Energy Spectra of Near Relativistic Galactic Cosmic Rays and Solar Energetic Particles

-

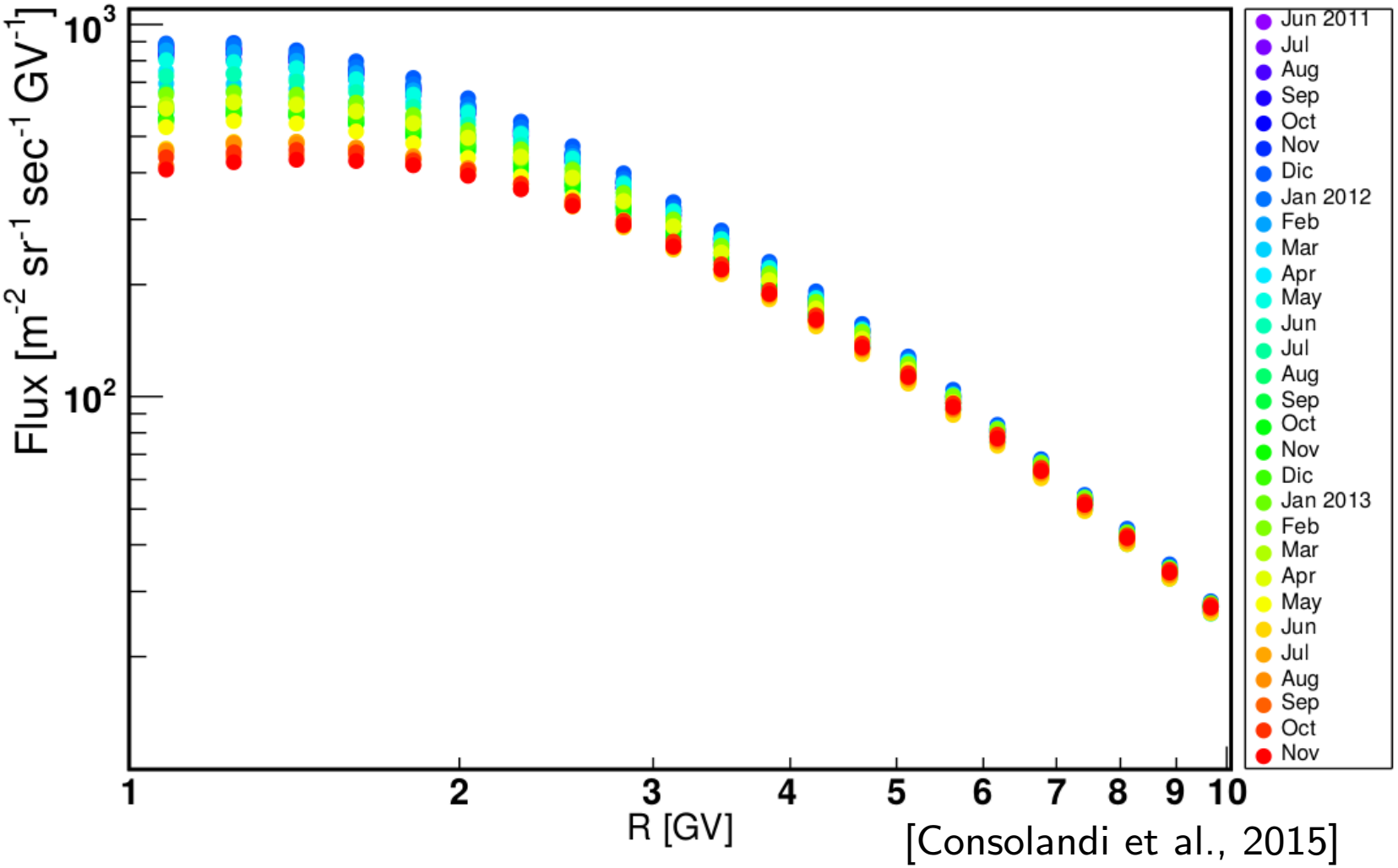
Extending the Measurement Capabilities of EPHIN

Patrick Kühl

Disputation, 26.09.2017

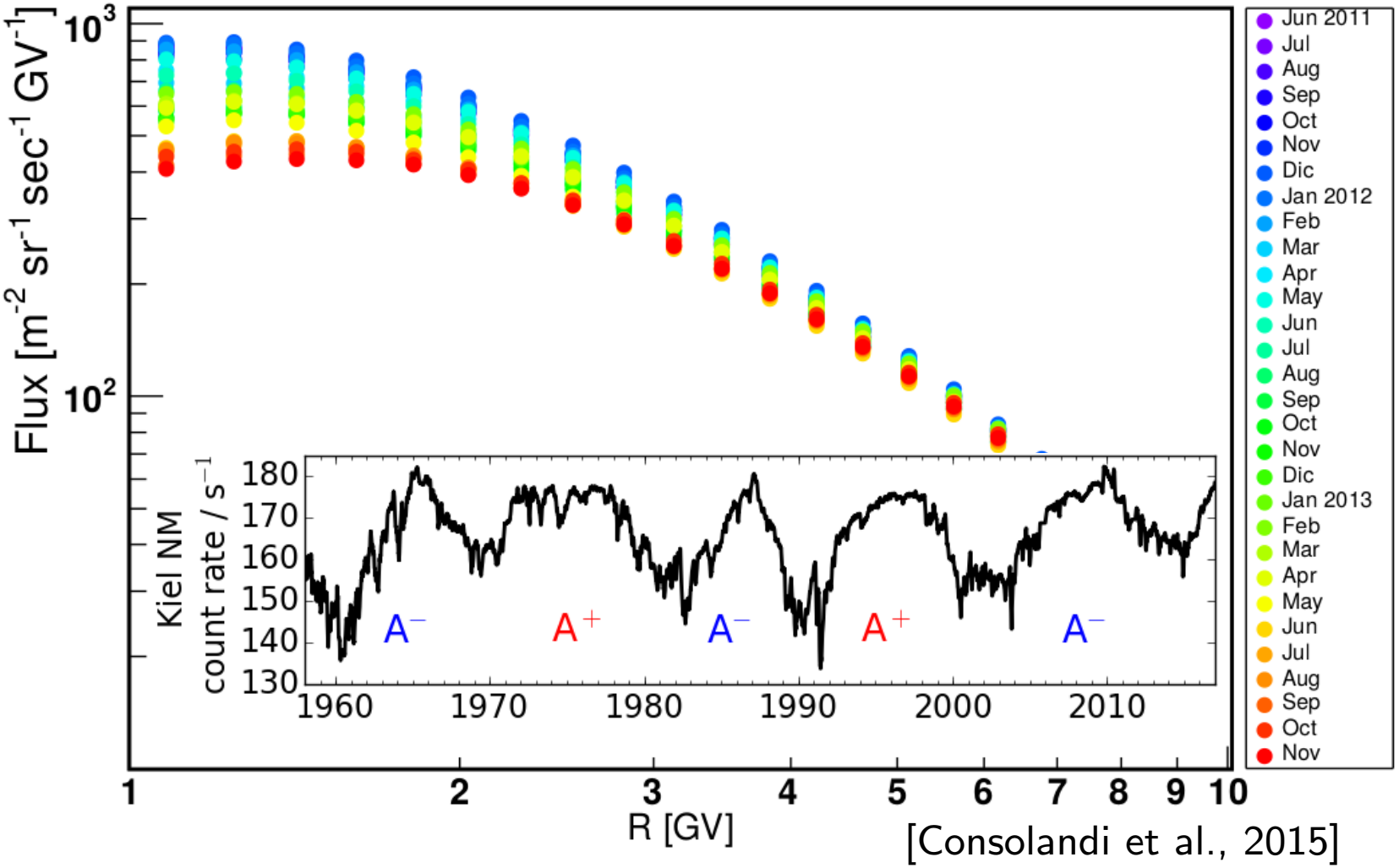

AMS
AMS

Galactic Cosmic Rays (GCRs)



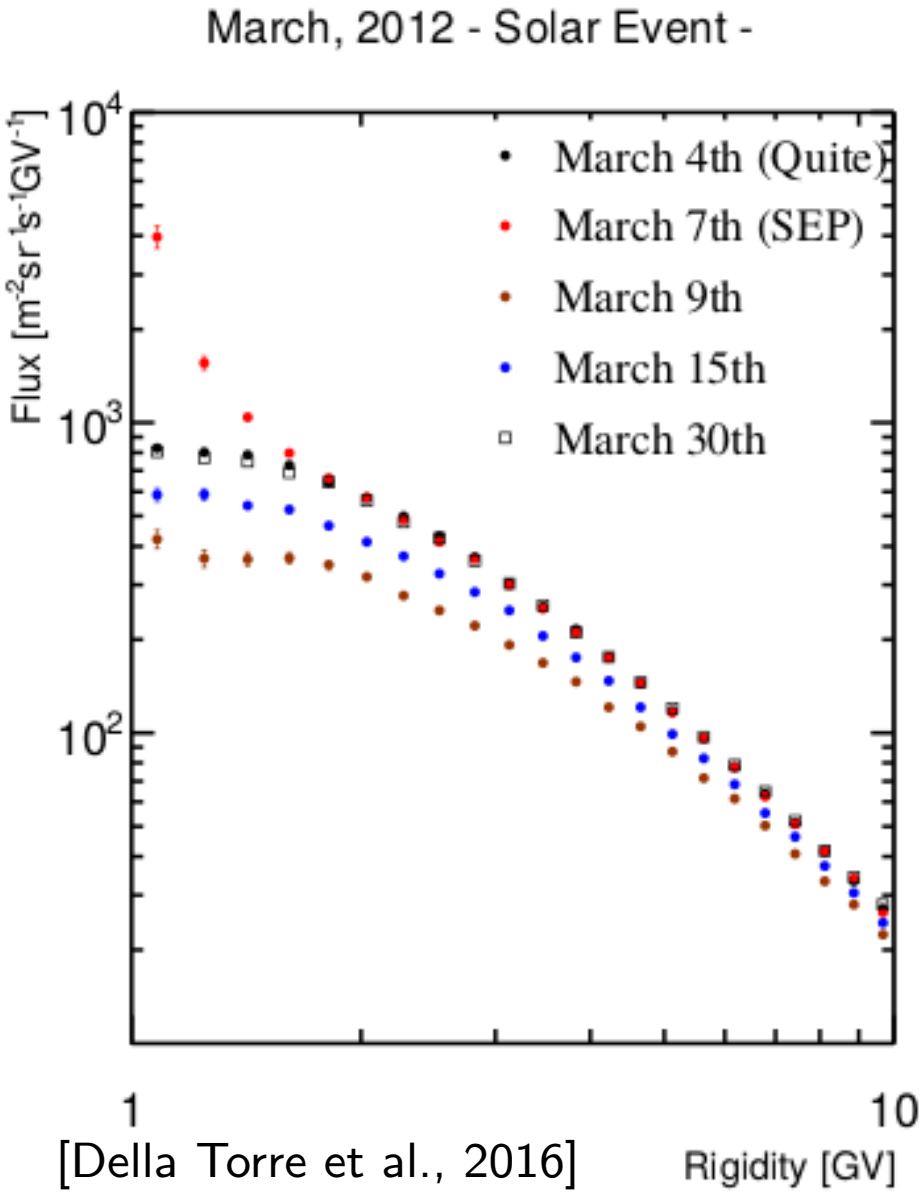
[Consolandi et al., 2015]

Galactic Cosmic Rays (GCRs)



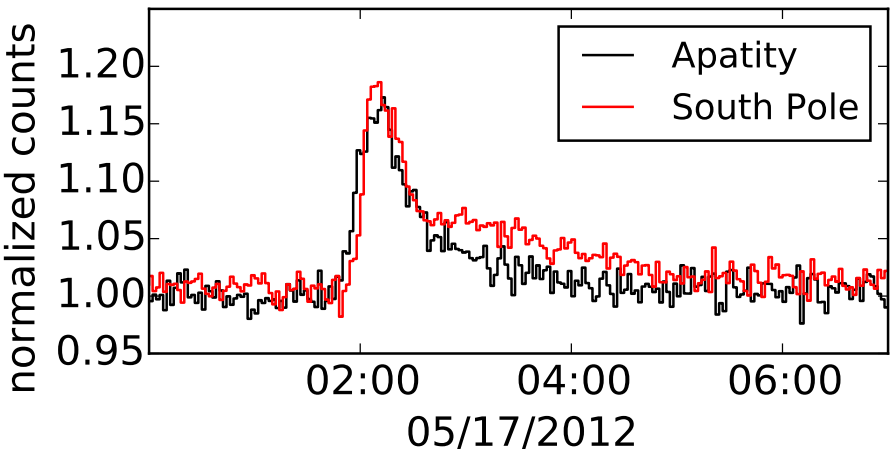
[Consolandi et al., 2015]

Solar Energetic Particles (SEPs)

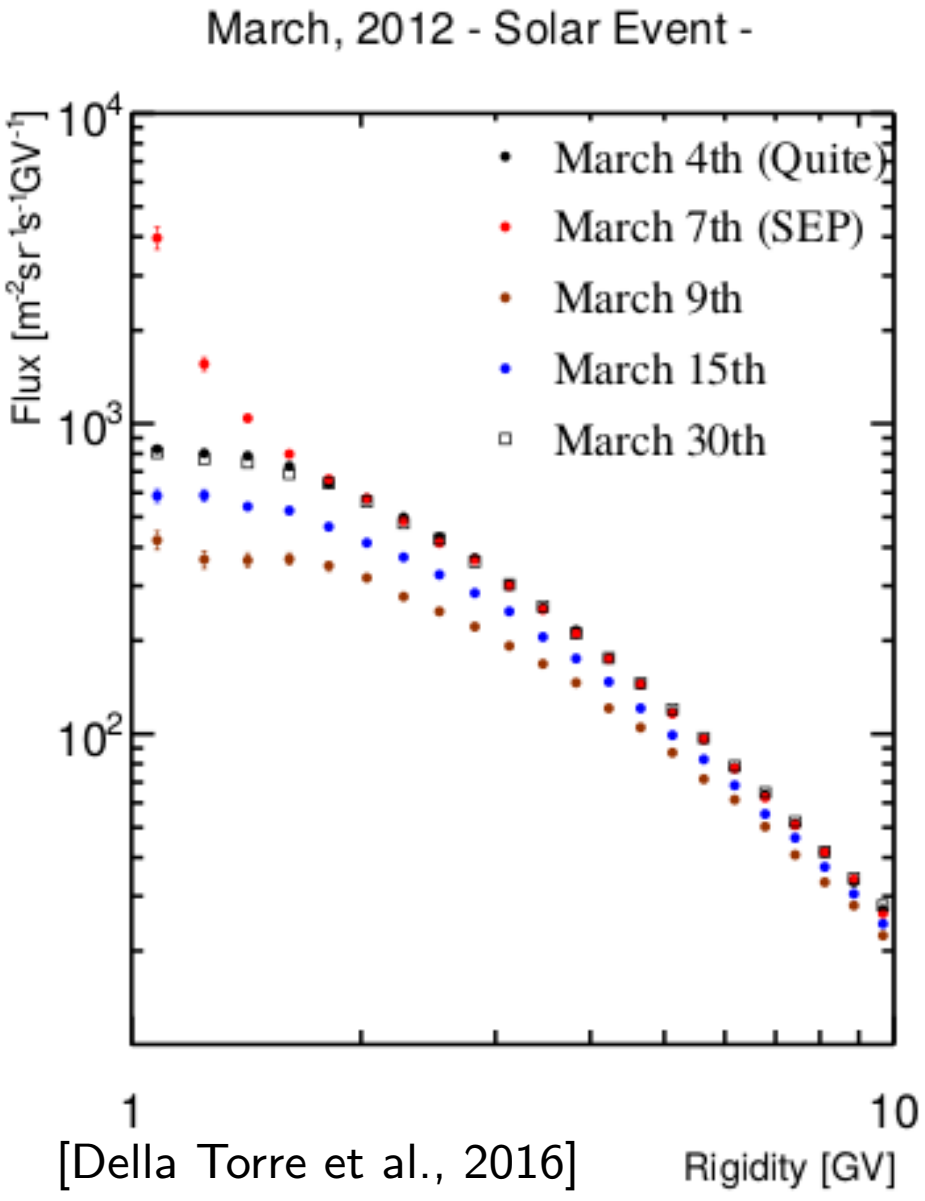


[Della Torre et al., 2016]

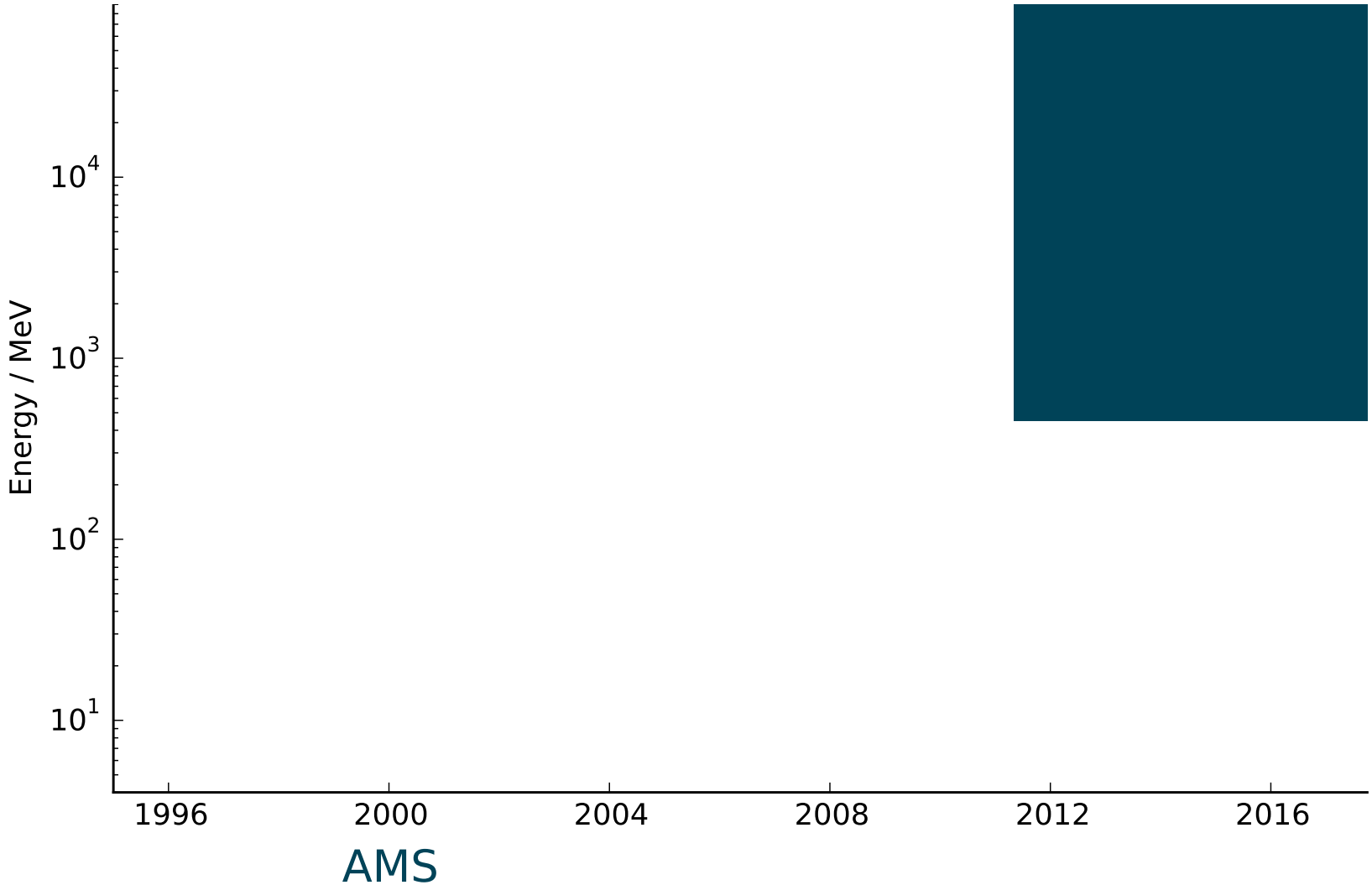
Solar Energetic Particles (SEPs)



- Ground level enhancement (GLE)

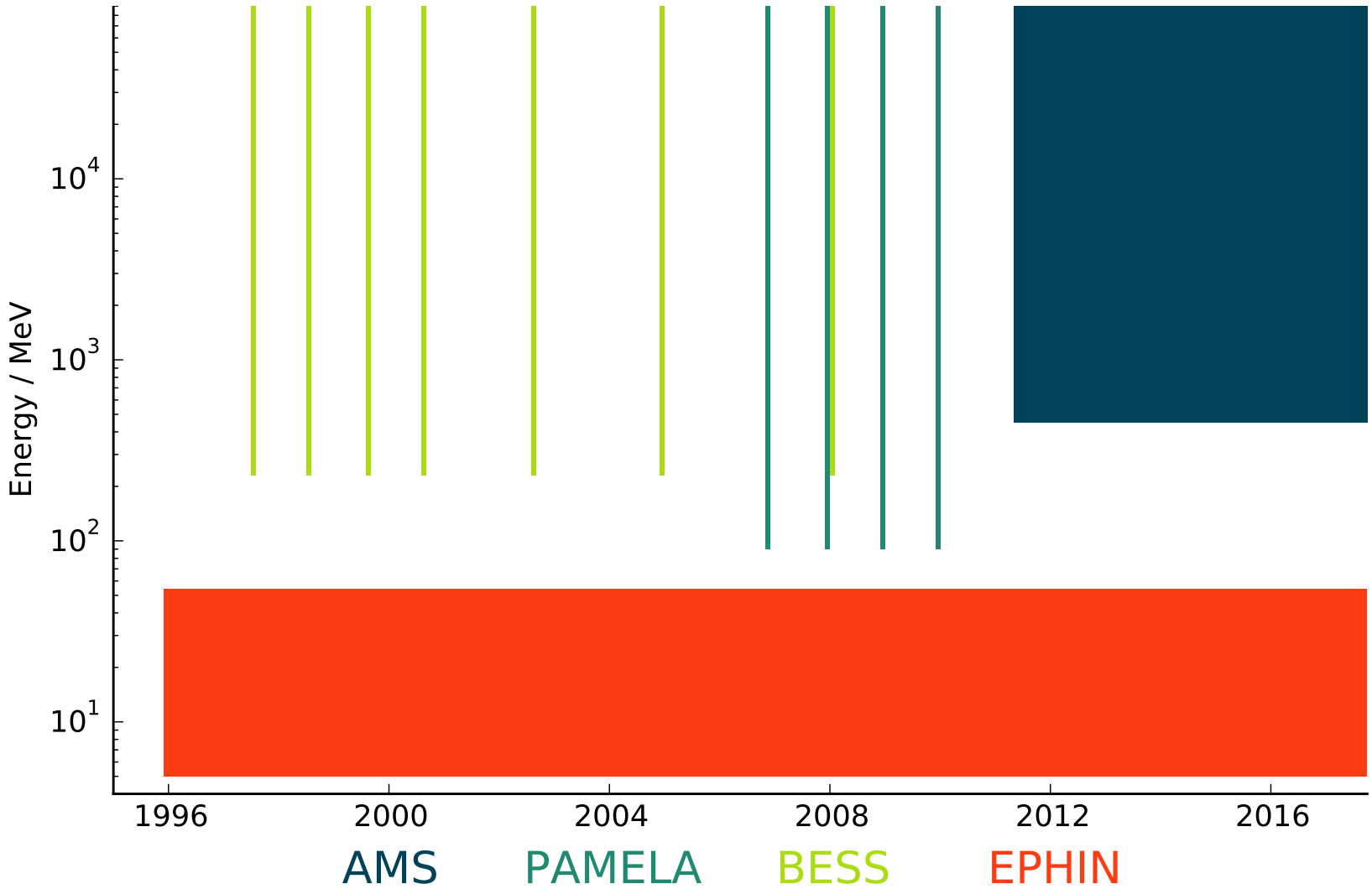


[Della Torre et al., 2016]


Energy / MeV
10^4
10^3
10^2
10^1
1996
2000
2004
2008
2012
2016
AMS


Energy / MeV
10^4
10^3
10^2
10^1
1996
2000
2004
2008
2012
2016
AMS
PAMELA


Energy / MeV
10^4
10^3
10^2
10^1
1996
2000
2004
2008
2012
2016
AMS
PAMELA
BESS


Energy / MeV
10^4
10^3
10^2
10^1
1996
2000
2004
2008
2012
2016
AMS
PAMELA
BESS
EPHIN

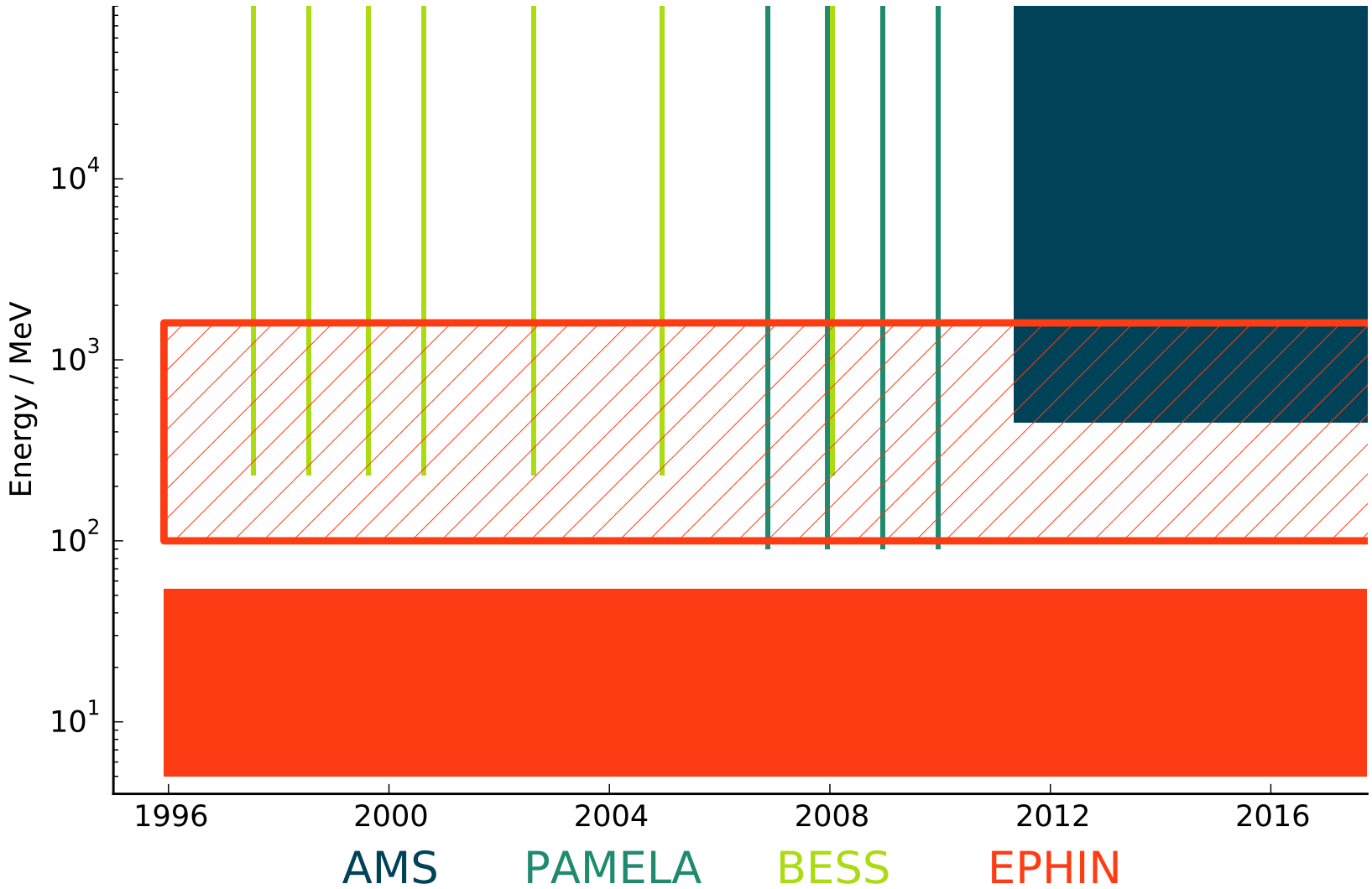
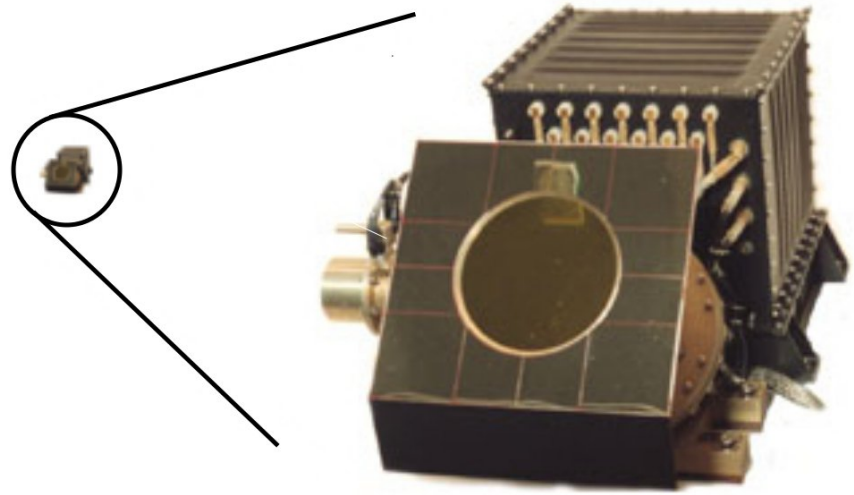

