Advanced Course on Higgs Physics

1st Graduate Week of the Quantum Universe Research School

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

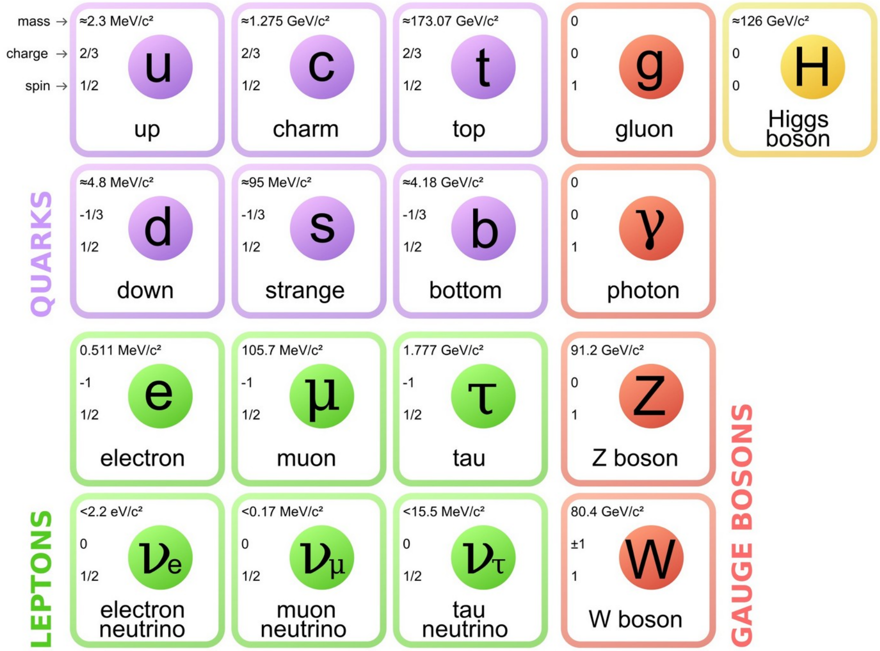
Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

DESY.

Accessing the fundamental laws of Nature

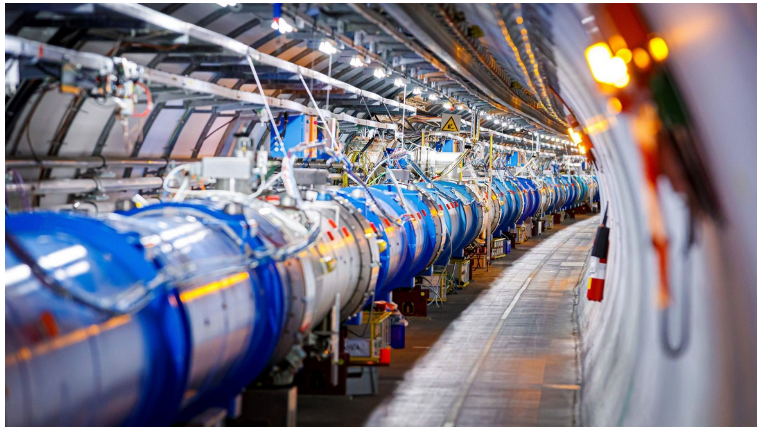
- Particle Physics aims to understand the **fundamental building blocks of Nature** (***elementary particles***) and the **interactions** between them



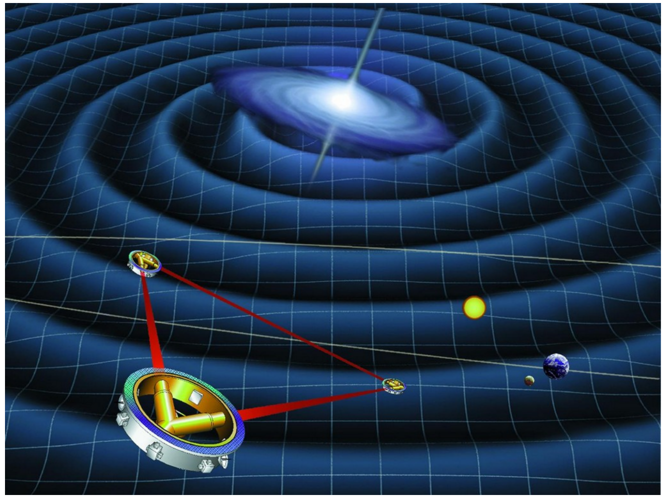
Known particles as of 2012

- Probe **higher energies** and **infinitesimally short distances** → probe the **early Universe**

- **High-energy particle colliders** like Large Hadron Collider at CERN (or HERA at DESY!)



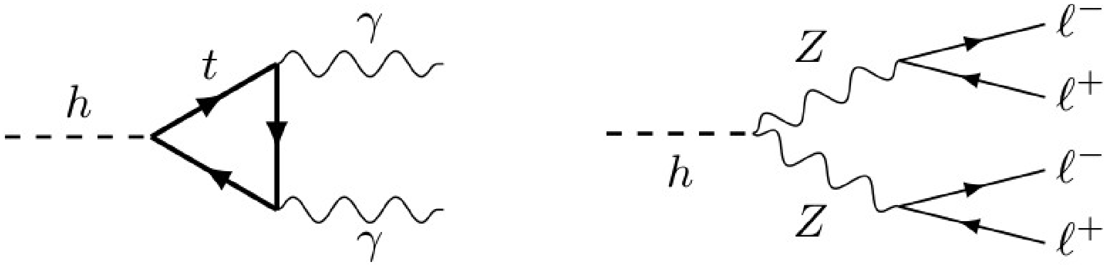
- But not only! There is a multitude of experiments aiming for short distances and/or early times, like **precision (low-energy) measurements**, or **cosmological observations of early-Universe relics**

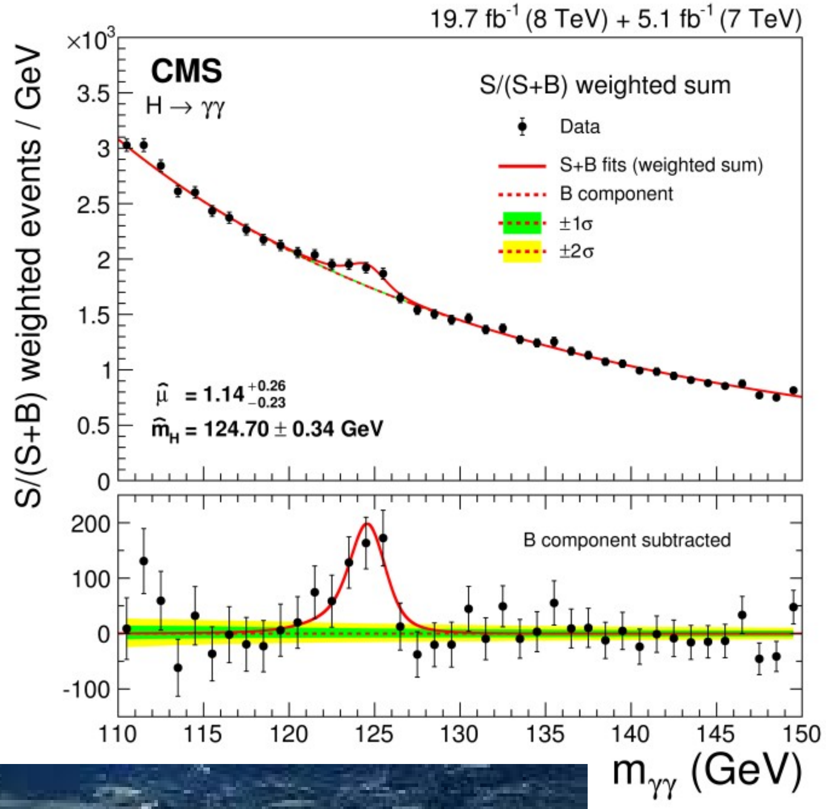


Artist view of space-based interferometer LISA that will search for primordial gravitational waves

Higgs discovery in 2012: a milestone for Particle Physics

- *4th July 2012*: discovery of **a** **Higgs boson** of mass 125 GeV by ATLAS and CMS collaborations at CERN Large Hadron Collider was a major milestone for Particle Physics
  → *discovery channels: $h\to\gamma\gamma$ and $h\to ZZ^*\to 4\ell$*





[CMS '12]

- 2013 Nobel Prize for F. Englert and P. Higgs

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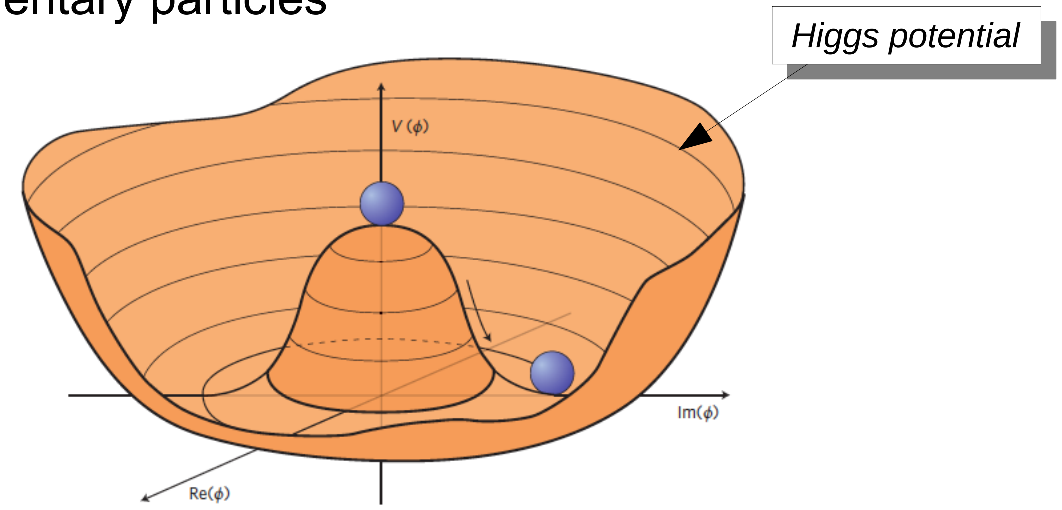
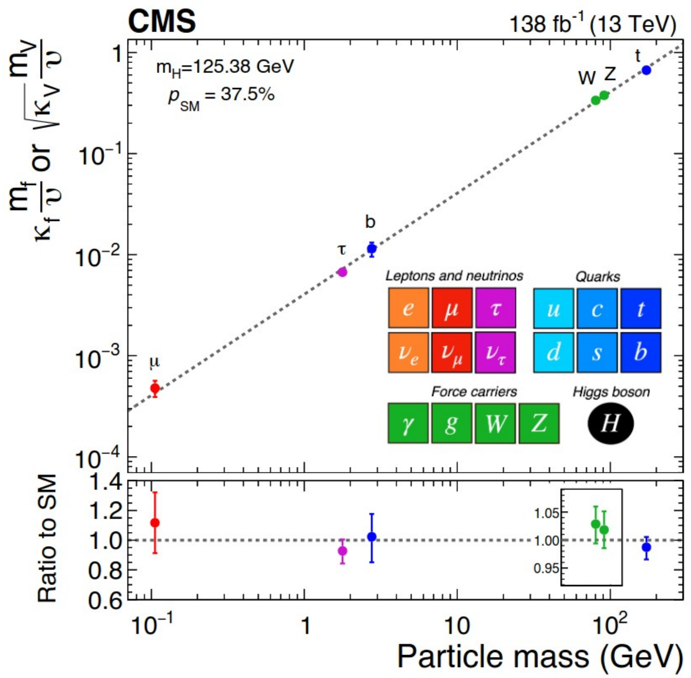
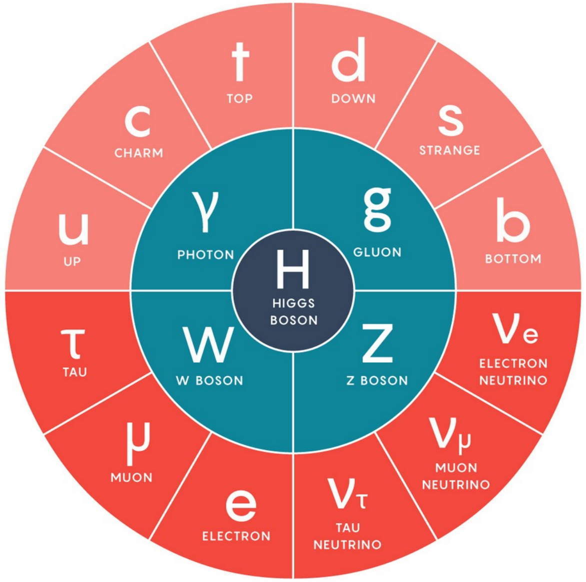
  → *Brout-Englert-Higgs mechanism* confirmed as **origin of masses** of elementary particles





[CMS, Nature '22]

- Particle content of **Standard Model** of Particle Physics (SM) is "complete" → *is this the end of the story?*



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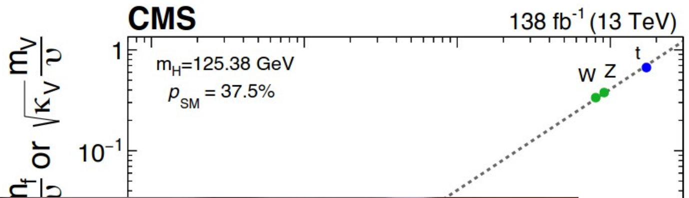
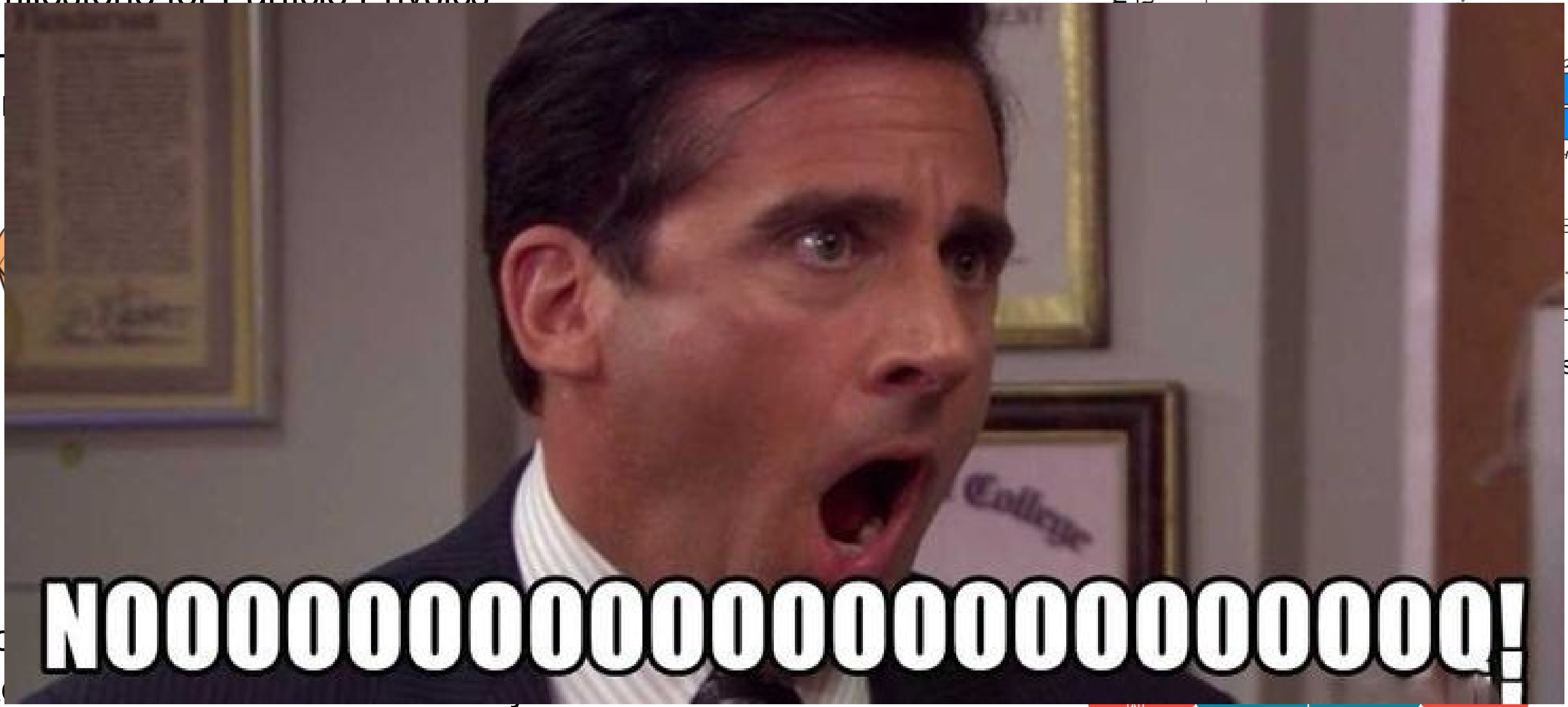
  → *Brout-*

  of eleme

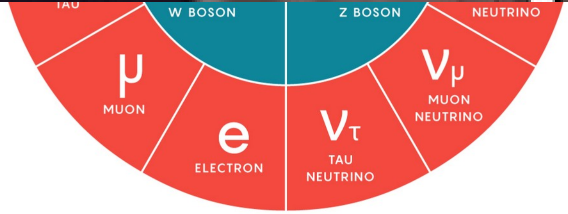


[CMS, Nature '22]



