High- and Ultra-High-Energy Cosmic Rays

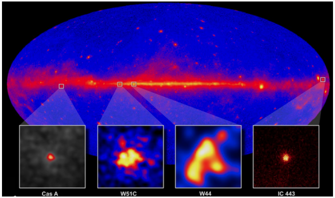
GT noyaux dans le cosmos

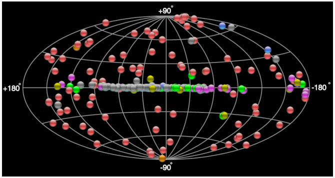
February 10, 2022

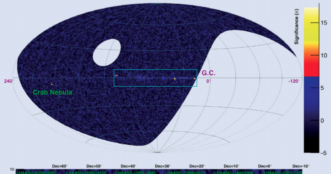
Olivier Deligny

From classical astronomy to high- and ultra-high energy photons

Classical astronomy: study of thermal emission and absorption processes in heated environments (black-body radiation of stars)



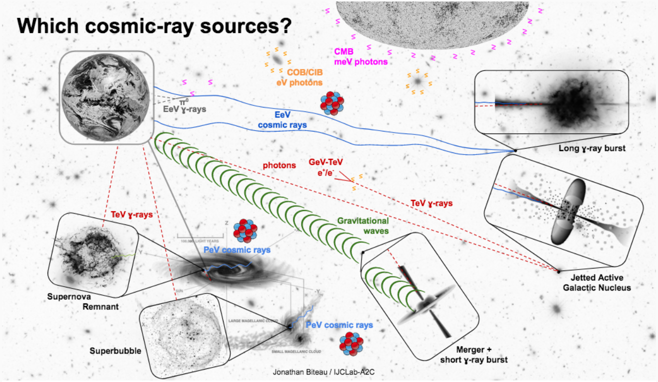




- GeV gamma rays – already too high energies to trace thermal processes
- TeV gamma rays uncovered by Cherenkov Telescopes (H.E.S.S., MAGIC, VERITAS)
- New: PeV gamma rays by high-altitude air shower arrays (TIBET, LHAASO)
- Large panoply of processes at the origin of these photons:
  - Tracing high energy particles
  - Locating cosmic particle accelerators

Astroparticle Physics

Probe of the "high-energy Universe", i.e. the extreme phenomena that generate and store high-energy particles in the Milky Way and beyond

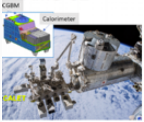


Jonathan Biteau / IJCLab-A2C

- Different messengers: particles, namely cosmic rays, gamma rays and neutrinos, and gravitational waves
- Access to processes that cannot be identified with photons only

Multi-messenger observatories


AMS-02

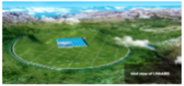


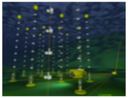
CALET

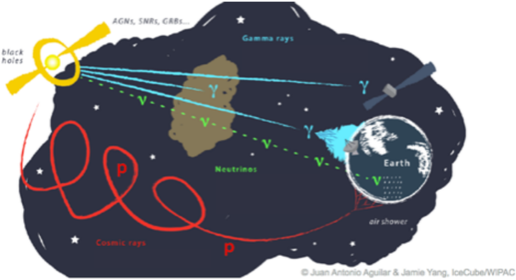

PAMELA


Fermi LAT


TIBET-ASgamma


LHAASO


ANTARES



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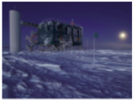

ICECUBE


HAWC


TA


Auger

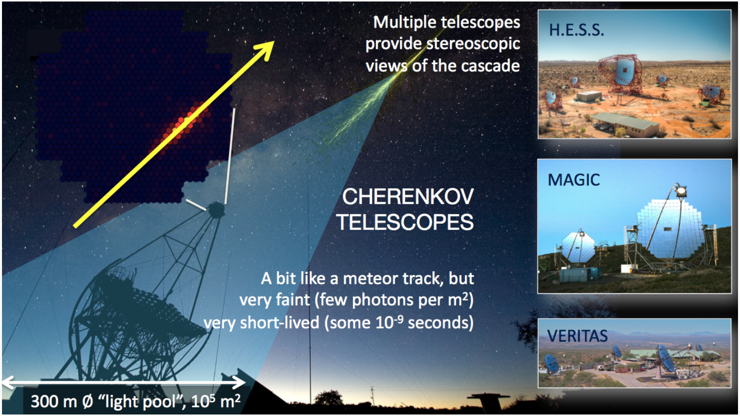

H.E.S.S.


