# Brane, Bulk,

# and

# Superluminal Travel

Galileo Inst, June 2012

Tom Weiler, Vanderbilt Univ

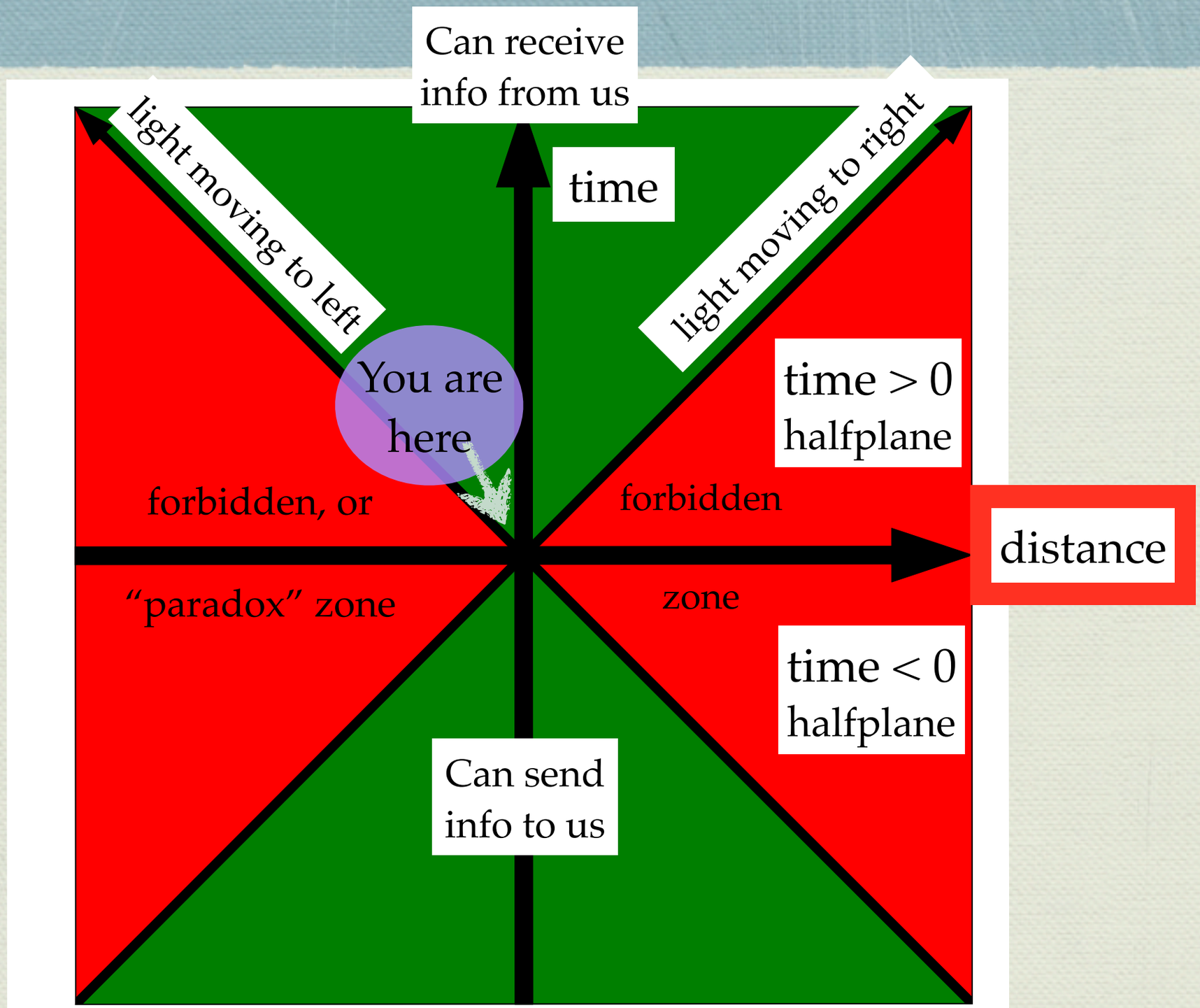
# Some entity in any collection has to be the mostest --

## But neutrinos faster than light !?&*#%!


Usain Bolt at the Beijing Olympics

# Why superluminal motion is profound:

## (Spacetime Diagram, with future cone, past cone, and forbidden regions/negation of cause and effect)



Consider the "vacuum Cerenkov" process

$$\nu \to e^+ e^- \nu \,.$$

Now boost to a frame where t'=0, so that

$$e^+ e^- \nu \leftrightarrow \nu$$

- With the boost, the neutrino is confused and radiates;
- algebra gives

$$\gamma = \frac{v}{\sqrt{v^2-1}} \sim \frac{1}{\sqrt{2\,(v-1)}} \sim \frac{1}{\sqrt{2 \times 2.5 \times 10^{-5}}} \sim 140\,.$$

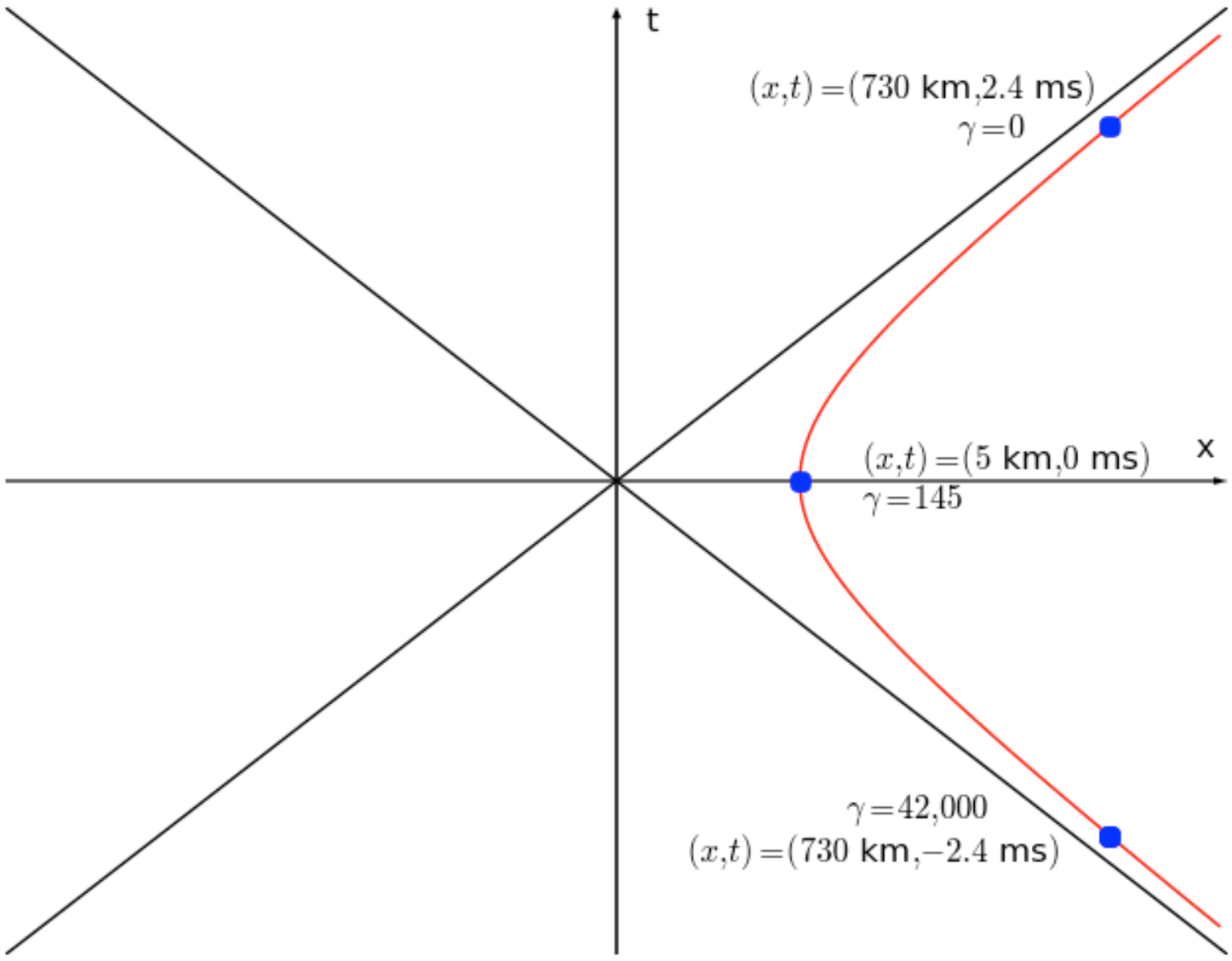
- The threshold energy is then $\gamma \times (2m_e) \sim 140\mathrm{MeV}\,.$ (Cohen-Glashow)

