Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

Probes of dark matter and physics beyond the Standard Model with the Pierre Auger Observatory

1. The Pierre Auger Experiment
2. Photon and Neutrino flux upper limits
3. Superheavy dark matter perturbative and non-perturbative decays
4. Cosmological constraints
5. Conclusions/outlook

on behalf of the Pierre Auger collaboration
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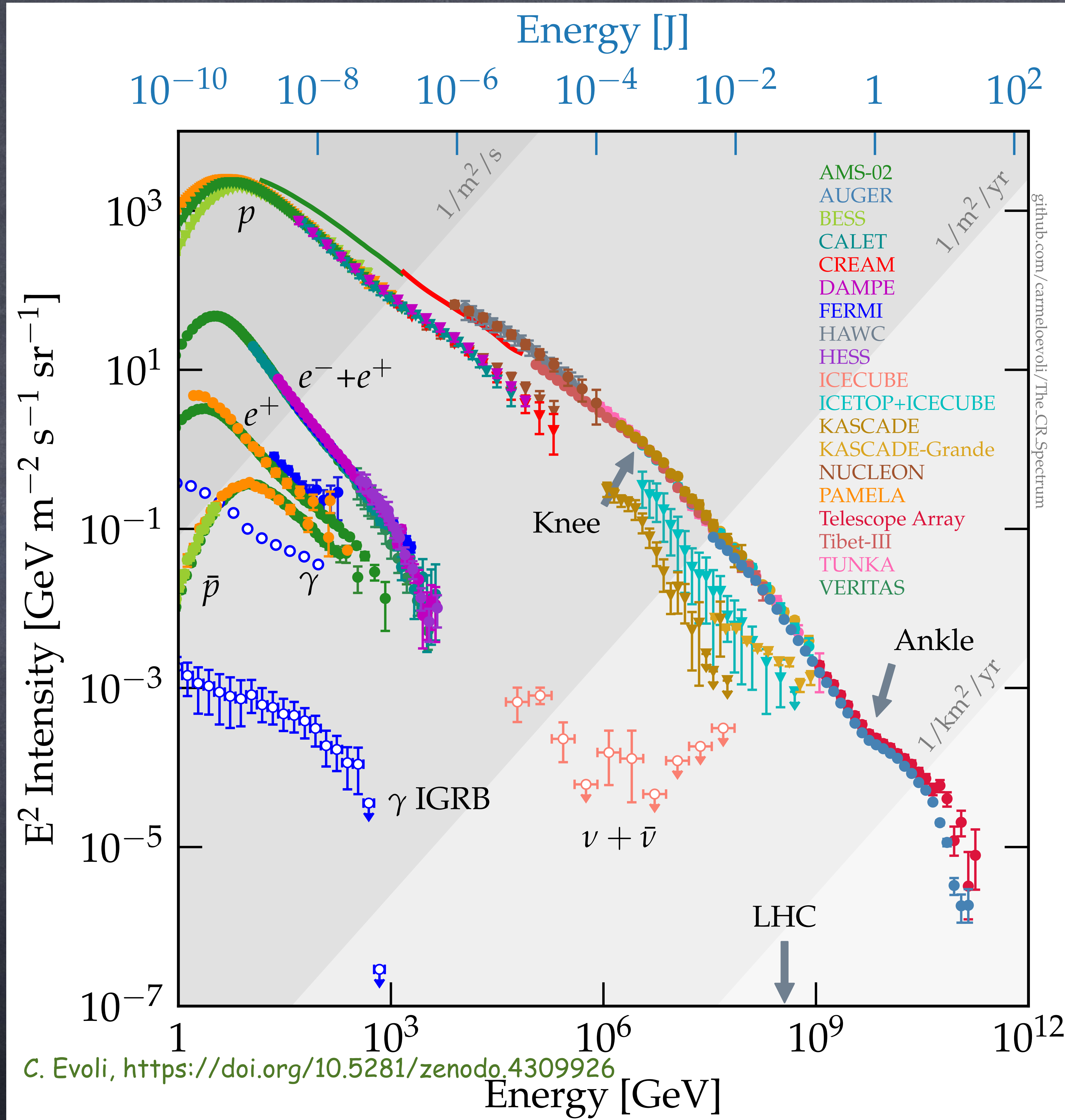
for TeVPA 2025, Valencia, Spain

Bundesministerium
für Forschung, Technologie
und Raumfahrt



C. Evoli, https://doi.org/10.5281/zenodo.4309926

Pierre Auger Spectra

current Auger exposure ~ 125,000 km² sr yr (surface detector, zenith angle < 80°)

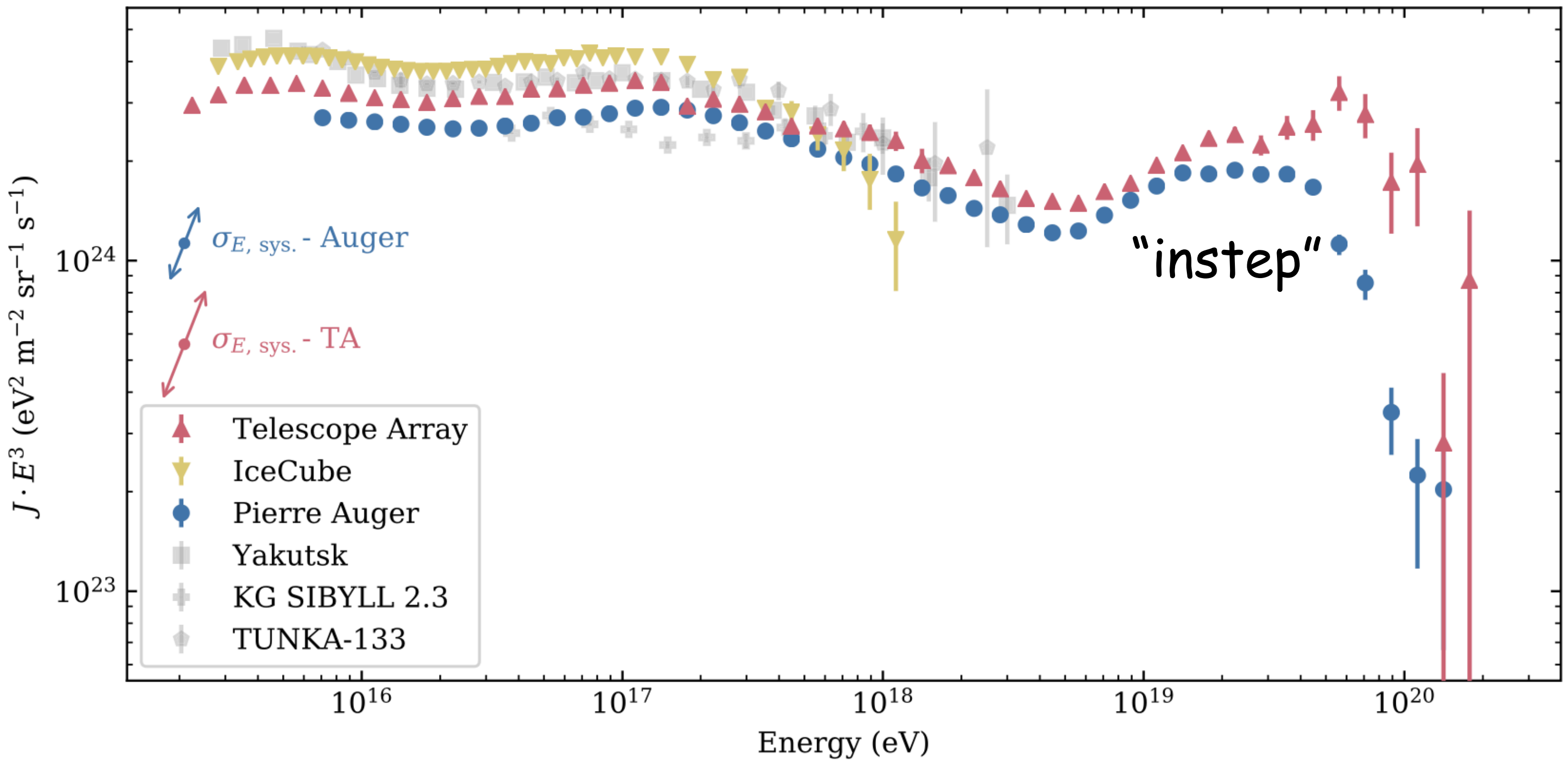
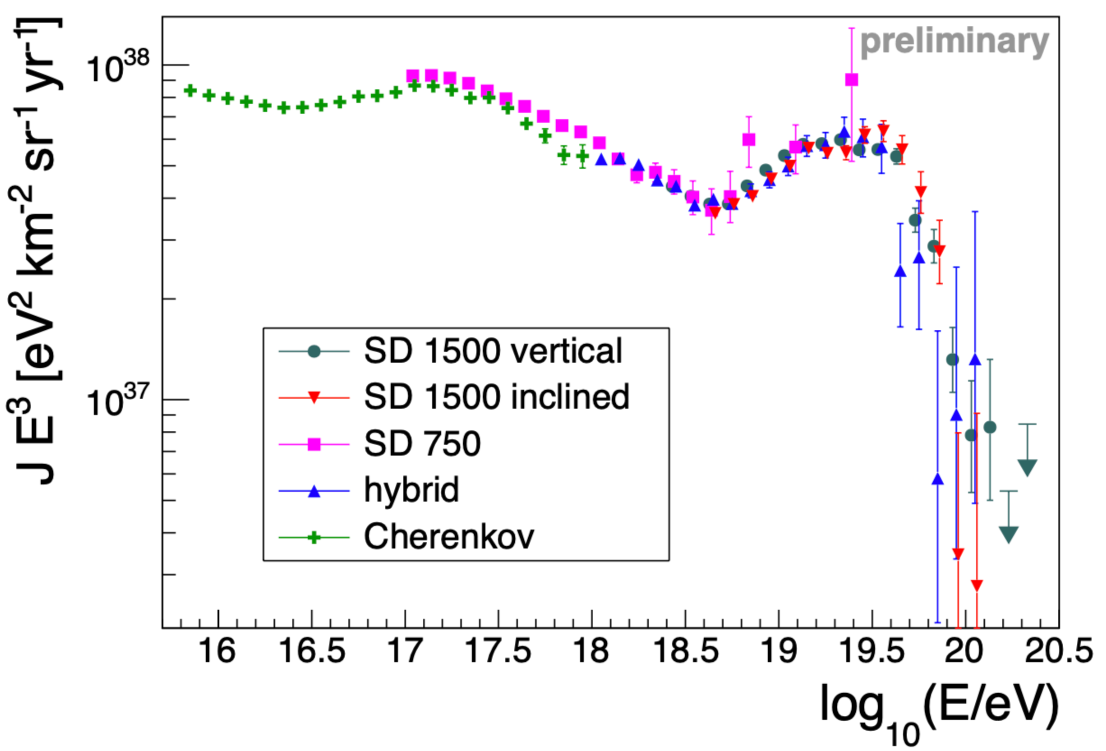


