Fundamental Physics at Extreme High Energies

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Outline:

- Introduction
- Testing (new?) strong interactions
- Lorentz invariance violation
- Topological defects & superheavy dark matter
- Summary

Determining nuclear composition: $X_{\max}$ and RMS($X_{\max}$)

- Bethe-Heitler model: $N_{\max} \propto E_0$ and $X_{\max} \propto \ln(E_0)$

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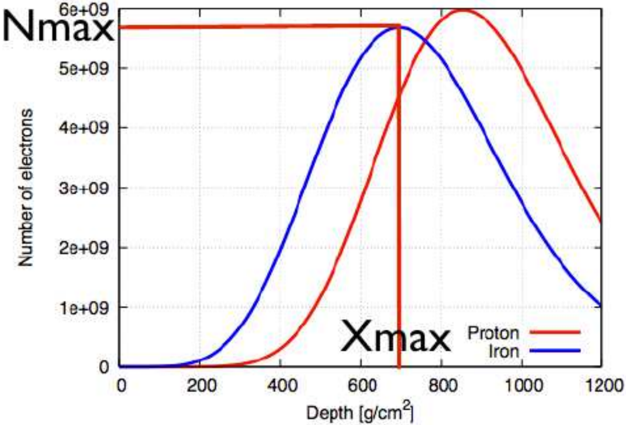

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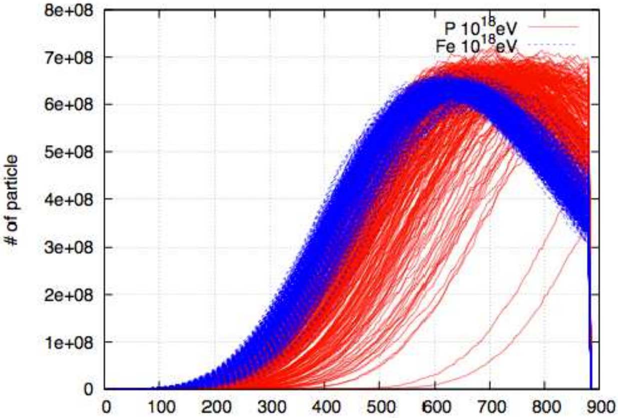

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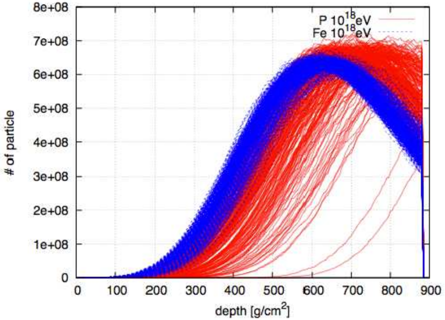
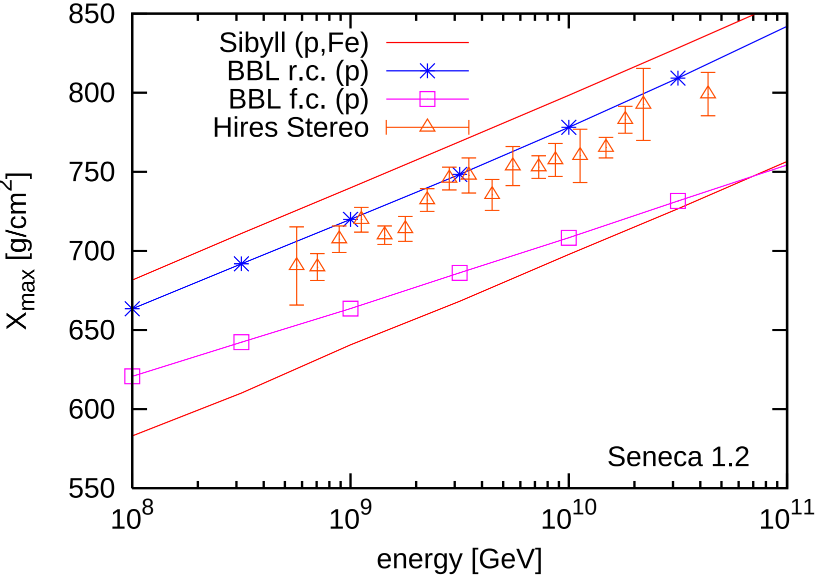


