Neutrino Superluminality - Models and Constraints

Fermilab Theory Seminar

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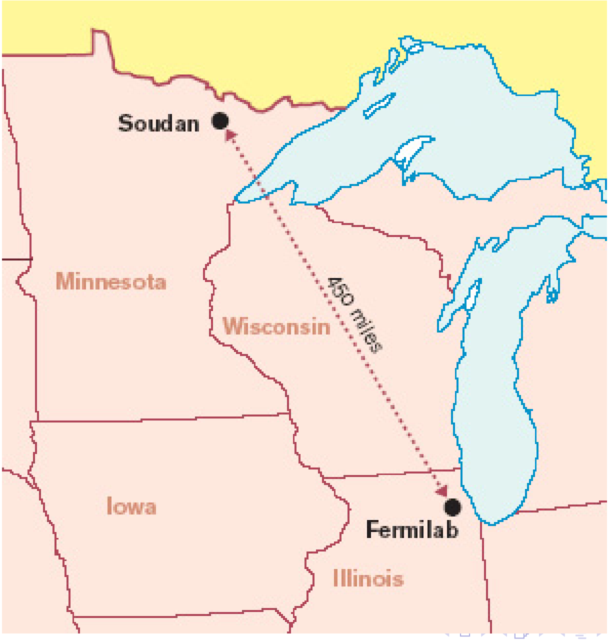
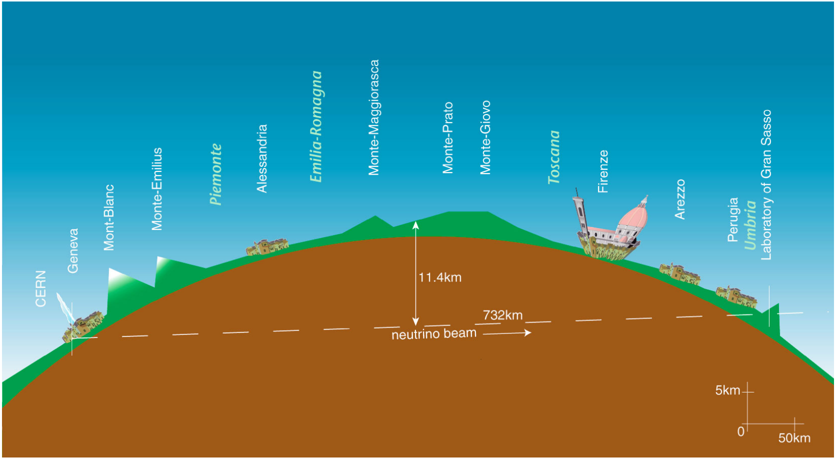
partly based on [A. Hebecker, AK, arXiv:1111.6579]

Outline

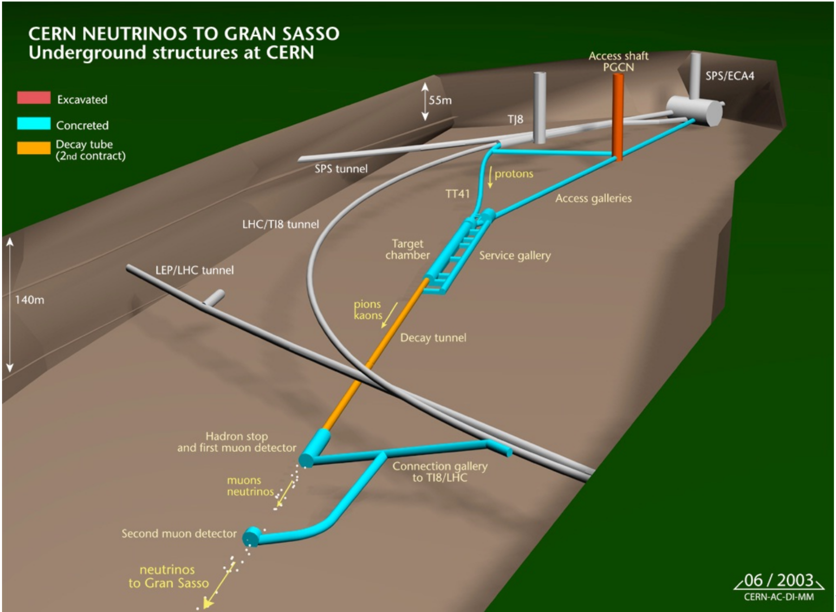
MINOS and OPERA



MINOS and OPERA



MINOS and OPERA



MINOS and OPERA

MINOS *arXiv:0706.0437*

- $E_{peak} \sim 3$ GeV
- $v^2 - 1 = (10.2 \pm 5.8) \times 10^{-5}$

OPERA *arXiv:1109.4897v1*

- $\langle E \rangle \sim 17$ GeV
- $10.5 \mu s$ extractions
- $v^2 - 1 \sim 5 \times 10^{-5}$ at 6.1σ

