Title: Phenomenological aspects of emergent phenomena

Date: May 24, 2011 03:30 PM

URL: http://pirsa.org/11050064

Abstract: Recently, emergent phenomena have started to attract more attention. Instead of assuming a symmetric world, one begins with a chaotic one. In this talk, I will describe this picture, discuss the main constraints on emergence, and then present a few phenomenological procedures that can be implemented to study the emergent phenomena.

Phenomenological Aspects of Emergent Phenomena

Mohamed Anber
University of Toronto

Perimeter Institute
May 24th 2011

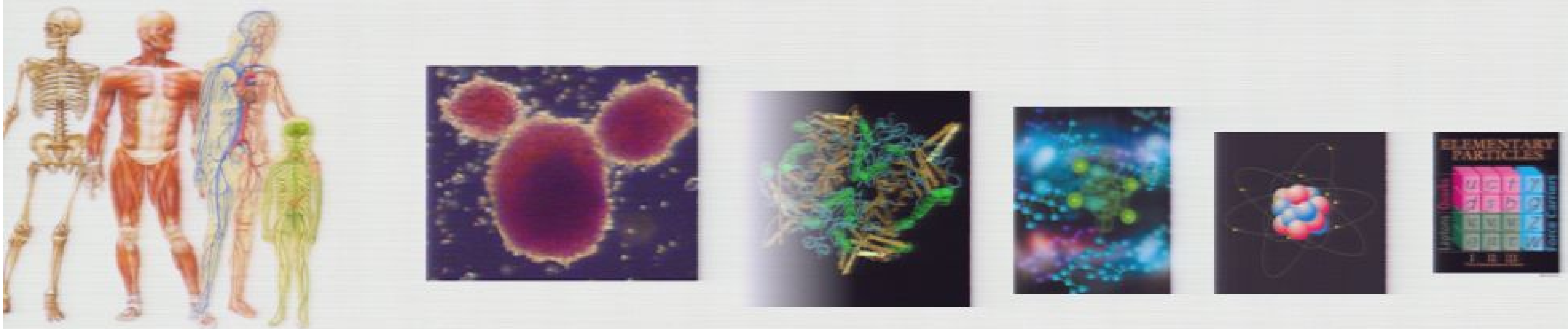
With John F. Donoghue, and Ufuk Aydemir
UMASS, Amherst

Outline

- What is emergence?
- Why emergence?
- Emergence of symmetries
- Phenomenological procedure

Emergence

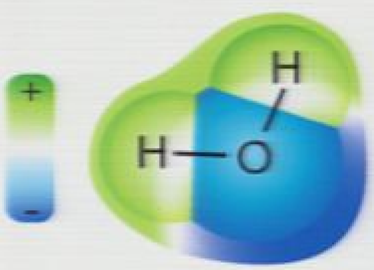
- Reductionism: big → smaller, novel properties at each layer

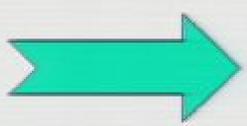


- Emergence is a way certain patterns arise out of the constituent parts of a system that do not have these patterns to begin with.

Emergence

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





Emergence

I will be talking about the emergence of **SYMMETRIES**

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.

From chaos to symmetries

- Holgan Nielsen dream:

At some emergence scale all excitations are present

- At low energy, only those protected by emergent symmetries are observed (SM)
- Include gravity: spacetime is emergent!

Top-down approach

Top down approach (I will not be talking about)

- String net condensation
- Causal set theory
- Hořava-Lifshitz gravity

Bottom-up approach

- again: I will be talking about the emergence of **SYMMETRIES**

- I will be talking about the **PHENOMENOLOGY:** bottom-up approach

Main points

- Constraints on emergent theories

Phenomenological Procedure:

- The emergence of a universal limiting speed

- Emergence of gauge symmetry and experimental constraints

Constraints on emergent theories

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

1) has a conserved current (Noether current) $\partial^\mu J_\mu = 0$ carried by the field

2) J_μ Lorentz invariant

3)massless

Constraints on emergent theories

- There is NO consistent QFT with spin greater or equal 2

1) conserved current (Noether current) $\partial_\mu \theta^{\mu\nu} = 0$

$$\theta^{\mu\nu} = g^{\beta\nu}\frac{\partial(\mathcal{L}=\sqrt{g}R)}{\partial g_{\mu\beta}} - g^{\mu\nu}(\mathcal{L}=\sqrt{g}R) \qquad g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

2) $\theta^{\mu\nu}$ is Lorentz invariant

3) massless

- This is a disaster: no gluons or gravitons!

Constraints on emergent theories

- Ways to evade Weinberg-Witten theorem

1) The existence of a fundamental gauge invariance

$$h_{\mu\nu} \to h_{\mu\nu} + \partial_\mu \xi_\nu + + \partial_\mu \xi_\nu$$

2 physical polarizations Vs 10 components

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

3) spacetime is emergent

Constraints on emergent theories

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

1) has a conserved current (Noether current) $\partial^\mu J_\mu = 0$ carried by the field

2) J_μ Lorentz invariant

3)massless

Constraints on emergent theories

- There is NO consistent QFT with spin greater or equal 2

1) conserved current (Noether current) $\partial_\mu \theta^{\mu\nu} = 0$

$$\theta^{\mu\nu} = g^{\beta\nu} \frac{\partial(\mathcal{L} = \sqrt{g}R)}{\partial g_{\mu\beta}} - g^{\mu\nu}(\mathcal{L} = \sqrt{g}R) \qquad g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

2) $\theta^{\mu\nu}$ is Lorentz invariant

3) massless

- This is a disaster: no gluons or gravitons!

Constraints on emergent theories

- Ways to evade Weinberg-Witten theorem

1) The existence of a fundamental gauge invariance

$$h_{\mu\nu} \to h_{\mu\nu} + \partial_\mu \xi_\nu + + \partial_\mu \xi_\nu$$

2 physical polarizations Vs 10 components

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

3) spacetime is emergent

Constraints on emergent theories

- There is NO consistent QFT with spin greater or equal 2

1) conserved current (Noether current) $\partial_\mu \theta^{\mu\nu} = 0$

$$\theta^{\mu\nu} = g^{\beta\nu} \frac{\partial(\mathcal{L} = \sqrt{g}R)}{\partial g_{\mu\beta}} - g^{\mu\nu}(\mathcal{L} = \sqrt{g}R) \qquad g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

2) $\theta^{\mu\nu}$ is Lorentz invariant

3) massless

- This is a disaster: no gluons or gravitons!

