7th International Symposium on Ultra High Energy Cosmic Rays (UHECR)

# Various constraints on BSM physics from extensive air showers and from UHE gamma-ray and neutrino searches

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# Searches for Lorentz Invariance Violation

# Lorentz Invariance Violation

*Lorentz invariance has always proved resilient to decades of tests remarkably accurate*

- LIV: Smoking gun of various BSM frameworks (quantum gravity, string theory, and some alternatives to general relativity)
- Large number of ways to realise LIV...
- "Standard Model Extension (SME)" framework
    - Lorentz- and CPT-violating terms *not* violating gauge symmetries
    - Emblematic **[Coleman & Glashow PRD 59 (1999) 116008]** implementation:
        - All renormalisable, rotationally and translationally invariant terms in a preferred frame
        - CPT-even terms dominant at high energy, defining energy-momentum eigenstates different from low-energy mass eigenstates
        - ☛ "Velocity-mixing" effects turning on gradually with $E$, yielding to different maximum attainable velocities

# Effects of changes in dispersion relation

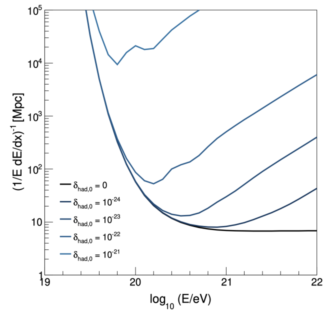
- Beyond Coleman & Glashow, dispersion relations modified at high $E$ by non-renormalizable effects at the Planck scale $M_{\mathrm{Pl}}$:

$$E_i^2 - p_i^2 = m_i^2 + \sum \delta_{i,n} E_i^{2+n}, \quad \delta_{i,n} = \frac{\eta_{i,n}}{M_{\mathrm{Pl}}^n}$$

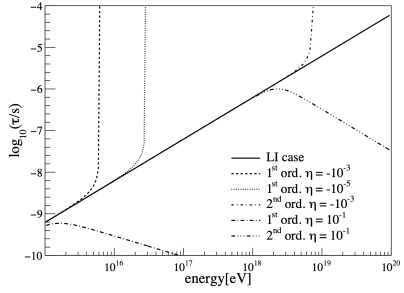
**Cf. [Aloisio et al., PRD 62 (2000) 053010]**

- Modification of reaction thresholds for non-zero $\delta_{i,n}$

- Pion photoproduction

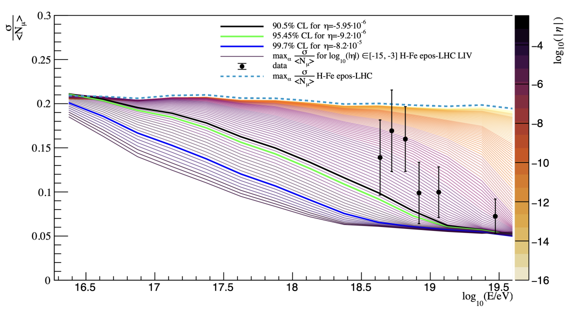



- Pion lifetime



# Constraints from $N_\mu$ data in EAS

- For $\eta < 0$, $\pi^0$ decay suppressed above a critical energy
- Change in shower development: $\pi^0$ interact instead of decaying
- Decrease of e.m. component
- Increase of muon number




- $\eta > -5.95 \times 10^{-6}$ (90% C.L.)

**Cf. [Pierre Auger Collab., ICRC2021 and in preparation]**

# Generically breaking of CPT

- Ex: gauge-invariant CPT perturbation of QED

$$\mathcal{L} = \mathcal{L}_{\mathrm{QED}} - \frac{1}{4}(k_F)_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

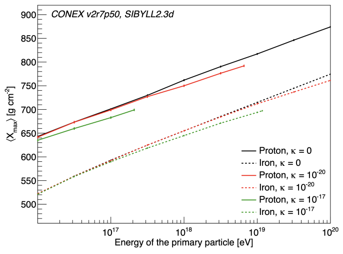
with $(k_F)_{\mu\nu\rho\sigma} \propto \kappa$ relating photon phase velocity and maximal fermion velocity through

