Using Geant4 to interpret data from MAVEN's Solar Energetic Particle (SEP) detector

Patrick Dunn, Space Sciences Laboratory, University of California, Berkeley

MAVEN

Mars Atmosphere and Volatile Evolution Mission

- Presented material includes contributions from the entire SEP team:

  Davin Larson, Instrument Lead
  Robert Lillis, Scientist
  Christina Lee, Scientist
  Ali Rahmati, Scientist
  All located at Space Sciences Lab, University of California, Berkeley

1. Mars Atmosphere and Volatile EvolutioN (MAVEN) Mission

2. Solar Energetic Particle (SEP) Instrument

3. Geant4 Simulations for SEP

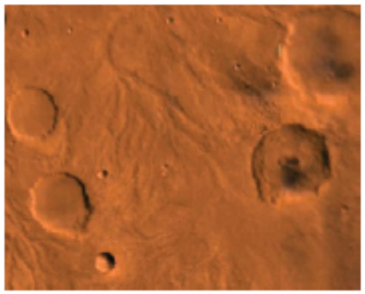
Mars Atmosphere and Volatile EvolutioN

Three major science objectives:

1) determine the ***current state of the upper atmosphere*** and the processes that control it
2) measure the ***current escape rate*** of gases and to space and determine how the escape rate depends on the controlling processes
3) extrapolate to the ***total atmospheric loss to space over Mars' history***

MAVEN

CU/LASP • GSFC • UCB/SSL • LM • JPL

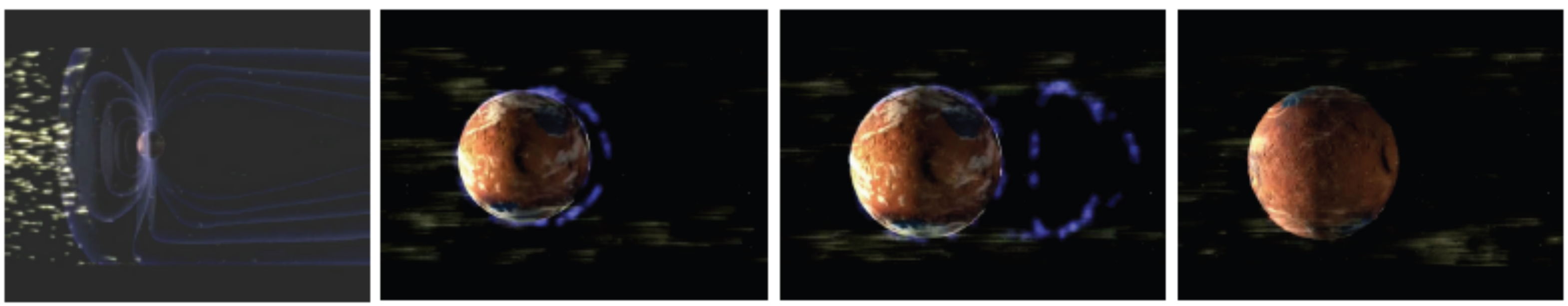


Ancient Valleys

Mars' atmosphere is cold and dry today, but there was once liquid water flowing over the surface.

Where did the water and early atmosphere go?

- *H_2O and CO_2 can go into the crust or be lost to space.*
- *MAVEN will focus on volatile loss to space.*



Turn-off of the Martian magnetic field allowed turn-on of solar-wind stripping of the atmosphere ~ 3.7 billion years ago; combined with solar-EUV-driven loss, resulted in the present thin, cold atmosphere.

MAVEN
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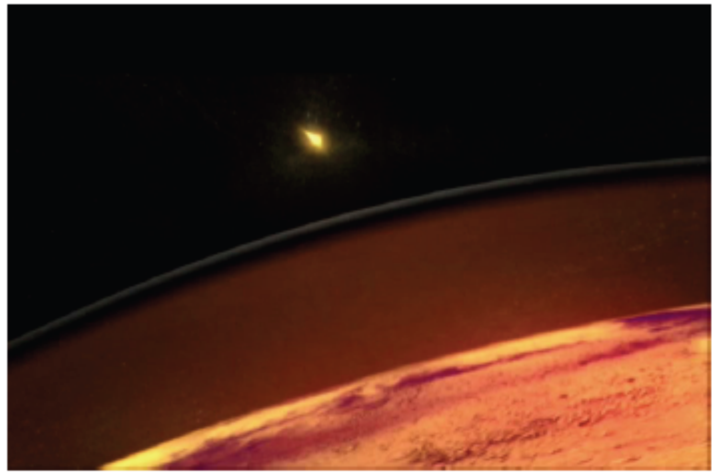
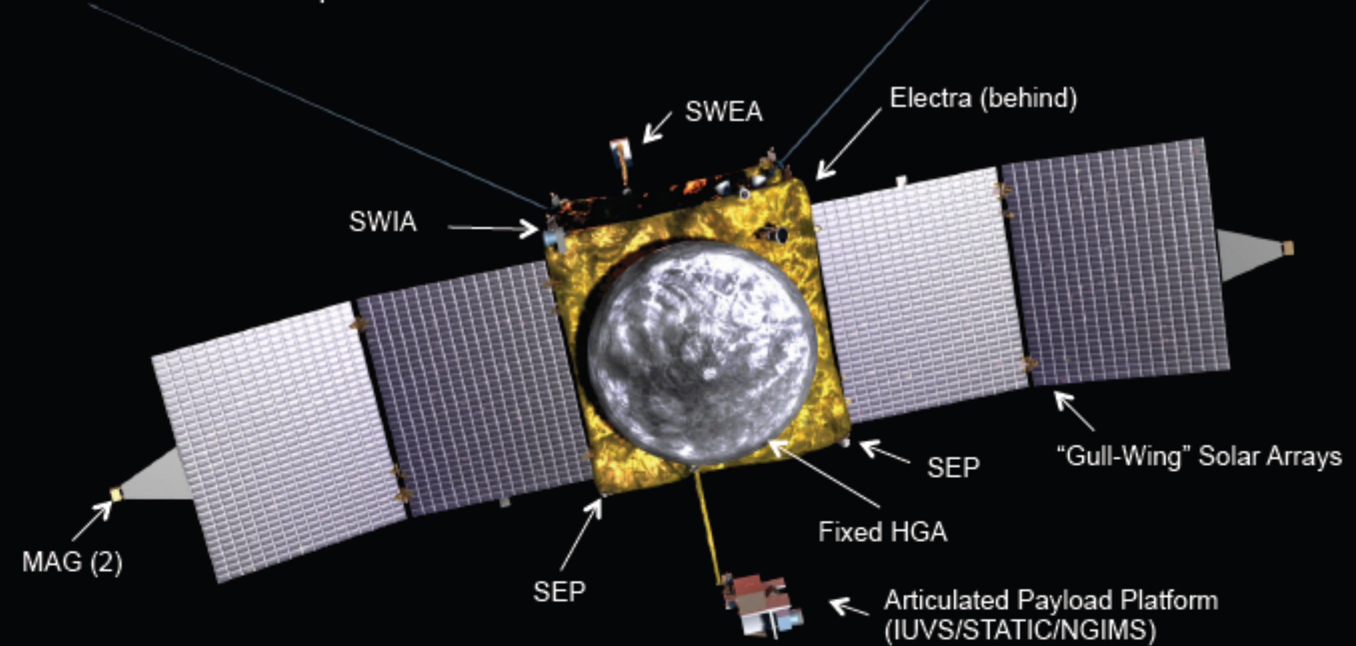


- Determine the structure and composition of the Martian upper atmosphere today
- Determine rates of loss of gas to space today
- Measure properties and processes that will allow us to determine the integrated loss to space through time

MAVEN will answer questions about the history of Martian volatiles and atmosphere and help us to understand the nature of planetary habitability.

The MAVEN Spacecraft

- 3-axis attitude control (wheel based)
- Mono-propellant propulsion system
- Single-fault tolerant during all critical events
- Launch (Wet) Mass: 2550 kg max
- Observatory Dry Mass: 903 kg max
- Power: 1135 W at Mars Aphelion

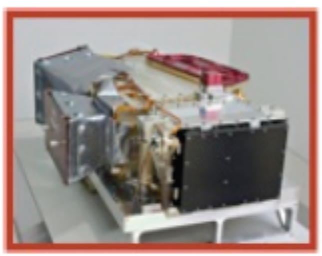


The MAVEN Science Instruments

Mass Spectrometry Instrument

Neutral Gas and Ion Mass Spectrometer; Paul Mahaffy, GSFC

Remote-Sensing Package



Imaging Ultraviolet Spectrometer; Nick Schneider, LASP

Particles and Fields Package

Solar Energetic Particles; Davin Larson, SSL

SupraThermal and Thermal Ion Composition; Jim McFadden, SSL

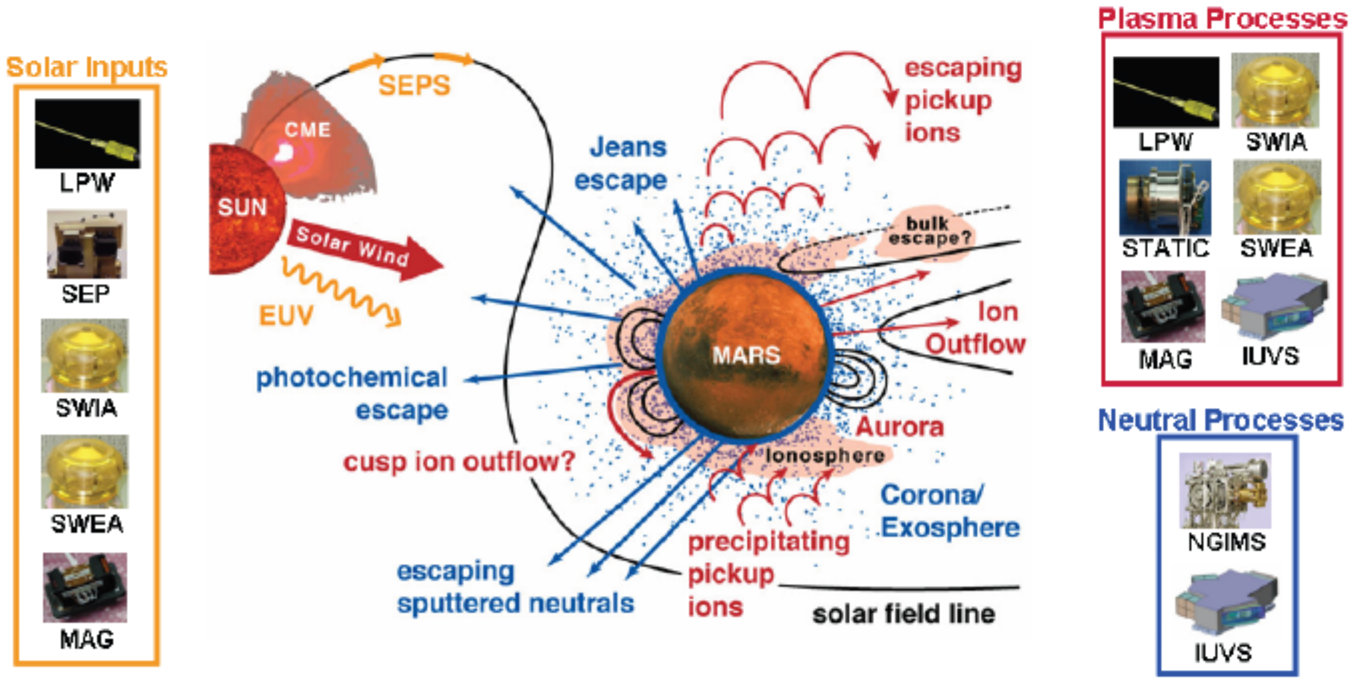
Solar Wind Electron Analyzer; David Mitchell, SSL

Solar Wind Ion Analyzer; Jasper Halekas, SSL

Langmuir Probe and Waves; Bob Ergun, LASP

Magnetometer; Jack Connerney, GSFC

MAVEN IS MEASURING THE DRIVERS, RESERVOIRS, AND ESCAPE RATES

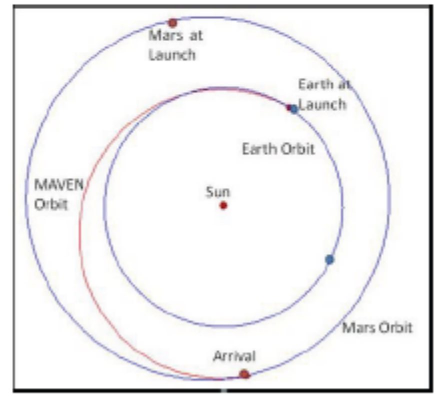


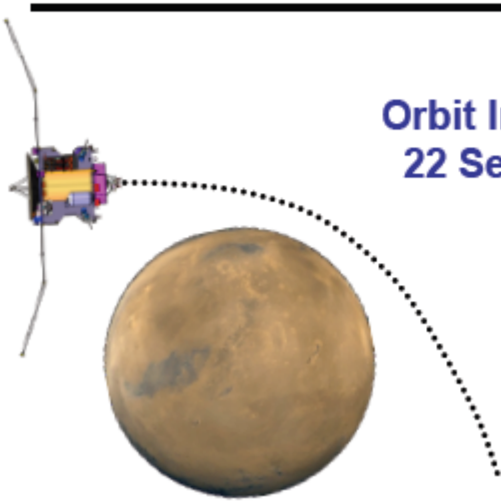
- MAVEN will determine the present state of the upper atmosphere and today's rates of loss to space.
- Measurements will allow determination of the net integrated loss to space through time.

MAVEN Mission Architecture

20-Day Launch Period: November 18 – December 7, 2013

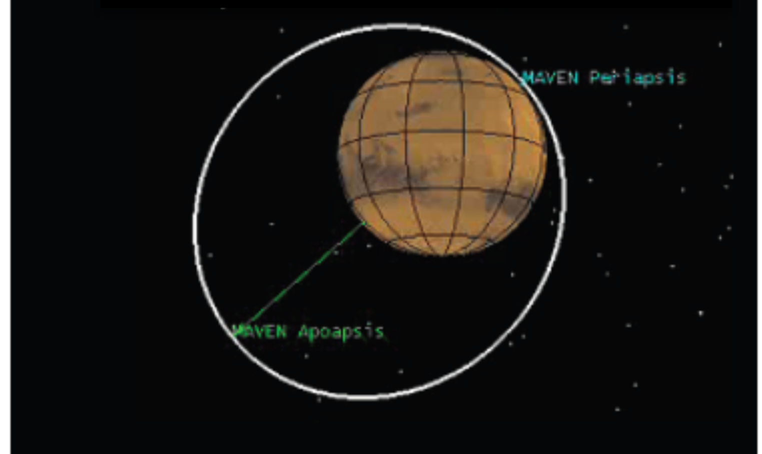
Ten Month Ballistic Cruise to Mars





Orbit Insertion: 22 Sept 2014

Just completed 4th Earth year since MOI



Solar Energetic Particle (SEP) Instrument

Measurements will help address important SEP-related questions

1) How & to what degree is the Mars atmosphere shielded
   - by the planetary-scale magnetosphere?
   - by the crustal magnetic fields?

