Quantum Gravity & Flavor

Probing New Frontiers with Neutrinos

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Rome, Italy

Open Questions in the SM:

Neutrino Masses,
Flavor Puzzle,
Baryogenesis,
Dark Matter,
Dark Energy,
Hierarchy Problem…

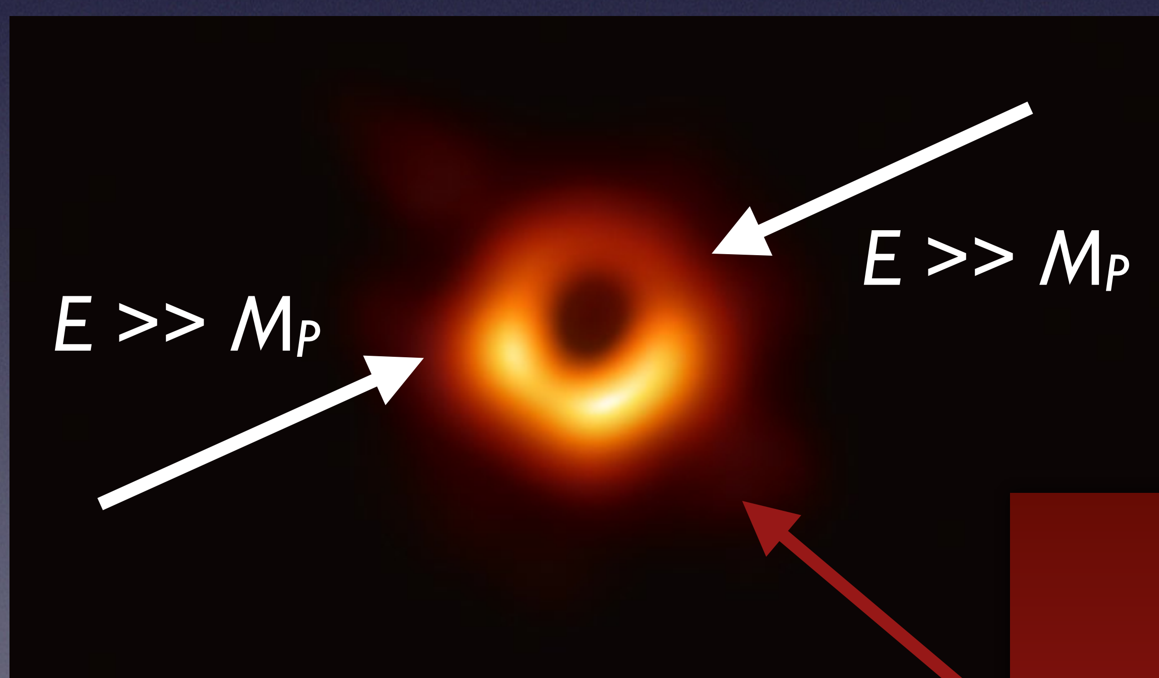
Worries of a Typical Particle Theorist

Limitations of the EFT Mindset

Tacit assumption in QFT/EFT:

higher energies ~ shorter distances ~ more fundamental

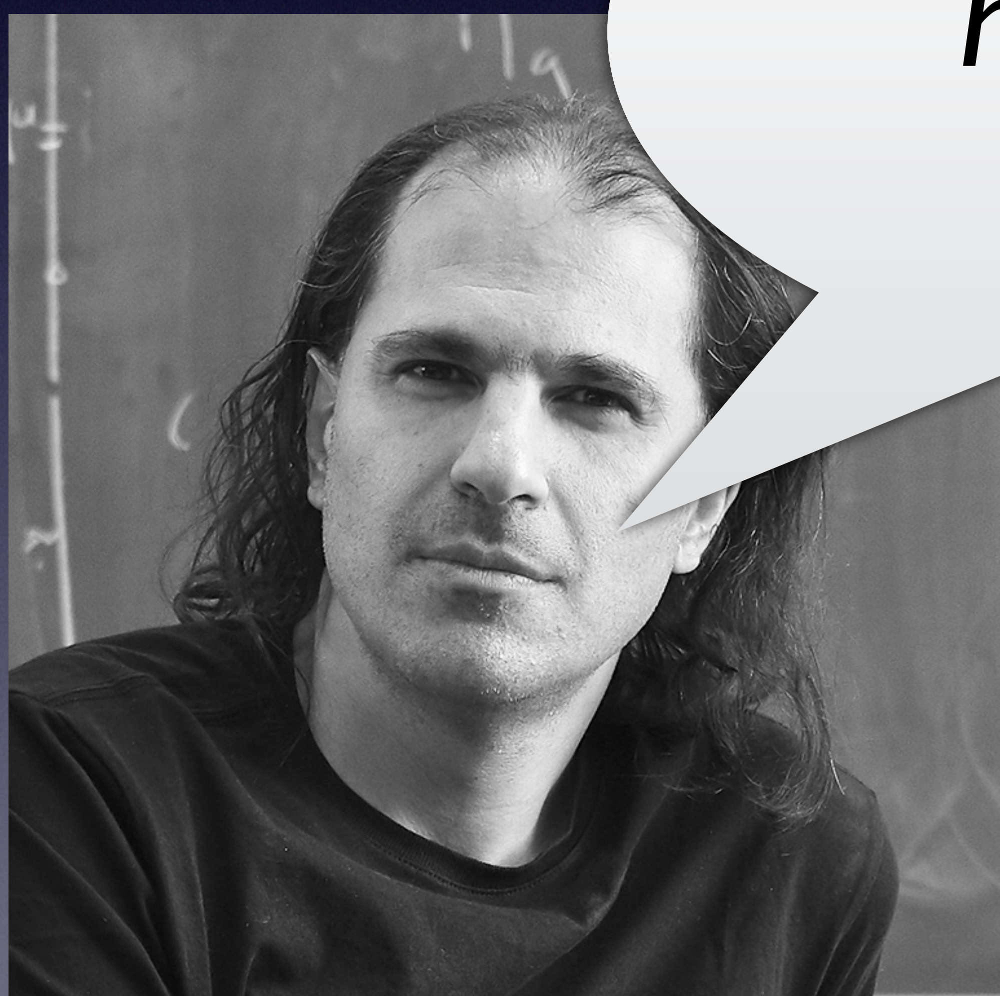
But for $E >> M_P$:



Black Hole production:
Black Hole grows with E
⇒ for large E:

higher energies ~ larger distances

Limitations of the EFT Mindset



"The World is not a crappy Metal"

Nima Arkani-Hamed @ Harvard, 10/7/2021

3 Lessons from Black Holes

No Hair Theorem

A stationary Black Hole is completely characterized by 3 quantities: mass, charge & angular momentum

Israel, 1967

3 Lessons from Black Holes

Violation of the 2nd law of thermodynamics?

What happens to entropy falling into a Black Hole?
→ growth of Black Hole horizon A compensates for loss of entropy behind BH event horizon

Bekenstein, Hawking, 1971-1974

- Black Holes have temperature → Hawking Radiation
- Information Loss → Breaking of Global Symmetries

Witten, 2000; Harlow, Ooguri, 2019

- Horizon ≙ Environment for Decoherence
→ Breaking of Unitarity

Hawking, 1975, Page, 1980

Semiclassically, Black Holes act as a sink for information and global quantum numbers

3 Lessons from Black Holes

More or less expected to hold also in Quantum Gravity

Quantum-to-Classical transition

Flavor

Neutrino Masses

Holographic Bound

Holographic Bound

First Law of Black Hole Mechanics

$dA_{BH} \sim dM = T\, dS_{BH}$ (Bardeen, Carter, Hawking 1973)

