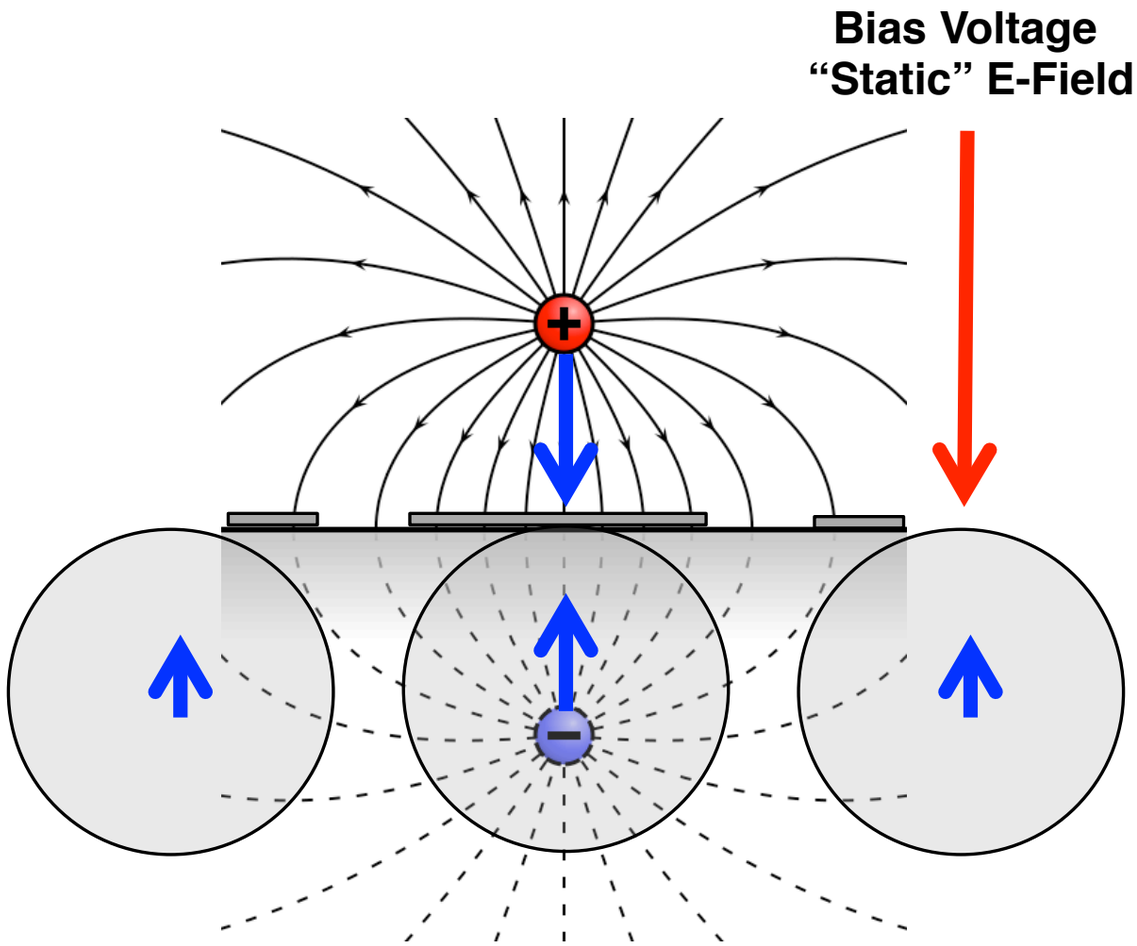
- How do you work out particle energy -> LET in Silicon

- In principle its just the deposited energy/track length, but complicated by track geometry

- Penetration angle algorithm for ions from Hoang et al



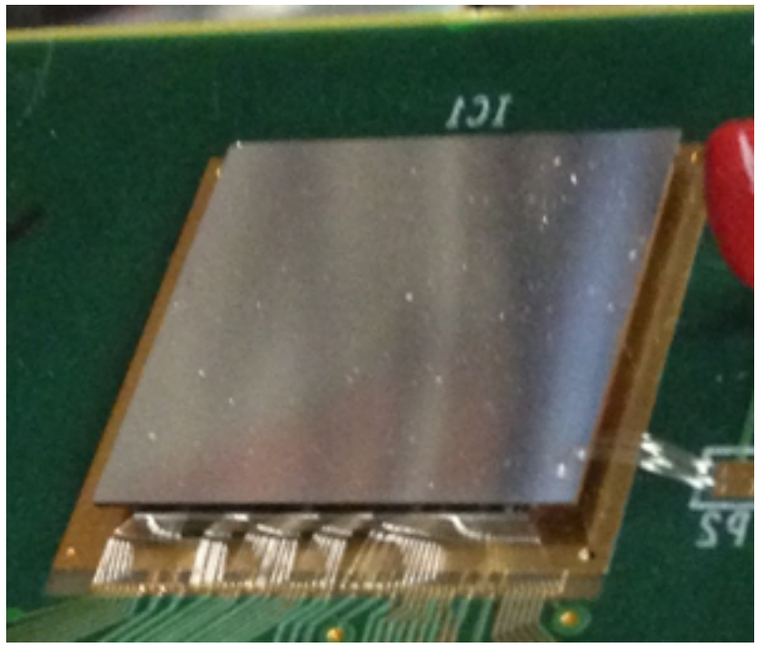
Cluster Length -> Track Length

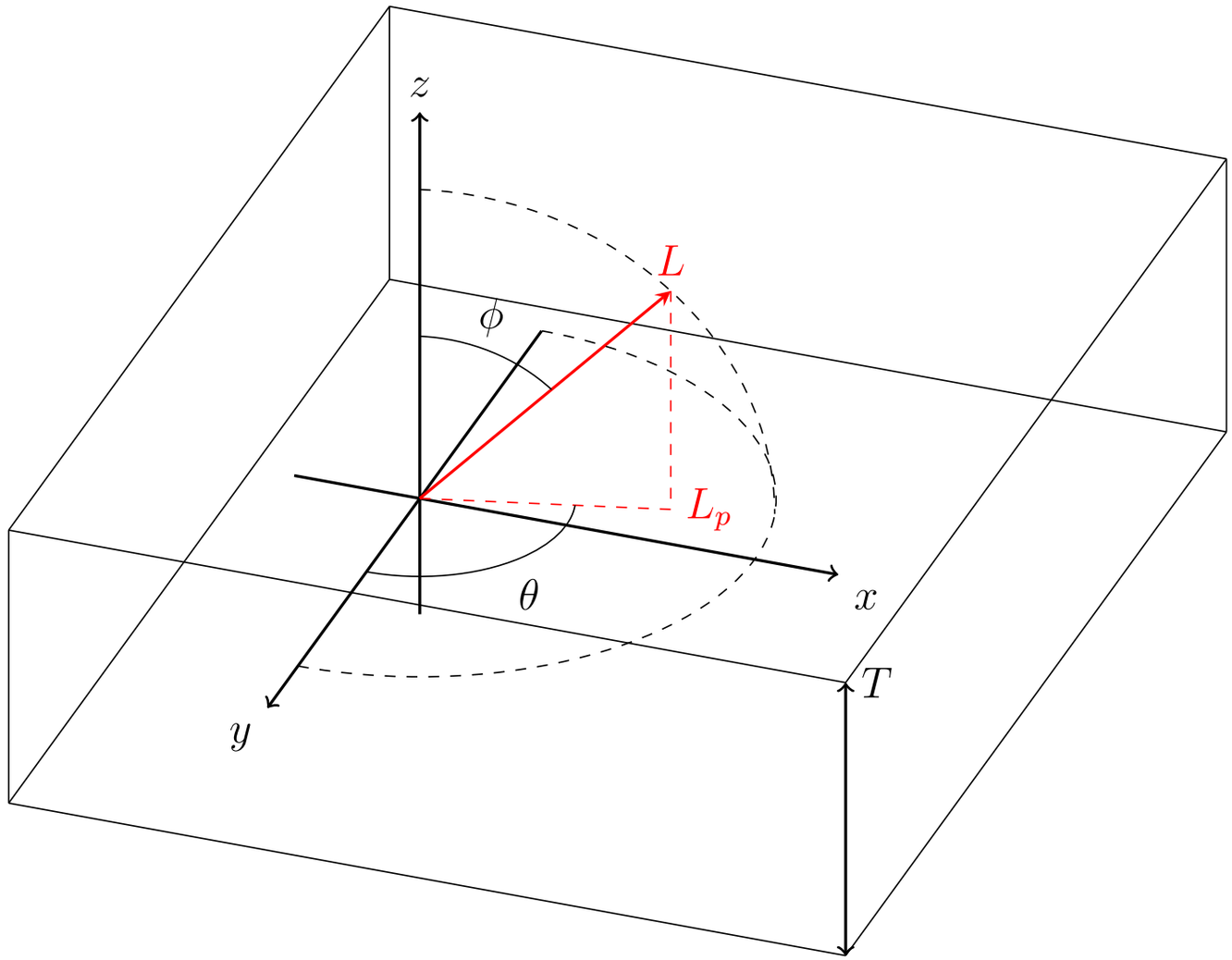


An “Image Charge” from a real charge above a conducting plane

- **As the liberated charges drift in the the sensor towards the conducting solder pads and solder-bumps…**
- **…The induced image charge in the them causes a counter current to flow…**
- **…Which is seen as a current at the input to the pixel’s analog charge-sensitive preamp…**
- **…And, when the drifting charges reach the conducting implants, they neutralize the image charges, stopping the input current.**
- **So, if the charge is sufficient, a much larger area of pixels are influenced than just receive the drifting charges…**

Calculation of Track Angles

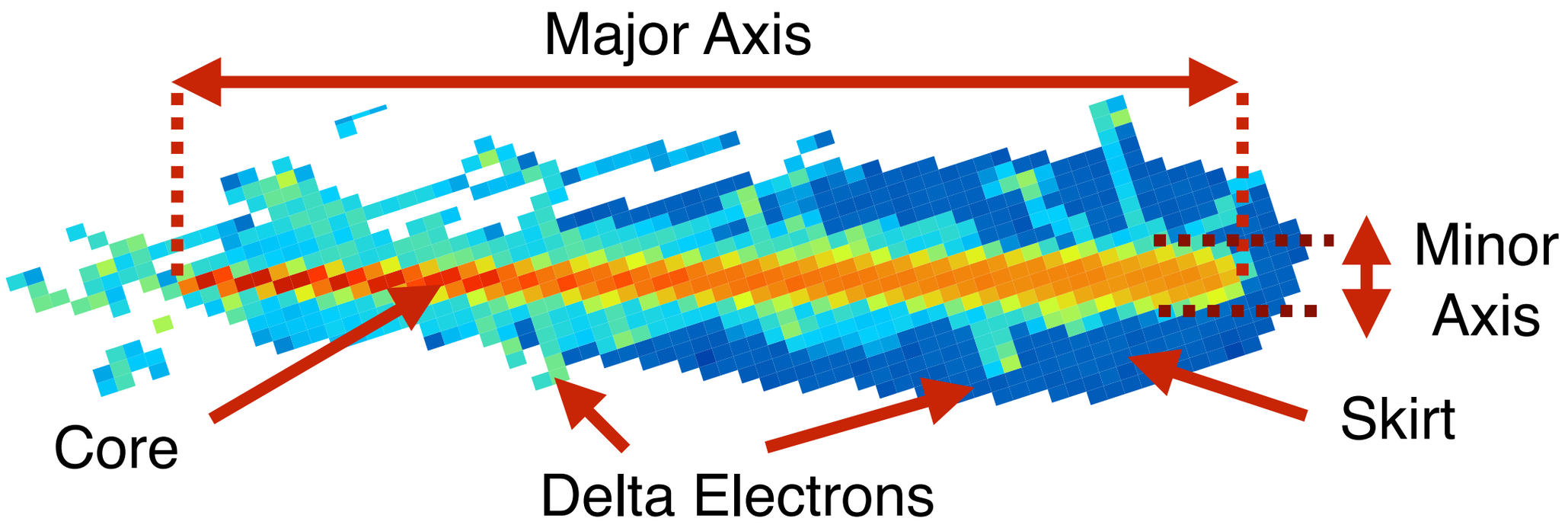




- 4π view of sky, 1π discrimination (slope cannot tell up from down, projection of a line symmetric around 180 degrees)

- Assumption of sensor penetration for slope, work on corrections for stopping protons in progress.

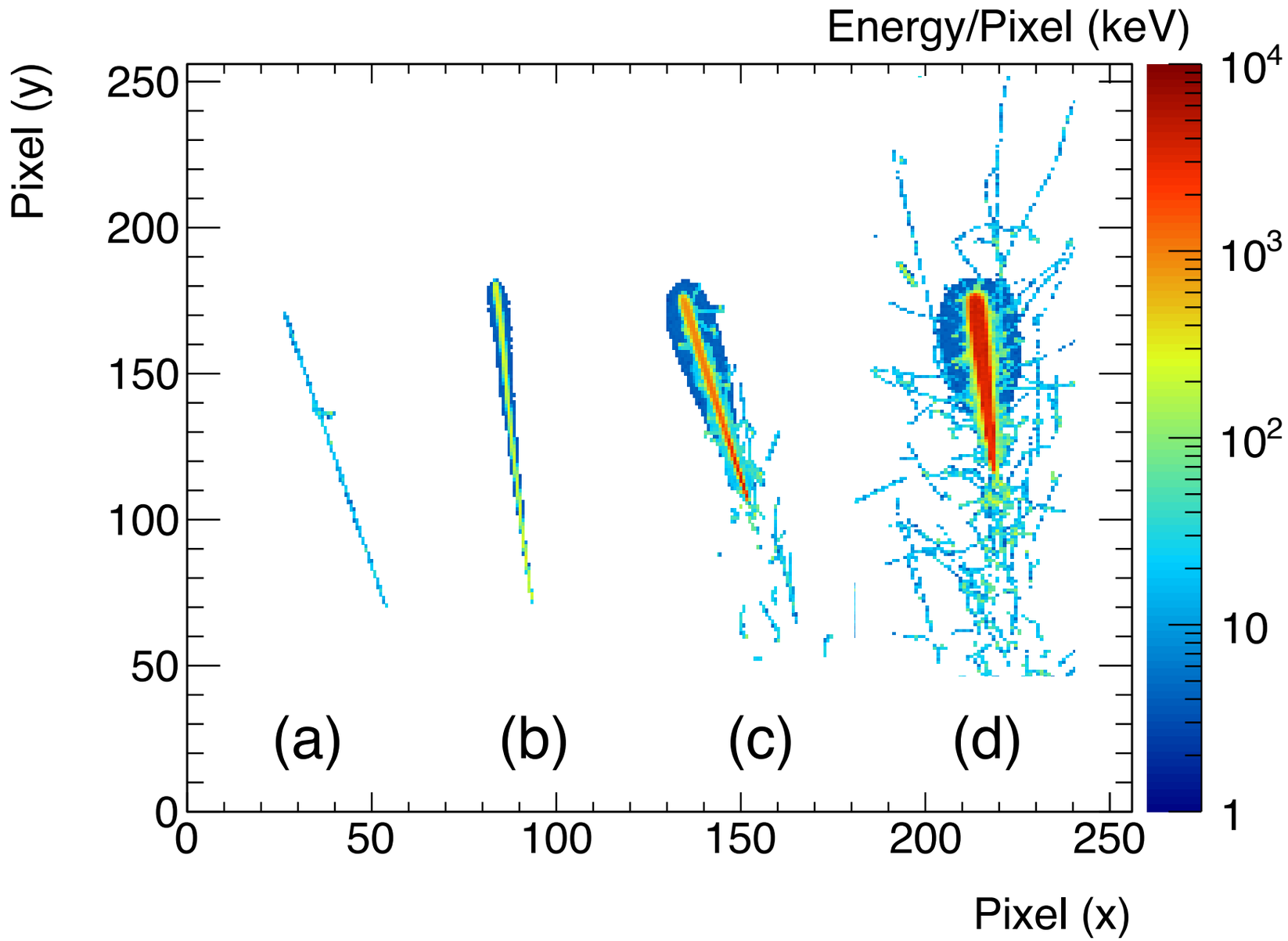
Slope Calculation for Heavier Tracks



$$\tan(\phi) = \frac{55}{T}\left(\text{major} - \frac{\text{minor} - 1.5}{\text{major} + 1}.\text{minor}\right)$$

"LET Estimation of Heavy Ion Particles based on a Timepix- Based Si Detector", Hoang et al (2012)

LET and Angular Information



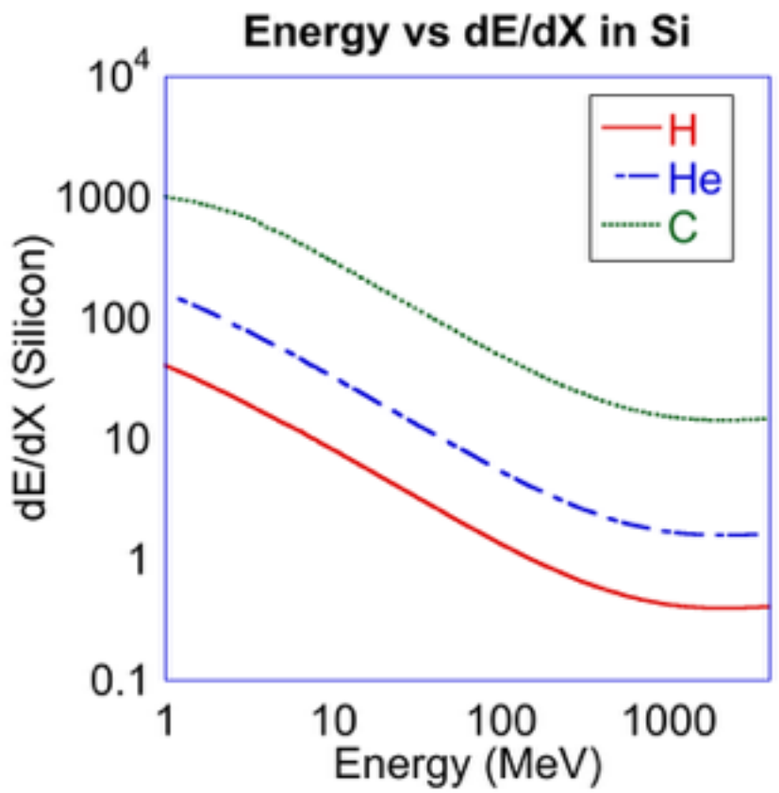
(a) $\mathrm{LET_{Si}} = 0.52\,\mathrm{keV\,\mu m^{-1}}$ Alt. $= 71.0°$ Az. $= 84.6°$

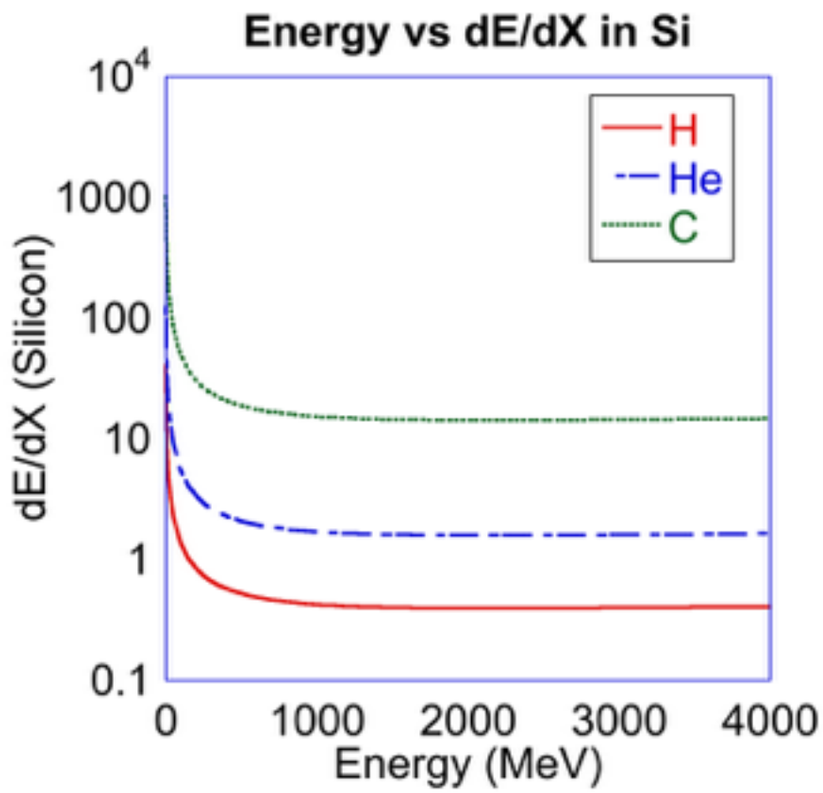
(b) $\mathrm{LET_{Si}} = 5.45\,\mathrm{keV\,\mu m^{-1}}$ Alt. $= 82.0°$ Az. $= 84.0°$

(c) $\mathrm{LET_{Si}} = 54.8\,\mathrm{keV\,\mu m^{-1}}$ Alt. $= 66.7°$ Az. $= 81.4°$

(d) $\mathrm{LET_{Si}} = 233\,\mathrm{keV\,\mu m^{-1}}$ Alt. $= 84.2°$ Az. $= 81.1°$