2) What are the ways in which incident SEPs of various energies affect the atmosphere?
   - SEP spectrum degradation with altitude?
   - Sputtering by energetic neutrals created via charge exchange?
   - Bulk heating from SEP collisions with neutrals ?
   - SEP impact ionization → dissociative recombination → escape
   - Electronic excitation → auroral emission?
   - Molecular dissociation → effect on atmospheric chemistry?
   - Ionospheric currents?

SEPs in the atmosphere: energy partitioning is complicated and energy dependent

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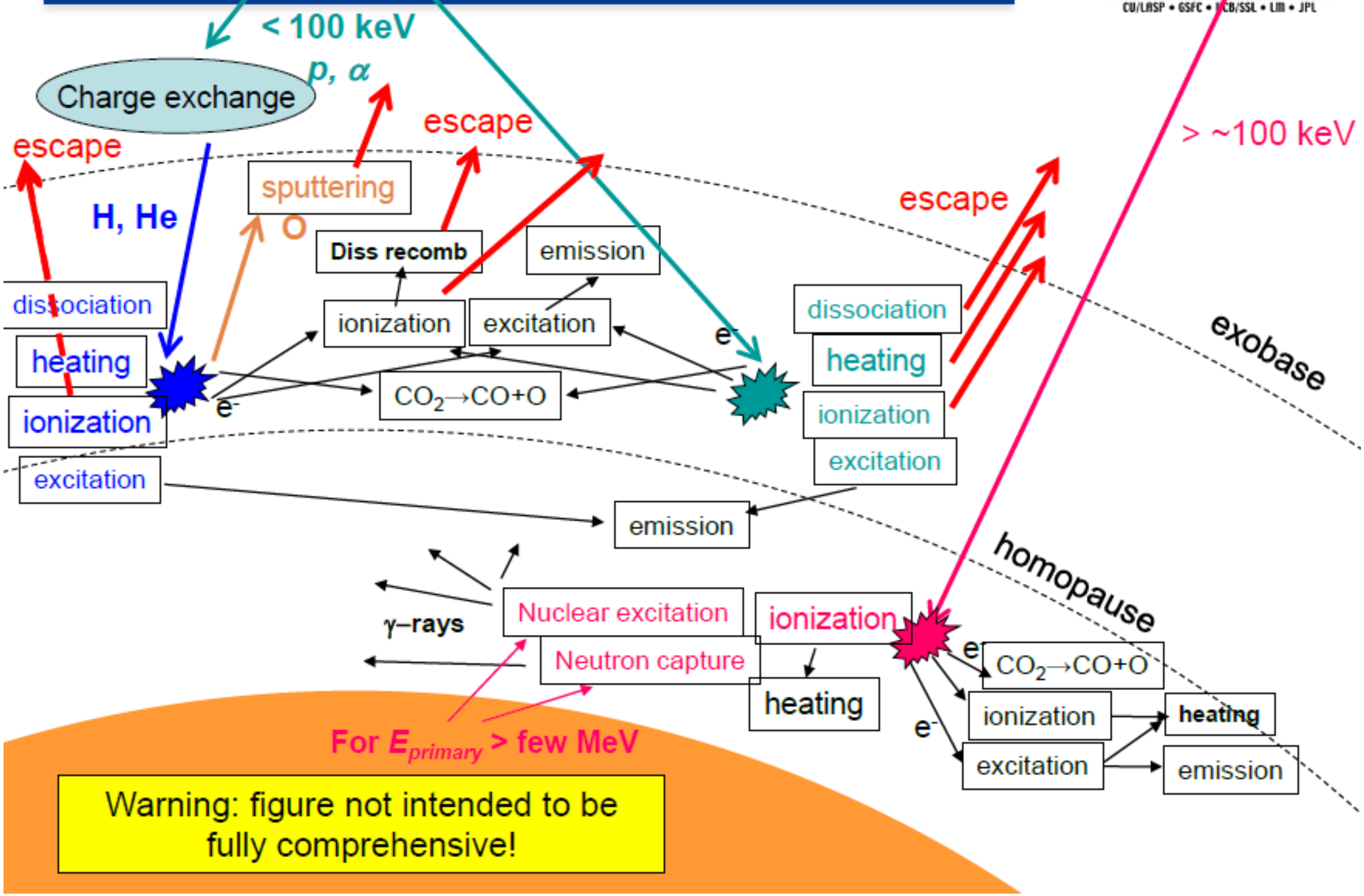
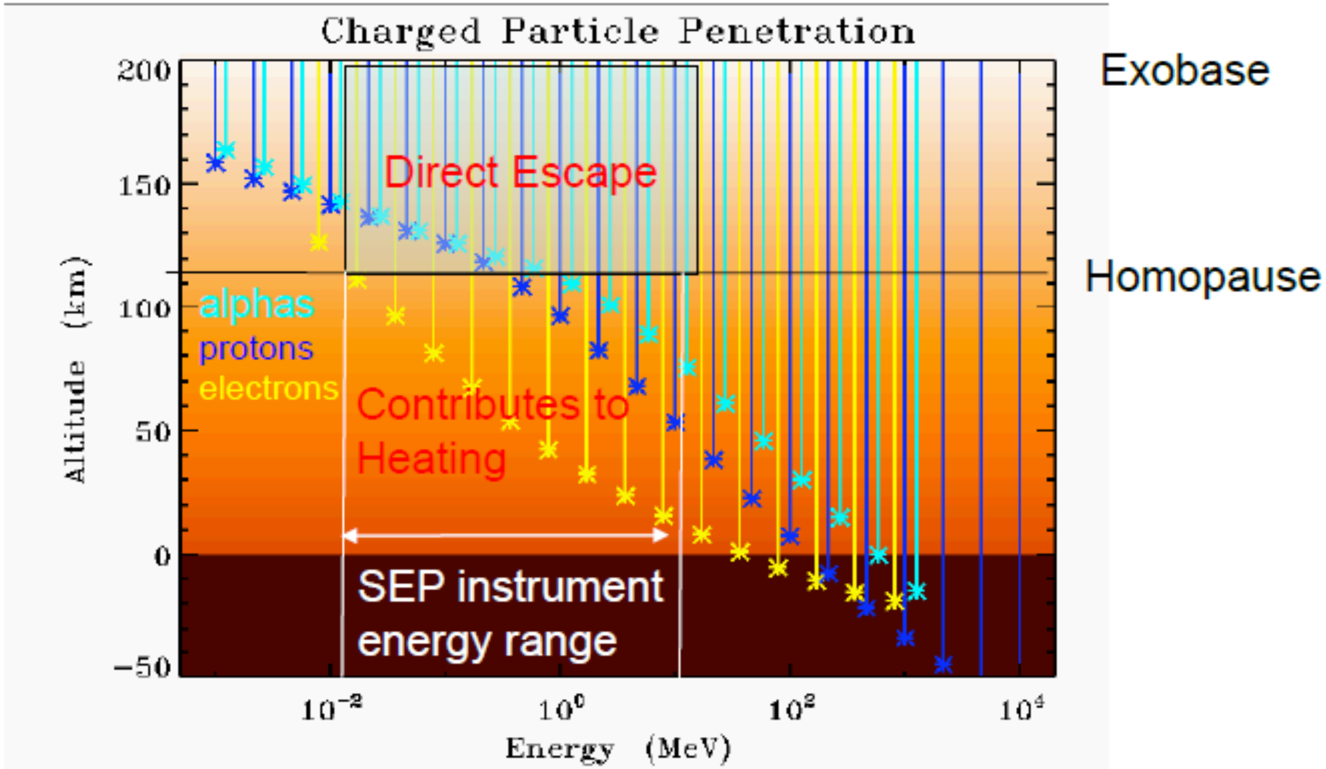


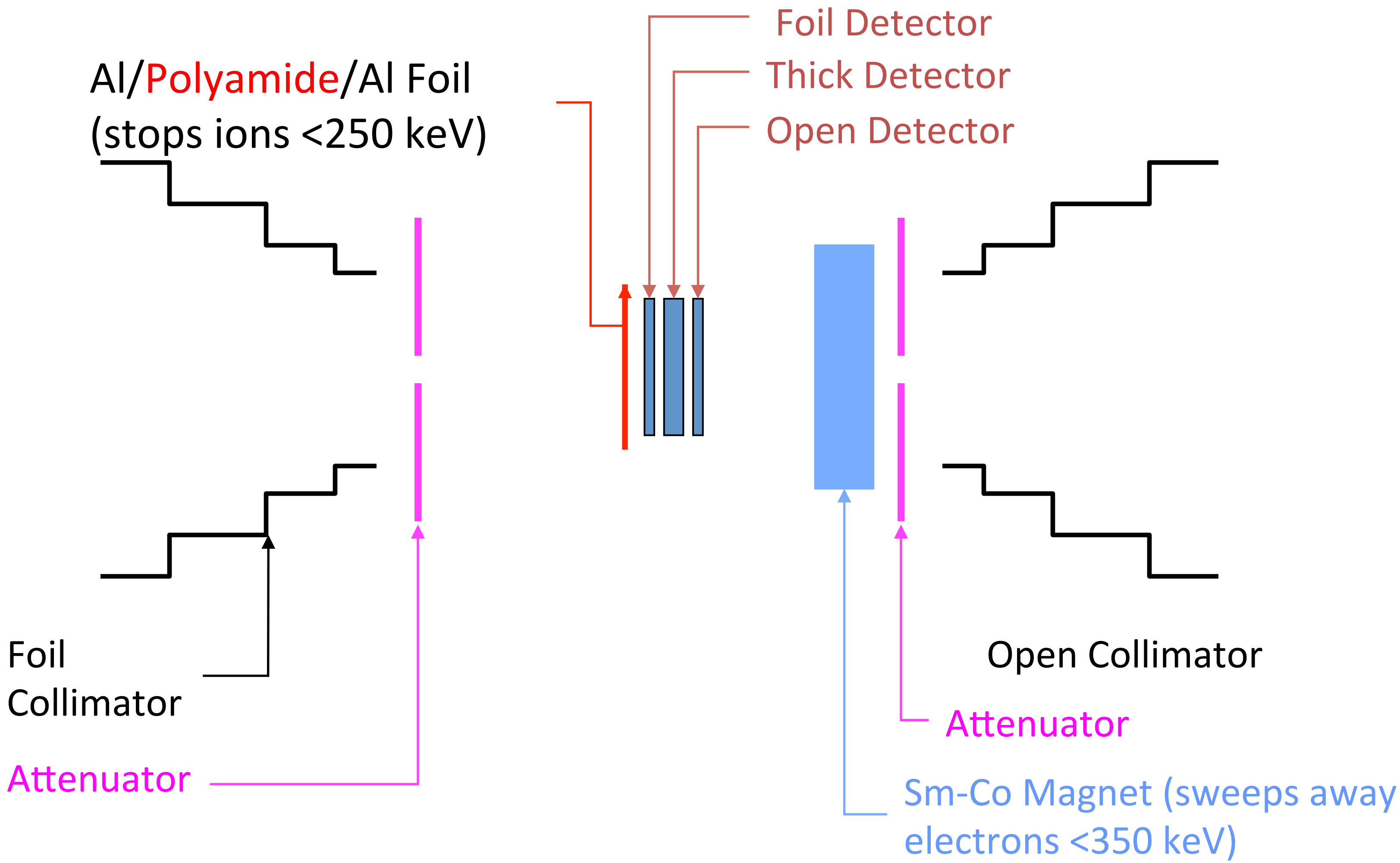
SEP instrument will measure particles that penetrate to altitudes important for escape processes.