A rocket ship moving at $\gamma$ intercepts CERN's neutrino at $(t, x)_{\text{OPERA}}$,
and a ground station replies with another neutrino:

$$\text{At } t' = \gamma\, t - \beta\gamma\, x = -t\,, \text{with } \frac{x}{t} = v_\nu\,,$$

- the reply neutrino arrives at CERN simultaneous with the emission of the original neutrino, the rocket effecting a
- Closed Timelike Curve (CTC)
- algebra gives $$\gamma = \frac{v^2+1}{v^2-1} \sim \frac{2}{2\,(v-1)} \sim \frac{1}{2.5\times 10^{-5}} \sim 40,000$$

# The “spacelike” hyperbola, negation of cause and effect, paradox, and a skeptical Einstein:



# And now some theoretical modeling:

- Experimental constraints -- non-tachyonic dispersion rel'n, SN87a, ... -- seem to require superluminal neutrinos to travel in "extra dimensions" (fundamental to string theory).

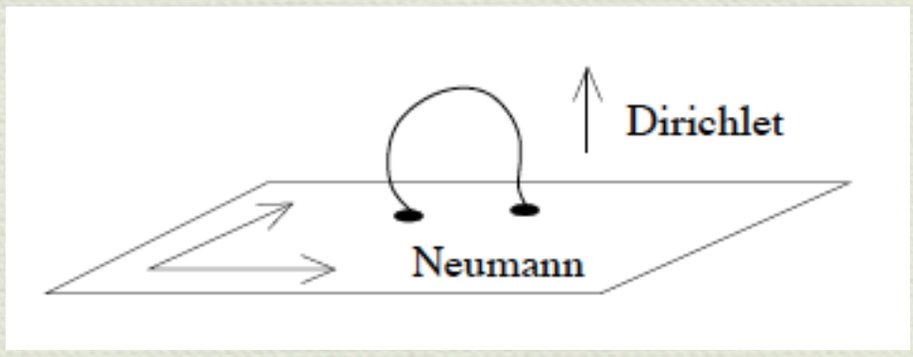
- We turn to brane vs. bulk, and geometry,

  originally formulated in the pre-OPERA years.

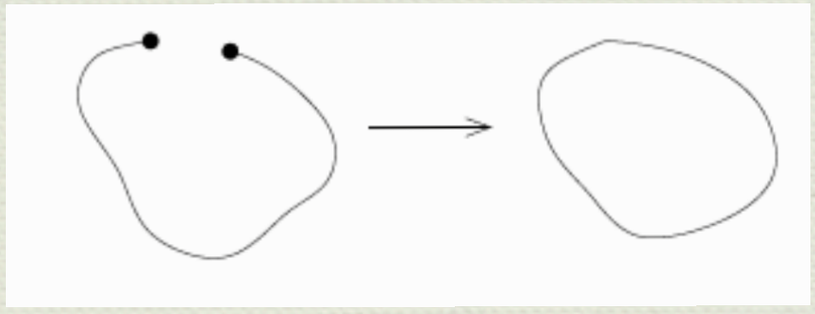
# (Mem)branes and the incredible bulk, shortcuts offering apparent time-travel

Einstein's gravity is geometry.
Wherever there is space and time, there is geometry.
And so in the brane and bulk,
there is gravity, and extra neutrinos (?) and ...

## The ADD universe has open and closed strings:

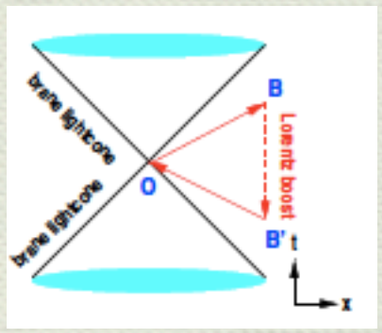



Open strings have gauge charge at the ends, stuck to the brane -- all SM particles



Closed strings are not confined -- gravitons, sterile neutrinos, singlet Higgses

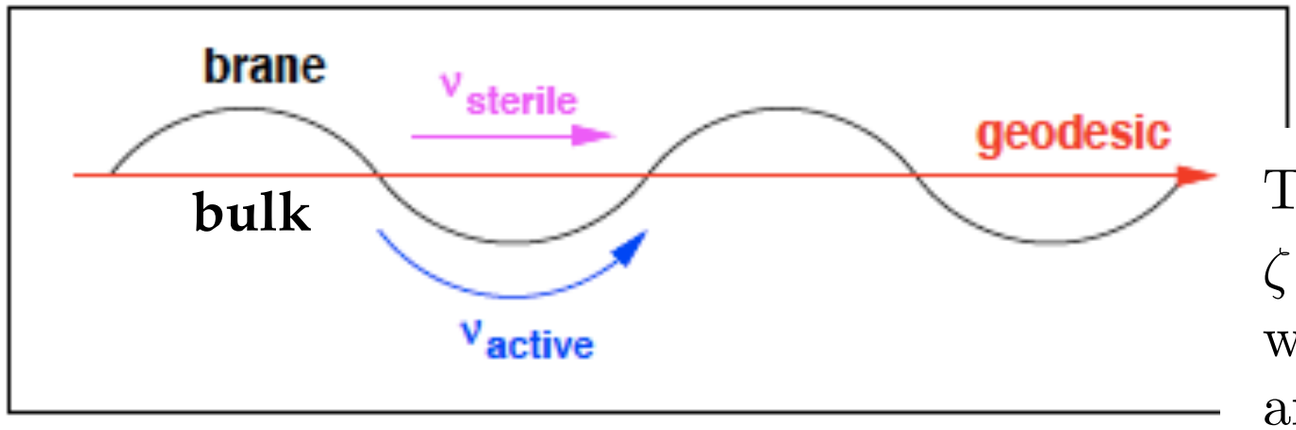
# Neutrinos in-the-bulk, pre-Opera (for street cred):




**Sterile-active neutrino oscillations and shortcuts in the extra dimension**

Heinrich Päs[1], Sandip Pakvasa[1], Thomas J. Weiler[2]

(2005)




The relative time advance is given by

$\zeta \equiv \left(\frac{Ak}{2}\right)^2$

where $A$ is the fluctuation amplitude and $k$ is the fluctuation wave number.

**Neutrino time travel**

(2007)

James Dent[1], Heinrich Päs[2], Sandip Pakvasa[3], and Thomas J. Weiler[1]

## Abstract

We discuss a possible new resonance in active-sterile neutrino oscillations arising in theories with large extra dimensions. Fluctuations in the brane effectively increase the path-length of active neutrinos relative to the path-length of sterile neutrinos through the extra-dimensional bulk. Well below the resonance, the standard oscillation formulas apply. Well above the resonance, active-sterile oscillations are suppressed. We show that a resonance energy in the range of $30-400$ MeV allows an explanation of all neutrino oscillation data, including LSND data, in a consistent four-neutrino model.


The quantum mechanics of the model is simple. The flavor-oscillation amplitude for a propagating neutrino is

$$A(\nu_\alpha \to \nu_\beta) = \langle \nu_\beta | \, e^{-iHt} | \nu_\alpha \rangle \, .$$

A component of $Ht$ that is proportional to the identity cannot affect flavor change, and can be subtracted.

The remainder is $\delta(Ht) = (\delta H)t + H(\delta t)$.