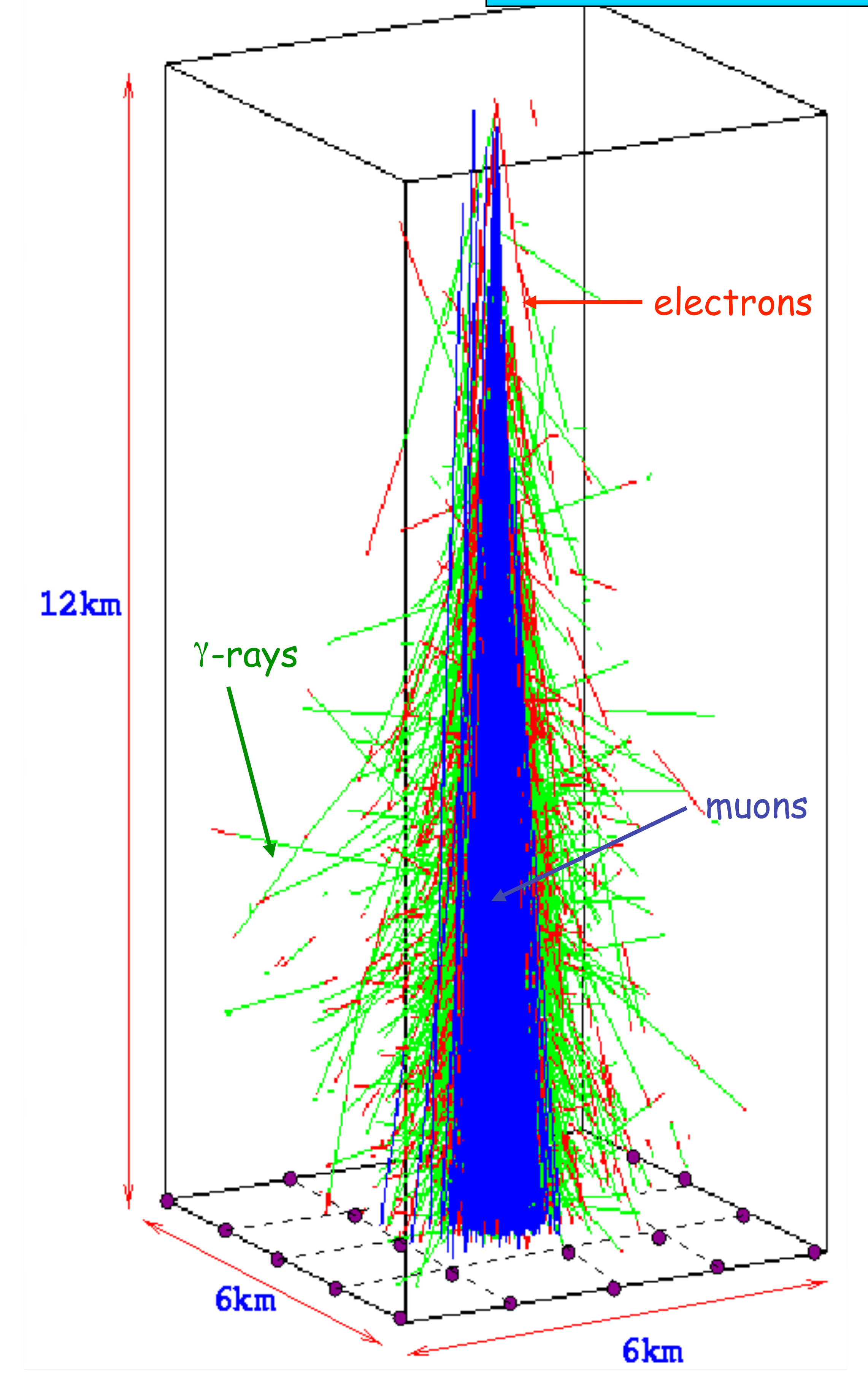
Fig. 9. Recent measurements of the all-particle flux from the TA [109], IceCube [81], Pierre Auger [33,48,67], Yakutsk [110], KASCADE-Grande [111], and TUNKA [112] experiments, which define the spectral features in the UHE region, are shown. Those with upgrades specifically described in this white paper are shown in color. The direction and magnitude of the systematic uncertainty in the energy scale for Auger and TA is indicated by the corresponding arrows.

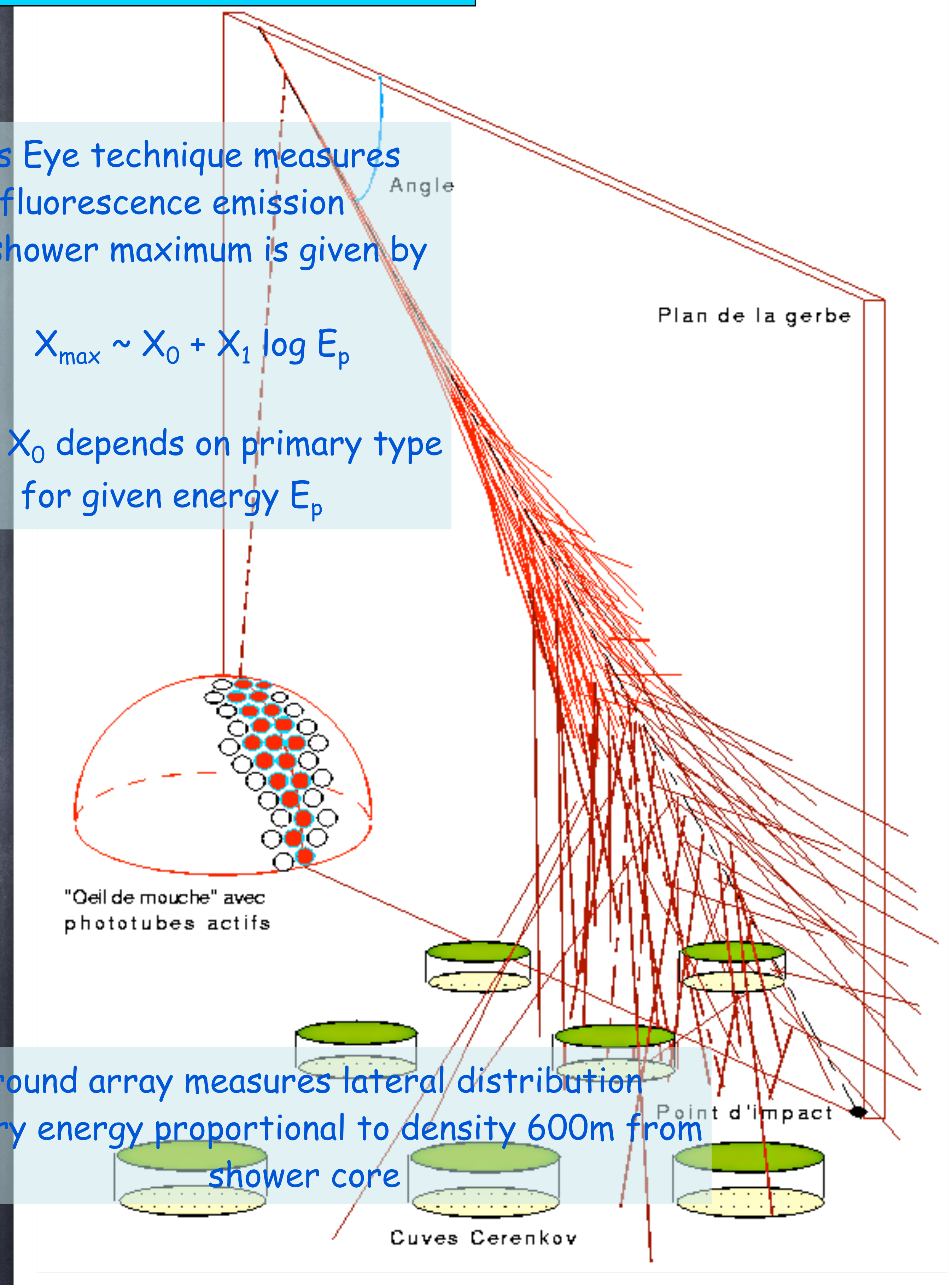
A. Coleman et al., Cosmic and Energy Frontiers, Astropart. Phys. 147 (2023) 102794