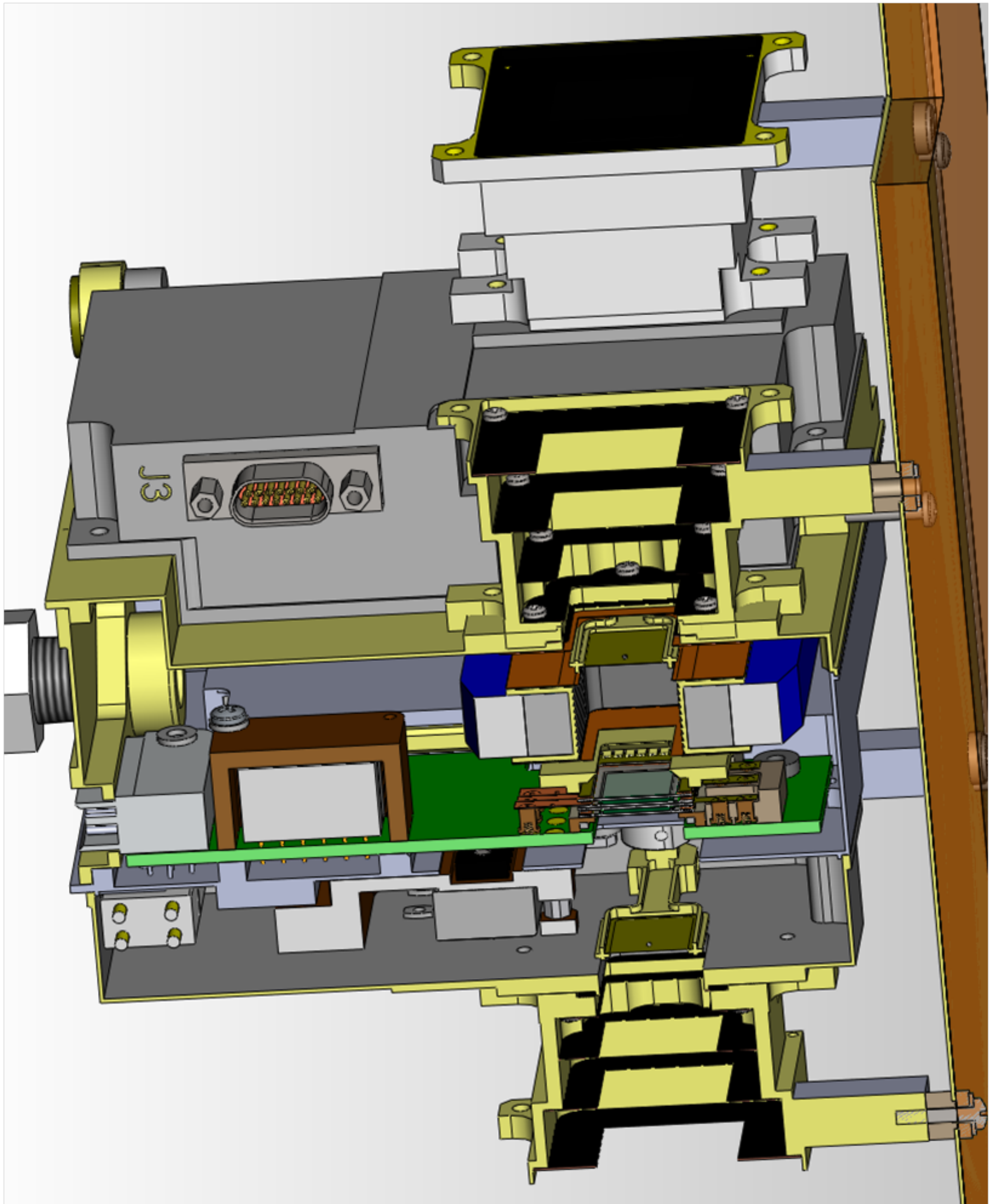


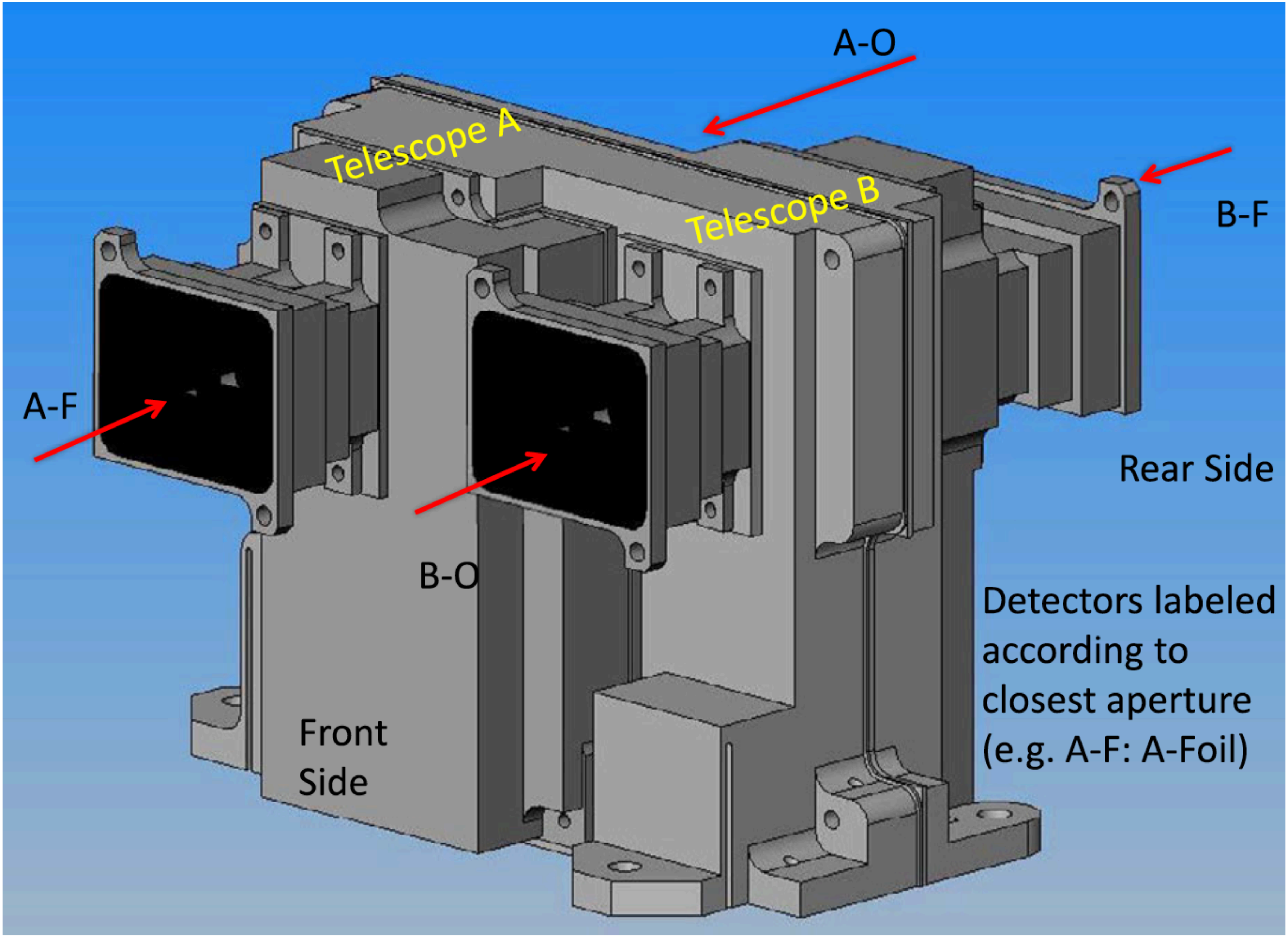
Analytic calculation by D. Brain

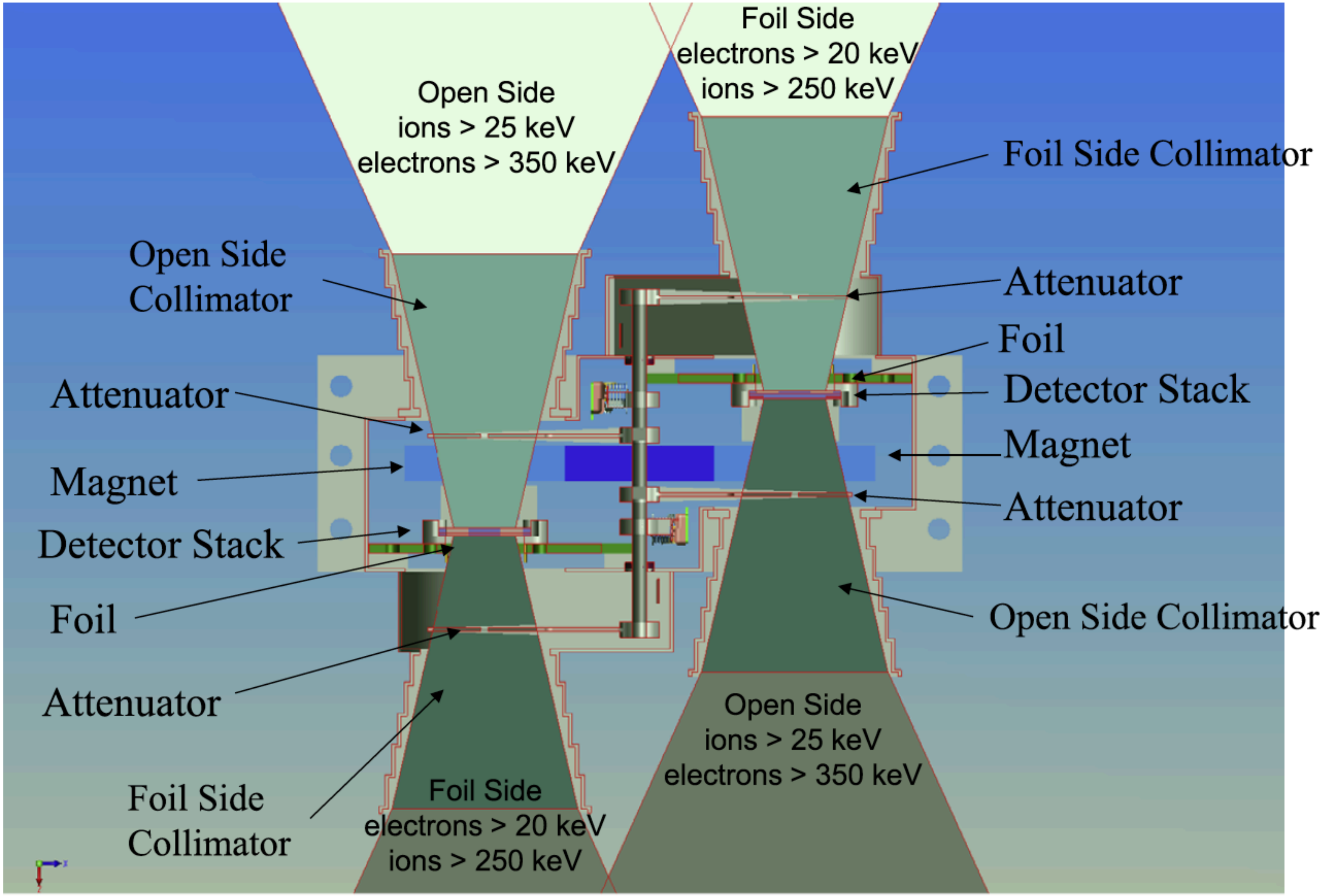
- The bulk of SEP event total energy is generally below 50 keV, deposited mostly between 100 km and 130 km [LeBlanc et al., 2002], though events widely vary.
- We will measure particles that penetrate to 50 km-150 km, providing important constraints on modeling of atmosphere/ionosphere dynamics.

Basic design of SEP instrument




J3


A-O
Telescope A
Telescope B
B-F
A-F
B-O
Rear Side
Front
Side
Detectors labeled
according to
closest aperture
(e.g. A-F: A-Foil)


Foil Side
electrons > 20 keV
ions > 250 keV
Open Side
ions > 25 keV
electrons > 350 keV
Foil Side Collimator
Open Side
Collimator
Attenuator
Foil
Detector Stack
Magnet
Attenuator
Magnet
Detector Stack
Foil
Open Side Collimator
Attenuator
Open Side
ions > 25 keV
electrons > 350 keV
Foil Side
Collimator
Foil Side
electrons > 20 keV
ions > 250 keV

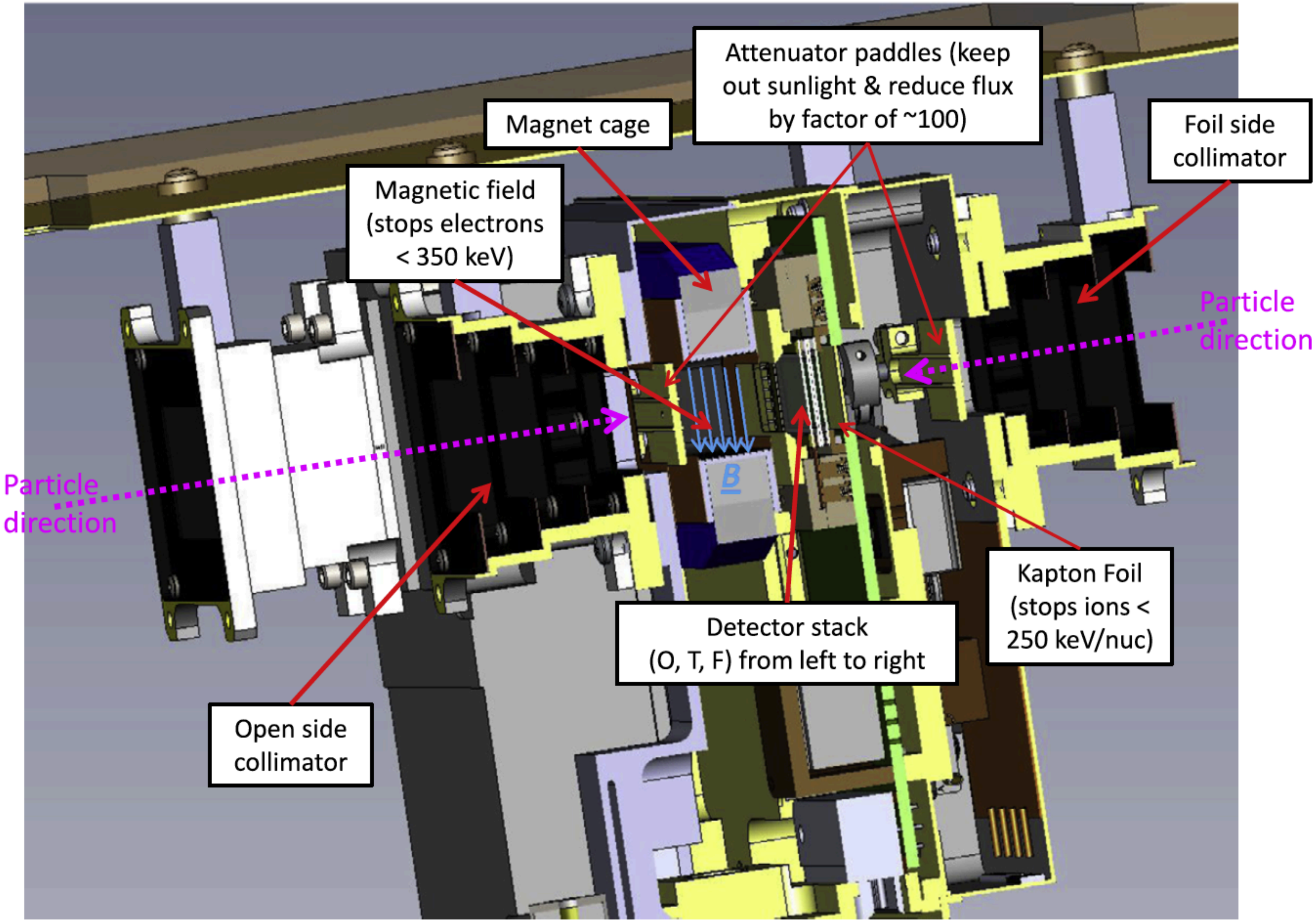
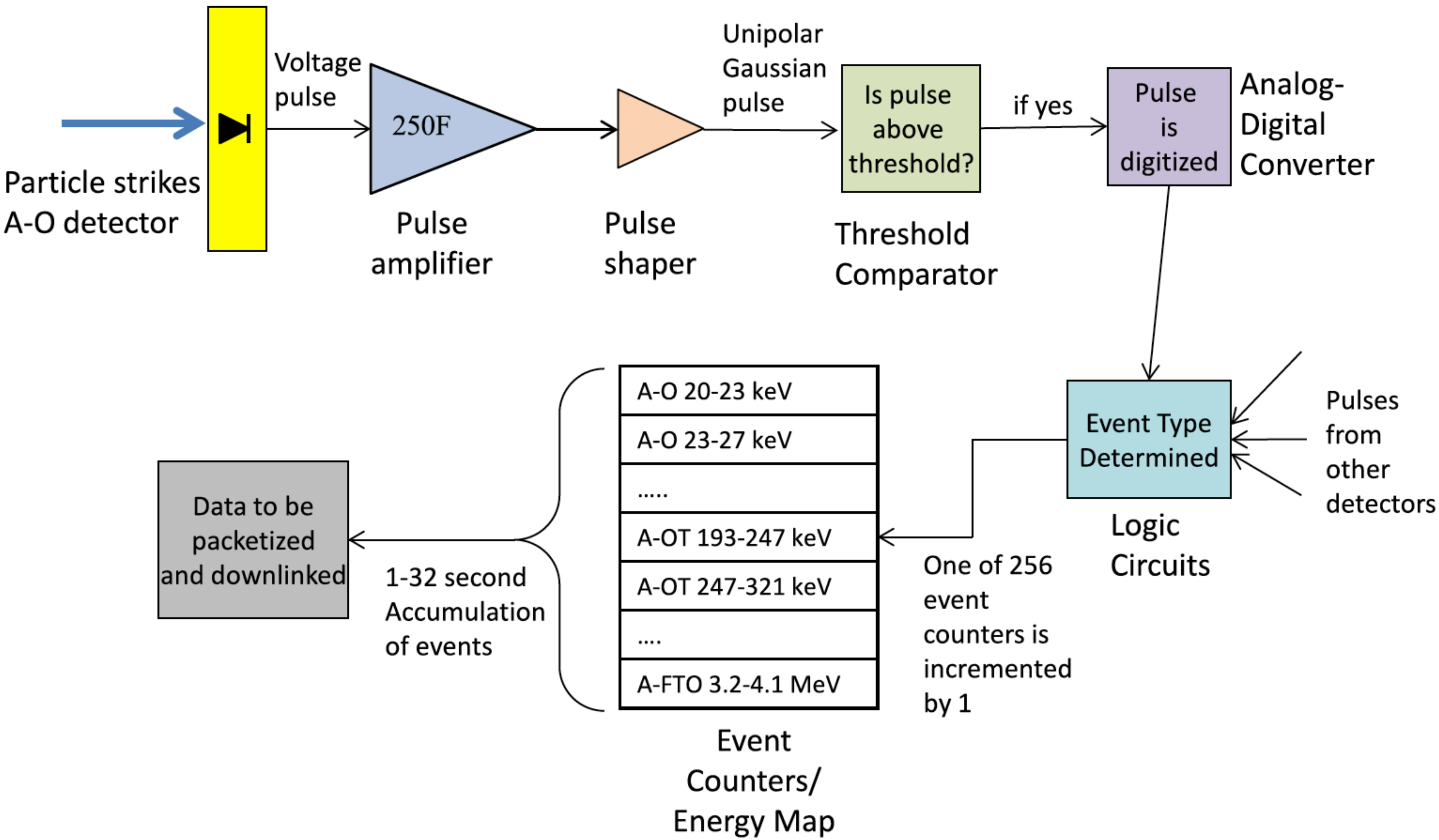