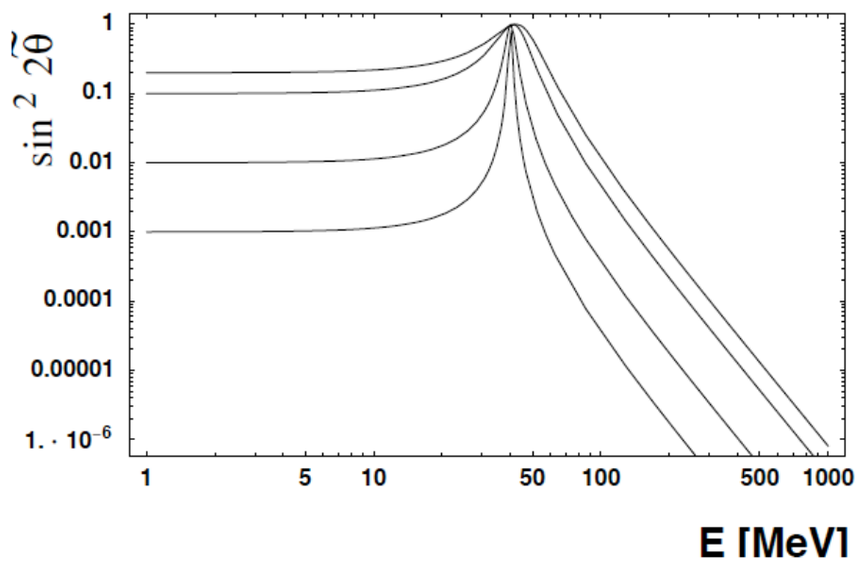



Figure 2: Oscillation amplitude $\sin^2 2\tilde{\theta}$ as a function of the neutrino energy $E_\nu$, for a resonance energy of $E_{\rm res} = 40$ MeV. The different curves correspond to different values for the standard angle, $\sin^2 2\theta = 0.2, 0.1, 0.01, 0.001$ (from above).

# Baseline-dependent neutrino oscillations with extra-dimensional shortcuts

Sebastian Hollenberg,[1,*] Octavian Micu,[1,†] Heinrich Päs,[1,‡] and Thomas J. Weiler[2,§]

(2009)

We choose a warp factor of the form $\eta(u) = e^{-k|u|}$, with $k$ assumed to be a (presently) unknown constant of Nature with dimension of inverse length [24]. Standard Model neutrinos live in the 4D Minkowski spacetime, while the sterile neutrinos experience the full five dimensional metric. We may choose the direction of the brane component of neutrino velocity to be along $x$; this allows us to set $dy$ and $dz$ to zero from here on. Our line element is reduced to

$$d\tau^2 = dt^2 - e^{-2k|u|}\, dx^2 - du^2 \,. \tag{13}$$

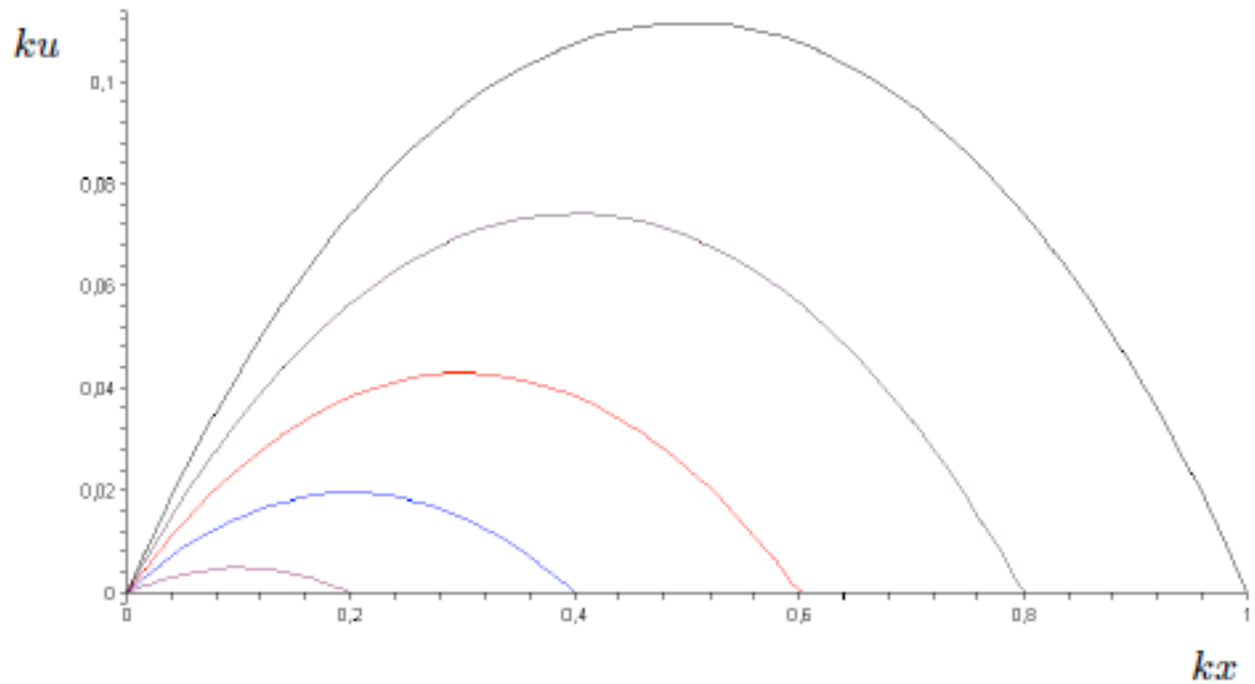



FIG. 1: Sterile neutrino travel path in the extra dimension for a travel "distance" $kl = 0.2, 0.4, 0.6, 0.8, 1$ as measured on the brane.

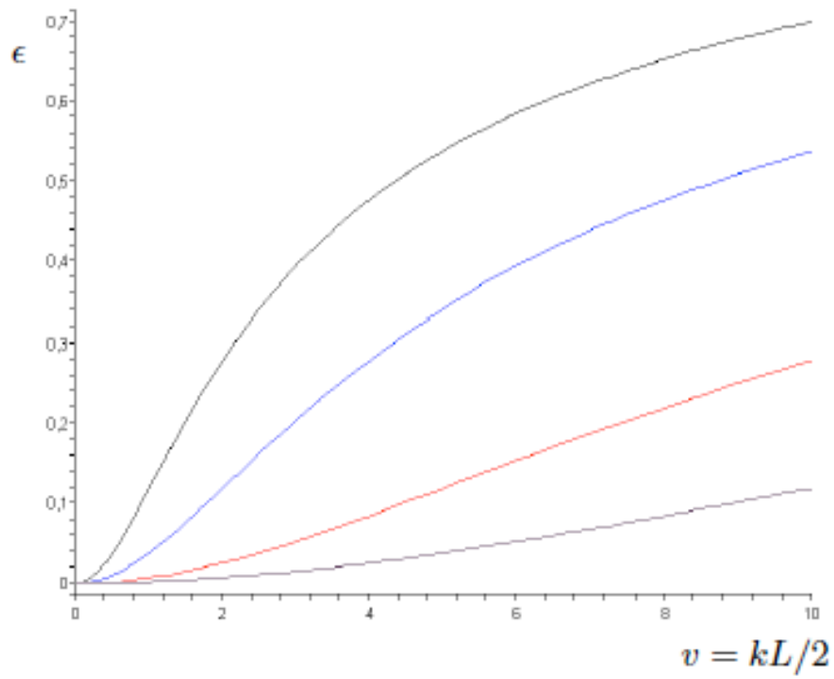
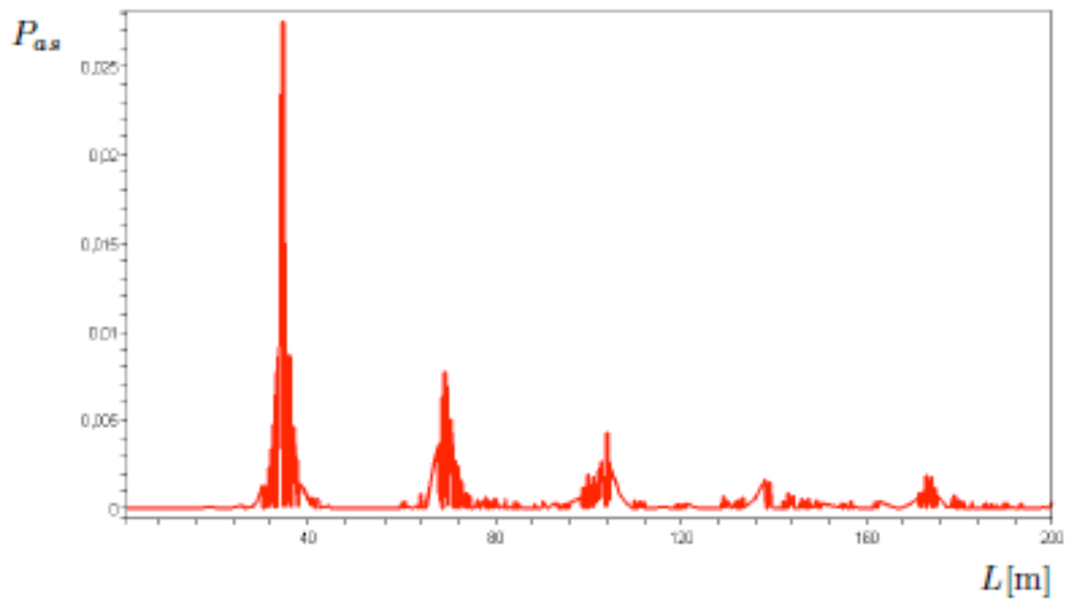



FIG. 2: The shortcut parameter as a function of scaled baseline length $v = kL/2$. Curves are parametrized by geodesic mode number $n = 1, 2, 5, 10$ (from top to bottom).