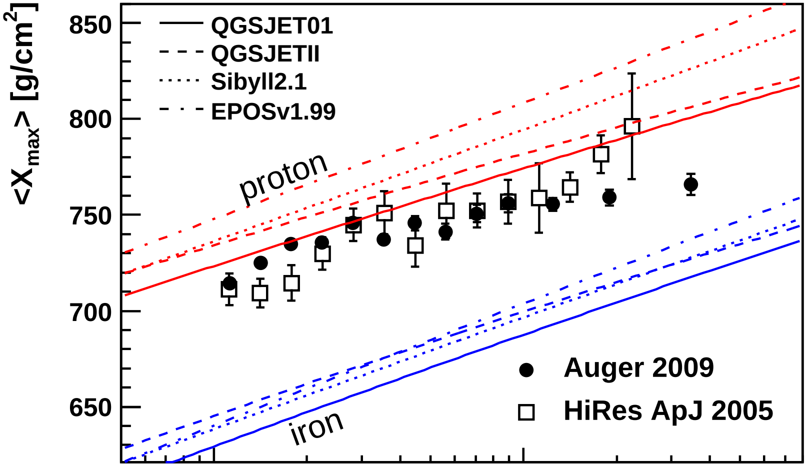
- RMS$(X_{\max})$ has smaller theoretical error than $X_{\max}$

Restricting QCD: BFKL, Color Glass Condensates, . . .

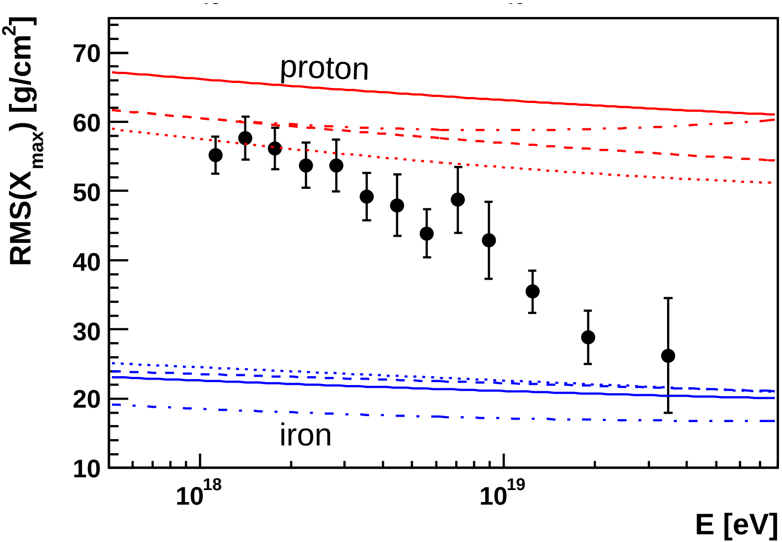


[Drescher, Dumitru, Strikman '04]

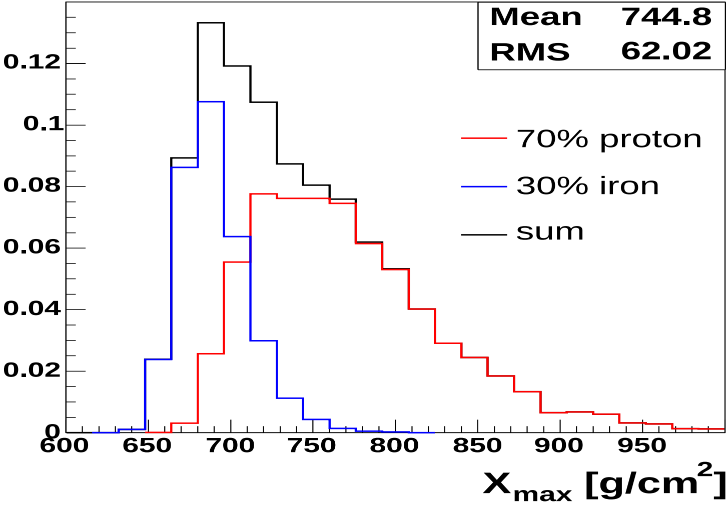
Nuclear composition via $X_{\max}$:



Nuclear composition via RMS($X_{\max}$) from Auger:

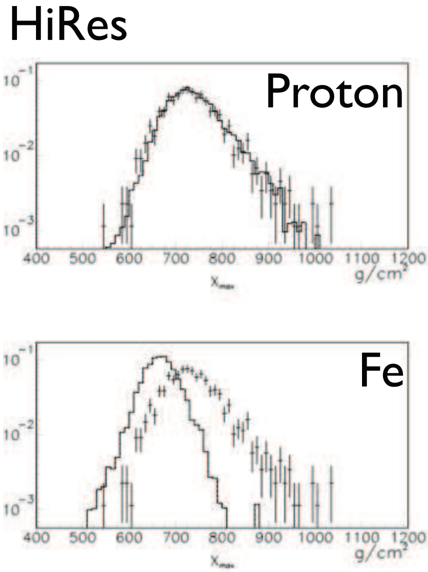


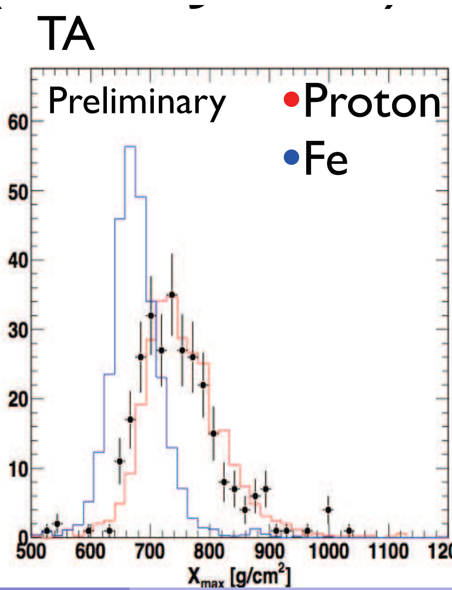
Mixed composition:



$$\sigma^2 = \sum_i f_i \sigma_i^2 + \sum_{i<j} f_i f_j (X_{\max,i} - X_{\max,j})^2$$

Nuclear composition from HiRes/TA:





What goes wrong?

- internal discrepancy in PAO:
  - AGN correlations favor protons
  - RMS($X_{\max}$) favors heavy
  - energy spectrum, $X_{\max}$ and RMS($X_{\max}$) difficult to fit
- experimental discrepancy: HiRes/TA $\Leftrightarrow$ Auger
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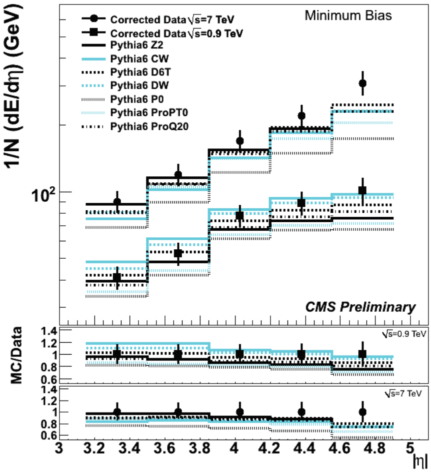
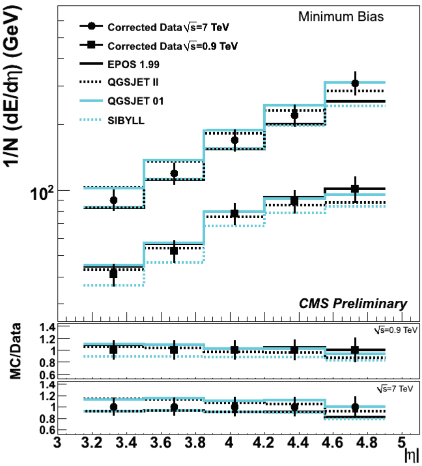
Comparison of MCs to LHC data: Energy flow

PYTHIA as typical HEP model



Cosmic ray interaction models



What can/should be changed?

