THE RISE AND FALL OF TOP-DOWN MODELS AS MAIN UHECR SOURCES

M. Kachelrieß
Institutt for fysikk, NTNU Trondheim, Norway

The motivation and the current status of top-down models as sources of ultrahigh energy cosmic rays (UHECR) are reviewed. Stimulated by the AGASA excess, they were proposed as the main source of UHECRs beyond the GZK cutoff. Meanwhile searches for their signatures have limited their contribution to the UHECR flux to be subdominant, while the theoretical motivation for these searches remained strong: Topological defects are a generic consequence of Grand Unified Theories and superheavy particles are a creditable dark matter candidate. While Fermi/GLAST results should help to improve soon bounds on topological defects from the diffuse gamma-ray background, the most promising detection method are UHE neutrino searches. Superheavy dark matter can be restricted or detected by its characteristic galactic anisotropy combined with searches for UHE photons.

1 Introduction

Cosmic Rays (CR) are observed in an energy range extending over more than eleven decades, with a flux described by a nearly featureless power-law starting from subGeV energies up to $3 \times 10^{20}$ eV. Soon after the first CR with energy beyond $10^{20}$ eV was observed in 1963 at the Vulcano Ranch experiment, it was shown that the universe is filled with thermal relic photons from the big-bang. Greisen\footnote{1} and independently Zatsepin and Kuzmin\footnote{2} pointed out that as a consequence of pion-production on these photons, $p + \gamma_3K \rightarrow \Delta^* \rightarrow N + \pi$, the energy-loss-length $(1/E)(dE/dt)$ of protons should decrease dramatically around $E_{\text{GZK}} \sim 5 \times 10^{19}$ eV. Nuclei exhibit an even more pronounced cutoff at a (for iron) somewhat higher energy, while photons are absorbed over a few Mpc due to pair-production on the radio background. Thus, the ultrahigh energy (UHE) CR spectrum should steepen at $E_{\text{GZK}}$ for any homogeneous distribution of proton or nuclei sources\footnote{3}.

It is the decrease of the UHECR horizon scale below $\sim 100$ Mpc that may make astronomy with charged particles possible: Within this distance, the positions of powerful objects like active galactic nuclei are known and the effect of deflections of protons in (extra-) galactic magnetic fields\footnote{4} may be sufficiently small to allow us the identification of sources. Even if the identification of individual sources may be not possible, the large-scale structure of sources is not yet averaged out along the line-of-sight and results in specific anisotropy patterns\footnote{5}. The “GZK puzzle” of the 90s was the observation of a surprisingly large number of events above $10^{20}$ eV, in particular by the AGASA experiment, while no promising nearby sources could be identified in the direction of these UHECRs. Moreover, the arrival directions of UHECRs were found to be consistent with isotropy on medium and large angular scales prior to an analysis\footnote{6} of the cumulative auto-correlation function of all publicly available data, while the significance of the observed small-scale clustering\footnote{7} remained disputed. Finally, the acceleration of CRs to energies beyond $10^{20}$ eV was (and still is) a challenge for all known astrophysical sources.

The extension of the UHECR spectrum beyond the GZK cutoff as observed by AGASA, the missing correlation of the UHECR arrival directions with powerful nearby sources and the difficulty to accelerate particles in astrophysical accelerators up to energies $E \gtrsim 10^{20}$ eV prompted models that do not accelerate charged particles (“bottom-up models”) but use the stable secondaries produced in the fragmentation of superheavy particles (“top-down models”). Note that the study of both main variants of top-down models, superheavy dark matter (SHDM) and topological defects (TD), is well motivated independently of UHECR observations: The latter
are a generic prediction of Grand Unified Theories, in particular if supersymmetry is included\cite{8}, while brane inflation\cite{9} would result in the production of macroscopic superstrings. Superheavy dark matter is an attractive DM candidate, because (meta-) stable particles with masses around 10^{13} GeV are produced during inflation with the correct abundance\cite{10} to be today the main source of DM. In the following, we update the review\cite{11} of the status of these models.

