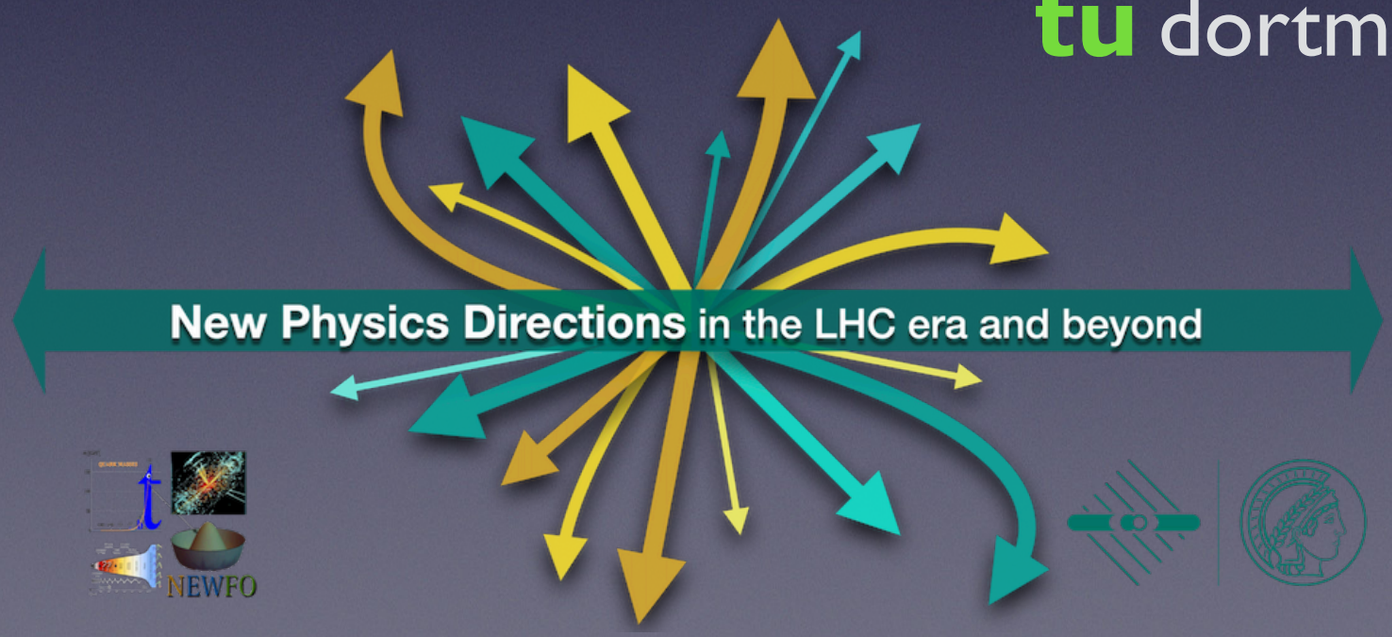
UV/IR-Mixing
and
Physics Beyond the Standard Model

Heinrich Päs

Fakultät Physik
tu dortmund

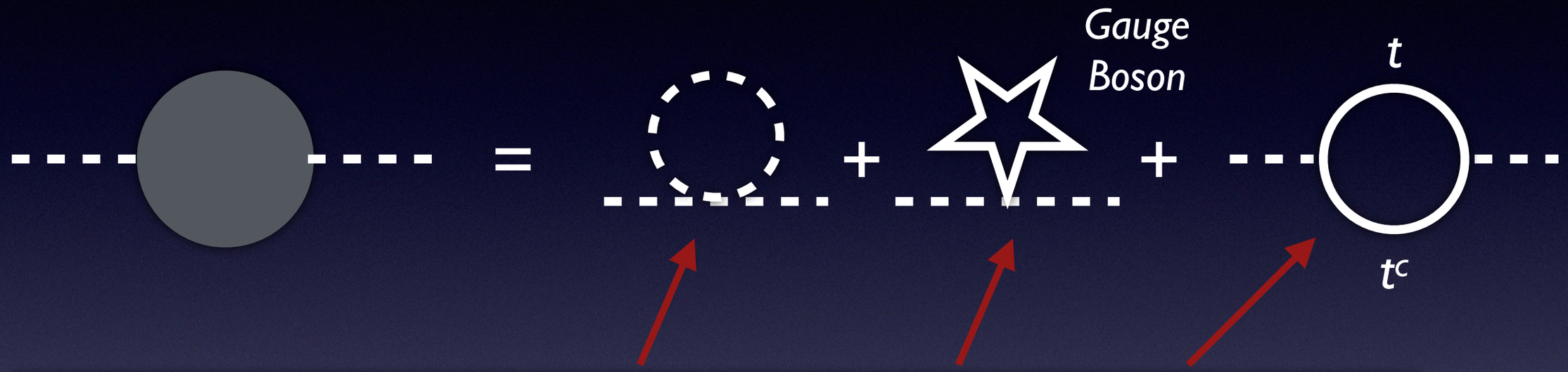


And lest I should be exalted above measure through the abundance of the revelations, there was given to me a thorn in the flesh, the messenger of Satan to buffet me, lest I should be exalted above measure.

(2 Corinthians 12:7-10)

Hierarchy Problem Recap

1-Loop Contribution to the Higgs mass



$$\Delta m_H^2 = (\Lambda^2 / 16\,\pi^2)\,(3\lambda + (1/8)\,(3g^2+3g'^2) - 3\,y_t^2) \sim \Lambda^2$$

With $\Lambda \sim M_P \Rightarrow \Delta m_H \sim M_P \sim 10^{19}\ GeV \sim 10^{17}\ m_{EW} \sim 10^{17}\ m_H$

>> observed Higgs mass: $m_H = 125\ GeV$
→ unnatural cancellation required in SM
with a UV cutoff scale Λ!

Hierarchy Problem Recap

Traditional Solutions:

Supersymmetry: Introduce SUSY partners f ↔$\tilde{f}$ for all SM particles → Cancellation of boson & fermion contributions to m_H above a SUSY breaking scale ~ 1 TeV where SUSY partners of SM fermions and bosons get produced.

Large extra dimensions: Lower Planck scale to O(1 TeV) → suppressed Δm_H

Compositeness/Technicolor: Higgs assumed to be composite. Higgs decomposition: cutoff scale << M_P

- Problem: No new physics has been found at the electroweak/TeV scale → Solutions become increasingly unnatural themselves!