Pierre Auger collaboration, V. Nowotny, ICRC 2021

Atmospheric Showers and their Detection





Fly's Eye technique measures fluorescence emission

The shower maximum is given by

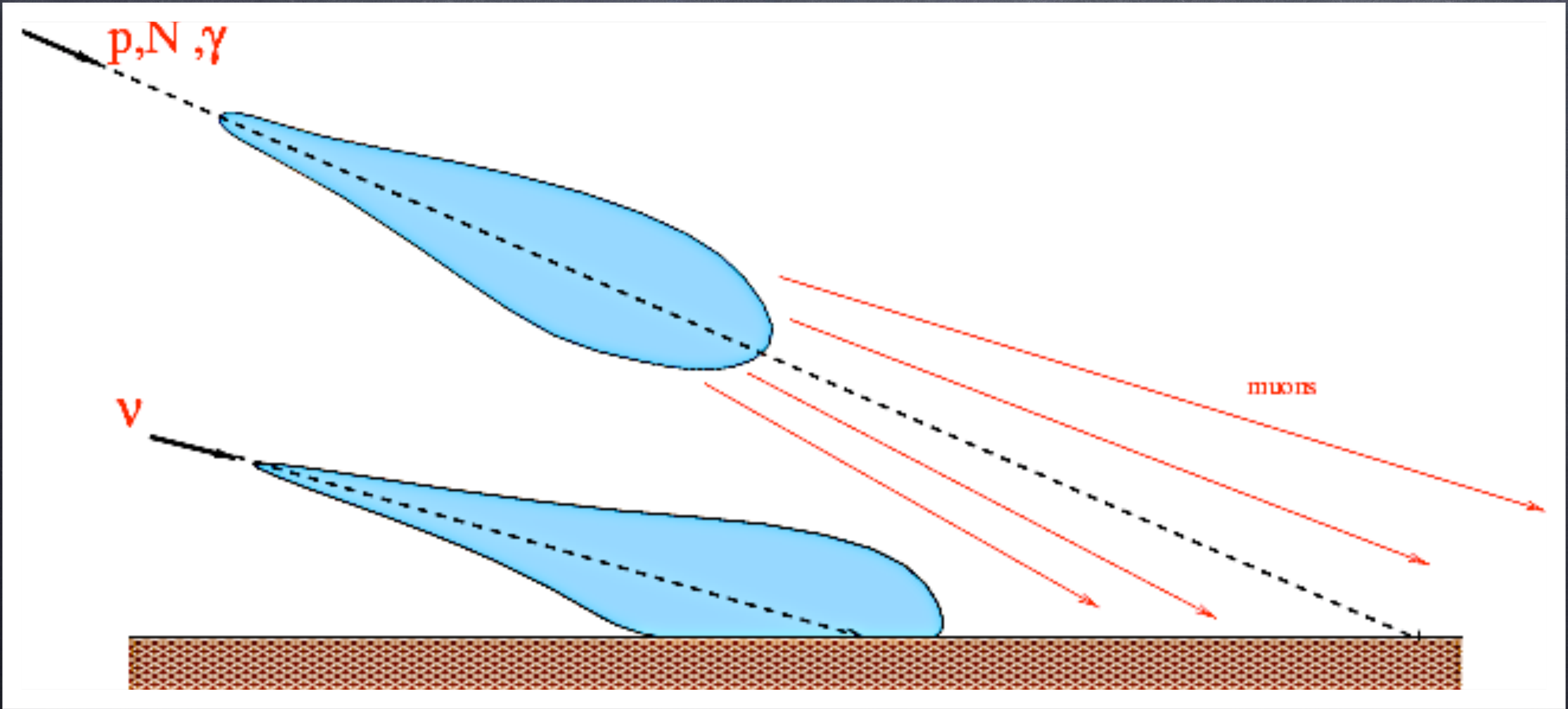
$$X_{max} \sim X_0 + X_1 \log E_p$$

where X_0 depends on primary type for given energy E_p

Ground array measures lateral distribution

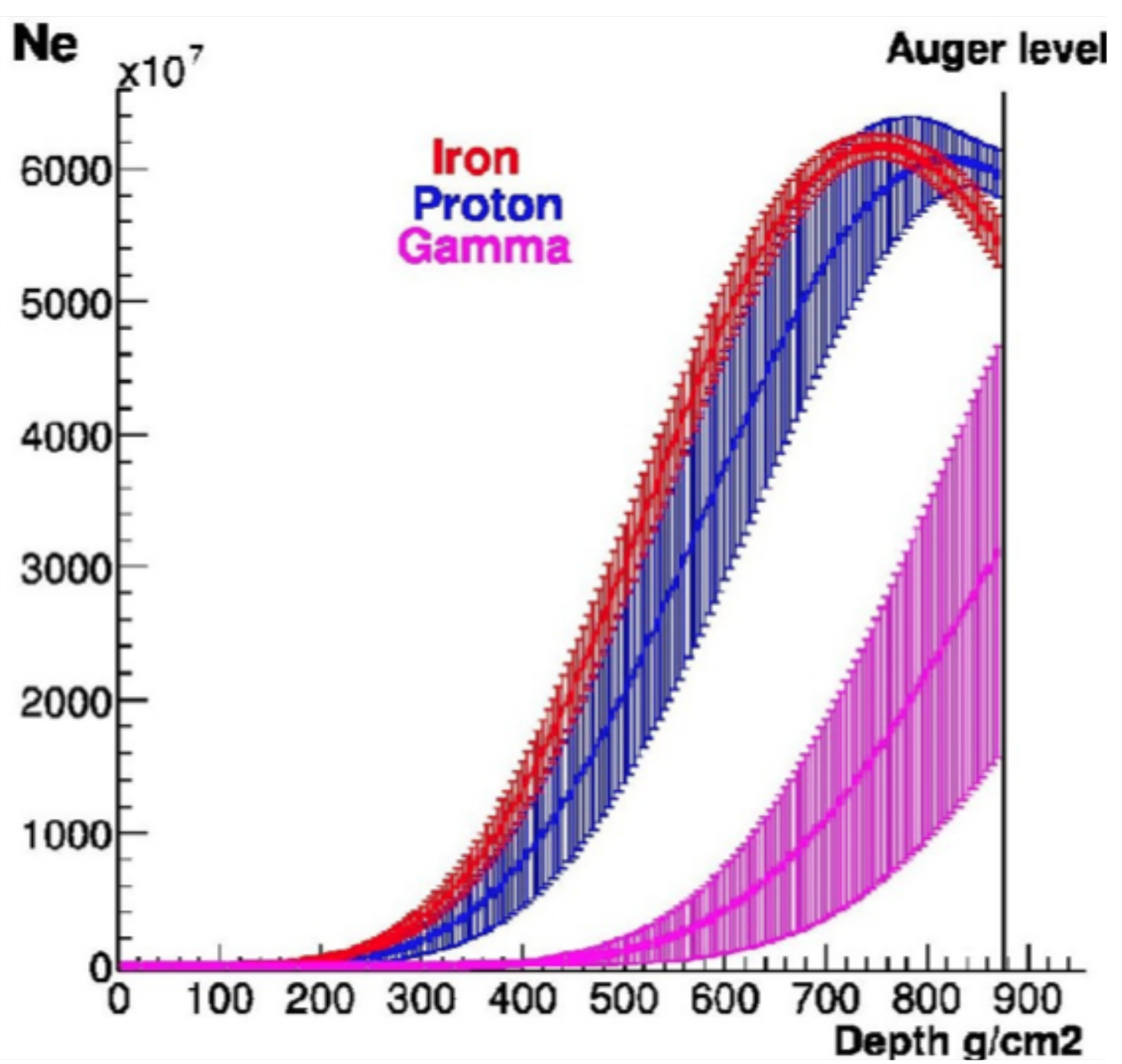
Primary energy proportional to density 600m from shower core

Cosmic ray versus neutrino induced air showers



Mass Composition

Depth of shower maximum X_{max} and its distribution contain information on primary mass composition



