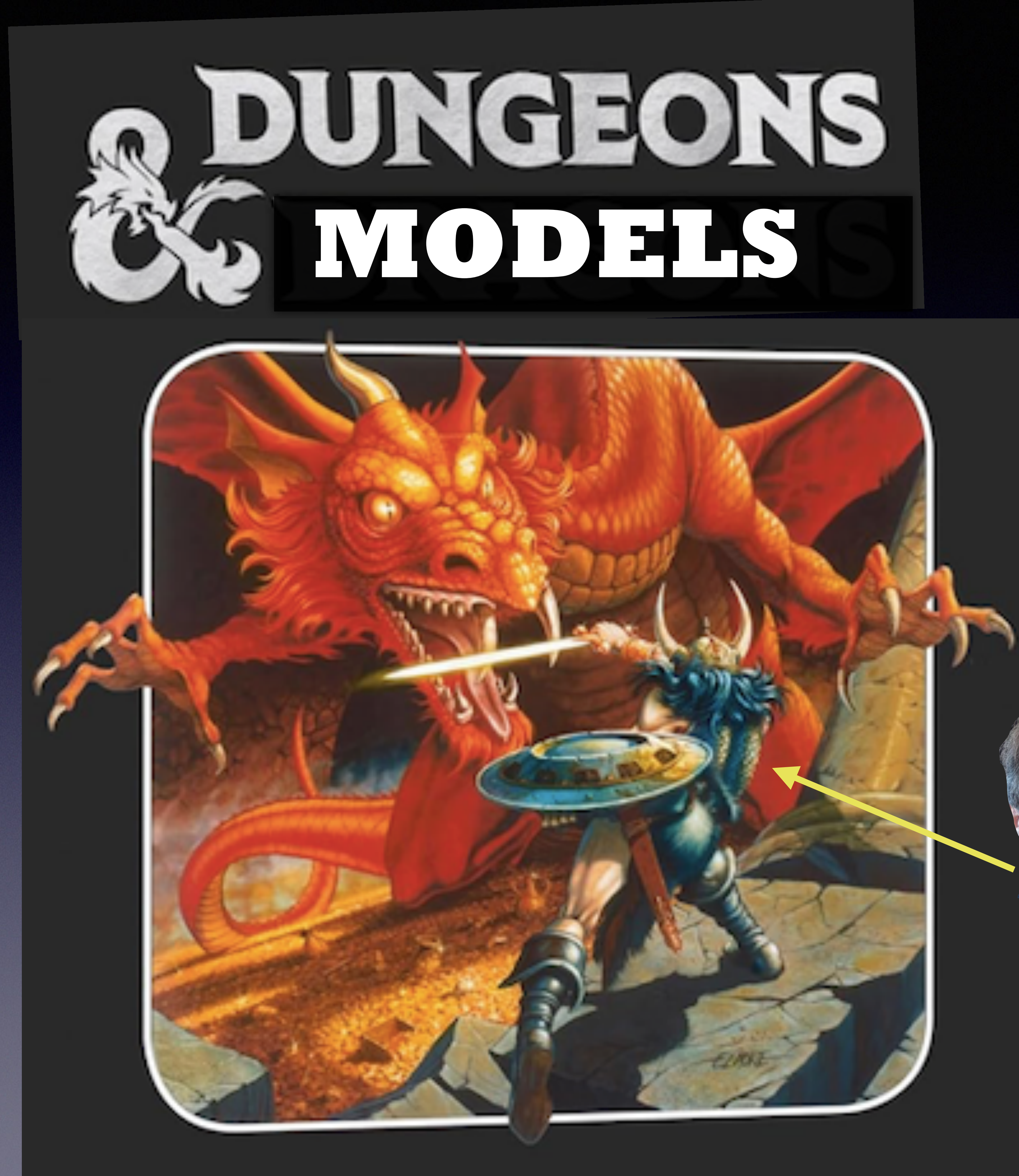
The Sage, the Slayer
and
What Came First: The Forest or the Deer?

Heinrich Päs
tu dortmund

This is how most of you know Martin:

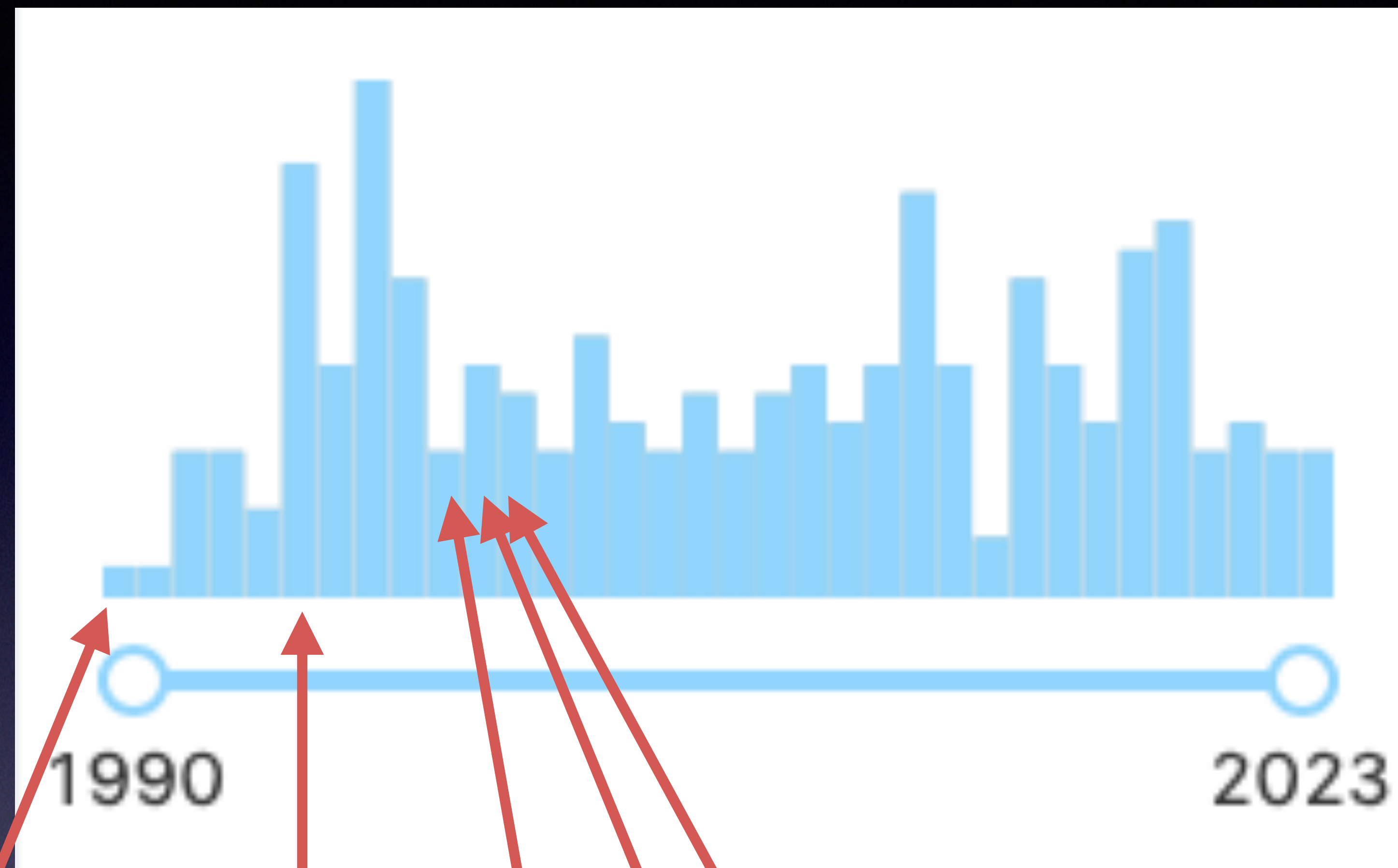


But back in the day when I first met Martin he was more like:

So how did Martin evolve from Nuclear Sage to Model Slayer ?

Master, countless models are invading the realm of physics. You need to resume fighting the evil!

So how did Martin evolve from Nuclear Sage to Model Slayer ?



Muto — *becoming a nuclear sage*

Kovalenko — *using 0vBB for model slaying*

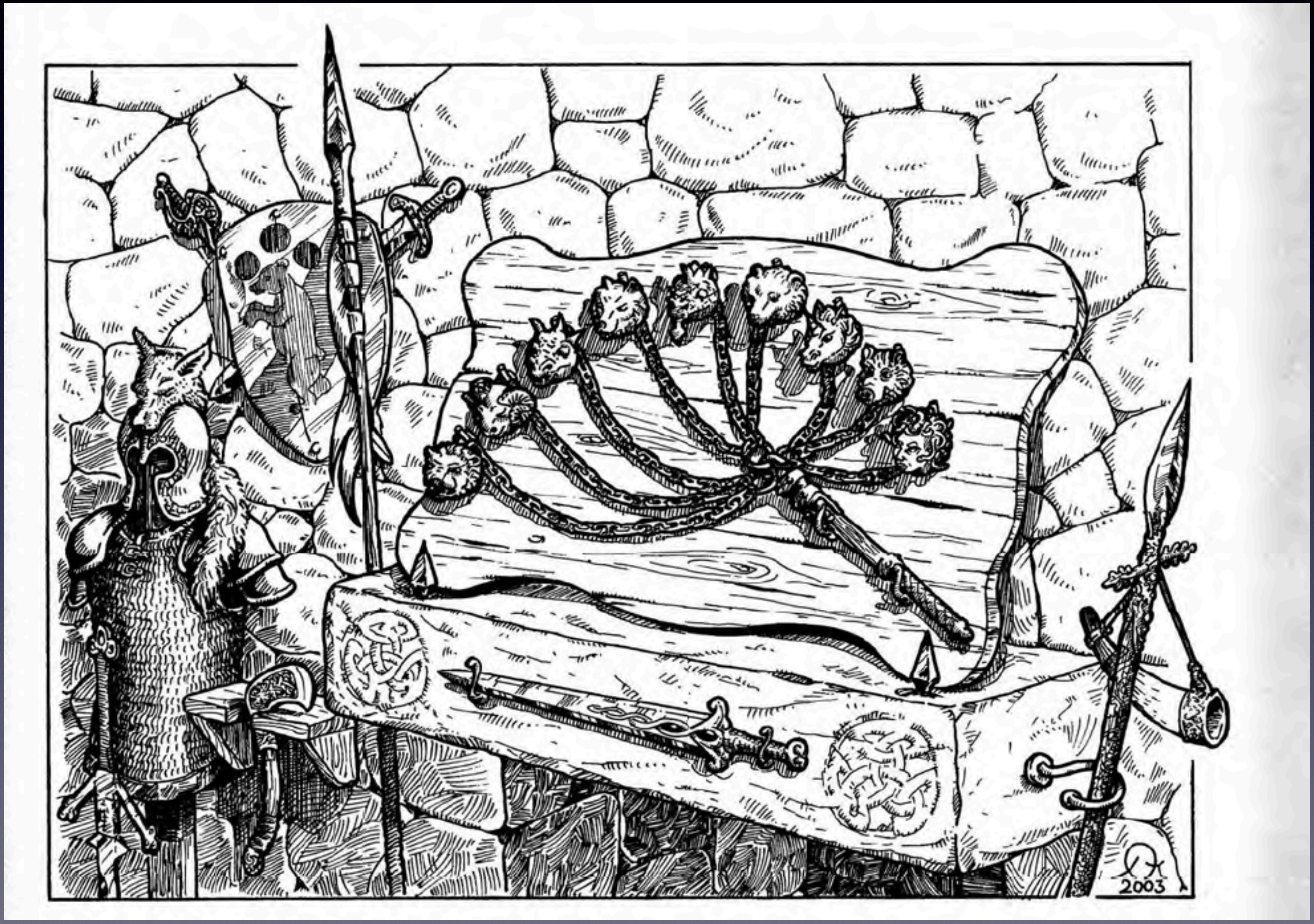
Jose — *using neutrinos for model slaying*

Werner — *using colliders for model slaying*

Steve King — *using everything for model slaying*

The famous “no-no that doesn’t work” gesture

What Weapons to choose?



