Daniel, Its been a long time!

1) **On Time Reversal Violating Nucleon Nucleon Potentials. (Talk).**
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In *Quebec 1974, Proceedings, Few Body Problems In Nuclear and Particle Physics*, Quebec 1975, 106-107.

LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Keywords
Bookmarkable link to this information

2) **Possible Decay Modes of a Light Neutral Lepton Produced by Neutral Currents.**
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Published in **Phys.Rev.D14:1926,1976**.

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3) **Tests for the Structure of the Neutral Current.**
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4) **Flavor Conservation in an SU(3) x U(1) x U(1) Model.**
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Published in **Phys.Rev.D16:2289,1977**.

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5) **The Adler-Weisberger Relation and the Quark Model.**
John F. Donoghue, Daniel Wyler, (Carnegie Mellon U.) . COO-3066-98, Jul 1977. 21pp.
Published in **Phys.Rev.D17:280,1978**.

References | LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Keywords | Cited 10 times
Journal Server [doi:10.1103/PhysRevD.17.280]
ADS Abstract Service
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$$\frac{1}{g_A^2} = 1 + \frac{2m_N^2}{\pi g_{\pi NN}^2} \int_{m_\pi}^{\infty} \frac{d\nu}{\nu} \sqrt{\nu^2 - m_\pi^2} \left(\sigma_{\rm tot}^{\pi^- p}(\nu) - \sigma_{\rm tot}^{\pi^+ p}(\nu)\right)$$

vs

$$g_A = 5/3\ (\ 1 - \delta\ )$$

Reflections on one of Daniel's classics

CERN-TH.4254/85

EFFECTIVE LAGRANGIAN ANALYSIS OF NEW INTERACTIONS

AND FLAVOUR CONSERVATION

W. Buchmüller

CERN – Geneva

and

D. Wyler

Theoretische Physik, ETH, Zürich

If we assume that the standard model indeed describes physics well in the energy range up to the W-mass, but, in view of the above, take it to be an effective low energy theory in which heavy fields have been integrated out, then it is compelling to describe the phenomena up to energies of order Λ by an effective Lagrangian technique, where fields are considered as classical. [This is done for the low energy interactions of (light) pions[3)] where f_π corresponds to Λ.] Such a procedure is quite general and independent of the new interactions at scale Λ; all one must do is to impose SU(3)×SU(2)×U(1) invariance (and possibly further conservation laws, such as baryon number conservation, etc.). It contains, however, the assumption that no additional fields are present, such as coloured scalars with masses $O(m_W)$ (which could, of course, be included in a further analysis). ← **

Phenomenology of emergent gauge symmetry

Emergence – new DOF and new description emerging from a hidden underlying description
- example: fluids and Navier-Stokes Eq. emerging from atoms bumping into each other

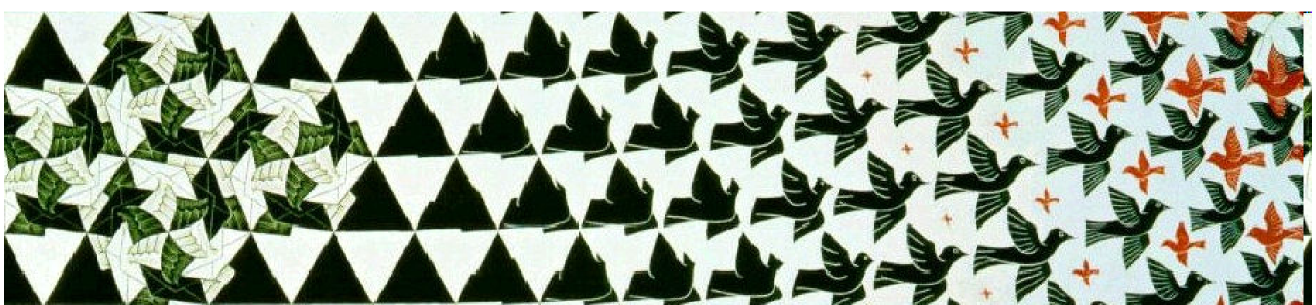
Can gauge symmetries (i.e. those of SM) be emergent?

1) Motivations

2) Constraints

3) Some ideas for phenomenology

4) Outlook



Unification paradigm

The unification theme:
Electricity and magnetism unified by Maxwell
Weak and electromagnetic interactions unified in Standard Model
SU(3)xSU(2)xU(1) can be grand unified
Search on for ultimate unified theory of everything

But really no gauge unification yet:
Maxwell was really identification of U(1) of EM
SM is gauge **mixing** not gauge unification SU(3)xSU(2)xU(1)

Unification is very attractive but not historically compelling

Emergent fields: Waves from interacting masses

Take a series of masses interacting with neighbors:

$$S = \int dt\, L[y_i, \dot{y}_i] = \int dt \sum_i [\frac{1}{2} m \dot{y}_i^2 - V(y_i - y_{i-1})] \approx \int dt \sum_i [\frac{1}{2} m \dot{y}_i^2 - \frac{1}{2} k (y_i - y_{i-1})^2]$$

Go to the continuum limit:

$$y_j(t) \equiv \sqrt{\frac{1}{ka}} \phi(x,t) \qquad\qquad x = aj$$

Get a field satisfying the wave eq. (= massless 1D Klein Gordon equation)

$$S = \int dx dt \frac{1}{2} [\frac{1}{v^2} (\frac{\partial \phi}{\partial t})^2 - (\frac{\partial \phi}{\partial x})^2] = \int dx dt \frac{1}{2} \partial_\mu \phi \partial^\mu \phi$$

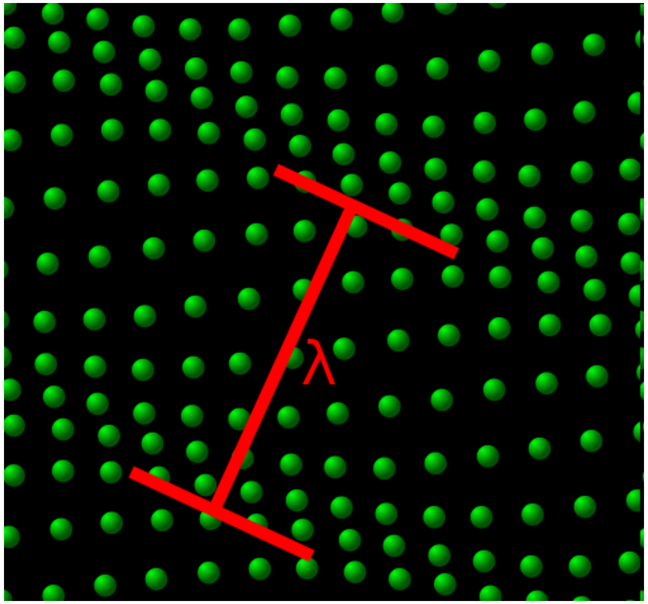
with

$$\partial_\mu = (\frac{1}{v_s} \frac{\partial}{\partial t}, -\frac{\partial}{\partial x}) \qquad\qquad v = \sqrt{\frac{ka^2}{m}}$$

