The impact of photonuclear reaction models on propagation of ultrahigh energy cosmic rays

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Introduction

- Pierre Auger observes ultra high energy cosmic ray (UHECR) and found the feature of the transition to the heavier elements from their results of the observation of the Xmax above 2×10^{18} eV [1].
- There were many attempts to interpret both of their results of the Xmax and the energy spectrum assuming extragalactic sources in the phenomenological way.
- In the propagation, the most important interaction of the nuclei at the highest energies is photonuclear reactions with cosmic microwave background (CMB) photons. Especially giant dipole resonances (GDRs) of the nuclei are important.
- In this work, the random phase approximation (**RPA) calculations** in density functional theory (**DFT)** [2, 3] are applied to the calculations of photonuclear reactions in the propagation.

Method

- **RPA calculations of 27 stable nuclei** (^{12}C ^{13}C ^{14}N ^{15}N ^{16}O ^{17}O ^{18}O ^{19}F ^{20}Ne ^{21}Ne ^{22}Ne ^{23}Na ^{24}Mg ^{25}Mg ^{26}Mg ^{27}Al ^{28}Si ^{32}S ^{36}Ar ^{40}Ca ^{48}Ti ^{51}V ^{52}Cr ^{53}Cr ^{54}Cr ^{55}Mn ^{56}Fe) for photo nuclear reactions were done.
- We input E1 strength function of the RPA calculations to TALYS [4].
  → We obtained cross sections and branching ratios of GDRs.
  Fig. 1 shows comparison of cross sections of GDRs using different models (SkM* [5], SLy4 [6] and UNEDF1 [7]).
- One dimensional cosmic ray propagation from extragalactic sources to the earth was simulated with CRPropa whose cross sections and branching ratios of 27 nuclei were replaced with calculated ones.
  → We compared simulated energy spectrum and ln A on the earth with simulated ones using default settings of CRPropa.

