ICRC2021
12-23 July 2021
Berlin, Germany (online)

The altitude profile of the cosmic ray atmospheric cut-off

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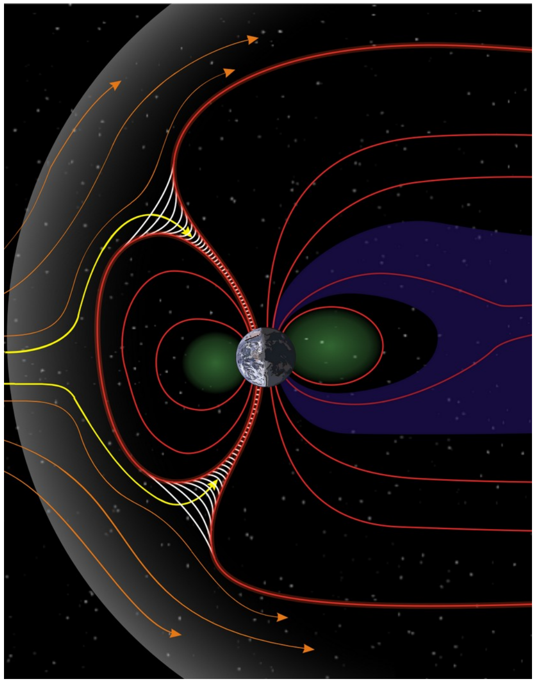
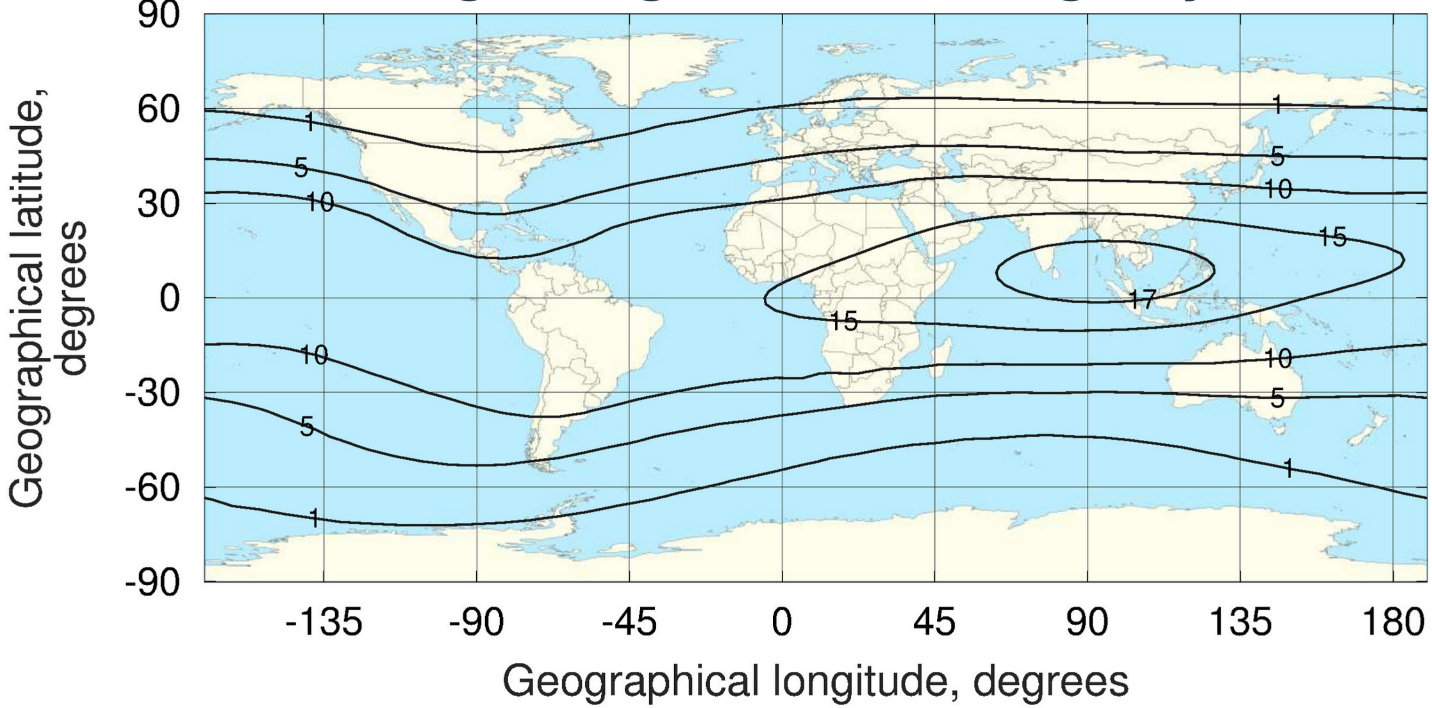
Introduction: geomagnetic cut-off