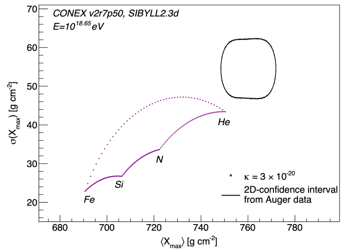
$$v_\gamma = \left(\frac{1-\kappa}{1+\kappa}\right)^{1/2} v_{\mathrm{f,max}}$$

  - $\kappa < 0$:
    - Photon decay for $E \geq 2m_e \left(\frac{1-\kappa}{-2\kappa}\right)^{1/2}$
    - $\pi^0$ stability for $E \geq m_{\pi^0} \left(\frac{1-\kappa}{-2\kappa}\right)^{1/2}$
  - $\kappa > 0$: vacuum Cherenkov radiation above a critical energy

# Constraints from $X_{\max}$ data

- Ex: vacuum radiation effects $\kappa > 0$ **Cf. [Duenkel, Niechciol & Risse PRD 107 (2023) 083004]**
- Vacuum radiation of $e^+/e^-$: faster descent in energy of e.m. sub-showers
- Mean $X_{\max}$ vs $E$ significantly changed for large enough $\kappa$

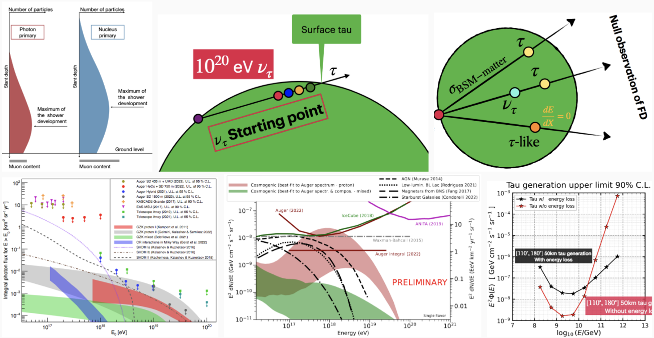



- Limits obtained from constraints requiring couples of $(X_{\max}, \sigma(X_{\max}))$ from any combination of primaries to fall within the observed range
- $\kappa < 3 \times 10^{-20}$
- NB: $\kappa < -6 \times 10^{-21}$ **Cf. [Duenkel, Niechciol & Risse PRD 104 (2021) 015010]**

# UHE gamma rays and neutrinos

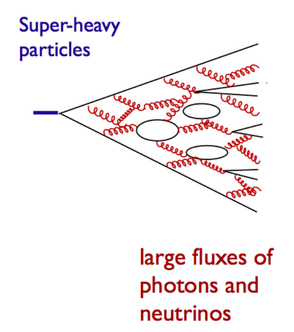
# UHE multi-messengers




- UHE gamma rays [Auger, TA]: Horizon limited to a few Mpc
- Neutrinos [IceCube, KM3NET, Auger, Trinity, GRAND, POEMMA, ...]: Cosmological horizon
- Leptons $\tau$ [Auger, ANITA, ...]: BSM tests of neutrino production

# Production in decay byproducts

- Decay of a particle with mass $M_X \gg m_W$




- Soft or collinear (real) radiative corrections enhanced by large logarithmic factors at high scale
- Cascades in the QCD sector described by fragmentation functions evolved to high scale **[Sarkar & Toldra 2002, Aloisio+ 2004]**
- Fragmentation in the EW sector as well **[Berezinsky, Kachelriess and Ostapchenko, PRL 89, 171802 (2002)]**

- DM example: Expected number of "prompt" $i$ $(\gamma/\nu/p)$ from fragmentation of decay byproducts:

$$n_i^{\mathrm{prompt}}(E) = \frac{1}{4\pi M_X \tau_X} \int_{>E} dE' \frac{dN_i}{dE'} \int d\mathbf{n}\, \omega_i(E',\mathbf{n}) \int_0^\infty ds\, \rho_{\mathrm{DM}}(\mathbf{x}_\odot + s\mathbf{n})$$

