Time & space varying neutrino masses from soft topological defects.

by Dvali, Funcke, Vachaspati 2112.02107.

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Mass of neutrinos

Traditionally,
some physics at high energies.

Supersymmetry
Banakli, Smirnov (1997)
Dvali, Nir (1998)

Seesaw
Yanagida (1979)
Gell-Mann, Ramond, Slansky (1979)

Extra dimensions
Arkani-Hamed, Dimopoulos, Dvali, March-Russell (1998)
Dienes, Dudas, Gherghetta (1998)

Time-varying neutrino mass

Neutrinos coupled
to some light scalar field.

Kawasaki, Murayama, Yanagida (1992)
Yukawa coupling to light scalar

Stephenson, Goldman, McKellar (1996)
neutrino clouds and structure formation

Fardon, Nelson, Weiner (2003)
as dark energy

In some cases, the cosmology bound (CMB, BAO)

$$\Sigma m_\nu < 0.12 \text{ eV}$$

from $N_{\rm eff}$, free-streaming, CMB peak shift

can be relaxed to larger value.

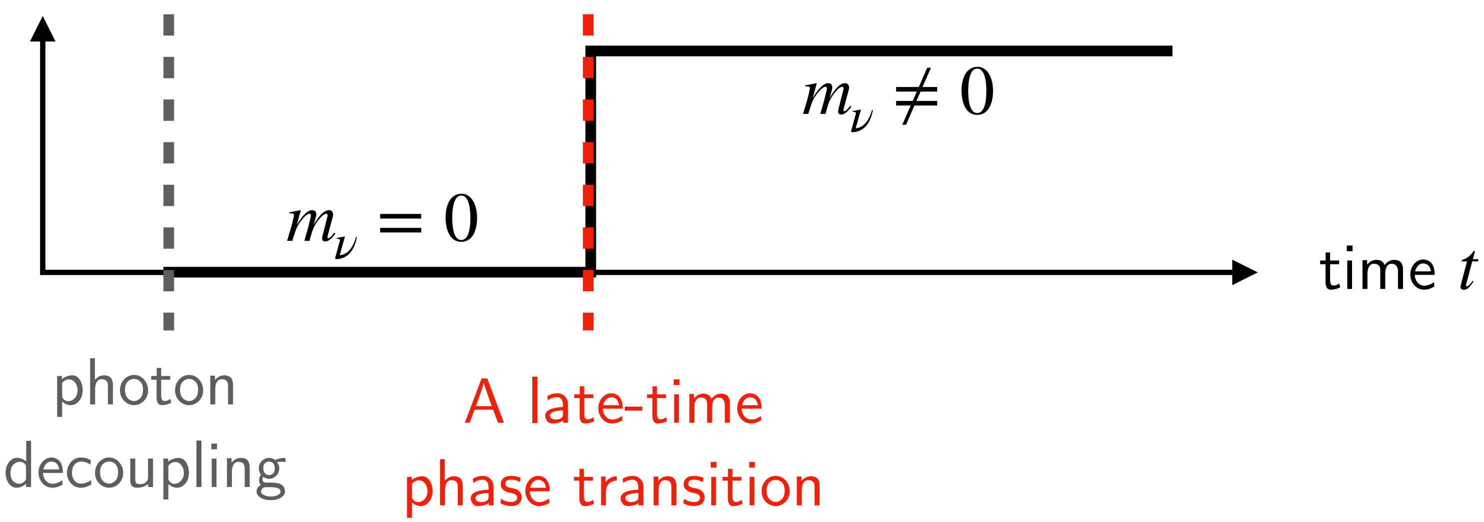
(e.g. m_ν just grows ver recently.)

Another avenue

Dvali and Funcke 1602.03191

Neutrino mass from gravitational θ-term

required only Standard Model particles.



which could also be of the first-order and/or supercooled.