Haiku of the Day:

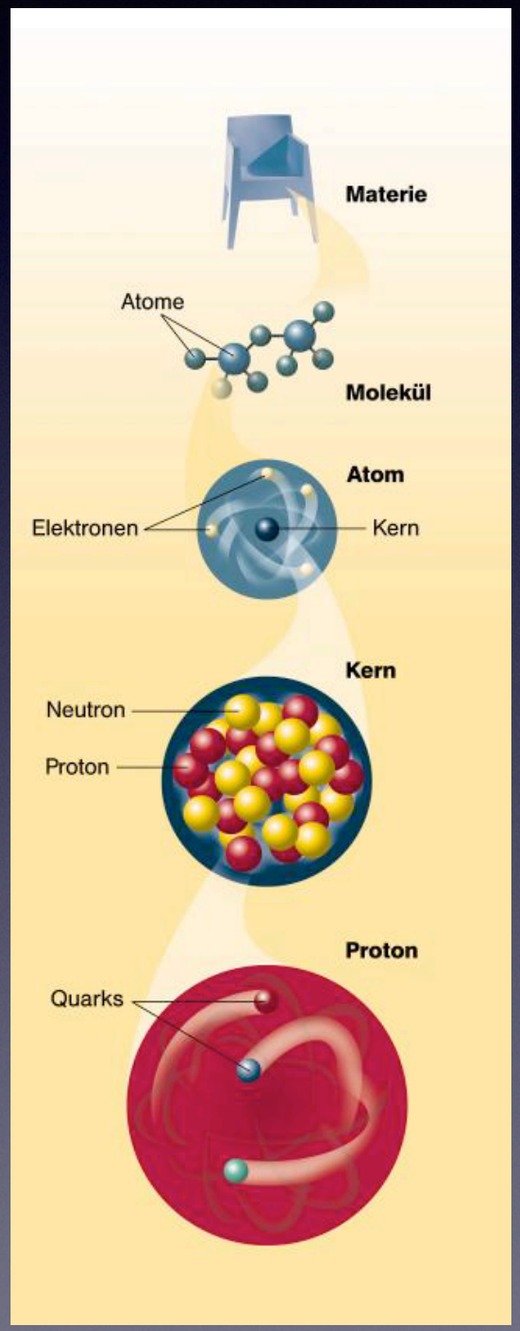
Maybe
the Absence of New Physics
IS the New Physics

"We are confronted with the need to reconsider the guiding principles that have been used for decades to address the most fundamental questions about the physical world…

…revolutionary and unprejudiced ideas are needed for a real paradigm change…"

(Gian Giudice)

"Guiding principles… used for decades?"
"Revolutionary and unprejudiced ideas?"

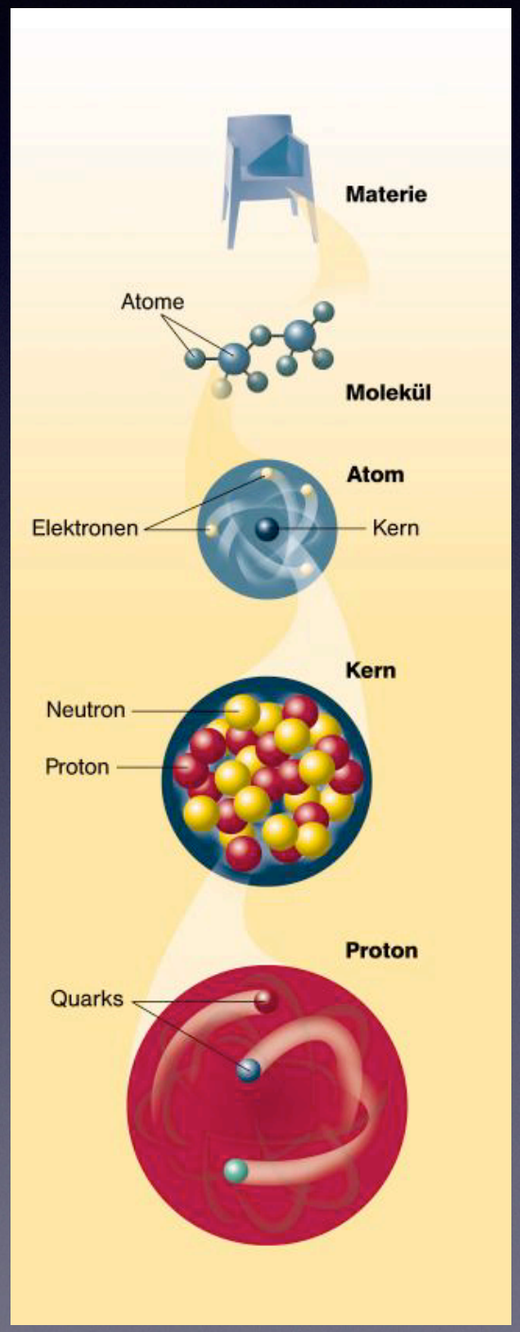


Source: DESY

Tacit assumption:

higher energies
~ shorter distances
~ more fundamental

"Guiding principles… used for decades?"
"Revolutionary and unprejudiced ideas?"



Source: DESY

Tacit assu n:

~~correct~~ ?

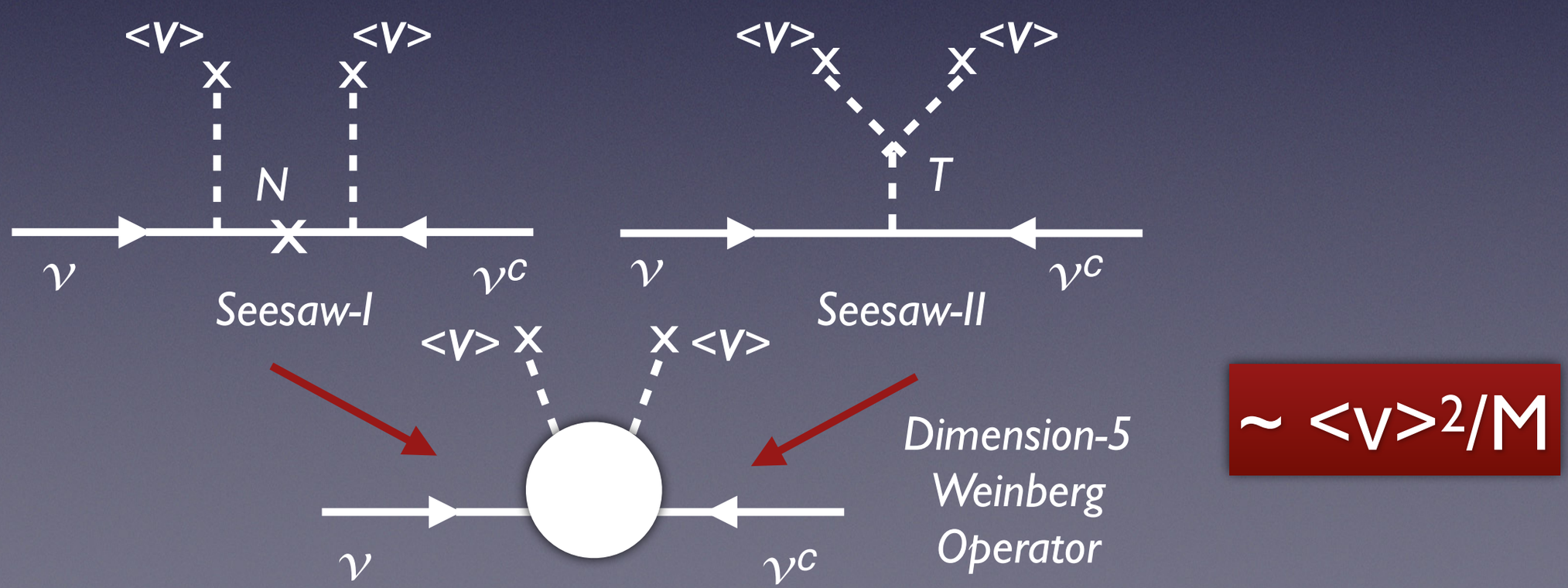
energies
orter distances
~ more fundamental