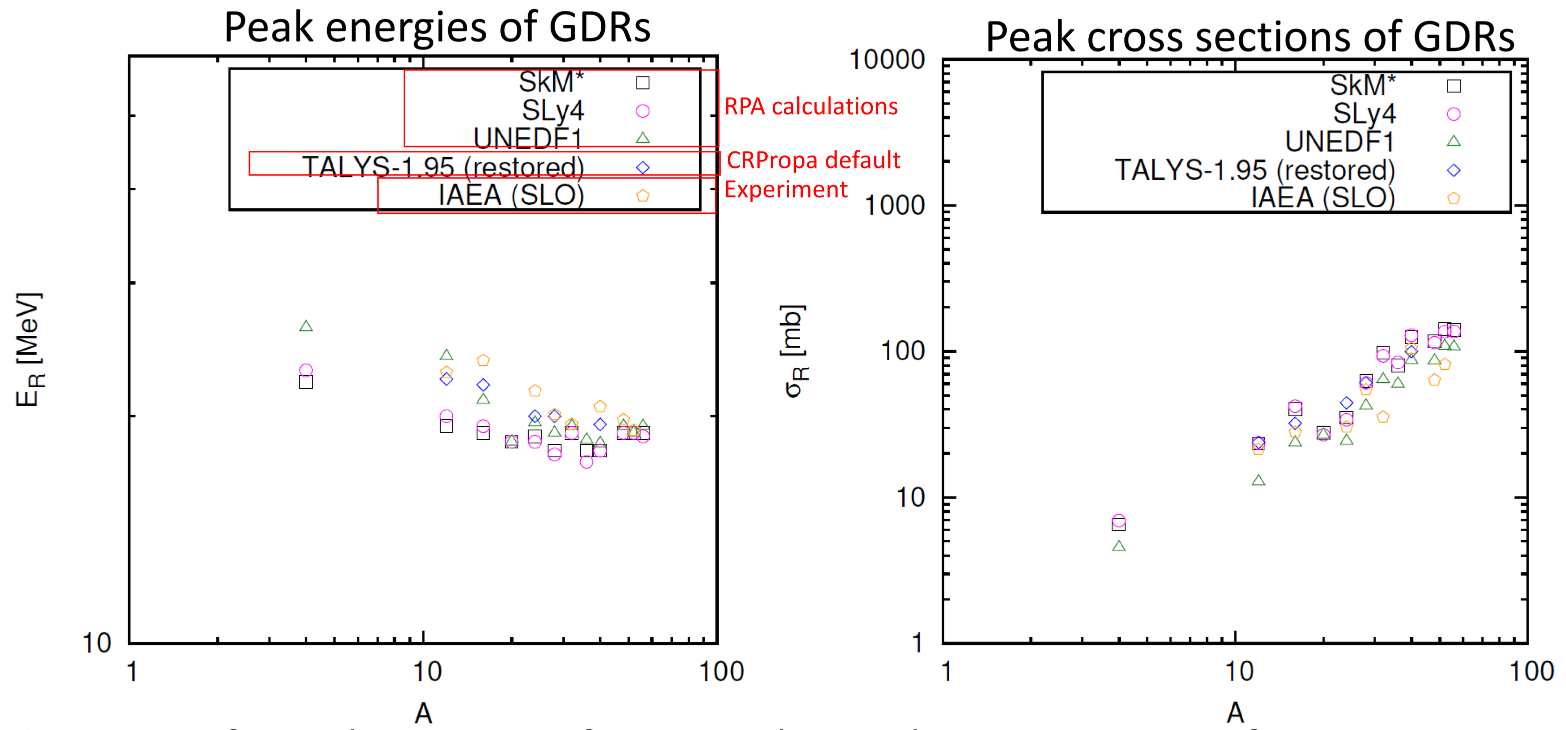


Figure 1: Left: peak energies of GDRs Right: Peak cross sections of GDRs

Results

The following astrophysical parameters of extragalactic sources are taken not to contradict the experimental data for the results of CRPropa.

- Injection energy spectrum: $dN/dE \propto E^{0.80}$
- Broken exponential rigidity dependent cutoff $\log(R_{cut}/\mathrm{eV}) = 18.20$.
- Evolution of number of sources $(1 + z)^{4.2}$ in the comoving unit volume.
- Energy scale of the data is shifted up by +12%. This shift is within the systematic uncertainty 14% of the experimental data
- Relative abundance of five elements are assumed at the source at 10^{18} eV. Relative fraction of the H, He, N, Si and Fe nuclei are 0.0, 0.939, 0.052, 0.008 and 0.0002, respectively.
- [8] is used as the extragalactic background light model.

We simulated the propagation with these parameters using different photonuclear reaction models and compared with the experimental data. We fitted only the normalization of the energy spectrum with E > $10^{18.7}$ eV to compare different models. Fig. 2, Fig. 3, Fig. 4 and Fig. 5 show the results of the comparison. The difference of the spectral shape between the RPA calculations and CRPropa is much larger than the statistical uncertainty of the experimental data.