Attenuator paddles (keep out sunlight & reduce flux by factor of ~100)
Magnet cage
Foil side collimator
Magnetic field (stops electrons < 350 keV)
Particle direction
B
Particle direction
Kapton Foil (stops ions < 250 keV/nuc)
Detector stack (O, T, F) from left to right
Open side collimator

Table 1 Comparison of the SEP Level 1 requirements versus the instrument performance

Requirement (ions only)	MAVEN Level 1 requirement	SEP instrument performance
Energy range	50 keV to 5 MeV	20 keV to 6 MeV
Energy resolution $\Delta E/E$	50 %	$<$ 25 % (better at lowest energy)
Energy flux range	10 to 10^6 eV/[cm^2 s sr eV]	3 to 3×10^6 eV/[cm^2 s sr eV]
Energy flux precision	30 %	$<$ 10 % (based on modelling)
Time cadence	1 hour	1–32 seconds (mode-dependent)

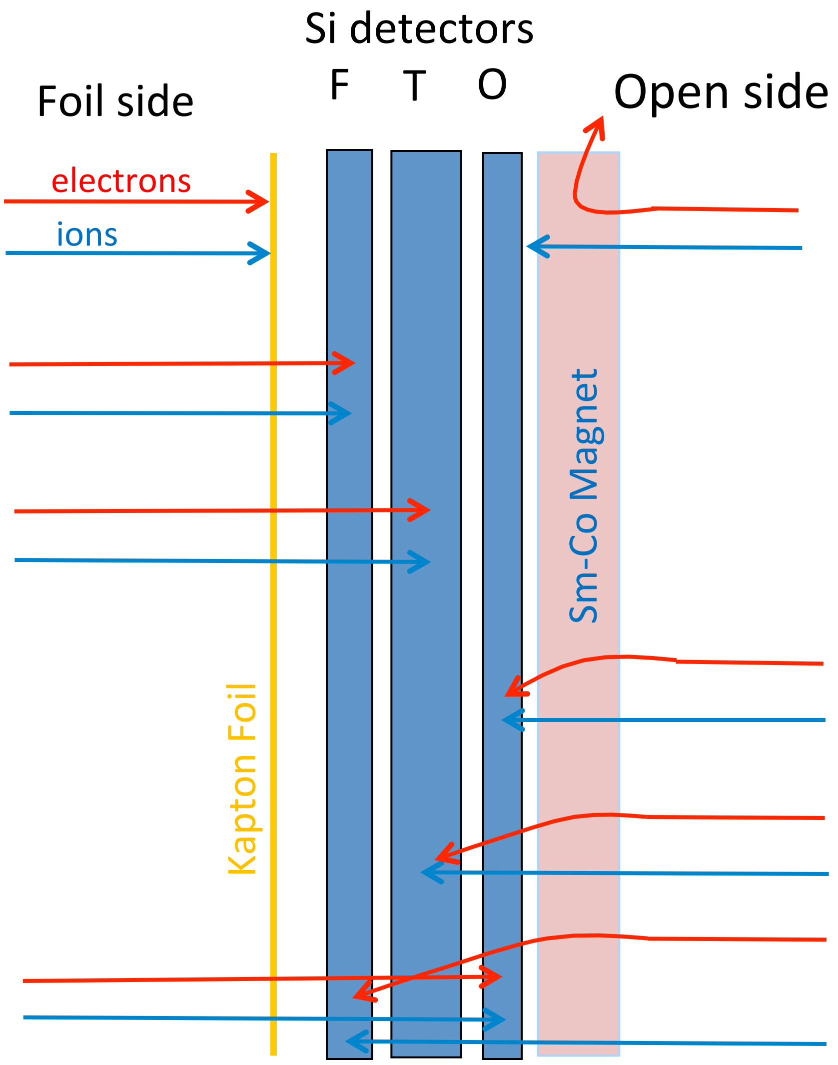
SCHEMATIC DESCRIPTION OF SEP SIGNAL PROCESSING



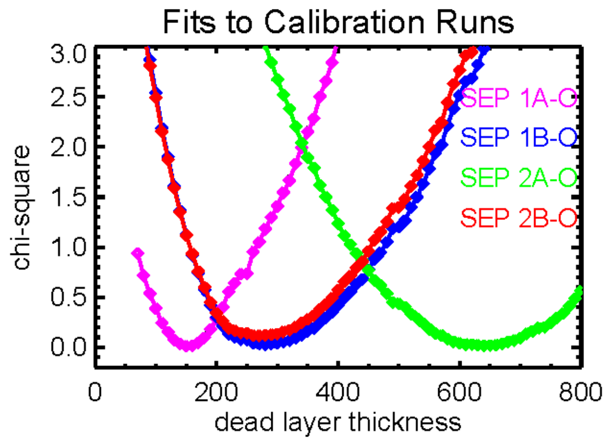
Basic separation strategy: 3 detectors, 2 filters

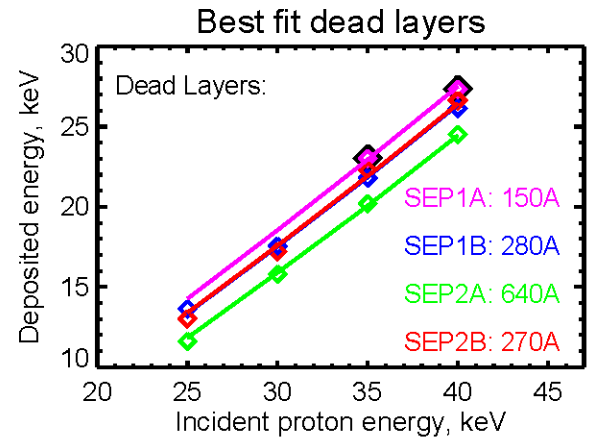
Energy ranges for counted events

	Electrons		Ions	
keV	Foil side	Open side	Foil side	Open side
No count	<20	<350	<250	<15
F	20-700	X	250-6000	X
FT	350-1300	X	6000-11,000	X
O	X	350-700	X	15-6000
OT	X	350-1300	X	6000-11,000
FTO	300-2000		>11,000	

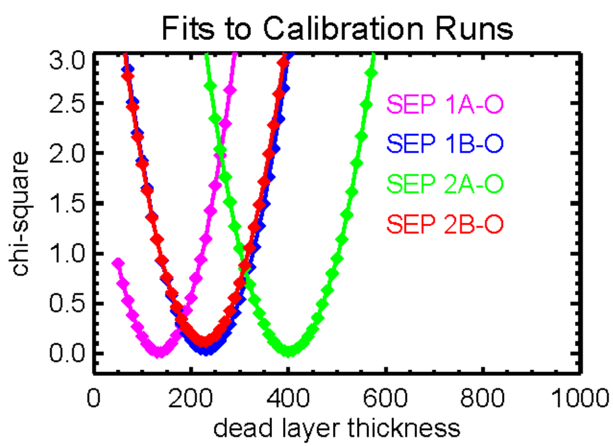


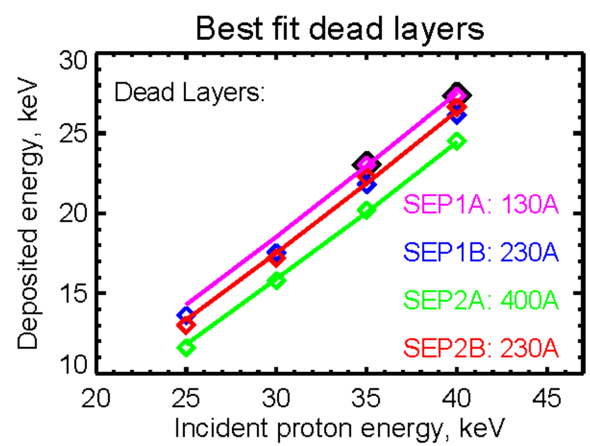
DETERMINING THICKNESS OF DETECTOR “DEAD” LAYERS





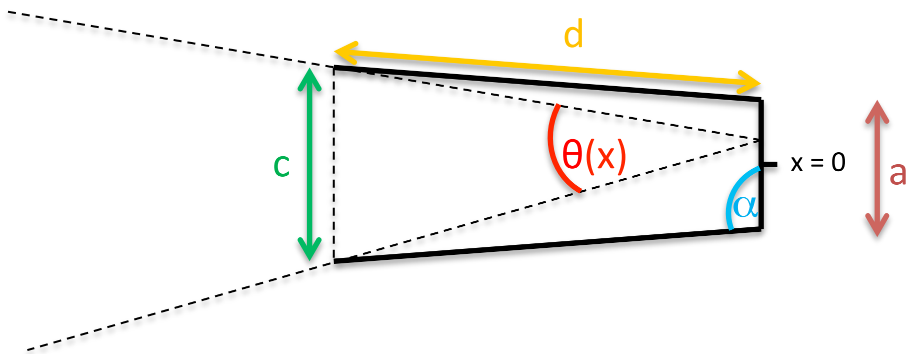
Oops! Misplaced volume.

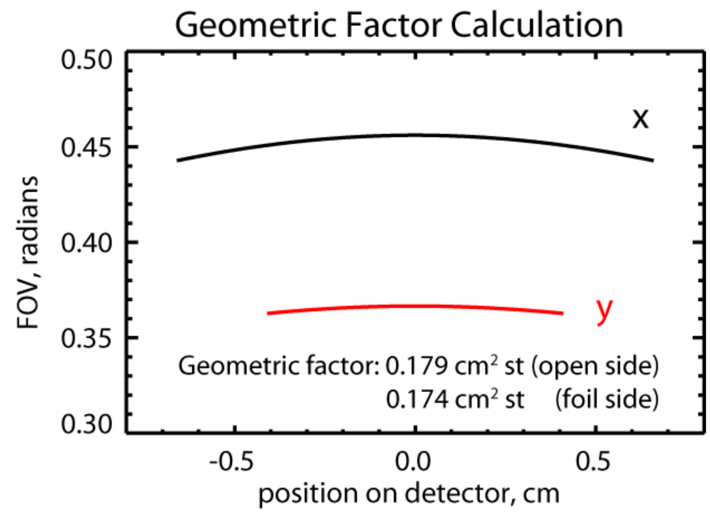




OK, much better! ☺

GEOMETRIC FACTOR CALCULATED GEOMETRICALLY





- Rectangular field of view: consider x,y separately
- Determine opening angles θ(x),ϕ(y) as a function of position on the detector.
- Integrate across the detector in x and y.
- Geometric factors:
  - 0.179 cm² st (open side)
  - 0.174 cm² st (foil side)
- GEANT4 simulations on following slide.

