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Neutron production in simulations of extensive air showers

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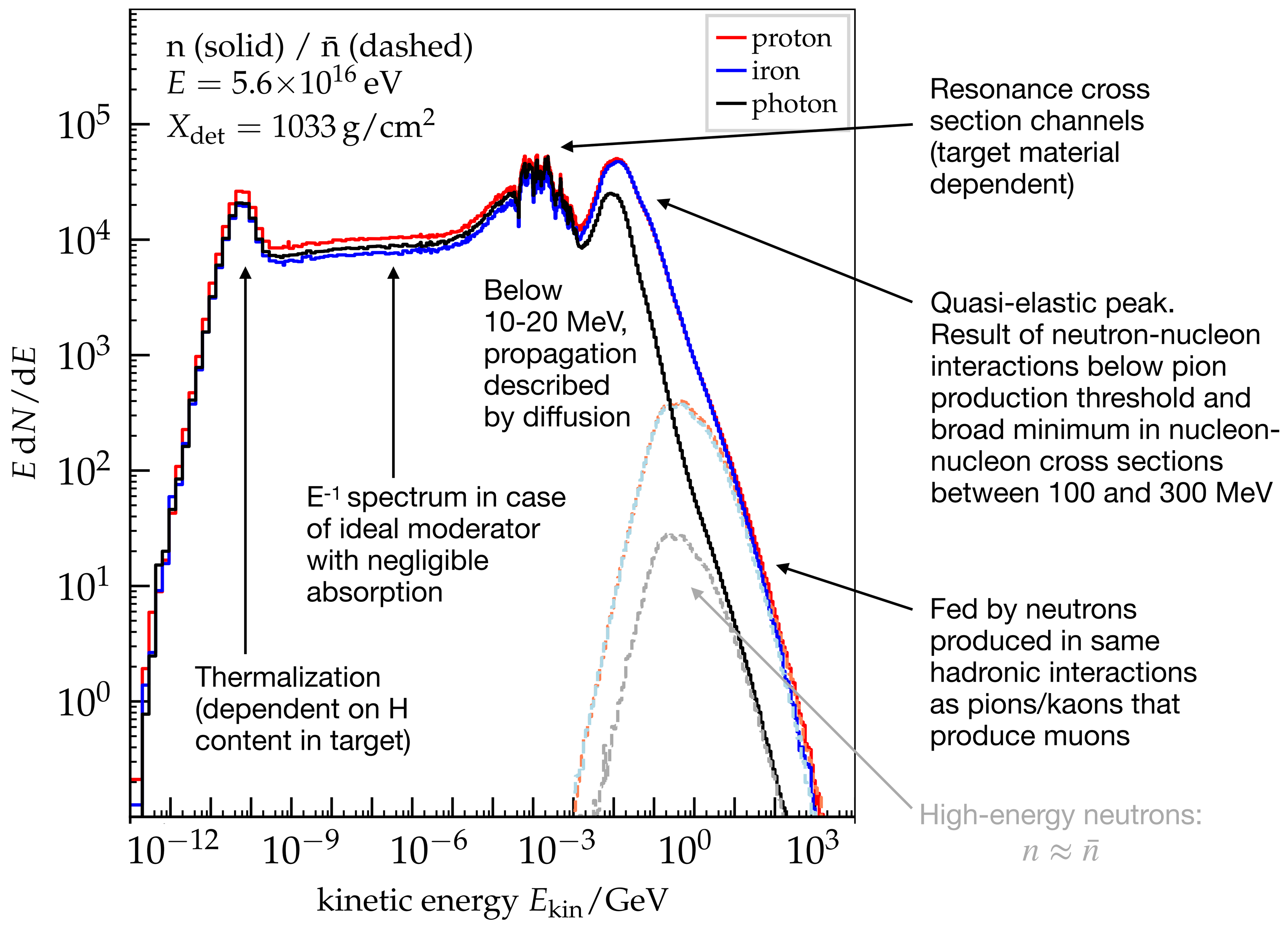
Overview

Study of neutrons produced in simulated air showers

- energy spectrum from meV to TeV
- arrival times at different atmospheric depths
- longitudinal evolution and lateral distributions
- dependencies on primary mass and energy
- comparisons to muonic component

Vertical showers for five primary energies ($5.6\times10^{14\ldots18}$ eV) considered