- Particle c

  “complet



The motivation for New Physics

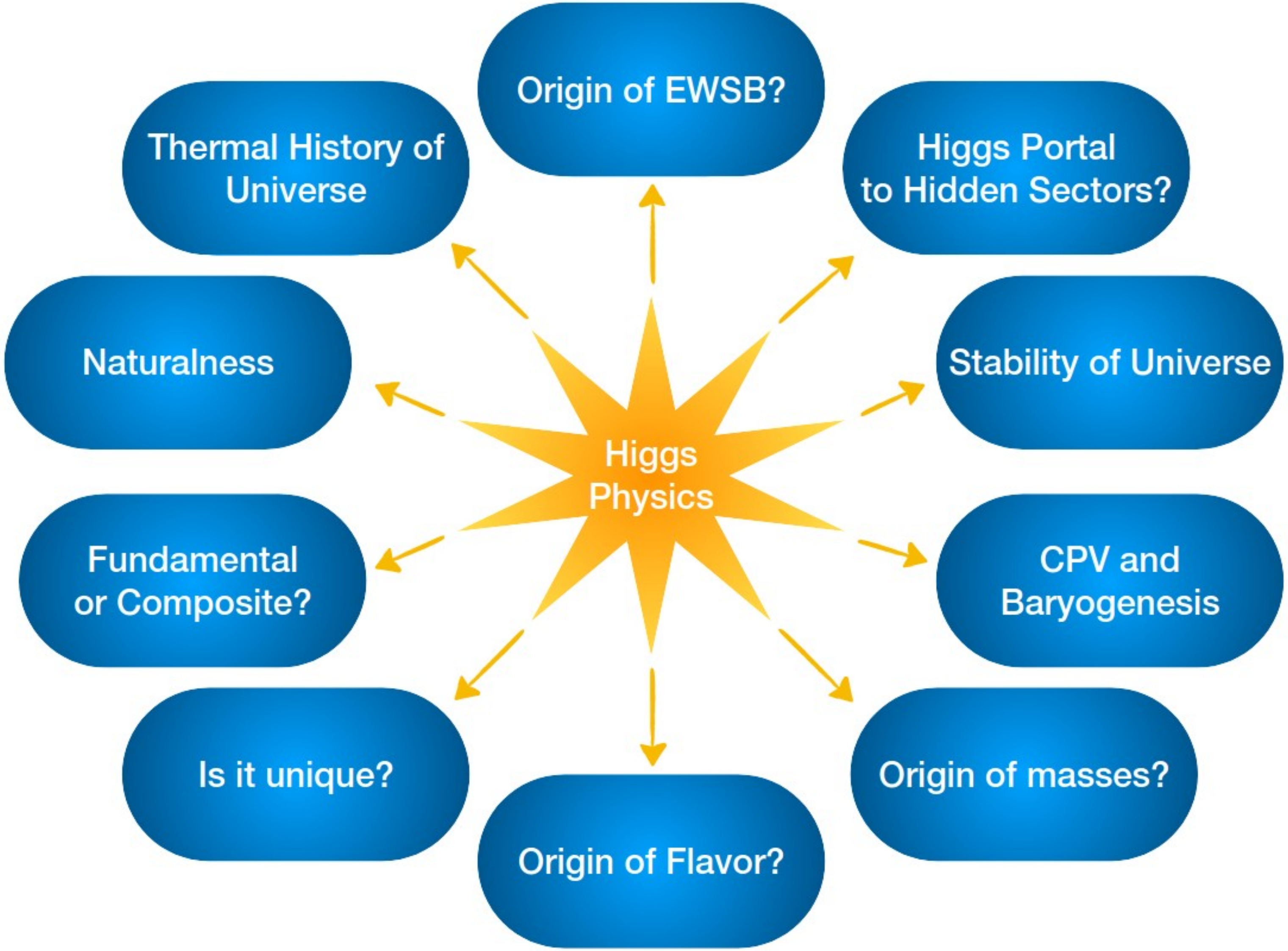
- In spite of the Higgs discovery, many questions remain unsolved, e.g.
  - Form and origin of Higgs potential (i.e. *why* do particles get masses, not just *how*)
  - Gauge hierarchy problem, i.e. why is gravity so much weaker than the other forces (or why is the Planck scale so much higher than the electroweak scale)
  - Reason for three fermion families and origin of flavour
  - Origin of matter-antimatter asymmetry of the Universe
  - Dark Matter
  - Structure of Higgs sector (no good guiding principle!)

  Etc.

- Not addressed by our current best description of Particle Physics, the Standard Model (SM)
  → **New Physics must exist beyond-the-Standard-Model (BSM)!**

- Many open problems relate to Higgs sector
  → the 125-GeV Higgs boson will certainly play a **key role in understanding the nature of BSM Physics**
  → BSM models often feature **additional Higgs bosons/scalars**

Goal of this lecture series: explain the central role of the Higgs boson to probe New Physics



[Snowmass report on Higgs Physics 2209.07510]

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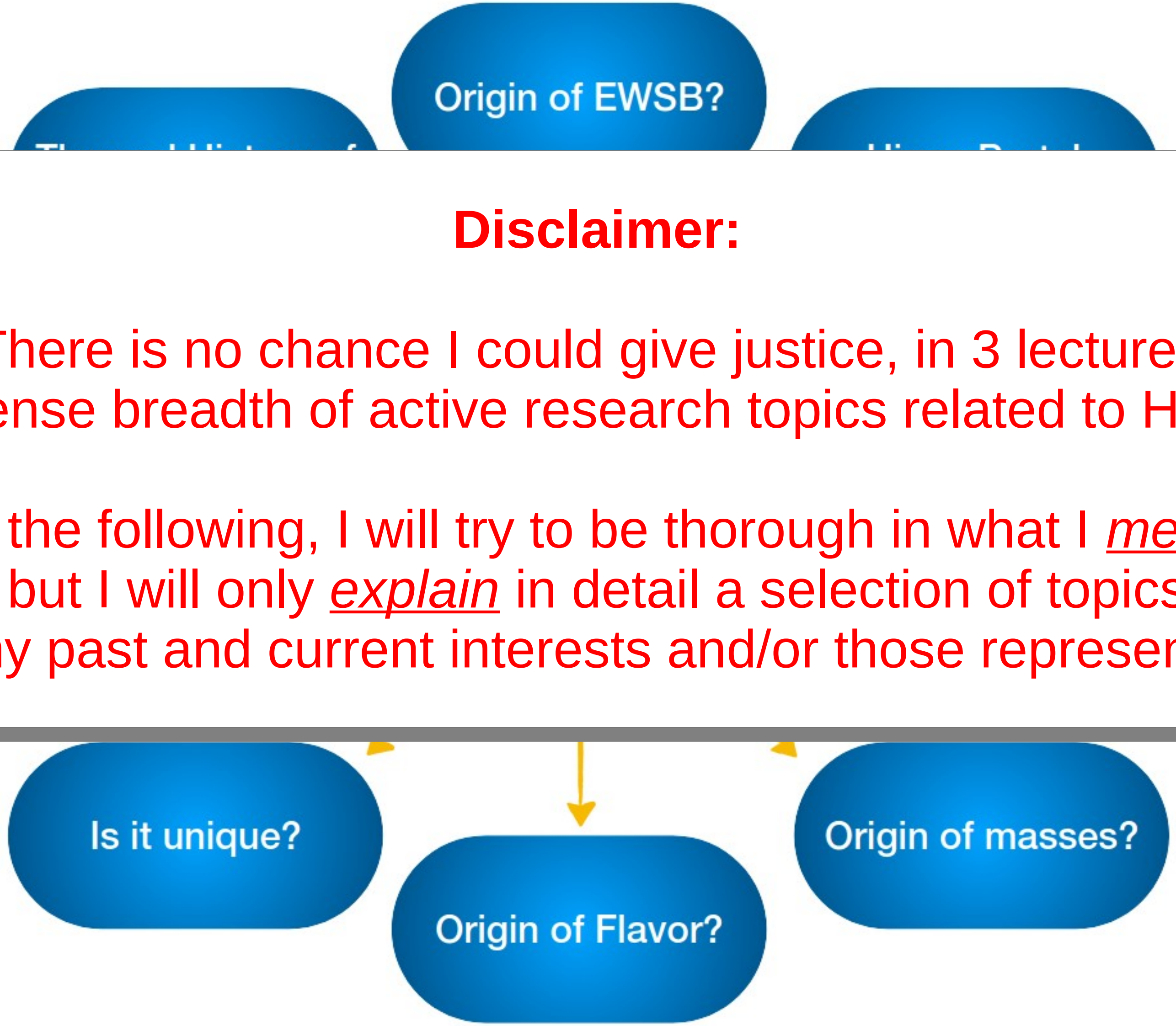


Disclaimer:

There is no chance I could give justice, in 3 lectures,
to the immense breadth of active research topics related to Higgs Physics

→ in the following, I will try to be thorough in what I *mention*,
but I will only *explain* in detail a selection of topics
(related to my past and current interests and/or those represented at DESY)

[Snowmass re

Outline of the lectures

- Part 1: Why a Higgs boson is needed
- Part 2: Connections between Higgs Physics and unanswered questions of Particle Physics (and possible solutions to them)
- Part 3: What can be learnt from the Higgs boson at high-energy colliders – an overview
- Part 4: The Higgs boson mass as a precision observable – calculations and interpretations
- Part 5: The Higgs boson potential, its trilinear coupling, and relations with early-Universe evolution

Part 1:
The need for a Higgs boson

Masses of elementary particles

- Strong, weak and electromagnetic fundamental interactions described as **gauge theories**
  - Quantum Chromodynamics (QCD) → $SU(3)_c$
  - Electroweak (EW) interactions → $SU(2)_L \times U(1)_Y$
- Underlying gauge theories is the principle of **gauge invariance**, which strongly constrains allowed terms in the Lagrangian.

  For instance, under a finite local transformation V(x) of a gauge group G, a gauge field A_μ transforms as

$$A_\mu \xrightarrow{V\in G} VAV^{-1} + \frac{i}{g}V(\partial_\mu V^\dagger)$$

  thus a mass term $m_A^2 A_\mu A^\mu$ is **forbidden by gauge invariance**
- Additionally, the currently-known fermions are **chiral**, i.e. weak interactions treat left-handed and right-handed fermions differently → **mass terms for chiral fermions are also forbidden by gauge invariance**

  e.g.

$$m_e \bar{e}_L e_R + \text{h.c.}$$

Y=+1
& part of $SU(2)_L$ doublet

Y=-2
& part of $SU(2)_L$ singlet

- How can we explain the **observed masses** of EW gauge bosons and fermions?

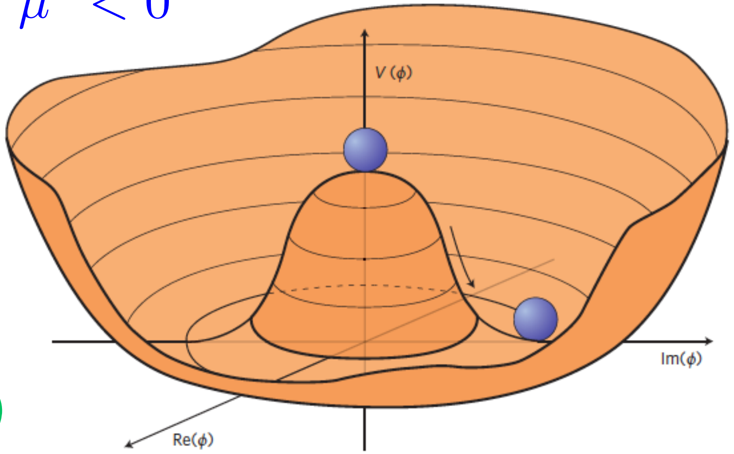
  → **Brout-Englert-Higgs mechanism**

Brout-Englert-Higgs mechanism

- **Idea** (in its minimal realisation): introduce a scalar* Φ – the **Higgs field** – doublet under $SU(2)_L$ and with hypercharge Y=+1, and with potential

$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4$$

$$\lambda > 0$$
$$\mu^2 < 0$$



* Why a scalar? → so that it can get a vacuum expectation value without breaking Lorentz symmetry

- The potential $V(\Phi)$ itself (and thus also the Lagrangian of the theory) obeys the fundamental $SU(2)_L \times U(1)_Y$ gauge symmetry but the **vacuum does not**

- In other words, the Higgs field acquires a non-zero **vacuum expectation value v** that triggers the **spontaneous breaking of the EW symmetry (EWSB)**

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \longrightarrow \langle\Phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

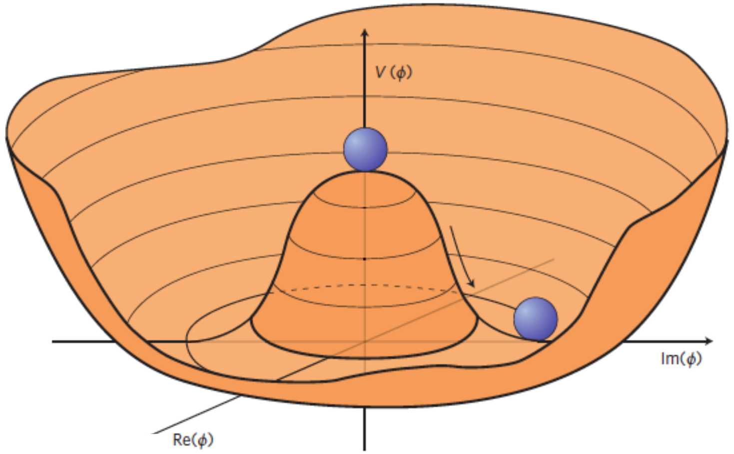
- Vacuum remains symmetric under $\mathbf{U(1)_{QED}}$ gauge group (otherwise there would be charge breaking with strong phenomenological consequences!)

$$SU(2)_L \times U(1)_Y \xrightarrow{\text{EWSB}} U(1)_{\text{QED}}$$

Brout-Englert-Higgs mechanism and particle masses

$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4 \qquad \lambda > 0 \quad \mu^2 < 0$$

$$SU(2)_L \times U(1)_Y \xrightarrow{\text{EWSB}} U(1)_{\text{QED}}$$



- Masses of gauge bosons via **scalar kinetic term**, with covariant derivative

$$D_\mu\Phi = \partial_\mu\Phi - \frac{1}{2}i\begin{pmatrix} g_2W^3_\mu + g_YB_\mu & \sqrt{2}g_2W^+_\mu \\ \sqrt{2}g_2W^-_\mu & -gW^3_\mu + g_YB_\mu \end{pmatrix}\Phi$$

with $\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}$ *h: Higgs boson*
G^0, $G^\pm$: Goldstone bosons and $W^\pm_\mu = \frac{1}{\sqrt{2}}(W^1_\mu \mp iW^2_\mu)$

which gives $$|D_\mu\Phi|^2 \supset \frac{1}{4}g_2^2v^2W^+_\mu W^{-\,\mu} + \frac{1}{4}(g_2^2 + g_Y^2)v^2Z_\mu Z^\mu \qquad (\blacktriangle)$$

where $Z_\mu = \dfrac{g_2W^3_\mu - g_YB_\mu}{\sqrt{g_2^2 + g_Y^2}}$

- **Before EWSB:**
  Φ → 4 degrees of freedom (d.o.f.) + 4 massless gauge bosons of $SU(2)_L$ x $U(1)_Y$ (W_1, W_2, W_3, B) → 4x2=8 d.o.f.

