Small neutrino masses from chiral gravitational anomaly

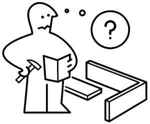
Lena Funcke

Massachusetts Institute of Technology

In collaboration with Gia Dvali, Georg Raffelt, Tanmay Vachaspati, and others
(1602.03191, 1608.08969, 1811.01991, 1905.01264, 2102.13618, and 2112.02107)

Workshop "Recent Advances in Fundamental Physics", Tbilisi, 30 September 2022

Question: Origin of Small Neutrino Masses?



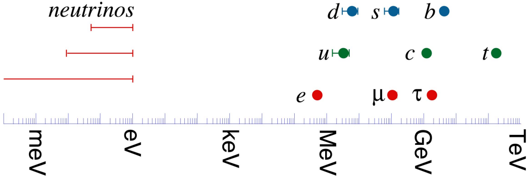


Image credits: IKEA and Murayama (2018).

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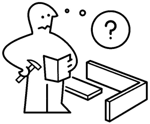

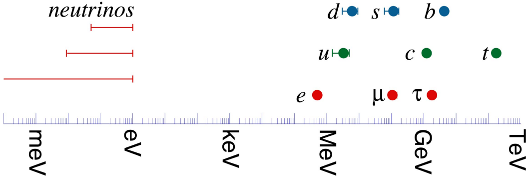

High-Energy Models

"Seesaw" mechanisms, large extra dimensions, ...

Image credits: IKEA and Murayama (2018).

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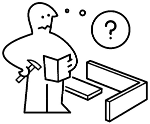

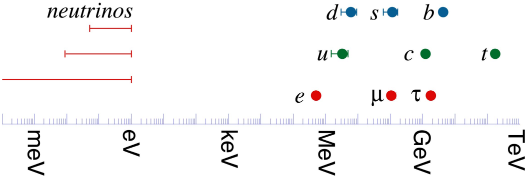

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“Seesaw” mechanisms, large extra dimensions, ...

Neutrino masses from Higgs condensate, suppressed by new high-energy physics.

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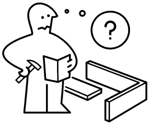

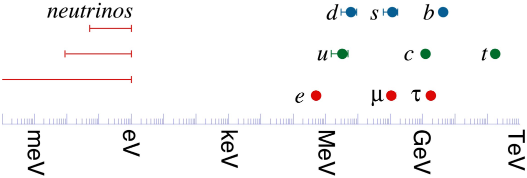

Low-Energy Model → Small neutrino masses from gravitational θ-term.

High-Energy Models → "Seesaw" mechanisms, large extra dimensions, ...
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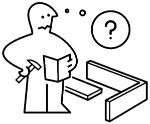

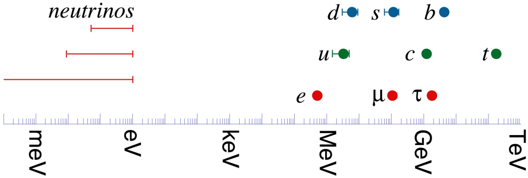

Low-Energy Model

Small neutrino masses from gravitational θ-term.

↓

Neutrino condensate and effective masses at new infrared gravitational scale.

High-Energy Models

"Seesaw" mechanisms, large extra dimensions, ...

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Neutrino masses from Higgs condensate, suppressed by new high-energy physics.

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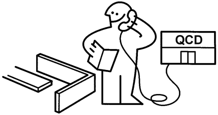
Reminder: Non-Perturbative QCD Vacuum



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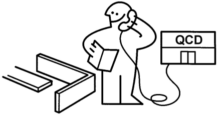

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Quantity	QCD with 3 quarks
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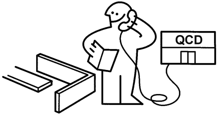

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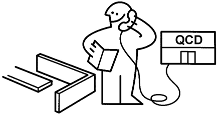

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Axial $U(1)_A$ anomaly	$\partial_\mu j_5^\mu = G\tilde{G} + m_q \bar{q}\gamma_5 q$	[4]

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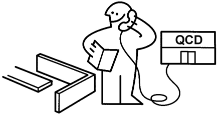

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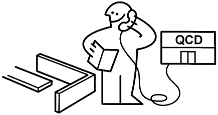

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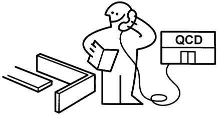

