KING'S College LONDON

Higgs Criticality

Electroweak Vacuum Metastability as a Window to Beyond the Standard Model Physics

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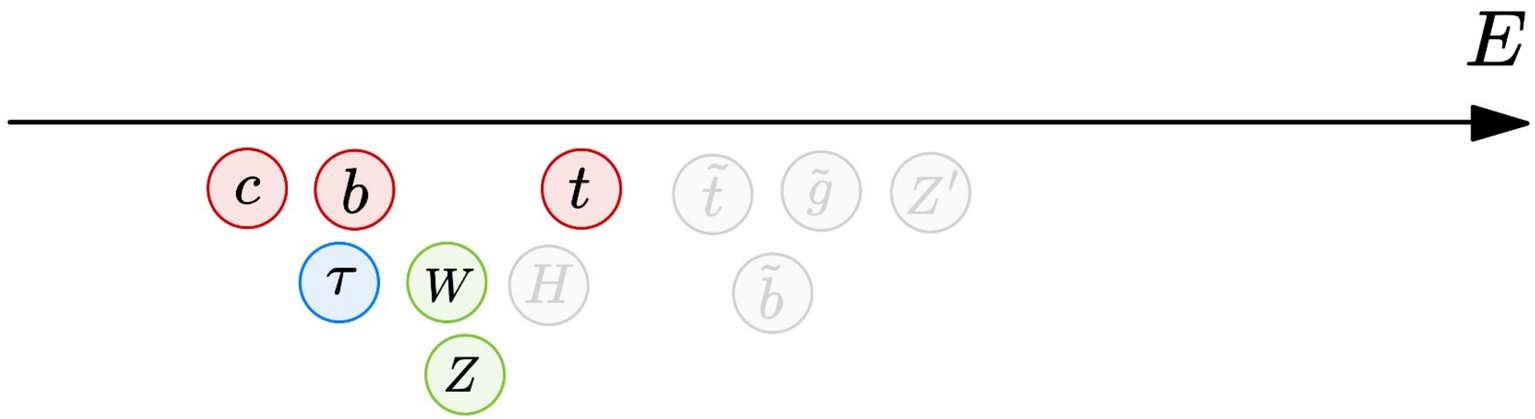
Maximilian Detering, 26 June 2026

The Hierarchy Problem

Naturalness expectation

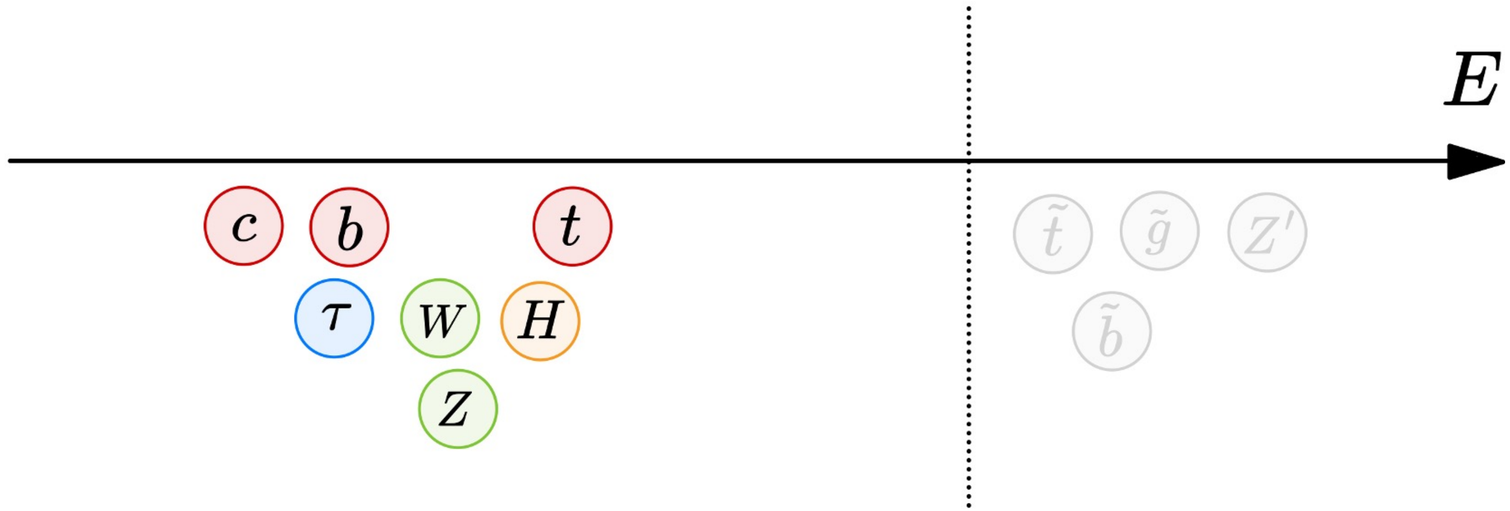
't Hooft '79, Giudice '08, Craig '22, McCullough '24, ...



