Title: Emergence and Effective Field Theories in Gravitational Physics

Date: Oct 28, 2011 11:00 AM

URL: http://pirsa.org/11100072

Abstract: This talks will focus on a particular example of emergent phenomenon in a particular system. By adding to our repertoire of emergent phenomena, it may help deepen our discussions of the topic in the abstract. The system belongs to the new family that has swept condensed matter physics and goes by the name of topological insulators, which paradoxically also includes superÂ°uids and superconductors for these too have no low energy excitations in the bulk. While no one cared much about insulators (except while standing on one of them to change a light bulb or fuse) things changed when it was realized that insulators come in two kinds. The topological ones have gapless excitations at the edge while the others do not. The bulk topological quantum number implies a gapless edge and prevents any smooth or continuous perturbation like disorder from producing a gap. Consider the d dimensional bulk superconductor with its N-particle wavefunction Â©(r1; ; ; rN). The gapless edge has dÂ¡1 spatial dimensions and a d dimensional Euclidean spacetime. Let G(r1; ; ; rN) denote its N-point correlation functions of Heisenberg Â¯eld operators. It had been noticed that quite remarkably Â©(r1; ; ; rN) = G(r1; ; ; rN) for a family of superconductors and superÂ°uids. How can a nonrelativistic thing like a wave function in the bulk equal relativistic correlation function at the edge? Ashvin Vishwanath (Berkeley) and I showed that this follows from the approximate Lorentz invariance of the Euclidean action. Our explanation along with necessary background will be furnished.

Emergence and Effective Field Theories in Gravitational Physics

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Introduction PN models EFT models EFT & Explanatio

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- Emergence$_{\text{PHYS}}$: very roughly, emergent phenomena or properties figure in upper-level models but not in base-level models.
  - Often—perhaps always—upper-level models describe emergent$_{\text{PHYS}}$ phenomena.
- Emergence$_{\text{PHIL}}$: very roughly, emergent phenomena or properties cannot be explained by, predicted from, and/or reduced to the base-level model.

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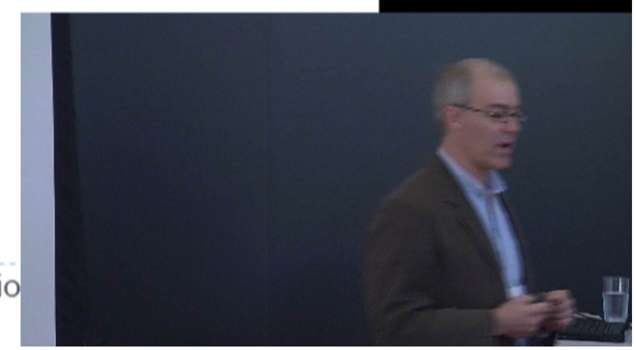
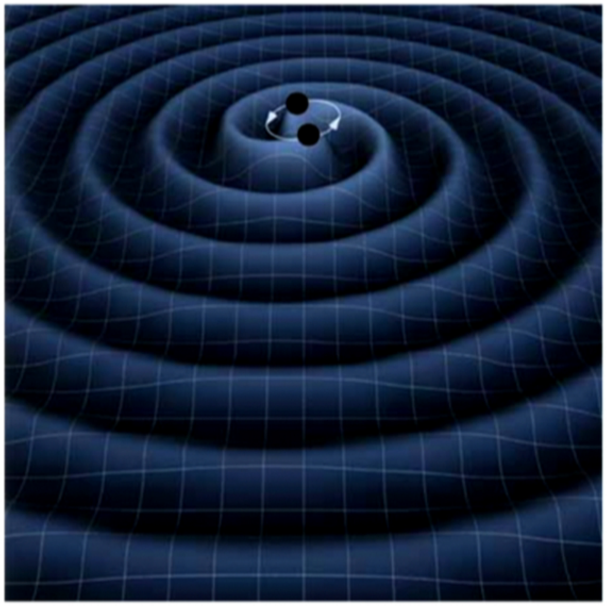
- Emergence$_{PHIL}$: very roughly, emergent phenomena or properties cannot be explained by, predicted from, and/or reduced to the base-level model.
  - Most philosophers used to think there are no emergent$_{PHIL}$ phenomena in physics. One thing we have learned from Batterman's work is that the question of whether a phenomenon is emergent$_{PHIL}$ is non-trivial and interesting!

