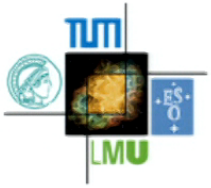
Title: Small Neutrino Masses from Gravitational Anomaly: A New Class of Models and Its Cosmological and Phenomenological Implications

Date: Dec 19, 2017 11:00 AM

URL: http://pirsa.org/17120025

Abstract: The Standard Model of particle physics and its implications for cosmology leave several fundamental questions unanswered, including the strong CP problem and the origins of neutrino masses, dark matter, and dark energy. Previous directions of model building beyond the Standard Model have usually focused on new high-energy physics. As an alternative direction, we have developed a class of low-energy neutrino mass and axion models at a new infrared gravitational scale, which is numerically coincident with the scale of dark energy. In this seminar, I will present this novel class of models and expand on the aspect of gravitational neutrino mass generation. My talk will also cover the wide-ranging cosmological and phenomenological model predictions, in particular the invalidity of the cosmological neutrino mass bound, enhanced neutrino decays, and soft topological defects.

ARNOLD SOMMERFELD
CENTER FOR THEORETICAL PHYSICS



Neutrino Masses from Gravitational Anomaly

A New Class of Models and Its Cosmological and Phenomenological Implications

Lena Funcke

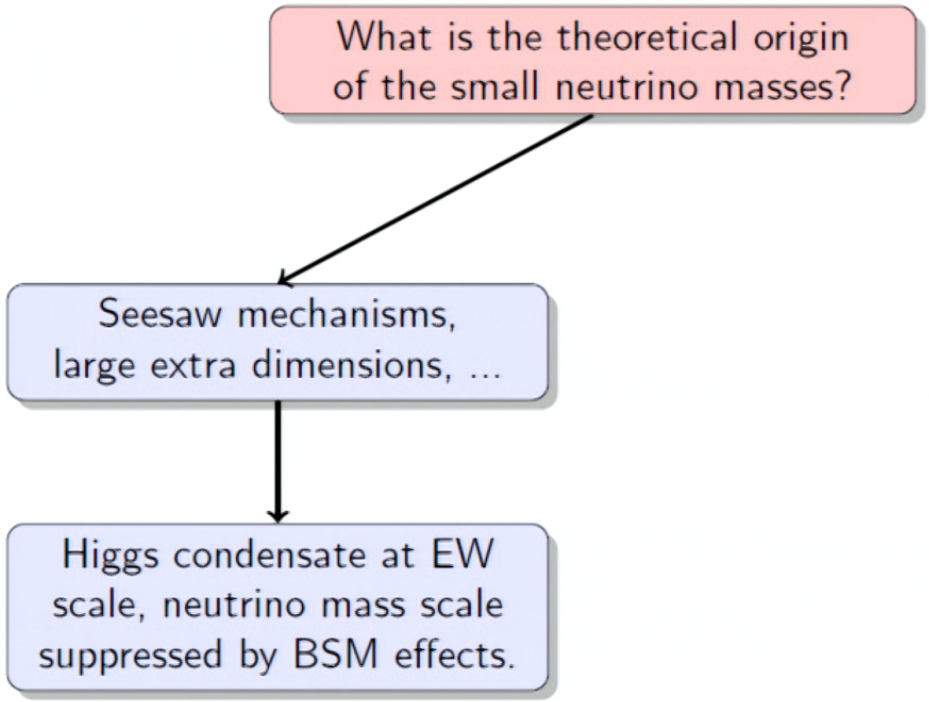
In collaboration with Gia Dvali

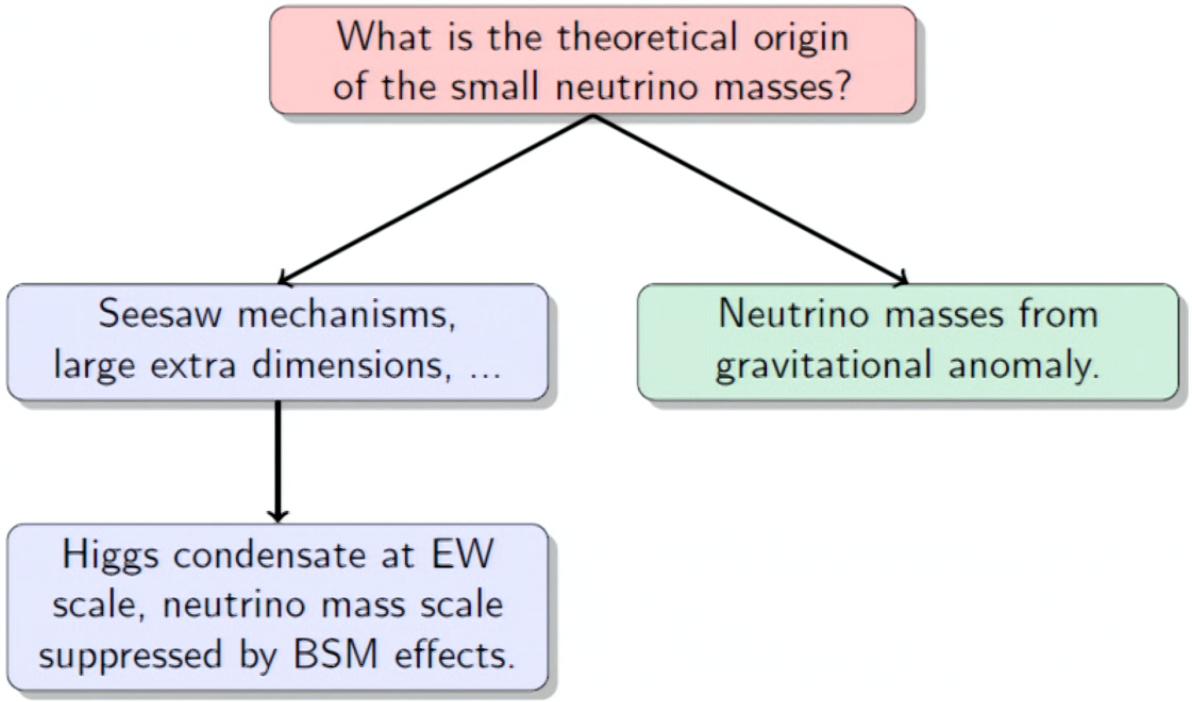
December 19, 2017, Perimeter Institute

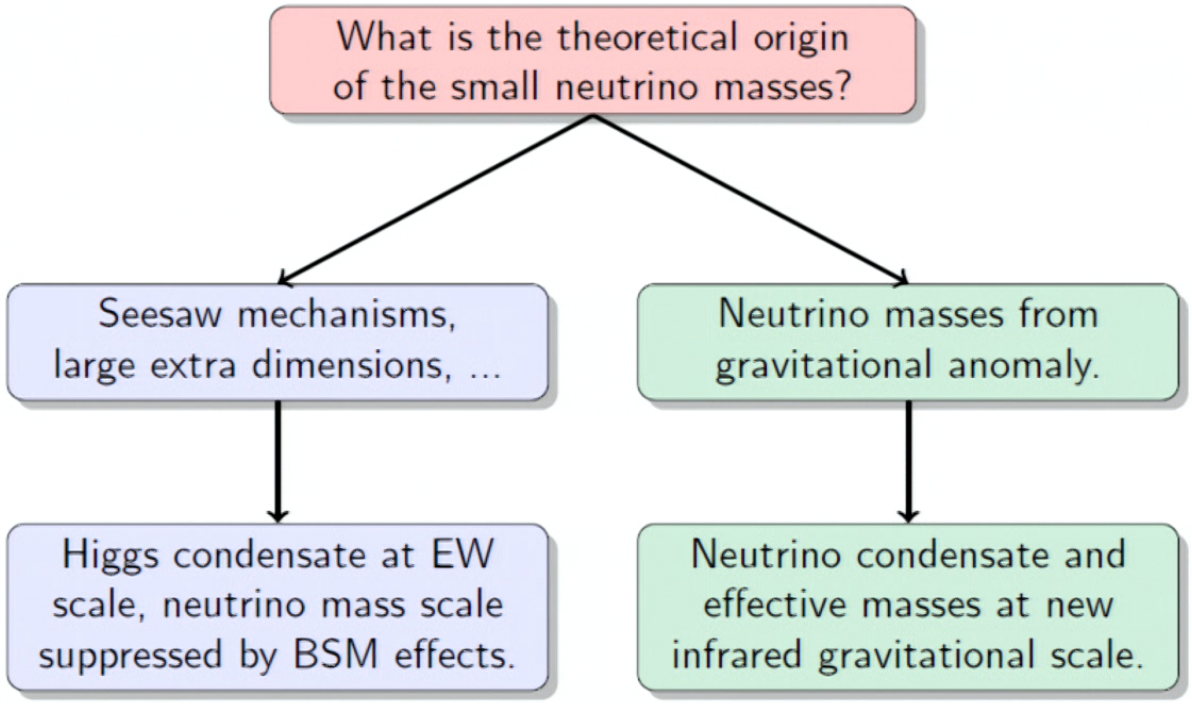
What is the theoretical origin of the small neutrino masses?

What is the theoretical origin of the small neutrino masses?

Seesaw mechanisms, large extra dimensions, ...


What is the theoretical origin of the small neutrino masses?