A theorist who values experiment…

P

Seesaw

Early On:

Adopting Effective Field Theory ideas as a weapon

Towards a superformula for neutrinoless double beta decay

H. Päs [1], M. Hirsch [2], H.V. Klapdor-Kleingrothaus [3], S.G. Kovalenko [4]

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A superformula for neutrinoless double beta decay II: the short range part

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Editor: P.V. Landshoff

Systematic study of the $d = 5$ Weinberg operator at one-loop order

Florian Bonnet,[a] Martin Hirsch,[b] Toshihiko Ota[c] and Walter Winter[a]

Systematic decomposition of the neutrinoless double beta decay operator

Florian Bonnet,[a] Martin Hirsch,[b] Toshihiko Ota[c,d] and Walter Winter[a]

Long-lived heavy neutral leptons from mesons in effective field theory

Rebeca Beltrán,[a] Giovanna Cottin,[b,c] Juan Carlos Helo,[d,c] Martin Hirsch,[a] Arsenii Titov[e] and Zeren Simon Wang[f,g]

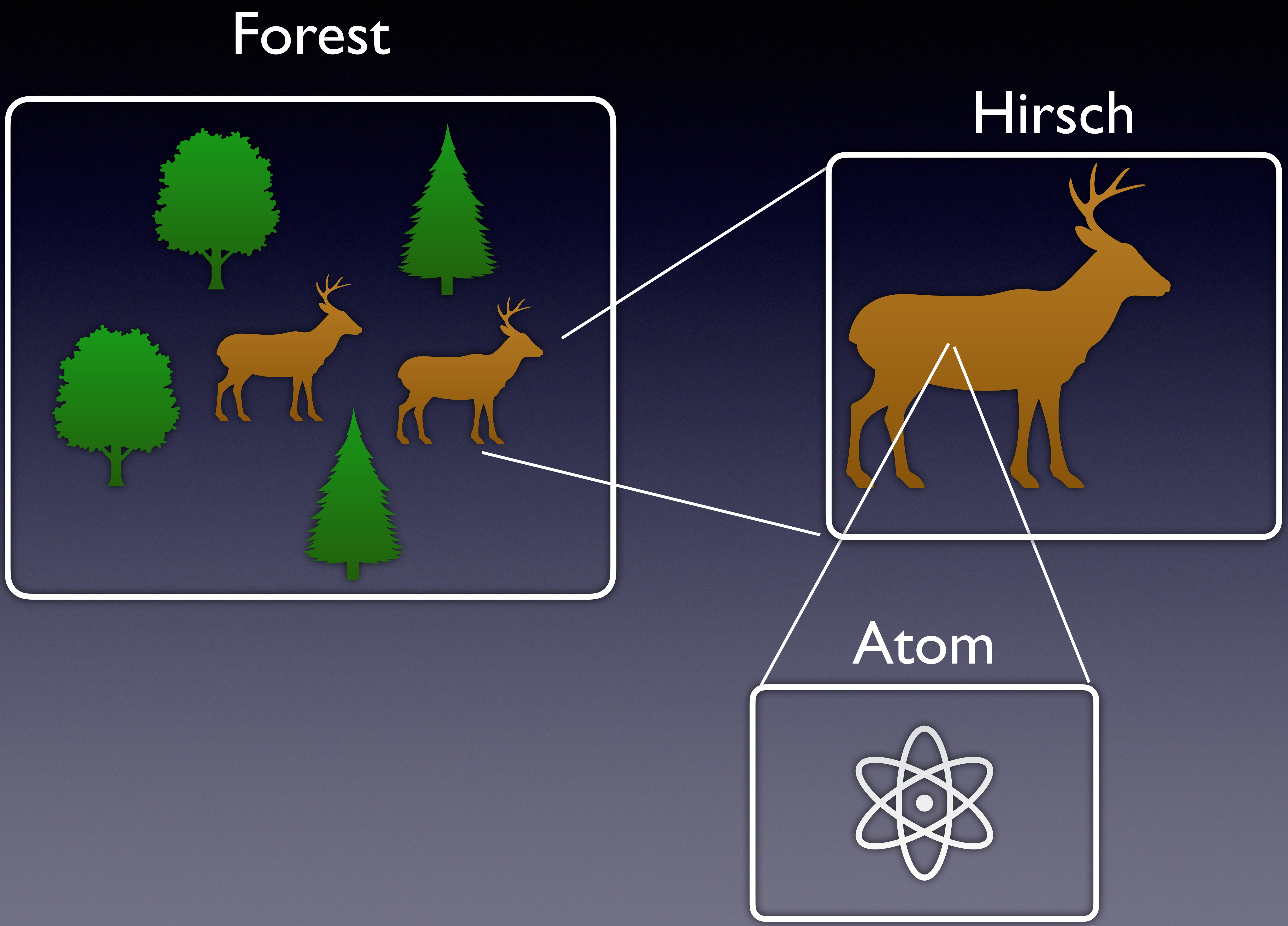
Mapping the SMEFT to discoverable models

Ricardo Cepedello,[a] Fabian Esser,[b] Martin Hirsch[b] and Veronica Sanz[b,c]

SMEFT goes dark: Dark Matter models for four-fermion operators

Ricardo Cepedello,[a] Fabian Esser,[b] Martin Hirsch[b] and Veronica Sanz[b,c]

