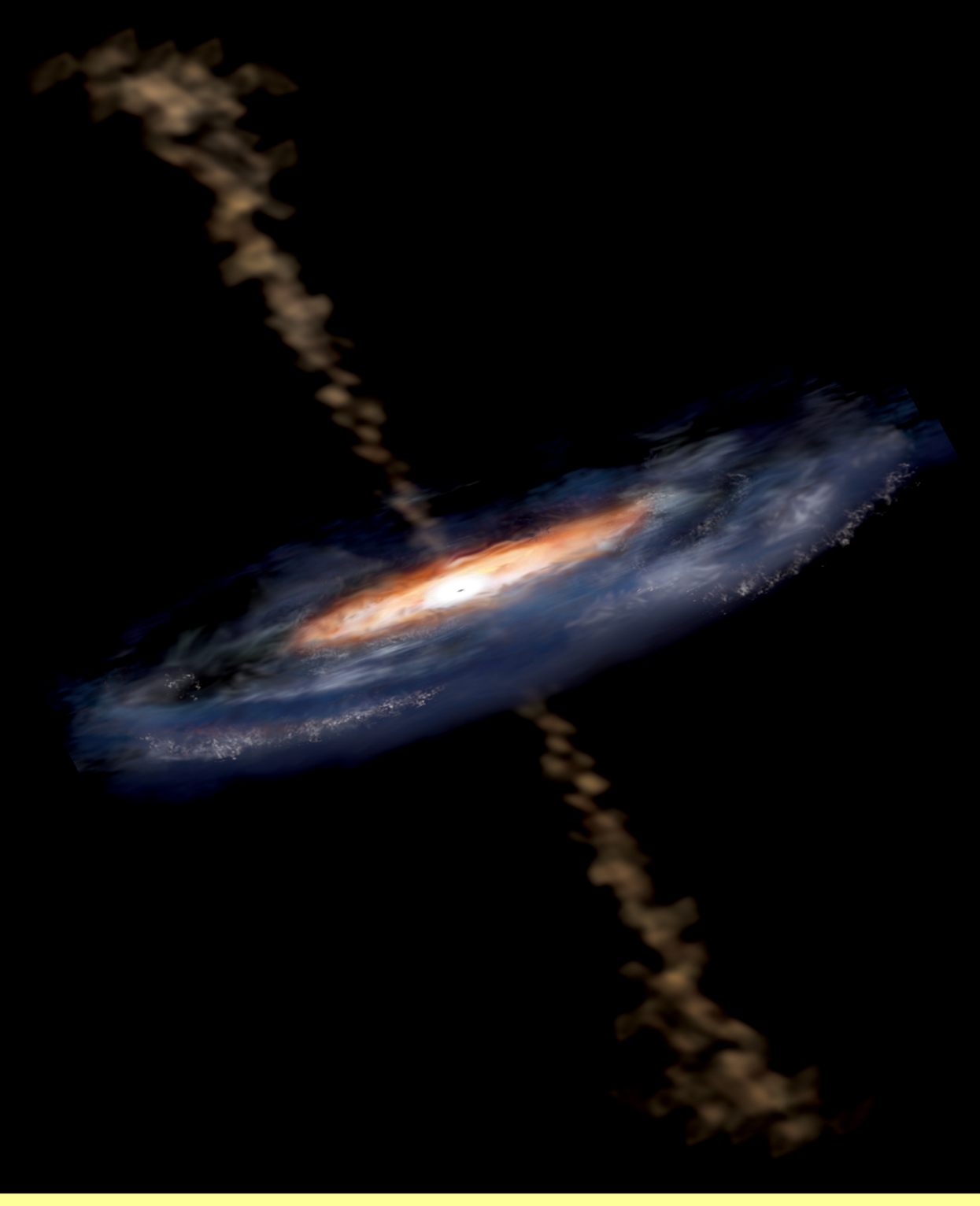
Cosmic Ray Sources: Probed by UHE proton, nuclei, photon and neutrino fluxes

