Testing Fundamental Laws with Neutrino Telescopes

Particle Physics with Neutrino Telescopes workshop

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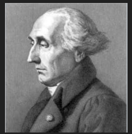
What is a fundamental law?

A scientific law is a statement based on repeated experiments or observations that describe some aspect of the natural world.

- Newton's second law
  (also referred Momentum conservation)
- First law of Thermodynamics
  (also referred energy conservation)
- Coulomb law

Why this sounds a bit outdated?

Emmy Noether changed everything!



- **Today we are more used to put the statements as symmetries.**
- Today not always based on repeated experiments or observations.

$$\mathcal{S} = \int \mathrm{d}^{D-1}x\,\mathrm{d}t\,\mathcal{L}$$

Symmetries ⟷ **Noether Theorem** ⟷ **Fundamental LAWs**

Symmetries (-> Fundamental Laws) are the cornerstone of modern physics

- Gauge symmetries → Interaction
- Space time symmetries → Dispersion relations, E and P conservation.
- CP, CPT, and more → Other conserved quantities.

How do we test it?

Effective Field Theory tells us to go to high energies

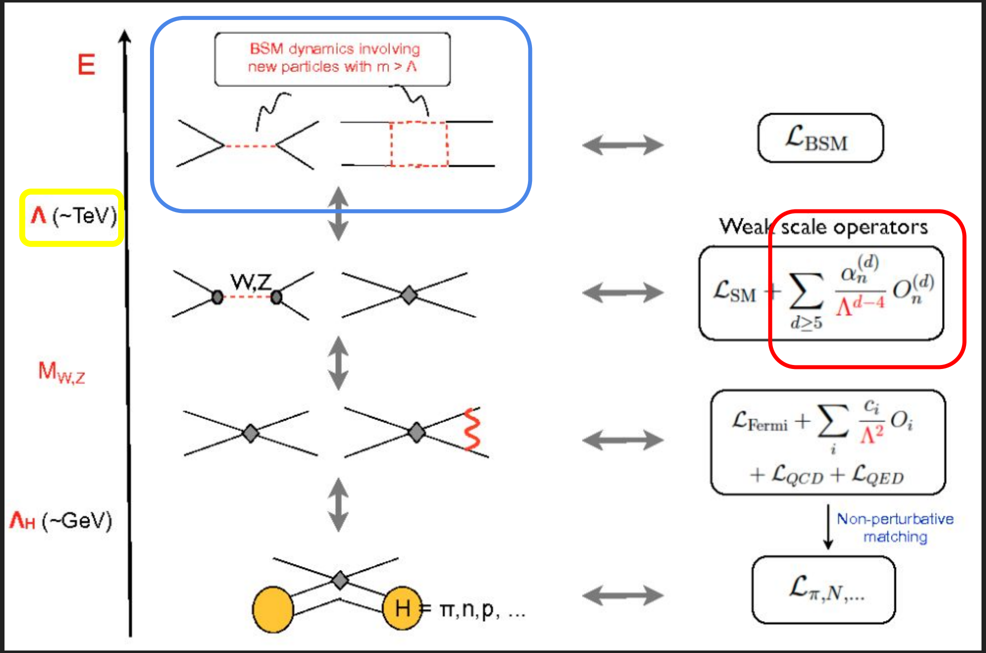
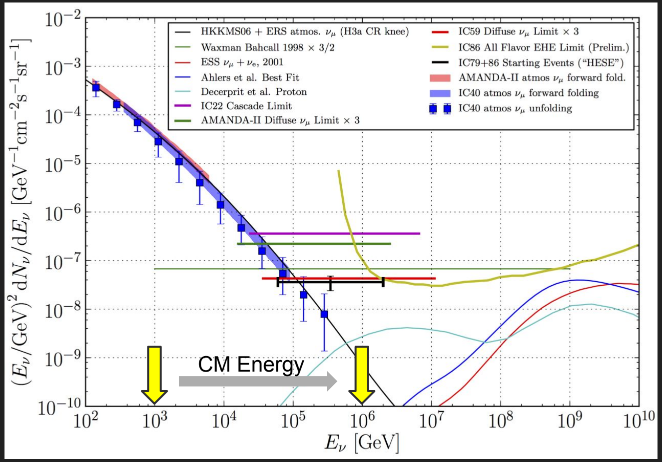


Fig. from: Prog.Part.Nucl.Phys. 71 (2013) 2-20
Vincenzo Cirigliano, Michael J. Ramsey-Musolf

- At high energies the effect will appear as effective operators.
- At very high energies we can see the new dynamics.