Knob	S_{mu}	$<X_{max}>$	RMS_{Xmax}
Compositionheavier	↑	↓ (shallower)	↓ (narrower)
Mixed composition	↑ (mean of mix)	↓ (mean of mix)	↑ (broader -- lots)
Cross section ↑	---	↓ (shallower)	↓ (narrower)
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only option: reduce π^0

"restoration of chiral symmetry?" *[Farrar '12]*

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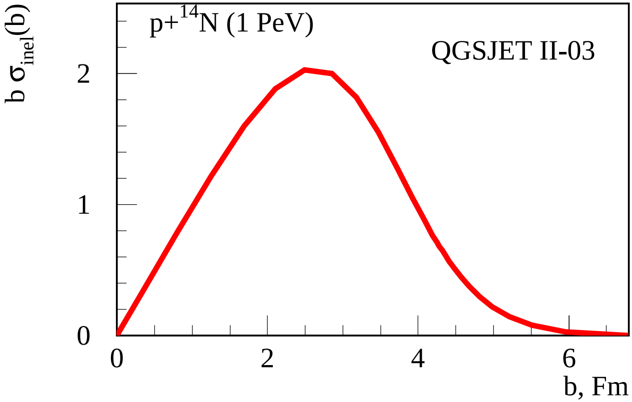

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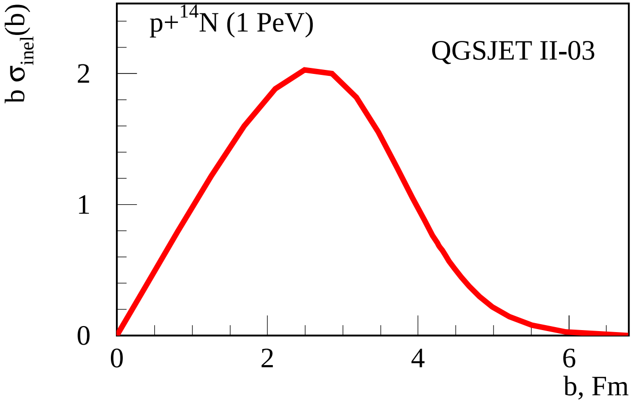

- Exceptions: large extra dimensions, classicalisation, ...

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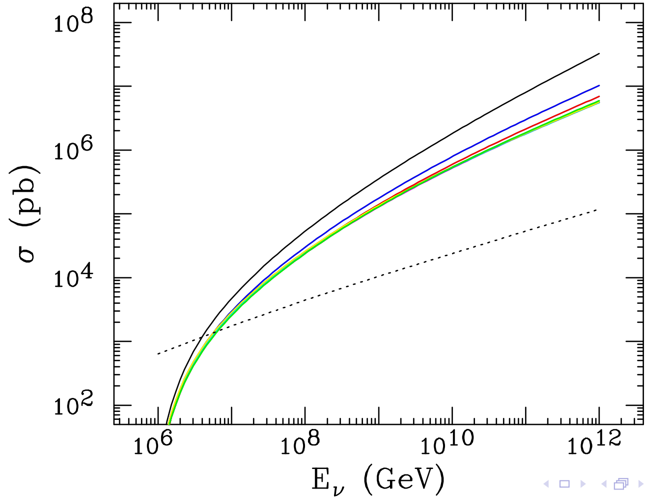

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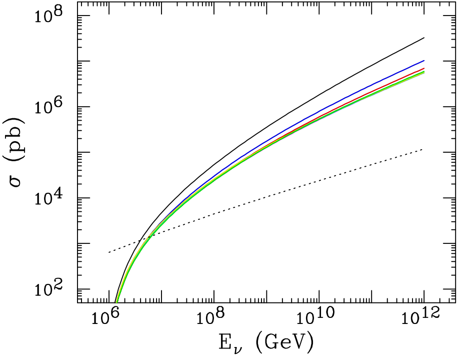