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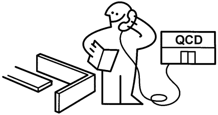

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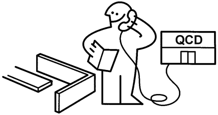

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Fermion flavor symmetry	$U(3)_L \times U(3)_R$ exact if $m_\nu = 0$	
(Pseudo)Goldstone bosons	$1(\eta') + 8(\pi, K, \eta)$	
Axial $U(1)_A$ anomaly	$\partial_\mu j_5^\mu = G\tilde{G} + m_q \bar{q}\gamma_5 q$	[4]
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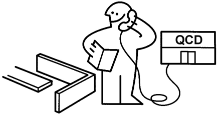

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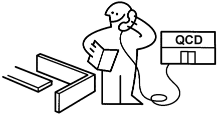

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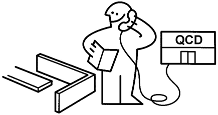

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Fermion flavor symmetry	$U(3)_L \times U(3)_R \rightarrow U(1)^3$?	[7]
(Pseudo)Goldstone bosons	$1(\eta') + 8(\pi, K, \eta)$	
Axial $U(1)_A$ anomaly	$\partial_\mu j_5^\mu = R\tilde{R} + m_\nu \bar{\nu}\gamma_5\nu$	[6]
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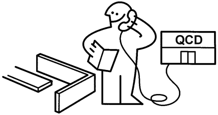

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Axial $U(1)_A$ anomaly	$\partial_\mu j_5^\mu = R\tilde{R} + m_\nu \bar{\nu}\gamma_5\nu$	[6]
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The Model: Theoretical Foundations

Quantity	QCD without quarks
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Dvali (2005); Dvali, Jackiw, and Pi (2006); Dvali, Folkerts, and Franca (2014).

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Topological susceptibility	$\langle G\tilde{G}, G\tilde{G} \rangle_{p\to 0} = \text{const.} \neq 0$
Effective Lagrangian	$\mathcal{L} = \frac{1}{2}E^2 + \theta E + \text{higher orders}$

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Massless field: $\langle C, C\rangle_{p\to 0} \propto 1/p^2$, vacuum is at $E = \text{const.}$

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Massive pseudoscalar	$\eta' = \bar{q}\gamma_5 q \Rightarrow \partial^\mu \eta' = j_5^\mu = \bar{q}\gamma^\mu\gamma_5 q$

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Chern-Simons three-form	$C \equiv A\mathrm{d}A - \frac{3}{2}AAA$
Topological susceptibility	$\langle G\tilde{G}, G\tilde{G}\rangle_{p\to 0} = \text{const.} \neq 0$
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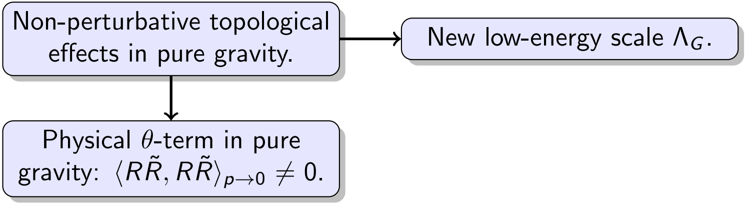

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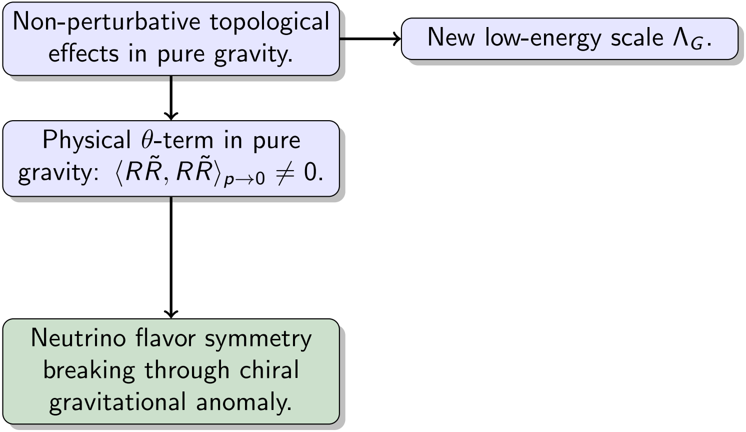

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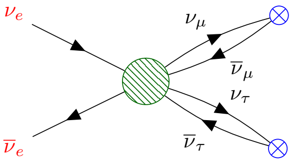