Neutrino Telescopes look good!



How do we test it?

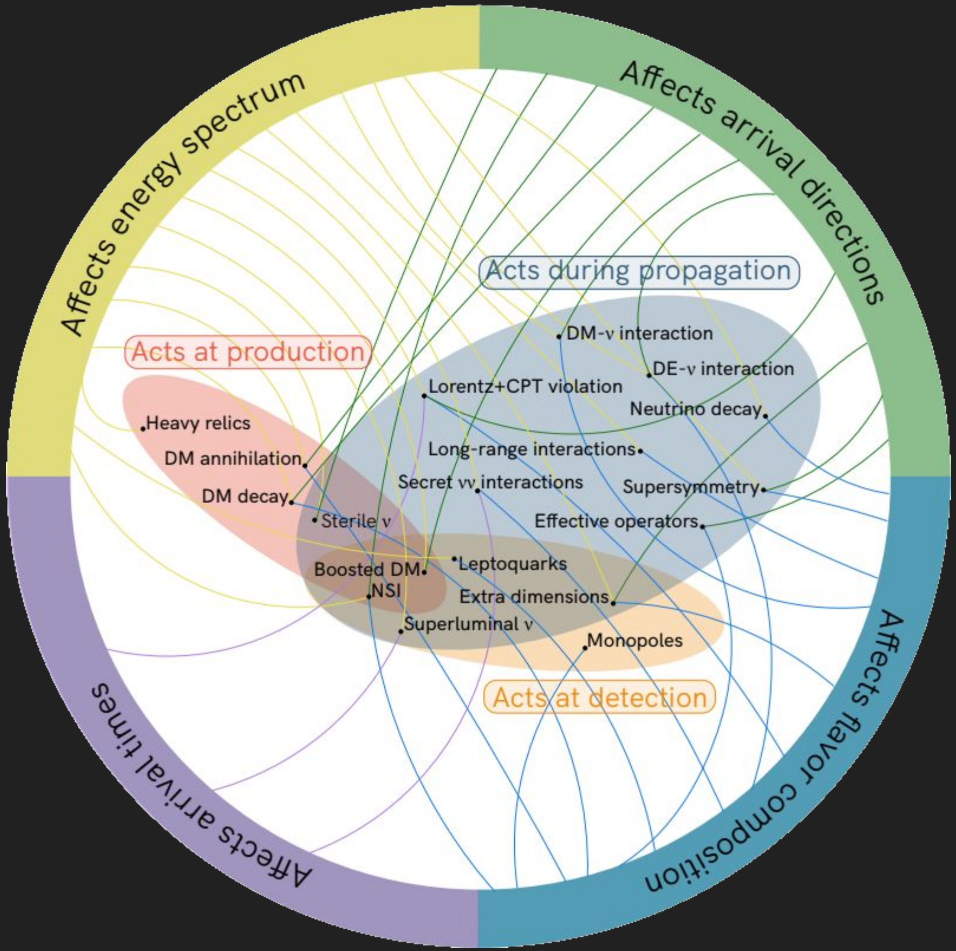
- Traditionally (ex. Coliders) we looked at production and detection.

- Despite neutrino telescopes measure very high energies is hard to compete with Colliders to measure the effect of new operators.
  - A lot less statistics
  - Only O(10-100) improvement in energy over the cutoff.
  - Very forward process.
  - New dynamics (LQ, Z' …) may be interesting since a priori we have flux. Talk by Tianlu Yuan and Pilar Coloma
  - Why not photons or even CR: Talks by Alessandro De Angelis and Antonella Castellina

$$\mathcal{L}_{SM} + \sum_{d \geq 5} \frac{\alpha_n^{(d)}}{\Lambda^{d-4}} O_n^{(d)}$$

- Neutrino Telescopes measure **Neutrinos!**

  - Neutrinos propagate in a very non trivial manner.