Phonons

Another realization:

Atoms bumping into each other
- described as acoustic waves



$$L = \int d^3x[\frac{1}{2}\partial_\mu\phi\partial^\mu\phi]$$

$$\partial_\mu = (\frac{1}{v_s}\frac{\partial}{\partial t}, -\nabla)$$

Generates massless wave equation:

$$[\frac{1}{v^2}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}]\phi = 0$$

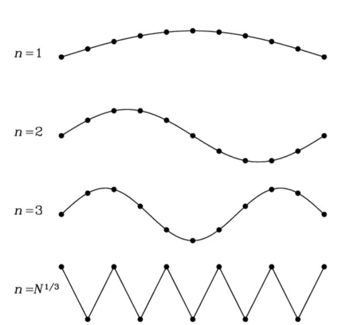
$$E = pv_s$$

Another motivation: Dreams of a Finite Theory

All field theories have divergences at high energy
- QM sums over all intermediate states at all energies
- not relevant at low energy – renormalization

But, for a final theory at high energies desire finiteness

String theory resolution
- more divergent as you go up in energy, then magic resolution



Possible emergent resolution:
- intermediate states finite at high energy
- high energy cutoff
- in some ways, a more conservative approach

Emergence in particle physics

Pions are emergent phenomena

Starts with a theory of quarks and gluons

$$\mathcal{L} = -\frac{1}{4}F^2 + \bar{\psi} i D \psi$$

-confinement – quarks and gluons do not propagate far

Ends with nonlinear theory of scalar bosons – Goldstone bosons of chiral symmetry

$$\mathcal{L} = \frac{F^2}{4} Tr[\partial_\mu U \partial^\mu U^\dagger] \qquad \text{with} \qquad U = exp[i\frac{\tau \cdot \phi}{F_\pi}]$$

- Only hint of QCD in $\pi^0 \to \gamma\gamma$ – measures the number of colors

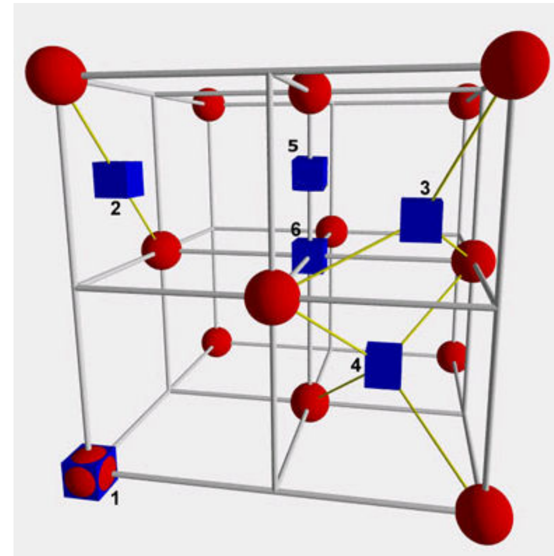
But chiral symmetry is not emergent here

ChPTh mirrors the chiral symmetry of QCD

Is it possible to have emergent symmetry?

Emergent symmetry

Three emergent symmetries in phonon/string examples:



1) **Translation symmetry**

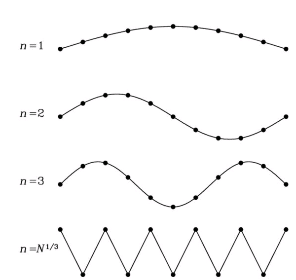
$$x \rightarrow x + c$$

2) **Lorentz-like symmetry**

$$L = \int d^3x \left[\frac{1}{2}\partial_\mu \phi \partial^\mu \phi\right]$$

leads to extra invariance

$$x'^\mu = \Lambda^\mu_\nu x^\nu$$



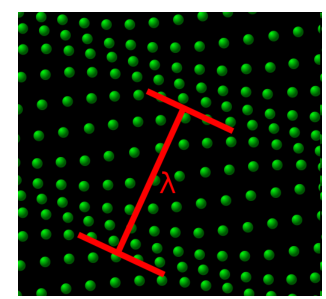
3) **Shift symmetry:**

- why the massless wave equation?

shift symmetry $\phi \rightarrow \phi$ +c

corresponds to translating the overall system

-no cost in energy

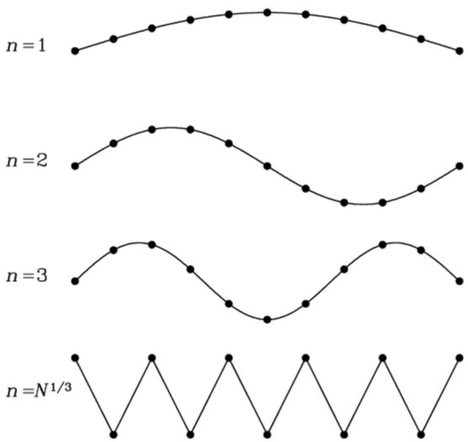


These are not symmetries of the original system but emerge in continuum limit

Key to phenomeonlogy: violation of emergent symmetry

In examples of emergence: strings and phonons

1) **Translation invariance violated at small scales**



2) **Waves do not exist at small wavelength**
Emergent DOF no longer exist

3) **Next order in L is not Lorentz invariant:**

$$V(y_i - y_{i-1}) = \frac{1}{2}k(y_i - y_{i-1})^2 + \frac{1}{4}\lambda(y_i - y_{i-1})^4 + \ldots.$$

Then there is a new term in the action without Lorentz-like symmetry

$$S = \int dxdt \frac{1}{2}[\frac{1}{v^2}(\frac{\partial\phi}{\partial t})^2 - (\frac{\partial\phi}{\partial x})^2 + \bar{\lambda}(\frac{\partial\phi}{\partial x})^4]$$

These are generic features of an emergent symmetry

Symmetry is not forever

Thinking from the top down –emergent gauge symmetry

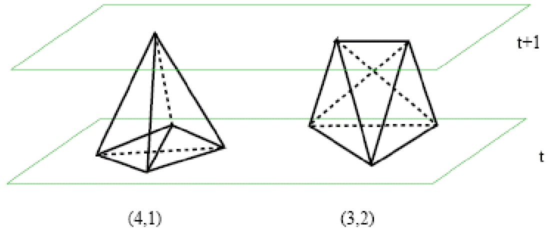
Random dynamics argument **Holgar Nielsen**