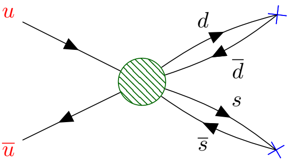

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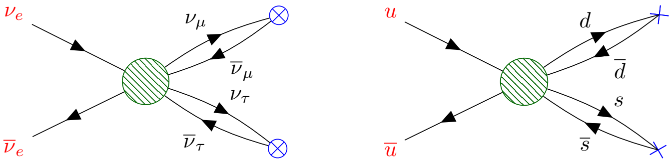

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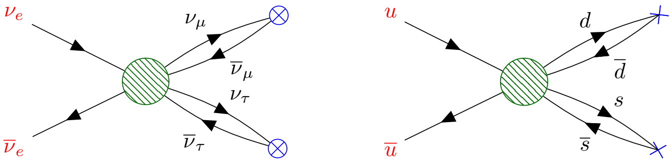

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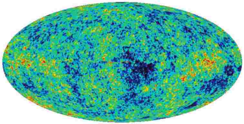

[9] Archidiacono, Hannestad (2014).

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

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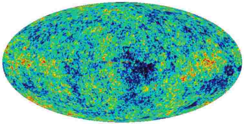
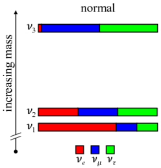


~ 4 meV

Lower bound from Δm_ν and gravity [10].



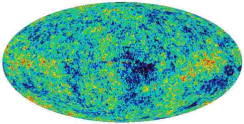
[9] Archidiacono, Hannestad (2014). [10] Tanabashi *et al.* (Particle Data Group) (2018).
Image credits: NASA / WMAP Science Team [http://map.gsfc.nasa.gov/] and Patterson (2005).

Constraints: Symmetry Breaking Scale Λ_G

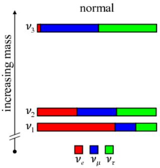
Neutrino condensate $|\langle\bar{\nu}\nu\rangle| \sim$ scale $\Lambda_G^3 \sim$ temperature $T_{\chi\mathrm{SB}}^3$

$\Lambda_G \ll m_e$

~ 0.3 eV — Upper bound from SM and cosmology [9].



~ 4 meV — Lower bound from Δm_ν and gravity [10].



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

[9] Archidiacono, Hannestad (2014). [10] Tanabashi *et al.* (Particle Data Group) (2018).
Image credits: NASA / WMAP Science Team [http://map.gsfc.nasa.gov/] and Patterson (2005).

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Weakened cosmological neutrino mass bounds.

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Image credit: KATRIN [http://www.ikp.kit.edu/].

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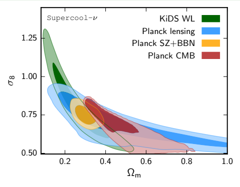
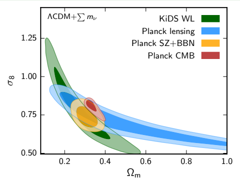


$\sigma_8(\Omega_m)$ for late m_ν



vs. $\sigma_8(\Omega_m)$ for ΛCDM

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Image credit: KATRIN [http://www.ikp.kit.edu/]. Plots: Lorenz, LF, Calabrese, Hannestad (2018).

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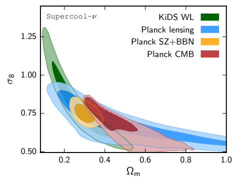
Impact on other cosmic parameters. Decaying dark energy?



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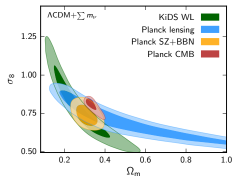

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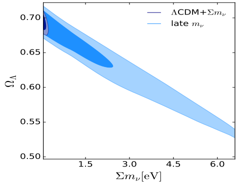

$\Omega_\Lambda(m_\nu)$ for both models

[11] Aghanim *et al.* (Planck) (2018). [12] Aker *et al.* (KATRIN) (2019).

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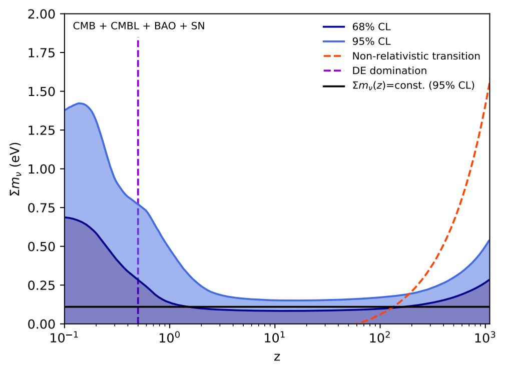

[14] Lorenz, LF, Löffler, Calabrese (2021).