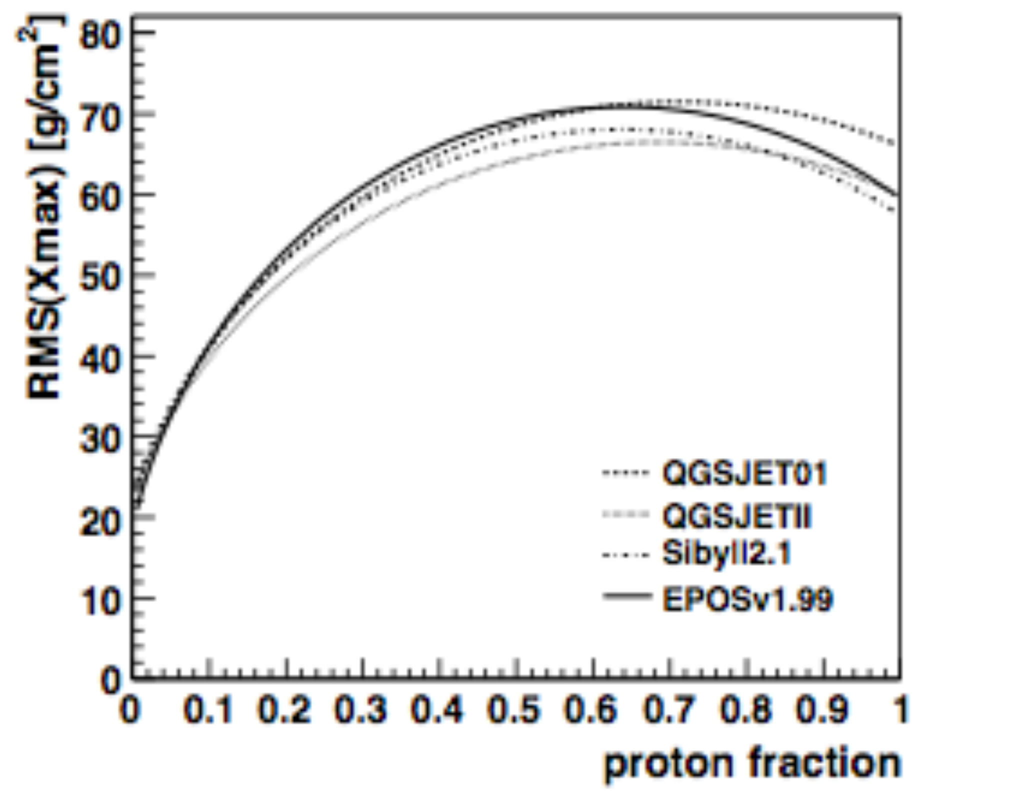
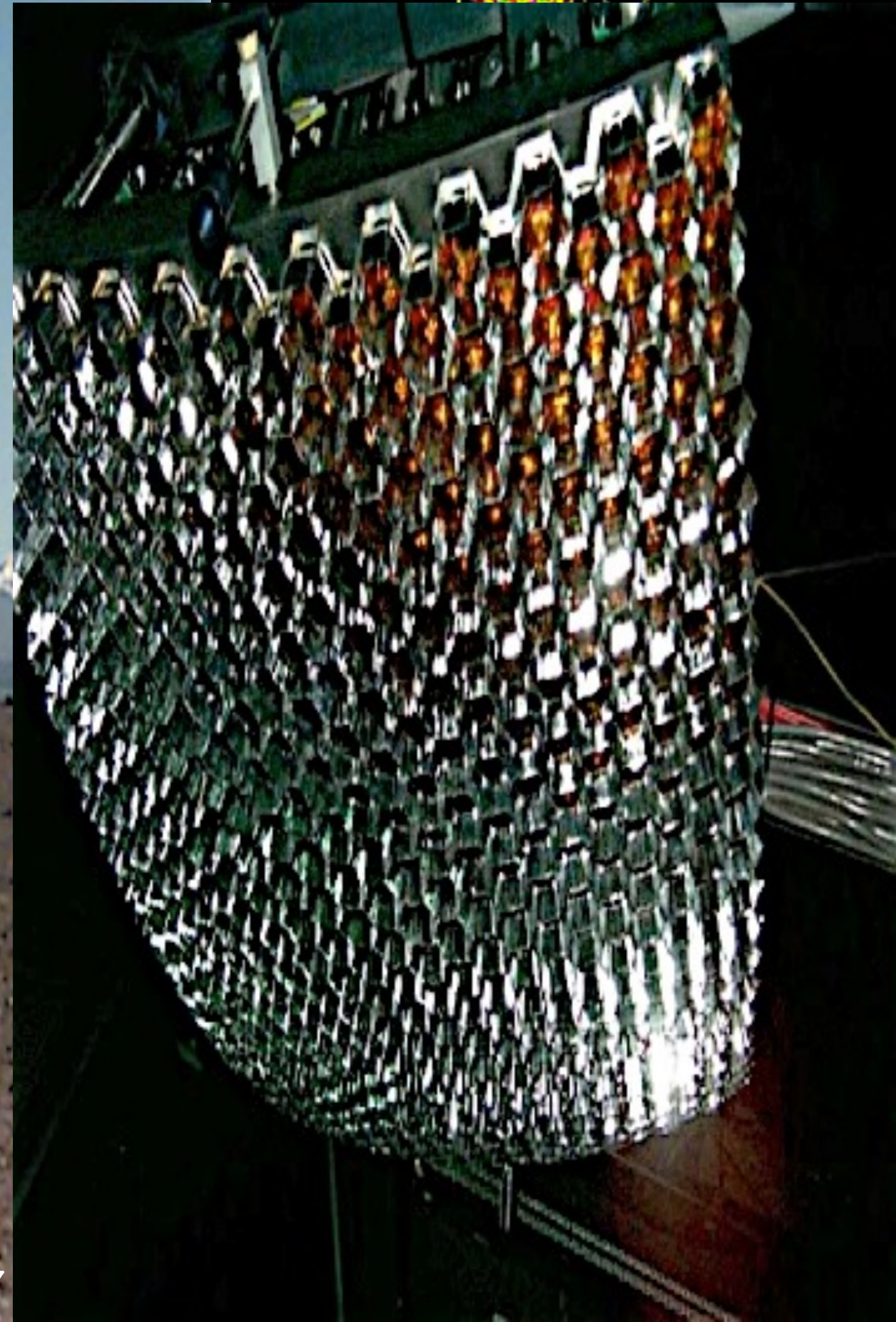
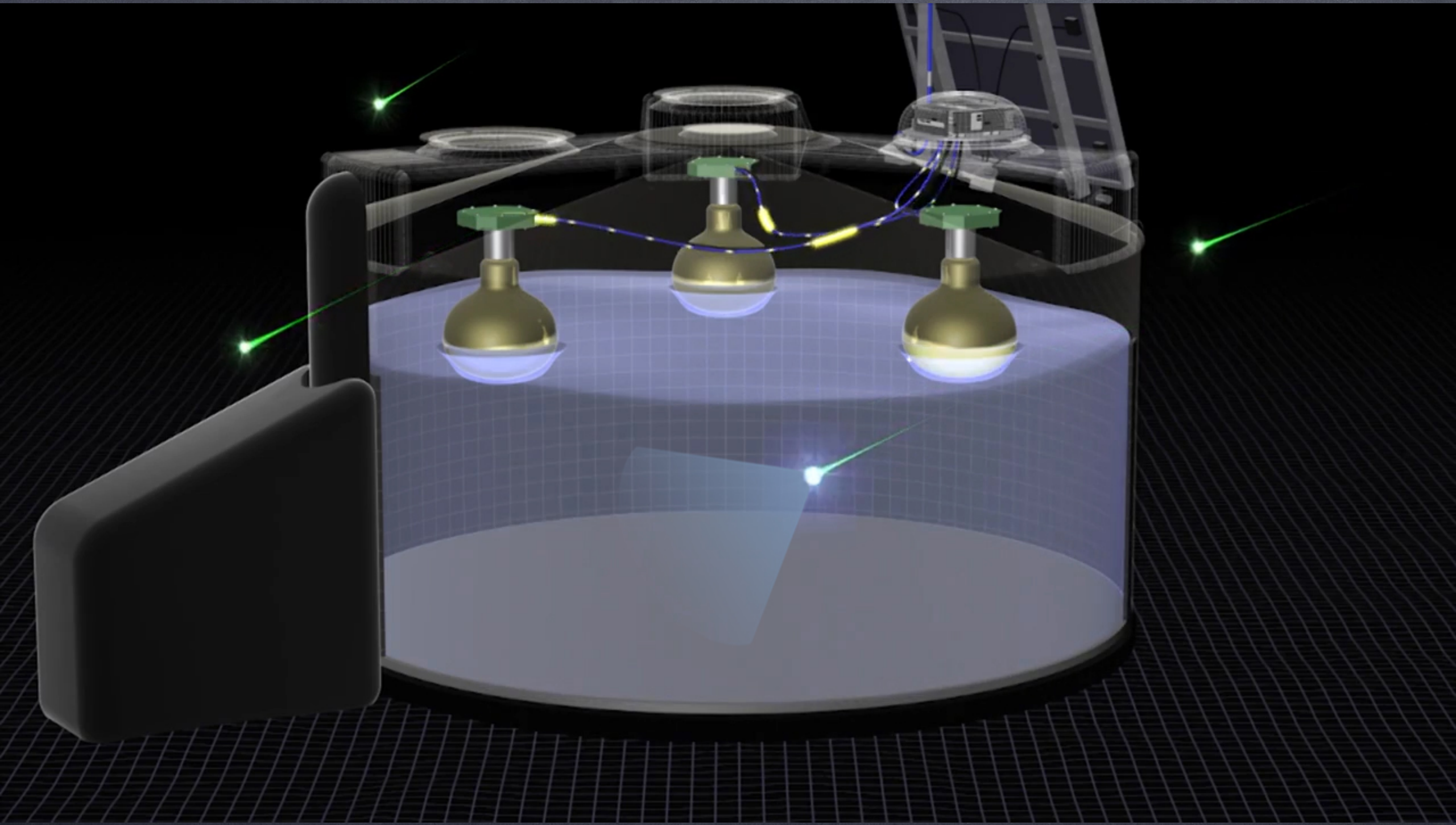