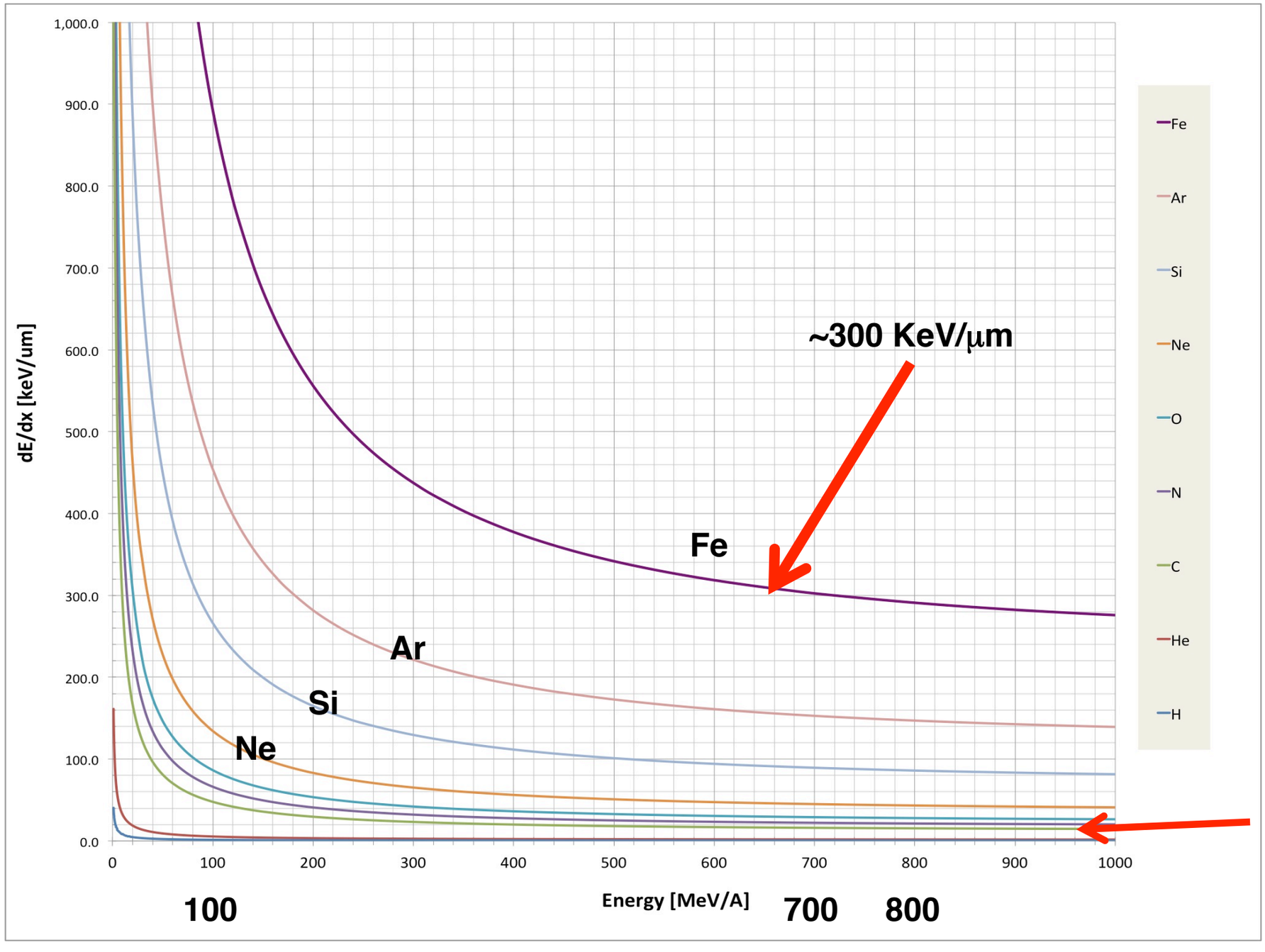
With track length one can calculate LET -> check dE/dX





- Assumption - most of the space radiation field is either (a) high energy and an ion mix (true for GCR) or (b) a slow(ish) proton (true for SAA)

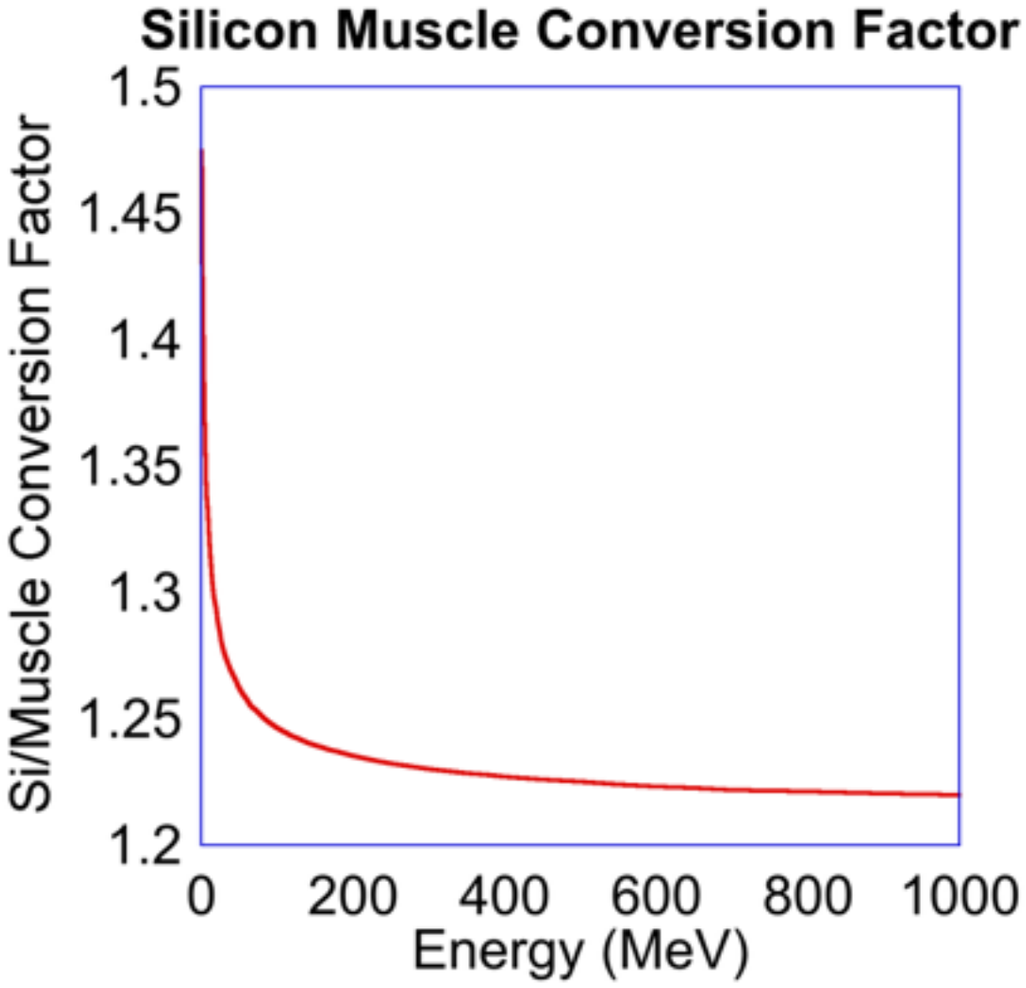
Very Heavy Ions

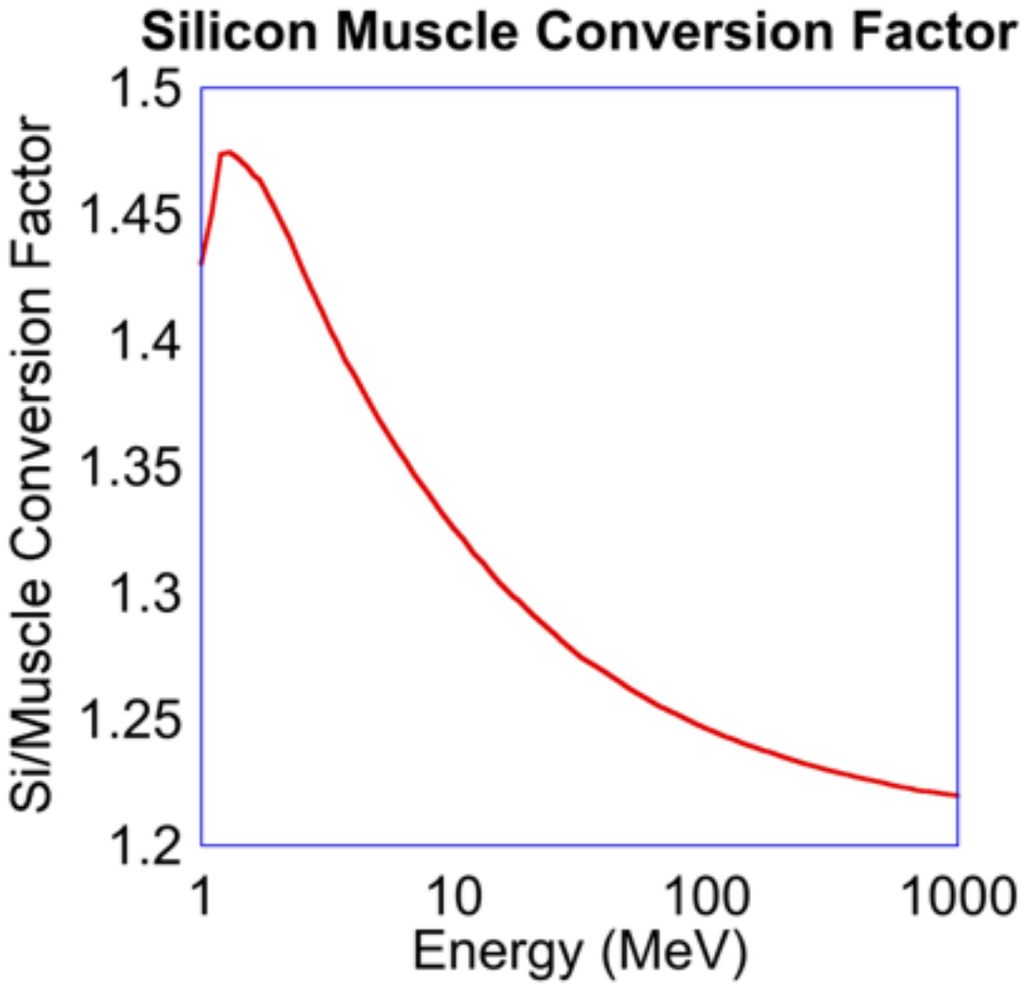


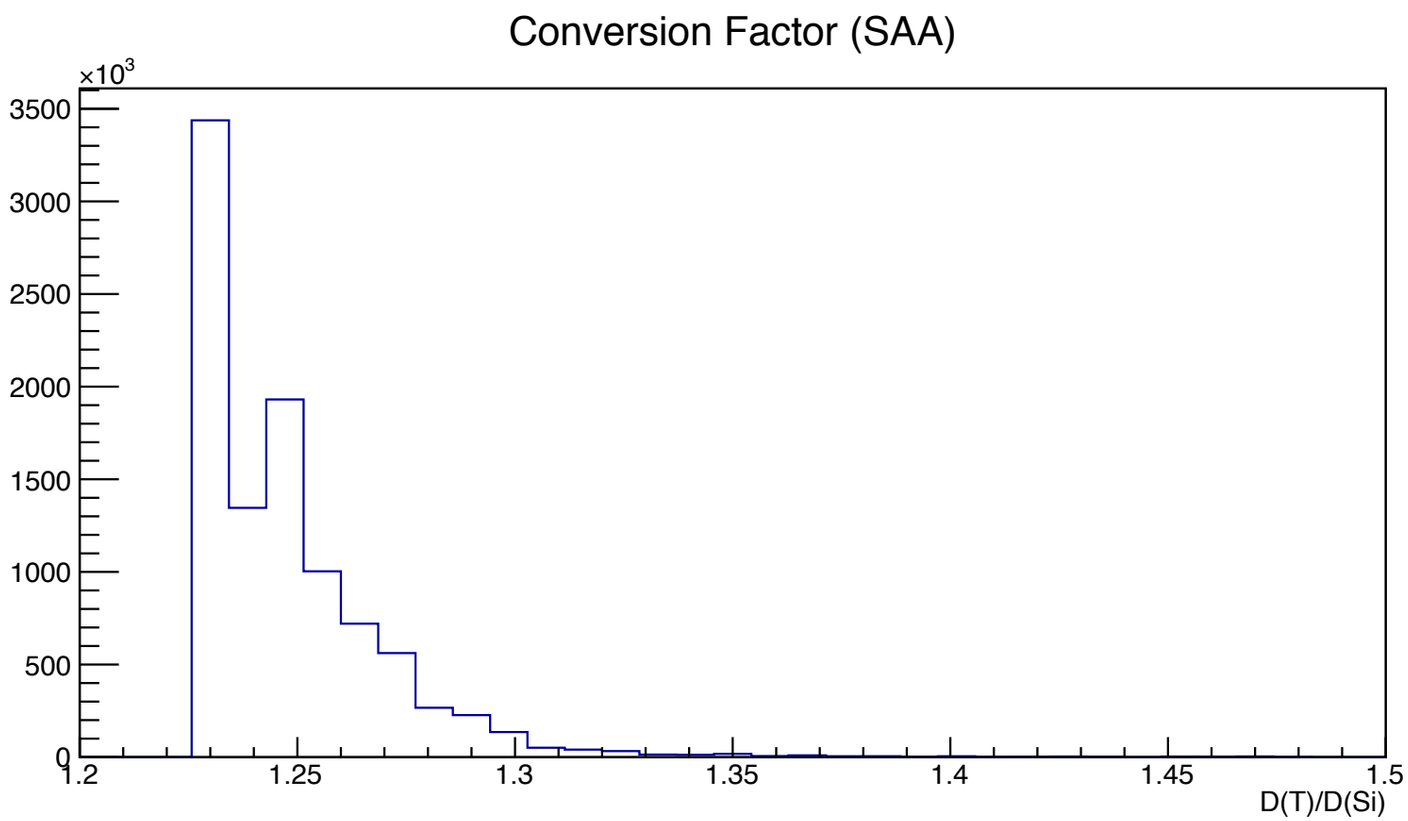
(dE/dx in Si)

$C_{Si \rightarrow m}$

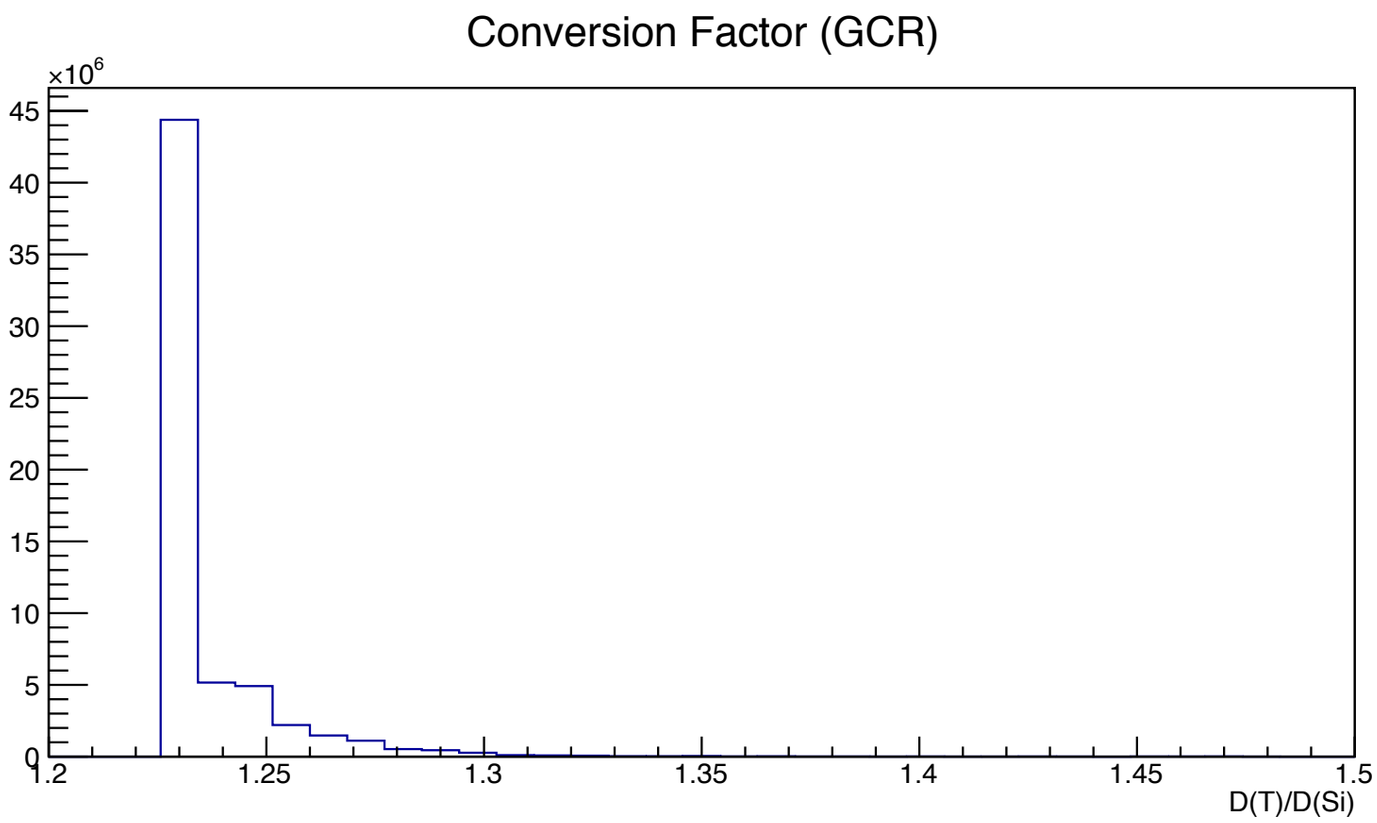
Armed with LET and an E guess







SAA - Mostly Protons
Extended high C tail



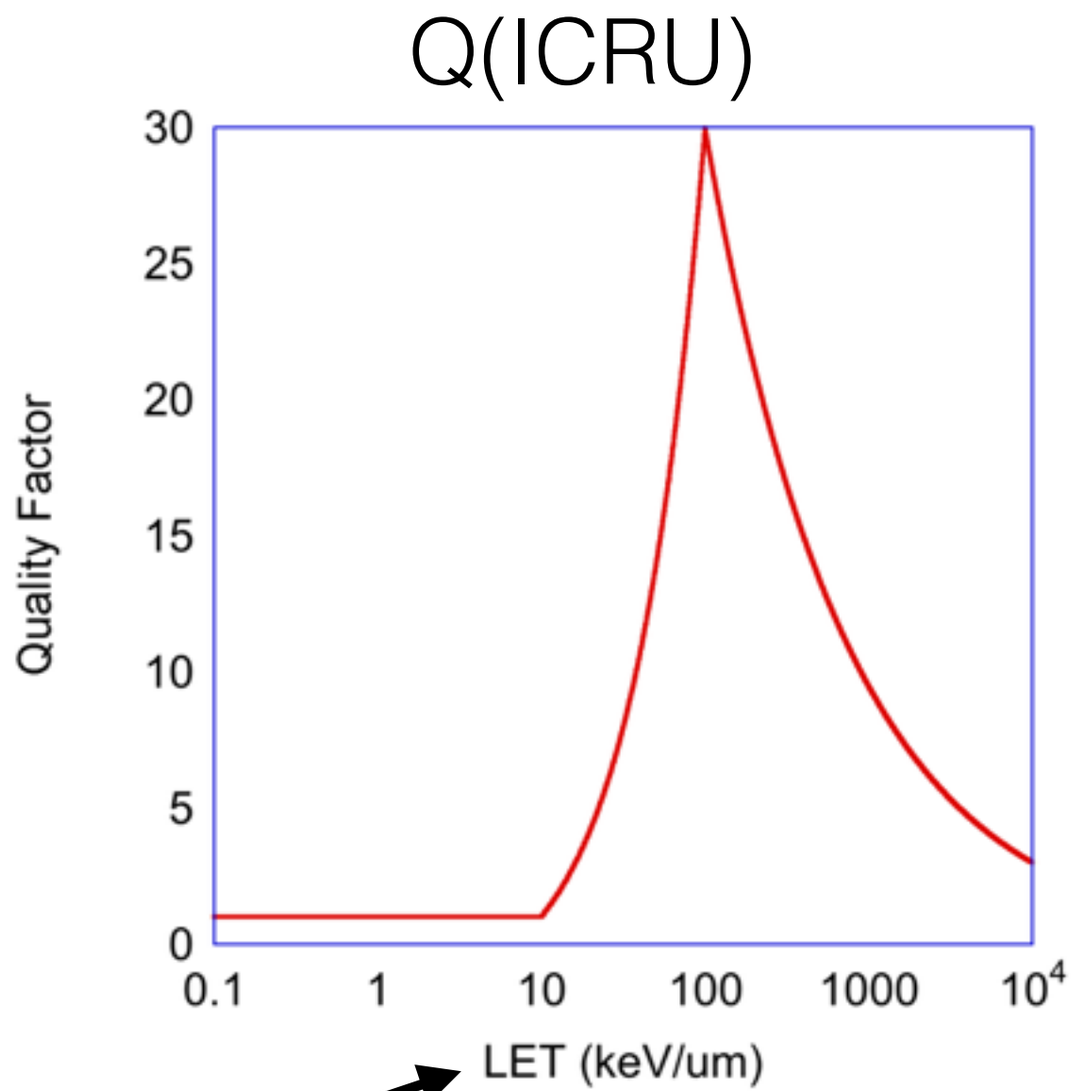
GCR - Mixed High E ions, mostly bottom bin

Biological Relevance - Q Factor

$$Q(\mathrm{LET}_m)$$

$$\mathrm{LET}_m = \mathrm{LET}_{Si}.C_{Si \to m}$$

- Heavy ions quality factors a matter of discussion
- Use d-Ray spectrum to identify ion charge