VERITAS


MAGIC

Extensive air showers

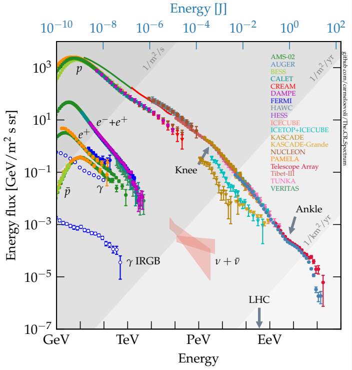
Credits: W. Hoffman



- Telescopes capturing the isotropic fluorescence emission at higher energies (de-excitation of nitrogen molecules excited by ionisation electrons left after the passage of the showers)
- Large surfaces of particle detectors at the ground level

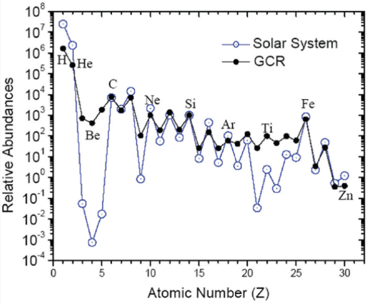
CR energy spectrum

Compilation: C. Evoli, 10.5281/zenodo.4396125

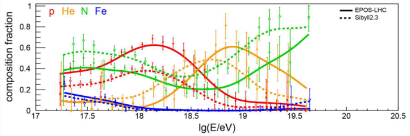


- Nearly a power law, with spectral features
- Heliosphere “bubble” shielding <GeV energies (confirmed by Voyager)
- Contribution of light elements dominant at GeV energies and important up to the “knee” (3×10^{15} eV), after which heavier elements gradually take over up to a few 10^{17} eV – Calls for a rigidity-dependent acceleration:
  - Most abundant element in the interstellar medium: hydrogen
  - Heavier elements accelerated to higher energies for two decades above the knee
- No Galactic confinement/anisotropies above the ankle (5×10^{18} eV): extragalactic origin

CR composition



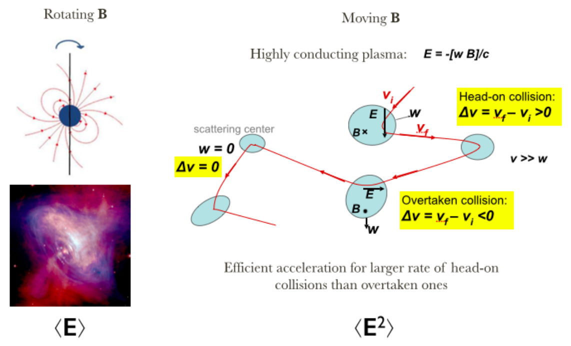
Auger Collaboration, 2017



- Galactic CR composition similar to that of ISM, except:
  - Li, Be, B, F, Sc-Mn produced by spallation of heavier primaries
  - Overabundance of ^{22}Ne/^{20}Ne
  - Mass-dependent enrichment of volatiles w.r.t. H
  - Constant overabundance ($\times$20) of refractories w.r.t. H
- Extragalactic composition: elements getting heavier at UHE from all contemporary observatories **[A.A. Watson, JHEAp 33 (2022) 14]**
- Caveat: reliance to hadronic-interaction models

CR accelerators?

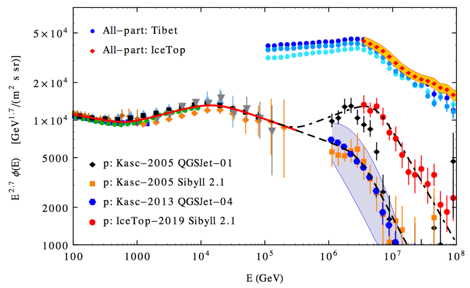
Acceleration of charged particles → Electric fields (not expected in space plasma)



- Non-MHD flows: $\mathbf{E} \cdot \mathbf{B} \neq 0$, $\mathbf{E}^2 - \mathbf{B}^2 > 0$
- Gaps in magnetospheres (pulsars...)
- Magnetic reconnection
- Ideal Ohm's law in highly conducting plasma
- Fermi-type scenarios: magnetized turbulence, shear flows, shock waves

Current picture of Galactic CRs

Small variations on top of power-law shape revealed by precision measurements of mass-discriminated spectra

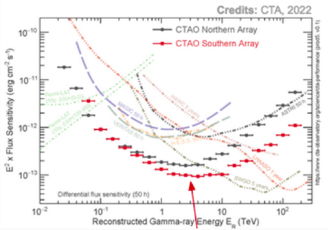

P. Lipari & S. Vernetto, Astropart. Phys. 120 (2020)

- Hardening and softening established in the proton spectrum
- Same hardening established for He and other nuclei
- Hardening origin in terms of source properties or propagation effects?