QFT/EFT paradigm

More concrete:

Particle physics is accurately described by EFT with UV cutoff $\Lambda \leq M_{P.}$ Substructure and dofs at shorter distances can be ignored (physics effects described by local operators involving only llight dofs) as long as momenta & field strengths $\ll \Lambda$

Example:



$\sim \langle v \rangle^2/M$

According to the EFT paradigm, nature is a neatly constructed set of Russian Matryoshka dolls:

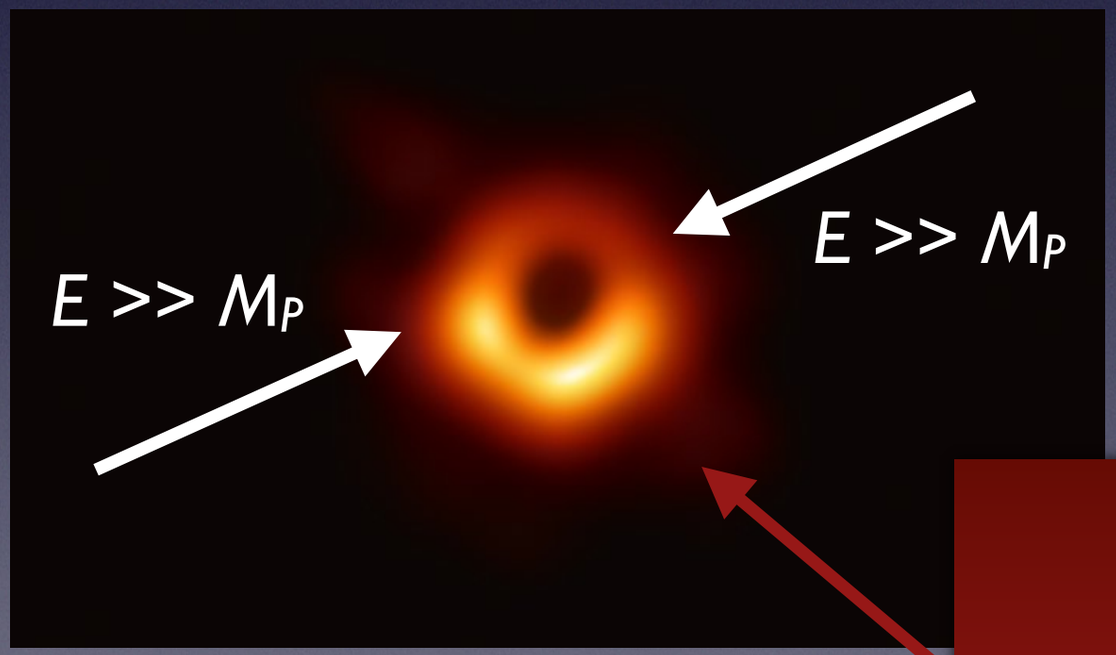
According to the EFT paradigm, nature is a neatly constructed set of Russian Matryoshka dolls:

QFT/EFT limitations

More concrete:

Are there links between UV and IR that are not properly addressed by the QFT/EFT paradigm?

But for $E >> M_P$:



Black Hole production:
Black Hole grows with E
$\Rightarrow$ for large E:

higher energies ~ larger distances

"The entire reductionist paradigm is… basically wrong"

(Nima Arkani-Hamed)

Can we be more concrete?

Outline

- The Cohen-Kaplan-Nelson bound
- UV/IR Mixing within the SM
- UV/IR Mixing beyond the SM
- UV/IR Mixing and Naturalness

The CKN bound

- QFT/EFT breaks down at UV cutoff Λ
- But what is Λ?
- And what about the IR?

A. Cohen, D. Kaplan, A. Nelson (CKN), PRL 1999

→ Consider Black Hole physics

Black Hole Thermodynamics

Hawking 1971: $dA_{BH} \geqslant 0$

No Hair Theorem

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

The CKN bound

Violation of the 2nd law of thermodynamics?

What happens to entropy falling into a Black Hole?

→ Bekenstein (1971-1974): growth of Black Hole horizon *A* compensates for loss of entropy behind BH event horizon

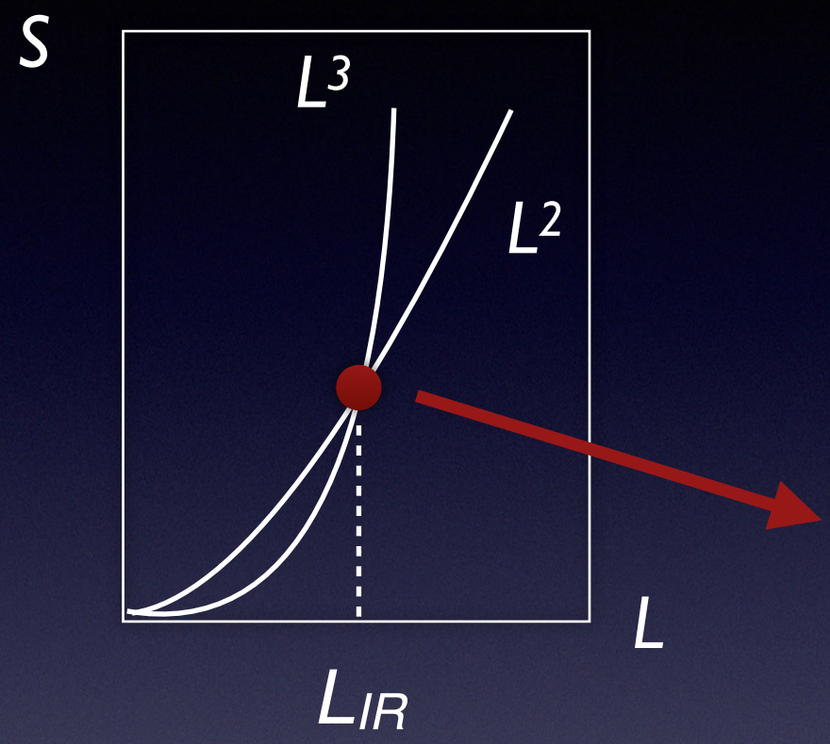
$dM = T\, dS_{BH}$ ("first law of BH mechanics", Bardeen, Carter, Hawking 1973)

