Exotic physics from cosmic rays

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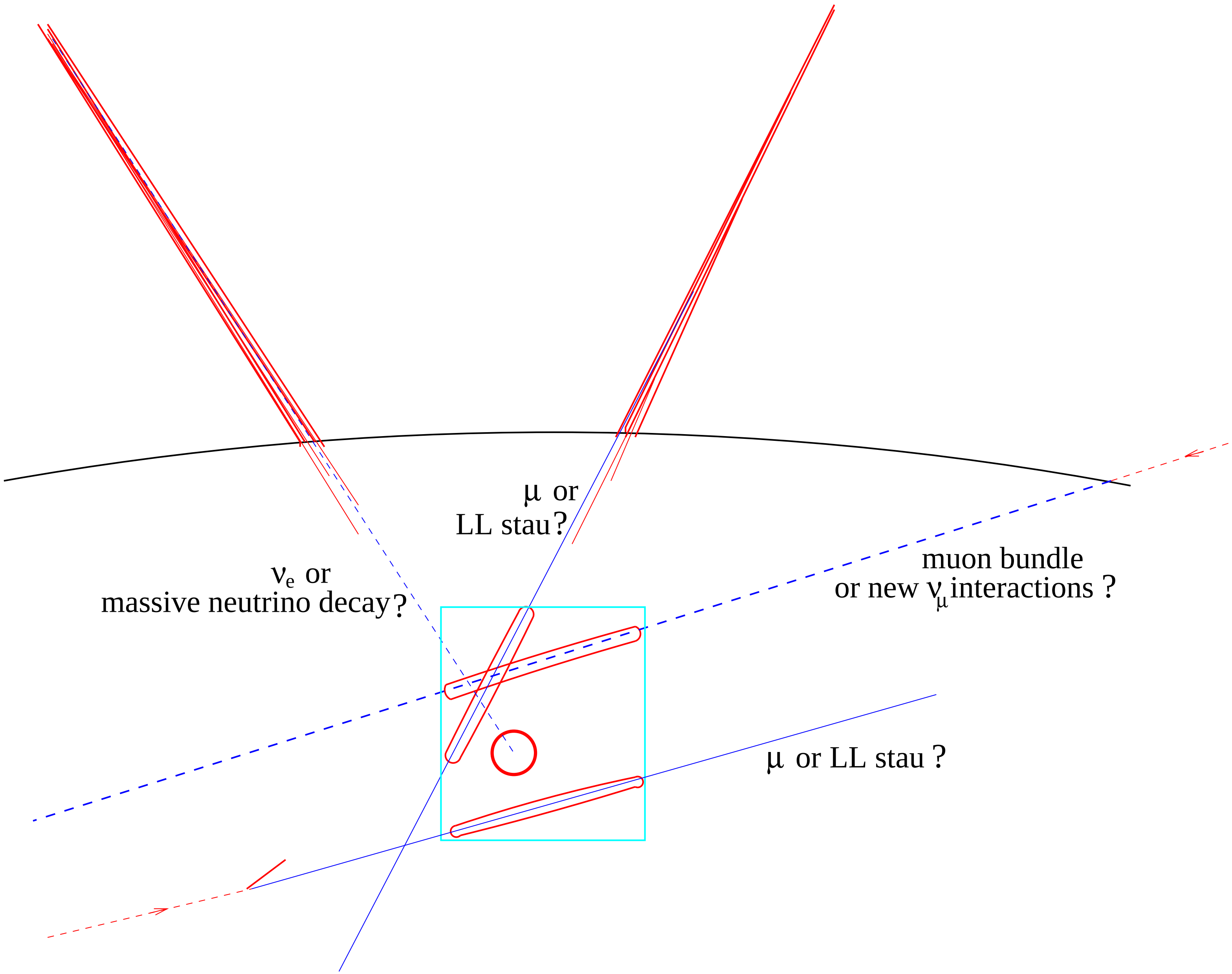
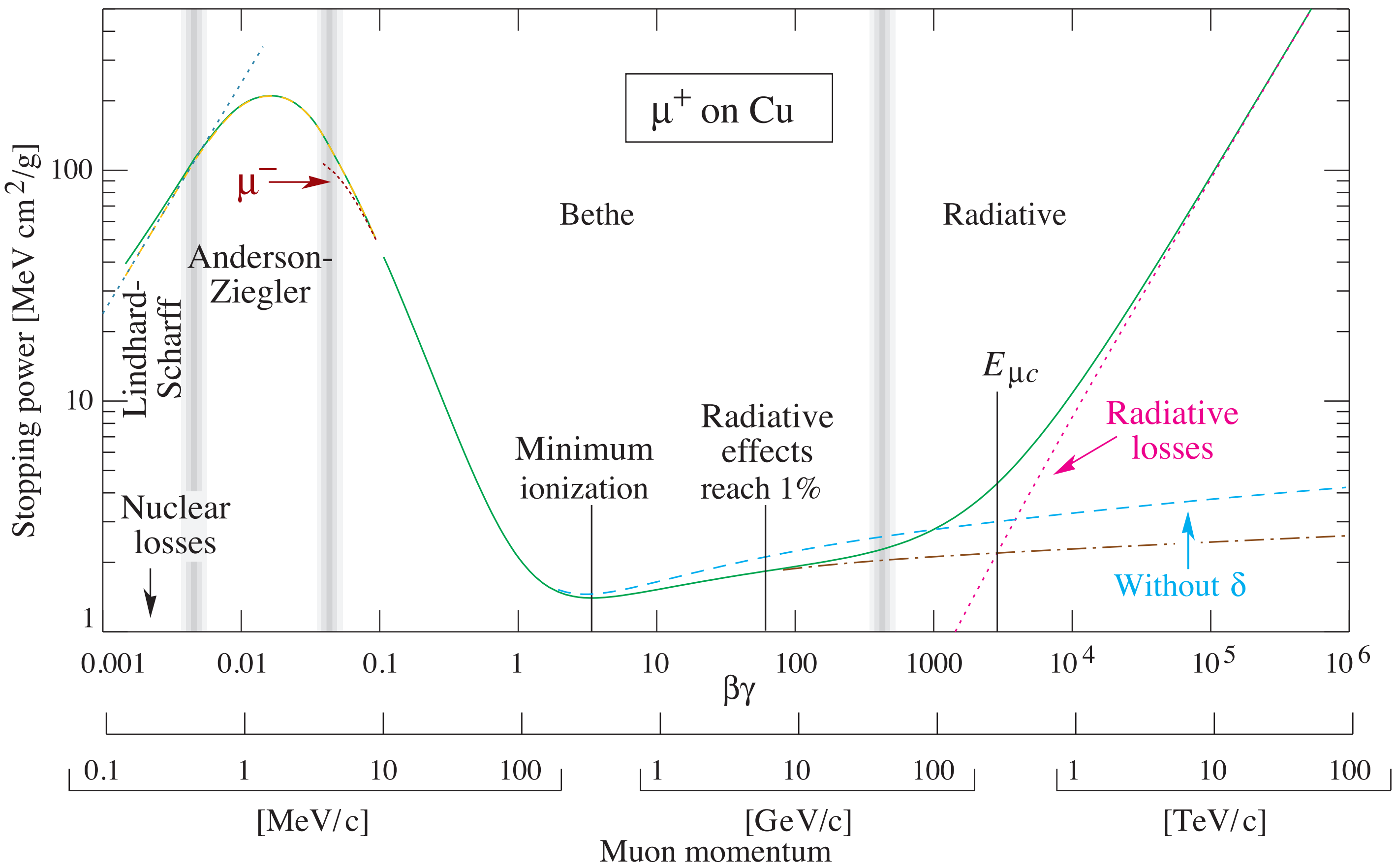
- Long-lived charged particles
- New neutrino interactions (TeV gravity, classicalons)
- A 50 MeV neutrino at LSND/MiniBooNE and ν telescopes

