Emergent Gauge Symmetries in Particle Physics and Cosmology

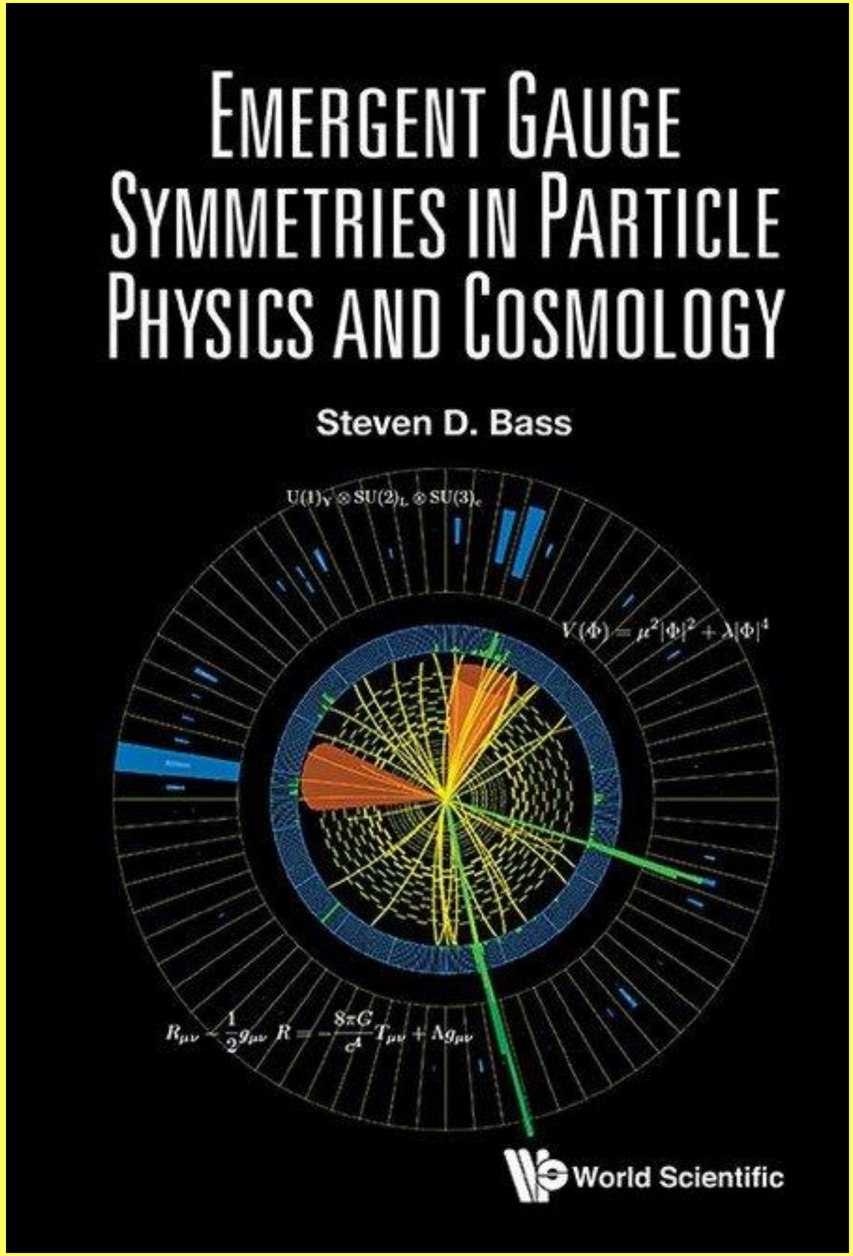
Steven Bass

- The Standard Model works very well at LHC and in precision measurements, much better than many expected.
- Mathematically consistent up to Planck scale, Physicswise....?
- Open puzzles with neutrinos, baryogenesis, dark matter, dark energy...
- New particles and/or new principles? How special is the Standard Model?

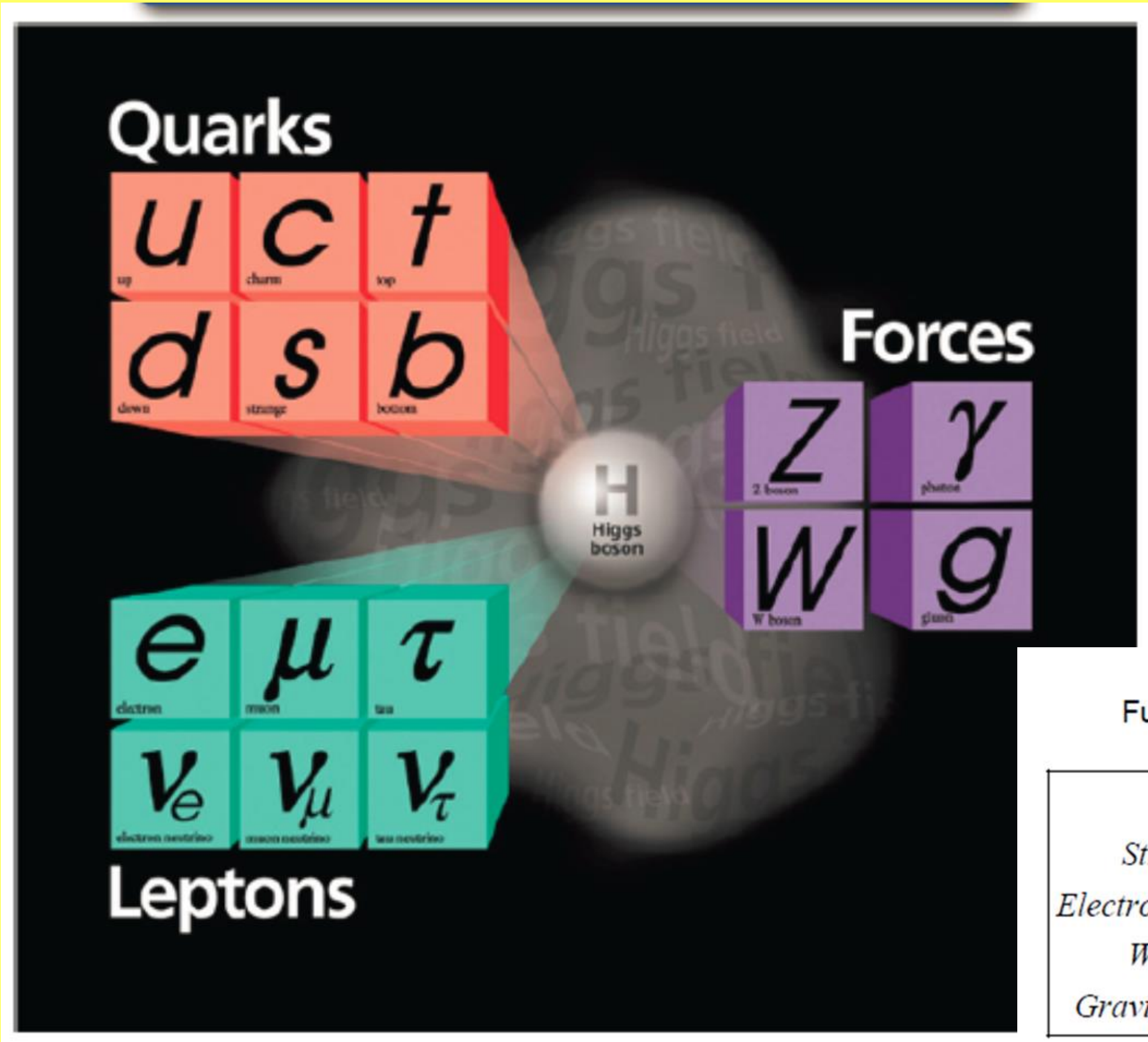
- Idea of an emergent Standard Model
  - Gauge symmetries „dissolving„ in extreme ultraviolet at ~ 10^{16} GeV .
- Scale hierarchies in particle physics
  - Cosmological constant scale ~ m_ν ≪ Higgs mass ≪ Planck mass