Lorenz, Funcke, Calabrese, Hannestad (1811.01991)

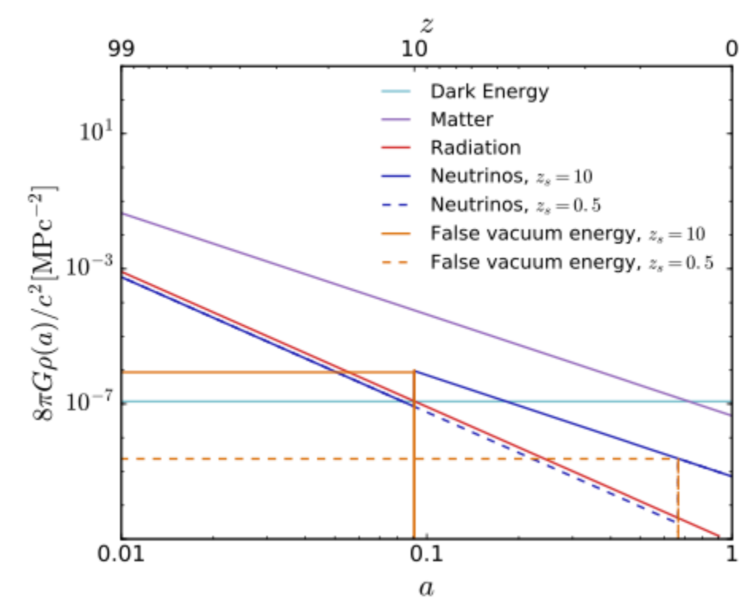


FIG. 1. Energy densities for different components present in our analysis: neutrinos with a time-varying mass generated at $z_s = 10$ ($z_s = 0.5$) and corresponding to $\sum m_\nu = 0.2$ eV today with solid (dashed) curves, false vacuum energy, standard dark energy, matter (baryons and cold dark matter), and radiation.

Dvali & Funcke (2016): neutrino masses generation from gravitational θ-term

Analogue to the QCD θ-term. $\mathscr{L} \supset \theta G\tilde{G}$

Gravity case $\mathscr{L} \supset \theta_G R\tilde{R}$

R : Riemann tensor

Quantity	QCD	Gravity
Anomalous axial $U(1)$ symmetry	$q \to \exp(i\gamma_5\chi)q$	$\nu \to \exp(i\gamma_5\chi)\nu$
Anomalous axial $U(1)$ current	$j_5^\mu = \bar{q}\gamma^\mu\gamma_5 q$	$j_5^\mu = \bar{\nu}\gamma^\mu\gamma_5\nu$
Corresponding anomalous divergence	$\partial_\mu j_5^\mu = G\tilde{G} + m_q\bar{q}\gamma_5 q$	$\partial_\mu j_5^\mu = R\tilde{R} + m_\nu\bar{\nu}\gamma_5\nu$
Corresponding pseudoscalar	$\eta' \to \bar{q}\gamma_5 q/\Lambda^2$	$\eta_\nu \to \bar{\nu}\gamma_5\nu/\Lambda_G^2$
Chern-Simons three-form	$C \equiv AdA - \frac{3}{2}AAA,$	$C_G \equiv \Gamma \mathrm{d}\Gamma - \frac{3}{2}\Gamma\Gamma\Gamma$
Chern-Pontryagin density	$E \equiv G\tilde{G} = \mathrm{d}C$	$E_G \equiv R\tilde{R} = \mathrm{d}C_G$
Topological vacuum susceptibility	$\langle G\tilde{G}\rangle_{q\to 0} = -\theta m_q\langle\bar{q}q\rangle$	$\langle R\tilde{R}\rangle_{q\to 0} = -\theta_G m_\nu\langle\bar{\nu}\nu\rangle$