EFT Philosophy

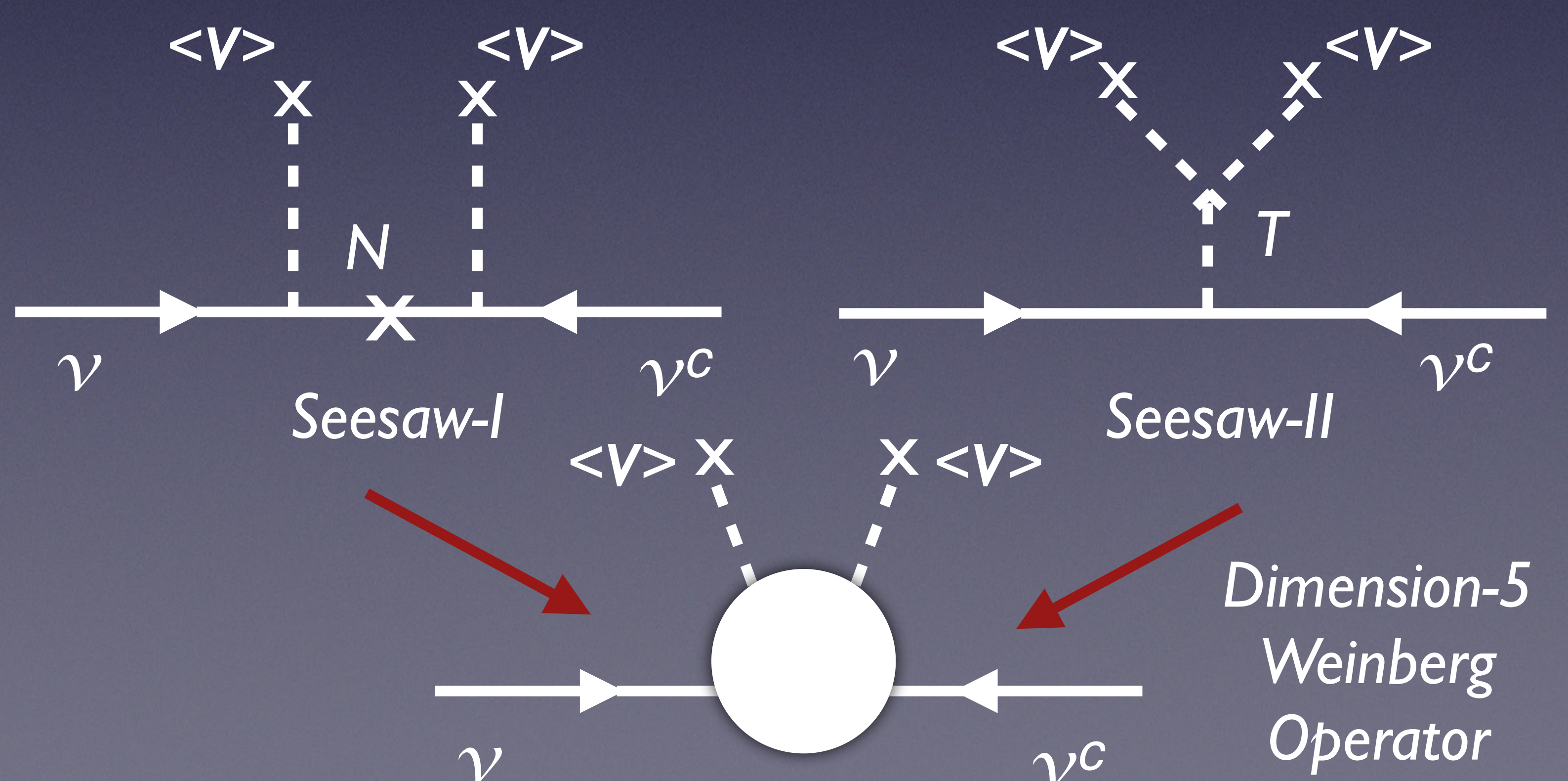


QFT/EFT paradigm & limitations

Common Paradigm:

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 light dofs) as long as momenta & field strengths $\ll \Lambda$

Example:



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

But….:

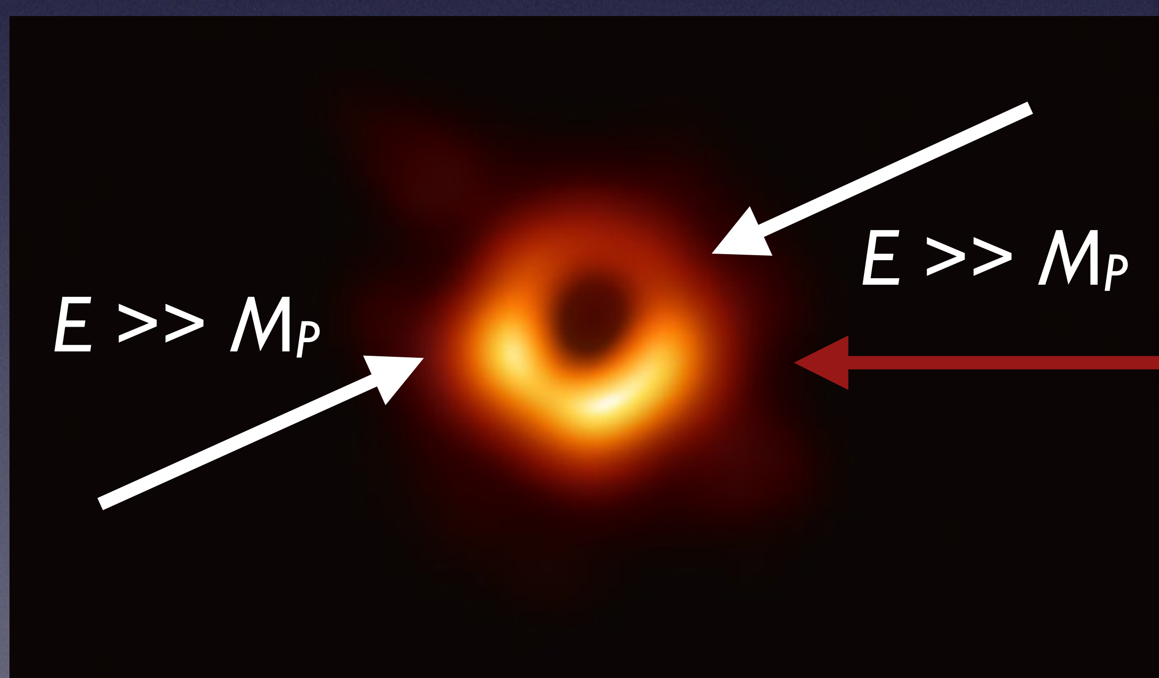
Is this really justified?

QFT/EFT paradigm & limitations

Tacit assumption:

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

Nima Arkani-Hamed, talk@Harvard, Oct 2021:
"Entire reductionist paradigm is… basically wrong"

Indication of a breakdown of our usual way to do particle physics with QFTs/EFTs?

Do we actually even have to slay the model we used for model slaying ?