2 Top–down models and their signatures

Top–down model is a generic name for all proposals in which the observed UHECR primaries are produced as decay products of some superheavy particles $X$. These $X$ particles can be either metastable or be emitted by topological defects at the present epoch. In both cases, the range of masses that was suggested by the AGASA excess\cite{12} is rather narrow, 10^{12} GeV $\lesssim m_X < \text{few} \times 10^{13}$ GeV. The lower limit follows directly from the highest CR energies observed, $E_{\text{max}} = (2-3) \times 10^{20}$ eV, while the upper limit can be derived by comparing the integral flux predicted in these models with the non-observation of UHECRs above $E_{\text{max}}$.

2.1 Superheavy dark matter

The suggestion\cite{13,14} of superheavy metastable relic particles as UHECR sources was originally motivated by the AGASA excess, although it was soon realized that stable or metastable particles in this mass range are generically good DM candidates\cite{10}. Since they constitute (part of) the CDM, their abundance in the galactic halo is enhanced by a factor $\sim 2 \times 10^5$ above their extragalactic abundance. Therefore, the proton and photon flux is dominated by the halo component and the GZK cutoff is avoided\cite{13}. The ratio $r_X = \Omega_X(t_0/\tau_X)$ of the product of the relic abundance $\Omega_X$ and the age of the universe $t_0$ and the lifetime $\tau_X$ of the $X$ particle is $r_X \sim 10^{-11}$, if the UHECR flux is fixed to the observations of AGASA. The numerical value of $r_X$ is not predicted in the generic SHDM model, but calculable as soon as a specific particle physics and cosmological model is fixed.

Various mechanisms exist that produce particles with a non-thermal distribution in the early Universe. Since the energy density of non-relativistic particles decreases slower than the one of radiation, their abundance increases by the factor $a(t_0)/a(t_*)$ with respect to radiation, where $a(t_0)$ and $a(t_*)$ are the scale factors of the universe today and at the epoch of particle generation, respectively. If particle production happens at the earliest relevant time, i.e. during inflation, this factor can become extremely large, $\sim 10^{22}$. Not surprisingly, such a small energy fraction can be transferred to SHDM by many different mechanisms, as thermal production at reheating\cite{13,15}, the non-perturbative regime of a broad parametric resonance at preheating\cite{16}, and production by topological defects\cite{13,17}.

Here we recall only the generation of SHDM by gravitational interactions from vacuum fluctuations at the end of inflation\cite{10,18}. Numerical calculations\cite{18} for the present abundance of fermionic SHDM can be approximated as

$$\Omega_X h^2 \approx \frac{T_R}{10^8 \text{ GeV}} \begin{cases} (m_X/H_I)^2, & m_X \ll H_I \\ \exp(-m_X/H_I), & m_X \gg H_I \end{cases} \quad (1)$$

with $H_I \approx 10^{13}$ GeV as value for the Hubble parameter during inflation. In general, two values of the SHDM mass are consistent with the observed abundance $\Omega_{\text{CDM}} = 0.105$ of CDM\cite{19} for a specific value of the reheating temperature $T_R$. Choosing the larger of the two possible masses in Eq. (1) together with the highest value allowed by the gravitino problem for the reheating temperature, $T_R = 10^9$ GeV, leads to an abundance of SHDM as observed by WMAP, while secondaries of SHDM decays could explain at the same time (part of) the cosmic rays at the highest energies, $E \gtrsim 10^{20}$ eV.
The lifetime of the superheavy particle has to be in the range $t_0 \sim 10^{17} \text{ s} \lesssim \tau_X \lesssim 10^{28} \text{ s}$, i.e. longer or much longer than the age of the Universe, if UHECRs are produced by SHDM decays. Therefore it is an obvious question to ask if such an extremely small decay rate can be obtained in a natural way. A well-known example of how metastability can be achieved is the proton: In the standard model B–L is a conserved global symmetry, and the proton can decay only via non-renormalizable operators. Similarly, the $X$ particle could be protected by a new global symmetry which is only broken by higher-dimensional operators suppressed by $M^d$, where for instance $M \sim M_{\text{Pl}}$ and $d \geq 7$ is possible. The case of discrete gauged symmetries has been studied in detail. Another possibility is that the global symmetry is broken only non-perturbatively, either by wormhole or instanton effects. Then an exponential suppression of the decay process is expected and lifetimes $\tau_X > t_0$ can be naturally achieved.