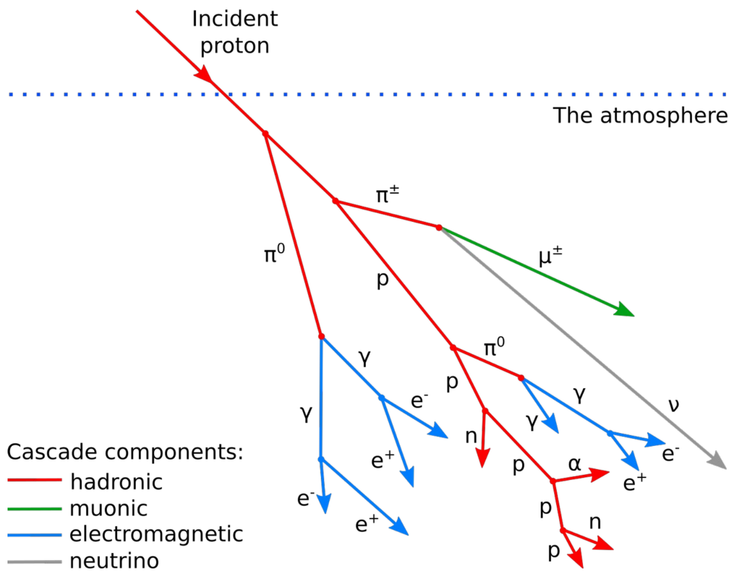


(NASA)