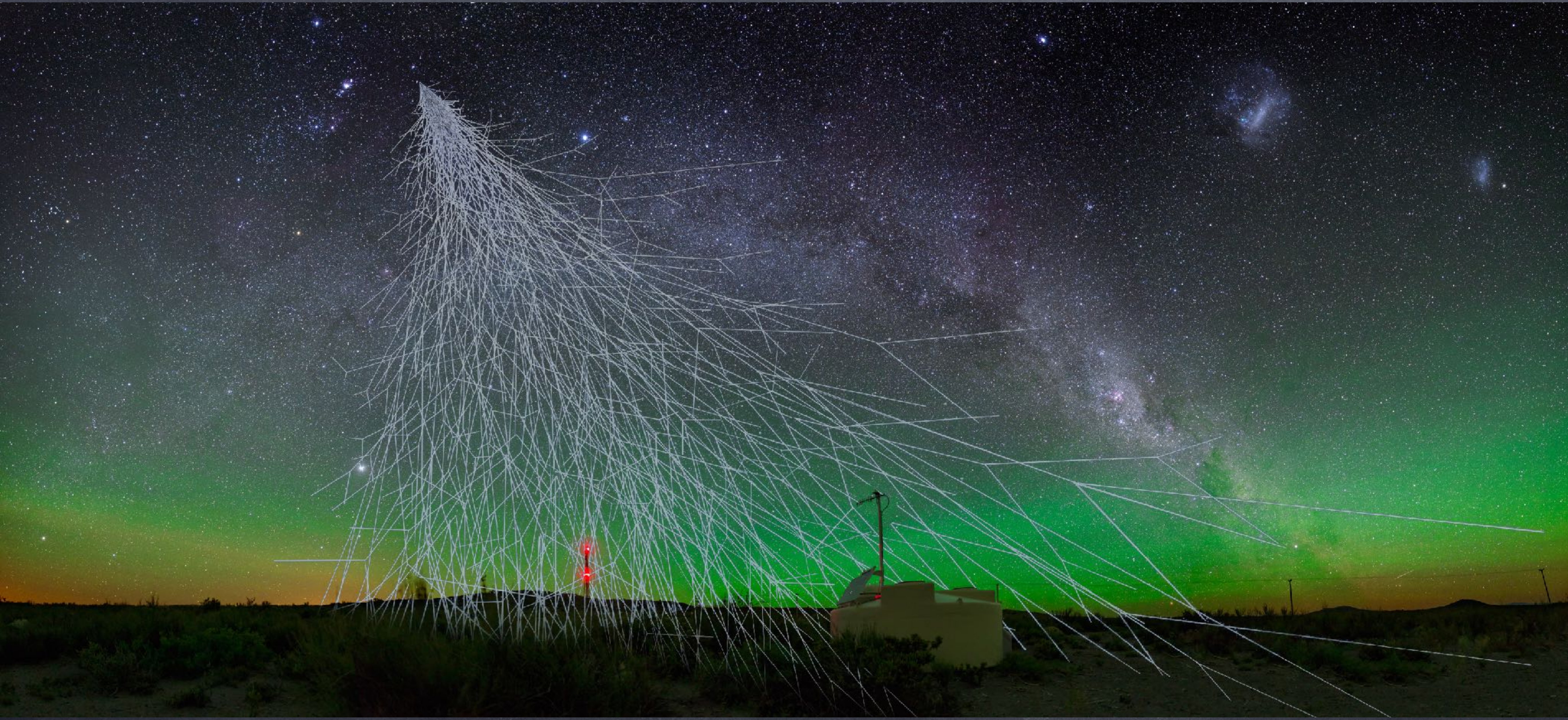
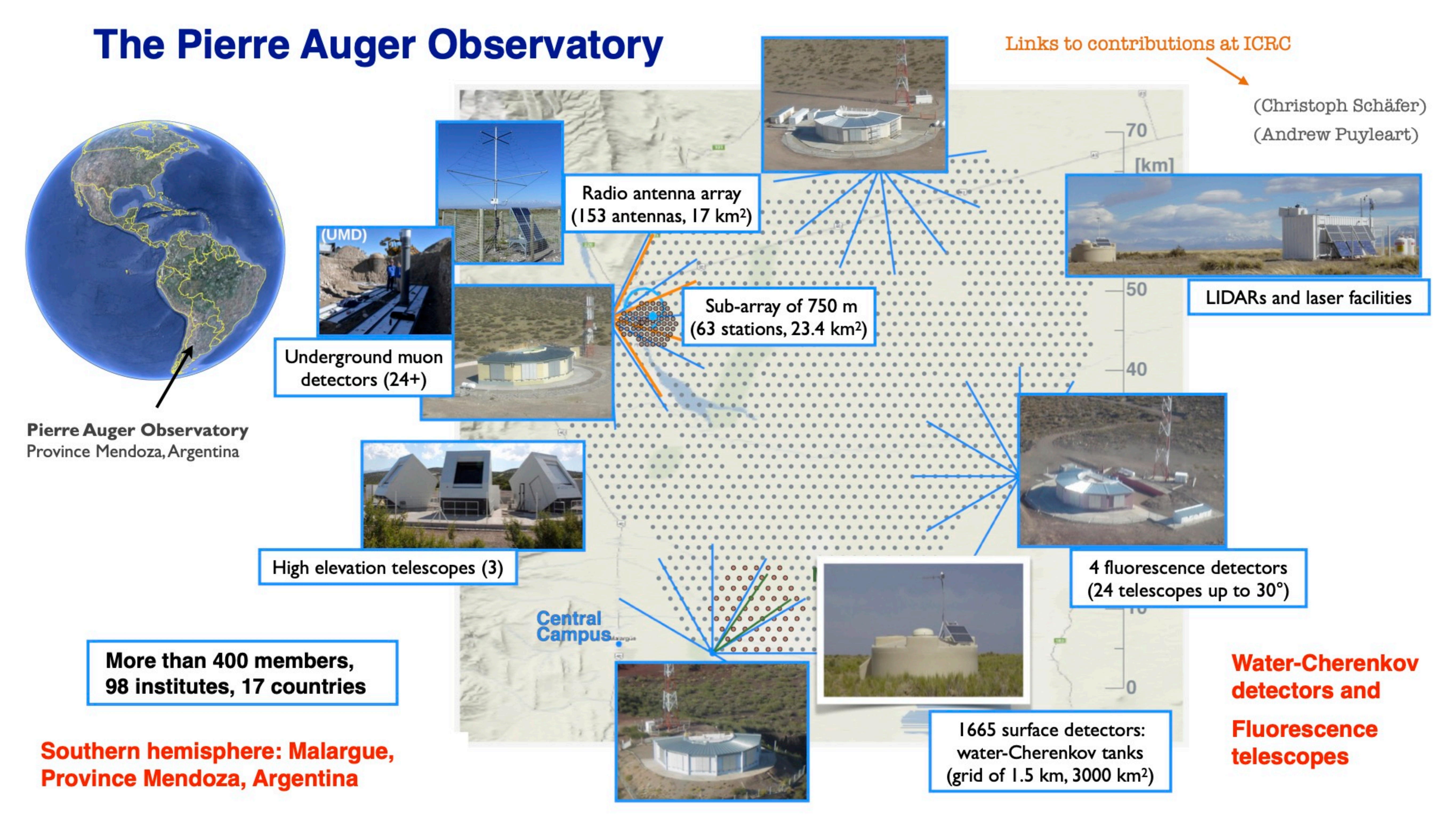