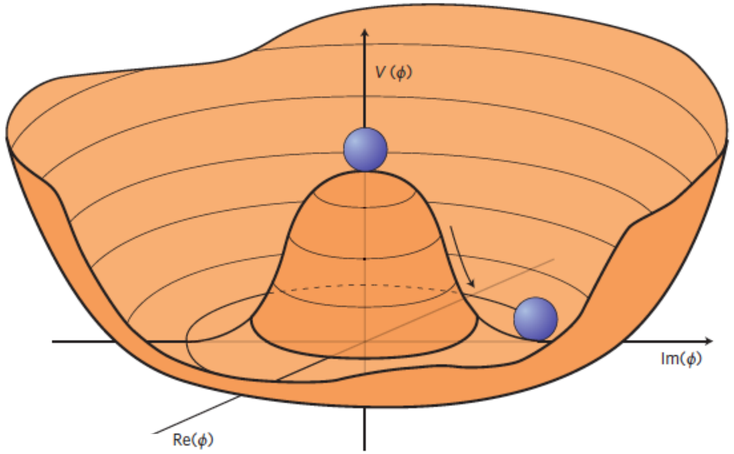
- **After EWSB:** would-be Goldstone bosons are “eaten” by gauge bosons which become massive
  h → 1 d.o.f + 3 massive gauge bosons $W^\pm$, Z → 3x3=9 d.o.f + 1 massless photon A → 2 d.o.f.

  Exercise: rederive equation (▲) + find the expression of the photon A in terms of W_3 and B

Brout-Englert-Higgs mechanism and particle masses

$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4 \qquad \lambda > 0 \quad \mu^2 < 0$$

$$SU(2)_L \times U(1)_Y \xrightarrow{\text{EWSB}} U(1)_{\text{QED}}$$



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where $Z_\mu = \dfrac{g_2 W^3_\mu - g_Y B_\mu}{\sqrt{g_2^2 + g_Y^2}}$

- Masses of fermions (e.g. electron) via **Yukawa-interaction term**

$$\mathcal{L} \supset -y_e \bar{L}_L \Phi e_R + \text{h.c.} \xrightarrow{\text{EWSB}} -\frac{y_e}{\sqrt{2}} v \bar{e}_L e_R + \text{h.c.}$$

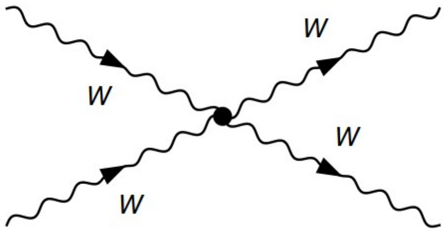
Y=+1
conjugate of
$SU(2)_L$ doublet

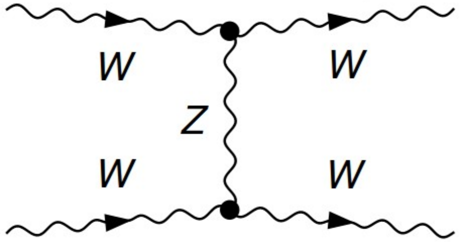
Y=+1
$SU(2)_L$ doublet

Y=-2
$SU(2)_L$ singlet

Where to find "the" Higgs boson? A unitarity argument

- Higgs-less alternatives to BEH mechanism were also devised (e.g. technicolor)
  → How to **test** the BEH mechanism? At what scale can the Higgs boson be found?
- Consider a massive W boson W_μ with momentum $k^\mu = (E,0,0,k)$
  → 3 possible polarisations such that $k_\mu \cdot \varepsilon^\mu = 0$ and $\varepsilon_\mu \cdot \varepsilon^\mu = -1$
  → 2 transverse polarisations $\varepsilon_{T1}{}^\mu = (0,1,0,0)$, $\varepsilon_{T2}{}^\mu = (0,0,1,0)$
  + 1 longitudinal polarisation $\varepsilon_L{}^\mu = (k/M_W,0,0,E/M_W) \sim k^\mu/M_W$ for $E \gg M_W$
- Consider the 2→2 scattering of longitudinally polarised W bosons $\mathbf{W_L W_L \to W_L W_L}$
  → *without a Higgs boson*, only gauge-boson diagrams like

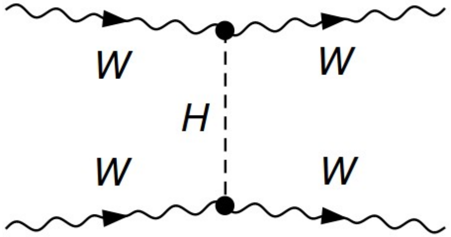




$$\mathcal{A} \sim g_2^2 \frac{E^2}{M_W^2}$$

Loss of unitarity for large E (from ~M_W/g_2)!

→ adding a Higgs boson in the theory:



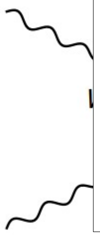
$$\mathcal{A}_h \sim -g_2^2 \frac{E^2}{M_W^2}$$

$$\Rightarrow \mathcal{A}_{\text{tot}} \sim g_2^2 \frac{M_h^2}{M_W^2}$$

A Higgs boson unitarises the theory if its mass < ~1 TeV

Where to find "the" Higgs boson? A unitarity argument

- Higgs-less alternatives to BEH mechanism were also devised (e.g. technicolor)
  → How to test the BEH mechanism? At what scale can the Higgs boson be found?
- Consider a massive W boson W_μ with momentum $k^\mu = (E,0,0,k)$
  → 3 pos
  → 2 tra
  + 1 long
- Conside
  → *witho*



No lose theorem (for LHC)

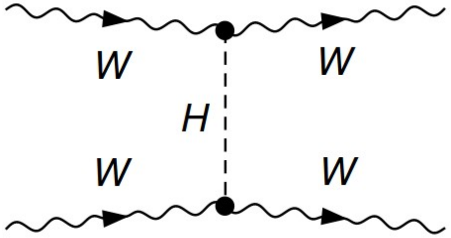
→ **either a Higgs boson exists below/around the TeV scale, to unitarise gauge boson scattering in EW gauge theory**

or

→ **some new strong dynamics would appear at ~ TeV scale**

In other words, theory guaranteed that the LHC would see something!

→ adding a Higgs boson in the theory:

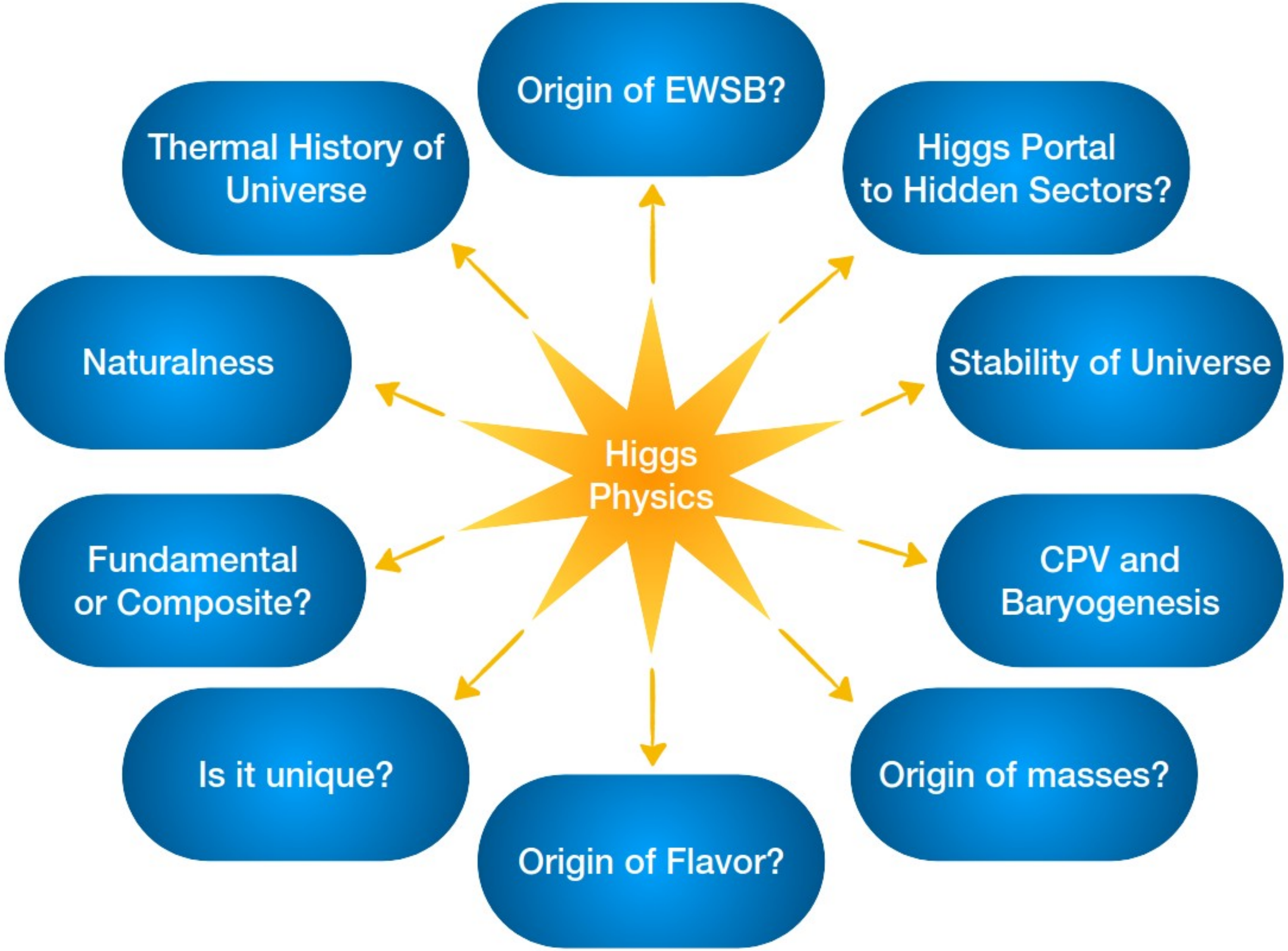


$$\mathcal{A}_h \sim -g_2^2 \frac{E^2}{M_W^2} \qquad \Rightarrow \mathcal{A}_{\text{tot}} \sim g_2^2 \frac{M_h^2}{M_W^2}$$

A Higgs boson unitarises the theory if its mass < ~1 TeV

Part 2:
Probing New Physics with the Higgs boson

Goal of this lecture series: explain the central role of the Higgs boson to probe New Physics



[Snowmass report on Higgs Physics 2209.07510]

Hierarchy problems in Higgs Physics

Slide adapted from [Salam '23],
itself adapted from [Giudice]

$$\mathcal{L} \supset -\frac{1}{4} F^a_{\mu\nu} F^{a,\mu\nu} + \bar{\psi}_i \gamma_\mu D^\mu_{ij} \psi_j$$

→ entirely constrained by gauge symmetry, tested to high precision (e.g. LEP)

$$\mathcal{L} \supset -y_{ij} \bar{\psi}_i \Phi \psi_j + \mu^2 |\Phi|^2 + \lambda |\Phi|^4 - V_0$$

Yukawa couplings: Hierarchy of fermion masses and flavour

Higgs mass term: Gauge hierarchy problem

Quartic Higgs coupling: UV behaviour and vacuum stability *(more later)*

Vacuum energy: Cosmological constant problem

Naturalness and the gauge hierarchy problem

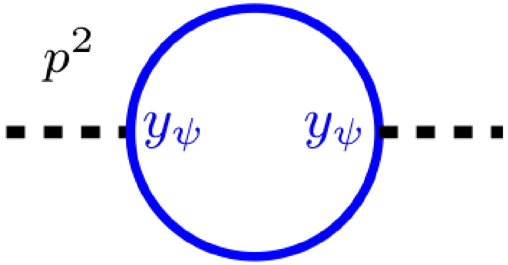
- The EW scale is around m_{EW}~100 GeV (v=246 GeV) while the Planck scale, at which effects of quantum gravity must manifest themselves is M_{Pl}~10^{19} GeV → why are there 17 orders of magnitude between m_{EW} and M_{Pl}?
  → **(gauge) hierarchy problem**

- At a more concrete level, the Higgs mass also poses a theoretical problem, as it is not ***protected*** from large (quadratic) corrections – unlike for fermions and gauge bosons, nothing forbids scalar mass terms

- Let's consider the effect of a heavy BSM fermion ψ, of mass M ~ M_{pl} with a Lagrangian

$$\mathcal{L} \supset \bar{\psi}(i\gamma^\mu \partial_\mu - M)\psi - y_\psi \bar{\psi}\psi h$$

  and let's compute the leading corrections to the Higgs mass in this toy model



$$\Delta^{(1\ell)} m_h^2 = -(-iy_\psi)^2 \int \frac{d^dk}{i(2\pi^2)} \mathrm{tr}\left[\frac{i(\not{k}+M)}{k^2-M^2}\frac{i((\not{p}-\not{k})+M)}{(p-k)^2-M^2}\right]$$

$$\approx -\frac{y_\psi^2}{4\pi^2} M_{\mathrm{Pl}}^2 \quad \text{with } p^2 \ll M^2 \quad \& \; Q = M \approx M_{\mathrm{Pl}}$$

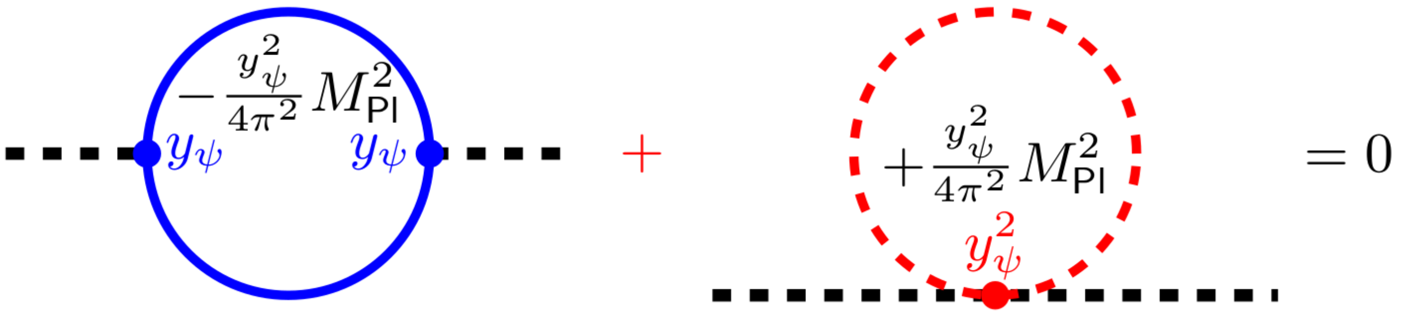
- Getting the Higgs mass right at 125 GeV would imply a tuning between tree-level mass and loop corrections to **32 digits!!!** → **technical hierarchy problem**

Solutions to the gauge hierarchy problem: Supersymmetry

- **Supersymmetry (SUSY)**: [Wess, Zumino '74] and many more
  Extend space-time symmetry (Poincaré group) by introducing **new symmetry between fermions and bosons**
  (SUSY is only option to circumvent Coleman-Mandula theorem [Coleman, Mandula '67], see [Haag, Lopuszanski, Sohnius '75])
  → Each fermion (boson) has a bosonic (fermionic) superpartner, with same mass and related couplings,
  e.g. for toy model of previous slide, ψ has a superpartner $\tilde{\psi}$, with interaction terms

$$\mathcal{L} \supset -y_\psi \bar{\psi}\psi h - y_\psi^2 \tilde{\psi}^* \tilde{\psi} h^2$$

such that



- *NB:* **SUSY must be broken**, otherwise selectron would have mass 511 keV and would have had to be seen already
- But SUSY can be broken *(super)softly*, i.e. **without reintroducing quadratic divergences in m_h**
- Numerous phenomenological models, such as Minimal Supersymmetric Standard Model (MSSM), Next-to-MSSM (NMSSM), Dirac gaugino models, etc., however so far no sign of SUSY at the LHC...