Energy / MeV
10^4
10^3
10^2
10^1
1996
2000
2004
2008
2012
2016
AMS
PAMELA
BESS
EPHIN

Table of Contents

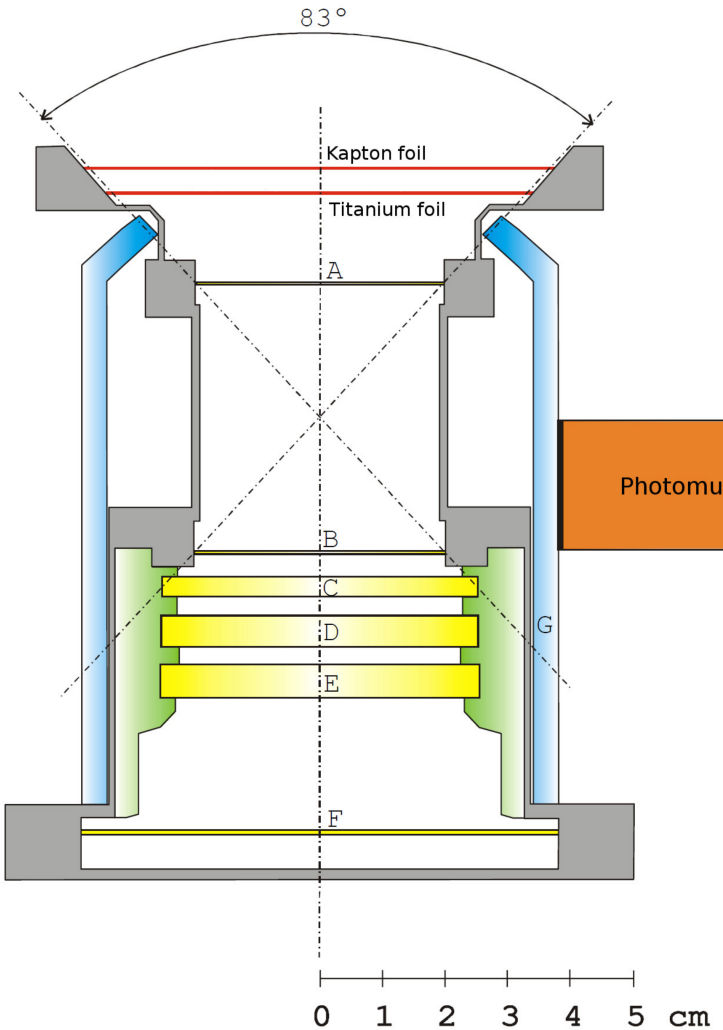
[AMS-02: Kountine, 2012; Bindi, 2015
EPHIN: Müller-Mellin et al., 1995]

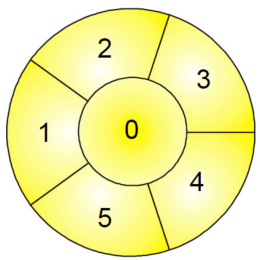


AMS-02	EPHIN
7500 kg	3.55 kg
500 x 400 x 300 cm^3	35 x 33 x 19 cm^3
10 Mbit/sec	172 bit/sec
4500 cm^2 sr	4.5 cm^2 sr
$\approx$ 0.4 - 1000 GeV	5 - 50 MeV
ISS	L1
May 2011	Dec 1995

[AMS-02: Kountine, 2012; Bindi, 2015
EPHIN: Müller-Mellin et al., 1995]

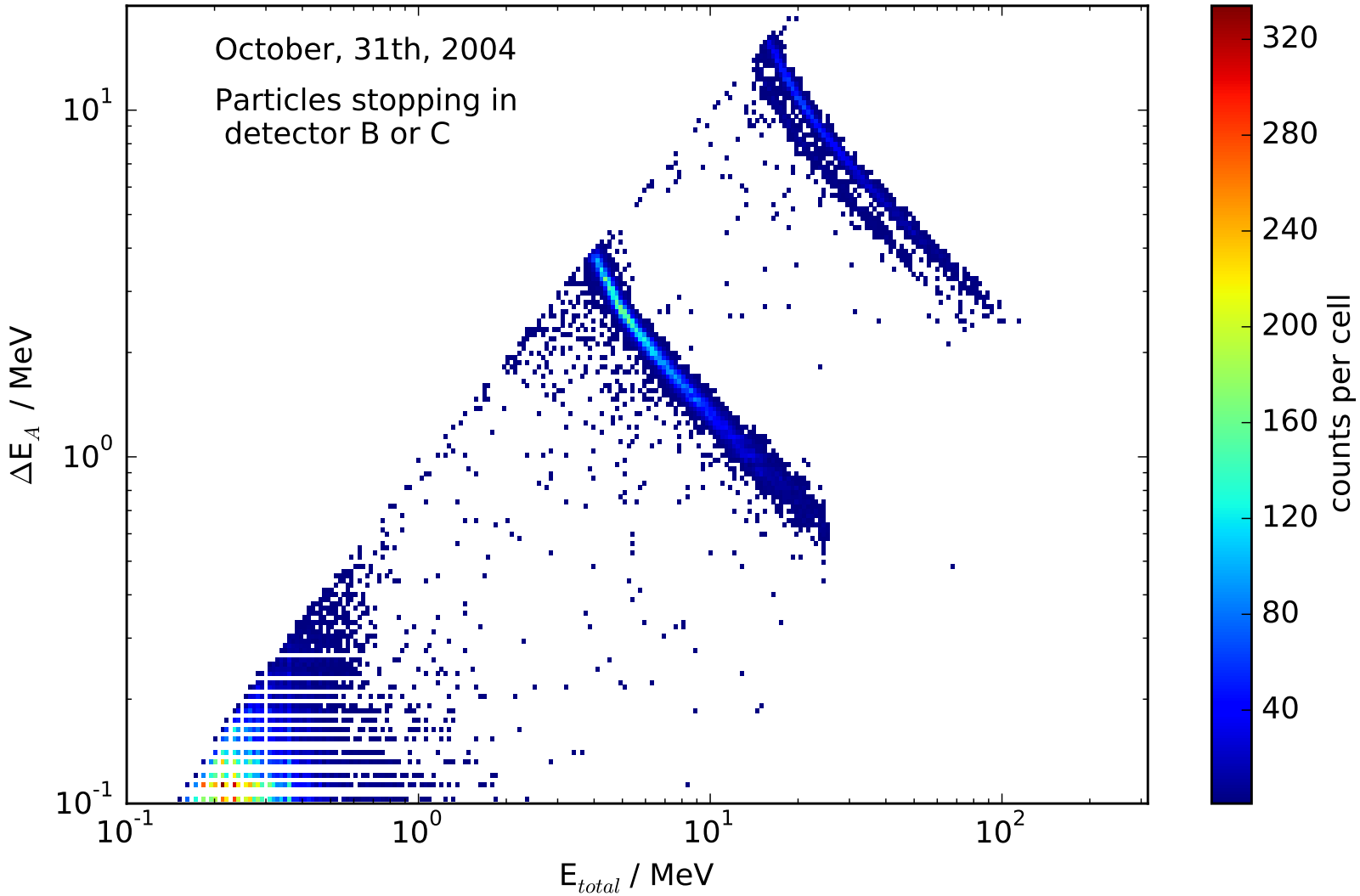
The Electron Proton Helium INstrument



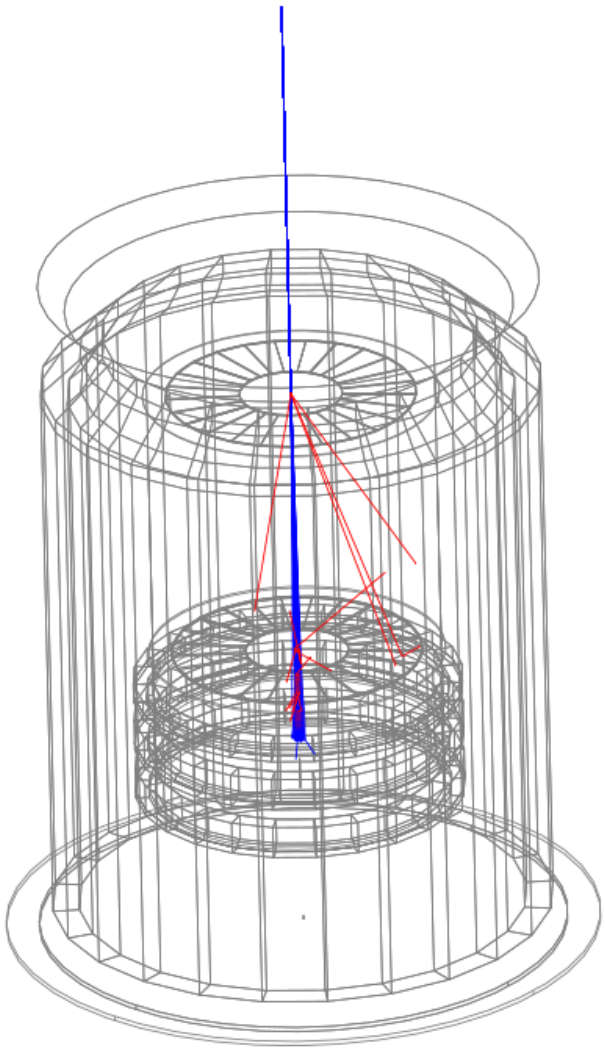


A and B detectors

[adapted from Gómez-Herrero, 2003]


October, 31th, 2004
Particles stopping in
detector B or C
10^1
10^0
10^{-1}
ΔE_A / MeV
10^{-1}
10^0
10^1
10^2
E_{total} / MeV
320
280
240
200
160
120
80
40
counts per cell

Extension of the Measurement Capabilities



required information:

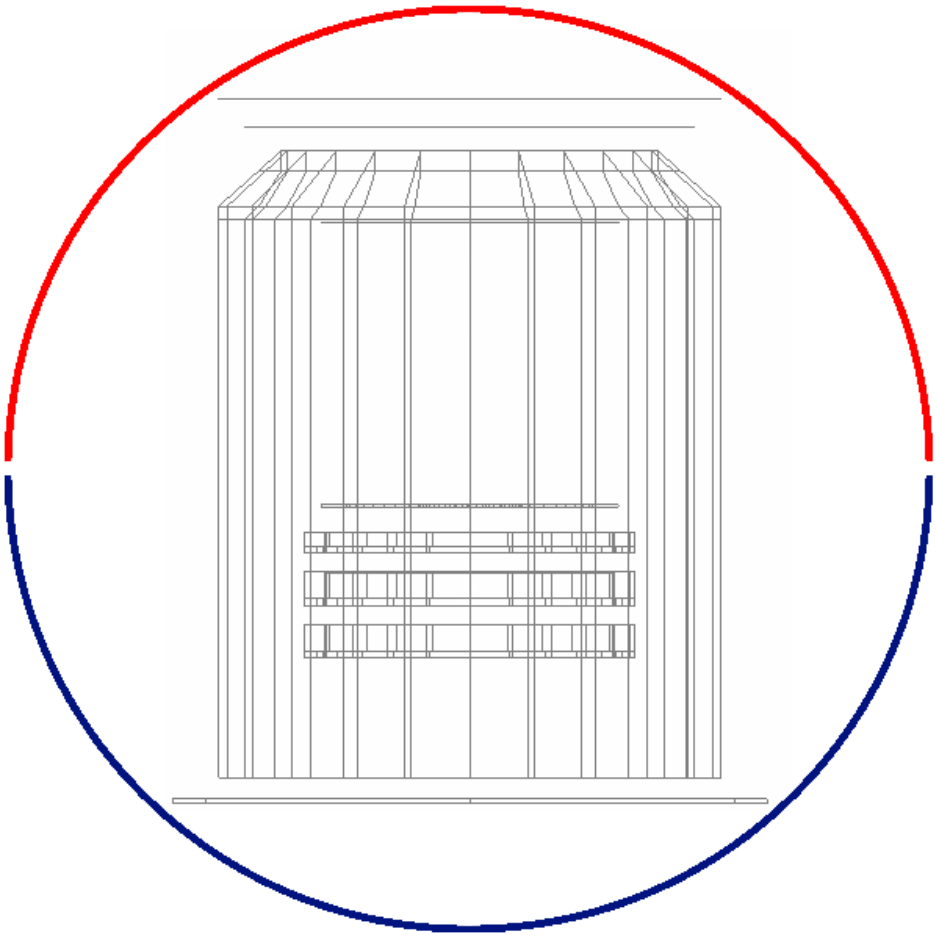
- total energy
- particle species

available information:

- energy losses in all detectors

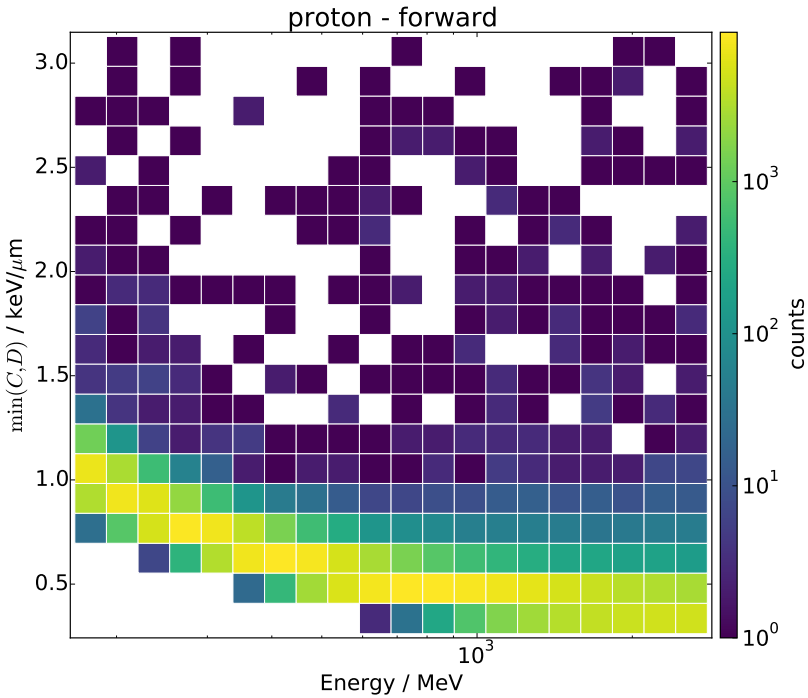
approach:

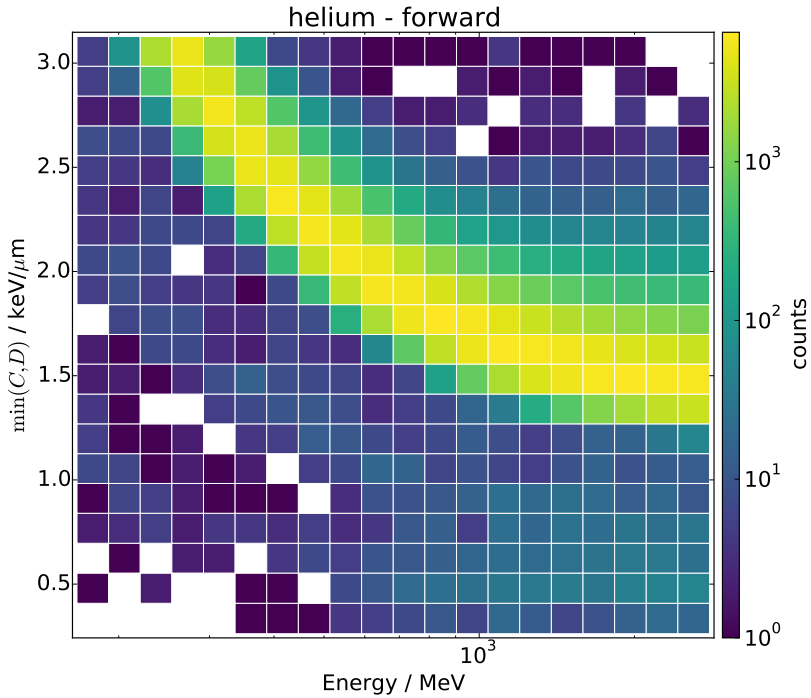
- GEANT4 Monte Carlo simulation



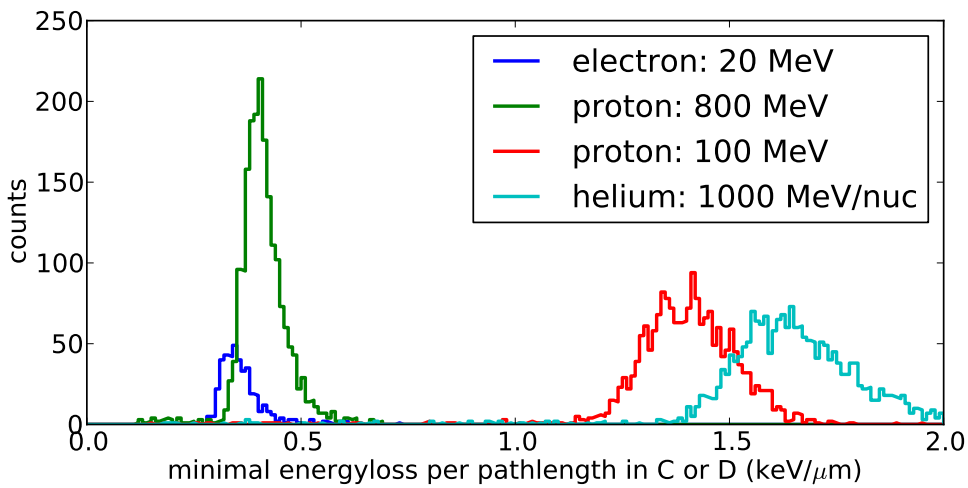
- forward penetrating particles
- backward penetrating particles

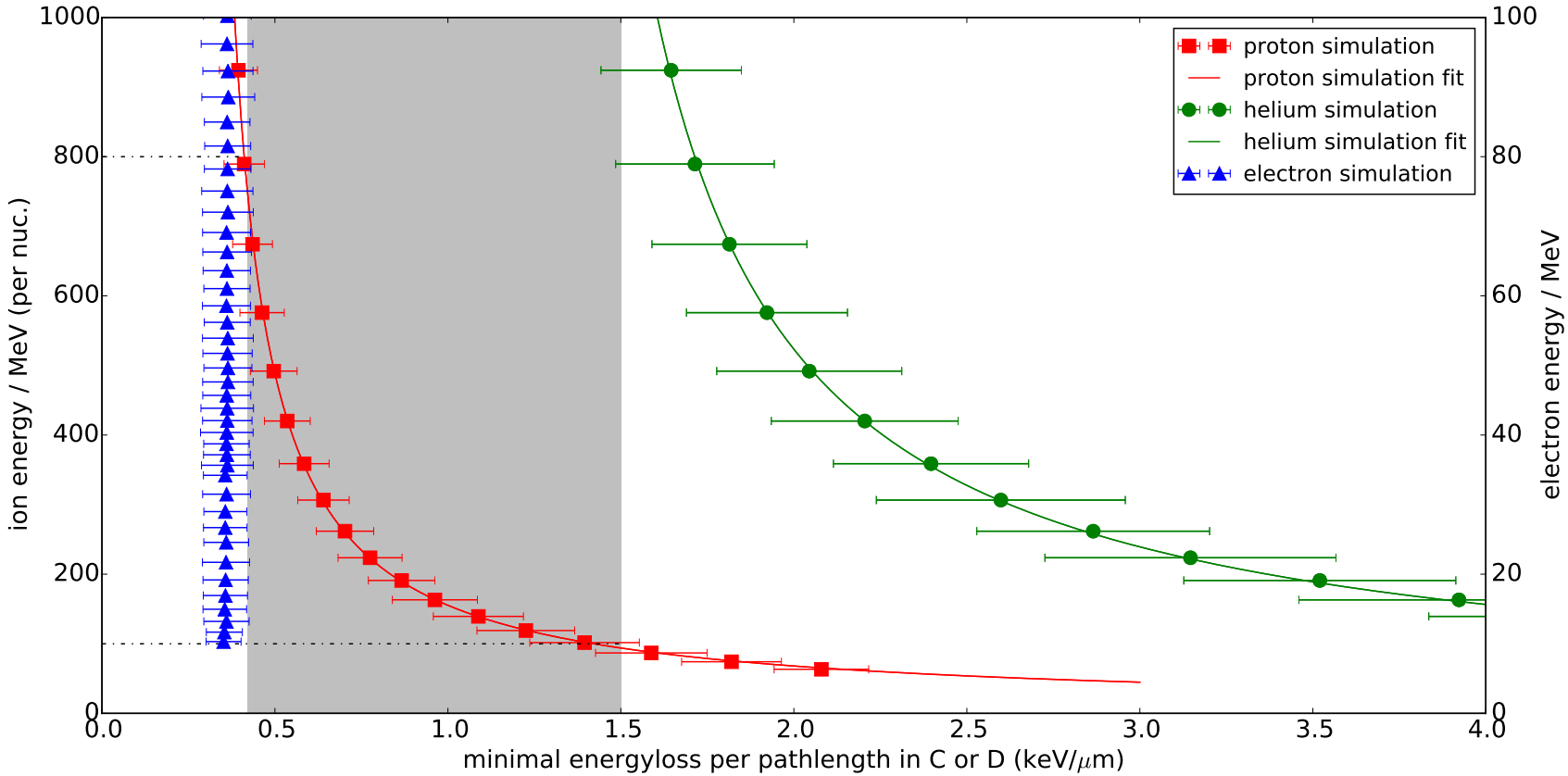
forward penetrating particles



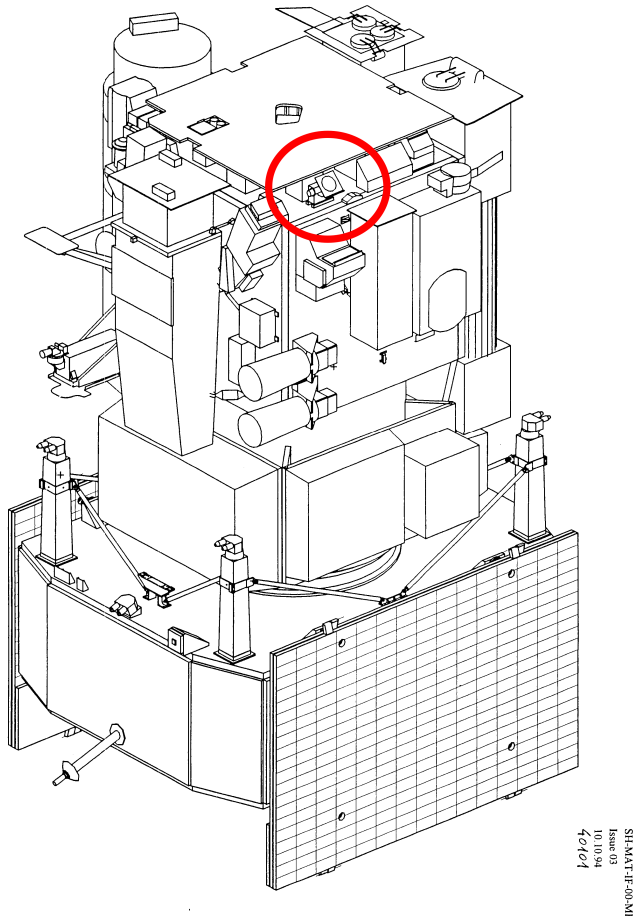


[Kühl et al. 2015, PoS]

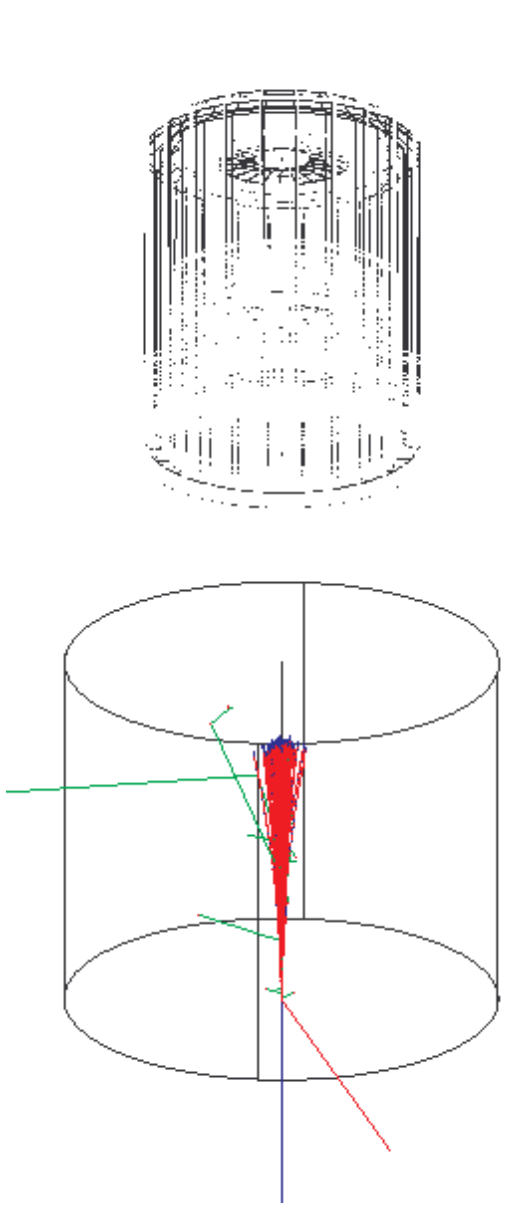




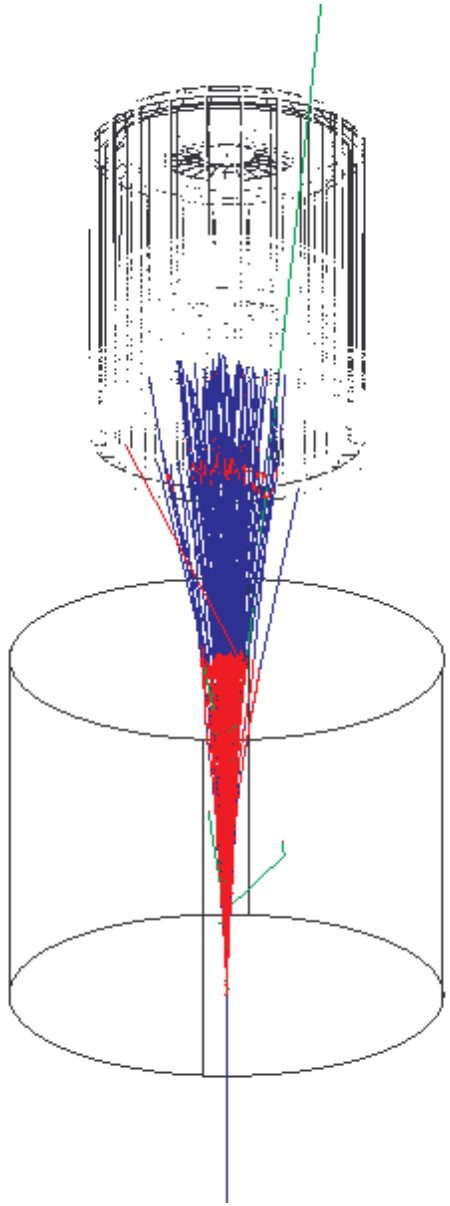
[adapted from Kühl et al. 2015, PoS]



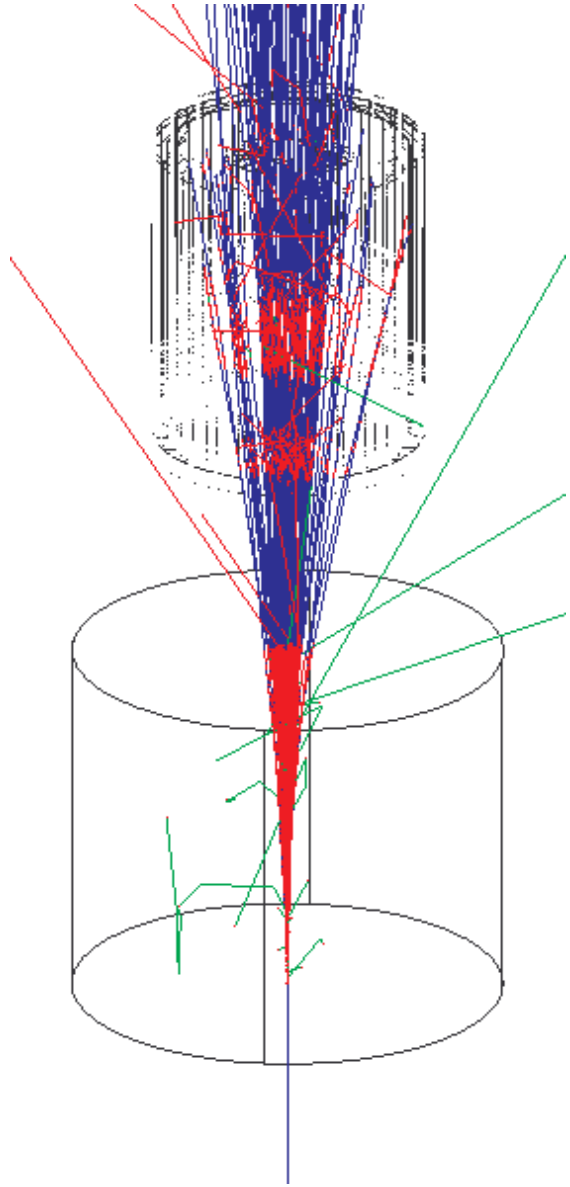
[Courtesy of SOHO (ESA & NASA)]