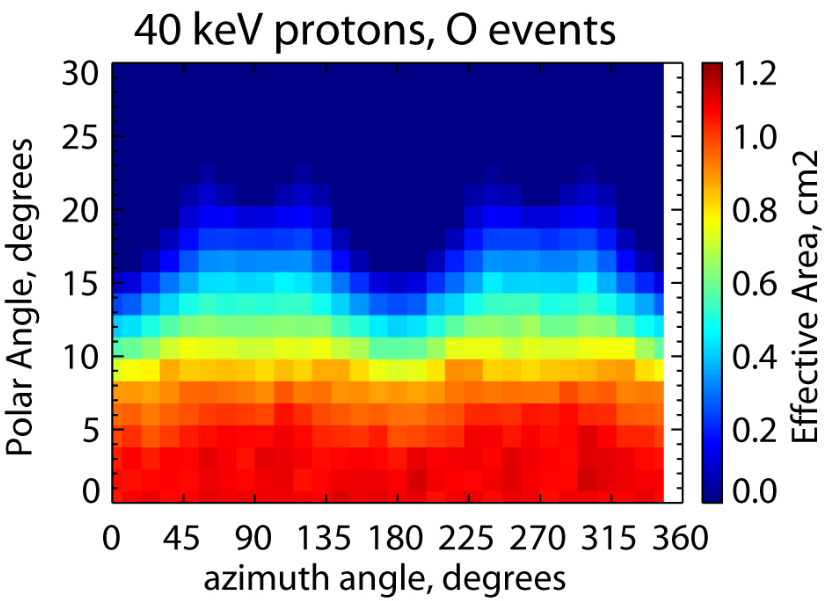
$$p_1^2 = d^2 + \left(\frac{a}{2} + x\right)^2 - 2d\left(\frac{a}{2} + x\right)\cos\alpha$$

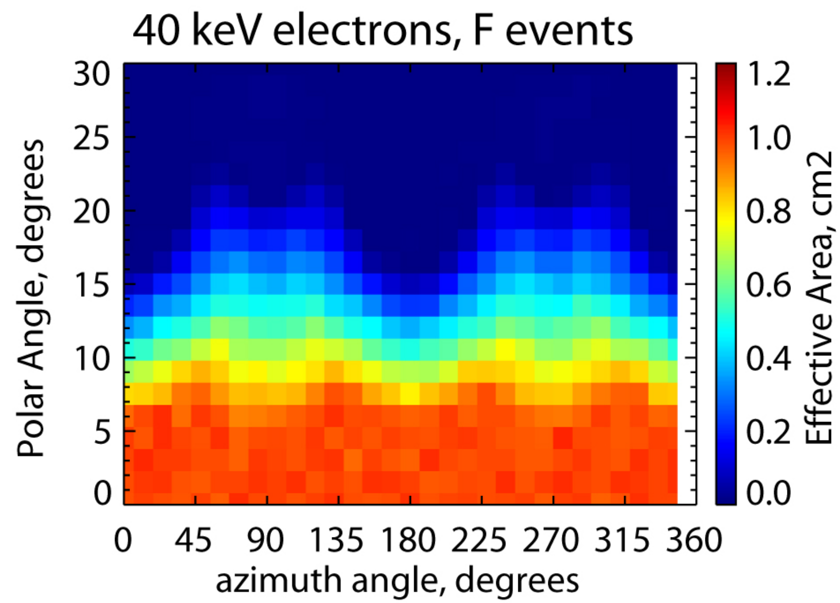
$$p_2^2 = d^2 + \left(\frac{a}{2} - x\right)^2 - 2d\left(\frac{a}{2} - x\right)\cos\alpha$$

$$\theta(x) = \cos^{-1}\left(\frac{p_1^2 + p_2^2 - c^2}{2p_1p_2}\right)$$

$$GF = \int_{-b/2}^{b/2}\int_{-a/2}^{a/2}\theta(x)\phi(y)\,dx\,dy$$

GEOMETRIC FACTOR CALCULATED WITH GEANT4 SIMULATIONS



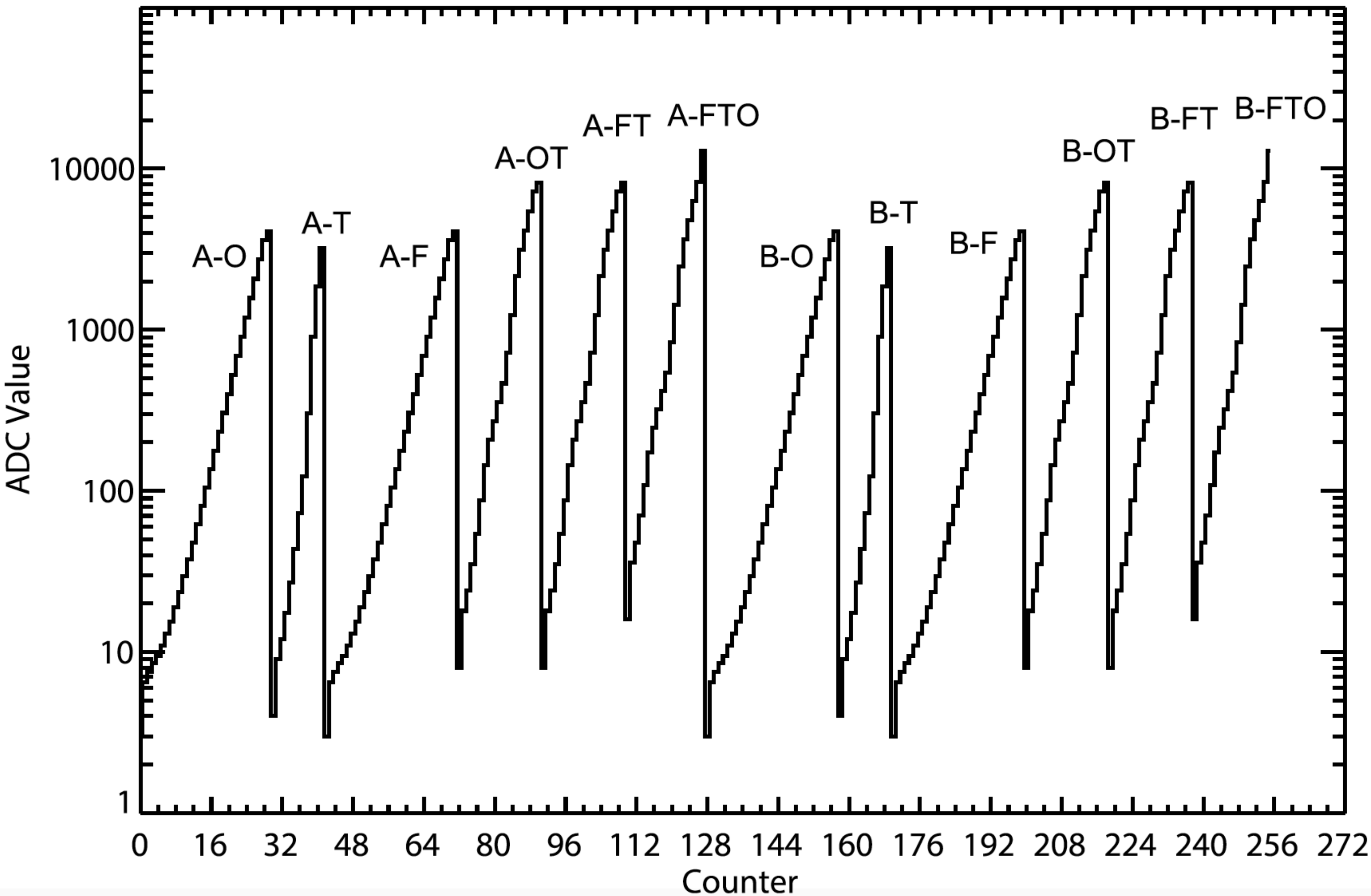


- 40 keV electrons. Foil side.
- Beam Area : 7.07 cm²
- # particles per angle: 20,000
- *GF* = 0.1689 ±.0025 cm^2 sr
- 1.47% error from counting statistics
- 2.87% lower than simple geometric value of 0.174 cm^2 sr (see previous slide)

- 40 keV protons. Open side.
- Beam Area : 7.07 cm²
- # particles per angle: 20,000
- *GF* = 0.1769 ±.0027 cm^2 st
- 1.54% error from counting statistics
- 1.17 % lower than simple geometric value of 0.179 cm^2 sr (see previous slide).

$$GF = \frac{A_{beam}}{N_{incident}} \int_0^{2\pi} d\phi \int_0^{\pi/2} N_{detected}(\phi,\theta) \sin\theta d\theta$$