LET in Tissue

$$Q\,(\mathrm{NASA}) \propto \frac{z^2}{\beta^2}$$

Equivalent Dose in muscle

Silicon->Muscle Conversion Factor

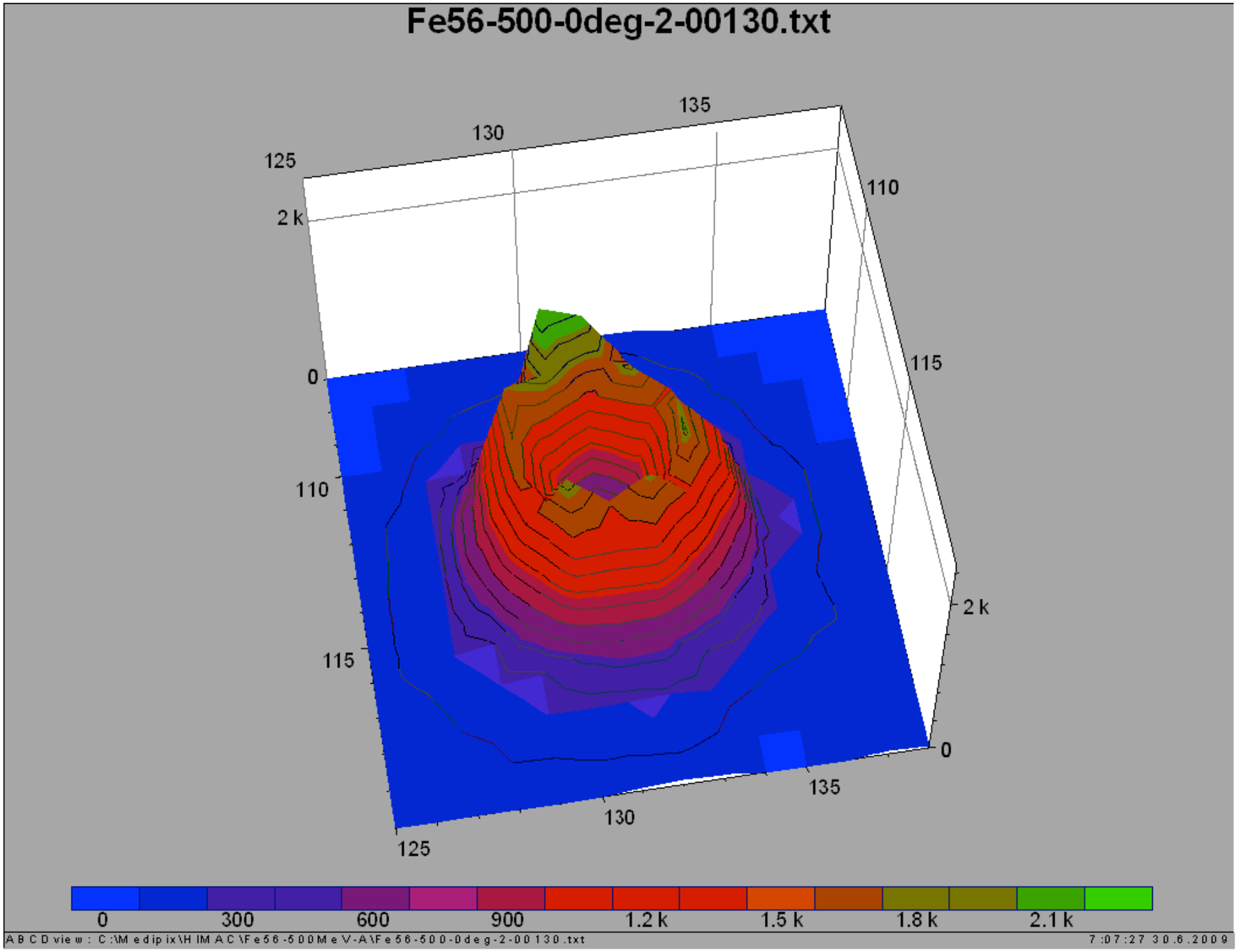
$$E_{D(m)} = D_{Si} \cdot C_{Si \to m} \cdot Q(\mathrm{LET}_m)$$

Dose to Silicon

ICRU Quality Factor

- Assumptions
- Penetration of sensor
- Implicitly, anything low energy is probably a proton
- Proportional energy measurement in Tpx

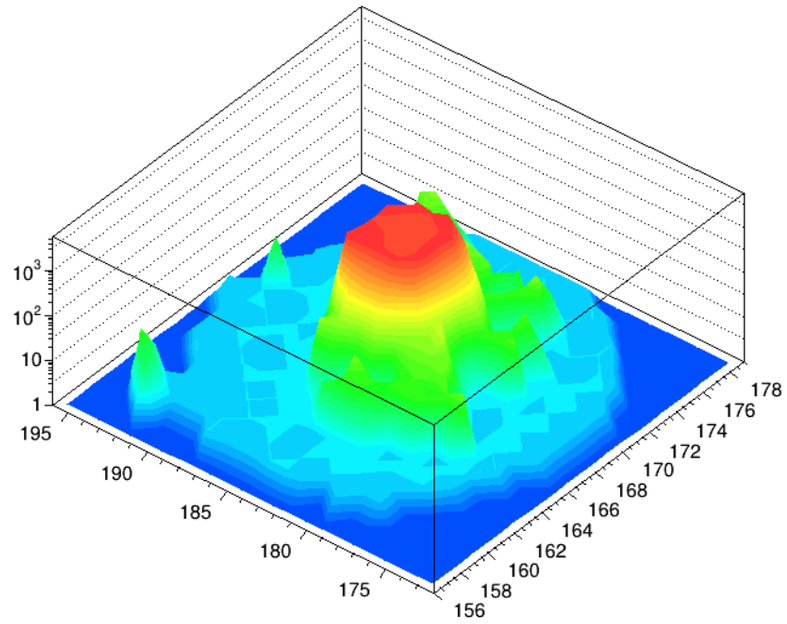
Compensation for the “Volcano Effect”

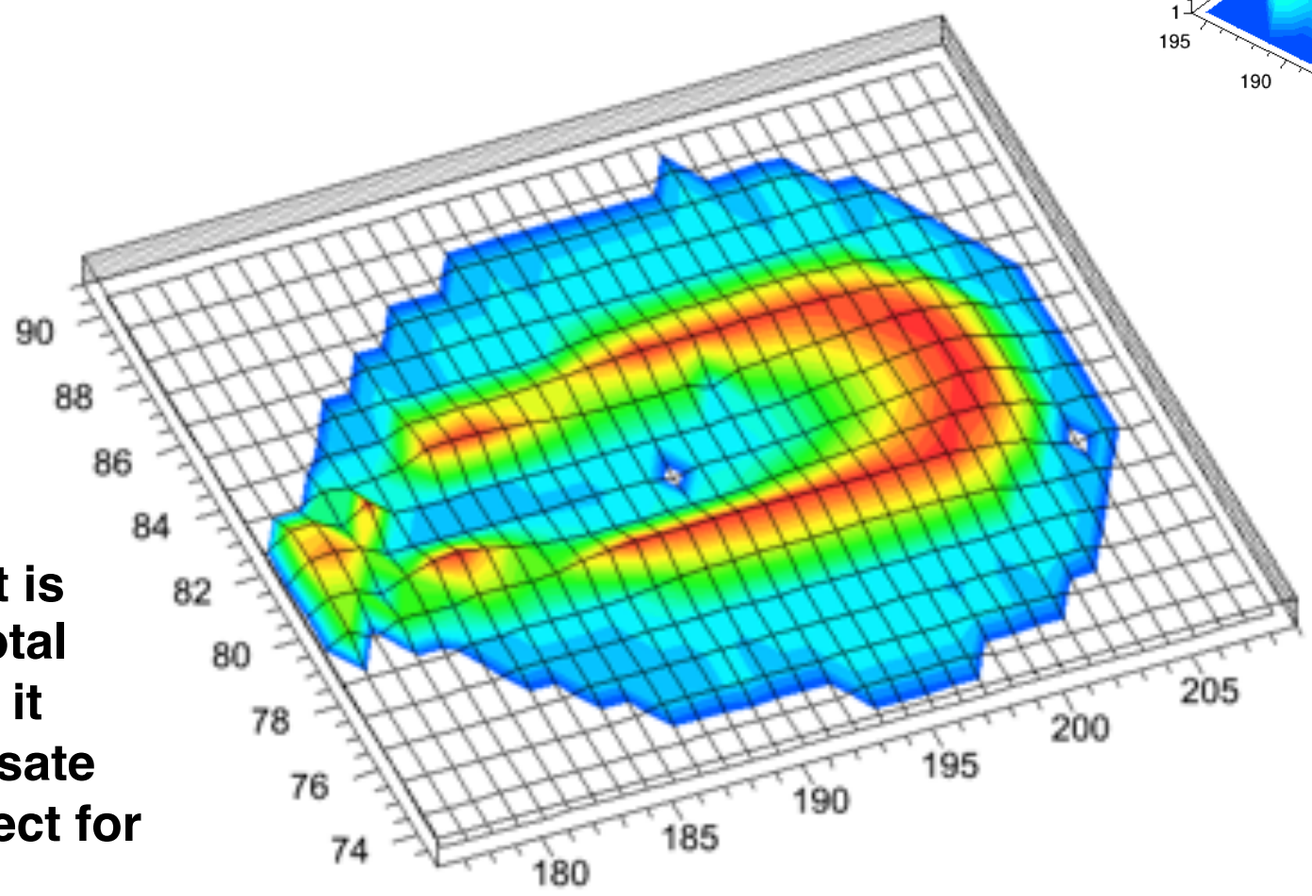


500 MeV/u Fe an normal incidence to the sensor from HIMAC in Chiba, Japan producing a “Volcano”

The Skirt and Volcano Compensation

The “Skirt” is due to the Dipole Electric Field, which is induced on the Timepix Input pads that occurs with the charge separation in the Bias Voltage field. (Jan Jakubek)

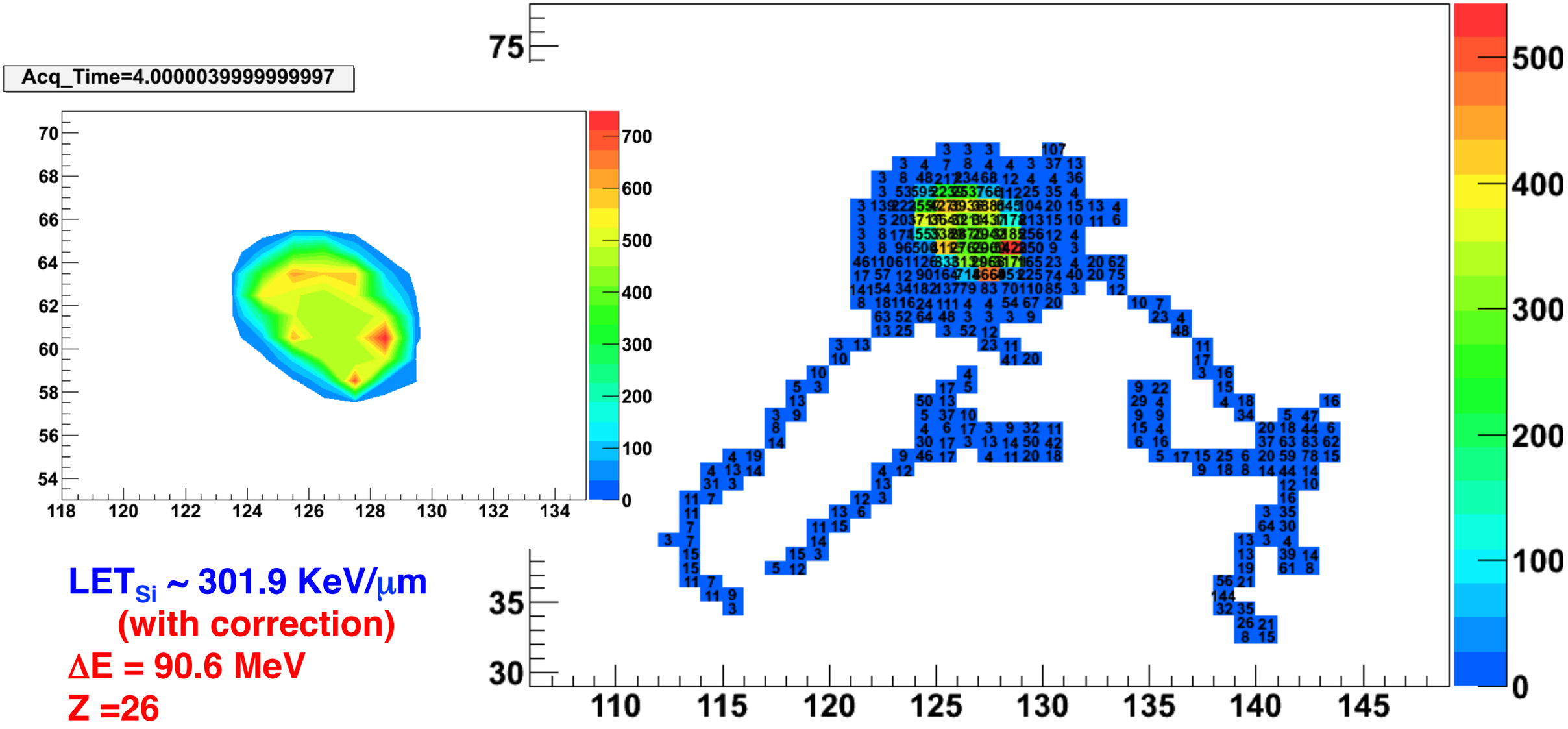




…Because this effect is proportional to the total charge, and as such, it allows us to compensate for the “Volcano” effect for the highest charge deposits… (John Idarraga)

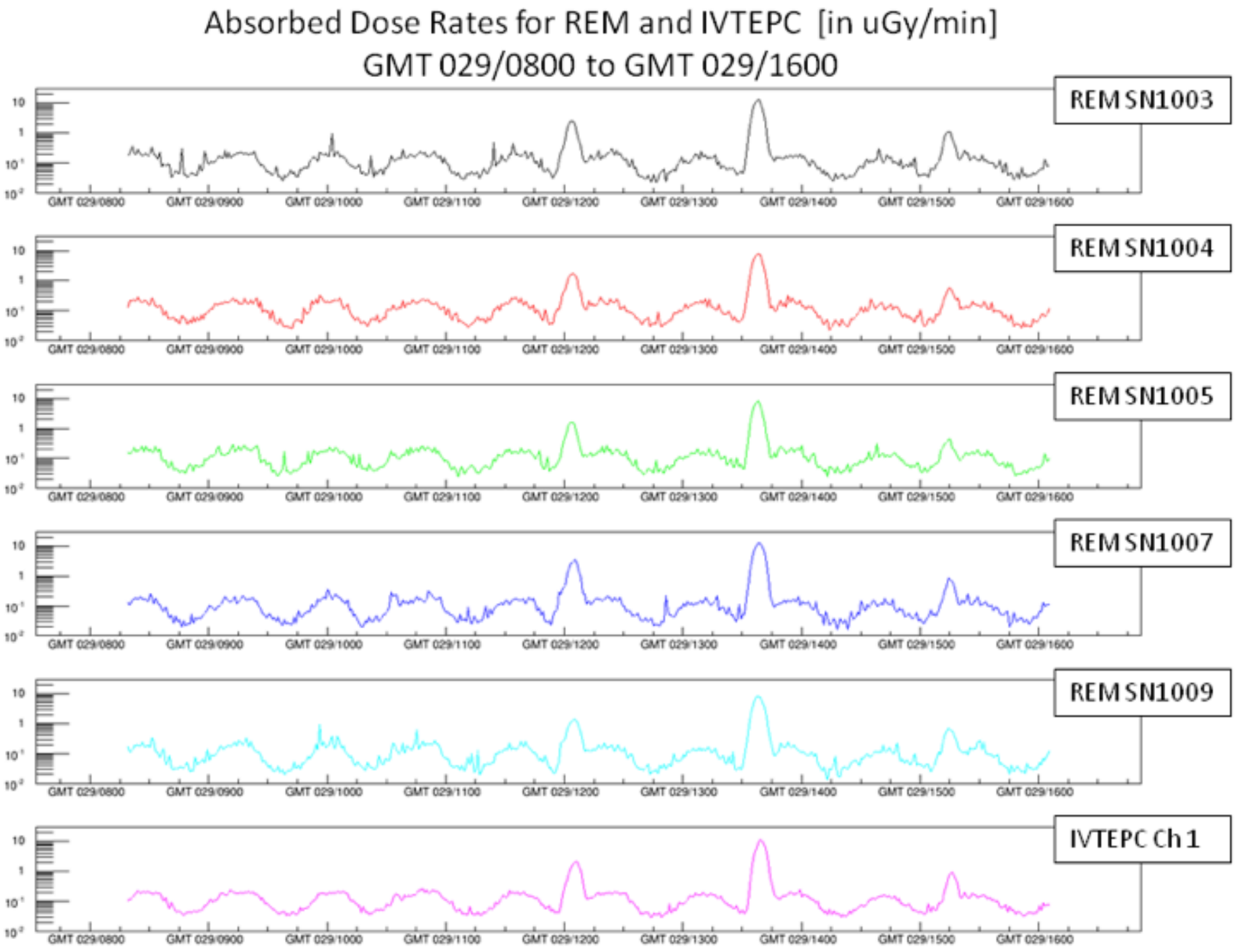
UNIVERSITY OF HOUSTON
Learning. Leading.

A “Fast” Heavy Ion (>650 KeV/μm)