- The number of models in the literature is large for new physics in neutrino telescopes.
- Most of the models produce effects during the propagation that can be observed in:
  - Energy
  - Direction
  - Topology
  - Time

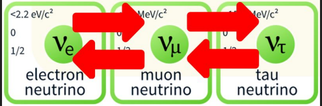
Propagation seams to be a good place to start!

arXiv:1907.08690 Carlos A. Argüelles, Mauricio Bustamante, Ali Kheirandish, Sergio Palomares-Ruiz, JS, Aaron C. Vincent

Physics of Neutrino Oscillation (Propagation)

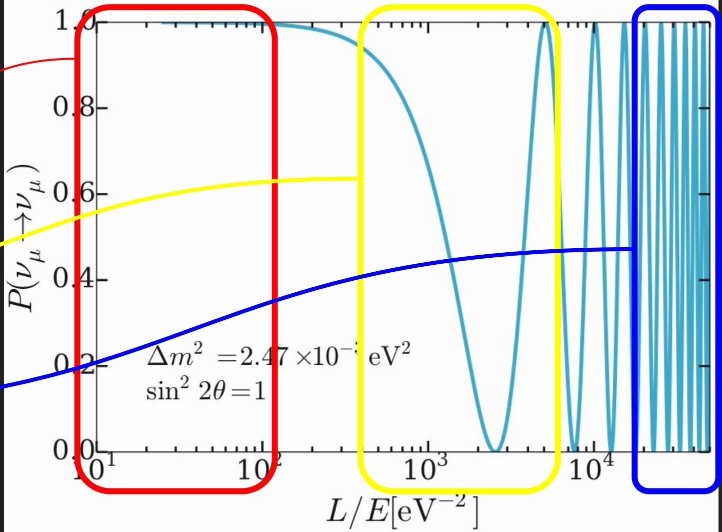
Neutrinos propagate as quantum states with a non-trivial hamiltonian.

$$H = \frac{1}{2E} U M^2 U^\dagger + V_m$$

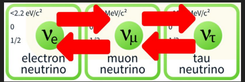


For a two level approximation:

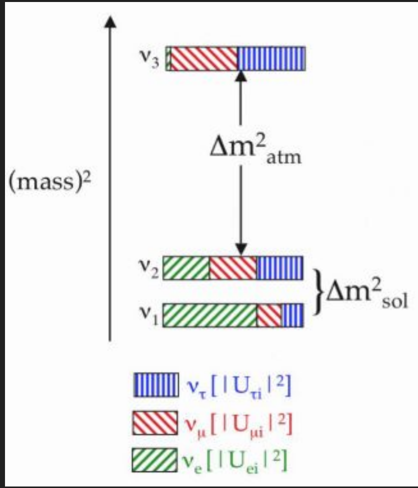
- $\sin^2 2\theta$: oscillation amplitude
- Δm^2: oscillation frequency
  - $L/E \ll 1/\Delta m^2 \rightarrow$ no oscillations
  - $L/E \sim 1/\Delta m^2 \rightarrow$ oscillations
  - $L/E \gg 1/\Delta m^2 \rightarrow$ fast oscillations ("averaged")



Current Status of Neutrino Oscillations



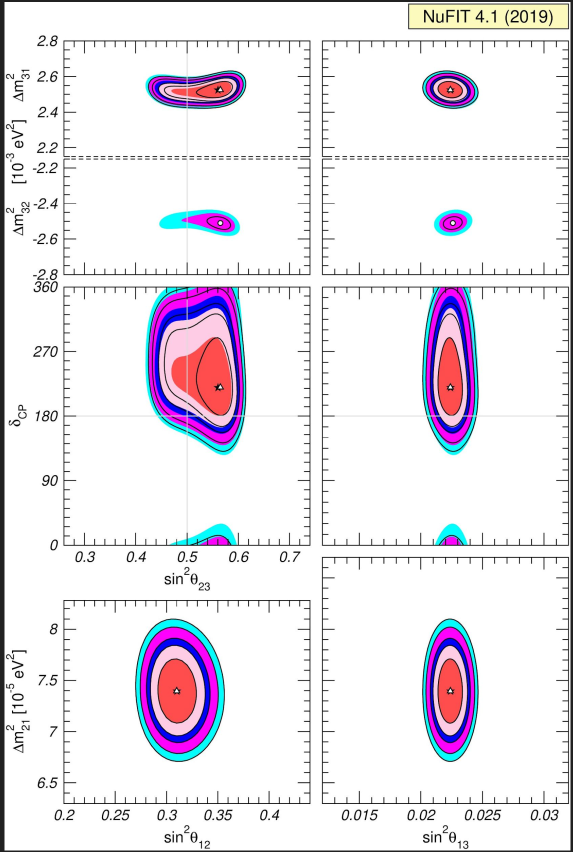
- The mixings in the neutrino sector are large
- The mas differences are tiny
- And the absolute mass is very small compared with other particles in SM