An example of a metastable SHDM particle in a semi-realistic particle physics model is the crypton. Cryptons are bound-states from a strongly interacting hidden sector of string/M-theory. Their mass is determined by the non-perturbative dynamics of this sector and, typically, they decay only through high-dimensional operators. For instance, flipped SU(5) motivated by string theory contains bound-states with mass $\sim 10^{12}$ GeV and $\tau \sim 10^{15}$ yr. Choosing $T_R \sim 10^5$ GeV results in $r_X \sim 10^{-11}$, i.e. the required value to explain the UHECR flux above the GZK cutoff. This example shows clearly that the SHDM model has no generic “fine-tuning problem.” Other viable candidates suggested by string theory were also discussed. Another well-suited candidate for superheavy dark matter is the lightest supersymmetric particle within the scenario of superheavy supersymmetry. This is a unique case where the SHDM has weak interactions and respects perturbative unitarity despite the large mass hierarchy $m_X \gg m_Z$.

Finally, we comment on the case of stable SHDM. Since the annihilation cross section of a (point) particle is bounded by unitarity, $\sigma_{\text{ann}} \propto 1/M_X^2$, the resulting flux of UHE secondaries is too small to be observable without an additional enhancement of the annihilation rate.

### 2.2 Topological defects

Topological defects such as (superconducting) cosmic strings, monopoles, and hybrid defects can be effectively produced in non-thermal phase transitions during the preheating stage. Therefore the presence of TDs is not in conflict with an inflationary period of the early Universe. They can naturally produce particles with high enough energies but have problems to produce large enough fluxes of UHE primaries, because of the typically large distance between TDs. Then the flux of UHE particles is either exponentially suppressed or strongly anisotropic if a TD is nearby by chance.

*Ordinary strings* can produce UHE particles, e.g., when string loops self-intersect or when two cusp segments overlap and annihilate. In the latter case, the maximal energy of the produced fragmentation products is not $m_X/2$, but can be much larger due to the high Lorentz factors of the ejected $X$ particles.

*Superconducting strings:* Cosmic strings can be superconducting in a broad class of particle models. Electric currents can be induced in the string either by a primordial magnetic field that decreases during the expansion of the Universe or when the string moves through galactic fields at present. If the current reaches the vacuum expectation value of the Higgs field breaking the extra U(1), the trapped particles are ejected and can decay.

*Monopolium* $M$, a bound-state of a monopole–antimonopole pair, was the first TD proposed as UHECR source. It clusters like CDM and is therefore an example for SHDM. The galactic density of monopoles is constrained by the Parker limit: the galactic magnetic field should not be eliminated by the acceleration of monopoles. Reference concluded that the resulting limit on the UHECR flux produced by Monopolium annihilations is 10 orders of magnitude too low.
Cosmic necklaces are hybrid defects consisting of monopoles connected by a string. These defects are produced by the symmetry breaking $G \rightarrow H \times U(1) \rightarrow H \times Z_2$, where $G$ is semi-simple. In the first phase transition at scale $\eta_m$, monopoles are produced. At the second phase transition, at scale $\eta_s < \eta_m$, each monopole gets attached to two strings. The basic parameter for the evolution of necklaces is the ratio $r = m/(\mu d)$ of the monopole mass $m$ and the mass of the string between two monopoles, $\mu d$, where $\mu \sim \eta_s^2$ is the mass density of the string and $d$ the distance between two monopoles. While for $r \ll 1$ necklaces evolve in the scaling regime of a usual string network, monopoles dominate the evolution in the opposite limit $r \gg 1$. Analytical estimates suggested that for a reasonable range of parameters strings lose their energy and contract through gravitational radiation in such a way that a sufficient fraction of monopole-antimonopole pairs annihilate in the nearby universe at the present epoch producing X particles. In particular, it was argued, that the model predicts a UHECR flux close to the observed one without violating the EGRET bound. Numerical studies of the evolution of necklaces found that the lifetime of necklaces is generally much shorter than the age of the Universe. More recently, it has been argued, that monopoles attached to the strings acquire large velocities, leading to fast annihilations or to the escape of monopole-antimonopole pairs. In both cases, necklaces would have been transformed to a standard cosmic string network at the present epoch.