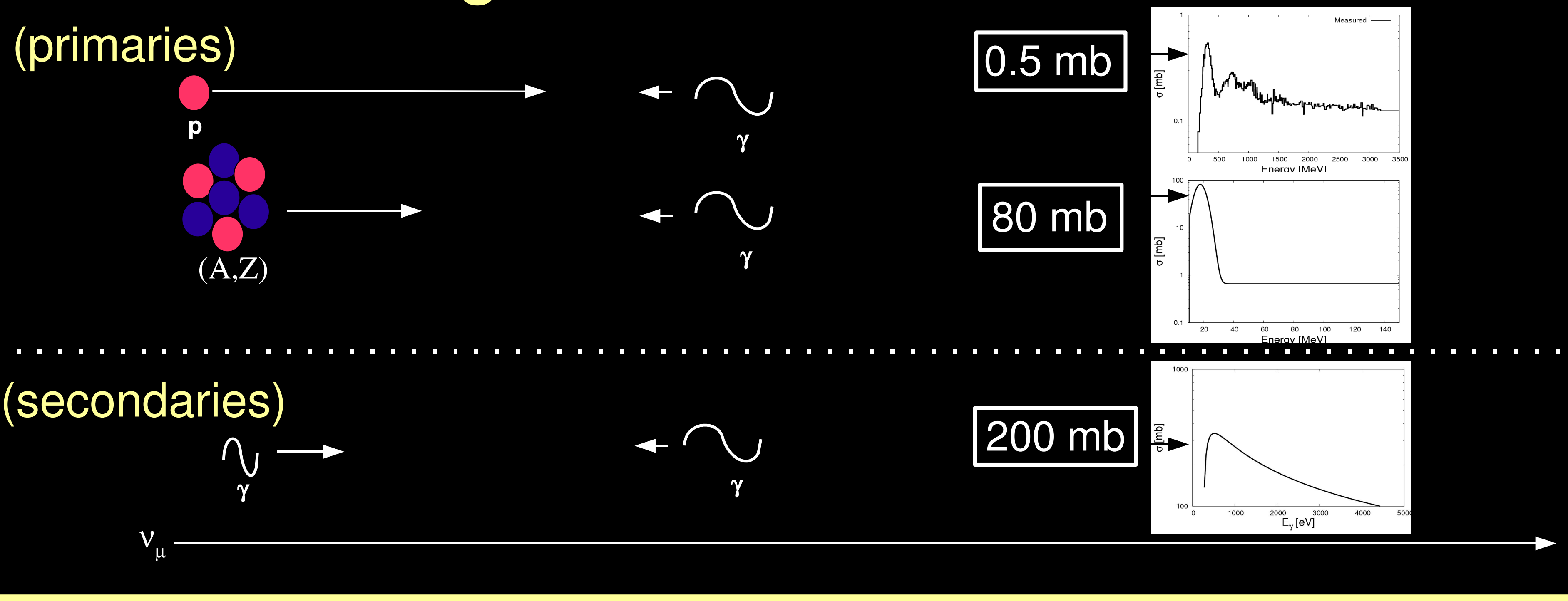


The interaction of UHE protons and nuclei both in the intense radiation fields thought to exist in the acceleration sites of UHECR and with the radiation fields in extragalactic space through which they propagate are of crucial importance with regards the secondary emission produced. In the accelerator the intense radiation fields present may lead to both large losses of protons through pion production and near complete disintegration of nuclei. The fluxes of both the primary cosmic rays at Earth and the secondaries they produce provide key insights into the nature of their origin.

High Energy Astrophysics Theory Group

The different interaction lengths of ultra high energy protons, nuclei, photons, and the production of neutrinos means that the detection of these particles from the accelerator can be used to provide a probe into the source's radiation environment. As an example, both protons and nuclei appear to be observed in the ultra high energy cosmic ray flux detected at Earth with energies > 10^{18} eV by the Pierre Auger observatory. If these measurements are correct, then the acceleration of nuclei to these high energies is consequently required to occur with very few energy loss interactions within the source radiation field, hence allowing few secondary particles to be produced.