Cracow School of Theoretical Physics, June 15-20, 2025

New WSPC book



Quarks, leptons and gauge bosons



Fundamental Interactions

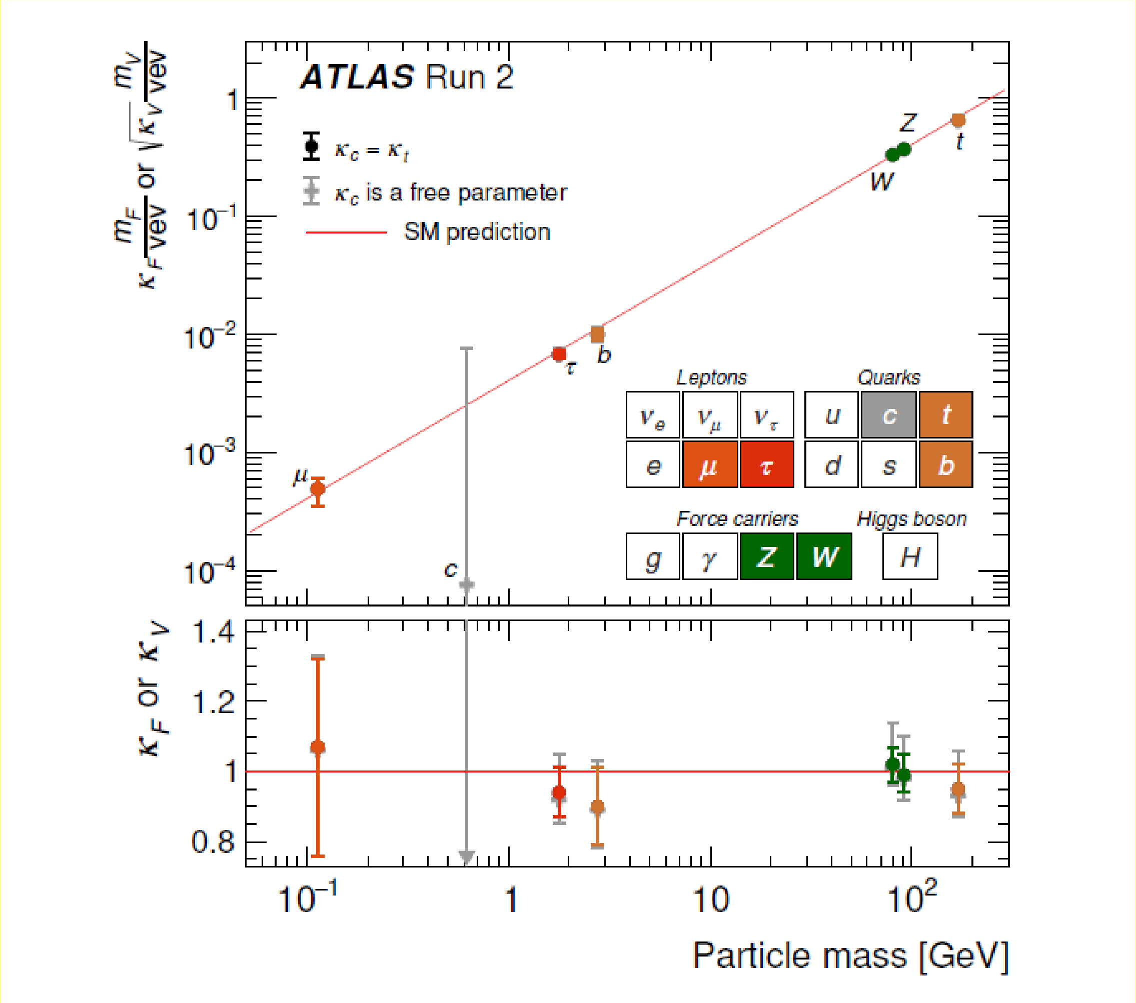
	Strength
Strong	$\alpha_s = \frac{g_s^2}{4\pi\hbar c} \sim 1^{\dagger}$
Electromagnetic	$\alpha_{em} = \frac{e^2}{4\pi\hbar c} \sim \frac{1}{137}$
Weak	$G_F m_p^2 \sim 10^{-5\dagger}$
Gravitational	$G_N m_p^2 \sim 10^{-36}$

Standard Model working very well

- Higgs discovery at CERN
  - Very SM like
  - Higgs self coupling an issue for future measurements

$$\frac{1}{\sqrt{2}}G_F = \frac{g^2}{8m_W^2}.$$

$$\lambda = \frac{m_h^2}{2v^2} = 0.13.$$

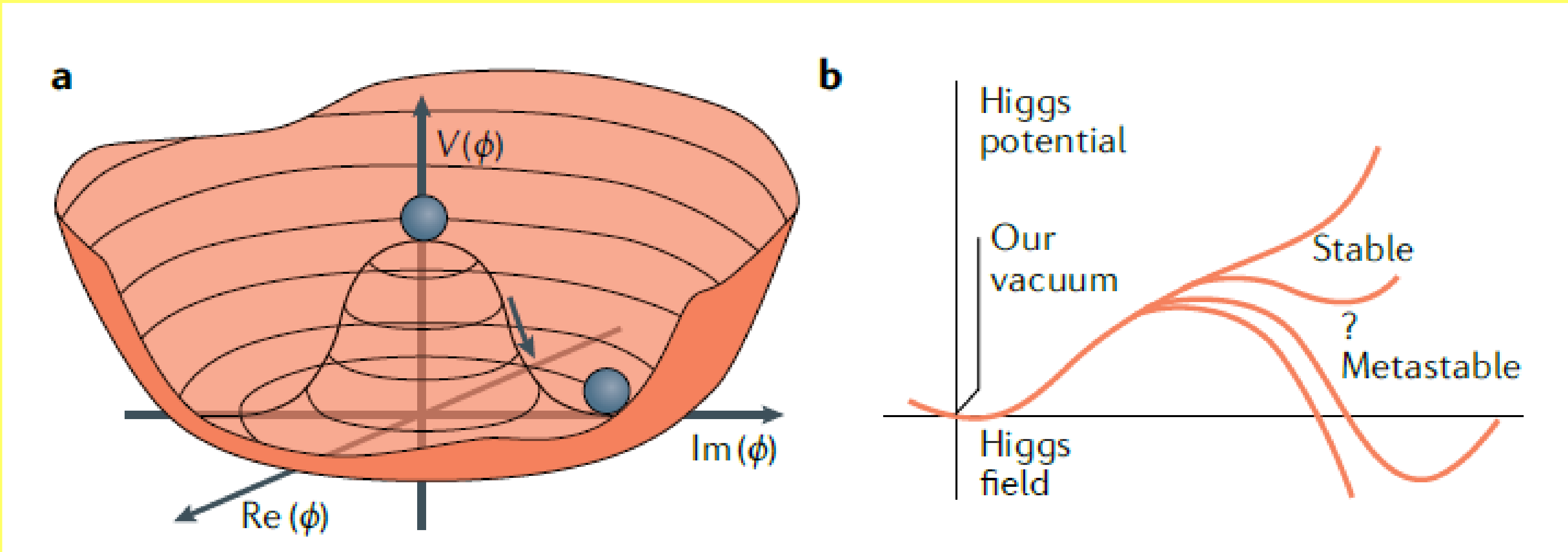


$$m_W^2 = \frac{1}{4}g^2v^2, \quad m_Z^2 = \frac{1}{4}(g^2 + g'^2)v^2$$

$$m_f = y_f\frac{v}{\sqrt{2}} \qquad (f = \text{quarks and charged leptons})$$

Higgs Potential

- The SM Higgs comes with good UV behaviour



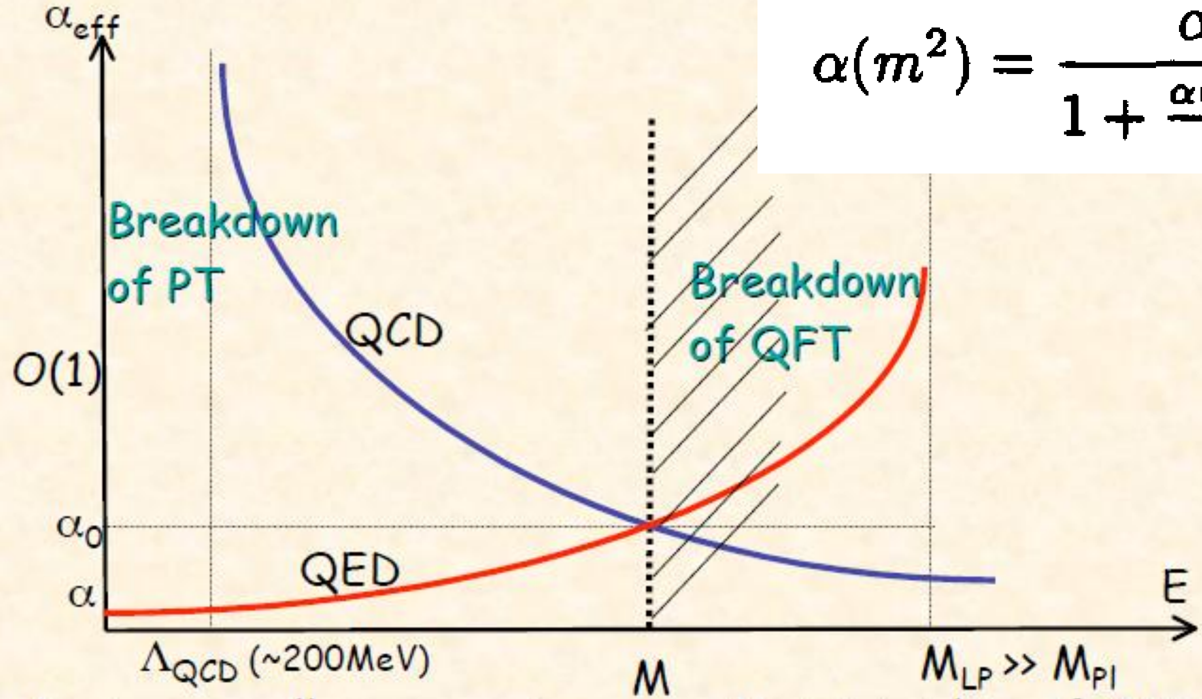
  - Brout-Englert-Higgs mechanism preserves gauge invariance with massive W and Z gauge bosons
  - Renormalizable
  - Perturbative Unitarity with measured Higgs mass
  - Vacuum Stability

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

Running couplings in particle physics

The situation for QED and QCD can be summarized in a graph

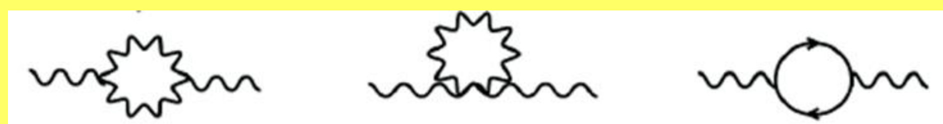
$$\alpha(m^2) = \frac{\alpha(\lambda^2)}{1 + \frac{\alpha(\lambda^2)}{3\pi} \ln \frac{\lambda^2}{m^2}} .$$



If we keep α_0 small we cannot remove M => triviality of QED

If we work at $q^2 \gg \Lambda_{QCD}^2$ we may hope to use PT for QCD (AF)

$$\alpha_s(Q^2) = \frac{g^2}{4\pi} = \frac{12\pi}{(33 - 2f)\ln(\frac{Q^2}{\Lambda^2_{\rm qcd}})}$$