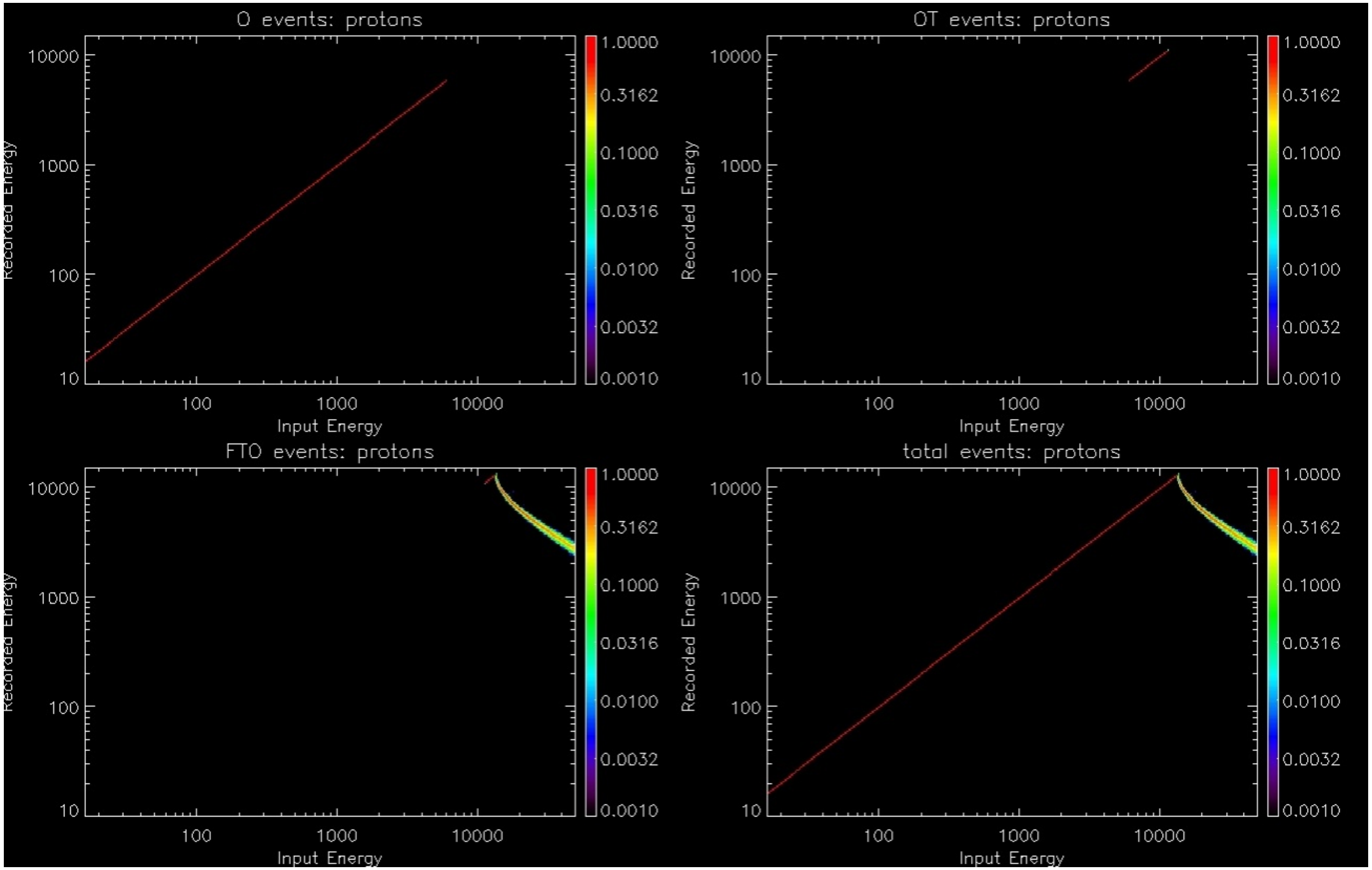
SEP ENERGY MAP



DETECTOR RESPONSE TO NORMALLY INCIDENT BEAM JUST ABOVE APERTURES

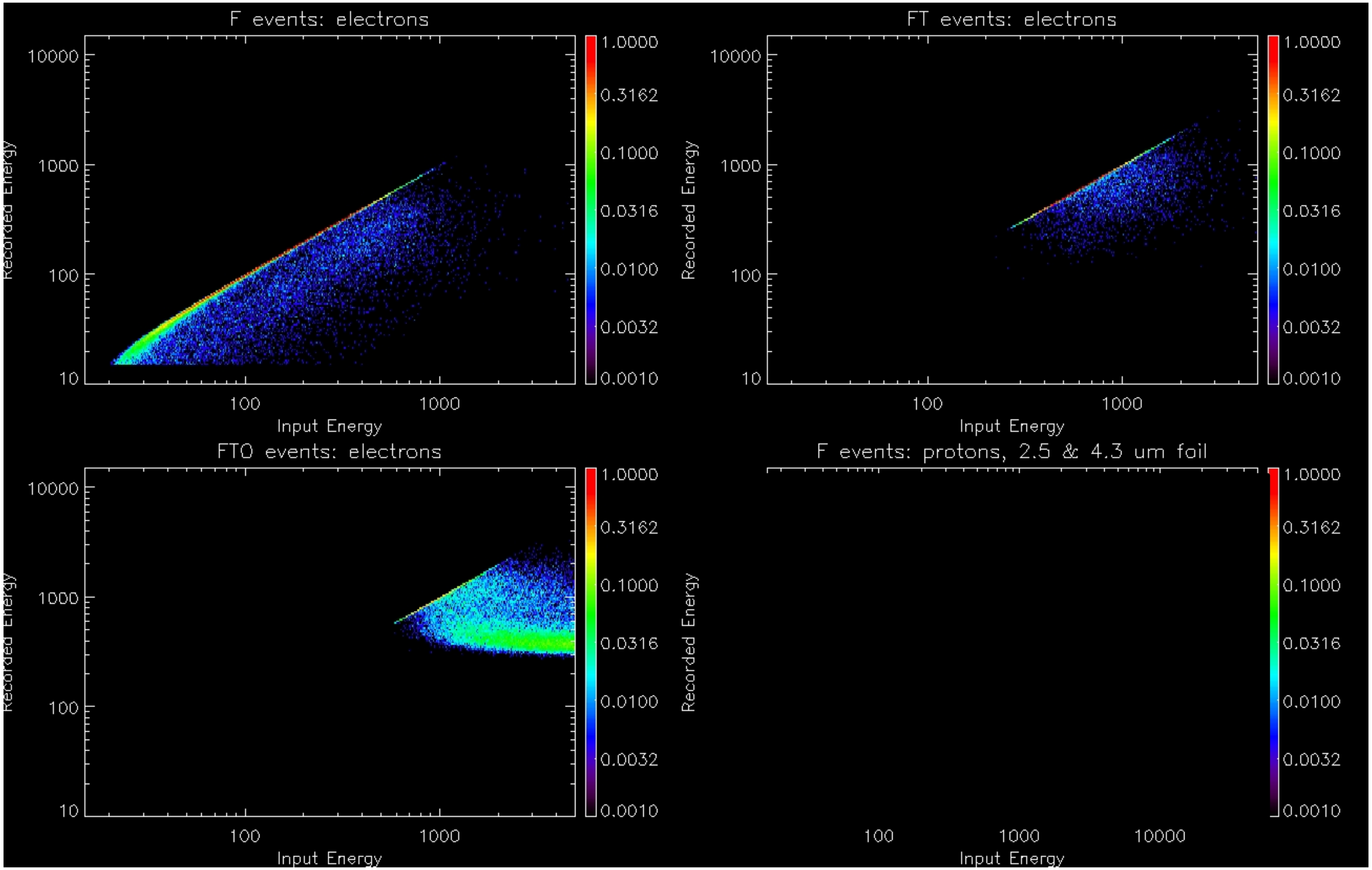
ION RESPONSE MATRICES

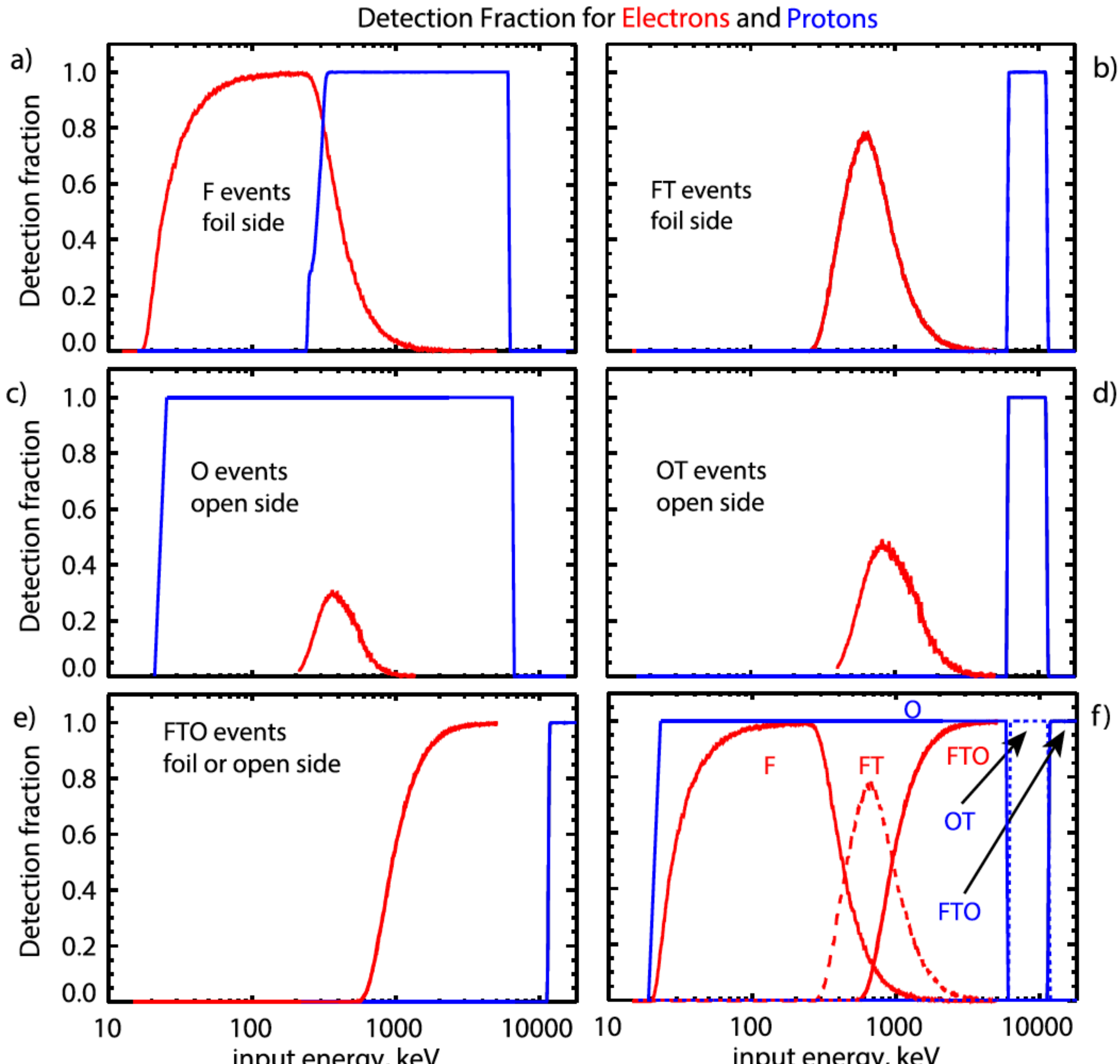
- Since ions deposit most of their energy at the very end of their trajectory, proton response matrix for O, OT and FTO events is quite clean.



ELECTRON RESPONSE MATRICES

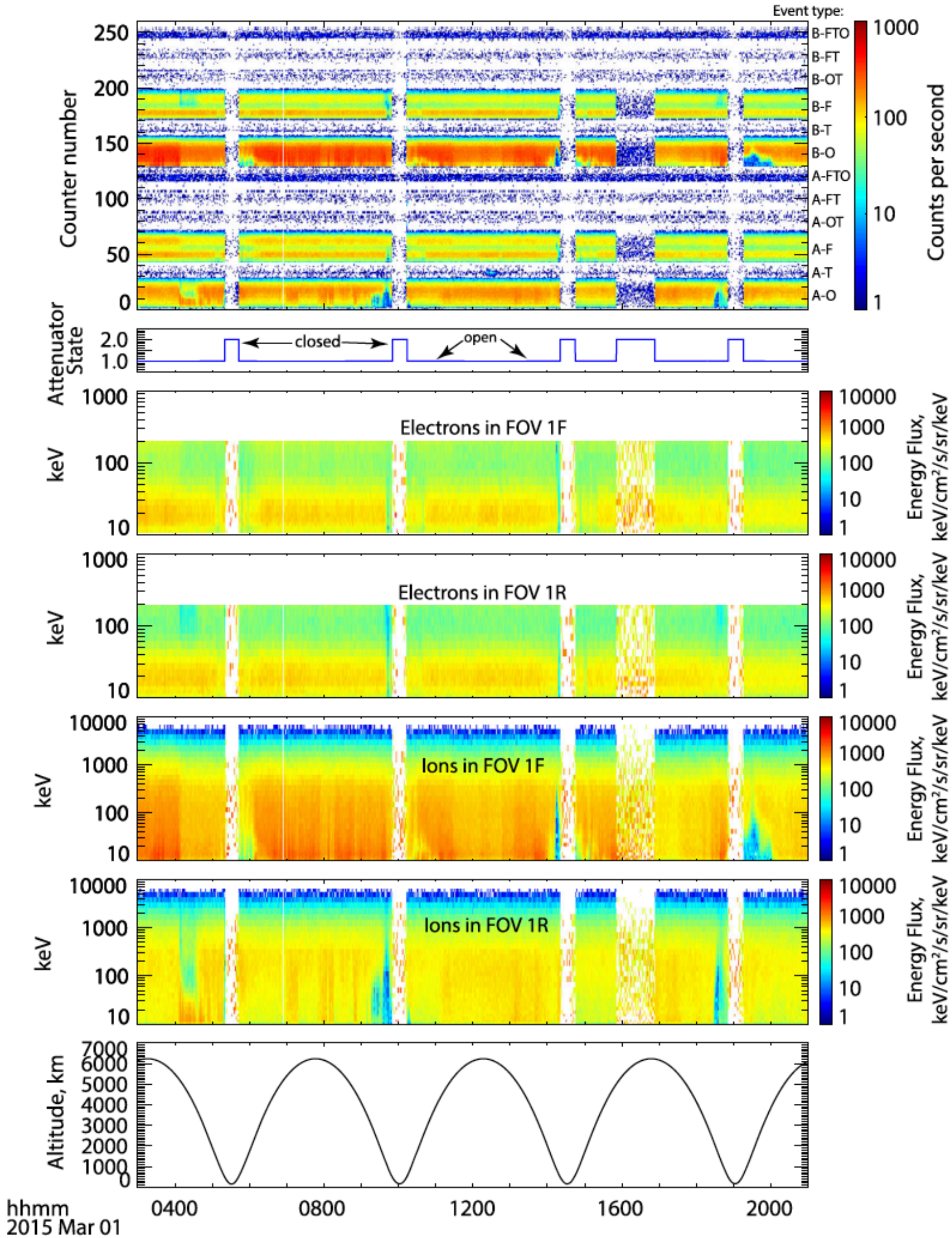
- Electrons deposit their energy over a much longer distance than ions. Response matrices are much less diagonal.



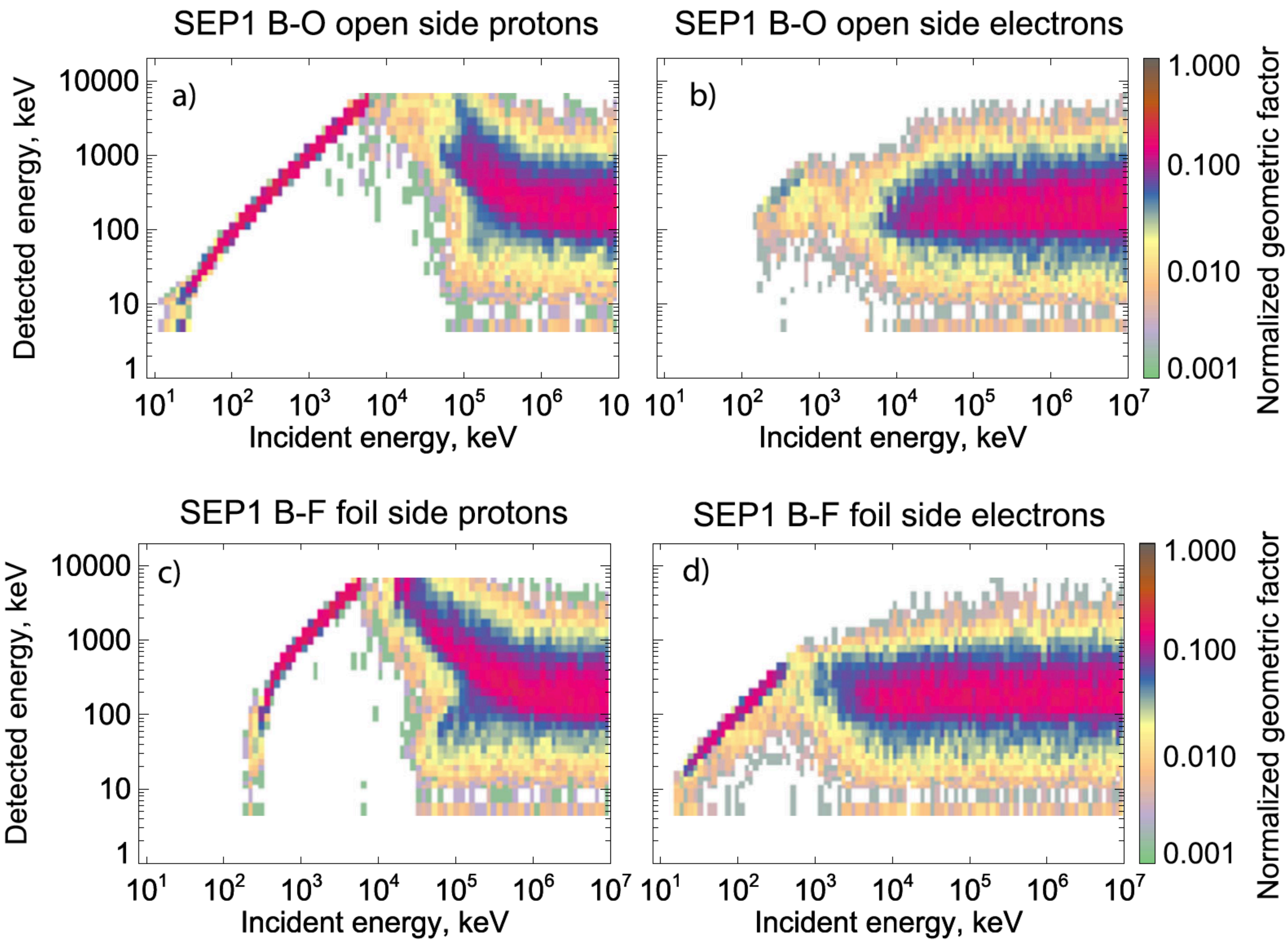


Detection Fraction for Electrons and Protons
a)
b)
c)
d)
e)
f)
Detection fraction
1.0
0.8
0.6
0.4
0.2
0.0
F events
foil side
FT events
foil side
O events
open side
OT events
open side
FTO events
foil or open side
O
F
FT
FTO
OT
FTO
10
100
1000
10000
input energy, keV