Marseille, April 2013


μ or
LL stau?
ν_e or
massive neutrino decay?
muon bundle
or new ν_μ interactions ?
μ or LL stau ?

LONG-LIVED CHARGED PARTICLES



muon range in ice: 6 km at 10 TeV; 18 km at 1000 TeV

150 GeV stau range in ice: 45 km at 10 TeV; 3000 km at 1000 TeV

UPGOING LL STAU EVENTS

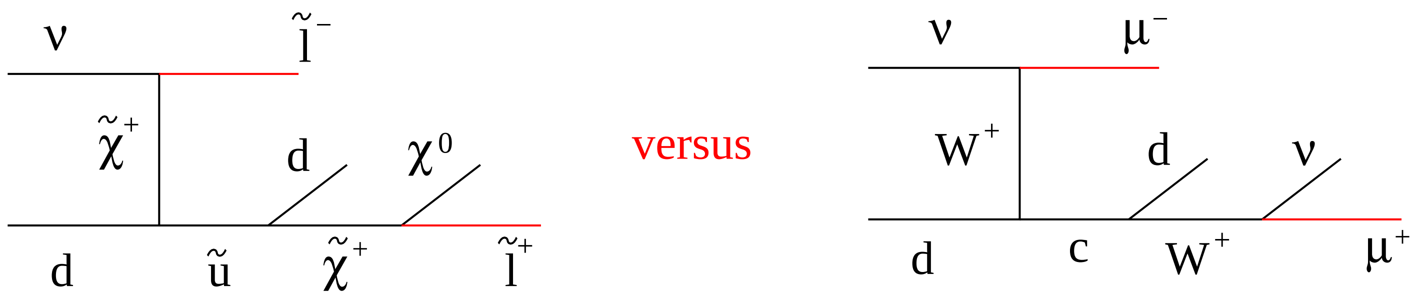
Albuquerque et al, Reno et al, Ahlers et al, Xiao-Jun et al

- Larger reach than muons. Inside the telescope $\tilde{\tau}$ ionizes like a 100 GeV muon, but it keeps going...

- Pair produced: Two parallel traces with a 100 m separation

- Small cross section $\propto (m_W/m_\chi)^4$ with a very high kinematical threshold

$$\sqrt{\hat{s}} = \sqrt{2xm_pE_\nu} \geq m_{\tilde{\tau}} + m_{\tilde{q}} \rightarrow \ E_\nu \gtrsim 1000 \text{ TeV}$$



NEAR-HORIZONTAL LL STAU EVENTS

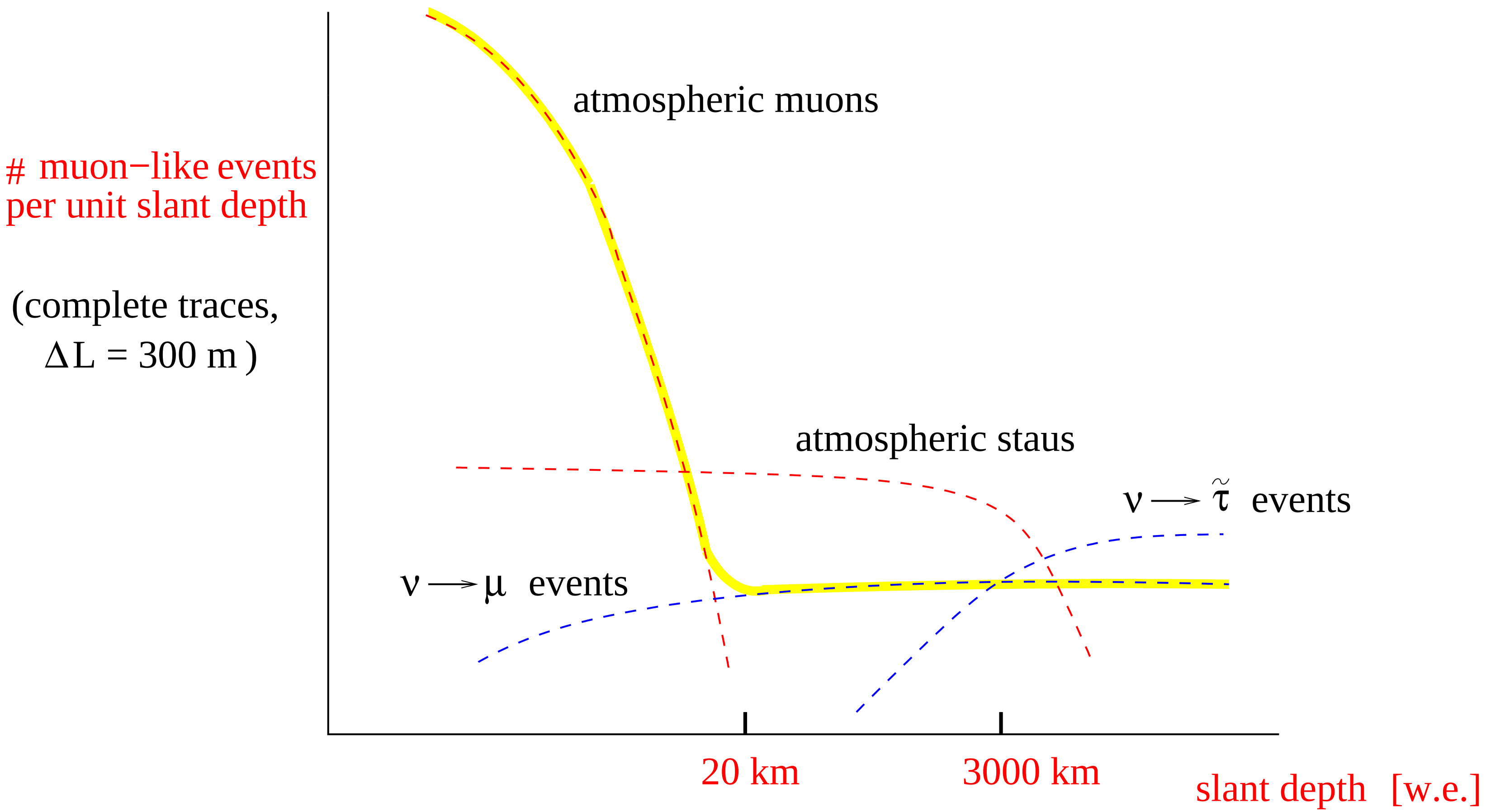
Ahlers et al, Ando et al, Peng-fei et al

• Atmospheric LL staus produced in the collision of primary or secondary hadrons with air nuclei. Any SUSY event (gluino or squark production) results into a LL stau pair

• Very energetic staus ($E_{\tilde{\tau}} \gtrsim 10^6$ GeV), with a very long reach. They could be separated from the muons inside the shower imposing a slant depth cut

• Given the LHC results ($m_{SUSY} \gtrsim 900$ GeV) the usual scenarios are disfavored, but...

