The emergence of a universal limiting speed

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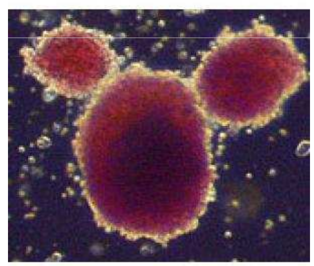
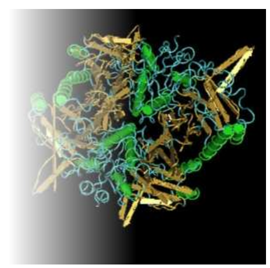
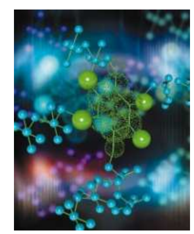
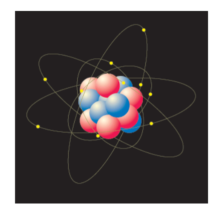
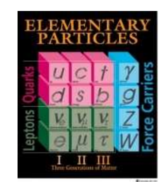
arXiv: 1102.0789

Outline

- What is emergence?
- Why emergence?
- Constraints on emergent theories
- Universal limiting speed

Emergence

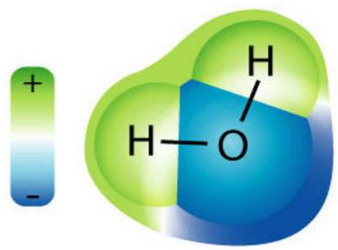
- Reductionism: big → smaller, novel properties at each layer

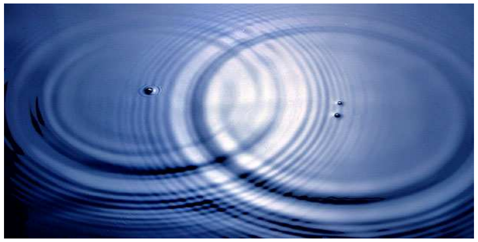







- Emergence is a way certain patterns arise out of the constituent parts of a system that do not have these patterns to begin with.

Emergence

- New properties of matter: temperature, friction, color, viscosity, Navier Stokes eqs., etc.





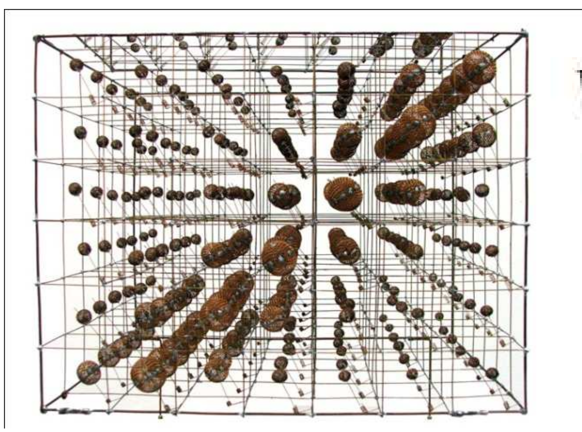
Emergence

- I will be talking about the emergence of **SYMMETRIES, specifically Lorentz symmetry**

- I will take a **phenomenological** approach

Emergence

- Example: emergence of phonons on a lattice



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

$$\mathcal{L} = \sum_i \frac{1}{2}\dot{y}_i^2 - V(y_i - y_{i-1})$$

$$i \to x$$

$$y_i \to \phi$$

$$s = \int dt d^3x \left[(\partial_{\mu\phi}\partial^\mu \phi) + \lambda\left(\frac{\partial\phi}{\partial x}\right)^4\right]$$

$$\phi\left(\frac{1}{v_s^2}\partial_t^2 - \partial_\lambda^2\right)\phi$$

Lorentz symmetry

Why Emergence?

- ***An alternative to unification*** (the higher the energy the higher the symmetry)
- Maxwell: electricity+magnetism=electromagnetic
- Glashow-Weinberg-Salam model $SU(2)_L \times U(1)_y$
- Similarly, higher groups $SU(5)$?
- Include gravity, string theory?
- But: Maxwell never unified
- $SU(3) \times SU(2)_L \times U(1)_y$ is not group unification

Why Emergence?