A (diminishing) resonance at each brane crossing

# L*E resonances

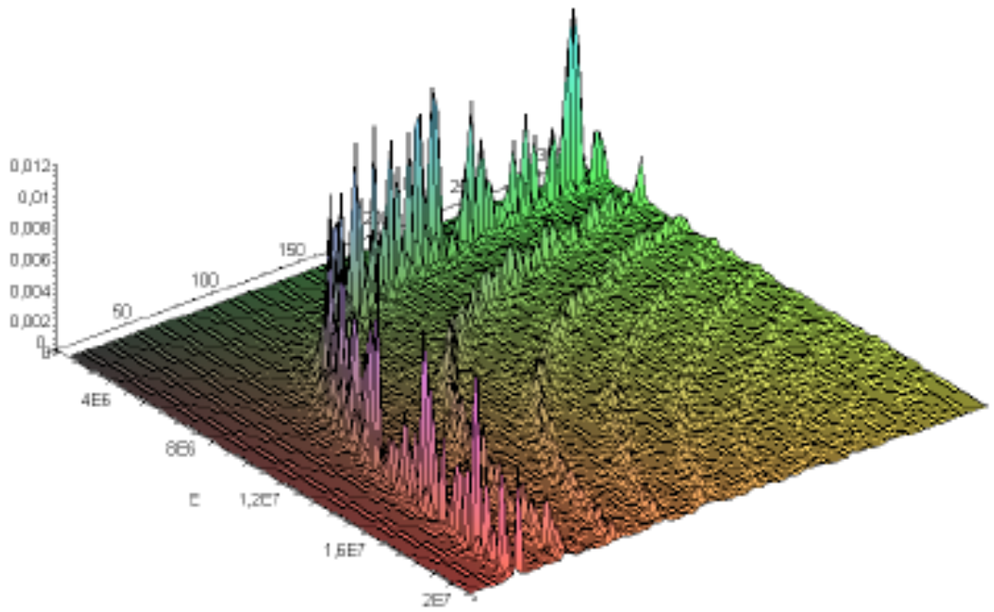
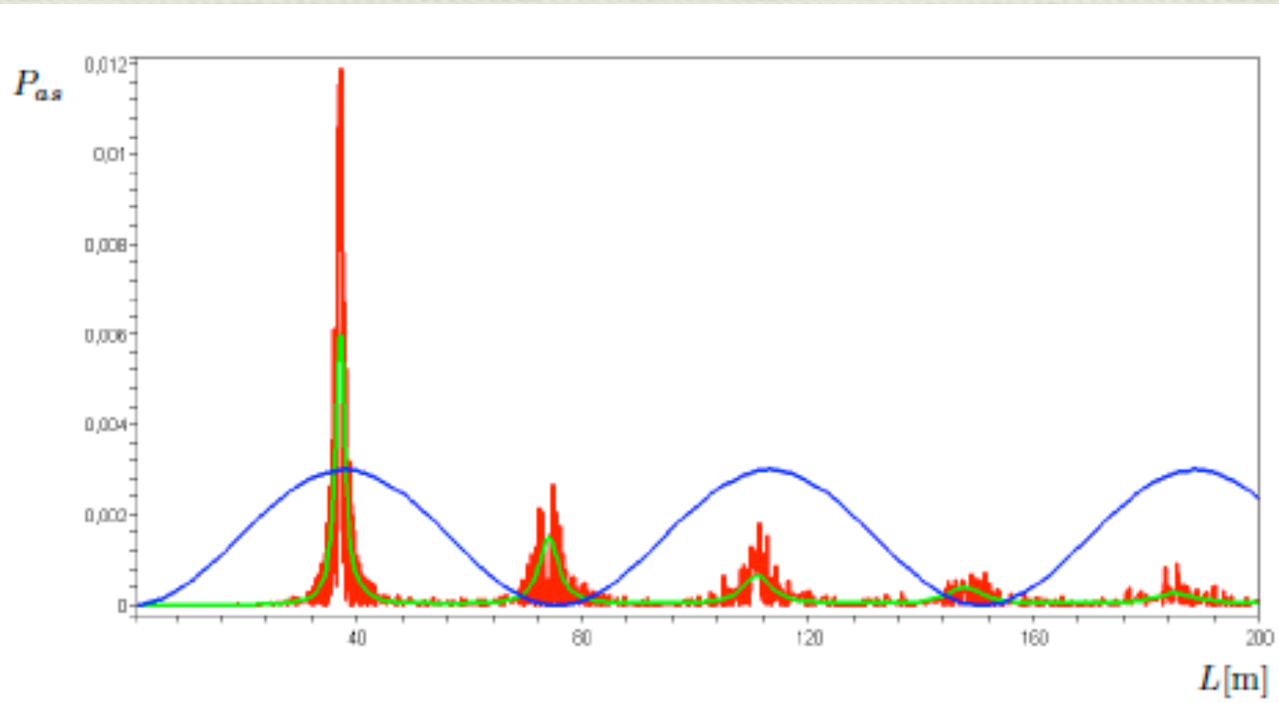
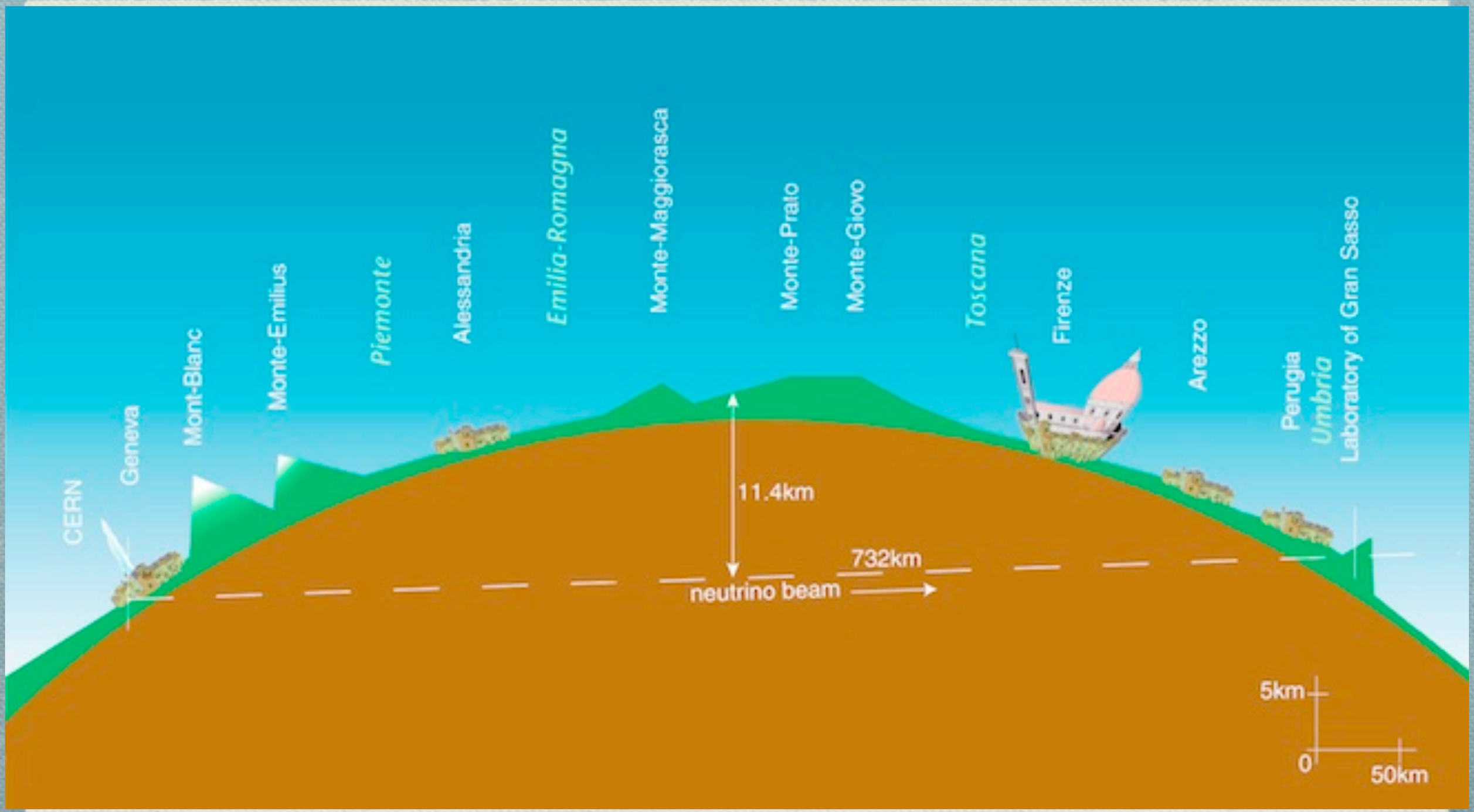