Constraints on emergent theories

- Ways to evade Weinberg-Witten theorem

1) The existence of a fundamental gauge invariance

$$h_{\mu\nu} \to h_{\mu\nu} + \partial_\mu \xi_\nu + +\partial_\mu \xi_\nu$$

2 physical polarizations Vs 10 components

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

3) spacetime is emergent

Constraints on emergent theories

- ***(2) Universal Lorentz symmetry:*** although it is easy to have Lorentz invariance for individual species, it is more difficult to have universal speed of light.

- ***(3) Nielsen Ninomiya no go theorem:*** you can not put chiral fermions on a lattice. The SM is chiral!

Constraints on emergent theories

- Ways to evade Weinberg-Witten theorem

1) The existence of a fundamental gauge invariance

$$h_{\mu\nu} \to h_{\mu\nu} + \partial_\mu \xi_\nu + + \partial_\mu \xi_\nu$$

2 physical polarizations Vs 10 components

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

3) spacetime is emergent

Constraints on emergent theories

- ***(2) Universal Lorentz symmetry:*** although it is easy to have Lorentz invariance for individual species, it is more difficult to have universal speed of light.

- ***(3) Nielsen Ninomiya no go theorem:*** you can not put chiral fermions on a lattice. The SM is chiral!

Main points

✓ Constraints on emergent theories

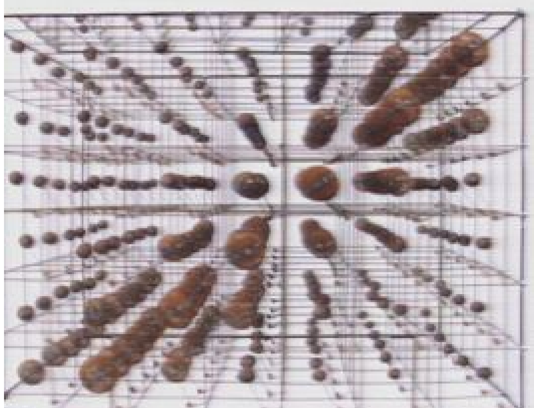
Phenomenological Procedure:

- The emergence of a universal limiting speed
- Emergence of gauge symmetry and experimental constraints

Phenomenological procedure

- ***We use different techniques***
- If symmetries are emergent?
- We test how likely some symmetries are emergent.
- Example: emergence of phonons on a lattices

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



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

$$i \to x$$
$$y_i \to \phi$$

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

Small violation

$$\phi\left(\frac{1}{c^2}\partial_t^2 - \partial_x^2\right)\phi$$

Emergent Lorentz

Universal limiting speed

- 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!

Universal limiting speed

- " 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

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

- 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

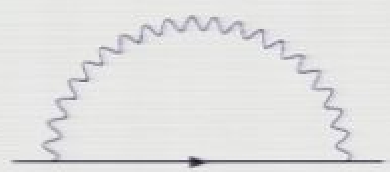
$$\mathcal{L}_r = -\frac{1}{4}F_{r\,\mu\nu}F_r^{\mu\nu} + i\bar{\psi}_r\left(\partial_0 + iec_g A_{r\,0}\right)\gamma^0\psi_r$$
$$-i\bar{\psi}_r\left(c_f\vec{\partial} + iec_f\vec{A}_r\right)\cdot\vec{\gamma}\psi_r\,,$$

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

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

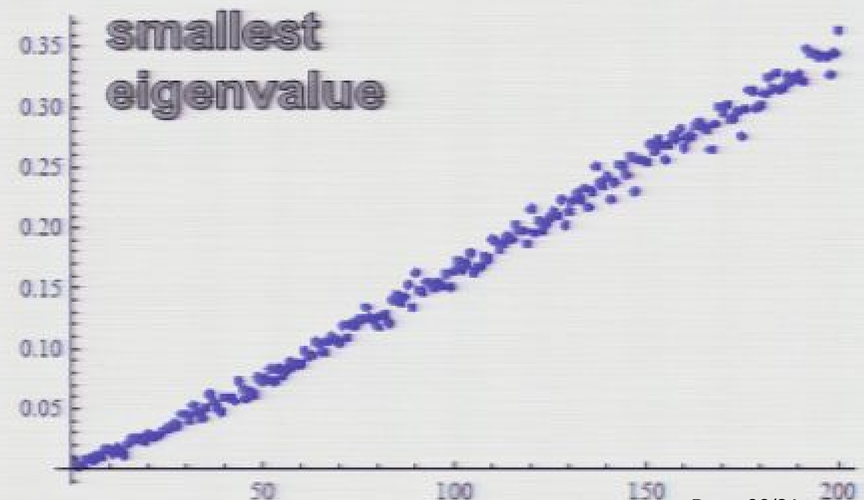
$$\beta(c_f) = \frac{8e^2}{3(4\pi)^2}\frac{(c_f - c_g)\left(4c_f^2 + 3c_f c_g + c_g^2\right)}{c_g\,(c_f + c_g)^2}$$

- 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

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



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

- As an example: non covariant QED

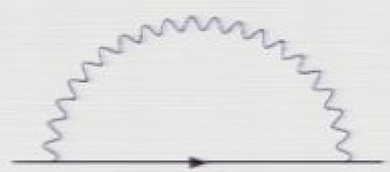
$$\mathcal{L}_r = -\frac{1}{4}F_{r\,\mu\nu}F_r^{\mu\nu} + i\bar{\psi}_r\left(\partial_0 + iec_g A_{r\,0}\right)\gamma^0\psi_r$$
$$-i\bar{\psi}_r\left(c_f\vec{\partial} + iec_f\vec{A}_r\right)\cdot\vec{\gamma}\psi_r\,,$$