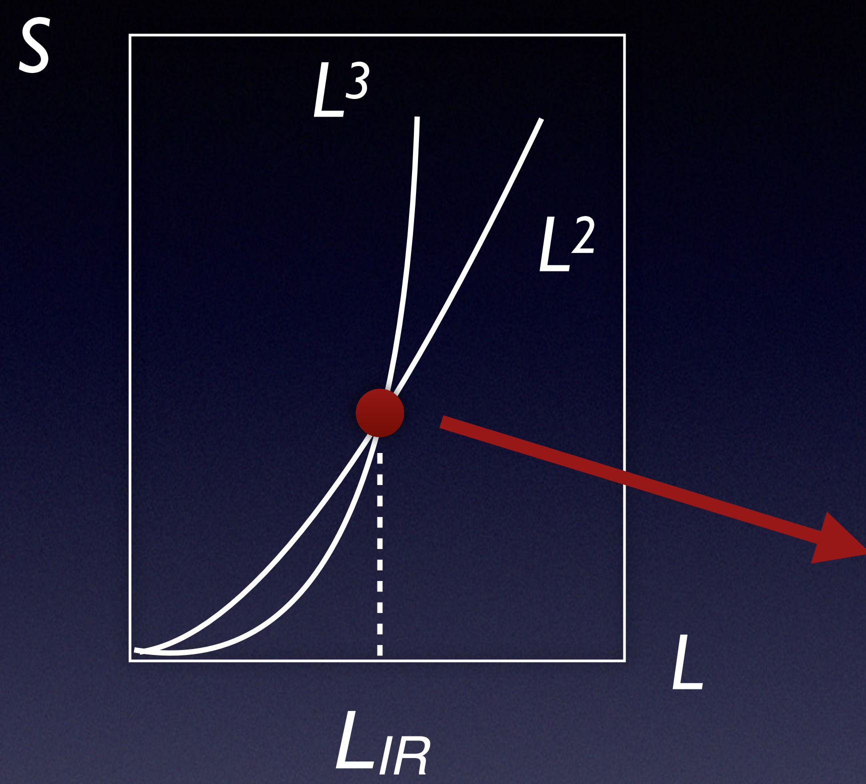
Holographic Bound

Maximum information in a spacetime region V = information in a Black Hole → grows with $A_{BH} \sim L^2$

t'Hooft, 1993; Susskind 1994

→ Contradiction to QFT where information in a volume grows with $\sim L^3$

Holographic Bound



Starting from this point, QFT overcounts dofs!

→ IR cutoff for QFT

QFT works only here!

CKN Bound

Excluding BHs entirely from the QFT model space

Bound from BH entropy still contains many states with Schwarzschild radius R_S < box size
⇒ even low E particles can collapse into BHs!

To avoid this, exclude all states with Schwarzschild radius R_S < box size:

$$\Rightarrow L_{IR} = R_S = 2\,GM \text{ with } G = 1/(2M_P^2) \Rightarrow R_S = M/M_P^2$$

Solve for L_{IR}:

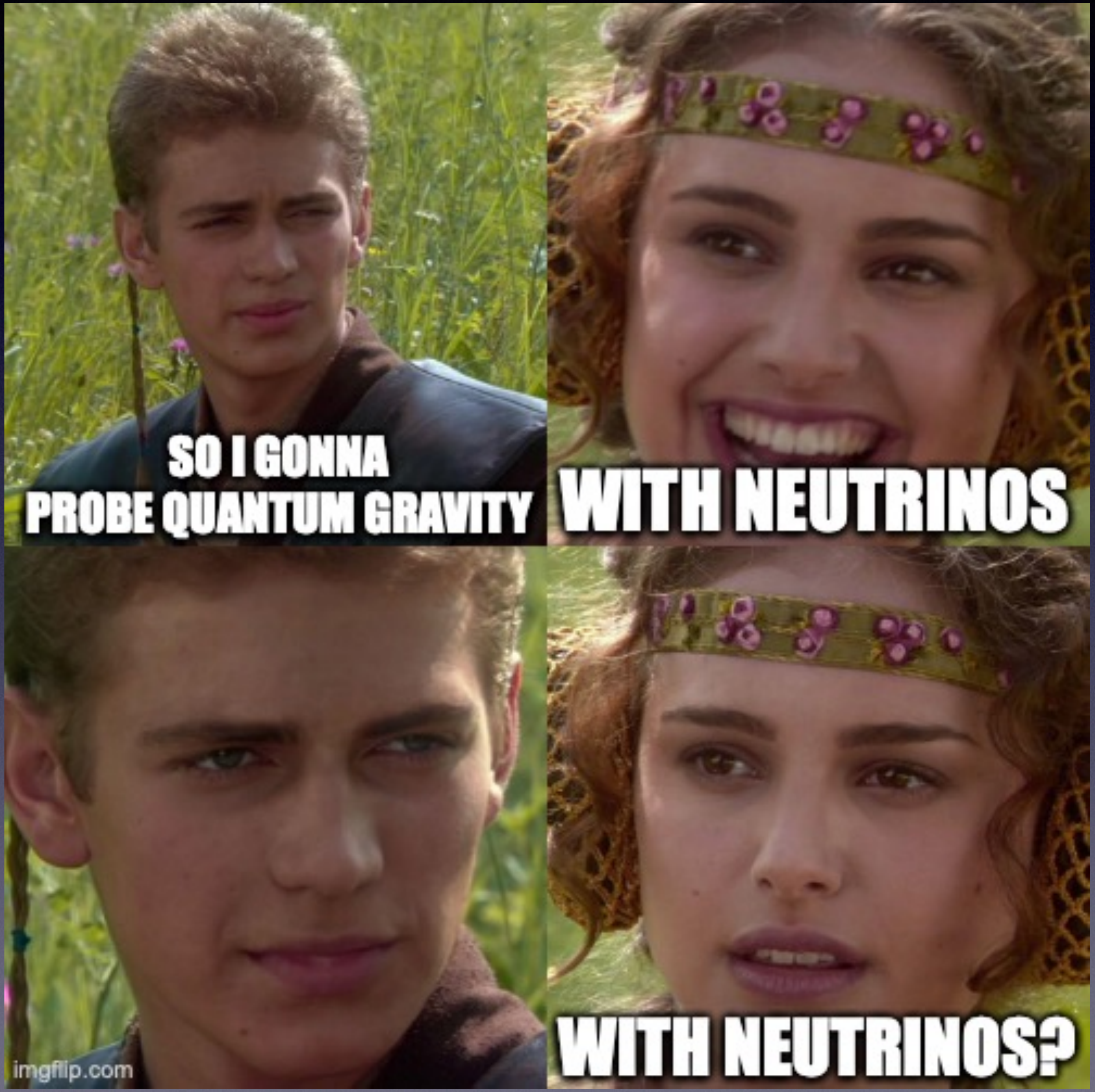
$$L_{IR} = M_P / \Lambda^2$$

Cohen, Kaplan, Nelson, 1999

→ Relation between UV cutoff Λ and IR cutoff L_{IR}

→ Implies $\Lambda < M_P$ as for $\Lambda = M_P \Rightarrow \Lambda = L_{IR}^{-1}$ → QFT nowhere valid!