Seesaw mechanisms, large extra dimensions, ...
Higgs condensate at EW scale, neutrino mass scale suppressed by BSM effects.


What is the theoretical origin of the small neutrino masses?
Seesaw mechanisms, large extra dimensions, ...
Neutrino masses from gravitational anomaly.
Higgs condensate at EW scale, neutrino mass scale suppressed by BSM effects.


What is the theoretical origin of the small neutrino masses?
Seesaw mechanisms, large extra dimensions, ...
Neutrino masses from gravitational anomaly.
Higgs condensate at EW scale, neutrino mass scale suppressed by BSM effects.
Neutrino condensate and effective masses at new infrared gravitational scale.

Motivation: State of the Art

Neutrino masses:

- Unnaturally small, probably no conventional Higgs coupling.
- Beyond Standard Model neutrino physics required.

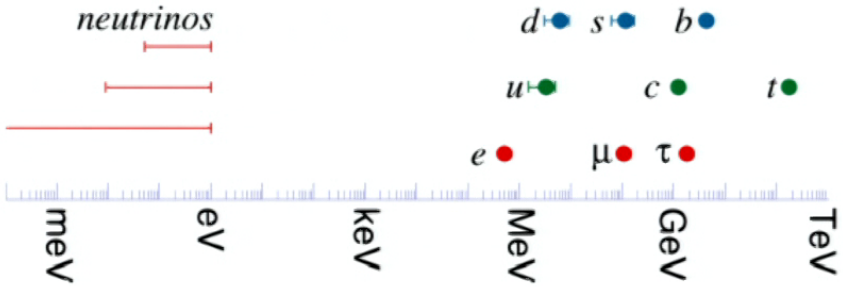


Image credits: IKEA and Murayama [http://hitoshi.berkeley.edu/].

Motivation: State of the Art

Neutrino masses:

- Unnaturally small, probably no conventional Higgs coupling.
- Beyond Standard Model neutrino physics required.

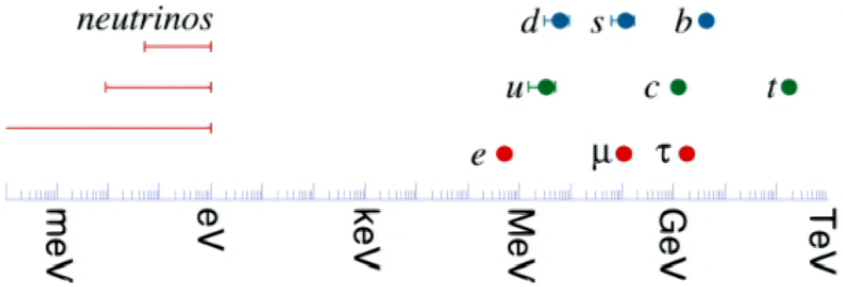


Image credits: IKEA and Murayama [http://hitoshi.berkeley.edu/].

Analogy: Non-Perturbative QCD Vacuum

Analogy: Non-Perturbative QCD Vacuum

- Chiral $U(3)$ quark symmetry breaking by topologically non-trivial QCD vacuum.

Analogy: Non-Perturbative QCD Vacuum

- Chiral $U(3)$ quark symmetry breaking by topologically non-trivial QCD vacuum.
- $U(1)_A$ puzzle: η' meson much heavier than other pseudo-Goldstone mesons.

Analogy: Non-Perturbative QCD Vacuum

- Chiral $U(3)$ quark symmetry breaking by topologically non-trivial QCD vacuum.
- $U(1)_A$ puzzle: η' meson much heavier than other pseudo-Goldstone mesons.