standard interaction

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

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

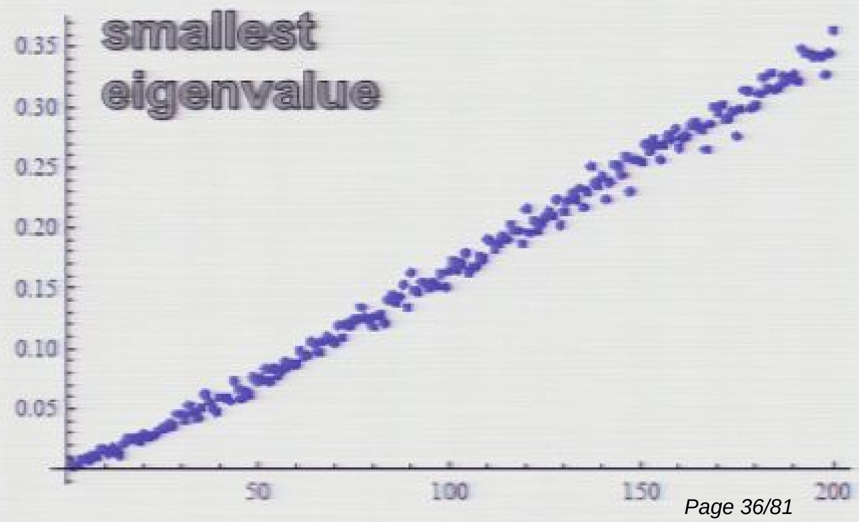
$$S_f\left(p^0,\vec{p}\right) = \frac{i}{p^0\gamma^0 - c_f\vec{p}\cdot\vec{\gamma}}$$



Universal limiting speed

- 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

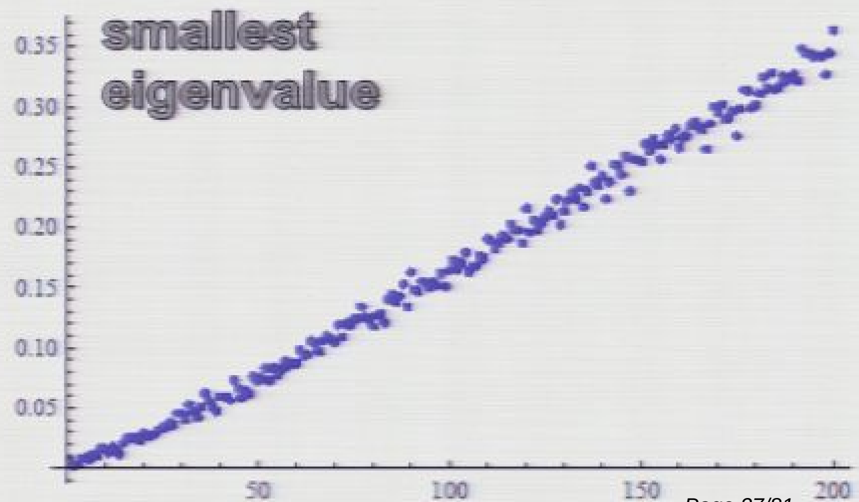
$$= i\bar{\psi}_a\gamma^0\partial_0\psi_a - ic_{f_a}\bar{\psi}_a\vec{\gamma}\cdot\vec{\partial}\psi_a + \frac{1}{2}\partial_0\phi_i\partial_0\phi_i$$
$$-\frac{1}{2}c_{b_i}^2\vec{\partial}\phi_i\cdot\vec{\partial}\phi_i - \bar{\psi}_a\left(u^i_{ab} + i\gamma^5 v^i_{ab}\right)\psi_b\phi_i$$



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

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



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

- As an example: non covariant QED

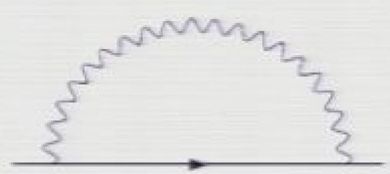
$$\mathcal{L}_r = -\frac{1}{4} F_{r\,\mu\nu} F_r^{\mu\nu} + i\bar{\psi}_r \left(\partial_0 + iec_g A_{r\,0}\right) \gamma^0 \psi_r$$
$$-i\bar{\psi}_r \left(c_f \vec{\partial} + iec_f \vec{A}_r\right) \cdot \vec{\gamma} \psi_r \,,$$

standard interaction

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

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

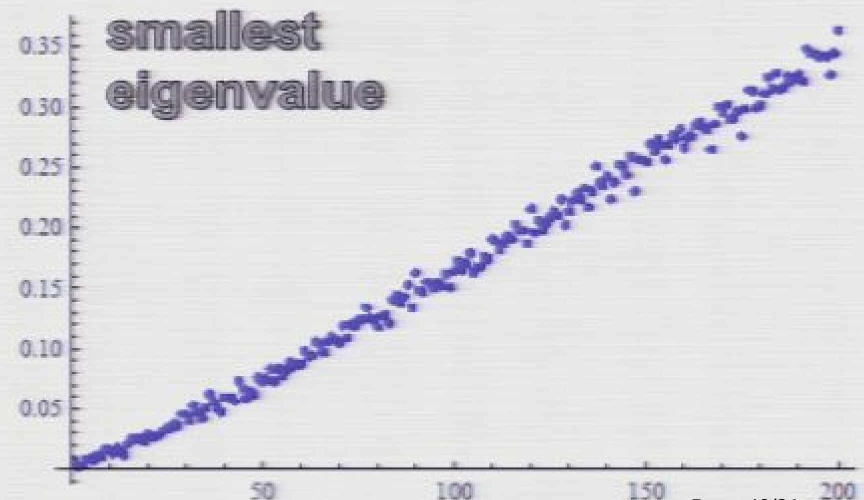
$$S_f\left(p^0, \vec{p}\right) = \frac{i}{p^0 \gamma^0 - c_f \vec{p} \cdot \vec{\gamma}}$$



Universal limiting speed

- 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

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



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** $|\eta| \lesssim 10^{-14}$ → $10^{10^{13}}$ GeV