Neutrinos & Gravity - An Unlikely Match

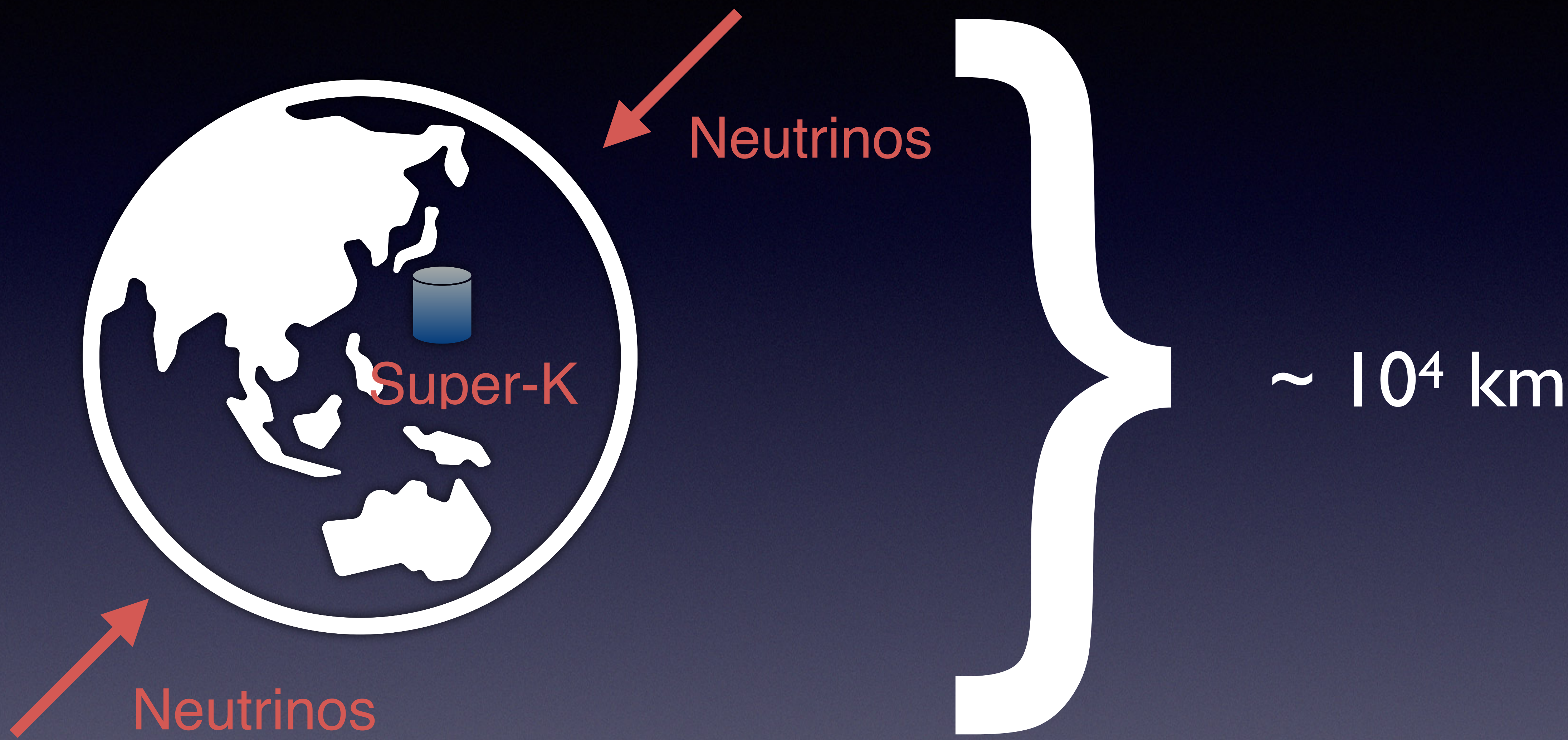



NOT SO FAST
MeMe(S)Generator.hu

Why Neutrinos ?

- Weak interactions
  → perfect quantum probes
- Flavor violation, Majorana(?)
  → global symmetry violation
- Seesaw
  → large energy scale
- Extragalactic neutrinos at neutrino telescopes probe extreme distances
- Huge energies up to (so far) 10^2 PeV

Atmospheric Neutrinos



→ Plugged into Holographic or CKN Bound

$\Lambda < 10^3$ TeV (Holographic) or $\Lambda < 300$ MeV (CKN)

Implications ?

- High scale Seesaws still valid?

  → Inverse Seesaw?, Dirac Masses?, Radiative Mass Models?

- Quantum-Gravitational Origin of Neutrino Masses?

  → Neutrino Anomalies?

- Holographic Scaling? Overlapping degrees of freedom? Depletion of QFT density of states?

  Friedrich, Cao, Carroll, Cheng, Singh, 2024;
  Banks, Draper, 2020

  → modified dispersion relations? — Carmona, Cortes, Indurain, 2000

  → energy-dependent neutrino masses & mixing angles? new resonances? — Döring, HP, Sicking, Weiler, 2020

Radiative Neutrino Masses and the CKN Bound

scotogenic model

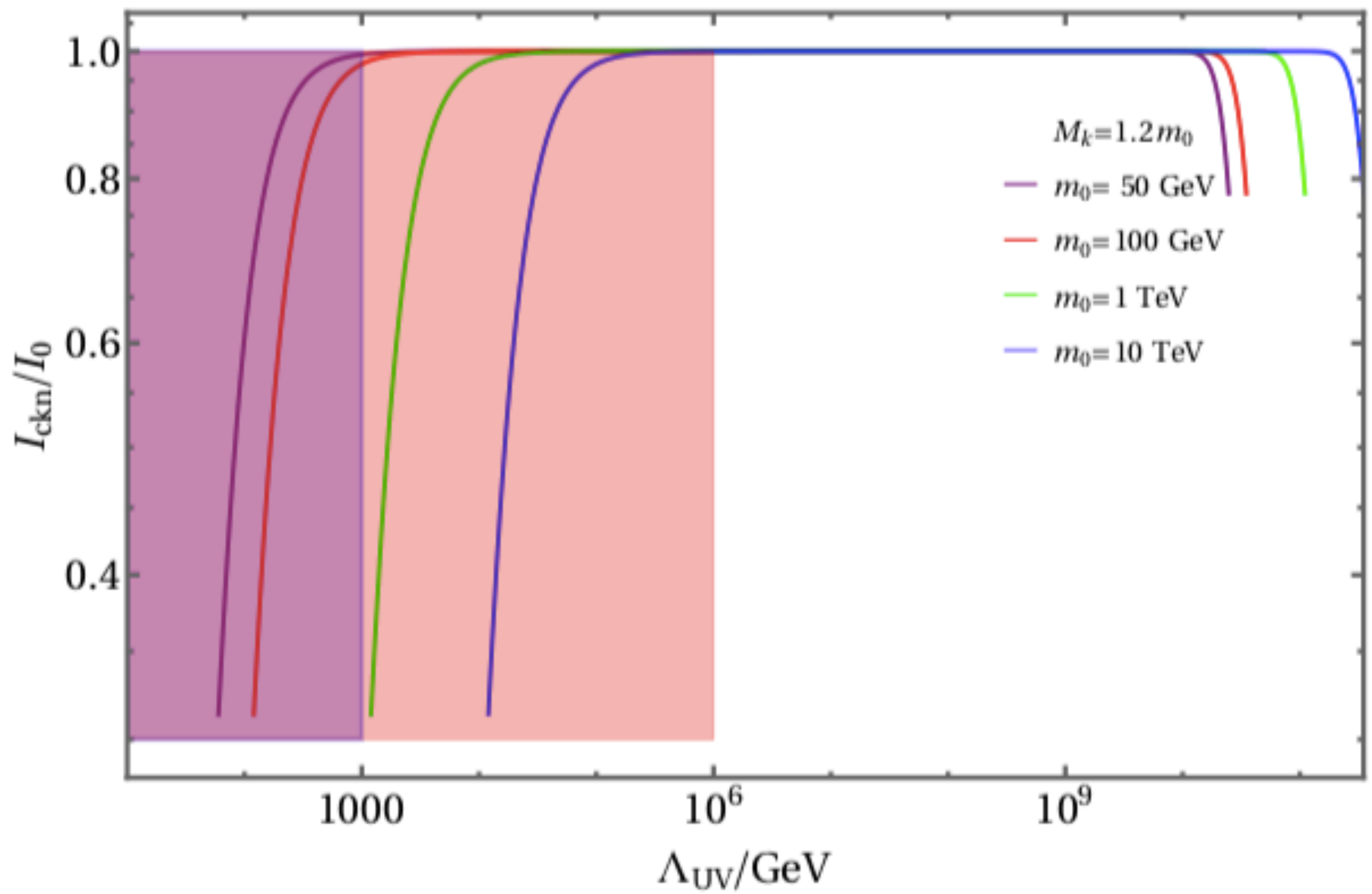
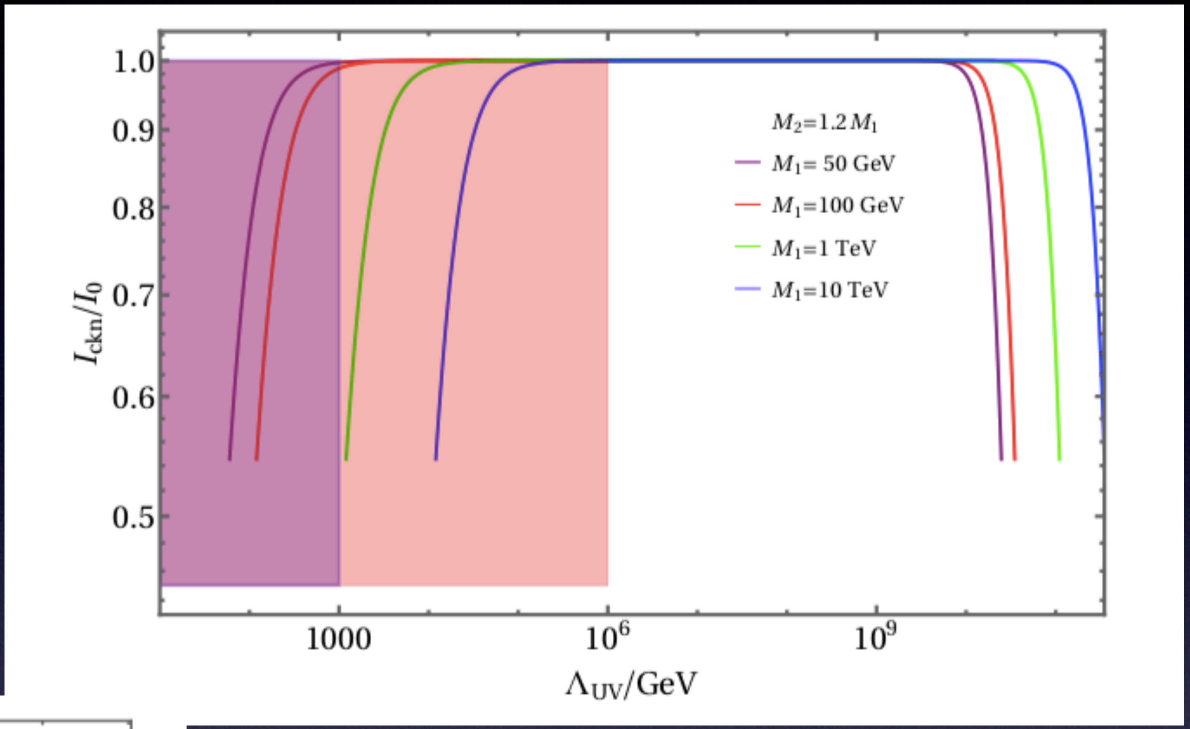