Production mechanisms across energy spectrum



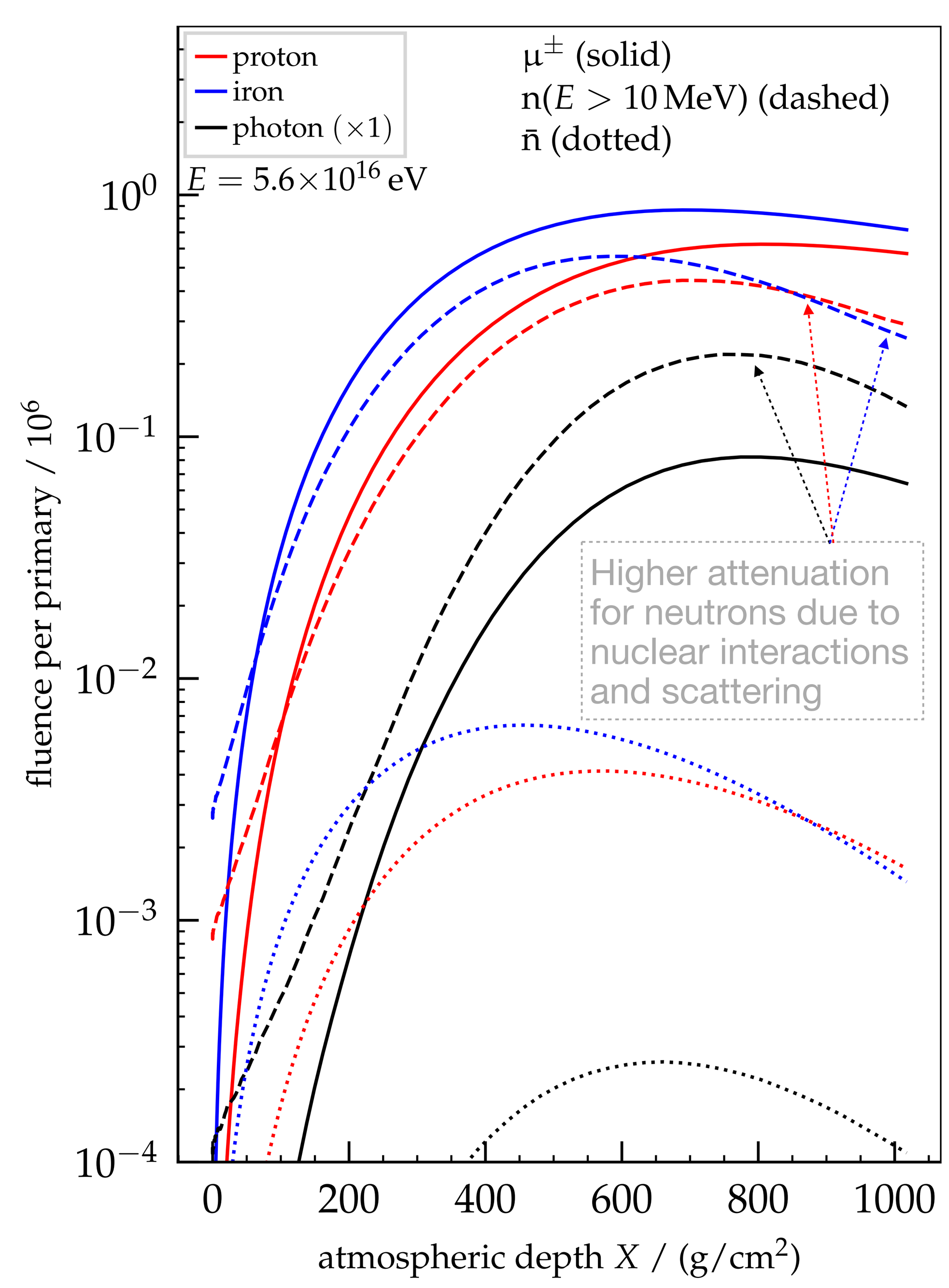
Two coincidences & implications for mass and energy scaling