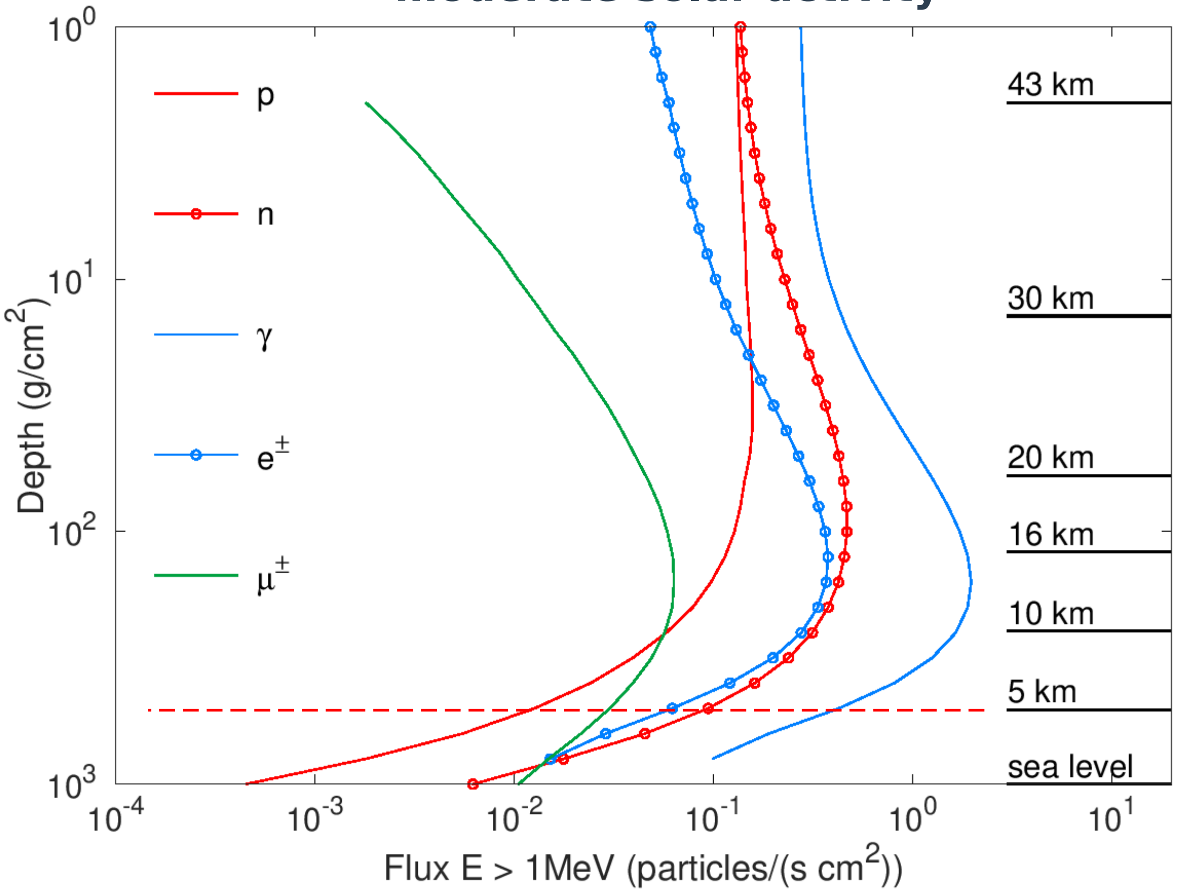
The geomagnetic cut-off rigidity (GV)



