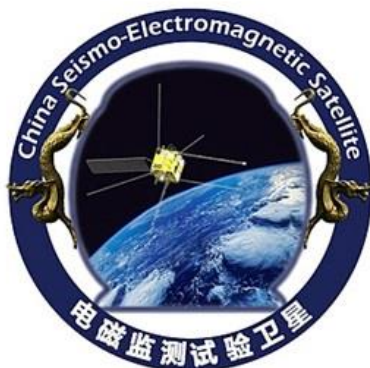




Istituto Nazionale di Fisica Nucleare

Università di Roma



The behavior of low-energy particles from space between the 24th and the 25th solar cycles: HEPD-01 as a successor of PAMELA

44th COSPAR Meeting

July 21st, 2022

Martucci M. ateo on behalf of the PAMELA & Limadou Collaborations

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COSPAR 2022

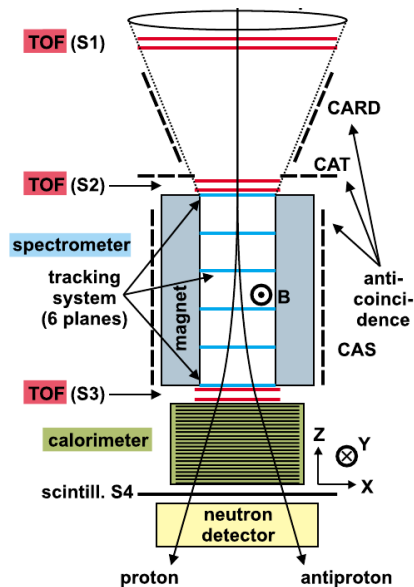
44th SCIENTIFIC ASSEMBLY

16-24 July 2022, Athens, Greece

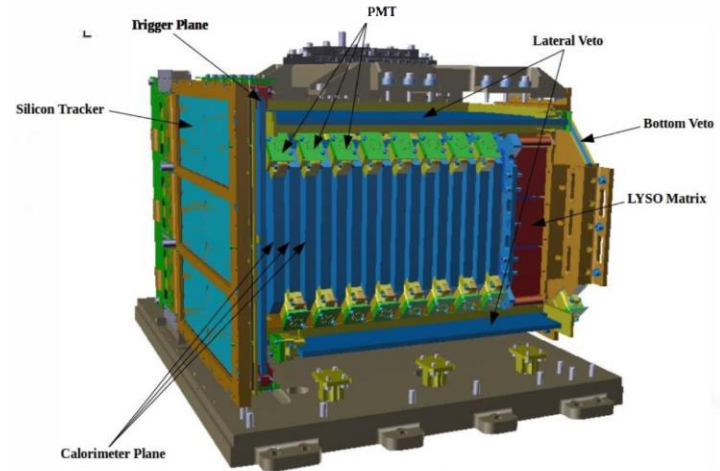
*a***MUSEd** by the Athenian **URANIA**

- ❑ Low-energy galactic particles (< 1 GeV) inside the Heliosphere are known to be continuously changing in time, mostly due to the activity of the Sun (**solar modulation**)
- ❑ Their transport is well described by the **Parker equation** during minima of solar activity, but the same cannot be said during periods of high activity when the Heliosphere is turbulent and the Sun-Earth environment is disturbed by transients like **Solar Energetic Particle Events (SEPs), Coronal Mass Ejections (CMEs)** etc.
- ❑ Moreover, some of these particles could interact with the geomagnetic field and they can remain **trapped**
- ❑ Having a detector that can follow 1 or more solar cycles during its data-taking is crucial to shed more light and better clarify some characteristics of the cycle itself
- ❑ **PAMELA** took precision data from 2006 to 2016, between 23rd and 24th solar cycles at Low-Earth Orbit . starting from 80 MeV
- ❑ In 2018, a new detector – the **High-Energy Particle Detector (HEPD-01)** was launched and is currently taking very good data on low-energy (~ 50 MeV) particles

- **Time-Of-Flight** : albedo rejection, charge/mass ID
- **Spectrometer**: dE/dx , rigidity
- **Electromagnetic Calorimeter** : e^+ / p , anti- p / e^- discrimination, E measurement
- **Neutron Detector** : e/h separation @ high energies
- **Veto** : rejects secondaries , out of acceptance particles