LET_{Si} ~ 301.9 KeV/μm
(with correction)
ΔE = 90.6 MeV
Z =26
E > 650 MeV/A

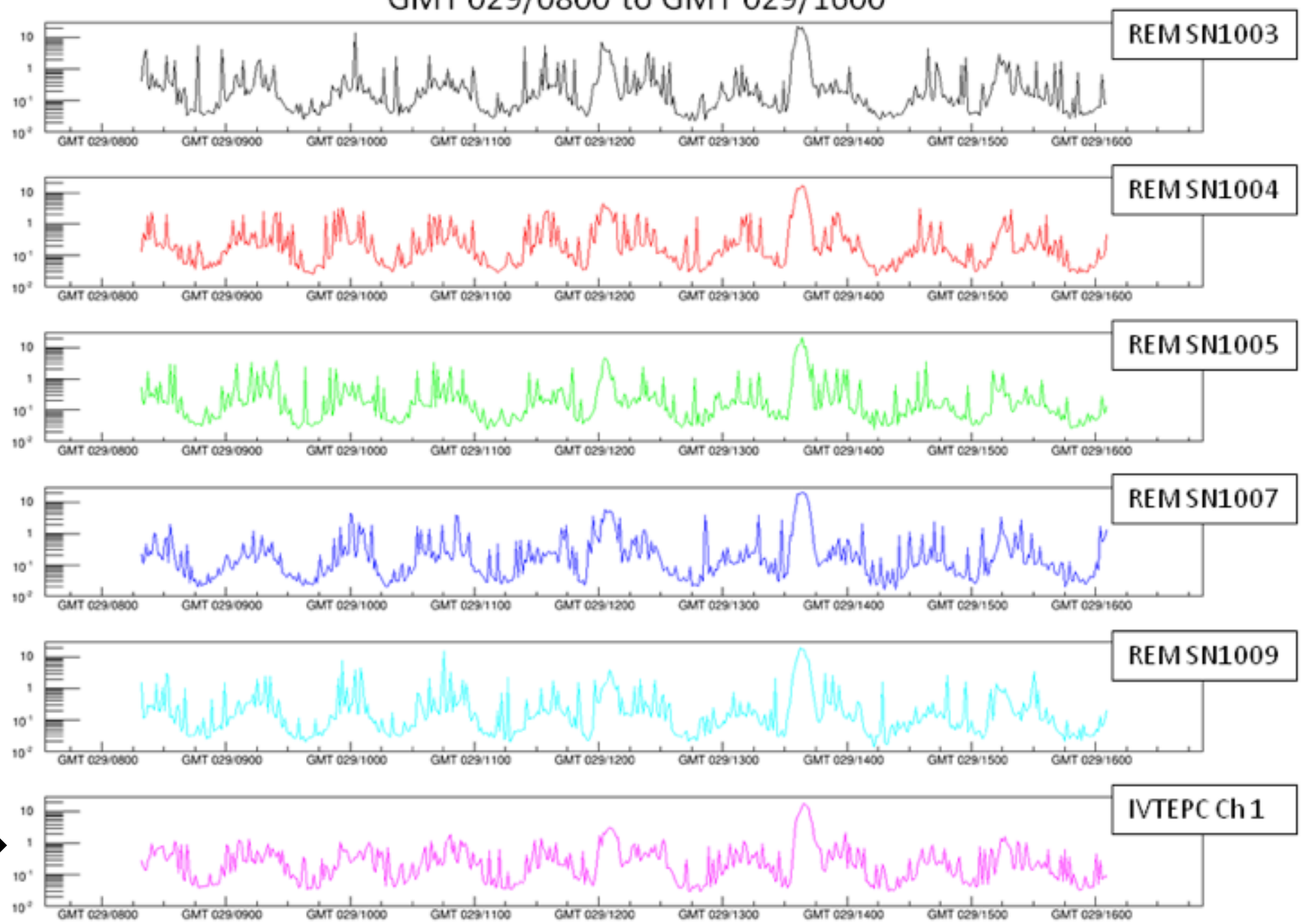
REM v. TEPC Absorbed Dose Rates



TEPC➔

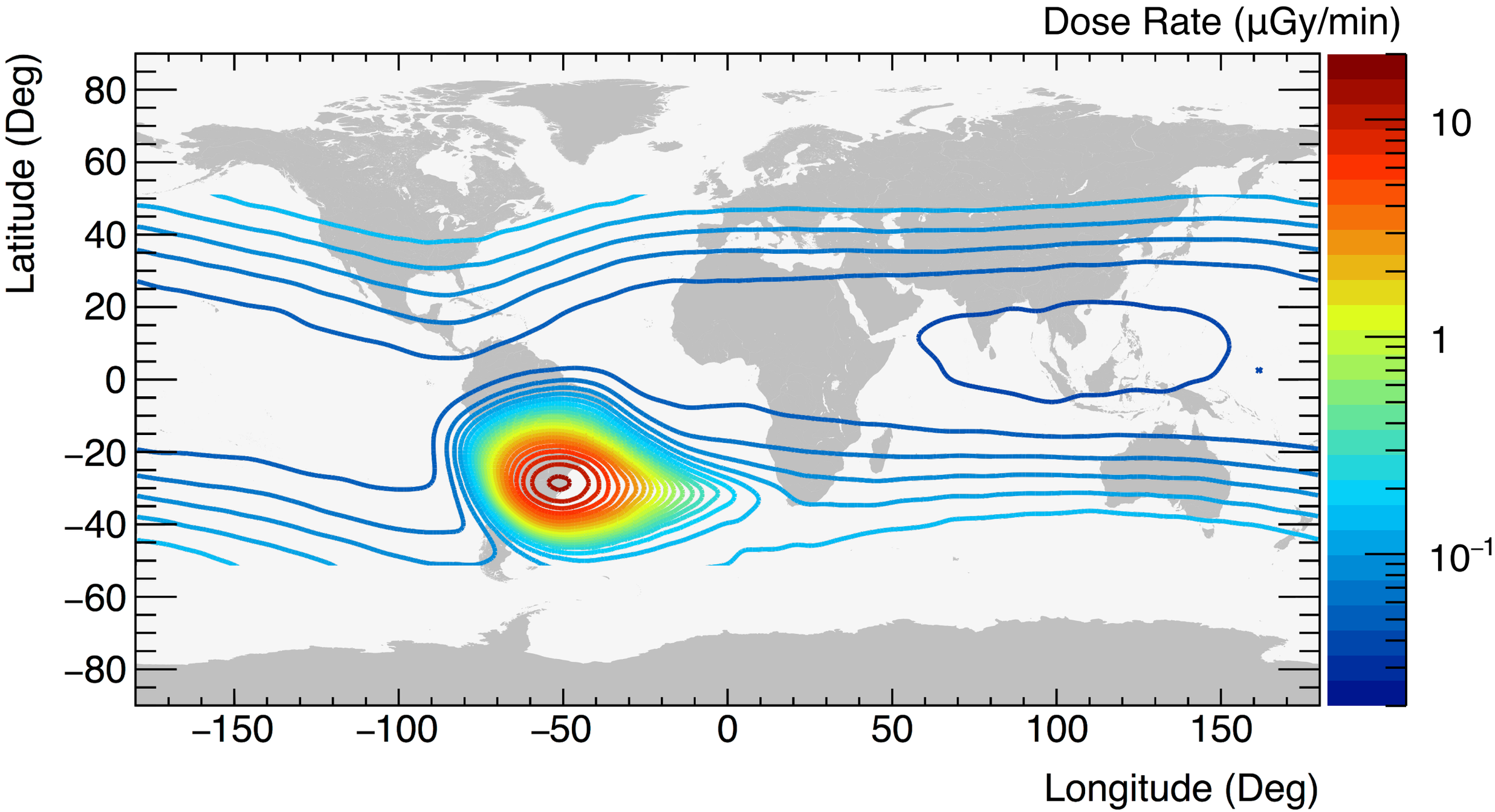
Tissue-Equivalent Proportional Counter

REM v. TEPC Dose Equivalent Rates

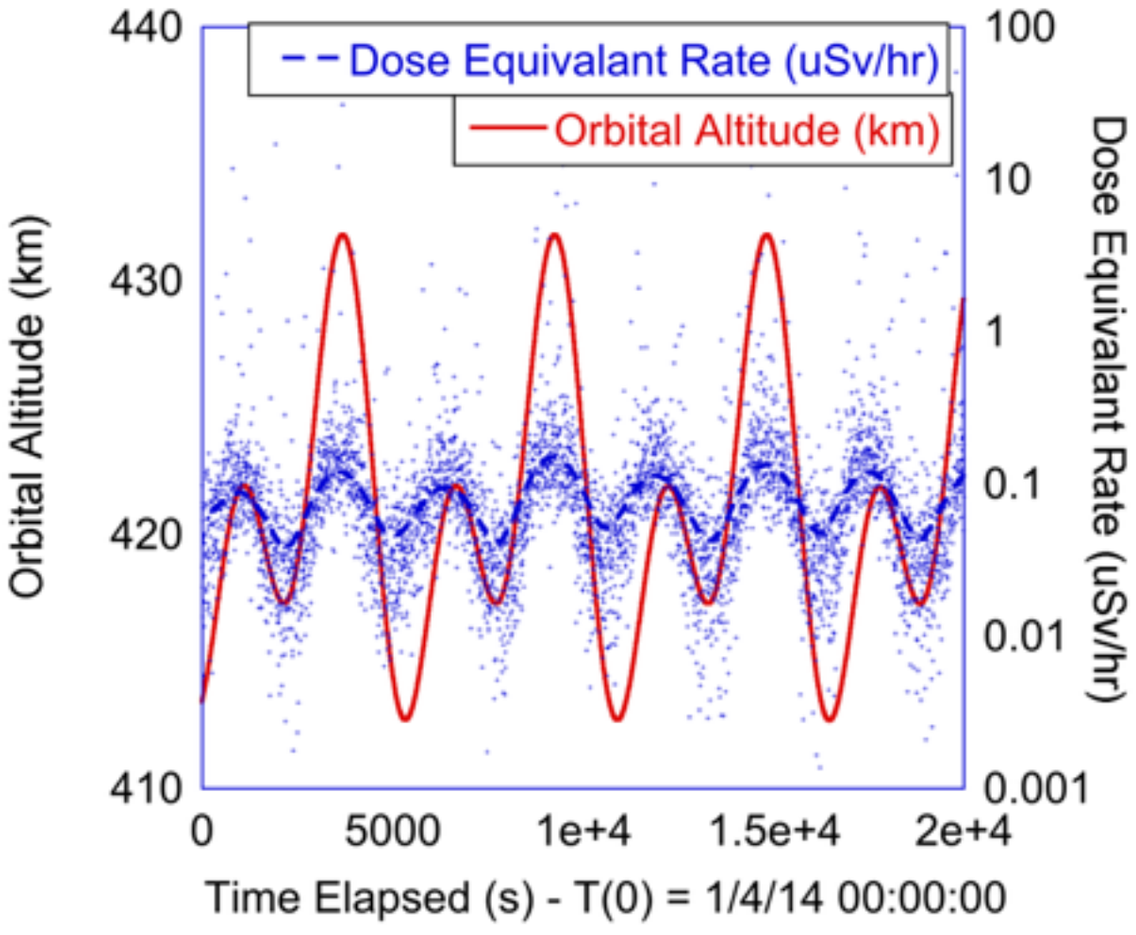


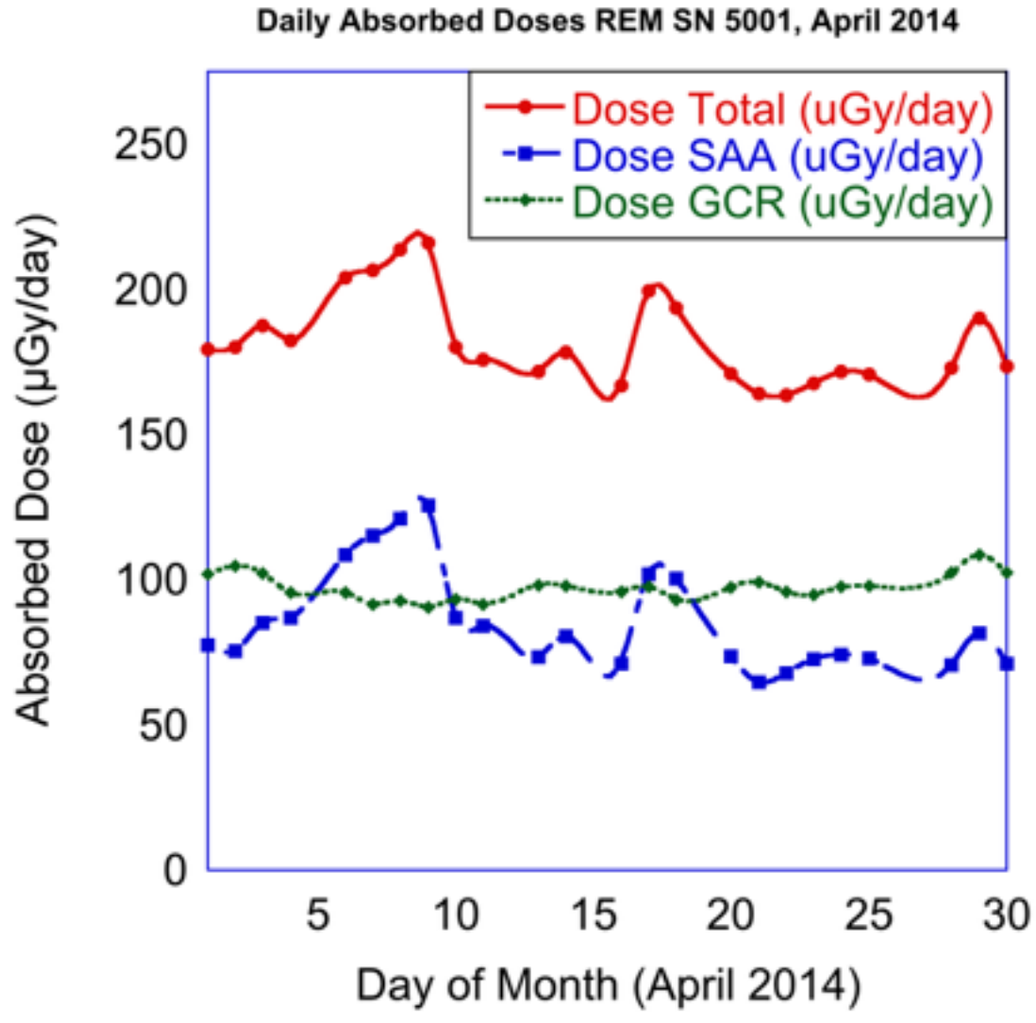
TEPC➔
Tissue-Equivalent Proportional Counter

Absorbed Dose Rate (uGy/min)

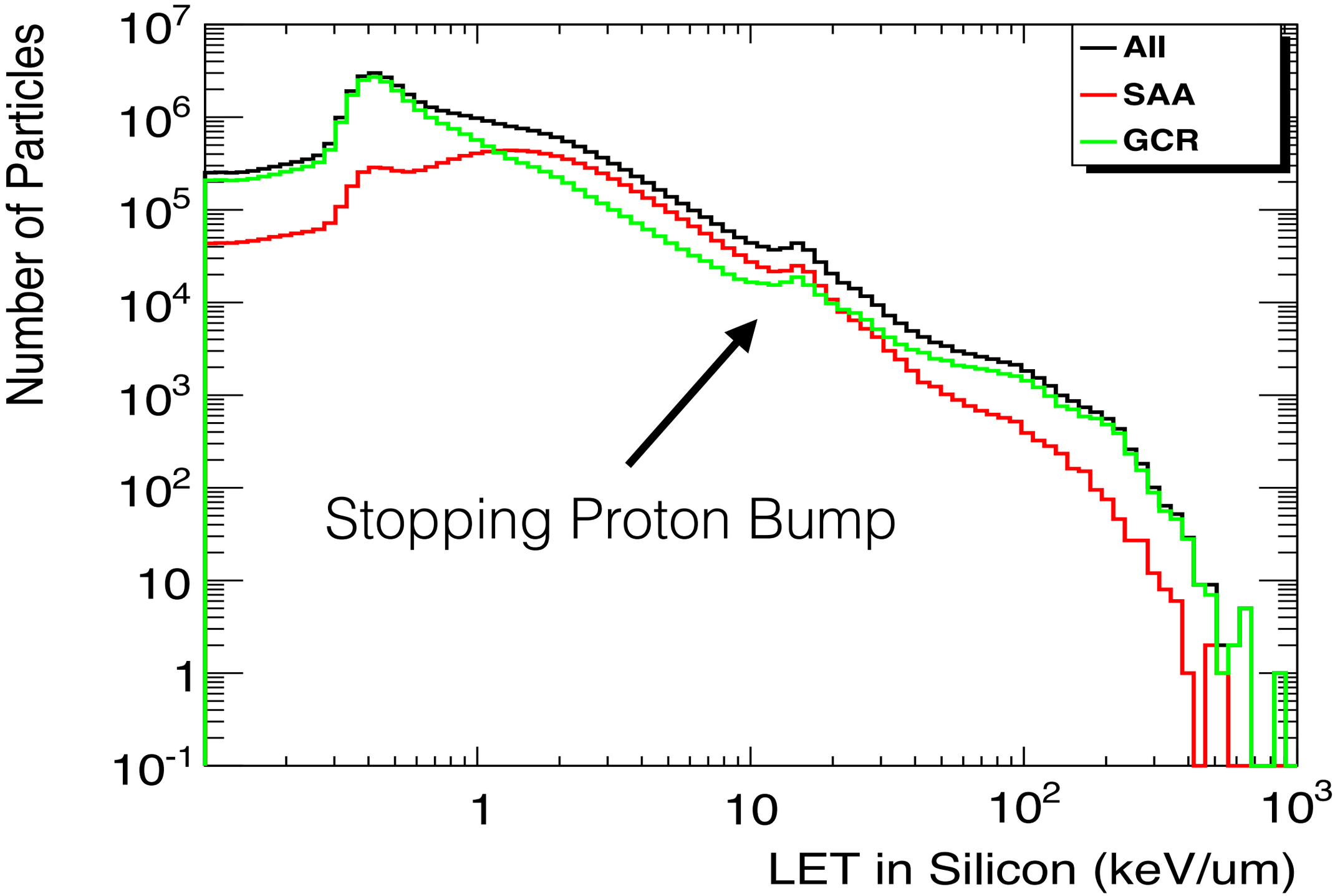


Clear distinction between trapped particles (SAA) and the rest

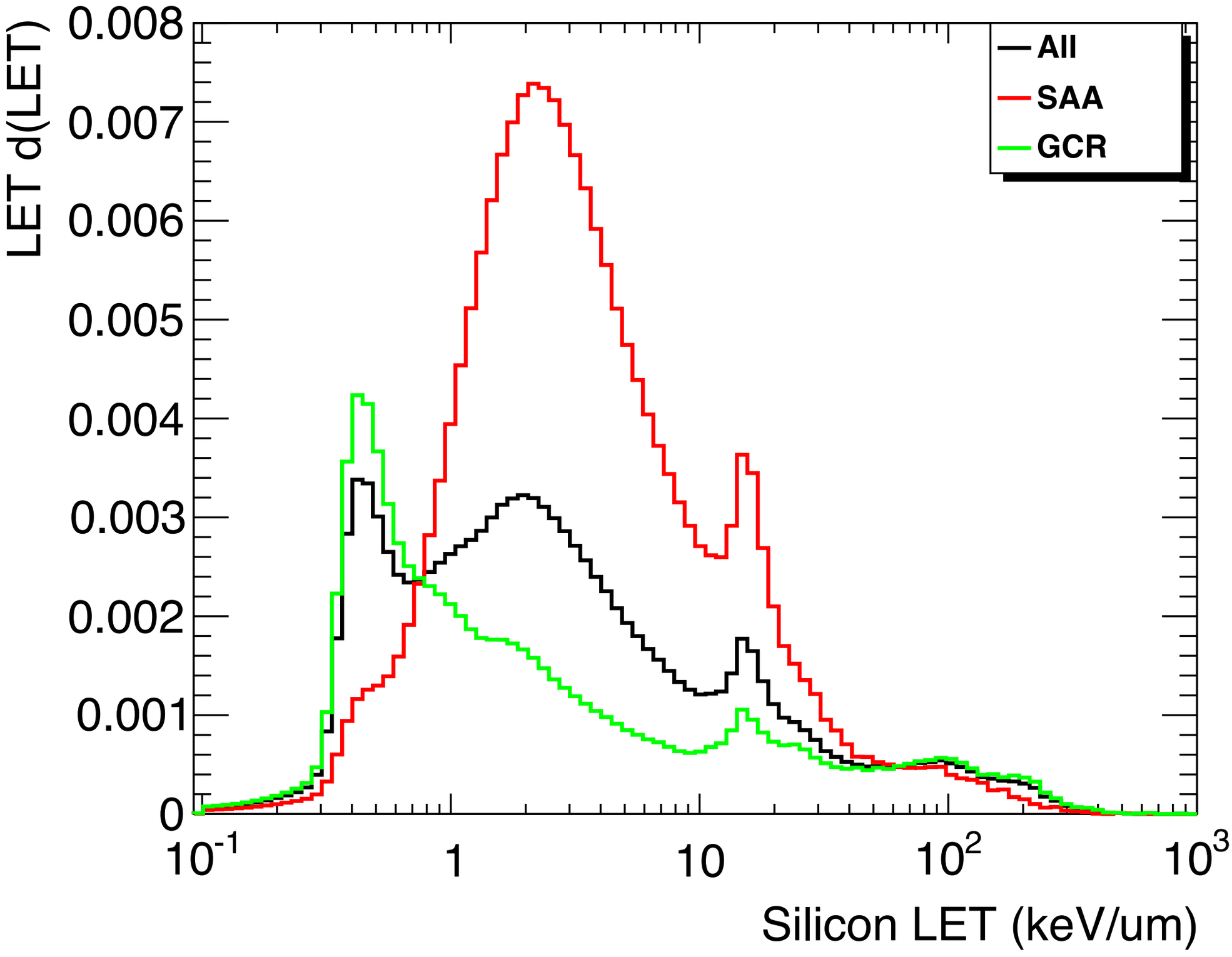

Dose Equivalant Rate (uSv/hr)
Orbital Altitude (km)
440
430
420
410
100
10
1
0.1
0.01
0.001
0
5000
1e+4
1.5e+4
2e+4
Orbital Altitude (km)
Dose Equivalant Rate (uSv/hr)
Time Elapsed (s) - T(0) = 1/4/14 00:00:00


Daily Absorbed Doses REM SN 5001, April 2014
Dose Total (uGy/day)
Dose SAA (uGy/day)
Dose GCR (uGy/day)
250
200
150
100
50
0
5
10
15
20
25
30
Absorbed Dose (µGy/day)
Day of Month (April 2014)

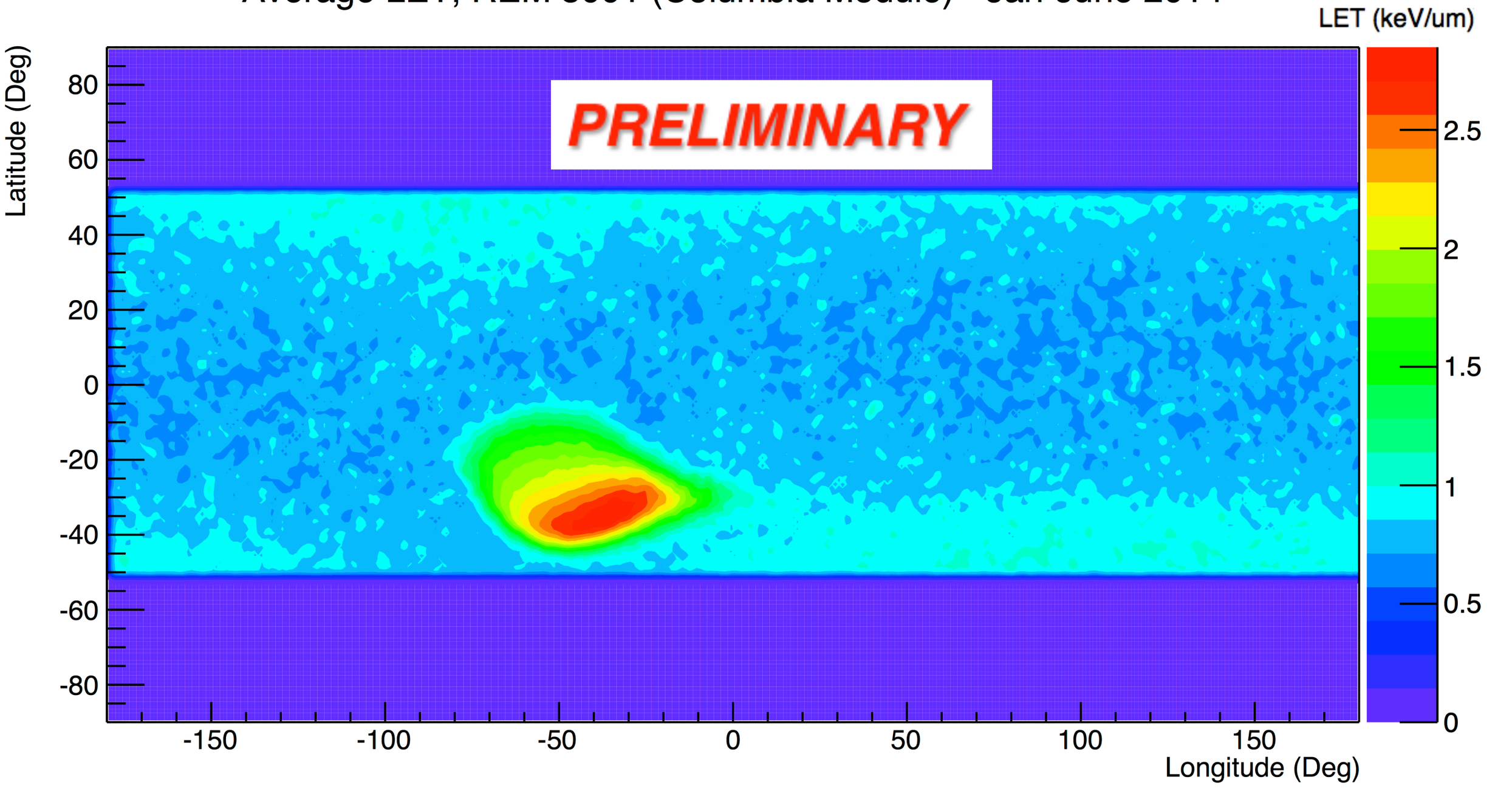
LET Spectra (Si)



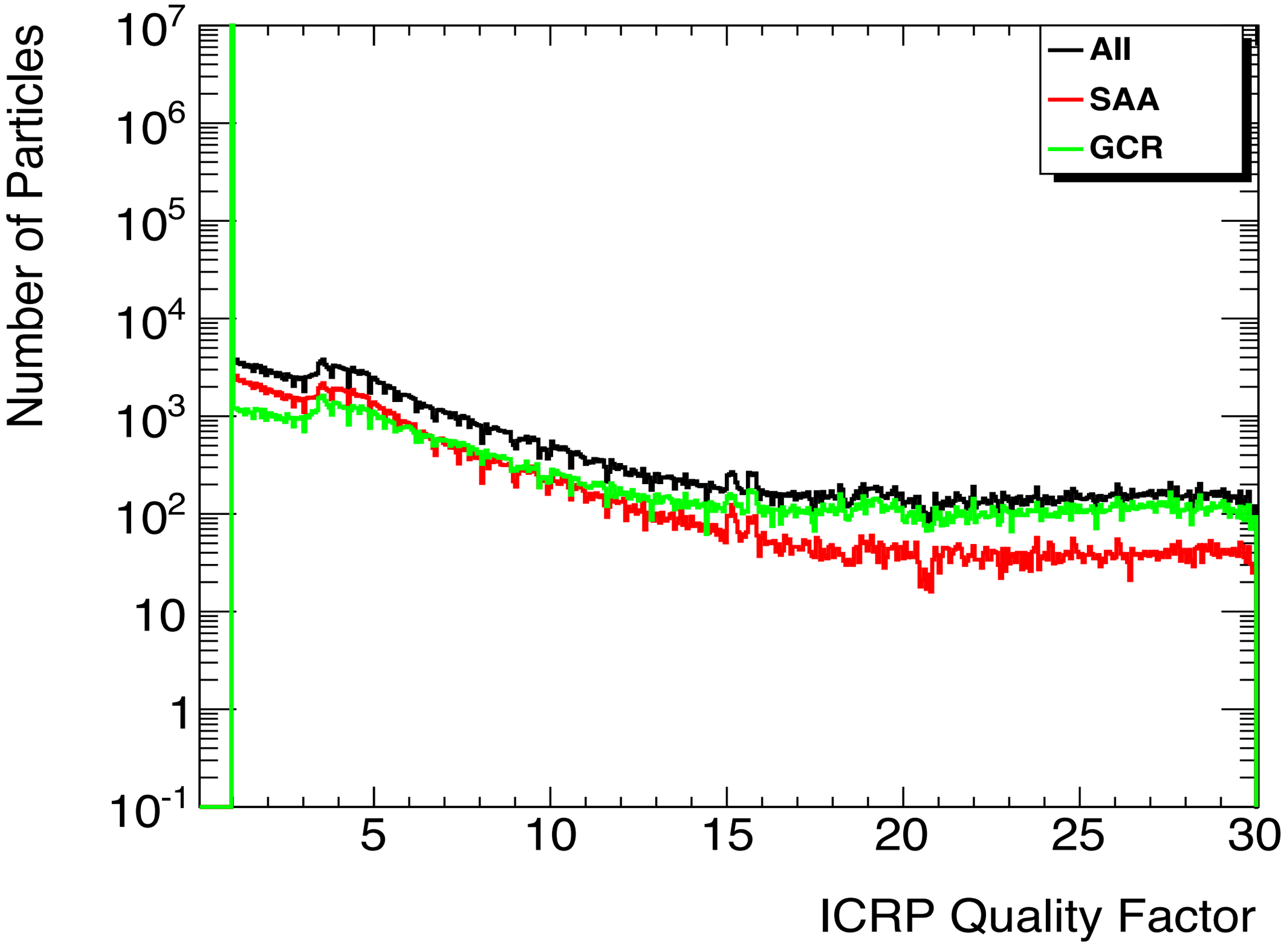
LET Spectra (Si)