- no deviations from SM at LHC

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$\Rightarrow$ generically preferred reference frame
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Lorentz invariance violation:

LIV becomes important, when

$$\frac{m^2}{p^2} \sim \frac{p^{n-2}}{M_{\rm Pl}^{n-2}}$$

or

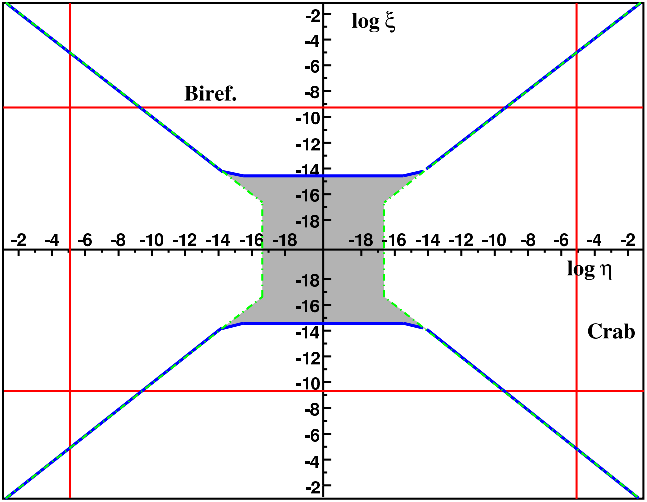
$$p_{\rm cr} \sim \sqrt[n]{m^2 M_{\rm Pl}^{n-2}}$$

n	$p_{\rm cr}$ for ν	$p_{\rm cr}$ for e^-	$p_{\rm cr}$ for p
2	$p \sim m_\nu \sim 1$ eV	$p \sim m_e$	$p \sim m_p$
3	$\sim$ GeV	~ 10 TeV	~ 1 PeV
4	~ 100 TeV	~ 100 PeV	~ 3 EeV

Bounds on LIV parameters from UHECRs:

- threshold for GZK may be changed
- GZK photons: upper threshold $E_{\rm max}$ for $\gamma\gamma \to e^+e^-$ introduced
- if $E_{\rm max} \ll 10^{20}$ eV, photon fraction too large
- if some UHE photons observed, photon decay $\gamma \to e^+e^-$ can be limited

Bounds on dim=5 LIV parameters: $\xi \leftrightarrow e$ and $\eta \leftrightarrow \gamma$



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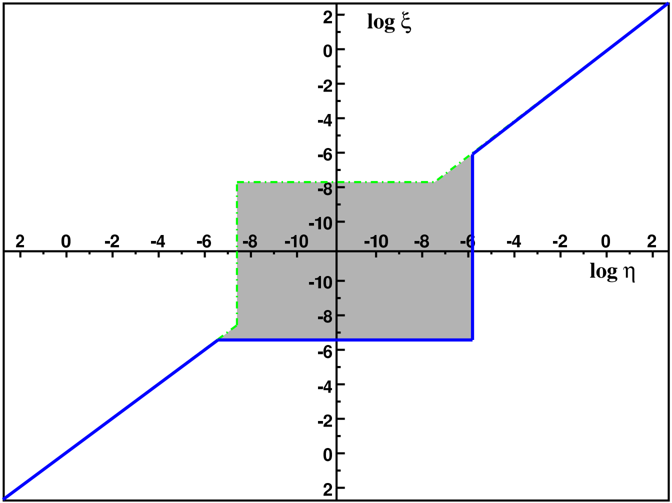

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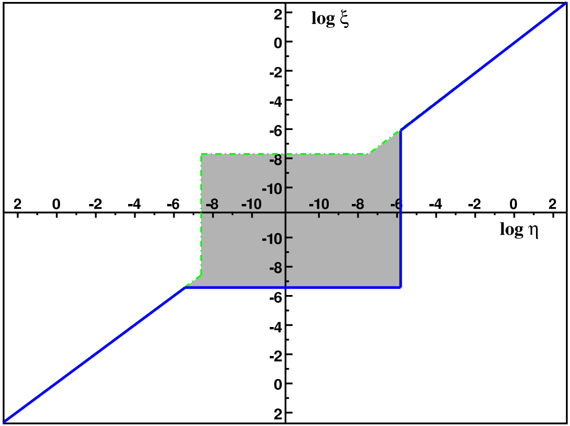