FIGURE 1. RMS(X_{max}) from different hadronic interaction models [23] and a two-component p/Fe composition model ($E = 10^{18}$ eV).



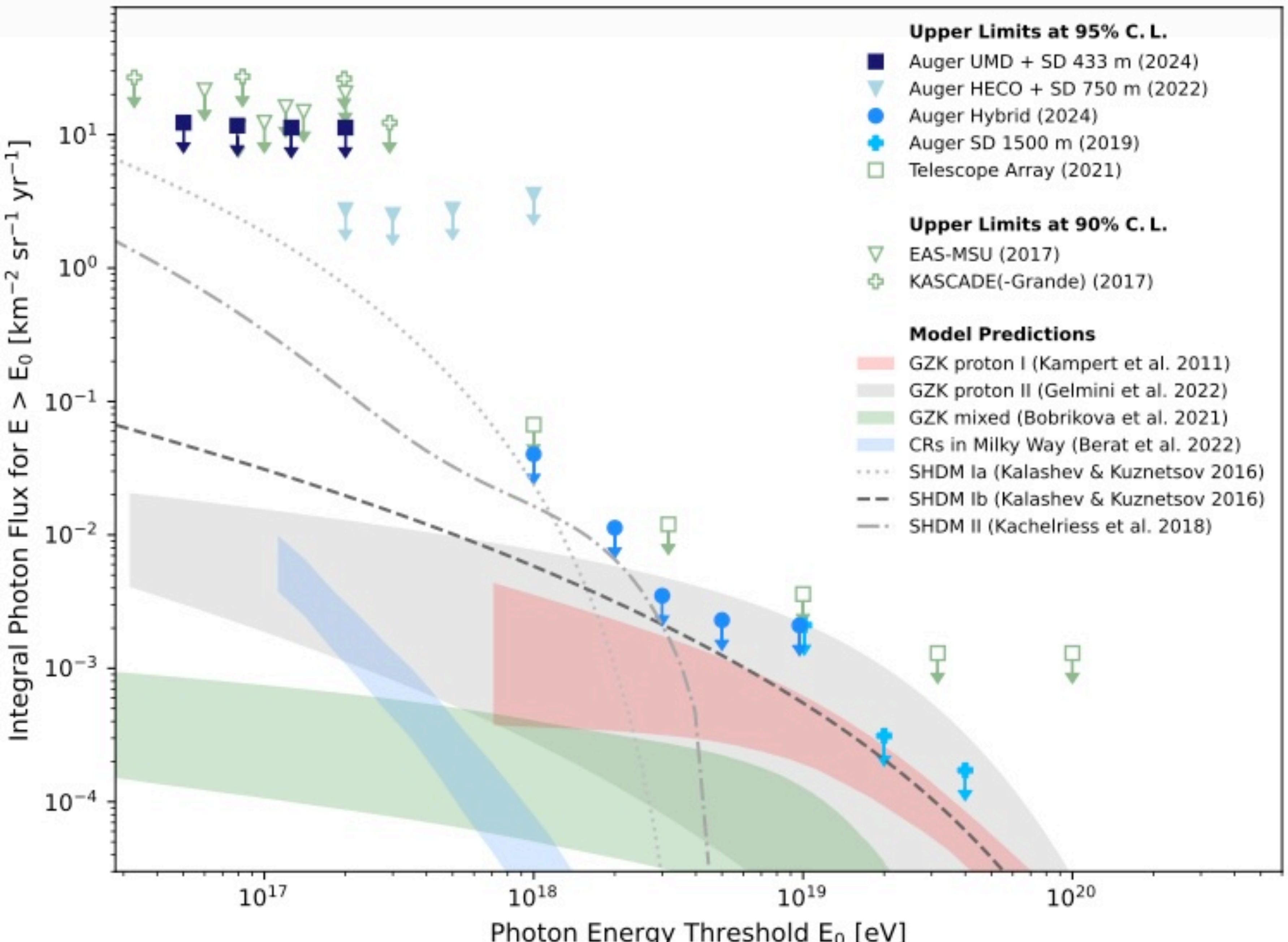






taken from R. Engel, Pierre Auger highlights, ICRC 2021

Photon flux upper limits

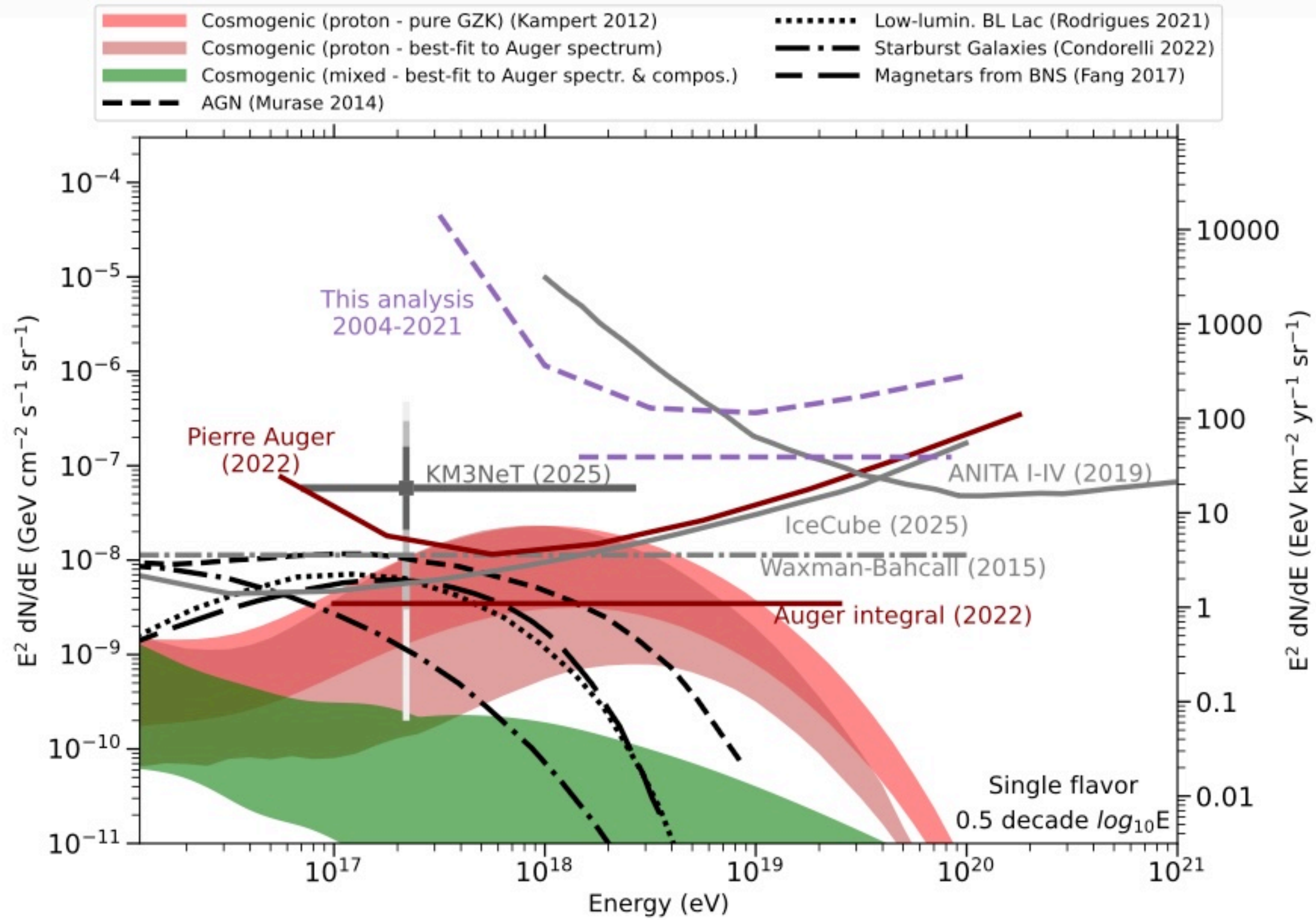


Pierpaolo Savina for the Pierre Auger collaboration, PoS (ICRC2025) 965

Pierre Auger collaboration, JCAP05 (2025) 061

Figure 5: Upper limits on the integral photon flux above threshold energy E_γ^{th} from this work (red markers, 95% CL) and previous Pierre Auger results at higher energies (blue and black markers, 95% CL), alongside limits from other experiments (90% CL, except Telescope Array at 95%). Shaded bands show cosmogenic flux predictions from UHECR interactions with galactic matter (gray), background radiation fields (violet, green, orange), and hot gas in the galactic halo (blue). Dashed lines denote super-heavy dark matter predictions (more details in [5]).

Neutrino flux upper limits

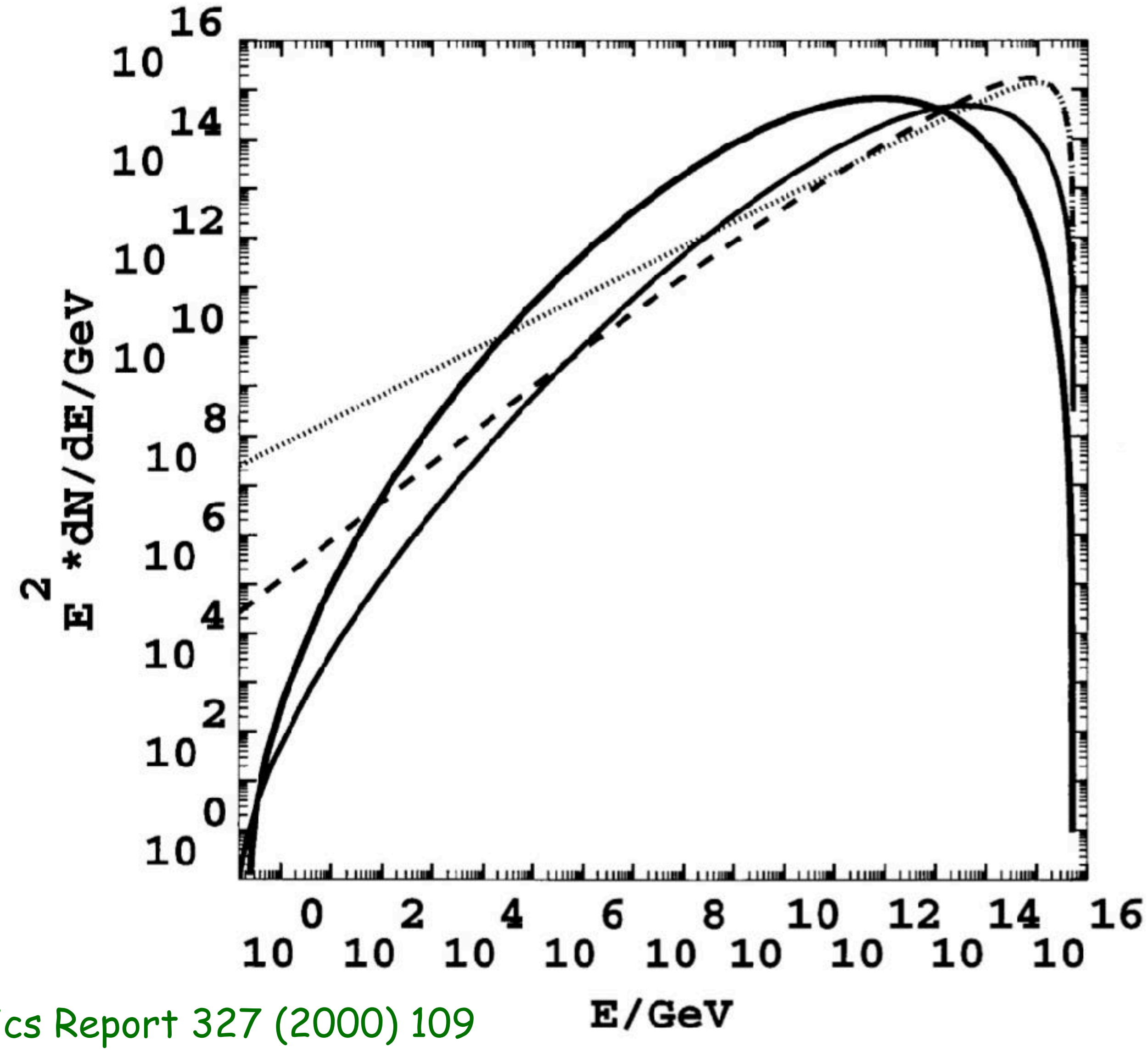


Srijan Seghal for the Pierre Auger collaboration, PoS (ICRC2025) 1170

Figure 4: Comparison of the *limits* (1 Jan 2004-31 Dec 2013 with *ToT+TH* triggers and 1 Jan 2014-31 Dec 2021 with *All* triggers) to the current upper limits on the diffuse flux of UHE neutrinos. IceCube limits from [10] are scaled for a E_ν^{-2} flux assumption. The predicted fluxes from a few cosmogenic and astrophysical ν models are also shown.

