UHE neutrinos

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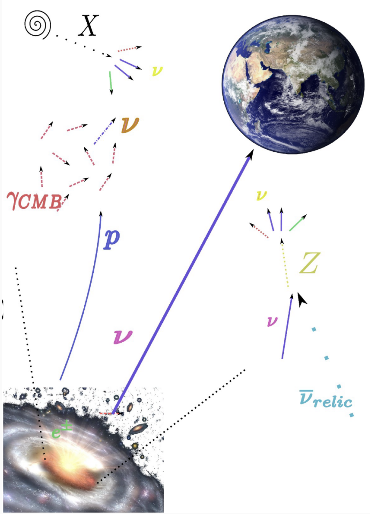
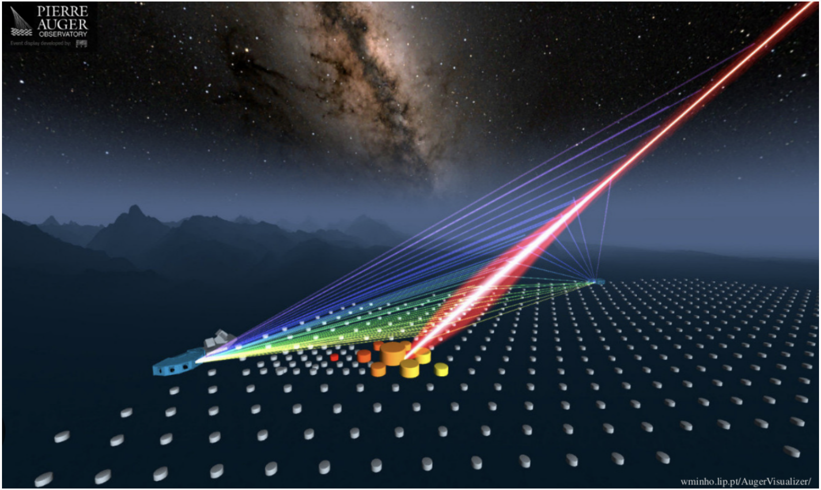
UHE neutrinos

- Cosmogenic:
  - $pp(\gamma) \to \pi^{\pm} X \to \ldots \nu_{\mu} \nu_{\mu} \nu_{e}$
  - $\implies E_{\nu} \simeq E_{p}/20$
  - UHE nuclei: photodisintegration $\to$ n
  - $\implies E_{\nu} \simeq E_{N}/3000$
- Scotogenic: $X \to xxx \to \ldots \nu\nu\nu \ldots$
- Cosmic string decay
- Debris from Z production (UHE ν + relic ν)

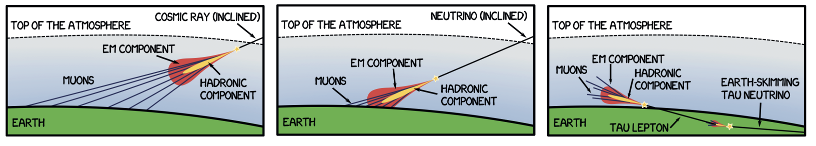


UHE cosmic rays in Auger

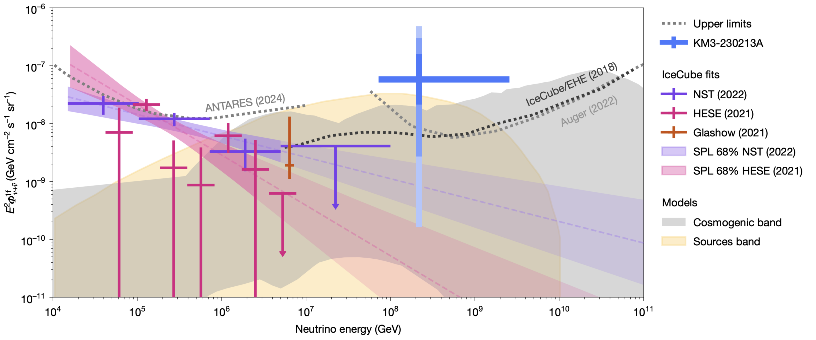


UHE neutrinos in Auger

- Extensive air showers from neutrinos, just like from CRs – yet, rate suppressed by cross-section
- Main challenge: distinguishing neutrino-induced air showers from the vast background initiated by CRs
- Searching for UHE neutrinos: looking for inclined showers with an electromagnetic component – or slightly upgoing showers coming from Earth-skimming τ-neutrinos: $\lambda_\nu \simeq L[3-4°]$, λ_τ ~O(10)km @1 EeV



