Fields Before Particles

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Image: Nicolas Brunner & Jamie Simmonds

Ontology: what there is

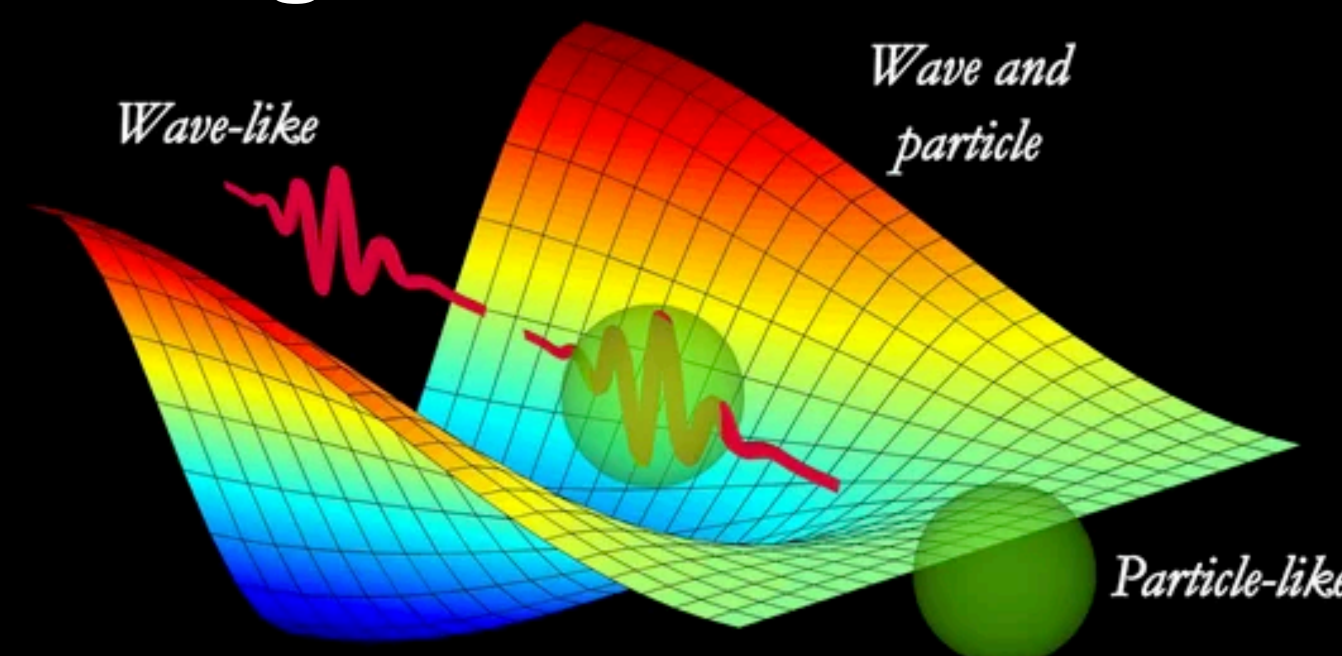
- Detlef Dürr: "Ontology: What there is. The stuff which physics is about. Why does physics need ontology? Because that is what physics is about."
- Feynman: "It is not philosophy we are after, but the behavior of real things."

Central question of this talk:

What is the relation between fields and particles?

I encourage us to not get hung-up on *essentialism*.
I am interested in what is the *more* fundamental, not *the* fundamental ontology.