# Secondary production of gamma rays

- Prompt electrons interact/radiate
  - ICS off CMB (dominant at these energies): negligible
  - Synchrotron emission
- Number of "secondary" photons from synchrotron emission by electron decay byproducts:

$$n_\gamma^{\rm sec}(E) = \frac{1}{4\pi} \int_{>E} \frac{dE'}{E'} \int d\mathbf{n}\, \omega_\gamma(E, \mathbf{n}) \int_0^\infty ds\, j(E', \mathbf{x}_\odot + s\mathbf{n})$$

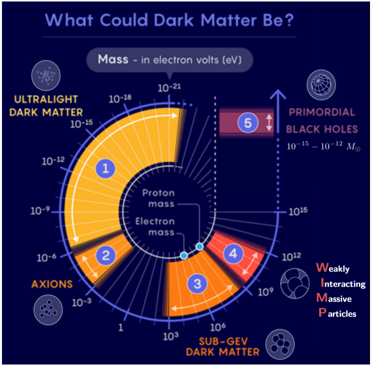
  - Emission rate:

$$j(E, \mathbf{x}) = \int_{m_{\rm e}}^{M_X/2} dE_{\rm e}\, \mathcal{P}(E, E_{\rm e}, \mathbf{x}) n_{\rm e}(E_{\rm e}, \mathbf{x})$$

  - $\mathcal{P}$: differential synchrotron power in GMF
- $n_\gamma^{\rm sec}(E) > n_\gamma^{\rm prompt}(E)$ for $M_X \geq 10^{12-13}$ GeV **[Munbodh and Profumo, arXiv:2405.00798, OD, arXiv:2408.17111]**

# Superheavy dark matter

# Superheavy dark matter?




- ☛ Superheavy particles?
  - Inflationary sector: $M_\phi \sim [1-3] \times 10^{13}$ GeV
  - Sterile neutrinos
    - New degrees of freedom $N_R$
    - BSM scale at $\sim 10^{13}$ GeV in "vanilla" seesaw

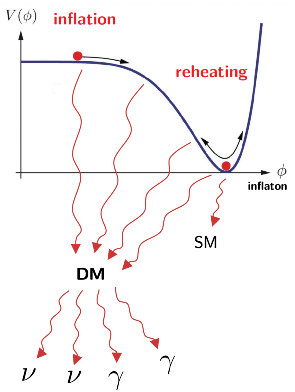
- Instability energy scale of SM: $\Lambda \sim 10^{[10-12]}$ GeV **[e.g. Degrassi+ 2012]**

☛ Hidden/Dark sector at high scale? (ie. superheavy particles interacting feebly with SM *not* through SM gauge interactions)

- Additional portal? e.g. axion (pseudo-scalar), Higgs (scalar), sterile neutrino (spin 1/2), vector (spin 1), etc.
- Gravitational SM/DS interactions

# Non-thermal production of SHDM particles

- Minimality: No coupling between SM and DM sectors but gravitational



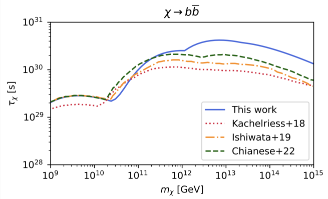

☛ DM production by "freeze-in" mechanism through s-channel SM+SM→DM+DM or $\phi + \phi$ →DM+DM **Cf. [Garny et al. PRL 116, 101302], [Mambrini & Olive PRD 103, 115009]**:

☛ SHDM production during inflation and Reheating between $t = H_{\rm inf}^{-1}$ and $t = \Gamma_{\phi}^{-1}$ at $T_{\rm rh}$: $\frac{dn_X(t)}{dt} + 3H(t)n_X(t) \simeq \sum_i \overline{n}_i^2 \Gamma_i$