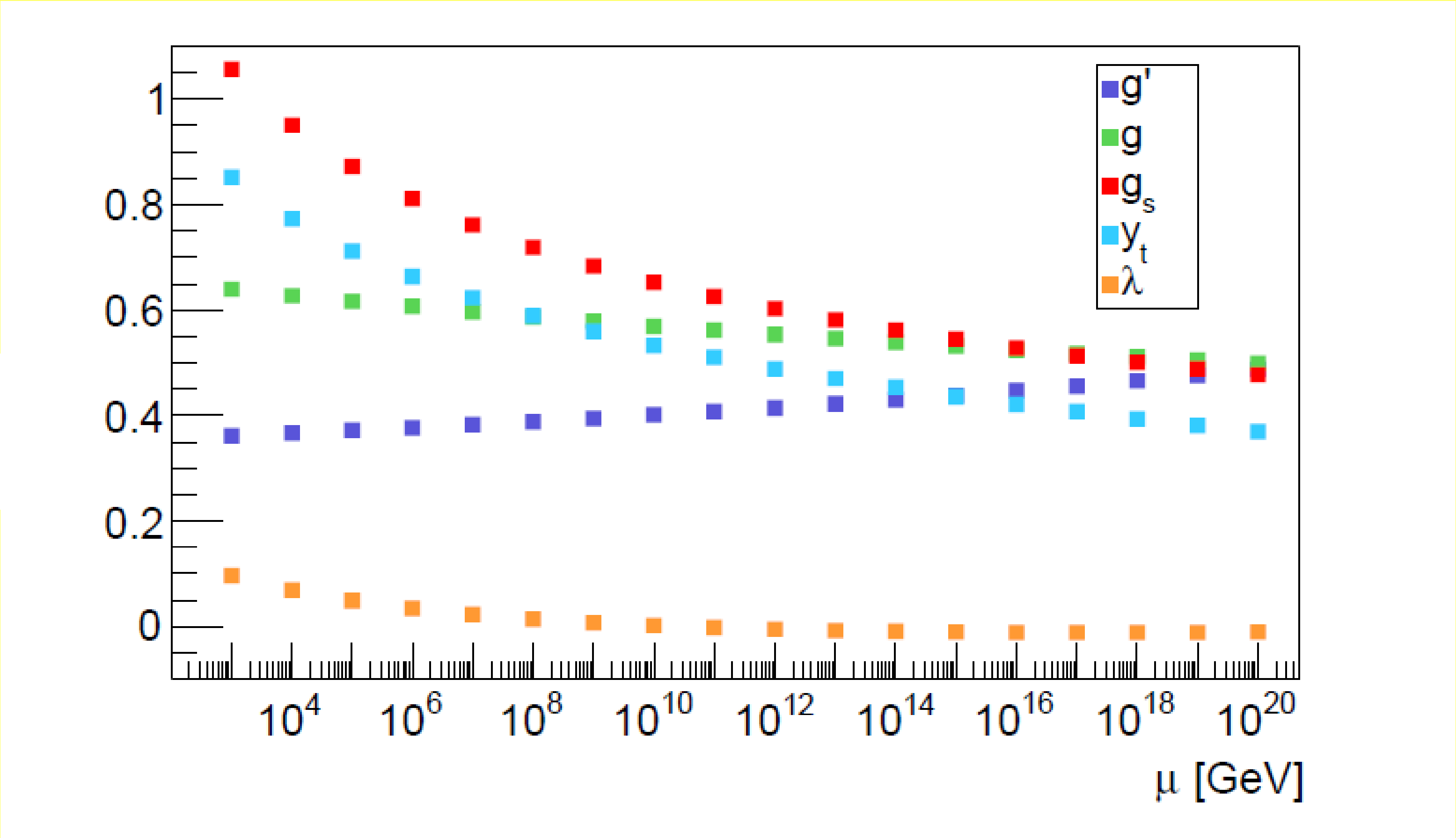


Running couplings

- Running Standard Model parameters [C++ code of Kniehl et al, 2016]

$$V(\phi) = \mu^2 \phi\phi^* + \lambda(\phi\phi^*)^2$$

$$\lambda = \frac{m_h^2}{2v^2} = 0.13.$$

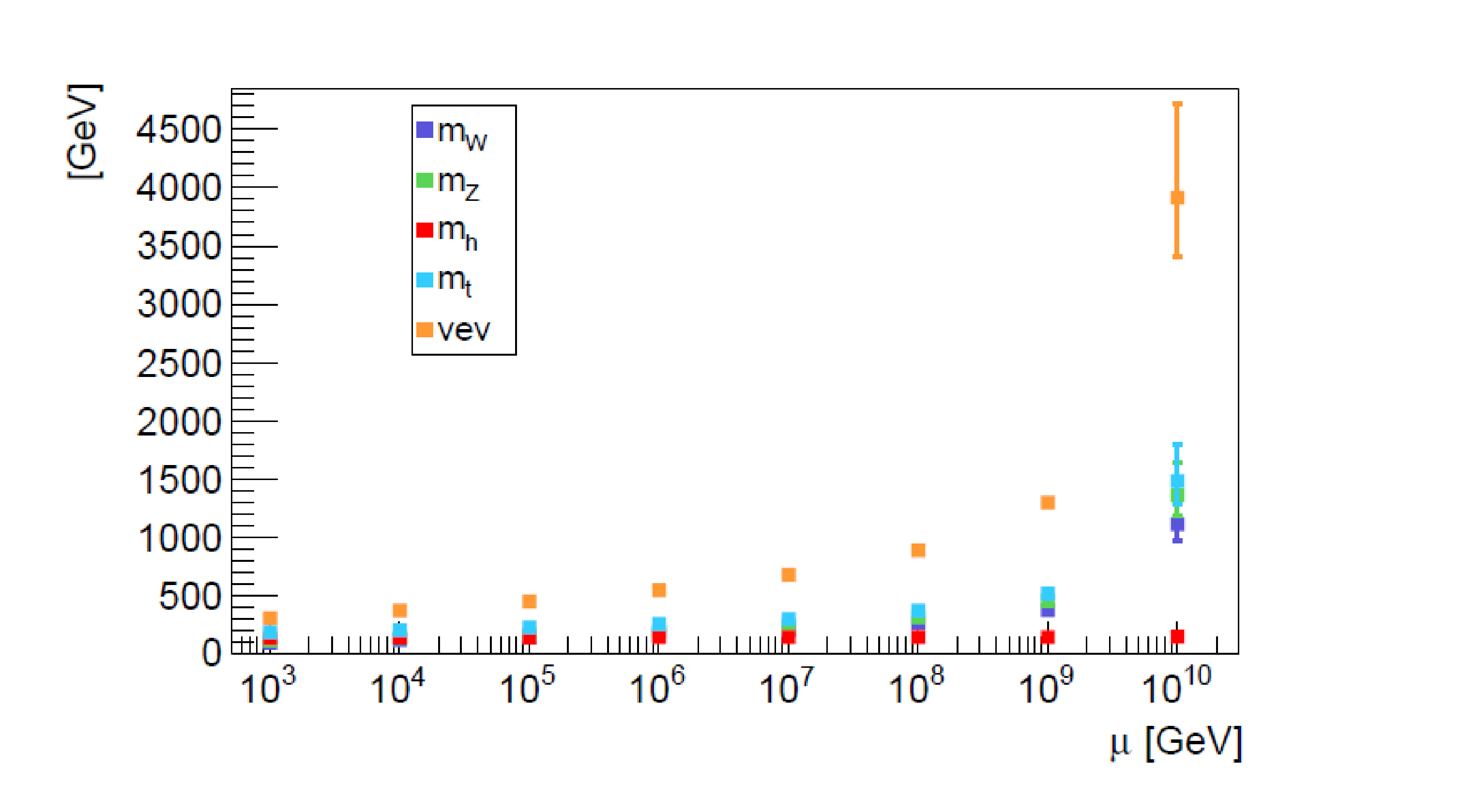


$$m_W^2 = \frac{1}{4} g^2 v^2, \quad m_Z^2 = \frac{1}{4}(g^2 + g'^2) v^2$$

$$m_f = y_f \frac{v}{\sqrt{2}} \qquad (f = \text{quarks and charged leptons})$$

Running masses and Higgs vev

- Running Standard Model parameters [C++ code of Kniehl et al, 2016]
  - Running W, Z, top and Higgs masses and Higgs vev