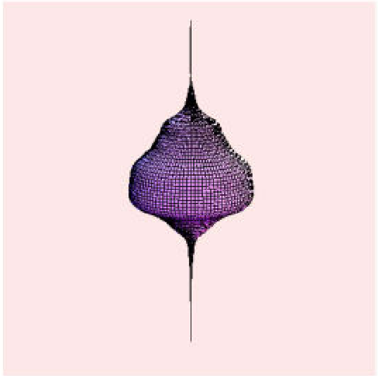
At Planck scale (or beyond), theory is very complicated and essentially random. Excitations of all forms. But the only excitations that can propagate far are those which are "protected":
- Gauge bosons and chiral fermions

With gravity included this would also require emergence of smooth spacetime at low E

Related:

Ambjorn, Loll - Dynamical triangulation and emergence of space time





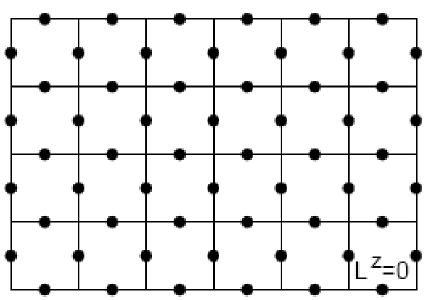
Explicit realizations in condensed matter systems

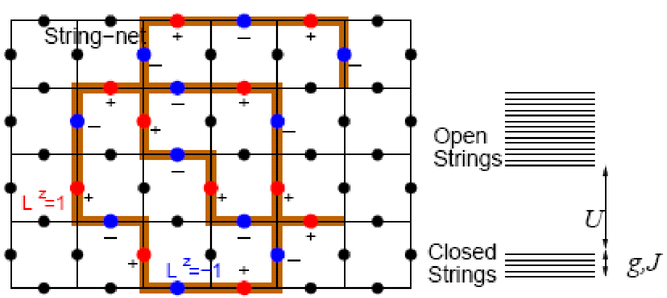
Hamiltionian system with emergent gauge symmetry:
- on discrete lattice
- “string net condensation”

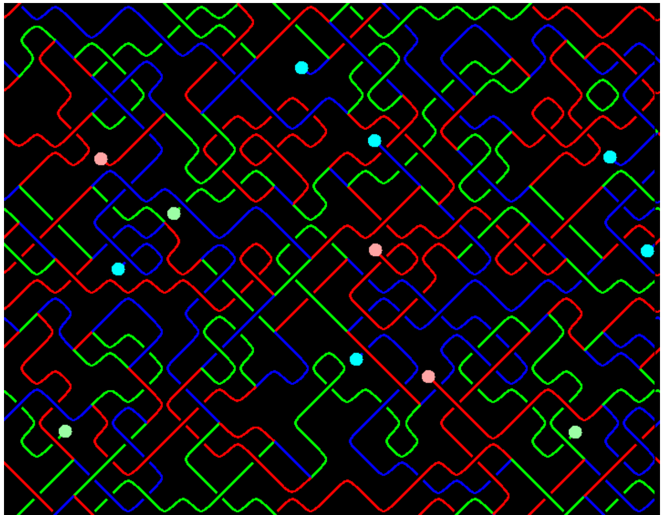
Xiao-gang Wen

Basically – **transverse excitations don’t cost energy**
- 2 DOF
- massless
- therefore gauge boson

can add symmetry factors to make any gauge theory







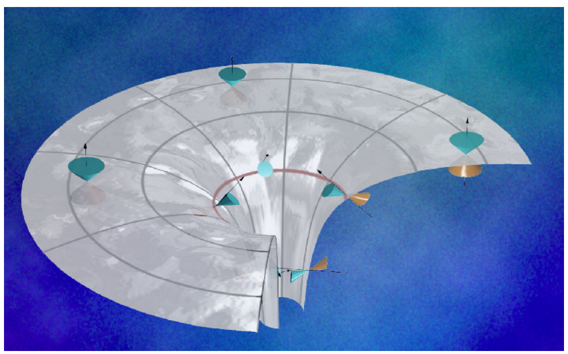
Other Condensed Matter systems

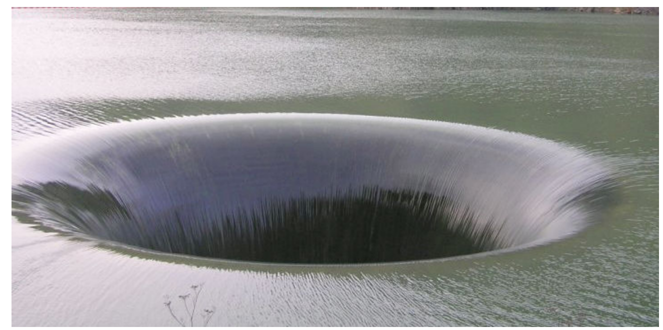
Acoustic and fluid analog models for GR

Unruh, Visser

Acoustic metric

$$g_{\mu\nu}(t,\vec{x}) \propto \begin{bmatrix} -(c_s^2 - v^2) & \vdots & -\vec{v} \\ \cdots\cdots\cdots\cdots & \cdot & \cdots\cdots \\ -\vec{v} & \vdots & I \end{bmatrix}.$$





G. Volovik analogies

The Universe in a Helium Droplet

GRIGORY E. VOLOVIK

Low Temperature Laboratory, Helsinki University of Technology and Landau Institute for Theoretical Physics, Moscow

Thinking from the bottom up

Some key ingredients/constraints

Deser et al theorem

Witten Weinberg

Nielsen Ninomiyo

Universal speed of light

Deser theorem

Massless spin two particle coupled to energy and momentum
- couples then to its own energy and momentum
- this coupling changes the energy momentum tensor

Iterate to get uniquely General Relativity

Also works for Yang-Mills if one assumes spin-one couples to its own charge.

This is good news for emergence:
- don’t need to fine tune interactions to match YM or GR
- goal is massless field and coupling to right current

Witten Weinberg

"Impossible to have composite gravitons or (non-abelian) gauge bosons from any Lorentz invariant theory"

Little appreciated fact: Gauge bosons are not Lorentz invariant
- need to be supplemented by a gauge change

$$A_\mu' = \Lambda_\mu{}^\nu A_\nu + \partial_\mu \chi(x)$$

Proof takes advantage of this fact:
A Lorentz invariant theory produces a covariant and conserved current
A massless particle from such a theory will have Lorentz covariant matrix element
But only two transverse polarizations allowed

WW take clever Lorentz transformation to lead to a contradiction

Implication: Lorentz invariance may be key issue
- emergence of Lorentz invariance also?