The current picture

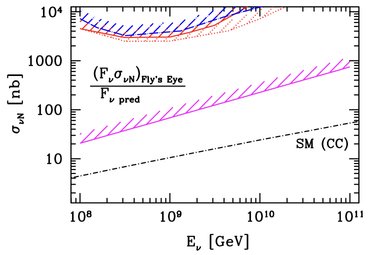


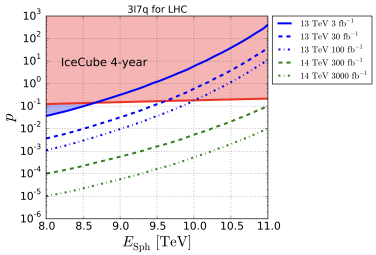
☛ expected in Auger: 30...

Neutrino-nucleon cross section

- Neutrino-nucleon cross section: "laboratory" of particle physics
  - SM predictions from NC/CC interactions
  - Non-perturbative SM enhancements through "sphalerons"?
  - BSM (microscopic black holes, leptoquarks, sterile ν, etc.)?
- 20 years of literature, but based on outdated cosmogenic fluxes of neutrinos a/o questionable/disputed physics models

Left: A. Ringwald & H. Tu, Phys.Lett.B 525 (2002) 135-142 – Right: J. Ellis et al., JHEP 05 (2016) 085





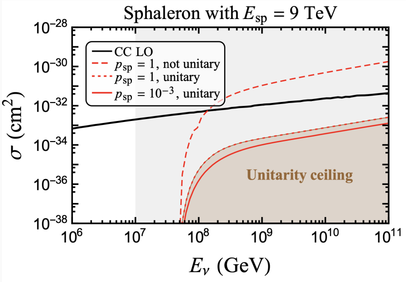
- Easier detection than in HE *pp* collisions

The case of neutrino-induced sphaleron transitions

- Striking prediction of SM: non-perturbative B+L violating processes

$$q\nu_e \to 8\overline{q} + \overline{\mu} + \overline{\nu}_\tau, \quad q\nu_\mu \to 8\overline{q} + \overline{e} + \overline{\tau}, \quad \ldots$$

- Mechanism to produce baryon asymmetry from transmutation of a primordial lepton asymmetry
- Not exponentially-suppressed at $T = 0$ for $\sqrt{s} > E_{\rm sph}$? s-wave restricted process? Highly disputed in literature...



- Cross section: $\sigma_{\nu N}(E_\nu) = \sum_q \int_0^1 {\rm d}x\, f_q(x,\mu)\sigma_{q\nu}(2xm_N E_\nu)$
- Partonic cross section for $\sqrt{s} > E_{\rm sph}$ parameterised as

$$\sigma_{q\nu}(s) = \frac{p}{m_W^2}$$

The case of upscattering $\nu \mathrm{n} \to N_{\mathrm{R}} \mathrm{x}$

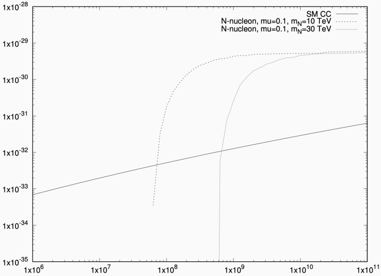
- Right-handed neutrinos N_{R}?
- "Dipole portal": tiny magnetic moment induced by loop effects:

$$\mathcal{L}_{\mu_\nu} = \mu_\nu \bar{\nu} \sigma_{\mu\nu} N F^{\mu\nu} + \mathrm{h.c.}$$

- New upscattering & downscattering channels governed by one free parameter μ_ν:

$$\nu e \longleftrightarrow N e, \; \nu \mathrm{n} \longleftrightarrow N \mathrm{n}$$