- ***It happens all the time***
- e.g. in condensed matter systems:
- phonons, magnons, etc
- These are “particle like” excitations, but by no means fundamental.

Constraints on emergent theories

- ***Weinberg-Witten theorem*** (a no-go for emergent theories)
- There is NO consistent QFT with $j \geq 1$

1) has a conserved current (Noether current) $\partial^{\mu} J_{\mu} = 0$

carried by the field

2) J_{μ} Lorentz invariant

3)Massless

This is disastrous: no gluons or gravitons!

Constraints on emergent theories

- Ways to evade Weinberg-Witten theorem

1) The existence of a fundamental gauge invariance

2) Lorentz symmetry is emergent: non-relativistic gluons and gravitons

Hořava-Lifshitz gravity

Constraints on emergent theories

- It is easy to have particles that obey a relativistic dispersion relation.
- These particles emerge with different speed.
- How then we explain a universal limiting speed c?

$$1/\sqrt{1-c_e^2/c^2} \approx 1/\sqrt{\eta}$$

- Astrophysical bound: Cherenkov radiation, and synchrotron emission $|\eta| \lesssim 10^{-14}$

B. Altschul hep-ph/0608332, 1005.2994, G. D. Moore, A. E. Nelson hep-ph/0106220

- A true challenge!

Constraints on emergent theories

- " The biggest challenge for this program is to explain why the infrared limit should exhibit Lorentz invariance, to the high level of accuracy required by observations. While the theory may naturally flow to $z = 1$ at long distances, different species of low-energy probes may experience distinct effective limiting speeds of propagation, not equal to the speed of light. Setting all these speeds equal to c would represents a rather unpleasant amount of fine tuning. "

P. Horava, arXiv: 1101.1081

Universal limiting speed

- In the absence of any form of interactions between particles, their speeds are frozen

- In general, different fields interact and influence each other's propagation velocity

$$\mathcal{L}_{UV} = \mathrm{K.E.} + \mathcal{L}_{int}(c_1, c_2, ..., e_1, e_2, ...)_{UV}$$

- According to the Wilsonian RG, the same Lagrangian will describe the system at different energy scales

Universal limiting speed

- In LI theories, the Lorentz symmetry prevents the renormalization of the speed, and one can set c = 1 as a dentition of natural units.
- However, if different species carry different limiting velocities, then these velocities get renormalized and must be treated in the same manner as coupling constants.

Universal limiting speed

- We considered different types of interactions: Yukawa, U(1), SU(N), and in all cases we showed ***there is a stable IR fixed line at a universal speed of light***. (M.A. and John F. Donoghue arXiv: 1102.0789)

Universal limiting speed

- As an example: non covariant QED

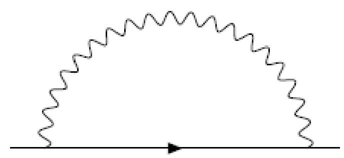
$$\mathcal{L}_r = -\frac{1}{4} F_{r\,\mu\nu} F_r^{\mu\nu} + i\bar{\psi}_r \left(\partial_0 + iec_g A_{r\,0}\right) \gamma^0 \psi_r$$
$$-i\bar{\psi}_r \left(c_f \vec{\partial} + iec_f \vec{A}_r\right) \cdot \vec{\gamma} \psi_r \,,$$

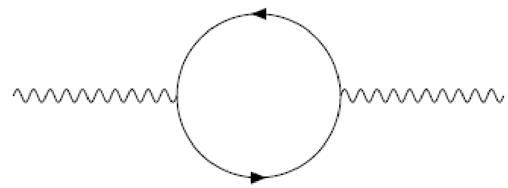
standard interaction

$$F_{r\,\mu\nu} = \partial_\mu A_{r\,\nu} - \partial_\nu A_{r\,\mu}, \text{ and } \partial_\mu = (\partial_0, c_g \vec{\partial})$$

$$D_{g\,\mu\nu}(k^0, \vec{k}) = \frac{-i\eta_{\mu\nu}}{(k_0)^2 - c_g^2 \vec{k}^2}$$

$$S_f\left(p^0, \vec{p}\right) = \frac{i}{p^0\gamma^0 - c_f \vec{p} \cdot \vec{\gamma}}$$