$$m_h^2 = 2\lambda v^2$$

$$m_W^2 = \frac{1}{4}g^2v^2, \quad m_Z^2 = \frac{1}{4}(g^2 + g'^2)v^2$$

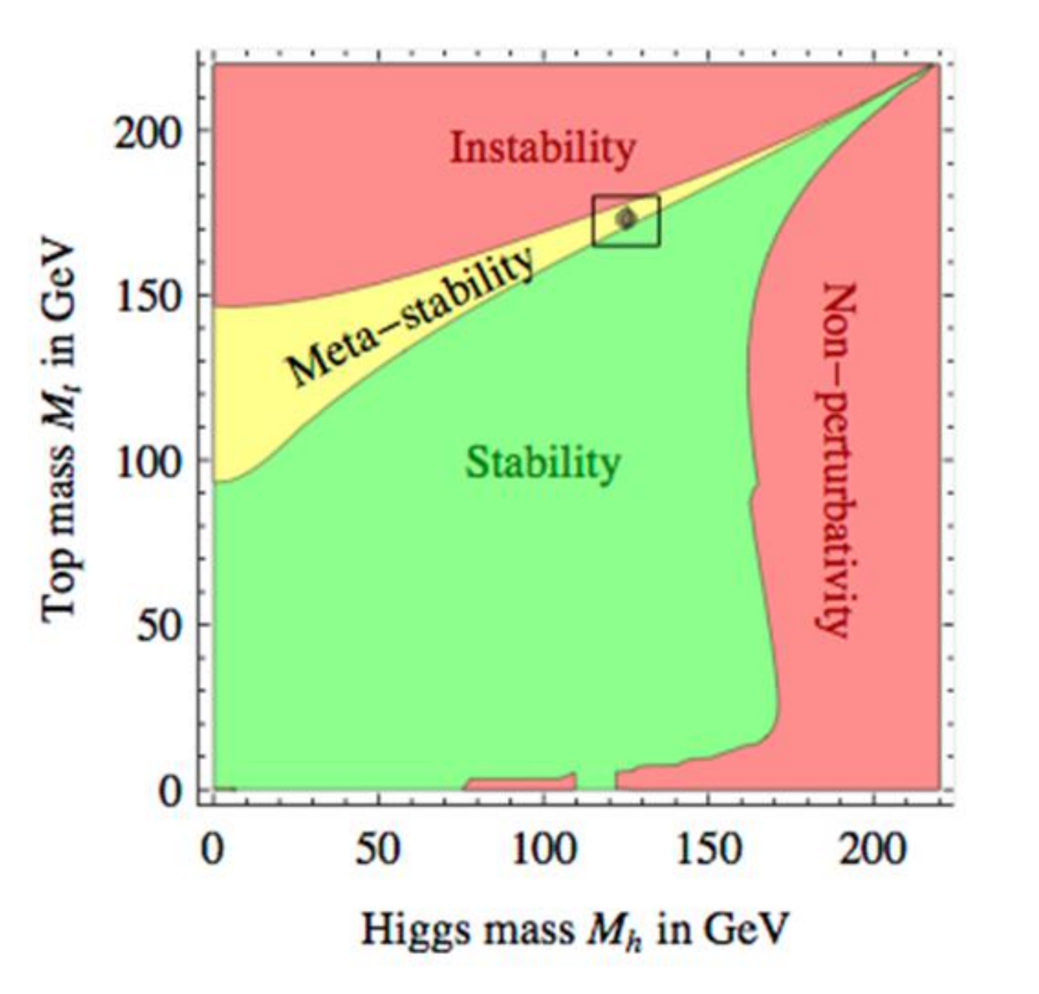
$$m_f = y_f \frac{v}{\sqrt{2}} \qquad (f = \text{quarks and charged leptons})$$

Results from LHC: Critical physics in UV ?

- LHC: So far just Standard Model Higgs and no new particles

- Running couplings/masses.
- Remarkable: the Higgs and top mass sit in window of possible parameter space where the SM is a consistent theory up to the Planck scale wth vacuum close to the border of a stable and meta-stable.

- Possible critical phenomena in the extreme ultraviolet.
- Implicit reduction in the number of fundamental couplings.

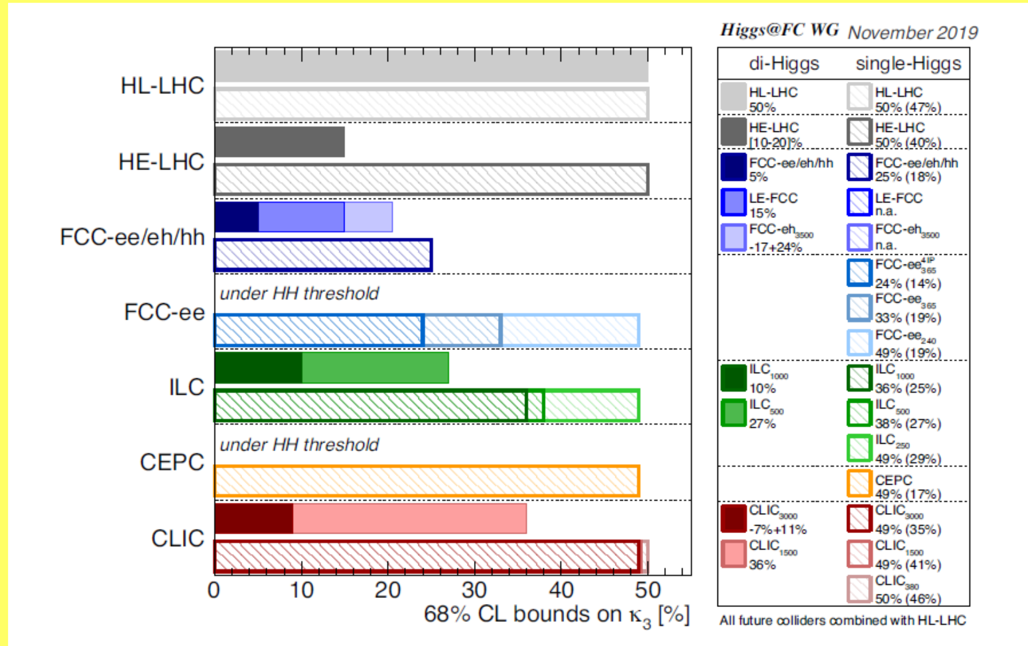


$$V(\phi) = \mu^2 \phi\phi^* + \lambda(\phi\phi^*)^2$$

Higgs self-coupling perspectives

- Higgs self-coupling λ challenging to measure!

collider	di-Higgs (1) excl.	di-Higgs (2.a) glob.	single-Higgs (3) excl. with HL-LHC	single-Higgs (3) excl. w/o HL-LHC	single-Higgs (4) glob.
HL-LHC	$^{+60}_{-50}$% (50%)	52%	47%	–	50%
HE-LHC	10-20% (n.a.)	n.a.	40%	80%	50%
ILC_{250}	–	–	29%	37%	49%
ILC_{350}	–	–	28%	37%	46%
ILC_{500}	27% (27%)	27%	27%	32%	38%
ILC_{1000}	10% (n.a.)	10%	25%	30%	36%
$CLIC_{380}$	–	–	46%	120%	50%
$CLIC_{1500}$	36% (36%)	36%	41%	78%	49%
$CLIC_{3000}$	$^{+11}_{-7}$% (n.a.)	n.a.	35%	63%	49%
FCC-ee_{240}	–	–	19%	21%	49%
FCC-ee_{365}	–	–	19%	21%	33%
FCC-ee_{365}^{4IP}	–	–	14%	14%	24%
FCC-eh	17-24% (n.a.)	n.a.	n.a.	n.a.	n.a.
FCC-ee/eh/hh	5% (5%)	6%	18%	19%	25%
LE-FCC	15% (n.a)	n.a	n.a.	n.a.	n.a.
CEPC	–	–	17%	18%	49%



[de Blas et al, JHEP 2020]

- Standard Model prediction

$$\lambda = \frac{m_h^2}{2v^2} = 0.13.$$

Open puzzles

- SM is mathematically self consistent but is is physics-wise and where does it come from?
- Neutrinos
  - Tiny masses, CP violation, Dirac or Majorana
- Baryogenesis
  - Matter-antimatter asymmetry in the Universe
- Fermion families
  - Why are there 3?
- Dark Matter – 27% of energy budget
  - Suggested by galaxy properties, CMB, gravitational lensing
- Dark Energy/Cosmological Constant – 68% of energy budget
  - Accelerating expansion of the Universe
- Hierarchies of scales, μ_{CC} << Higgs mass << Planck scale
- Primordial inflation: Suggested by flatness, isotropy, homogeneity, absence of magnetic monopoles...

Emergent Symmetries and Particle Physics

- Are (gauge) symmetries always present ?

  (Gauge symmetries determine our particle interactions)

  Making symmetry as well as breaking it

- Emergence: Many body system exhibits collective behaviour in the IR which is qualitatively different from that of its more primordial constituents as probed in the UV.
  - » *Can give extra symmetry in the IR, absent in the UV.*
  - Gauge symmetries dissolving in the UV instead of extra unification
- Standard Model as long range tail of critical system which sits close to Planck scale [Jegerlehner, Bjorken, Nielsen ...].
- Examples in quantum many-body physics: Fermi-Hubbard, Superfluid ^{3}He-A

Emergent symmetries

- Analogy:

  Imagine an Ant crawling on a carpet. From afar the carpet looks flat and translationally invariant. Up close, e.g. as perceved by the ant, the carpet develops structure with hills and bumps.

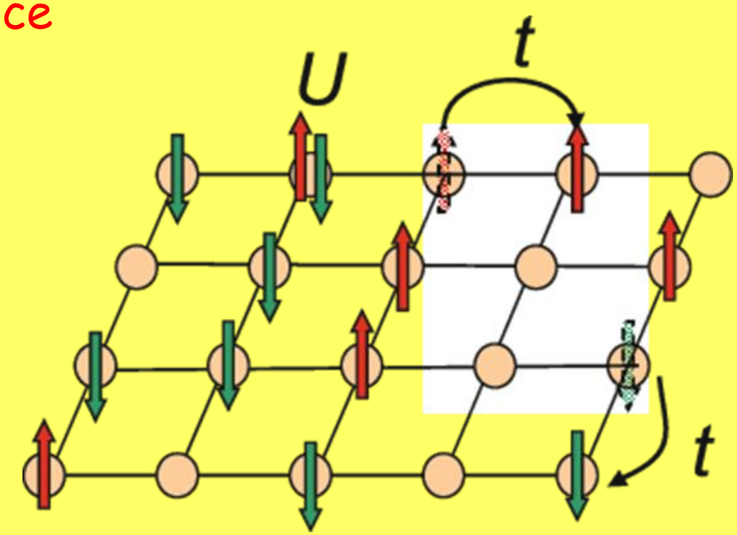
  The translational invariant symmetry is perceived in the infrared, but dissolves up close in the ultraviolet when one looks closely at it.

  Also classical physics emerging from quantum physics.