Quantity	QCD
$U(1)_A$ symmetry	$q \to \exp(i\gamma_5\alpha)q$

Analogy: Non-Perturbative QCD Vacuum

- Chiral $U(3)$ quark symmetry breaking by topologically non-trivial QCD vacuum.
- $U(1)_A$ puzzle: η' meson much heavier than other pseudo-Goldstone mesons.
- Resolution: non-perturbative effects [1]. Give rise to physical θ-term: $\mathcal{L} \supset \theta G\tilde{G}$.

Quantity	QCD
$U(1)_A$ symmetry	$q \to \exp(i\gamma_5\alpha)q$
$U(1)_A$ current	$j_5^\mu = \bar{q}\gamma^\mu\gamma_5 q$
Corresponding pseudoscalar	$\eta' \to \bar{q}\gamma_5 q$
Anomalous divergence	$\partial_\mu j_5^\mu = G\tilde{G}$ [2]

[2] Adler (1969); Bell and Jackiw (1969).

Analogy: Non-Perturbative QCD Vacuum

- Chiral $U(3)$ quark symmetry breaking by topologically non-trivial QCD vacuum.
- $U(1)_A$ puzzle: η' meson much heavier than other pseudo-Goldstone mesons.
- Resolution: non-perturbative effects [1]. Give rise to physical θ-term: $\mathcal{L} \supset \theta G \tilde{G}$.

Quantity	QCD
$U(1)_A$ symmetry	$q \to \exp(i\gamma_5\alpha)q$
$U(1)_A$ current	$j_5^\mu = \bar{q}\gamma^\mu\gamma_5 q$
Corresponding pseudoscalar	$\eta' \to \bar{q}\gamma_5 q$
Anomalous divergence	$\partial_\mu j_5^\mu = G\tilde{G}$ [2]

[1] Hooft (1976); Witten (1979); Veneziano (1979).
[2] Adler (1969); Bell and Jackiw (1969).

Analogy: Non-Perturbative QCD Vacuum

- Chiral $U(3)$ quark symmetry breaking by topologically non-trivial QCD vacuum.
- $U(1)_A$ puzzle: η' meson much heavier than other pseudo-Goldstone mesons.
- Resolution: non-perturbative effects [1]. Give rise to physical θ-term: $\mathcal{L} \supset \theta G\tilde{G}$.

Quantity	QCD
$U(1)_A$ symmetry	$q \to \exp(i\gamma_5\alpha)q$
$U(1)_A$ current	$j_5^\mu = \bar{q}\gamma^\mu\gamma_5 q$
Corresponding pseudoscalar	$\eta' \to \bar{q}\gamma_5 q$
Anomalous divergence	$\partial_\mu j_5^\mu = G\tilde{G} + m_q\bar{q}\gamma_5 q$ [2]
Vacuum correlator	$\langle G\tilde{G}\rangle = -\theta m_q\langle\bar{q}q\rangle$ [3]

[1] Hooft (1976); Witten (1979); Veneziano (1979).
[2] Adler (1969); Bell and Jackiw (1969). [3] Shifman, Vainshtein, and Zakharov (1980).

Analogy: Non-Perturbative QCD Vacuum

- Chiral $U(3)$ quark symmetry breaking by topologically non-trivial QCD vacuum.
- $U(1)_A$ puzzle: η' meson much heavier than other pseudo-Goldstone mesons.
- Resolution: non-perturbative effects [1]. Give rise to physical θ-term: $\mathcal{L} \supset \theta G\tilde{G}$.

Quantity	QCD
$U(1)_A$ symmetry	$q \to \exp(i\gamma_5\alpha)q$
$U(1)_A$ current	$j_5^\mu = \bar{q}\gamma^\mu\gamma_5 q$
Corresponding pseudoscalar	$\eta' \to \bar{q}\gamma_5 q$
Anomalous divergence	$\partial_\mu j_5^\mu = G\tilde{G} + m_q\bar{q}\gamma_5 q$ [2]
Vacuum correlator	$\langle G\tilde{G}\rangle = -\theta m_q\langle\bar{q}q\rangle$ [3]

[1] Hooft (1976); Witten (1979); Veneziano (1979).
[2] Adler (1969); Bell and Jackiw (1969). [3] Shifman, Vainshtein, and Zakharov (1980).

New: Analogous Effects in Gravity Coupled to Neutrinos

Quantity	QCD
$U(1)_A$ symmetry	$q \to \exp(i\gamma_5\alpha)q$
$U(1)_A$ current	$j_5^\mu = \bar{q}\gamma^\mu\gamma_5 q$
Corresponding pseudoscalar	$\eta' \to \bar{q}\gamma_5 q$
Anomalous divergence	$\partial_\mu j_5^\mu = G\tilde{G} + m_q\bar{q}\gamma_5 q$
Vacuum correlator	$\langle G\tilde{G}\rangle = -\theta m_q\langle\bar{q}q\rangle$

New: Analogous Effects in Gravity Coupled to Neutrinos

Assumption:

Gravitational θ-term made physical by non-perturbative semi-classical or quantum effects (such as virtual micro black holes): $\mathcal{L} \supset \theta_G R\tilde{R}$ [4].

Quantity	QCD
$U(1)_A$ symmetry	$q \to \exp(i\gamma_5\alpha)q$
$U(1)_A$ current	$j_5^\mu = \bar{q}\gamma^\mu\gamma_5 q$
Corresponding pseudoscalar	$\eta' \to \bar{q}\gamma_5 q$
Anomalous divergence	$\partial_\mu j_5^\mu = G\tilde{G} + m_q\bar{q}\gamma_5 q$
Vacuum correlator	$\langle G\tilde{G}\rangle = -\theta m_q\langle\bar{q}q\rangle$

[4] Deser, Duff, and Isham (1980).

New: Analogous Effects in Gravity Coupled to Neutrinos

Assumption:

Gravitational θ-term made physical by non-perturbative semi-classical or quantum effects (such as virtual micro black holes): $\mathcal{L} \supset \theta_G R\tilde{R}$ [4].

Consequences:

Axial neutrino anomaly and new massive neutrino-bilinear pseudoscalar η_ν arise [5].

Quantity	QCD
$U(1)_A$ symmetry	$q \to \exp(i\gamma_5\alpha)q$
$U(1)_A$ current	$j_5^\mu = \bar{q}\gamma^\mu\gamma_5 q$
Corresponding pseudoscalar	$\eta' \to \bar{q}\gamma_5 q$
Anomalous divergence	$\partial_\mu j_5^\mu = G\tilde{G} + m_q\bar{q}\gamma_5 q$
Vacuum correlator	$\langle G\tilde{G}\rangle = -\theta m_q\langle\bar{q}q\rangle$

[4] Deser, Duff, and Isham (1980). [5] Dvali (2005); Dvali, Jackiw, and Pi (2006); Dvali, Folkerts, and Franca (2014).