Universal limiting speed

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

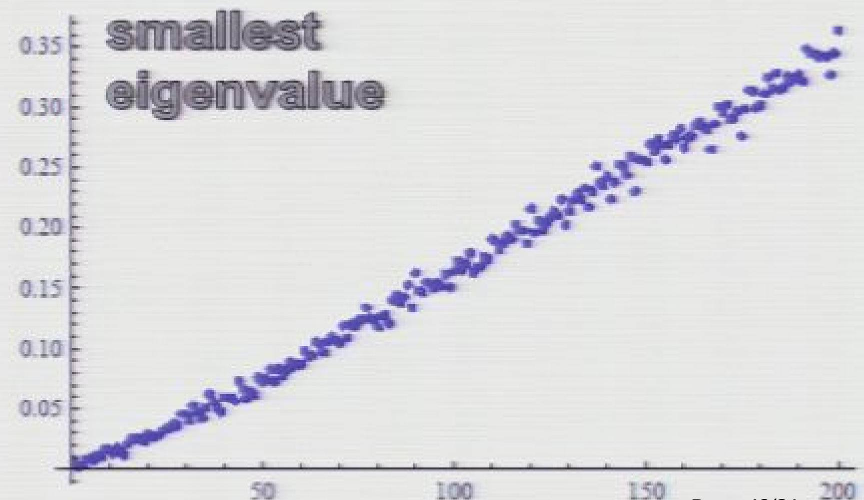
$$\beta(c_f) = \frac{8e^2}{3(4\pi)^2}\frac{(c_f - c_g)\left(4c_f^2 + 3c_f c_g + c_g^2\right)}{c_g (c_f + c_g)^2}$$

- 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

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



Universal limiting speed

- However the coupling itself runs:

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

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

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

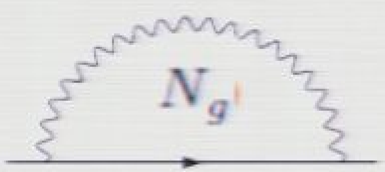
Logarithmic running

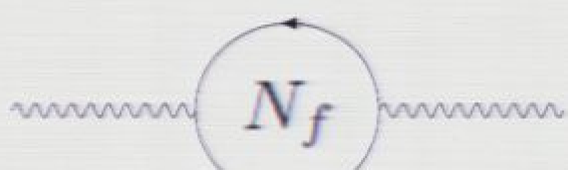
$$\eta(\mu) = \eta_* \left[\frac{\log\left(\frac{\Lambda^2}{\mu_*^2}\right)}{\log\left(\frac{\Lambda^2}{\mu^2}\right)} \right]^{\frac{2b}{5}} = \eta_* \left[\frac{g^2(\mu)}{g^2(\mu_*)} \right]^{\frac{2b}{5}}$$

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

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.
- Most of the U(1) fields are massive and decouple





Universal limiting speed: toward model building

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

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

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

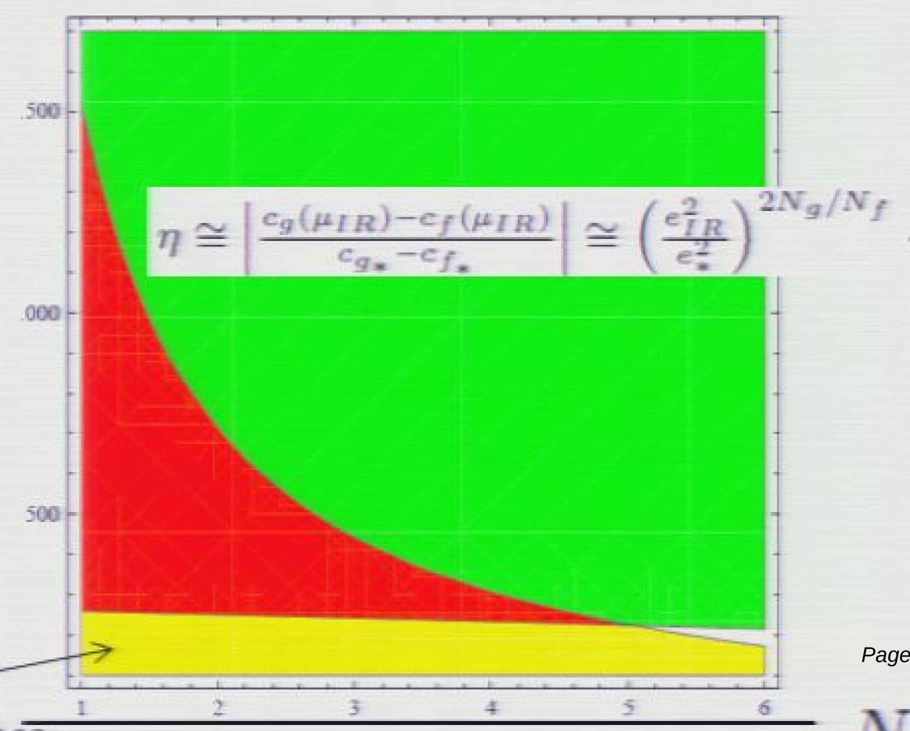
$$\eta \cong \left|\frac{c_g(\mu_{IR}) - c_f(\mu_{IR})}{c_{g_*} - c_{f_*}}\right| \cong \left(\frac{e_{IR}^2}{e_*^2}\right)^{2N_g/N_f} < 10^{-14}$$

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

μ_*/μ_{IR} =10^{16}

$e_*^2 < 4\pi$

N_g



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.

Universal limiting speed: toward model building

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

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

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

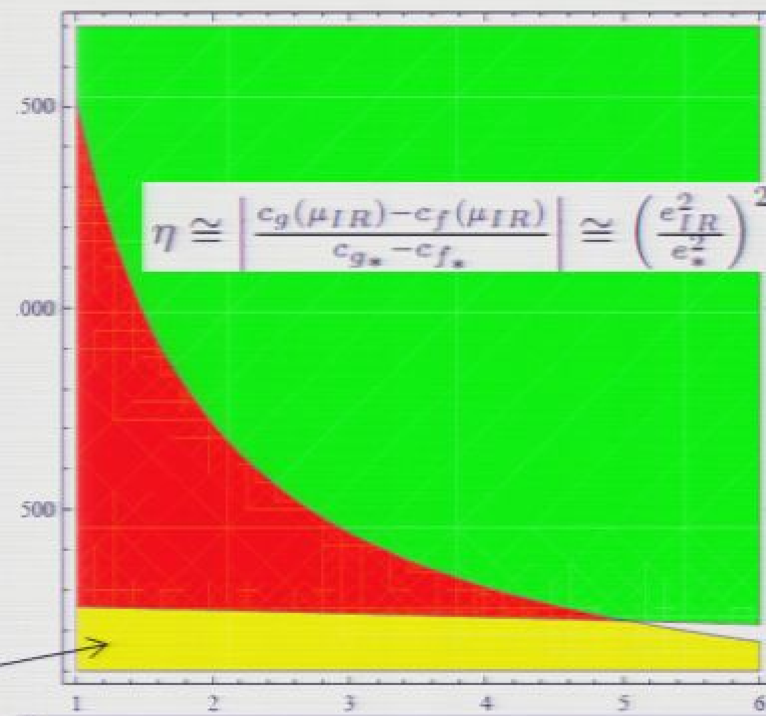
$$\eta \cong \left|\frac{c_g(\mu_{IR})-c_f(\mu_{IR})}{c_{g_*}-c_{f_*}}\right| \cong \left(\frac{e_{IR}^2}{e_*^2}\right)^{2N_g/N_f} < 10^{-14}$$

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

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

$e_*^2 < 4\pi$

N_g



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.