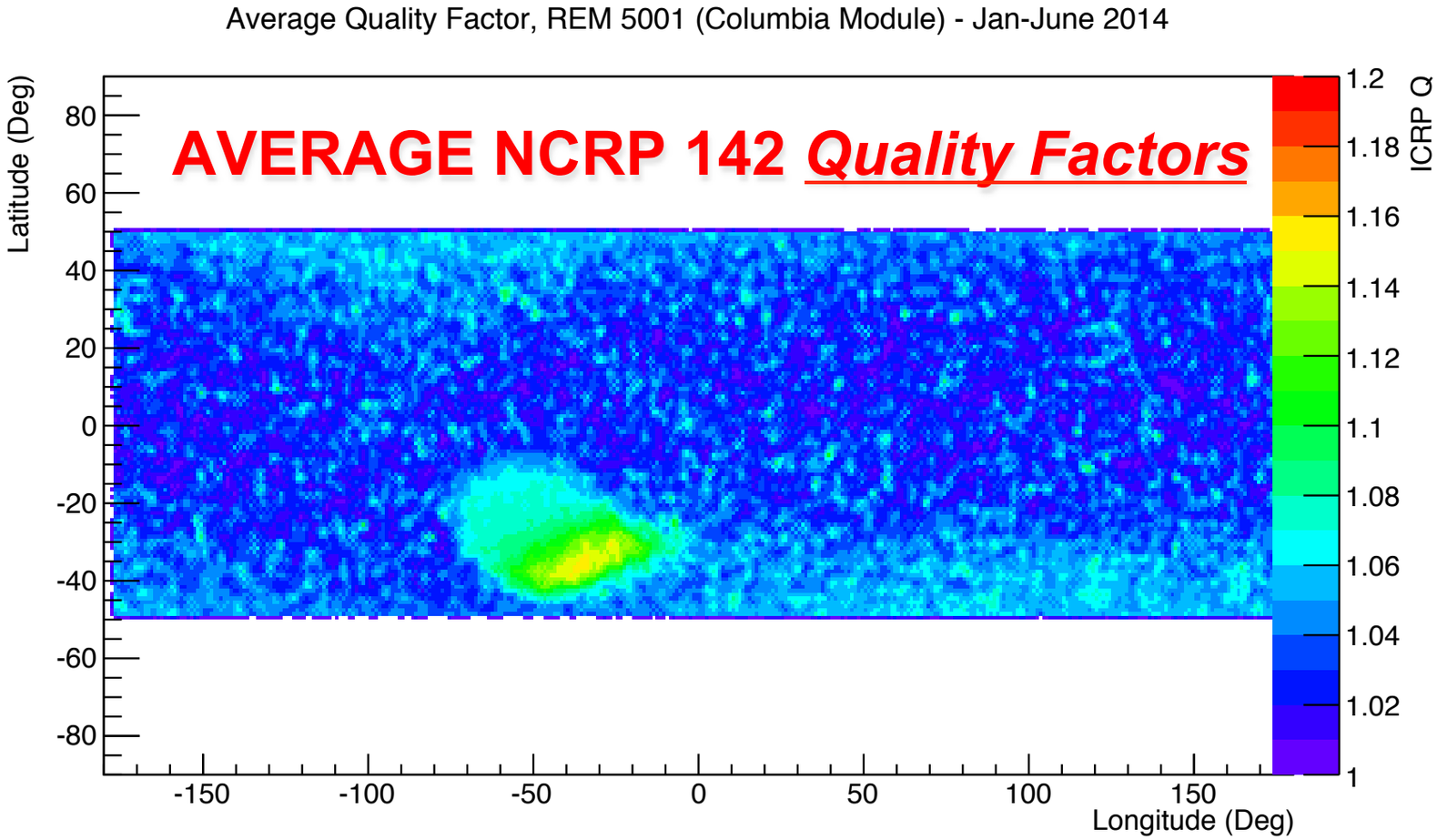


Average LET, REM 5001 (Columbia Module) - Jan-June 2014

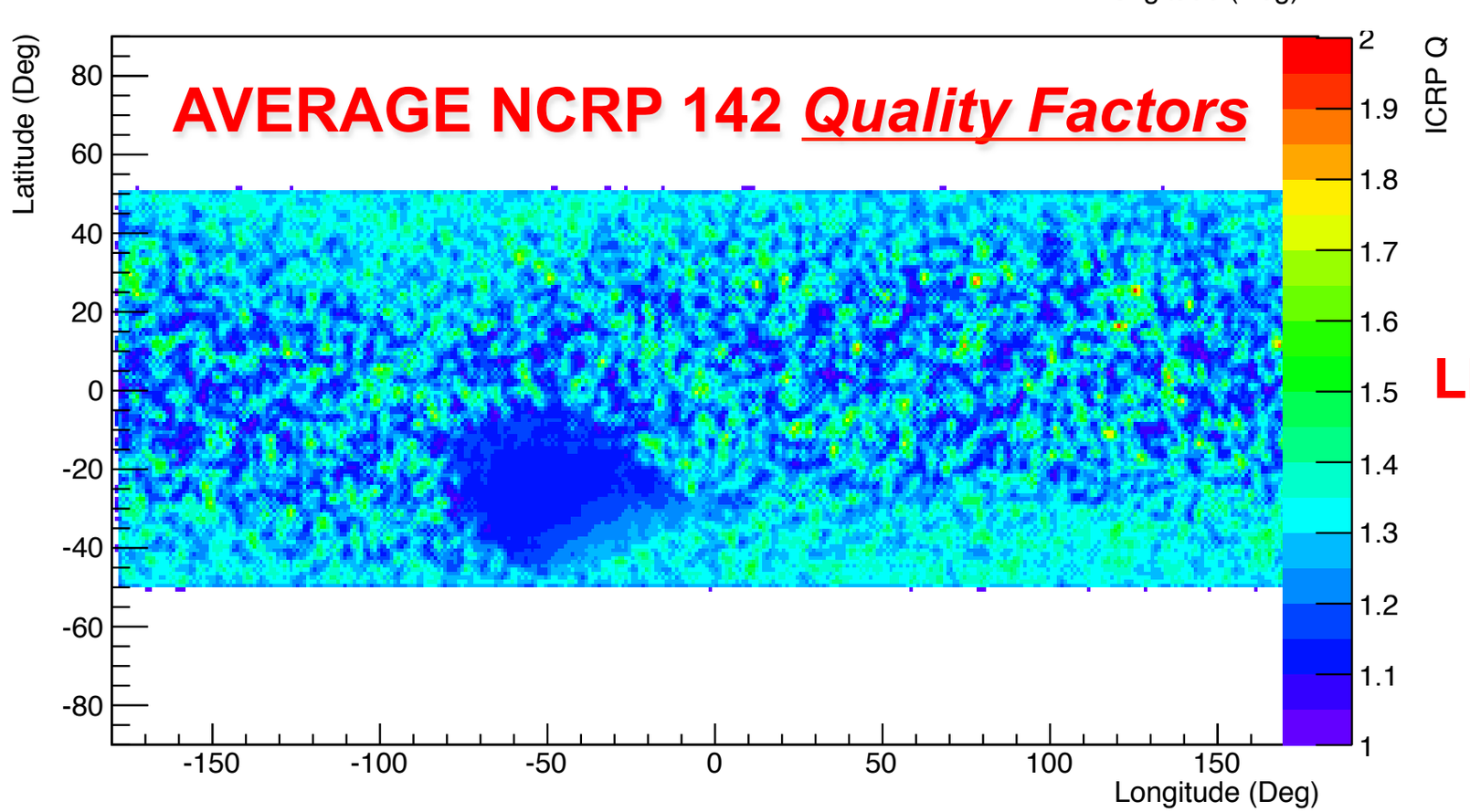


Average Quality Factors



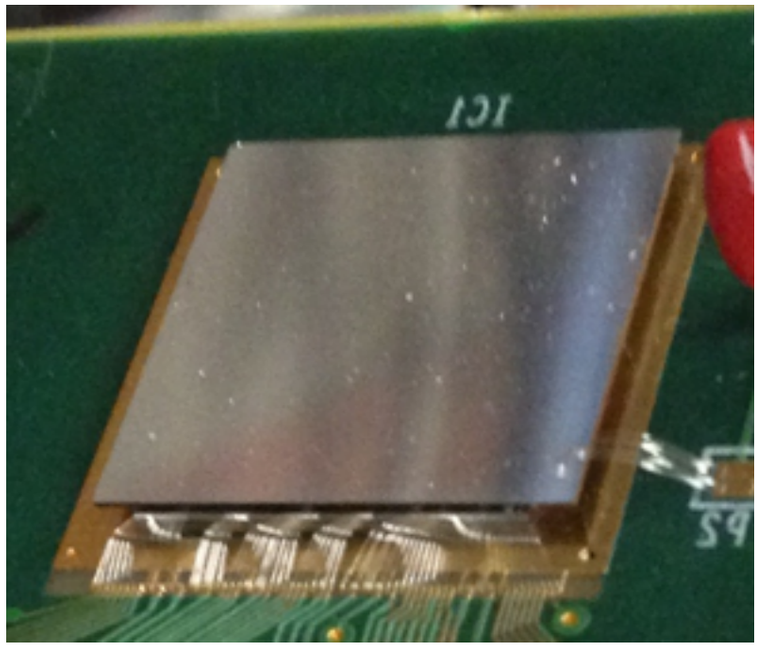


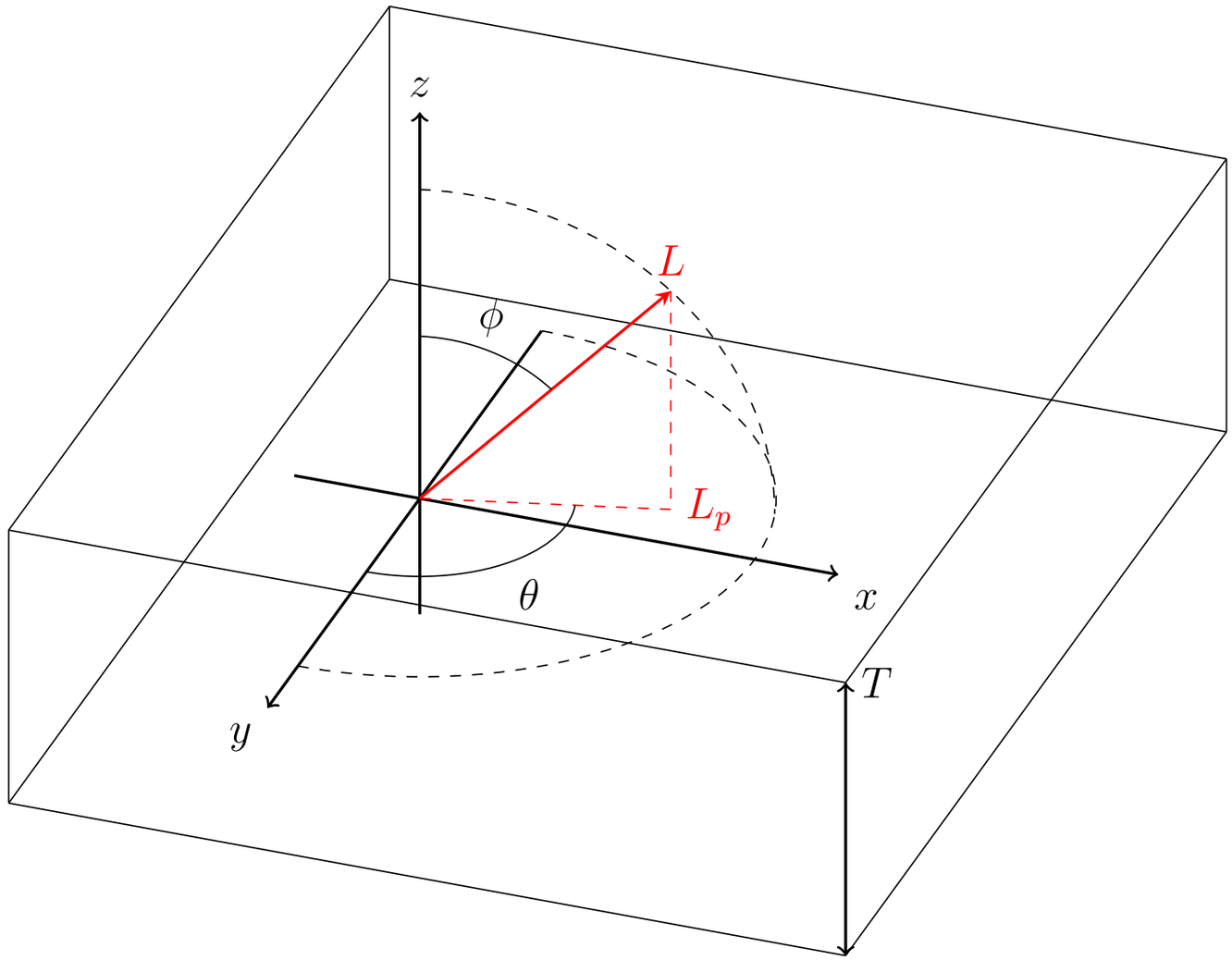
All Protons & Z > 1 Charged Particles



LET > 1 KeV/μm Cut

Calculation of Track Angles





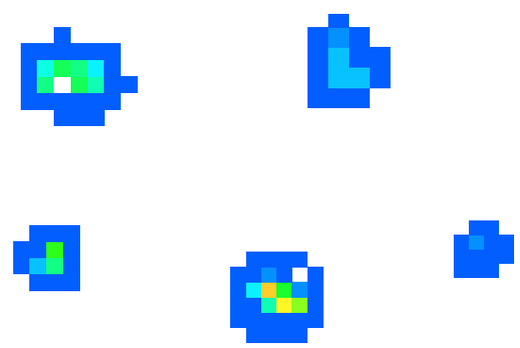
- 4π view of sky, 1π discrimination (slope cannot tell up from down, projection of a line symmetric around 180 degrees)

- Assumption of sensor penetration for slope, work on corrections for stopping protons in progress.

Caveats - Limitations of Angular Discrimination

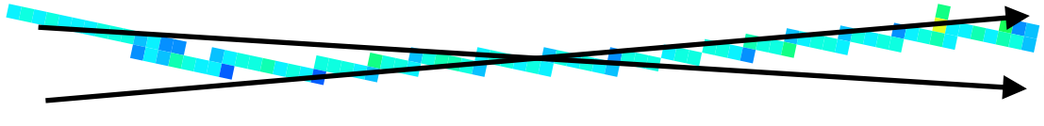
- **Detectors move around**

- Limits of around 15 degrees on θ for low ϕ

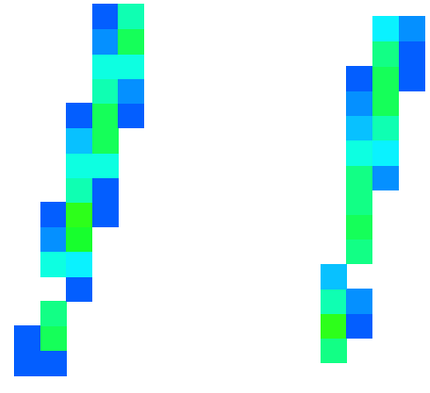


Low ϕ (perpendicular) tracks (poor θ discrimination)

- Detectors change their view of the sky



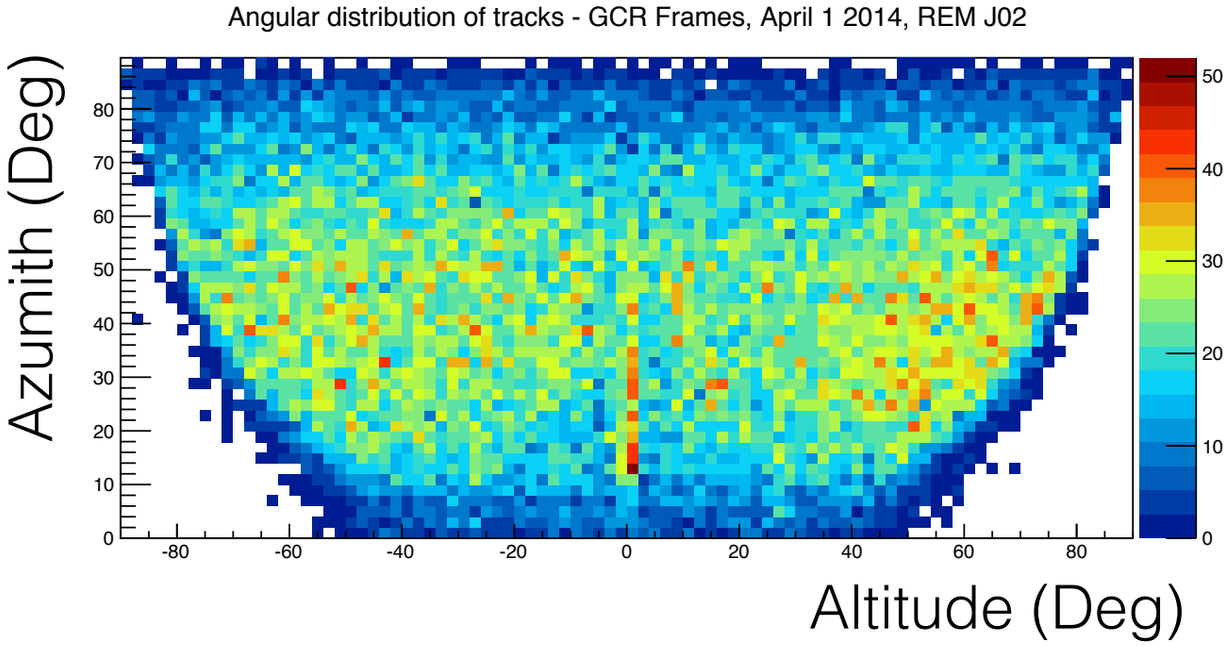
Angular space wraps in the timepix

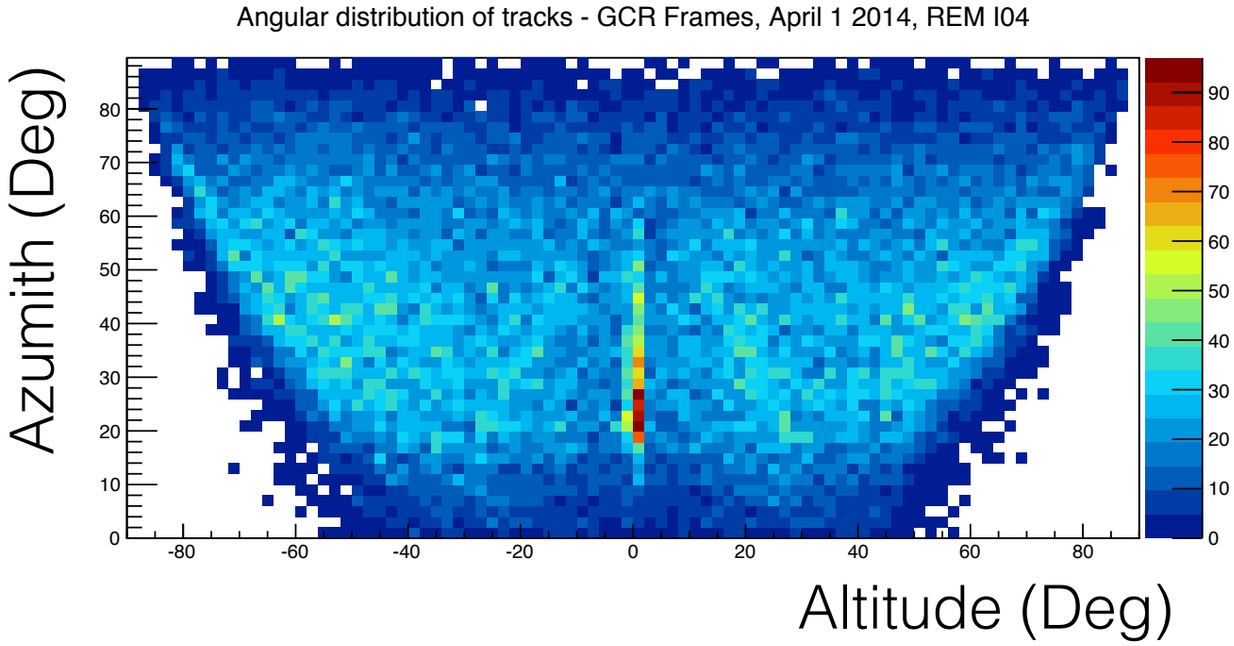


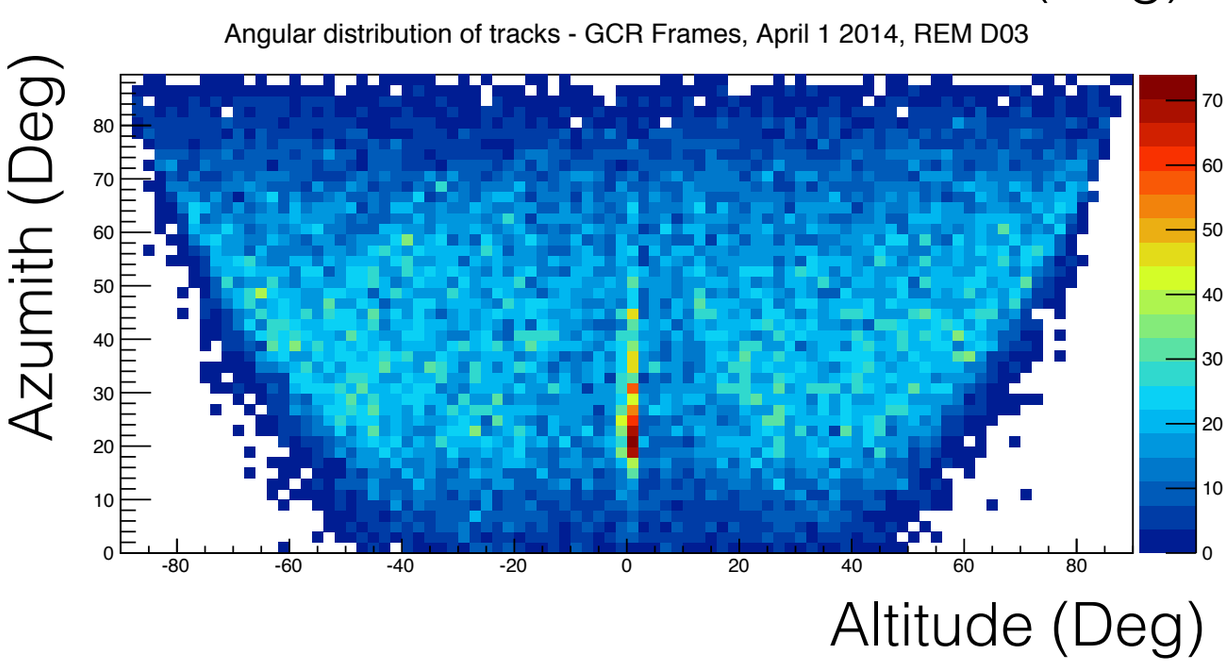
High ϕ tracks (good θ discrimination)