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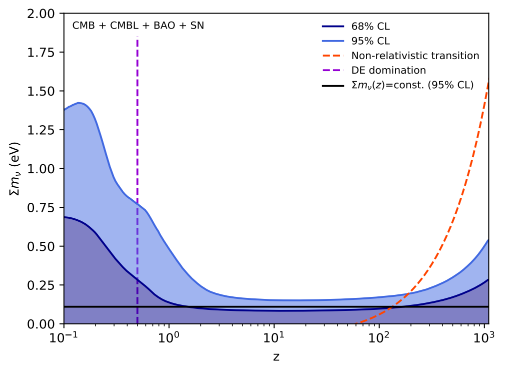

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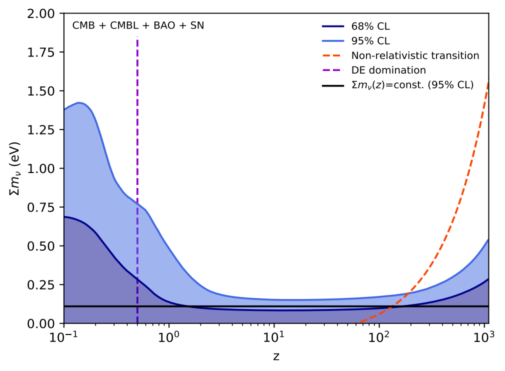
  $\Rightarrow$ Parameter degeneracy and/or new physics?



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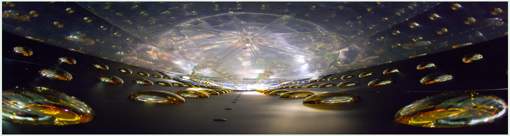
- Observable at Daya Bay? $\Delta t = 6$ y, $\Delta d = v \Delta t = 4 \times 10^{13}\ \mathrm{m} \sim \xi$



[15] Dvali, LF, Vachaspati (2021). Image credit: Roy Kaltschmidt, Berkeley Lab.

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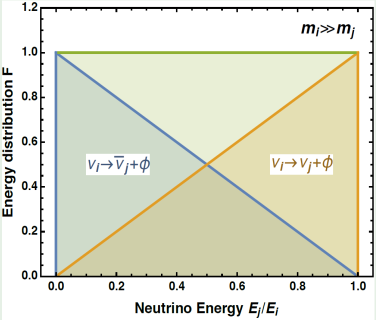

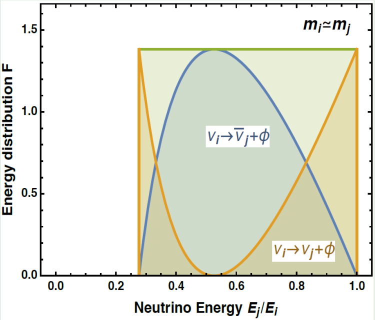

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Gravity measurements:

- Different polarization intensities of gravitational waves [16].
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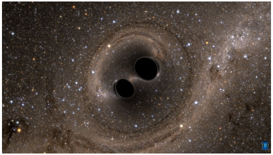

[16] Jackiw, Pi (2003).
Image credits: The SXS Project [https://www.ligo.caltech.edu/]

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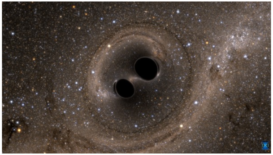

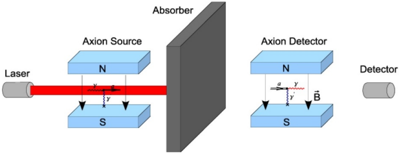

New particle detection:

- Searching for new ϕ bosons in axion-like experiments [17].
- ...

[16] Jackiw, Pi (2003). [17] Dvali, LF (2016b), "Domestic Axion" solution to strong CP problem.
Image credits: The SXS Project [https://www.ligo.caltech.edu/] and Kim, Carosi (2008).

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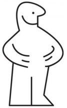

Thanks for listening!

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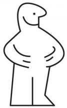

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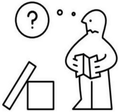


Do you have any questions?