Emergence as explanatory failure

- Both emergent [$\equiv$emergent$_{\mathrm{PHIL}}$] and resultant phenomena are determined by (supervene on) base-level physics.
- Emergence is a failure of explanation at the base level (cf. Wayne, *Synthese* 2010).

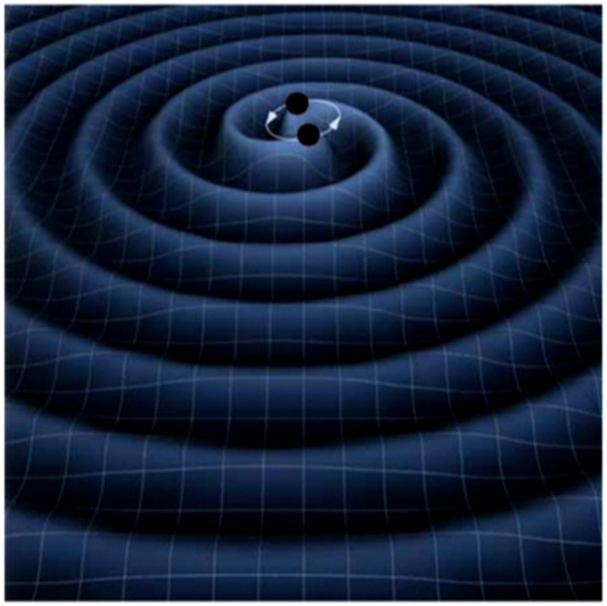


EFTs in gravitational physics



EFTs in gravitational physics

- EFTs have been used very successfully in gravitational physics.
- An inspiral system consists of two compact bodies (e.g., black holes or neutron stars) spiralling inward and emitting gravitational radiation.
- Traditionally, these systems have been modeled using post-Newtonian methods.