Holographic Bound

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

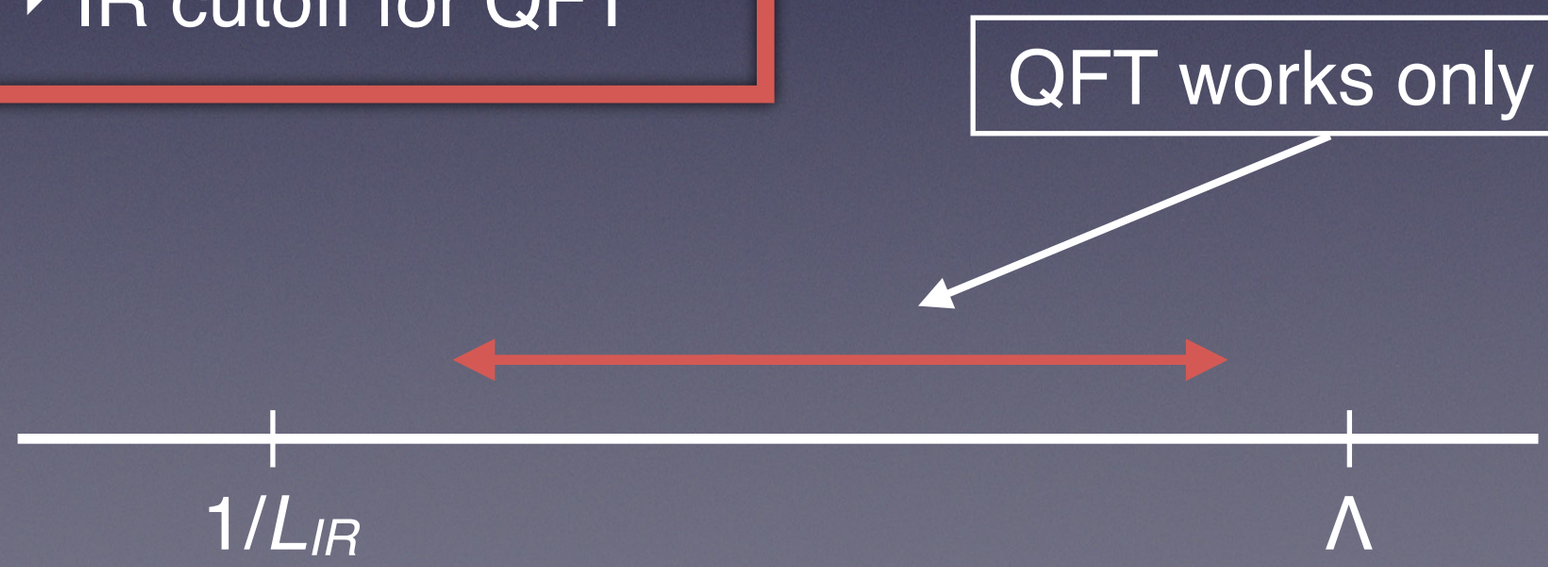
→ Contradiction to QFT where information in a volume grows with ~ L^3

The CKN bound



Starting from this point, QFT overcounts dofs!
(t'Hooft 1993, Susskind 1994)

→ IR cutoff for QFT



The CKN bound

The CKN Bound

Yet: Bound from BH entropy still contains many states with Schwarzschild radius $R_S >$ box size
$\Rightarrow$ even low E particles can collapse into BHs!

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

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

Consider now configuration of maximum energy concentration describable in QFT without gravity:
Box of maximum volume $V=L_{IR}^3$ filled with maximum energy density $\rho = \Lambda/\Lambda^{-3} = \Lambda^4$

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

The CKN bound

The Schwarzschild radius of this configuration is given by
$R_S = M/M_P^2$ with $M = \rho\ V = \Lambda^4\ L_{IR}^3$

$\Rightarrow R_S = \Lambda^4\ L_{IR}^3\ /M_P^2$ is = IR cutoff L_{IR}

Solve for L_{IR}:

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

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

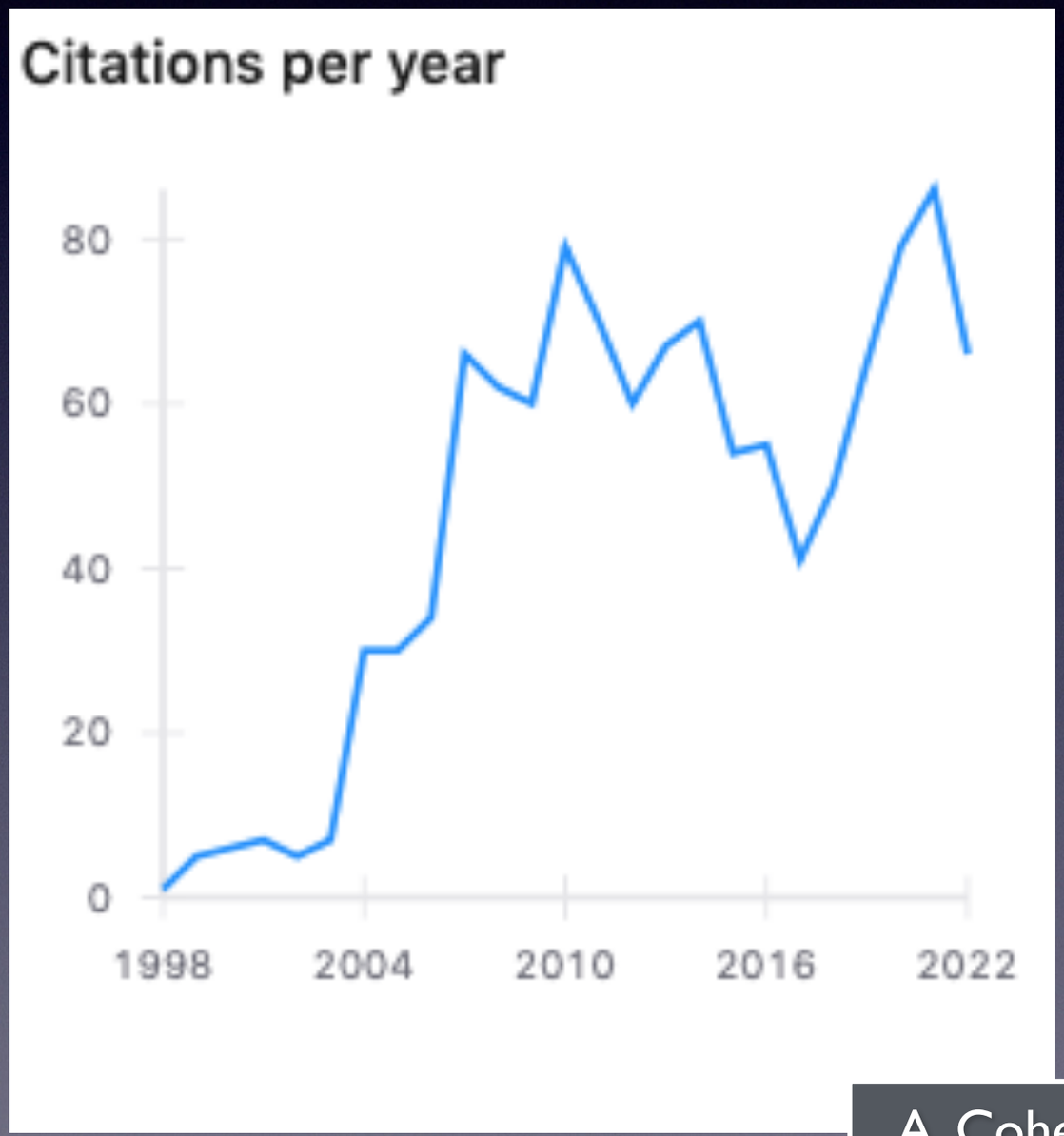
→ Relation between UV cutoff Λ
and IR cutoff L_{IR}

Note:

- This implies $\Lambda < M_P$ since for $\Lambda = M_P \Rightarrow \Lambda = L_{IR}^{-1}$,
  i.e. zero range of validity for QFT
- The larger L_{IR} the smaller Λ and vice versa