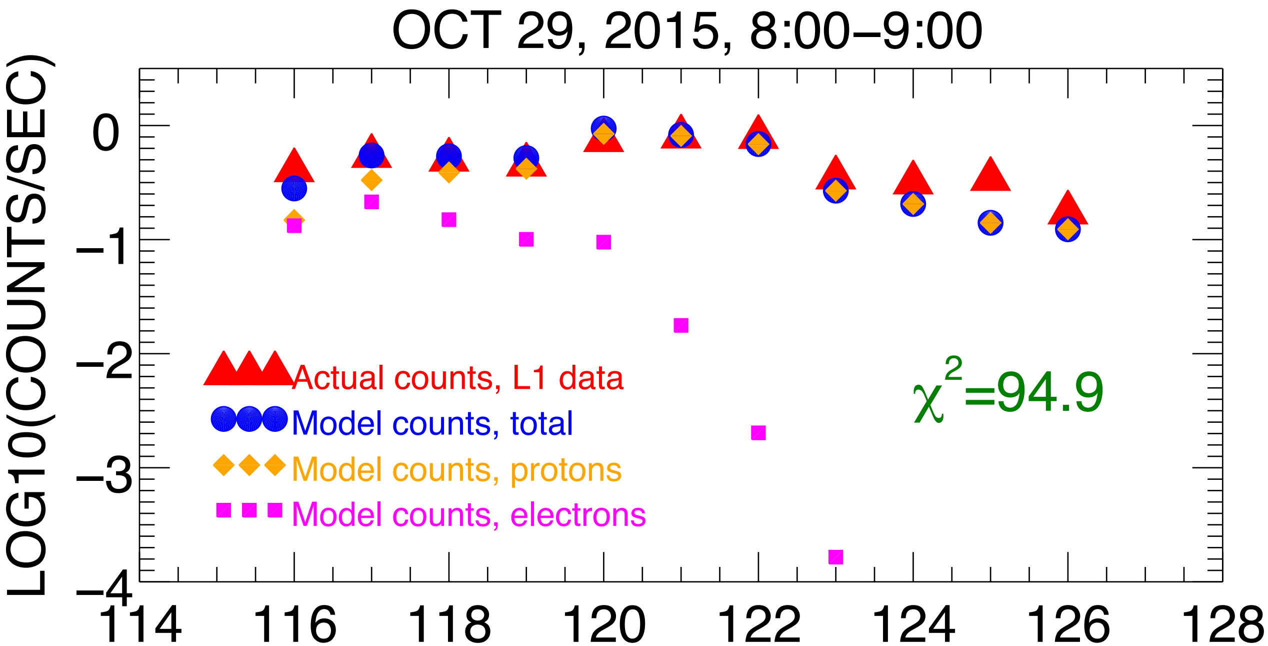
EXAMPLE OF SEP DATA USING BEAM RESPONSE



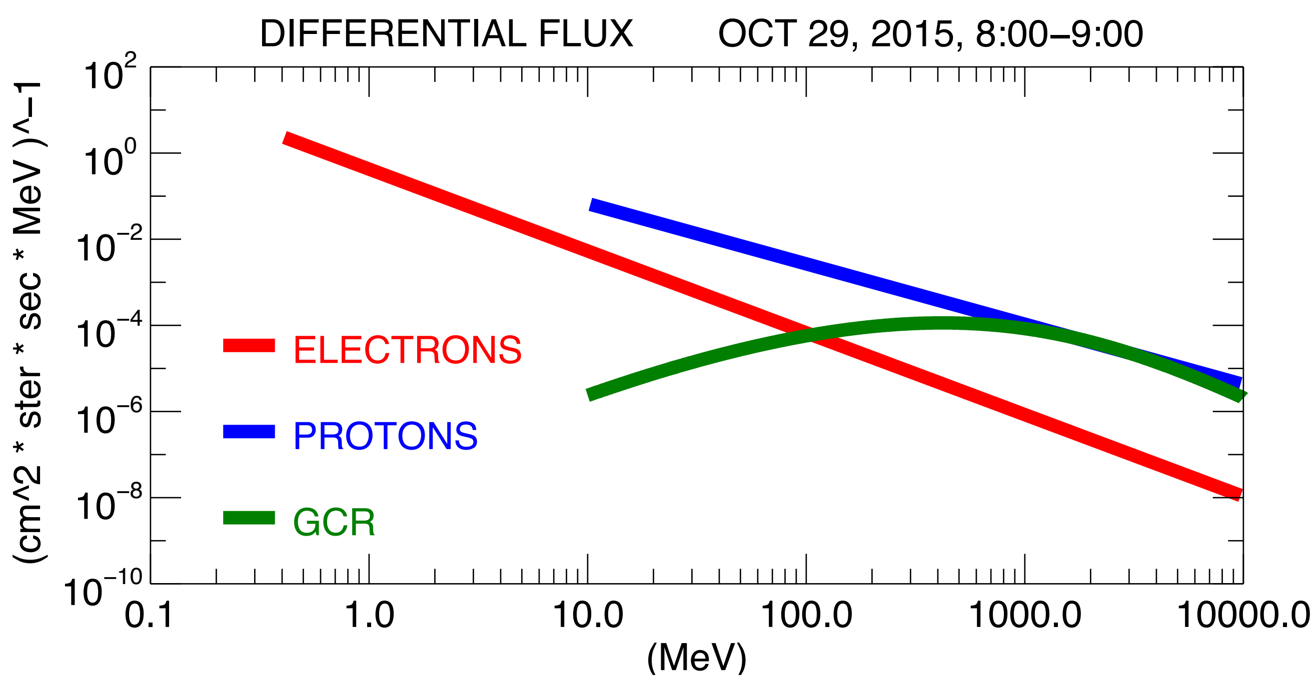
DETECTOR RESPONSE TO ISTOTROPIC SOURCE SURROUNDING THE INSTRUMENT


SEP1 B-O open side protons
SEP1 B-O open side electrons
SEP1 B-F foil side protons
SEP1 B-F foil side electrons
a)
b)
c)
d)
Detected energy, keV
Incident energy, keV
Normalized geometric factor
10000
1000
100
10
1
10^1 10^2 10^3 10^4 10^5 10^6 10^7
1.000
0.100
0.010
0.001

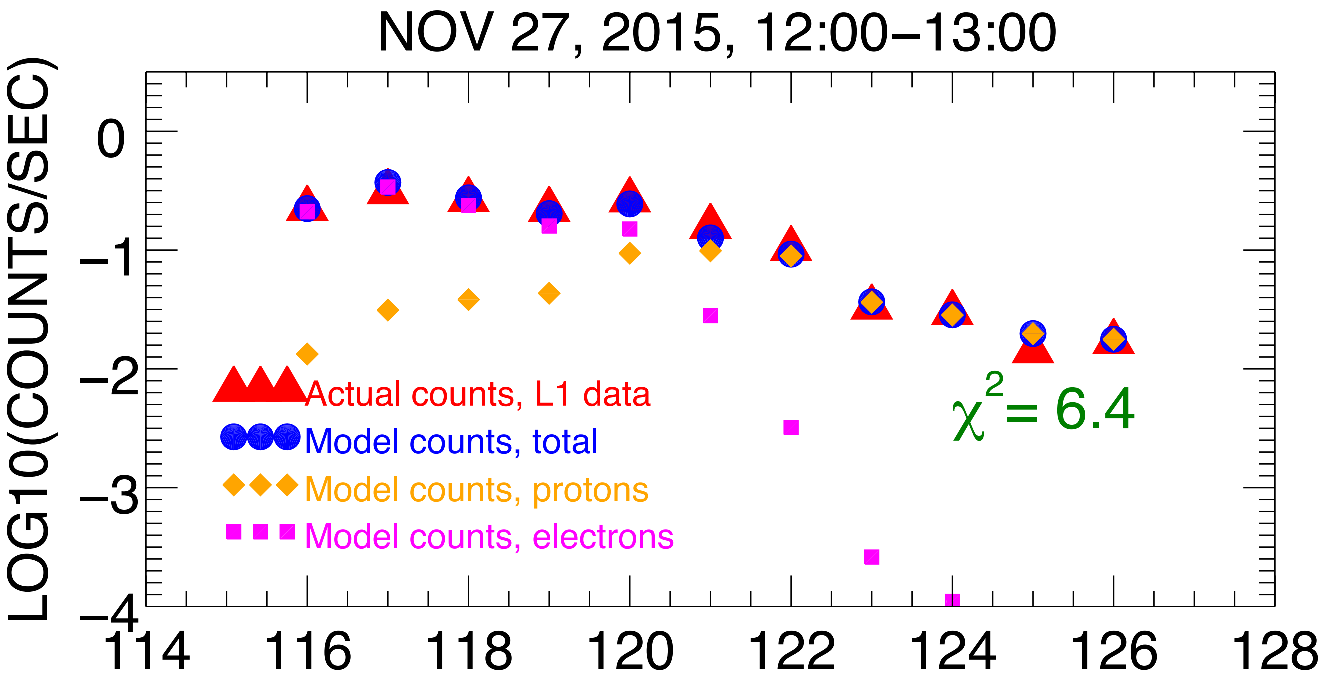
ATTEMPTS TO EXTEND ENERGY SPECTRUM

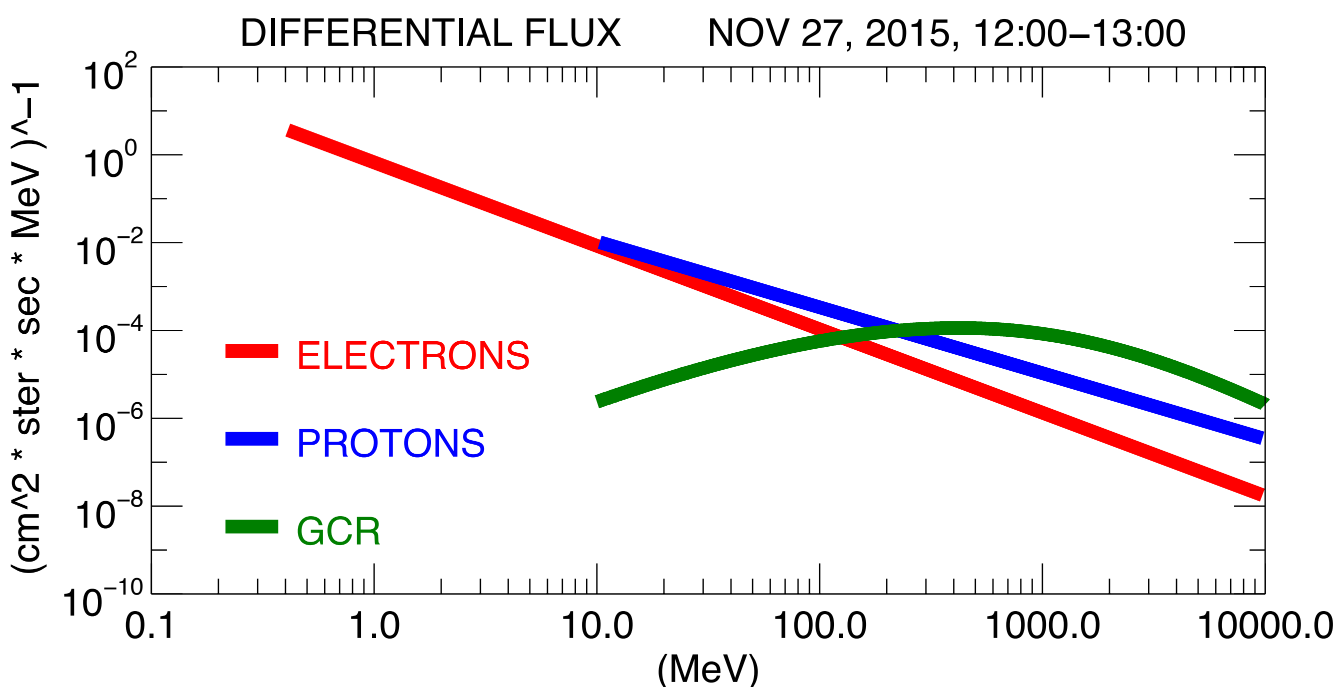


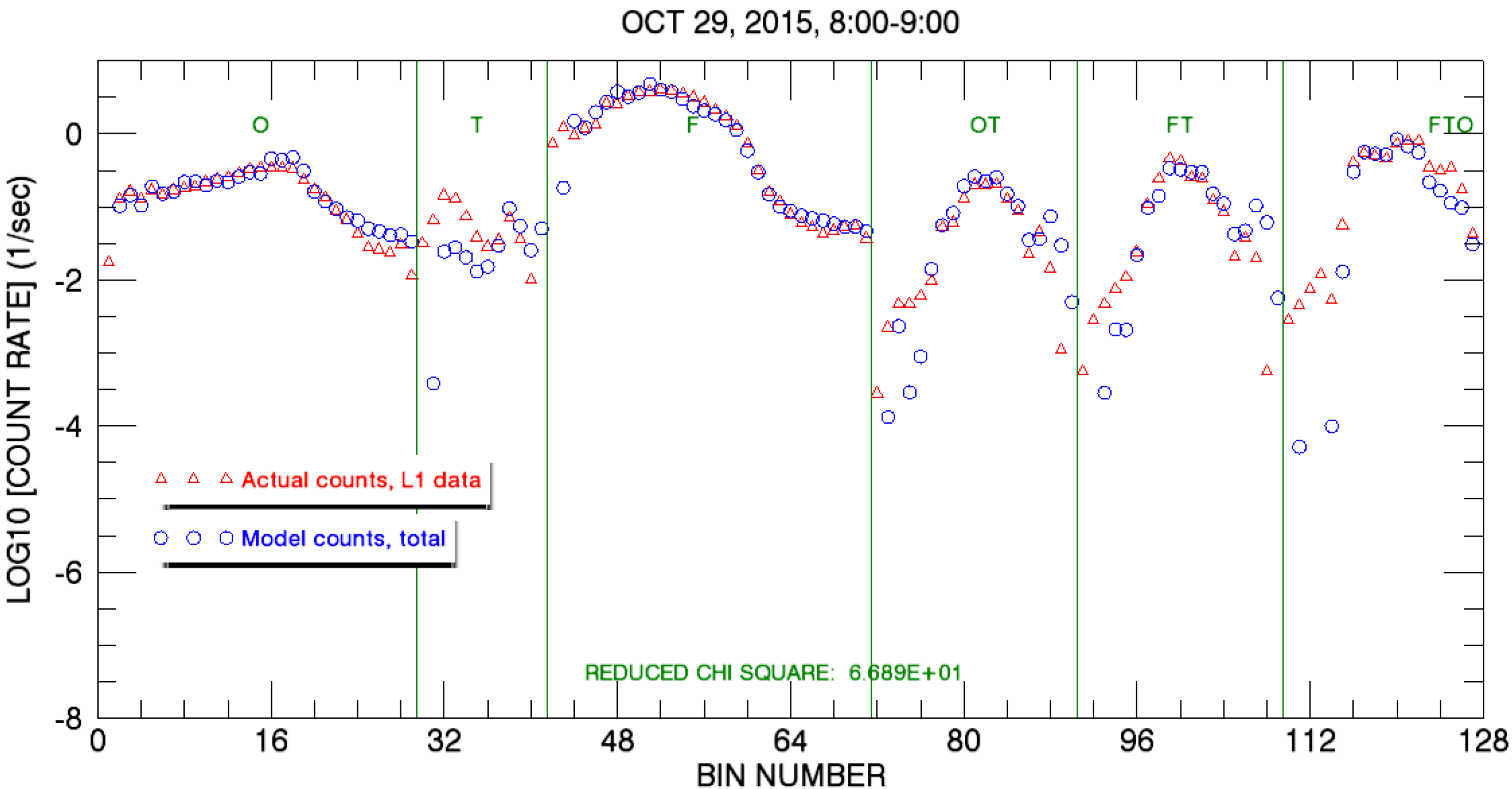
OCT 29, 2015, 8:00–9:00
LOG10(COUNTS/SEC)
0
–1
–2
–3
–4
114
116
118
120
122
124
126
128
Actual counts, L1 data
Model counts, total
Model counts, protons
Model counts, electrons
χ²=94.9