Assumption: pure gravity contains a non-zero topological vacuum susceptibility

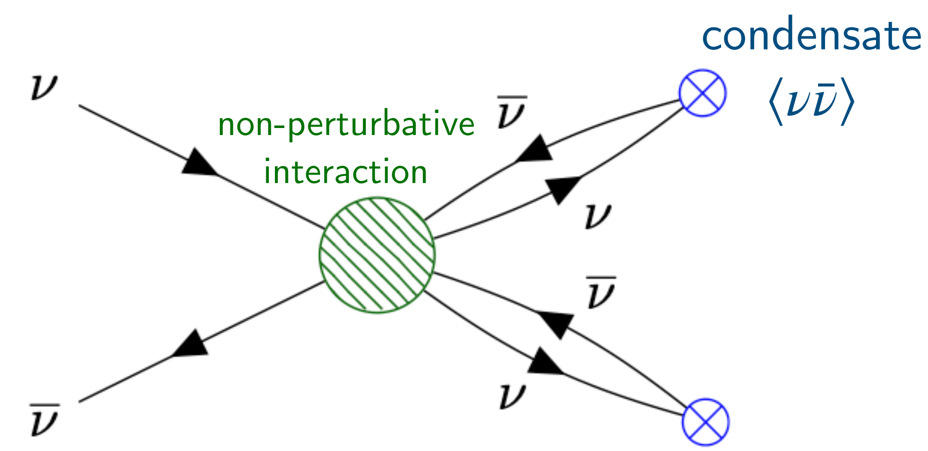
$$\langle R\tilde{R}, R\tilde{R}\rangle_{q\to 0} \equiv \lim_{q\to 0}\int d^4x\, e^{iqx}\langle T[R\tilde{R}(x)R\tilde{R}(0)]\rangle = \text{const} \neq 0,$$

Neutrino condensate $\nu\bar{\nu} = \langle\nu\bar{\nu}\rangle e^{i\phi} = v^3 e^{i\phi}.$

of mass $m_\nu \sim \langle\nu\bar{\nu}\rangle^{1/3} \sim \left\langle R\tilde{R}, R\tilde{R}\right\rangle_{q\to 0}^{1/8} = \Lambda_G$

from effective mass term $\mathcal{L} \supset g_v v\bar{\nu}\nu.$

Free-streaming neutrino constraint: $\Lambda_G \lesssim \mathrm{eV}$



Neutrino flavor symmetry gets
spontaneously broken by neutrino condensate
and explicitly broken by the chiral gravitational anomaly.

generating (pseudo)Goldstone boson $\phi \equiv \{\phi_k, \eta_\nu\}$

η_ν acquired mass from the chiral gravitational anomaly
in the same sense of η' meson in QCD.

ϕ_k is not really massless,
but get very small mass contribution from W and charged l.

$$m_{\phi_k} = \frac{1}{4\pi} G_F \, m_l \, \Lambda_G^2$$

$\Rightarrow$ break the neutrino flavor explicitly and relate to domain walls (later)

Cosmological consequences

Relaxing cosmological neutrino bound

Phase transition at $T_{\Lambda_G} \sim \Lambda_G \sim m_\nu < T_{\rm CMB} \sim 0.3$ eV
or in supercooled case: $T_{\Lambda_G} < \Lambda_G \sim m_\nu < 1.5$ eV
Lorenz, Funcke, Calabrese, Hannestad (1811.01991)

Enhanced neutrino decay

Below Λ_G, ν decays to the lightest state, binds-up, and becomes dark radiation.

$$\nu_i \to \nu_j + \phi_k \qquad \nu_j + \bar{\nu}_j \;\to\; \phi_k + \phi_k$$

Topological defects from flavor symmetry breaking

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Symmetry braking in Majorana case

$$\mathcal{L}_\nu = \sum_{i=1}^{3} i\bar{\nu}_{Li}\partial\!\!\!/\nu_{Li} + \mathrm{h.c.},$$

Flavor symmetry $G = U(3)_L = \dfrac{SU(3)_L \times U(1)_L}{Z_3}.$

$U(1)_L$ is broken explicitly by chiral gravitational anomaly.

Goldstone bosons for $k = 1,\ldots,8$

$$\phi \equiv \{\phi_k, \eta_\nu\}$$

VEV of the condensate in the neutrino mass eigenbasis is

$$\Phi_{ij} \equiv \nu_{Li}^T C \nu_{Lj},$$

$$V(\Phi) = \alpha\,\mathrm{Tr}(\Phi^\dagger\Phi) + \beta\,\mathrm{Tr}(\Phi^\dagger\Phi\Phi^\dagger\Phi) + \ldots$$
$$+ \gamma \det\Phi + \mathrm{h.c.} + \ldots,$$

$$\langle\Phi\rangle = \begin{pmatrix} \langle\Phi_{11}\rangle & 0 & 0 \\ 0 & \langle\Phi_{22}\rangle & 0 \\ 0 & 0 & \langle\Phi_{33}\rangle \end{pmatrix}$$

which is still invariant under Z_2 $\{\mathrm{id}, e^{i\pi\cdot\mathrm{id}}\}$.