- Softening origin? Injected spectra from sources (SNRs? SNRs+others?) with a large variety of shapes, combining to form an average spectrum that has a nearly power law form
- Need to bridge mass-discriminated direct and indirect measurements...

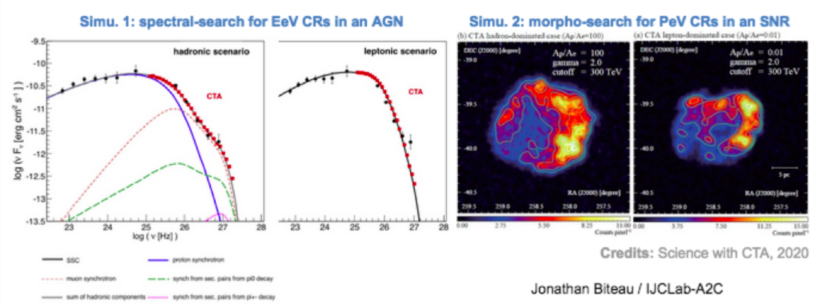
The γ-ray window on cosmic-ray accelerators

- γ rays as by-products of accelerated/confined leptons/hadrons interacting with dust (p, He) a/o photons
- Wide fov detectors (now: HAWC, LHAASO; tomorrow SWGO) competitive for steady sources $>$ 10 TeV



Credits: CTA, 2022

- Cherenkov telescopes (now: HESS, MAGIC, VERITAS; tomorrow: CTA), competitive for steady/transient sources in the 10s GeV–10s TeV



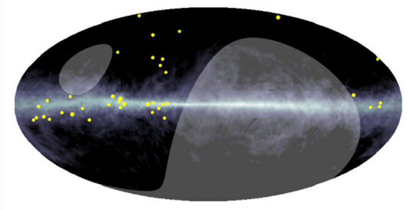
Simu. 1: spectral-search for EeV CRs in an AGN

Simu. 2: morpho-search for PeV CRs in an SNR

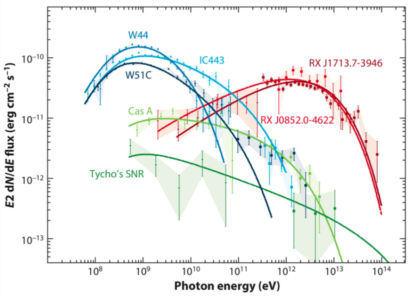
Credits: Science with CTA, 2020

Searching for PeVatrons with γ rays

M. Amenomori et al., PRL 126 (2021) 141101

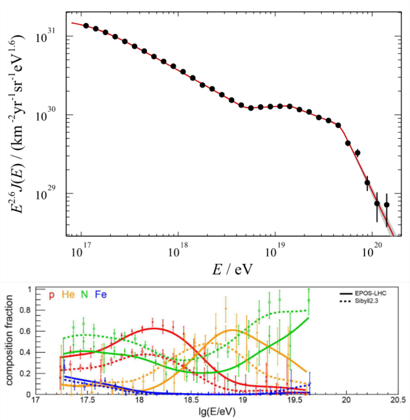


S. Funk, Ann. Rev. Nuc. Part. (2015)



- Diffuse PeV flux from the Galactic disk, p gas $\rightarrow$ nπ^0 $\rightarrow \gamma\gamma$
- A dozen of unidentified sources up to a few 100s of TeV **[Z. Cao et al., Nature 594 (2021) 33]**
- Protons accelerated to knee energies in the Galaxy
- Typical spectra for several of the most prominent SNRs
- Hard spectra in the GeV-TeV
- $\simeq$ 10 TeV cutoffs
- No smoking-gun of CR PeVatrons, yet