Nielsen Ninomiya

"Can't have chiral fermions on a lattice"

chiral fermions means LH without RH or RH without LH

- Standard Model starts with massless chiral fermions

$$\{\tilde{D}(p), \gamma^5\} = 0$$

$$D(p) = \sum_\mu \gamma_\mu d_\mu(p)$$

Zeros of a vector field on a manifold equals the Euler characteristic
- for periodic lattice – Euler char. =0
- implies zero modes paired in chirality

Universal speed of light

-easy to have many emergent waves with Lorentz invariant wave equation

-But in general will get different speeds of “light”
- - not true Lorentz invariance

Wen’s and other CM- like examples suffer from this defect

Summary of issues

If there are massless bosons, they may organize into gauge theory and GR

-but getting massless spin 1 and 2 may be problematic

-Seems likely that Lorenz invariance and spacetime needs to be emergent also
- but there are obstacles here also

Phenomenology

General idea – small violation of emergent gauge symmetries

- Testing breaking of general covariance
  - -with Ufuk Aydemir and Mohamed Anber

- Testing gauge non-invariance in conjunction with Lorentz violation (to appear)

Other "emergence motivated" ideas – it time permits

Other emergent symmetries? (work with Preema Pais)
- If SU(3)xSU(2)xU(1), why not more?

Could the world be non-chiral? (work with Mohamed Anber, Ufuk Aydemir, Preema Pais)

Small violations of symmetries:

Symmetries (and DOF) only exist at low energy:
- suppressed terms can reveal lack of symmetry

Loops as diagnostics:

-loop diagrams feel all energies
- with a cutoff, often violate gauge symmetries
- emergent theories do have a cutoff – HE DOF are missing
- no reason to expect cutoff to respect symmetry, since symmetry does not exist at HE
- likely loops probe lack of symmetry at high energy

Standard approach: (Buchmuller Wyler)
-effective Lagrangian with all gauge invariant opererators
- **reflects underlying assumption** – symmetries are forever
- not correct for emergent theories
- in principle can differentiate between unification paradigm and emergent paradigm!

Violations of general covariance 1: Graviton mass

If metric is primary field, no possibility of a mass term:

- only term with not derivatives is the cosmological constant

But using $h_{\mu\nu} = g_{\mu\nu} - \eta_{\mu\nu}$ we can form Pauli-Fierz mass term

$$\frac{m^2}{4}(h^{\mu\nu}h_{\mu\nu} - h^2)$$

But essentially totally forbidden even for the tiniest masses

Quick summary:

1) If m is "big" (i.e. bigger than the curvature at present)
   - vDVZ discontinuity – propagator modification is O(1)
     - bending of starlight is off by 25%
2) If m is "small"
   - propagator can be OK, but instability in Minkowski, dS and FRW (Grisa, Sorbo)
   - only stable in AdS

We live in FRW => graviton mass = 0 identically

Violations of general covariance 2:

Anber, Aydemir, JFD

Gravity is BEST for testing gauge violations
- gravity is already suppressed by $1/M_P^2$
- violations also suppressed, but can stand out more

Leading terms formed with full metric occurs with two derivatives

-adding non-covariant terms to the actions
-these are sample calculations
-the tightest constraints come from nonlinear analysis - use full metric

$$\mathcal{L} = \mathcal{L}_{EH} + \sum_{i=1}^{7} a_i \mathcal{L}_i + \mathcal{L}_m \,.$$

with

$$\begin{aligned}
\mathcal{L}_1 &= -g^{\mu\nu}\Gamma^{\alpha}_{\mu\lambda}\Gamma^{\lambda}_{\nu\alpha}\,, \quad \mathcal{L}_2 = -g^{\mu\nu}\Gamma^{\alpha}_{\mu\nu}\Gamma^{\lambda}_{\lambda\alpha} \\
\mathcal{L}_3 &= -g^{\alpha\gamma}g^{\beta\rho}g_{\mu\nu}\Gamma^{\mu}_{\alpha\beta}\Gamma^{\nu}_{\gamma\rho}\,, \quad \mathcal{L}_4 = -g^{\alpha\gamma}g_{\beta\lambda}g^{\mu\nu}\Gamma^{\lambda}_{\mu\nu}\Gamma^{\beta}_{\gamma\alpha} \\
\mathcal{L}_5 &= -g^{\alpha\beta}\Gamma^{\lambda}_{\lambda\alpha}\Gamma^{\mu}_{\mu\beta}\,, \quad \mathcal{L}_6 = -g^{\mu\nu}\partial_\nu\Gamma^{\lambda}_{\mu\lambda} \\
\mathcal{L}_7 &= -g^{\mu\nu}\partial_\lambda\Gamma^{\lambda}_{\mu\nu}\,, \qquad (3)
\end{aligned}$$

Linear analysis:

- only 4 independent terms at linear order

$$\mathcal{L}_1^{(2)} = -\frac{1}{4}(-T_1 + 2T_2)\,, \quad \mathcal{L}_2^{(2)} = -\frac{1}{4}(2T_3 - T_4)$$
$$\mathcal{L}_3^{(2)} = -\frac{1}{4}(3T_1 - 2T_2)\,, \quad \mathcal{L}_4^{(2)} = -\frac{1}{4}(4T_2 - 4T_3 + T_4)$$
$$\mathcal{L}_5^{(2)} = -\frac{T_4}{4}\,, \qquad (6)$$

with

$$T_1 = \partial_\gamma h_{\alpha\beta}\partial^\gamma h^{\alpha\beta}\,, \quad T_2 = \partial_\gamma h_{\alpha\beta}\partial^\beta h^{\alpha\gamma}$$
$$T_3 = \partial_\alpha h \partial_\beta h^{\alpha\beta}\,, \quad T_4 = \partial_\alpha h \partial^\alpha h\,.$$

Equations of motion:

$$(-1 - a_1 + 3a_3)\Box h^{\alpha\beta} + (1 + a_1 - a_3 + 2a_4)\left(\partial^\alpha\partial_\gamma h^{\beta\gamma} + \partial^\beta\partial_\gamma h^{\alpha\gamma}\right) + (-1 + a_2 - 2a_4)\,\eta^{\alpha\beta}\partial_\mu\partial_\nu h^{\mu\nu} + (-1 + a_2 - 2a_4)\,\partial^\alpha\partial^\beta h + (1 - a_2 + a_4 + a_5)\,\eta^{\alpha\beta}\Box h = 16\pi G T^{\alpha\beta}\,, \qquad (7)$$