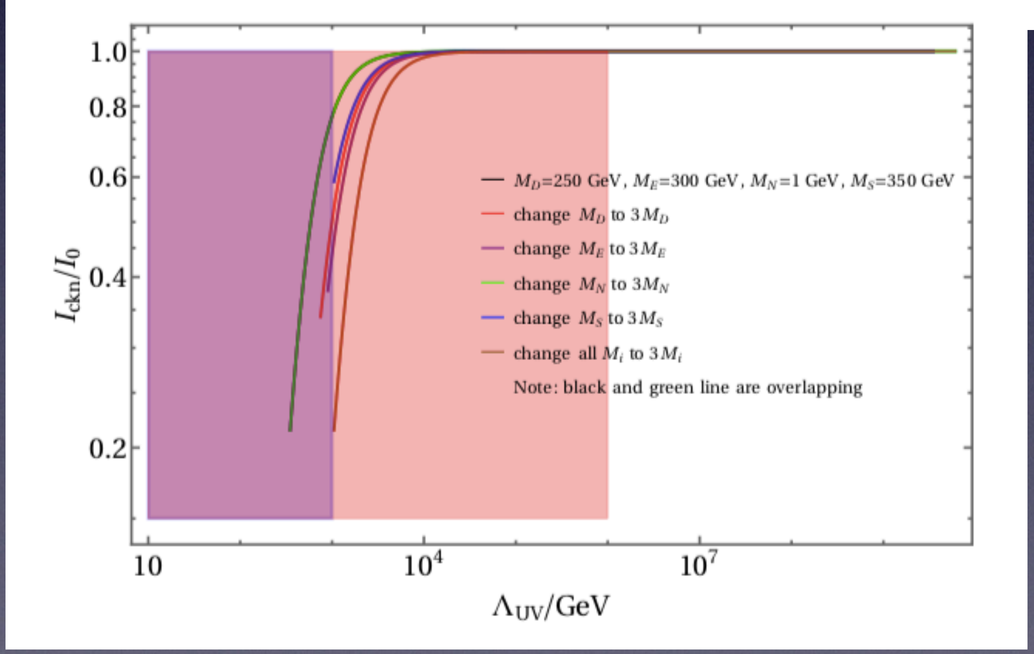
Figure 3: Relative discrepancy between the neutrino mass with and without the influence of the CKN bound for the scotogenic model. Different mass choices for the free parameters are considered. The allowed range of Λ_{UV} in the calculation of the magnetic moment of the muon is displayed as a red background. The area allowed by both the magnetic moment of the electron and muon is shown as the violet region.

Adolf, Hirsch, HP, 2023

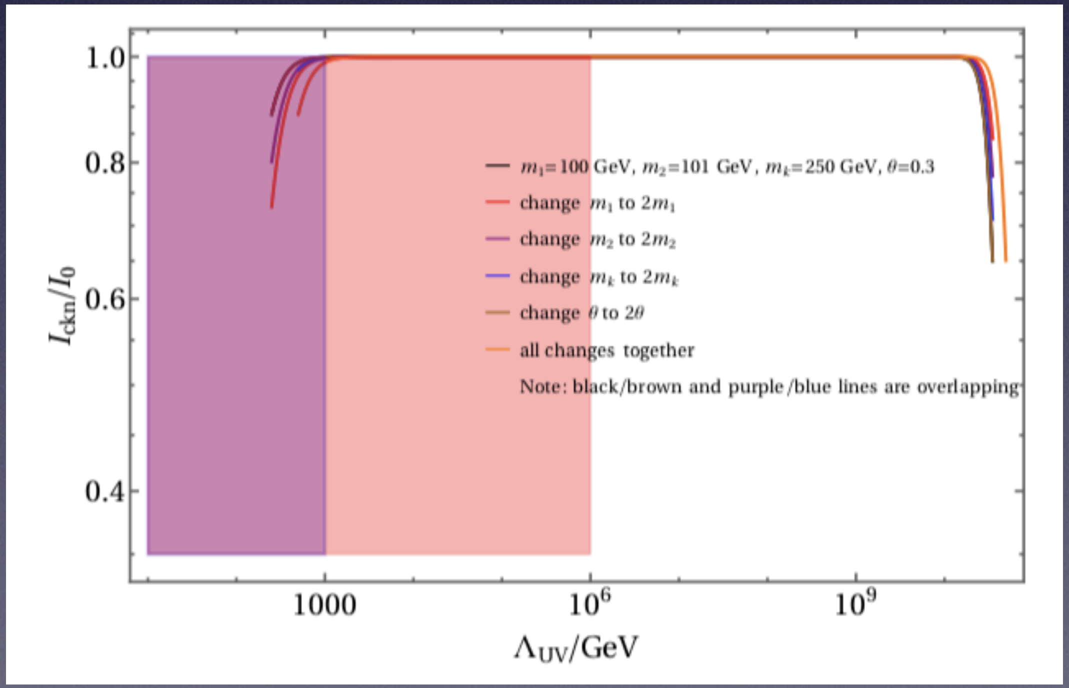
Radiative Neutrino Masses and the CKN Bound

Zee model





inverse scotogenic model



Adolf, Hirsch, HP, 2023

ScotoSinglet model

CKN Bound & Evolving Dark Energy

Potential solution to the "cosmological constant problem"

- Vacuum fluctuations $\rho \sim \langle 0 | T_{\mu\nu} | 0 \rangle$ contribute to dark energy density with $\langle \rho \rangle \sim \Lambda^4 \sim M_P^4 \sim 10^{76}$ GeV^4 compared to the observed $\langle \rho \rangle \sim (10^{-3}$ eV$)^4$

- Adopting $L_{IR} \sim H_0^{-1}$, the current Hubble horizon implies $\Lambda \sim 10^{-3}\ eV$ in agreement with observation!