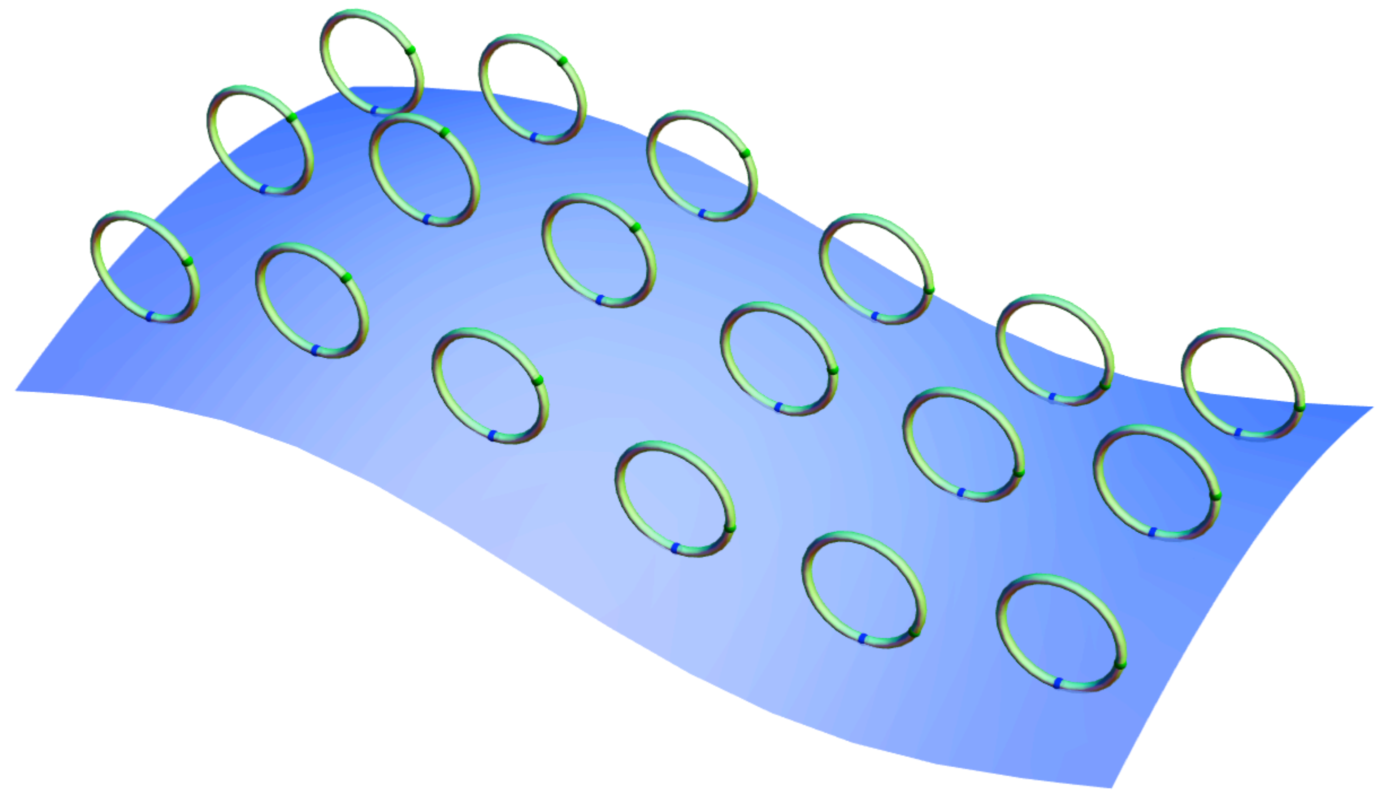
Cognitive dissonance?



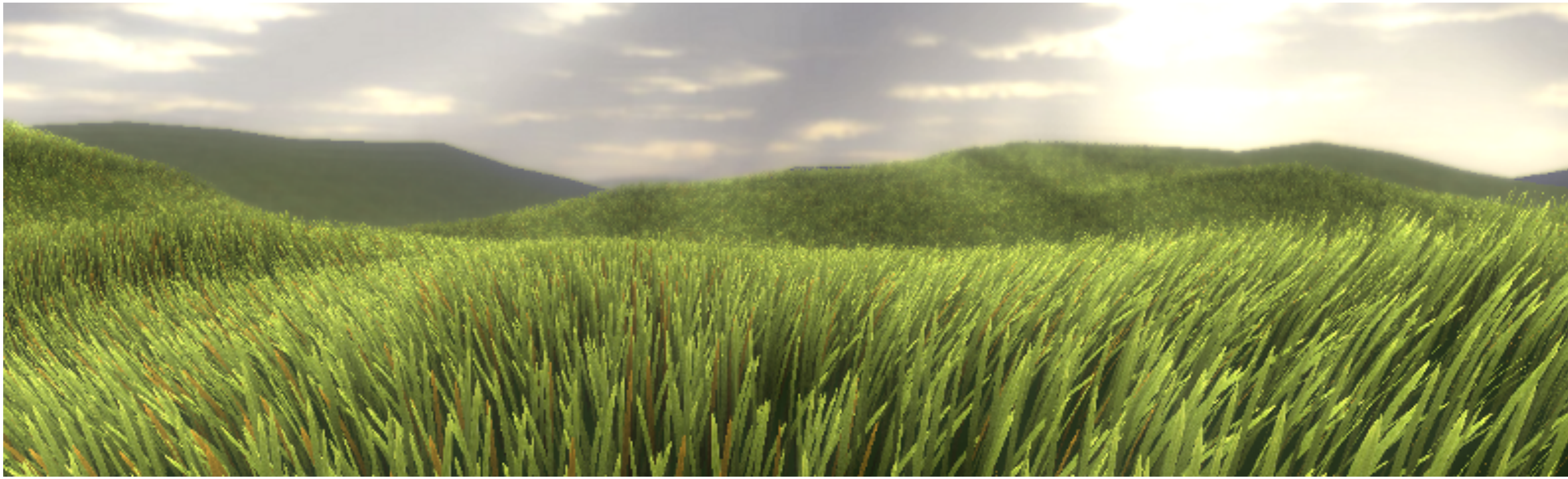
Outline

1. Fields and symmetries
   "symmetry-first physics"
2. Gauge invariance: covariant derivative
3. Interacting QFT concerns - Haag/LSZ
4. Decoherence - emergence of particles