150 MeV



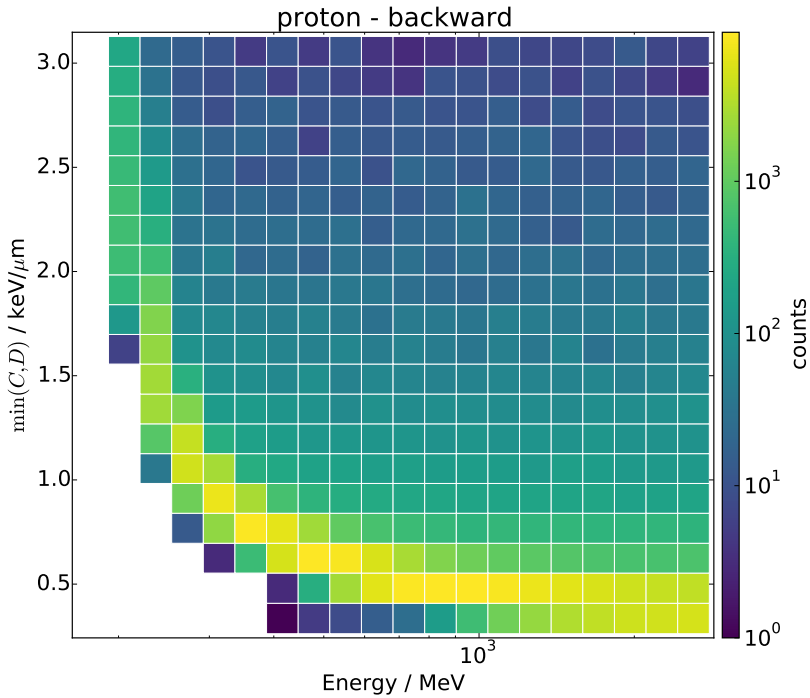
180 MeV

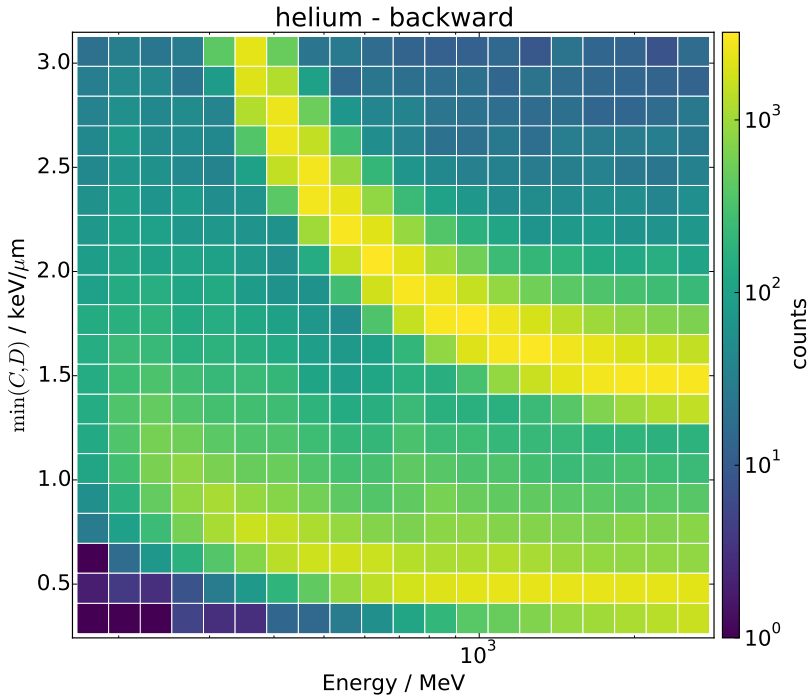


200 MeV

[Kühl et al. 2015, PoS]

backward penetrating particles





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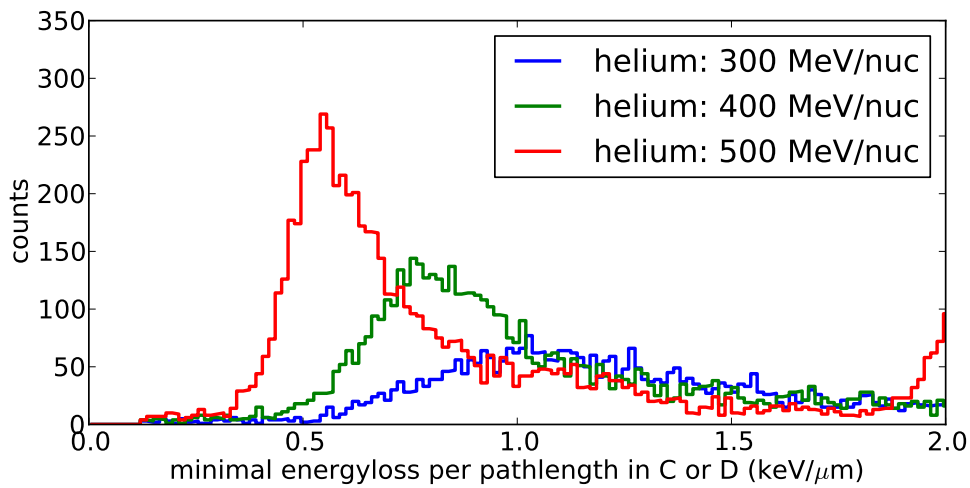
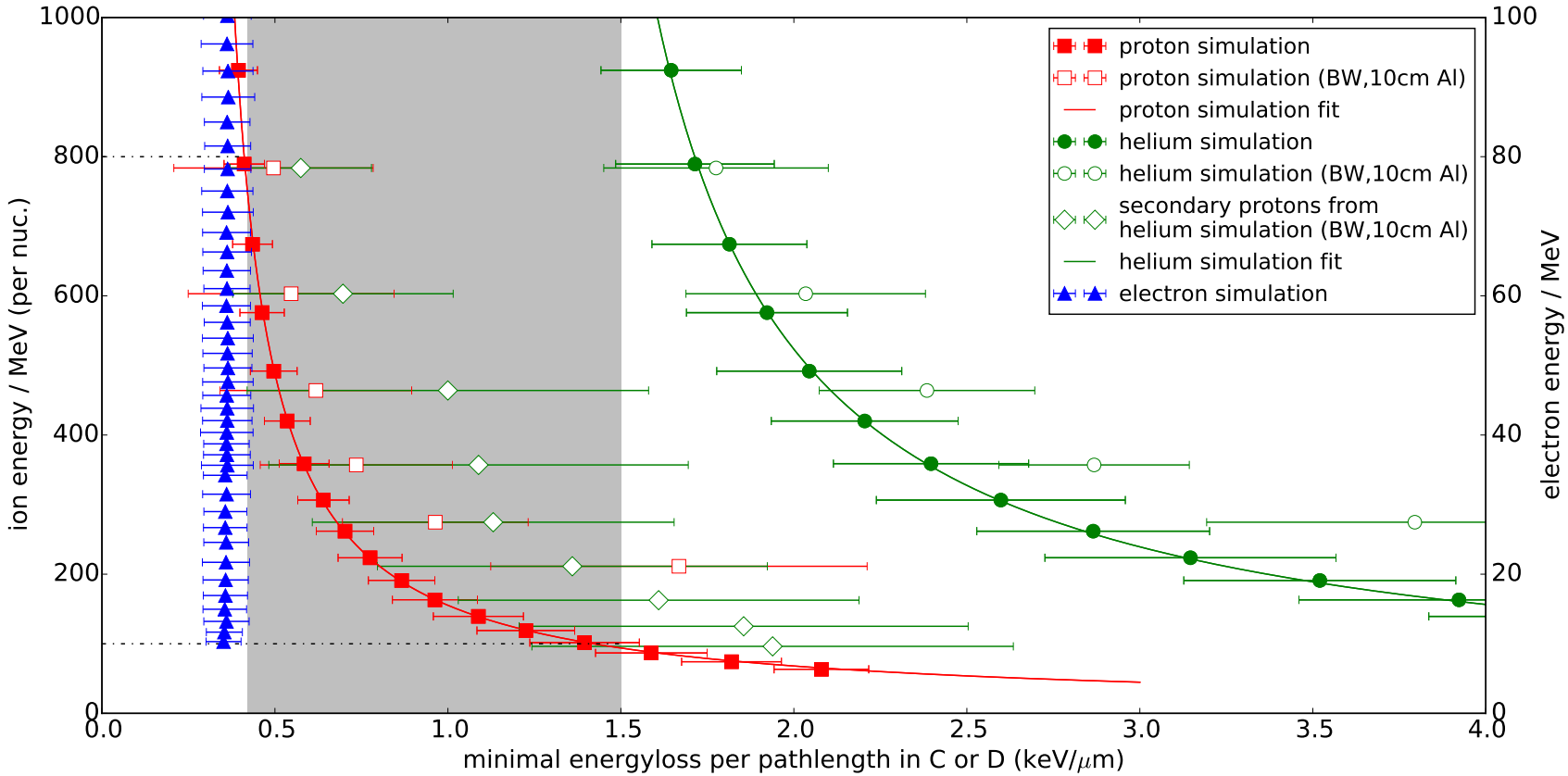
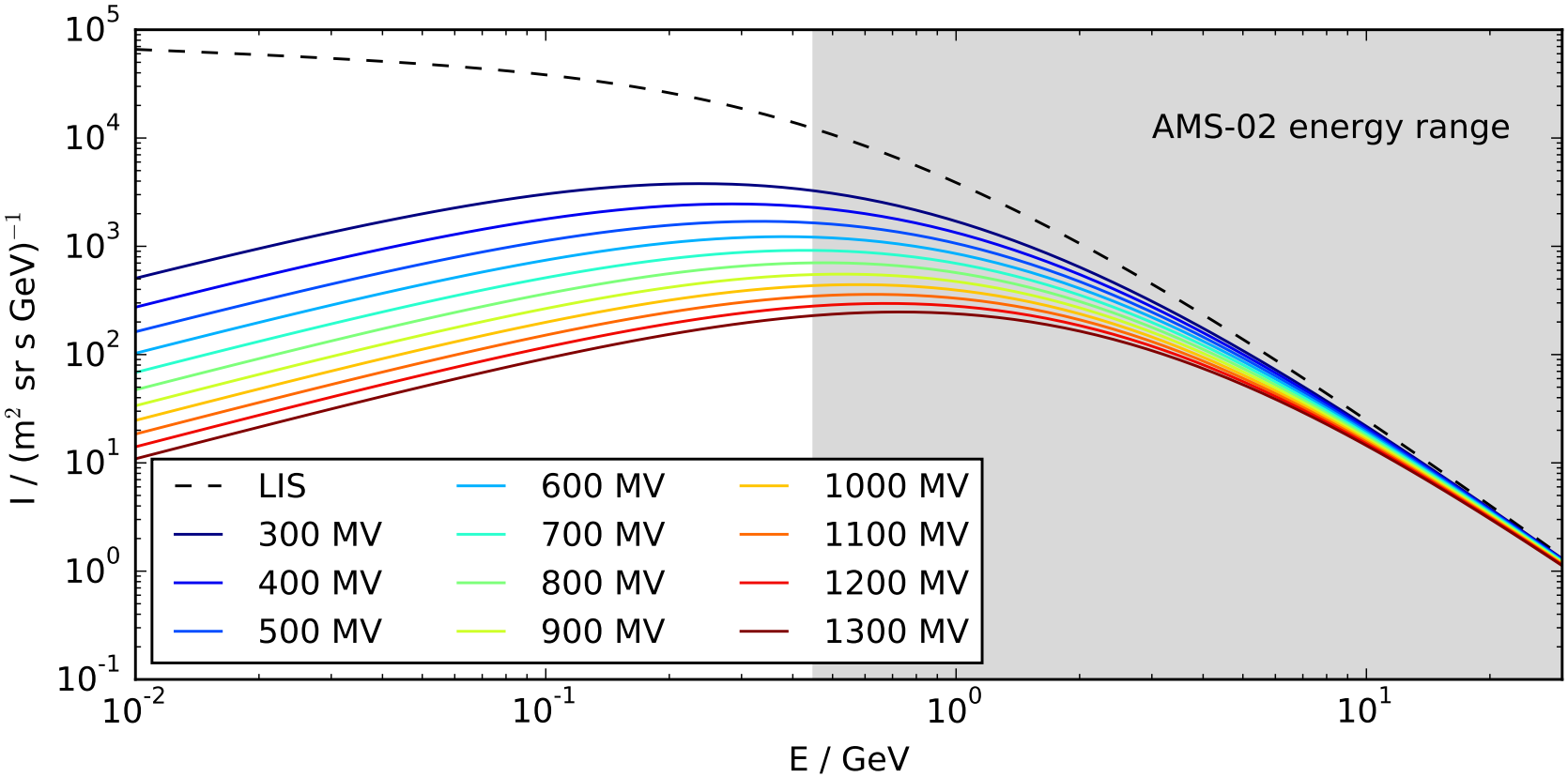


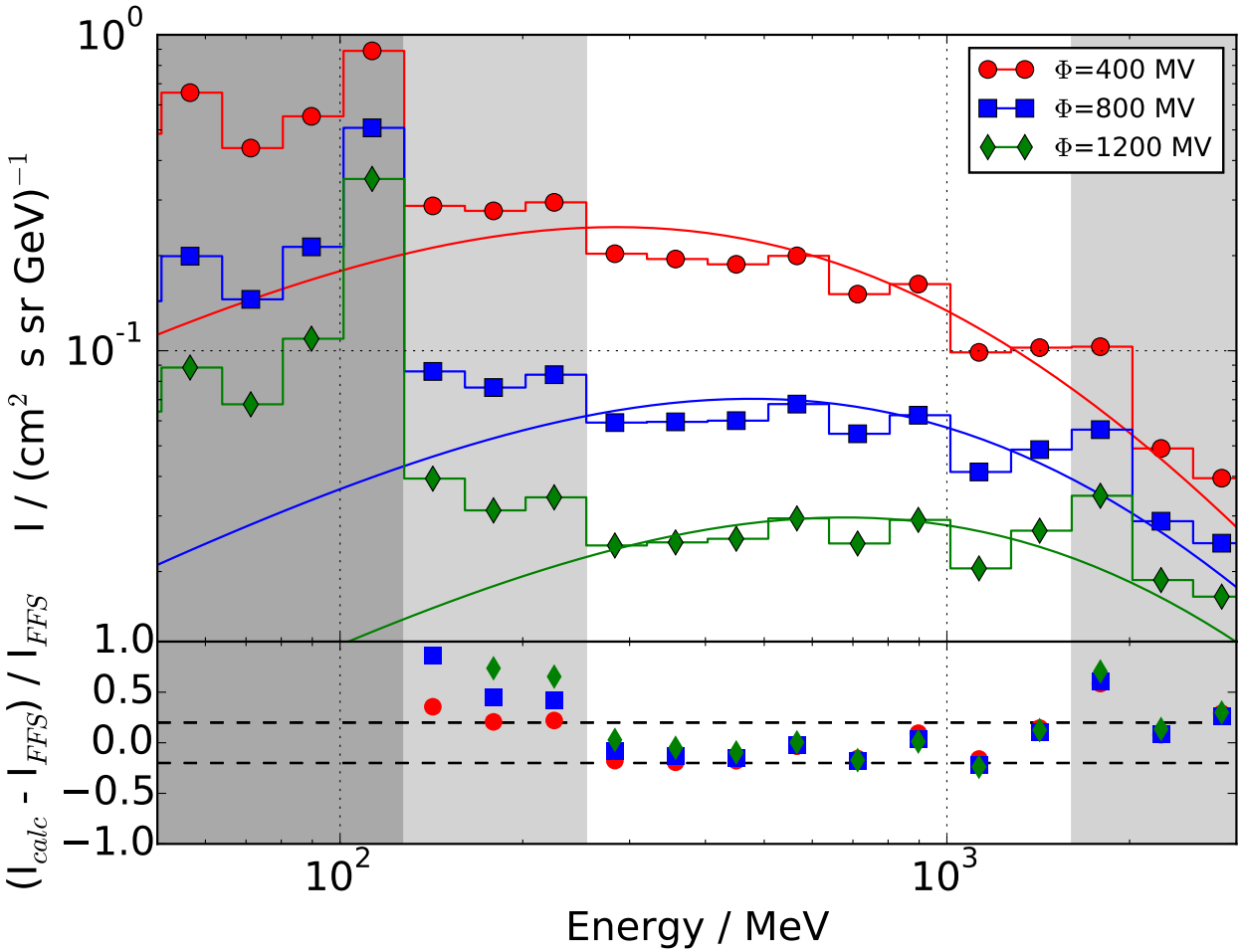


[Kühl et al. 2015, PoS]

Galactic Cosmic Rays (GCRs)

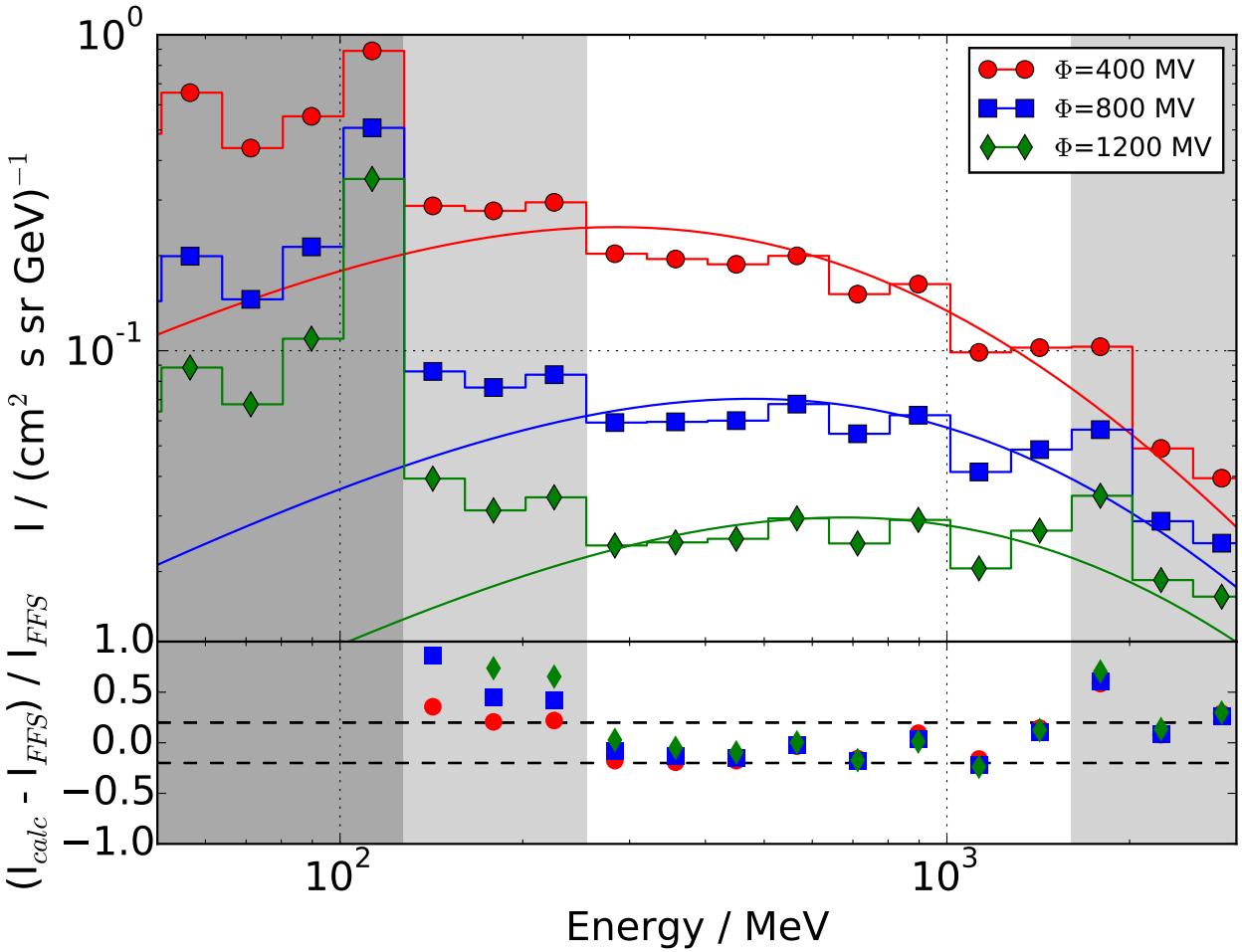


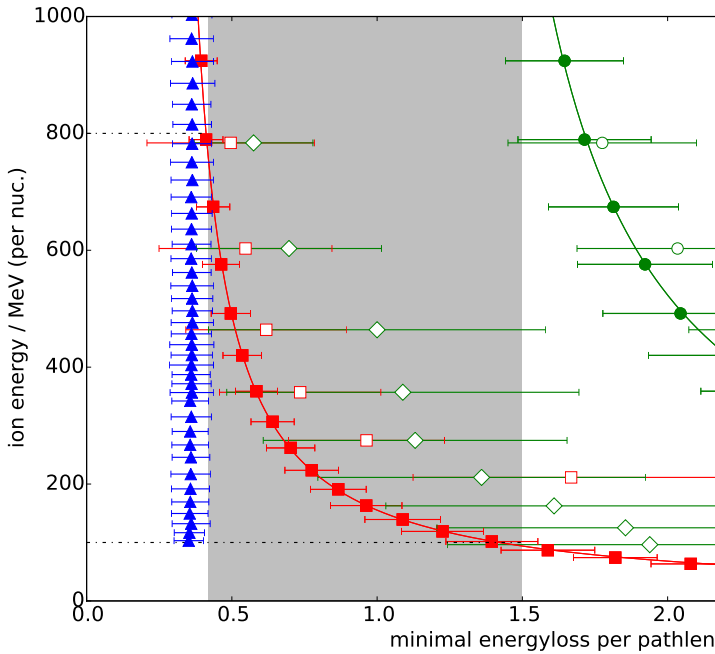
- Force Field Solution as approximation of the GCR spectrum



[Kühl et al. 2016, Solar Physics]

- 250 MeV - 1.6 GeV : systematic uncertancies below 20%
- statistical errors are in the order of $\approx$ 10%, 2% and 0.5% (for a given day, month/CR, year)





[Kühl et al. 2016, Solar Physics]

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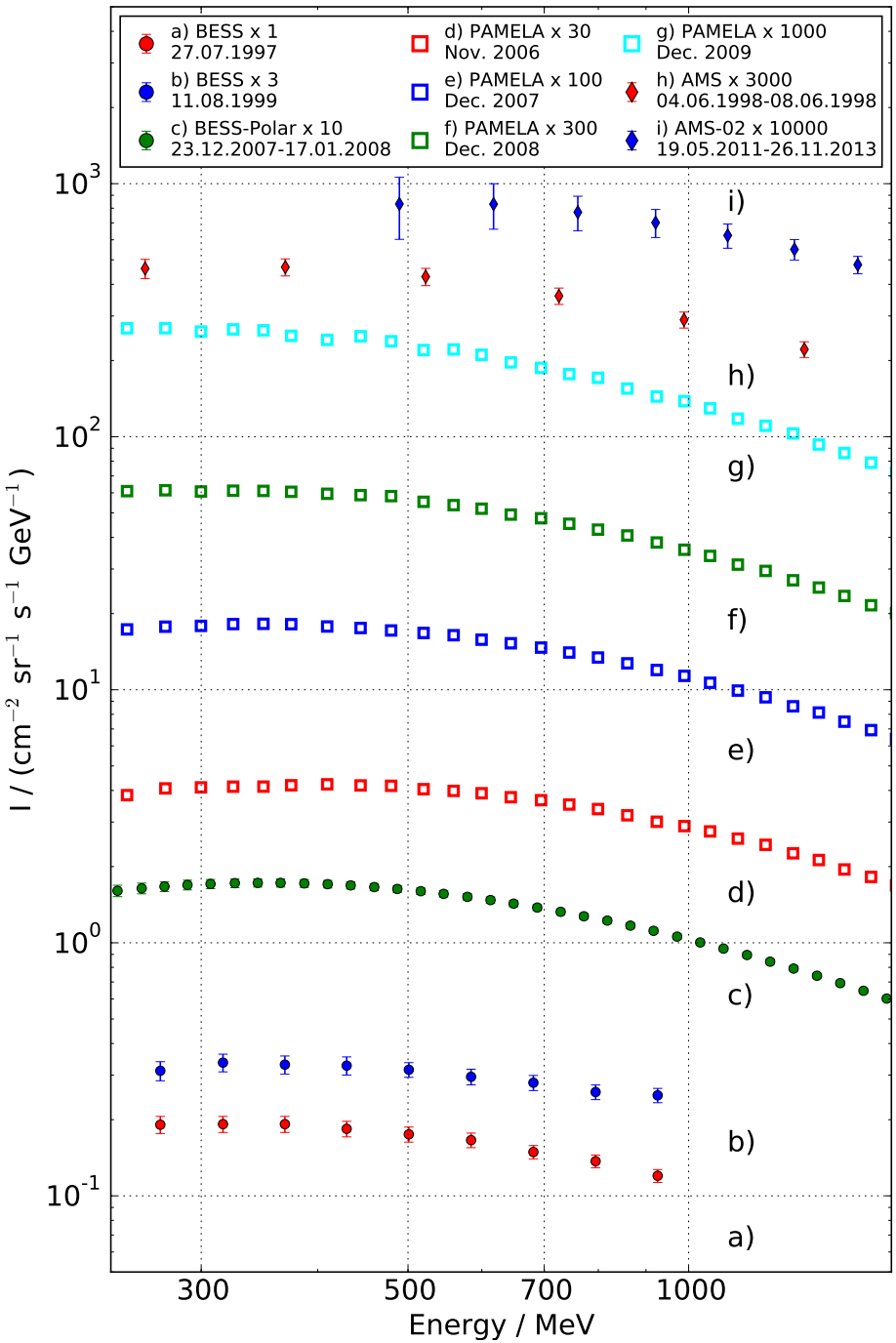
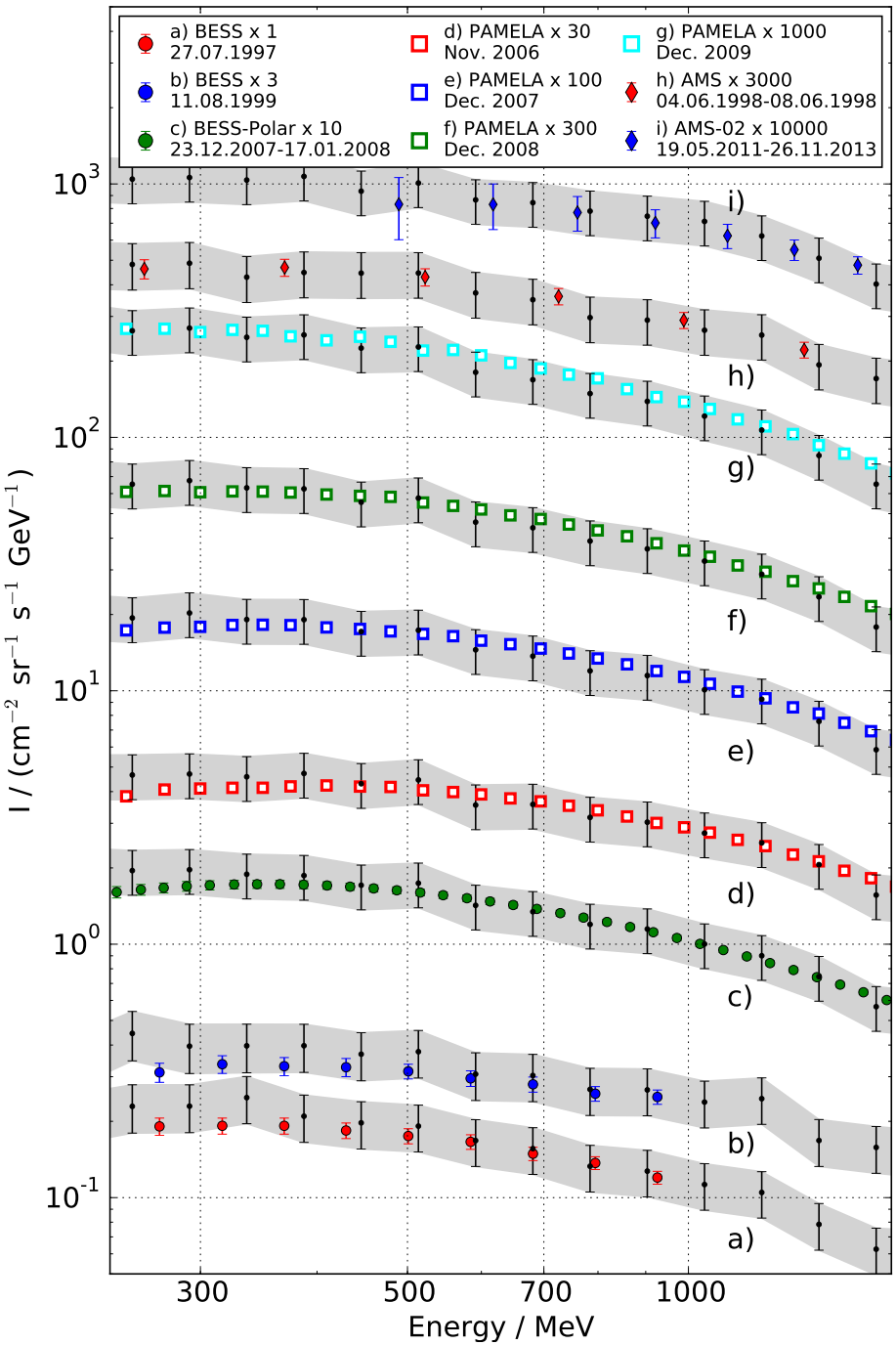