- Viable regions in the $(H_{\rm inf}, M_X)$ plane to match the DM relic density for various Reheating efficiency ($\epsilon \simeq 4T_{\rm rh}(M_{\rm Pl}H_{\rm inf})^{-1/2}$ defined between 0 and 1, characterizing the duration of the Reheating period)
- Even $M_X \sim M_{\rm GUT}$ still viable for $H_{\rm inf} \sim 10^{13}$ GeV

# Lifetime constraints

[e.g. Das et al. Phys.Rev.D 107 (2023) 103013]

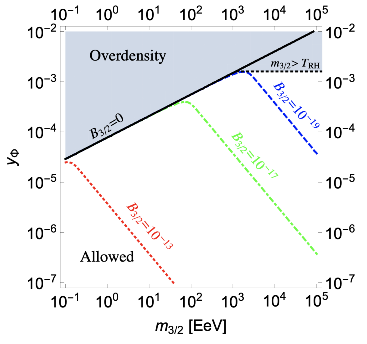



*How to get such long $\tau_X$ for superheavy $M_X$?*

- Non-perturbative effects through "instantons" responsible for meta-stability of particles otherwise protected from decay by a quantum number **[Kuzmin and Rubakov, Phys. Atom. Nucl. 61, 1028 (1998), Pierre Auger Collab., Phys. Rev. Lett. 130 (2023) 061001]**
- Sterile neutrinos themselves DM and feebly coupled **[Uehara, JHEP 12, 034, Feldstein et al., Phys. Rev. D 88, 015004 (2013), Dev et al. JCAP 08, 034], Barman et al. JHEP 12, 072]**
- Particles coupled with sterile neutrinos alone **[Dudas et al. Phys. Rev. D 101, 115029 (2020), Pierre Auger Collab., Phys. Rev. D 109, L081101 (2024)]**

# High scale supergravity – The case of the EeV gravitino

- Supersymmetry broken at high scale $\tilde{m}^2$ above the inflationary scale ($M_\phi \sim 3 \times 10^{13}$ GeV from density-perturbation amplitude in CMB)?
- SUSY particles never being produced by either thermal processes during reheating or by the decay of the inflaton



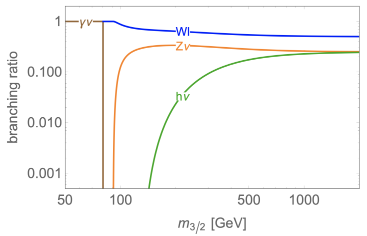

☛ Gravitino exception:
$M_{3/2} > M_\phi^2/\sqrt{3}M_{\rm Pl} \sim 10^8$ GeV

- Production from thermal bath (gluons): $T_{\rm rh} \sim [10^{10}–10^{12}]$ GeV
- Linear increase of $y_\phi$ with $M_{3/2}$ to counterbalance $1/\tilde{m}^2$ couplings
- Alternative: $B_{3/2} \neq 0$:
$$y_\phi < \left(\frac{B_{3/2}}{10^{-18}}\right)^{-1} \left(\frac{M_{3/2}}{10^8\ \text{GeV}}\right)^{-1}$$

Cf. [Dudas et al. PRL 119 (2017) 051801]

# $R$-parity violation operators

- $R$-parity (stability of the proton) $\implies$ LSP stable DM candidate
- Limits on RPV couplings: baryon- and lepton-number violating interactions out-of-equilibrium in the early universe to preserve the baryon asymmetry
- High-scale SUSY: sparticles never in the thermal bath to mediate interactions washing out the baryon asymmetry




- Bilinear RPV operator:

$$W = W_{\text{MSSM}} + \mu' L H_u$$

- Lepton number not conserved
- Baryon number conserved

**Cf. [Dudas et al. PRD 98 (2018) 015030], [Allahverdi et al. JHEP 02 (2024) 192]**

- $\mu' < 10^{-5} \left( \frac{M_{3/2}}{10^8 \text{ GeV}} \right)^{-2}$ GeV (Weak-scale SUSY: $\mu' < 20$ keV from the preservation of the baryon asymmetry)