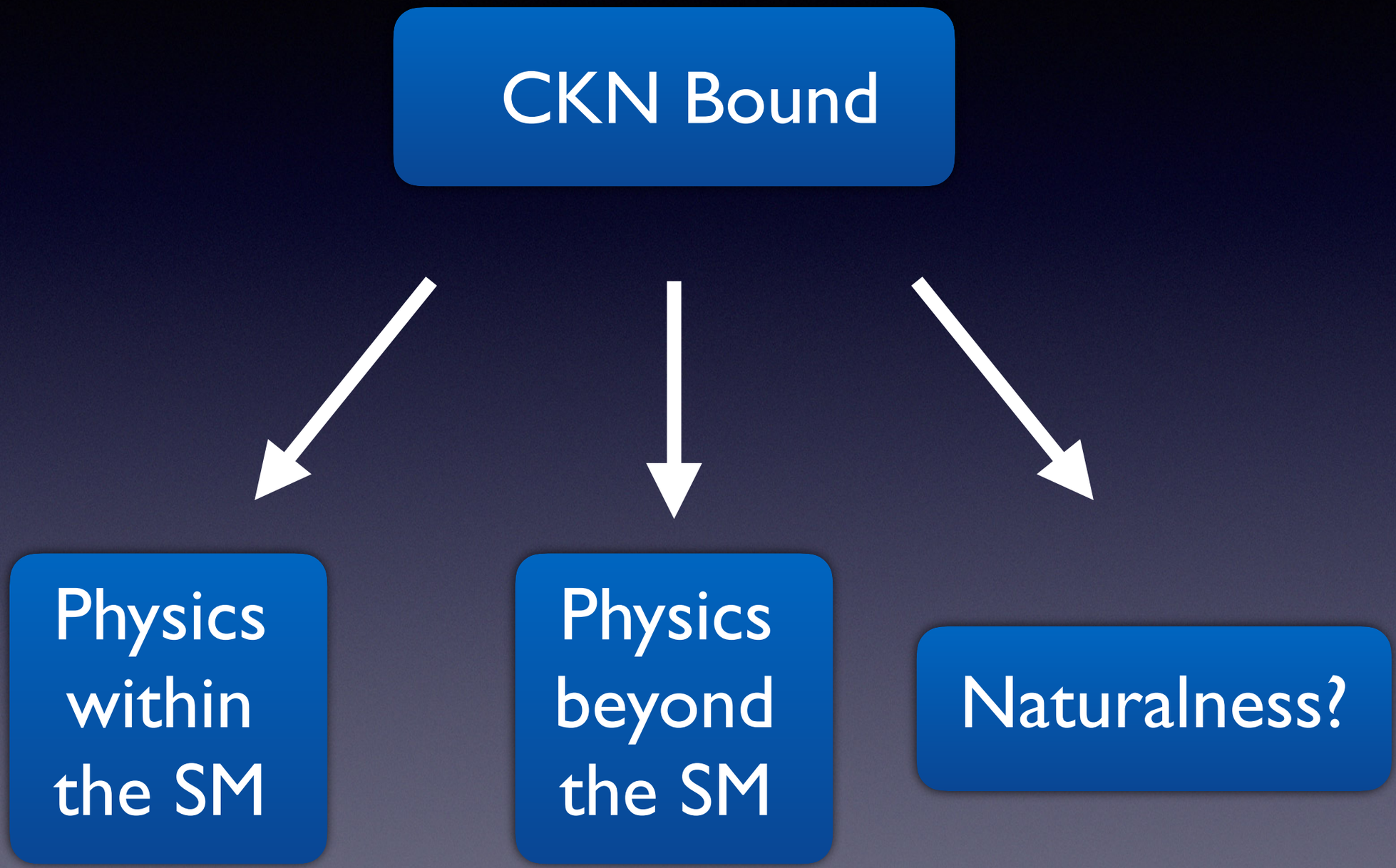
The CKN bound

April 2024: 1273 citations



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

The CKN bound



UV/IR Mixing & Physics Within the SM

Probing the CKN Bound: Radiative Corrections

→ effect on anomalous magnetic moments of electrons and muons

$$a(L,\Lambda) = \left(\frac{\alpha}{2\pi}\right)\left(1 - \frac{\pi^2}{mL} - \frac{m^2}{3\Lambda^2} + \cdots\right)$$

Minimum deviation:

$$\Lambda \sim m\left(\frac{M_p}{m}\right)^{1/4}, \qquad L \sim \frac{1}{m}\left(\frac{M_p}{m}\right)^{1/2}$$

$$a - \frac{\alpha}{2\pi} \sim \frac{\alpha}{2\pi}\sqrt{\frac{m}{M_p}} = \begin{cases} 10^{-14} & m = m_e \\ 10^{-13} & m = m_\mu \end{cases}$$

A. Cohen, D. Kaplan, arXiv: 2103.04509

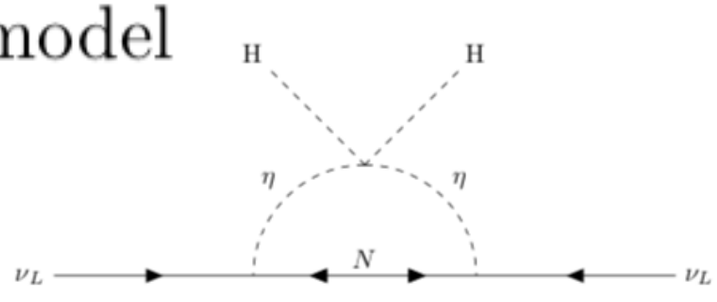
One order of magnitude below experimental uncertainties for electron!

UV/IR Mixing & Physics Beyond the SM

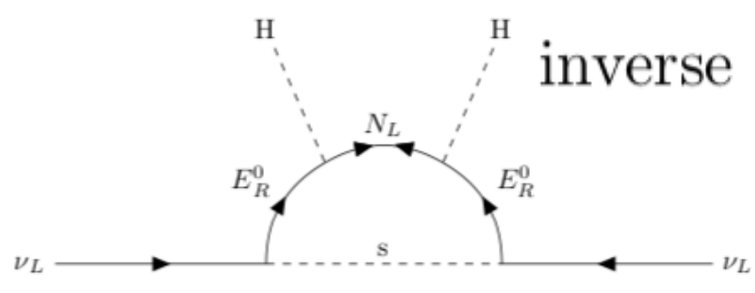
→ effect on radiative neutrino mass models