Backup – String-Wall Network in Majorana Case

Topological defects

- Inter-string separation: $\xi = 10^{14}\ \mathrm{m}\left(\frac{\lambda}{1}\right)\left(\frac{\Lambda_G}{1\ \mathrm{meV}}\right)^{\frac{7}{2}}\left(\frac{1}{a_G}\right)$
- Domain wall width: $\delta_{\mathrm{DW}} = \frac{1}{m_{\phi_k}} = 8 \times 10^{14}\ \mathrm{m}\left(\frac{m_\tau}{m_l}\right)\left(\frac{1\ \mathrm{meV}}{\Lambda_G}\right)^2$

Impact on neutrino mixing angles

- Winding: $\langle \Phi(\theta) \rangle = \omega^T(\theta)\langle \Phi \rangle \omega(\theta) \neq \langle \Phi(0) \rangle$ changes flavor
- Time scale: $\Delta(\theta_{ij}, \alpha_k, \delta) = \mathcal{O}(1)$ after $\Delta t = \xi / v$, $v = 230\ \mathrm{km/s}$
- Example: $\Delta t = d/v \sim 1\ \mathrm{h}$ for $\xi < \delta_{\mathrm{DW}} = 8 \times 10^8\ \mathrm{m}$, $\Lambda_G = 1\ \mathrm{eV}$

Experimental constraints

- Daya Bay data: $\sin^2(2\theta_{13}) = 0.0856 \pm 0.0029$, angle could exhibit time-dependent change of $\sin^2(2 \times 2\pi v t / \delta_{\mathrm{DW}}) \lesssim 2 \times 0.0029$
- Still viable: $\xi < \delta_{\mathrm{DW}}$ with $\Lambda_G \lesssim 0.2\ \mathrm{meV}$ and $\xi > \delta_{\mathrm{DW}}$

Dvali, LF, Vachaspati (2021).

Backup – Binned Reconstruction of Neutrino Masses

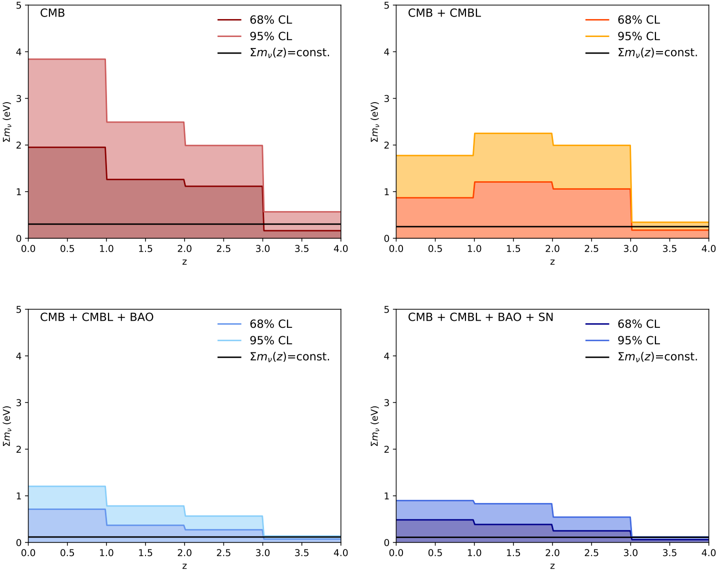


Image credit: Lorenz, LF, Löffler, Calabrese (2021).

Backup – Reconstruction with Wider Redshift Bins

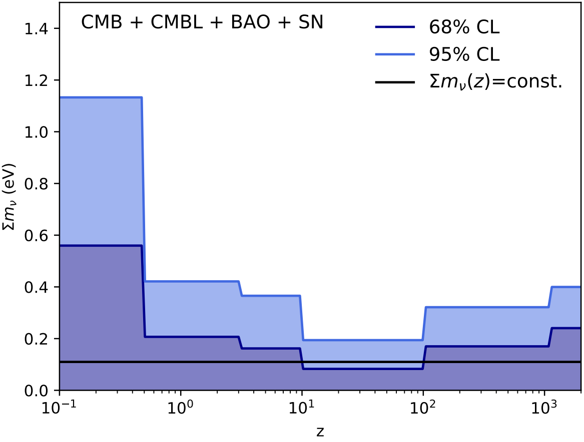


Image credit: Lorenz, LF, Löffler, Calabrese (2021).