FIG. 5: Oscillation probability (vertical) in the $L$-$E$ plane,




red curve: paths;  green curve: path-integral sum;
red curve: standard 4D vacuum oscillation

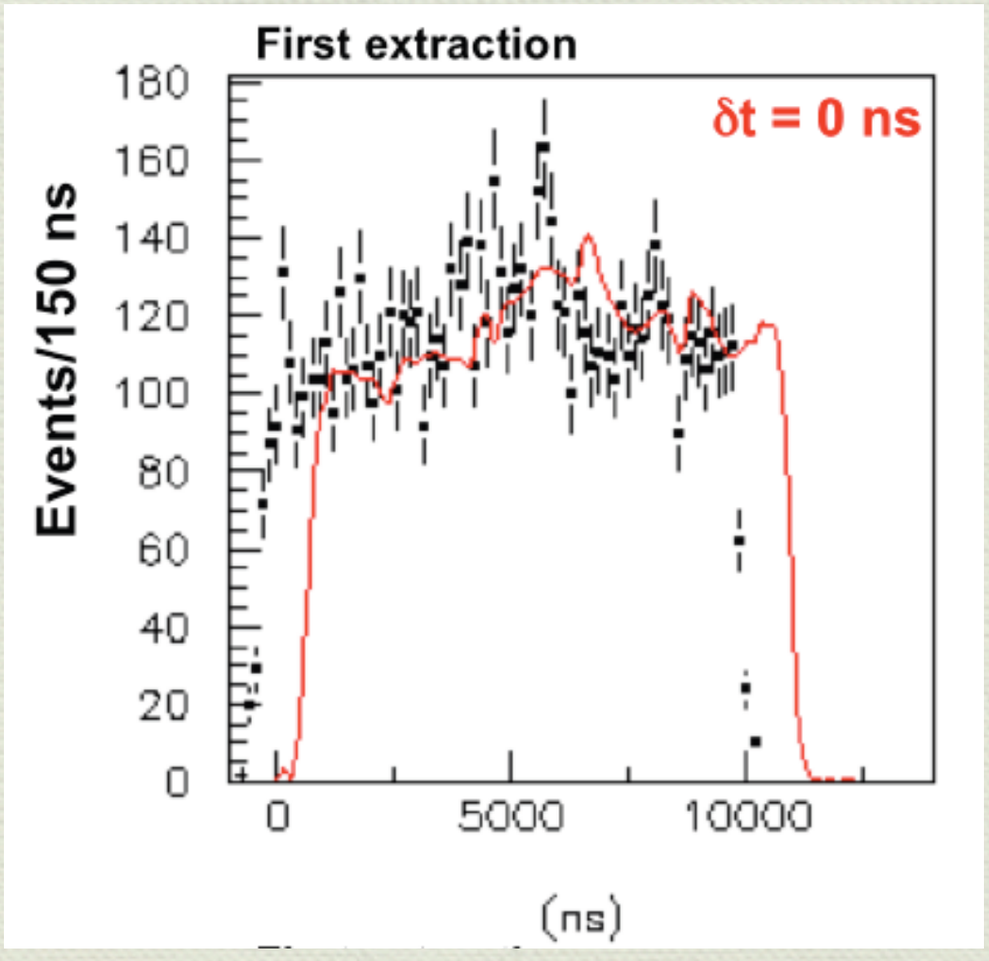
# Schematic of the Neutrino Experiment:

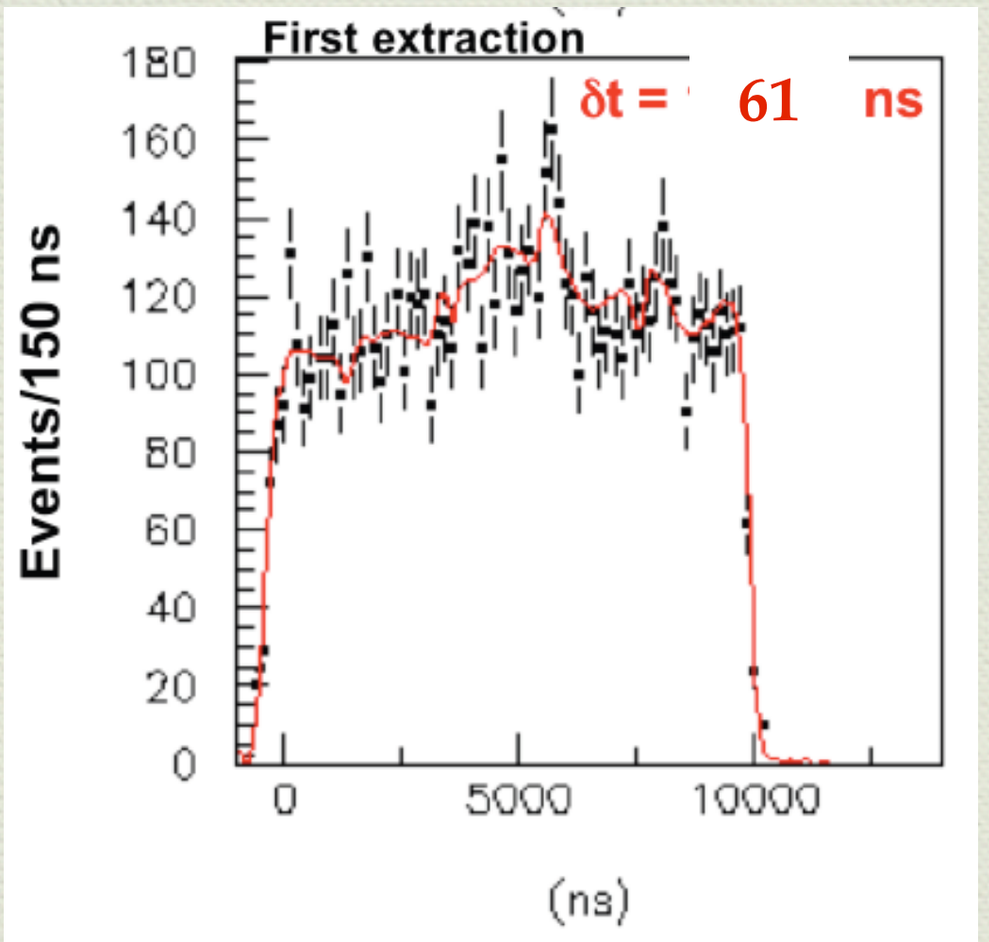


September 2011:
!! OPERA Experiment infers faster-than-light NEUTRINOS !!