$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.523^{+0.032}_{-0.030}$

NuFIT 4.1 (2019)

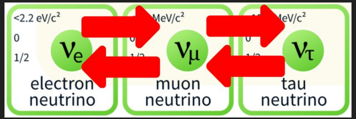
$$|U|^{\text{w/o SK-atm}}_{3\sigma} = \begin{pmatrix} 0.797 \to 0.842 & 0.518 \to 0.585 & 0.143 \to 0.156 \\ 0.244 \to 0.496 & 0.467 \to 0.678 & 0.646 \to 0.772 \\ 0.287 \to 0.525 & 0.488 \to 0.693 & 0.618 \to 0.749 \end{pmatrix}$$



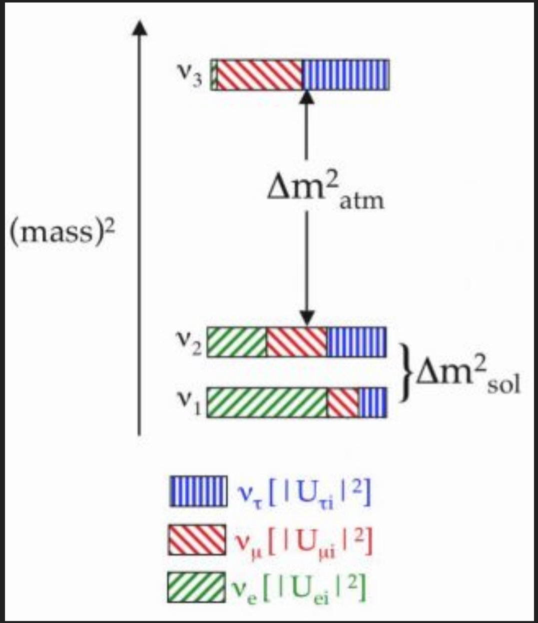
Talk by Michele Maltoni

JHEP 01 (2019) 106 NuFIT 4.1 (2019) www.nu-fit.org

A very sensitive phenomena!



$$H = U \begin{pmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix} U^\dagger + \begin{pmatrix} V_{NC} + V_{CC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix}$$



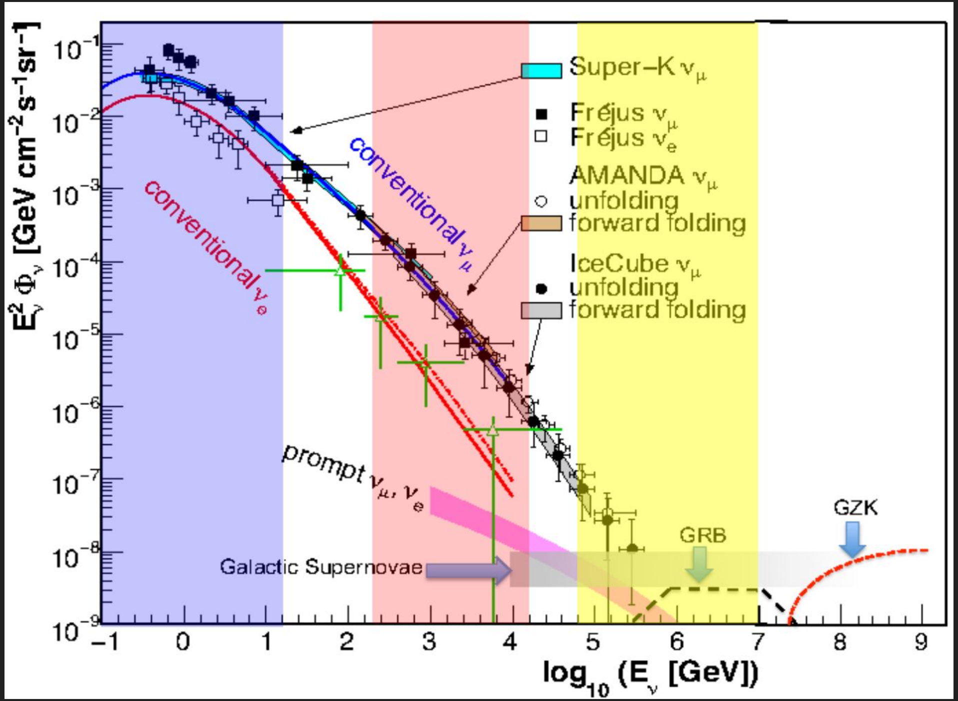
- Neutrino oscillations are observed from MeV to hundreds of GeV