AMS-02	2011 - 2013
AMS	June 1998
PAMELA	Dec. 2009
PAMELA	Dec. 2008
PAMELA	Dec. 2007
PAMELA	Nov. 2006
BESS-Polar	Dec. 2007
BESS	Aug. 1999
BESS	July 1997

[Kühl et al. 2016, Solar Physics]



AMS-02	2011 - 2013
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PAMELA	Dec. 2009
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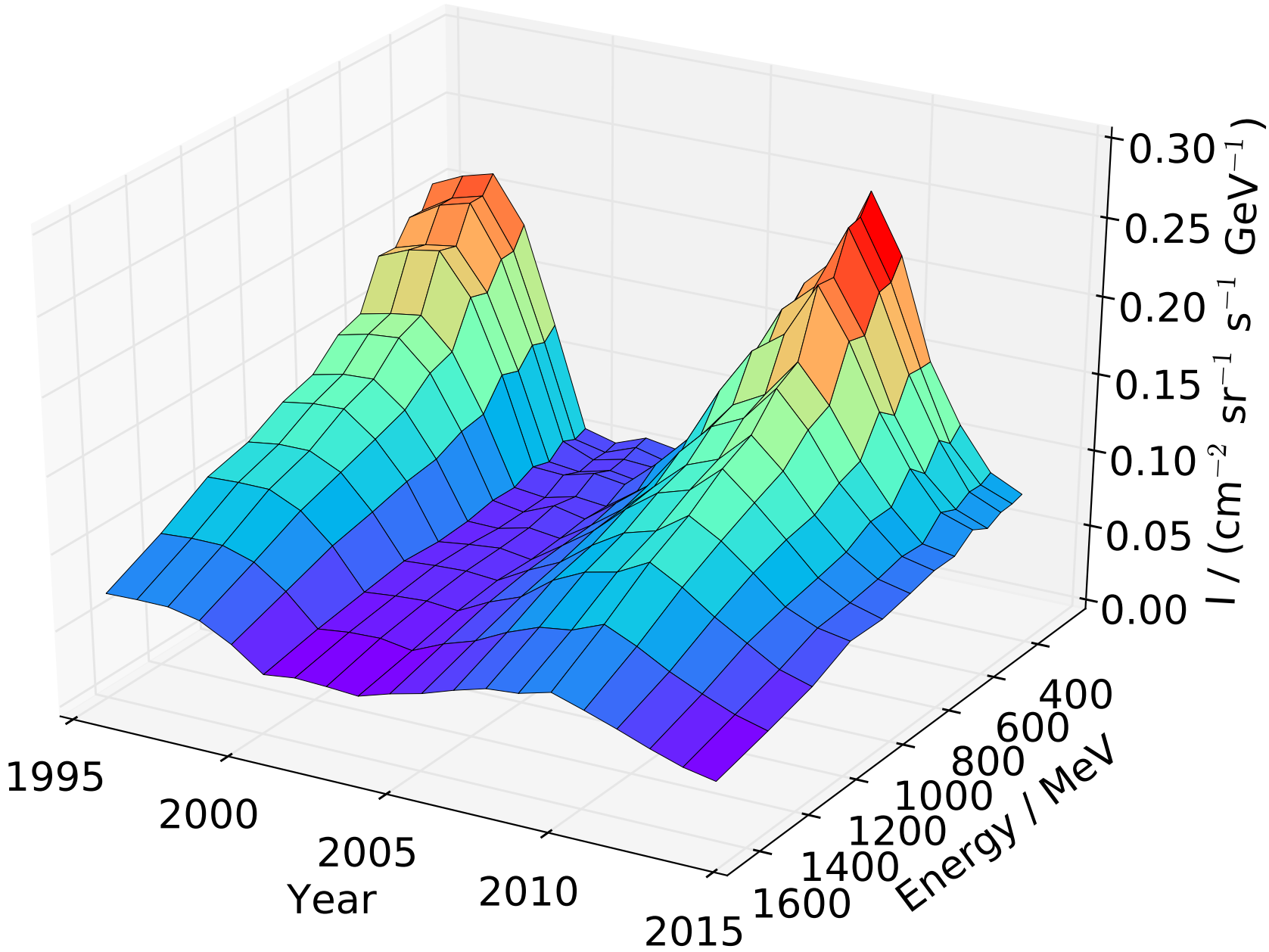
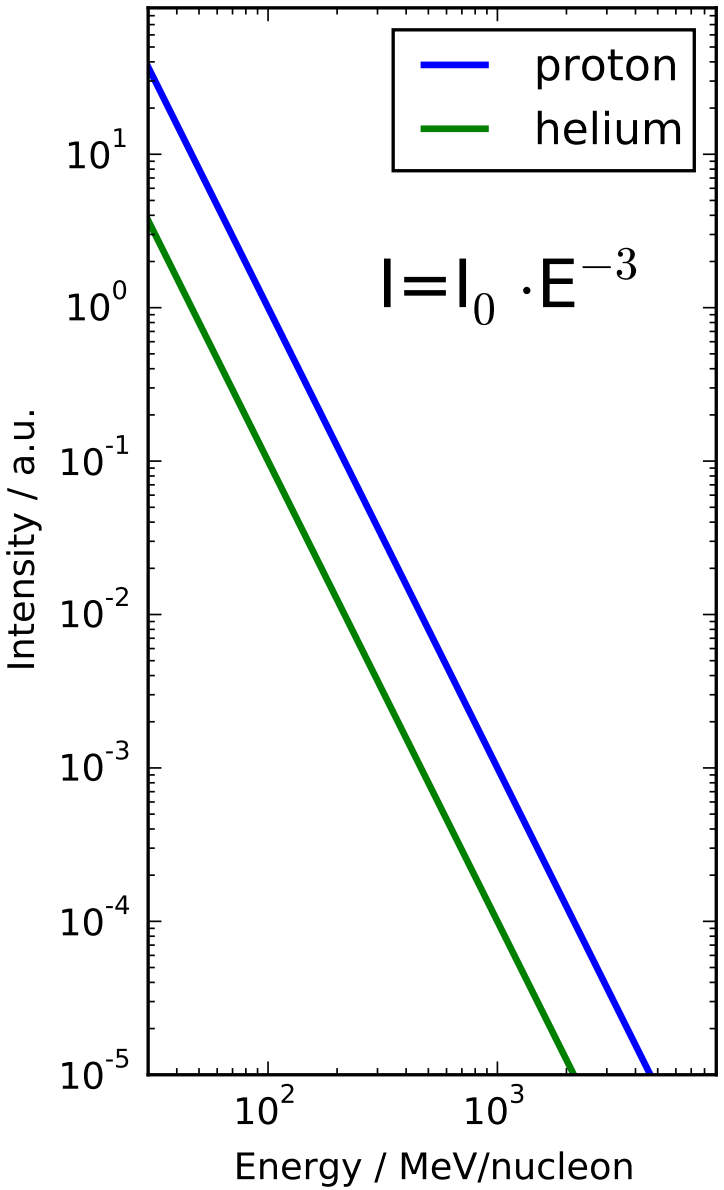
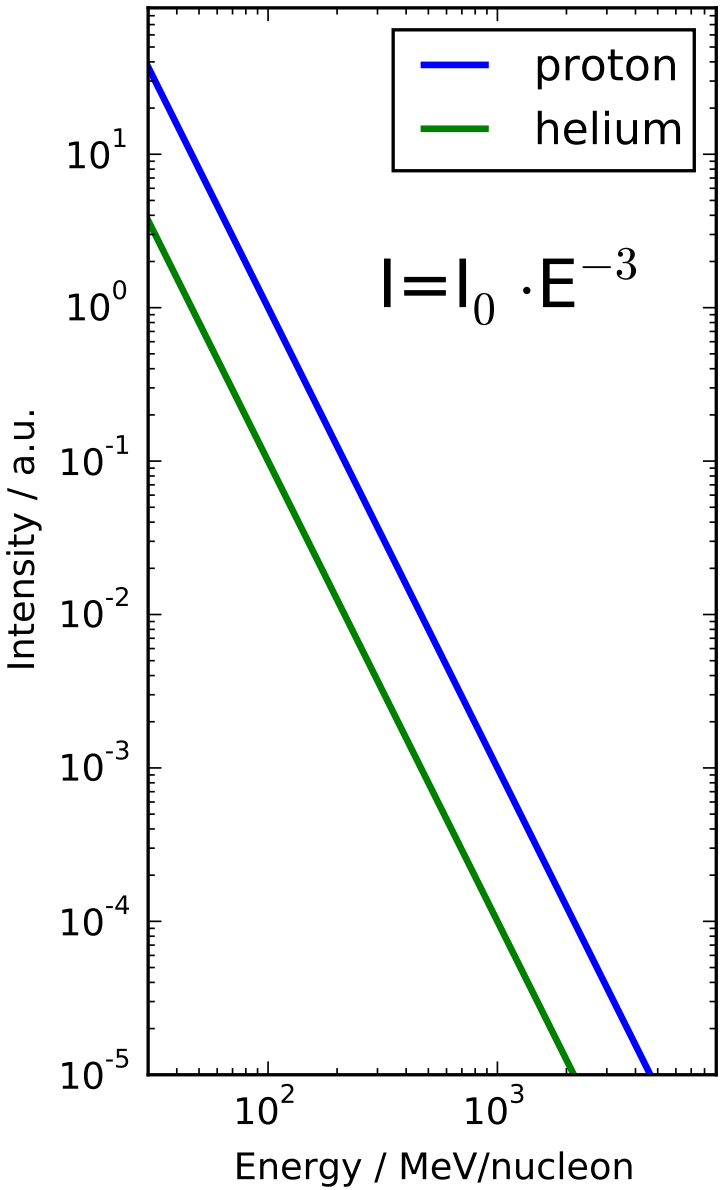
[Kühl et al. 2016, Solar Physics]

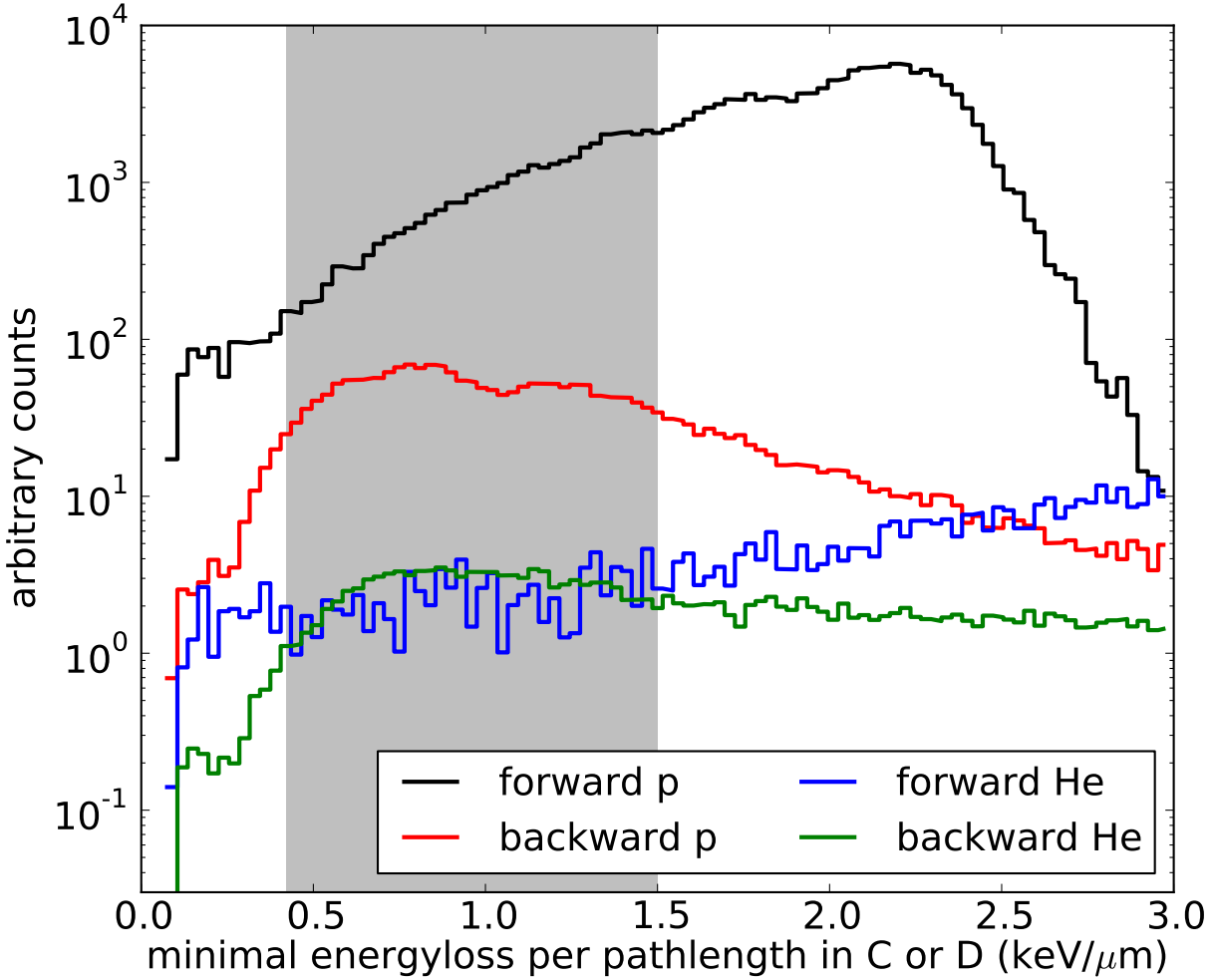

1995
2000
2005
2010
2015
Year
400
600
800
1000
1200
1400
1600
Energy / MeV
0.00
0.05
0.10
0.15
0.20
0.25
0.30
I / (cm^{-2} sr^{-1} s^{-1} GeV^{-1})

Solar Energetic Particle (SEP) Events

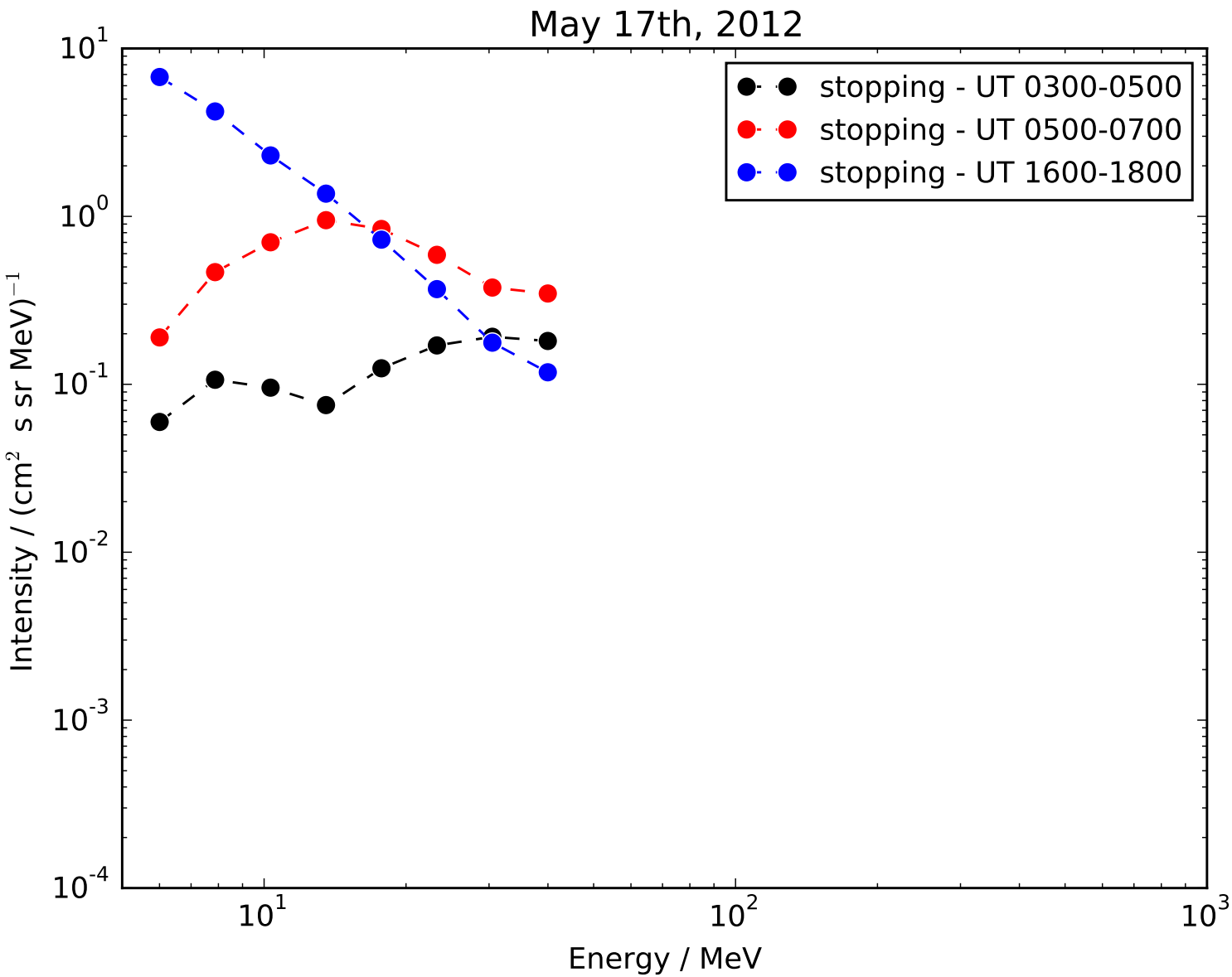


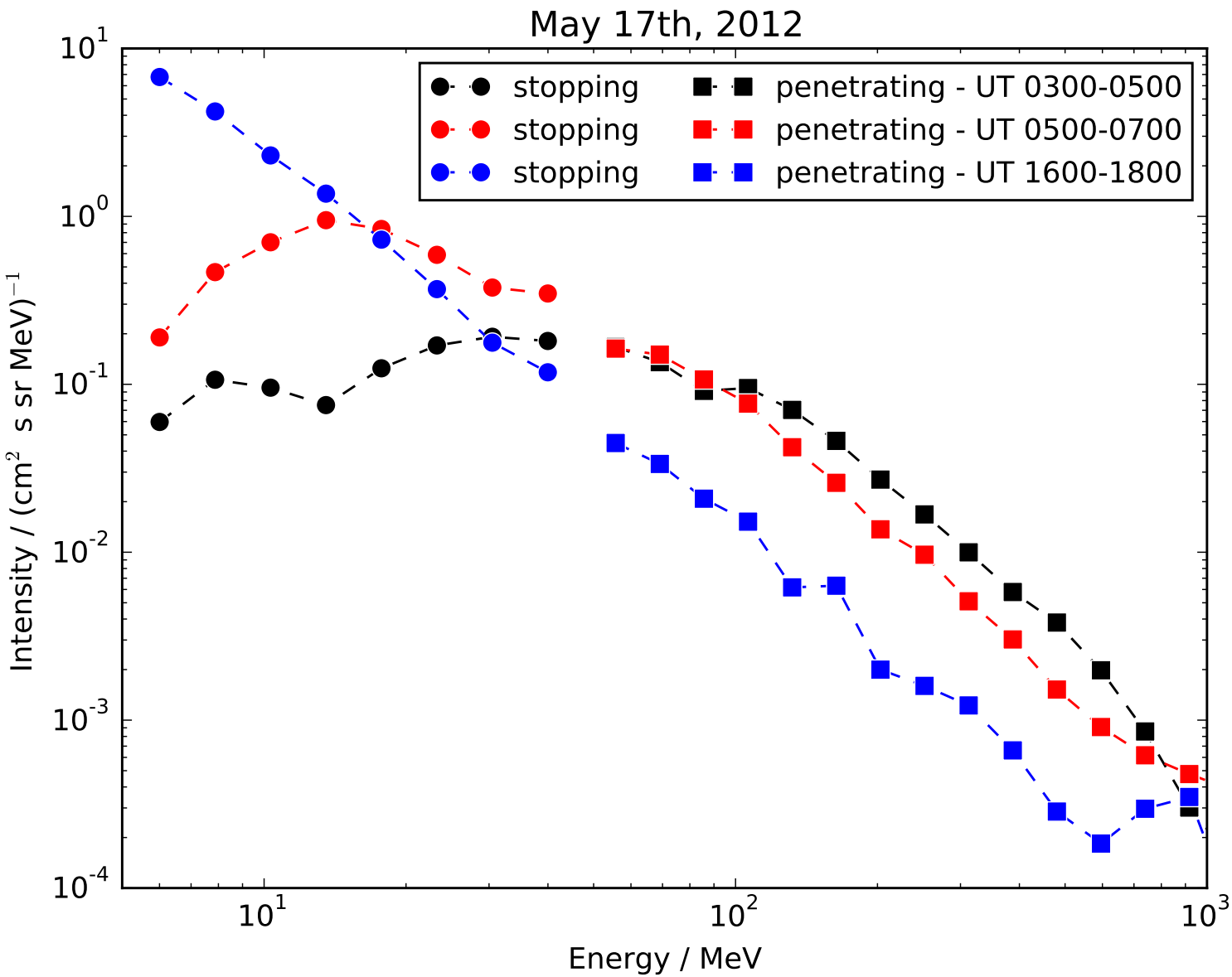
Solar Energetic Particle (SEP) Events

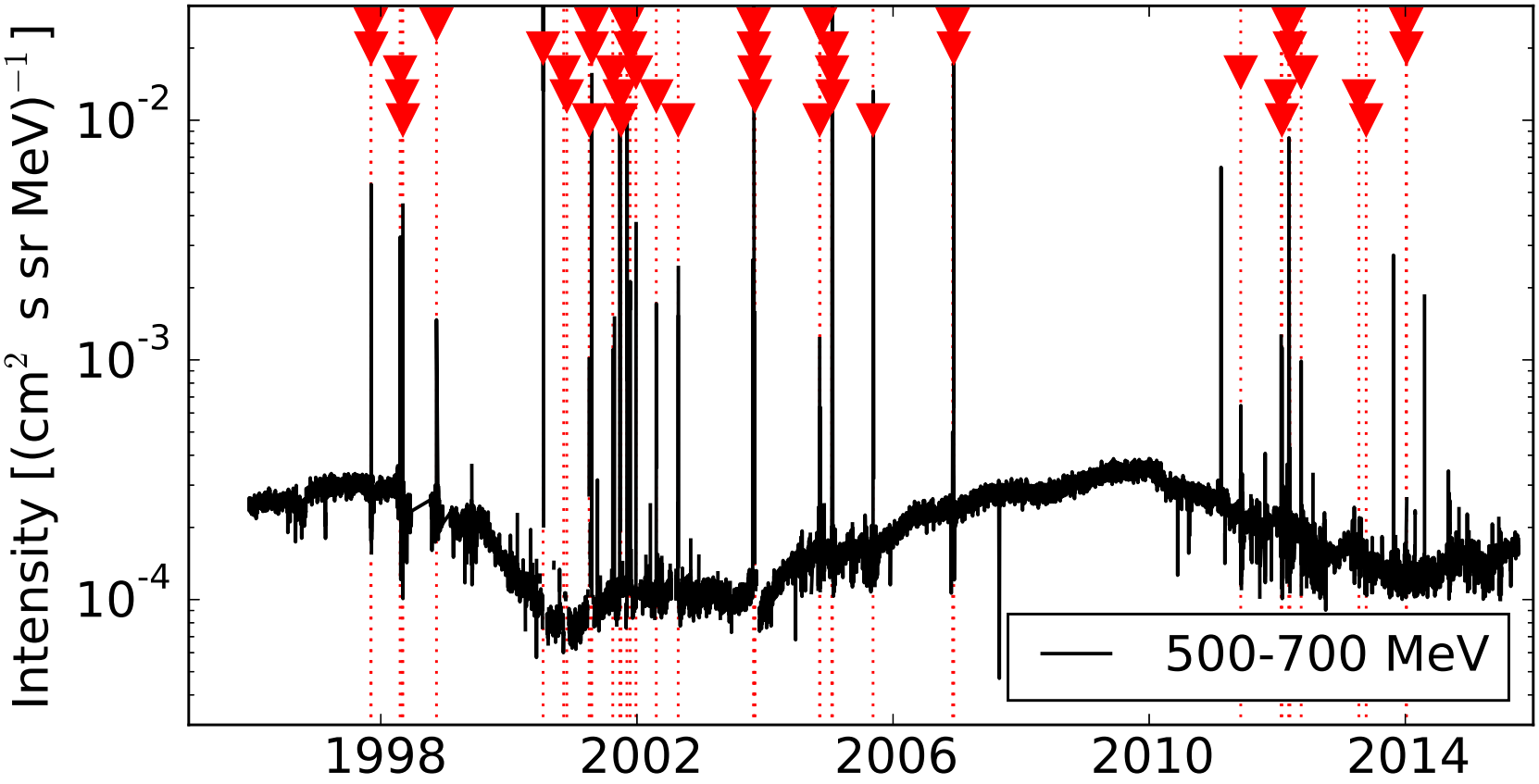




[Kühl et al. 2015, A&A]

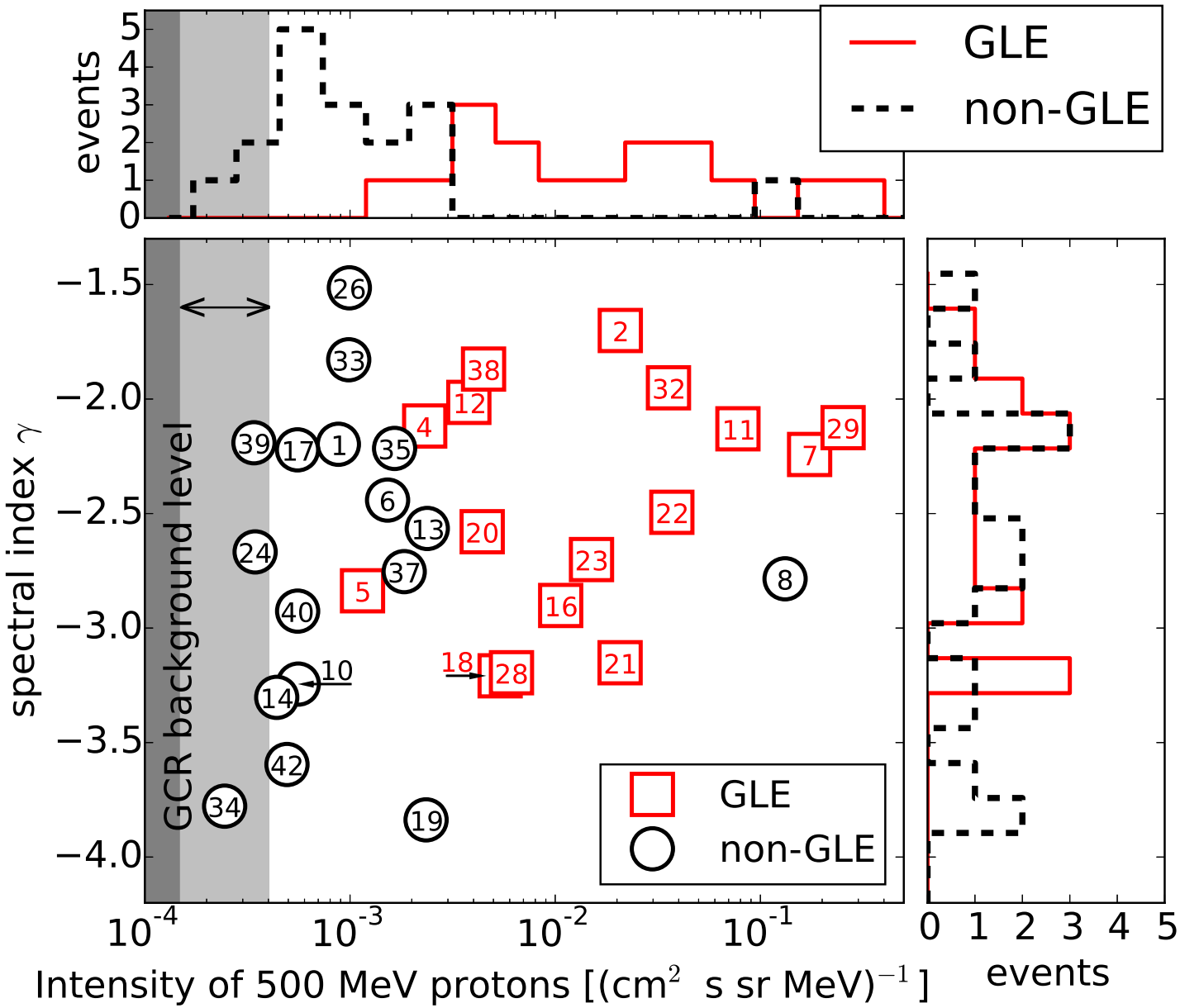

May 17th, 2012
stopping - UT 0300-0500
stopping - UT 0500-0700
stopping - UT 1600-1800
Intensity / (cm^2 s sr MeV)$^{-1}$
Energy / MeV
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3


May 17th, 2012
stopping
stopping
stopping
penetrating - UT 0300-0500
penetrating - UT 0500-0700
penetrating - UT 1600-1800
Intensity / (cm^2 s sr MeV)$^{-1}$
Energy / MeV
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3