$$\delta t = 61 \text{ ns early, or } v = c + 2.5 \times 10^{-5} c$$

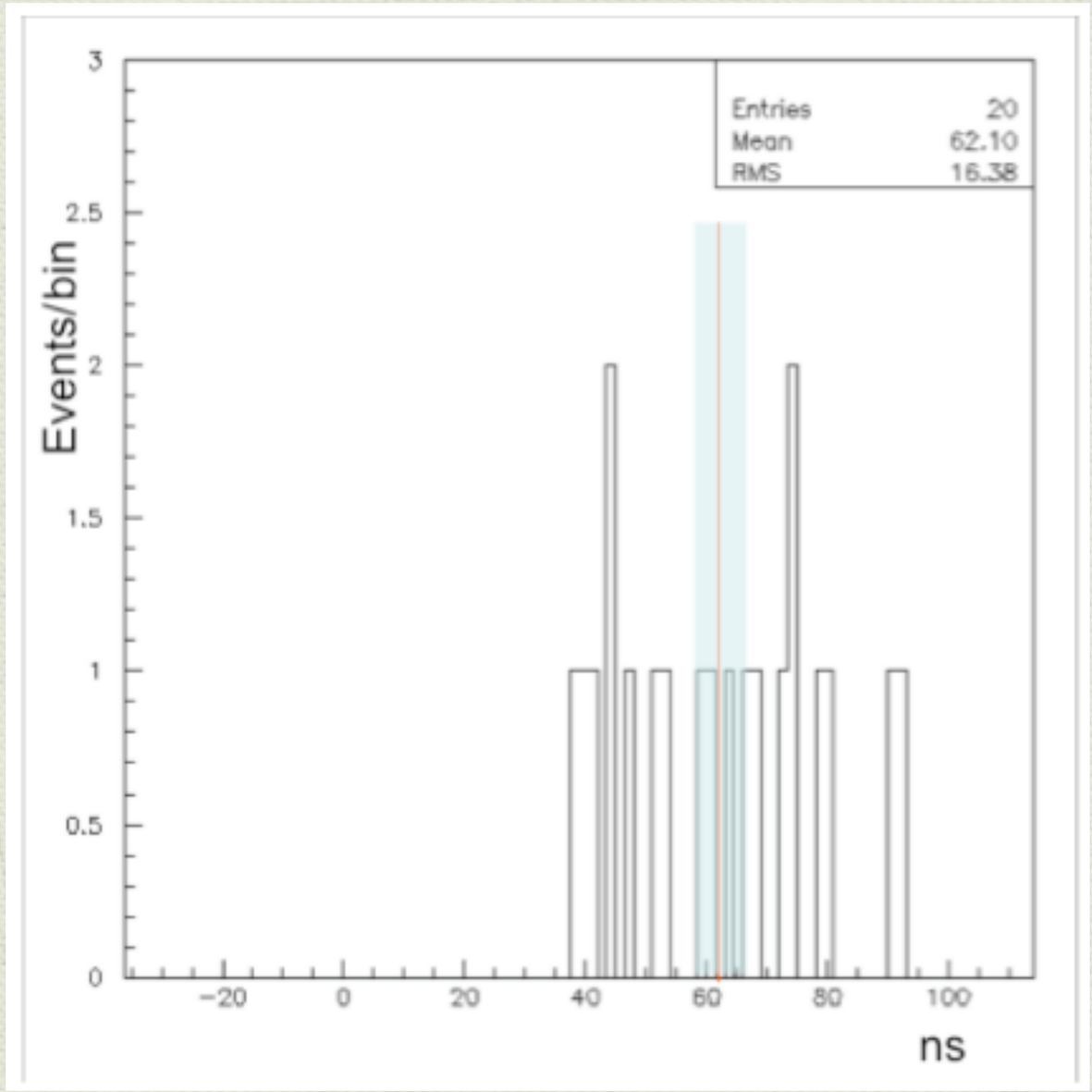
Fitting data without, and with, superluminal speed:

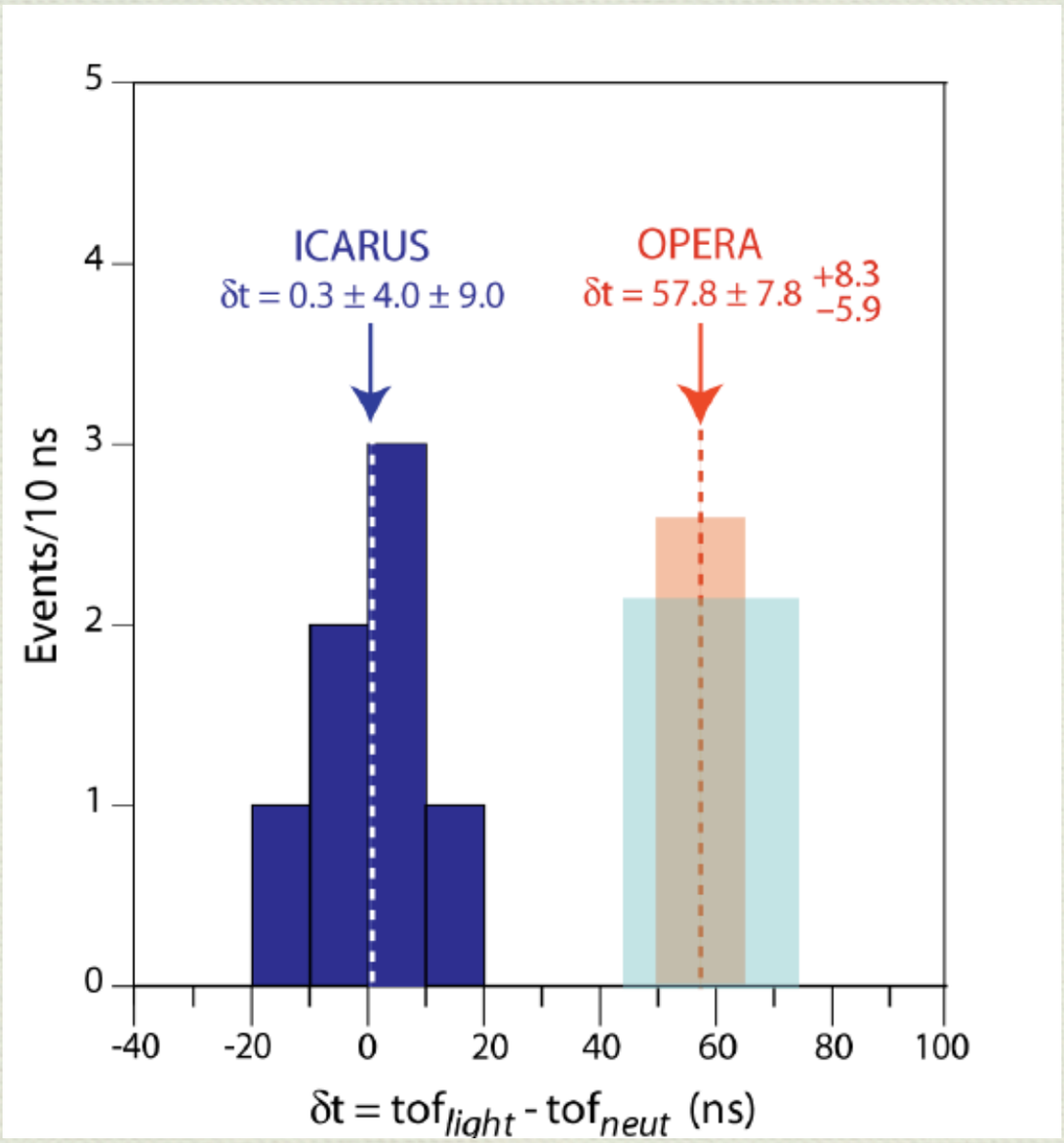


After Geneva optimizes the beam for NEUTRINO experiments, OPERA (Nov 2011) and ICARUS (March 16, 2012) detectors find:

## OPERA: no events within 37 ns of light arrival time!



# Whereas neutrinos want to arrive bi-modally:

$$\lambda_{osc} = 2.57\text{km} \times \left(\frac{E_\nu}{\text{GeV}}\right)\left(\frac{\text{eV}^2}{\delta m^2}\right)$$