Solutions to the gauge hierarchy problem: Compositeness

- **Compositeness:** see e.g. [Agashe, Contino, Pomarol '04], [Giudice, Grojean, Pomarol, Rattazzi '07] + refs therein
  Light scalars already known in Nature, e.g. pions, but these are *not fundamental*, rather bound – or in other words composite – states
  → Introduce a new strongly coupled sector, with a global symmetry group G, spontaneous broken down to H at a scale f

$$G \xrightarrow{SSB} H \supset SU(2)_L \times U(1)_Y$$

NB: only a part of H is gauged!

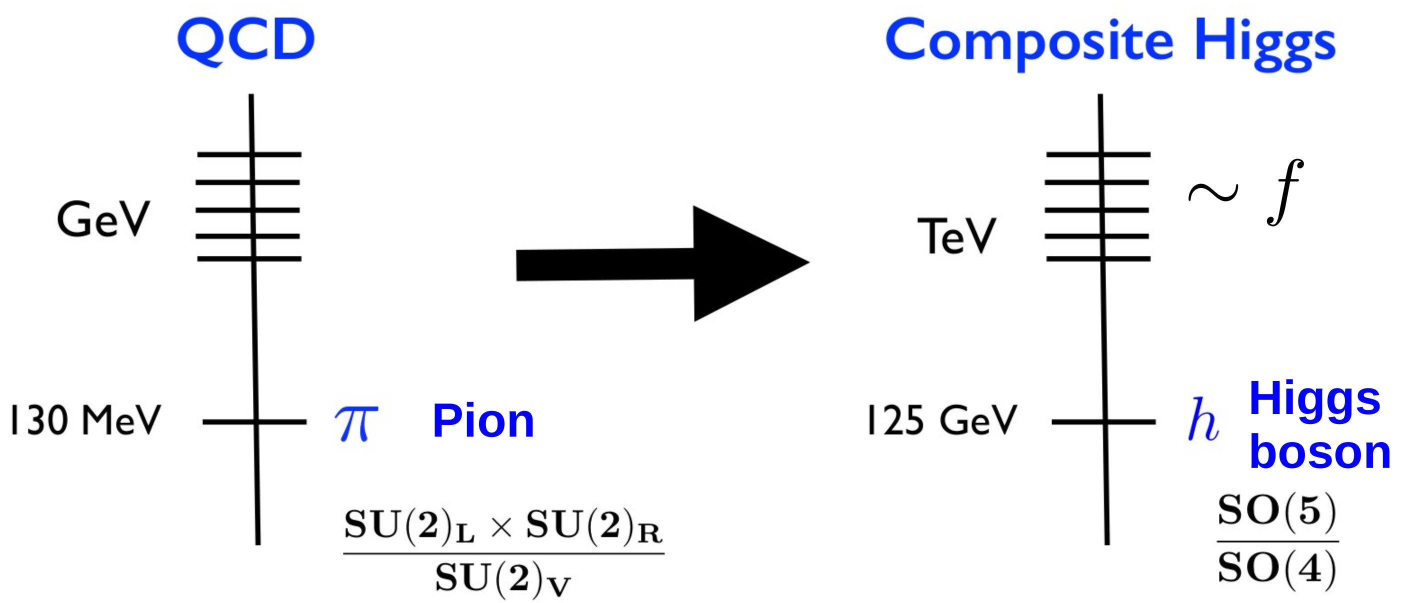
→ **Higgs boson appears as a pseudo-Goldstone boson** → naturally light

Minimal model (1 Higgs doublet):
→ G = SO(5) (10d); H = SO(4) (6d)

Composite Two-Higgs-Doublet Model:
→ G = SO(6) (15d); H = SO(4) x SO(2) (7d)

- Ratio v/f determined by *misalignment* between directions of G/H and $SU(2)_L x U(1)_Y / U(1)_{QED}$ breakings

- *Partial compositeness* to explain quark mass paterns

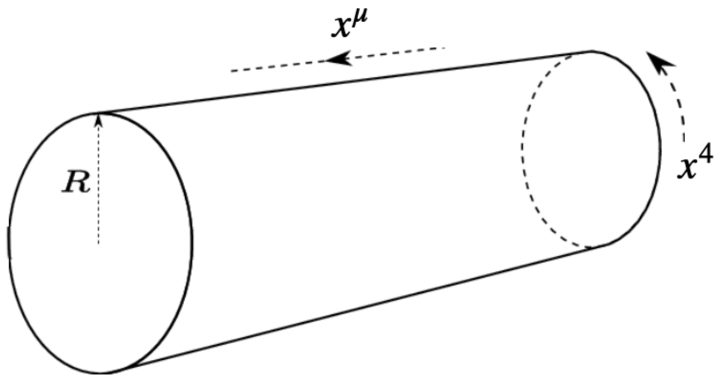


Spontaneous breaking of chiral symmetry in QCD

Minimal Composite Higgs Model

Figure adapted from [Grojean '23]

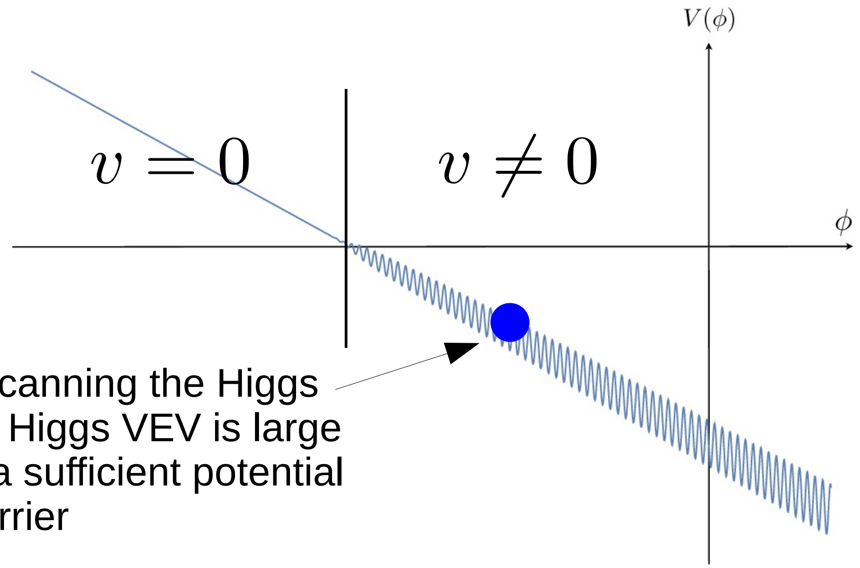
Other solutions to the gauge hierarchy problem



- **Large Extra-dimensions:** [Arkani-Hamed, Dimopoulos, Dvali '98]
  (see e.g. Randall-Sundrum models, [Randall, Sundrum '99])
  Add at least one more dimension of space-time, which is compactified
  → tower of excited states + effective Planck scale in 4d is lowered

- **Gauge-Higgs unification:** [Manton '79], [Fairlie '79], [Hosotani '83], etc.
  Hosotani mechanism: In 5d, a gauge boson contains 5 components
  → 4 components of a 4d gauge boson + 1 component to 4d Higgs boson (which triggers EWSB)
  → Higgs mass is then again protected by gauge symmetry in 5d

- **Cosmological relaxation:**
  see e.g. [Graham, Kaplan, Rajendran '15], [Espinosa et al. '15]
  Promote the Higgs mass term μ^2 to a dynamical field,
  the **relaxion**, and give this field a potential and interactions
  with the Higgs boson (and VEV) such that it selects the
  appropriate value of μ^2



Relaxion stops scanning the Higgs mass μ^2 when the Higgs VEV is large enough to create a sufficient potential barrier

- and many more...

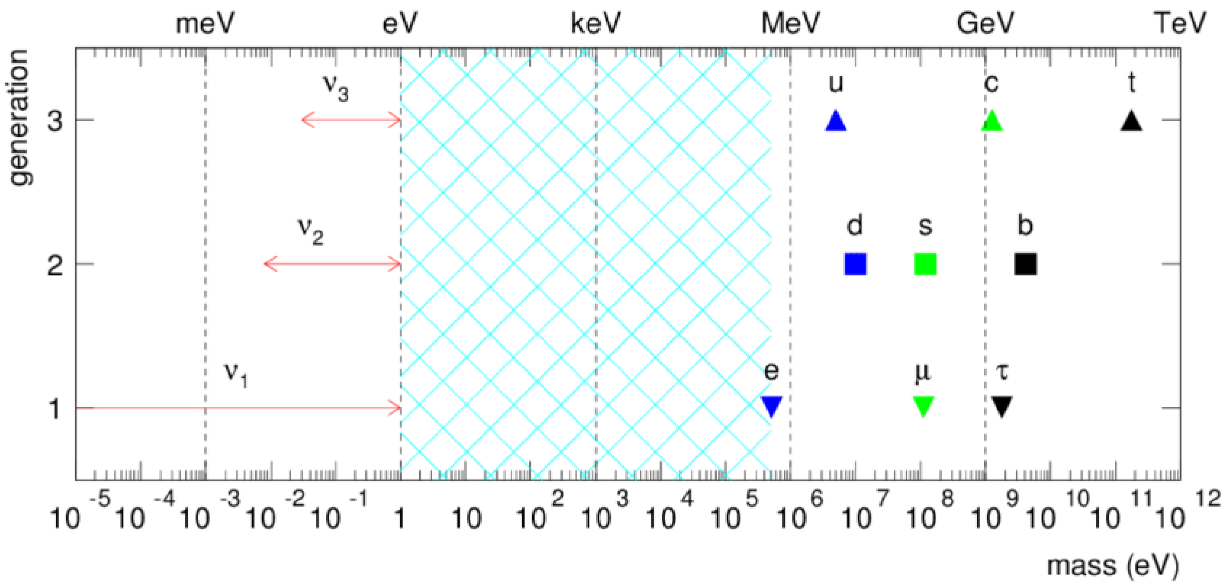
The Yukawa hierarchy problem and flavour

- Fermion mass patterns completely unexplained
  why is $m_t \sim 3 \times 10^5\, m_e$? (not to mention neutrinos…)

- Fermion masses in SM → entirely determined by Yukawa couplings between fermions and Higgs boson
  → why does the Higgs treat the three fermion families (identical w.r.t gauge symmetries) so differently?

- No guiding principle in Yukawa interactions in SM

- Gauge symmetries act on all three fermion families in the same way → something must treat the families differently → for instance a "horizontal symmetry" ?



[de Gouvea, hep-ph/0411274]

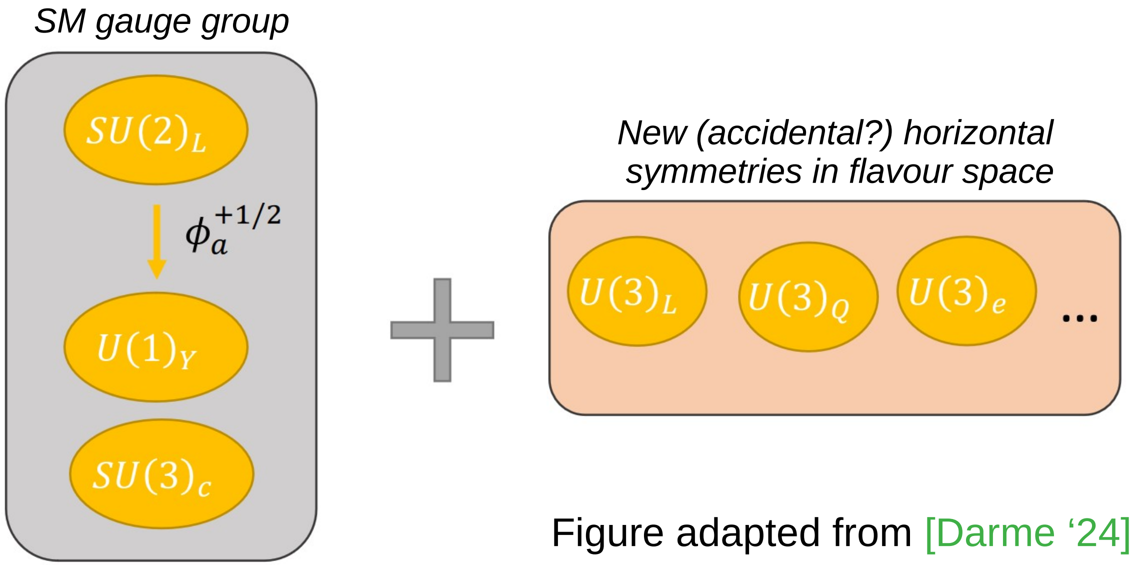
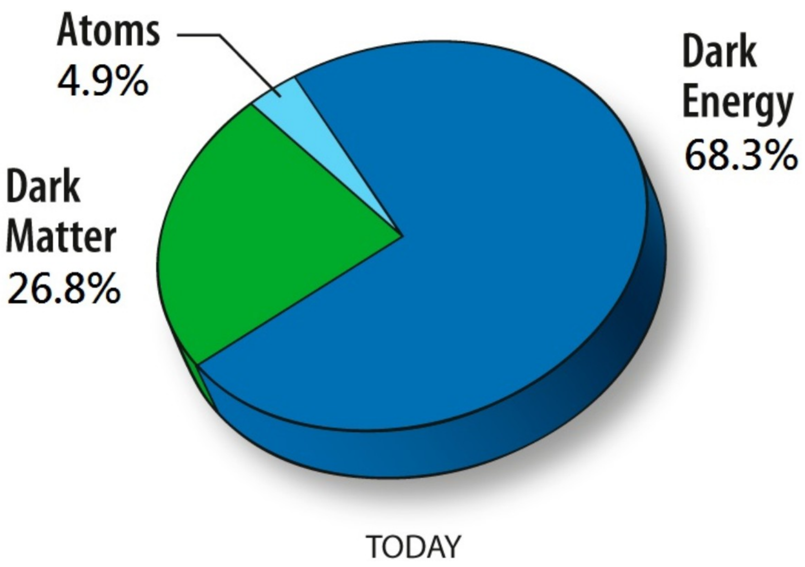