Symmetry breaking pattern $SU(3)_L \to Z_2 \times Z_2,$

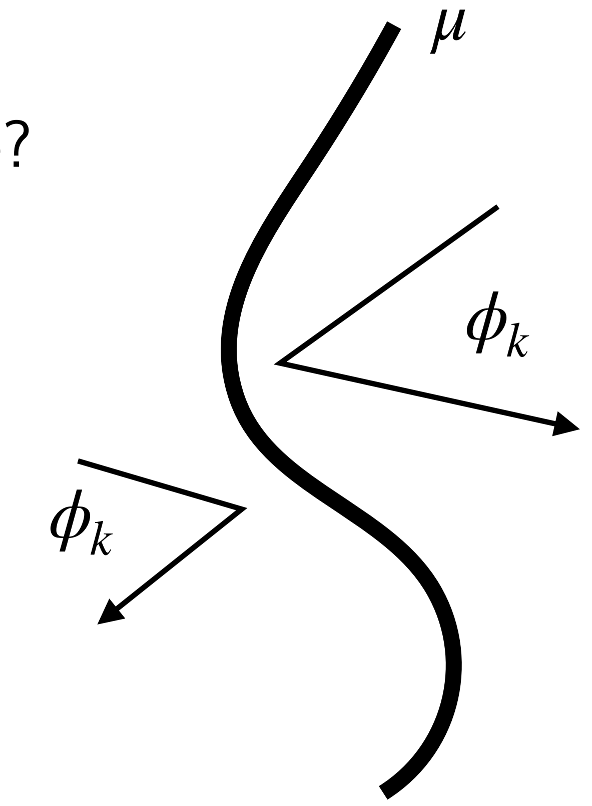
$$g_1 = \mathrm{diag}(1,-1,-1), \quad g_2 = \mathrm{diag}(-1,1,-1)$$
$$g_3 = \mathrm{diag}(-1,-1,1), \quad g_4 = \mathbb{1}.$$

Cosmic strings Existence: $\pi_1(G/H) \neq \mathrm{id}$

Majorana neutrino case $\pi_1(SU(3)/(Z_2 \times Z_2)) = Z_2 \times Z_2,$

Global symmetry ⇒ global strings

String network



How many strings are there in the observables universe?
or How close do strings live?

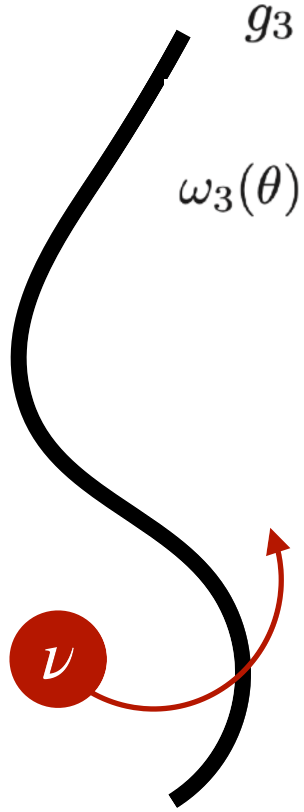
String separation: $$\xi = \sqrt{\frac{\lambda^2 \Lambda_G^7 t}{a_G^2 T_\nu^8}} = 10^{14}\ \mathrm{m} \left(\frac{\lambda}{1}\right) \left(\frac{\Lambda_G}{1\ \mathrm{meV}}\right)^{\frac{7}{2}} \left(\frac{1}{a_G}\right)$$

calculated by equating the forces from tension and ϕ_k-scattering
and evolved into the "friction" regime (strings reach terminal velocity).