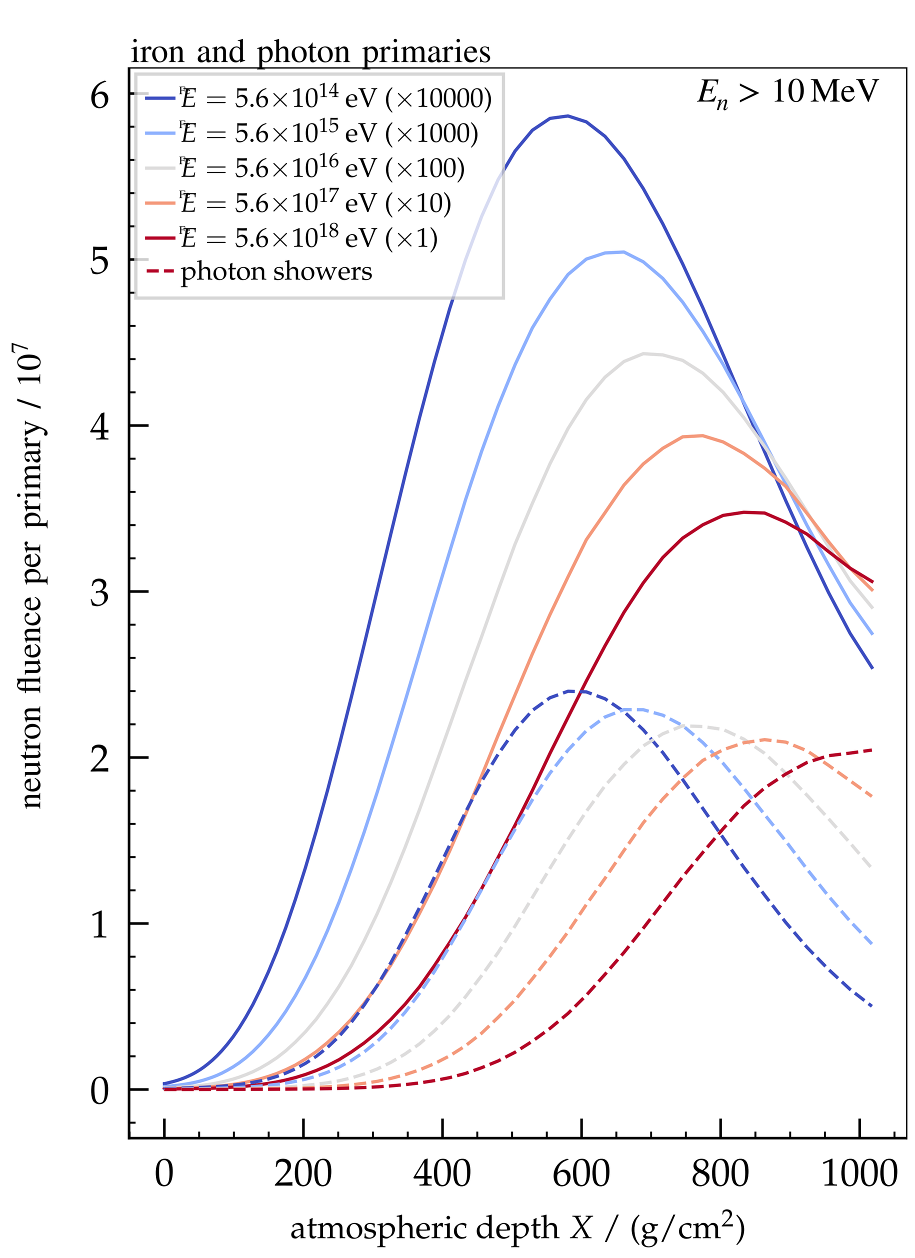
Mass dependence

- Difference between primaries evolves with atmospheric depth
- Countering effects:

  additional hadronic energy for heavier primaries (N_n ↑)
  vs.
  increased attenuation prior to reaching ground (N_n ↓)

- Differences in muon fluence between primaries more constant (larger attenuation length)





Energy dependence

- At maximum: neutron number scales with energy as with muons
- Neutrons in showers with higher energy suffer less attenuation as maximum deeper
- Result: number of neutrons reaching ground scales linearly with energy for hadronic primaries (at ~850 g/cm²)
- Contrasts with E^β (where $\beta\approx0.9$) scaling of muons