HOW TO LOOK FOR A MODEL-INDEPENDENT SIGNAL?



- High-energy (not finishing inside the detector) muon-like tracks
- Possible anomalies at slant depths between 10 and 3000 km

NEW NEUTRINO INTERACTIONS

- Neutrinos are weakly interacting particles. The relative effect of the new physics would be larger than on quarks or charged leptons

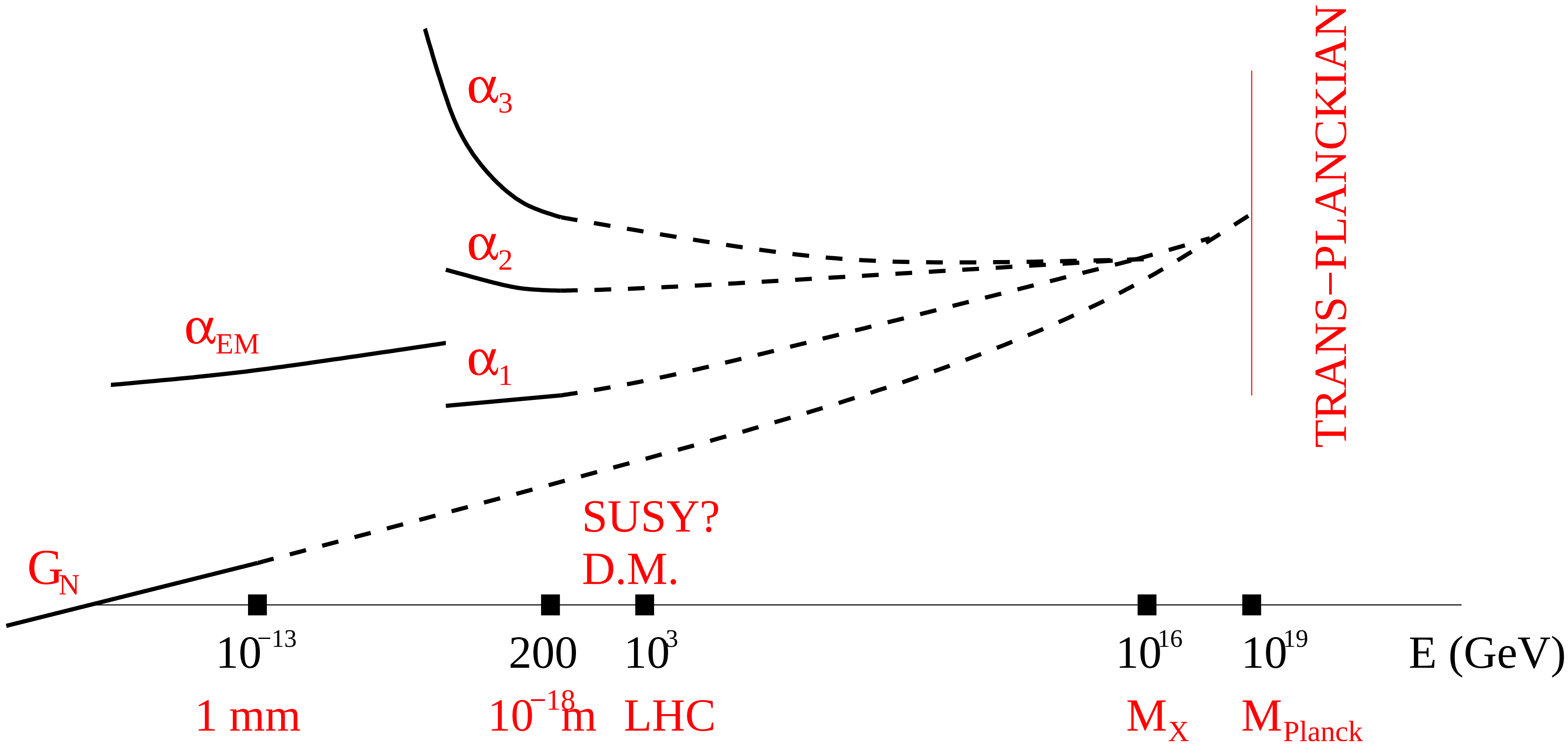
- At high energies their interactions with matter may become stronger

- The atmospheric neutrino flux drops (the spectral index changes from -2.7 to -3.7) at energies $E > 100$ GeV. There *must* be a cosmic flux related to the production and propagation of cosmic rays