The Hierarchy Problem

Post-LHC Reality

't Hooft '79, Giudice '08, Craig '22, McCullough '24, ...



⇒ symmetry based solutions pushed towards increasing level of fine-tuning

Cosmological self-tuning

A natural fine-tuning

Hierarchy Problem

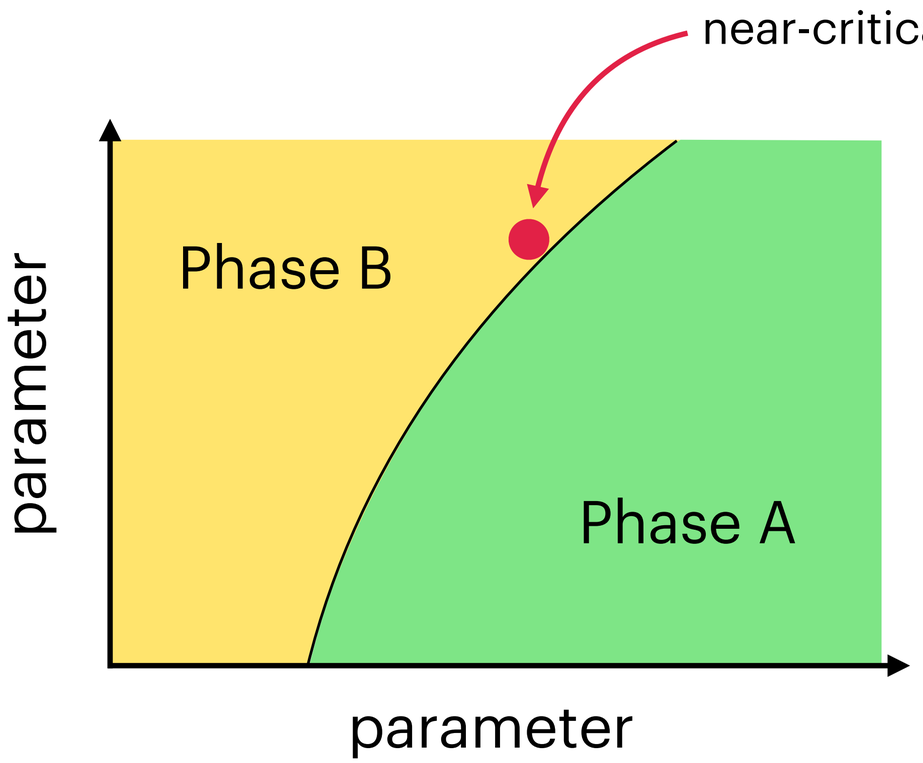
Why does the Higgs mass as a fundamental parameter appear to be so fine-tuned within the UV completion?

But what if ...

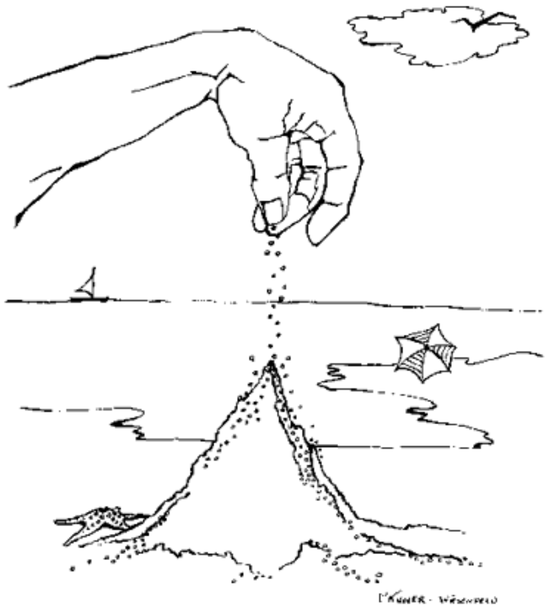
... the Higgs mass was not a unique fundamental parameter but the result of dynamical evolution?