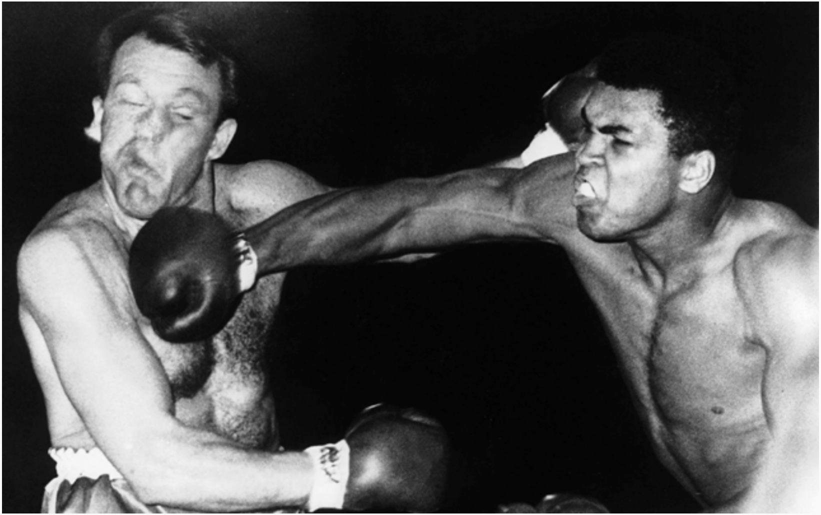
UHECRs



Auger Collaboration, EPJC 81 (2021) 966

- Extragalactic origin above the ankle energy?
- Steepening at UHE expected from energy losses (GZK cutoff)...
- ...but unexpected “instep” steepening at $\simeq 10^{19}$ eV **[Auger Collaboration, PRD 102 (2020) 062005]**
- Composition getting heavier with E, with little mixing...
- ...cutoff at the sources?
- Second knee-to-ankle region: complex intertwining of phenomena hid beneath the featureless all-particle flux

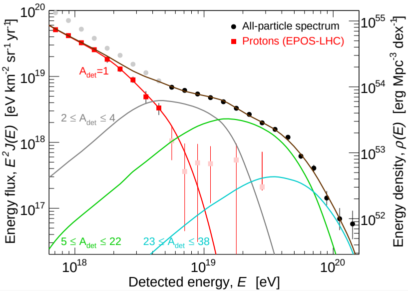
10^{20} eV nuclei in the cosmos



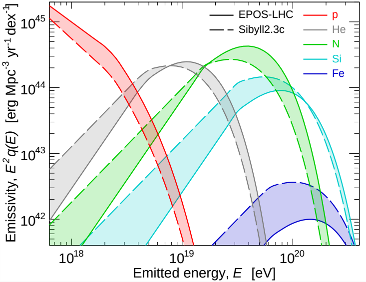
Inferring UHE accelerator properties

Inferring properties of the acceleration processes and source environments

Q. Luce et al., Paris-Saclay Astroparticle Symposium 2021



Q. Luce et al., Paris-Saclay Astroparticle Symposium 2021



- Abundance dominated by intermediate elements at the sources
- In-source interactions shaping ejection spectra of protons differently from nuclei
- Upper end of GCRs not reaching the ankle energy
- “B component”? **[A.M. Hillas, J. Phys. G 31 (2005) R95]**

Inferring UHE accelerator properties: the model

- Ejection spectra: power-law spectra, max. acceleration energy E^{Z}_{max},
- Composition: nuclei represented by five stable ones: hydrogen (^{1}H), helium (^{4}He), nitrogen (^{14}N), silicon (^{28}Si) and iron (^{56}Fe)
- Flux on Earth:

$$J(E) = \frac{c}{4\pi} \sum_{A,A'} \iint \mathrm{d}z\mathrm{d}E' \left| \frac{\mathrm{d}t}{\mathrm{d}z} \right| S(z) q_{A'}(E') \frac{\mathrm{d}\eta_{AA'}(E,E',z)}{\mathrm{d}E}$$

- Energy losses and spallation processes described by $\eta_{AA'}(E,E',z)$: fraction of particles with energy E and mass number A from parent particles with energies $E' > E$ and mass numbers $A' > A$
- Relevant processes entering $\eta_{AA'}(E,E',z)$: pair production, photo-pion production and photodissociation off CMB/EBR photon fields