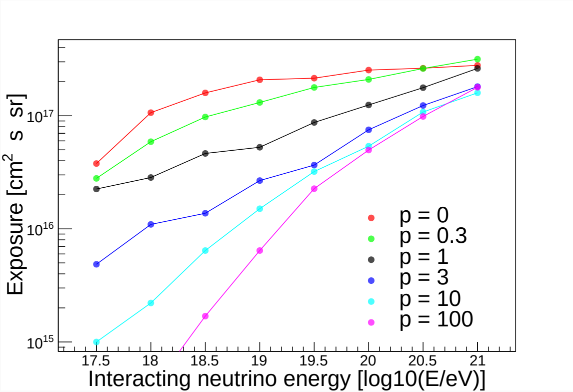
- From νMSM: Deca-TeV N_{R} unstable, decaying into τ



- Constraints from LHC up to 13 TeV
- Limited to30 TeV by kinematical thresholds

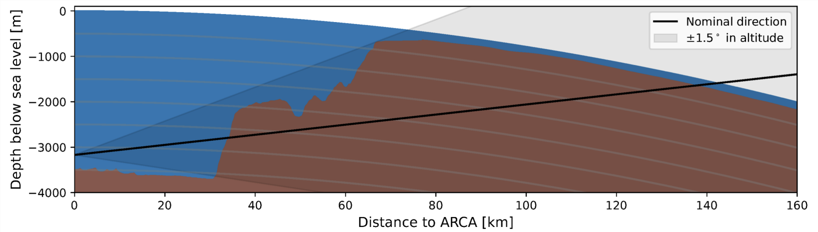
13-30 TeV window for M_N

Earth-skimming channel and enhanced cross-section



- ☛ UHE: Neutrino interaction forced by sphaleron transitions $\longrightarrow$ "universal" behaviour shaped by τ escaping range (a few kilometers)
- ☛ No sensitivity for $p \geq 0.5$
- ☛ Enhanced cross-section $\implies$ Earth-skimming channel switched off

The KM3-230213A event



- Standard interpretation: $\nu_\mu \mathrm{n} \longrightarrow \mu X$ close to the detector (in water)
- $\lambda_\nu \simeq 1300$ km (SM) $\longrightarrow \simeq 100$ km (BSM)
- $\mu \longrightarrow \tau$: $\lambda_\tau \simeq 50$ km @ 1 EeV, $E_\tau \simeq 10\ E_\mu$
- Highly speculative, "BSM^2"; yet solving puzzle Auger/KM3Net

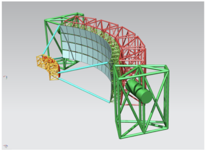
Neutrino telescope @Auger?

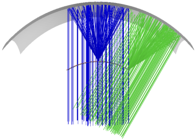
- ☛ Andes from 50-to-200 km away from one FD site
- ☛ Observing τ-induced showers emerging from Andes through Cherenkov light emission
- ☛ Infrastructure already existing
- ☛ Know-how
- ☛ Concurrent Trinity project, observing Earth-skimming events from the top of a low-altitude mountain

Simulations

- $5° \times 160°$ FOV
- $\theta_{\mathrm{pix}} = 0.3°$
- aperture area $A = 1\,\mathrm{m}^2$
- NSB from mountain: 0.1 NSB Auger
- 4 pixels for trigger

e.g.:

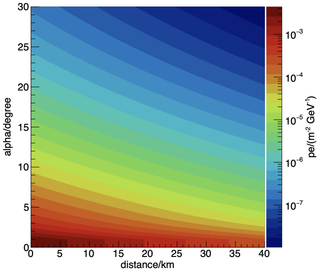




left: MACHETE design (Otte et al), right: ray-tracing (L. Scherne, BSc Thesis, KIT)