With several string types depending on the element of the symmetry,

$$g_1 = \mathrm{diag}(1,-1,-1), \quad g_2 = \mathrm{diag}(-1,1,-1)$$
$$g_3 = \mathrm{diag}(-1,-1,1), \quad g_4 = \mathbb{1}.$$

When a neutrino passes by a string...



$$g_3 = \mathrm{diag}(-1,-1,1),$$

$$\omega_3(\theta) = \begin{pmatrix} \cos(\theta/2) & \sin(\theta/2) & 0 \\ -\sin(\theta/2) & \cos(\theta/2) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrino's mass varies.

consider 2 components here

$$\langle\phi\rangle = \omega_3^T(\theta) v\, \omega_3(\theta)$$
$$= v \begin{pmatrix} \cos^2(\theta/2) & \cos(\theta/2)\sin(\theta/2) \\ \cos(\theta/2)\sin(\theta/2) & \sin^2(\theta/2) \end{pmatrix}$$

$$\mathscr{L} \supset \nu_i^T \partial\!\!\!/ \nu_i + g\phi_{ij}\nu_i^T\gamma^0\nu_i$$
$$\nu_i^T \partial\!\!\!/ \nu_i + gv(\nu_1^T, \nu_2^T)\begin{pmatrix} c^2 & cs \\ cs & s^2 \end{pmatrix}\gamma^0\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$

Definitions of ν_1 and ν_2 are arbitrary without reference.

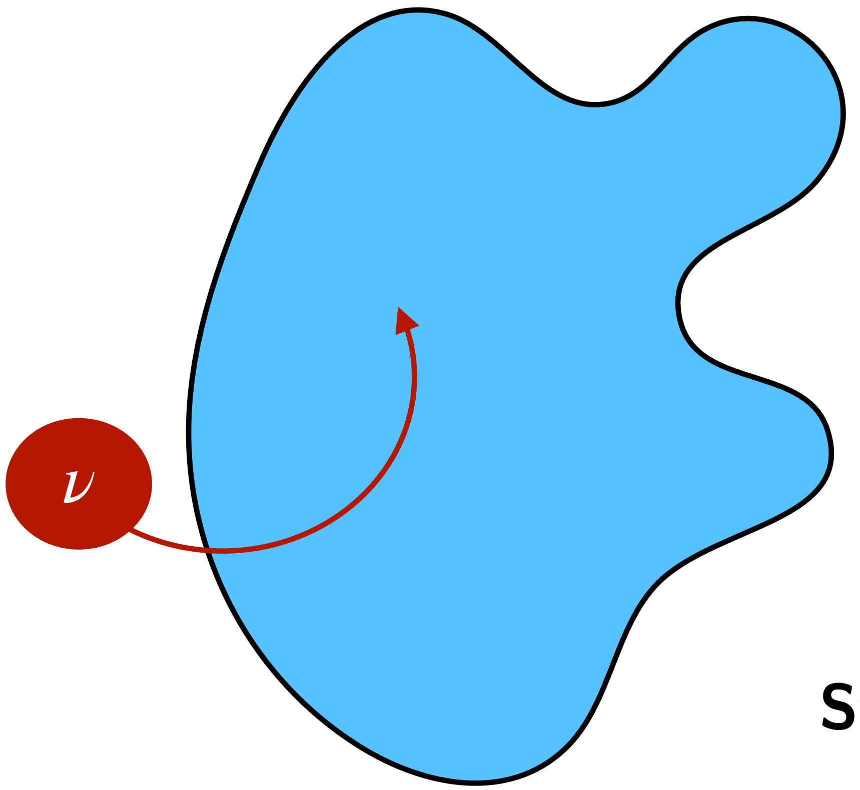
$$m_{\nu_i}(\theta=0) = gv\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \to m_{\nu_i}(\theta=\pi) = gv\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

One needs to identify the neutrino flavor via interaction with charged lepton and W.
This further breaks explicitly the residual $Z_2 \times Z_2$ symmetry because of mass of ϕ_k.