Part 1: Fields and symmetries



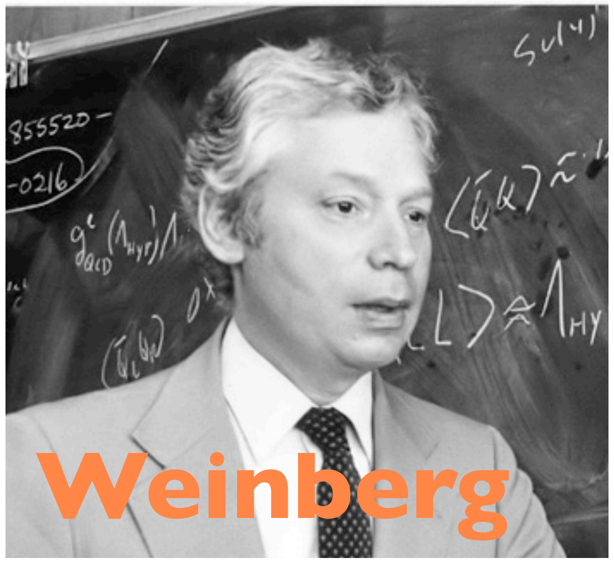
Fields



Fields are a formal way to embody:

1. Local interactions
2. The gauge principle

Weinberg: fields≠wavefunctions≠particles



"In fact, it was quite soon after the Born-Heisenberg-Jordan paper of 1926 that the idea came along that in fact ***one could use quantum field theory for everything***, not just for electromagnetism... Although this is often talked about as *second quantization*, I would like to urge that this description should be banned from physics, because a quantum field is not a quantized wave function. ... ***In its mature form, the idea of quantum field theory is that quantum fields are the basic ingredients of the universe, and particles are just bundles of energy and momentum of the fields.*** In a relativistic theory the wave function is a functional of these fields, not a function of particle coordinates. **Quantum field theory hence led to a more unified view of nature than the old dualistic interpretation in terms of both fields and particles."**

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Weinberg, S. (1996). What is quantum field theory, and what did we think it is?

Orthodox QM as I see it:

State vector in a Hilbert space

$$\exists \, |\Psi\rangle \text{ of the world, and } \exists \, \{|n\rangle\} \text{ such that } \langle n|n\rangle = 1 \text{ and } \langle n|n'\rangle = 0 \tag{1}$$

Superposition principle:

$$|\Psi\rangle = \sum_n a_n \, |n\rangle \tag{2}$$

Observables are eigenvalues of Hermitian operators:

"eigenstate-eingenvalue link"

$$\hat{H} \, |n\rangle = E_n \, |n\rangle \tag{3}$$

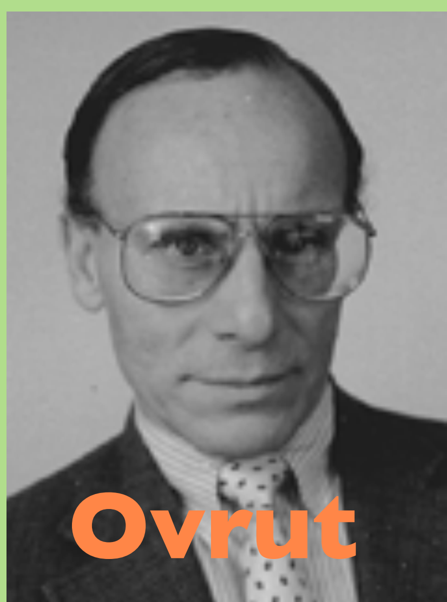
Born rule:

$$P(n) = |\langle n|\Psi\rangle|^2 = |a_n|^2 \tag{4}$$

To the orthodoxy, I would emphasize

Wigner's theorem: (Ovrut's retelling) (also related to Stone's theorem of untiary groups)

The generators of the representation of a transformation in a Hilbert space are the operators representing the classical Noether charges that are conserved under that transformation.