Universal limiting speed

$$\beta(c_g) = \frac{4e^2}{3(4\pi)^2}\frac{\left(c_g^2 - c_f^2\right)}{c_f c_g},$$

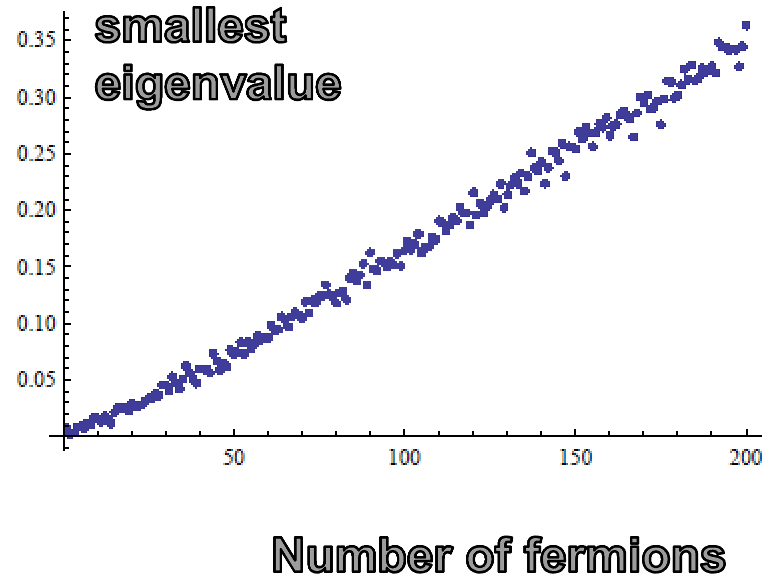
$$\beta(c_f) = \frac{8e^2}{3(4\pi)^2}\frac{(c_f - c_g)\left(4c_f^2 + 3c_f c_g + c_g^2\right)}{c_g\,(c_f + c_g)^2}$$

- By studying the eigenvalues at $c_f = c_g$ we find $c_f = c_g$ is an IR attractive fixed line.

Universal limiting speed

- The same universal behavior is exhibited in Yukawa, SU(N), and in a mixed system (Yukawa-electrodynamics).
- The same behavior works for the general case

$$\mathcal{L} = i\bar{\psi}_a\gamma^0\partial_0\psi_a - ic_{f_a}\bar{\psi}_a\vec{\gamma}\cdot\vec{\partial}\psi_a + \frac{1}{2}\partial_0\phi_i\partial_0\phi_i - \frac{1}{2}c_{b_i}^2\vec{\partial}\phi_i\cdot\vec{\partial}\phi_i - \bar{\psi}_a\left(u_{ab}^i + i\gamma^5 v_{ab}^i\right)\psi_b\phi_i$$



Universal limiting speed

- However the coupling itself runs:

$$\eta = \frac{c_b}{c_f} - 1$$

$$\beta(\eta) = \mu \frac{\partial \eta}{\partial \mu} = \frac{b g^2}{4\pi^2 c^3} \eta + \mathcal{O}(\eta^2) \qquad c_f \approx c_b \approx c.$$

$$\frac{g^2(\mu)}{4\pi c^3} = \frac{4\pi g_*^2}{5 \log(\frac{\Lambda^2}{\mu^2})}$$

Logarithmic running

$$\eta(\mu) = \eta_* \left[\frac{\log\left(\frac{\Lambda^2}{\mu_*^2}\right)}{\log\left(\frac{\Lambda^2}{\mu^2}\right)} \right]^{\frac{2b}{5}} = \eta_* \left[\frac{g^2(\mu)}{g^2(\mu_*)} \right]^{\frac{2b}{5}}$$

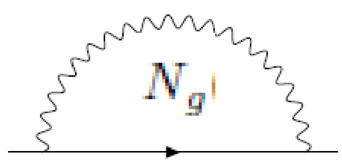
UV $\eta_* \sim 10^{-1}$ **IR** $|\eta| \lesssim 10^{-14}$ $\Rightarrow$ $10^{10^{13}}$ GeV

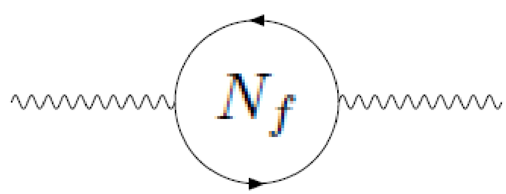
Emergent scale!