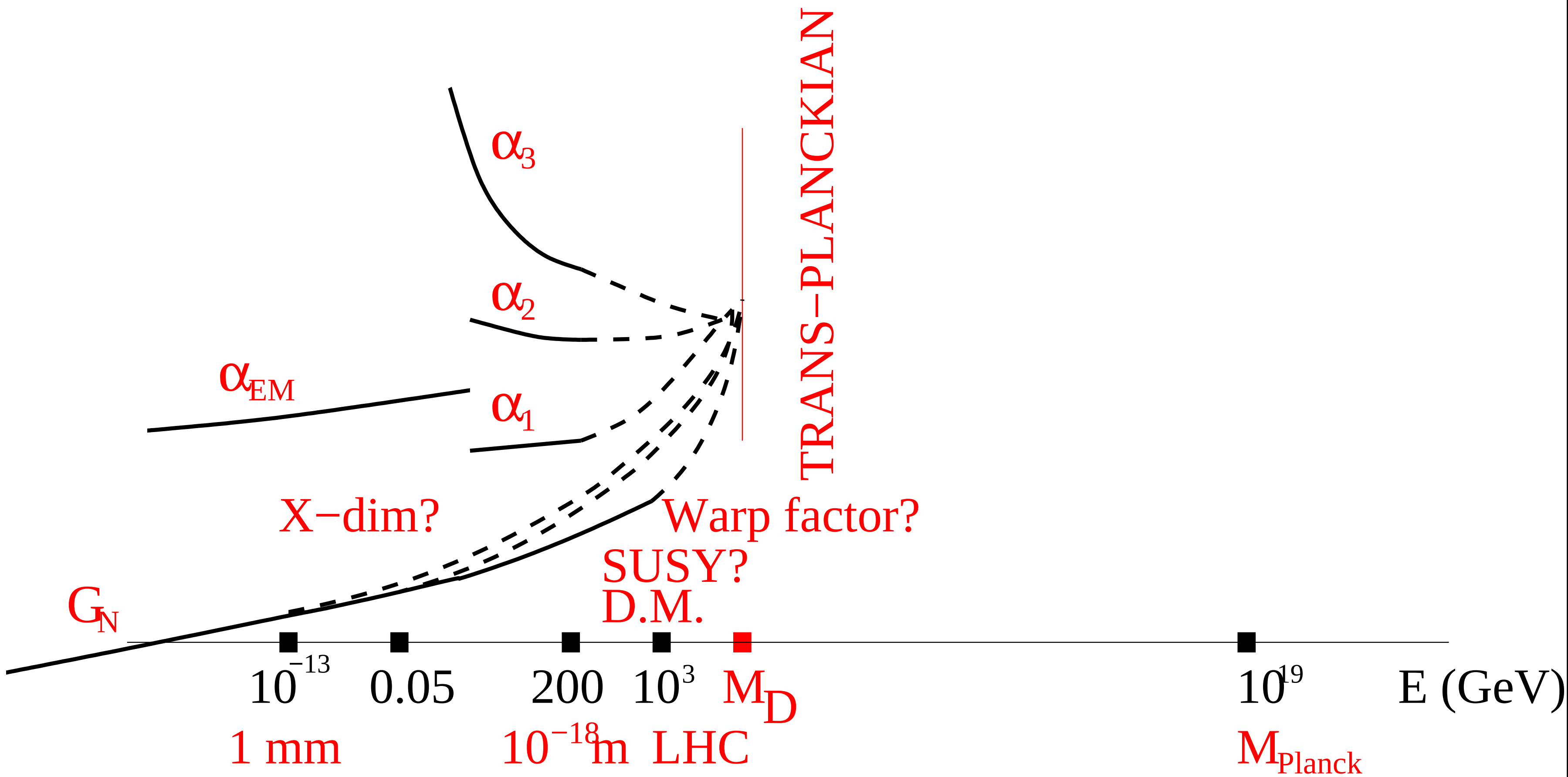
- Both the observation or the absence of neutrino interations above PeV energies have consequences on models for new physics

What kind of effects could be expected?

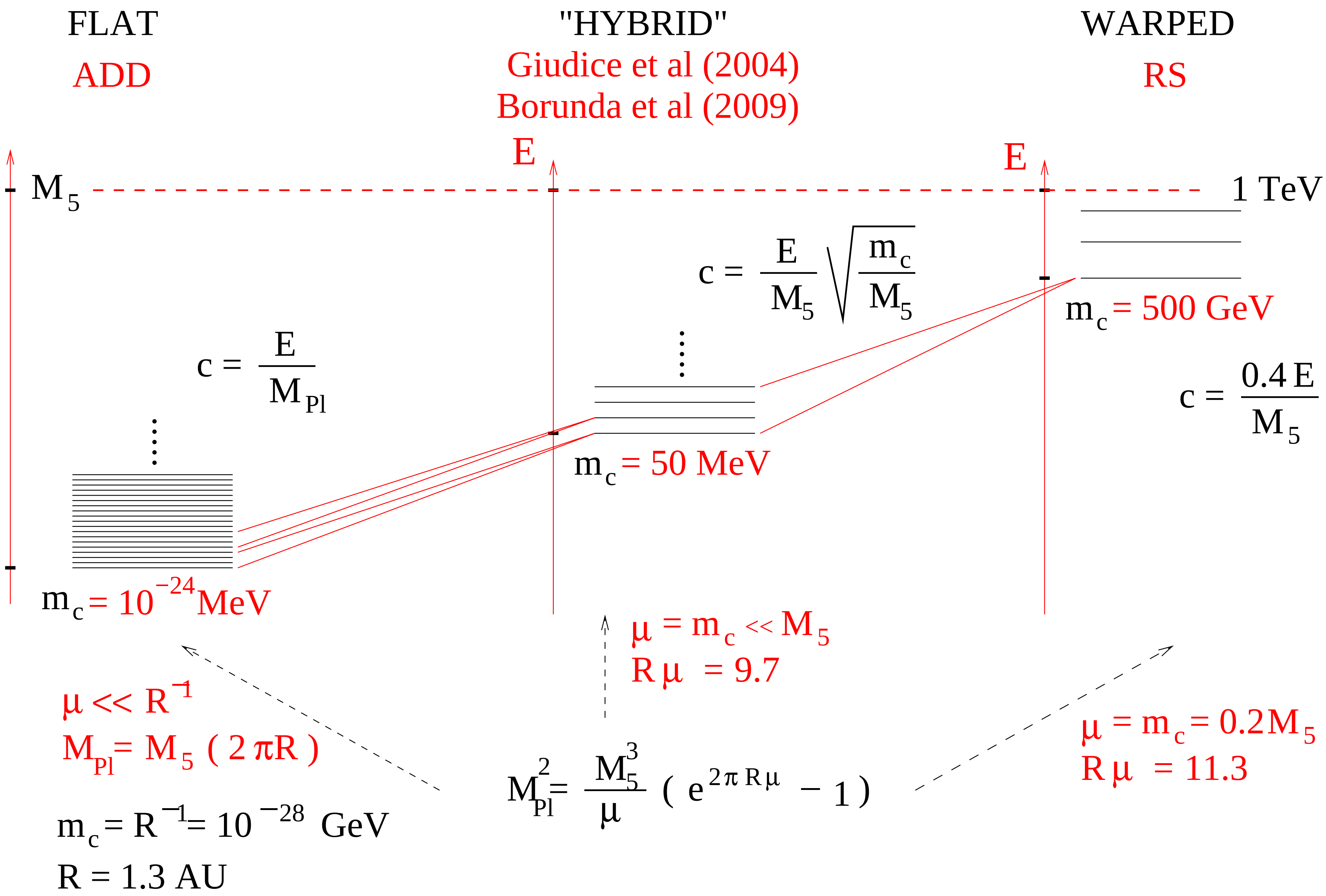
Where is the New Physics? How *different* is it?



Where is the New Physics? How *different* is it?