Leads to domain walls of width $\delta_{\mathrm{DW}} = \dfrac{1}{m_{\phi_k}} = 8 \times 10^{14}\ \mathrm{m}\left(\dfrac{m_\tau}{m_l}\right)\left(\dfrac{1\ \mathrm{meV}}{\Lambda_G}\right)^2$

$$\omega_3(\theta) = \begin{pmatrix} \cos(\theta/2) & \sin(\theta/2) & 0 \\ -\sin(\theta/2) & \cos(\theta/2) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$g_3 = \mathrm{diag}(-1, -1, 1),$$



Domain walls of width

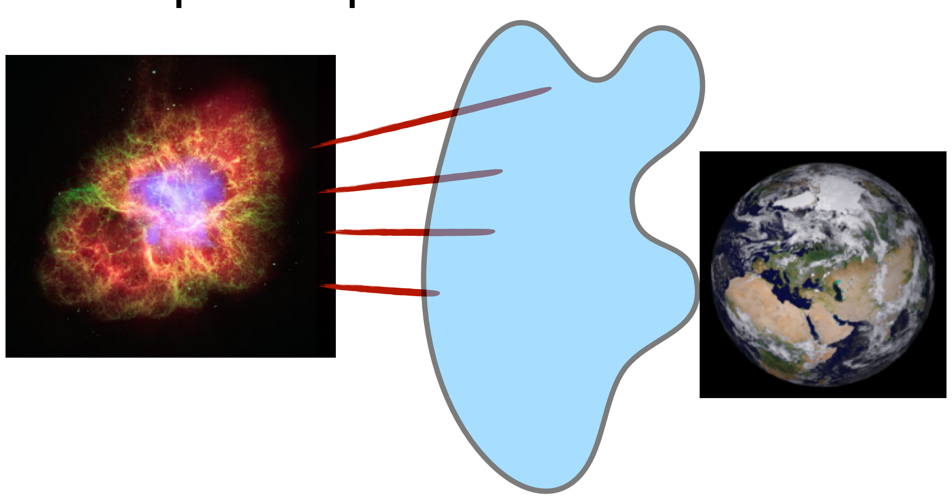
$$\delta_{\mathrm{DW}} = \frac{1}{m_{\phi_k}} = 8 \times 10^{14}\ \mathrm{m} \left(\frac{m_\tau}{m_l}\right) \left(\frac{1\ \mathrm{meV}}{\Lambda_G}\right)^2$$

When a neutrino passes by a domain wall, $\langle \Phi \rangle$ and the neutrino's mass matrix changes.

$$m_{\nu_i}(\theta = 0) = gv \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \ \rightarrow \ m_{\nu_i}(\theta = \pi) = gv \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

Switching between the normal hierarchy (NH): $m_1 < m_2 < m_3$ and the inverted hierarchy (IH): $m_3 < m_1 < m_2$.

Example: supernova neutrinos



A domain wall separates SN and Earth.
SN with IH emits ν_e.
In this model, neutrino then decays to the lightest state, ν_3.
After neutrinos pass the domain wall, the hierarchy switches.
At Earth, we would detect the lightest NH state, ν_1.

Observations

Time and space varying neutrino mass due to defects

String separation: $$\xi = \sqrt{\frac{\lambda^2 \Lambda_G^7 t}{a_G^2 T_\nu^8}} = 10^{14}\ \mathrm{m} \left(\frac{\lambda}{1}\right)\left(\frac{\Lambda_G}{1\ \mathrm{meV}}\right)^{\frac{7}{2}}\left(\frac{1}{a_G}\right)$$

Domain walls of width: $$\delta_{\mathrm{DW}} = \frac{1}{m_{\phi_k}} = 8 \times 10^{14}\ \mathrm{m} \left(\frac{m_\tau}{m_l}\right)\left(\frac{1\ \mathrm{meV}}{\Lambda_G}\right)^2$$

Characteristic time expected to encounter one of them:

$$t = \min(\xi, \delta_{\mathrm{DW}})/v$$

where the solar system moves with $v \sim 230\ \mathrm{km/s}$

Interestingly, the 15-year experiments (like DUNE)
will operate, while the solar system moves by 10^{14} m.

The current 10-year DUNE data already rules-out $\xi < 8 \times 10^8$ m.

Thanks.

For Dirac case, the neutrino flavor symmetry and its breaking pattern are different.
The defects like monopoles, domain walls, strings, and skyrmions are present.
But they decay quite quickly, compared to the Majorana case.