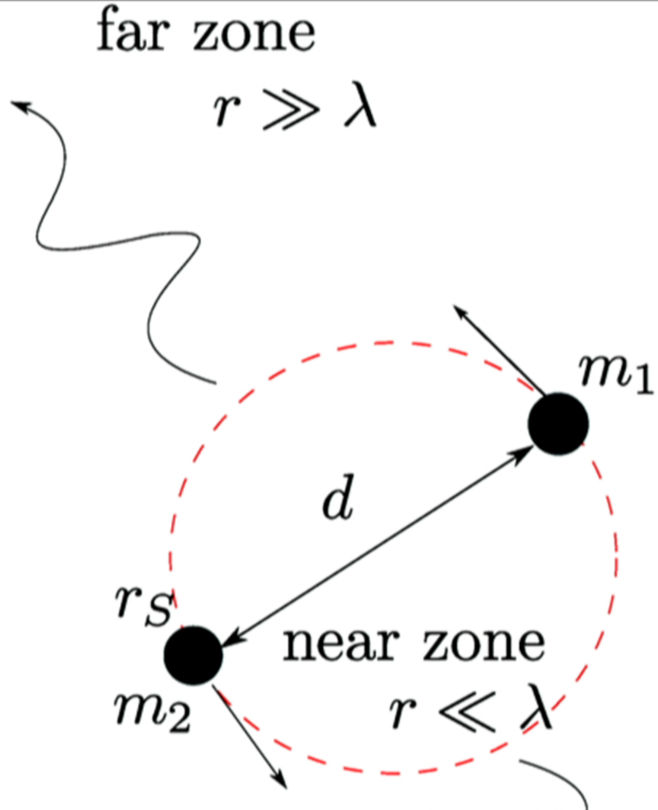


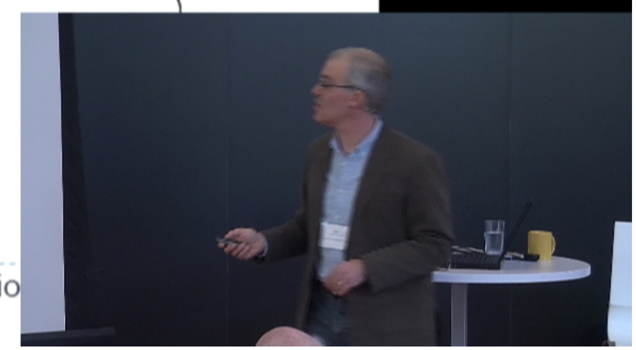
The argument

- I argue that EFT models in gravitational physics underwrite base-level explanations. This is because
  - PN models underwrite base-level explanations, and
  - EFTs provide explanations at least as good as and independent of PN models.
- I conclude that EFTs do not predict or describe any emergent phenomena in inspiral systems modeled by PN methods.

Two-body inspiral systems

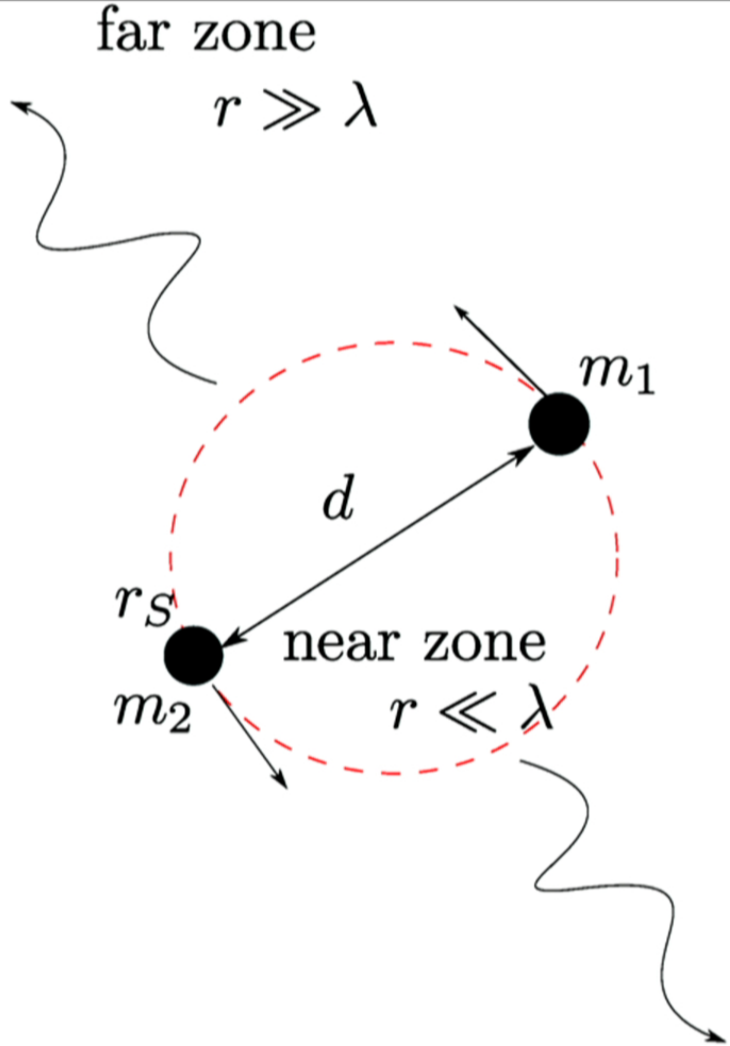
- Typical length scales
  $r_s \sim 1$ km
  near zone $\sim d \sim 100$ km
  $\lambda \sim 10^6$ km
  far zone $\sim$ light years





Two-body inspiral systems

- Typical length scales
  r_s ~ 1 km
  near zone ~ *d* ~ 100 km
  λ ~ 10^6 km
  far zone ~ light years
- Gravitational wave detectors, such as LIGO (Laser Interferometer Gravitational-Wave Observatory) aim to detect the gravitational waves emitted from these sorts of events.