Nuclear-physics inputs: Photodissociation cross sections

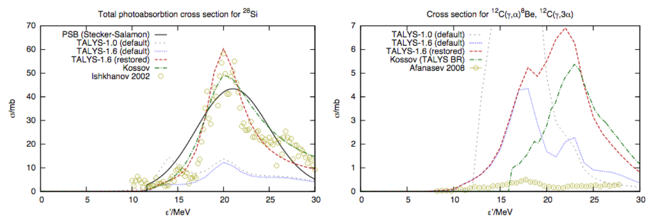
- Dominant interactions:
  - Giant dipolar resonance for photon energies below 30 MeV (in the nucleus restframe) $\Longrightarrow$ center of mass energy of the order of several MeV (the energy necessary to split off an individual nucleon)
  - Quasi-deuteron processes causing the emission of multiple nucleons for photon energies between 30 MeV and 150 MeV
- Simplest model in astrophysics: GDR peak approximated by a box function $\Longrightarrow$ (semi-)analytical solutions of transport equations
- Puget-Stecker-Bredekamp (PSB) model: one-dimensional path along the representative isotopes of each mass lighter than iron $\Longrightarrow$ good first-order approximation but absence of emission of light fragments
- E. Khan et al. [Astropart.Phys. 23 (2005) 191-201]: isobars affected by competitive channels – numerous open channels including those in which β-decay can compete

Nuclear-physics inputs: Photodissociation cross sections

- Photodissociation cross sections not that known especially for exclusive channels in which charged fragments are ejected
- Phenomenological approaches: TALYS model
    - working for nuclei heavier than carbon
    - complemented by additional data-driven parameterizations for lighter elements (behavior of very light nuclei challenging for theoretical models)
    - Lorentz-type fits to the giant dipole resonance region for the majority of measured cross-section parameters
    - Isotopes without measurements predicted in a rather simplistic way (apparent when making comparisons among isobars where absorption cross sections are equal)
- Of highest relevance for radiation and disintegration modeling:
    - absorption cross sections
    - inclusive yields of nucleons and light fragments
    - yields of residual nuclei

TALYS – Uncertainties

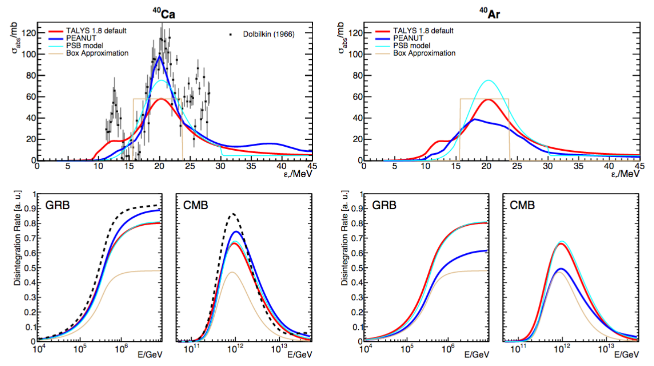
Credits: Alves Batista et al. JCAP 10(2015)063



- Khan et al.: TALYS used with the giant dipole resonance parameters compiled in the atlas of GDR parameters
- Publicly available versions of TALYS: parameters from the RIPL-2 database
- Khan et al. (“TALYS-1.6 (restored)”) in much better agreement with the available measurements
- All versions of TALYS: overshooting of cross sections for α-particle ejection

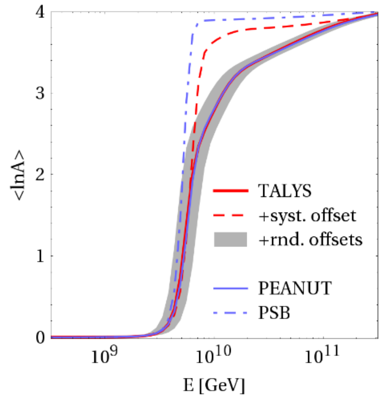
Uncertainties in interaction rates

Credits: Fedynitch et al. PoS(ICRC2017)559



- Calcium-40: double magic, not Argon $\Longrightarrow$ differences in cross sections expected
- Uncertainties in interaction rates:
  - Differences among models relatively small where data is available
  - Up to a factor 2 in the opposite case