$$\hat{U}_{\text{trans}}(x^{\mu}) = e^{-i\,\hat{P}_{\mu}\,x^{\mu}} \tag{5}$$

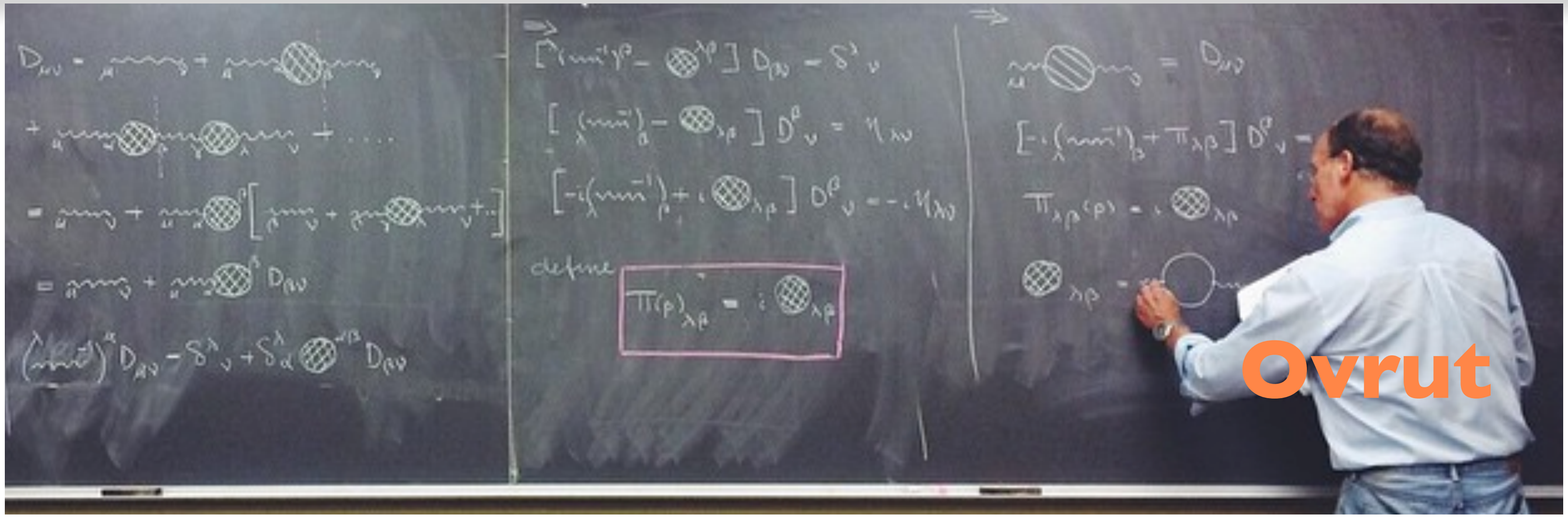
$$\hat{U}_{\text{rot}}(\theta^{\mu\nu}) = e^{-i\,\frac{1}{2}\,\hat{M}_{\mu\nu}\,\theta^{\mu\nu}} \tag{6}$$

How physical symmetries are represented in the Hilbert space!

Derivative QM concepts include:

- Schrödinger equation: $i\hbar\,\partial_t\,|\Psi\rangle = \hat{H}\,|\Psi\rangle$
- Wave function: $\Psi(x) = \langle x|\Psi\rangle = \langle 0|\,\psi(x)\,|\Psi\rangle$

Symmetry-first physics



- ***Enumerate the degrees of freedom*** in the system. For relativistic representations, these are the familiar scalar, vector, spinor, tensor, ...
- ***Quantize once:*** promote the dynamical variables to being opperators in a quantum Hilbert space.
- ***Wigner/Stone:*** require that the generators of physical symmetries satisfy the algebras of those symmetries.

Correlaries are:

- Schrödinger equation
- Wave function
- $p \rightarrow -i \hbar \partial_x$
- ETCR: $[x, p] = i\hbar$
- Spin-statistics

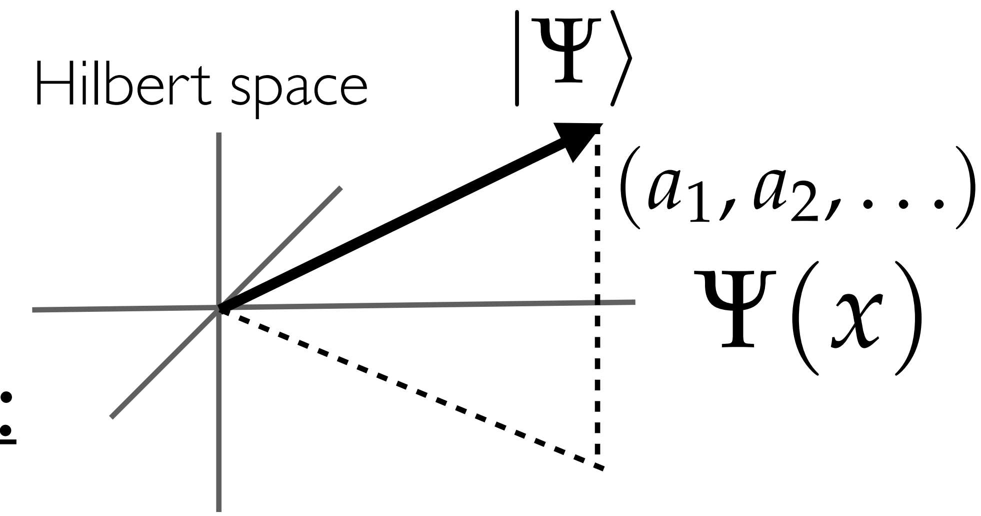
Reece, R. (2006). A Derivation of the Quantum Mechanical Momentum Operator in the Position Representation.