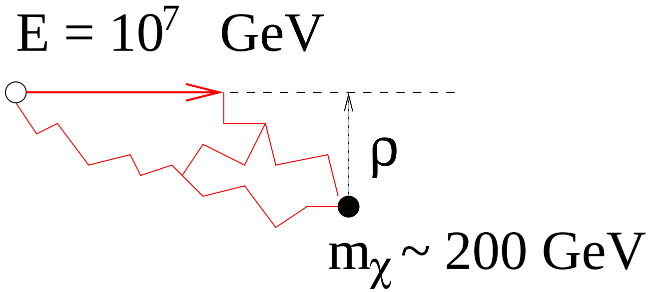


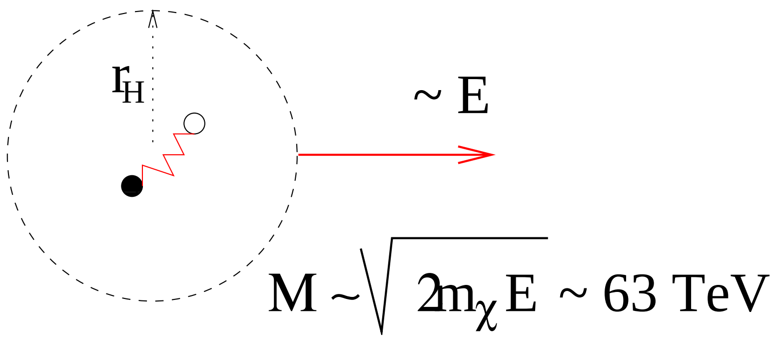
1 Extra dimension



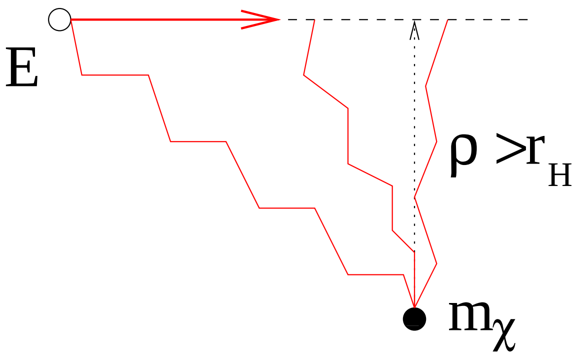
Trans-Planckian collisions

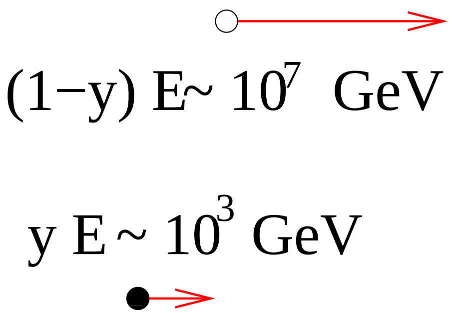
- Black Hole (or *classicalon*) production: $\sigma_{BH}^{q\chi} \approx \frac{1}{M_D^2}\left(\frac{s}{M_D^2}\right)^{\frac{1}{n+1}}$

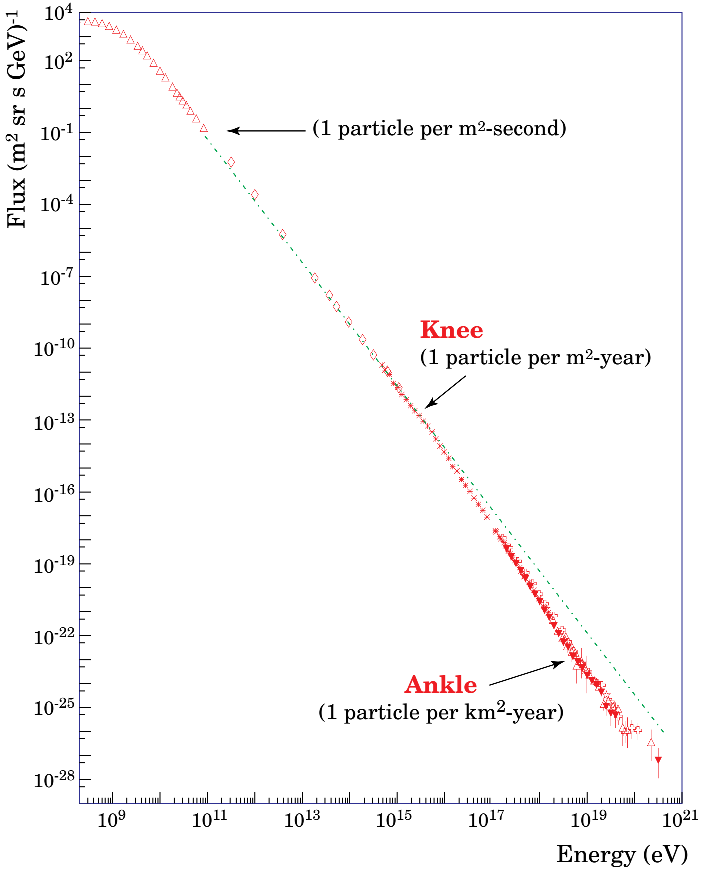


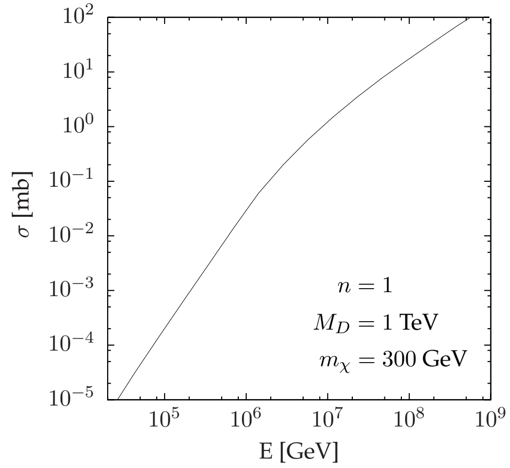


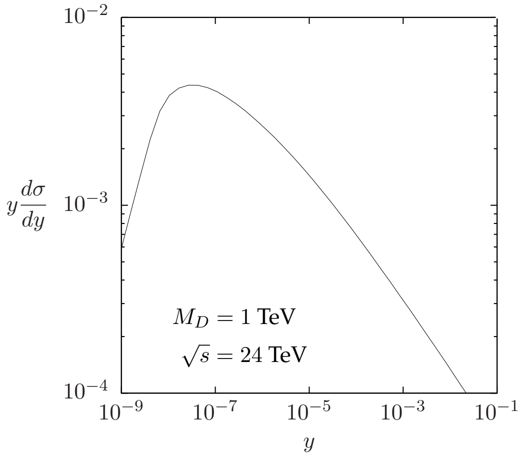
- Eikonal process: $\sigma_{eik}^{q\chi} \approx \frac{1}{M_D^2}\left(\frac{s}{M_D^2}\right)^{1+\frac{4}{n}}$











Could the cosmic-ray *knee* be caused by strong p–χ interactions?

Yes

JCAP **0807** (2008) 014, JCAP **0812** (2008) 003, JCAP **0906** (2009) 027

Implications in UHE neutrino physics

• If DM interacts strongly with matter above the energy threshold E_{knee}, then neutrinos should do the same.