parametrization of n_{pe} from Cherenkov

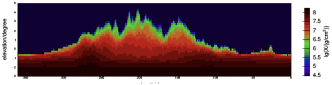
N. Otte PRD 2018

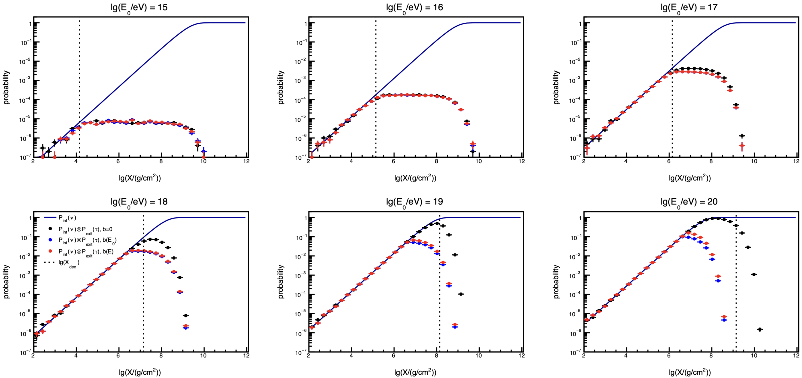


Results

Simulation of $\nu_\tau \to \tau \to$ shower

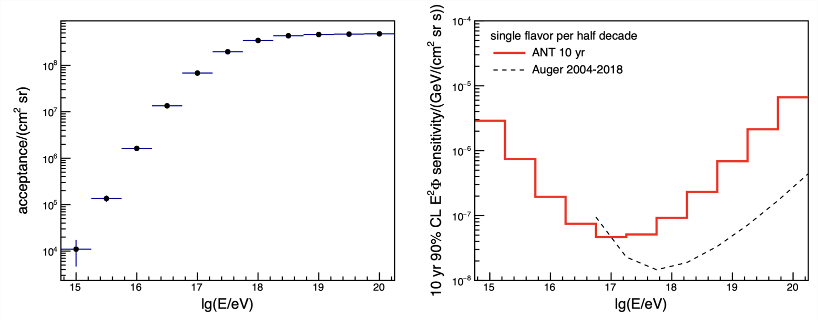
$(X_{\rm dec} = \gamma\, c\, \tau\, \rho)$





- ☛ NB: SM cross-section
- ☛ Ideal config. for BSM scenario

Acceptance and Sensitivity, 10 m^2 years



- ☛ NB: SM cross-section
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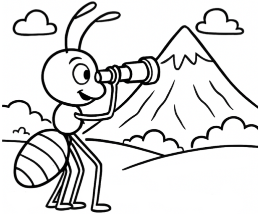
Conclusions & Outlook

ANT Auger Neutrino Telescope



- explore UHECR-related νs in Auger
- Cherenkov telescope behind Coihueco
- sensitivity around 10^{17} eV
- 10 m^2 years $\rightarrow E^2\Phi \sim 4 \times 10^{-8}\mathrm{GeV/cm^2\,sr\,s}$
- easily scalable to N m^2 years
- cost?
- actual NSB from Andes? (snow!) $\rightarrow$ measure on site!
- compare to “professional” τ sims
- check Cherenkov parametrization
- better define trigger and selection criteria
- reconstruction?
- Western EarthCare transits
- hybrid? (radio...)

BACK-UP

Neutrino-induced sphaleron transitions

- ☛ Striking prediction of SM: non-perturbative B+L violating processes
  - SU(2) gauge group: topologically distinct ground states separated by an energy barrier
  - Sphaleron: extremal saddle point on top of the barrier with half-integer topological winding number and energy $E_{\rm sph} \simeq 9$ TeV
  - Sphaleron transition: $\Delta B = \Delta L = 3\Delta n$

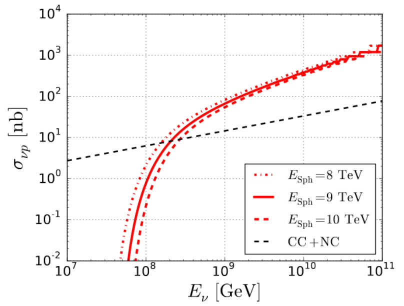
$$\Delta n = -1 : \; qq \rightarrow 7\overline{q} + 3\overline{\ell}$$

$$\Delta n = +1 : \; qq \rightarrow 11q + 3\ell$$

  - Mechanism to produce baryon asymmetry from transmutation of a primordial lepton asymmetry
- ☛ Large theoretical uncertainties on sphaleron production rate
- ☛ Recent estimate (S. Tye & S. Wong, Phys. Rev. D 92, 045005) way more favorable than previously for experimental prospects for $\sqrt{s} > E_{\rm sph}$
- ☛ Previous study: "Search for Sphalerons: IceCube vs. LHC", J. Ellis, K. Sakurai & M. Spannowsky, JHEP 05 (2016) 085