Potential problem: $10.5 \mu s$ extractions vs. $0.06 \mu s$ effect

OPERA *arXiv:1109.4897v2*

- $3ns$ bunches
- $v^2 - 1 \sim 5 \times 10^{-5}$ again

Energy dependence at OPERA

- $E > 20$ GeV: $\langle E \rangle = 40.7$ GeV, $\delta t \sim 68.1 \pm 19.1^{+7.3}_{-6.9}$
- $E < 20$ GeV: $\langle E \rangle = 13.8$ GeV, $\delta t \sim 54.7 \pm 18.4^{+7.3}_{-6.9}$

SN1987A

In 1987, a SN was observed in the LMC

- Distance $\sim 1.5 \times 10^9$ lh
- $E_\nu \approx 7 \ldots 40$ MeV, no energy dependence
- ν observed by three observatories $\sim$ 3 hours in advance of γ

Conservative conclusion:

$$v^2 - 1 < 10^{-9}$$

at this energy, in interstellar space. Alternative explanations:

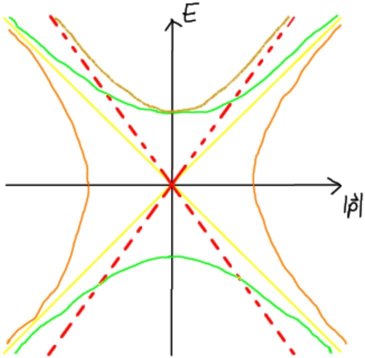
- coincidence
- only some neutrinos are (sub)luminal, e.g. due to flavor or lepton number
- strong energy dependence, i.e. power law $v \propto E^\alpha$.

Cohen-Glashow Strahlung

[Cohen,Glashow]

Superluminality from a LV dispersion relation $p^2 \sim m^2 + \Delta \cdot \vec{p}^2$

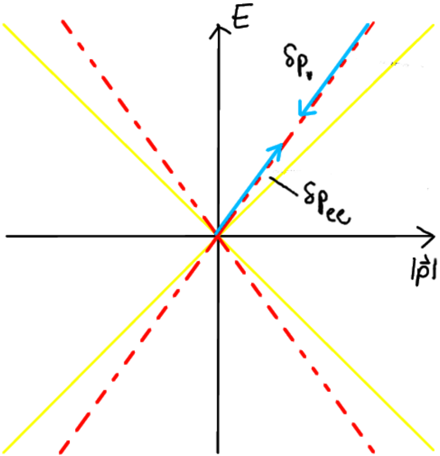
- In terms of effective metric, $\tilde{g}_{\mu\nu} p^\mu p^\nu = \tilde{m}^2, \quad -\frac{\tilde{g}^{00}}{\tilde{g}^{ii}} \sim 1 + \Delta$
- $v_{gr} = \partial E / \partial |\vec{p}| \longrightarrow (1 + \Delta/2)$ as limiting velocity



- slope $\rightarrow$ group velocity

Cohen-Glashow Strahlung

Consider $\nu \longrightarrow \nu + e^{+} + e^{-}$



$p_{ee}^{2} = \delta p_{\nu}^{2} > 0 \longrightarrow$ kinematically allowed!

Cohen-Glashow Strahlung

Quick argument for functional dependence on E and Δ

- Consider $E_\nu\sqrt{\Delta}$ as effective neutrino mass.
- three body EW decay rate $\sim G_F^2 m_{eff}^5$
- multiply $\sqrt{\Delta}$ to go from "rest" frame with $\Gamma = \frac{1}{m_{eff}}\int\ldots$ to earth frame with $\frac{1}{E}\int\ldots$
- $G_F^2 m_{eff}^5 = G_F^2 E^5 \Delta^{5/2} \rightarrow G_F^2 E^5 \Delta^3$

CG result:

$$\Gamma_{CG} = G_F^2 \frac{E^5\Delta^3}{14\cdot 192\pi^3}$$

Finite final state masses: $E_{TH} = 2m/\sqrt{\Delta}$

Cohen-Glashow Strahlung

- indiv. processes dominated by events with high energy loss

$$\Gamma_{CG} = G_F^2 \frac{1}{14} \frac{E^5 \Delta^3}{192\pi^3}$$

- model dependence in literature
- very strong energy dependence
- very sensitive to Δ