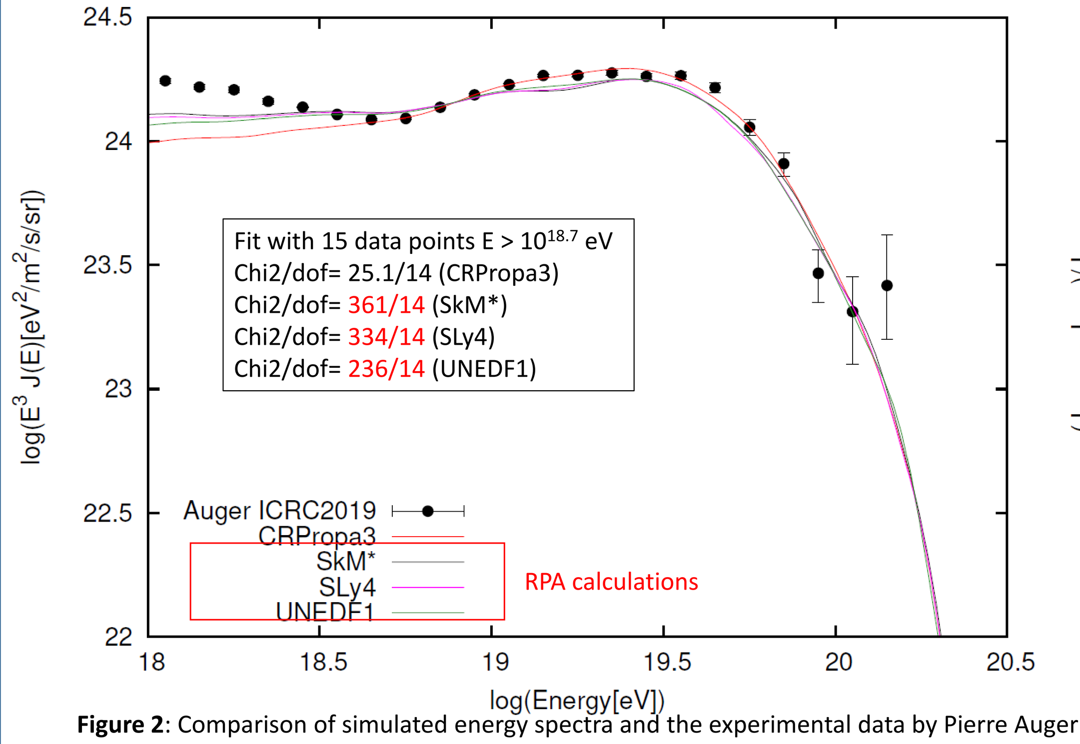


Figure 2: Comparison of simulated energy spectra and the experimental data by Pierre Auger [1]. E > $10^{18.7}$eV data were used to fit the normalization of simulated energy spectra with the same astrophysical parameters.

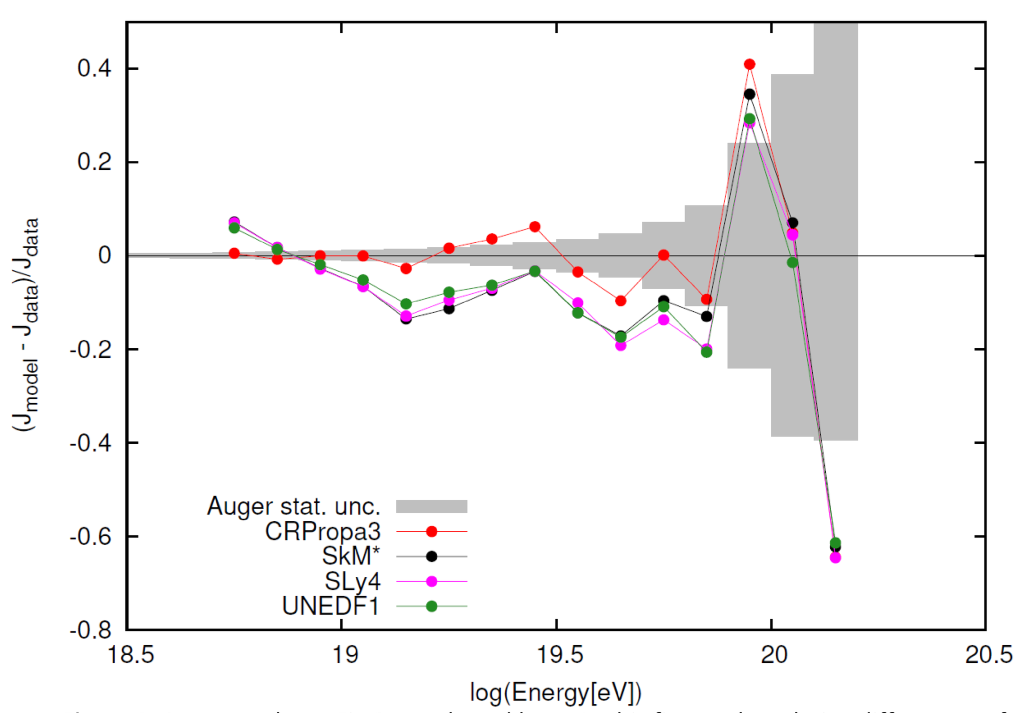


Figure 3: Same results as Fig.2 are plotted here. In this figure, the relative differences of the model predictions of the intensities J_{model} from the data J_{data} are plotted. The statistical uncertainties of the data are described as hatched region.