Working with Martin is always good to get you on the covers of the tabloids

CKN bound & UV/IR Mixing

- 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

CKN bound & UV/IR Mixing

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

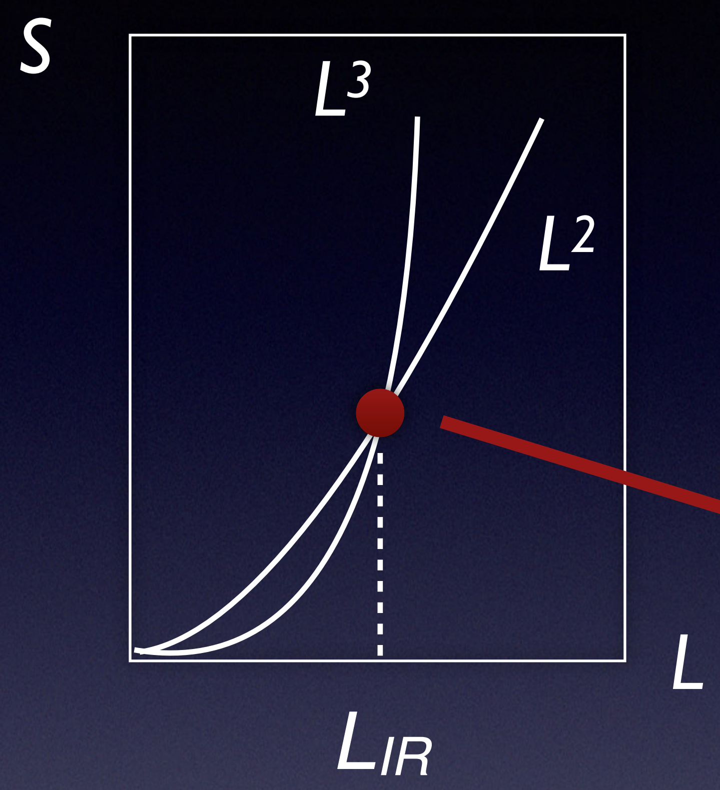
$dM = T\, dS_{BH}$ ("first law of BH mechanics", Bardeen, Carter, Hawking 1973)

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 $\sim L^3$

CKN bound & UV/IR Mixing



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

→ IR cutoff for QFT

QFT works only here!

CKN bound & UV/IR Mixing

The CKN Bound

Yet: 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:

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

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

CKN bound & UV/IR Mixing

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

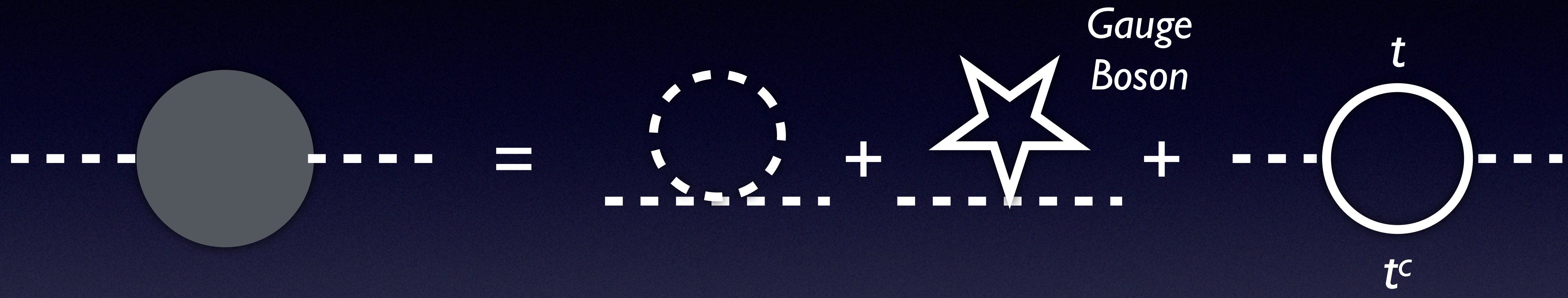
→ Relation between UV cutoff Λ
and IR cutoff L_{IR}

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

Hierarchy Problem - the most famous issue of EFTs

1-Loop Contribution to the Higgs mass



$$\Delta m_H^2 \sim \Lambda^2$$

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!

CKN bound & UV/IR Mixing

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 $\rho \sim \langle 0 | T_{\mu\nu} | 0 \rangle$ contribute to the 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

→ 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

CKN bound & UV/IR Mixing

Open questions

- The SM cutoff is not 10^{-3} eV $\rightarrow$ massive problems with phenomenology!
- CKN cutoffs are motivated by having QFT without quantum gravity in between. Where do they come from?
- How to generalize to other finetuning problems such as the electroweak hierarchy problem?

Causal Diamonds and the Hierarchy Problem

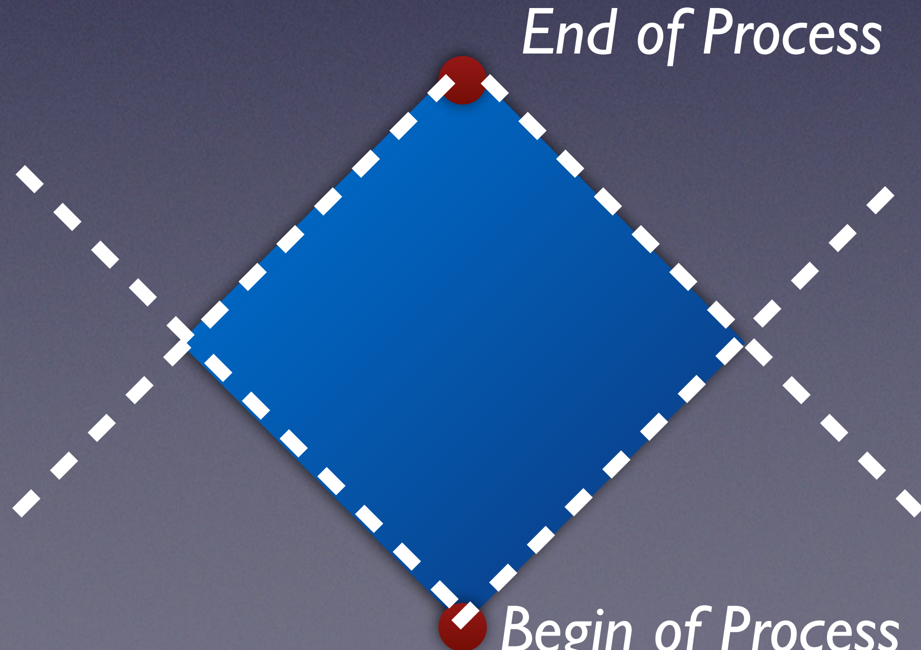
What's the horizon for an unstable particle?