• The c.o.m. energy at the knee is $\sqrt{s} = \sqrt{2m_\chi E_{knee}}$. This $\sqrt{s}$ is reached in ν–p collisions at

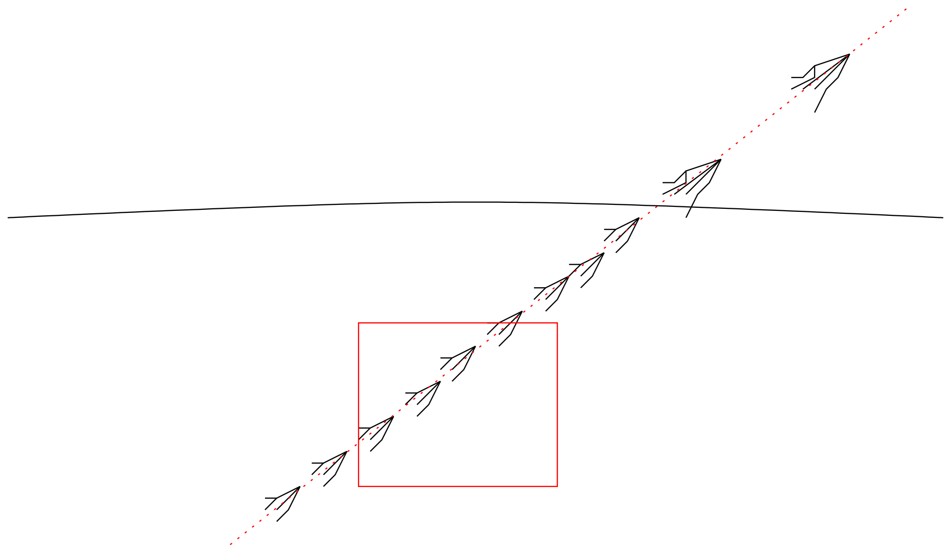
$$E_\nu = \frac{m_\chi}{m_p} E_{knee} \approx 10^8 \text{ GeV}$$

• Therefore, we would not observe (cosmogenic) neutrino events of energy $E \geq 10^8$ GeV at neutrino telescopes.

• What kind of signal should we search in ν telescopes? Why we have not seen these strongly interacting neutrinos in air showers?

The ν–p interaction is very soft

• A 10^8 GeV neutrino would interact several times in the atmosphere and then every 10 meters of ice, depositing around 1–10 TeV of energy ($y \approx 10^{-5}$) in each interaction.



• Neutrino interactions of *large* cross section but *small* inelasticity. At a telescope, similar to the muon bundle from a 10^{10} GeV cosmic ray, but able to reach from even larger zenith angles.

No *regular* neutrinos at very high energies

LONG-LIVED HEAVY (50 MeV) NEUTRINOS

- Homestake, GALLEX, SAGE,... IMB, Kamiokande, Super K, ... KEK, K2K,... SNO, KamLAND,... **Neutrinos have masses and mixings (!)**

$$\begin{cases} \Delta m^2_{12} \approx 7.9 \times 10^{-5}\ \mathrm{eV}^2 \\ \Delta m^2_{23} \approx 2.5 \times 10^{-3}\ \mathrm{eV}^2 \\ \qquad \approx \Delta m^2_{13} \end{cases} \qquad \begin{cases} \sin^2\theta_{12} \approx 0.30 \\ \sin^2\theta_{23} \approx 0.50 \\ \sin^2\theta_{13} \approx 0.025 \end{cases}$$

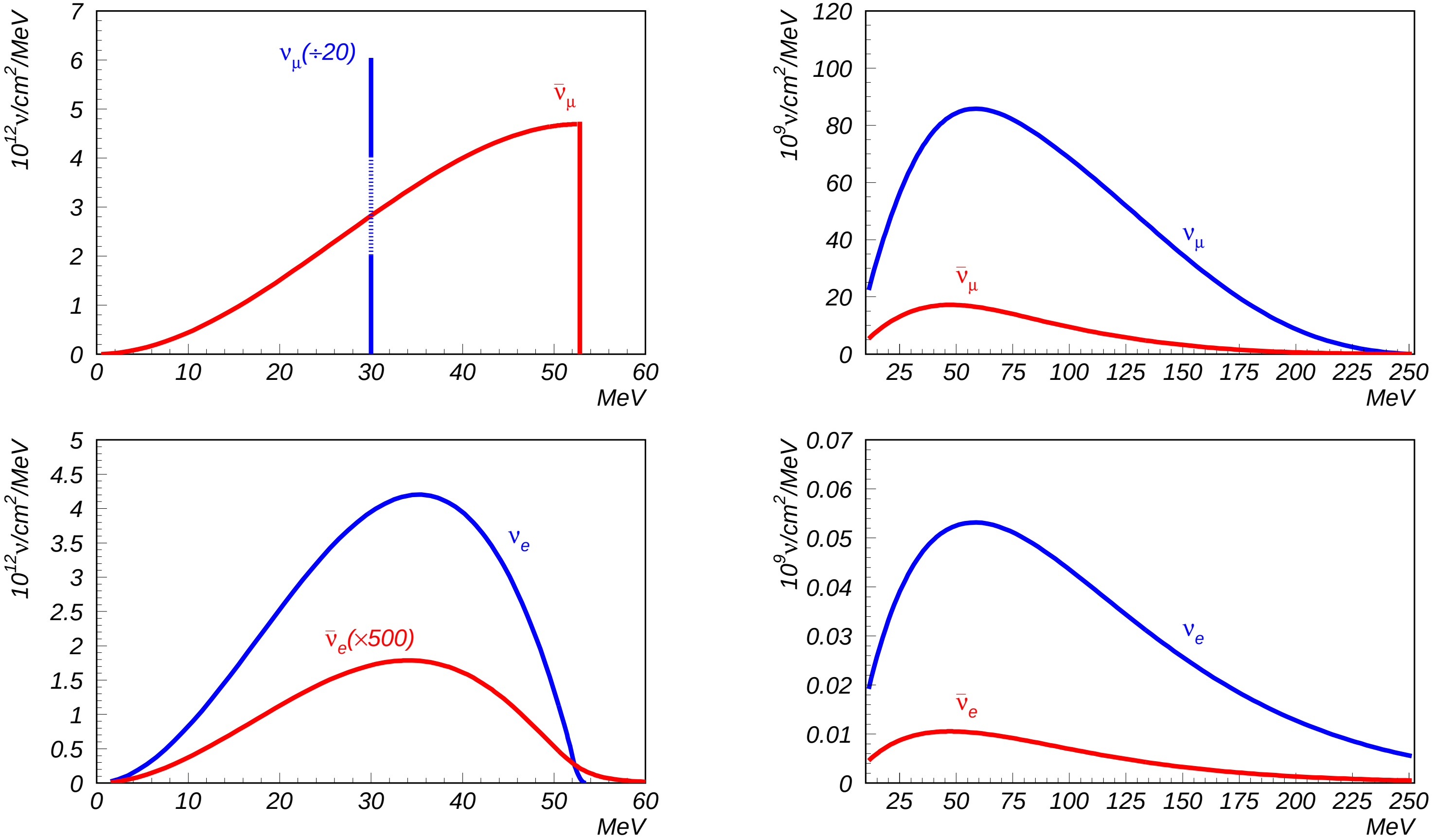
Is it $y_\nu\, H L \nu^c$ or $\frac{1}{\Lambda_\nu} HHLL$?