Main points

✓ Constraints on emergent theories

Phenomenological Procedure:

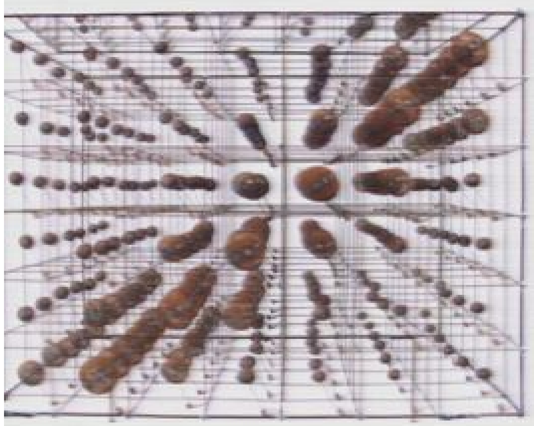
✓ The emergence of a universal limiting speed

- Emergence of gauge symmetry and experimental constraints

Phenomenology of emergent gravity

- ***We use different techniques***
- If symmetries are emergent?
- We test how likely some symmetries are emergent.
- Example: emergence of phonons on a lattices

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



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

$$i \to x$$

$$y_i \to \phi$$

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

Small violation

$$\phi \left(\frac{1}{c^2}\partial_t^2 - \partial_x^2\right)\phi$$

Emergent Lorentz

Phenomenology of emergent gravity

- We test how likely gauge symmetries (redundancy) are emergent.
- We test any small deviation from exact symmetry: smoking gun for emergence?
- All deviations are suppressed by a large scale
- Largest scale is M_p . But gravity is already suppressed by this scale.
- So, any deviations should appear in the gravity sector.

Phenomenology of emergent gravity

- People have studied gravity with broken Lorentz
- General covariance (general coordinate transformation, diffeomorphism (Diff)) is sacred
- Testing the breaking of Diff has not been done before (exception: Pauli-Fierz)

Phenomenology of emergent gravity

M.A. J. F. Donoghue, and U. Aydemir, arXiv:0911.4123

- Effective field theory framework: write down all operators consistent with your symmetry (Lorentz) (on top of General Relativity GR)

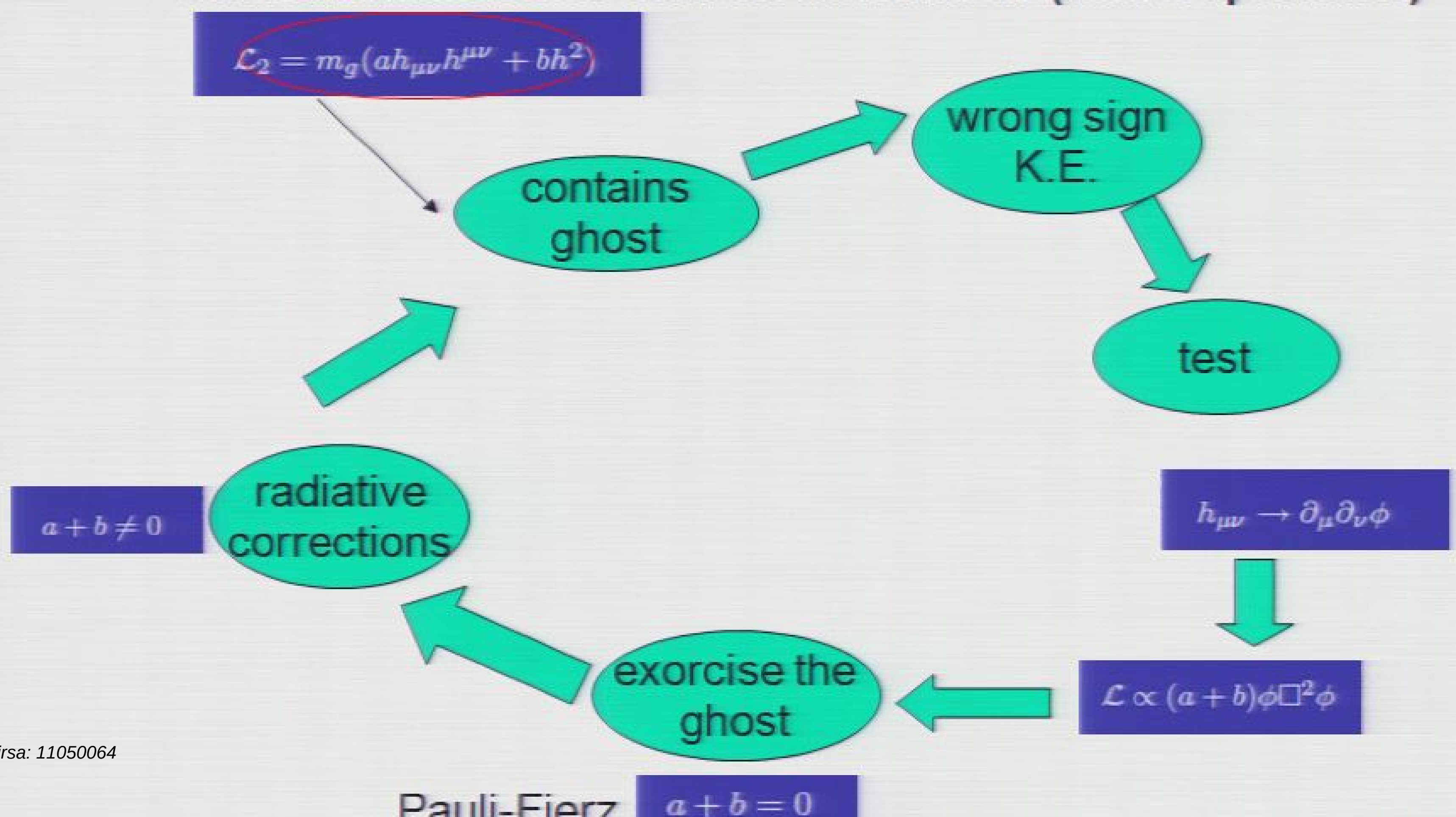
$$\mathcal{L} = \sqrt{g}R$$

- We consider flat background

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Phenomenology of emergent gravity