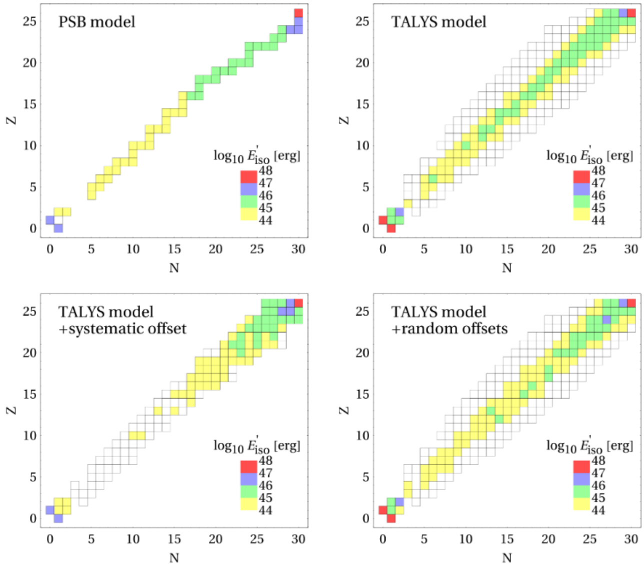
Nuclear cascades in sources



- Uncertainties estimated by varying cross sections randomly within error scales estimated from the EXFOR database
- Hard heavy-to-light transition for simplified models
- Sizable impact on the interpretation of the source composition

Nuclear cascades in sources

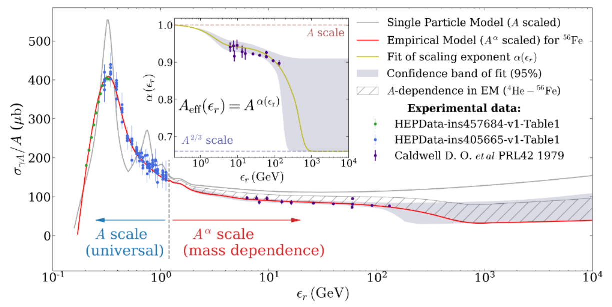
Credits: Fedynitch et al. PoS(ICRC2017)559



Nuclear-physics inputs: Photomeson cross sections

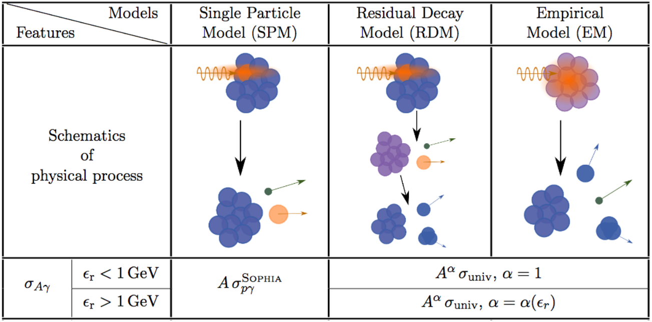
- Photon energies above 150 MeV: Photomeson production
- Single Particle Model, allowing (semi-)analytical solutions of transport equations
  - Photon interacting with one nucleon without affecting the rest of the nucleus
  - Final state: products of the γN interaction and one remnant nucleus with $A-1$ nucleons
  - Cross section scaling with A: $\sigma_{A\gamma} = A\sigma_{p\gamma}$

Credits: Morejon et al. JCAP 11(2019)007



Nuclear-physics inputs: Photomeson cross sections

Credits: Morejon et al. JCAP 11(2019)007



Models Features		Single Particle Model (SPM)	Residual Decay Model (RDM)	Empirical Model (EM)
Schematics of physical process				
$\sigma_{A\gamma}$	$\epsilon_{\mathrm{r}} < 1\,\mathrm{GeV}$	$A\,\sigma_{p\gamma}^{\textsc{Sophia}}$	$A^{\alpha}\,\sigma_{\mathrm{univ}},\ \alpha = 1$	
	$\epsilon_{\mathrm{r}} > 1\,\mathrm{GeV}$		$A^{\alpha}\,\sigma_{\mathrm{univ}},\ \alpha = \alpha(\epsilon_r)$	

- Data-driven approaches to improve the SPM in three main aspects:
  - Absorption cross section: energy dependent mass scaling exponent at high energy to account for nuclear shadowing effects
  - Pion production cross section: mass scaling exponent to parameterize pion production cross section for different nuclei (influenced by nuclear medium effects)
  - Nuclear fragmentation: parametrization of nuclear breakups

Outlook

- Disintegration rates depending on current photo-nuclear interaction models
- Typical astrophysical parameterizations oversimplified, artificial bias in the calculations
- Uncertainties from nuclear models: significant role in the interpretation of UHECR observations
- Progress needed for light- and intermediate-mass range nuclei for a higher predictive power of the models