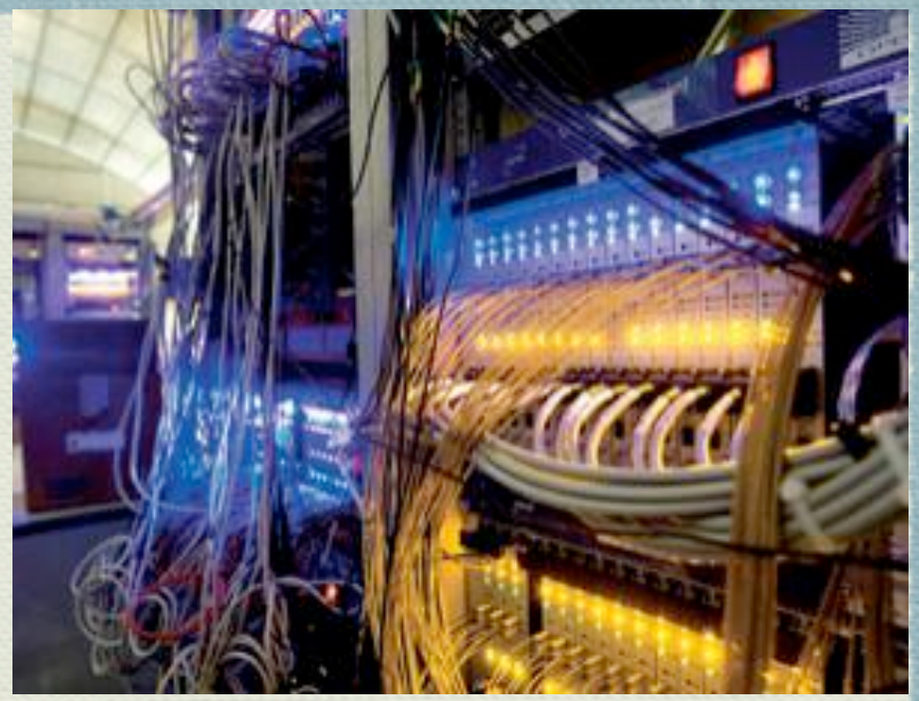
- which implies a number of oscillations

$$N_{osc} = \frac{L}{\lambda_{osc}} = \left(\frac{732\text{km}}{2.57\text{km}} \sim 300\right)\left(\frac{\delta m^2}{\text{eV}^2}\right)\left(\frac{\text{GeV}}{E_\nu}\right)$$

- which implies (two) mass states decohere, arriving separately with active probabilities $\cos^2\theta$ and $\sin^2\theta$.
- Maybe there is a "but ...", but .....

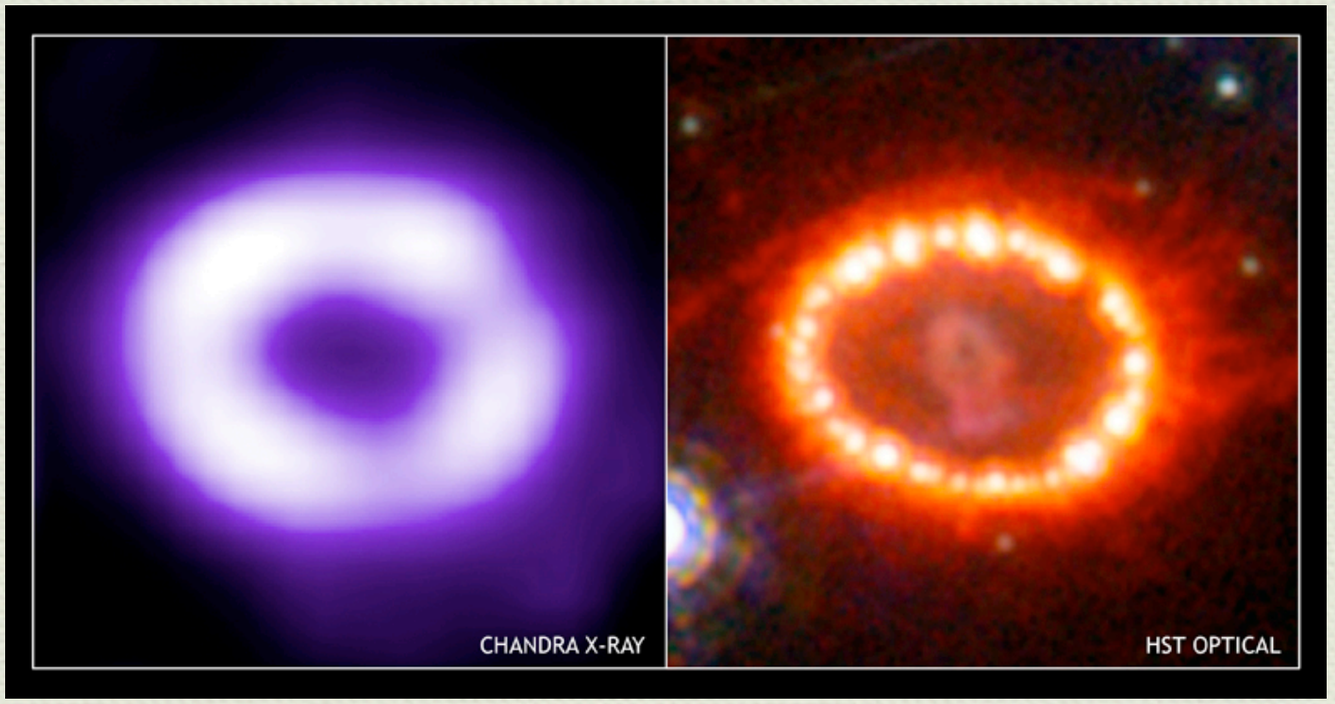
# So the present experimental situation is uninspiring

- And the big revelation from OPERA:
  - One fiber optic cable connection likely responsible for the 60ns.



A new data set is being taken, but there is no motivation for a revolutionary result.

# Meanwhile, have neutrino events from Supernova 1987A (LMC)




- From 170,000 light-years away, 30 $\nu_e$ events arrived just a few hours before the light signal.
- Had the nu's preceded light by the OPERA amount, they would have arrived four years earlier.

# And a Post-OPERA neutrino paper (with abstract):

(2 Dec 2011)

## A model of superluminal neutrinos

D. Marfatia,[1] H. Päs,[2] S. Pakvasa,[3] and T. J. Weiler[4]

Motivated by the tentative observation of superluminal neutrinos by the OPERA experiment, we present a model of active-sterile neutrino oscillations in which sterile neutrinos are superluminal and active neutrinos appear superluminal by virtue of neutrino mixing. The model demonstrates some interesting possibilities and challenges that apply to the OPERA result.

Model failed twice for SuperK (with similar L/E):
(i) steriles at OPERA => steriles at SuperK, but SK data says no
(ii) OPERA => decoherence at much larger L of SK,
yet SK sees coherent oscillation dip and peak

# What's next?

- "Extraordinary claims [time-traveling particles] require extraordinary evidence."
  - In progress, testing by the MINOS experiment in the US (Fermilab ---> Soudan MN,

    and eventually by many other experiments in Japan and Europe, including more data from OPERA and ICARUS

  Possible distortions of Einstein's time are too important not to test,

  and test,

  and test again.

- And perhaps Geneva's LHC itself will make a "negative-time traveling" discovery!