scotogenic model

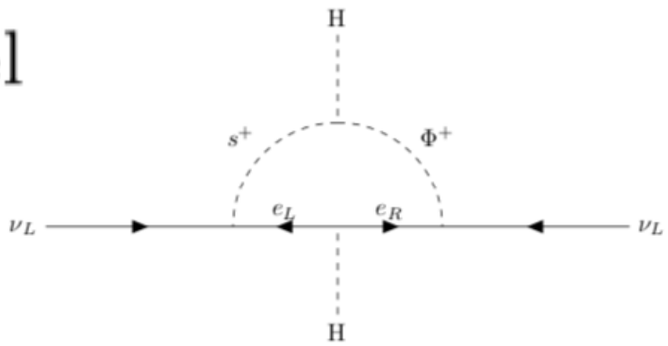
E. Ma 2006



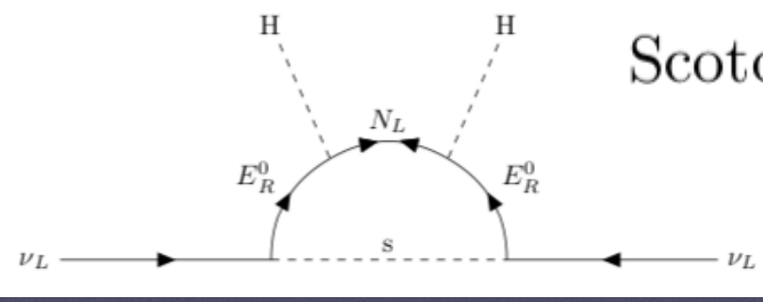
inverse scotogenic model



Zee model



ScotoSinglet model



P. Adolf, M. Hirsch, H. Päs, JHEP 2023, arXiv:2306.15313

UV/IR Mixing & Physics Beyond the SM

scotogenic model

E. Ma 2006

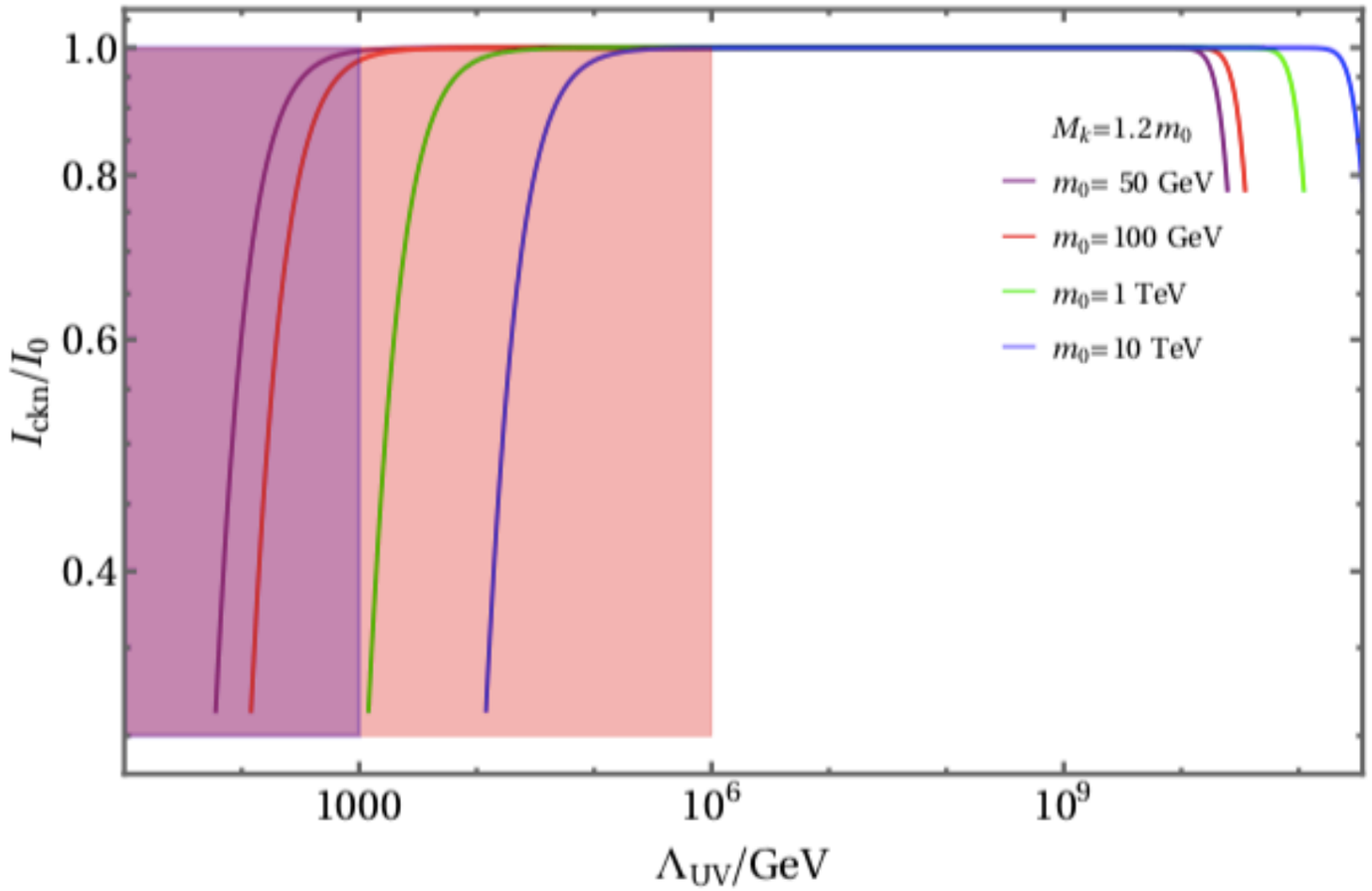
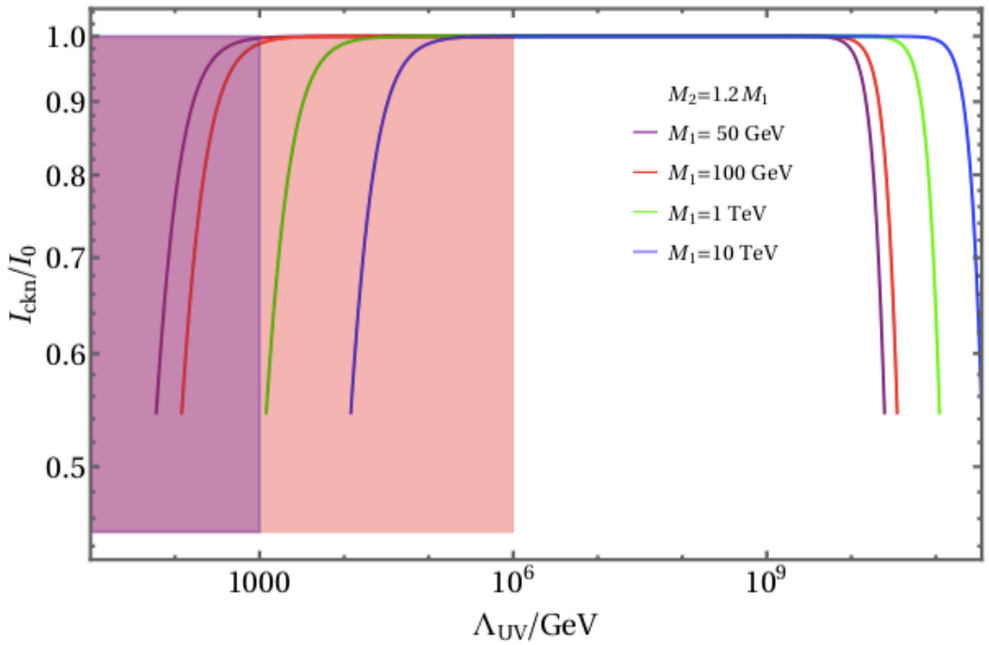