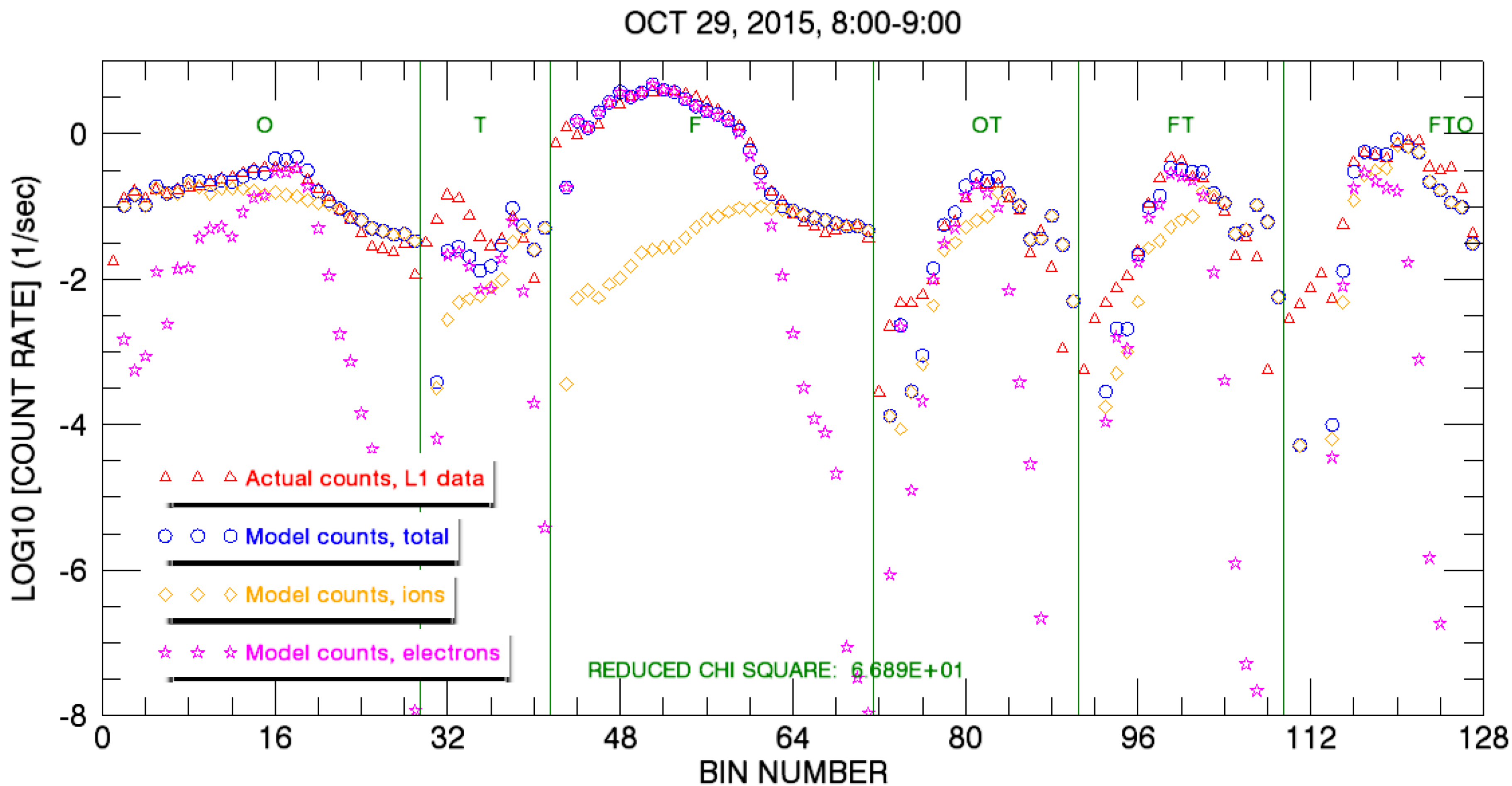


DIFFERENTIAL FLUX
OCT 29, 2015, 8:00–9:00
(cm^2 * ster * sec * MeV)^–1
10²
10⁰
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁰
0.1
1.0
10.0
100.0
1000.0
10000.0
(MeV)
ELECTRONS
PROTONS
GCR

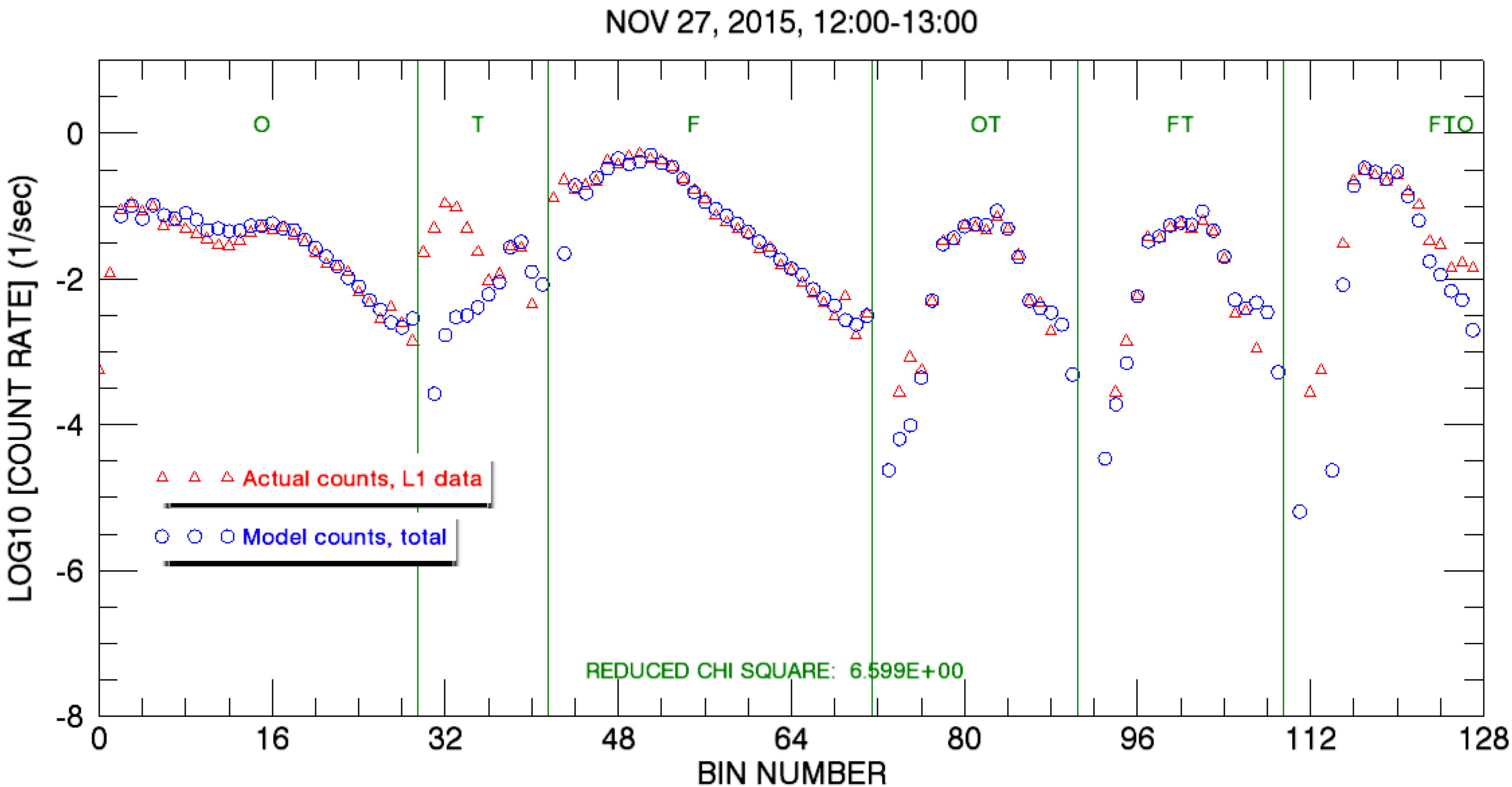

NOV 27, 2015, 12:00–13:00
LOG10(COUNTS/SEC)
0
–1
–2
–3
–4
114
116
118
120
122
124
126
128
Actual counts, L1 data
Model counts, total
Model counts, protons
Model counts, electrons
$\chi^2 = 6.4$

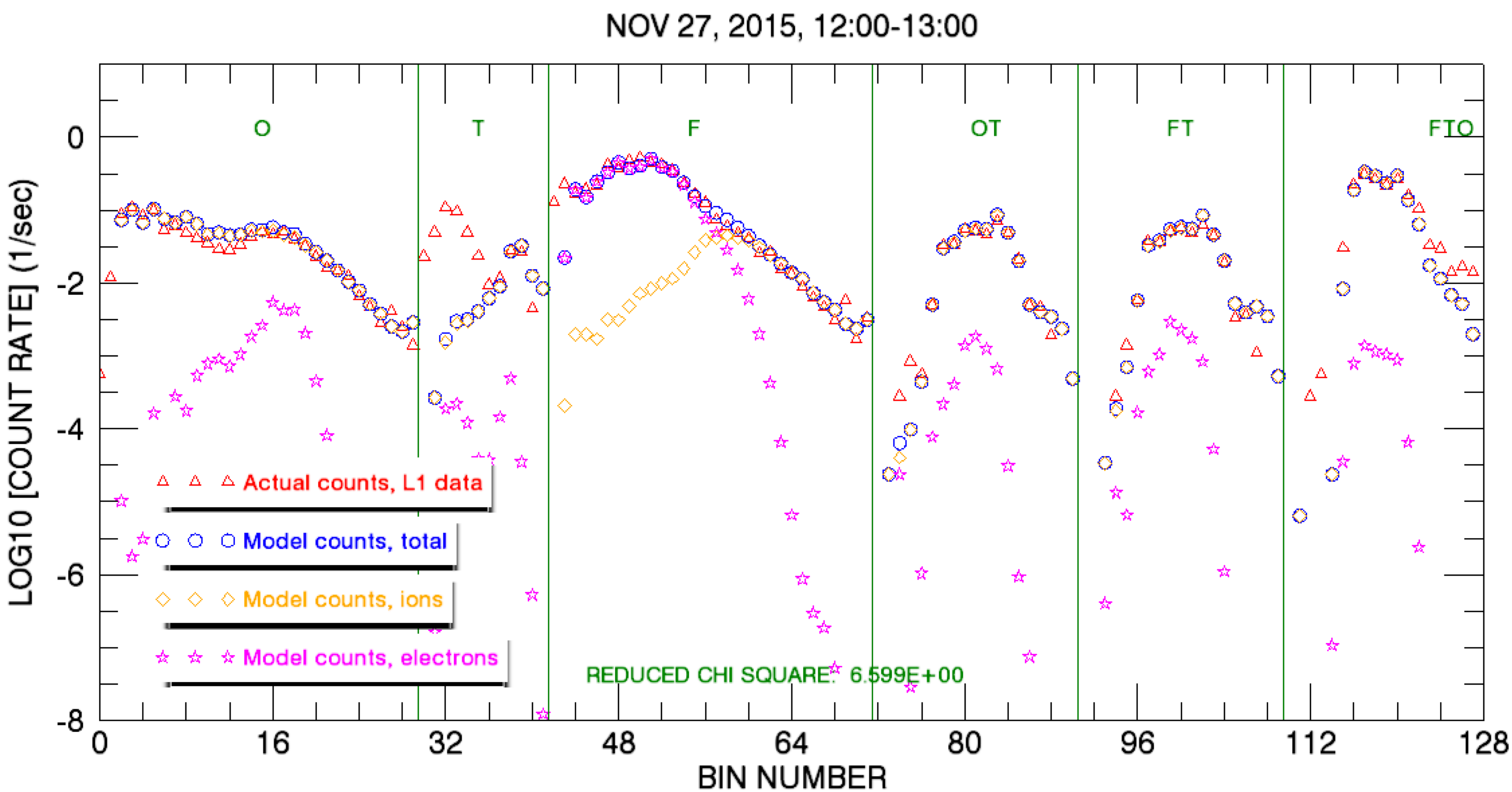

DIFFERENTIAL FLUX NOV 27, 2015, 12:00–13:00
(cm^2 * ster * sec * MeV)^–1
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
0.1
1.0
10.0
100.0
1000.0
10000.0
(MeV)
ELECTRONS
PROTONS
GCR


OCT 29, 2015, 8:00-9:00
LOG10 [COUNT RATE] (1/sec)
BIN NUMBER
O
T
F
OT
FT
FTO
Actual counts, L1 data
Model counts, total
REDUCED CHI SQUARE: 6.689E+01
0
-2
-4
-6
-8
0
16
32
48
64
80
96
112
128



OCT 29, 2015, 8:00-9:00
O
T
F
OT
FT
FTO
Actual counts, L1 data
Model counts, total
Model counts, ions
Model counts, electrons
REDUCED CHI SQUARE: 6.689E+01
LOG10 [COUNT RATE] (1/sec)
BIN NUMBER
0
-2
-4
-6
-8
0
16
32
48
64
80
96
112
128


NOV 27, 2015, 12:00-13:00
O
T
F
OT
FT
FTO
Actual counts, L1 data
Model counts, total
REDUCED CHI SQUARE: 6.599E+00
LOG10 [COUNT RATE] (1/sec)
BIN NUMBER
0
-2
-4
-6
-8
0
16
32
48
64
80
96
112
128


NOV 27, 2015, 12:00-13:00
LOG10 [COUNT RATE] (1/sec)
BIN NUMBER
O
T
F
OT
FT
FTO
Actual counts, L1 data
Model counts, total
Model counts, ions
Model counts, electrons
REDUCED CHI SQUARE: 6.599E+00
0
-2
-4
-6
-8
0
16
32
48
64
80
96
112
128