New: Analogous Effects in Gravity Coupled to Neutrinos

Assumption:

Gravitational θ-term made physical by non-perturbative semi-classical or quantum effects (such as virtual micro black holes): $\mathcal{L} \supset \theta_G R\tilde{R}$ [4].

Consequences:

Axial neutrino anomaly and new massive neutrino-bilinear pseudoscalar η_ν arise [5].

Quantity	Gravity
$U(1)_A$ symmetry	$q \to \exp(i\gamma_5\alpha)q$
$U(1)_A$ current	$j_5^\mu = \bar{q}\gamma^\mu\gamma_5 q$
Corresponding pseudoscalar	$\eta' \to \bar{q}\gamma_5 q$
Anomalous divergence	$\partial_\mu j_5^\mu = G\tilde{G} + m_q\bar{q}\gamma_5 q$
Vacuum correlator	$\langle G\tilde{G}\rangle = -\theta m_q\langle\bar{q}q\rangle$

[4] Deser, Duff, and Isham (1980). [5] Dvali (2005); Dvali, Jackiw, and Pi (2006); Dvali, Folkerts, and Franca (2014).

New: Analogous Effects in Gravity Coupled to Neutrinos

Assumption:

Gravitational θ-term made physical by non-perturbative semi-classical or quantum effects (such as virtual micro black holes): $\mathcal{L} \supset \theta_G R\tilde{R}$ [4].

Consequences:

Axial neutrino anomaly and new massive neutrino-bilinear pseudoscalar η_ν arise [5].

Quantity	Gravity
$U(1)_A$ symmetry	$\nu \to \exp(i\gamma_5\chi)\nu$
$U(1)_A$ current	$j_5^\mu = \bar{\nu}\gamma^\mu\gamma_5\nu$
Corresponding pseudoscalar	$\eta_\nu \to \bar{\nu}\gamma_5\nu$
Anomalous divergence	$\partial_\mu j_5^\mu = R\tilde{R} + m_\nu\bar{\nu}\gamma_5\nu$ [6]
Vacuum correlator	$\langle R\tilde{R}\rangle = -\theta_G\, m_\nu\langle\bar{\nu}\nu\rangle$ [7]

[4] Deser, Duff, and Isham (1980). [5] Dvali (2005); Dvali, Jackiw, and Pi (2006); Dvali, Folkerts, and Franca (2014).
[6] Delbourgo and Salam (1972); Eguchi and Freund (1976). [7] Dvali and LF (2016a).

Our Model [7]: Neutrino Condensation

Non-perturbative quantum gravitational effects.

[7] Dvali and LF (2016a).

Our Model [7]: Neutrino Condensation

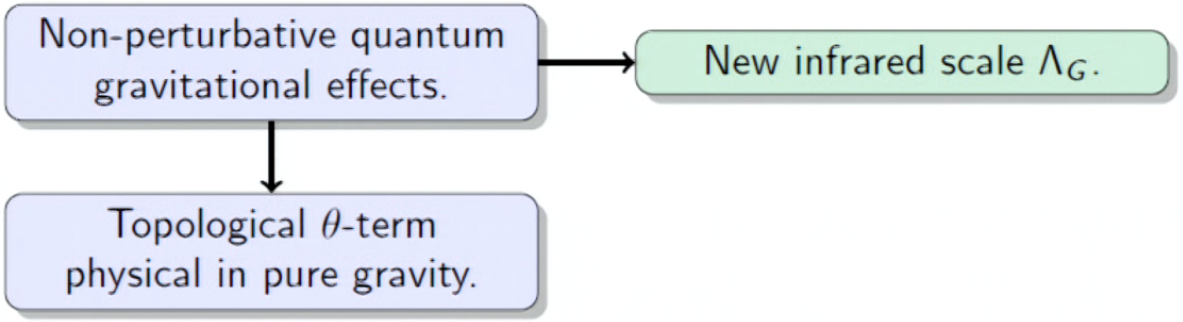
Non-perturbative quantum gravitational effects.

↓

Topological θ-term physical in pure gravity.

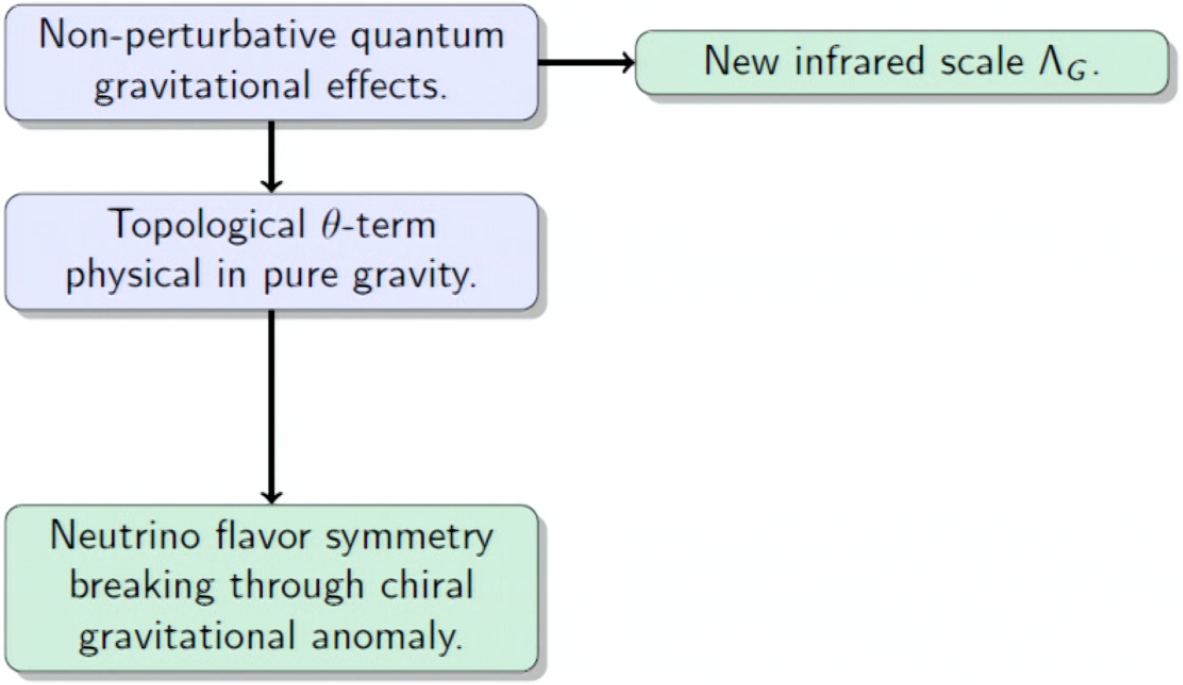
[7] Dvali and LF (2016a).