Enhancement of neutrino-nucleon cross section

- *pp* collisions: difficult to distinguish from SM cross section in EAS (see however Physics Letters B 761 (2016) 213 based on X_{max})
- νN collisions more favorable



- Cross section: $\sigma_{\nu N}(E_\nu) = \sum_q \int_0^1 \mathrm{d}x\, f_q(x,\mu)\sigma_{q\nu}(2xm_N E_\nu)$
- Partonic cross section for $\sqrt{s} > E_{\mathrm{sph}}$ parameterised as $\sigma_{q\nu}(s) = \frac{p}{m_W^2}$
- NB: Unitarity bound not considered

- Uncertainty in sphaleron production rate $\rightarrow$ Cross-section normalization p left free
- Constraints on p from non-observation of UHE neutrinos

Sphaleron interaction $\Delta n = -1$

- Instanton/Sphaleron transitions induced by $(\overline{qqq})_1(\overline{qqq})_2(\overline{qqq})_3(\bar{\ell}_1\bar{\ell}_2\bar{\ell}_3)$ gauge-invariant operator (index=generation)
- Sphaleron-induced neutrino-quark collision:

$$q\nu \rightarrow 8\bar{q} + 2\bar{\ell}$$

- Lepton production – Each generation represented:

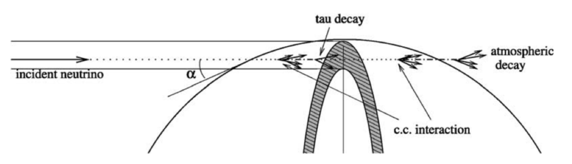
$$q\nu_e \rightarrow 8\bar{q} + \bar{\mu} + \bar{\nu}_\tau$$

$$q\nu_\mu \rightarrow 8\bar{q} + \bar{e} + \bar{\tau}$$

$$\ldots$$

- Secondary production of leptons (from t and W decays) neglected
- Energy distribution: uniform

Earth-skimming channel I



☛ Monte Carlo to estimate the expected number of escaping τ leptons:

- Simulated neutrinos with flavour randomly selected propagating though the Earth;
- Emerging angle randomly selected within [0,5] degrees;
- Computation of mean free path to select whether a propagated particle interacts or escapes;
- Neutrinos can interact by CC, NC or spheralon production; production of quark and two random leptons;
- Quarks, electrons and muons are not propagated, while neutrinos and tau are saved in the stack;
- Tau particle can decay and lose energy during propagation;
- Simulations end when all the particles escape.

Earth-skimming channel

Notes on how to calculate (approximately) the exposure from the MC simulations for a given p:

$$\mathcal{E}(E_\nu) = \frac{N_{\text{det}}}{N_{\text{sim}}} \pi A \Delta T \sin^2 \alpha_m$$

- N_{sim} – # of simulated neutrinos with energy E_ν
- A – surface, 3000 km^2
- ΔT – time period, about 15 years
- α_m – 5 degrees
- N_{det} – # of detected tau-induced showers
- MC: $N_{\text{sim}} \to N_{\text{acc}}$: # of emerging tau leptons with energy E_τ and horizontal angle α
- Q: how to estimate N_{det} from N_{acc}?

Earth-skimming channel

$$N_{\text{det}} = \sum_{i=1}^{N_{\text{acc}}} \frac{1}{N_{\text{dec}}} \sum_{j=1}^{N_{\text{dec}}} \epsilon(E_\tau^i, h^j)$$

- h – "shower center altitude", defined 10 km after the decay point
- $\epsilon(E_\tau^j, h^j)$ – detection efficiency: 1 if $h \leq 1000 + 500 \log_{10}(E_\tau)$ (0 if $h > 1000 + 500 \log_{10}(E_\tau)$), with h in meters and E_τ in EeV
- For each emerging tau lepton, simulate N_{dec} decay points, and extend the decay point 10 km further to get h^j and hence $\epsilon(E_\tau^j, h^j)$
- Repeat everything for each E_ν and get as previously the event rate

$$\mu(p) = \int \mathrm{d}E_\nu\, \mathcal{E}(E_\nu; p) \Phi(E_\nu)$$

- Repeat everything for each p and plot $\mu(p)$ vs p