Example: Fermi-Hubbard Model

- Strongly correlated electron system on 2D lattice

$$\mathcal{H} = -t \sum_{(ij)\sigma} c^\dagger_{i\sigma} c_{j\sigma} + U \sum_i c^\dagger_{i\uparrow} c_{i\uparrow} c^\dagger_{i\downarrow} c_{i\downarrow}.$$

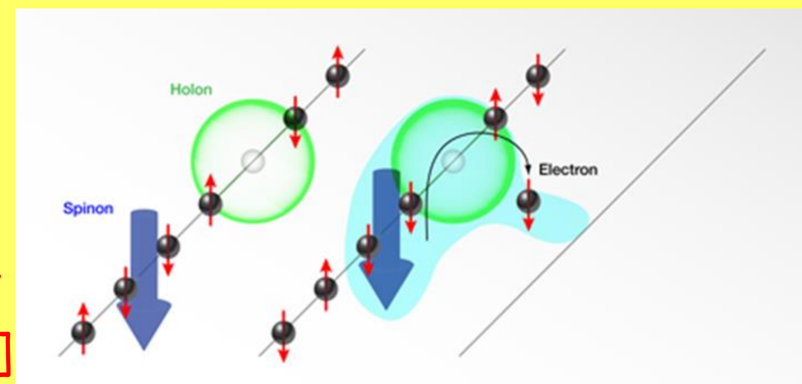


- Low energy limit at half filling, behaves like Heisenberg magnet

$$\mathcal{H}_{\text{eff}} = J \sum_{i,j} (c^\dagger_{i\alpha} \sigma_{\alpha\beta} c_{i\beta}).(c^\dagger_{j\alpha} \sigma_{\alpha\beta} c_{j\beta})$$

$$J = 4t^2/U$$

- Quasi-particles with spin-charge separation
- „Spinons" feel new local SU(2) gauge symmetry
  - [PW Anderson and collaborators, PRB 1988]

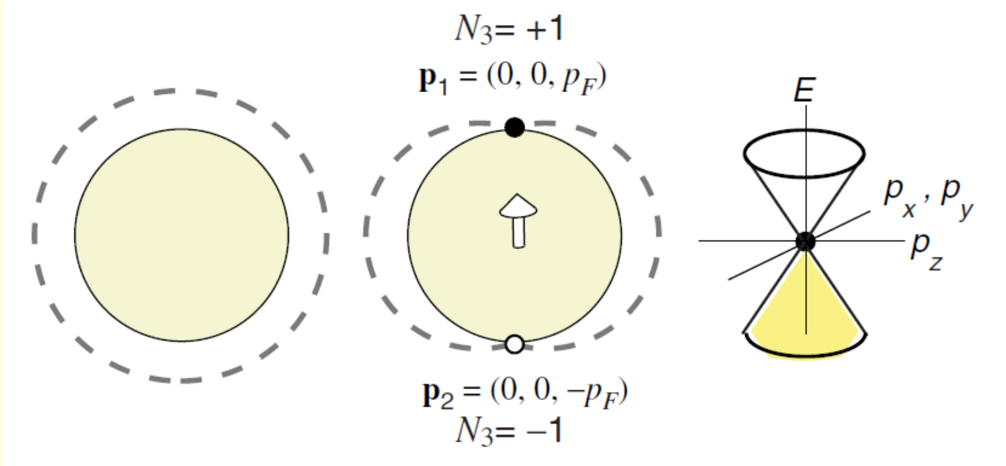


Superfluid ^{3}He-A with Fermi points

- Emergent gauge symmetries (SU(2) and U(1)) plus chiral fermions and limiting velocities. Spin dof becomes dynamical to an internal observer [Volovik].

$$E^2(p) = \left(\frac{p^2}{2m} - \mu\right)^2 + c_\perp^2 (\mathrm{p} \times \hat{\mathrm{l}})^2,$$

[Anderson+Morel, 1961]



- Gap with Fermi points at $\Delta(\vartheta) = p_F c_\perp \sin\vartheta$

- Green's function and topology in momentum space

$$\mathcal{G}^{-1}(p_0) = e_i{}^k \Gamma^i.(p_k - p_k^0) + \text{ higher order terms}$$

$$N_3 = \mathrm{tr}\mathcal{N}, \quad \mathcal{N} = \frac{1}{24\pi^2} \epsilon_{\mu\nu\lambda\gamma} \int_\sigma \mathrm{d}S^\gamma \, \mathcal{G}\partial_{p_\mu}\mathcal{G}^{-1}\mathcal{G}\partial_{p_\nu}\mathcal{G}^{-1}\mathcal{G}\partial_{p_\lambda}\mathcal{G}^{-1}$$

$$H = +c\sigma.p \to e_i{}^k \Gamma^i.(p_k - p_k^0)$$

$$E^2 \to g^{\mu\nu}(p_\mu - eA_\mu - e\tau.W_\mu)(p_\nu - eA_\nu - e\tau.W_\nu) = 0$$

Towards an emergent particle physics

- (Topological-like) phase transition ← new dof including gauge symmetries
  - E.g., Statistical system near critical point.
  - Long range tail is renormalised (finite) QFT

    [Wilson and Kogut, Peskin and Schroeder]
  - If contains (massless) J=1 excitations → gauge theory!

- Unitarity with massive J=1 bosons → Higgsed and Yang-Mills structure

- Small gauge groups most probably prefered

- Possible hint for emergence scenario
  - Vacuum Stability and perhaps new critical phenomena in the UV
  - SM parameters perhaps correlated with physics deep in the UV through vacuum stability.

An Emergent Standard Model

- Standard Model as an effective theory with infinite tower of higher dimensional operators, suppressed by powers of the (large) emergence scale M

- Global symmetries tightly constrained by gauge invariance and renormalisability when restricted to dimension 4 operators, e.g. QED

$$\mathcal{L} = \bar{\psi} i \gamma^{\mu} D_{\mu} \psi - m \bar{\psi} \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

- Can be broken in higher dimensional operators, suppressed by powers of M

- Examples, lepton and baryon number violation, Weinberg, PRL 1979
- E.g. Lepton number violation ← Majorana neutrino masses at mass dimension 5 (Weinberg)

$$O_5 = \frac{(\Phi L)_i^T \lambda_{ij} (\Phi L)_j}{M}$$

$$m_{\nu} \sim \Lambda_{\mathrm{ew}}^2 / M$$

Also Lorentz violation at D=6 ? (Bjorken)

Emergent Particle Physics

- The low energy expansion at a glance

Table 5.1. Typical operators in a low energy expansion. The large ultraviolet scale M here is taken to be about 10^{16} GeV. The operators at $D = 1, 2, 3$ are tamed by the symmetries. Table adapted from [Jegerlehner (2014a)].

	dimension	operator	scaling behaviour
	·	∞–many	
	·	irrelevant	
↑	·	operators	
no data	$D = 6$	$B_6, (\Box\phi)^2, (\bar{\psi}\psi)^2, \ldots$	$(E/M)^2$
|	$D = 5$	$L_5, \bar{\psi}\sigma^{\mu\nu}F_{\mu\nu}\psi, a\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu}, \ldots$	(E/M)
| experimental data ↓	$D = 4$	$(\partial\phi)^2, \phi^4, (F_{\mu\nu})^2, \bar{\psi}i\gamma^\mu D_\mu\psi, \ldots$	$\ln(E/M)$
	$D = 3$	$\phi^3, \bar{\psi}\psi$	(M/E)
	$D = 2$	$\phi^2, (A_\mu)^2$	$(M/E)^2$
	$D = 1$	ϕ	$(M/E)^3$

- Coupling constants and masses „conspire“ to give a stable SM vacuum.

Emergent Symmetries

- At low energies a QFT is governed by the values of a relatively small number of relevant and marginal couplings or operators.
- These few relevant and marginal operators can be invariant under a wider range of field transformations than a generic, irrelevant operator would be.
- The effect of irrelevant operators are strongly suppressed at low energies, making it appear that the theory has the larger symmetry group.
- Thus, symmetry can be emergent in the low energy theory (infra-red), even if it is not present in the microscopic theory,

  e.g. associated with IR fixed point.

Standard Model and energy scales - Axions

- Introduce new pseudoscalar coupling to the QCD topological charge density Q
- M is large condensate scale for the axion, axion potential has minimum to cancel θ angle, with light mass excitation of this replacing strong CP violation

$$\mathcal{L} = -\frac{1}{2}\partial_\mu a \partial^\mu a + \frac{1}{64\pi^2}\left[\frac{a}{M} + \theta\right]\epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma} - \frac{if_q}{M}\partial_\mu a \bar{q}\gamma_5\gamma^\mu q - \frac{if_l}{M}\partial_\mu a \bar{l}\gamma_5\gamma^\mu l$$

$$m_a^2 = \frac{F_\pi^2}{M^2}\frac{m_u m_d}{(m_u + m_d)^2}m_\pi^2$$

- Non-renormalisable dimension-5 operators for
  - L violation (Majorana neutrino mass)
  - Two photon(gluon) – axion coupling interactions

Where are we?

- SM makes sense up to very high scales
  - How special is the Standard Model?

- We know just the QCD, EW scales plus (here) the M scale where the Higgs self-coupling might cross zero

- Possible emergent SM with BSM in the higher dimensional operators and SM parameters linked to physics at the highest scales through vacuum stability

- The scale of emergence here comes in the same ball park as relevant to (Majorana) neutrino masses plus (to come) dark energy and inflation.

- Next, connections to cosmology...

Extra reading

- *SDB, PTRSA 382 (2023) 20230092*

PHILOSOPHICAL TRANSACTIONS A

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The cosmological constant and scale hierarchies with emergent gauge symmetries

Steven D. Bass[1,2]

- *SDB, Phil. Trans. Royal Society 380 (2021) 20210059*

- *SDB + J Krzysiak, Phys. Lett. B 803 (2020) 135351*
- *SDB + J Krzysiak, Acta Phys. Polon. B 51 (2020) 1251*

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Vacuum energy with mass generation and Higgs bosons

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Emergent Gauge Symmetries in Particle Physics and Cosmology, Lecture 2

Steven Bass

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- Mathematically consistent up to Planck scale, Physicswise....?
- Open puzzles with neutrinos, baryogenesis, dark matter, dark energy...
- New particles and/or new principles? How special is the Standard Model?