Backup – Reconstruction with Linear Splines

Mass reconstruction with Bayesian regression splines and variable knots

⇒ Two new parameters: the knots (change points) z_1 and z_2

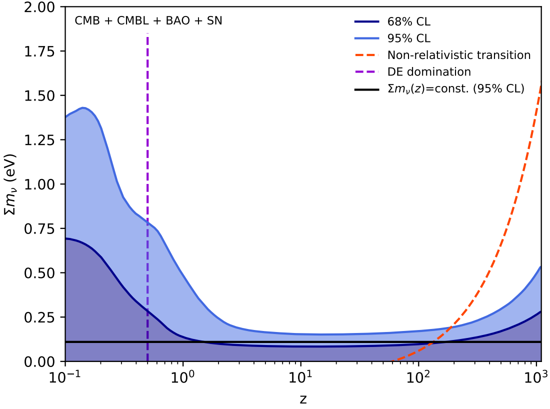
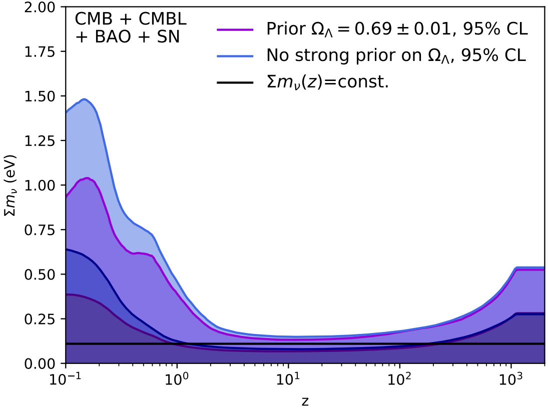


Image credit: Lorenz, LF, Löffler, Calabrese (2021).

Backup – Dark Energy and Neutrino Masses

Impose prior on Ω_Λ to test degeneracy between Ω_Λ and m_ν

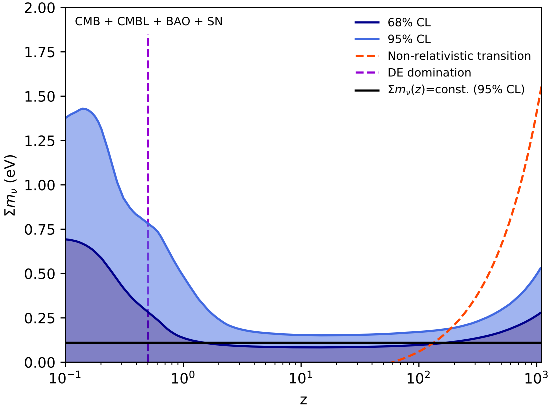
$\rightarrow$ Constraint on $\sum m_\nu(z=0)$ decreases by 42% but is still large



Backup – Constrain Extended Neutrino Models

Reconstruction results can be converted into neutrino mass bound for neutrino decay models [1]: $\sum m_\nu < 0.21$ eV (95% CL) [2]

$\rightarrow$ Bound too low for possible KATRIN detection of $m_\beta \geq 0.2$ eV



[1] e.g., Chacko et al. (2019), [2] Lorenz, LF, Löffler, Calabrese (2021).

Backup – Data Sets and Redshift Ranges

Data set	Redshift range
Planck 2018 CMB TTTEEE	mostly $z = 1100$
Planck 2018 CMB lowl	mostly $z = 1100$
Planck 2018 CMB lowE	mostly $z = 8, 1100$
Planck 2018 CMB lensing	$0 \leq z \leq 1100$
BAO (6dF)	$z = 0.106$
BAO (SDSS DR7 BOSS MGS)	$z = 0.15$
BAO (SDSS DR12 BOSS)	$z = 0.38, 0.51, 0.61$
BAO (SDSS DR14 eBOSS quasars)	$z = 1.52$
BAO (SDSS DR14 eBOSS Ly-α)	$z = 2.34$
BAO (SDSS DR14 eBOSS cross Ly-α-QSO)	$z = 2.35$
SN (Pantheon)	$0.01 < z < 2.3$

Backup – Three-form Higgs Effect

- Chern-Pontryagin density: $E_G \equiv R\tilde{R} = \varepsilon^{\mu\nu\rho\sigma} R^{\alpha}_{\beta\mu\nu} R^{\beta}_{\alpha\rho\sigma} = \mathrm{d}C_G$
- Chern-Simons three-form: $C_G \equiv \Gamma \mathrm{d}\Gamma - \frac{3}{2}\Gamma\Gamma\Gamma$