Reece, R. (2007). Quantum Field Theory: An Introduction.

Wave function vs state vector vs field

<u>discrete basis:</u>

$$|\Psi\rangle = \sum_n |n\rangle\langle n|\Psi\rangle = \sum_n a_n\,|n\rangle$$



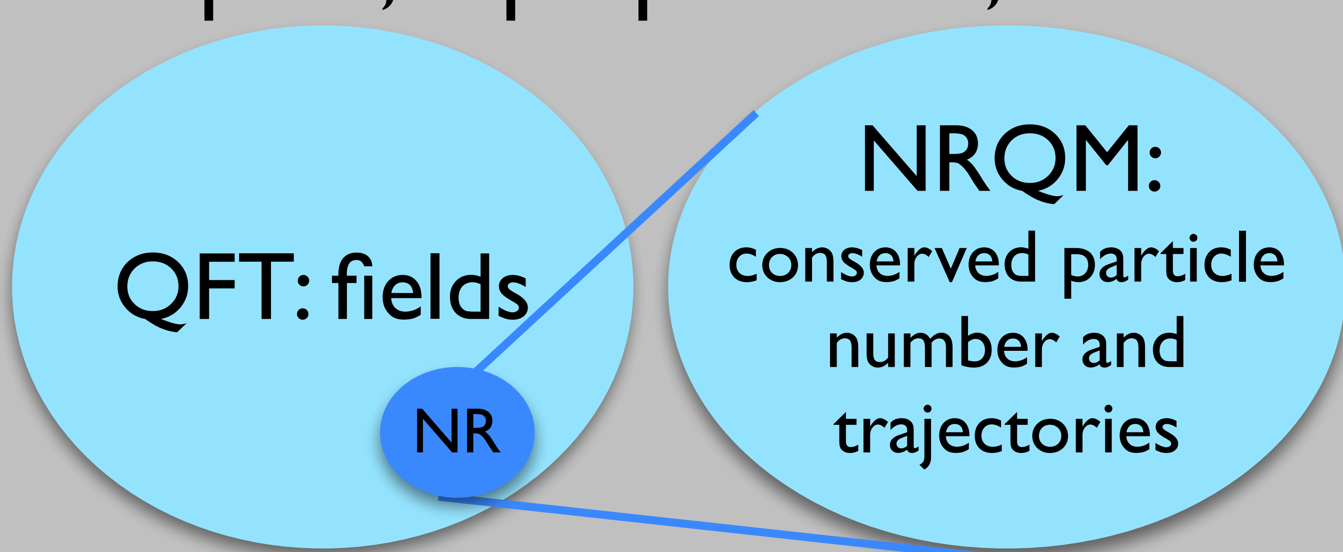
<u>continuous basis (e.g. position/spacetime):</u>

$$|\Psi\rangle = \int dx\,|x\rangle\langle x|\Psi\rangle = \int dx\,\Psi(x)\,|x\rangle$$

⇒ wave function: $\Psi(x) = \langle x|\Psi\rangle \overset{\text{in QFT}}{=} \langle 0|\,\psi(x)\,|\Psi\rangle$ (*local field*: $\psi(x)$)

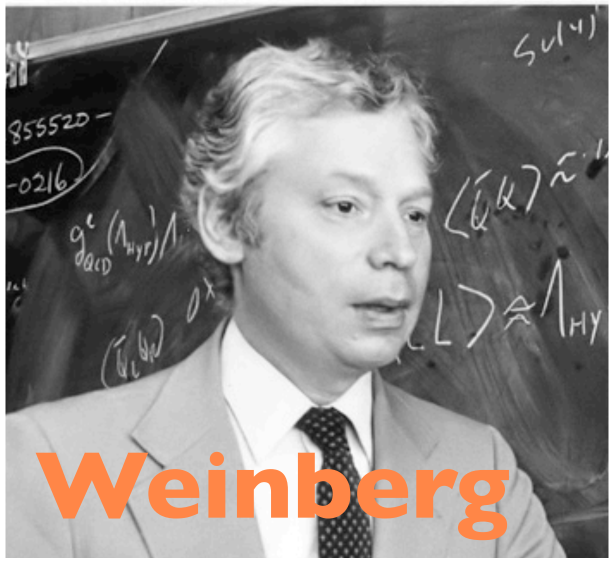
<u>Quantum Mechanics</u>

Hilbert space, superpositions, Born rule...



