technische universität
dortmund

Radiative neutrino masses and the Cohen–Kaplan–Nelson bound

Patrick Adolf

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in collaboration with Hirsch (IFIC, Valencia), Päs (TU Dortmund), Krieg, Tabet (TU Dortmund)

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Neutrino Frontiers, GGI, Florence

Outline

Bekenstein bound

- QFT: Box with size L and energy cutoff Λ_{UV}, entropy $S_{\mathrm{QFT}} \sim \Lambda_{\mathrm{UV}}^3 L^3$
- Black hole: Entropy $S_{\mathrm{BH}} \equiv \pi L^2 M_{\mathrm{P}}^2$
- For any fixed energy Λ_{UV}, S_{QFT} outruns S_{BH} by increasing L
  - → Over-count degrees of freedom 't Hooft '93, Susskind '94
- Take Bekenstein bound as fixed limit:
  - → $L^3 \Lambda_{\mathrm{UV}}^3 \lesssim \pi L^2 M_{\mathrm{P}}^2$
- New (IR) cutoff L
  - → L is not independent of Λ_{UV}, since it has to scale as $L \sim \Lambda_{\mathrm{UV}}^{-3}$

A. Cohen, D. Kaplan, A. Nelson, PRL (1999), arxiv: hep-th/9803132

Cohen–Kaplan–Nelson bound

- Problem: Bekenstein bound contains states with $R_S \gg L$
  - → Also low-energy states can turn into black holes
- Cohen, Kaplan, Nelson propose stronger constraint excluding black hole states

$$R_S \leq L$$

$$\rightarrow L \leq \frac{M_P}{\Lambda_{UV}^2}$$

- Always satisfies Bekenstein bound as $S_{max} \simeq S_{BH}^{3/4}$
- Possible energy range of EFTs from $\Lambda_{IR} = 1/L$ to Λ_{UV}

A. Cohen, D. Kaplan, A. Nelson, PRL (1999), arxiv: hep-th/9803132

Applications in the literature

- CKN bound introduces momentum cutoffs:

$$\int_0^\infty \mathrm{d}l \frac{l^3}{(l^2+\Delta)^3} \to \int_{\frac{1}{L}}^{\Lambda_{\mathrm{UV}}} \mathrm{d}l \frac{l^3}{(l^2+\Delta)^3}$$

- Magnetic moment of the electron and muon Cohen, Kaplan, Nelson, PRL '99, Cohen, Kaplan '21
  - → Minimal expected correction to electron magnetic moment is just one order of magnitude smaller than experimental uncertainties
- Hierarchy problem and causal diamonds Kephart, Päs '22
- Cosmological constant problem Cohen, Kaplan, Nelson, PRL '99

Dark energy density and the CKN bound

- Quantum corrections to the dark energy density scale as $\sim \Lambda_{\mathrm{UV}}^4$ Weinberg, RMP '89
  - → taking M_{P} as Λ_{UV} → many orders of magnitude larger than measurements
- CKN propose Hubble length as IR cutoff:

$$L = 1/H \rightarrow \rho_{\mathrm{DE}} \sim (10^{-3}\,\mathrm{eV})^4$$

  - → matches dark energy density today
- Interesting consequence: $H = H(z) \rightarrow \rho_{\mathrm{DE}} = \rho_{\mathrm{DE}}(z)$
- DESI collaboration finds up to **3.9σ** preference for time-dependent dark energy model over the ΛCDM DESI collab. '24

Dark energy density and the CKN bound

- CKN setup: $\rho_{\mathrm{DE}}(z) = \Lambda_0 + \nu \frac{M_{\mathrm{P}}^2 H(z)^2}{16\pi^2}$

→ Using Freedman equation and 0th component of Energy-Momentum-Tensor leads to:

→ $\Omega_\Lambda(z) = \Omega_\Lambda^0 + \Omega_{\mathrm{M}}^0 \frac{\nu}{6\pi - \nu}\left[(1+z)^{3-\frac{\nu}{2\pi}} - 1\right]$

- Performing a best-fit by using Supernova data, DESI BAO data and Hubble measurements:

  $H_0 = 68.69 \pm 2.39\,(69.24 \pm 2.41)\,\mathrm{km}/(\mathrm{Mpc\,s})$

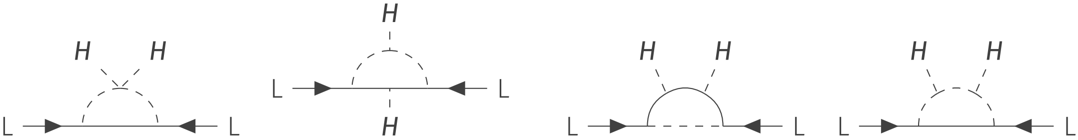
  $\Omega_{\mathrm{M}}^0 = 0.354 \pm 0.012\,(0.344 \pm 0.012)$

- Fits data better than ΛCDM model with $\Delta\chi^2 = -4.6$

P. Adolf, M. Hirsch, S. Krieg, H. Päs, M. Tabet (2024), arxiv:2406.09964

Radiative neutrino mass models and CKN bound

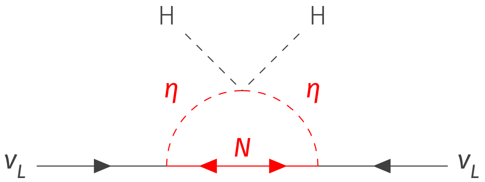
- Impact on the lowest order of mass generation
- All genuine 1-loop neutrino models can be categorized into four different topologies:



- One model of every topology: **Scotogenic model**, Zee model, inverse Scotogenic model, ScotoSinglet model

C. Arbeláez et al., JHEP 08 (2022), arXiv: 2205. 13063 [hep-ph]

Scotogenic Model



- Simplest version: Extend SM by new scalar doublet η, singlet fermions N_i and Z_2 symmetry →provides dark matter candidate
- Fermion Lagrangian:

$$L_N \supset h_{ij}\left(\nu_i \eta^0 - l_i \eta^+\right) N_j + \frac{1}{2} M_i N_i N_i + \mathrm{h.\,c} \tag{1}$$

- Scalar Potential:

$$V \supset \frac{\lambda_5}{2}\left[\left(H^\dagger \eta\right)^2 + \left(\eta^\dagger H\right)^2\right] \tag{2}$$

E. Ma, PRD 73 (2006), arXiv: hep-ph/0601225

Z. Tao, PRD 54 (1996), arXiv: hep-ph/9603309

Scotogenic Model

- Consider limit $m_R^2 - m_I^2 = \lambda_5 v^2 \ll m_0^2 = \frac{m_R^2+m_I^2}{2}$ to reduce number of free parameters
- CKN bound changes the integral

$$(M_\nu)_{ij} \approx \frac{\lambda_5 v^2}{32\pi^2} \sum_k h_{ik} h_{jk} I_{0,\mathrm{scoto}}(M_k, m_0) \to (M_\nu)_{ij} \approx \frac{\lambda_5 v^2}{32\pi^2} \sum_k h_{ik} h_{jk} I_{\mathrm{ckn,scoto}}(M_k, m_0, \Lambda_{\mathrm{UV}}, \Lambda_{\mathrm{IR}}(\Lambda_{\mathrm{UV}}))$$

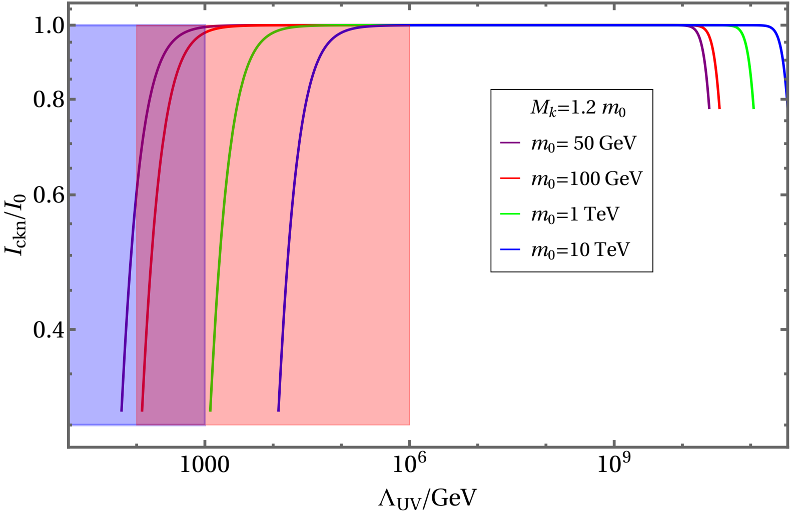
P. Adolf, M. Hirsch, H. Päs, JHEP ’23

with

$$I_{0,\mathrm{scoto}}(M_k, m_0) = \frac{M_k}{m_0^2 - M_k^2}\left(1 - \frac{M_k^2}{m_0^2 - M_k^2} \ln\left(\frac{m_0^2}{M_k^2}\right)\right)$$

$$I_{\mathrm{ckn,scoto}}(M_k, m_0, \Lambda_{\mathrm{UV}}, \Lambda_{\mathrm{IR}}(\Lambda_{\mathrm{UV}})) = \frac{M_k}{m_0^2 - M_k^2}\left(-\frac{m_0^2(\Lambda_{\mathrm{IR}}^2 - \Lambda_{\mathrm{UV}}^2)}{(m_0^2 + \Lambda_{\mathrm{IR}}^2)(m_0^2 + \Lambda_{\mathrm{UV}}^2)} + \frac{M_k^2}{m_0^2 - M_k^2} \ln\left(\frac{(m_0^2 + \Lambda_{\mathrm{UV}}^2)(M_k^2 + \Lambda_{\mathrm{IR}}^2)}{(m_0^2 + \Lambda_{\mathrm{IR}}^2)(M_k^2 + \Lambda_{\mathrm{UV}}^2)}\right)\right)$$

Scotogenic Model



Summary

- CKN bound imposes momentum cutoffs relevant for loop calculations
- Using the Hubble length as IR cutoff a time-dependent dark energy model can be constructed matching new DESI measurements
- In case of the four radiative neutrino mass models the parameter space changes
- Choice of Λ_{UV} still unknown
- Cutoffs are only meant to indicate the range in which QFT can be applied without considering also the influence of gravity