Conservation constraint $\partial^\alpha T_{\alpha\beta} = 0$

In general: $\partial_\alpha h^{\alpha\beta} = 0\,,$ and $a_4 = a_5$

Then:

$$(1 + a_1 - 3a_3)\Box h^{\alpha\beta} + (1 - a_2 + 2a_4)\,\partial^\alpha\partial^\beta h = -16\pi G\left(\overset{(2)}{T^{\alpha\beta}} - \Lambda\eta^{\alpha\beta}\,\overset{(2)}{T}\right) \qquad (C1)$$

$$\Lambda = \frac{1 - a_2 + a_4 + a_5}{2 - a_1 - 3a_2 + 3a_3 + 2a_4 + 4a_5}$$

Check: two special combinations are equivalent to gauge fixing – no deviation from GR

Propagator analysis:

$$
\begin{aligned}
D_{\mu\nu,\rho\sigma}(k) \; = \; & -A\eta_{\mu\nu}\eta_{\rho\sigma}/k^2 + B\left(\eta_{\mu\rho}\eta_{\nu\sigma} + \eta_{\mu\sigma}\eta_{\nu\rho}\right)/k^2 \\
& +A\left(\eta_{\mu\nu}k_\rho k_\sigma + \eta_{\rho\sigma}k_\mu k_\nu\right)/k^4 \\
& -B\left(\eta_{\mu\rho}k_\nu k_\sigma + \eta_{\mu\sigma}k_\nu k_\rho + \eta_{\nu\sigma}k_\mu k_\rho\right. \\
& \left. +\eta_{\nu\rho}k_\mu k_\sigma\right)/k^4 + Ck_\mu k_\nu k_\rho k_\sigma/k^6 \,, \qquad (13)
\end{aligned}
$$

$$
\begin{aligned}
A &= \frac{1 - a_2 + 2a_4}{(1 + a_1 - 3a_3)(2 - a_1 - 3a_2 + 3a_3 + 6a_4)} \\
B &= \frac{1}{2(1 + a_1 - 3a_3)} \\
C &= \frac{1 - a_1 - 2a_2 + 3a_3 + 4a_4}{(1 + a_1 - 3a_3)(2 - a_1 - 3a_2 + 3a_3 + 6a_4)}
\end{aligned}
$$

Normalization of Newton's constant

- through nonrelativistic masses

$\frac{G_{\rm eff}}{2k^2}T^{00}_{(1)}T^{00}_{(2)}$ with $G_{\rm eff} = 2G(2B - A)$

Stability – ghost analysis

- propagating scalar d.o.f. causes trouble with the mass term
- here it appears less lethal – because of derivative coupling

$$-\frac{GB}{k^2}\frac{a_1+a_2-3a_3-2a_4}{2-a_1-3a_2+3a_3+6a_4}T_{(1)}T_{(2)}$$

Simple constraint on sign of coefficients:

$$a_1 + a_2 - 3a_3 - 2a_4 < 0$$

Modest constraint from light bending:

Sun-photon coupling proportional to:

$$\frac{G_{\text{eff}}}{2k^2}\frac{2-a_1-3a_2+3a_3+6a_4}{1-a_1-2a_2+3a_3+4a_4}$$

Constraints on $a_i \sim 10^{-4}$

Parameterized Post-Newtonian (PPN) expansion:

- general expansion of metric theories around Newtonian limit

$$U \sim v^2 \sim p/\rho \sim \Pi \sim \mathcal{O}(2)$$

Expansion of equations of motion:

$$g_{00} = -1 + \overset{(2)}{g}_{00} + \overset{(4)}{g}_{00} + \dots, \quad g_{ij} = \delta_{ij} + \overset{(2)}{g}_{ij} - \overset{(2)}{g}_{ij} + \dots$$
$$g_{0i} = \overset{(3)}{g}_{0i} + \overset{(5)}{g}_{0i} + \dots, \qquad (29)$$

Parameterized form used to test alternative theories of gravity Will

$$\begin{aligned} g_{00} = {} & -1 + 2U - 2\beta U^2 - 2\xi\Phi_W + (2\gamma + 2 + \alpha_3 + \zeta_1 - 2\xi)\Phi_1 + 2(3\gamma - 2\beta + 1 + \zeta_2 + \xi)\Phi_2 \\ & + 2(1 + \zeta_3)\Phi_3 + 2(3\gamma + 3\zeta_4 - 2\xi)\Phi_4(\zeta_1 - 2\xi)A - (\alpha_1 - \alpha_2 - \alpha_3)w^i w^i U \\ & - \alpha_2 w^i w^j U_{ij} + (2\alpha_3 - \alpha_1)w^i V_i \\ g_{0i} = {} & -\tfrac{1}{2}(4\gamma + 3 + \alpha_1 - \alpha_2 + \zeta_1 - 2\eta)V_i - \tfrac{1}{2}(1 + \alpha_2 - \zeta_1 + 2\xi)W_i - \tfrac{1}{2}(\alpha_1 - 2\alpha_2)w^i U - \alpha_2 w^j U_{ij} \\ g_{ij} = {} & (1 + 2\gamma U)\delta_{ij} \end{aligned}$$

$$\begin{aligned} U &= \int d^3x' \frac{\rho'}{|\vec{x} - \vec{x}'|} \\ U_{ij} &= \int d^3x' \frac{\rho' (x - x')_i (x - x')_j}{|\vec{x} - \vec{x}'|^3} \\ V_i &= \int d^3x' \frac{\rho' v'_i}{|\vec{x} - \vec{x}'|} \\ W_i &= \int d^3x' \frac{\rho' \vec{v}' \cdot (\vec{x} - \vec{x}')(x - x')_i}{|\vec{x} - \vec{x}'|^3} \\ \Phi_1 &= \int d^3x' \frac{\rho' v'^2}{|\vec{x} - \vec{x}'|}, \Phi_2 = \int d^3x' \frac{\rho' U'}{|\vec{x} - \vec{x}'|} \\ \Phi_3 &= \int d^3x' \frac{\rho' \Pi'}{|\vec{x} - \vec{x}'|}, \Phi_4 = \int d^3x' \frac{p'}{|\vec{x} - \vec{x}'|} \\ \mathcal{A} &= \int d^3x' \frac{\rho' [\vec{v}' \cdot (\vec{x} - \vec{x}')]^2}{|\vec{x} - \vec{x}'|^3} \\ \mathcal{B} &= \int d^3x' \frac{\rho' d\vec{v}'/dt \cdot (\vec{x} - \vec{x}')}{|\vec{x} - \vec{x}'|} \\ \Phi_W &= \int d^3x' \rho' \rho'' \frac{\vec{x} - \vec{x}'}{|\vec{x} - \vec{x}'|^3} \cdot \left(\frac{\vec{x}' - \vec{x}''}{|\vec{x} - \vec{x}''|} - \frac{\vec{x} - \vec{x}''}{|\vec{x}' - \vec{x}''|} \right) \end{aligned}$$