- **We start from terms with no derivatives (dim-2 operators)**



Phenomenology of emergent gravity

- Pauli-Fierz: vDVZ discontinuity, wrong prediction for light bending

$$G^{GR}_{\mu\nu,\alpha\beta} = \frac{1}{2}\frac{\eta_{\mu\alpha}\eta_{\nu\beta}+\eta_{\mu\beta}\eta_{\nu\alpha}-\eta_{\mu\nu}\eta_{\alpha\beta}}{k^2}$$

$$G^{PF}_{\mu\nu,\alpha\beta} = \frac{1}{2}\frac{\eta_{\mu\alpha}\eta_{\nu\beta}+\eta_{\mu\beta}\eta_{\nu\alpha}-\frac{2}{3}\eta_{\mu\nu}\eta_{\alpha\beta}}{k^2-m^2}$$

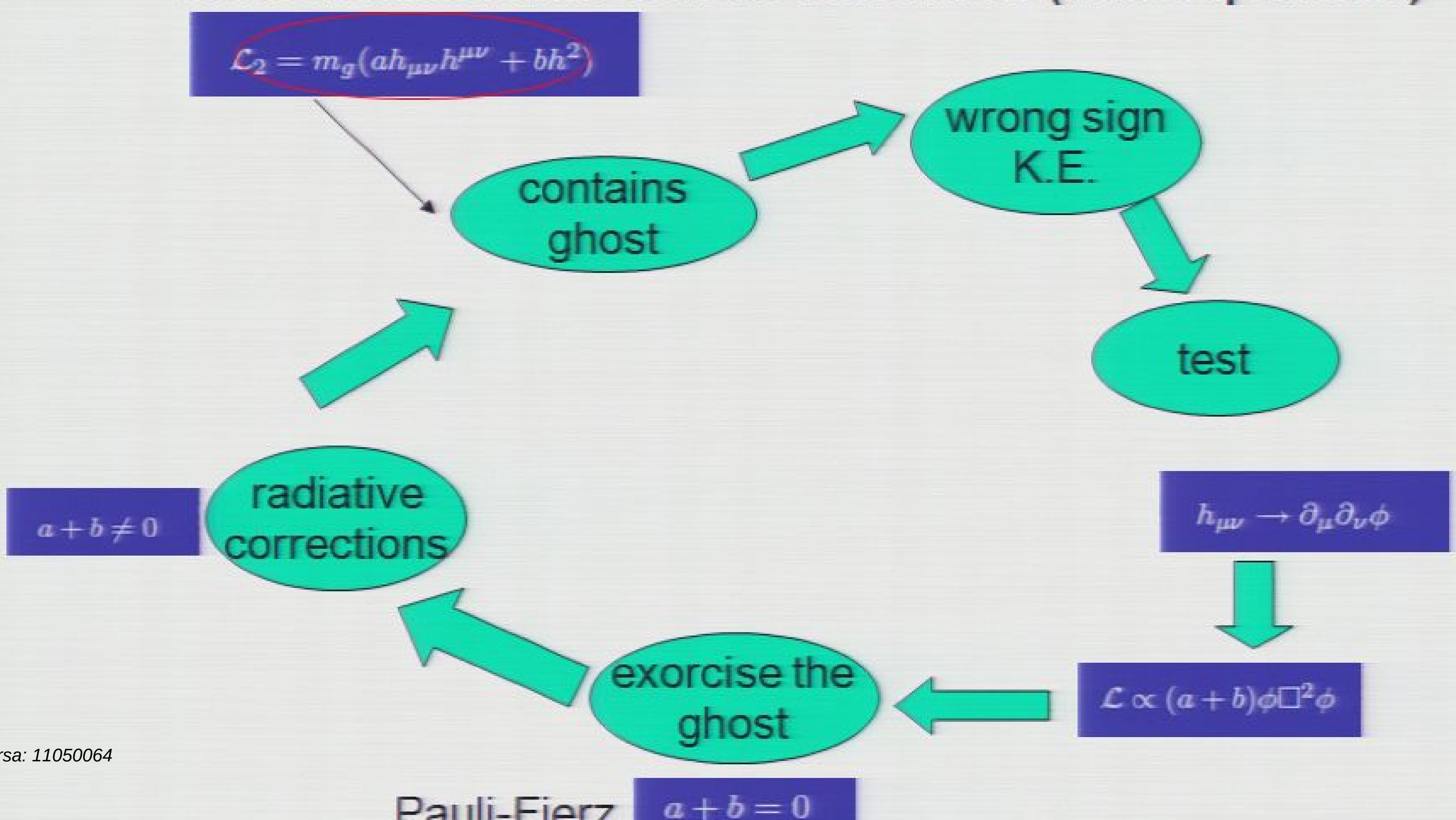
- Many studies, essentially $m = 0$

Phenomenology of emergent gravity

- The massive gravity contains 2-dim operators.
- We can go ahead and list all possible 3, 4, etc dim operators.
- However, we will do with 4 dim operators, and namely with two derivatives
- These terms have the same number of derivatives as in GR.