Our Model [7]: Neutrino Condensation



[7] Dvali and LF (2016a).

Our Model [7]: Neutrino Condensation



[7] Dvali and LF (2016a).

Our Model [7]: Neutrino Condensation

Non-perturbative quantum gravitational effects.

→ New infrared scale Λ_G.

↓

Topological θ-term physical in pure gravity.

↓

Neutrino flavor symmetry breaking through chiral gravitational anomaly.

→ Condensation of neutrinos below χSB scale Λ_G.

[7] Dvali and LF (2016a).

Our Model [7]: Neutrino Condensation

Non-perturbative quantum gravitational effects.

→ New infrared scale Λ_G.

↓

Topological θ-term physical in pure gravity.

↓

Neutrino flavor symmetry breaking through chiral gravitational anomaly.

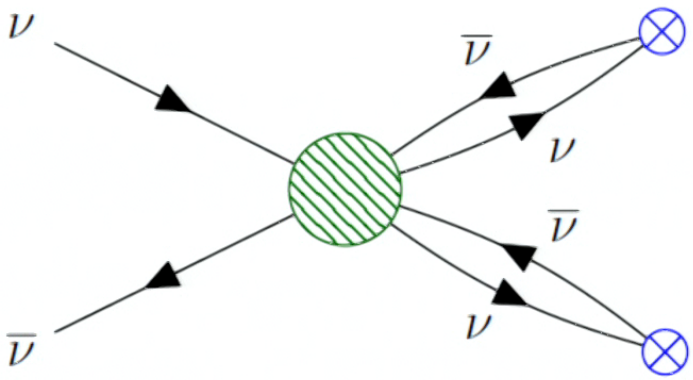
→ Condensation of neutrinos below χSB scale Λ_G.

→ Emergence of η_ν and 17 massless Goldstones ϕ_k.

[7] Dvali and LF (2016a).

Our Model [7]: Neutrino Mass Generation

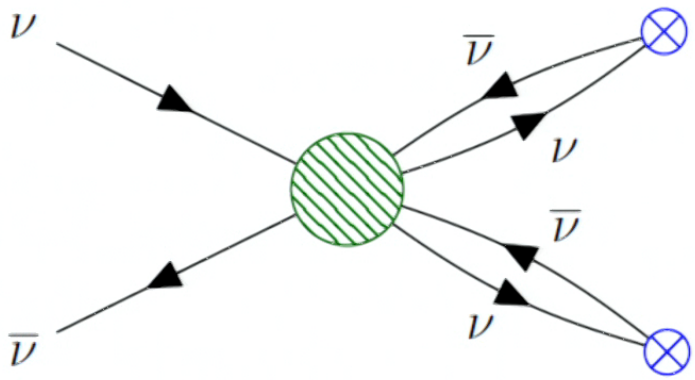
- Effective small neutrino mass generation through non-perturbative coupling to neutrino condensate.



[7] Dvali and LF (2016a).

Our Model [7]: Neutrino Mass Generation

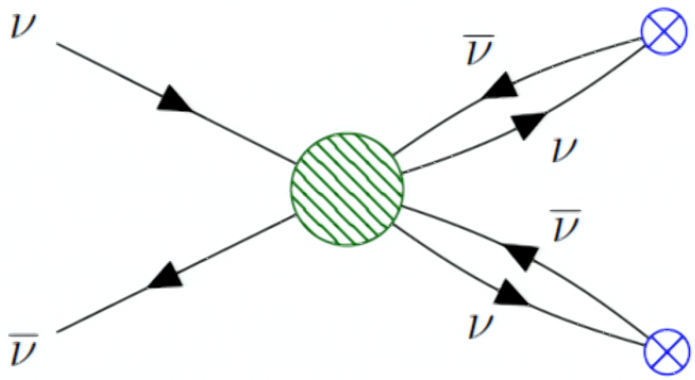
- Effective small neutrino mass generation through non-perturbative coupling to neutrino condensate.
- Coupling analogous to 't Hooft vertex in QCD [8].



[7] Dvali and LF (2016a). [8] 't Hooft (1986).

Our Model [7]: Neutrino Mass Generation

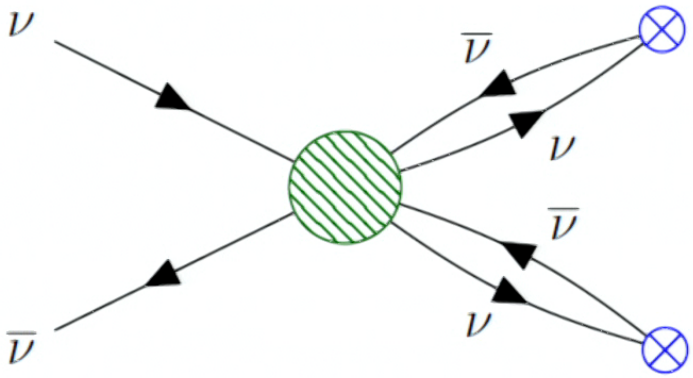
- Effective small neutrino mass generation through non-perturbative coupling to neutrino condensate.
- Coupling analogous to 't Hooft vertex in QCD [8].
- Effective potential determines neutrino mass hierarchy.



[7] Dvali and LF (2016a). [8] 't Hooft (1986).

Our Model [7]: Neutrino Mass Generation

- Effective small neutrino mass generation through non-perturbative coupling to neutrino condensate.
- Coupling analogous to 't Hooft vertex in QCD [8].
- Effective potential determines neutrino mass hierarchy.
- Independent of Dirac or Majorana nature of neutrinos.



[7] Dvali and LF (2016a). [8] 't Hooft (1986).

Phenomenological Bounds on Symmetry Breaking Scale Λ_G

Assumption: condensate $|\langle\bar{\nu}\nu\rangle|$ = scale Λ_G^3 = temperature $T_{\chi\mathrm{SB}}^3$.

Phenomenological Bounds on Symmetry Breaking Scale Λ_G

Assumption: condensate $|\langle\bar{\nu}\nu\rangle|$ = scale Λ_G^3 = temperature $T_{\chi\mathrm{SB}}^3$.