$\Gamma^{-1}(17 \text{ GeV}) \sim 600$ km, $\Gamma^{-1}(60 \text{ GeV}) \sim 1$ km, $\Gamma^{-1}(100 \text{ TeV}) \sim$ **pm**

- CNGS beam has $\langle E \rangle = 17$ GeV, but long tail-
  Reducing Γ for $E = 17$ GeV not enough.
- ICE CUBE 'upwards' events $E > 100\,TeV$
- For $E_\nu \gtrsim 40\,GeV$, $\nu \longrightarrow \pi + \pi + \nu$ opens up!
- ICARUS has searched for decay results

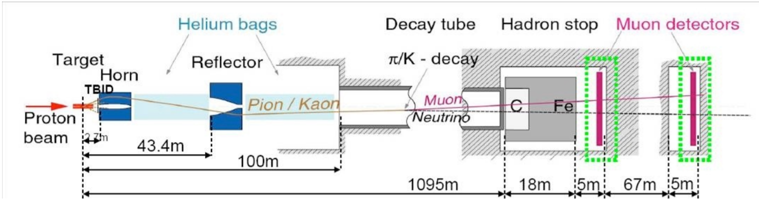
Pion Decay Kinematics

[Gonzalez-Mestres][Cowsik et al]
Consider $\pi^+ \longrightarrow \overline{\mu} + \nu$

Again, effective neutrino mass $\sqrt{\Delta} E_\nu$ affects kinematics.

Decay channel closes for $E > m_\pi / \sqrt{\Delta} \sim 20$ GeV

This would turn off CNGS neutrino production from pions!



Matter dependence?

All these problems are absent if SL is *[A Hebecker, AK]*

- **universal** (effectively restores standard kinematics for decays)
- **only present inside matter** (SL constraints and SN1987A)

Remarks

- SL must end very quickly outside matter, e.g. from synchrotron loss, $\delta v_e < 10^{-14}$ *[Altschul]*
- Fine tuning *[Giudice et al.]* from loop effects is avoided
- Lepton SL is not sufficient because of $\nu \longrightarrow \pi + \pi + \nu$ at ICE CUBE.

Alternatives?

- SL from neutrino oscillation effects *[Päs et al]*?
- 'deformed relativity': modified LT, conservation laws $\rightarrow$ covariant SL dispersion relation. Kinematical constraints go away *[Amelino-Camelia et al.]* but SN1987A remains difficult, field theory realization?
- New paper by *[Ciuffoli,Evslin,Bi,Zhang]*

For some more details $\rightarrow$ J. Evslin

Environmental SL from a Tensor

The earth is a source of LV *[Dvali, Vikman]*

$$\mathcal{L} \supset \frac{1}{M} t_{\mu\nu} T_{\psi}^{\mu\nu} - \frac{1}{M^*} t_{\mu\nu} T_{\nu}^{\mu\nu}$$

Pre CG proposal: $m_t^{-1} > R_E$, $M > M_{PL}$

- No fundamental LV
- Earth sources t with $1/M$
- t makes neutrino SL with $1/M^*$,
  $g_{\mu\nu}^{eff} = \langle \eta_{\mu\nu} - \frac{1}{M^*} t_{\mu\nu} \rangle \propto (1 + \frac{2\epsilon}{3}, -1 + \frac{\epsilon}{3}, -1 + \frac{\epsilon}{3}, -1 + \frac{\epsilon}{3})$
- results in the CG dispersion relation

Can this be adapted to our proposal?

- If quarks+gluons source t, they can't be SL (relative sign!)
- Use vector and couple it to B? ICE CUBE?
- Short range $\rightarrow$ t sourced by small volume, M, M^* low!

Matter dependence

Order of magnitude estimate: To obtain universality, assume LV spurion $\theta_{\mu\nu}$ and

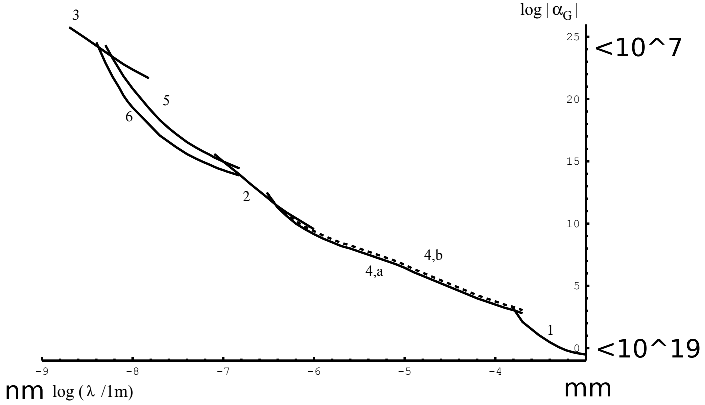
$$\mathcal{L} \supset -\frac{m^2}{2}\phi^2 + \frac{1}{\Lambda}\phi\theta_{\mu\nu}T^{\mu\nu}$$