Tuning toward critical points is actually ubiquitous in dynamical systems!

Criticality



- Evolution in various dynamical systems driven towards a critical point
- Example: self-organised criticality in various driven-dissipative systems with discontinuous transition



from *How nature works*

Bak, Tang, Wiesenfeld ‘87
Bak, Tang, Wiesenfeld ‘88
Bak ‘96

Self-organised localisation

Giudice, McCullough, You '21

How could SOC be realised in particle physics / cosmology?

- Evolution of scalar fields and vacua
- Order parameter: vacuum expectation values of scalar fields
- Control parameter: coupling and mass

Consider scanning field ϕ with scalar potential

$$V(\phi) = \underbrace{V_{\text{scan}}(\phi)}_{\text{smooth}} + \underbrace{(\phi - \phi_c)\,\mathcal{O}}_{\text{discontinuous}}$$

See also
Khoury, Parrikar '19
Khoury '21
Kartvelishvili, Khoury, Sharma '21
Khoury, Wong '23
Khoury, Steingasser '22

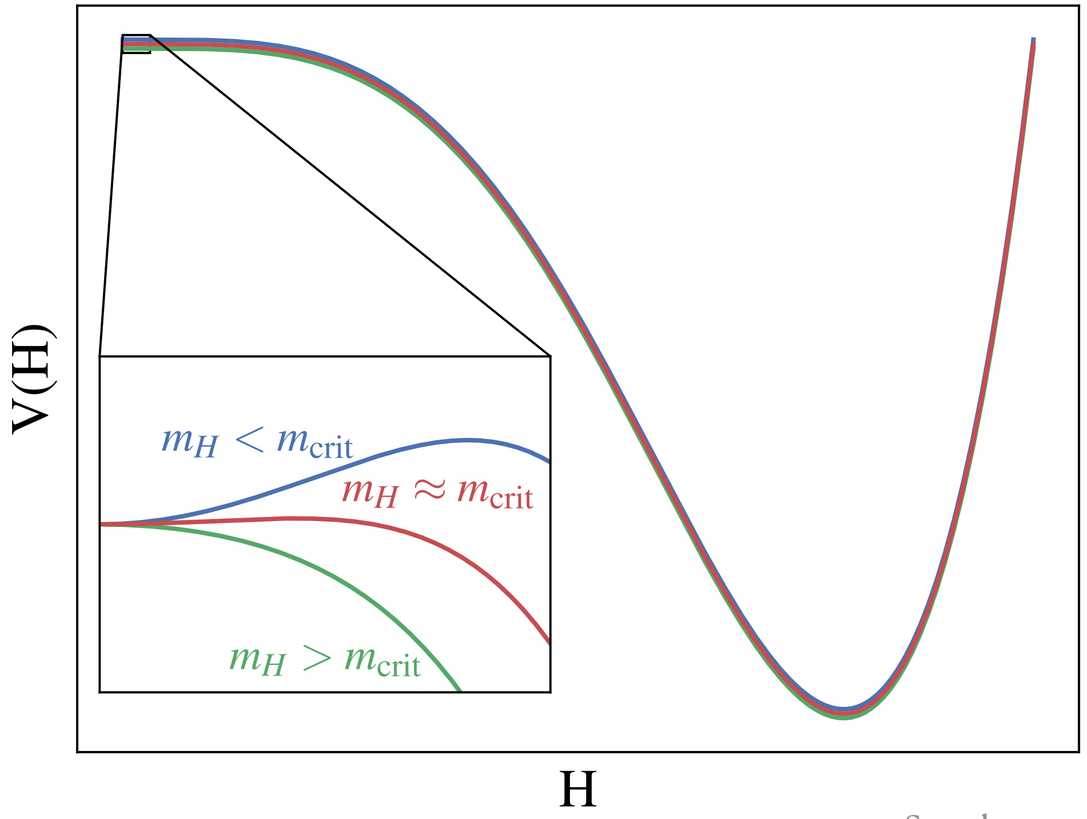
where $\langle \mathcal{O} \rangle$ is the order parameter of the phase transition