If LIV exists, then probably not of EFT type

Bottom-up versus top-down models

Bottom-up models

- acceleration in electromagnetic fields

$\Rightarrow$ charged particles: protons, nuclei, electrons

- photons and neutrinos as secondaries

Top-down models

- relics from early universe $\leftrightarrow$ DM
  - non-thermal or thermal
  - point particle or non-perturbative solutions
  - stable or decaying
- fragmentation products: mainly photons, neutrinos

Top-Down Models

UHECR primaries are produced by decays of supermassive particle X with $M_X \gtrsim 10^{12}$ GeV.

- topological defects: monopoles, strings, ...
- superheavy metastable particles

Advantages:

- no acceleration problem
- no visible sources
- if $X \in$ CDM, no GZK-cutoff
- theoretically motivated; testable predictions

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- Small fluctuations of field Φ obey

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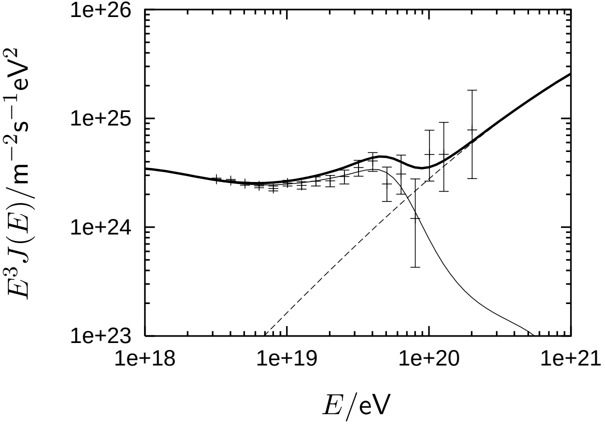
- In inflationary cosmology

$$\Omega_X h^2 \sim \left(\frac{M_X}{10^{12}\text{GeV}}\right)^2 \frac{T_{RH}}{10^9\text{GeV}}$$

dependent only on cosmology, for $M_X \lesssim H_I$

Signatures of SHDM decays

- flat spectra $dE/E^{1.9}$ up to $m_X/2$



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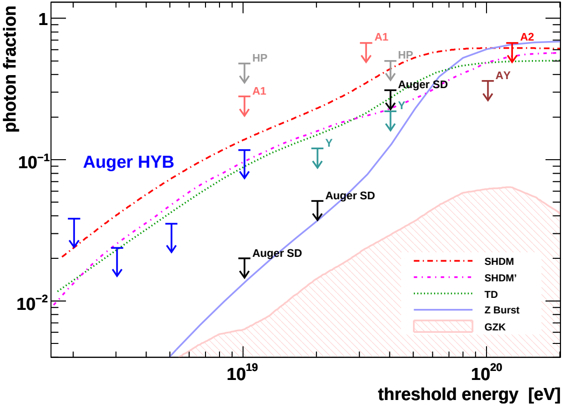

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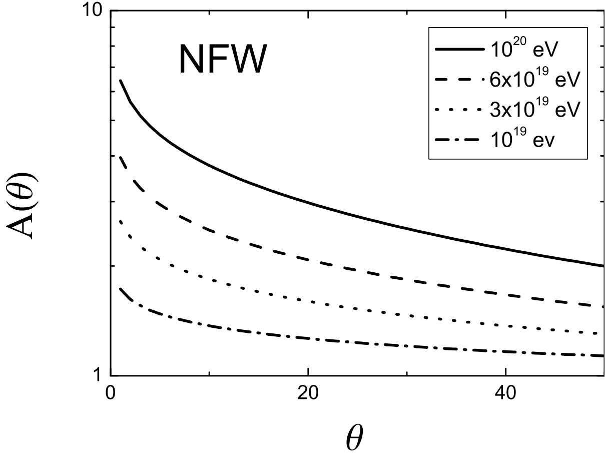
- galactic anisotropy:



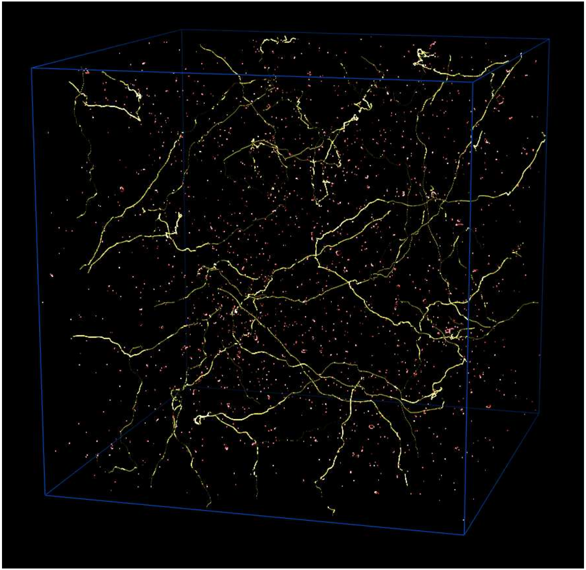
Topological defect models

+ "generic" in SUSY-GUTs
+ produced during reheating

- typical density: one per horizon/correlation length
- main energy loss low-energy radiation?

Topological defect models

[*Allen, Shellard '06*]



- box $2ct$
- matter epoch
- scaling regime

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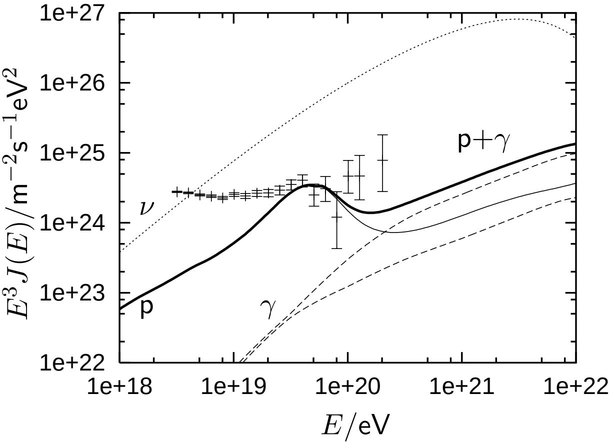
- hybrid defects: cosmic necklaces
  - $G \to H \otimes U(1) \to H \otimes Z_2$
  - monopoles $M \sim \eta_m/e$ connected by strings $\mu_s \sim \eta_s^2$
  - parameter $r = M/(\mu d)$:
  - $r \ll 1$ normal string dynamics
  - $r \gg 1$ non-rel. string network

Status of topological defect models – necklaces:



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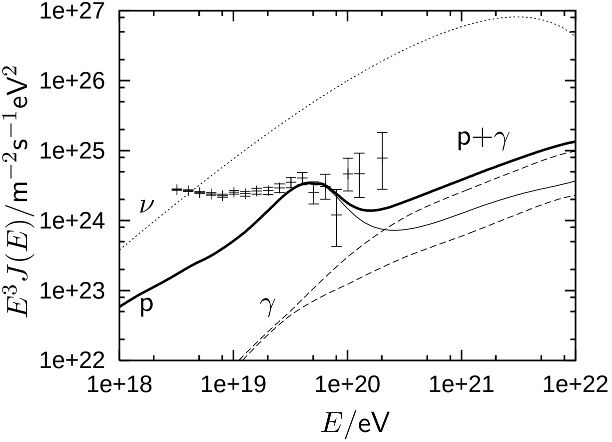

- large neutrino fluxes possible
- UHE photon fraction reduced

Summary

- composition of UHECR is crucial both for astrophysics and strong interactions
- exremely strong limits on ETF-like LIV
- LHC limits on large extra dimensions
- no positive evidence for superheavy dark matter from its three key signatures:
  - spectral shape
  - photons
  - galactic anisotropy
- SHDM remains an interesting DM candidate

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⇒ both should be searched for as subdominant sources of UHECRs; potential for UHE neutrinos

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