2.3 Signatures of top-down models

Superheavy dark matter has several clear signatures: 1. No GZK cutoff, instead a flatter spectrum compared to astrophysical sources up to the kinematical cutoff close to $m_X/2$. 2. Large neutrino and photon fluxes compared to the proton flux. 3. Galactic anisotropy. 4. If low-scale supersymmetry is realized by nature and $R$ parity conserved, then the lightest supersymmetric particle (LSP) is an additional UHE primary. 5. No correlation of the CR arrival directions with astrophysical sources at the highest energies, $E \gtrsim 10^{20}$ eV.

1. Spectral shape: The fragmentation spectra of superheavy particles calculated by different methods and different groups agree quite well, cf. Ref. for a detailed discussion. This allows one to consider the spectral shape as a signature of models with decays or annihilations of superheavy particles. The predicted spectrum in the SHDM model, $dN/dE \propto E^{-1.9}$, cannot fit the observed UHECR spectrum at energies $E \leq (6-8) \times 10^{19}$ eV. Thus only events at $E \geq (6-8) \times 10^{19}$ eV, and in particular the AGASA excess could be explained in this model. Discarding the AGASA results, the necessity for SHDM decays is obviously reduced: A two-component fit to the experimental data from the PAO using protons from uniformly, continuously distributed extragalactic astrophysical sources and photons from SHDM is shown in the left panel of Fig. Although the quality of the fit including SHDM is good, it is clear that the presence of the cutoff in the energy spectrum makes an additional component at $E > 10^{20}$ eV unnecessary.

The UHECR flux in topological defects like cosmic strings has a GZK cutoff that is however less pronounced than for astrophysical sources, because of the flatter generation spectrum of the UHE particles and the dominance of photons. The resulting shape made it, even neglecting all other constraints, impossible to explain the AGASA excess with TDs.

2. Chemical composition: Since at the end of the QCD cascade quarks combine more easily to mesons than to baryons, the main component of the UHE flux are neutrinos and photons from pion decay. Therefore, a robust prediction of this model is photon dominance with a photon/nucleon ratio of $\gamma/N \simeq 2-3$, becoming smaller at the largest $x = 2E/M_X$. This ratio can be reduced for TD models because of the strong absorption of UHE photons, but is still much higher than expected from astrophysical sources. Large UHE neutrino fluxes, especially of TD models, are another signature of top-down models.

Since the mass scale $M_X$ is far above those tested at accelerators, one may wonder how new
physics between the weak scale and $M_X$ can influence the $\nu : \gamma : N$ ratio. The answer is that this ratio is extremely stable, since the underlying $\pi^\pm : \pi^0 : N$ ratio at hadronization, $Q^2 \sim \Lambda_{\text{QCD}}^2$, is only weakly dependent on the “prehistory” of the QCD cascade at higher virtualities. One may consider the small changes induced by weak-scale supersymmetry in the secondary spectra as one example, while a more extreme example is a SHDM particle that is coupled at tree-level only to neutrinos. Even in this case, the resulting electroweak cascade leads to a large fraction of photons as secondaries.

3. Galactic anisotropy: The UHECR flux from SHDM should show a galactic anisotropy, because the Sun is not in the center of the Galaxy. The magnitude of this anisotropy depends on how strong the CDM is concentrated near the galactic center. Since the decay rate is in contrast to annihilation rate only linear in the number density $n_X(r)$, differences in the CDM profile impact not too much the resulting anisotropy.

4. LSP as UHE primary: An experimentally challenging but theoretically very clean signal both for supersymmetry and for top-down models would be the detection of the LSP as an UHE primary. A decaying supermassive $X$ particle initiates a particle cascade consisting mainly of gluons and light quarks but also of gluinos, squarks and even only electroweakly interacting particles for virtualities $Q^2 \gg m_W^2, M_{\text{SUSY}}^2$. When $Q^2$ reaches $M_{\text{SUSY}}^2$, the probability for further branching of the supersymmetric particles goes to zero and their decays produce eventually UHE LSPs. Signatures of UHE LPSs are a Glashow-like resonance at $10^9$ GeV $M_e/\text{TeV}$, where $M_e$ is the selectron mass, and up-going showers for energies where the Earth is opaque to neutrinos.