→ Localisation near the critical point ϕ_c of the discontinuity of the order parameter

Higgs Criticality

- Application to Higgs naturalness: ϕ scans the quadratic term, $m_h^2 \to m_h^2(\phi)$
- Order parameter is the Higgs condensate
- SOL needs discontinuity in order parameter

  $\to$ critical point where Higgs self coupling vanishes



$$V = m_h^2 H^\dagger H + \lambda (H^\dagger H)^2$$

running coupling → instability scale defined by $\lambda = 0$

See also
Degrassi et al. '12
Buttazzo et al. '13
Steingasser '24

A generic prediction

Higgs metastability bound

If m_h^2 is set by living at a critical edge at the TeV scale, then the instability scale is lowered into the TeV range (a larger m_h^2 would remove our vacuum)

→ there is accessible new physics coupled to the Higgs

Crucially: *different structure* from symmetry-based (SUSY/composite) solutions.

Self-organised localisation, landscape/vacuum-selection, Higgs-driven crunching: distinct mechanisms, same flavour

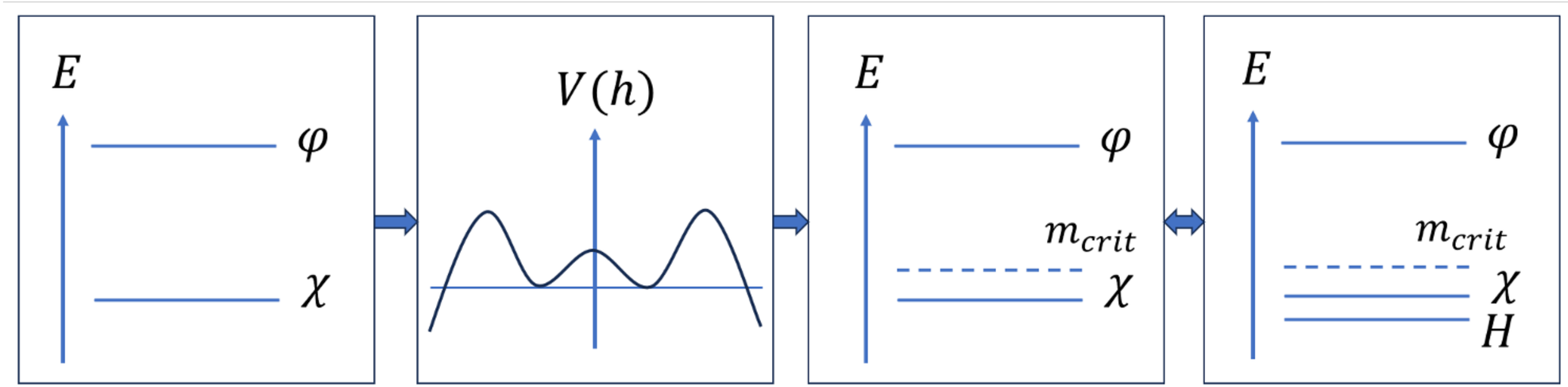
early-universe dynamics drive the Higgs to a critical point

We stay *agnostic* about the specific mechanism, yet there is a universal implication:

$$\text{Higgs metastability bound} \quad m_h^2 \leq \frac{1}{2}\mu_{\text{instab.}}^2 \, e^{-3/2} \, \beta_\lambda$$

Steingasser '24
Detering, Enguita, Gavela, Steingasser, You '25

What new physics?