- $\rho_E = 3\ldots5 \times 10^{-17}$ GeV^4
- Sourced locally:
$$\langle\phi\rangle \sim \frac{\rho_E}{m^2\Lambda}$$
- $\Delta \sim \frac{\rho_E}{m^2\Lambda^2}$, DV Case: $\Delta \sim \frac{\rho_E}{m^2 MM^*}$
- For $\Delta = 5 \times 10^{-5}$ and $m^{-1} \sim 10^{-10}\ldots10^{-6}$ met

$$\Lambda \sim 0.1 \text{ GeV} \ldots 1 \text{ TeV}$$

Short range 5th force bounds

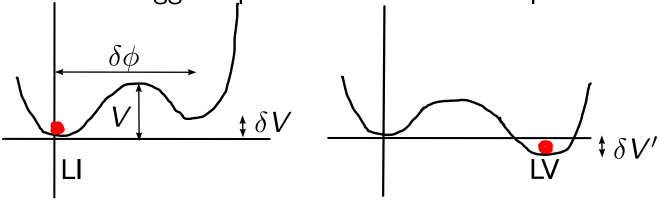
[Bordag et al.], New Developments in the Casimir Effect



$$V(r) = \frac{G_N m_1 m_2}{r}\left(1 + \alpha e^{-mr}\right)$$

Superluminality from a phase transition?

Idea: let matter trigger a phase transition to a 'superluminal phase'



Properties of the domain wall:

- Wall thickness $b \sim \delta\phi/\sqrt{V}$
- Surface tension $\sigma \sim \delta\phi^2/b$
- Critical bubble $R_c \sim \sigma/\delta V$

Simple ren. model:

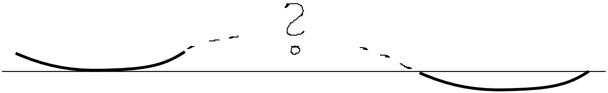
$$\mathcal{L} \supset \frac{\lambda}{4}\left[\left(\phi - \frac{\mu}{\sqrt{\lambda}}\right)^2 - \frac{\mu^2}{\lambda}\right]^2 + \mu^2\phi^2\,\epsilon - \frac{\phi}{\Lambda}\theta_{\mu\nu}T^{\mu\nu}$$

$m \sim \mu, V \sim \mu^3/\lambda, \delta\phi \sim \mu/\sqrt{\lambda}, \sigma \sim \mu^3/\lambda$

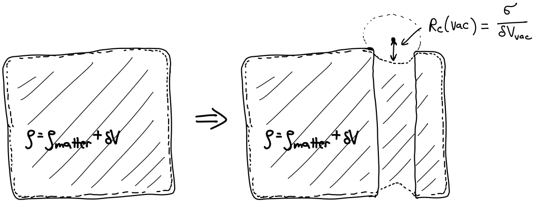
Want $\Delta \sim \delta\phi/\Lambda \sim \frac{m}{\sqrt{\lambda}\Lambda} \longleftrightarrow \sigma$

In order to find viable model, need to relax assumptions about the potential

$$-V(\phi) + f(\phi)\theta_{\mu\nu}T^{\mu\nu} + g(\phi)T \ldots$$



- Critical bubble in vacuum small (synchrotron bounds)



- Can we have $\sigma \sim \delta\phi\sqrt{V}$ small enough to have negligible force of separation?
- Could SL phase be only inside earth? (very large critical bubble in matter)
- Large model building freedom $\rightarrow$ ongoing work

Conclusions

- MINOS and OPERA observe compatible early neutrino arrival times $\sim v^2 - 1 \sim 5 \times 10^{-5}$
- SN1987A indicates no superluminality at MeV energies and/or in empty space for SN neutrinos
- LV superluminality changes kinematics $\Rightarrow$ CG-effect, pion decay problem
- We leave neutrino oscillations untouched and stay within effective field theory
- This leads us to universal superluminality as a matter effect
- Simple communication of matter effect in contradiction with precision measurements
- More general effective Lagrangians could provide enough freedom to have a SL phase transition inside Earth