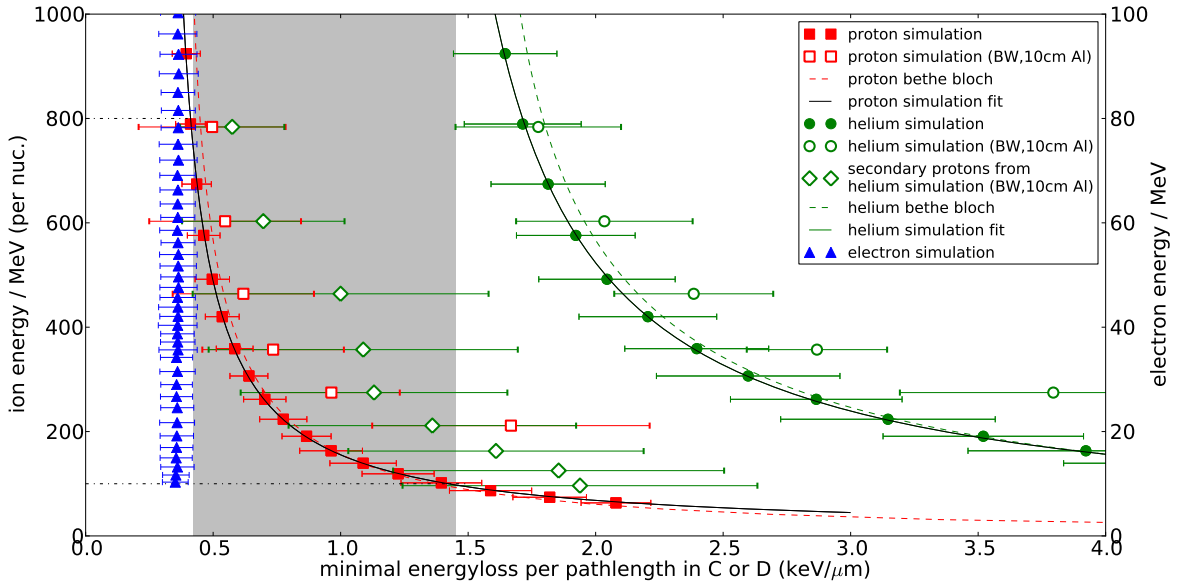


[Kühl et al. 2017, Solar Physics]

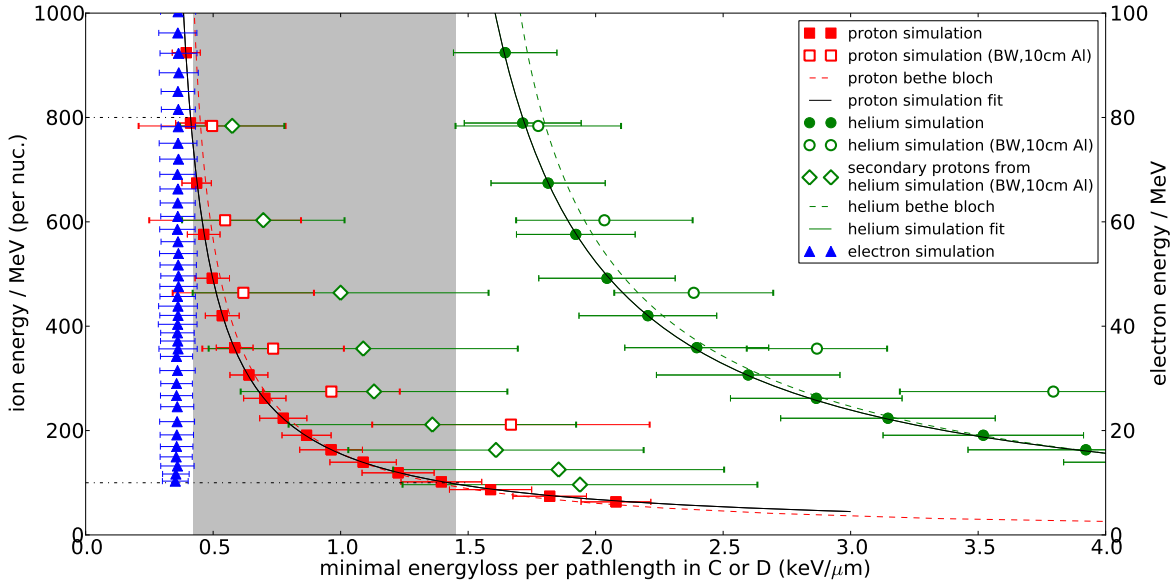
- 42 events with proton energies above 500 MeV
- 32 events in solar cycle 23; 10 events in solar cycle 24
- GLEs 55 to 71 have been found (exception: GLE 58)



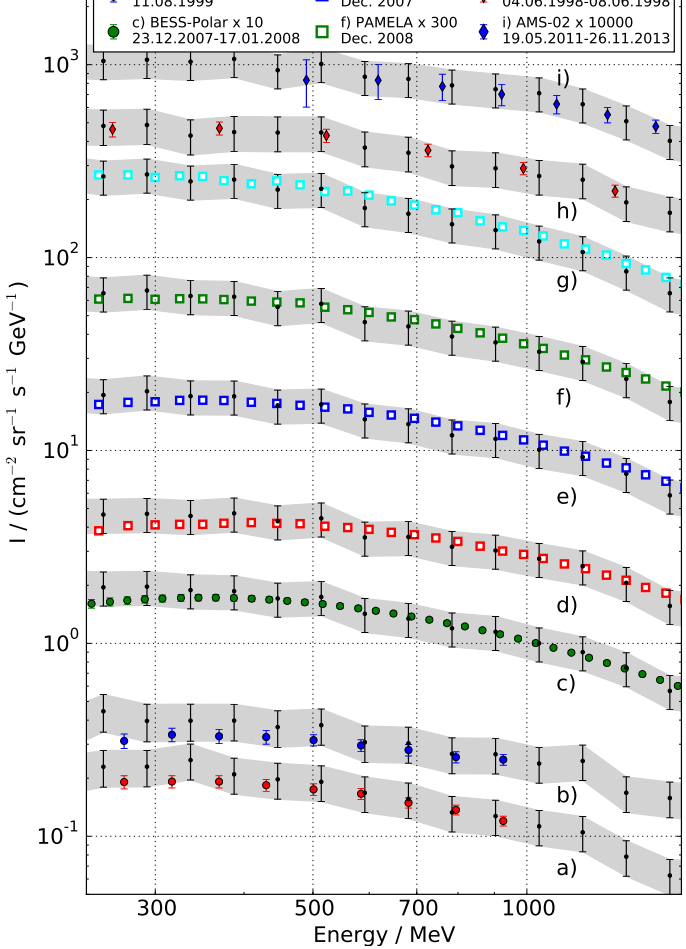
[Kühl et al. 2017, Solar Physics]

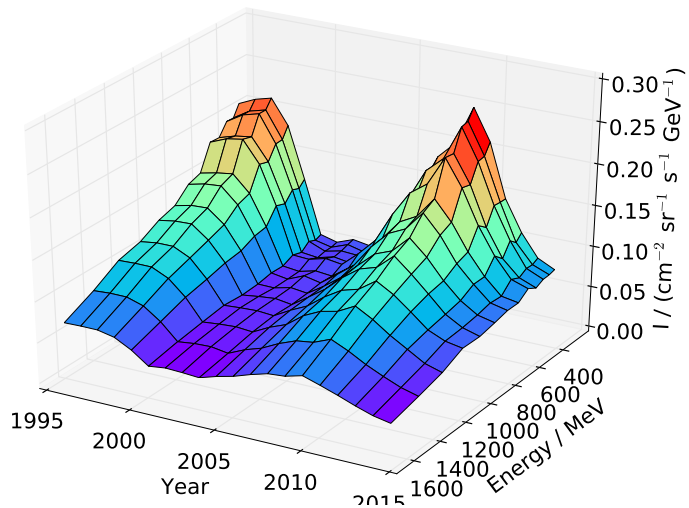


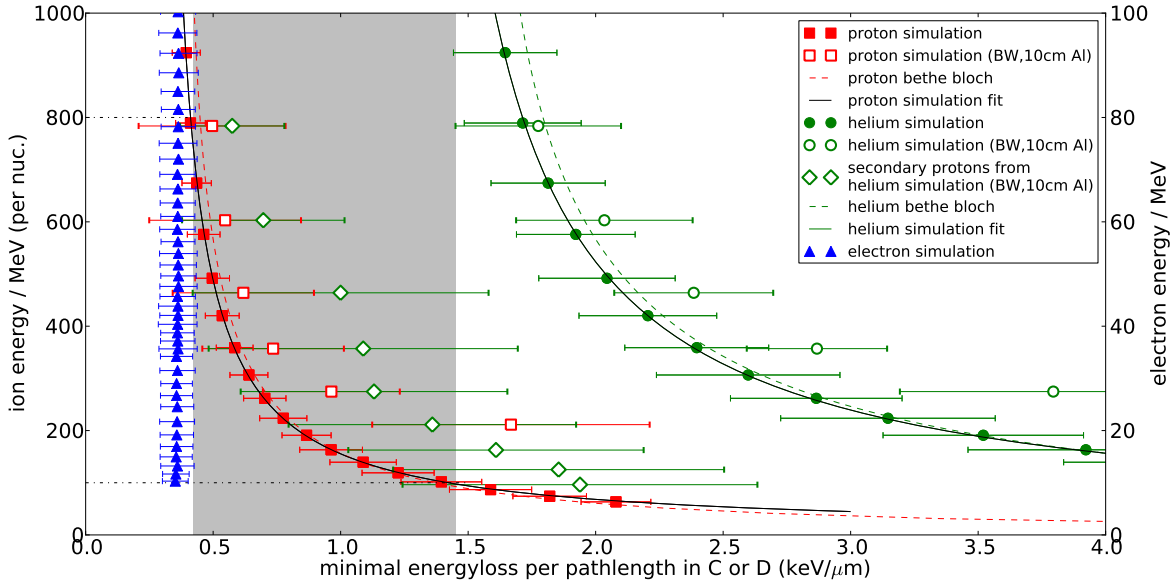
- new method extending the energy range of EPHIN based on instrument simulations

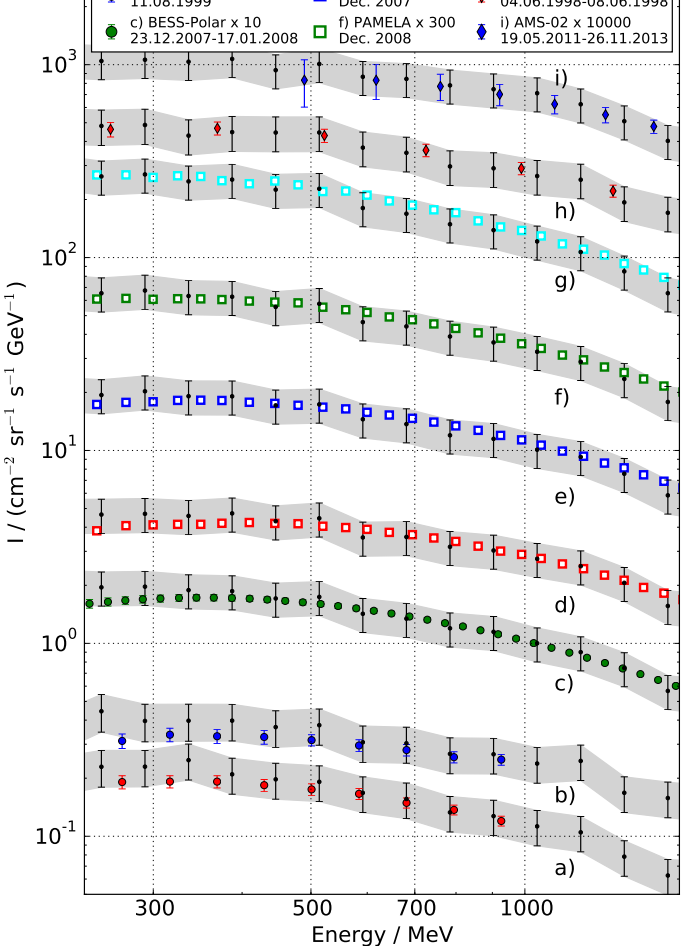


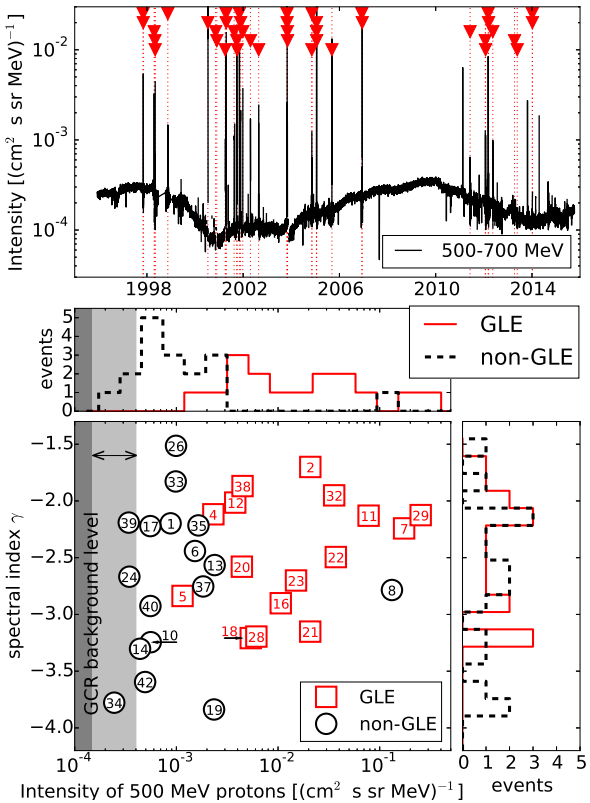
- new method extending the energy range of EPHIN based on instrument simulations
- estimation of uncertainties and validation against other missions
- annual GCR spectrum from 250 MeV up to 1.6 GeV



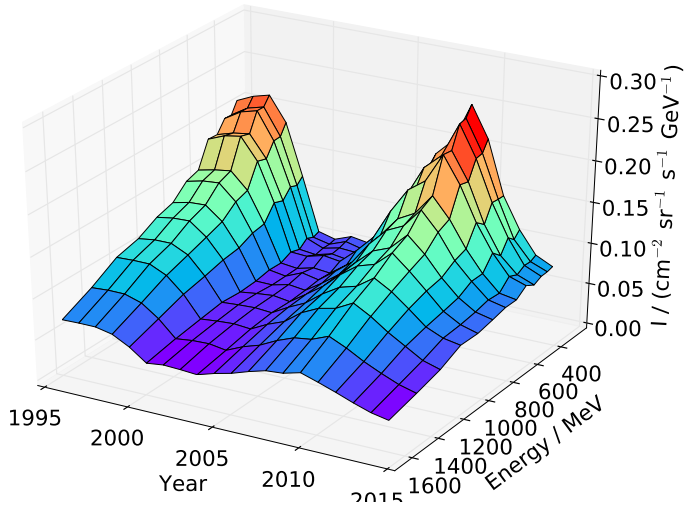


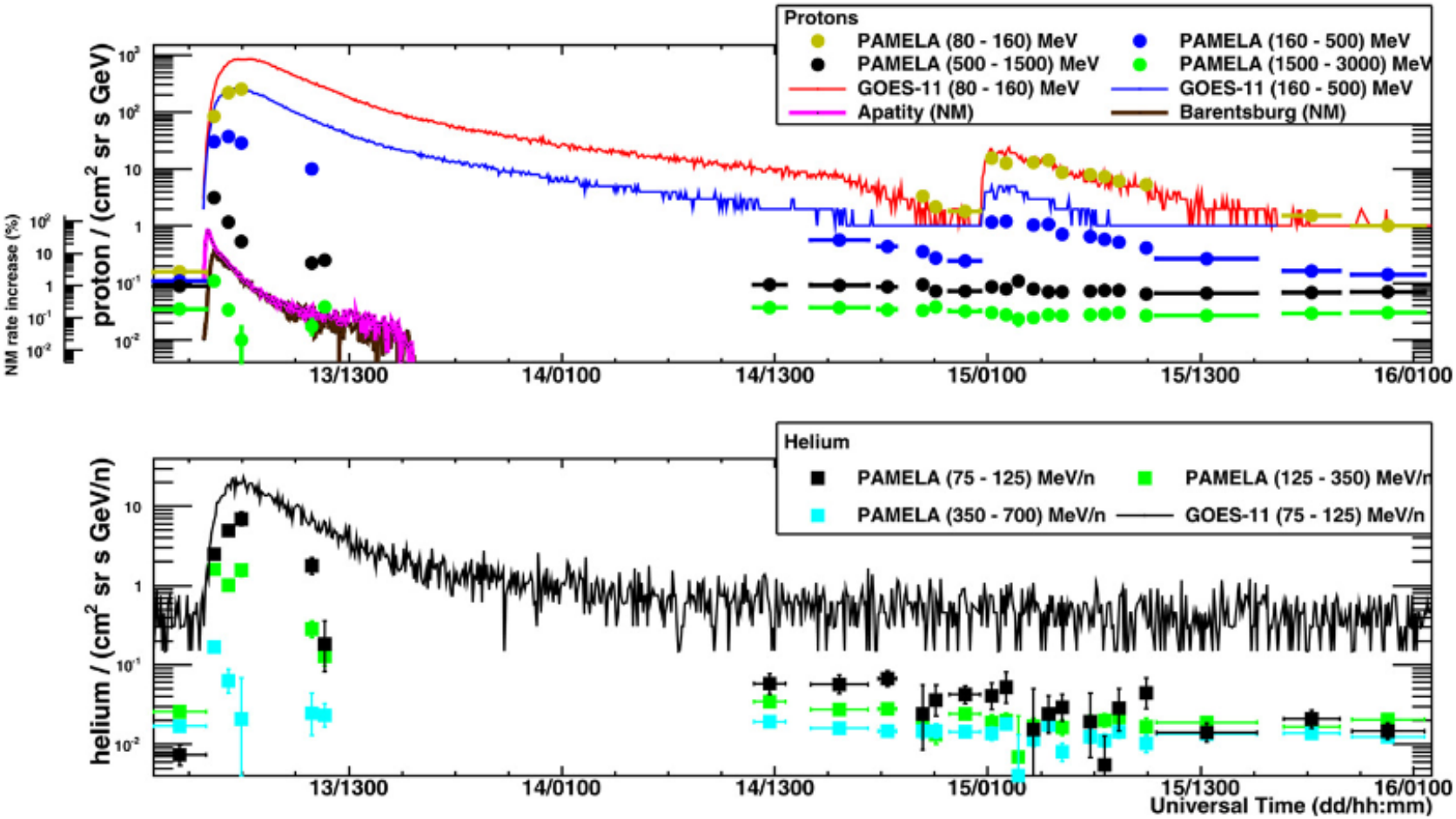




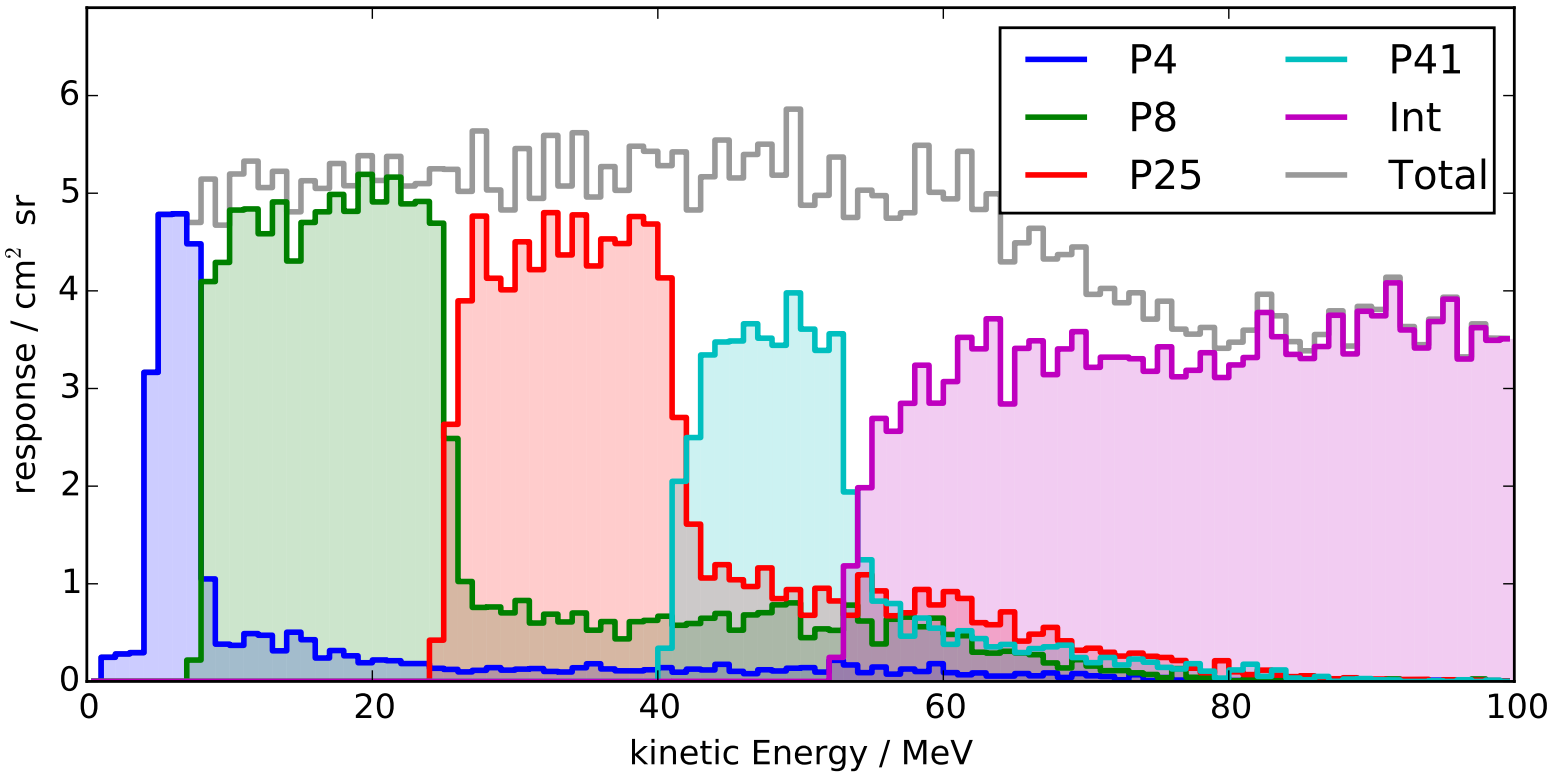


- new method extending the energy range of EPHIN based on instrument simulations
- estimation of uncertainties and validation against other missions
- annual GCR spectrum from 250 MeV up to 1.6 GeV
- SEP events with protons above 500 MeV identified
- statistical analysis based on spectral properties

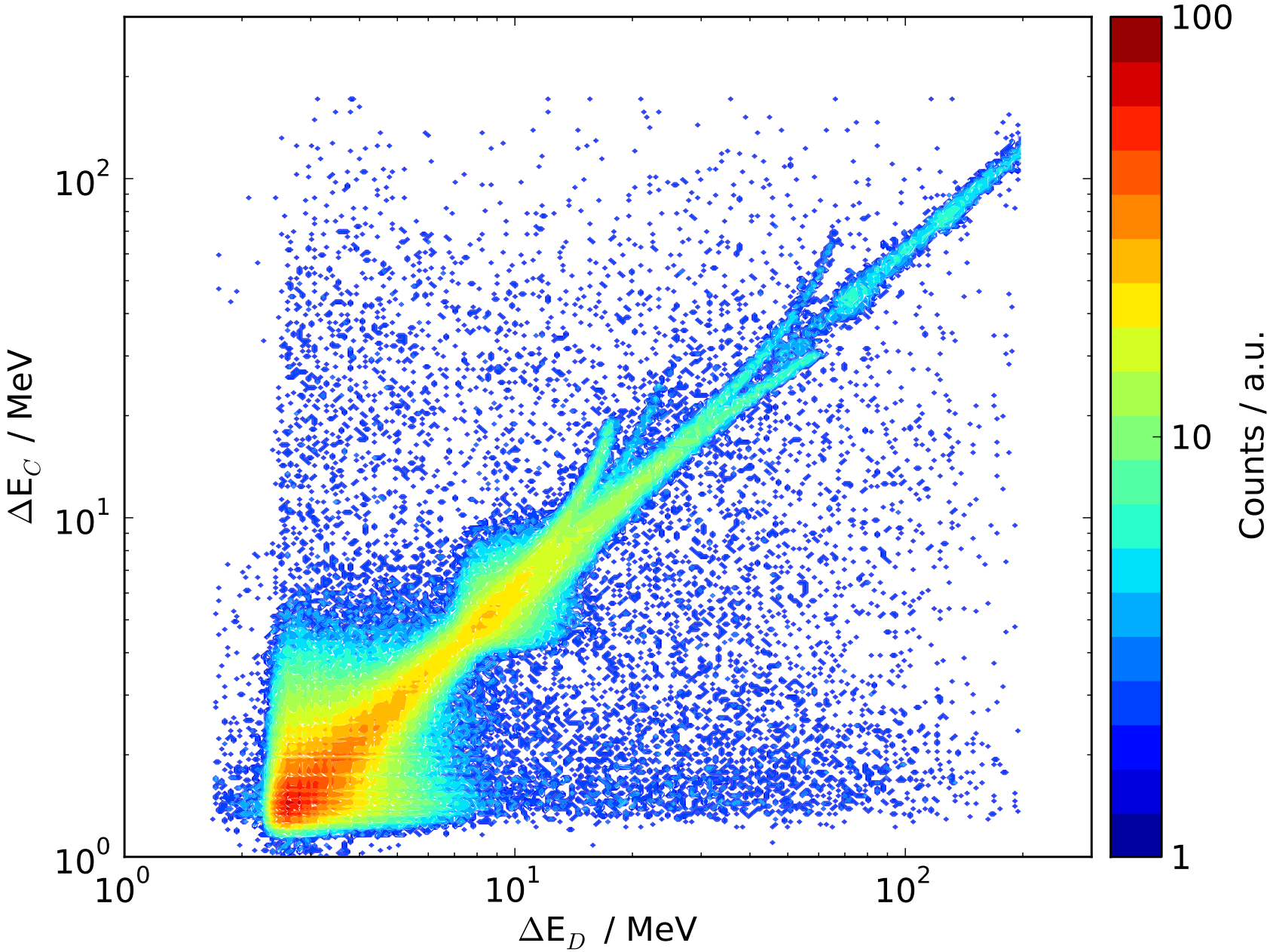


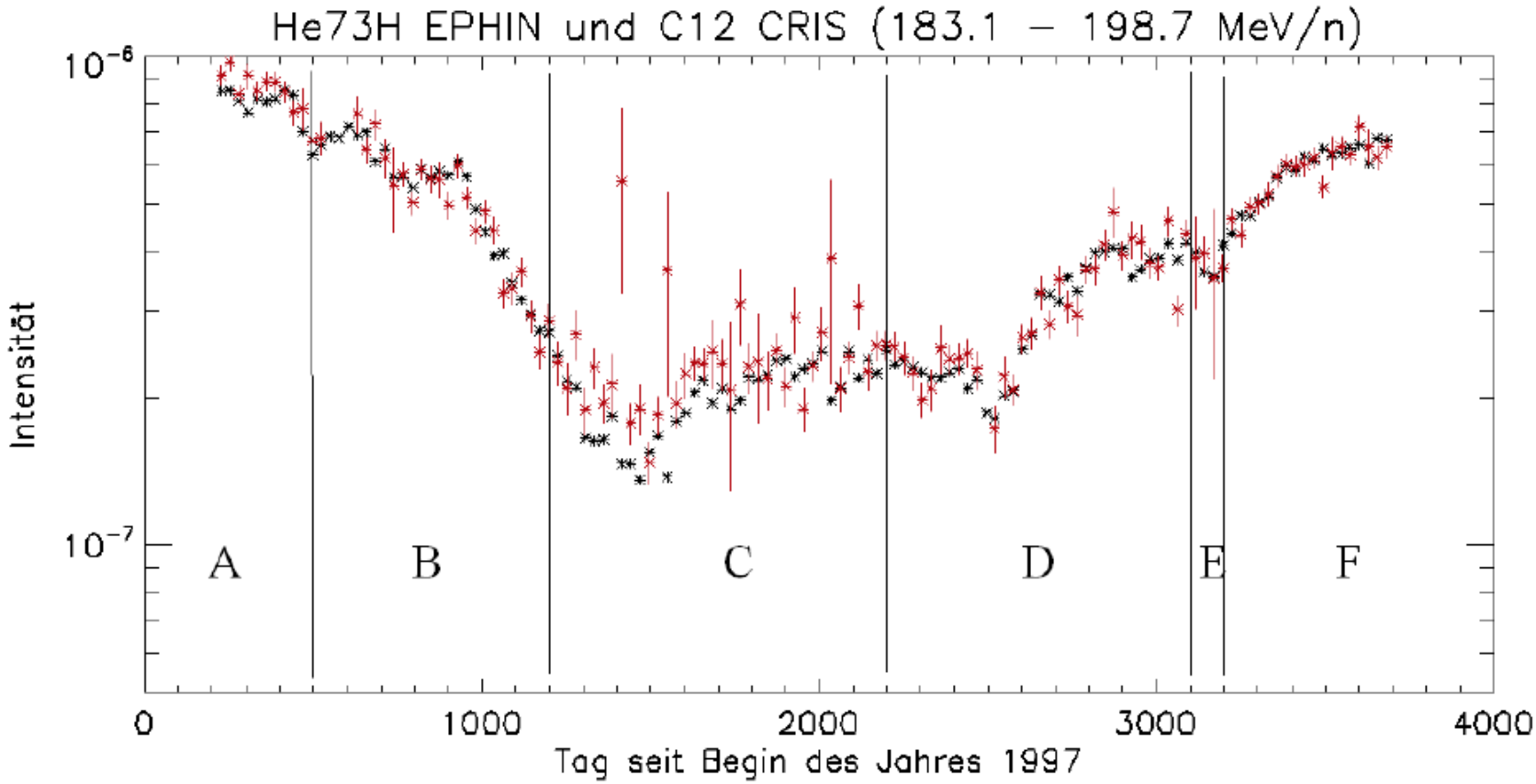


[Adriani et al., 2011]