80 MeV – 1.2 TeV

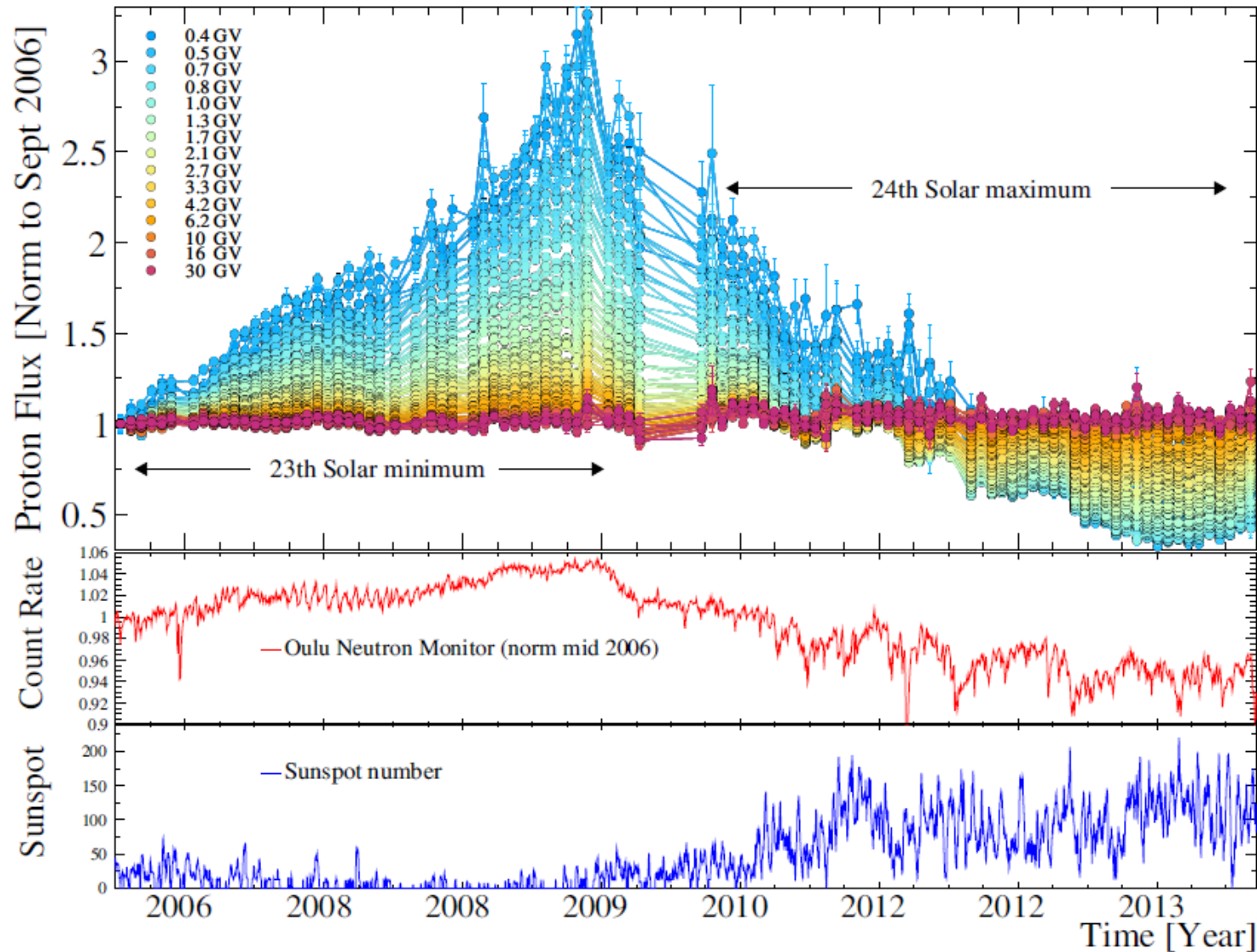


- **Tracker** : particle trajectory
- **Trigger** : starts acquisition
- **Calorimeter**
 1. **TOWER** : energy deposit, range
 2. **LYSO** : enlarge energy threshold
- **Veto** : rejects secondaries , out of acceptance particles

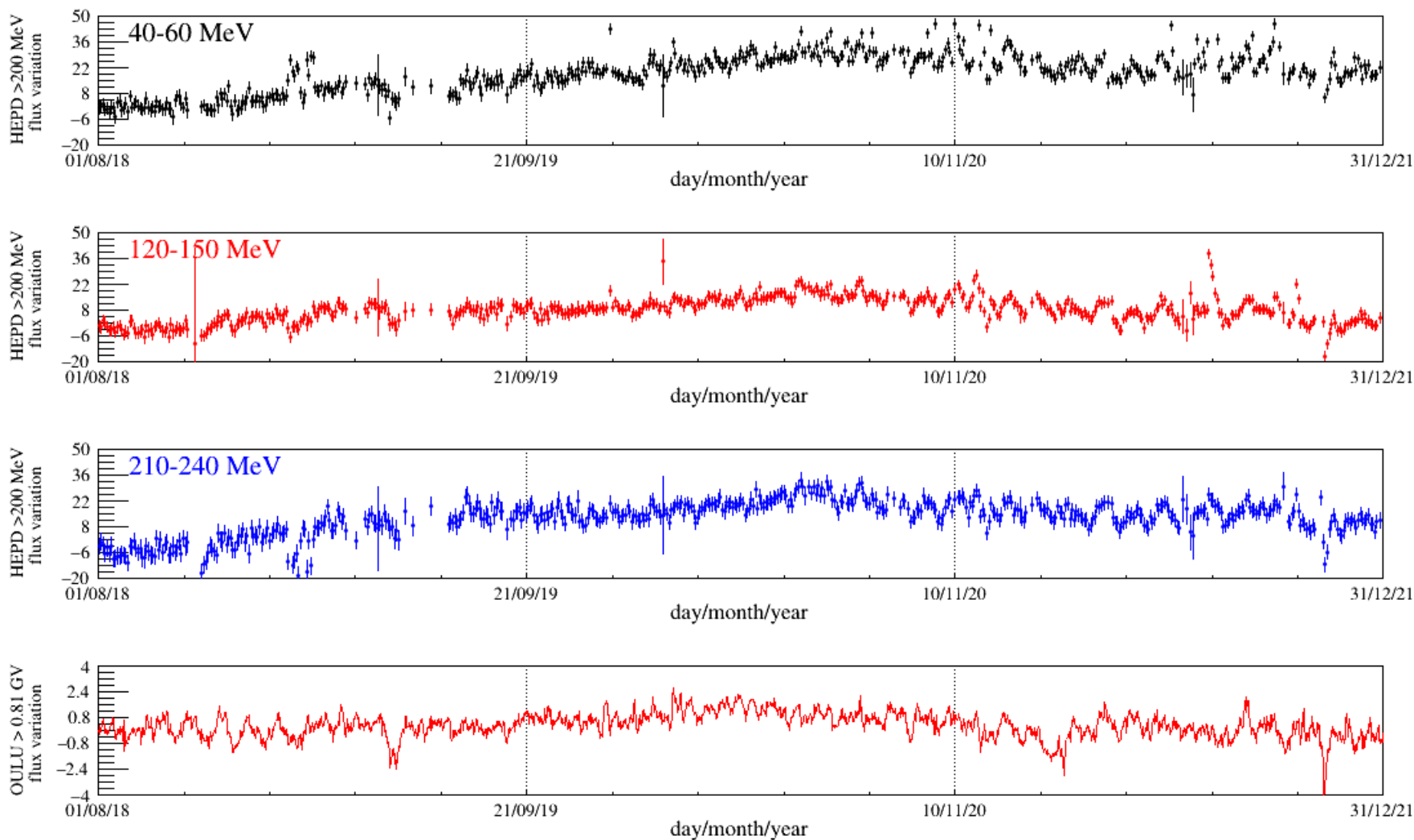
50 - 250 MeV (protons)
 3 – 100 MeV (electrons)
 50 – 250 MeV/n (nuclei)