# Cosmic-strings

# UHECRs from cosmic strings

- Cosmic strings produced during GUT scale phase transitions
- Regions of space-time in the symmetry unbroken phase due to boundary conditions that topologically restrict their decay

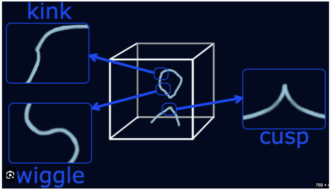
- Under certain circumstances, energy stored in the unbroken vacuum phase liberated in the form of the GUT scale quanta of the gauge and scalar fields

☛ Source of UHECRs/UHE$\nu$s/UHE$\gamma$s

- Transition example: $SU(2)_L \times U(1)_Y \times U(1)_{B-L} \rightarrow SU(2)_L \times U(1)_Y$:
  - 3 RHNs $N_{iR}$ – sourcing “vanilla” seesaw
  - Gauge field $Z'$
  - Scalar field $\Phi$ with non-zero vev
  - CS$\rightarrow N_{iR}/Z'/\Phi \rightarrow$ UHECRs/UHE$\nu$s/UHE$\gamma$s

# UHE$\nu$s from moduli fields

- Moduli: scalar fields with gravitational-strength couplings to matter
- Predicted in supersymmetric particle theories, including string theory
- Decay into gravitinos




- At late times, sharp bursts of high-energy moduli emitted from cusps
- Large Lorentz factors
- Weak-scale quanta boosted to UHE

- UHE$\nu$ flux:

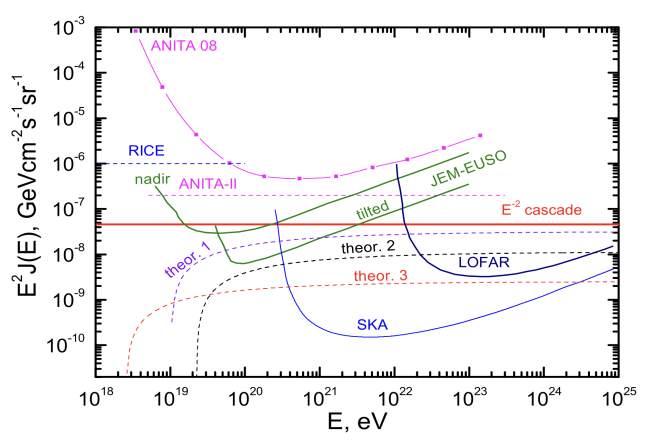
$$J_\nu(E,z) = \frac{1}{(4\pi)^2} \int \frac{dV(z)}{(1+z)r^2(z)} d\dot{N}_b \, dN_X^b(k) \, \zeta_\nu(E,z,k) \propto (G\mu)^3$$

  - $d\dot{N}_b$: Rate of bursts
  - $dN_X^b(k)$: Number of moduli emitted per burst
  - $\zeta_\nu(E,z,k)$: Spectrum of $\nu$ from modulus with momentum $k$

**Cf. [Berezinsky, Sabancilar & Vilenkin, PRD 84, 085006]**

# UHEν signatures

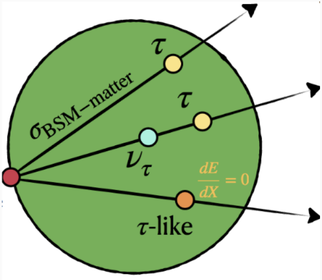
Cf. [Berezinsky, Sabancilar & Vilenkin, PRD 84, 085006]

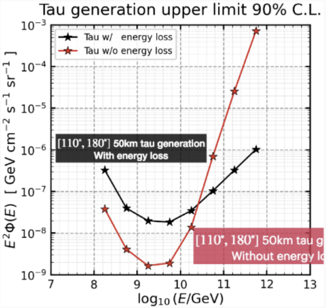



- Clear signatures: $E^{-2}$ spectrum above $\simeq 10^{10}$ GeV
- Probing $G\mu$ as low as $10^{-20}$ (currently $G\mu \lesssim 10^{-15}$ from GW)