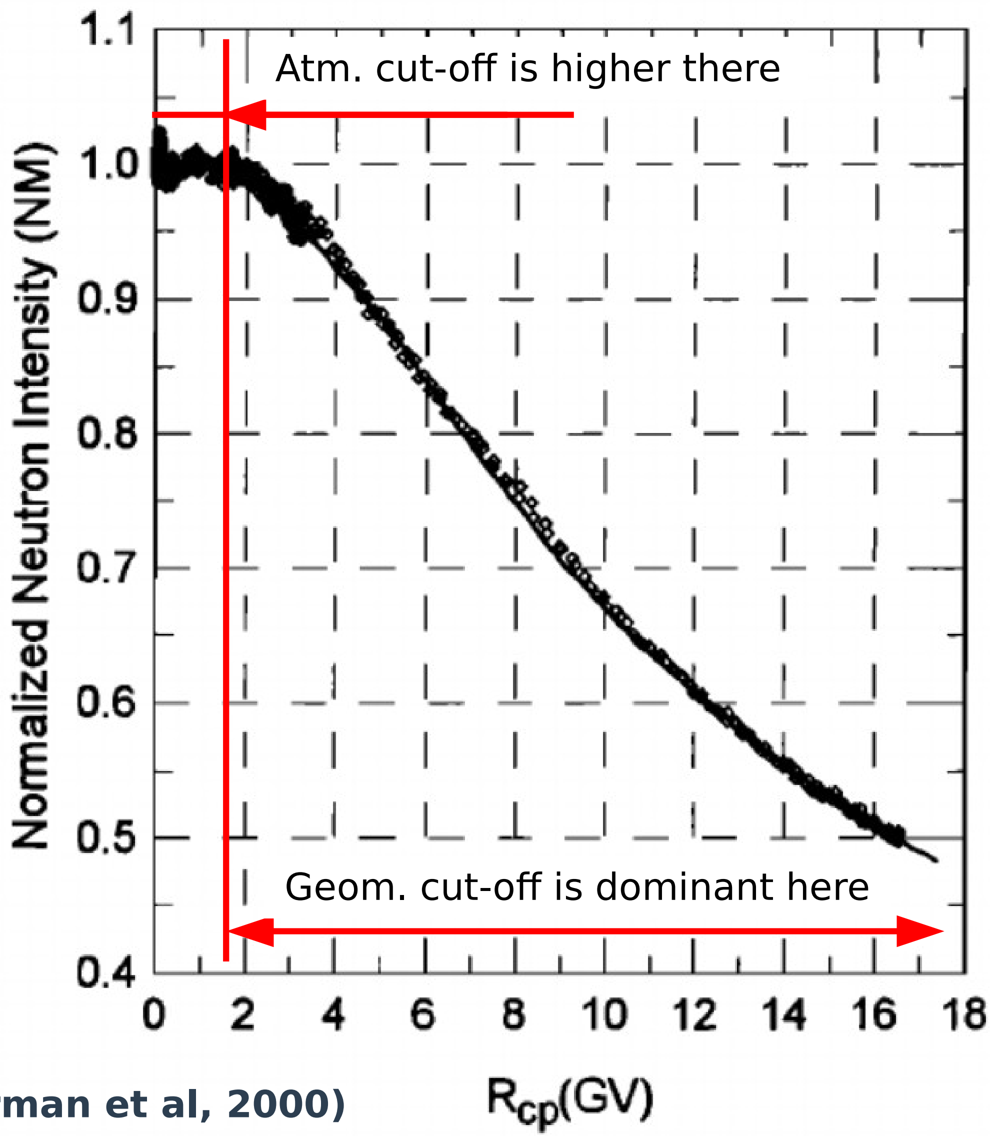
Introduction: atmospheric cut-off



Averaged cascade from GCR during moderate solar activity



Cut-offs in latitude NM surveys



(Dorman et al, 2000)

- **The atmospheric cut-off is dominant in the polar regions ($P_{geom.cut}$ ≈ 0 GV)**
- **The atmospheric cut-off is about 1 GV (433 MeV) for protons at the sea level**

Motivation: sub-GLE definitions

Raukunen O., Vainio R., Tylka A.J. et al., J. Space Weather Space Clim. 2018, 8:A04:

“...so-called sub-GLEs, i.e., large SEP events with increases of protons above 300 MeV, but not with sufficient intensities to be detected with ground level neutron monitors.”

Briefly: sub-GLE, if E > 300 MeV.

Poluianov S.V., Usoskin I.G., Mishev A.L. et al., Solar Phys. 2017, 292:176:

“A sub-GLE event is registered when there are near-time coincident and statistically significant enhancements of the count rates of at least two differently located high-elevation neutron monitors and a corresponding enhancement in the proton flux measured by a space-borne instrument(s), but no statistically significant enhancement in the count rates of neutron monitors near sea level.”

Briefly: sub-GLE, if registered by 2 high-altitude polar NMs and not seen by any other NMs.