5. Correlations: Since in the SHDM model the contribution from other galaxies is strongly suppressed and other TDs like cosmic strings do not cluster, no correlation of the CR arrival directions with matter is expected at the highest energies, $E \gtrsim 10^{20}$ eV. Hence already the correlation of UHECR arrival directions with matter along the supergalactic plane suggested by the PAO data excludes top-down models in the relevant energy range, while a correlation with a specific astrophysical source class like active galactic nuclei would be a conclusive proof for the dominance of astrophysical sources in the considered energy range.
3 Observational constraints

3.1 UHECR observations

1. Spectral shape and the GZK suppression: Figure 2 shows the modification factor \( \eta(E) = \frac{J_p(E)}{J_{p,\text{unm}}(E)} \), i.e. the ratio of the spectrum \( J_p(E) \) calculated with all energy losses and of the unmodified spectrum \( J_{p,\text{unm}}(E) \) calculated with adiabatic energy losses only, for the simplest model of uniformly distributed proton sources together with data\[^{13}\] from Akeno-AGASA, HiRes, and PAO. The predicted modification factor \( \eta(E) \) shows a dip due to pair-production (\( \eta_{ee} \)) and a subsequent suppression by roughly two orders of magnitude due to the GZK effect (\( \eta_{\text{total}} \)). After rescaling their energies within the range allowed by the experimental uncertainties, the data of all three experiments show good agreement with the prediction in the dip region. In the energy range where the flux is mainly modulated by the GZK effect, the two experiments with the largest exposure (PAO and HiRes) follow too the flux expected from uniformly distributed astrophysical sources, while the data of the AGASA experiment show an excess above \( 10^{20} \) eV. The prevailing interpretation of the AGASA excess has changed with time: Nowadays it is considered as an experimental artefact, although its exact origin is unclear. Additionally to the problem of small-number statistics, cosmic variance and potential problems with the energy calibration one should note that also the PAO data show a certain tension between the energy determination using surface and fluorescence detectors.

![Figure 2: The pair-production dip and GZK suppression as predicted by simplest model of uniformly distributed proton sources compared to Akeno-AGASA, HiRes, and Auger data, from Ref. [45].](image)

Experimentalists prefer to quantify the significance of the GZK suppression in a model-independent way by fitting a broken power-law \( J \propto E^{-\gamma} \) to their data above \( \sim 10^{19} \) eV. The HiRes collaboration\[^{16}\] was the first to find with this method a 5\( \sigma \) evidence for the GZK suppression: The best-fit power-law to their data has an exponent \( \gamma = 5.1 \) above the break energy \( 5.6 \times 10^{19} \) eV and \( \gamma = 2.8 \) below the break down to the ankle at \( E = 4.5 \times 10^{18} \) eV. Extrapolating the \( \gamma = 2.8 \) spectrum above \( 5.6 \times 10^{19} \) eV, calculating the expected event number above the break and comparing with the observed one, the HiRes collaboration derived a 5.3\( \sigma \) deficit. The PAO collaboration\[^{17}\] presented more recently a similar analysis. Using a method which is independent of the true slope the CR spectrum, they rejected a straight power-law extension above \( 4 \times 10^{19} \) eV with more than 6\( \sigma \). In both data sets, the energy where the flux is reduced by a factor two coincides reasonably well with theoretical calculations.

In summary, the spectral shape of the observed spectra of HiRes, PAO and older experiments like Yakutsk and Fly’s Eye are in good agreement with the simplest model of uniformly distributed astrophysical sources of protons. The AGASA excess is interpreted as an experimental artefact. As a result the SHDM flux is not fixed, but bounded from above by the experimental data.

2. Chemical composition: Extensive air showers induced by photons can be distinguished by
several properties from showers initiated by protons or nuclei: First, the muon content of photon induced EAS is smaller compared to hadronic showers. Second, photon showers have a large elongation rate $dX_{\text{max}}/dE$ and develop thus their maxima deeper in the atmosphere. Finally, the geomagnetic effect induces a characteristic anisotropy in the arrival directions of photon showers.

The muon content of air showers was used first by the AGASA experiments to derive an upper limit on the fraction of photons in UHECRs. From eleven events at $E > 1 \times 10^{20}$ eV, six were measured within in a sub-array equipped with muon detectors. In two of them with energies about $1 \times 10^{20}$ eV, the muon density was almost twice higher than predicted for gamma-induced EAS, while the muon content of the remaining four EAS only marginally agreed with that predicted for gamma-induced showers. Improved limits were later derived by a combination of AGASA and Yakutsk data using the same technique.