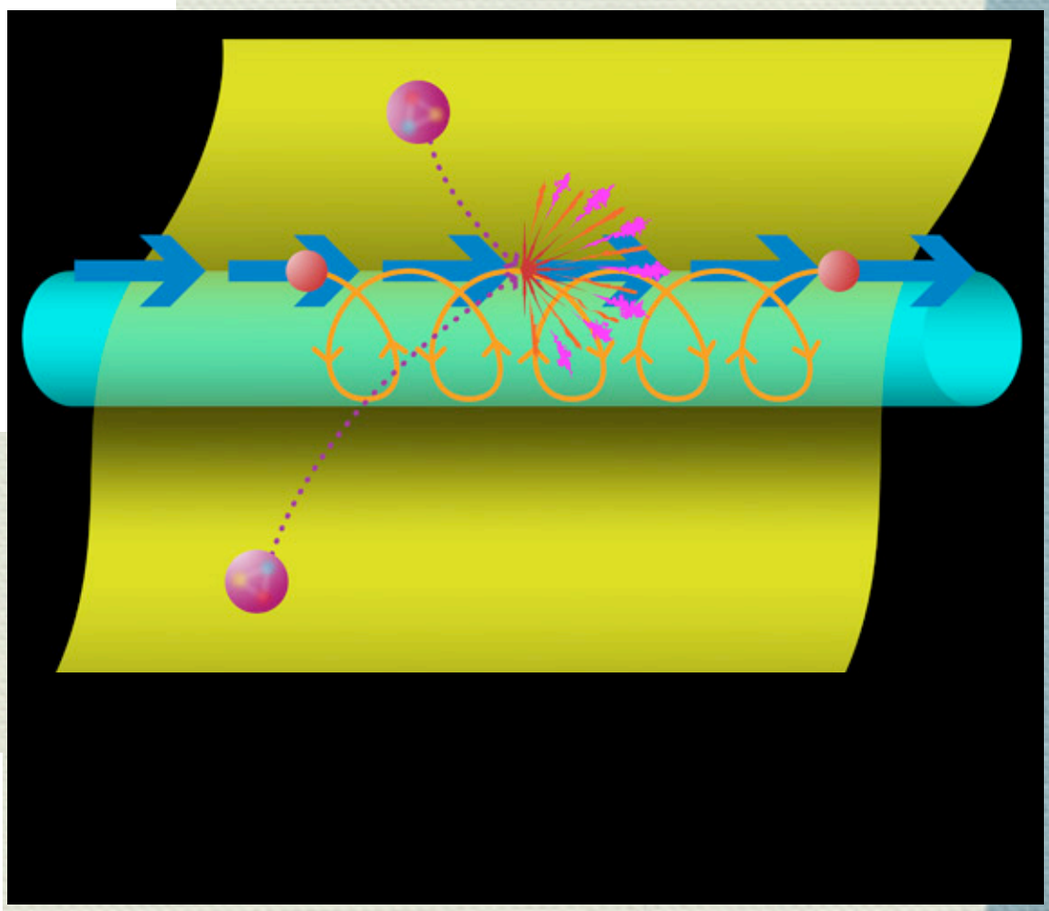
# And for Atlas and CMS detectors at the LHC:

**Causality-Violating Higgs Singlets at the LHC**

C. M. [1,*] and Thomas J. Weiler[1,†]

[1] *Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, USA*

(2011)



following on (2009):

**Closed timelike curves in asymmetrically warped brane universes**

Heinrich Päs[1], Sandip Pakvasa[2], James Dent[3], Thomas J. Weiler[3]

## Abstract

We construct a simple class of compactified five-dimensional metrics which admits closed timelike curves (CTCs), and derive the resulting CTCs as analytic solutions to the geodesic equations of motion. The associated Einstein tensor satisfies all the null, weak, strong and dominant energy conditions. In particular, no negative-energy "tachyonic" matter is required. In extra-dimensional models where gauge charges are bound to our brane, it is the KK modes of gauge-singlets that may travel through the CTCs. From our brane point of view, many of these KK modes would appear to travel backward in time. We give a simple model in which time-traveling Higgs singlets can be produced by the LHC, either from decay of the Standard Model Higgses or through mixing with the SM Higgses. The signature of these time-traveling singlets is a secondary decay vertex pre-appearing before the primary vertex which produced them. The two vertices are correlated by momentum conservation.


consider the following form for the metric

$$d\tau^2 = \eta_{ij} dx^i dx^j + dt^2 + 2\, g(u)\, dt\, du - h(u)\, du^2$$

Godel-vonStockum-Tipler like

Intrinsically flat - it's a "rotating torus"

Now set $Det = g^2 + h$ equal to one.
Maintains Minkowski metric on brane, and offers analytic solutions to geodesic ($E$-$L$) eqns.

the general metric function $g(u)$ is

$$g(u) = g_0 + A - \sum_{n=1}^{\infty} \left\{ a_n \cos\left(\frac{2\pi\, n\, u}{L}\right) + b_n \sin\left(\frac{2\pi\, n\, u}{L}\right) \right\}$$

$g(0) = g_0$ and $A \equiv \sum_{n=1}^{\infty} a_n$ are constants. An analogous expansion

# Find CTCs for "co-rotating" particles

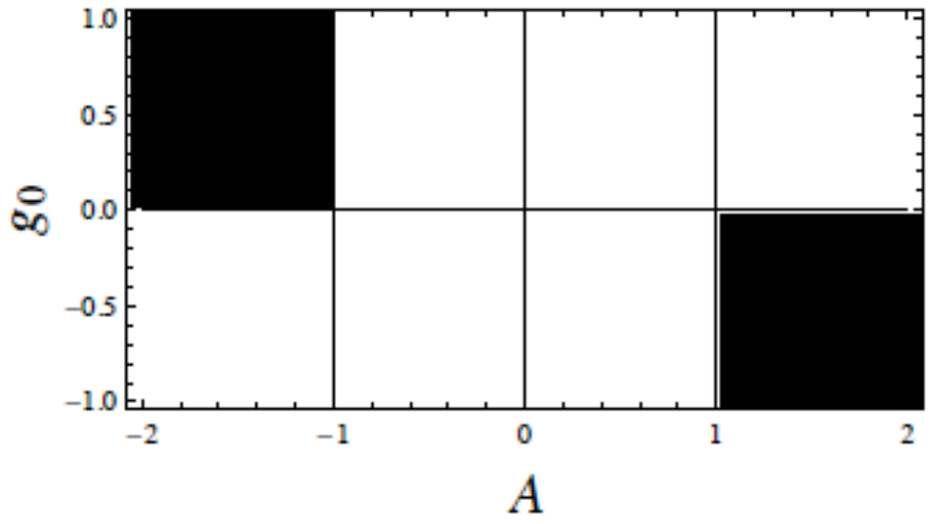
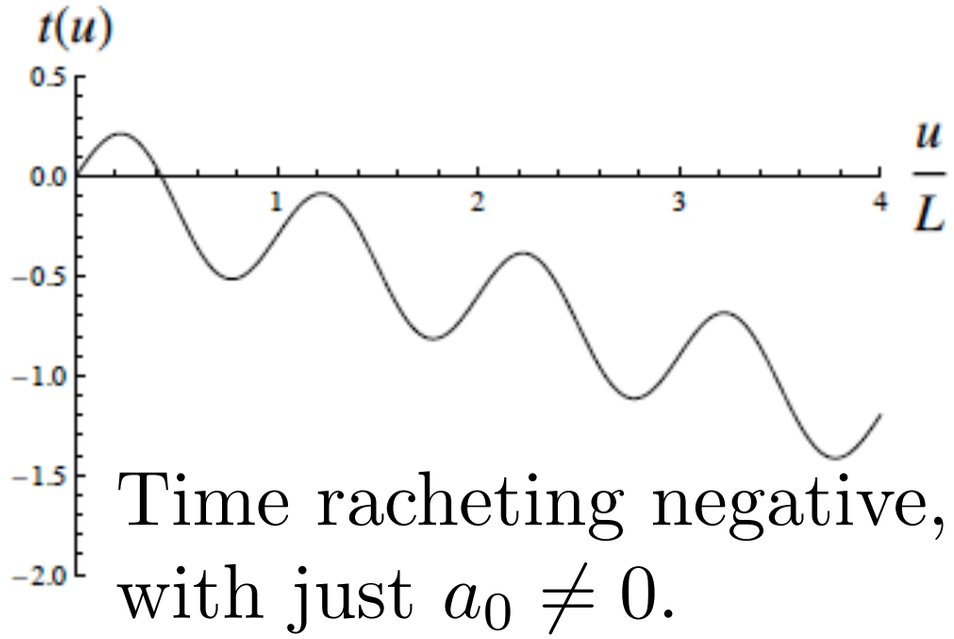



FIG. 5: The two regions in the $g_0$–$A$ plane for which CTCs are possible.




Time racheting negative, with just $a_0 \neq 0$.

# The (verbal) conclusion

The mathematics of Einstein's equations allows logical paradoxes, including the temporal confusion of cause and effect, the mixing of past and future times that occurs if any particle travels faster than light. Whether Nature has chosen to adopt this bizarre option is one of her deep secrets. However, incredibly sophisticated and sensitive instrumentation is now able to investigate this option, by measuring pre-arrival times.

(And a new revolution is overdue.)