Figure adapted from [Darme '24]

The cosmological constant and its fine-tuning problem



- Cosmological observations → Universe expanding at accelerating pace

- Explained in ΛCDM model by cosmological constant, corresponding to a vacuum energy:

  [Planck '15] $\rho_{vac} \sim 2.5 \times 10^{-47}$ GeV^4

- Value of Higgs potential at EW minimum not fixed by theoretical arguments, nor constrained by colliders

$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4 + V_0$$

$$\longrightarrow V_{\text{min}} = \frac{1}{2}\mu^2 v^2 + \frac{1}{4}\lambda v^4 + V_0 \;= -1.2 \times 10^8 \text{ GeV}^4 + V_0 = \rho_{\text{vac}} \sim 2.5 \times 10^{-47} \text{ GeV}^4$$

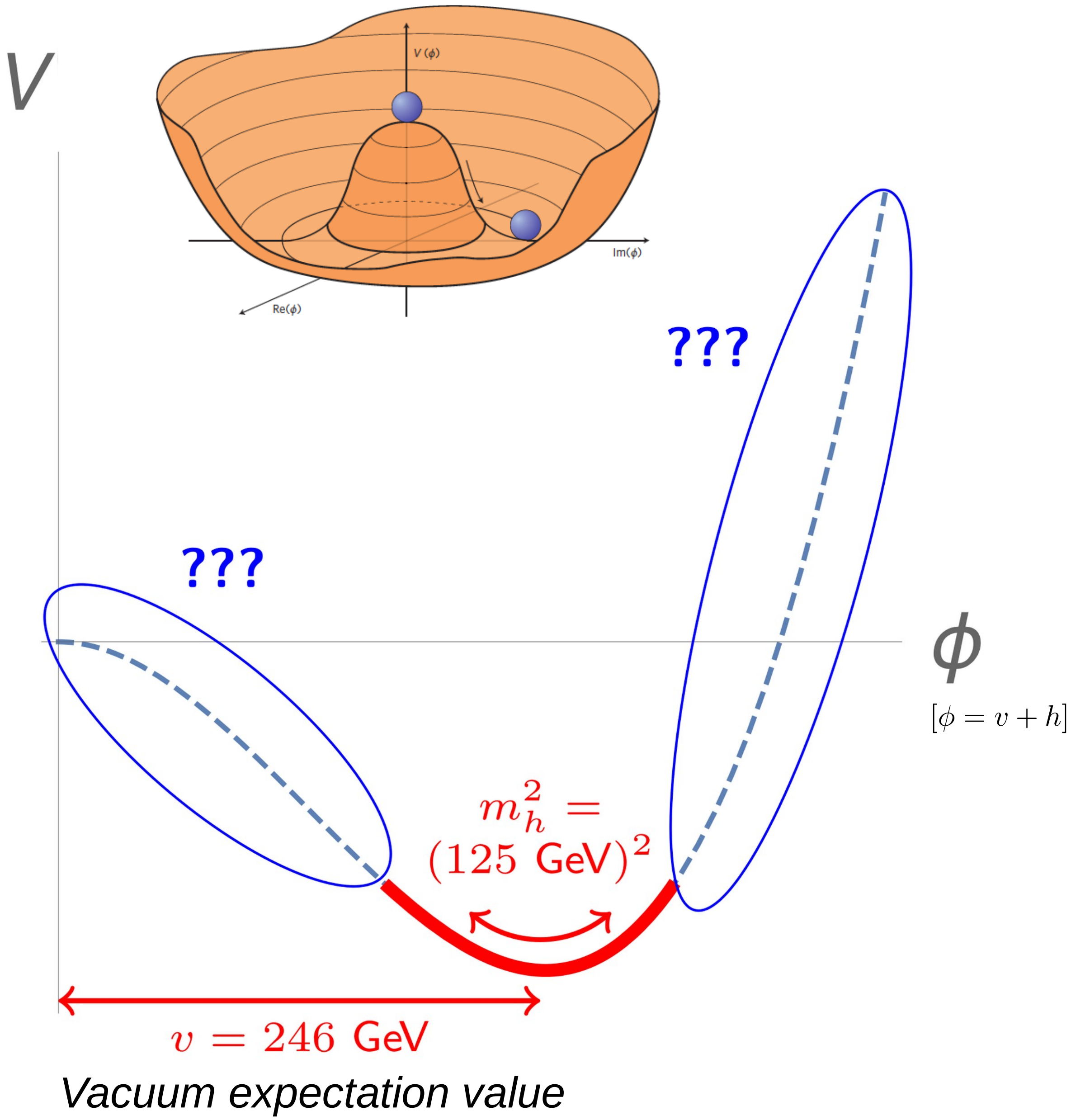
- Cancellation/fine-tuning of **~55 digits** needed in V_0 to reproduce the measured vacuum energy!

  → **cosmological constant problem**

- Possible solutions involve anthropic principle (multiverse), modifications of GR/ΛCDM, or of QFT, etc.

Form of the Higgs potential and trilinear Higgs coupling

- Brout-Englert-Higgs mechanism = **origin of electroweak symmetry breaking** ...
  … but very little known about the **Higgs potential** causing the phase transition



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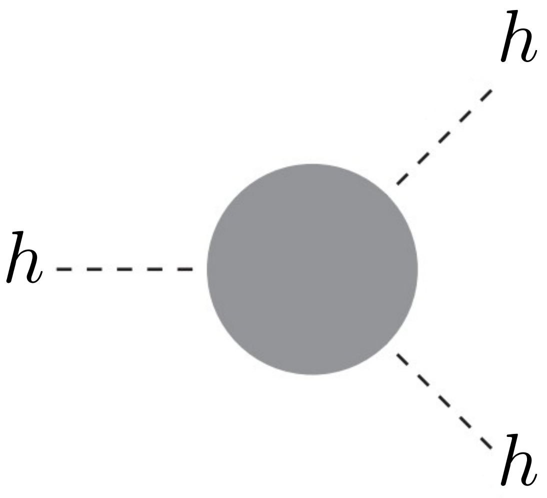

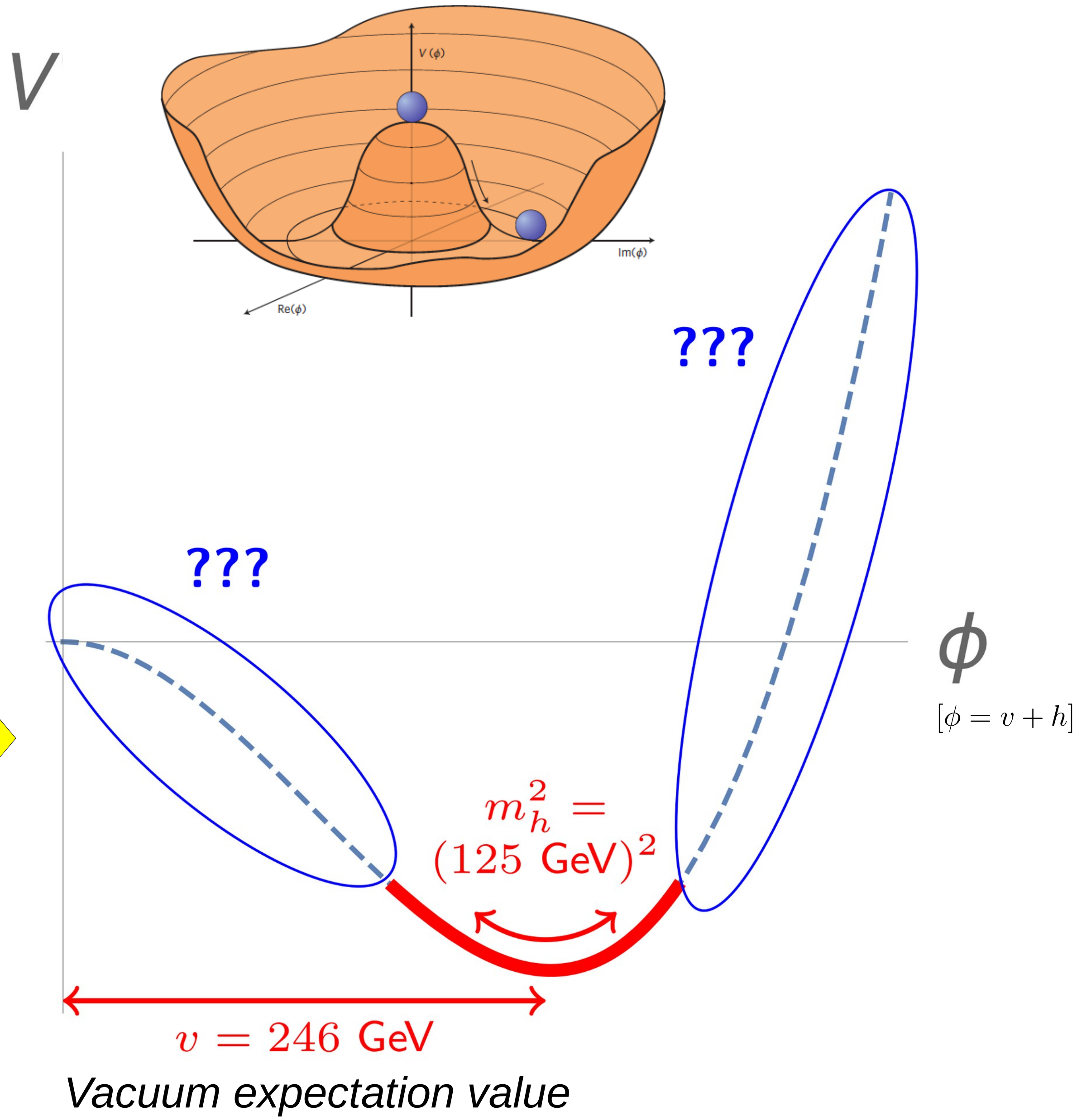

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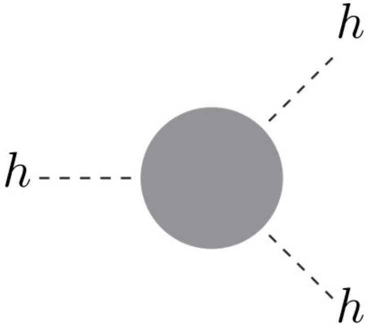
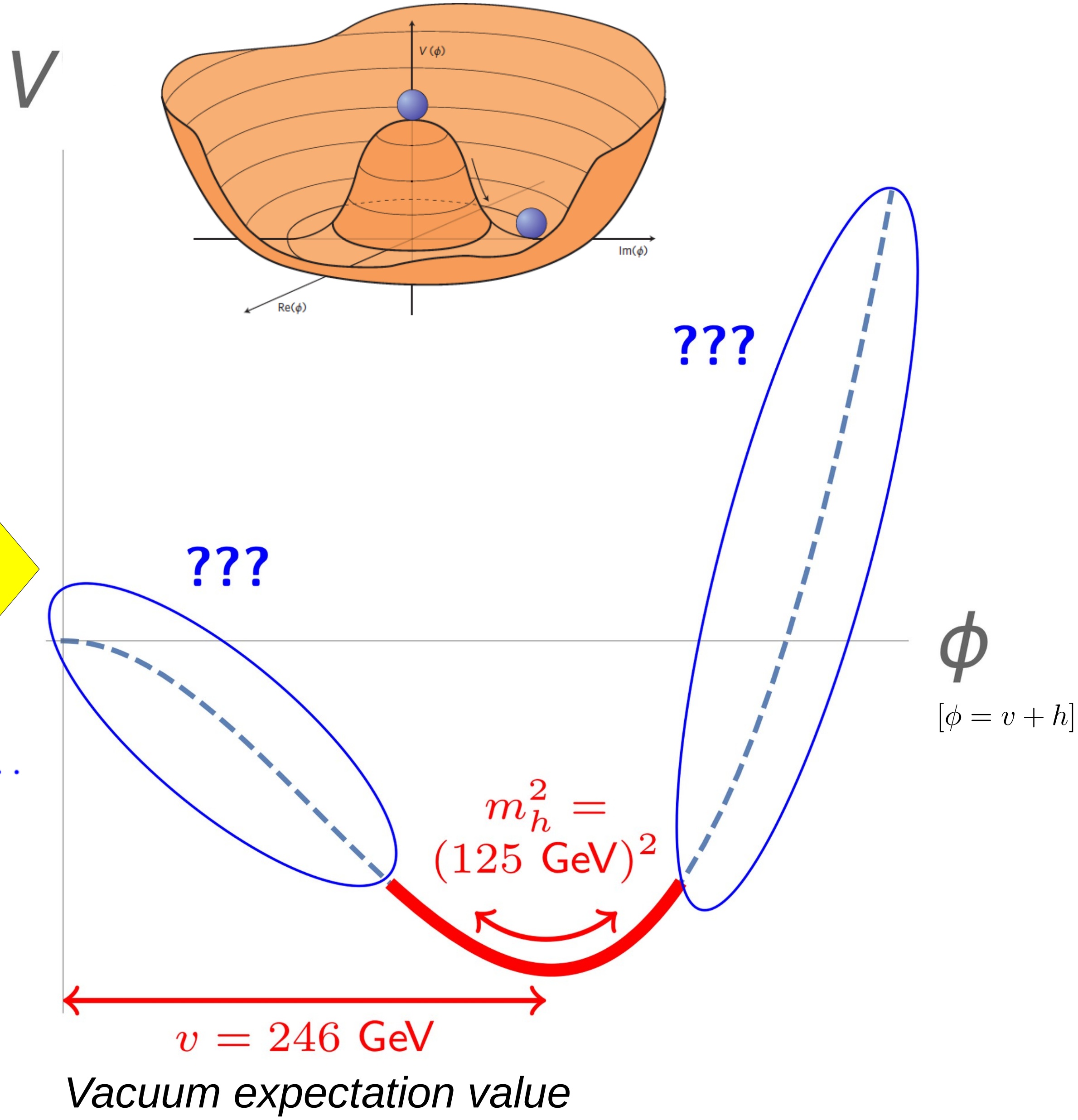




In the SM: $V^{(0)}_{\text{SM}} = \frac{1}{2} m_h^2 h^2 + \frac{1}{3!} \underbrace{\left(\frac{3m_h^2}{v}\right)}_{\equiv(\lambda^{(0)}_{hhh})^{\text{SM}}} h^3 + \frac{1}{4!} \underbrace{\left(\frac{3m_h^2}{v^2}\right)}_{\equiv(\lambda^{(0)}_{hhhh})^{\text{SM}}} h^4 + \cdots$

In general:

$$V^{(0)} = \frac{1}{2} m_h^2 h^2 + \frac{1}{3!} \overbrace{\kappa_\lambda \left(\frac{3m_h^2}{v}\right)}^{\equiv\lambda_{hhh}} h^3 + \frac{1}{4!} \kappa_4 \left(\frac{3m_h^2}{v^2}\right) h^4 + \cdots$$

