Gamma-ray sources in the solar system: the Moon emission

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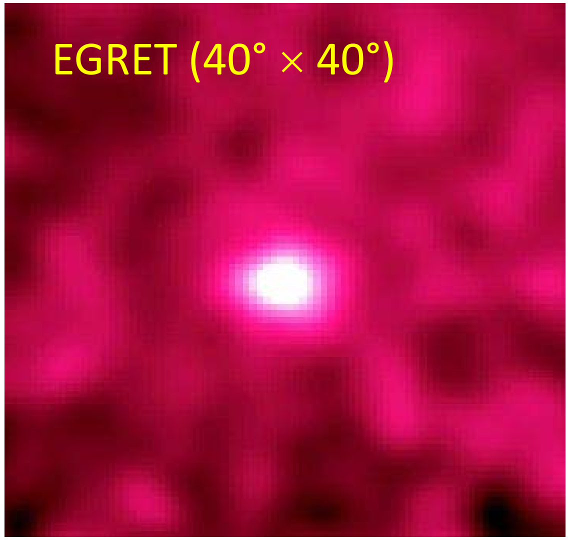
(Steady) gamma-ray sources in the solar system

- The Sun (see Elena's talk)
  - Interactions of charged CRs with the solar atmosphere
  - Inverse Compton emission due to CR electrons scattering off solar photons in the heliosphere
- The Earth
  - Interactions of charged CRs with the atmosphere
    - Earth's Limb
- The Moon
  - Interactions of charged CRs with the lunar surface
- Gamma-ray emission studies are a probe for CR fluxes in the solar system
  - The gamma-ray fluxes depend on the solar cycle

Gamma rays from the Moon

- Gamma rays are produced in the interactions of primary CRs with the lunar surface mainly via π^0 decays
  - First seen by EGRET
- The lunar gamma-ray flux is sensitive to:
  - Primary CR composition and spectra
  - Lunar surface composition
  - Interaction process of primary CRs with the lunar regolith



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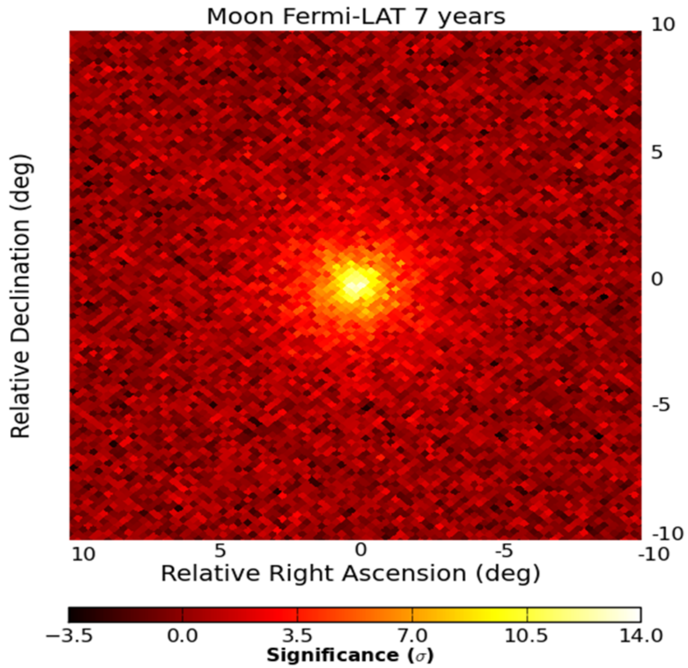