- Effective Lagrangian for C_G: $\mathcal{L} = \frac{1}{2\Lambda_G^4} E_G^2 + \theta_G E_G +$ higher orders [3]
- With neutrino: $\mathcal{L} = \frac{1}{2\Lambda_G^4} E_G^2 - \frac{1}{\Lambda_G}\eta_\nu E_G + \frac{1}{2}\partial_\mu \eta_\nu \partial^\mu \eta_\nu$, $\eta_\nu = \frac{1}{\Lambda_G^2}\bar{\nu}\gamma_5 \nu$

- Equation of motion for η_ν: $\Box \eta_\nu + \frac{1}{\Lambda_G} E_G = 0$, in vacuum: $R\tilde{R} = 0$.
- Equation of motion for C_G: $\left(\Box + \Lambda_G^2\right) E_G = 0$, mass gap generated.

[3] Dvali (2005); Dvali, Jackiw, and Pi (2006); Dvali, Folkerts, and Franca (2014).

Backup – Formation of Condensate

- *High-energy formulation:* vacuum angle θ_G made unobservable due to arbitrary shift by chiral rotation of massless neutrino field
- *Low-energy formulation:* $E_G = R\tilde{R}$ screened in vacuum by massless neutrino, as C_G "eats up" pseudoscalar η_ν and becomes massive

- Integrated e.o.m. of E_G: $\langle R\tilde{R}\rangle_{q\to 0} \simeq -\theta_G m_\nu \Lambda_G^3 = -\theta_G m_\nu \langle\bar{\nu}\nu\rangle$
- From Lagrangian: $\mathcal{L} = \frac{1}{2\Lambda_G^4} E_G^2 - \frac{1}{\Lambda_G}\eta_\nu E_G + \frac{1}{2}\partial_\mu\eta_\nu\partial^\mu\eta_\nu - \frac{1}{2}m_\nu\Lambda_G\eta_\nu^2$

- Effective potential: $V(\hat{X}) = \sum_n \frac{1}{n} c_{2n}\,\mathrm{Tr}[(\hat{X}^+\hat{X})^n]$, $\hat{X}_{\alpha_L}^{\alpha_R} \equiv \langle\bar{\nu}_{\alpha_L}\nu_{\alpha_R}\rangle$
- Extrema: $\frac{\partial V}{\partial x_j} = x_j^* \left(\sum_n c_{2n}|x|_j^{2(n-1)}\right) = 0$ for $\hat{X} = \mathrm{diag}(x_1, x_2, x_3)$

Dvali, LF (2016a).

Backup – Structure of Fermion Condensates

- Flavor structure of condensate determined by minimization of effective potential for following order parameters:

$$\hat{X}_{i\bar{j}} \equiv \psi_i \psi_{c\bar{j}}\,,\ X_{ij} \equiv \psi_i C \psi_j\,,\ \bar{X}_{\bar{i}\bar{j}} \equiv \psi_{c\bar{i}} C \psi_{c\bar{j}}\,,$$

- *1) Flavor-invariant terms*, $\mathrm{Tr}(\hat{X}^+\hat{X})$, $\mathrm{Tr}(\hat{X}^+\hat{X}\hat{X}^+\hat{X})$, ..., $\mathrm{Tr}(X^+X)$, $\mathrm{Tr}(\bar{X}^+\bar{X})$, $\mathrm{Tr}(\hat{X}X^+\bar{X}\hat{X})$, ... In effective potential: infinite polynomial of invariants scaled by powers of Λ_G.

- *2) Explicitly flavor-breaking terms*, break anomalous $U(1)_A$, leave invariant anomaly-free subgroup Z_{2N_F}. Operators:

$$\epsilon^{i_1\dots i_{N_F}}\epsilon^{\bar{j}_1\dots\bar{j}_{N_F}}\hat{X}_{i_1\bar{j}_1}\dots\hat{X}_{i_{N_F}\bar{j}_{N_F}}\,.$$

- Effective potential invariant under symmetry group $SU(N_F)\times SU(N_F)\times U(1)_V\times Z_{2N_F}$, spontaneously broken by condensate.