Solar Modulation

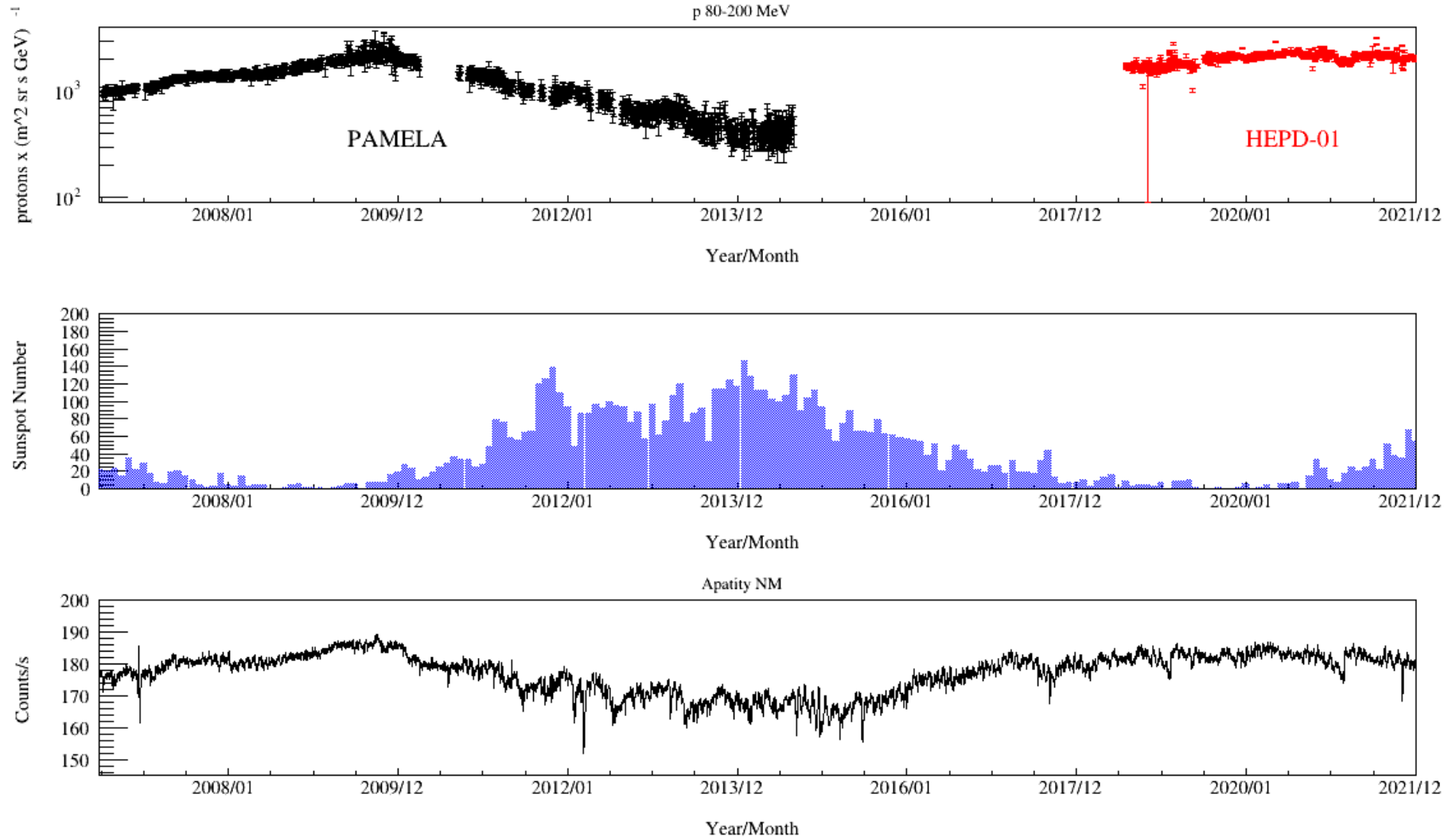
PAMELA results during 23/24 cycles



HEPD-01 results during 25 cycle

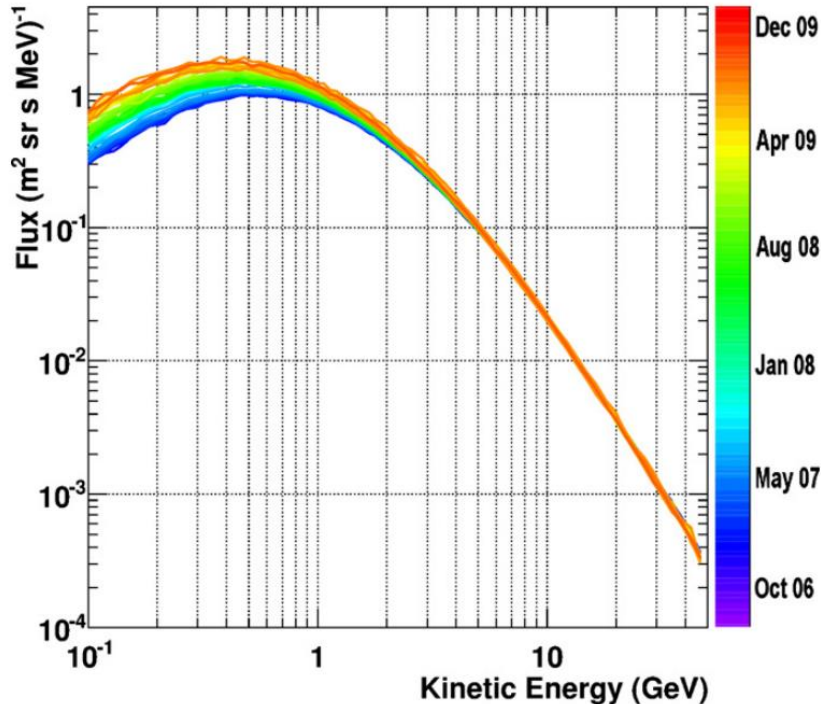


PAMELA + HEPD-01

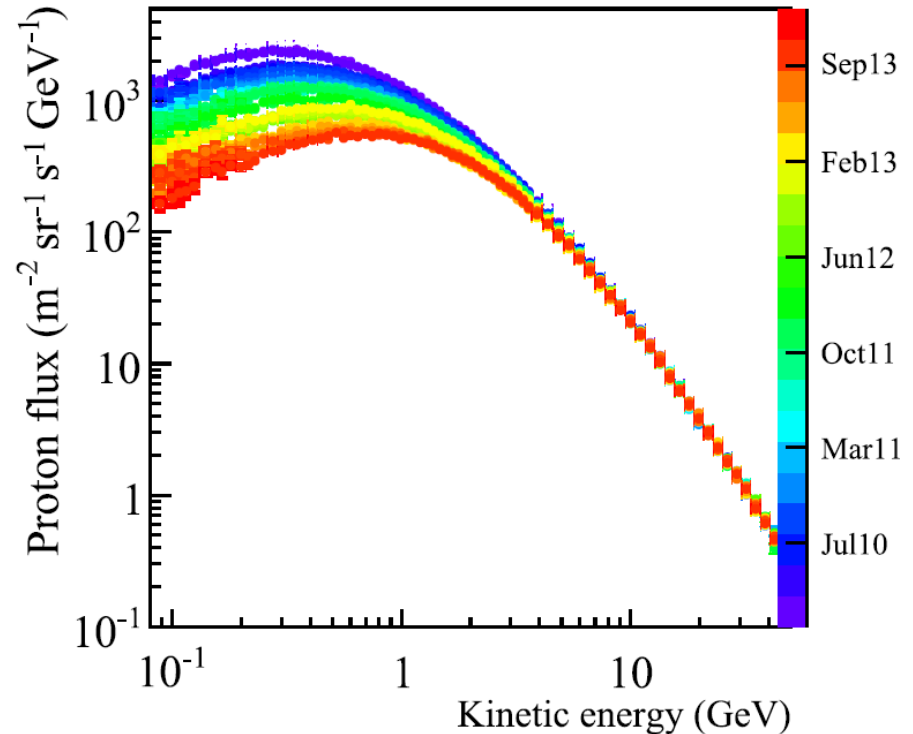


PAMELA proton spectra

Adriani, O. *et al* 2013 *ApJ* 765 2