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

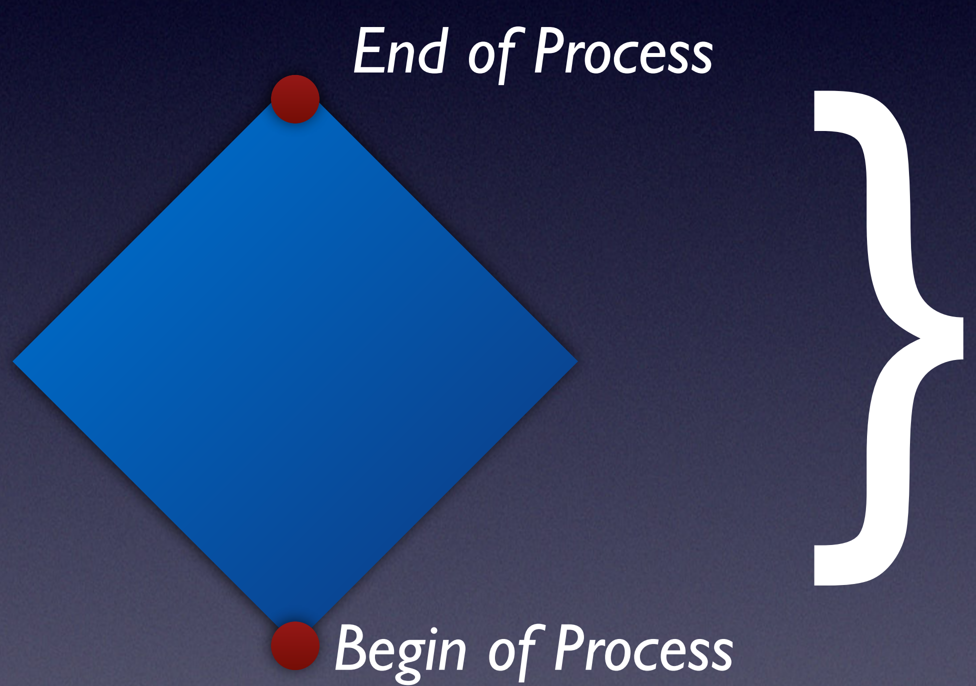


R. Bousso & L. Susskind, PRD 2012, arXiv:1105.3796

Causal Diamonds and the Hierarchy Problem

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]

Causal Diamonds and the Hierarchy Problem

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

- 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:

  $\Rightarrow$

  Λ = 100 GeV - 1 TeV
- Predicts new physics / quantum gravity below 10^6 TeV !
- Maybe the absence of new physics at the TeV scale is the new physics

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

Probing the CKN Bound: Radiative Corrections

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

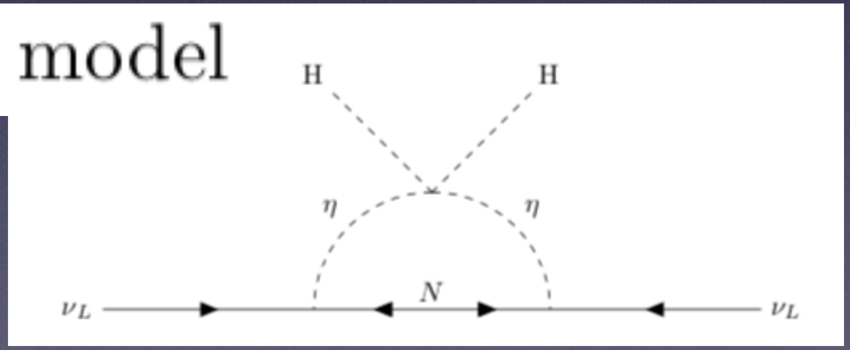
→ effect on anomalous magnetic moments of electrons and muons

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

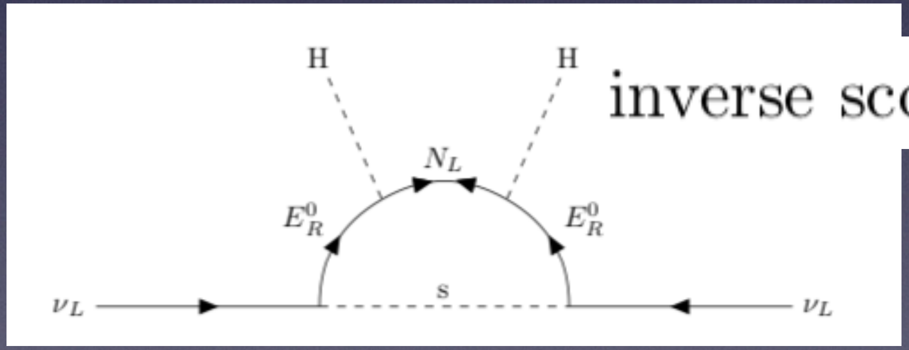
→ effect on radiative neutrino mass models