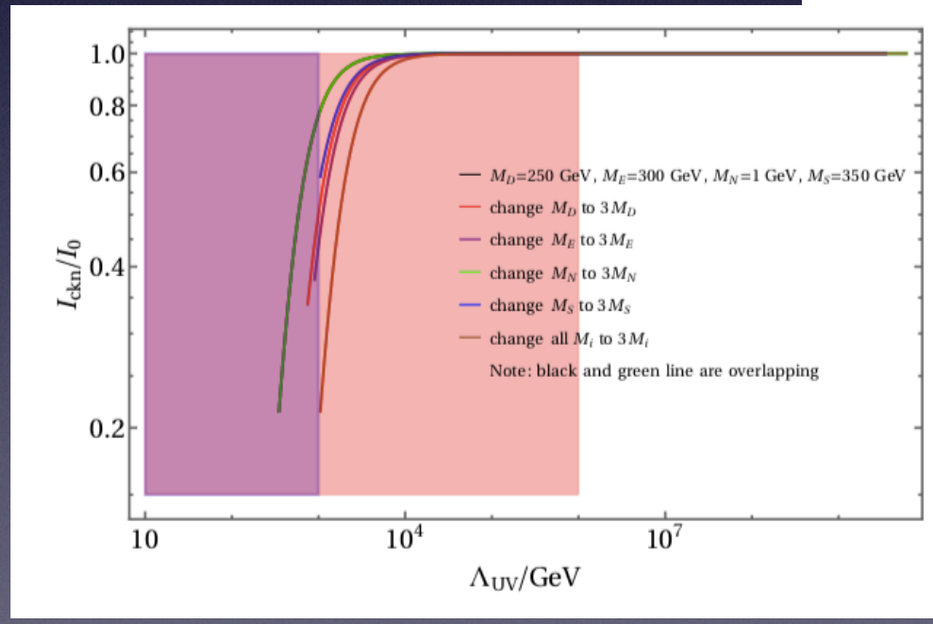
Figure 3: Relative discrepancy between the neutrino mass with and without the influence of the CKN bound for the scotogenic model. Different mass choices for the free parameters are considered. The allowed range of Λ_{UV} in the calculation of the magnetic moment of the muon is displayed as a red background.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

P. Adolf, M. Hirsch, H. Päs, JHEP 21023, arXiv:2306.15313

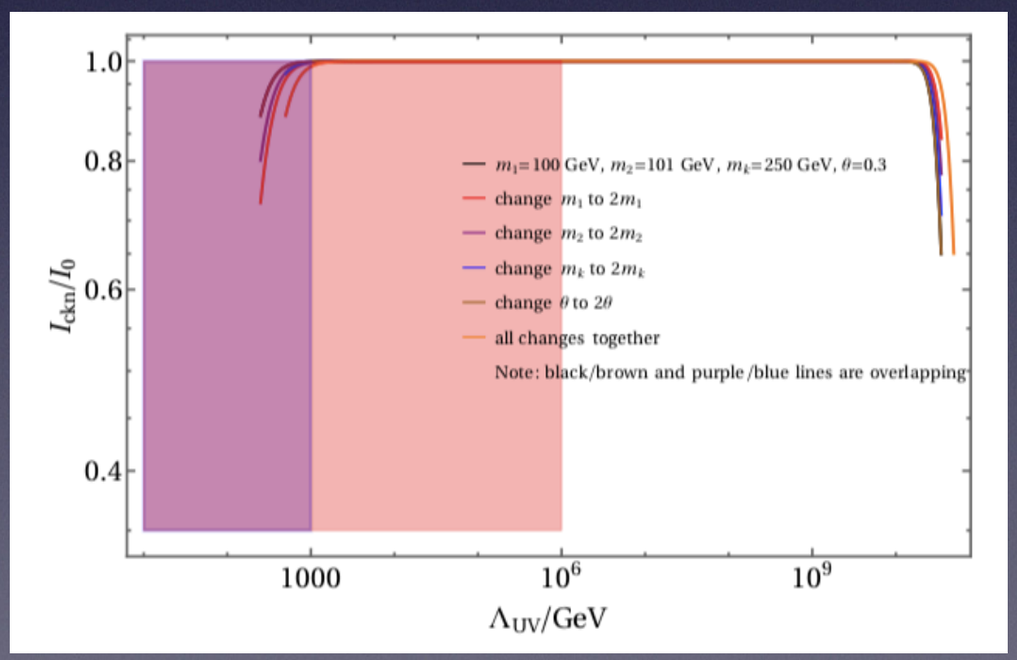
UV/IR Mixing & Physics Beyond the SM

Zee model





inverse scotogenic model



ScotoSinglet model

P. Adolf, M. Hirsch, H. Päs, JHEP 2023, arXiv:2306.15313

UV/IR Mixing & Physics Beyond the SM

O(1) effect on generated neutrino mass

→

UV/IR Mixing has significant consequences for the parameter space of radiative neutrino mass models

P. Adolf, M. Hirsch, H. Päs, JHEP 2023, arXiv:2306.15313

CKN bound & Naturalness

Intriguing consequence:
CKN & cosmological constant problem

The CKN bound suggests a solution to the "cosmological constant problem" of the unnaturally small dark energy density in the universe

Vacuum fluctuations $\rho \sim < 0 \mid T_{\mu\nu} \mid 0 >$ contribute to the dark energy density with $< \rho > \sim \Lambda^4 \sim M_P^4 \sim 10^{76}$ GeV^4 compared to the observed $< \rho > \sim 10^{-3}$ eV^4

→ mismatch of 120 orders of magnitude!

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

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

What's more:

HARD SCIENCE — NOVEMBER 2, 2022

The Hubble tension: Is cosmology in crisis?

We know the Universe is expanding, but scientists don't agree on the rate. This is a legitimate problem.

Hubble crisis, DESI result, "early dark energy"

PREPARED FOR SUBMISSION TO JCAP

DESI 2024 VI: Cosmological Constraints from the Measurement of Baryon Acoustic Oscillations

Quantamagazine

COSMOLOGY

Dark Energy May Be Weakening, Astrophysics Study Finds

- Quintessence? → How to stabilize flat potential?
- CKN: A smaller Hubble horizon in the early universe ~ larger UV cutoff ~ larger dark energy density

CKN bound & Naturalness

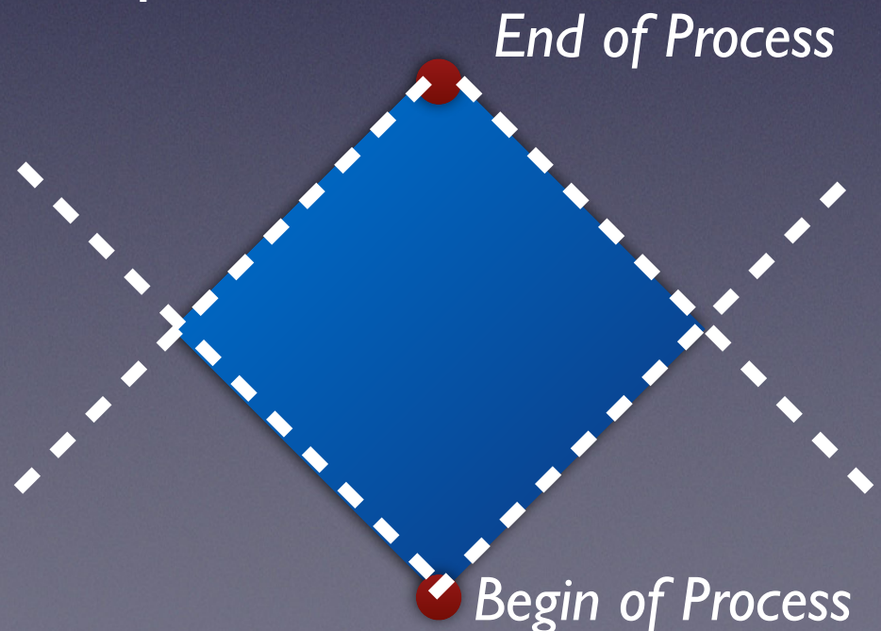
What's the horizon for an unstable particle?