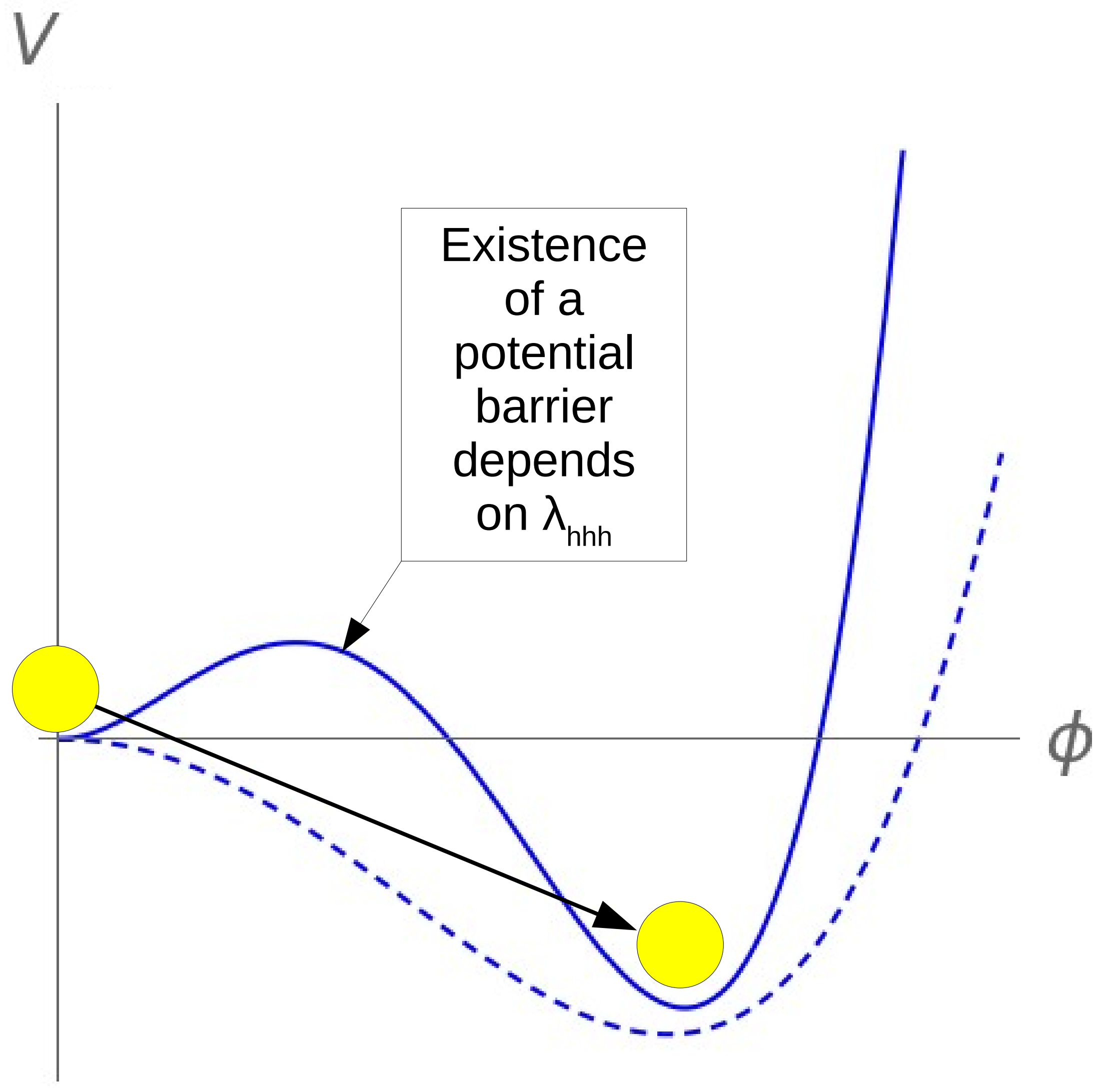
with $\kappa_\lambda \equiv \lambda_{hhh}/(\lambda^{(0)}_{hhh})^{\text{SM}}$ and $\kappa_4 \equiv \lambda_{hhhh}/(\lambda^{(0)}_{hhhh})^{\text{SM}}$

Form of the Higgs potential and baryon asymmetry

- Brout-Englert-Higgs mechanism = **origin of electroweak symmetry breaking** ...
  … but very little known about the **Higgs potential** causing the phase transition

- Shape of the potential determined by **trilinear Higgs coupling λ_{hhh}**

- Among **Sakharov conditions** necessary to explain **baryon asymmetry via electroweak phase transition** (EWPT):
  - ***Strong first-order EWPT***
    → barrier in Higgs potential
    → typically significant deviation in λ_{hhh} from SM



Baryogenesis

- **Observed Baryon Asymmetry of the Universe (BAU)**

$$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6.1 \times 10^{-10}$$ [Planck ‘18]

n_b: baryon no. density
$n_{\bar{b}}$: antibaryon no. density
n_γ: photon no. density

- **Sakharov conditions** [Sakharov ‘67] for a theory to explain BAU:
  1) Baryon number violation
  2) C and CP violation
  3) Loss of thermal equilibrium

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  2) C and CP violation
  3) Loss of thermal equilibrium

In the SM

→ Sphaleron transitions (break B+L)
→ C violation (SM is chiral), but not enough CP violation
→ No loss of th. eq. → in SM, the EWPT is a crossover

SM phase diagram

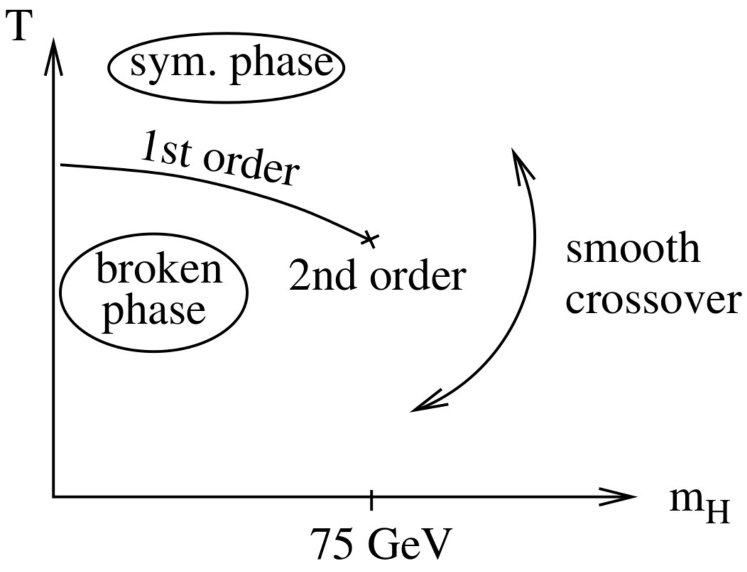


Figure from [Cline '06]

- SM cannot reproduce the BAU → **BSM physics needed!**

Electroweak Baryogenesis

- Many scenarios proposed, including:
  - Grand Unified Theories
  - Leptogenesis
  - **Electroweak Baryogenesis** (EWBG) [Kuzmin, Rubakov, Shaposhnikov, '85], [Cohen, Kaplan, Nelson '93]

- **Sakharov conditions** in EWBG

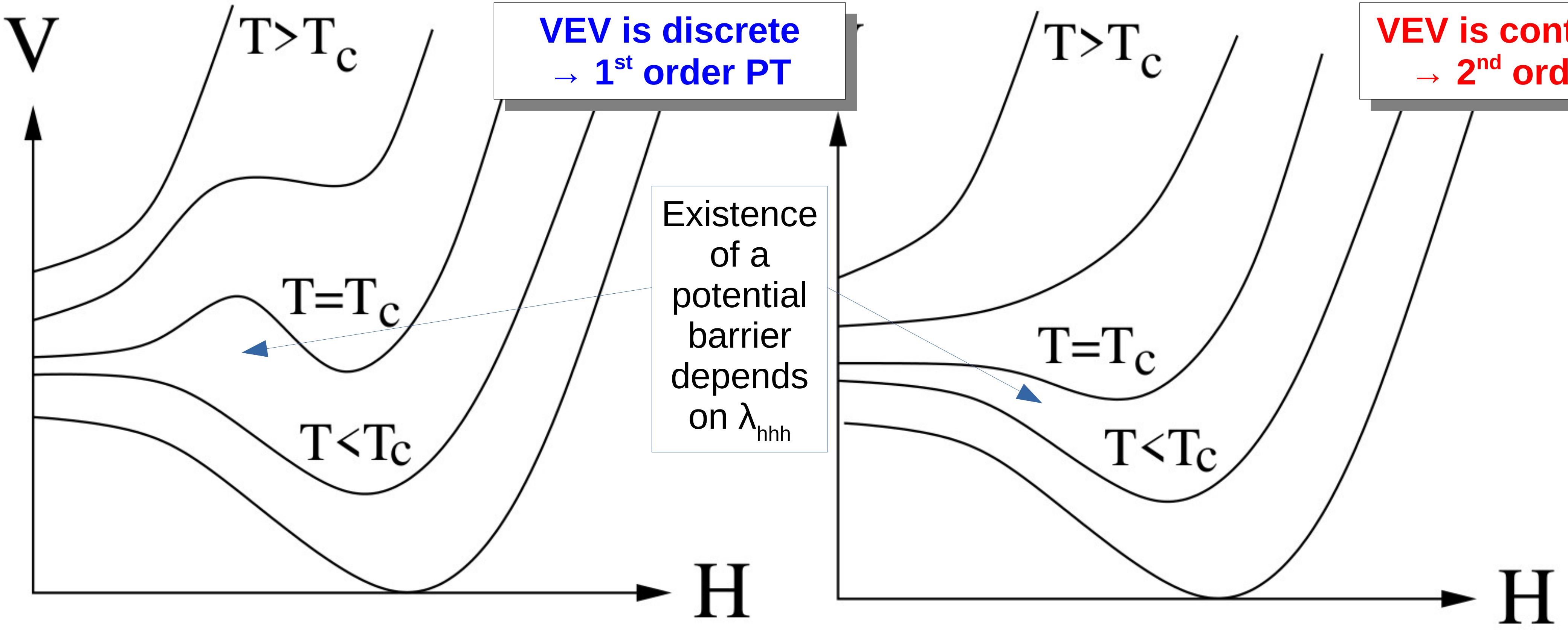
1) Baryon number violation → Sphaleron transitions (break B+L)

2) C and CP violation → C violation + CP violation in extended Higgs sector

3) Loss of thermal equilibrium → Loss of th. eq. via a strong 1st order EWPT

The Higgs potential and the Electroweak Phase Transition

Possible thermal history of the Higgs potential:



VEV is discrete → 1st order PT

VEV is continuous → 2nd order PT

Existence of a potential barrier depends on λ_{hhh}

Figure from [Cline '06]

- **λ_{hhh} determines the nature of the EWPT!**

  ⇒ deviation of λ_{hhh} from its SM prediction typically needed to have a strongly first-order EWPT [Grojean, Servant, Wells '04], [Kanemura, Okada, Senaha '04]

Electroweak Baryogenesis – a brief sketch

- **Sakharov conditions** in EWBG
  1) Baryon number violation → Sphaleron transitions (break B+L)
  2) C and CP violation → C violation + CP violation in extended Higgs sector
  3) Loss of thermal equilibrium → Loss of th. eq. via a strong 1st order EWPT

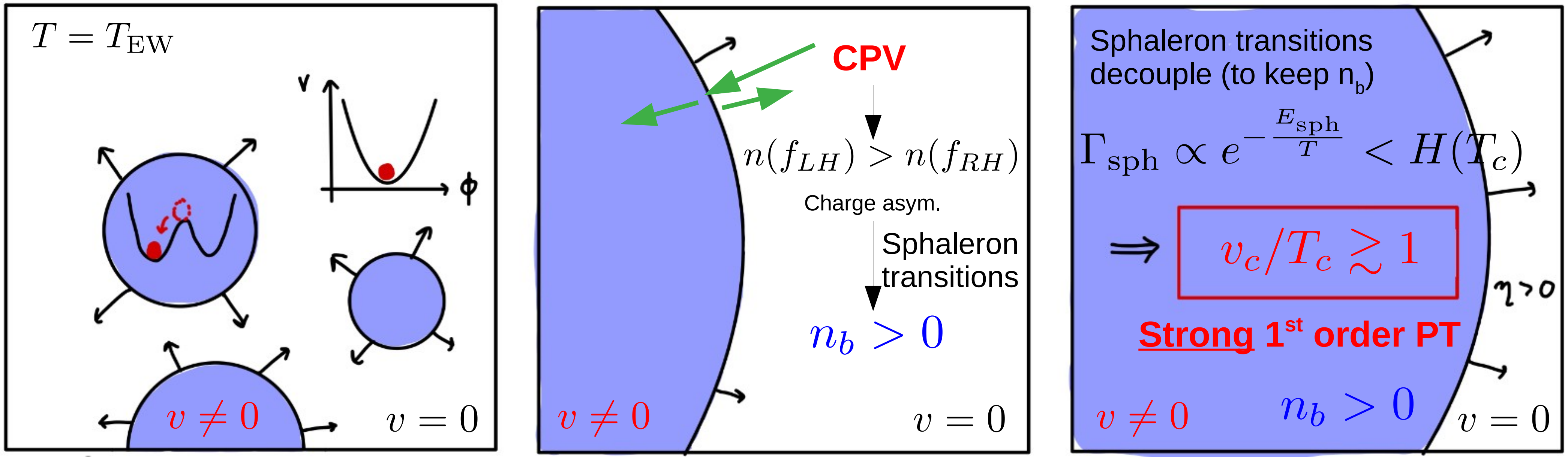
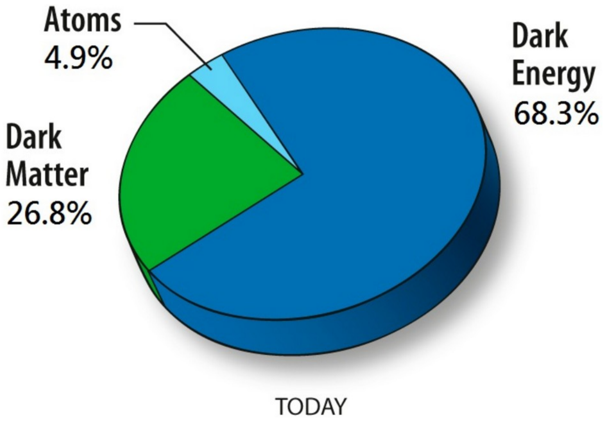


Figure adapted from [Biermann '22]

1) Bubble nucleation *2) Baryon number generation* *3) Baryon number conservation*

- EWBG only involves phenomena around the EW scale → **testable in the foreseeable future** via **λ_{hhh}**, collider searches, gravitational waves or primordial black holes (sourced by 1st order EWPT)

Higgs portal to dark sectors



- **Dark matter (DM)**
  - Non-relativistic matter (→ can't be neutrinos)
  - Only/mostly gravitational interactions → several types of astrophysical evidence (e.g. galaxy rotation curves, etc.)
  - Collisionless (c.f. Bullet cluster) & pressureless
  - Needed to seed large-structure formation