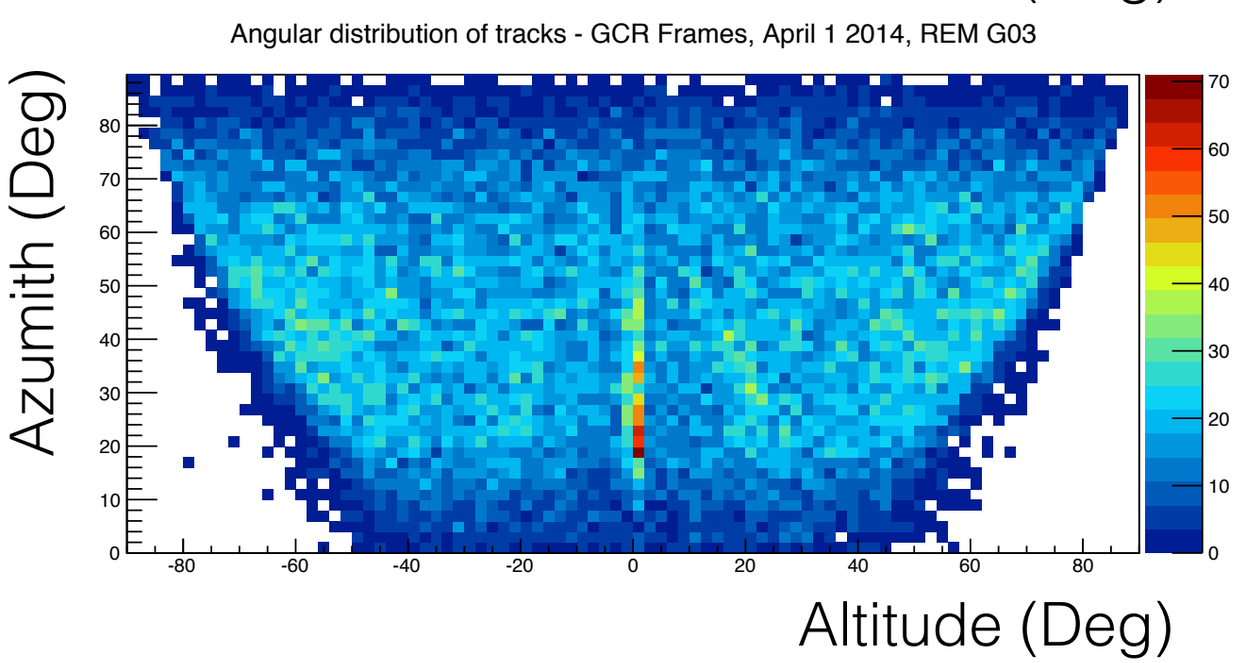
GCR Angular Distributions 1st April 2014

500 um unit



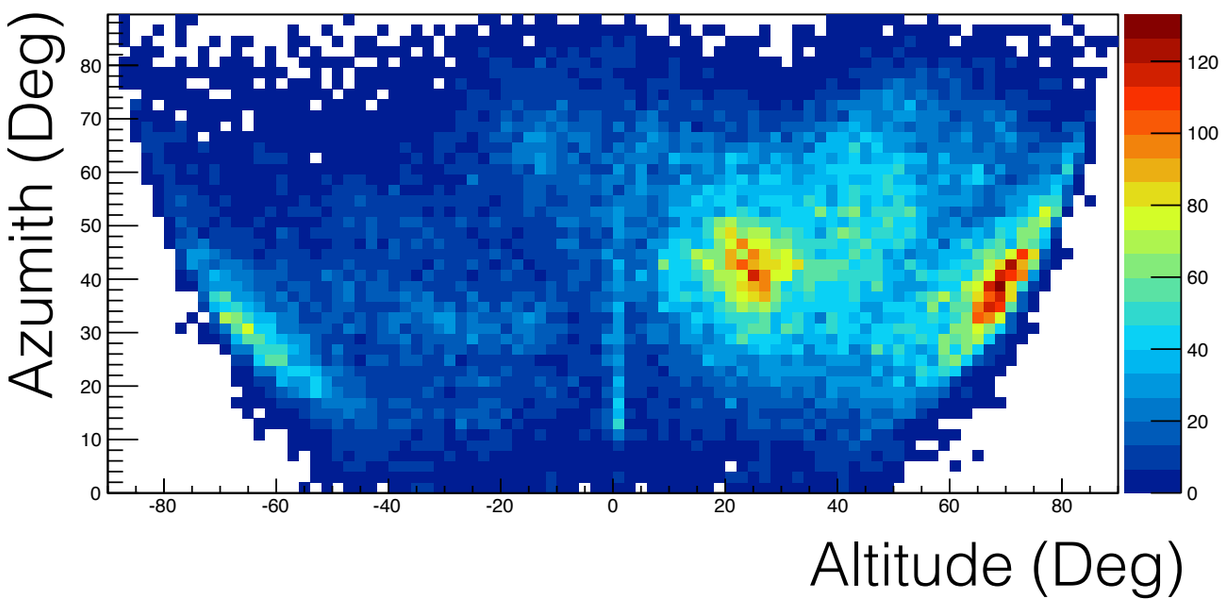


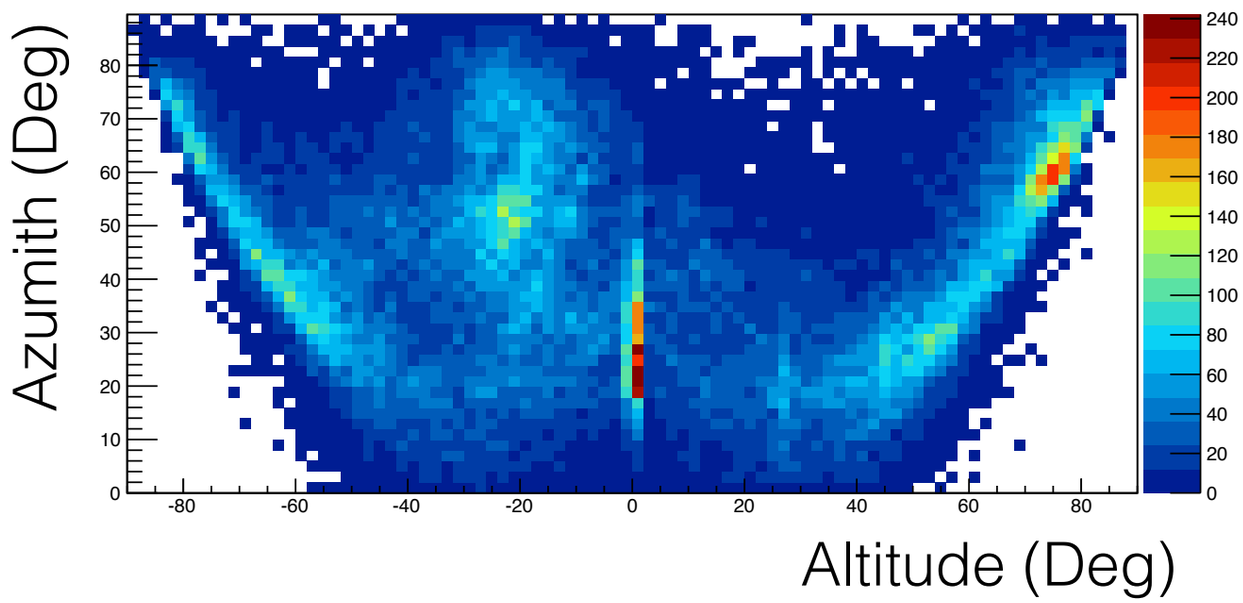


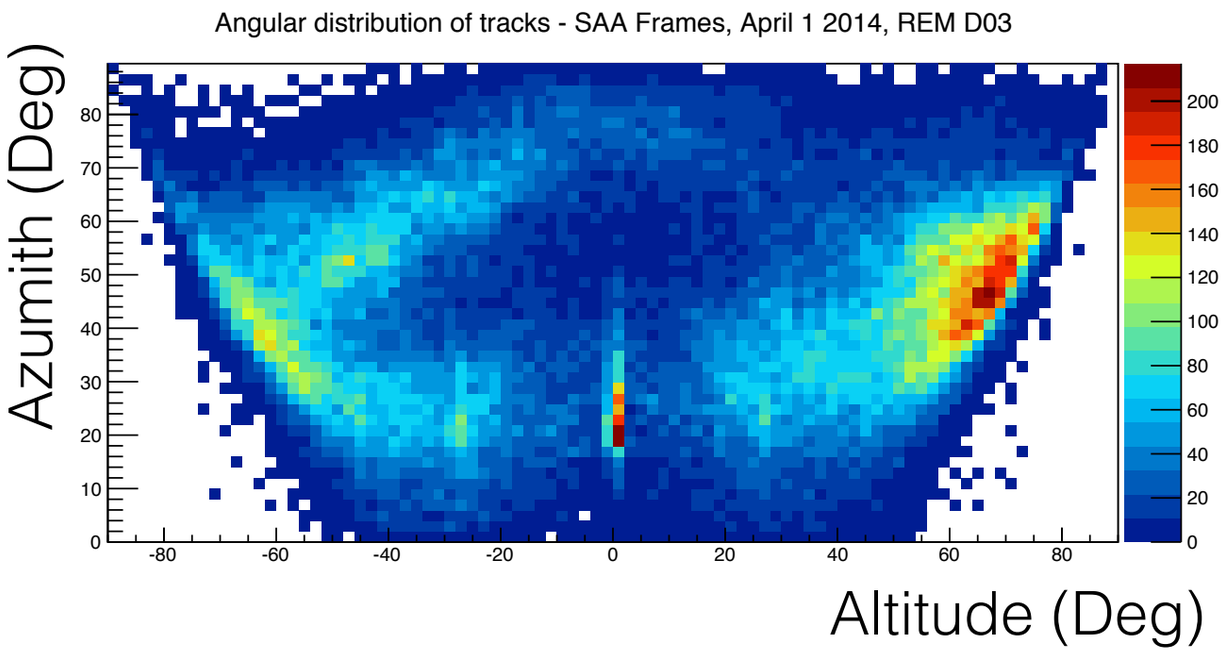


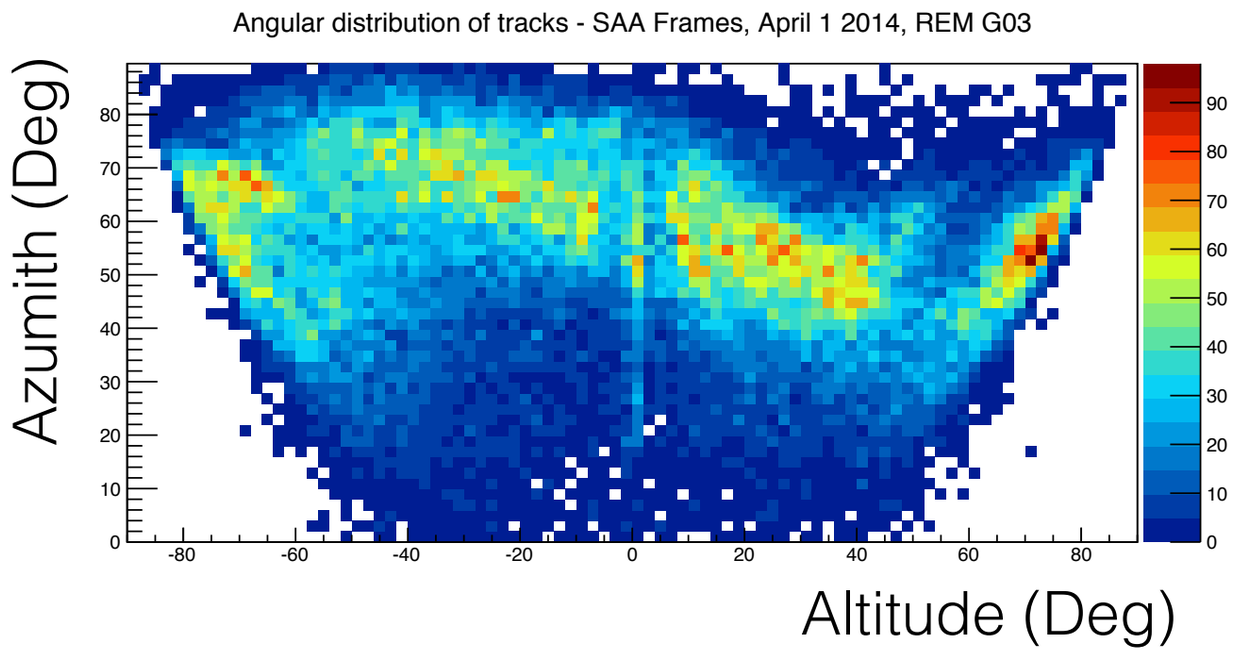
SAA Angular Distributions 1st April 2014