Causal Diamond:

-Largest spacetime region that can be causally probed during a process

-Minkowski space equivalent of horizon in curved/ expanding spacetimes

-intersection of light cones starting/ending at start and endpoints of a process

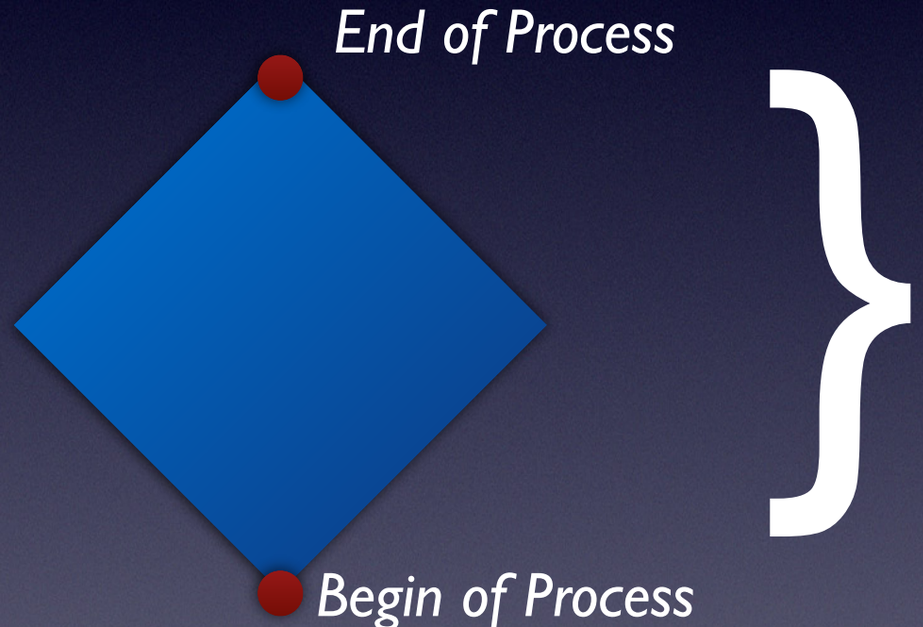


R. Bousso & L. Susskind, PRD 2012, arXiv:1105.3796

CKN bound & Naturalness

The Causal Diamond for a decaying Higgs

The Causal Diamond is defined by the Higgs lifetime:



$\Delta t \sim (4\ \text{MeV})^{-1} = L_{IR}$

$$\Lambda = \sqrt{\frac{M_P}{L_{IR}}} = \sqrt{4\ \text{MeV} \cdot 10^{19}\ \text{GeV}} \sim 10^8 \text{GeV}$$

H. Päs & T. Kephart, arXiv: 2209.03305 [hep-ph]

CKN bound & Naturalness

$$\Lambda = \sqrt{\frac{M_P}{L_{IR}}} = \sqrt{4\ \mathrm{MeV} \cdot 10^{19}\ \mathrm{GeV}} \sim 10^8 \mathrm{GeV}$$

- Reduces finetuning for Higgs mass by 11 orders of magnitude, yet still not natural!
- Combine with reduced Planck scale for large extra dimensions, $M_P' < M_P$ with $M_P' \sim 10^6$ TeV:

  ⇒

  Λ = 100 GeV - 1 TeV
- Predicts new physics / quantum gravity below 10^6 TeV !

H. Päs & T. Kephart, arXiv: 2209.03305 [hep-ph]

CKN bound & Naturalness

Is this more than numerology?
Is there any connection with gravity?
Plus: The CKN bound indicates when QFT becomes unreliable, it doesn't provide an estimate of quantum corrections!

Let's do some free-wheeling brain storming:

"a loose collection of musings, references, and word association, the essay equivalent of throwing spaghetti at the wall."

(Anonymous JHEP Referee)

CKN bound & Naturalness

Hidden Symmetries from Entanglement & the Higgs Causal Diamond

H. Päs & T. Kephart, arXiv: 2209.03305 [hep-ph]

Basic Idea: The Higgs mass (or scalar masses in general) is protected by a symmetry originating from quantum gravity and broken by decoherence through the diamond's horizon

"oneway membrane for information: traced over

- Causal diamond: also observer-independent environment for decoherence
- The smaller the causal diamond, the larger the spacetime region traced out, the larger the symmetry-breaking effect and the resulting Higgs mass

CKN bound & Naturalness

- “Non-Wilsonian” Hidden Symmetry: A symmetry that mixes various scales and reveals itself only when all individual Feynman diagrams contributing to an observable have been summed

Origin?

- The Bell singlet:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

has a symmetry not apparent from the constituents.

Entanglement? But the Higgs is a single particle!

CKN bound & Naturalness

"One-particle entanglement is as good as two-particle entanglement"

(M. Terra Cunha, J. Dunnigham, Vlatko Vedral, quant-ph/0606149)

$$\psi = \frac{1}{\sqrt{2}}(|\uparrow\rangle - |\downarrow\rangle) \quad \hat{=} \quad \psi = \frac{1}{\sqrt{2}}(|10\rangle - |01\rangle) \quad \equiv \quad \psi = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

Looks like a multiple-slit experiment!

CKN bound & Naturalness

But it's not about non-locality!

- QM: various choices of Hilbert space basis possible
- Well known: Interacting QFTs give rise to momentum-space entanglement. Also, entanglement entropy can serve as an order parameter for symmetry breaking!

Balasubramanian, McDermott, Van Raamsdonk 2012;
Han & Akhoury 2011; Klco & Savage 2021

But how does gravity enter the game?

"GR=QM"
"the… feature… that we ordinarily call interference can be a special case of… entanglement. If we believe in… ER=EPR, this implies the presence of an Einstein-Rosen bridge connecting the superposed wave packets for a single particle. (Lenny Susskind)

Summary

- UV/IR Mixing caused by Gravity constrains the range of validity of QFTs: IR & UV cutoffs that are related
- Radiative neutrino mass models: sensitive to such effects
- Solution to the Cosmological Constant problem(?)
- Causal diamonds allow to generalize the argument to the electroweak hierarchy problem
- Solution to the hierarchy problem(??)
- New physics / quantum gravity below 10^6 TeV predicted
- Vague, speculative idea: Hidden symmetries from momentum-space entanglement broken by decoherence, potentially interesting relations to AdS/CFT, Black Hole information & emergent spacetime scenarios