All theories map onto a set of coefficients:

-phenomenology provides bounds on paramerters

We have matched one of the terms to PPN analysis

- a_3 =a
- sample analysis

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + a\mathcal{M}_{\mu\nu} = 8\pi G\, T_{\mu\nu}\,, \qquad (20)$$

where $M_{\mu\nu} = \mathcal{B}_{\mu\nu} + \mathcal{D}_{\mu\nu}$, and the functions $\mathcal{B}_{\mu\nu}$ and $\mathcal{D}_{\mu\nu}$ are given by

$$\begin{aligned}\mathcal{B}_{\mu\nu} = & -\frac{1}{2}g_{\mu\nu}g_{\alpha\beta}g^{\gamma\delta}g^{\epsilon\eta}\Gamma^{\alpha}_{\gamma\epsilon}\Gamma^{\beta}_{\delta\eta} + g^{\alpha\beta}g^{\gamma\delta}g_{\nu\phi}g_{\mu\epsilon}\Gamma^{\epsilon}_{\alpha\gamma}\Gamma^{\phi}_{\beta\delta} \\ & + 2g^{\phi\epsilon}g^{\alpha\gamma}g_{\delta\epsilon}g_{\phi\beta}\Gamma^{\beta}_{\mu\alpha}\Gamma^{\delta}_{\nu\gamma}\,, \qquad (21)\end{aligned}$$

$$\mathcal{D}_{\mu\nu} = \Gamma^{\lambda}_{\alpha\lambda}\mathcal{A}^{\alpha}_{\mu\nu} + \mathcal{A}^{\alpha}_{\mu\nu,\alpha}\,, \qquad (22)$$

and

$$\mathcal{A}^{\alpha}_{\mu\nu} = g^{\alpha\beta}g_{\gamma\mu}\Gamma^{\gamma}_{\nu\beta} + g^{\alpha\beta}g_{\gamma\nu}\Gamma^{\gamma}_{\mu\beta} - \Gamma^{\alpha}_{\mu\nu}\,. \qquad (23)$$

Can be expanded in post-Newtonian form:

$$\begin{aligned}R_{00} &= \overset{(2)}{R}_{00} + \overset{(4)}{R}_{00} + \dots\,, \quad \mathcal{M}_{00} = \overset{(2)}{\mathcal{M}}_{00} + \overset{(4)}{\mathcal{M}}_{00} + \dots \\ R_{0i} &= \overset{(3)}{R}_{0i} + \overset{(5)}{R}_{0i} + \dots\,, \quad \mathcal{M}_{0i} = \overset{(3)}{\mathcal{M}}_{0i} + \overset{(5)}{\mathcal{M}}_{0i} + \dots \\ R_{ij} &= \overset{(2)}{R}_{00} + \overset{(4)}{R}_{ij} + \dots\,, \quad \mathcal{M}_{ij} = \overset{(2)}{\mathcal{M}}_{ij} + \overset{(4)}{\mathcal{M}}_{ij} + \dots\,.\end{aligned}$$

Complicated analysis

-kudos to Mohamed Anber (needs a postdoc job!)

$$\overset{(4)}{\mathcal{M}}_{00} = -\frac{15}{2}\overset{(2)}{g}_{00,i}\overset{(2)}{g}_{00,i} + 3\overset{(2)}{g}_{ii,j}\overset{(2)}{g}_{00,j} - 2\overset{(2)}{g}_{00,00} + 2\overset{(4)}{g}_{00,jj}$$
$$-4\overset{(3)}{g}_{0j,0j} - 6\overset{(2)}{g}_{ij}\overset{(2)}{g}_{00,ij} + \frac{3}{2}\overset{(2)}{g}_{ij,k}\overset{(2)}{g}_{ij,k} - \overset{(2)}{g}_{jk,i}\overset{(2)}{g}_{ij,k}$$

$$\overset{(4)}{\mathcal{M}}_{ii} = -\frac{3}{4}\overset{(2)}{g}_{ii,j}\overset{(2)}{g}_{00,j} + \frac{3}{4}\overset{(2)}{g}_{kk,j}\overset{(2)}{g}_{ii,j} - \frac{3}{2}\overset{(2)}{g}_{ii,00} + \overset{(3)}{g}_{0i,0i}$$
$$-\frac{3}{8}\overset{(2)}{g}_{00,i}\overset{(2)}{g}_{00,i} + \frac{9}{8}\overset{(2)}{g}_{ik,j}\overset{(2)}{g}_{ik,j} - \frac{3}{4}\overset{(2)}{g}_{ij,k}\overset{(2)}{g}_{kj,i}$$
$$-\frac{3}{2}\overset{(2)}{g}_{kp}\overset{(2)}{g}_{ii,kp} + \frac{1}{2}\left(3\overset{(4)}{g}_{ii,kk} - 2\overset{(4)}{g}_{ik,ik}\right), \qquad \text{(C3)}$$

$$\overset{(2)}{g}_{ij,k}\overset{(2)}{g}_{ij,k} = \nabla^2\left[\frac{9}{2}U^2 + \Phi_W - 7\Phi_2 + \frac{1}{2}U_{ij}U_{ij}\right]$$
$$\overset{(2)}{g}_{ij}\overset{(2)}{g}_{ij,kk} = \nabla^2\left[-2U^2 - \Phi_W + 7\Phi_2\right]$$
$$\overset{(2)}{g}_{jk}\overset{(2)}{g}_{ii,jk} = \nabla^2\left[4U^2 + 2\Phi_W + 2\Phi_2\right]$$
$$\overset{(3)}{g}_{0i,0i} = \nabla^2\left[\Phi_1 - \mathcal{A} - \mathcal{B}\right]$$
$$\overset{(2)}{g}_{00,i}\overset{(2)}{g}_{00,i} = \nabla^2\left[2U^2 - 4\Phi_2\right]$$
$$\overset{(2)}{g}_{ii,k}\overset{(2)}{g}_{jj,k} = \nabla^2\left[8U^2 - 16\Phi_2\right]$$
$$\overset{(2)}{g}_{00,00} = \nabla^2\left[\Phi_1 - \mathcal{A} - \mathcal{B}\right]$$
$$\overset{(2)}{g}_{ik,j}\overset{(2)}{g}_{ij,k} = \nabla^2\left[\frac{1}{2}U^2 + \Phi_W + \Phi_2 + \frac{1}{2}U_{ij}U_{ij}\right]$$
$$\overset{(2)}{g}_{00,i}\overset{(2)}{g}_{kk,i} = \nabla^2\left[4U^2 - 8\Phi_2\right]$$
$$\overset{(2)}{g}_{00}\overset{(2)}{g}_{00,kk} = \nabla^2\left[4\Phi_2\right]$$
$$\overset{(2)}{g}_{ij}\overset{(2)}{g}_{00,ij} = \nabla^2\left[2U^2 + \Phi_W + \Phi_2\right].$$