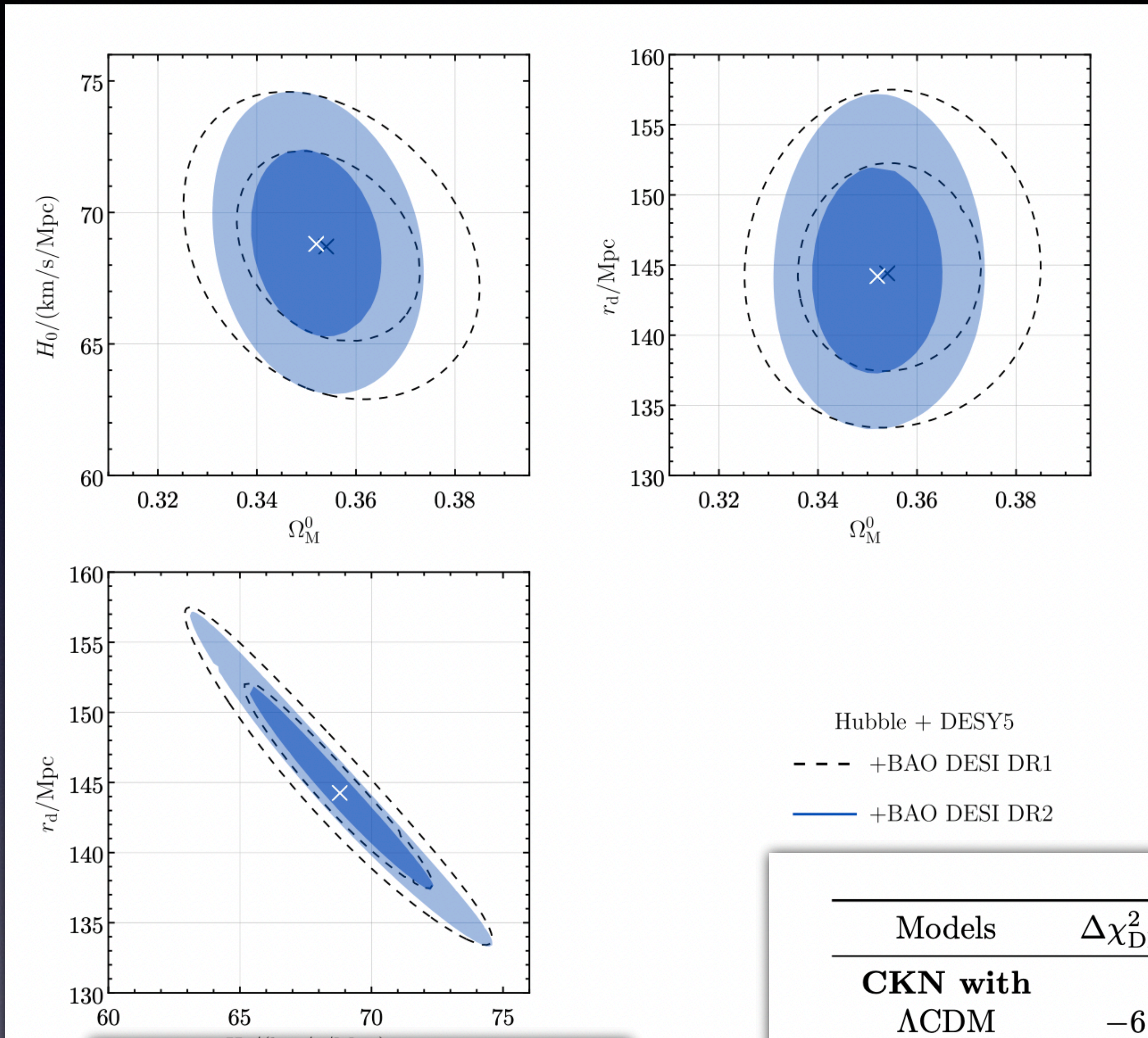
Cohen, Kaplan Nelson, 1999

- Suggests an Evolving Dark Energy density:

$$\rho_{\mathrm{DE}}(z) = \Lambda_0 + \nu \frac{M_{\mathrm{Pl}} H^2(z)}{16\pi^2}$$

Adolf, Hirsch, Krieg, HP, Tabet, 2024

Fitting the DESI BAO Data



Adolf, Hirsch, Krieg, HP, Tabet,
2024 & 2025

- BAO, Hubble & Supernova data
- Better fit than ΛCDM
- Trend strengthens with 2025 data release
- No CMB data included yet!

Models	$\Delta\chi^2_{DR2-DR1}$	
	DESY5	Pantheon+
CKN	−2.85	−2.84
νCKN	−2.91	−3.76
ΛCDM	−0.52	−1.93
ωCDM	−3.72	−3.59
$\omega_0\omega_a$CDM	−3.29	−3.13

Models	$\Delta\chi^2_{DESY5}$	ΔAIC_{DESY5}	$\Delta\chi^2_{Pantheon+}$	$\Delta AIC_{Pantheon+}$
CKN with				
ΛCDM	−6.90	−6.90	−2.05	−2.05
ωCDM	3.14	1.14	2.26	0.26
$\omega_0\omega_a$CDM	5.74	1.74	2.43	−1.57
νCKN with				
ΛCDM	−6.94	−4.94	−3.07	−1.07
ωCDM	3.09	3.09	1.24	1.24
$\omega_0\omega_a$CDM	5.69	3.69	1.41	−0.59

Implications ?

- Evolving Dark Energy
- No ΛCDM → Revise cosmological neutrino mass bound
- Also: Cosmological Neutrino Mass Bounds in conflict with Δm2's from atmospheric neutrino oscillations!

$$\Sigma m_\nu < 0.081\,\text{eV for SPT-3G D1} + \text{DESI},$$
$$\Sigma m_\nu < 0.048\,\text{eV for CMB-SPA} + \text{DESI}.$$

Camphuis et al.
(South Pole Telescope SPT-3G), 2025;
see also: Elbers et al. (DESI), 2025

→ Quantum-Gravity effects (CKN, Holographic?)

- Neutrinos coupled to Dark Energy? → Mass varying neutrinos?

Singh 1995; Hung 2000; Nelson, Fardon, Weiner 2004;
Hung & HP, 2005;
Craig, Green , Meyers, Rajendran, 2024;

Quantum-Gravitational Decoherence

Quantum Gravitational Decoherence

- Can be modeled as a sink term in the evolution equation

$$\frac{\mathrm{d}}{\mathrm{d}t}\varrho(t) = -i[H, \varrho(t)] - \frac{1}{L_{\mathrm{coh}}}\left(1 - \hat{D}\right)\varrho(t) - \mathcal{G}\varrho(t)$$

Ellis, Hagelin, Sredicki, Nanopoulos, 1984

- Quantum Gravity violates all global quantum numbers!
- Entails a democratic flavor distribution!
- Depends exponentially on propagation distance

$$P_{ee}(L) = \frac{1}{2} + \frac{1}{2}\cos^2(2\theta)e^{-2\gamma L}$$

(2ν-approximation)

Great sensitivity at neutrino telescopes!