$\Lambda_G \ll \Lambda_{\mathrm{QCD}}$

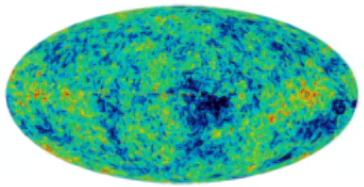
Phenomenological Bounds on Symmetry Breaking Scale Λ_G

Assumption: condensate $|\langle\bar{\nu}\nu\rangle|$ = scale Λ_G^3 = temperature $T_{\chi\mathrm{SB}}^3$.

$\Lambda_G \ll \Lambda_{\mathrm{QCD}}$

~ 256 meV

Upper bound from CMB constraints [9].



[9] Archidiacono and Hannestad (2014).

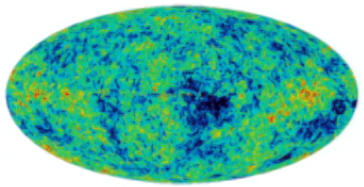
Image credits: NASA / WMAP Science Team [http://map.gsfc.nasa.gov/]

Phenomenological Bounds on Symmetry Breaking Scale Λ_G

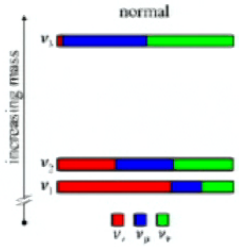
Assumption: condensate $|\langle\bar{\nu}\nu\rangle| =$ scale $\Lambda_G^3 =$ temperature $T_{\chi\mathrm{SB}}^3$.

$\Lambda_G \ll \Lambda_{\mathrm{QCD}}$

~ 256 meV — Upper bound from CMB constraints [9].



~ 4 meV — Lower bound from neutrino mass splitting [10].



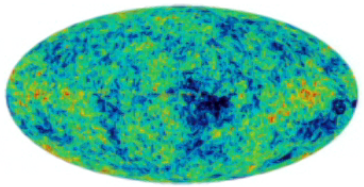
[9] Archidiacono and Hannestad (2014). [10] Olive *et al.* (Particle Data Group) (2014).
Image credits: NASA / WMAP Science Team [http://map.gsfc.nasa.gov/] and Patterson (2005).

Phenomenological Bounds on Symmetry Breaking Scale Λ_G

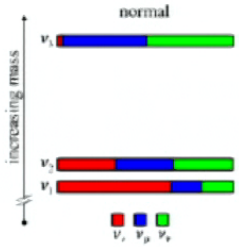
Assumption: condensate $|\langle\bar{\nu}\nu\rangle| =$ scale $\Lambda_G^3 =$ temperature $T_{\chi\mathrm{SB}}^3$.

$\Lambda_G \ll \Lambda_{\mathrm{QCD}}$

~ 256 meV — Upper bound from CMB constraints [9].



~ 4 meV — Lower bound from neutrino mass splitting [10].



$\rightarrow$ Neutrino vacuum condensate $\langle\bar{\nu}\nu\rangle$ on dark energy scale.

[9] Archidiacono and Hannestad (2014). [10] Olive *et al.* (Particle Data Group) (2014).
Image credits: NASA / WMAP Science Team [http://map.gsfc.nasa.gov/] and Patterson (2005).

Phenomenological Consequences

Invalidity of cosmological neutrino mass bound.

Phenomenological Consequences

Invalidity of cosmological neutrino mass bound.

- Relic neutrinos massless until late phase transition at $T_{\chi\mathrm{SB}} \lesssim \Lambda_G$.

Phenomenological Consequences

Invalidity of cosmological neutrino mass bound.

- Relic neutrinos massless until late phase transition at $T_{\chi\mathrm{SB}} \lesssim \Lambda_G$.
- After transition, neutrinos decay and bind up / partially annihilate.

Phenomenological Consequences

Invalidity of cosmological neutrino mass bound.

- Relic neutrinos massless until late phase transition at $T_{\chi\mathrm{SB}} \lesssim \Lambda_G$.
- After transition, neutrinos decay and bind up / partially annihilate.

  $\rightarrow$ No bound on sum of neutrino masses [11]: $\sum_\nu m_\nu \not\lesssim 0.2$ eV.

[11] Riemer-Sorensen *et al.* (2014).

Phenomenological Consequences

Invalidity of cosmological neutrino mass bound.

- Relic neutrinos massless until late phase transition at $T_{\chi\mathrm{SB}} \lesssim \Lambda_G$.
- After transition, neutrinos decay and bind up / partially annihilate.

  $\rightarrow$ No bound on sum of neutrino masses [11]: $\sum_\nu m_\nu \not\lesssim 0.2$ eV.

Masses up to $m_{\nu_e} \lesssim 2.2$ eV [12] allowed, measurable at KATRIN.

[11] Riemer-Sorensen *et al.* (2014). [12] Drexlin *et al.* (2013).
Image credit: KATRIN [http://www.ikp.kit.edu/].

Phenomenological Consequences

Invalidity of cosmological neutrino mass bound.

- Relic neutrinos massless until late phase transition at $T_{\chi\mathrm{SB}} \lesssim \Lambda_G$.
- After transition, neutrinos decay and bind up / partially annihilate.

  $\rightarrow$ No bound on sum of neutrino masses [11]: $\sum_\nu m_\nu \not\lesssim 0.2$ eV.

Masses up to $m_{\nu_e} \lesssim 2.2$ eV [12] allowed, measurable at 

.

Possible resolution of cosmological discrepancies?

- Tensions: e.g. H_0 and σ_8 parameters from different data sets [13].

[11] Riemer-Sorensen *et al.* (2014). [12] Drexlin *et al.* (2013). [13] Ade *et al.* (Planck Collaboration) (2016).
Image credit: KATRIN [http://www.ikp.kit.edu/].

Phenomenological Consequences

Invalidity of cosmological neutrino mass bound.

- Relic neutrinos massless until late phase transition at $T_{\chi\mathrm{SB}} \lesssim \Lambda_G$.
- After transition, neutrinos decay and bind up / partially annihilate.

  $\rightarrow$ No bound on sum of neutrino masses [11]: $\sum_\nu m_\nu \not\lesssim 0.2$ eV.

Masses up to $m_{\nu_e} \lesssim 2.2$ eV [12] allowed, measurable at 

.

Possible resolution of cosmological discrepancies?

- Tensions: e.g. H_0 and σ_8 parameters from different data sets [13].
- Simple solution: late neutrino masses and self-interactions [14]?

[11] Riemer-Sorensen *et al.* (2014). [12] Drexlin *et al.* (2013). [13] Ade *et al.* (Planck Collaboration) (2016).
Image credit: KATRIN [http://www.ikp.kit.edu/]. [14] Koksbang and Hannestad (2017).