Physical and instrumental approaches

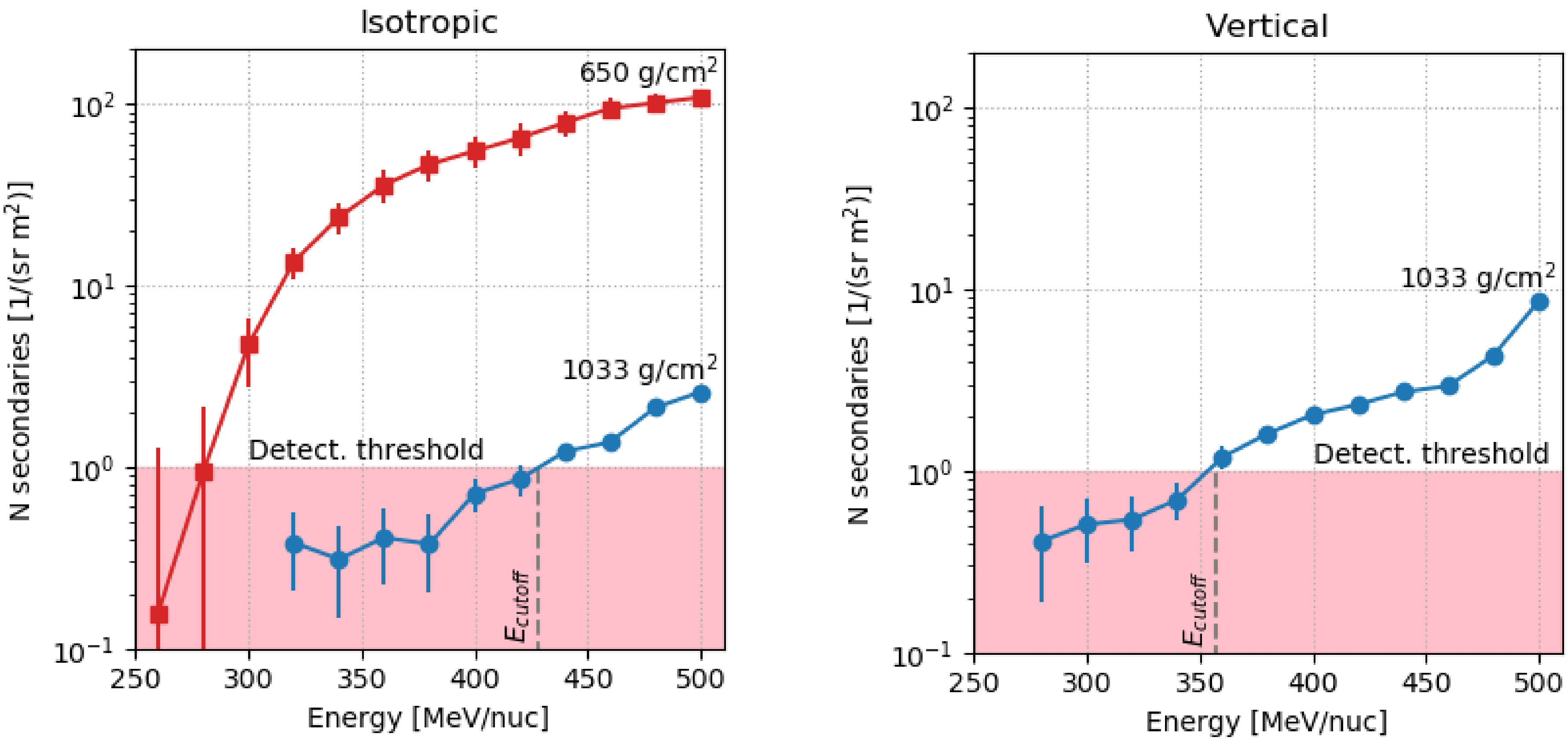
“Physical”:

- **Simulation of cosmic-ray cascades (Geant4/PLANETOCOSMICS)**
- **Incident protons: energies 200-500 MeV, vertical and isotropic angular distributions**
- **Registration of secondary neutrons at depths 600-1033 g/cm^2 (3.7-0 km a.s.l.)**
- **Criterion to get the cascade registered: at least 1 secondary neutron per cascade in average**