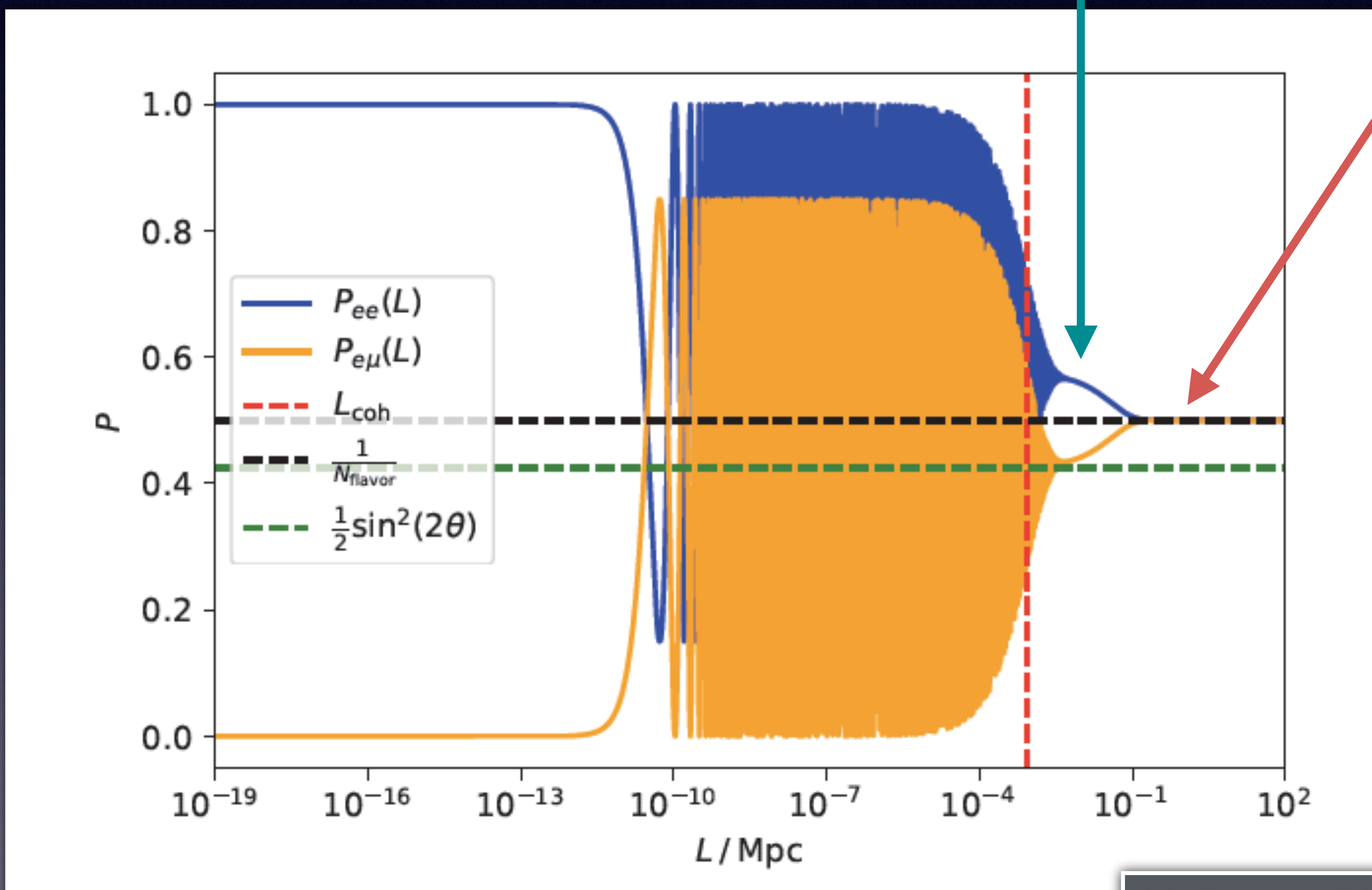
Klapdor-Kleingrothaus, HP, Sarkar, 2000;
Anchordoqui, Goldberg, Gonzalez-Garcia, Halzen, Hooper, Sarkar, Weiler, 2005;
Stuttard, Jensen, 2020; De Romeri, Giunti, Stuttard, Ternes, 2023;

QG Decoherence & Wave Pakets

$$\frac{\mathrm{d}}{\mathrm{d}t}\varrho(t) = -i[H,\varrho(t)] - \frac{1}{L_{\mathrm{coh}}}\left(1-\hat{D}\right)\varrho(t) - \mathcal{G}\varrho(t)$$

Wave Package Separation Decoherence

Quantum-Gravitational Decoherence



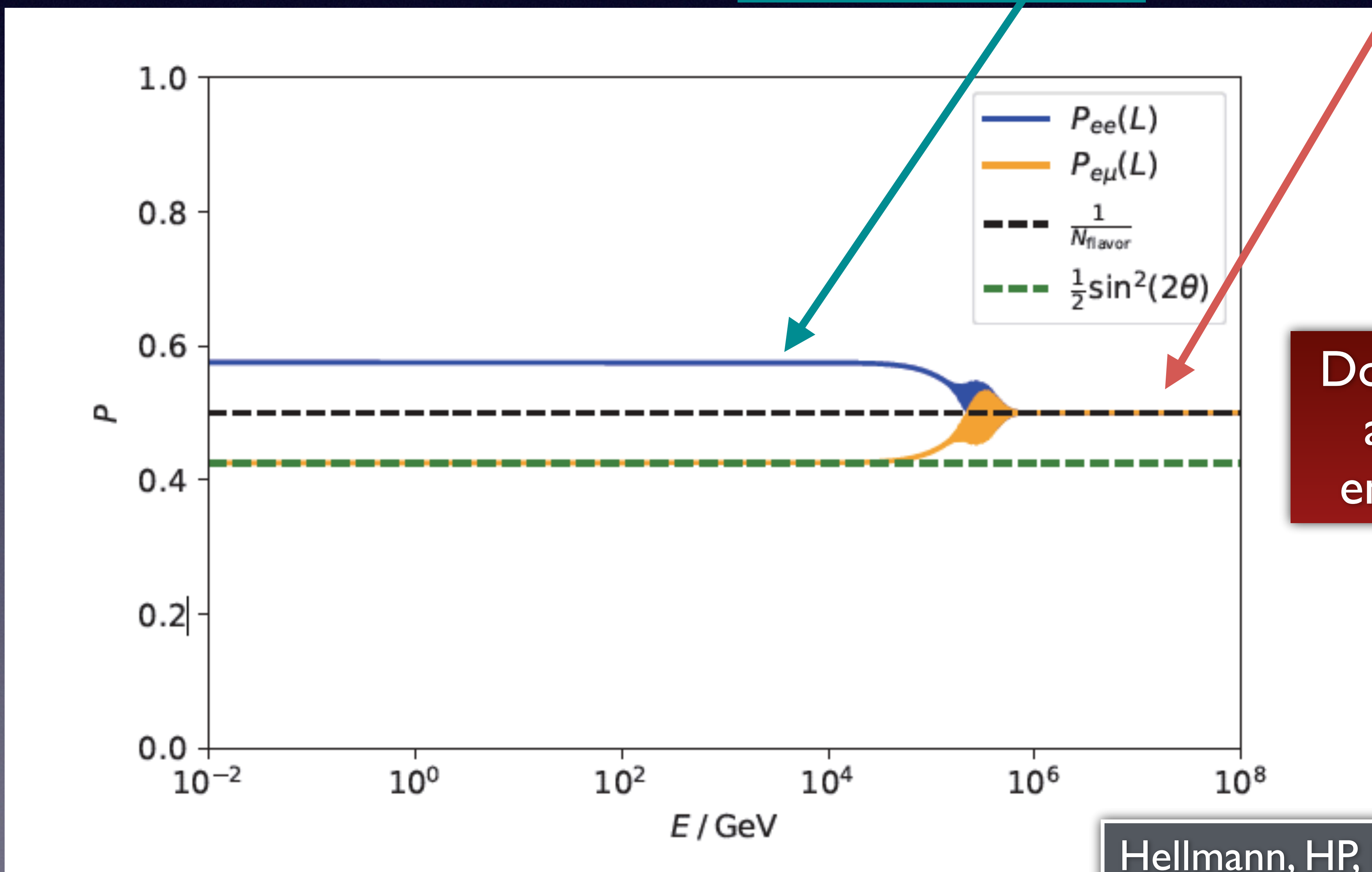
Hellmann, HP, Rani, 2022

QG Decoherence Wave Pakets

$$\frac{\mathrm{d}}{\mathrm{d}t}\varrho(t) = -i[H, \varrho(t)] - \frac{1}{L_{\mathrm{coh}}}\left(1 - \hat{D}\right)\varrho(t) - \mathcal{G}\varrho(t)$$

Wave Package Separation Decoherence

Quantum-Gravitational Decoherence



Dominates at high energies!