$$\varepsilon_i^2 = p^2 + m_i^2$$

- The quantum interference is very sensible to mass differences O(0.01eV)

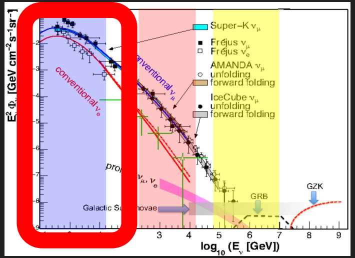
Data from Neutrino Telescopes

- Low E atmospheric:
  - Nu Oscillations (Talks by Tom Stuttard, Tarak Thakore, Thomas Ehrhardt, Alexander Trettin)
  - We know the flux
  - We should know better the flux
  - PID is hard
- High E atmospheric:
  - High scale oscillations, sterile, (Talk by Carlos Arguelles and Marjon Moulai)
  - Higher energies, good for new physics.(Talks Tianlu and P. Coloma)
  - We know the flux.
  - We should know better the flux.
- Astro. Neutrinos:
  - Very high energies! Higher than coliders.
  - Very large propagation distances. (Talks Mauricio and Tianlu)
  - Very low statistics.
  - We don’t know the flux.



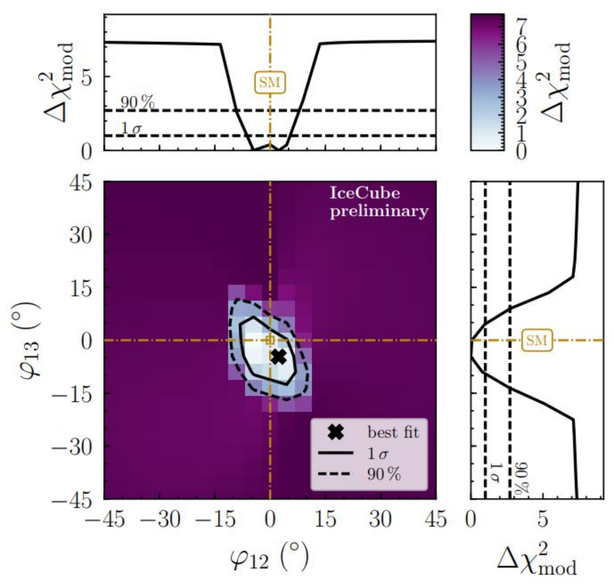
New Interactions with SM (NSI Low ATM)

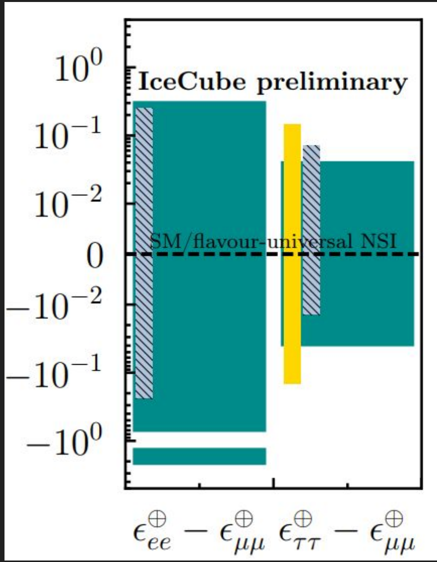
Talk by Thomas Ehrhardt



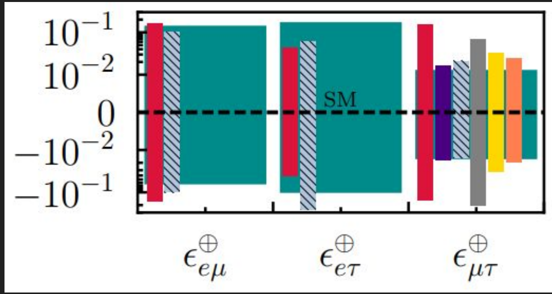
The low energy atmospheric neutrinos by IceCube are very competitive in the mu-tau sector.