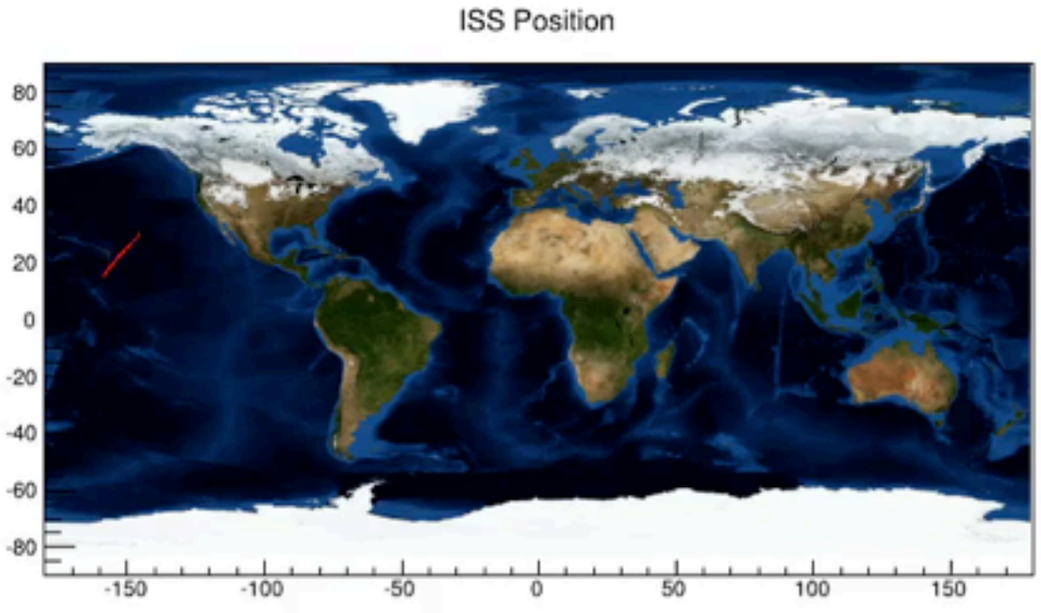
500 um unit

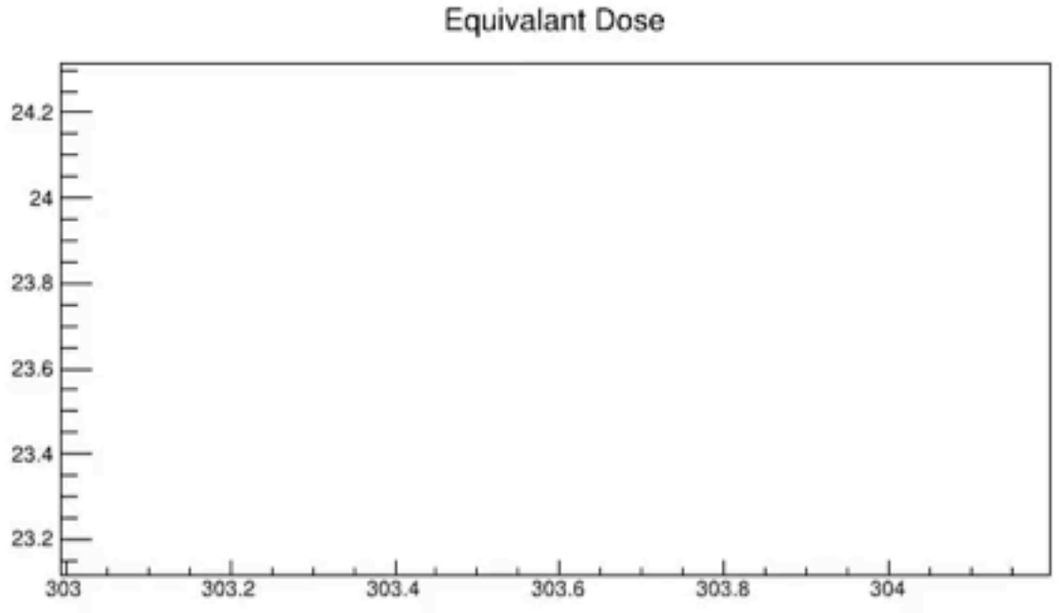


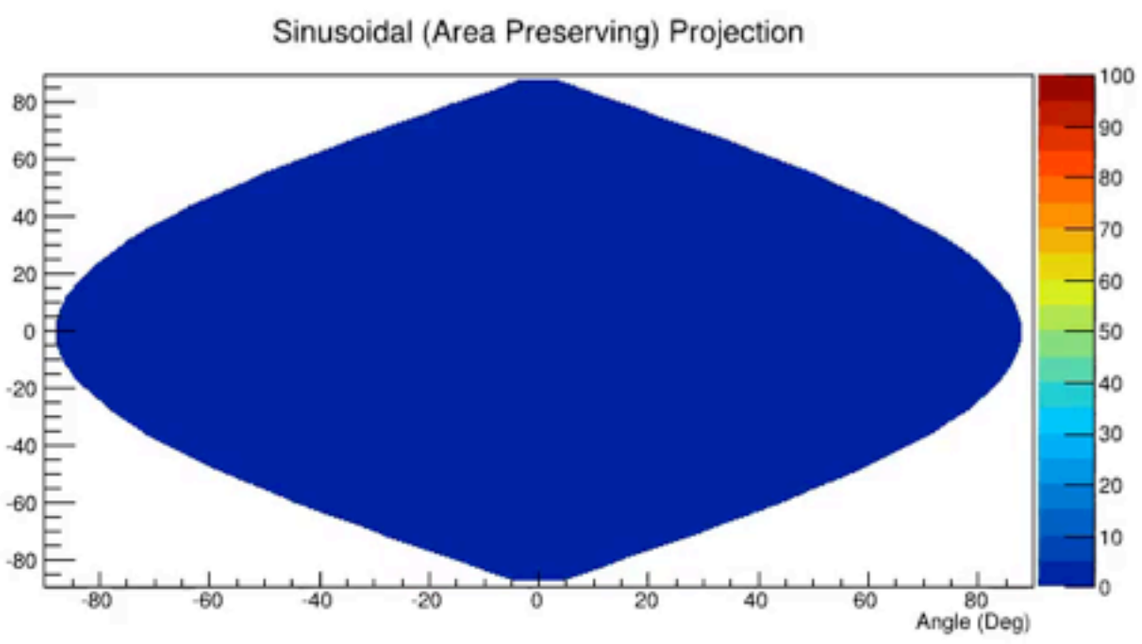


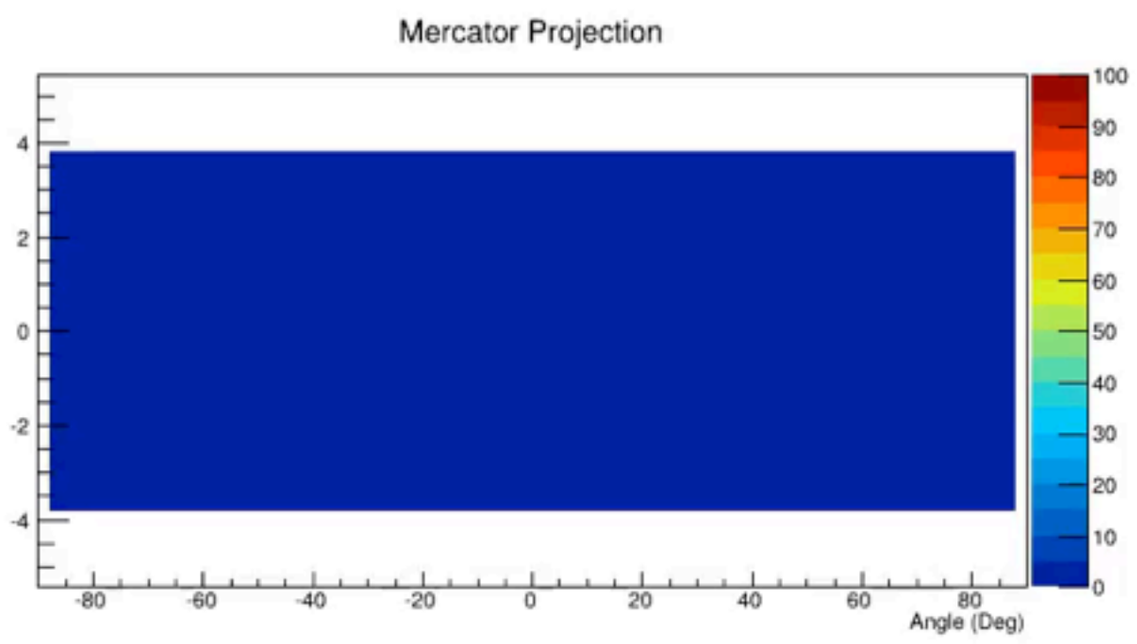




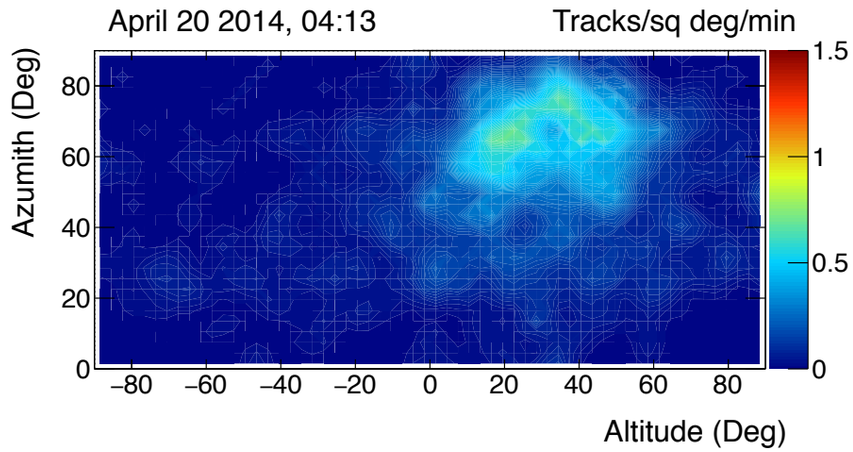


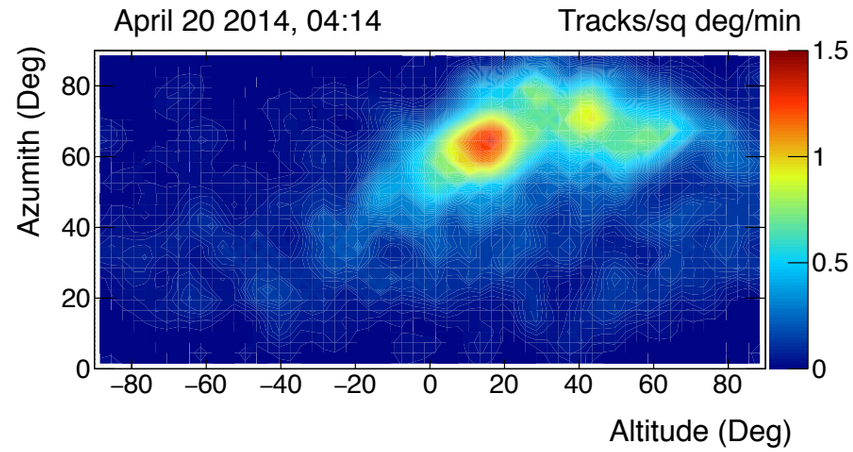


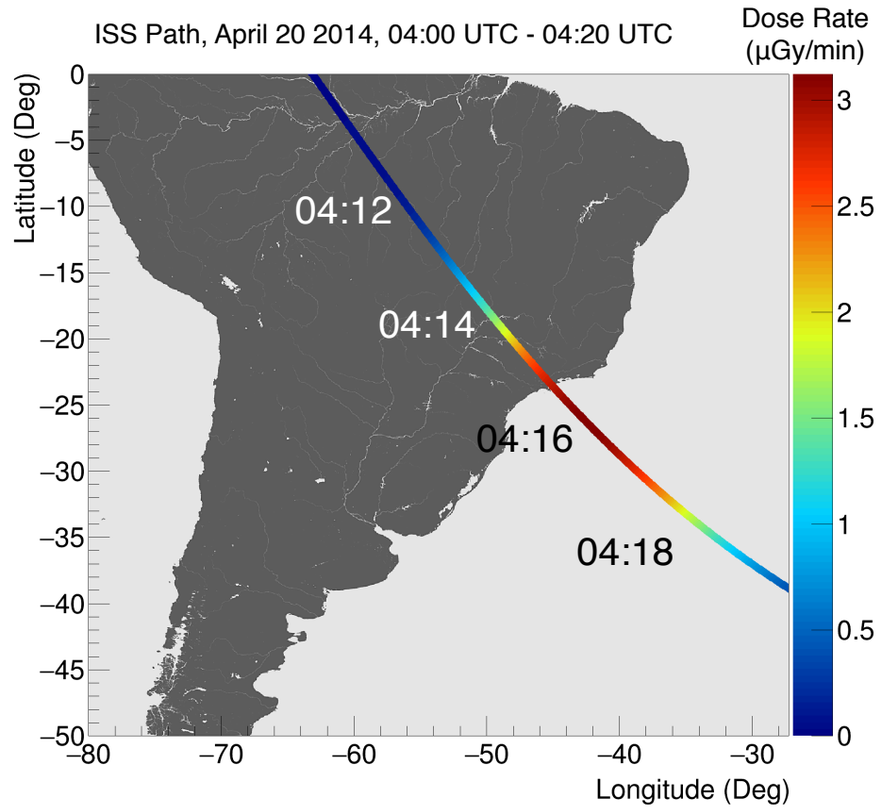


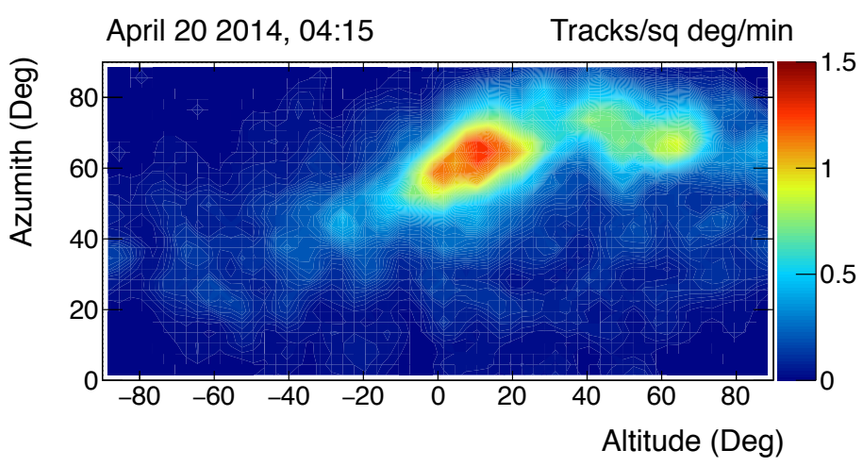


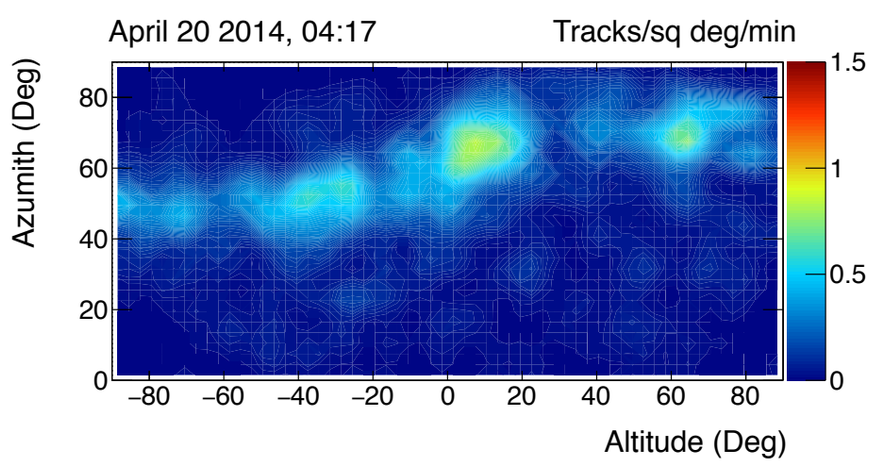
https://dl.dropboxusercontent.com/u/46291346/SAA_20_4_2013.mp4


April 20 2014, 04:13
Tracks/sq deg/min
Azumith (Deg)
Altitude (Deg)


April 20 2014, 04:14
Tracks/sq deg/min
Azumith (Deg)
Altitude (Deg)


ISS Path, April 20 2014, 04:00 UTC - 04:20 UTC
Dose Rate (μGy/min)
04:12
04:14
04:16
04:18
Latitude (Deg)
Longitude (Deg)


April 20 2014, 04:15
Tracks/sq deg/min
Azumith (Deg)
Altitude (Deg)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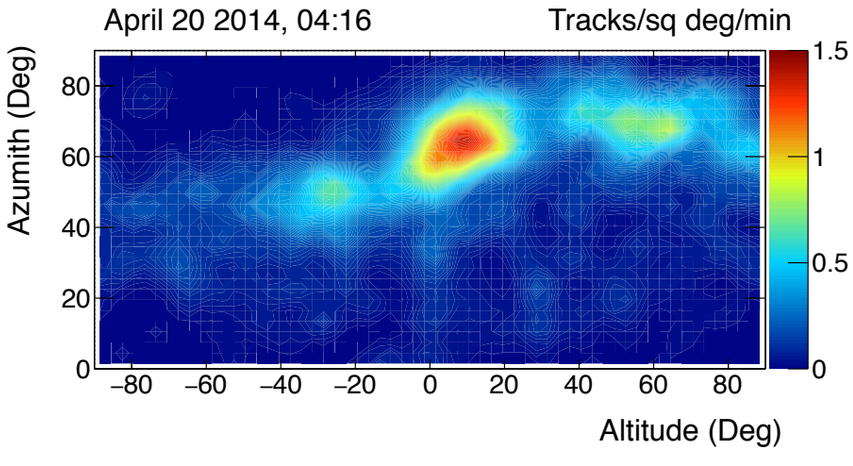
Tracks/sq deg/min
Azumith (Deg)
Altitude (Deg)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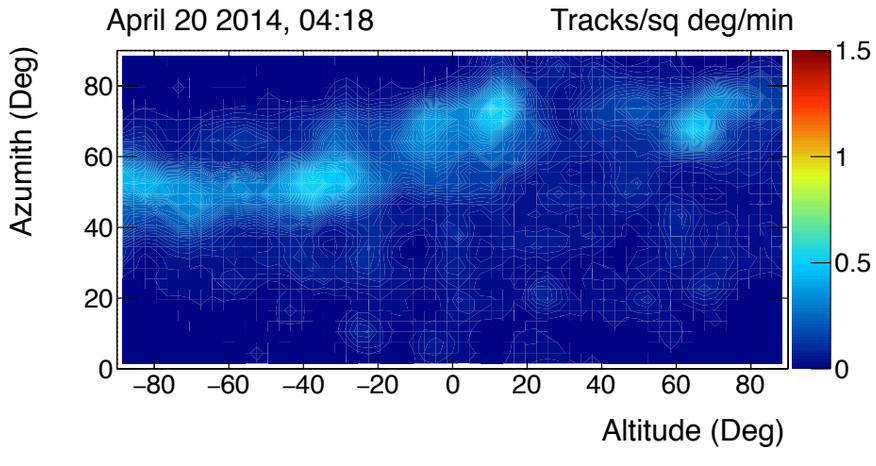
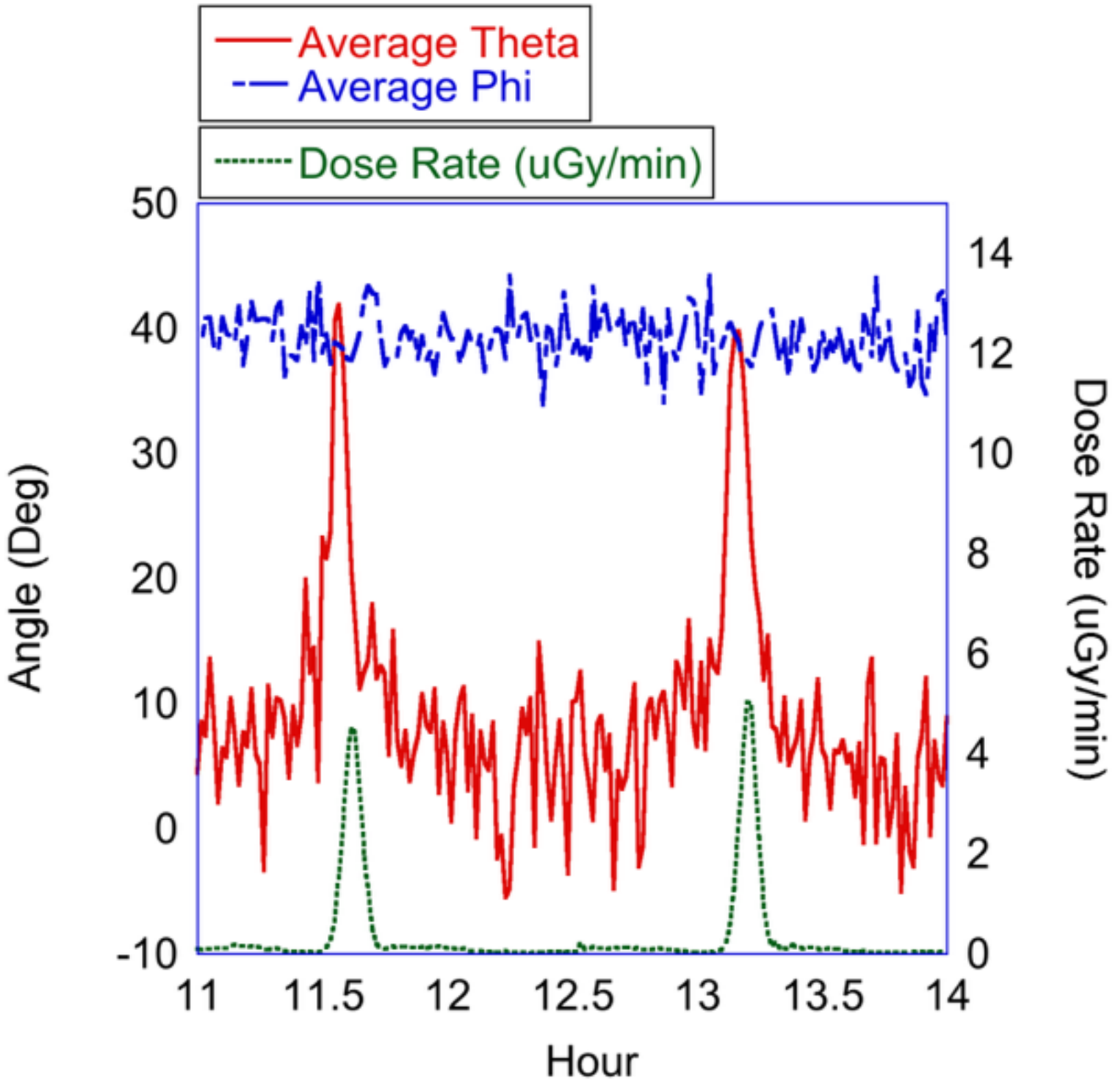
Tracks/sq deg/min
Azumith (Deg)
Altitude (Deg)


April 20 2014, 04:18
Tracks/sq deg/min
Azumith (Deg)
Altitude (Deg)

One Pass, April 1st 2014

- SAA associated with change in average angle
- Average theta for GCR (~5 degrees) - offset
- Average GCR phi 40 degrees) - should be 45

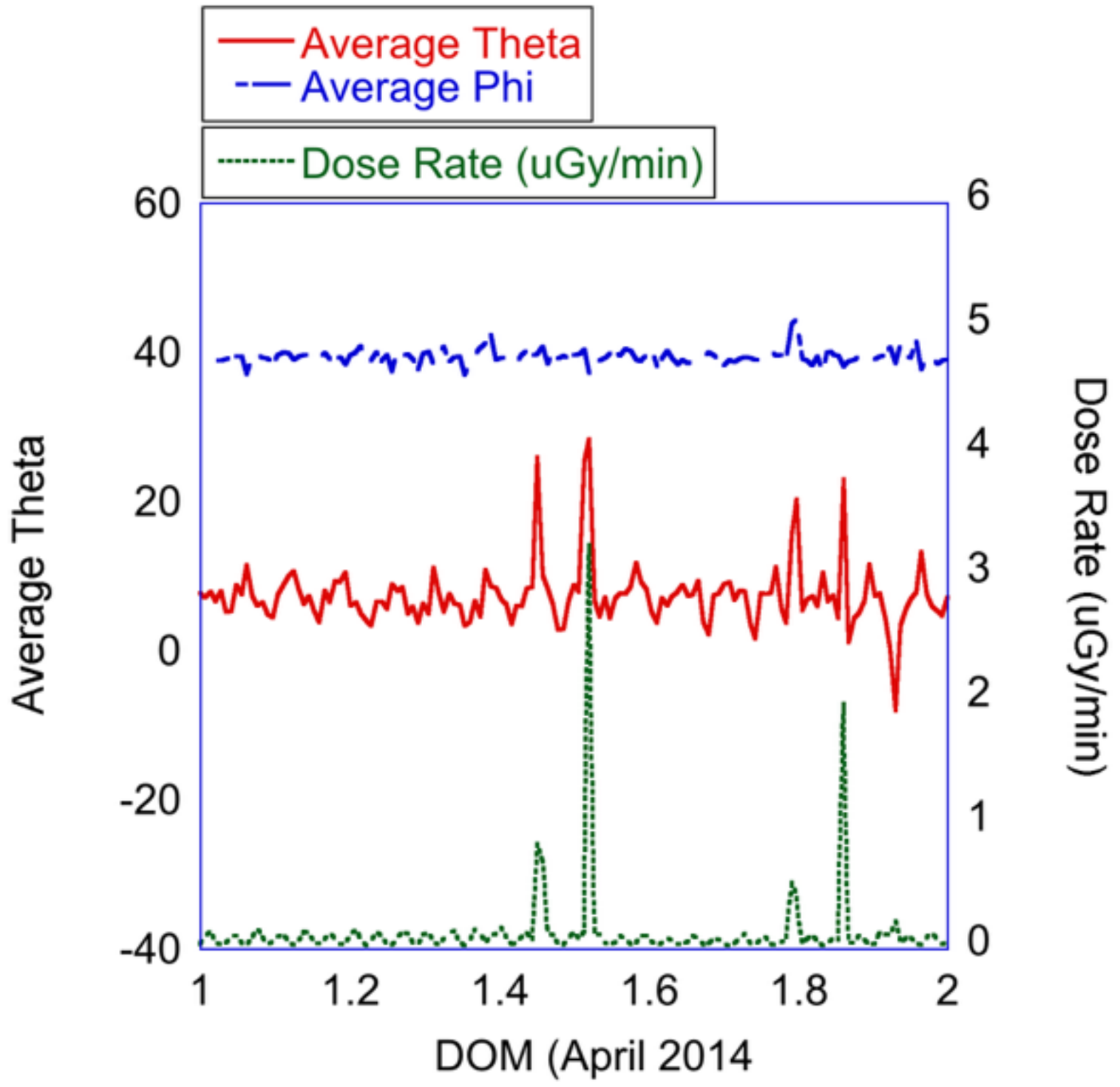


Angle and Dose Rate

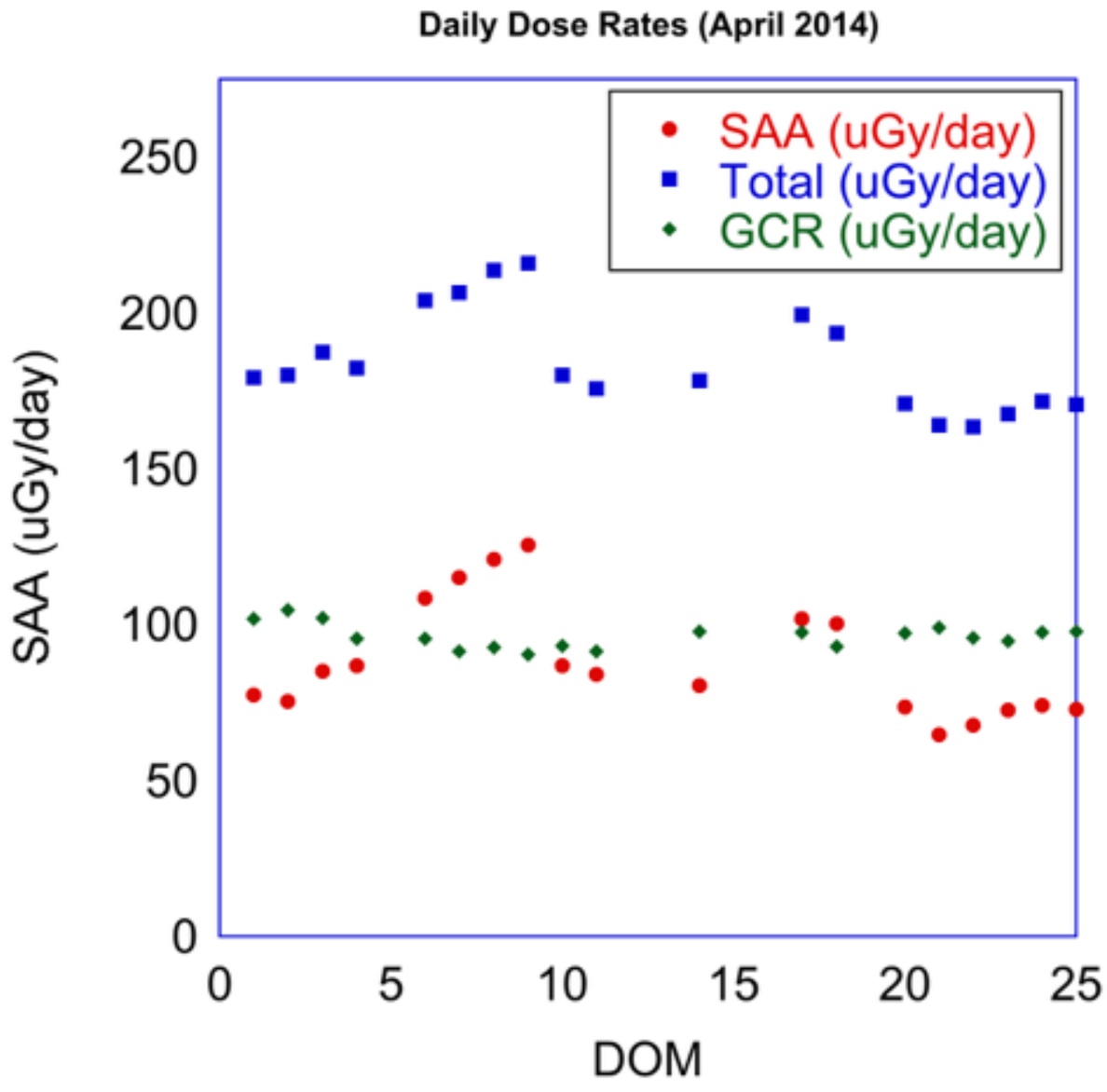
- SAA associated with change in average angle