$$U = \int d^3x' \frac{\rho'}{|\vec{x} - \vec{x}'|}$$
$$U_{ij} = \int d^3x' \frac{\rho'(x - x')_i (x - x')_j}{|\vec{x} - \vec{x}'|^3}$$
$$V_i = \int d^3x' \frac{\rho' v'_i}{|\vec{x} - \vec{x}'|}$$
$$W_i = \int d^3x' \frac{\rho' \vec{v}' \cdot (\vec{x} - \vec{x}')(x - x')_i}{|\vec{x} - \vec{x}'|^3}$$
$$\Phi_1 = \int d^3x' \frac{\rho' v'^2}{|\vec{x} - \vec{x}'|}, \Phi_2 = \int d^3x' \frac{\rho' U'}{|\vec{x} - \vec{x}'|}$$
$$\Phi_3 = \int d^3x' \frac{\rho' \Pi'}{|\vec{x} - \vec{x}'|}, \Phi_4 = \int d^3x' \frac{p'}{|\vec{x} - \vec{x}'|}$$
$$\mathcal{A} = \int d^3x' \frac{\rho' \left[\vec{v}' \cdot (\vec{x} - \vec{x}')\right]^2}{|\vec{x} - \vec{x}'|^3}$$
$$\mathcal{B} = \int d^3x' \frac{\rho' d\vec{v}'/dt \cdot (\vec{x} - \vec{x}')}{|\vec{x} - \vec{x}'|}$$
$$\Phi_W = \int d^3x' \rho' \rho'' \frac{\vec{x} - \vec{x}'}{|\vec{x} - \vec{x}'|^3} \cdot \left(\frac{\vec{x}' - \vec{x}''}{|\vec{x} - \vec{x}''|} - \frac{\vec{x} - \vec{x}''}{|\vec{x}' - \vec{x}''|}\right).$$

A few subtle features

- Conservation constraint needs to be imposed order by order:

$$\nabla^i \overset{(2)}{\mathcal{M}}_{ij} = 0$$
$$\nabla^0 \overset{(2)}{\mathcal{M}}_{00} + \nabla^i \overset{(3)}{\mathcal{M}}_{0i} = 0$$
$$\nabla^0 \overset{(3)}{\mathcal{M}}_{0i} + \nabla^i \overset{(4)}{\mathcal{M}}_{ij} = 0\,.$$

-Gauge freedom of usual analysis is no longer available
- complicates formulation
- gauge function is frozen

$$\begin{aligned} \mathcal{V} \;=\; & -\frac{83}{16}U^2 - \frac{5}{4}\Phi_W - \frac{45}{8}\Phi_1 + \frac{7}{2}\Phi_2 - 2\Phi_3 + \frac{33}{4}\Phi_4 \\ & + \frac{5}{4}\Phi_5 - \frac{1}{2}\mathcal{A} + \frac{29}{8}\mathcal{B} - \frac{1}{16}U_{ij}U_{ij}\,. \end{aligned} \tag{45}$$

-can't use "PPN gauge", but can transform usual results to match our form

$$\begin{aligned} g_{ij}^{\rm PPN} &= g_{ij} - 2\lambda_2 \chi_{,ij} \\ g_{0i}^{\rm PPN} &= g_{0i} - (\lambda_1 + \lambda_2)(V_i - W_i) \\ g_{00}^{\rm PPN} &= g_{00} - 2\lambda_2 \left(U^2 + \Phi_W - \Phi_2\right) - 2\lambda_1 \left(\mathcal{A} + \mathcal{B} - \Phi_1\right) \end{aligned}$$

Very strong constraint emerges

parameter	value	effect	limit
$\gamma - 1$	-3a	time delay	2.3×10^{-5}
		light deflection	4×10^{-4}
$\beta - 1$	$-\frac{85}{32}a$	perihelion shift	3×10^{-3}
		Nordtvedt effect	2.3×10^{-4}
ξ	$\frac{3}{8}a$	earth tides	10^{-3}
α_1	0	orbital polarization	10^{-4}
α_2	0	orbital polarization	4×10^{-7}
α_3	$\frac{13}{8}a$	orbital polarization	4×10^{-20}
ζ_1	$\frac{39}{8}a$	—	2×10^{-2}
ζ_2	$-\frac{179}{16}a$	binary acceleration	4×10^{-5}
ζ_3	$-a$	Newtons 3rd law	10×10^{-8}
ζ_4	$\frac{5}{8}a$	—	—

TABLE I: The values and limits on the PPN parameters [14].

Strongest constraint from rotating binary pulsars (Damour) -nonconservation of total momentum

constraint $a \sim 10^{-20}$

If interpreted as a mass scale:

$M_E \sim 10^{10}\, M_{Pl}$

However, I am still unsure about the interpretation of this constraint

Anber, Aydemir, JFD – ongoing

Lorentz breaking and gauge violation

-tied through Witten Weinberg theorem

-Lorentz breaking already a subject of study   Kostelecky et al

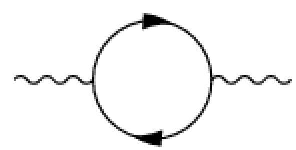
- but the impose SM gauge symmetries
- need to allow also for gauge violation (with or without LB)

Removing high energy photons in loops generates gauge invariance with/w.o. Lorentz breaking, leads to gauge violation

Example: preferred frame b_μ

$$S(k) = \frac{i}{\not{k} - m - \not{b}\gamma_5}\left(\frac{m^2 - \Lambda^2}{k^2 - \Lambda^2}\right),$$

Radiative corrections generate photon mass terms:



$$\Pi^{\mu\nu}_{b2}(0) = C_1 b^\mu b^\nu + C_2 b^2 g^{\mu\nu}$$

$$C_1 = -\frac{e^2}{12\pi^2} + \frac{e^2 m^2}{\pi^2 \Lambda^2}$$

$$C_2 = -\frac{e^2}{24\pi^2} - \frac{4e^2 m^2}{\pi^2 \Lambda^2}\left(\log(m/\Lambda) + 5/3\right)$$

Limits on photon mass – Lorentz conserving

Direct – 7×10^{-17} eV
Galactic magnetic fields – 3×10^{-27} eV

But how to interpret as a constraint on emergence?