⇒ QFT *is not* a different theory from QM. It is QM applied to a field ontology.

~~2nd Quantization?~~



"The wave fields φ, ψ, etc, are not probability amplitudes at all, but operators which create or destroy particles in the various normal modes. It would be a good thing if the misleading expression 'second quantization' were permanently retired."
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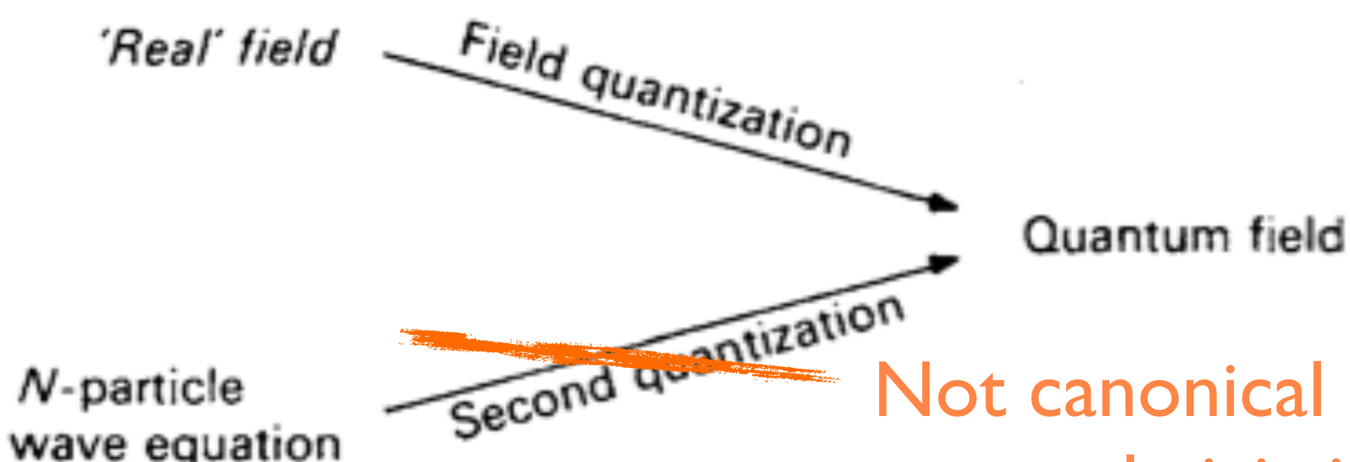
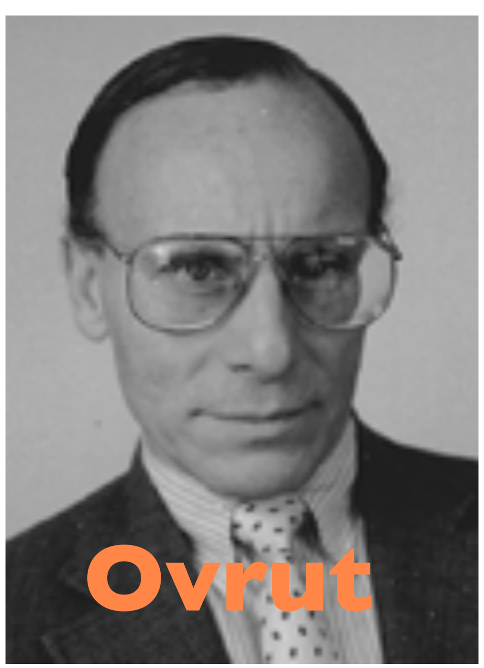
Weinberg, S. (1995). Quantum Theory of Fields, Vol. 1, p. 28.



Not canonical quantization but a nonrelativistic heuristic.



"We take the classical theory and ***quantize it once*** by representing its dynamical variables as operators in a Hilbert space."
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My paraphrase of QFT class with Burt Ovrut at Penn.

wave function: $\Psi(x) = \langle x|\Psi\rangle = \langle 0|\, \psi(x)\, |\Psi\rangle$

"**wavefunctions of quantum mechanics are *not part of the fundamental ontology of the world*. *They emerge, via certain approximations, in a low-energy, nonrelativistic regime.*** Nor are configuration spaces more fundamental than ordinary spacetime. Our quantum field theory is a theory on Minkowski spacetime. For certain states, namely, states of a definite particle number *n*, and for low-energy regimes, we can represent the state via a function on a 3*N*-dimensional space, but this representation is not available for arbitrary states.