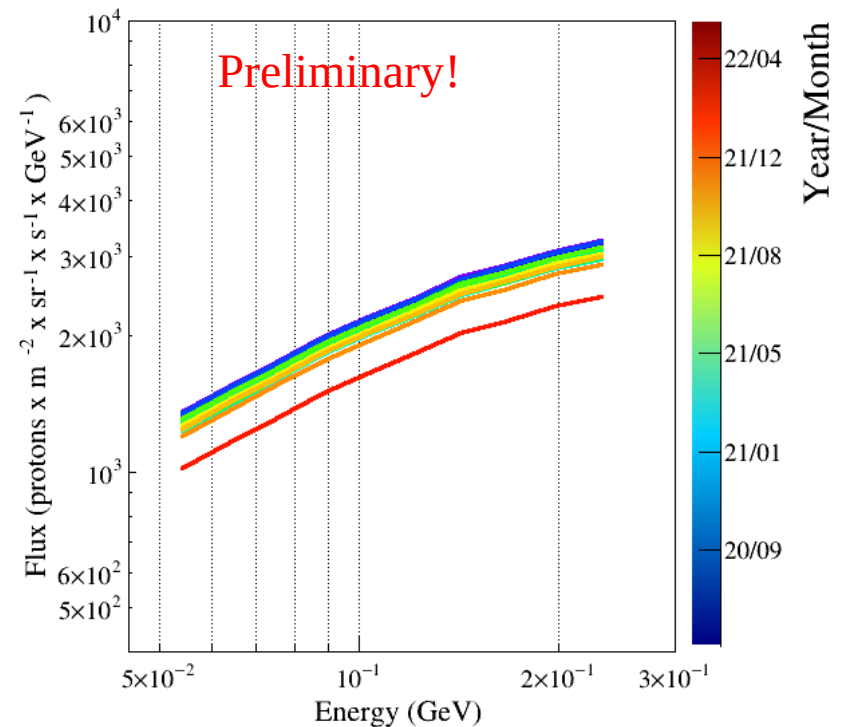
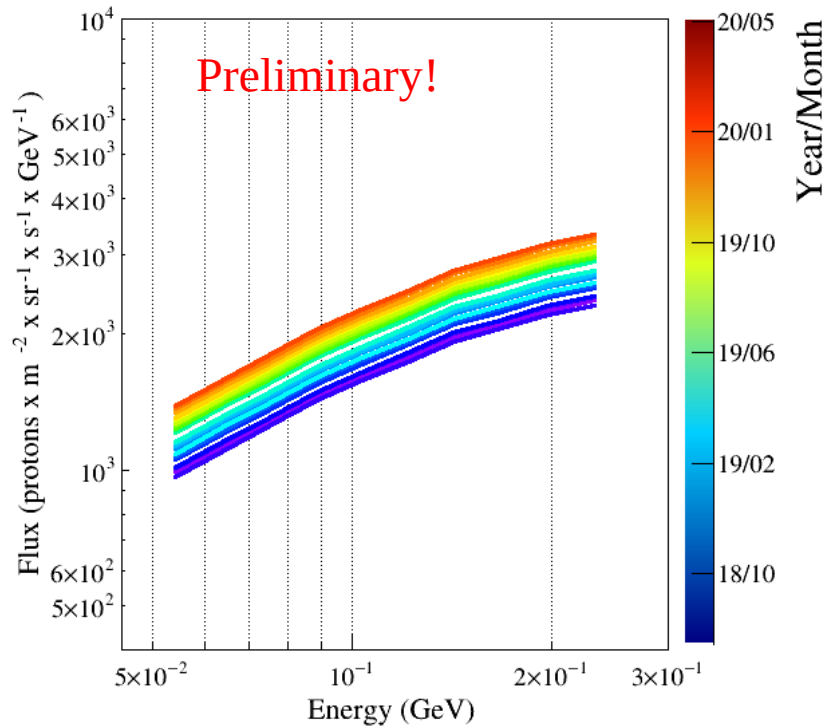


Martucci, M. *et al* 2018 *ApJL* 854 L2



- ❑ PAMELA published results on GCR proton modulation over the solar minimum (2006 – 2009) and during solar maximum (2010 – 2014) between 80 MeV and 50 GeV

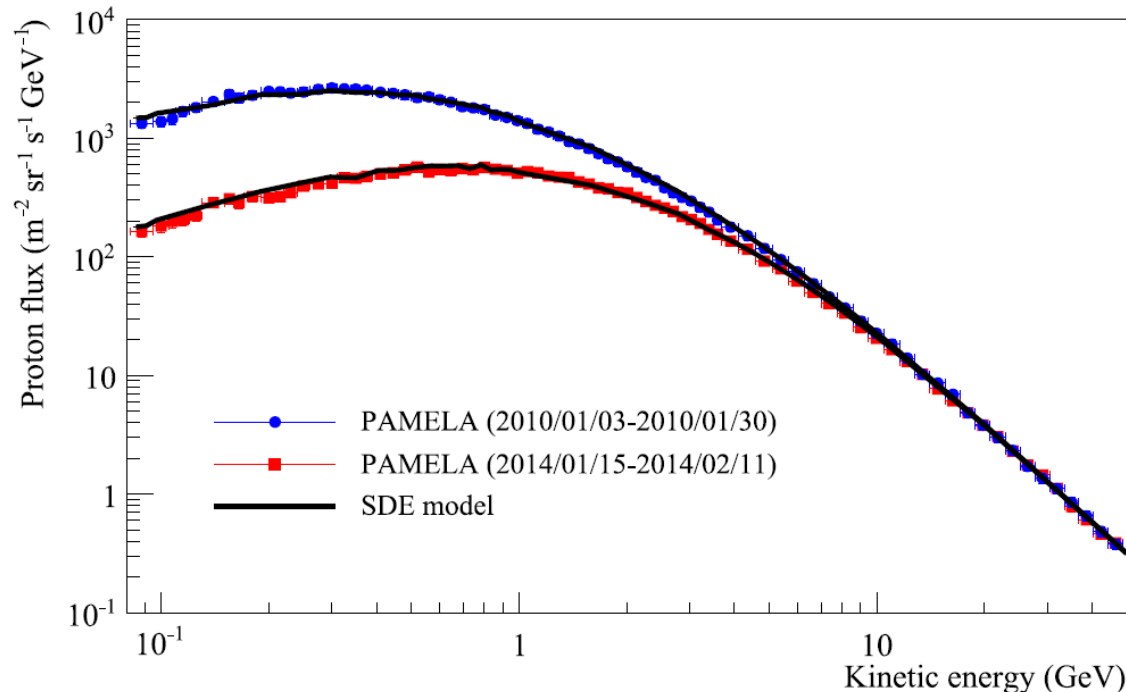
HEPD-01 proton spectra



- ❑ Preliminary results on GCR proton modulation during the end of the minimum (left) and the start of the maximum (right) measured by HEPD-01 between 50 MeV and 250 MeV
- ❑ White space in the right panel refer to the periods in which SEPs took place and data were removed