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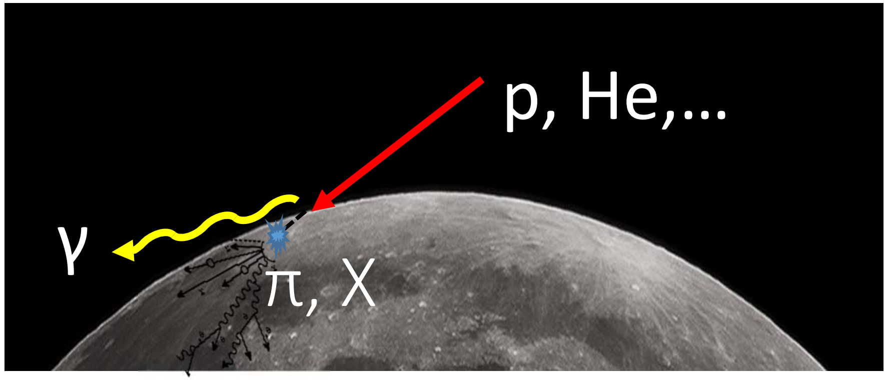
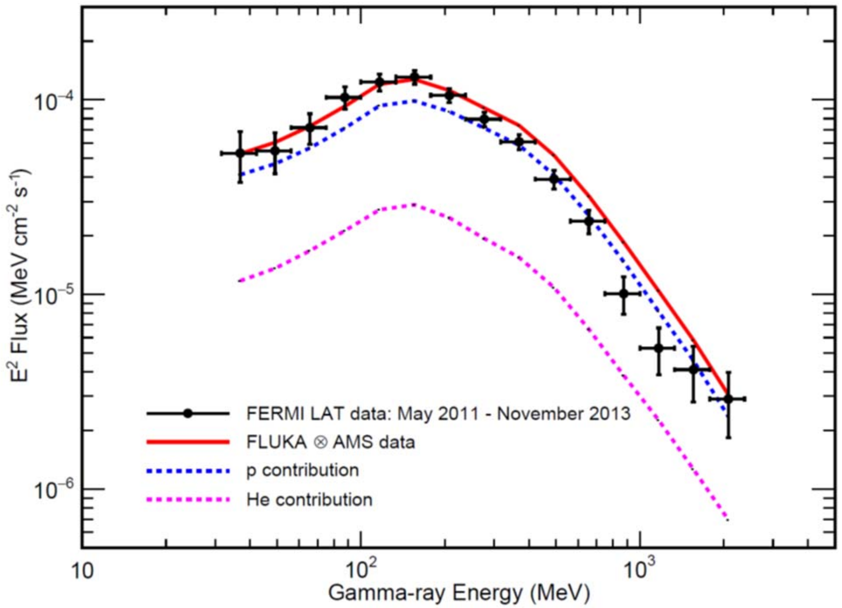


Fermi-LAT analysis of the Moon data

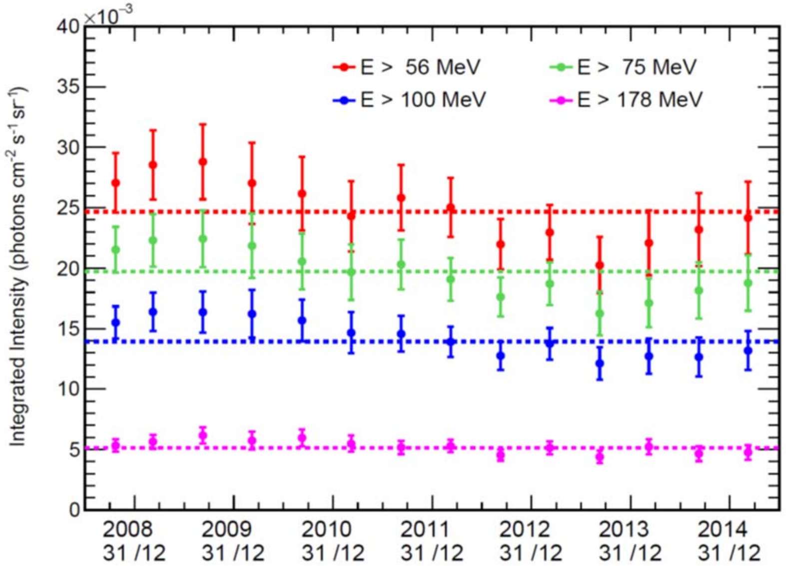
Phys. Rev. D 93, 082001 (arXiV 1604.03349)