Hellmann, HP, Rani, 2022

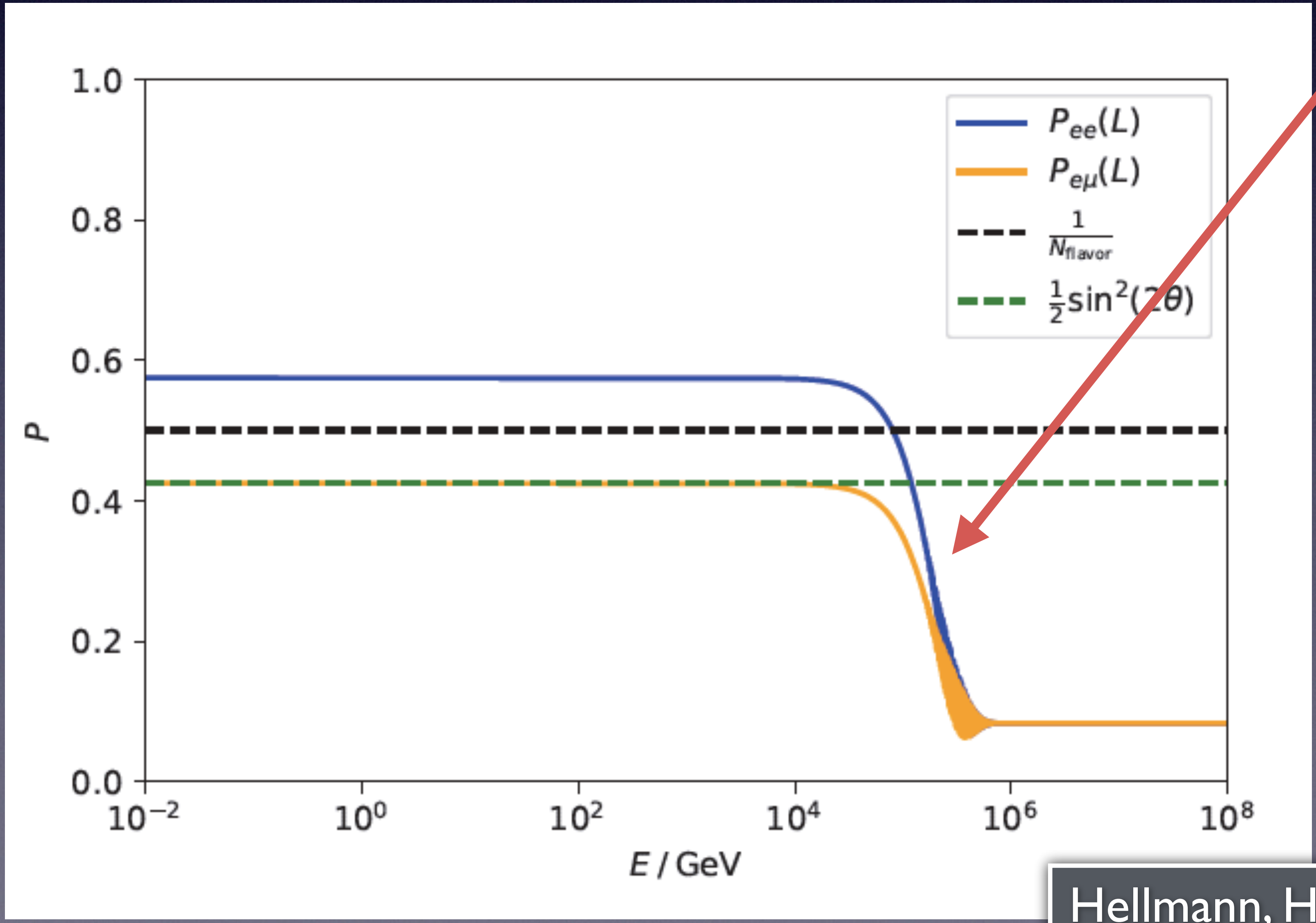
QG Decoherence & Dark Sectors

Search for Hidden Particles

Adding N-2 additional dark Fermions:

$$P_{ee}(L) = \frac{1}{N} + \frac{N-2}{2N}e^{-2\gamma L} + \frac{1}{2}\cos^2(2\theta)e^{-2\gamma L} + \frac{1}{2}\sin^2(2\theta)e^{-\left(\gamma+\frac{1}{L_{\rm coh}}\right)L}\left\{\cos(\omega L) + \frac{\gamma}{\omega}\sin(\omega L)\right\}$$

Democratic Flavor Distribution over ALL neutral fermions!

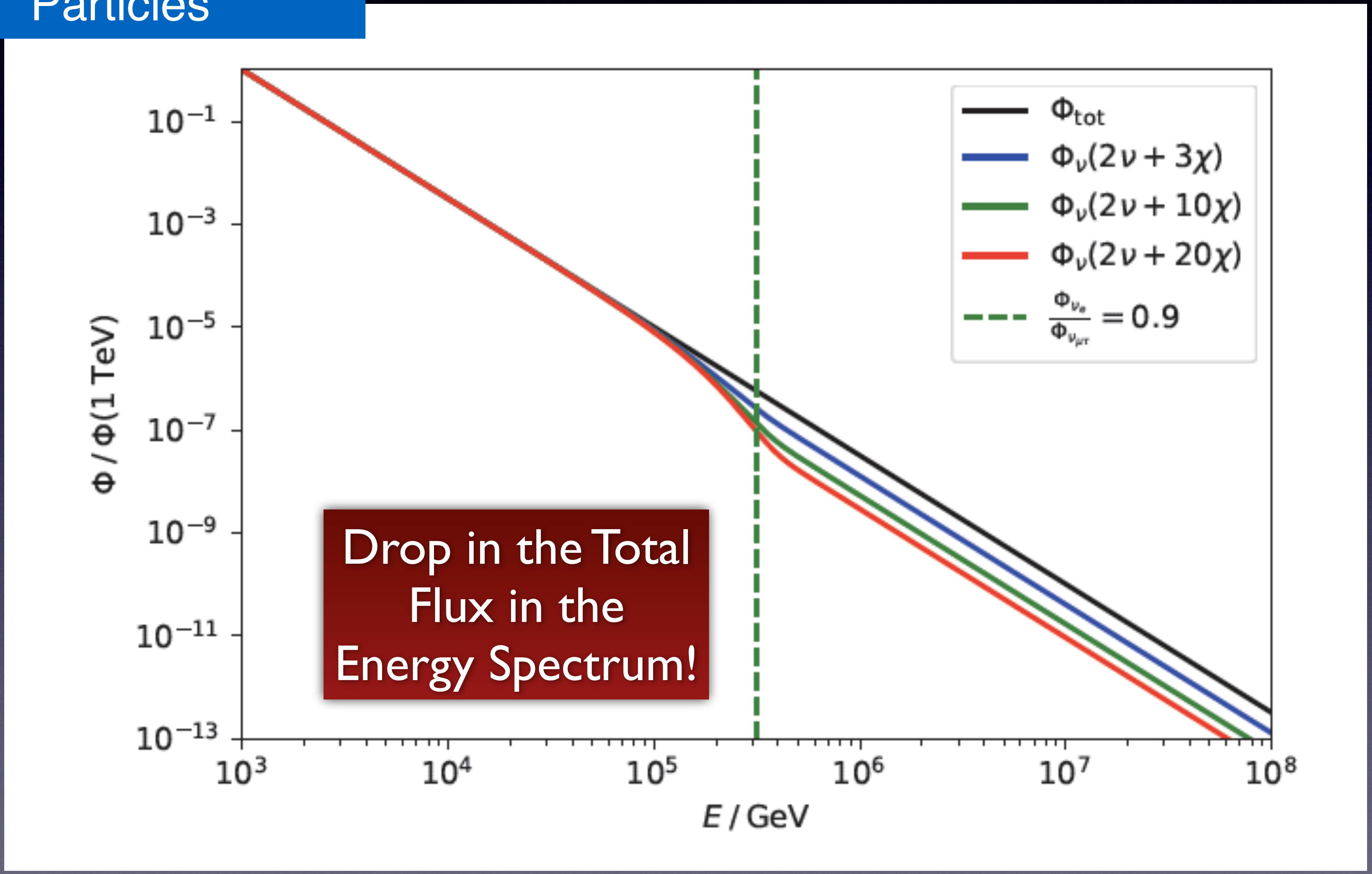


Drop in the Survival Probability!