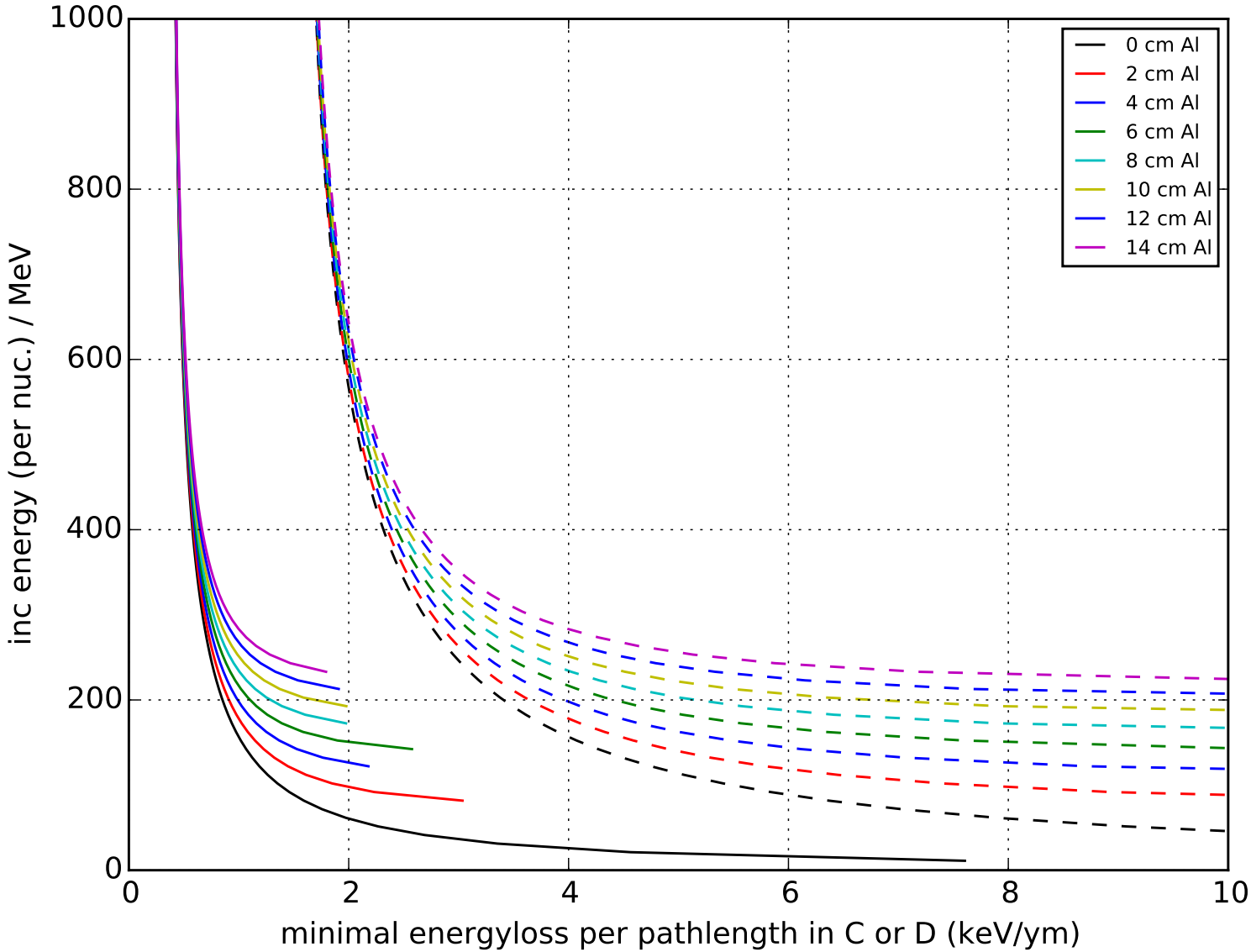


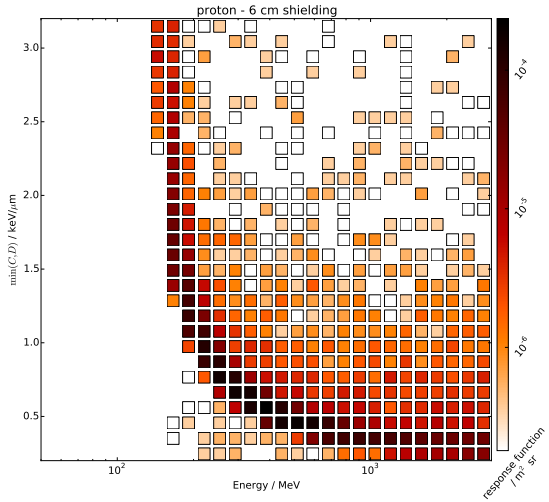
- energy dependent response R derived from instrument simulation
- derive particle instensity I from counts C:
  $C = R \cdot I$

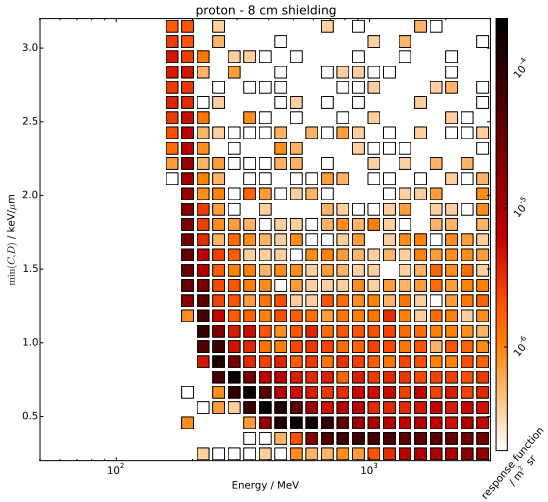

10^2
10^1
10^0
ΔE_C / MeV
10^0
10^1
10^2
ΔE_D / MeV
100
10
1
Counts / a.u.

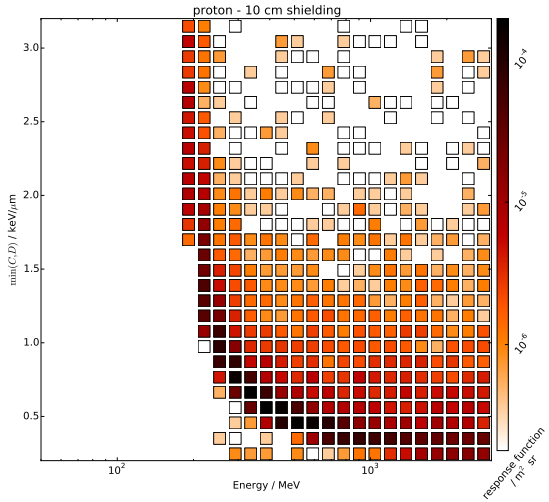


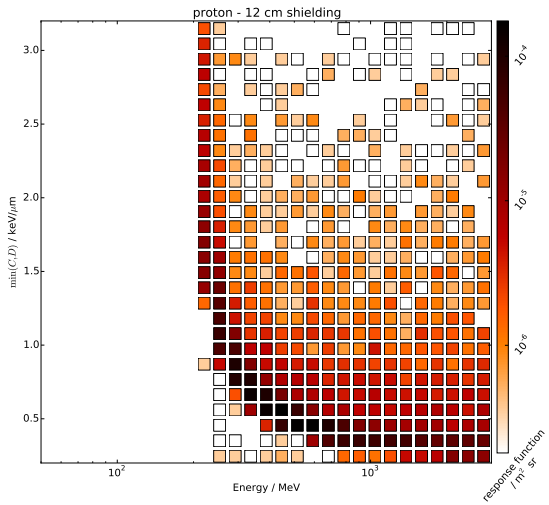
183 - 198 MeV/nuc Carbon (ACE/CRISS, black) and backward Helium (SOHO/EPHIN, red) [Labrenz 2014, priv. comm.]

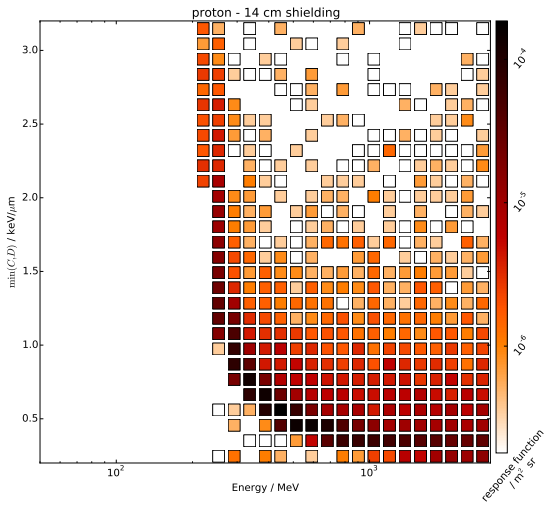

1000
800
600
400
200
0
0
2
4
6
8
10
inc energy (per nuc.) / MeV
minimal energyloss per pathlength in C or D (keV/ym)
0 cm Al
2 cm Al
4 cm Al
6 cm Al
8 cm Al
10 cm Al
12 cm Al
14 cm Al

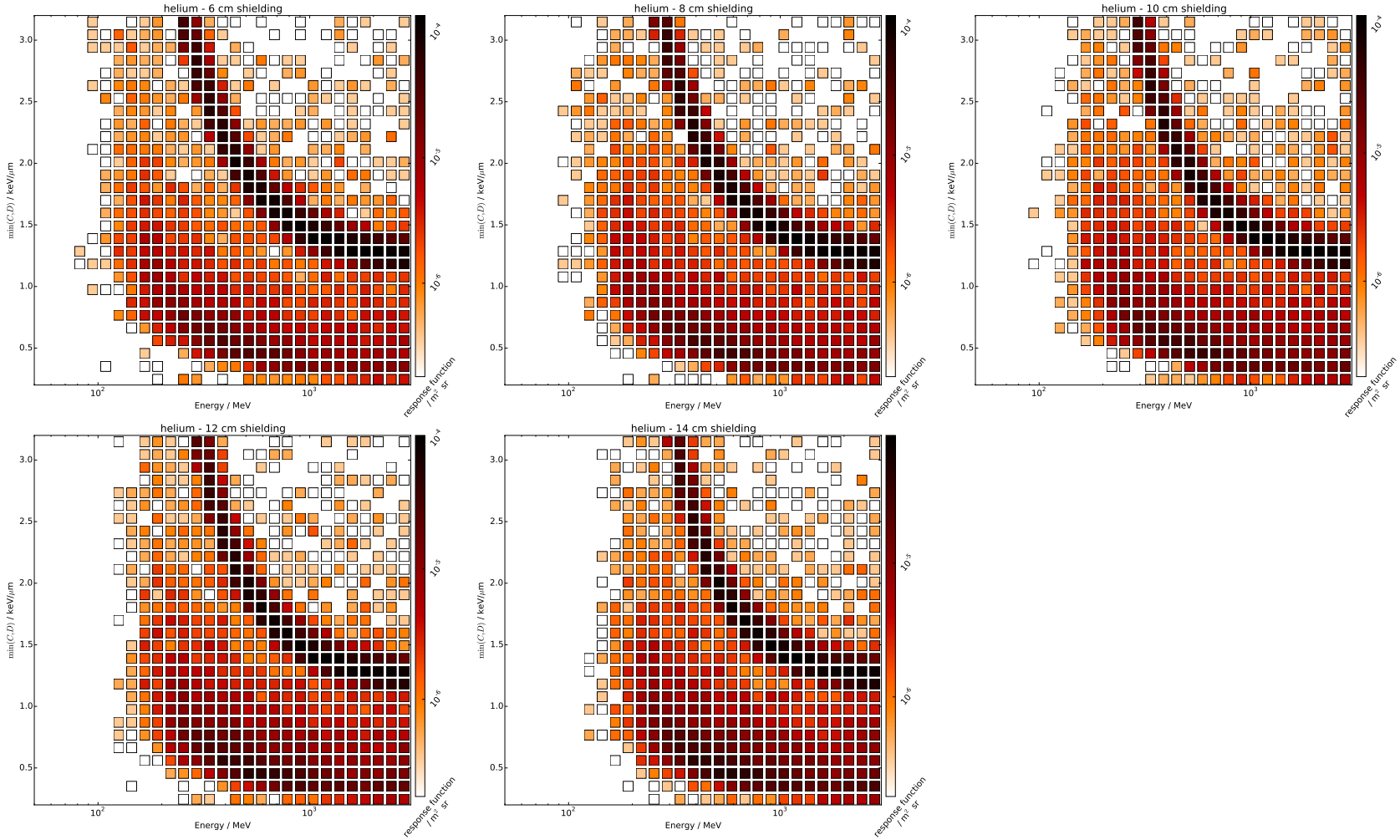

proton - 6 cm shielding
min(C,D) / keV/µm
Energy / MeV
response function / m² sr

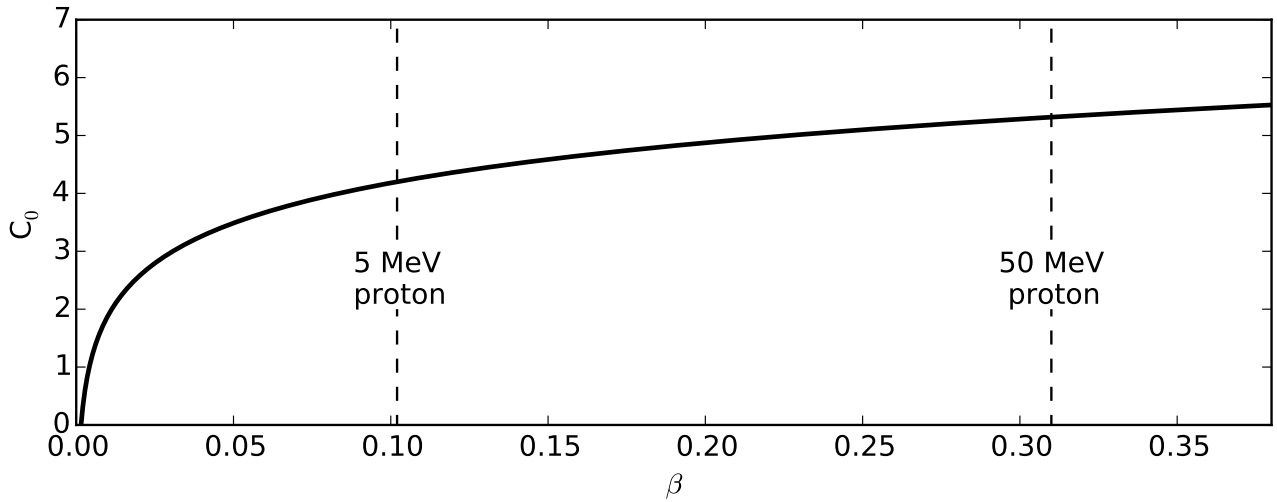

proton - 8 cm shielding
min(C,D) / keV/µm
Energy / MeV
response function / m² sr


proton - 10 cm shielding
min(C,D) / keV/µm
Energy / MeV
response function / m² sr


proton - 12 cm shielding
min(C,D) / keV/µm
Energy / MeV
response function / m² sr

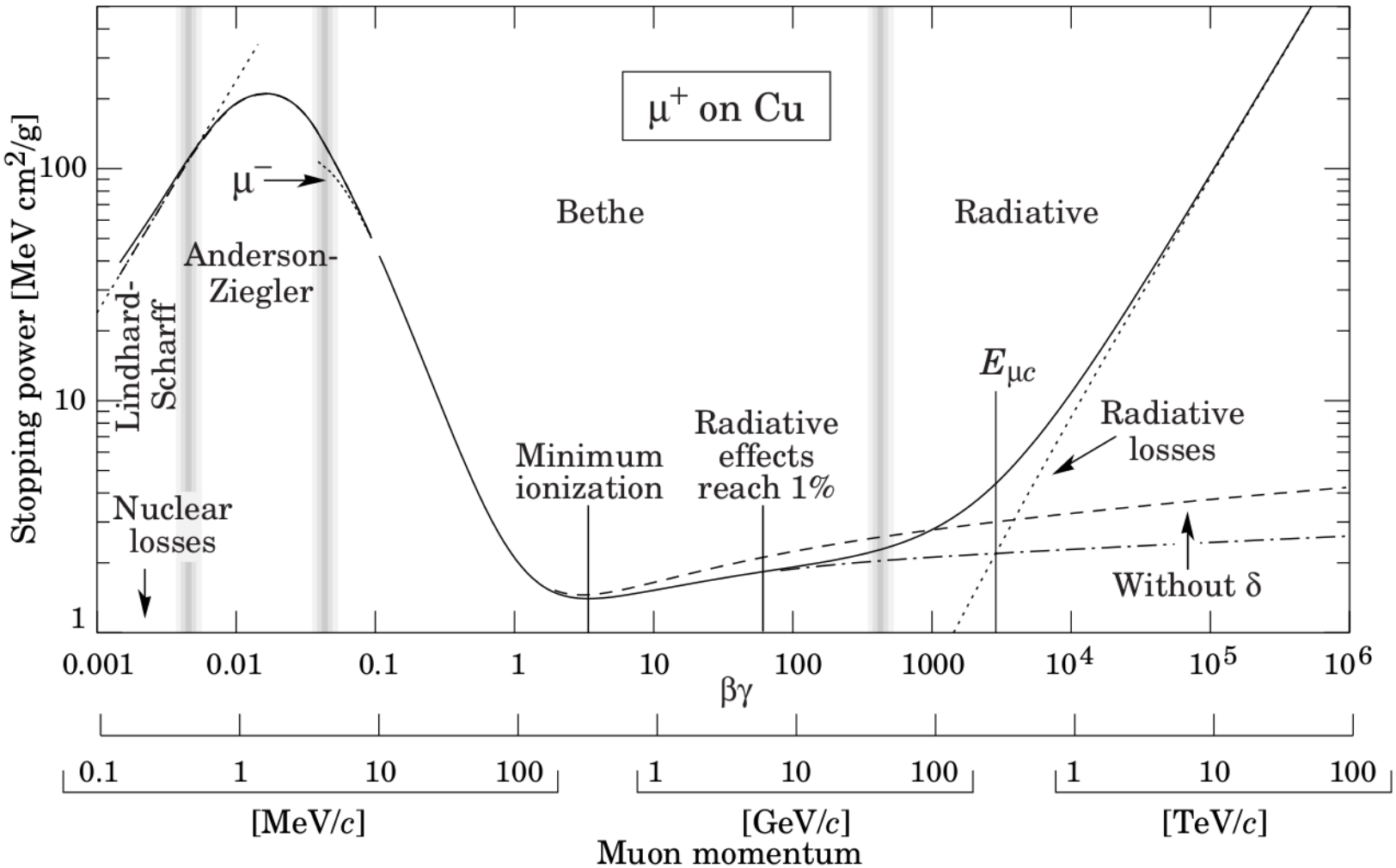

proton - 14 cm shielding
min(C,D) / keV/µm
Energy / MeV
response function / m² sr


helium - 6 cm shielding
helium - 8 cm shielding
helium - 10 cm shielding
helium - 12 cm shielding
helium - 14 cm shielding
min(C,D) / keV/µm
Energy / MeV
response function / m² sr

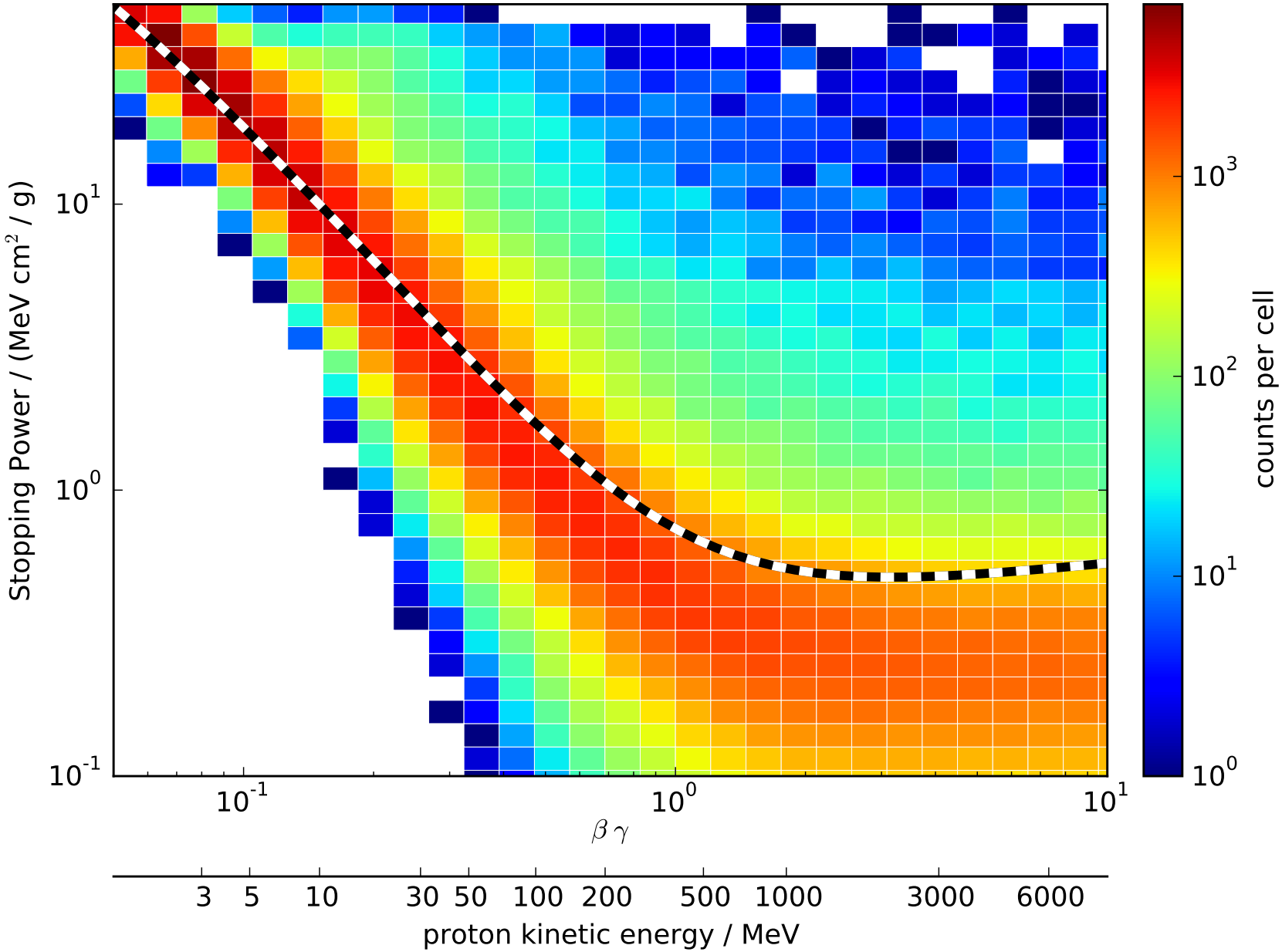


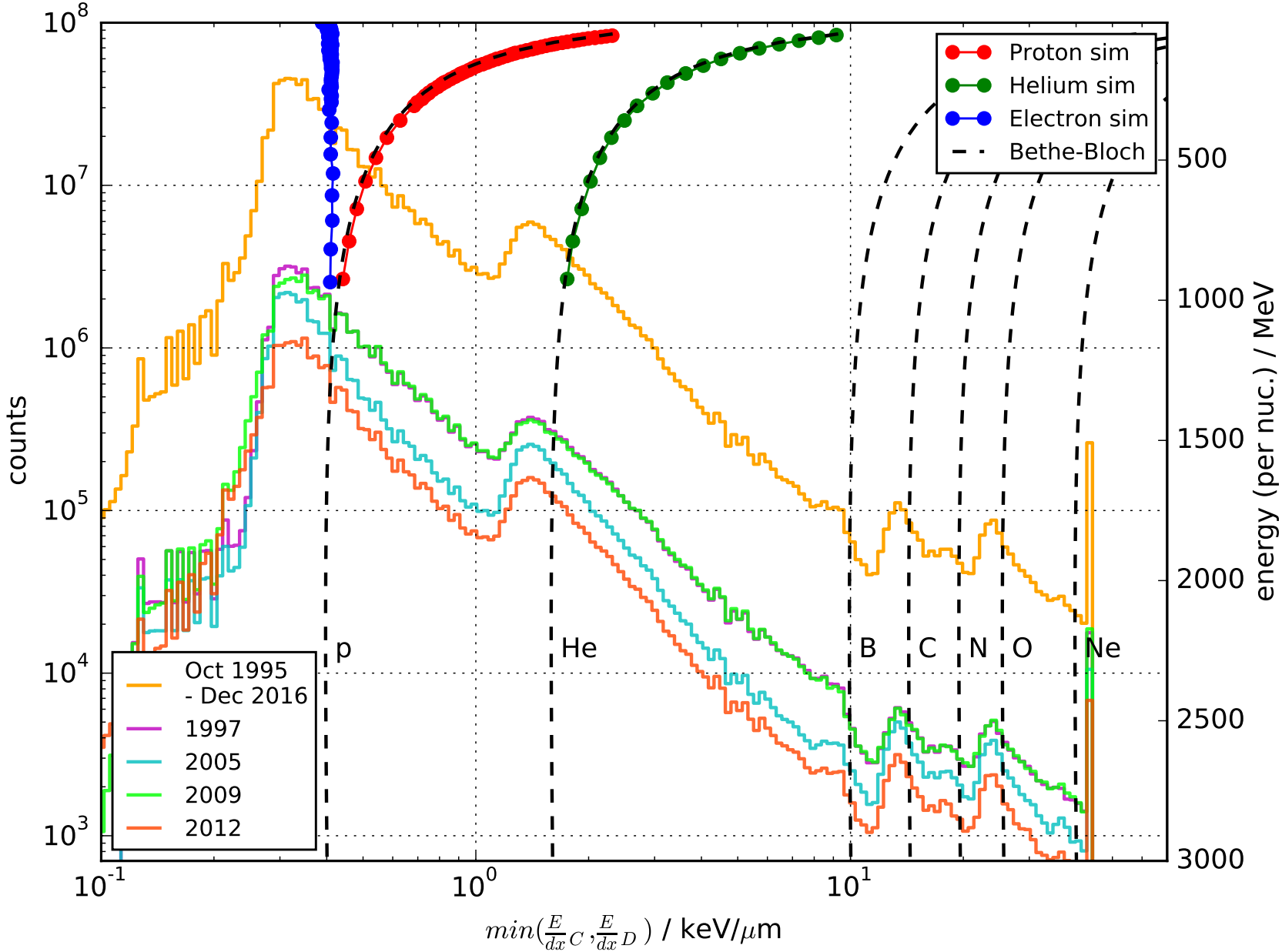
$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z_P^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \cdot \left(\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right)$$

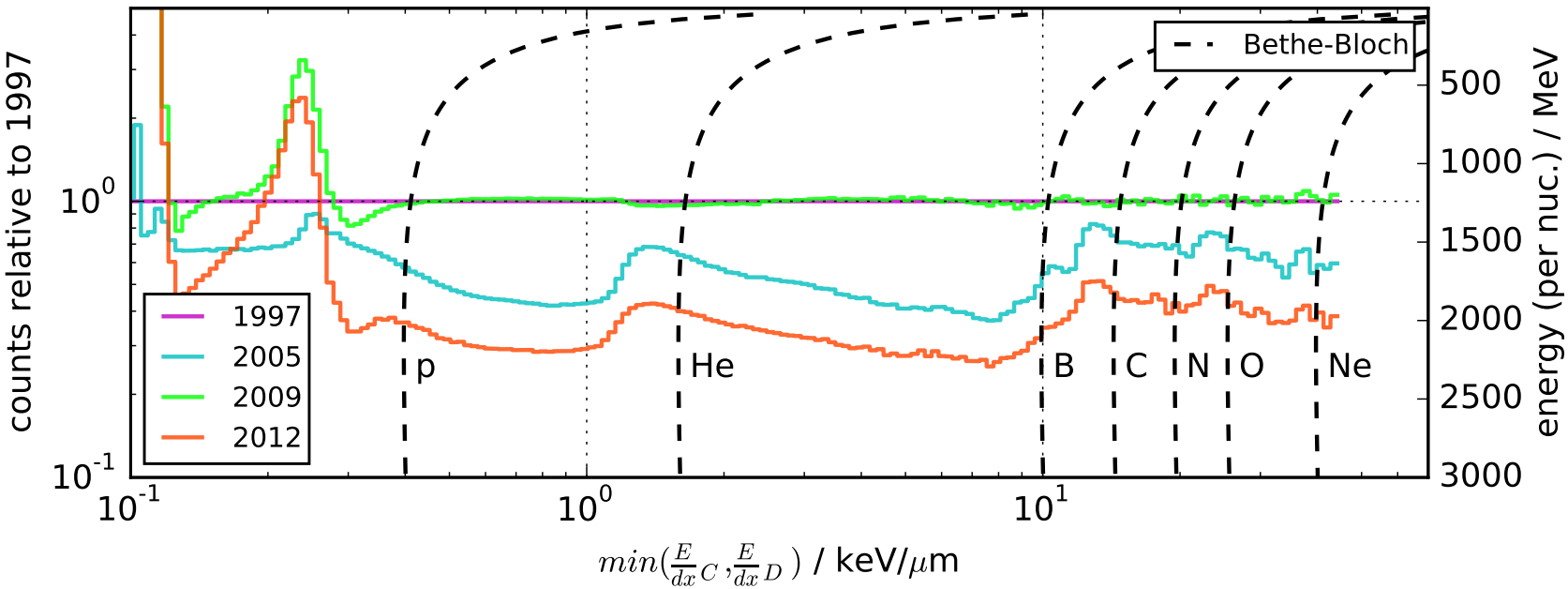
$$C_0 = \left(\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right)$$