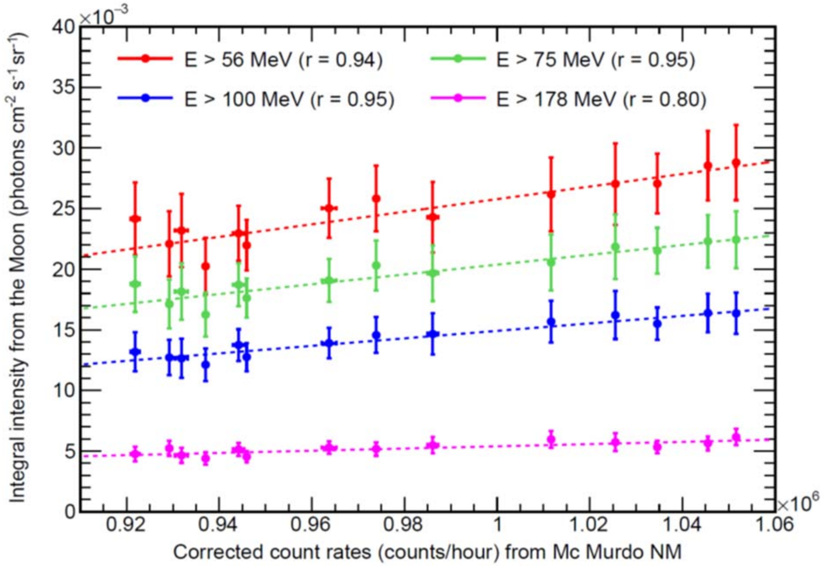
- Data analysis performed with the ON-OFF technique
  - ON: real Moon position in the field of view (FoV)
  - OFF: Moon position with time shifted forward/backward in the FoV
- Model:
  - Full MC simulation of CR interactions with the Moon based on FLUKA toolkit to evaluate the yield
    - A lunar surface chemical composition taken from the Apollo mission regolith sample
  - Then yield is folded with the CR spectra (proton and helium) taking also into account the Moon radius and distance
  - Validated with p and He data collected by AMS-02 in 2011-13



Time evolution of the Moon gamma-ray emission

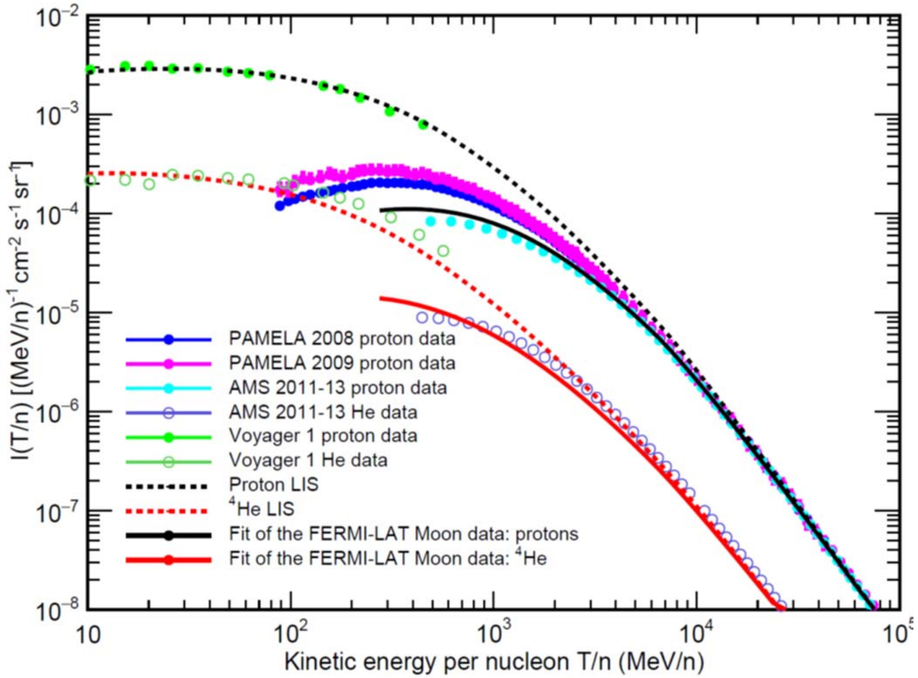
- The gamma-ray flux from the Moon is correlated with Solar activity
  - Solar modulation effect on charged CR impinging on the Moon
- The gamma-ray intensity from the Moon is strongly correlated with the counts in the neutron monitors (eg. McMurdo neutron monitor)
  - The correlation becomes weaker as the energy threshold increases