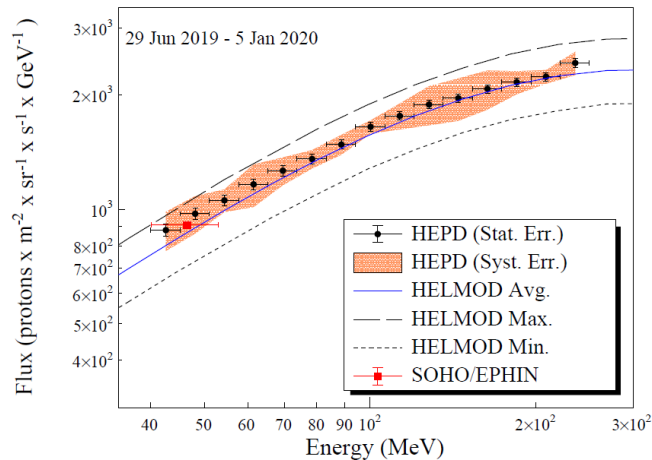
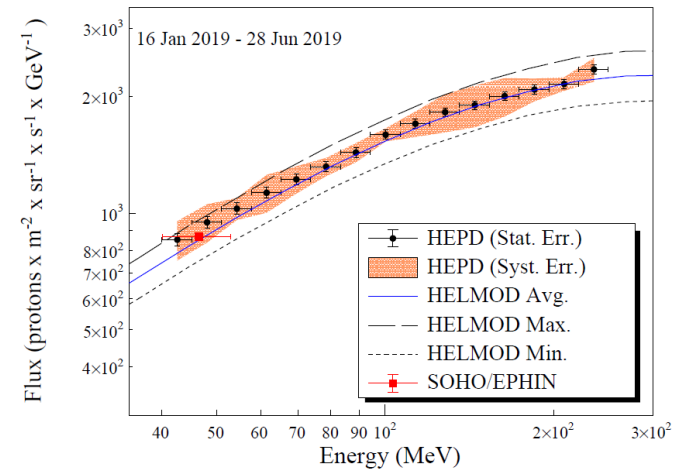
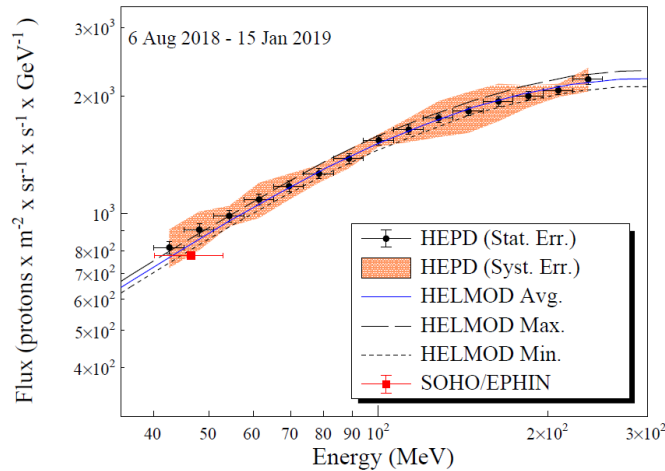
Martucci, M. *et al* 2018 *ApJL* 854 L2

- ❑ A full 3D numerical model based on solving Parker transport equation with the stochastic differential equation approach was used to compute the proton differential intensity at Earth
- ❑ This modeling approach and its validation against proton observations from PAMELA for the period 2006–2009 was already published
- ❑ PAMELA proton spectra registered in two Carrington rotations during 2010 (blue circles) and 2014 (red squares). Stochastic differential equations (SDE) model (black dashed curve) is superimposed on the observational data



PAMELA & HEPD-01: model comparisons

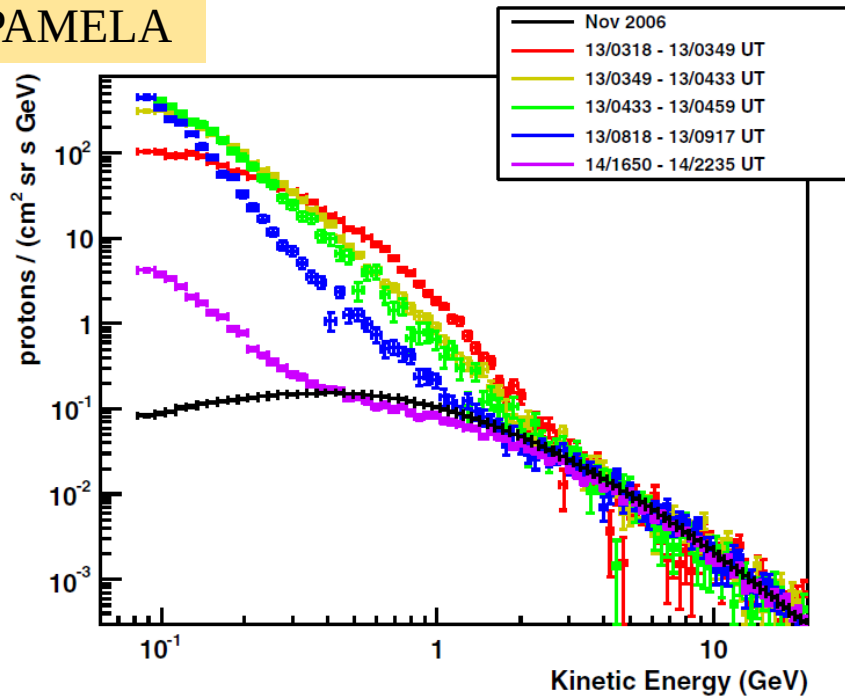
S. Bartocci *et al* 2020 *ApJ* 901 8



- Comparison with SOHO-EPHIN proton data shows a good agreement with HEPD-01 and the predicted HelMod model for GCR protons propagation is also in good agreement with HEPD-01 data
- Models during solar maxima are always more complicated due to the turbulence in the heliosphere → HEPD-01 (and the future HEPD-02) data could help constraining some of them