- Idea of an emergent Standard Model
  - Gauge symmetries „dissolving„ in extreme ultraviolet at ~ 10^{16} GeV .
- Scale hierarchies in particle physics
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Cracow Theoretical School, June 15-20, 2025

Emergent Symmetries and Particle Physics

- Are (gauge) symmetries always present ?

(Gauge symmetries determine our particle interactions)

Making symmetry as well as breaking it

- Emergence: Symmetries dissolving in the UV instead of extra unification

- Standard Model as long range tail of critical system which sits close to Planck scale [Jegerlehner, Bjorken, Nielsen ...]

[SDB, Phil Trans Royal Society A 380 (2021) 20210059]

Running couplings

- Running Standard Model parameters [C++ code of Kniehl et al, 2016]

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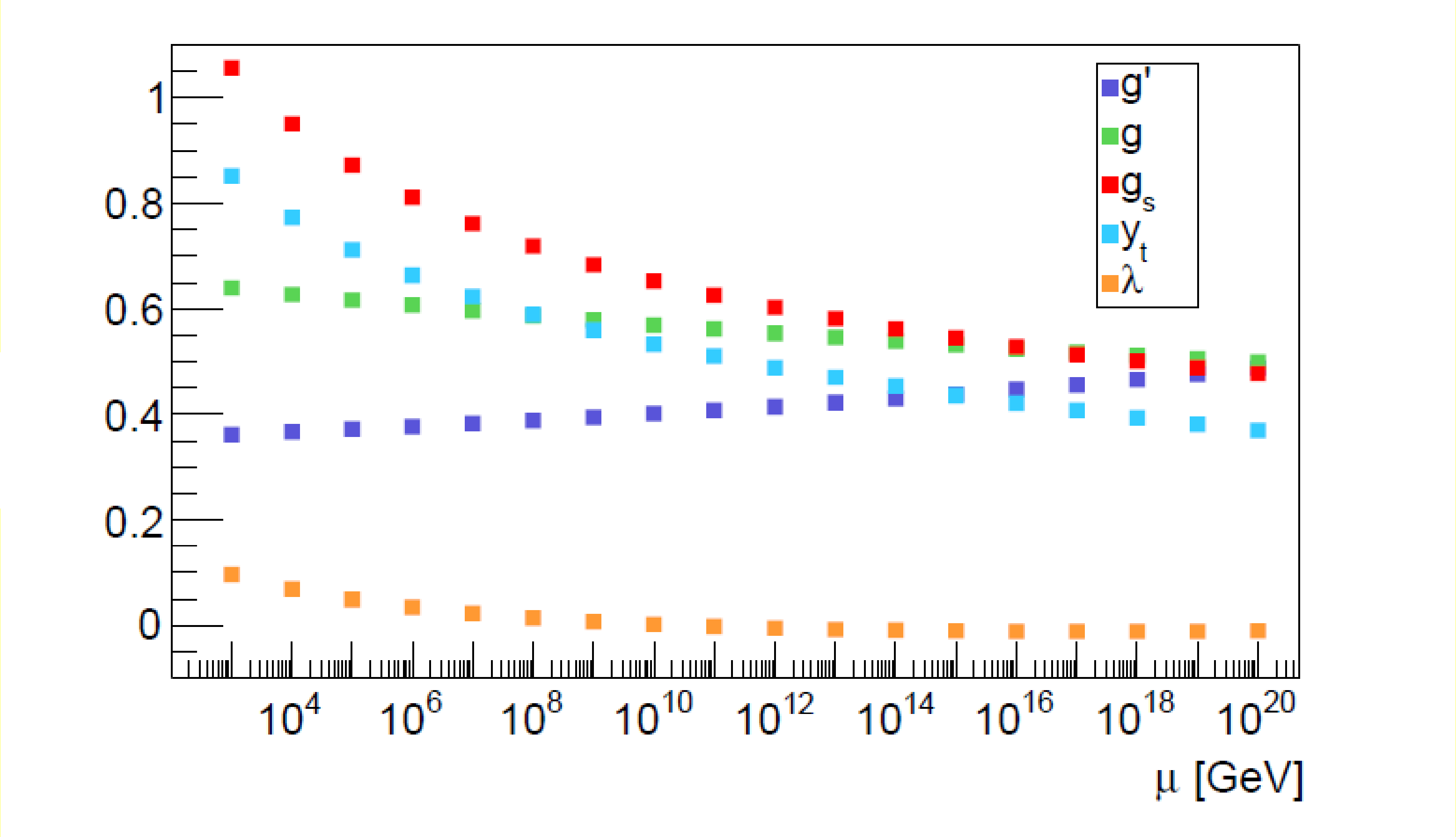
$$\lambda = \frac{m_h^2}{2v^2} = 0.13.$$



$$m_W^2 = \frac{1}{4} g^2 v^2, \quad m_Z^2 = \frac{1}{4}(g^2 + g'^2) v^2$$

$$m_f = y_f \frac{v}{\sqrt{2}} \qquad (f = \text{quarks and charged leptons})$$

Emergent particle physics

- Vacuum stability of the pure SM
  - Sits very close to the border of stable and metastable
  - Within one standard deviation of being stable up to the Planck scale

- Consider possible (topological-like) phase transition
  - New degrees of freedom with emergent gauge symmetries and J=1 excitations

- Long range tail of a statistical system near a critical point behaves as renormalized (finite) QFT.
- Ising model and φ^4 with critical dimension 4

  [Wilson and Kogut, Peskin and Schroeder]
  - If the low energy phase contains (massless) J=1 excitations, then it is a gauge theory!

Also RG evolution inducing new local and global emergent symmetries at IR fixed points

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- Global symmetries tightly constrained by gauge invariance and renormalisability when restricted to dimension 4 operators, e.g. QED

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- E.g. Lepton number violation ← Majorana neutrino masses at mass dimension 5 (Weinberg)

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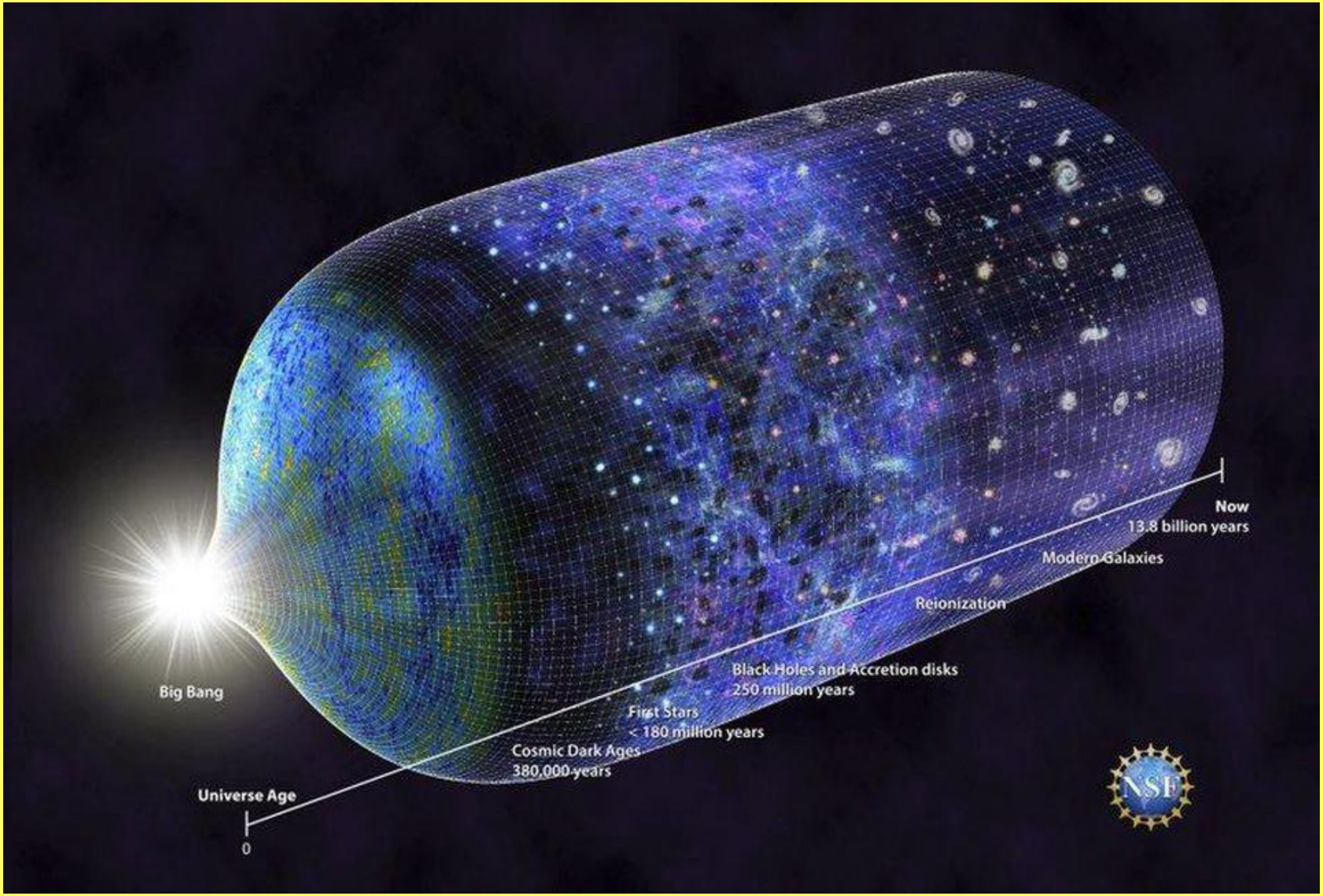
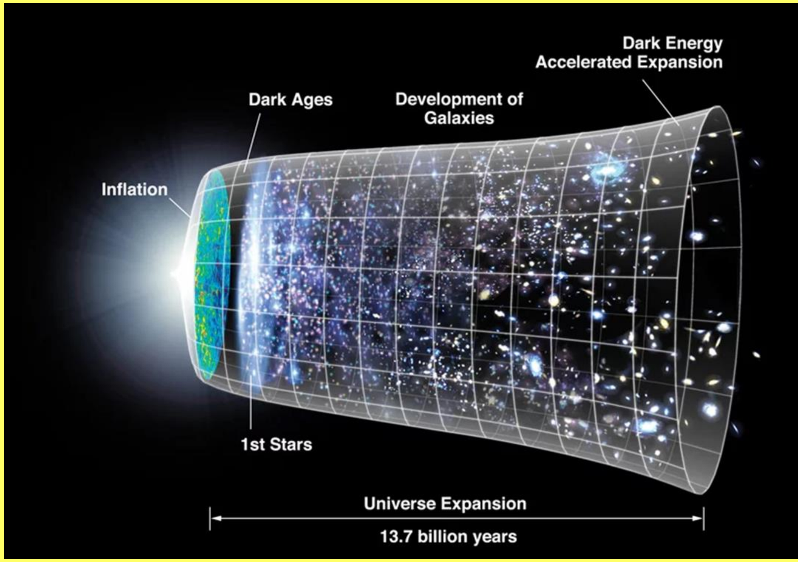
Also Lorentz violation at D=6 ? (Bjorken)