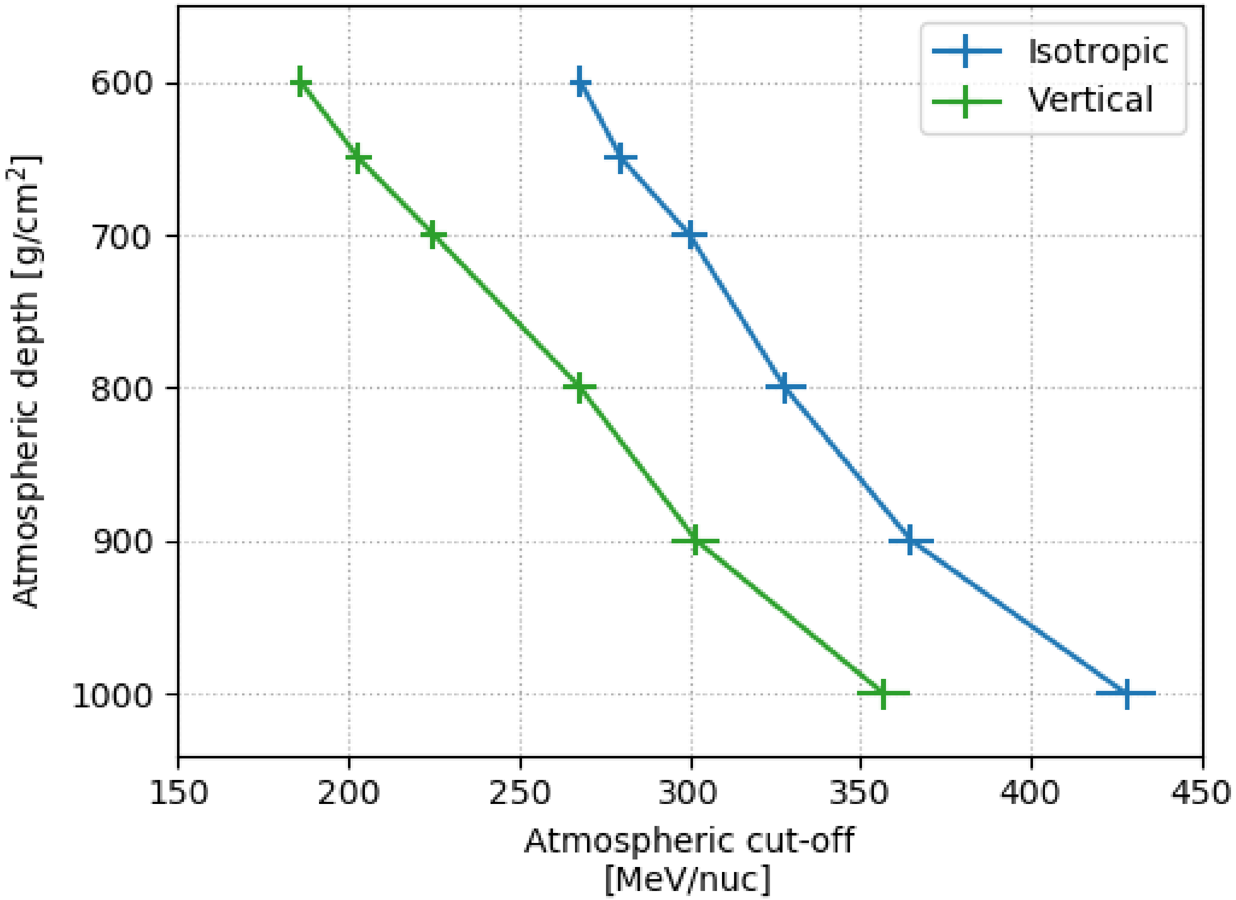
“Instrumental”:

- **NM yield functions for different altitudes (Mishev et al., 2020)**
- **Realistic spectrum of incident particles with isotropic angular distribution**
- **Detection threshold defined with the known sea-level cut-off energy (433 MeV)**
- **Criterion to get the cascade registered: response above the detection threshold**

Physical approach: cascade particles



Physical approach: atmospheric cut-offs



Instrumental approach

NM count rate:

$$N_i(h) = \int_0^\infty Y_i(E,h) J_i(E) dE$$

yield function

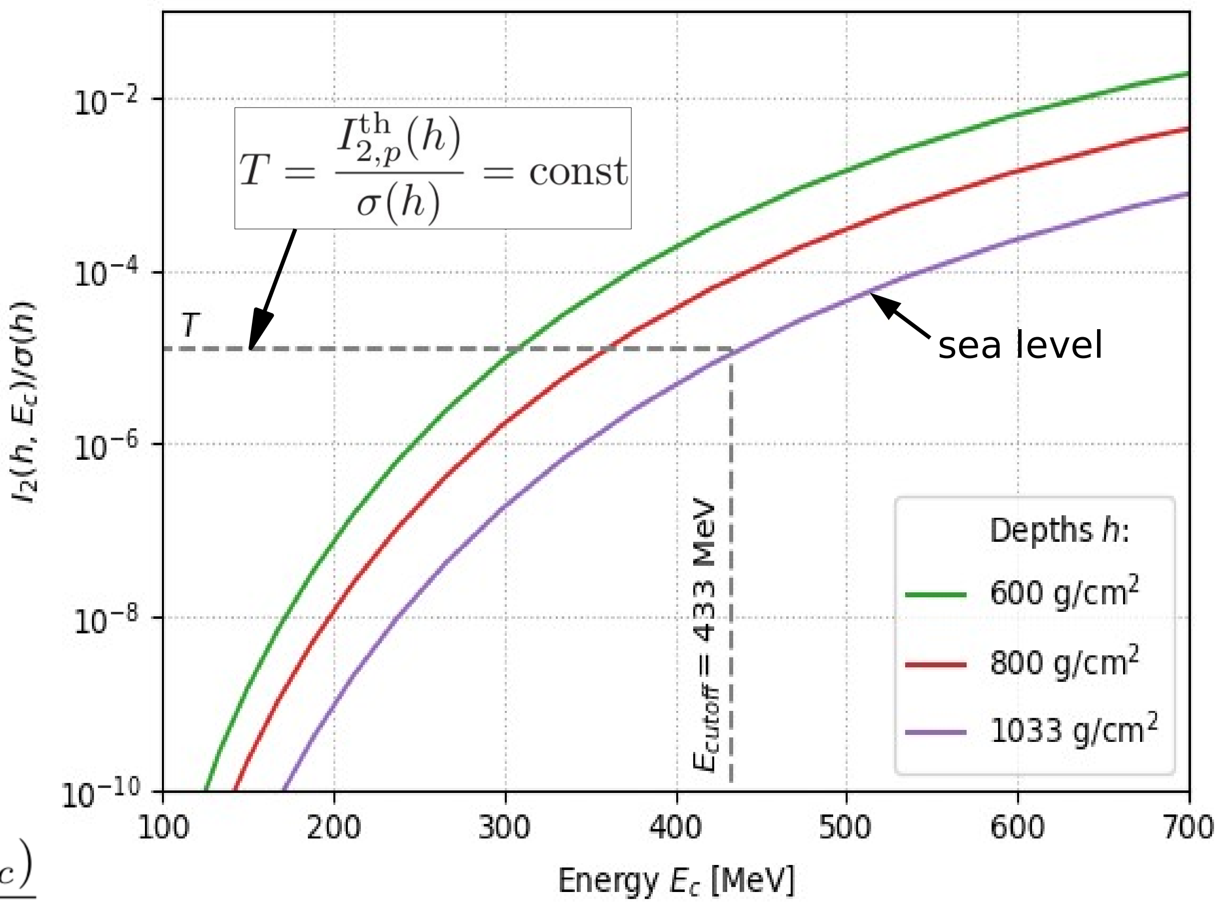
CR intensity

$$N_i(h) = \underbrace{\int_{E_c}^\infty Y_i(E,h) J_i(E) dE}_{I_{1,i}(h,E_c)} + \underbrace{\int_0^{E_c} Y_i(E,h) J_i(E) dE}_{I_{2,i}(h,E_c)}$$

main I_1

remainer I_2

some variable threshold E_c



NM counts have Poisson distrib.:
<N> and σ=sqrt(<N>)