Proton and He spectra reconstruction

- The Moon gamma-ray data allow to reconstruct the local CR p and He spectra
  - We start from the local interstellar spectra (LIS) model which reproduces experimental observations (eg. Voyager 1, AMS, Pamela)
  - We use the force field approximation to describe solar modulation on charged CRs
  - Then we fold the modulated spectra with the MC gamma-ray emission (i.e. gamma ray yields)
- Actually we fit the solar modulation potential to derive the p and He spectra

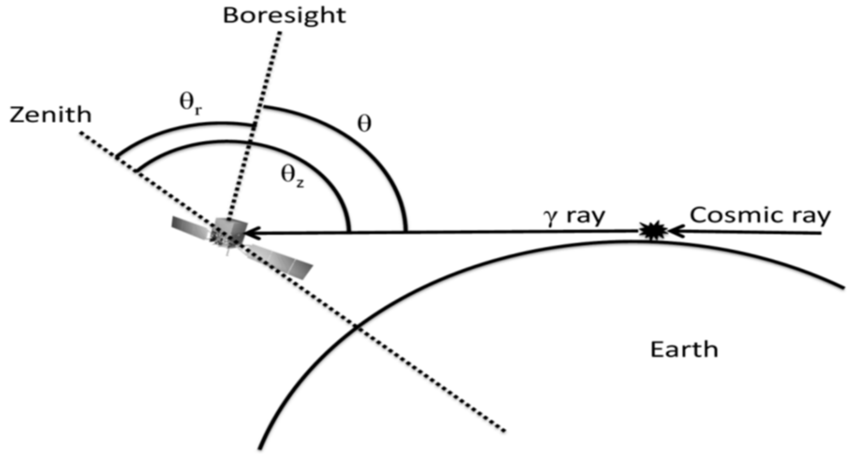


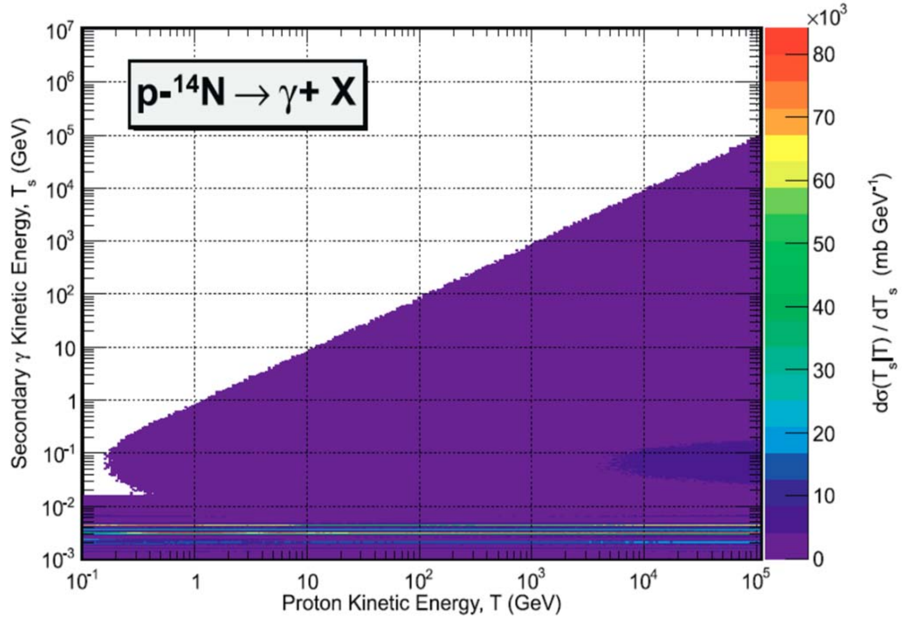
Planets

- The gamma-ray emission depends on the size of the planet body and its distance from the Earth
  - $\Phi_\gamma(E_\gamma) = \frac{\pi R^2}{d^2} \int dT\, Y(E_\gamma|T)\, I_{CR}(T)$
- Some differences are due to:
  - The chemical composition of the planet surface
  - Solid vs gaseous planet
  - Presence of atmosphere
- Roughly speaking the Moon (and Sun disk) measurement can be scaled for the planets to get an estimation of the gamma-ray emission
- The eAstrogam (AMEGO) ability to detect planets depends on the foreground level

Earth atmosphere γ emission (Earth's limb)