scotogenic model

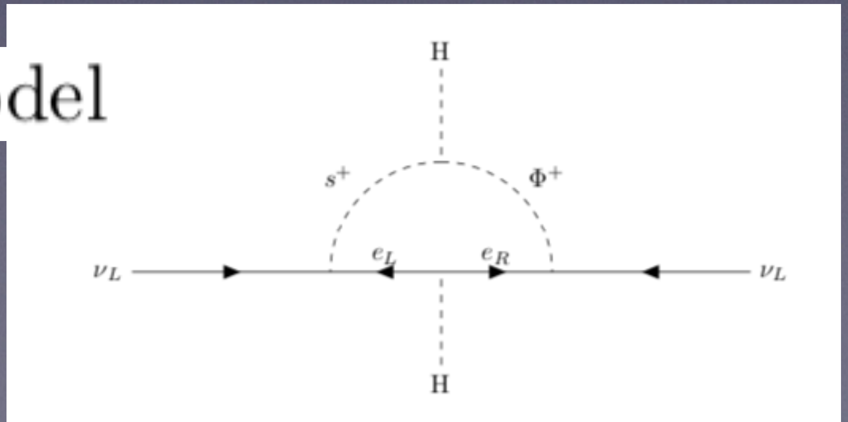
E. Ma 2006



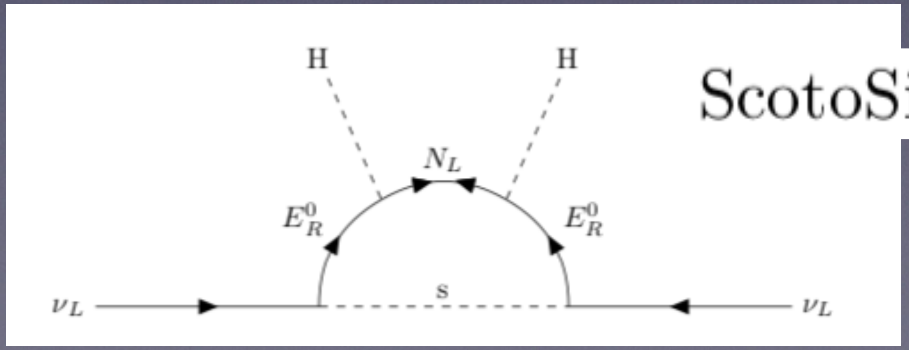
inverse scotogenic model



Zee model



ScotoSinglet model



Radiative Neutrino Masses and the CKN Bound

scotogenic model

E. Ma 2006

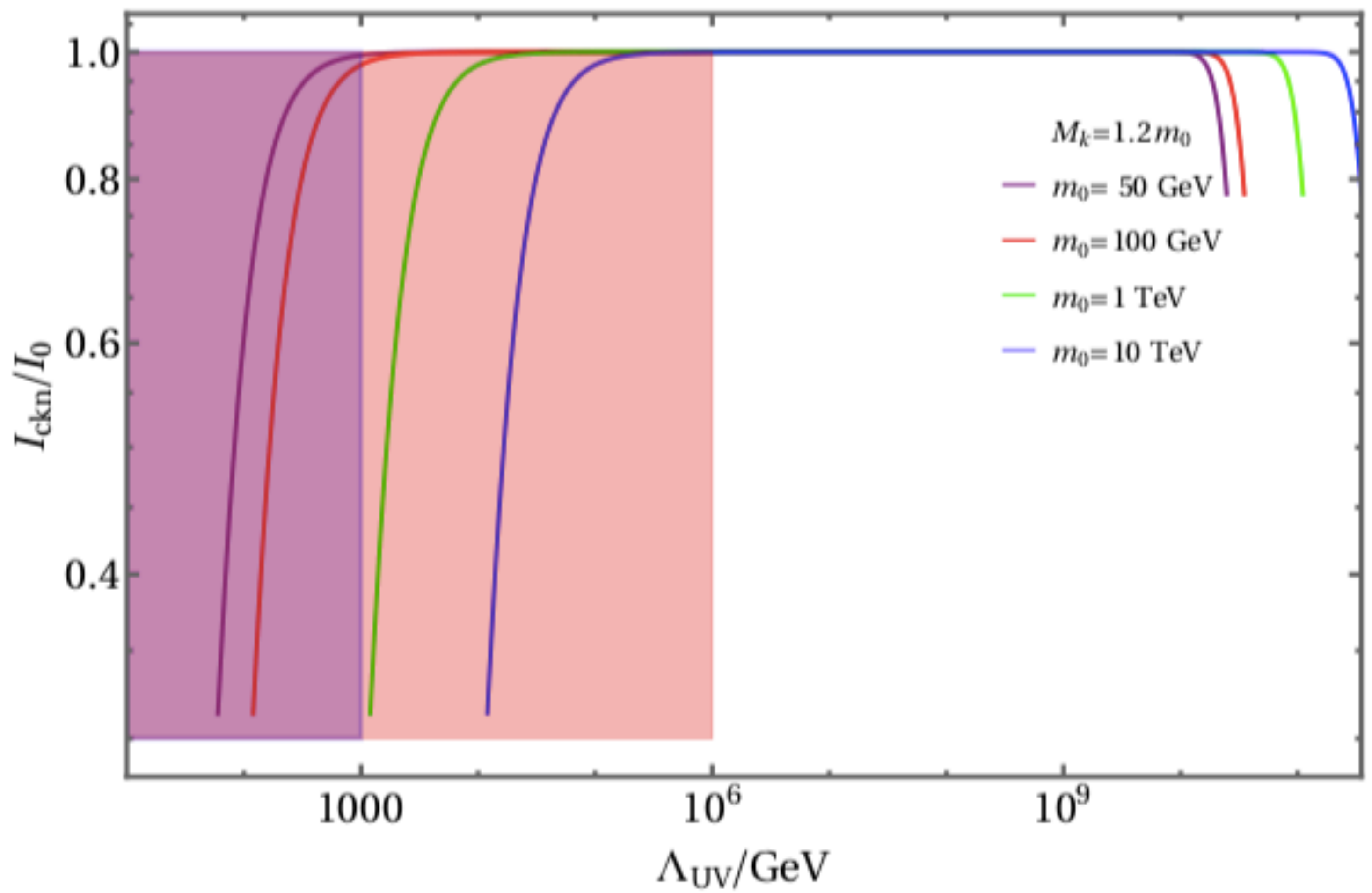
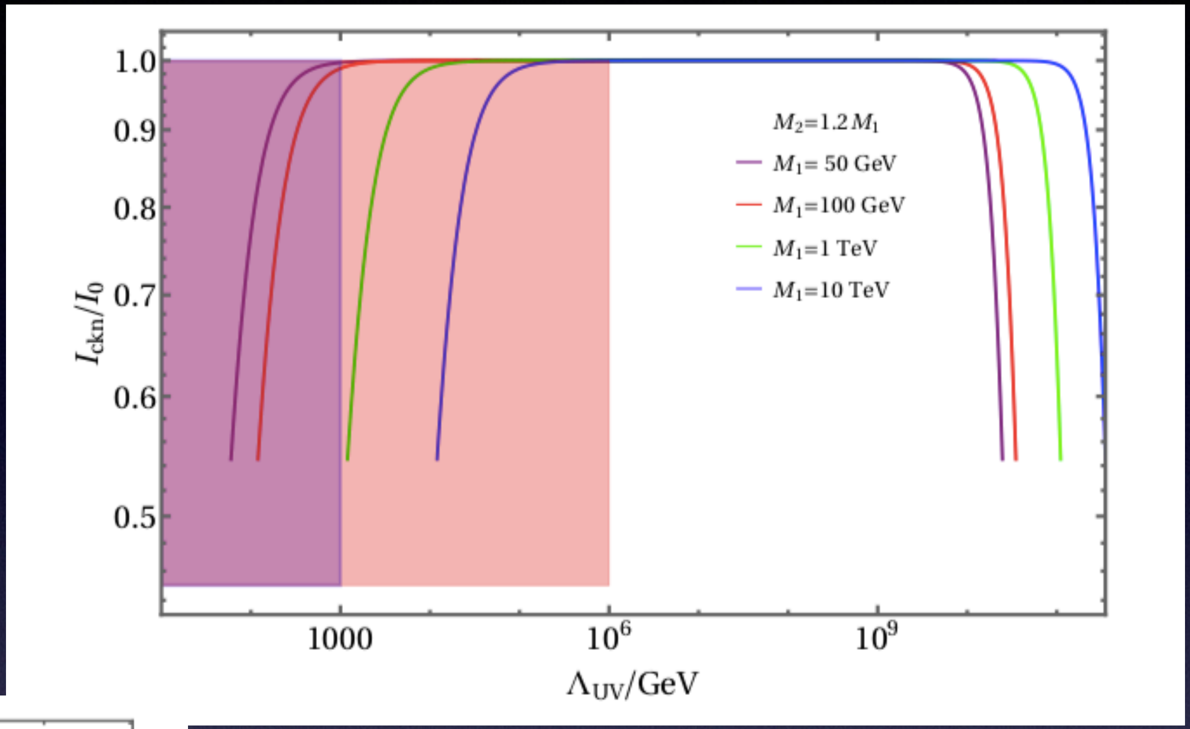