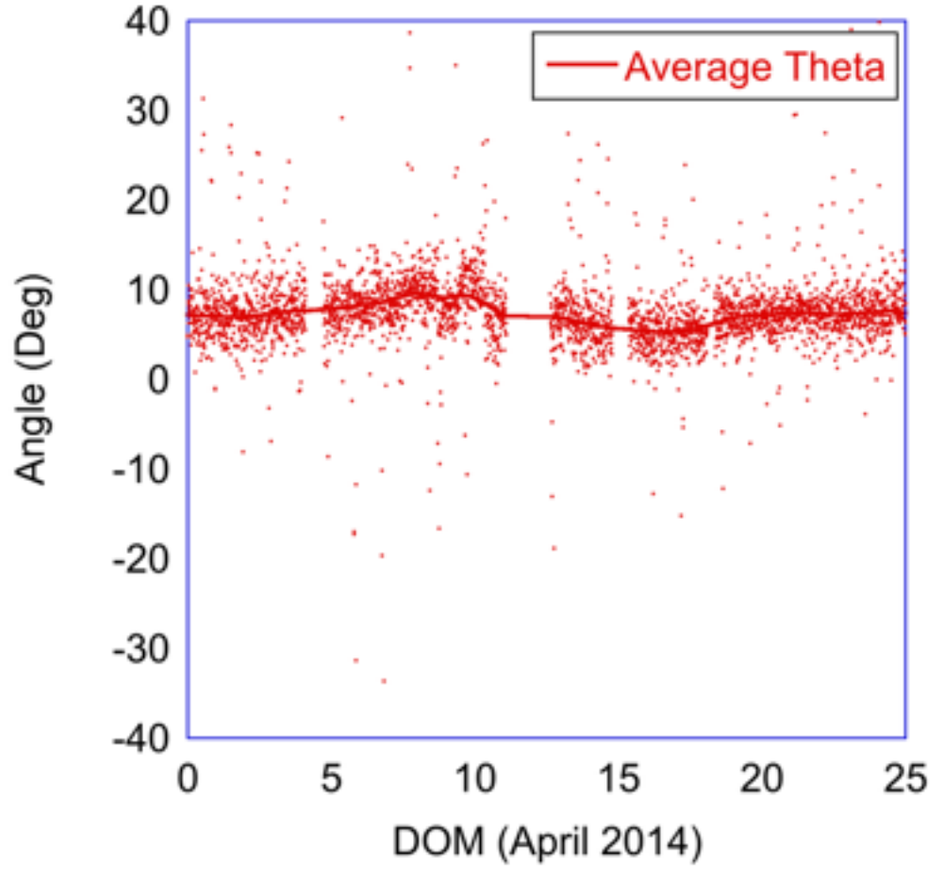
- Average theta for GCR (~5 degrees) - offset

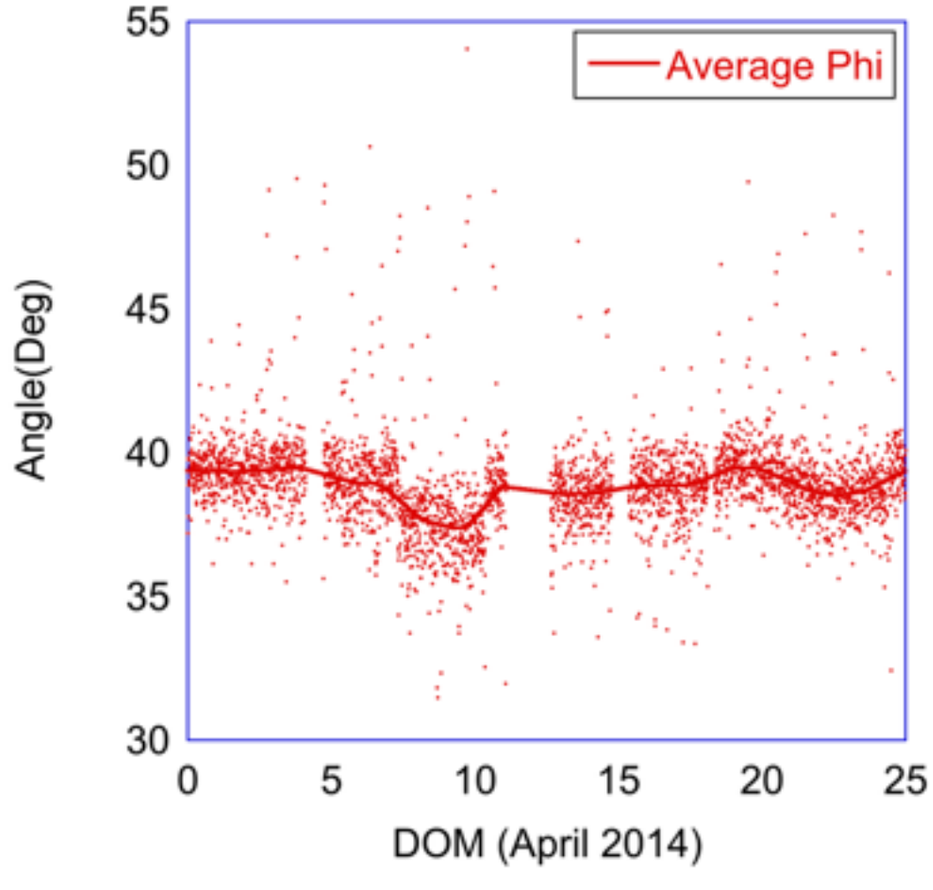
- Average GCR phi 40 degrees) - should be 45



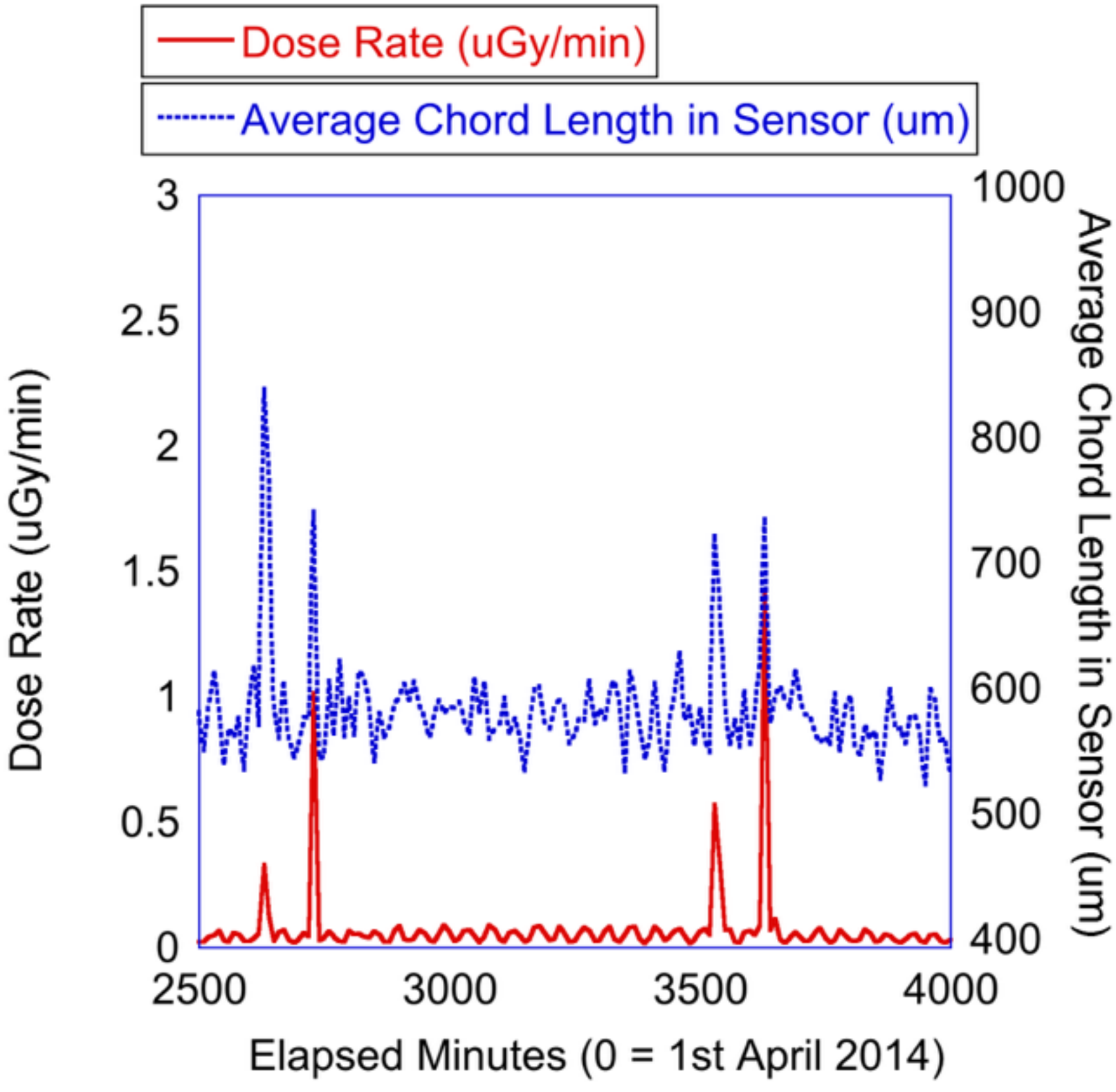
Dose Rate Correlations



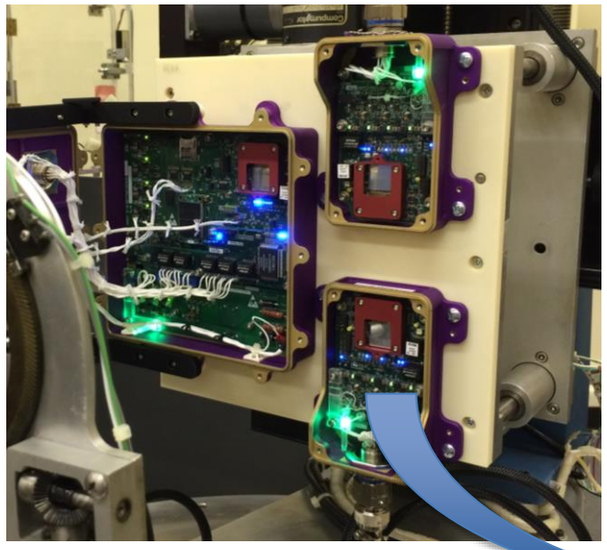


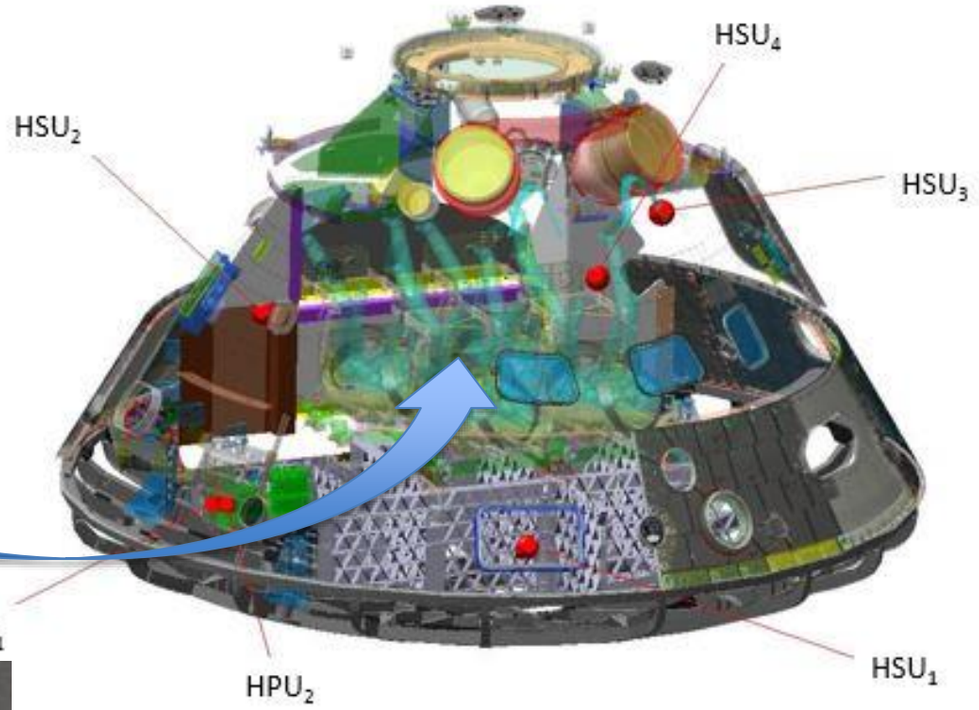


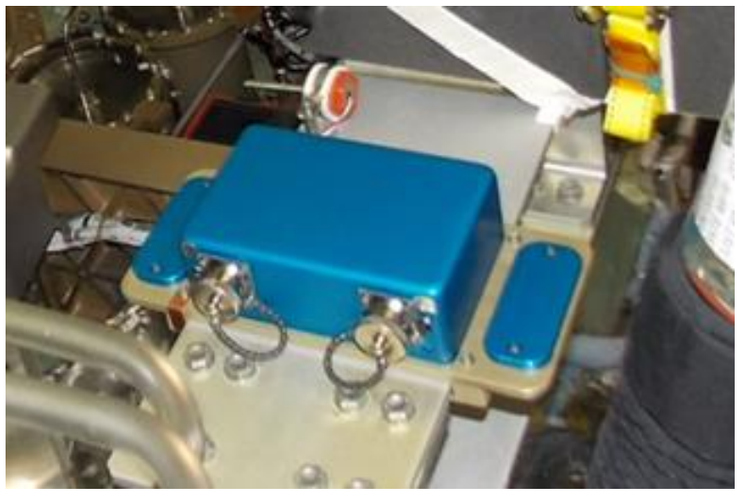
Mean Chord Lengths



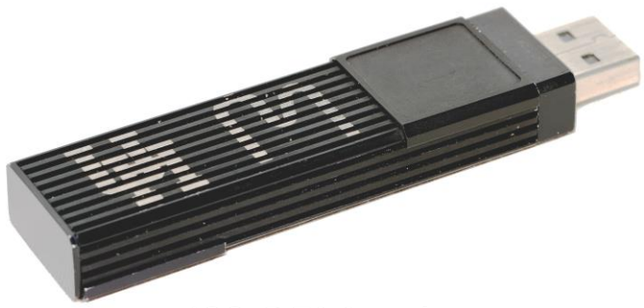
Future Plans - BIRD and HERA







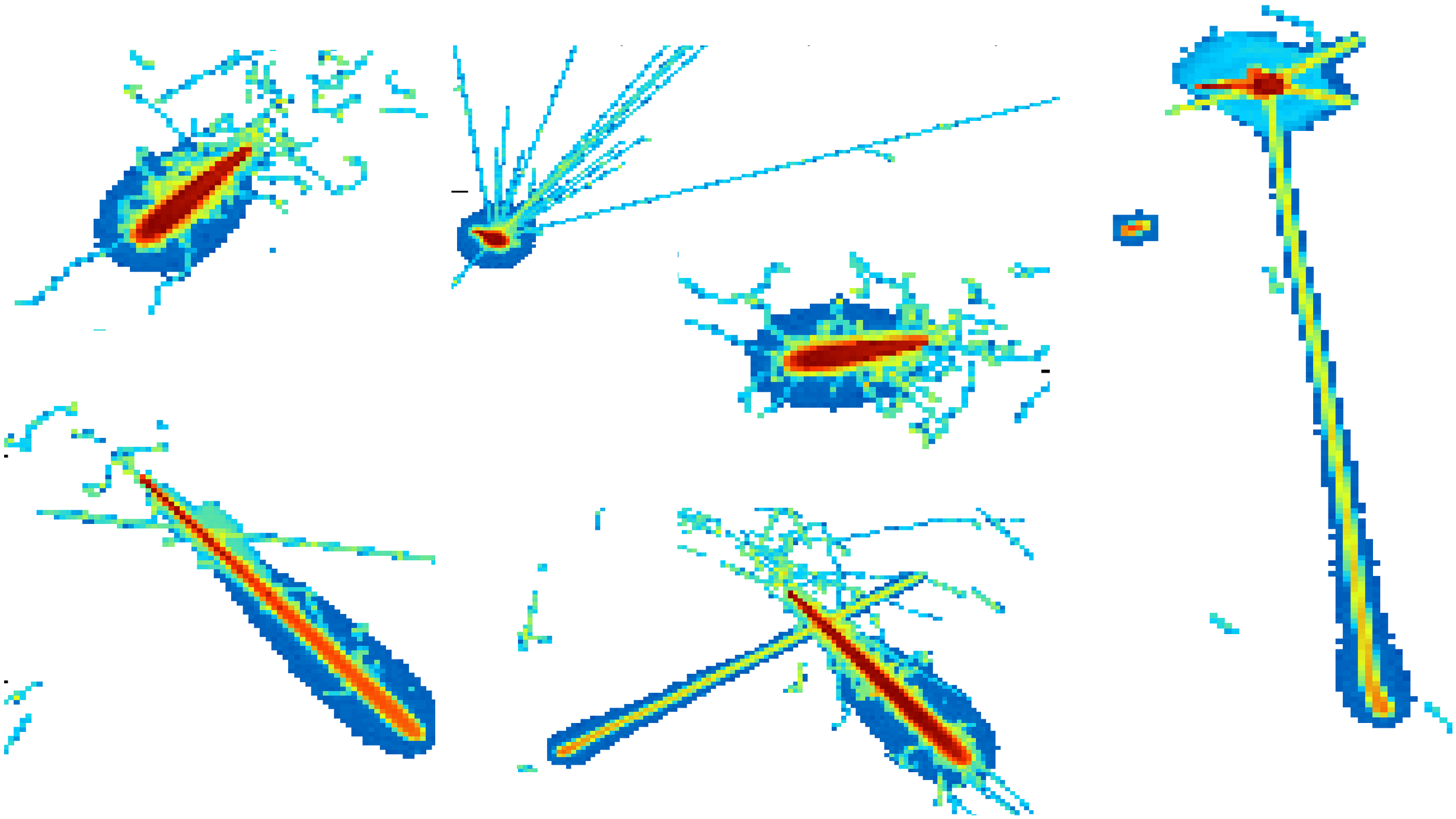
BIRD, as installed in EFT-1



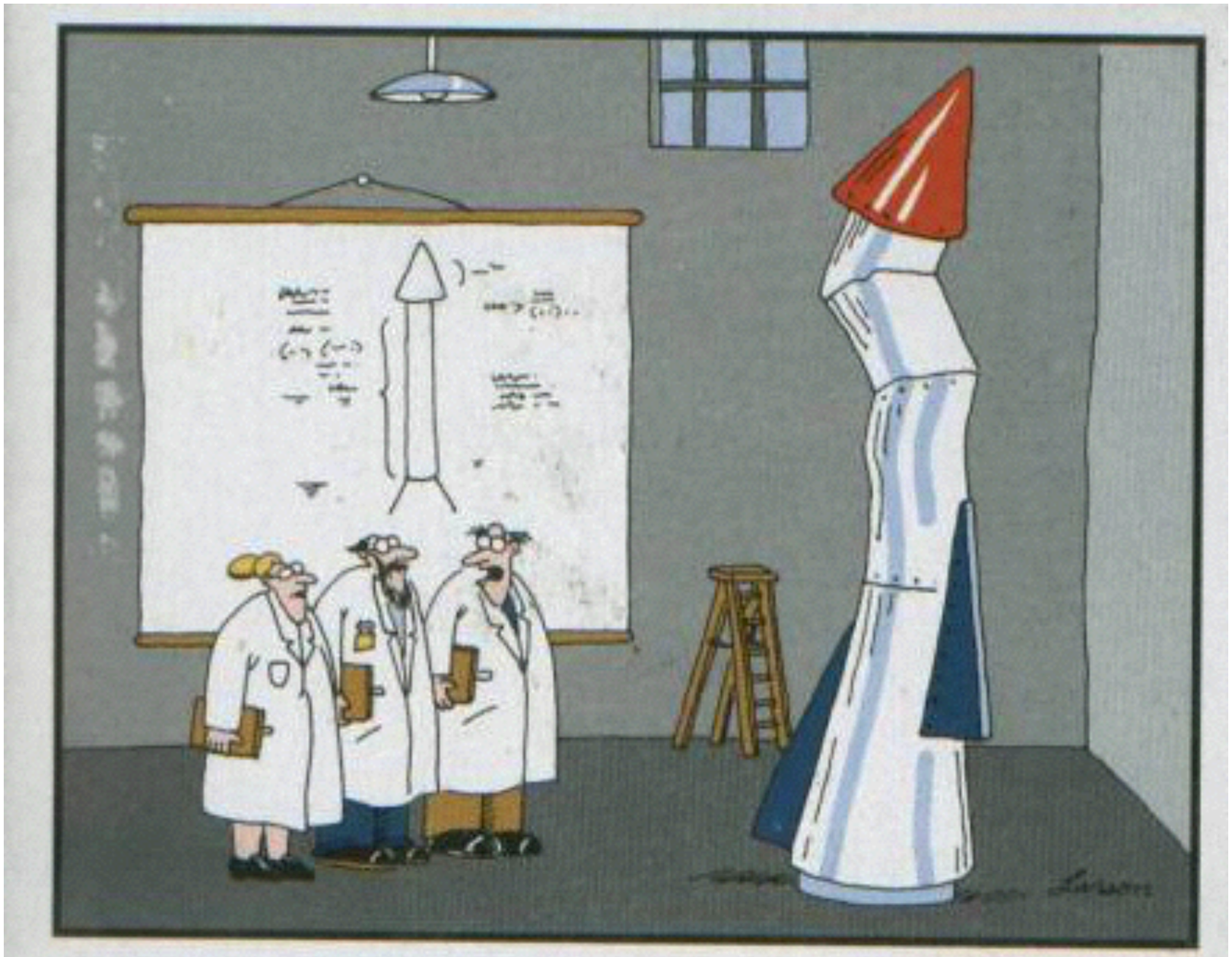
ISS-REM unit

BIRA flew on Orion ETF 1 (Dec 5th 2014)
HERA will fly on EM 1 and EM 2

Space Particle Zoo



Thanks for your attention



"It's time we face reality, my friends. ...
We're not exactly rocket scientists."