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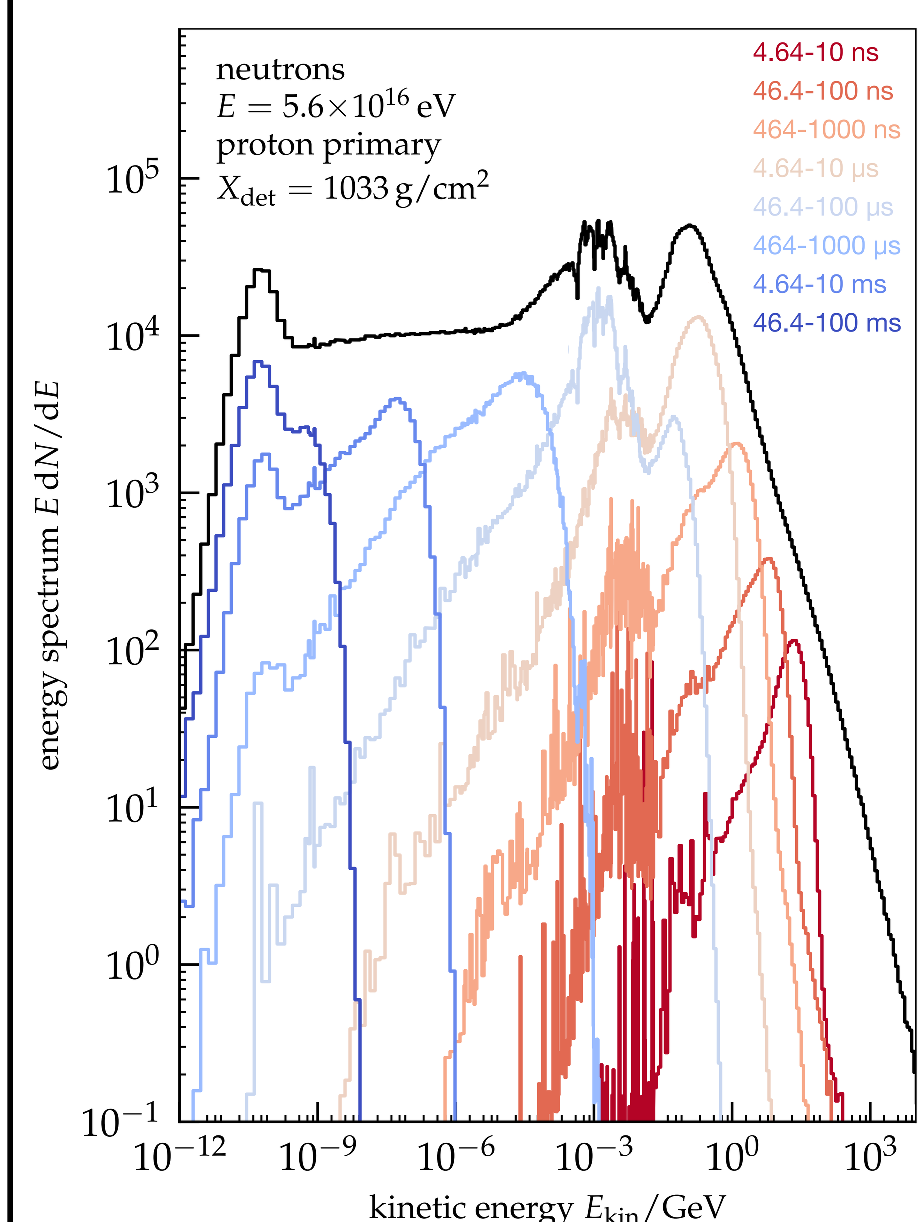
- Monte Carlo simulation package for particle transport and interactions with matter
- Validation: accelerators and cosmic ray measurements for different depths and conditions
- Allowed extension of study to thermal energies