SEPs and CMEs

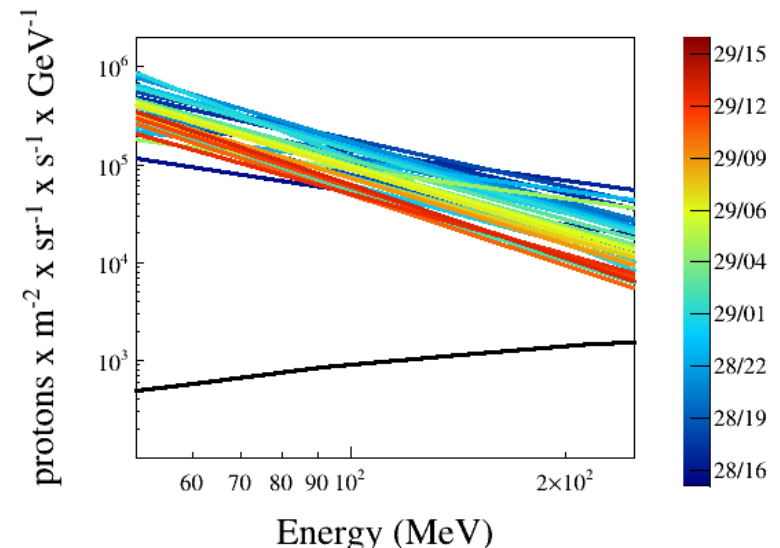
PAMELA



- ❑ Differential solar proton evolution during the SEP of Dec. 13, 2006 w.r.t. a quiet GCR background
- ❑ The spectral shapes seem to vary a lot during the first hours of the SEP itself
- ❑ Investigation of > 1 GeV energies was possible → **Ground-Level Enhancements**

HEPD-01

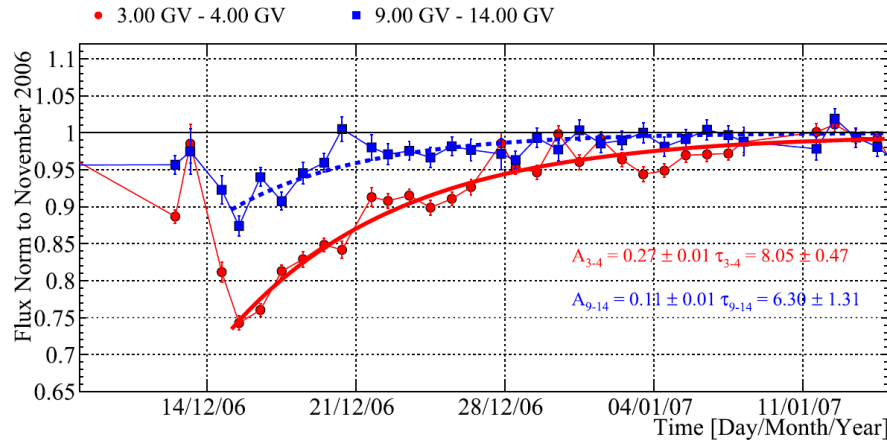
- ❑ Differential solar proton evolution during the SEP of Oct. 28 2021 w.r.t. a quiet GCR background
- ❑ The spectral shapes seem to vary during the first hours of the SEP itself
- ❑ Investigation of > 1 GeV energies is not possible, still HEPD-01 data could bridge a very interesting gap between low-energy and high-energy measurements