The PAO collaboration derived photon limits using $X_{\text{max}}$ measurement from the fluorescence method and using a hybrid approach. No photon-like events were reported and the resulting limits on the fraction of photons in UHECR flux are $2\%$ at $10^{19}$ eV, $5\%$ at $2 \times 10^{19}$ eV, and $30\%$ at $4 \times 10^{19}$ eV, respectively. These limits constrain the flux from top-down models to be a sub-dominant component of the UHECR flux even above the GZK energy, while they start to approach at low energies, $E = 10^{19}$ eV, the upper range of photons predicted by the GZK reaction. Searches for photons from SHDM at low energies should be therefore combined in the future with searches for the anisotropy pattern connected to the position of the Sun in the galactic halo.

Topological defect models are additionally constrained by the diffuse $\gamma$-ray background and by limits on UHE neutrinos. While it is anticipated that Fermi/GLAST will resolve part of the diffuse $\gamma$-ray background observed by EGRET and thus the resulting limits on TD models will become soon more stringent, at present there is not yet a change compared to older analyses. On the other hand, the PAO collaboration derived a new limit on the UHE neutrino flux from the non-observation of $\nu_{\tau}$ events that improves the old RICE bound. This limit constrains $E^2 j_{\nu}(E)$, i.e. the energy contained in neutrinos per energy decade, by a factor $\sim 10$ stronger than the corresponding EGRET limit for $E^2 j_{\gamma}(E)$ the injection of electromagnetic radiation. At present the $\nu_{\tau}$ limit is comparable to the EGRET bound, cf. Fig. 3.

### 3. Galactic anisotropy:

The UHECR flux from SHDM should show a galactic anisotropy because the Sun is not in the center of the Galaxy. The degree of this anisotropy depends on how strong the CDM is concentrated near the galactic center. Experiments in the southern hemisphere as the old Australian SUGAR experiment and the PAO do see the Galactic center and are thus most sensitive to a possible anisotropy of arrival directions of UHECR from SHDM. The SHDM hypothesis was found to be compatible with the SUGAR data at the $\sim 5–20\%$ level. The predictions for the SHDM anisotropies were updated recently, but not yet used for a limit by the PAO collaboration.

Although at low energies, say at $10^{18}$ eV, the UHECR flux is strongly dominated by CRs from astrophysical sources, the search for anisotropies in this energy range may be promising. The CR flux from astrophysical sources at these energies is, apart from a $0.6\%$ anisotropy induced by the (cosmological) Compton-Getting effect, isotropic and thus even the small anisotropy in the few percent level from SHDM decays may be a detectable signature. Already the 2005–2006 data from the PAO presented at the ICRC ’07 limit at the $95\%$ C.L. the amplitude of the first Rayleigh harmonics to less than $1.7\%$ at 1 EeV and to $3.2\%$ at 3 EeV. The corresponding prediction for a SHDM model with parameters as in Fig. 1 that respects both photon bounds and fits the observed spectrum are in the $2\%$ range. Note however that, since the energy estimate for proton and a photon primaries differ, the two numbers are not directly comparable and a proper analysis is required.
Figure 3: Proton (green), photon (magenta) and neutrino (blue) fluxes in a TD model with $M_X = 2 \times 10^{13}$ GeV, evolution $\dot{n}_X \propto t^{-3}$ and continuous distribution of sources (adopted from Ref. [42]) together with two determinations of the MeV–GeV diffuse photon background from EGRET data, CR data, and the new neutrino limit from PAO [49], (differential top, integral limit below for an assumed $1/E^2$ neutrino spectrum).

4 Conclusions

An unavoidable signature of top-down models is the chemical composition of the resulting ultrahigh energy radiation, because hadronization results in large neutrino and photon fluxes. The former is an especially prominent signature for topological defects, while the high photon/nucleon ratio at generation is reduced by strong absorption of UHE photons. The resulting electromagnetic cascades transfer this energy to the diffuse $\gamma$-ray background and its future observation by Fermi/GLAST will tighten constraints for TD models.

Superheavy dark matter is at present most stringently constrained by the non-observation of photons, while from the isotropy of the CR flux observed by PAO at low energies ($\gtrsim 10^{18}$ eV) a competitive limit may be derived. A combination of both search methods seems to be the most powerful way to increase the sensitivity of UHECR experiments to lower fluxes from SHDM.

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