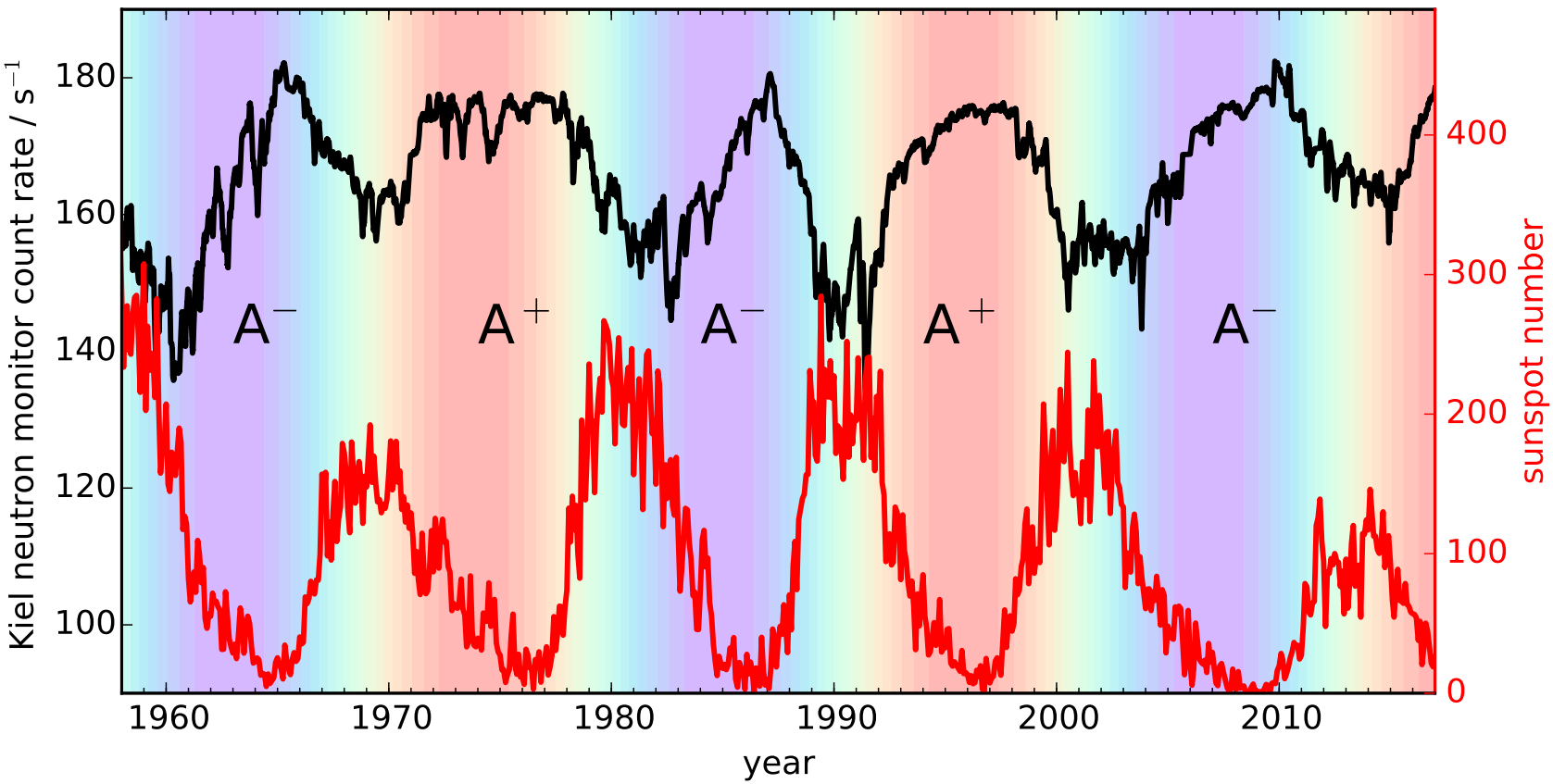


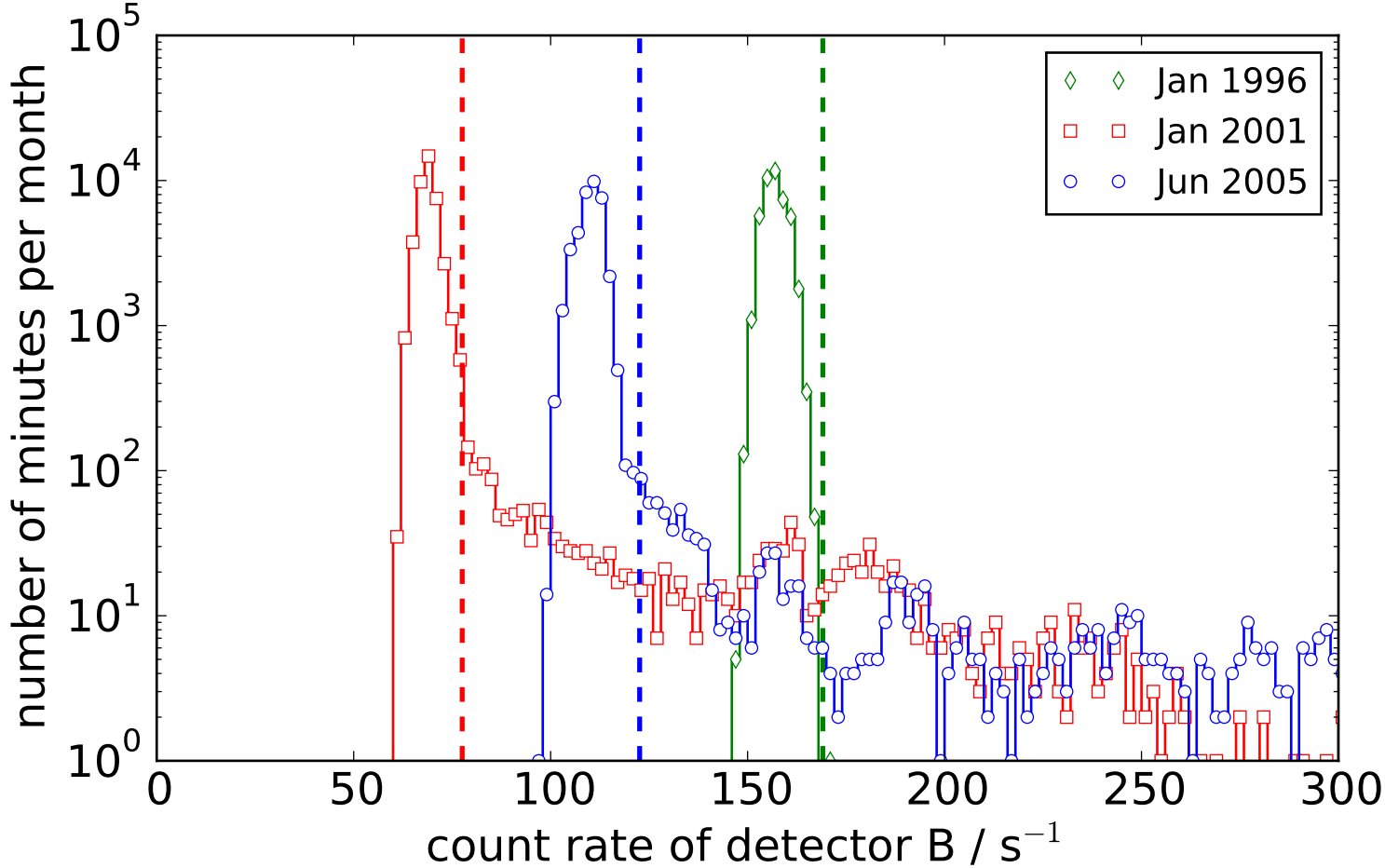
[Nakamura et al., 2010]


Stopping Power / (MeV cm^2 / g)
10^1
10^0
10^{-1}
10^{-1}
10^0
10^1
$\beta\,\gamma$
3 5 10 30 50 100 200 500 1000 3000 6000
proton kinetic energy / MeV
10^3
10^2
10^1
10^0
counts per cell


Proton sim
Helium sim
Electron sim
Bethe-Bloch
Oct 1995 - Dec 2016
1997
2005
2009
2012
p
He
B
C
N
O
Ne
counts
energy (per nuc.) / MeV
$min(\frac{E}{dx}_C, \frac{E}{dx}_D)$ / keV/μm

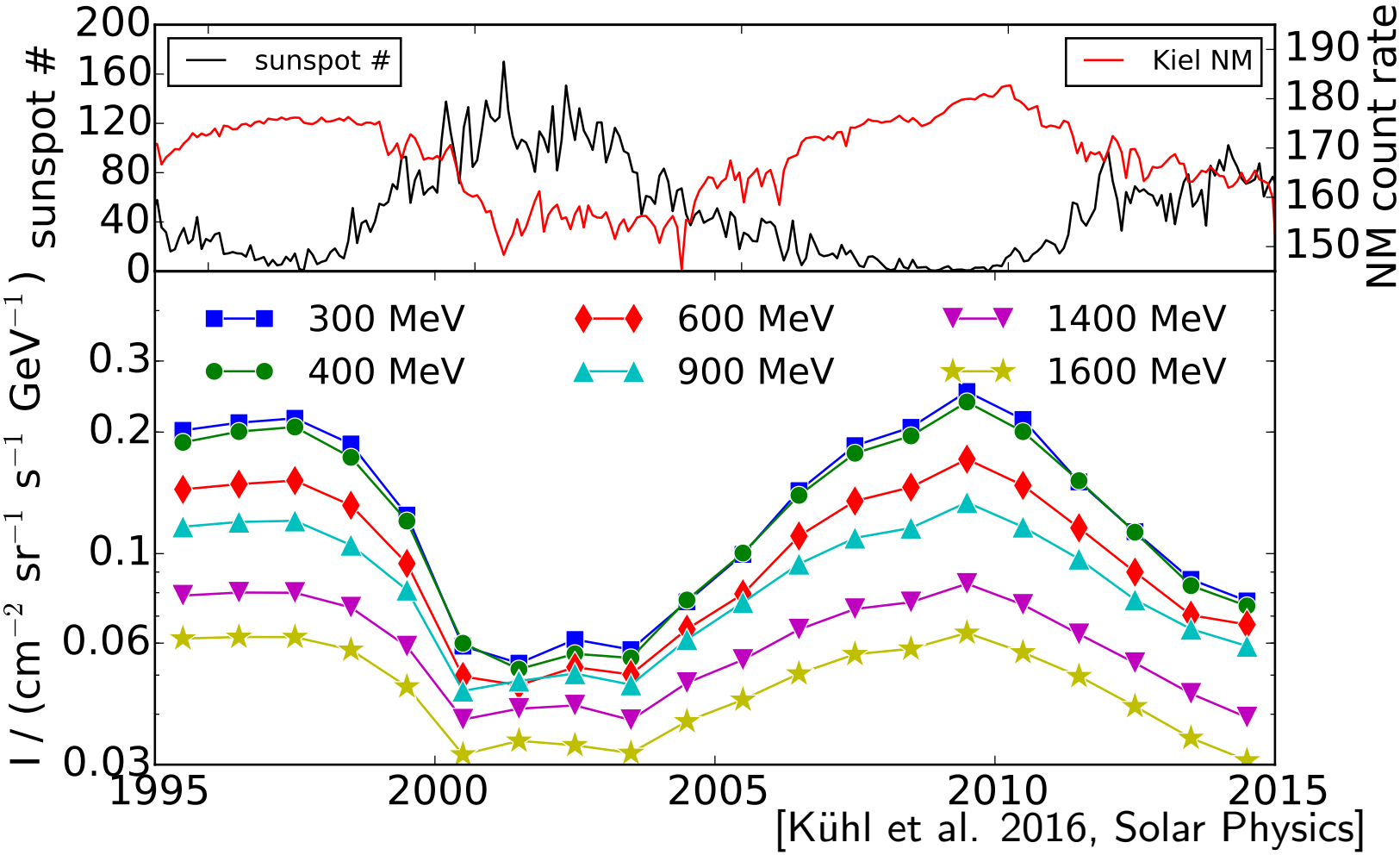

counts relative to 1997
10^0
10^{-1}
10^{-1}
10^0
10^1
$min(\frac{E}{dx}_C, \frac{E}{dx}_D)$ / keV/μm
energy (per nuc.) / MeV
500
1000
1500
2000
2500
3000
Bethe-Bloch
1997
2005
2009
2012
p
He
B
C
N
O
Ne


Kiel neutron monitor count rate / s^{-1}
180
160
140
120
100
A$^-$
A$^+$
A$^-$
A$^+$
A$^-$
1960
1970
1980
1990
2000
2010
year
400
300
200
100
0
sunspot number

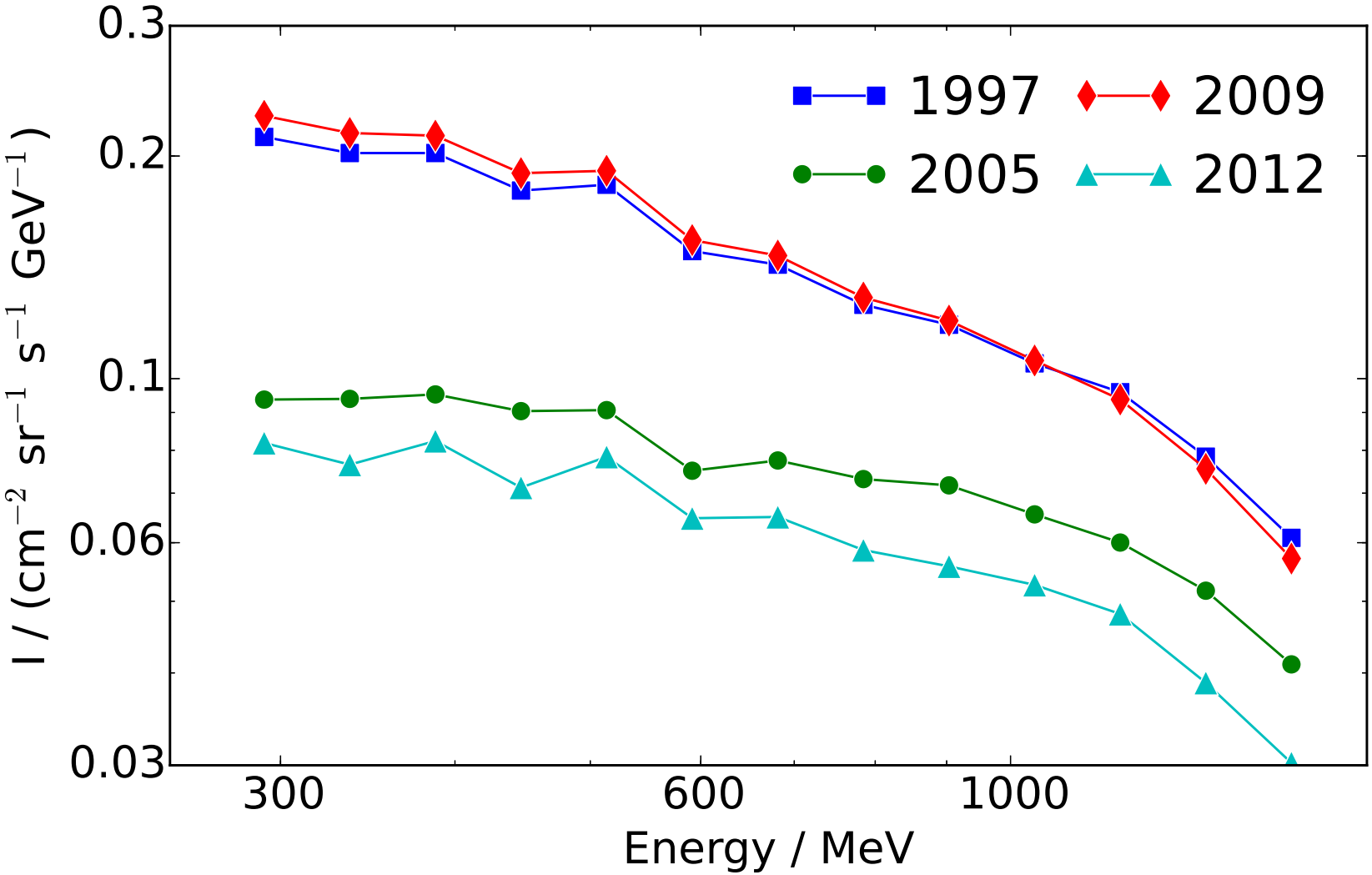


[Kühl et al. 2016, Solar Physics]

- histogram of the count rates of detector B
- peaks of the distributions: GCR
- higher count rates: SEP events $\rightarrow$ exclude from analysis



- annual GCR proton spectra from 250 MeV up to 1.6 GeV
- continuous measurements from 1995 to 2017 (ongoing)
- benchmark for GCR modulation simulations (including drift effects)


0.3
0.2
0.1
0.06
0.03
I / (cm^{-2} sr^{-1} s^{-1} GeV^{-1})
300
600
1000
Energy / MeV
1997
2009
2005
2012

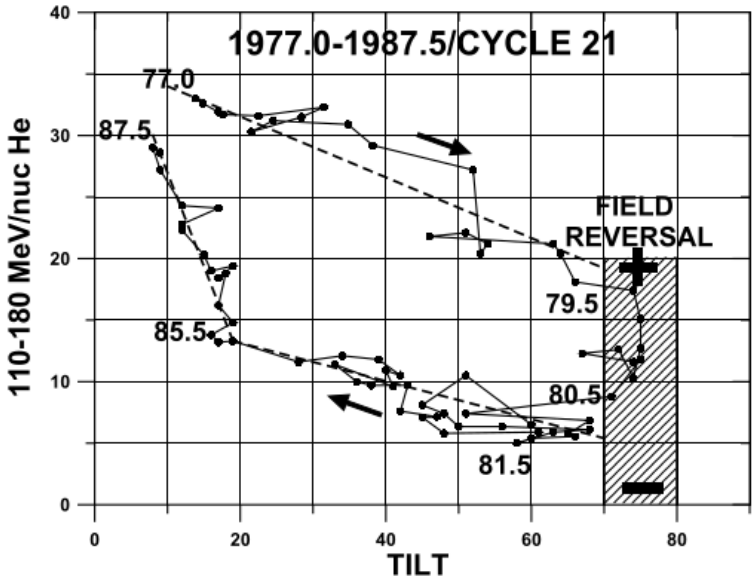


Figure 3a. The 1.2-GV Helium nuclei intensity (units the same as in Figure 1) with ACE carbon data as a proxy after 2001.7 versus heliospheric current sheet tilt for 11-year cycle 21 from ~1977 to 1987. Dashed lines are to guide the eye; their slopes are discussed in the text. Sample dates for the 52-day average data are shown as are the approximate times of the solar magnetic field reversal.

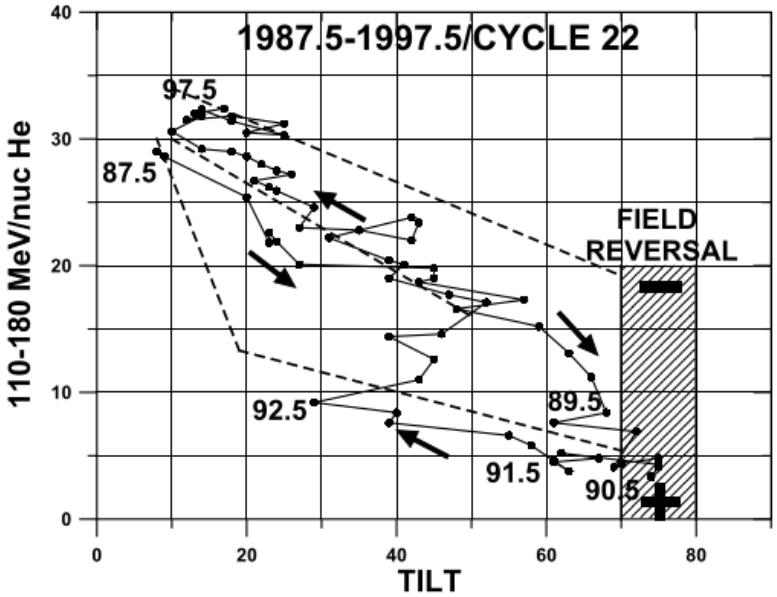
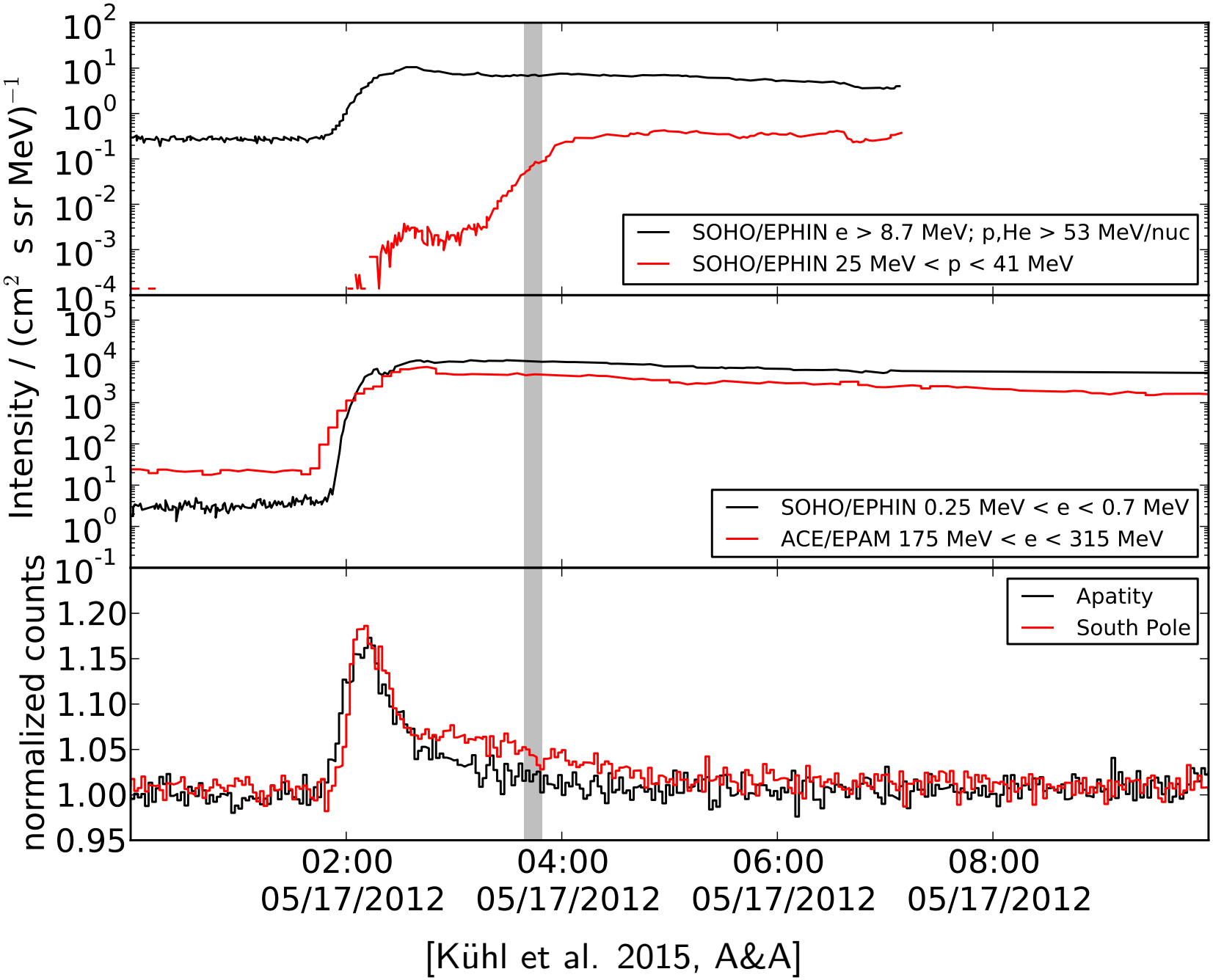


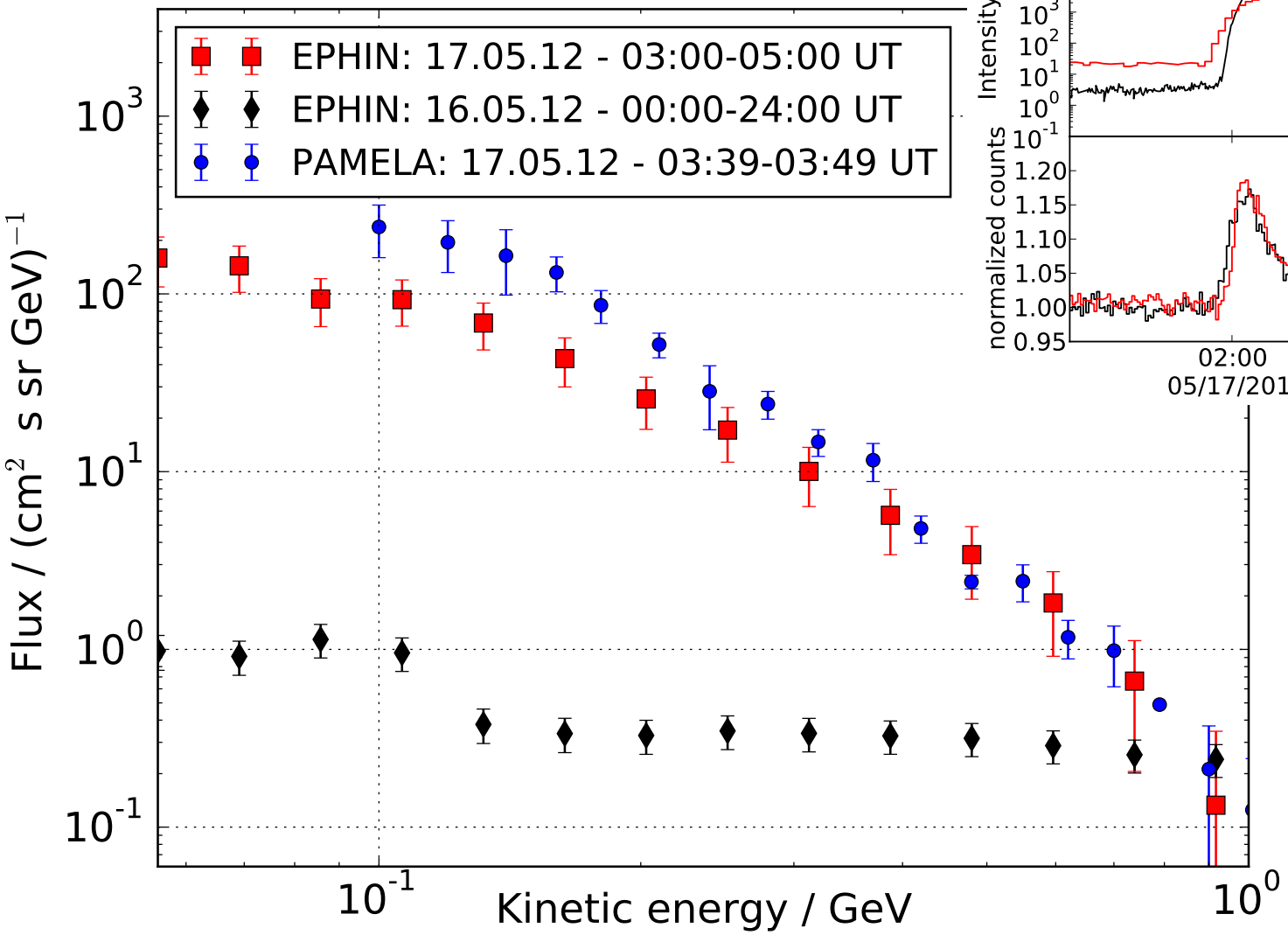
Figure 3b. Same as in Figure 3a but for solar 11-year cycle 22.