PAMELA & HEPD-01 results on CMEs

PAMELA

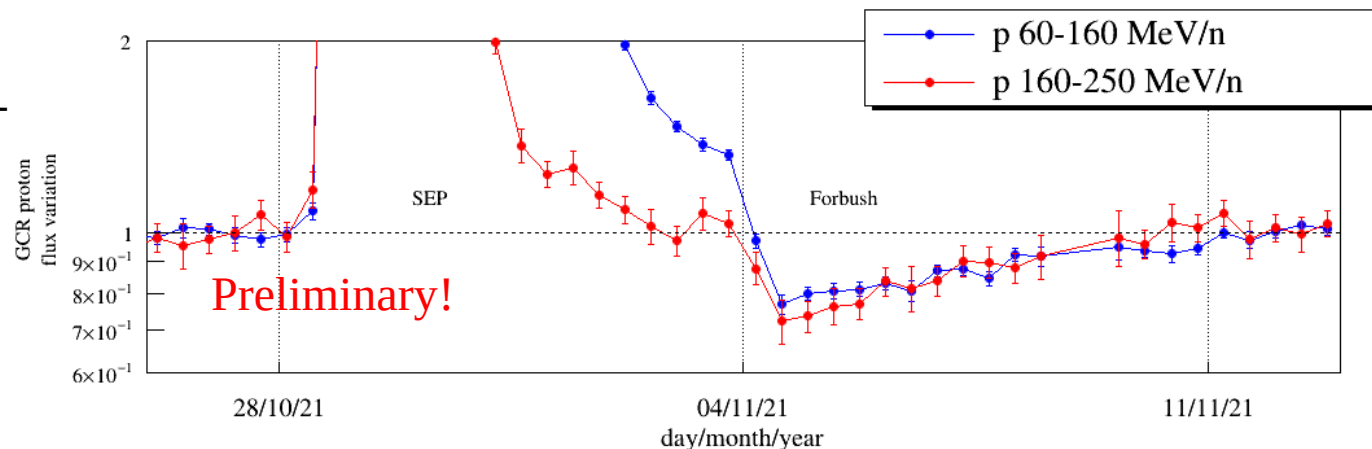
R. Munini *et al* 2018 *ApJ* 853 76



- ❑ PAMELA has shown good capabilities in studying Forbush decrease (FD) during very strong solar events (like the Dec. 13, 2006 one)
- ❑ Charge sign and energy dependence for the recovery time of FD was measured in proton, Helium, electrons and positrons

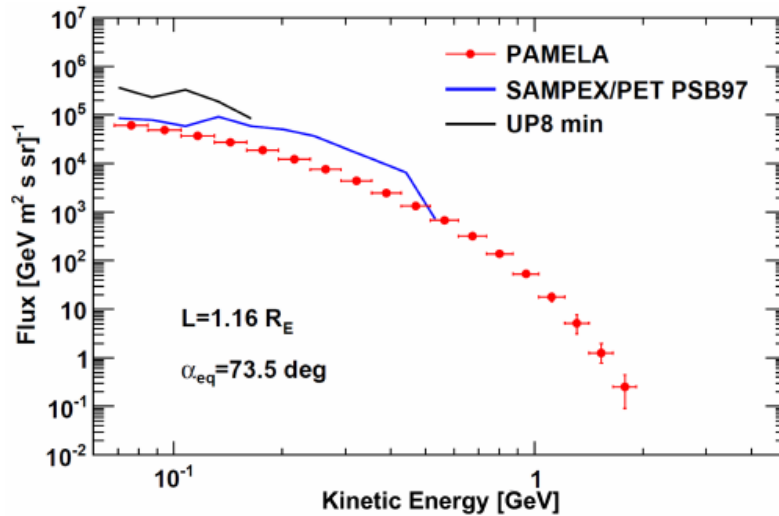
HEPD-01

- ❑ After a few days from the Oct. 28, 2021 SEP, - around Nov.4 – a CME reached the Earth causing a FD
- ❑ Study on charge sign dependence are ongoing



Trapped Particles

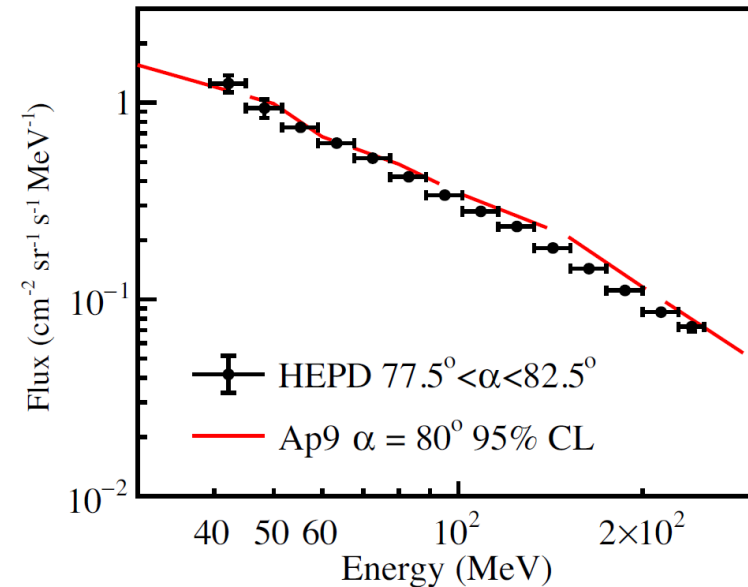
PAMELA



- ❑ PAMELA studied the distribution of trapped protons inside the South Atlantic Anomaly during the 2006-2009 period
- ❑ Comparison with models (like PSB87 and AP8) were performed
- ❑ Results published in O. Adriani *et al* 2015 *ApJL* **799** L4

HEPD-01

- ❑ HEPD-01 studied trapped protons in the same region between 2018 and 2020
- ❑ Experimental data were compared with the newest AP9 model
- ❑ Results published in M. Martucci *et al.* Phys. Rev. D **105**, 062001



- ❑ The low-energy particles inside the heliosphere are constantly changing due to the variations that occur at the level of the Sun and the interplanetary magnetic field
- ❑ These variations can be long duration (i.e. **solar modulation**) or short duration (**SEPs, Forbush decreases**). In other cases, populations are pretty much stable over time (**trapped protons**)
- ❑ PAMELA studied these phenomena from 2006 to 2016 in an energy range from 80 MeV to a few GeVs
- ❑ HEPD-01 proposes itself as a worthy successor to PAMELA, having already demonstrated excellent ability to study variations of particle populations inside the Heliosphere starting from 2018, during the 25th solar cycle
- ❑ HEPD-01 will not be the only instrument of this kind in orbit: in fact, a network of similar satellites will soon be launched, increasing the quantity and quality of possible observations from a few tens of MeVs upwards
- ❑ Recommended contribution: D1.3-0027-22, C1.1-0049-22, E1.17-0005-22, C1.3-0027-22