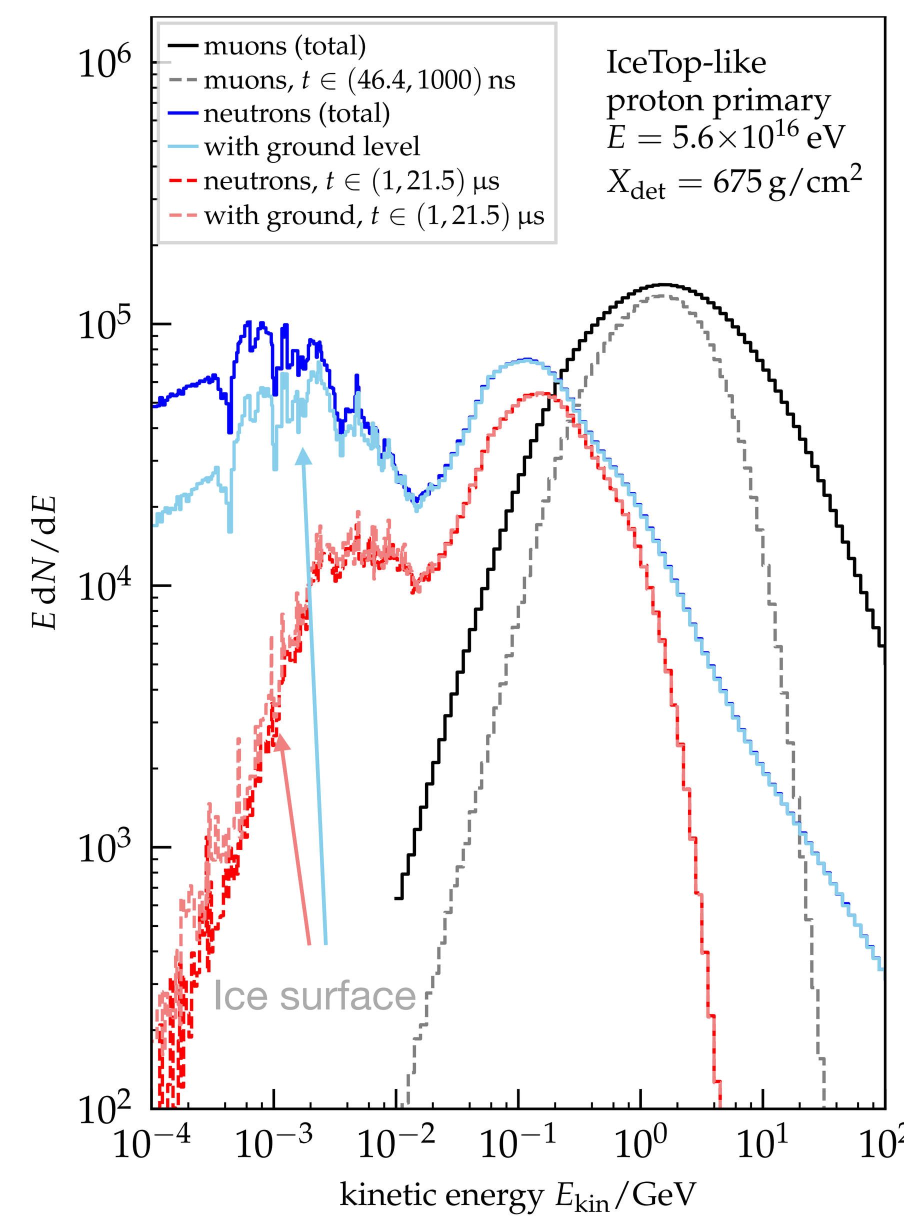
Arrival times at the ground



Many orders of magnitude

- Bulk of muons within 1 μs
- Bulk of neutrons after 1 μs

→ Signature for distinguishing neutrons from muons

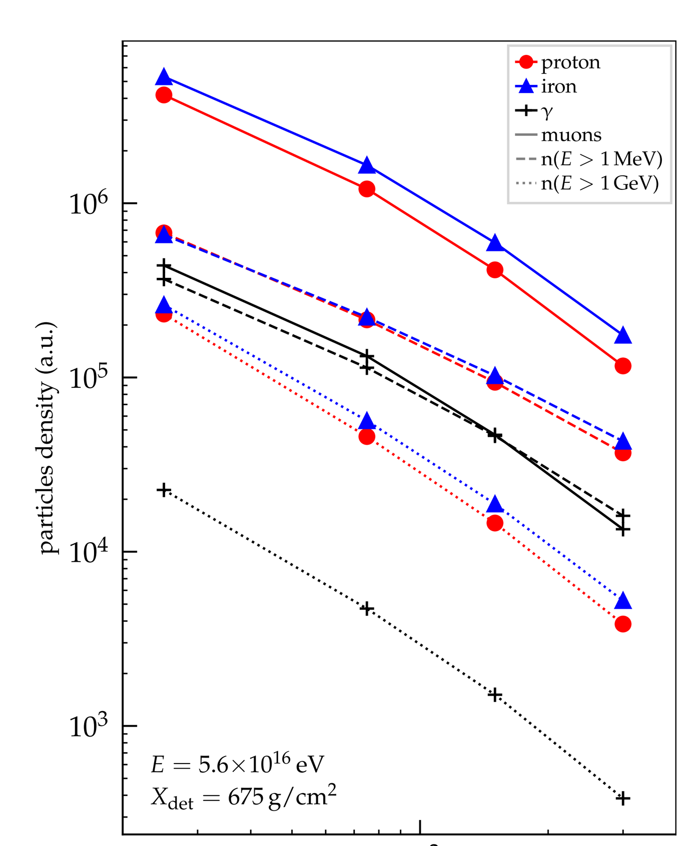


Minimal impact of ground properties in region where detection is possible with water-Cherenkov light and scintillation (≳ 1 MeV)

Red: arrival times where observatories typically acquire data

For larger delays: N_n comparable to N_μ

Lateral distributions



Slope for neutrons flatter than that of muons

Slope for proton primaries slightly steeper than for iron primaries (analogous to muonic component)

Photons: $N_n \approx N_\mu$

Takeaway:

- Neutrons often neglected in cosmic-ray / air-shower physics
- Distinct characteristics relative to other components
- Abundance alone justifies consideration of influence on existing + future measurements and potential to exploit