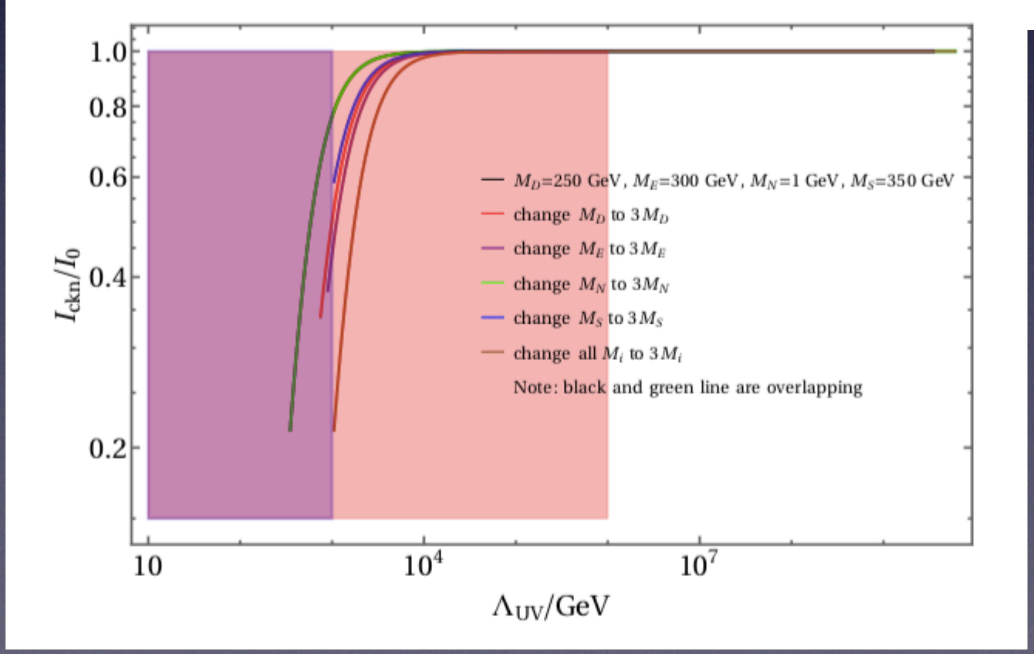
Figure 3: Relative discrepancy between the neutrino mass with and without the influence of the CKN bound for the scotogenic model. Different mass choices for the free parameters are considered. The allowed range of Λ_{UV} in the calculation of the magnetic moment of the muon is displayed as a red background.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

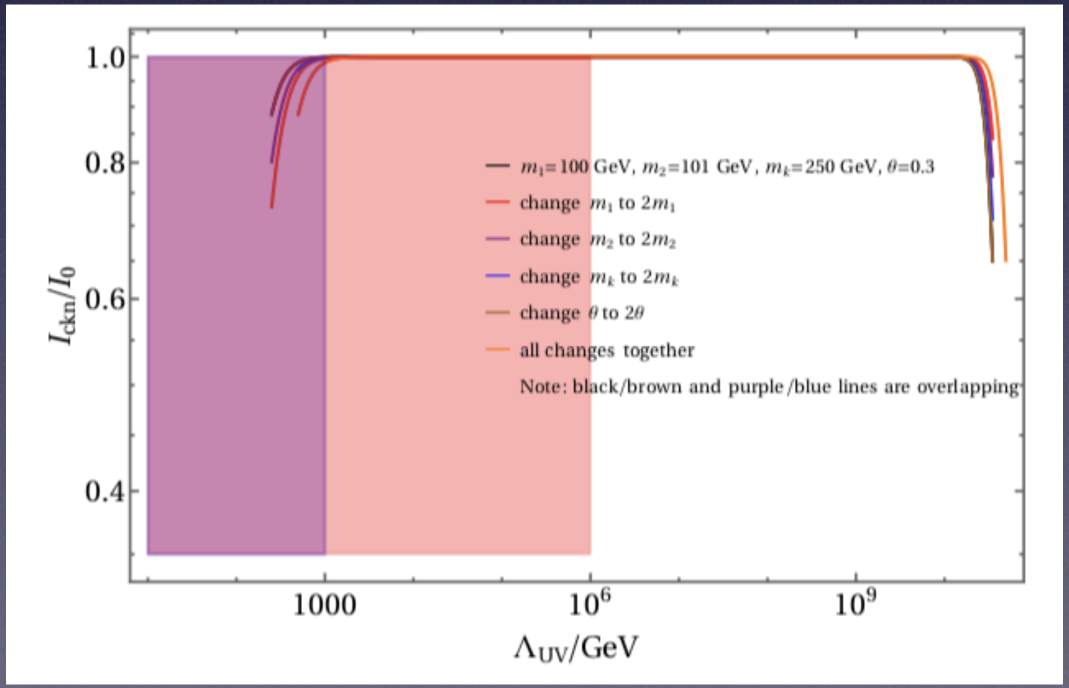
Radiative Neutrino Masses and the CKN Bound

Zee model





inverse scotogenic model



ScotoSinglet model

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

Radiative Neutrino Masses and the CKN Bound

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

Summary

- UV/IR Mixing caused by Gravity constrains the range of validity of QFTs: IR & UV cutoffs that are related
- Solution to the Cosmological Constant problem(?)
- Solution to the electroweak hierarchy problem(??)
- Radiative neutrino mass models: sensitive to such effects
- If you think your radiative neutrino mass model is dead or isn't - think twice!
- Maybe we have to slay the model we used for model slaying


Martin
Homer kills Death
EFT
Simpson

Thanks!

&

Looking forward to the next 30 years of physics with Martin!