4 messengers from the accelerator



However, once UHECR have left the source, they may still interact with background radiation during their propagation to Earth. With ~mb cross-sections (see fig.s to the left) and photon number densities ~400 cm^{-3} for the CMB, these interactions can be expected to occur on Mpc scales from the source. Following secondary photon production (the propagation of the neutrinos is unhindered), these photons may also interact with the radio background. With ~100 mb cross-sections and photon number densities of ~1 cm^{-3} these interactions will occur on Mpc scales from the point of creation of the secondary photon.

Source Losses: (primaries)

For a particular radiation field in the accelerator region, the interaction rates of our 4 messengers with the radiation field, of spectral shape n(E), are simply dictated by their cross-sections (shown above). The interaction rates for the messengers with the field are calculated as,

no. density of target photons

$$R=\frac{m_p^2c^4}{2E^2}\int_0^\infty d\epsilon\,\frac{n(\epsilon_\gamma)}{\epsilon_\gamma^2}\int_0^{2E\epsilon_\gamma/m_pc^2} d\epsilon_\gamma'\,\epsilon_\gamma'\,\sigma(\epsilon_\gamma')$$

energy loss rate

probability of interacting with each photon

Once calculated, these interaction rates can be easily understood since they simply reflect the radiation field (SED) in the accelerator. This follows from the different interaction cross-sections all starting with a resonant feature close to threshold. With the interaction rate being dominated by interactions in the resonance region close to threshold, it is expressible in the form,

$$R=\sigma\int_{\frac{E_\Delta-\Delta_E}{2\Gamma}}^{\frac{E_\Delta+\Delta_E}{2\Gamma}} n(\epsilon_\gamma)\,d\epsilon_\gamma$$

Furthermore, the relative interaction rates of our different messengers simply relate through this simplification, with the different interaction rates for our primary messengers,

$$E_{p\Delta}=310\,\mathrm{MeV}\,,\ \Delta_{E_p}=100\,\mathrm{MeV}$$
$$E_{A_{56}\Delta}=18\,\mathrm{MeV}\,,\ \Delta_{E_{A_{56}}}=8\,\mathrm{MeV}$$

So the relative interaction rates of protons and heavy nuclei in a source's radiation field are related by,

$$\begin{aligned}R_{A_{56},\gamma}(\Gamma)&\approx\frac{\sigma_{A_{56},\gamma}}{\sigma_{p,\gamma}}R_{p,\gamma}(15\Gamma)\\&=160\,R_{p,\gamma}(15\Gamma)\end{aligned}$$

Thus, the existence of UHECR nuclei arriving at Earth may put strong constraints on the primary losses both UHECR protons and nuclei may undergo in the accelerator.