  → **No SM particle can fit this!**

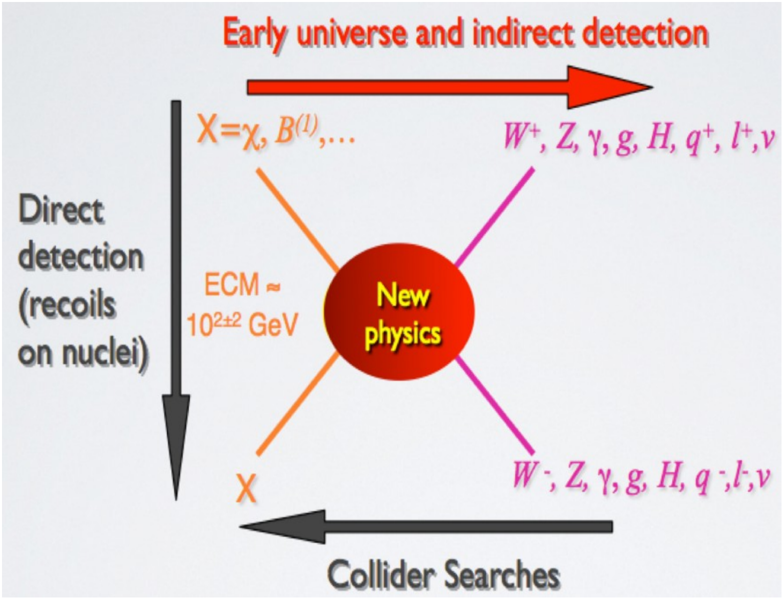
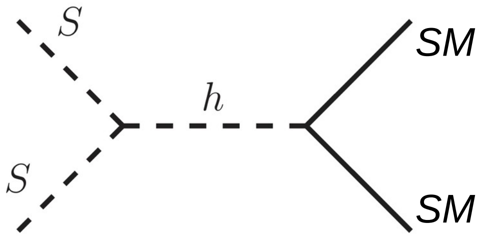


Figure from [Belanger '24]

- $|\Phi|^2$ is a gauge singlet → Higgs field provides a perfect way to write a **portal term** in the Lagrangian,
  e.g. simplest example = add to SM a singlet S, charged under a global Z_2 symmetry to stabilise DM

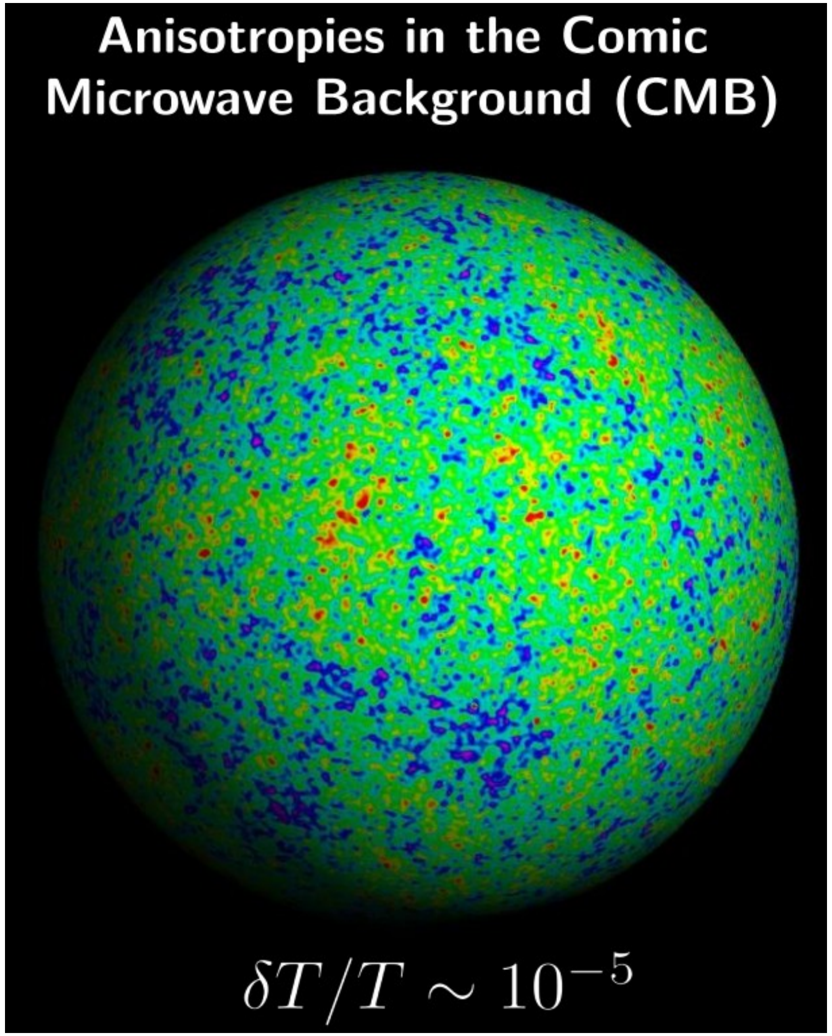
$$\mathcal{L}_{\mathbb{Z}_2\mathrm{SSM}} = \mathcal{L}_{\mathrm{SM}} - \lambda_{\mathrm{portal}} S^2|\Phi|^2 - \lambda_{\mathrm{dark}} S^4$$

$\lambda_{\mathrm{portal}}$: *controls DM relic density & detection*



- Plethora of models: inert singlets, doublets, triplets; Next-to-Two-Higgs-Doublet Model (N2HDM), S2HDM, etc.

Cosmic inflation



[Planck '18]

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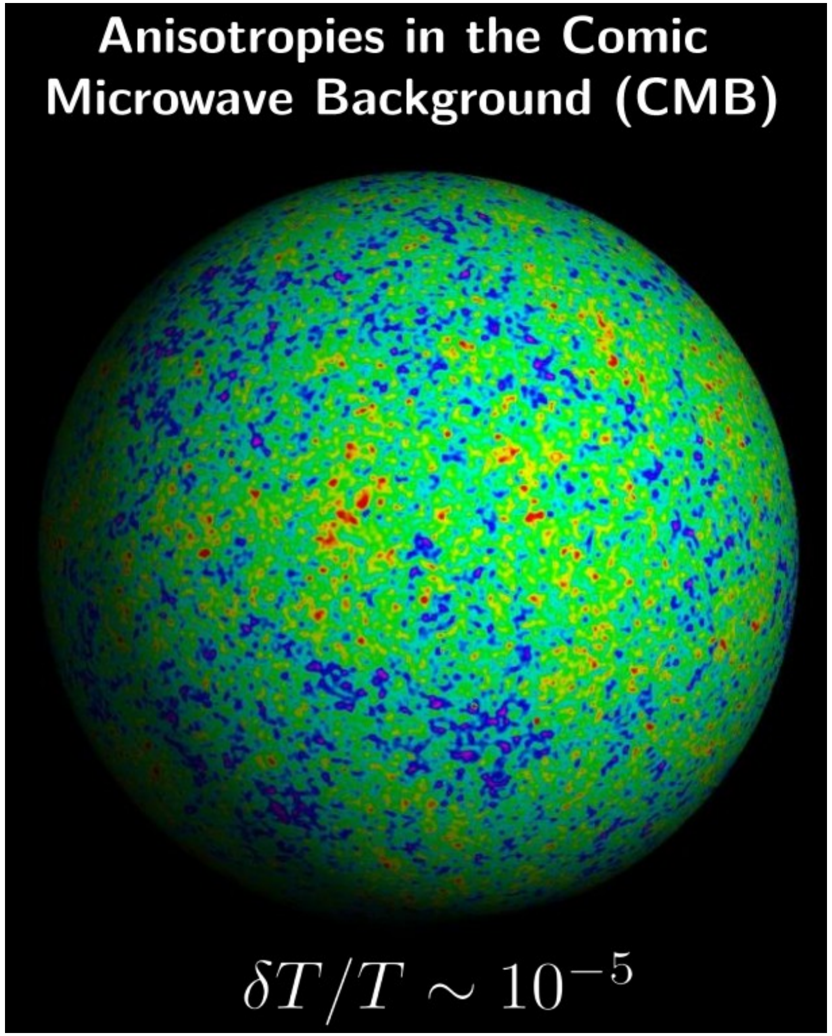

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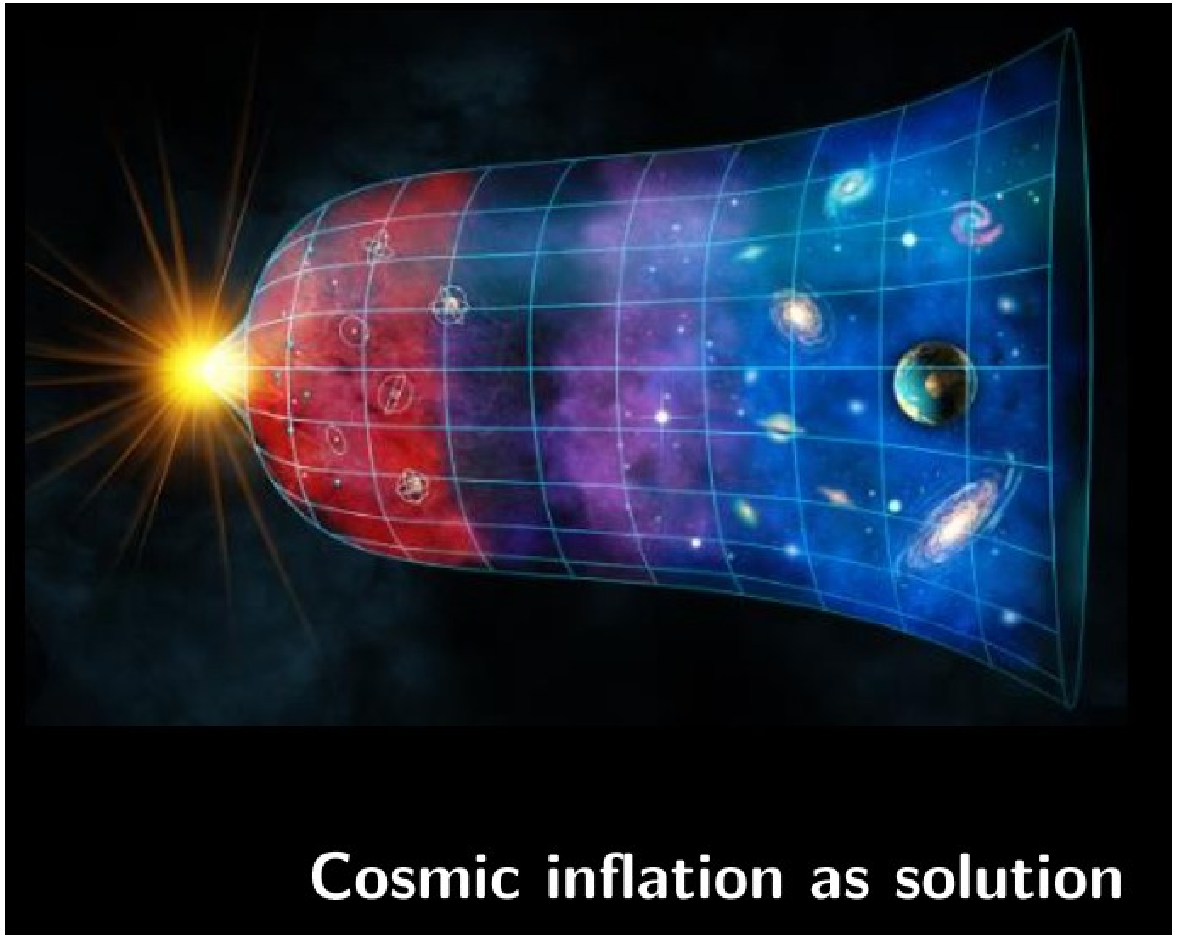


Figures adapted from [Pierre '23]

The Higgs boson as the inflaton

- Phase of exponential growth driven by scalar field – **inflaton** – with very flat potential → **slow-roll inflation**

- What if the Higgs boson plays the role of the inflaton? [Bezrukov, Shaposhnikov '07]
  → **Higgs inflation**
  → Higgs coupled **<u>non-minimally</u> to gravity**

Ricci scalar

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2}M_{\rm Pl}^2 R - \xi|\Phi|^2 R$$

(in Jordan frame)

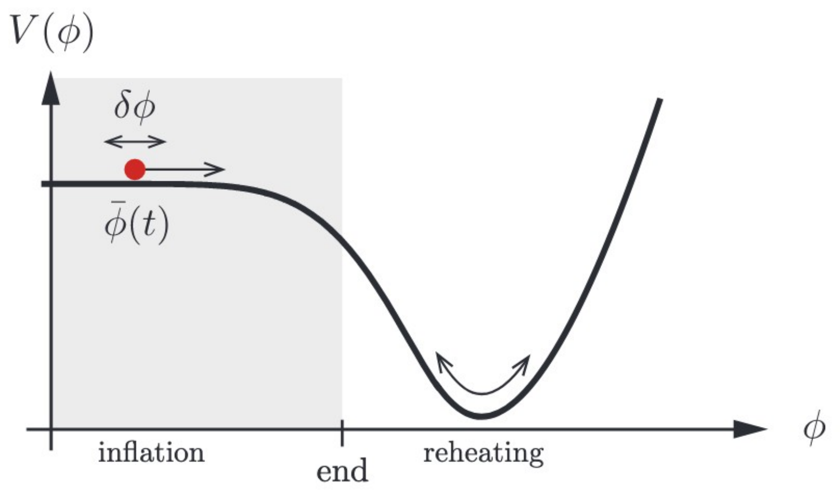
- Change from *Jordan frame* (in which Lagrangian is written) to *Einstein frame* (with canonical coupling to gravity)

$$g^E_{\mu\nu} = \Omega^2(h) g^J_{\mu\nu}, \qquad \text{with } \Omega^2(h) = 1 + \frac{\xi h^2}{M_{\rm Pl}^2}$$

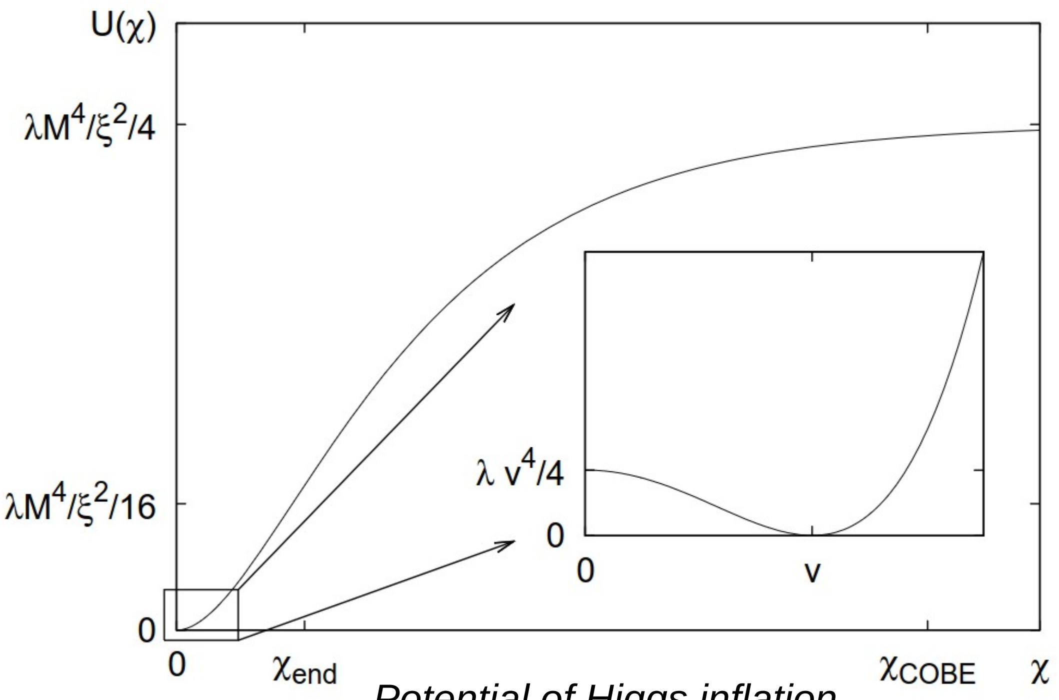
$$\Rightarrow \mathcal{L}^E \supset -\frac{1}{2}M_{\rm Pl}^2 R^E + \frac{1}{2}(\partial_\mu\chi)^2 - \underbrace{\frac{\lambda}{4\Omega^4(h(\chi))}\left(h(\chi)^2 - v^2\right)^2}_{\equiv U(\chi)}$$

χ: Higgs field in Einstein frame

- Numerous developments (non-minimal Higgs sectors, different couplings, etc.)