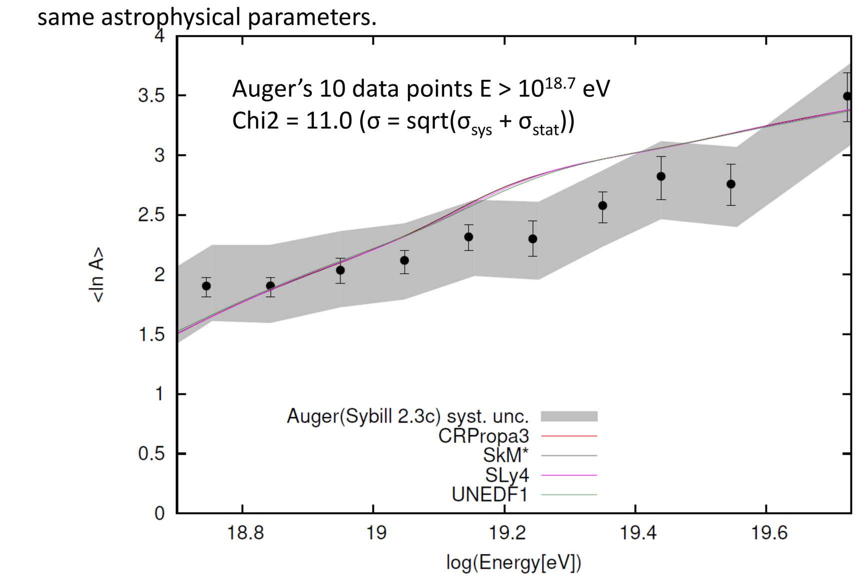


Figure 4: Comparison of simulated mean ln A of the same results as Fig. 2.