$$H = \frac{1}{2E_\nu} U M^2 U^\dagger + V_m + \sum_f V_f \, \varepsilon^{fV}$$





90% regions



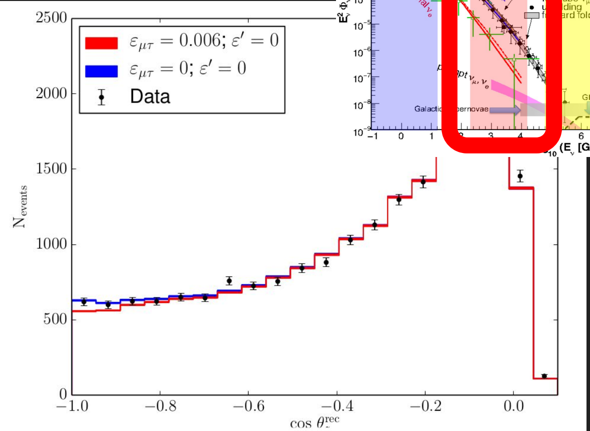
New Interactions with SM (NSI High ATM)

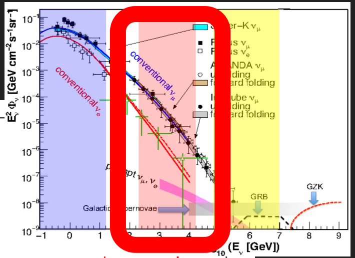
- NSI can also be constrained with high energy data around TeV.
- With only one year of through going muons data you get the stronger constraint in the mu-tau.

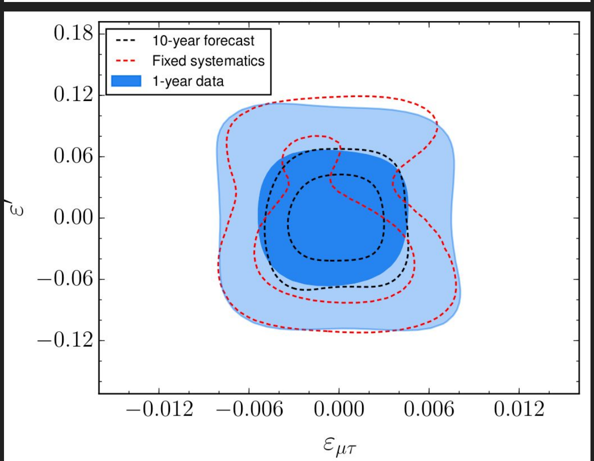
Results from:
JHEP 1701 (2017) 141 JS, Olga Mena, Sergio Palomares-Ruiz, Nuria Rius

For a global picture of NSI:
JHEP 1808 (2018) 180 Ivan Esteban, M.C. Gonzalez-Garcia, Michele Maltoni, Ivan Martinez-Soler, JS
JHEP 1906 (2019) 055 Ivan Esteban, M.C. Gonzalez-Garcia, Michele Maltoni