Phenomenology of emergent gravity

- **We start from terms with no derivatives (dim-2 operators)**



Phenomenology of emergent gravity

M.A. J. F. Donoghue, and U. Aydemir, arXiv:0911.4123

- Effective field theory framework: write down all operators consistent with your symmetry (Lorentz) (on top of General Relativity GR)

$$\mathcal{L} = \sqrt{g} R$$

- We consider flat background

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Phenomenology of emergent gravity

- Pauli-Fierz: vDVZ discontinuity, wrong prediction for light bending

$$G^{GR}_{\mu\nu,\alpha\beta} = \frac{1}{2}\frac{\eta_{\mu\alpha}\eta_{\nu\beta}+\eta_{\mu\beta}\eta_{\nu\alpha}-\eta_{\mu\nu}\eta_{\alpha\beta}}{k^2}$$

$$G^{PF}_{\mu\nu,\alpha\beta} = \frac{1}{2}\frac{\eta_{\mu\alpha}\eta_{\nu\beta}+\eta_{\mu\beta}\eta_{\nu\alpha}-\frac{2}{3}\eta_{\mu\nu}\eta_{\alpha\beta}}{k^2-m^2}$$

- Many studies, essentially $m = 0$

Phenomenology of emergent gravity

- The massive gravity contains 2-dim operators.
- We can go ahead and list all possible 3, 4, etc dim operators.
- However, we will do with 4 dim operators, and namely with two derivatives
- These terms have the same number of derivatives as in GR.

Phenomenology of emergent gravity

- We consider $$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\,\mathcal{L}_{dim_4}$$

$$\mathcal{L}_{dim-4} = \sum_{i=1}^{7} a_i \mathcal{L}_i$$

very small

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

$$f(\mathcal{L}_1, \mathcal{L}_2)$$

Phenomenology of emergent gravity

- **Linear analysis** $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

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

- **Energy momentum tensor is conserved**

$$2\,(a_3 + a_4)\,\Box \partial_\beta h^{\alpha\beta} + (a_1 + a_2 - a_3)\,\partial^\alpha \partial_\mu \partial_\nu h^{\mu\nu} + (a_5 - a_4)\,\partial^\alpha \Box h = 0\,.$$

- **For general values of** $\{a_i\}$ $\partial_\alpha h^{\alpha\beta} = 0\,,$ and $a_4 = a_5$

compatible with GR

Notice the misconception!
GR is not the general result!

Phenomenology of emergent gravity

- **The propagator:** $\mathcal{L} \sim h_{\mu\nu} O^{\mu\nu,\alpha\beta} h_{\alpha\beta}$ **with** $\Lambda \left(\partial^\alpha h_{\alpha\beta}\right)^2$

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

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

well behaved

but!!

Phenomenology of emergent gravity

- **Break Diff → other degrees of freedom appear**
- **Tensor + Vectors + Scalars**

graviton

does not interact with matter

worrisome ghost?

Phenomenology of emergent gravity

- **Hunting the ghost**

Spin-2

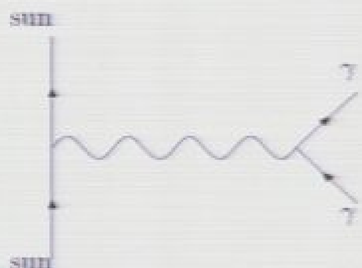
$$\frac{2G}{k^2}\left[T^{\mu\nu}_{(1)}T_{(2)\,\mu\nu}-\frac{1}{2}T_{(1)}T_{(2)}\right]$$
$$-\frac{G}{k^2}\frac{a_1+a_2-3a_3-2a_4}{2-a_1-3a_2+3a_3+6a_4}T_{(1)}T_{(2)}$$

to exorcise the ghost

$$a_1+a_2-3a_3-2a_4\leq 0$$

Experimental constraints on emergent gravity

- **Light bending test: linear theory**



scattering amp.

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

- **Experimental constraints from light bending**

$\{a_i\} \sim 10^{-5}$

Experimental constraints on emergent gravity

- **Nonlinear analysis: e.g.** $\mathcal{L}_3$

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

- **Conservation of energy-momentum** $\nabla^\mu T_{\mu\nu} = 0$

- **Geometry** $\nabla^\mu G_{\mu\nu} = 0$

$$\nabla^\mu \mathcal{M}_{\mu\nu} = 0$$

($\partial_\alpha h^{\alpha\beta} = 0$) for linear theory

Experimental constraints on emergent gravity

- Complete analysis: post-Newtonian formalism
- Why post-Newtonian?
- Exact solutions? difficult
- Departure from spherical symmetry? do not even try!
- We need a systematic way to test the theory beyond Newton: post-Newtonian

Experimental constraints on emergent gravity

- **What is post-Newtonian?: perturbation**

- **Expanding parameter:** v

- **Matter: perfect fluid**

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

- **Expansion**

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

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

Experimental constraints on emergent gravity

- Complete analysis: post-Newtonian formalism
- Why post-Newtonian?
- Exact solutions? difficult
- Departure from spherical symmetry? do not even try!
- We need a systematic way to test the theory beyond Newton: post-Newtonian

Experimental constraints on emergent gravity

- **What is post-Newtonian?: perturbation**
- **Expanding parameter:** v
- **Matter: perfect fluid**