# BSM with upgoing showers

# Upgoing showers: constraints



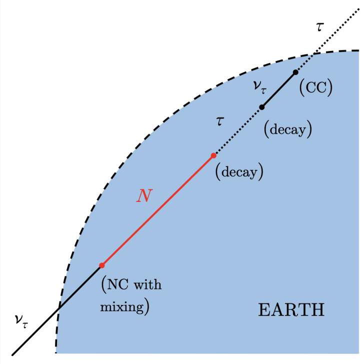



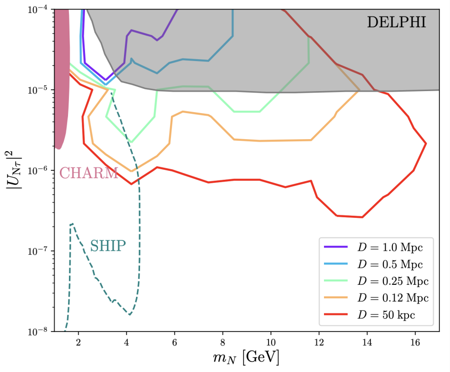

- "Anomalous ANITA events"
- Stringent limits from Auger
- Strong constraints on scenarios with input fluxes of BSM particles
- Ex: SHDM$\rightarrow \overline{N}_R N_R$ with seesaw-like mixing regulated by $\theta_{\text{mix}}$
  ☛ Need of an input flux of neutrinos...

# Another BOAT GRB221009A to probe GeV sterile neutrinos

**Cf. [Heighton et al., PRD 108, 055009]**

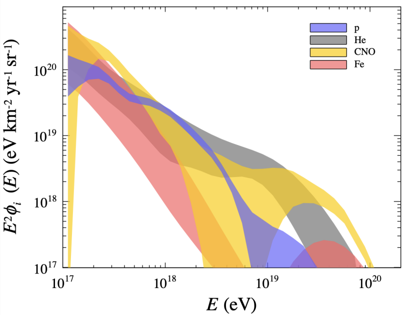
- Minimal extension of SM with one $N_R$ d.o.f.: $\mathcal{L} = \mathcal{L}_{SM} + \frac{m_N}{2}\overline{N}_R^c N_R - \frac{g}{\sqrt{2}} \sin\theta_{mix} W_\mu^+ \overline{N}_R^c \gamma^\mu P_L \tau - \frac{g}{2\cos\theta_{mix}} \sin\theta_{mix} Z_\mu \overline{N}_R^c \gamma^\mu P_L \nu_\tau + \text{h.c.}$
- Decay length of sterile neutrinos known from $\nu$MSM: comparable to Earth radius for $M_N \sim$ GeV and $\theta_{mix} \in [10^{-1.5}, 10^{-3}]$

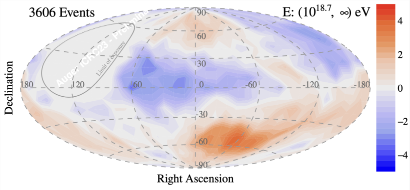


# Conclusions

# New questions on UHECRs




- ☛ Which model ?
  - Minimal model ? p→He→CNO→Si/Fe
  - Non-minimal model: sub-dominant component of protons at UHE?
- ☛ Sources?
  - Resolve anisotropies as a function of mass composition
- ☛ Photons/Neutrinos ?
  - Minimal vs non-minimal model
  - BSM

# Conclusions/Perspectives

- UHECRs: Ultimate laboratory of high-energy physics
- Future of UHECRs?

☛ Confirmation of the minimal model

- High-energy astrophysics : origin, dynamics, energetics of relativistic jets, compact objets ; astrophysics of magnetised plasmas in motion, strong gravity environments

☛ Non-minimal model

- Several (two at least) populations of sources
- BSM?

Une fourmi parlant français
parlant latin et javanais
ça n'existe pas, ça n'existe pas.
eh ! et pourquoi pas !

Robert Desnos

- Dark matter
- Phase Transitions and cosmic strings