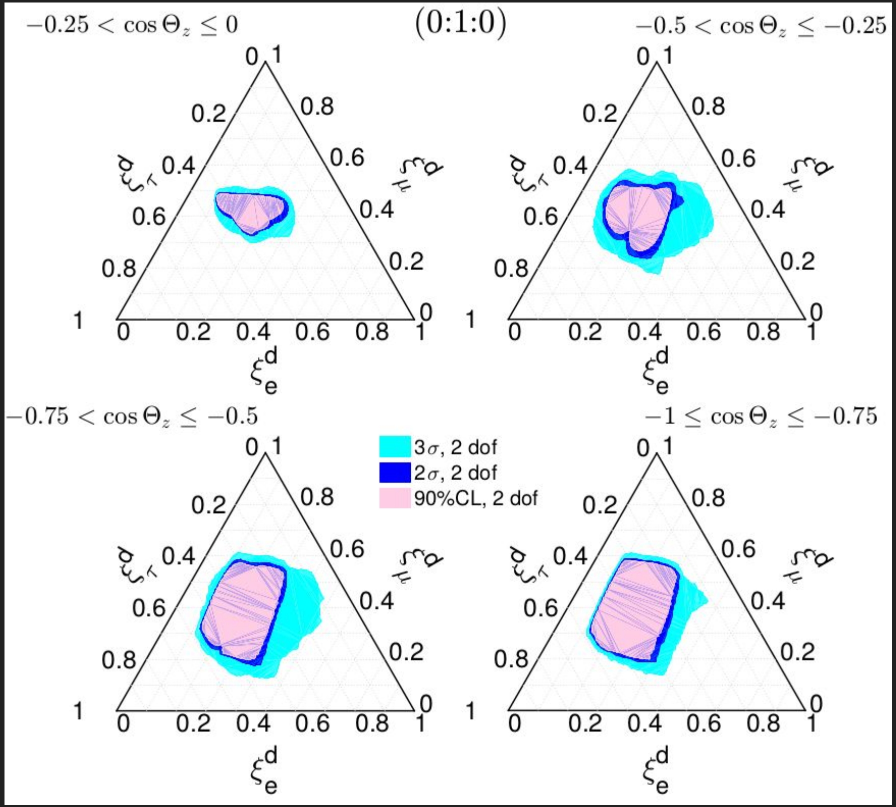
Previously with less accurate systematics:
JHEP 1306 (2013) 026 Arman Esmaili, Alexei Yu. Smirnov

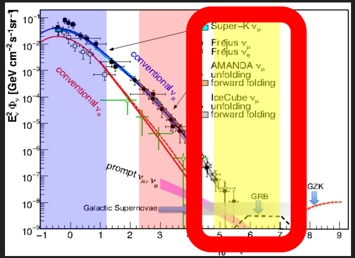






New Interactions with SM (NSI Astro)





Regions in the flavor triangle with NSI

- l The flavor content may change for different zenith Angles.
- l Very hard to measure, we need a lot more statistics.

Astropart.Phys. 84 (2016) 15-22 M.C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, N. Song

Space time symmetries

The violation of the spacetime symmetries can be implemented in QFT as a set of effective operators.

$$\mathcal{L} = \frac{1}{2}\overline{\Psi}_A(\gamma^\mu i\partial_\mu \delta_{AB} - M_{AB} + \widehat{\mathcal{Q}}_{AB})\Psi_B + \text{h.c.}$$

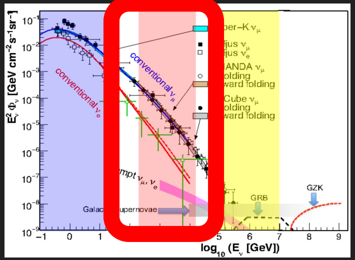
In neutrinos a correction to the dispersion relation is induced and may be flavor dependent.

$$H \sim \frac{m^2}{2E} + \sum_{d\geq 3} E^{d-3}(\mathring{a}^{(d)} - \mathring{c}^{(d)})$$

Phys.Rev. D85 (2012) 096005 Alan Kostelecky, Matthew Mewes

Space time symmetries (High ATM)

High energy part of the atmospheric flux by IceCube gives the strongest bound in the Dim 6 nu-tau effective operator for lorentz violation



$$H \sim \frac{m^2}{2E} + \sum_{d \geq 3} E^{d-3}\left(\mathring{a}^{(d)} - \mathring{c}^{(d)}\right)$$

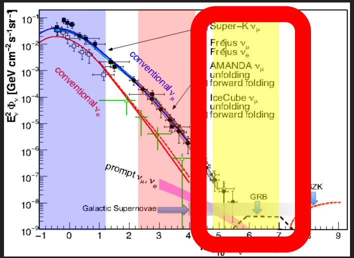
6	GRB vacuum birefringene	astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-42}$ to 10^{-35} GeV^{-2}
	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-31}$ GeV^{-2}
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$	$< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)