The post-Newtonian approach

- Standard approach to predicting and explaining the observable far-zone gravitational waves uses post-Newtonian approximation methods
- These are applications of singular perturbation theory to the Einstein Field Equations.
- The PN approach is effective where the bodies have low velocities, the gravitational field is weak, and the masses are about equal.
- Perturbation is in orders of v, the velocity of the masses.
- Inspiral systems are "[p]ossibly the most remarkable example of the unreasonable effectiveness of post-Newtonian theory" (Will 2007, 6)

Weak-field expansion

- Write the metric in the weak-field form
  - $$g^{\alpha\beta} = \eta^{\alpha\beta} + \sum_{n=1}^{\infty} G^{n}\, {}^{(n)}h^{\alpha\beta}$$

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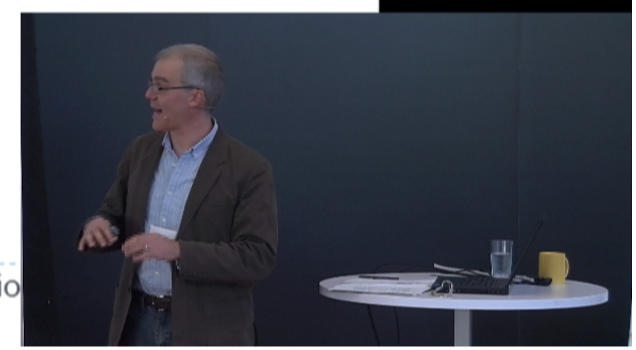
- $\eta^{\alpha\beta}$ is the Minkowski metric and ${}^{(n)}h^{\alpha\beta}$ is the perturbation component of order *n* of the metric.
- Write down the Einstein Field Equations as a wave equation.
  - $$\Box h_{\alpha\beta} = J_{\alpha\beta}$$



Weak-field expansion

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- Write down the Einstein Field Equations as a wave equation.
  - $$\Box h_{\alpha\beta} = J_{\alpha\beta}$$
- Expand in orders of velocity $v \ll c$ and solve.
- Above v^6 (3PN) finite size effects of the bodies become relevant (internal structure, tidal effects).
- The PN approximation treats finite size effects (of what is actually an extended body) as a point particle with higher-order multipole terms.

PN model: the near zone

- In the near-zone $r \sim d \ll \lambda$, because of the small distances and slow velocities one can ignore retardation effects, so the wave operator becomes a Laplacian.
- The equation to first order in the metric is
  - $$\nabla^2[{}^{(1)}h] = (\rho \sim \text{matter sources}),$$
- The equation to second order in the metric is
  - $$\nabla^2[{}^{(2)}h] = (\text{matter sources}) + (\text{terms that depend on } {}^{(1)}h).$$
- This yields equations for the metric in the near zone.
- However, the PN expansion diverges at 2nd and higher orders outside of the near zone, as $r \to \infty$.

PN model: the far zone

- In the far zone, again write the metric in the weak-field form
  - $$g^{\alpha\beta} = \eta^{\alpha\beta} + \sum_{n=1}^{\infty} G^n \, {}^{(n)}h^{\alpha\beta}$$
- In the far zone, get the most general Post-Minkowski expansion
  - $$\Box \, {}^{(n)}h_{\alpha\beta} = {}^{(n)}\Lambda_{\alpha\beta}[h \dots]$$
- To complete the PN model, use a matched asymptotic expansion: take the PN expansion that is valid for the near zone and PM results valid in the far zone, then match in the overlap region ($\sim d$, the orbital scale).

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- To complete the PN model, use a matched asymptotic expansion: take the PN expansion that is valid for the near zone and PM results valid in the far zone, then match in the overlap region ($\sim d$, the orbital scale).
- PN provides a consistent way to obtain a uniformly valid approximation of the metric for a given order in v (or h).

Corollaries

- PN methods involve singular limits.
  - So these explanations provide (another) counterexample to the claim that presence of a singular limit implies explanatory failure and emergence.

The EFT approach to inspiral systems

- EFT approach draws on the use of EFTs in quantum field theory and statistical mechanics to solve multi-scale problems.
- The EFT approach also seems unreasonably effective.
- Construct the effective action for an effective field at each scale and match coefficients at the boundaries to "integrate out" the shorter-range physics.
- Start by constructing the most general effective action consistent with the relevant degrees of freedom and symmetries of the system:

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- Construct the effective action for an effective field at each scale and match coefficients at the boundaries to “integrate out” the shorter-range physics.
- Start by constructing the most general effective action consistent with the relevant degrees of freedom and symmetries of the system:
  - $$S_{\text{eff}}[x^\alpha, g_{\alpha\beta}] = S_{\text{EH}}[g_{\alpha\beta}] + S_{pp}[x^\alpha, g_{\alpha\beta}]$$

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- First term yields geodesic motion; E and B tensors (and higher order terms) are constructed from the Riemann tensor and induce non-geodesic motion. They systematically encode internal structure of body into the near-zone EFT.
- S_{pp} models finite size effects of what is actually an extended body following a geodesic *as* a point particle undergoing non-geodesic motion.