Remainer normalized to std. dev.: $\frac{I_2(h, E_c)}{\sigma(h)}$

Atmospheric cut-off from both approaches

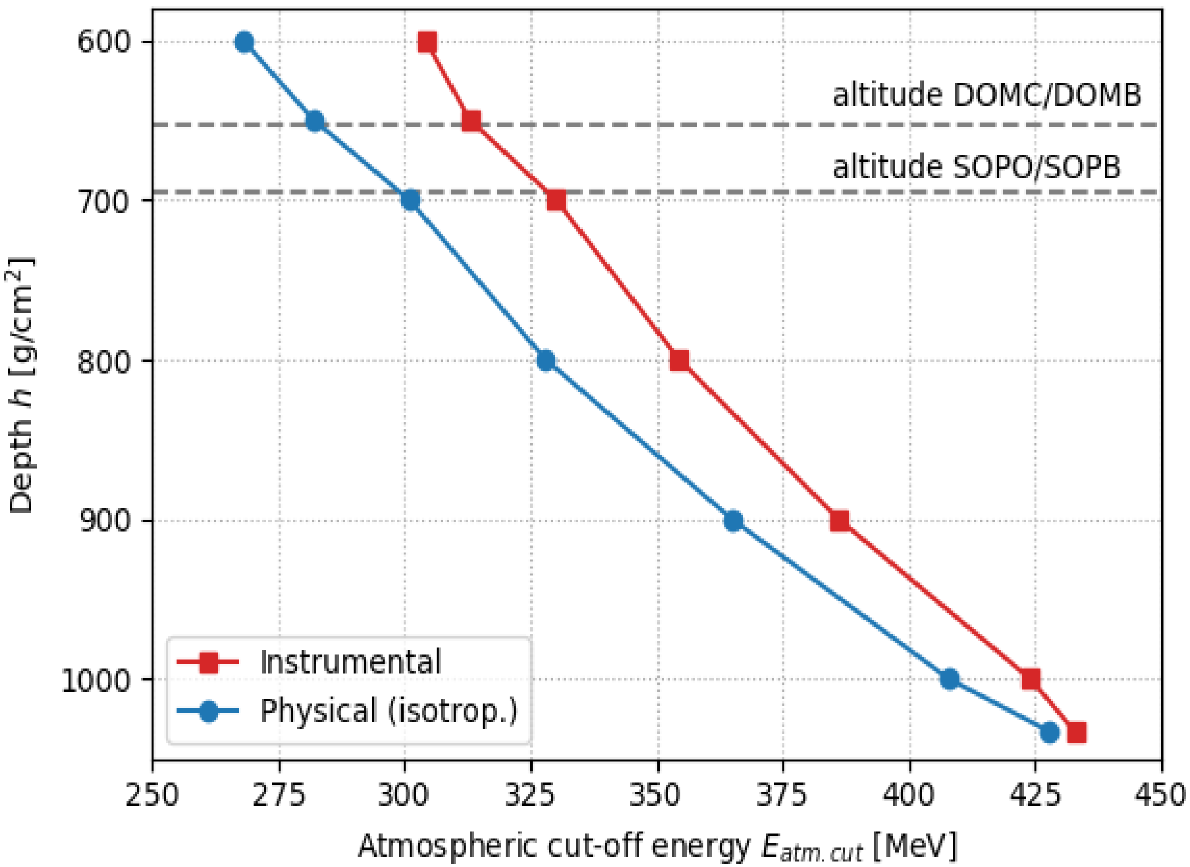
Neutron monitors:

- **DOMC/DOMB atmospheric cut-off:**

  317 MeV at 3233 m asl

- **SOPO/SOPB atmospheric cut-off:**

  320 MeV at 2820 m asl



Sub-GLE definitions

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Briefly: sub-GLE, if registered by 2 high-altitude polar NMs and not seen by any other NMs.

Conclusion from this work:

They agree well, no contradiction!

Summary

- **Calculated atmospheric cut-off energies for cosmic ray protons at different altitudes 0-3.7 km**
- **For the currently working high-altitude polar NMs, the cut-off energies are:**

  SOPO/SOPB - 320 MeV

  DOMC/DOMB - 317 MeV
- **Sub-GLE definitions by Raukunen (2018) and Poluianov (2017) are in good agreement. Indeed, sub-GLEs have particles with energies E > 300 MeV.**

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Thank you!