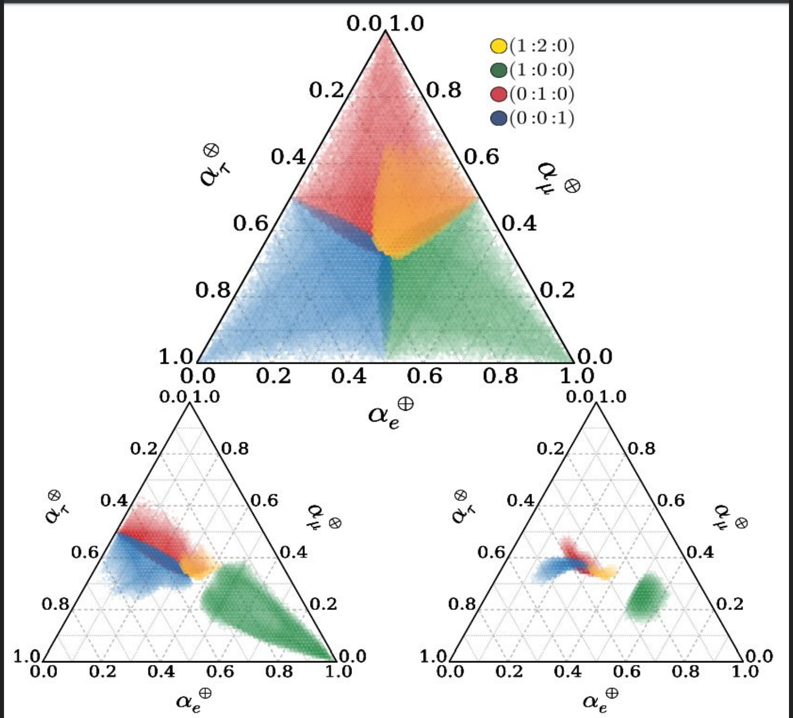
Nature Phys. 14 (2018) no.9, 961-966 IceCube Collaboration

Talk by Mauricio Bustamante for more flavor

Space time symmetries (Astrophysical)

- Top value at the current bound
  Already maximal effect!
- Bottom-Left O(1e-3) times the current bound potentially measurable
- Bottom-Right O(1e-5) times the current bound
- Source information is preserved.





Phys.Rev.Lett. 115 (2015) 161303 Carlos A. Argüelles, Teppei Katori, JS.
Phys.Rev.Lett. 115 (2015) no.16, 161302 Mauricio Bustamante, John F. Beacom, and Walter Winter
Phys.Rev. D98 (2018) no.12, 123023 Markus Ahlers, Mauricio Bustamante, Siqiao Mu

Neutrino Vs. Photon

Talk by Alessandro De Angelis for photons

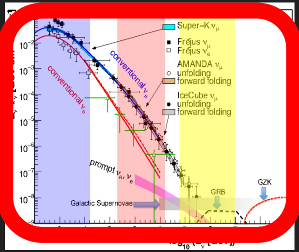
Let's change Vs. by AND!

Limits on Neutrino Lorentz Violation from Multi-messenger Observations of TXS 0506+056

arXiv:1807.05155
By John Ellis, Nikolaos E. Mavromatos, Alexander S. Sakharov, Edward K. Sarkisyan-Grinbaum.

$$\Delta v = -E/M_1$$

$$M_1 \gtrsim 3 \times 10^{16}\ \mathrm{GeV}$$



If they have mass they may arrive later!

On the possibility of determining the upper limit of the neutrino mass by means of the flight time.

Pisma Zh.Eksp.Teor.Fiz. 8 (1968) 333-334
by G.T. Zatsepin

$$\frac{\Delta t}{L} = \frac{1}{v} - 1 \approx \left(\frac{5.1\,\mathrm{ms}}{10\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{1\,\mathrm{eV}}\right)^2$$

Revisiting the idea:

Phys.Rev.Lett. 85 (2000) 3568-3571
John F. Beacom, R.N. Boyd, A. Mezzacappa
Phys.Rev. D69 (2004) 103002
Enrico Nardi, Jorge I. Zuluaga

Conclusions

- Neutrinos from the Sun and Atmosphere reveal a fundamental property of nature (Nu. Oscillations).
- Still very unknown particles.
- Most of the high energy atmospheric in NuTelescopes studies involve 1 year of data! There is a lot more that will come with the new sterile update and next analysis(Talk by Carlos Arguelles).
- Low+High energy is the way to go for atmospherics in neutrino telescopes. (NSI by Thomas)
- Improving particle ID will tell us more about flavor (Talks by Anna Pollmann, Lutz Köpke and Mauricio Bustamante)
- **Just starting!** IceCube and Antares are here and there will be a lot more (Km3Net, Orca, IceCube Gen2, Radio Detection, ...)

Thanks!

A very sensitive phenomena!