Connections with Cosmology



The Cosmological Constant



- Vacuum energy is measured just through the Cosmological Constant in General Relativity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

- Energy density $\rho_{\rm vac} = \Lambda \times c^4/(8\pi G)$

receives contributions from ZPEs, vacuum potentials (EWSB, QCD) plus gravitational term

$$\rho_{\rm vac} = \rho_{\rm zpe} + \rho_{\rm potential} + \rho_\Lambda ,$$

- The Cosmological Constant determines accelerating expansion of the Universe ← it is an observable and therefore RG scale invariant
  - Numerically, astrophysics (Planck) tells us $\rho_{vac} \sim (0.002\ \mathrm{eV})^4$

Cosmological Constant

- The Cosmological constant measures the vacuum energy density perceived by gravitation

$$\Lambda = 1.088 \times 10^{-56}\ \text{cm}^{-2}$$

$$\rho_{\text{vac}} = \Lambda \times c^4/(8\pi G)$$

- Astrophysics (Planck) tells us $\rho_{vac} \sim (0.002\ \text{eV})^4$

- Usual physics (particle, atomic…) measures differences between quantities
- Gravitation couples to everything.
- Before coupling to gravitation, can set the zero wherever you want, e.g. Normal ordering.

- Still, issue of small cosmological constant scale compared to (at least) the QCD and EW scales.

Cosmological Constant

- Is an observable and therefore RG scale invariant

$$\frac{d}{d\mu^2}\rho_{\rm vac} = 0.$$

$$\rho_{\rm vac} = \rho_{\rm zpe} + \rho_{\rm potential} + \rho_\Lambda\,,$$

- Scale dependence (explicit μ, in masses and couplings) cancels:
  What is left over?

- Curious: With finite Cosmological Constant there is no vacuum solution of Einstein's equations of GR with constant Minkowski metric (Weinberg, RMP)
  - No longer global space-time translational invariant
  - Metric is dynamical with accelerating expansion of the Universe

Cosmological Constant Scale

- With emergence spacetime translation invariance and zero cosmological constant makes sense at dimension 4
  - E.g. Global Minkowski metric works in laboratory experiments

- Cosmological constant scale then suppressed by power of M

- Then, scale of Cosmological Constant ~ scale of neutrino mass ~ 0.002 eV

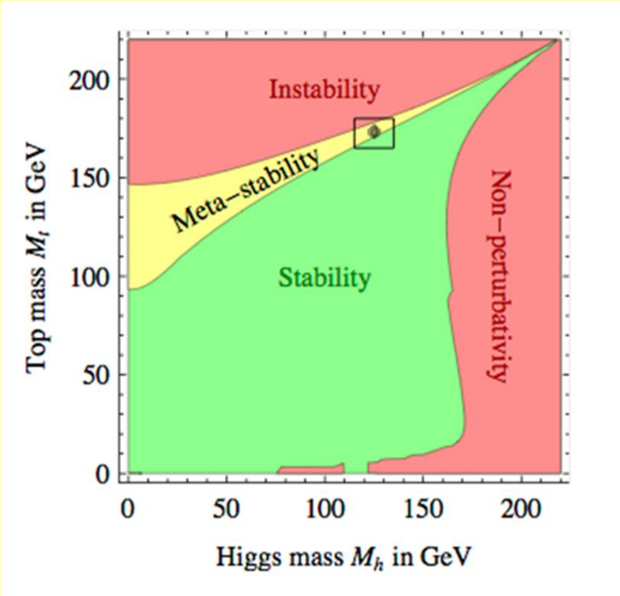
$$\mu_{\rm vac} \sim m_\nu \sim \Lambda_{\rm ew}^2/M$$

Gives M ~ 10^{16} GeV

[SDB+J.Krzysiak, PLB803 (2020) 13535,
SDB, Phil.Trans.Roy.Soc.Lond.A 382 (2023) 20230092]

Cosmological Constant

- Anthropic argument (Weinberg)
  - Cosmological Constant can be at most 10x bigger to allow galaxies to form
  - Corresponds to a factor of EW scale (and Higgs mass) constrained to be at most 30% bigger with matter contributions taken as fixed



  - Interesting that in the range of limits of a perturbative SM with maximum size of the Higgs mass

Hierarchy Puzzles - Zero Point Energies

- Zero point energies (important through Cosmological Constant)

$$\rho_{\rm zpe} = \frac{1}{2}\sum\{\hbar\omega\} = \frac{1}{2}\hbar \sum_{\rm particles} g_i \int_0^{k_{\rm max}} \frac{d^3k}{(2\pi)^3}\sqrt{k^2+m^2}.$$

- Symmetries – Covariance - and the correct vacuum Equation of State

$$\rho_{\rm zpe} = -p_{\rm zpe} = -\hbar\, g_i\, \frac{m^4}{64\pi^2}\left[\frac{2}{\epsilon} + \frac{3}{2} - \gamma - \ln\left(\frac{m^2}{4\pi\mu^2}\right)\right] + \dots$$

- For Standard Model particles, ρ_{zpe} comes from coupling to the Higgs
  - Proportional to particle masses, m^4
  - Imaginary part for Higgs with vacuum instability

$$m_h^2 = 2\lambda v^2$$

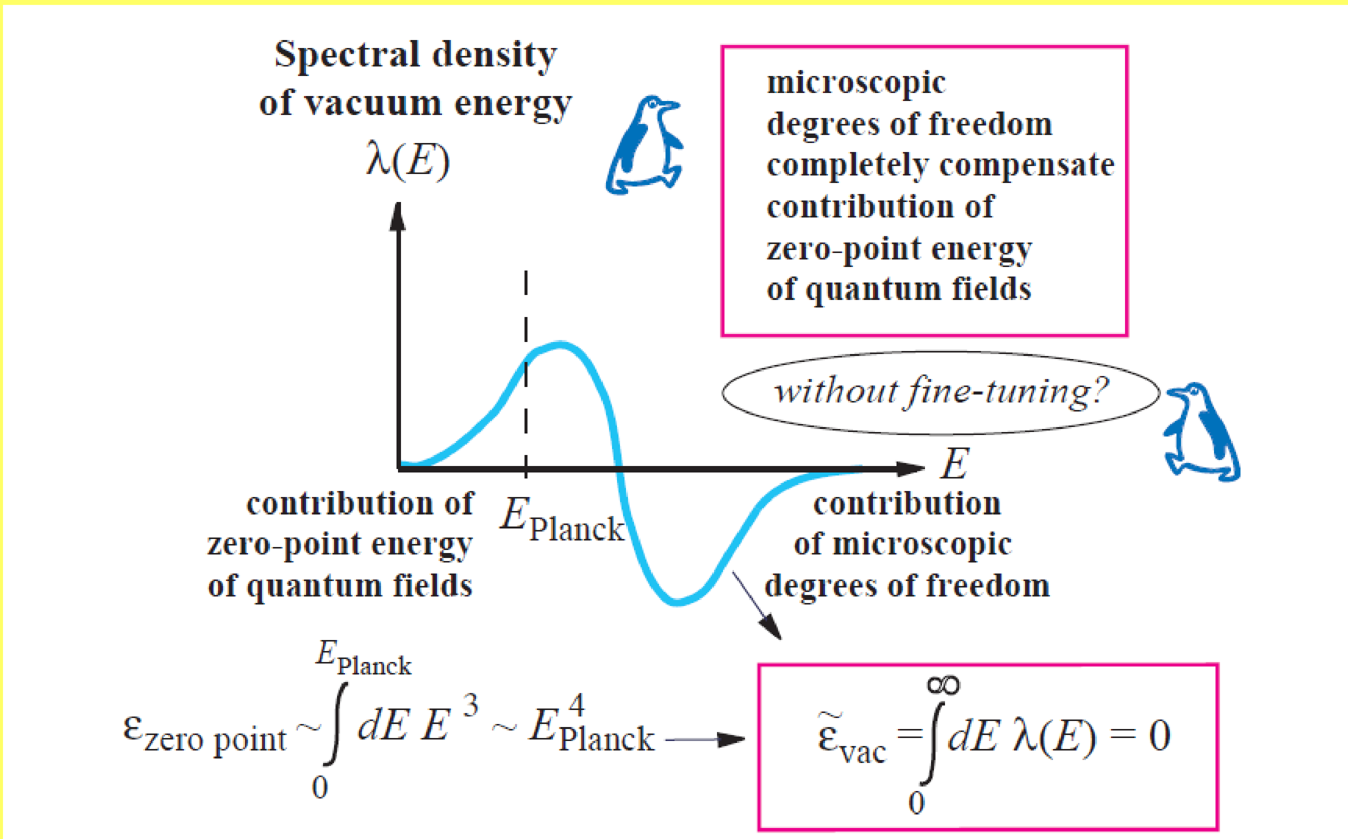
- (Using a brute force cut-off gives radiation EoS, $\rho=3p$, for leading term)
  - Reminds one of Anomalies with symmetries and UV regularisation…