Phenomenological Consequences

Invalidity of cosmological neutrino mass bound.

- Relic neutrinos massless until late phase transition at $T_{\chi\mathrm{SB}} \lesssim \Lambda_G$.
- After transition, neutrinos decay and bind up / partially annihilate.

  $\rightarrow$ No bound on sum of neutrino masses [11]: $\sum_\nu m_\nu \not\lesssim 0.2$ eV.

Masses up to $m_{\nu_e} \lesssim 2.2$ eV [12] allowed, measurable at 

.

Possible resolution of cosmological discrepancies?

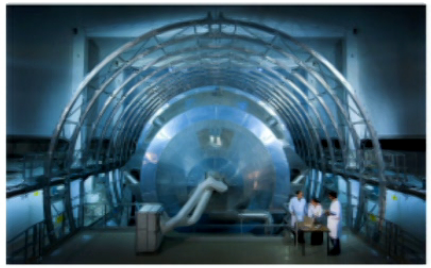
- Tensions: e.g. H_0 and σ_8 parameters from different data sets [13].
- Simple solution: late neutrino masses and self-interactions [14]?
- Extended solution: extra dark matter and dark radiation from late topological defects – skyrmions, monopoles, strings, domain walls?

[11] Riemer-Sorensen *et al.* (2014). [12] Drexlin *et al.* (2013). [13] Ade *et al.* (Planck Collaboration) (2016).
Image credit: KATRIN [http://www.ikp.kit.edu/]. [14] Koksbang and Hannestad (2017).

Phenomenological Consequences

Relic and sterile neutrinos:

- Relic neutrino overdensity on Earth: detection at PTOLEMY/KATRIN [15]?



KATRIN experiment.

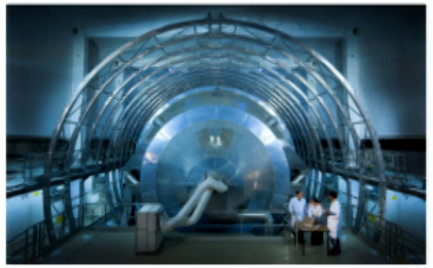
[15] Kaboth *et al.* (2010).

Image credits: Beiser, IceCube/NSF [http://gallery.icecube.wisc.edu/]

Phenomenological Consequences

Relic and sterile neutrinos:

- Relic neutrino overdensity on Earth: detection at PTOLEMY/KATRIN [15]?
- Sterile neutrino resolution of SBL anomalies without cosmic conflicts [16].



KATRIN experiment.

[15] Kaboth *et al.* (2010). [16] Abazajian *et al.* (2012).
Image credits: Beiser, IceCube/NSF [http://gallery.icecube.wisc.edu/]

Phenomenological Consequences

Relic and sterile neutrinos:

- Relic neutrino overdensity on Earth: detection at PTOLEMY/KATRIN [15]?
- Sterile neutrino resolution of SBL anomalies without cosmic conflicts [16].

KATRIN experiment.

Astrophysical neutrinos:

- Enhanced neutrino decays: deviations from equal flavor rate at IceCube [17].

IceCube experiment.

[15] Kaboth *et al.* (2010). [16] Abazajian *et al.* (2012). [17] Aartsen *et al.* (IceCube Collaboration) (2015).
Image credits: Beiser, IceCube/NSF [http://gallery.icecube.wisc.edu/] and KATRIN [https://neutrino.ikp.kit.edu/].

Phenomenological Consequences

Relic and sterile neutrinos:

- Relic neutrino overdensity on Earth: detection at PTOLEMY/KATRIN [15]?
- Sterile neutrino resolution of SBL anomalies without cosmic conflicts [16].

KATRIN experiment.

Astrophysical neutrinos:

- Enhanced neutrino decays: deviations from equal flavor rate at IceCube [17].
- Modified original SN neutrino spectra.

IceCube experiment.

[15] Kaboth *et al.* (2010). [16] Abazajian *et al.* (2012). [17] Aartsen *et al.* (IceCube Collaboration) (2015).
Image credits: Beiser, IceCube/NSF [http://gallery.icecube.wisc.edu/] and KATRIN [https://neutrino.ikp.kit.edu/].

Phenomenological Consequences

Frontiers of gravity measurements:

- Different polarization intensities of gravitational waves [18].

[18] Jackiw and Pi (2003).
Image credits: The SXS Project [https://www.ligo.caltech.edu/]

Phenomenological Consequences

Frontiers of gravity measurements:

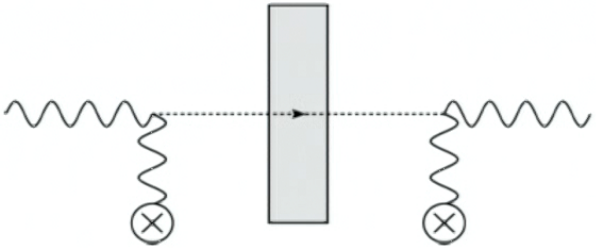
- Different polarization intensities of gravitational waves [18].
- New attractive gravity-competing short-distance force [19].

[18] Jackiw and Pi (2003). [19] Dvali and LF (2016b), "Domestic Axion" solution to strong CP problem.
Image credits: The SXS Project [https://www.ligo.caltech.edu/]

Phenomenological Consequences

Frontiers of gravity measurements:

- Different polarization intensities of gravitational waves [18].
- New attractive gravity-competing short-distance force [19].



Frontiers of new particle detection:

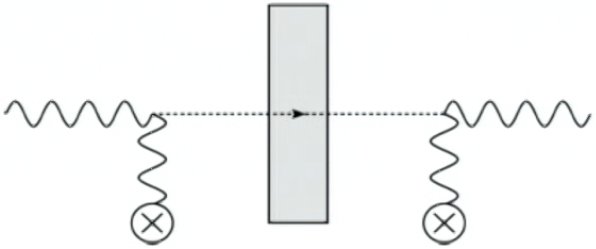
- "Shining light through walls" with axion-like particle η_ν.
- Flavor-violating processes within reach of LHC, Mu2e, etc.?

[18] Jackiw and Pi (2003). [19] Dvali and LF (2016b), "Domestic Axion" solution to strong CP problem.
Image credits: The SXS Project [https://www.ligo.caltech.edu/] and Redondo and Ringwald (2010).

Phenomenological Consequences

Frontiers of gravity measurements:

- Different polarization intensities of gravitational waves [18].
- New attractive gravity-competing short-distance force [19].