Universal limiting speed: toward model building

- We introduce $N_f \gtrsim 1$ fermions, and a large number of U(1) gauge fields N_g
- We assume that all the fermions emerge at some UV scale with a common speed c_{f_*}, and all gauge bosons emerge with a common speed c_{g_*}
- We assume the fermions have the same initial charge

e_* under the different gauge fields.





Universal limiting speed: toward model building

- One can easily write down the RG equations for the system and integrate them

$$e^2(\mu) = \frac{e_*^2}{1 + \frac{N_f e_*^2}{6\pi^2}\log\left(\frac{\mu_*}{\mu}\right)},$$

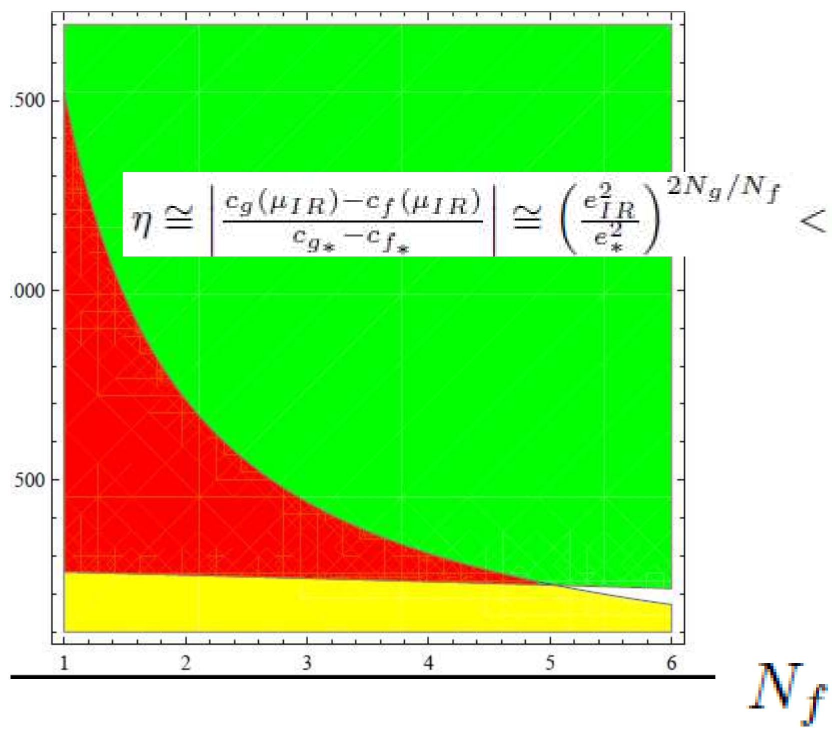
$$\frac{c_g(\mu) - c_f(\mu)}{c_{g_*} - c_{f_*}} \cong \left(\frac{e^2(\mu)}{e_*^2}\right)^{2N_g/N_f}.$$

$$\eta \cong \left|\frac{c_g(\mu_{IR}) - c_f(\mu_{IR})}{c_{g_*} - c_{f_*}}\right| \cong \left(\frac{e_{IR}^2}{e_*^2}\right)^{2N_g/N_f} < 10^{-14}$$

$e_{IR}^2/4\pi \approx 1/129$

$\mu_*/\mu_{IR} = 10^{16}$

$e_*^2 < 4\pi$



Universal limiting speed: toward model building

-We found that as we relax the perturbativity conditions, IR Lorentz symmetry can emerge with $|\eta| \lesssim 10^{-14}$ for N_f ~ 100, and N_g ~1000, even for $\mu_* / \mu_{IR} =$ 100.

- This opens up the possibility that many copies of hidden sectors may suppress Lorentz-violating effects already present at the TeV scale.

Conclusion

-Emergent phenomena is relatively new, and deserves more study

- We adopted a phenomenological procedure to study emergence

-Potential model for an emergent universal speed of light

-More phenomenological tests are on the way