Backup – Gravitational Wave Propagation

- Non-dynamical Chern-Simons modification of GR, proposed in [16]
- Angle θ_G assumed to be time-dependent, non-dynamical quantity

- Deformation of equations of motion of GR: $G_{\mu\nu} + C_{\mu\nu} = -8\pi G T_{\mu\nu}$, where $D_\mu C^{\mu\nu} = \frac{1}{8\sqrt{-g}} v^\nu R\tilde{R}$, $v_\nu \equiv \partial_\mu \theta_G$, and $v_\nu = (1/\mu, \mathbf{0})$
- Diffeomorphism breaking ($D_\mu C^{\mu\nu} \neq 0$) dynamically suppressed, Schwarzschild solution persists, gravitational waves travel at c

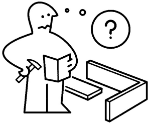
- Radiated power P per unit angle Ω for different polarizations:

$$\frac{dP_\pm}{d\Omega} \propto \left(1 \pm \frac{k}{\mu}\right)^{-2}$$

[16] Jackiw and Pi (2003).

Backup – The *CP* Problem of QCD

Strong *CP* problem [1]:
$\mathcal{L}_{\rm QCD} \supset \theta G\tilde{G}$, $\bar{\theta} < 10^{-10}$.



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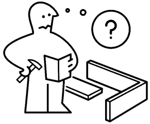

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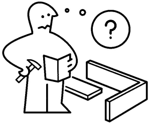

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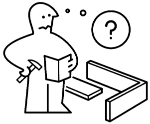

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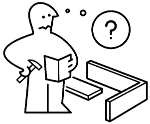

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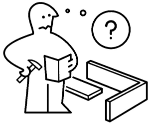

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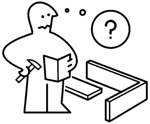

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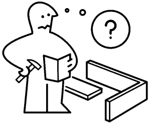

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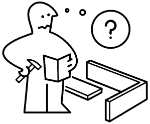

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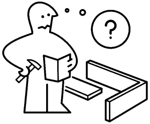

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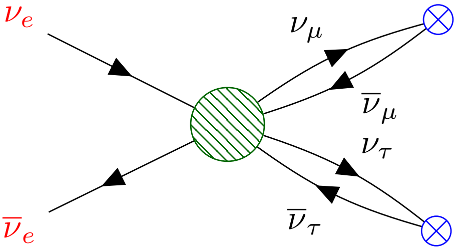
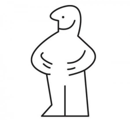
Gravity problem: threat
from gravitational anomaly. → Any intrinsic protection mechanism against gravity?

[1] Recent review: Kim (2016).

Backup – Generation of Light Fermion Masses

- Neutrino [2] and up quark [3] mass generation through non-perturbative coupling to neutrino condensate.





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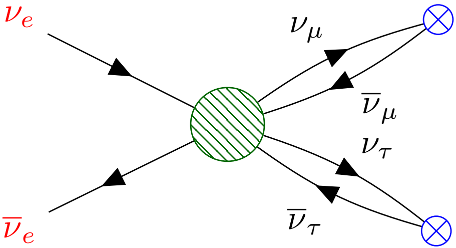

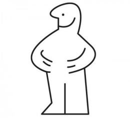

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Backup – Generation of Light Fermion Masses

- Neutrino [2] and up quark [3] mass generation through non-perturbative coupling to neutrino condensate.
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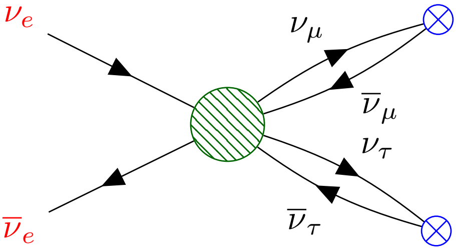
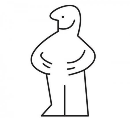
- No new scale or additional tuning: $m_u \sim \xi \langle \bar{\nu}\nu \rangle$, high-multiplicity parameter $\xi \sim 10^7$ replaces $Y_u \sim 10^{-5}$ [3].





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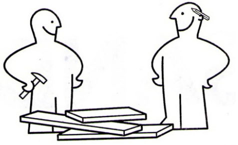
Neutrino and up-quark masses generated by IR $\langle\bar{\nu}\nu\rangle \equiv$ “second Higgs”.



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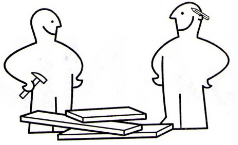

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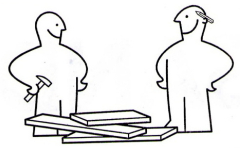

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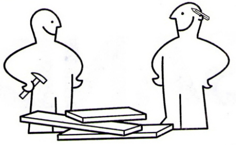

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Flavor-violation by infrared "Higgs boson" suppressed.