Top-Down Models

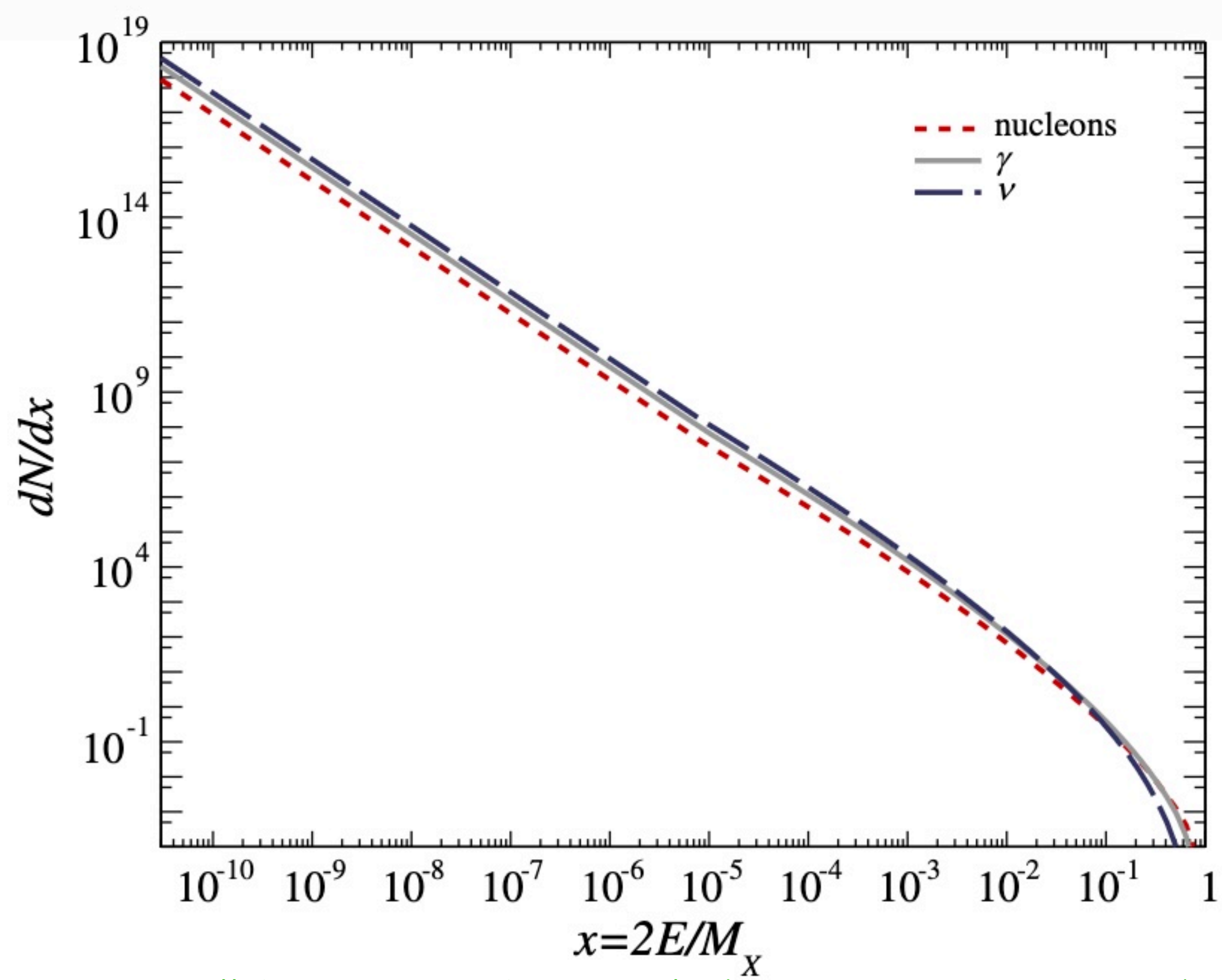
suggestion that highest energy cosmic rays are produced by decays from some higher energy scale, through fragmentation of quarks etc.



P. Bhattacharjee and G. Sigl, Physics Report 327 (2000) 109

Fig. 26. The fragmentation function for $E_{jet} = 5 \times 10^{15}$ GeV in MLLA approximation with SUSY (thick solid line peaking at 10^{12} GeV) and without SUSY (thin solid line) [see Eq. (57)] in comparison to the older expressions Eq. (61) (dashed line) and Eq. (62) (dotted line).

nowadays disfavored by predicted overproduction of gamma-rays



Pierre Auger collaboration, P. Abreu et al, Phys. Rev. D 107, 042002 (2023)

FIG. 1. Energy spectra of decay by-products of an SHDM particle ($M_X = M_{\rm Pl}$ here) in the $q\bar{q}$ channel, based on the hadronization process described in [43].

The flux in direction $\mathbf{n}$ of a species i into which the X-particle decays is given by

$$J_i(E,\mathbf{n}) = \frac{1}{4\pi M_X \tau_X} \int_0^\infty ds \rho_{\rm dm}(\mathbf{r}_\odot + s\mathbf{n}) f_i(s) \frac{dN_i}{dE},$$

where $\mathbf{r}_\odot$ is the position of the solar system, $f_i(s)$ is a possible attenuation factor, and $\rho_{\rm dm}(\mathbf{r})$ is the dark matter density profile.

For a mass scale m_X the constraint on the lifetime very roughly reads

$$\rho_{\rm dm}\frac{t_U}{\tau_X} \simeq \Omega_{\rm dm}\rho_{\rm crit}\frac{t_U}{\tau_X} \lesssim J_\gamma(fm_X)\,,$$

with t_U the age of the Universe and fm_X the characteristic γ-ray energy from X-particle decay. This implies

$$\frac{t_U}{\tau_X} \lesssim \frac{J_\gamma(fm_X)}{\Omega_{\rm dm}\rho_{\rm crit}} \sim 10^{-10}\,.$$

This is modified by extragalactic γ-ray absorption due to pair production, but (unabsorbed) galactic contribution is comparable. Numerically, thus very roughly

$$\tau_X \gtrsim 10^{27}\,{\rm s}\,.$$

Perturbative Superheavy Dark Matter Decay

For a coupling of the superheavy dark matter X of mass m_X to an operator Θ of dimension n of Standard Model fields of the form

$$\mathscr{L}_{\rm int} = \frac{g_{X\Theta}}{\Lambda^{n-4}} X\Theta$$

with Λ an energy scale, the X-particle has a lifetime

$$\tau_{X\Theta} = \left(\frac{2}{\pi}\right)^{n-1} \frac{\Gamma(n-1)\Gamma(n-2)}{4\pi M_X \alpha_{X\Theta}} \left(\frac{\Lambda}{M_X}\right)^{2n-8} ,$$

with $\alpha_{X\Theta} = g_{X\Theta}^2/(4\pi)$
Comparison with the Pierre Auger photon flux upper limits results in the following exclusion plot.

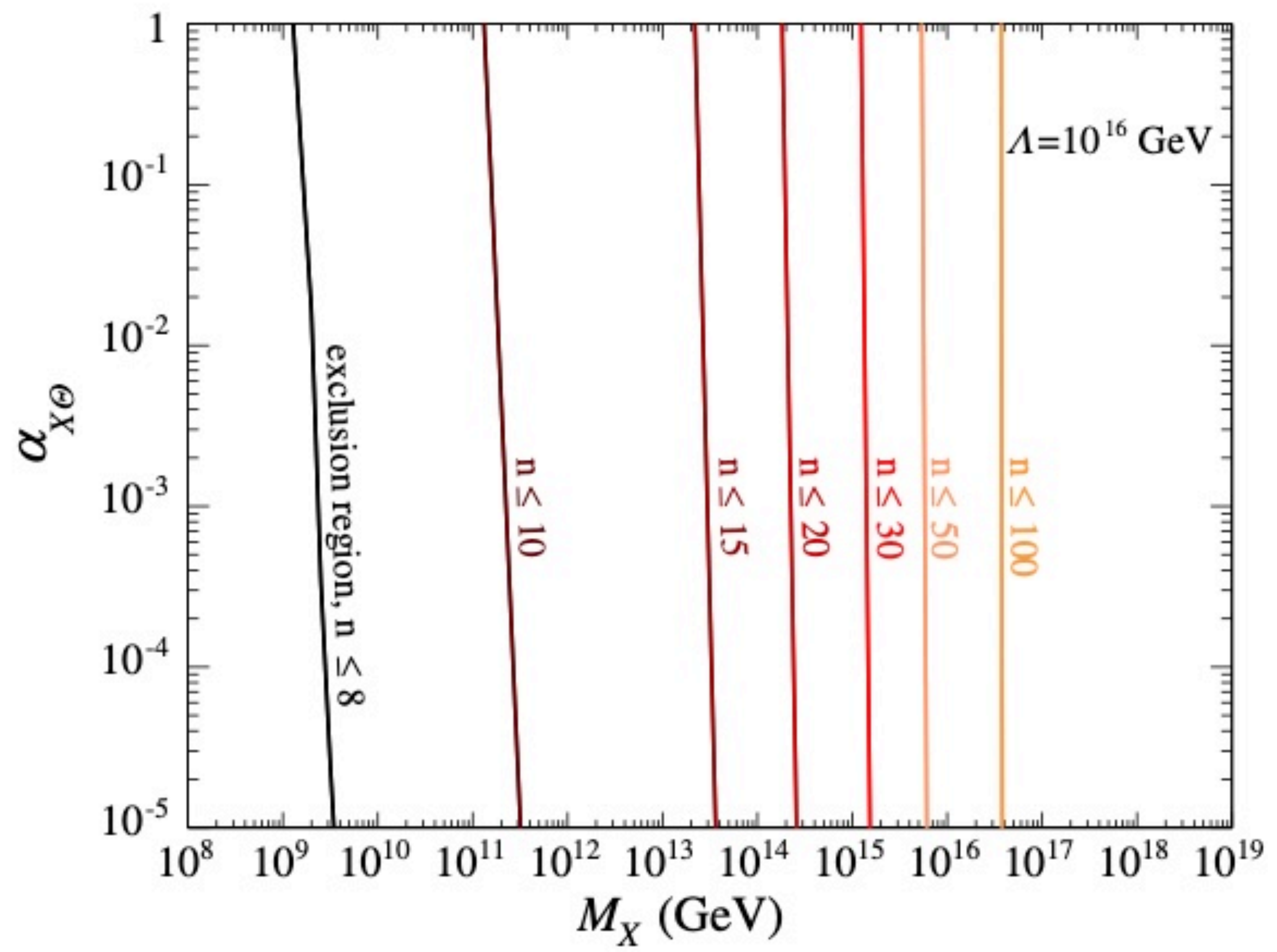


FIG. 4. Exclusion regions in the plane $(\alpha_{X\Theta}, M_X)$ for several values of mass dimension n of operators responsible for the perturbative decay of the super-heavy particle, and for an energy scale of new physics $\Lambda = 10^{16}$ GeV.