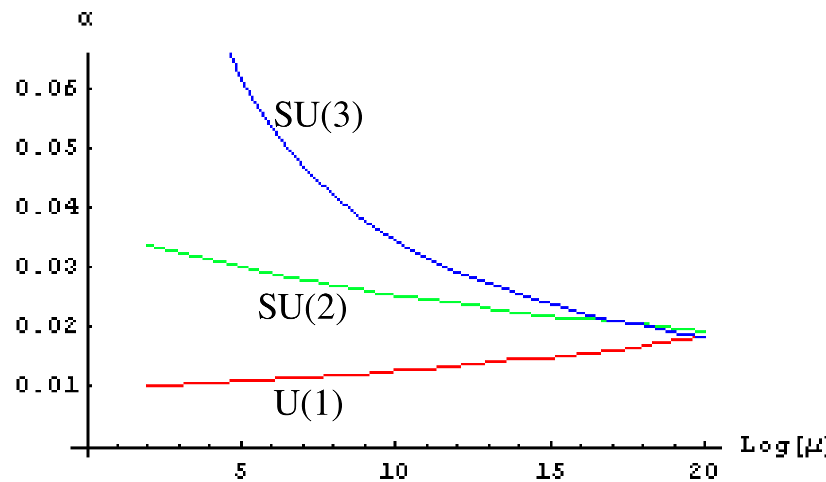
Possible that all positive dimensional operators are forbidden
- shift symmetry?

Can combined Lorentz violation plus gauge violation be more sensitive?:
- hard to make strong tests of high dimension gauge violating operators
- but with Lorentz violation, can possibly be sensitive

Studies underway

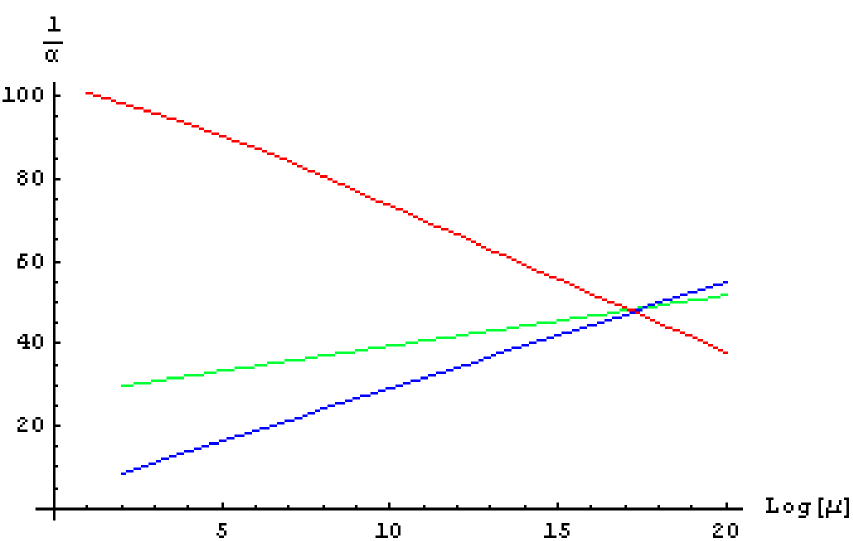
Other emergent symmetries?

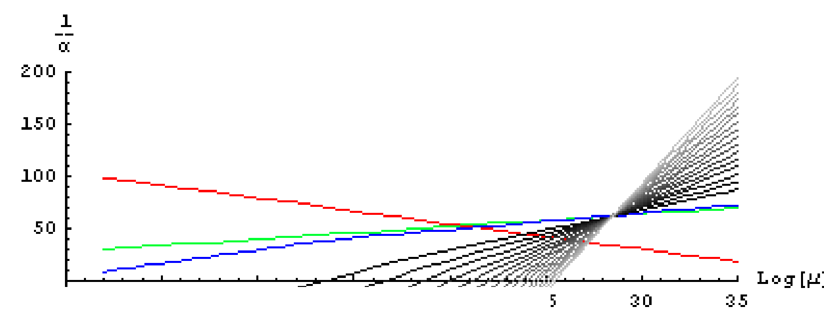
If SU(3)xSU(2)xU(1), why not more?



"Gauge federation" – Preema Pais

-many variants – some with new physics at TeV scales





Could the world be non-chiral?

(with Anber, Aydemir, Pais)

-in response to Nielsen Ninomiya theorem
-make all fermions in SM vectorial – both LH + RH
-Higgs coupling differentiates them
-also employed in lattice studies for the same reason

Start with: $\psi = \begin{pmatrix} a \\ b \end{pmatrix}$, c, f

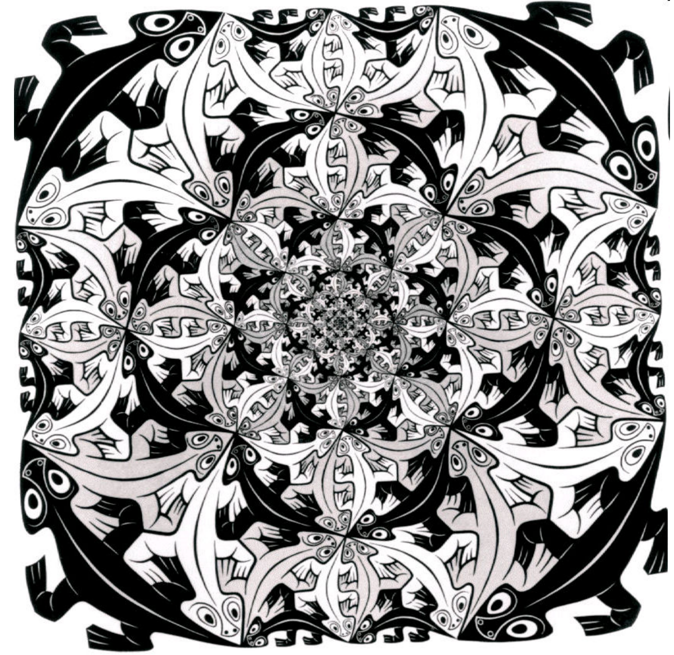
Mass eigenstates

$$\begin{aligned} u &\sim (a_L, c_R) \\ U &\sim (a_R, c_L) \\ d &\sim (b_L, f_R) \\ D &\sim (b_R, f_L) \end{aligned}$$

Needs fine-tuning to be consistent with EW constraints

Predicts heavy quarks and leptons at the LHC

Outlook:



Emergence idea alternative to unification

Emergence paradigm generally overlooked

Some incomplete theoretical ideas

Various obstacles/constraints known

NO phenomenology thus far

Start of phenomenology

- motivates some new ideas – federation, vector SM…

-symmetries are not forever
    - violation of Lorentz, gauge and general covariance symmetries

- constraints on the effects of emergence - level of 10^{-20}

Where will this go?