- *Persistent* anomalies in several experiments with neutrino beams from particle accelerators. Excess of 3 events with an electron in the final state per 1000 ν_μ CC-interactions. $\nu_\mu \to \nu_e$ oscillations unconsistent with ν-mass parameters (2 sterile neutrinos of $m \approx 1$ eV?).

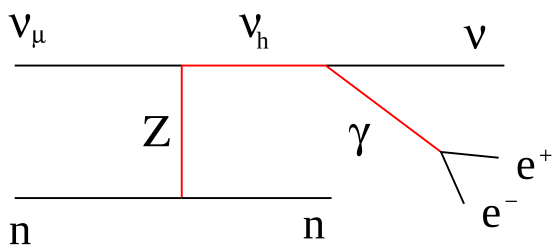
LSND, KARMEN, MiniBooNE, TRIUMF, T2K, NOMAD

• LSND observed **3** events with $\bar{\nu}_\mu \to \bar{\nu}_e$ then $\bar{\nu}_e p \to e^+ n$, with 2.2 MeV photon from neutron capture per **1000** $\overline{\nu}_\mu$ CC interactions

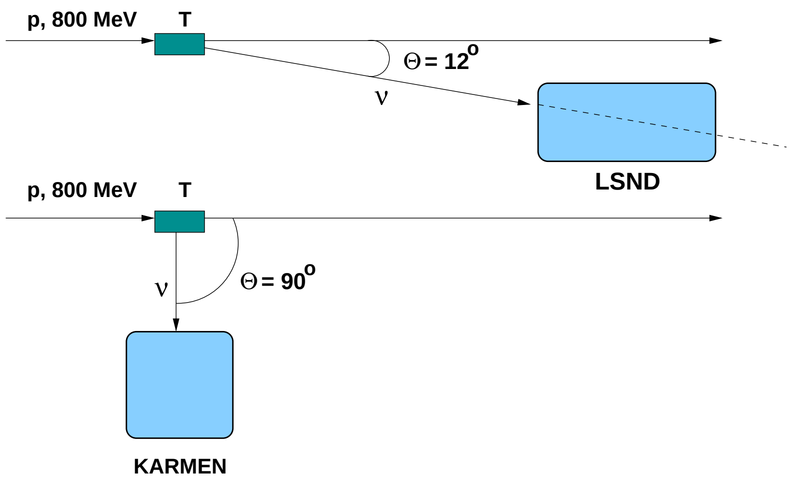
Fluxes: DAR (left) and DIF (right) $\pi^+ \to \mu^+ \nu_\mu\ ;\ \ \mu^+ \to \bar{\nu}_\mu e^+ \nu_e$

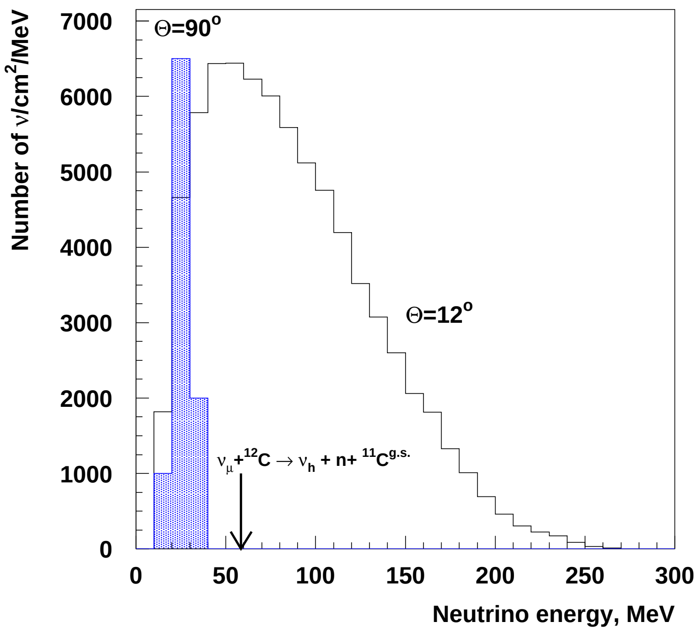


Gninenko's 50 MeV neutrino hypothesis to explain LSND

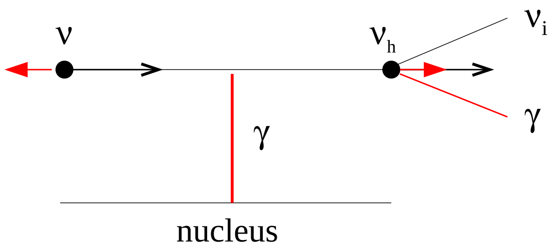


- Sterile ν_h with $|U_{\mu h}|^2 \approx 10^{-3}$–$10^{-2}$, $\nu_h \to \nu\gamma$ with $\tau_h \lesssim 10^{-8}$ s
- KARMEN did not confirm... ν_h would be above threshold there!

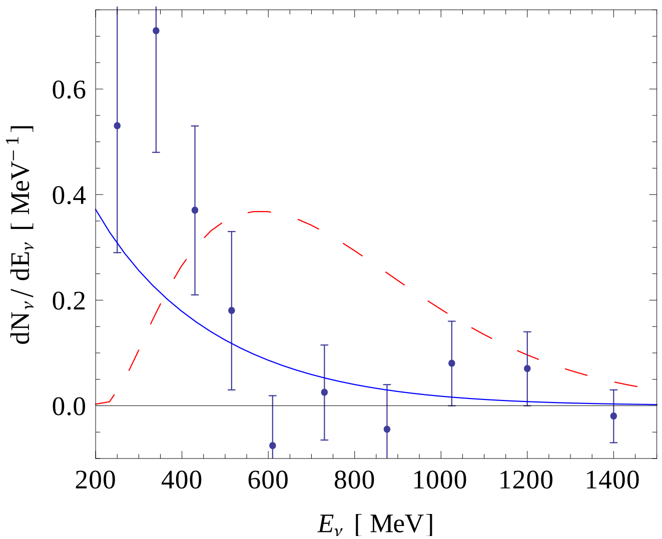


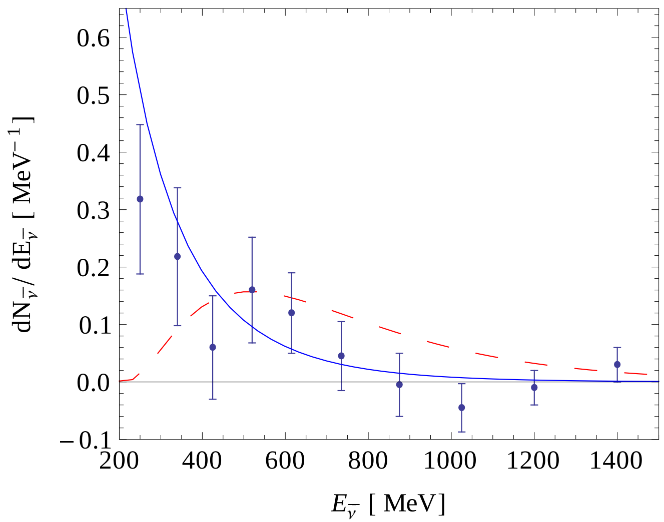


- We have defined [JHEP1301(2013)106] a variation of Gninenko's model able to explain also MiniBooNE consistently with other neutrino data (radiative muon capture at TRIUMF, T2K, single photon at NOMAD)