Pierre Auger collaboration, P. Abreu et al, Phys. Rev. D 107, 042002 (2023)

Instanton-induced Superheavy Dark Matter Decay

The X-particle lifetime is now

$$\tau_X = \frac{1}{M_X} \exp(4\pi/\alpha_X)\,,$$

Comparison with the Pierre Auger photon flux upper limits (scanning the energy dependent photon flux upper limits for each M_X) results in the following exclusion plot (corresponding to $\tau_X \sim 10^{26} - 10^{30}$ s) for the observed relic density

Pierre Auger collaboration, P. Abreu et al, Phys. Rev. D 107, 042002 (2023)
Pierre Auger collaboration, P. Abreu et al, Phys. Rev. Lett. 130, 061001 (2023)

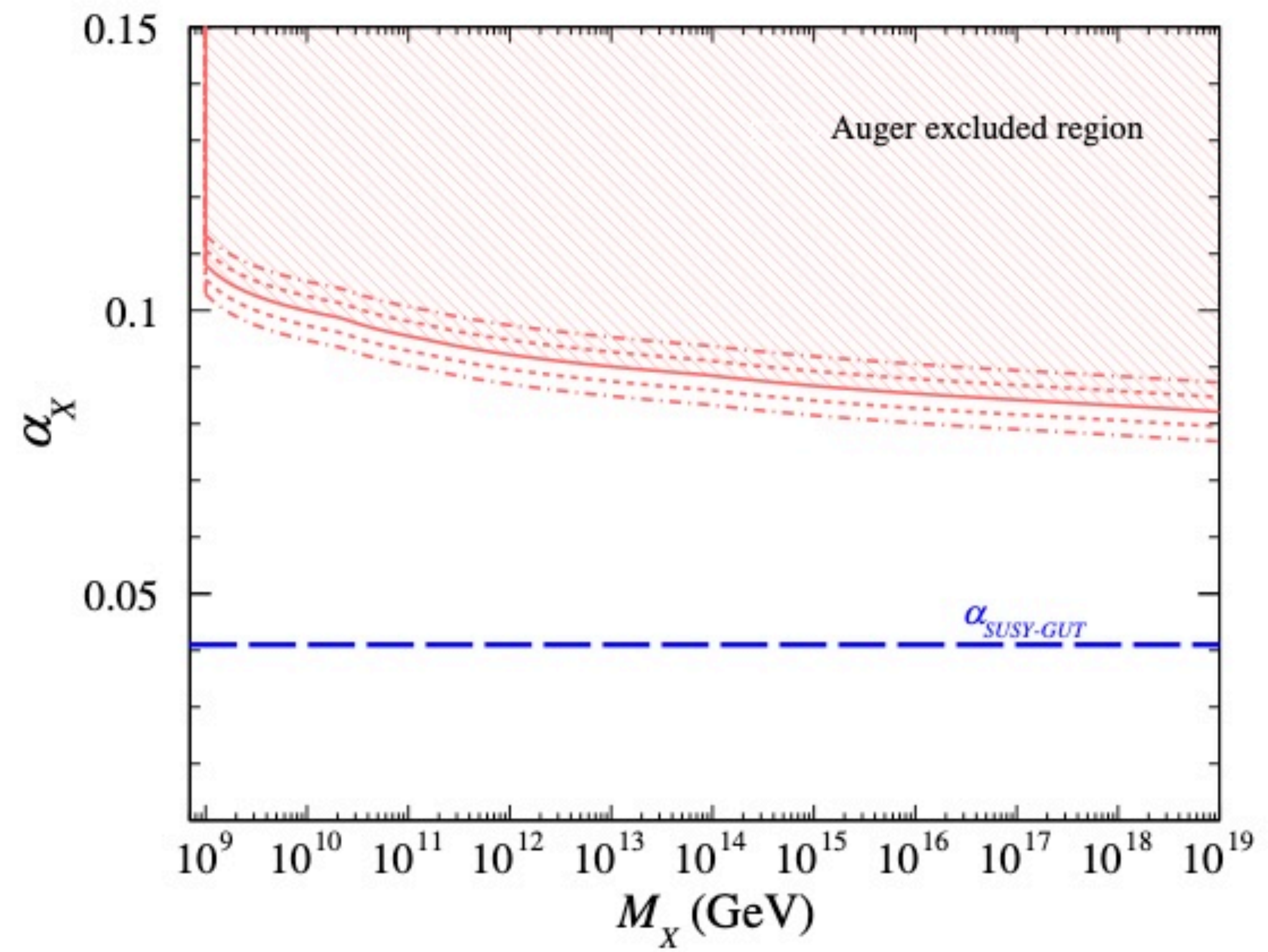


FIG. 5. Upper limits at 95% CL on the coupling constant α_X of a hidden gauge interaction as a function of the mass M_X of a dark matter particle X decaying into a dozen of $q\bar{q}$ pairs. The dotted and dashed-dotted lines represent the systematic uncertainties stemming from the quantum fluctuations about the instanton contribution to the transition amplitude (see text). For reference, the unification of the three SM gauge couplings is shown as the horizontal blue dashed line in the framework of supersymmetric GUT [81].

Cosmological Constraints

For a reheating temperature $T_{\rm rh}$ and the Hubble rate at the end of inflation $H_{\rm inf}$ the reheating efficiency is defined as $\epsilon = (\Gamma_\phi / H_{\rm inf})^{1/2} \simeq 4T_{\rm rh} / \left(M_{\rm Pl} H_{\rm inf}\right)^{1/2}$, with $\Gamma_{\rm inf}$ the inflation decay rate.

The dimensionless abundance $Y_X = n_X a^3 / T_{\rm rh}^3$ of X-particles is then governed by the Boltzmann equation

$$\frac{dY_X}{da} = \frac{a^3}{T_{\rm rh}^3 H(a)} \sum_i \Gamma_i n_i^3(a)\,,$$

the sum going over Standard Model and inflationary sectors, n_i the number densities of the relevant particles and $\Gamma_i = \left\langle \sigma_i v \right\rangle$ the thermally averaged cross section times velocity. The solution for $Y_{X,0}$ today then implies

$$\Omega_X \simeq 9.2 \times 10^{24} \frac{\epsilon^4 M_X}{M_{\rm Pl}} Y_{X,0}\,.$$

Comparison with the Pierre Auger photon flux upper limits results in the following exclusion plots.

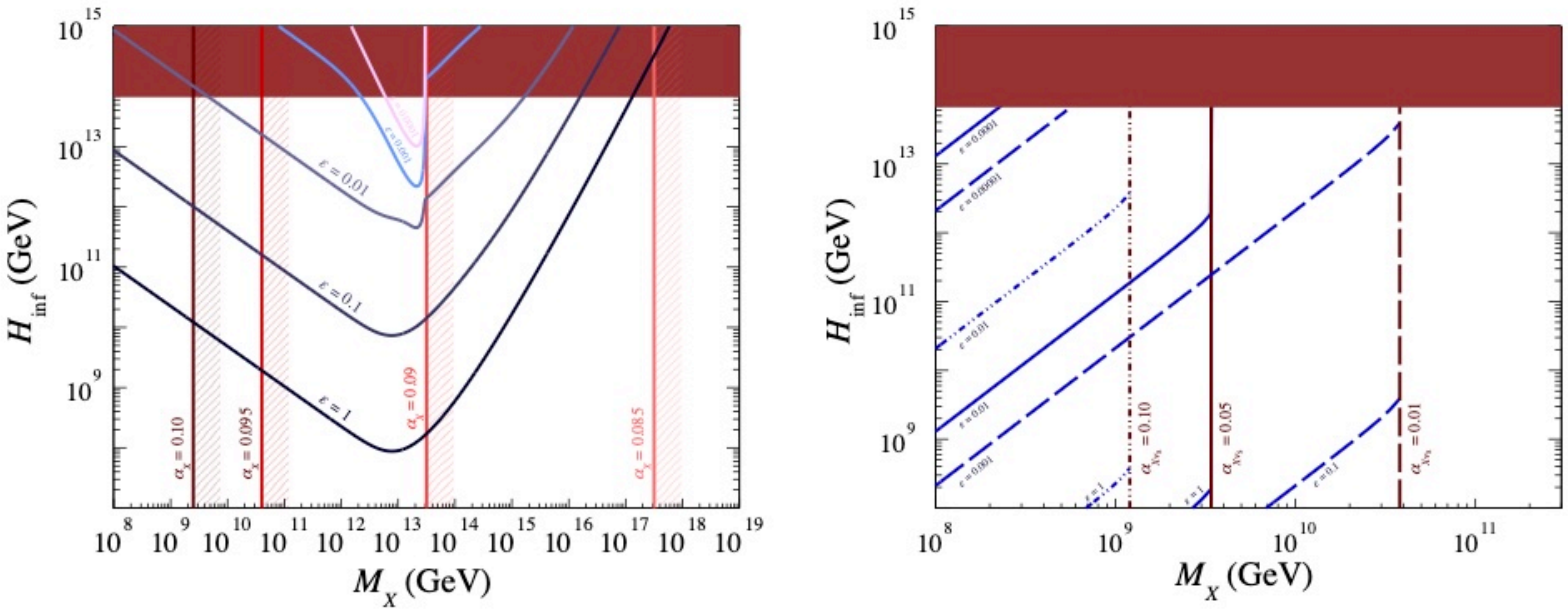


Figure 5: Left: Constraints in the $(H_{\rm inf}, M_X)$ plane, where viable values are delineated by the blue lines for different values of reheating efficiency ϵ. Additional constraints from the non-observation of instanton-induced decay of super-heavy particles allow for excluding the mass ranges in the red-shaded regions, for the specified value of the dark-sector gauge coupling. From [13]. Right: Same, adding the possibility of a radiative production of dark matter in the inflaton decay.

region above blue-to-black lines imply too high relic density, region below too low density

Pierre Auger collaboration, P. Abreu et al, Phys. Rev. D 107, 042002 (2023); Phys. Rev. Lett. 130, 061001 (2023)
O. Deligny for the Pierre Auger collaboration, J. Phys.: Conf. Ser. 3053012016 (2025)

Conclusions

1.) Ultrahigh energy particles produced in decays from a higher energy scale tend to be dominated by photons, rather than by nucleons and nuclei

2.) The Pierre Auger experiment has so far observed neither photons nor neutrinos and provides some of the strongest upper limits on their fluxes

3.) This allows to constrain beyond the Standard Model physics and in particular superheavy dark matter in terms of mass and coupling constants which we reviewed here. Above $\sim 10^9$ GeV the bounds on lifetime tend to be the strongest and about 8-10 powers of ten larger than the age of the Universe

4.) This also has cosmological implications when combined with requiring to reproduce the relic dark matter density. which we also discussed