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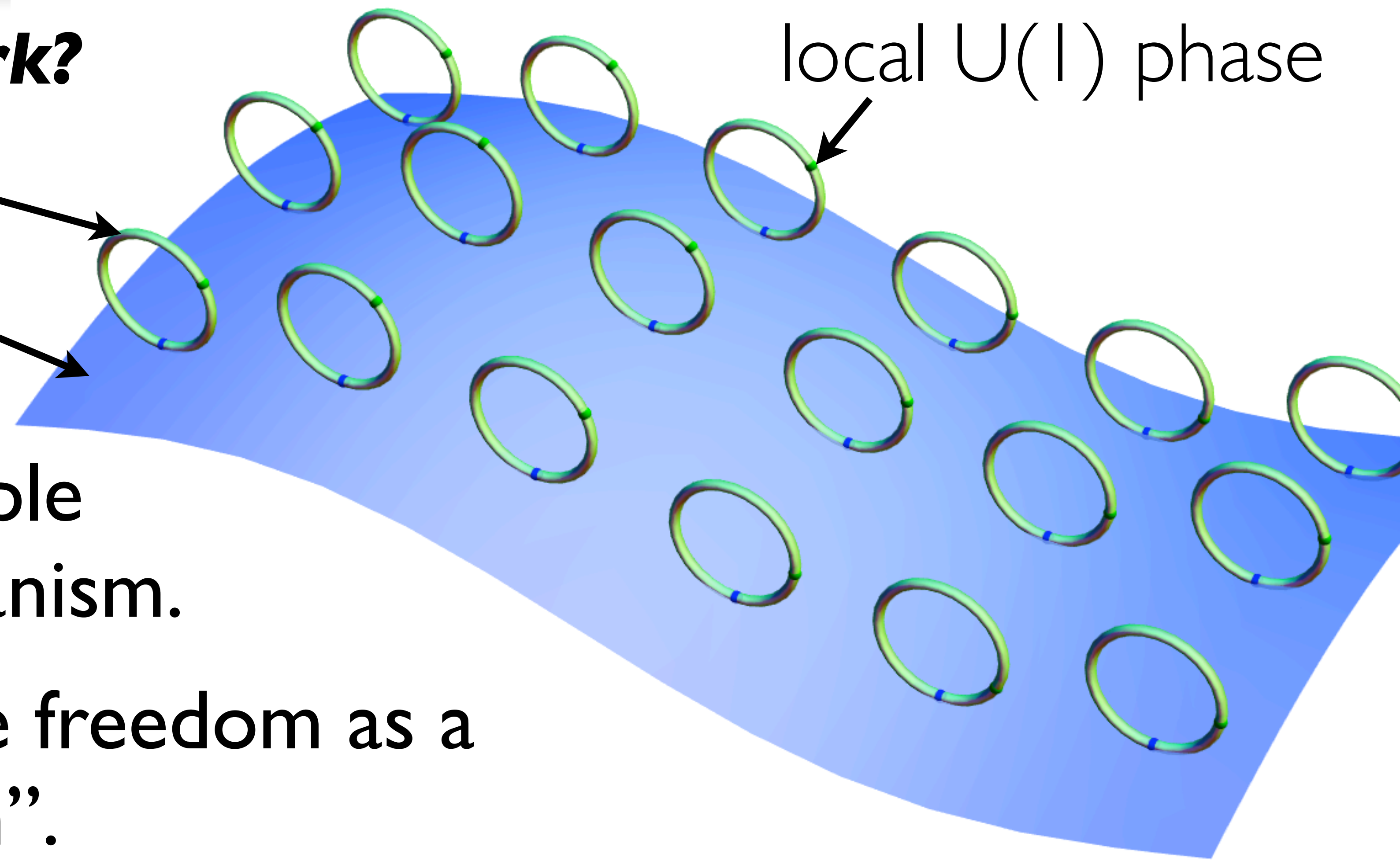
Myrvold, W. C. (2015). What is a wavefunction?

Gauge invariance is deep!

Why do gauge theories work?



- Loyalty to the gauge principle motivated the Higgs mechanism.
- Some have described gauge freedom as a "redundancy of description".
- But it is also a symmetry, similar to spatial rotations but in the *internal space of the field*.
- Can be rotated *locally*, independently at every spacetime point.
- What does it mean for the laws of nature to be describable by the continuous symmetries of Lie groups?

U(1) → QED

U(1) *local* gauge transformation of a Dirac field:

$$\psi(x) \to \psi'(x) = e^{i\,\theta(x)}\,\psi(x)$$

Free Dirac Lagrangian is no gauge invariant:

$$\mathcal{L} = i\,\bar{\psi}\,\gamma^{\mu}\,\partial_{\mu}\,\psi - m\,\bar{\psi}\,\psi$$

Because $\partial_{\mu}\,\psi(x) \to e^{i\,\theta}\,\partial_{\mu}\,\psi + i\,e^{i\,\theta}\,\psi\,\partial_{\mu}\,\theta$