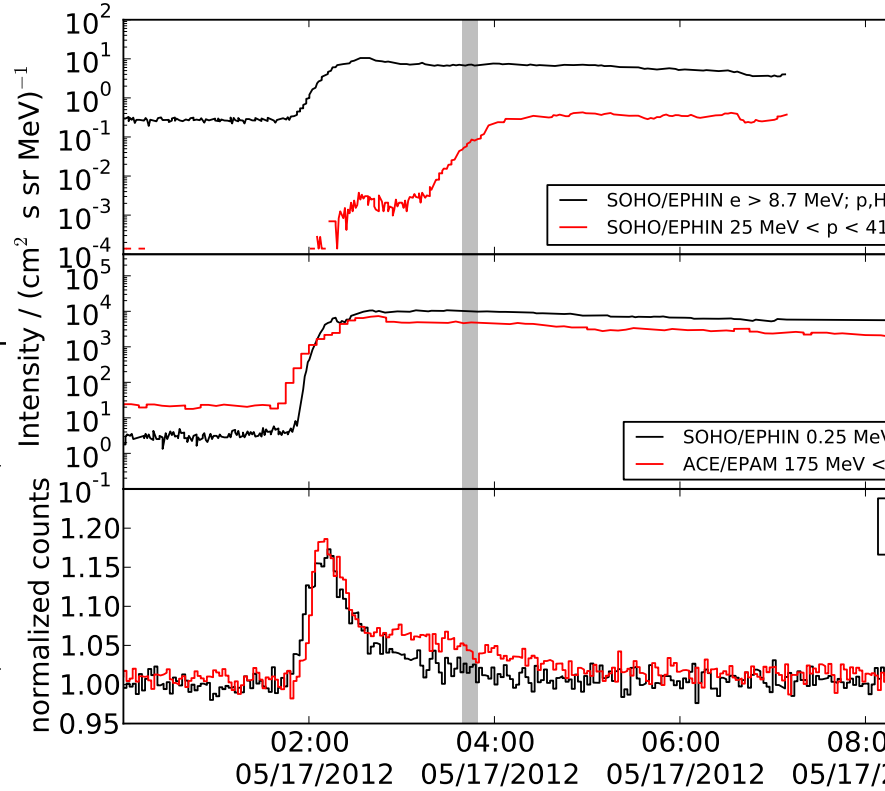
[Webber et al., 2005]

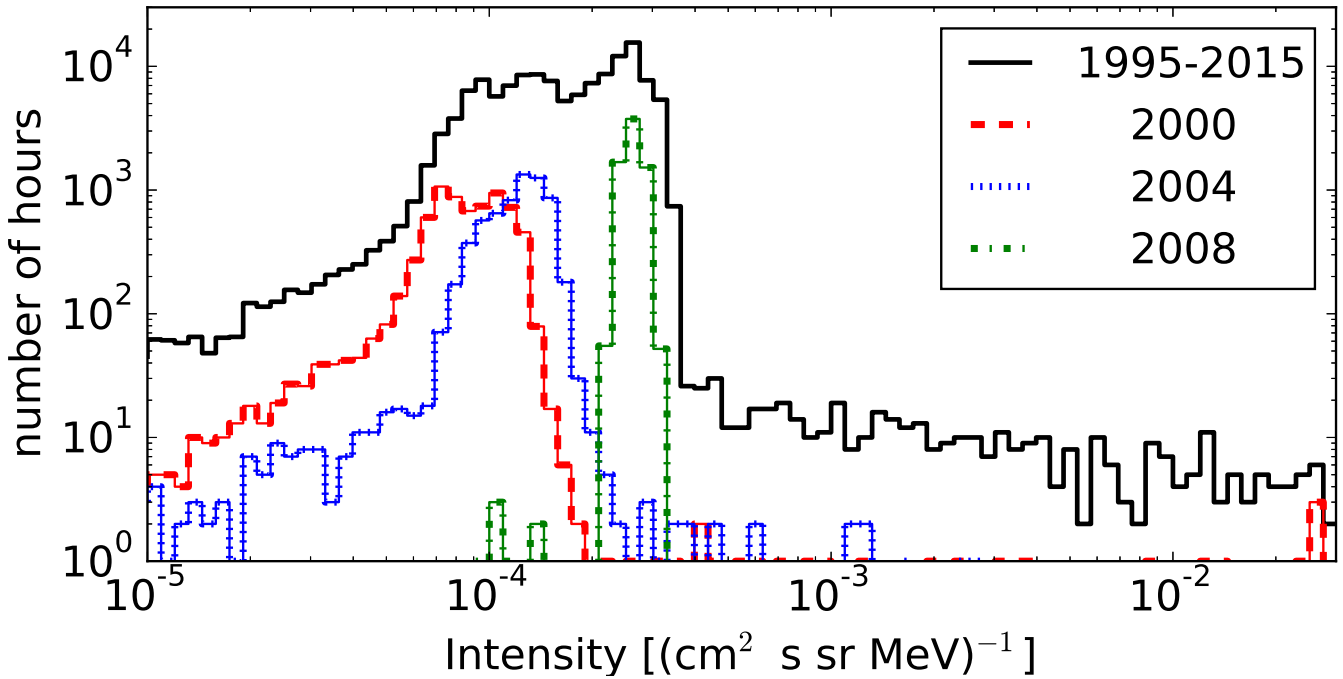


[Kühl et al. 2015, A&A]

[Kühl et al. 2015, A&A]

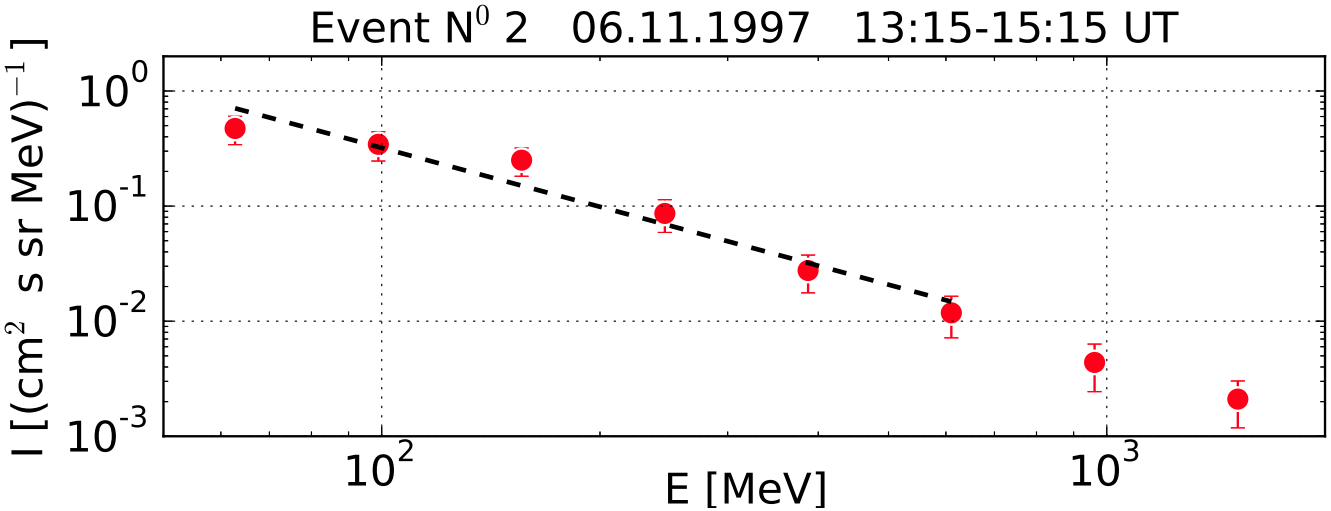






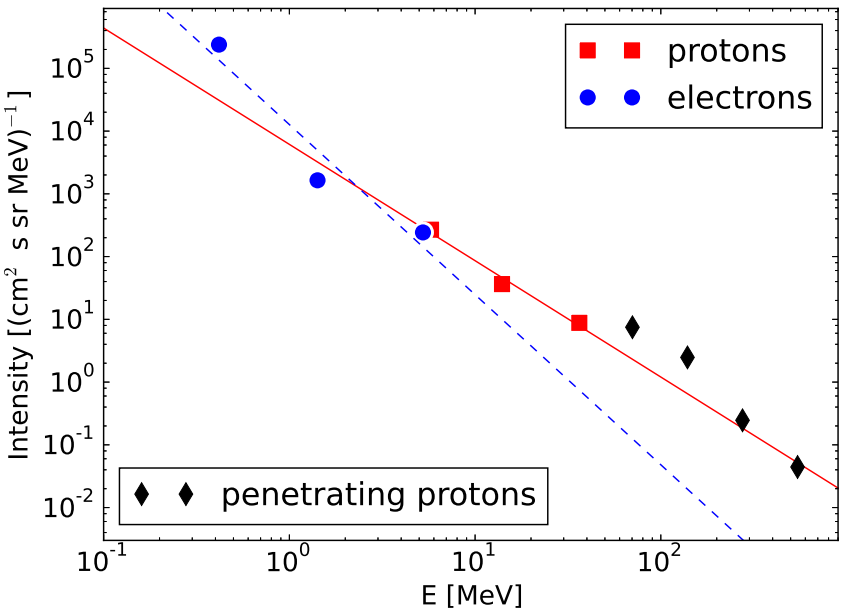
[Kühl et al. 2017, Solar Physics]

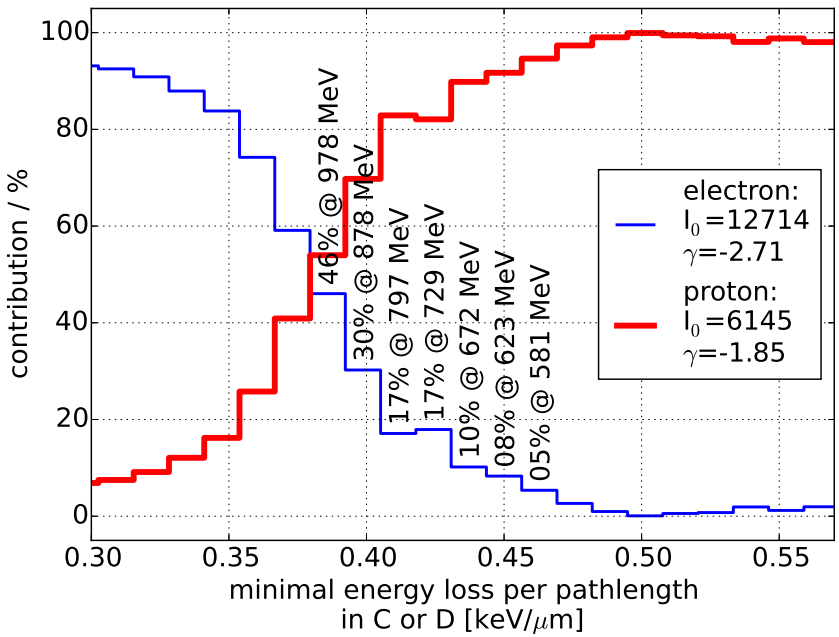
- hourly intensity of protons from 500 up to 700 MeV
- peak between 0.05 and 0.4 (cm^2 s sr MeV)$^{-1}$ due to GCR
- lower intensities: forbush decreases
- higher intensities: SEP candidates

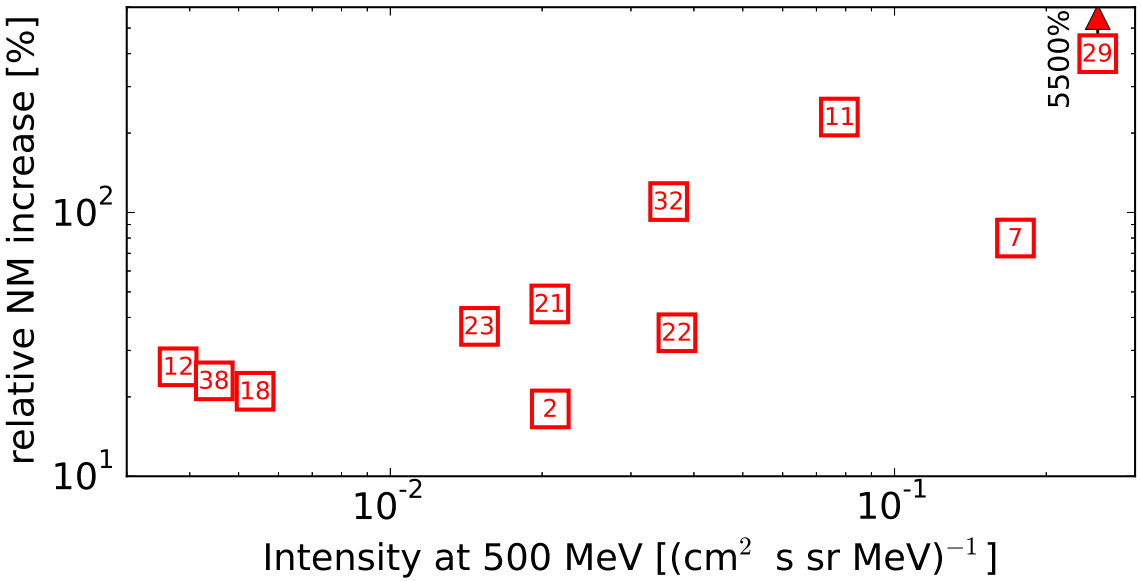


[Kühl et al. 2017, Solar Physics]

- define onset times (15 min resolution, 100-1000 MeV channel)
- derive spectrum in a two hour interval
  (starting 30 minutes after onset due to velocity dispersion)
- fit spectrum below 800 MeV with power-law
  (only for 33 events due to statistical limitations)

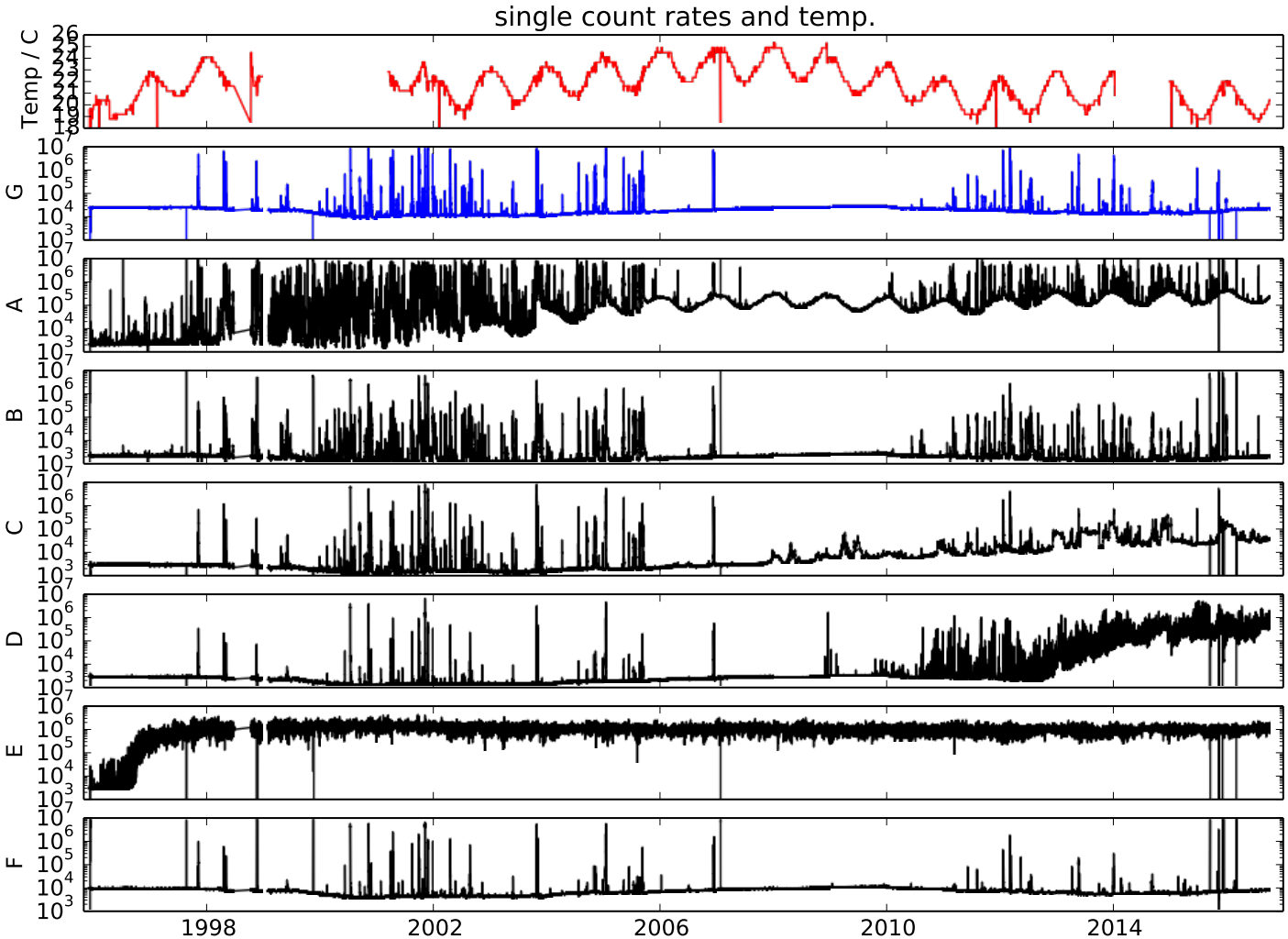

protons
electrons
penetrating protons
Intensity [(cm² s sr MeV)⁻¹]
E [MeV]

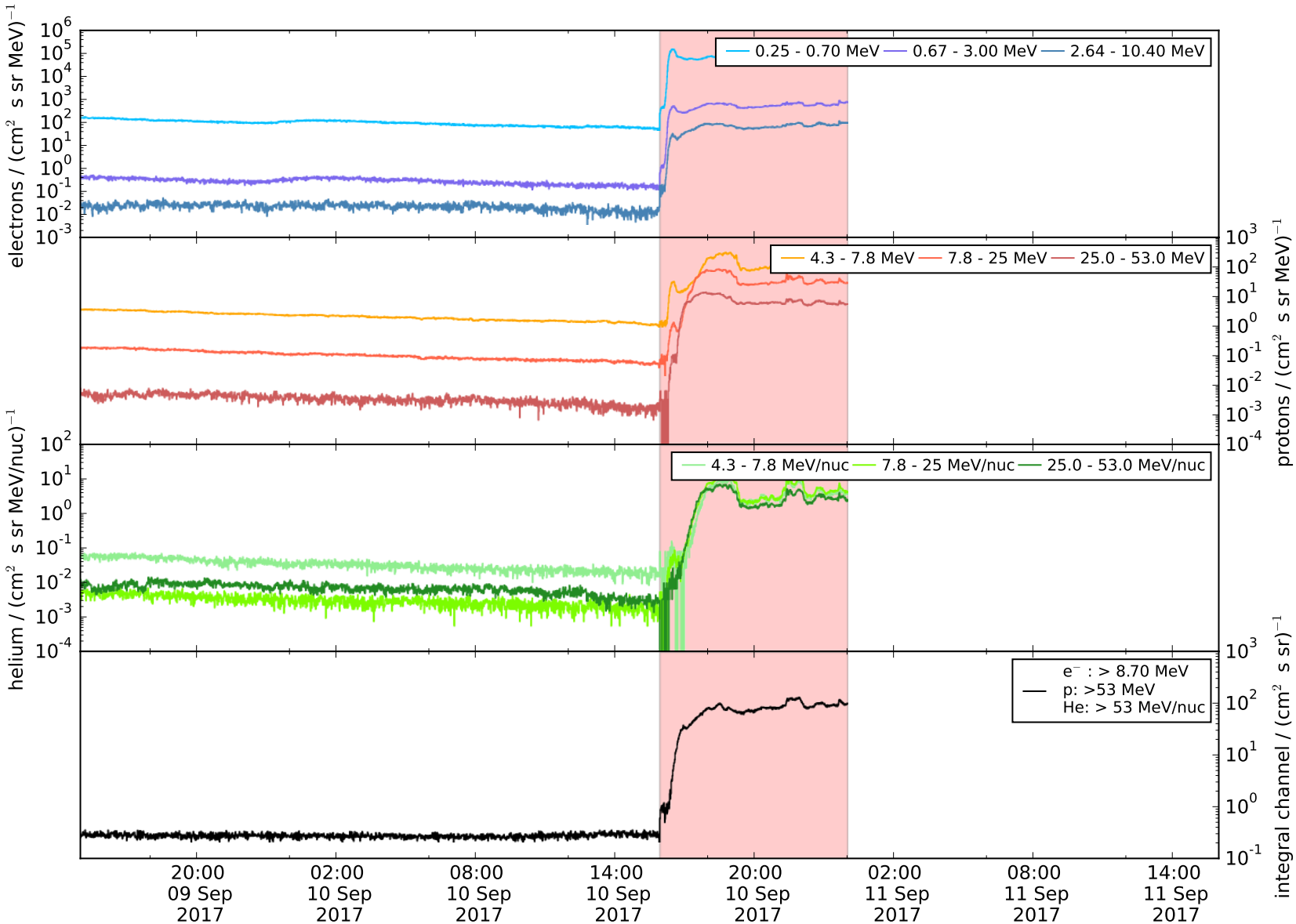

electron:
I0 =12714
γ=-2.71
proton:
I0 =6145
γ=-1.85
46% @ 978 MeV
30% @ 878 MeV
17% @ 797 MeV
17% @ 729 MeV
10% @ 672 MeV
08% @ 623 MeV
05% @ 581 MeV
contribution / %
minimal energy loss per pathlength
in C or D [keV/μm]

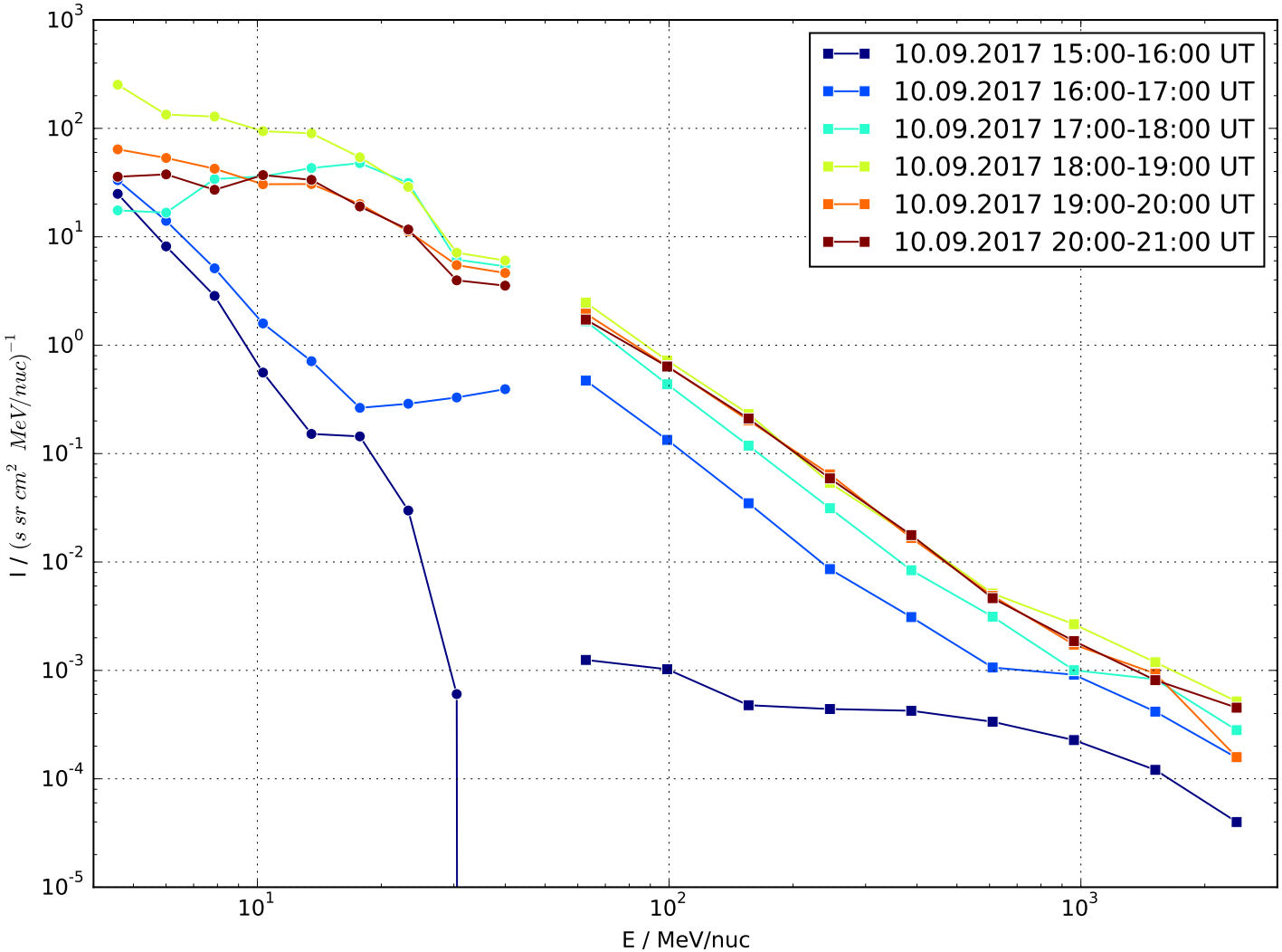


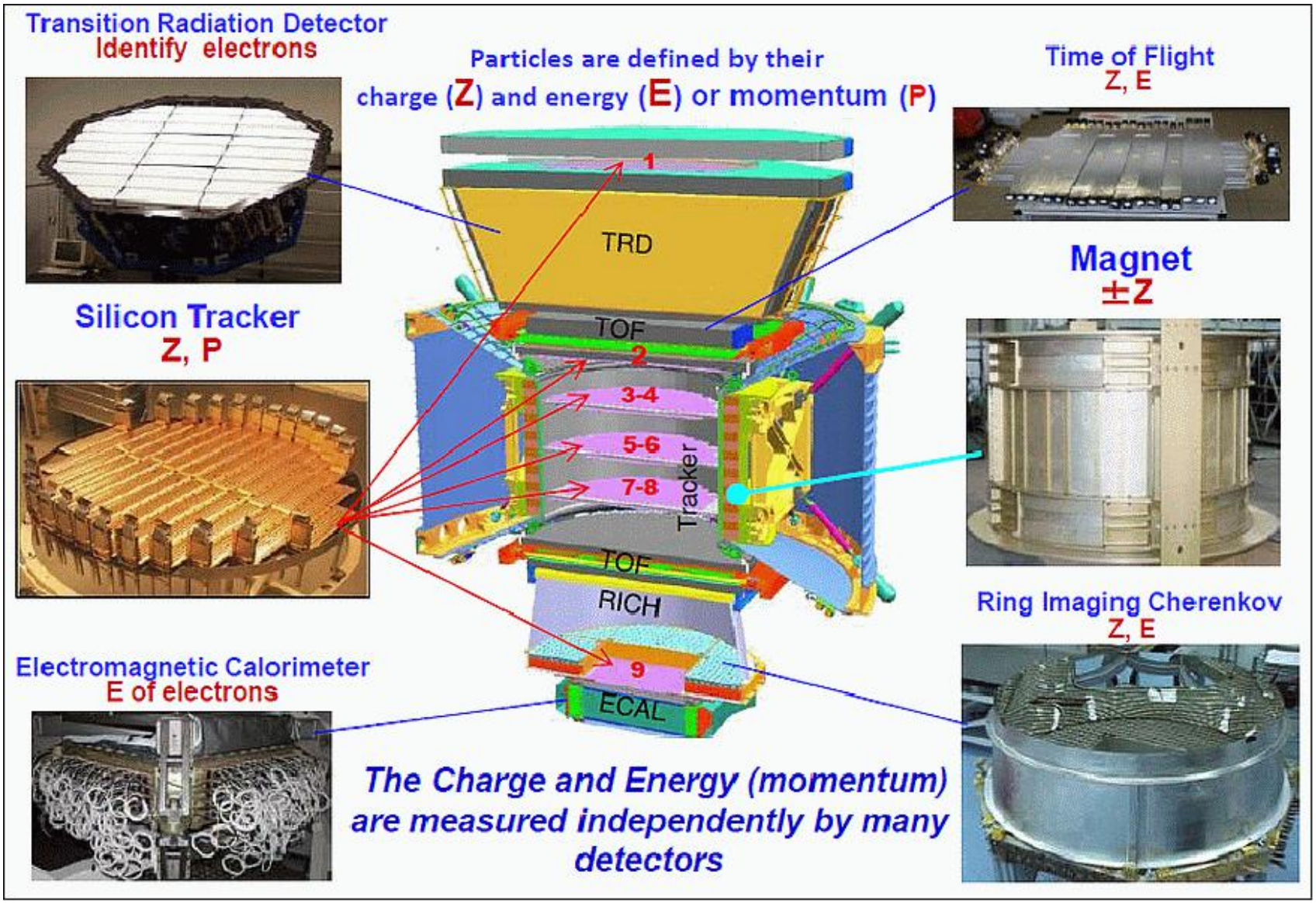
[Kühl et al. 2017, Solar Physics]

- NM count rate from McCracken, Moraal and Shea, 2012
- clear correlation (except for lowest intensities)
- event 29 (GLE 69, January 2005) is rather extreme
- scattering rather large, although spectral indices are similar
- asymptotic viewing direction? (Smart, Shea and Flückinger 2000)
  cutoff rigidities due to geomagnetic disturbances? (Danilova 1999)
  spectral break at higher energies?


single count rates and temp.
Temp / C
G
A
B
C
D
E
F
1998
2002
2006
2010
2014


electrons / (cm² s sr MeV)⁻¹
0.25 - 0.70 MeV
0.67 - 3.00 MeV
2.64 - 10.40 MeV
protons / (cm² s sr MeV)⁻¹
4.3 - 7.8 MeV
7.8 - 25 MeV
25.0 - 53.0 MeV
helium / (cm² s sr MeV/nuc)⁻¹
4.3 - 7.8 MeV/nuc
7.8 - 25 MeV/nuc
25.0 - 53.0 MeV/nuc
integral channel / (cm² s sr)⁻¹
e⁻ : > 8.70 MeV
p: >53 MeV
He: > 53 MeV/nuc
20:00 09 Sep 2017
02:00 10 Sep 2017
08:00 10 Sep 2017
14:00 10 Sep 2017
20:00 10 Sep 2017
02:00 11 Sep 2017
08:00 11 Sep 2017
14:00 11 Sep 2017


10.09.2017 15:00-16:00 UT
10.09.2017 16:00-17:00 UT
10.09.2017 17:00-18:00 UT
10.09.2017 18:00-19:00 UT
10.09.2017 19:00-20:00 UT
10.09.2017 20:00-21:00 UT
I / (s sr cm² MeV/nuc)⁻¹
E / MeV/nuc



[Courtesy of the AMS Collaboration]