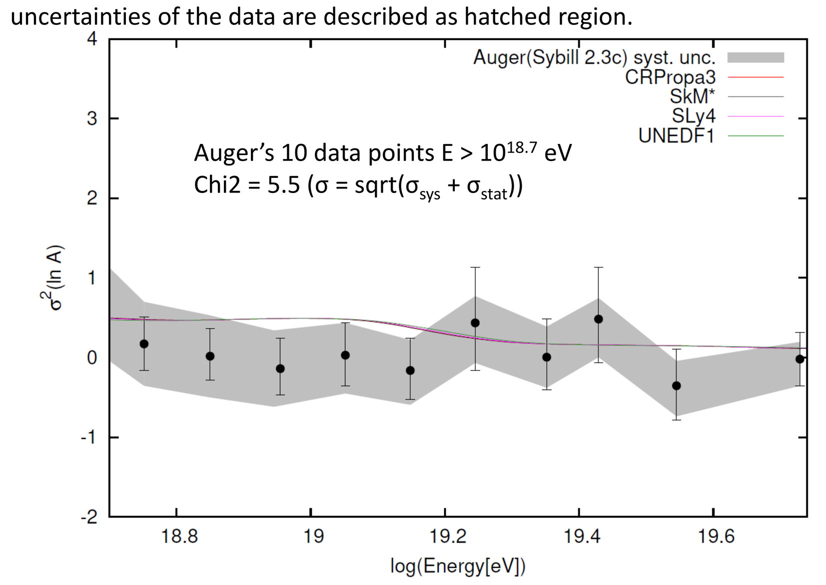
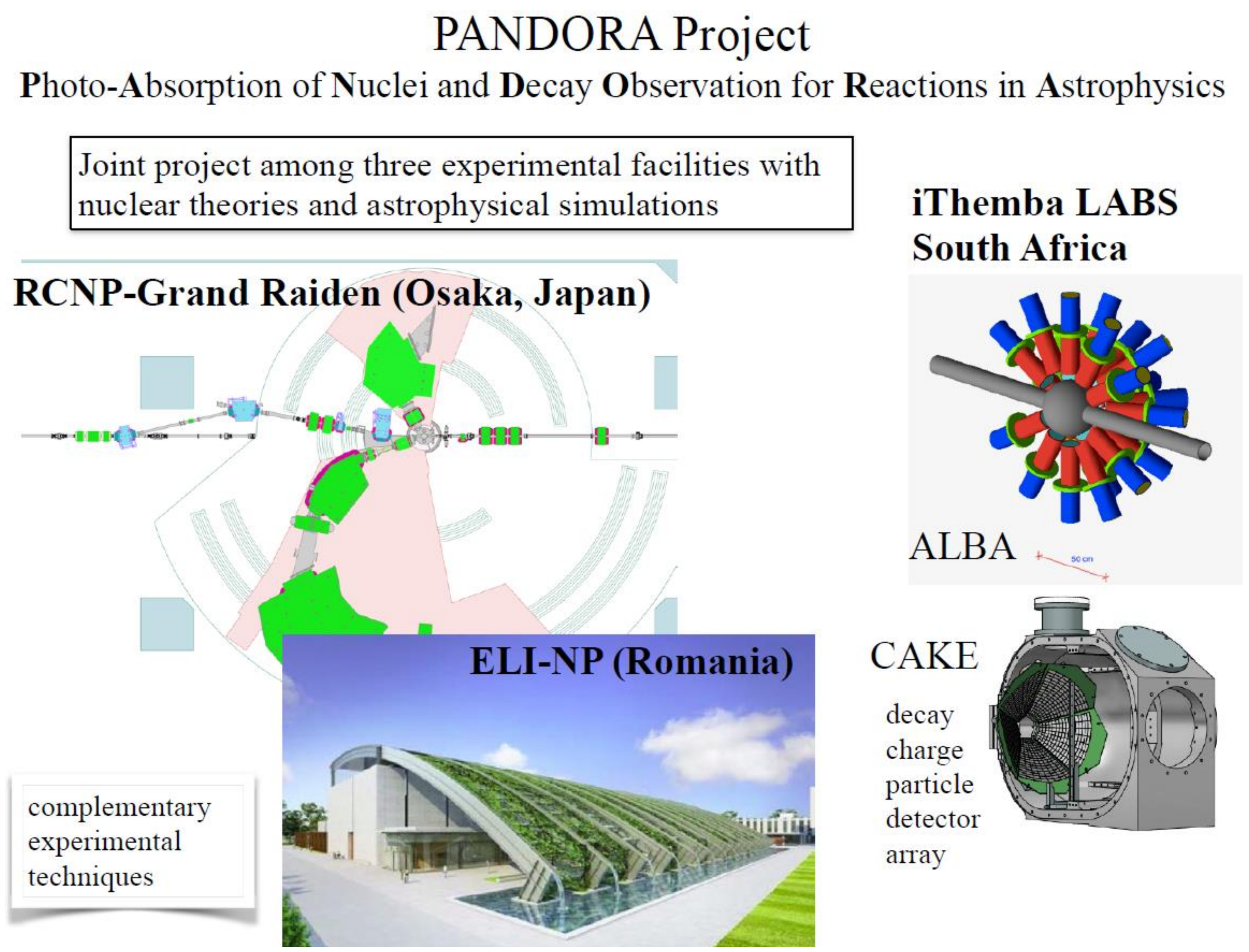


Figure 5: Comparison of simulated σ^2(ln A) of the same results as Fig. 2..

Conclusions and discussions

The peak energies and cross sections of GDRs using the RPA calculations are systematically different from CRPropa as shown in Fig. 1, and the difference results in the difference of the spectral shape shown in Fig. 2 and Fig. 3. We found that the difference is much larger than the statistical uncertainty of the experimental data. The model predictions of the peak energies and cross sections will be experimentally tested by the **PANDORA** project.



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