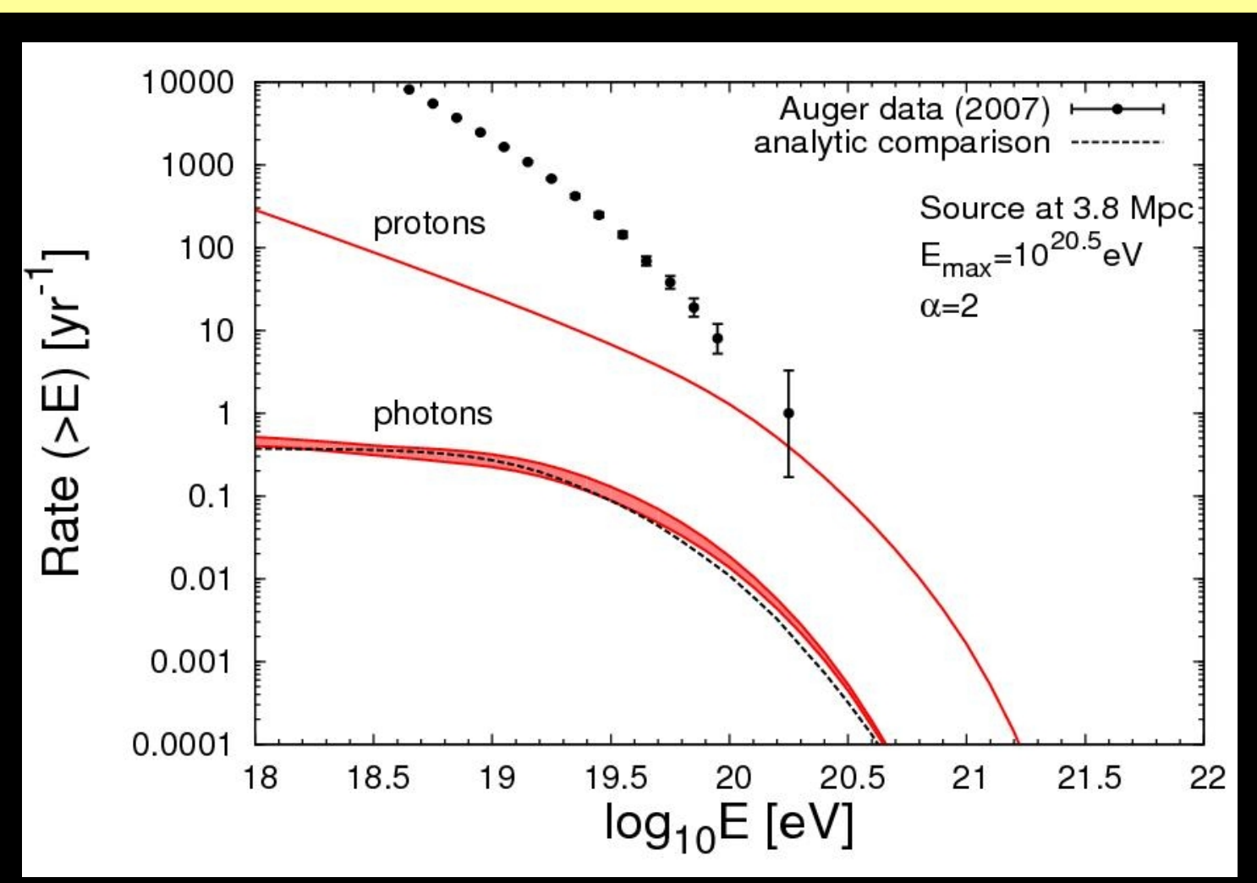
The radiation fields in extragalactic space, through which the UHECR must propagate before arriving at Earth are better known than those in the source region. The most populous photon target in extragalactic space is the CMB whose presence impedes UHE proton and nuclei with Lorentz factors such that these background photons, in the particle's rest-frame, have sufficient energy (above threshold) in order for the energy loss process to proceed. In this way, with the target well known, information about the source distribution itself may be extracted from the arriving UHECR flux at Earth.
Assuming that the UHECR arriving at Earth are predominantly protons, the flux of UHE photons can be determined for a given source distance.

Propagation Losses: (primaries and secondaries)

Thus, through the assumption that a given number of UHECR arrive from a particular source, the corresponding number of UHE-photons, expected to be produced via (neutral) pion production interactions en-route can be calculated. From the recent Pierre Auger Observatory data, obtained from approximately 1 year's worth of exposure, assuming 2 of the arriving events above 6×10^{19}eV came from Centaurus A (3.8 Mpc away), the arrival rate of these UHE-photons has been calculated (see fig. to the right).Thus, through these calculations of the UHE-photons from nearby candidate sources, these objects may be tested as to whether they are sources of the UHECR (protons) so far detected.

For this calculation, a source spectrum of the form

$$\frac{dN_p}{dE_p}=\frac{dN_p}{dE_p}(E_*)\left(\frac{E_p}{E_*}\right)^{-2}e^{-\left(\frac{E_p}{10^{20.5}\,\mathrm{eV}}\right)}$$



was assumed, with the normalisation energy E_* being fixed at 6×10^{19}eV, and the arrival rate above the normalisation flux $dN_p/dE_p(E_*)$ being fixed at this energy to be 2 per year (ie. ~10%) of the total flux detected.

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