Frontiers of new particle detection:

- "Shining light through walls" with axion-like particle η_ν.
- Flavor-violating processes within reach of LHC, Mu2e, etc.?

[18] Jackiw and Pi (2003). [19] Dvali and LF (2016b), "Domestic Axion" solution to strong CP problem.
Image credits: The SXS Project [https://www.ligo.caltech.edu/] and Redondo and Ringwald (2010).

Summary

Assumption: pure gravity contains physical θ-term.

Summary

Assumption: pure gravity contains physical θ-term.

Theoretical consequences:

- Neutrino condensation.
- Effective small neutrino mass generation.
- Independent of Higgs or Seesaw mechanisms.
- Works for both Dirac and Majorana neutrinos.

Summary

Assumption: pure gravity contains physical θ-term.

Theoretical consequences:

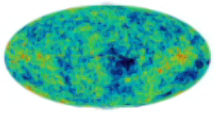
- Neutrino condensation.
- Effective small neutrino mass generation.
- Independent of Higgs or Seesaw mechanisms.
- Works for both Dirac and Majorana neutrinos.

Phenomenology:

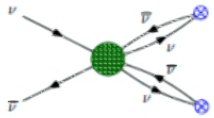
- Neutrino condensate on dark energy scale.
- Large neutrino masses still cosmologically allowed.
- Enhanced neutrino decays.
- Possible signatures at KATRIN, IceCube, etc.

Outlook: Ongoing and Planned Projects

Cosmology

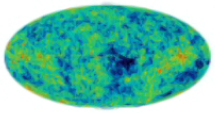


Particle Physics

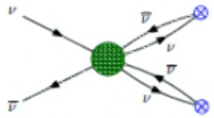


Outlook: Ongoing and Planned Projects

Cosmology



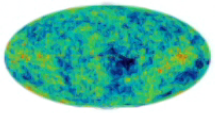
Particle Physics



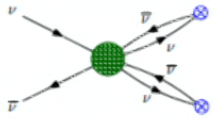
G. Dvali, *Flavor violation from deep infrared.*

Outlook: Ongoing and Planned Projects

Cosmology



Particle Physics

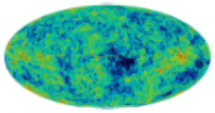


M. Shifman, A. Vainshtein, *Extending the low-energy frontier to models beyond gravity.*

G. Dvali, *Flavor violation from deep infrared.*

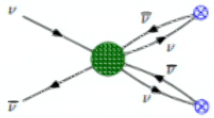
Outlook: Ongoing and Planned Projects

Cosmology



A. Vilenkin, *Soft topological defects from late cosmic phase transitions in the neutrino sector.*

Particle Physics

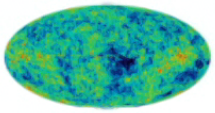


M. Shifman, A. Vainshtein, *Extending the low-energy frontier to models beyond gravity.*

G. Dvali, *Flavor violation from deep infrared.*

Outlook: Ongoing and Planned Projects

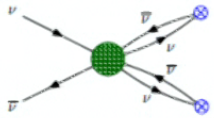
Cosmology



C. Lorenz, E. Calabrese, S. Hannestad, *Potential solutions to cosmic puzzles from phase transitions.*

A. Vilenkin, *Soft topological defects from late cosmic phase transitions in the neutrino sector.*

Particle Physics

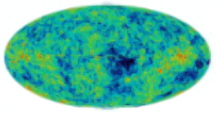


M. Shifman, A. Vainshtein, *Extending the low-energy frontier to models beyond gravity.*

G. Dvali, *Flavor violation from deep infrared.*

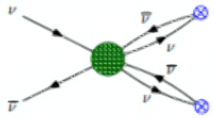
Outlook: Ongoing and Planned Projects

Cosmology



- L. Mirzagholi, *Relic neutrino overdensity on Earth with strong neutrino self-interactions.*
- C. Lorenz, E. Calabrese, S. Hannestad, *Potential solutions to cosmic puzzles from phase transitions.*
- A. Vilenkin, *Soft topological defects from late cosmic phase transitions in the neutrino sector.*

Particle Physics



- M. Shifman, A. Vainshtein, *Extending the low-energy frontier to models beyond gravity.*
- G. Dvali, *Flavor violation from deep infrared.*

General Message: IR Instead of UV Model Building?!

Resolutions of SM puzzles, e.g., small neutrino masses or strong *CP* problem?

General Message: IR Instead of UV Model Building?!

Resolutions of SM puzzles, e.g., small neutrino masses or strong *CP* problem?

UV

Seesaw mechanisms, grand unified theories, ...

General Message: IR Instead of UV Model Building?!

Resolutions of SM puzzles, e.g., small neutrino masses or strong *CP* problem?

UV

Seesaw mechanisms, grand unified theories, ...

UV scale suppresses masses $(m_\nu, m_{a_{\rm PQ}})$ and BSM effects.

General Message: IR Instead of UV Model Building?!

Resolutions of SM puzzles, e.g., small neutrino masses or strong *CP* problem?

UV

IR

Seesaw mechanisms, grand unified theories, ...

UV scale suppresses masses $(m_\nu, m_{a_{\mathrm{PQ}}})$ and BSM effects.

Neutrino masses and axion from gravitational θ-term.

General Message: IR Instead of UV Model Building?!

Resolutions of SM puzzles, e.g., small neutrino masses or strong *CP* problem?

UV

Seesaw mechanisms, grand unified theories, ...

UV scale suppresses masses $(m_\nu, m_{a_{\rm PQ}})$ and BSM effects.

IR

Neutrino masses and axion from gravitational θ-term.

BSM physics decouples due to IR vertex softening.

General Message: IR Instead of UV Model Building?!

Resolutions of SM puzzles, e.g., small neutrino masses or strong *CP* problem?

UV

IR

Seesaw mechanisms, grand unified theories, ...

UV scale suppresses masses $(m_\nu, m_{a_{\rm PQ}})$ and BSM effects.

Neutrino masses and axion from gravitational θ-term.

BSM physics decouples due to IR vertex softening.

New direction of model building, crucial for pheno and cosmology.

General Message: IR Instead of UV Model Building?!

Resolutions of SM puzzles, e.g., small neutrino masses or strong *CP* problem?

UV

IR

Seesaw mechanisms, grand unified theories, ...

UV scale suppresses masses $(m_\nu, m_{a_{\rm PQ}})$ and BSM effects.

Neutrino masses and axion from gravitational θ-term.

BSM physics decouples due to IR vertex softening.

New direction of model building, crucial for pheno and cosmology.

Thanks for listening!

Do you have any questions?