Hellmann, HP, Rani, 2022

QG Decoherence & Dark Sectors

Search for Hidden Particles

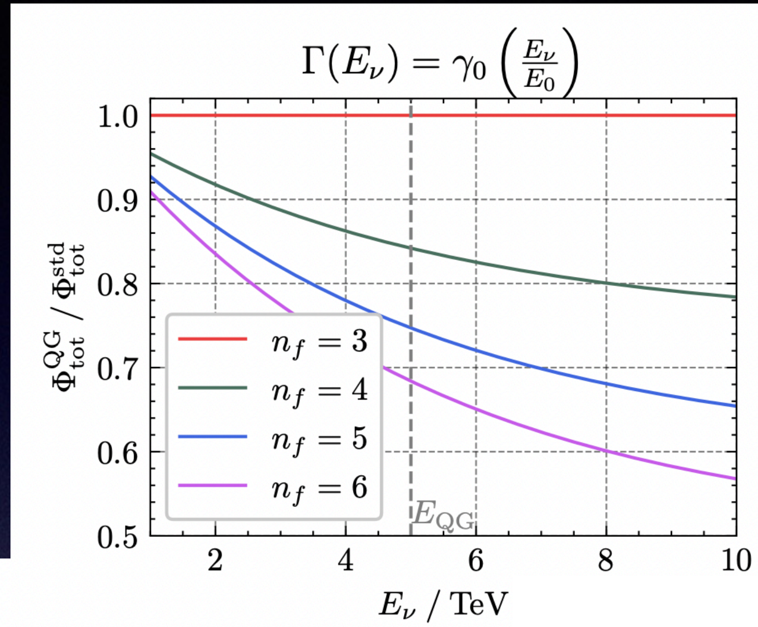


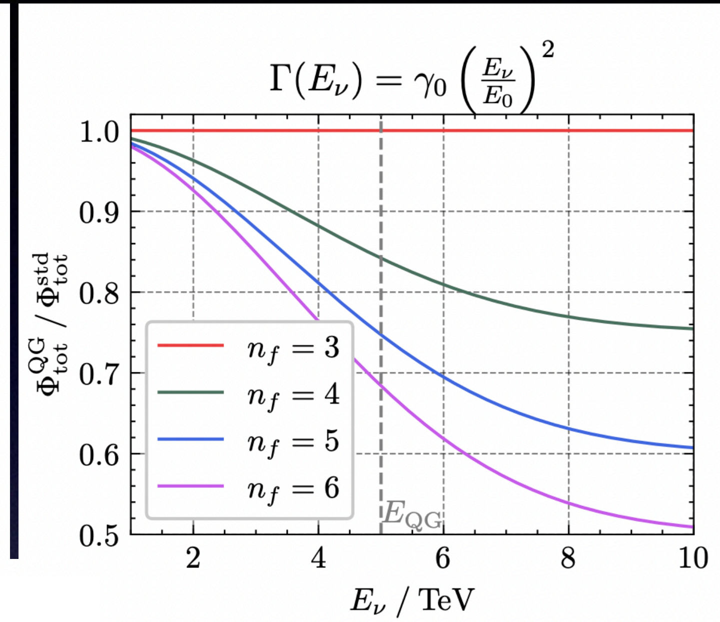
Drop in the Total Flux in the Energy Spectrum!

Hellmann, HP, Rani, 2022

QG Decoherence & Dark Sectors

Sensitivity Study for NGC1068 (79 signal events at 5.2σ) at IceCube





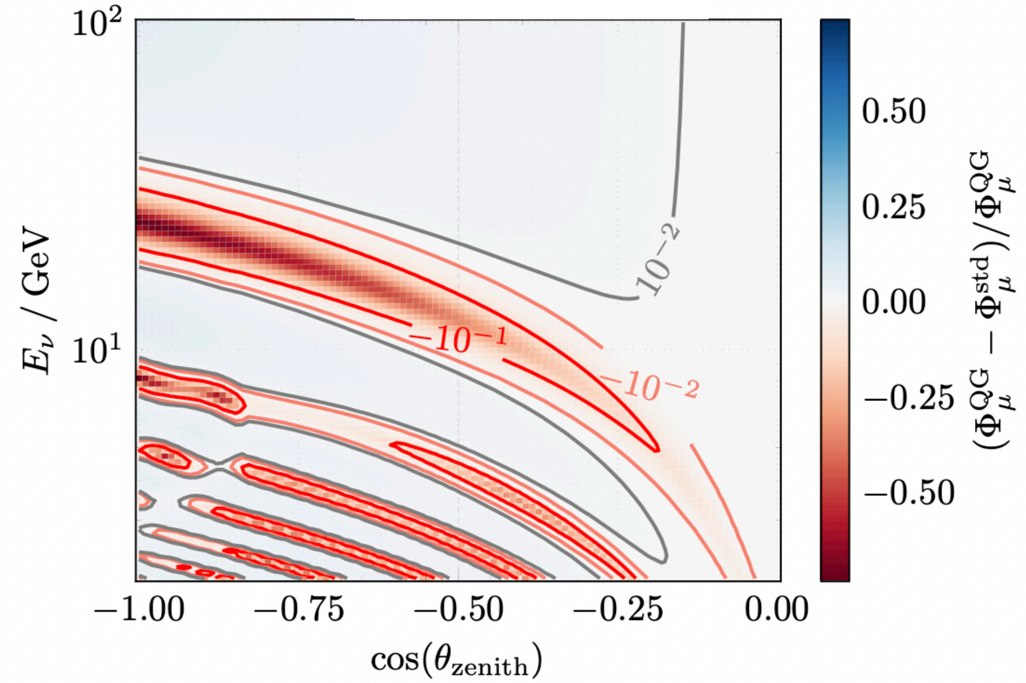


Figure 8: Muon neutrino oscillogram for $n_f = 4$ in case of the constant decoherence model and for the corresponding 95% C.L. $\gamma_0 = 1.41 \times 10^{-15}$ eV value. Shown is the relative muon neutrino flux deviation as a function of the energy E_ν and the zenith angle $\cos\theta_{zenith}$.

Domi, Eberl, Hellmann, Krieg, HP, 2025

Summary

- Quantum Gravity: Both UV and IR Effects! Holographic Scaling, UV/IR cutoffs for QFT, Global symmetry & unitarity violations
- Neutrinos: large baselines & energies, weak interactions
  → excellent quantum gravity probes
- UV/IR cutoffs (CKN, Holographic) limit applicability of QFT to oscillations on large baselines beyond 10^3 TeV or less
- CKN cutoff suggests Evolving Dark Energy that fits DESI BAO
- Cosmological ν mass bounds too tight!
  Quantum Gravity? Mass Varying Neutrinos?
- Quantum-Gravitational Decoherence may be sensitive to Hidden Flavors and testable at neutrino telescopes

Picture Credits: NASA (Spacetime Foam), Memes (imgflip.com, MeMe(S)generator.hu), Arkani-Hamed (Quanta Magazine), Nature Cover (Nature), EHT/ESO (Black Hole)

Probing the CKN Bound: Radiative Corrections

A. Cohen, D. Kaplan & A. Nelson,
PRL 1999, arXiv: hep-th/9803132

→ effect on anomalous magnetic moments of electrons and muons

P. Adolf, M. Hirsch, H. Päs, arXiv:2306.15313

→ effect on radiative neutrino mass models