- The decay length ($\lambda_{dec} > R$) and the helicity (+) of ν_h imply that MiniBooNE excess should concentrate at low energies



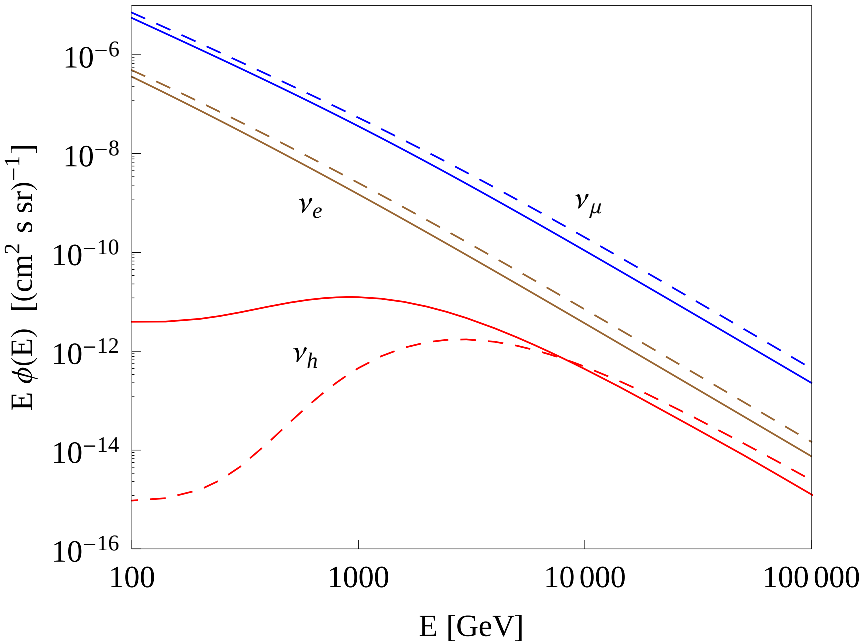


LSND: anomaly at $L \approx 30$ m for $E \approx 40$ MeV

MiniBooNE: anomaly at $L \approx 500$ m for $E \approx 300$ MeV

ν telescopes: anomaly at $L \approx 10$–100 km for $E \approx 1$ TeV ??

$$B(K^+ \to \mu^+ \nu_h) \approx B(K^+ \to \mu^+ \nu) \times |U_{\mu h}|^2 \, \bar{\rho}_h \qquad \bar{\rho}_h \approx 1 + \frac{m_h^2}{m_\mu^2}$$



Z–moment method

$$m_h = 60 \text{ MeV}$$

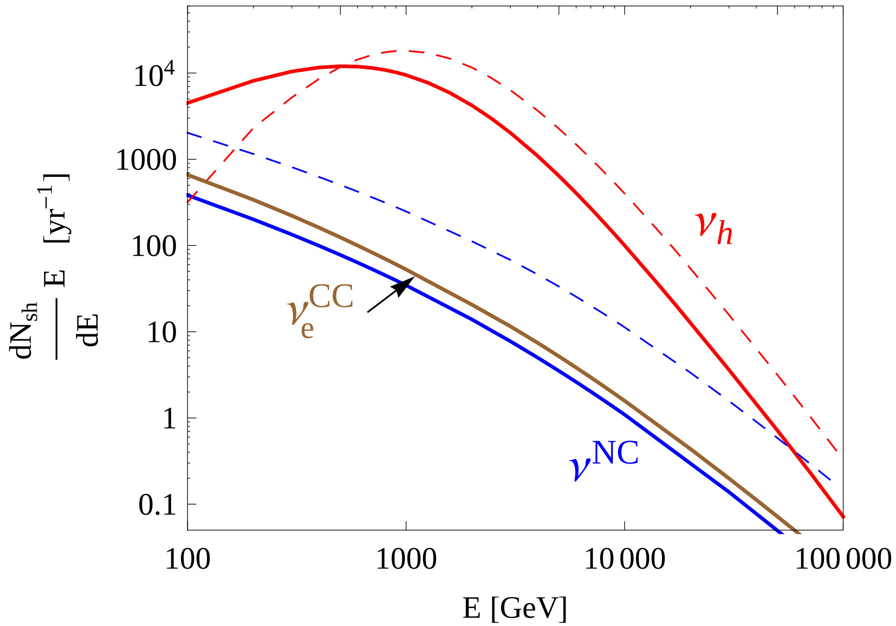
$$|U_{\mu h}|^2 = 0.005$$

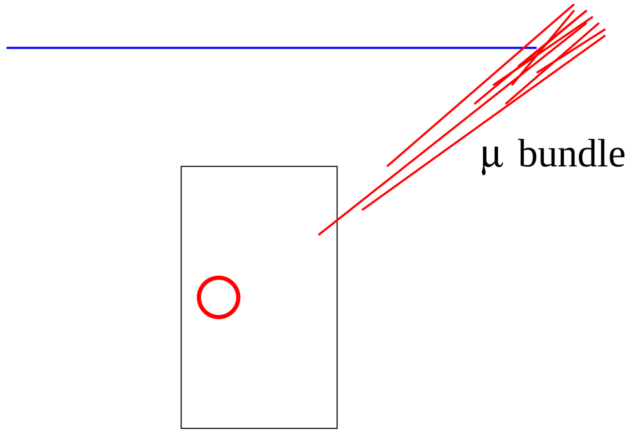
$$\tau_h = 10^{-9} \text{ s}$$

$$\lambda_{dec} = 5 \text{ km at } E = 1 \text{ TeV}$$

[PRD83(2011)091301]

• Contained events at ANTARES. In dashes the energy distribution of the parent neutrino.





• 14000 $\nu_h \to \gamma\nu$ events of energy above 500 GeV per year, versus 220 standard events ($\nu_e N \to eX$ and $\nu_{\mu,e} N \to \nu_{\mu,e} X$)

• At energies below 100 GeV ν_h does not reach the telescope, above 100 TeV its decay length becomes too large and the signal decreases.

SUMMARY

- **LL charged particles:** A plot of $\#$ *events* versus *slant depth* covering *all* depths could reveal massive particles or new muon sources (charm, EM decays of unflavored mesons).

- **New ν interactions:** The absence of *regular* neutrinos at ultrahigh energies and the appearence of *unusual* muon bundles at horizontal zenith angles could imply a new regime of strong neutrino interactions.

- **LL heavy neutrinos:** An excess of contained events could be correlated with the LSND and MiniBooNE anomalies. These events would only be downgoing and quasi-horizontal, possible *contaminated* by muons from the parent air shower.