Usual picture of slow-roll inflation



Potential of Higgs inflation (in Einstein frame)

Figure adapted from [Bezrukov, Shaposhnikov '07]

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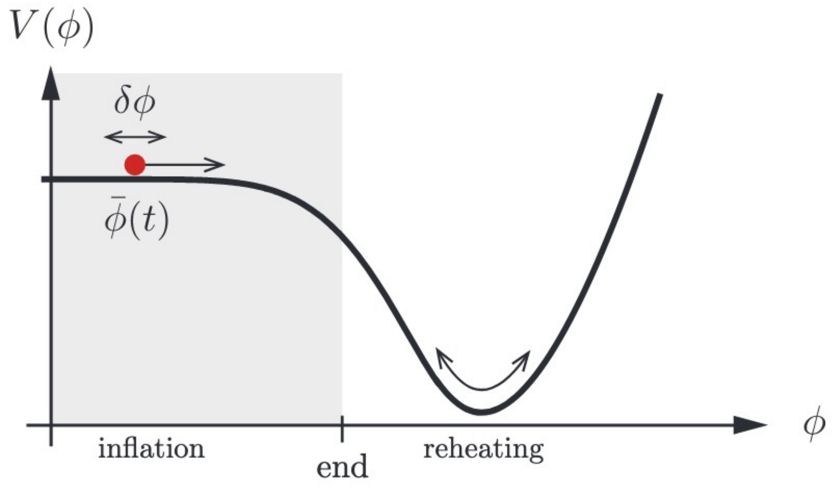

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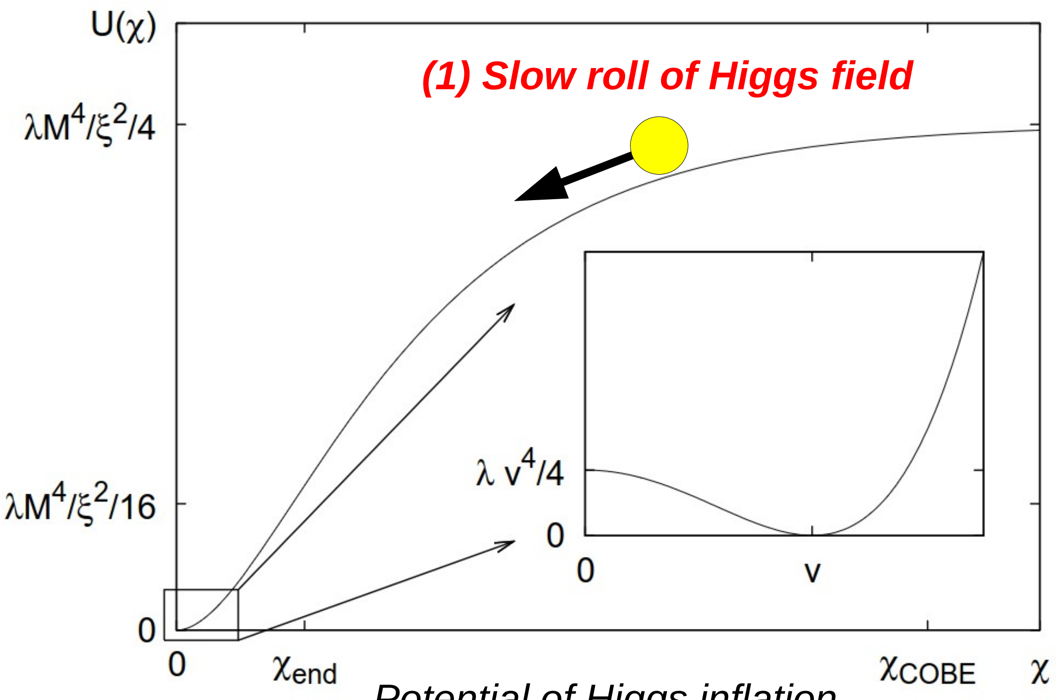

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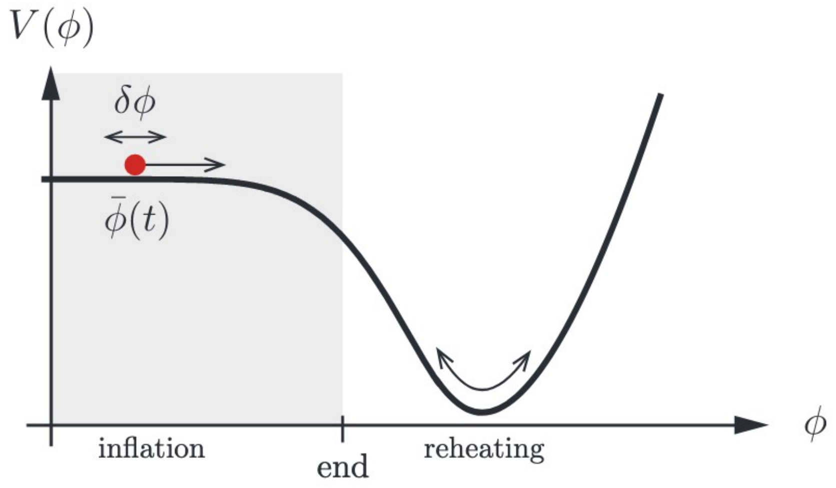

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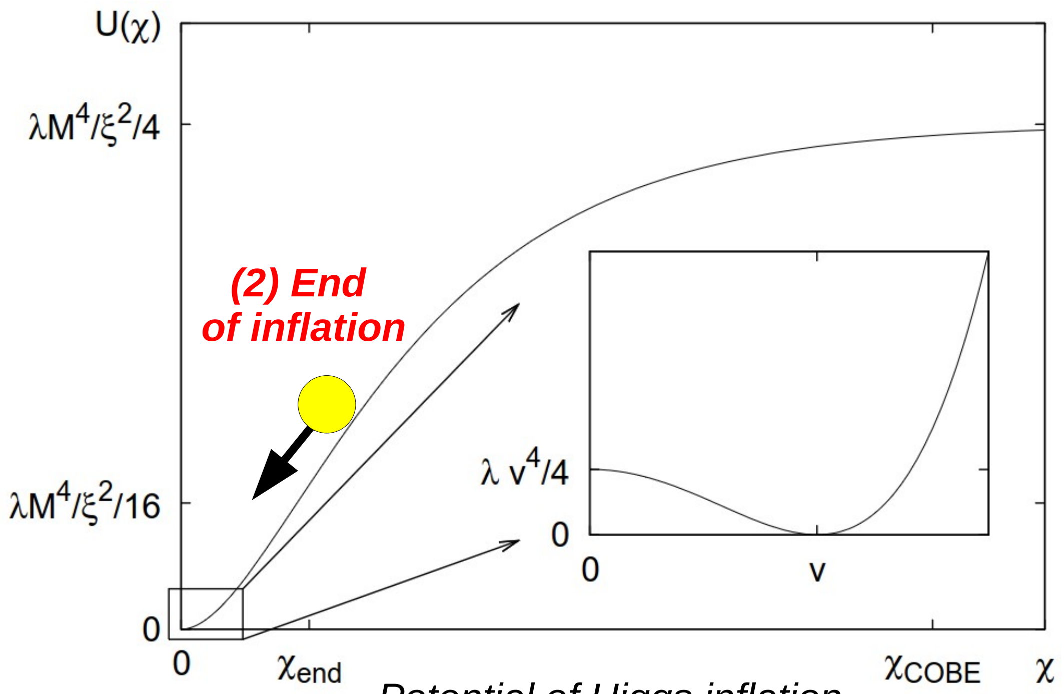

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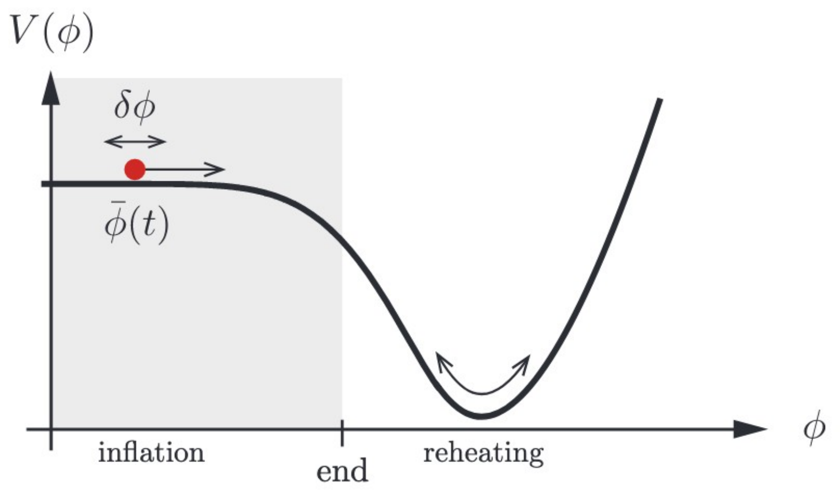

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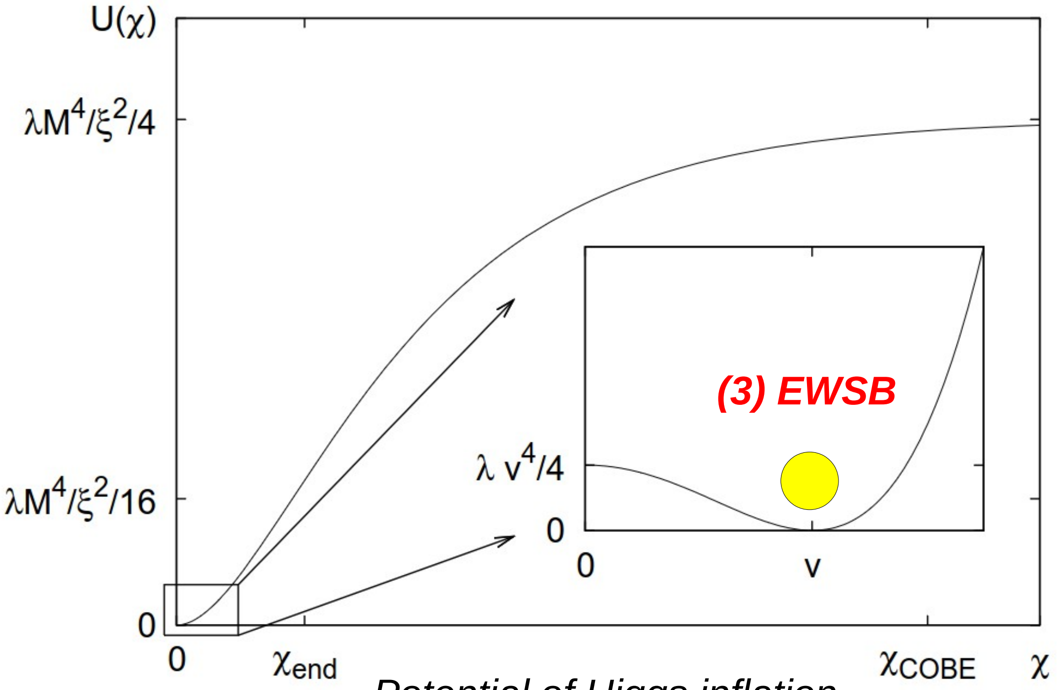


Potential of Higgs inflation (in Einstein frame)

Figure adapted from [Bezrukov, Shaposhnikov '07]

Neutrino masses and Higgs boson(s)

- SM contains **no right-handed neutrinos** → no neutrino masses
- However, since 1960's early signs of neutrino oscillations ("*solar neutrino deficit*"), eventually confirmed ~25 years ago
  → atmospheric neutrino oscillations in 1998
  → solar neutrino oscillations in 2001
  → 2015 Nobel Prize for Kajita and McDonald
  → **neutrinos do have masses** → **extension of SM needed!**

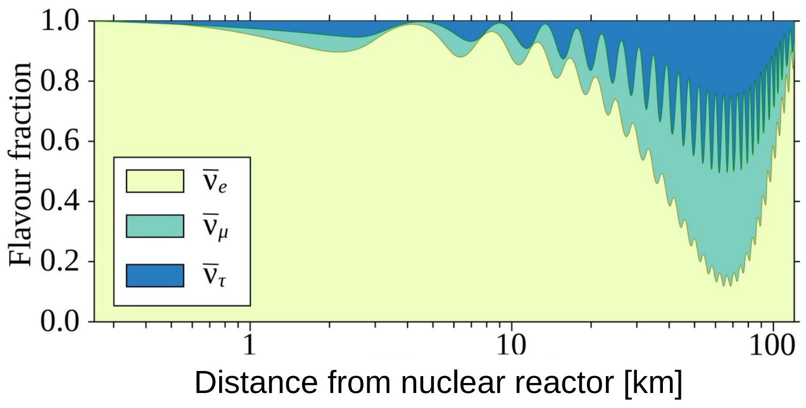


Figure from [Vogel, Wen, Zhang '15]

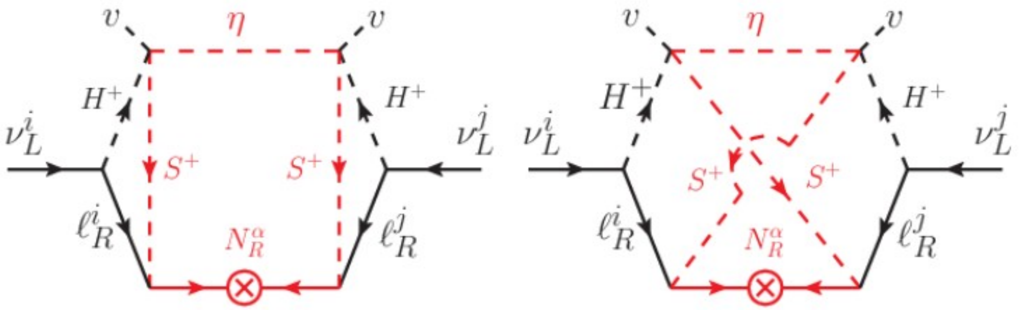
- Most common solutions rely on variants of **seesaw mechanism** (types I, II, III)
  → basic idea (type I): introduce, heavy, right-handed Majorana neutrinos (RHN) N_R

$$\mathcal{L}_{1-fam.} \supset \left(\overline{\nu_L}\ \overline{N_R^c}\right) \begin{pmatrix} 0 & y_\nu v/\sqrt{2} \\ y_\nu v/\sqrt{2} & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$ with $M_R \ggg v$

$$\Rightarrow m_{\nu_L} \sim \frac{y_\nu^2 v^2}{M_R}$$

However, this usually introduces a new hierarchy problem + is difficult to test experimentally

- Other possibility: **generate tiny neutrino masses via radiative effects from extended scalar sectors**
  → [Zee '80], [Babu '88], [Aoki, Kanemura, Seto '08], etc.
  → no longer need for very heavy RHN



*An example of radiative neutrino mass generation: the **Aoki-Kanemura-Seto model***
Figure from [Aoki, Enomoto, Kanemura '22]

Thank you very much for your attention!

Contact

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