Interpreting the „gravitational term"

- Volovik analogy with quantum liquids from condensed matter physics, based on Gibbs-Duhem relation

$$E - TS - \mu N = -pV$$

$$\epsilon_{\rm vac} \equiv \frac{(E - \mu N)}{V} = -p_{\rm vac}.$$



Open Cosmology Puzzles

- The scale of DE and Majorana neutrino masses are entering at the same order in the low energy expansion

$$\mu_{\rm vac} \sim m_\nu \sim \Lambda_{\rm ew}^2/M$$

- Time dependence of Dark Energy?
  - Possible time dependence in the coefficient in the low-energy expansion as we relax from the phase transition that produces the SM or in M, the scale of emergence.

- Scale ~ 10^{16} GeV similar to the typically taken in inflation models.
  - Might there be a connection?
  - Physics above M? Emergent gravitons like with ^{3}He-A?

- Dark matter candidates: Axions, BHs.
  - Also fluctuations in the system above the scale of emergence which might get frozen out. Condensed matter analogue with lattice vibrations in the Fermi-Hubbard system.

Dark matter candidates

- Candidates as new particles, PBHs or some new gravitational phenomena

- If new particles, then entering at D=?
- Axions, SUSY, 2HDMs come at different orders in low energy expansion,
- QCD axion Lagrangian with usual mass scale taken between ~ 10^9 GeV and ~ 10^{13} GeV (constraints from laboratory experiments and astrophysics)

$$\mathcal{L}_a = -\frac{1}{2}\partial_\mu a \partial^\mu a + \left[\frac{a}{M} - \Theta_{\rm QCD}\right]\frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{i f_\psi}{M}\partial_\mu a\, \bar{\psi}\gamma_5\gamma^\mu\psi - \ldots$$

- Nearby galaxies phenomenology (rotation curves), DM at D > 4 (?)

$$v_\infty^4 = G M_{\rm bar} a_0,$$

$$a_0 \approx 1.2 \times 10^{-10}\ {\rm ms}^{-2}\ \text{to within 10-20\%}$$

$$2\pi a_0 \approx a_H \approx a_\Lambda$$

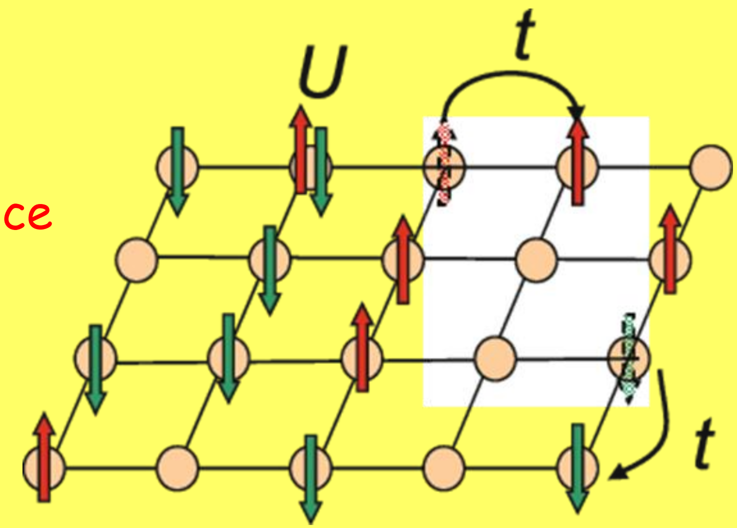
$$a_H = cH_0 \approx 1.1 \times 10^{-10}\ {\rm ms}^{-2}$$

$$a_\Lambda = c^2\sqrt{\Lambda/3} = cH_\infty \approx 0.9 \times 10^{-10}\ {\rm ms}^{-2}$$

Possible Analogy from Condensed Matter

- Recall Fermi-Hubbard model in low energy limit

- Strongly correlated electron system on 2D lattice



$$\mathcal{H} = -t \sum_{(ij)\sigma} c^{\dagger}_{i\sigma} c_{j\sigma} + U \sum_{i} c^{\dagger}_{i\uparrow} c_{i\uparrow} c^{\dagger}_{i\downarrow} c_{i\downarrow}.$$

$$J = 4t^2/U$$

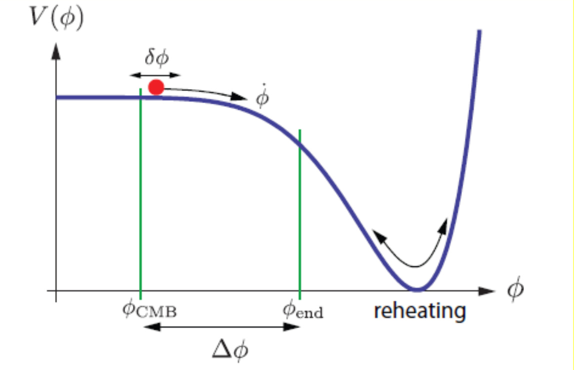
- Low energy limit at half filling, behaves like Heisenberg magnet:
  - Quasi-particles with spin-charge separation
  - „Spinons“ feel new local SU(2) gauge symmetry

  - Lattice was so far taken as fixed.
  - Lattice site vibrations correspond to bosonic phonon excitations. Possible analogy with Dark Matter along with emergent gauge system.

Inflation

- Primordial inflation suggested by flatness of the Universe, its isotropy and homogeneity plus lack of observed monopoles &tc that might have been formed in the very early Universe.
- Initial period of accelerated expansion by factor ~10^{26} in 10^{-33} seconds.

- Modelled via new „inflaton" scalar field with slow-roll potential



- Simplest models with a single „inflaton" fit to CMB amplitudes gives inflation scale V ~ 10^{16} GeV, expansion involves bigger than ~60 e-folds.

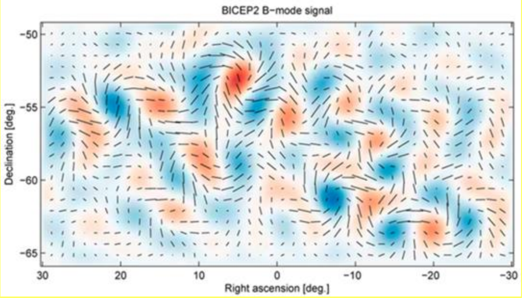
- The „re-heating" transition to Big Bang cosmology as the end of inflation with explosion of SM matter and radiation.

Inflation and GWs

- Degrees of freedom above the scale of SM emergence ?

- Gravitational waves from inflationary period expected to imprint on the CMB in terms of tensor to scalar ratio. Quantum fluctuations get stretched to superhorizon scales. Can re-enter the horizon at radiation or matter dominance. Tensor perturbations (GWs) can lead to polarization of the CMB – B modes
  - Connected to the scale of inflation.

$$V^{1/4} = 1.06 \times 10^{16}\,\mathrm{GeV} \left(\frac{r}{0.01}\right)^{1/4}$$



- From Planck, WMAP and BICEP2/Keck measurements combination

$$r_{0.05} < 0.036 \text{ at } 95\% \text{ confidence level}$$

Probing the highest scales

- Vacuum stability of the SM assuming that the Higgs self-coupling really behaves SM-like.

- Majorana neutrinos through the Weinberg operator

- Proton decays and axions ? Lorentz violations ?

- Dark energy physics with Cosmological Constant scale ~ 0.002 eV

- „Inflation“ physics ← can we see B-modes?

- High frequency gravitational waves ~ 10^9 Hz would be sensitive to early Universe physics at these energies. First experimentalist ideas how to measure.

Summary, Conclusions and Open Puzzles

- The SM is working very well in present experiments, from low energy precision up to 13 TeV collider energies.
- Nice ultraviolet behaviour.
  - Is mathematically consistent up to the Planck scale with (very close to) vacuum stability with the running Higgs coupling.
- Open physics puzzles: neutrinos, baryogenesis, families, DM, DE, inflation…

- Emergence
  - SM born in a topological-like phase transition below 10^{16} GeV
  - New global symmetry breaking in higher dimensional operator terms.
  - Cosmological constant linked to global symmetries of the metric for „pure vacuum“ Universe. Scale comes out with similar size to tiny Majorana neutrino masses.
  - Phase transition connection to inflation? CMB and high frequency GWs.
  - DM possibilites, how might any fluctuations from above the cut-off freeze out with coupling to gravity like fluctuating lattice sites with Fermi-Hubbard?

Extra reading

- *SDB, PTRSA 382 (2023) 20230092*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The cosmological constant and scale hierarchies with emergent gauge symmetries

Steven D. Bass[1,2]

- *SDB, Phil. Trans. Royal Society 380 (2021) 20210059*

- *SDB + J Krzysiak, Phys. Lett. B 803 (2020) 135351*
- *SDB + J Krzysiak, Acta Phys. Polon. B 51 (2020) 1251*


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Vacuum energy with mass generation and Higgs bosons

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Extra reading