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EFT: the orbital scale

- Assume
  - $$g_{\alpha\beta} = \eta_{\alpha\beta} + \frac{h^F{}_{\alpha\beta}}{m_{Pl}}.$$
- To integrate out orbital scale, split
  - $$h^F{}_{\alpha\beta} = h_{\alpha\beta} + H_{\alpha\beta}\,.$$
  - H are potential modes, short wavelength.
  - h are radiation modes, long wavelength.
- Integrate out H by computing the path integral
  - $e^{iS_{\mathrm{NR}}[h,x_a]} = \int D\, H_{k,\alpha\beta}(x^0)\;\; e^{i(S_{\mathrm{EH}}[h+H]+S_{pp}[h+H,x_a])}$
- This is matching the long-distance EFT (the radiation modes) to the orbital scale particle worldlines to obtain an effective action that depends only on h and x_a.

EFT: the far zone

- Write
  - $$e^{iS_{eff}[x_a]} = \int Dh_{\alpha\beta}(x) e^{iS_{\mathrm{NR}}[h,xa]}$$
- Compute diagrams with first-order radiative corrections (one loop diagrams).
- Use a prescription from QFT that
  - Real part of $S_{eff}[xa]$ yields coupled equations of motion of the two bodies.
  - Imaginary part yields the total power radiated by GWs.
- Finally, the latter gives the observable time-dependent phase (and the far-zone metric to a given order of approximation).

Predictive scope of EFTs

- EFTs have only reproduced the predictions of PN approximations for inspiral systems. But it is claimed that EFTs can yield higher-order results than those obtainable by PN methods.
- EFT models have begun to be applied successfully to other two-body problems, where finite size and/or strong field effects mean that the PN approximation is no longer valid. E.g., self-force problems in the strong-field, high m_1/m_2 sector (small body orbiting a black hole).

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- We'll find out more next month at PI's "Effective Field Theory and Gravitational Physics" conference.
- Predictive scope of EFT at least as good as PN.

Theoretical considerations

- Using only EFT models, one can derive the same uniformly valid ($r > r_s$) approximation to the full metric of GTR as obtained from PN models (Goldberger & Rothstein 2006).
- EFT and PN models are based on the same theoretical content of GTR: in PN, the Einstein Field Equations, in EFT the Einstein-Hilbert effective action, which encodes the EFEs.
- EFT and PN models make use of the same empirical facts about the inspiral system: initial and boundary conditions; finite size features of the compact bodies.
- EFT models have a wider domain of applicability in physical theory than do PN models (PN models, while historically prior, may be more *ad hoc*).

Explanatory power of EFTs

- EFT models underwrite at least as good explanations as do PN models in these inspiral systems. The explanans
  - …describe models with at least as good predictive scope and theoretical power.
  - …are based on the same theoretical considerations and empirical data as PN explanations.
  - … rely on elements of the model (*e.g.*, $H_{\alpha\beta}$) that correspond to physical properties of the inspiral system (approximately Newtonian near-zone potential).

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  - ... rely on elements of the model (*e.g.*, $H_{\alpha\beta}$) that correspond to physical properties of the inspiral system (approximately Newtonian near-zone potential).
- PN models underwrite base-level explanations of far-zone gravitational wave phenomena.
- So EFT models underwrite base-level explanations GWs.

EFTs and emergence

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- Therefore, EFTs do not predict or describe emergent phenomena in these systems.
- I suggest that…
  - This result generalizes to other accounts of emergence$_{\text{PHIL}}$.
  - The result generalizes to other types of gravitational systems in which other methods (non-PN) have traditionally been used.
  - This result generalizes to other areas of physics?