Split spectrum expected from naturalness: Light fermions and heavy scalars

Split spectrum can destabilise the Higgs potential

This implies an upper bound on the Higgs mass for the EW vacuum to exist

A cosmological mechanism could place the Higgs mass close to this critical boundary

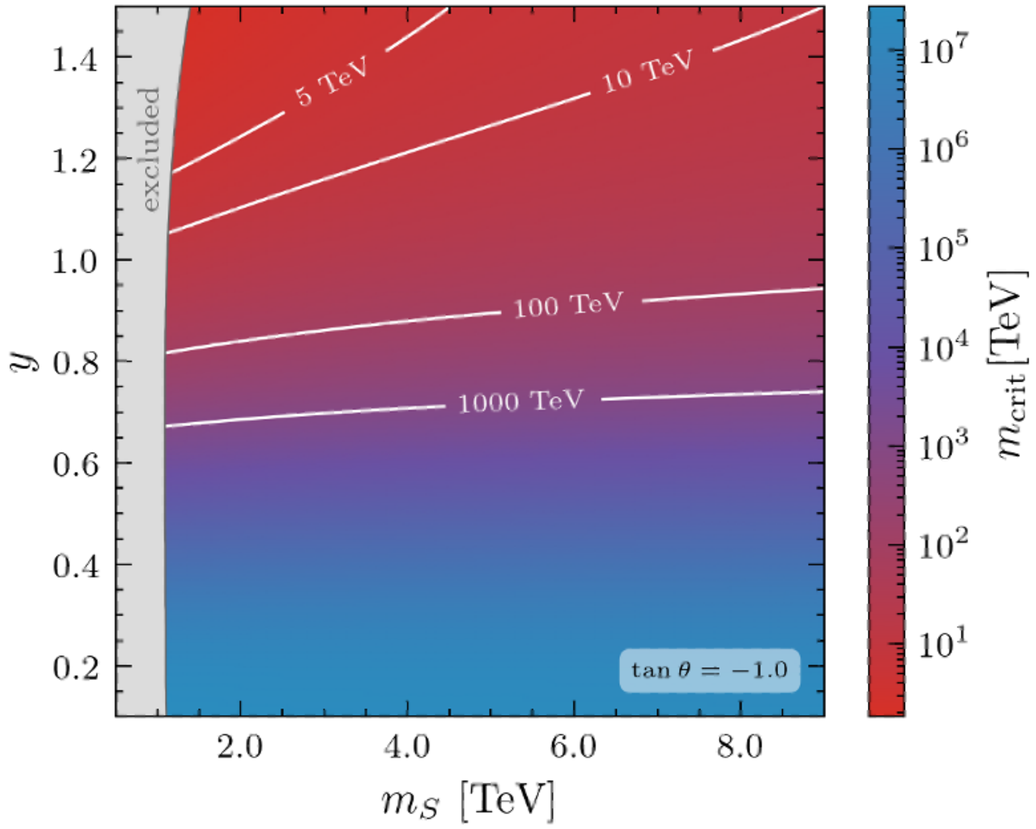
A toy model: The Singlet-Doublet model

- Independent motivation for a weak-scale vector-like fermion already exists: **thermal WIMP DM**
- A WIMP with the right relic abundance *can also* supply the critical boundary, through its Yukawa coupling to the Higgs
- Consider minimal vector-like extension

$$\mathscr{L}_{\mathrm{SD}} \supset -\frac{1}{2} m_S \psi^c \psi - m_D \chi_d \cdot \chi_u - y_1 \chi_u H^\dagger \psi - y_2 \chi_d \cdot H \psi + \mathrm{h.c}$$

- Higgsino-like model but our mechanism requires larger-than-SUSY Yukawas

Metastability in the Singlet-Doublet Model



- **Relic abundance** $\Omega_{\mathrm{DM}}h^2 = 0.12$ fixes band in (m_{DM}, y)
- **Metastability bound**: criticality requires the Yukawa to lower the instability scale to the TeV range, fixing another band

Conclusions

- Higgs near-criticality (parameters sitting at vacuum phase boundaries) looks fine-tuned in particle physics but is generic in dynamical systems → suggests a dynamical origin
- Self-Organised Localisation gives that origin: a scanning field localises onto the critical point ϕ_c via the feature it imprints in $V(\phi)$, driving the Higgs near-critical with no landscape measure
- The robust, mechanism-independent prediction: a lowered TeV-scale instability scale + accessible Higgs-coupled new physics, in a split spectrum (light vector-like fermions, heavy bosons)
- The light fermion can be a thermal WIMP → WIMP miracle linked to the hierarchy problem
- Concrete handle in the SD model: $m_{DM} \gtrsim 1.2\,\mathrm{TeV} \rightarrow$ bounded m_h and bounded heavy NP scale

Thank you !

Metastability in the Standard Model