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

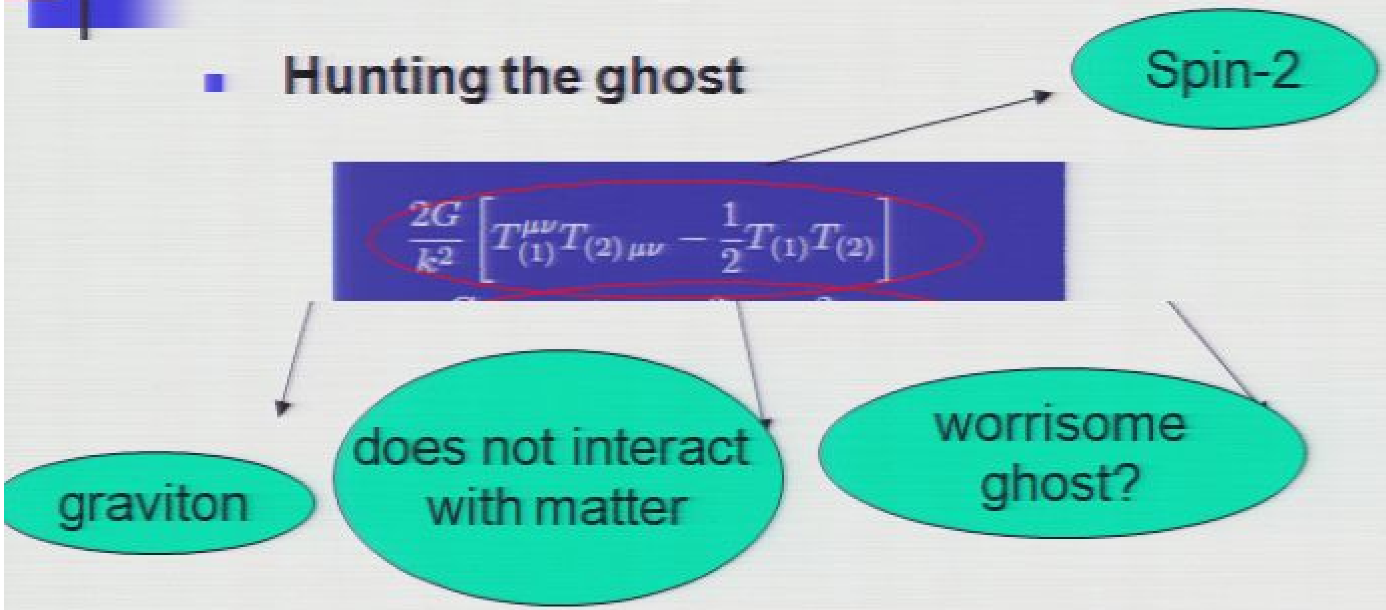
- **Expansion**

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

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

Phenomenology of emergent gravity

- **Hunting the ghost**



$$\frac{2G}{k^2}\left[T^{\mu\nu}_{(1)}T_{(2)\,\mu\nu} - \frac{1}{2}T_{(1)}T_{(2)}\right]$$

Phenomenology of emergent gravity

- **We consider** $S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\,\mathcal{L}_{dim_4}$

$\mathcal{L}_{dim-4} = \sum_{i=1}^{7} a_i \mathcal{L}_i$ → very small

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

$\mathcal{L}_6, \mathcal{L}_7$ → $f(\mathcal{L}_1, \mathcal{L}_2)$

Phenomenology of emergent gravity

- **The propagator:** $\mathcal{L} \sim h_{\mu\nu} O^{\mu\nu,\alpha\beta} h_{\alpha\beta}$ **with** $\Lambda \left(\partial^\alpha h_{\alpha\beta}\right)^2$

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

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

well behaved

but!!

Experimental constraints on emergent gravity

- Complete analysis: post-Newtonian formalism
- Why post-Newtonian?
- Exact solutions? difficult
- Departure from spherical symmetry? do not even try!
- We need a systematic way to test the theory beyond Newton: post-Newtonian

Experimental constraints on emergent gravity

- **What is post-Newtonian?: perturbation**
- **Expanding parameter:** v
- **Matter: perfect fluid**

$$
\begin{aligned}
g_{00} &= -1 + \overset{(2)}{g_{00}} + \overset{(4)}{g_{00}} + \dots, \quad g_{ij} = \delta_{ij} + \overset{(2)}{g_{ij}} + \overset{(4)}{g_{ij}} + \dots \\
g_{0i} &= \overset{(3)}{g_{0i}} + \overset{(5)}{g_{0i}} + \dots,
\end{aligned}
$$

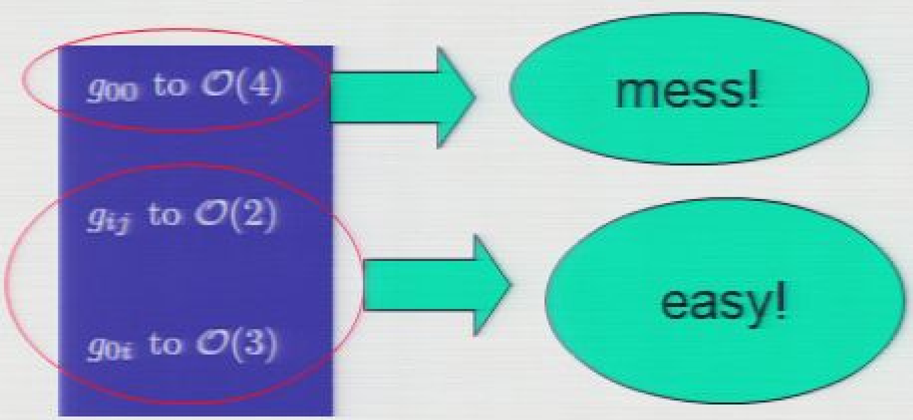
- **Expansion**

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

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

Experimental constraints on emergent gravity

- **Needed accuracy for solar-system tests**



Experimental constraints on emergent gravity

- **At the end**

compare

Parameterized post-Newtonian

$$
\begin{aligned}
g_{00} &= -1 + 2U - 2\beta U^2 - 2\xi \Phi_W + (2\gamma + 2 + \alpha_3 + \zeta_1 - 2\xi)\Phi_1 \\
&\quad + 2(3\gamma - 2\beta + 1 + \zeta_2 + \zeta)\Phi_2 + 2(1 + \zeta_3)\Phi_3 \\
&\quad + 2(3\gamma + 3\zeta_4 - 2\xi)\Phi_4 - (\zeta_1 - 2\xi)\mathcal{A}
\end{aligned}
$$

$$
\begin{aligned}
\overset{(4)}{g}_{00} &= \left(-1 + \frac{15}{2}a\right) U^2 + \left(1 - \frac{5}{2}a\right)\Phi_W \\
&\quad + \left(4 - \frac{11}{2}a\right)\Phi_1 + \left(3 - \frac{59}{2}a\right)\Phi_2 \\
&\quad + 2\Phi_3 + (6 - 24a)\Phi_4 - \frac{5}{2}a(\mathcal{A} + \mathcal{B}) \\
&\quad + \frac{a}{2} U_{ij} U_{ij} + a\mathcal{V}.
\end{aligned}
$$

PPN gauge!

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

new terms

Experimental constraints on emergent gravity

- **Read the parameters compare to experiment**

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	$\frac{5}{8}a$	—	—

preferred location effect

referred frame effect

Violation of Cons. f total momentum

Conclusion

-Emergent phenomena is relatively new, and deserves more study

- We adopted a phenomenological procedure to study emergence

-Our studies may indicate that if gauge invariance is emergent then it might be exact

-Mechanism to build models for an emergent universal speed of light

-More phenomenological tests are on the way