- Earth's limb gamma-ray emission is due to the interaction of charged CRs with the top layers of the atmosphere
  - This produces a bright emission
- In the low energy gamma-ray emission (<10 MeV) lines are expected due to Nitrogen gamma de-excitation
  - This feature could provide an opportunity to explore possible gamma-ray lines with eAstrogam (AMEGO)

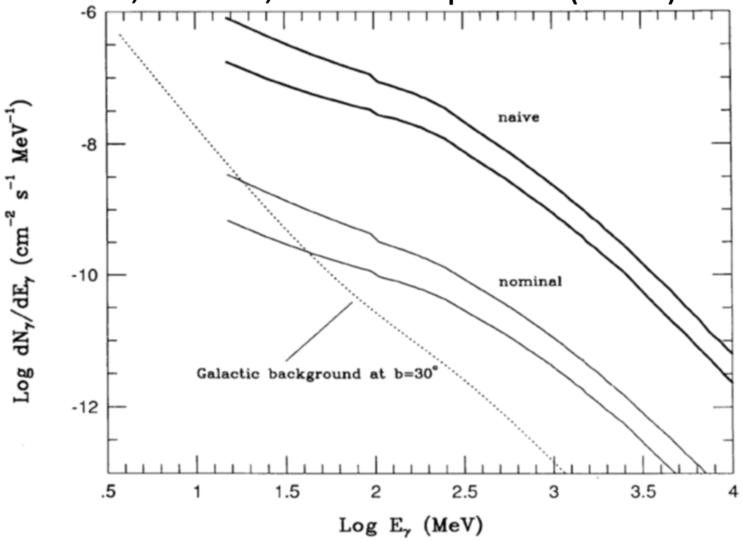


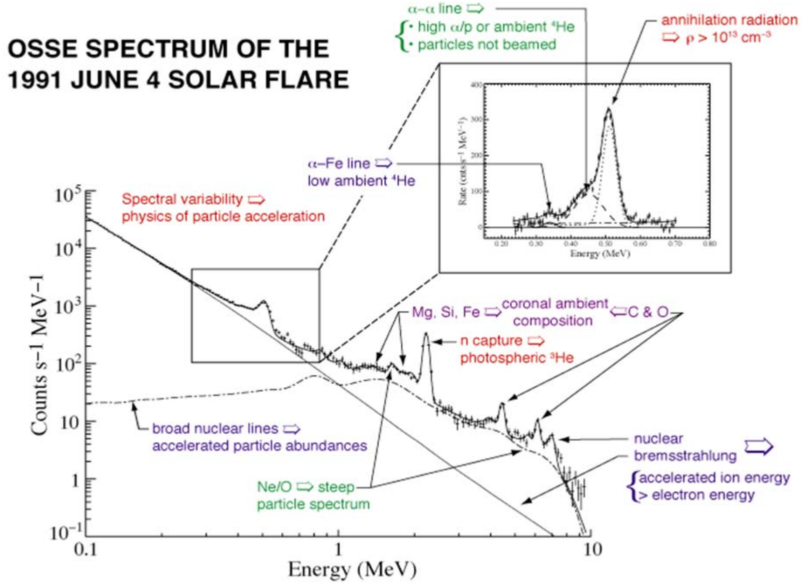


The Sun emission (see also Elena's talk)

- The gamma-ray emission is due to:
  - Interactions of charged CRs with the solar atmosphere (disk emission)
  - Inverse Compton emission due to CR electrons scattering off solar photons in the heliosphere
- We are currently working to derive a model for the disk emission down to 100 keV
  - Several gamma-ray lines are expected that can be observed with eAstrogam (AMEGO)

Seckel, Stanev, Gaisser ApJ 382 (1991) 652





Conclusion

- The energy range of e-ASTROGAM and AMEGO will match with the whole gamma-ray spectrum emitted by the Moon and Sun
  - The Moon gamma-ray energy spectrum is well understood, thus making it a “standard candle" for calibration
- e-ASTROGAM/AMEGO will extend the energy range observed by the Fermi LAT towards lower energies
  - This feature will provide the unique opportunity to explore possible gamma-ray lines in the subMeV region emitted in the Sun, Earth’s limb and possibly in the Moon
- The detection of the other planets (and asteroids) with eAstrogam/AMEGO will depend on the foreground level