Posit $D_{\mu}\,\psi \equiv (\partial_{\mu} - i\,q\,A_{\mu})\,\psi$ ***Covariant derivative***

$$\mathcal{L} = i\,\bar{\psi}\,\gamma^{\mu}\,\partial_{\mu}\,\psi + q\,\bar{\psi}\,\gamma^{\mu}\,\psi\,A_{\mu} - m\,\bar{\psi}\,\psi - \frac{1}{4}\,F_{\mu\nu}\,F^{\mu\nu}$$

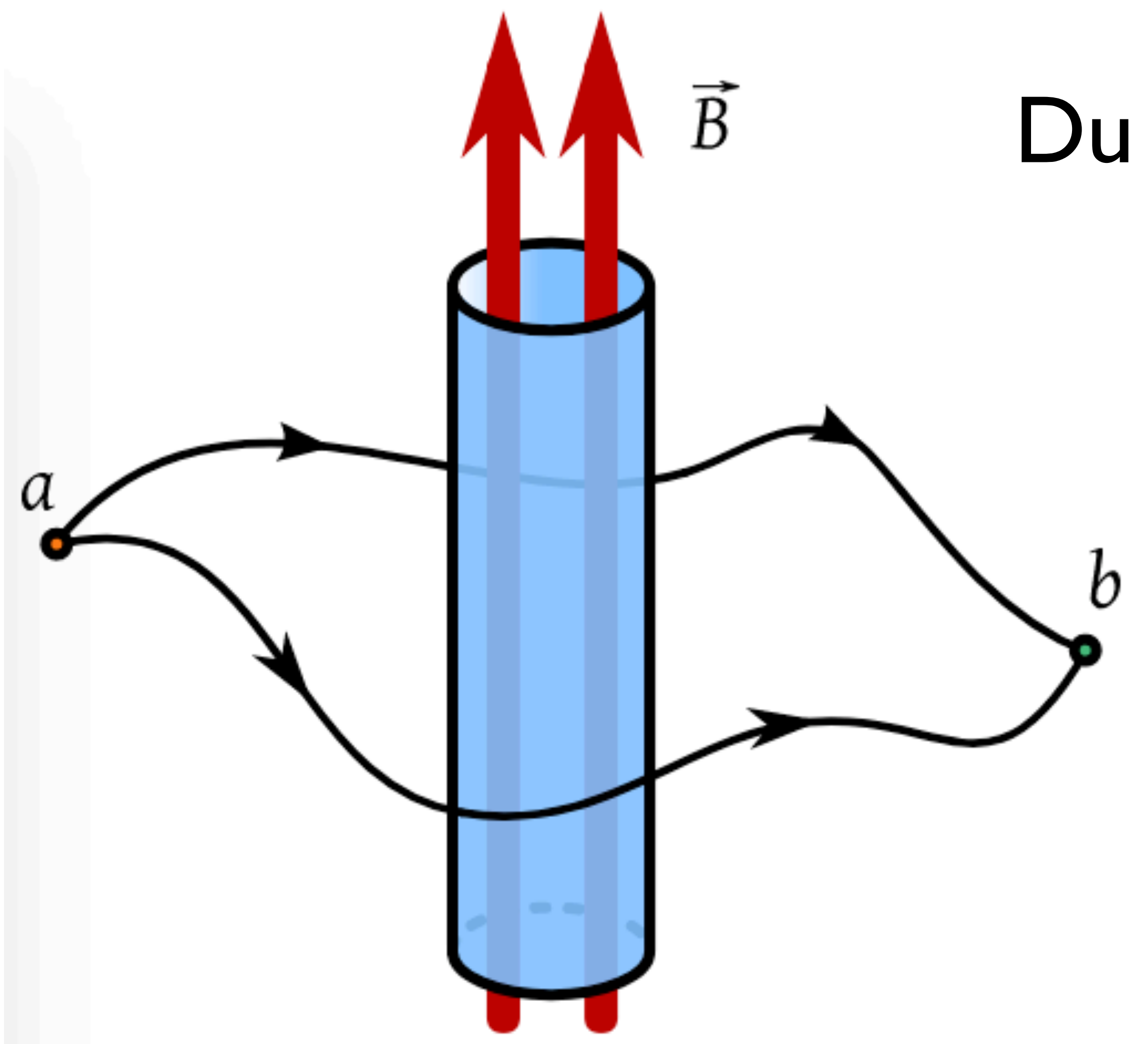
is now gauge invariant with the new ***connection*** field, *A*. But remember that *A*, itself is not:

$$A_{\mu} \to A_{\mu} + \frac{1}{q}\,\partial_{\mu}\,\theta$$

Aharonov-Bohm Effect

Nonholonomic system: path dependent

$$\varphi_{AB} = \frac{q}{\hbar}\int_P \mathbf{A}\cdot d\mathbf{x}$$



Due to stokes theorem:

$$\Delta\varphi = \frac{q\Phi_B}{\hbar}$$

is holonomic, path-independent.

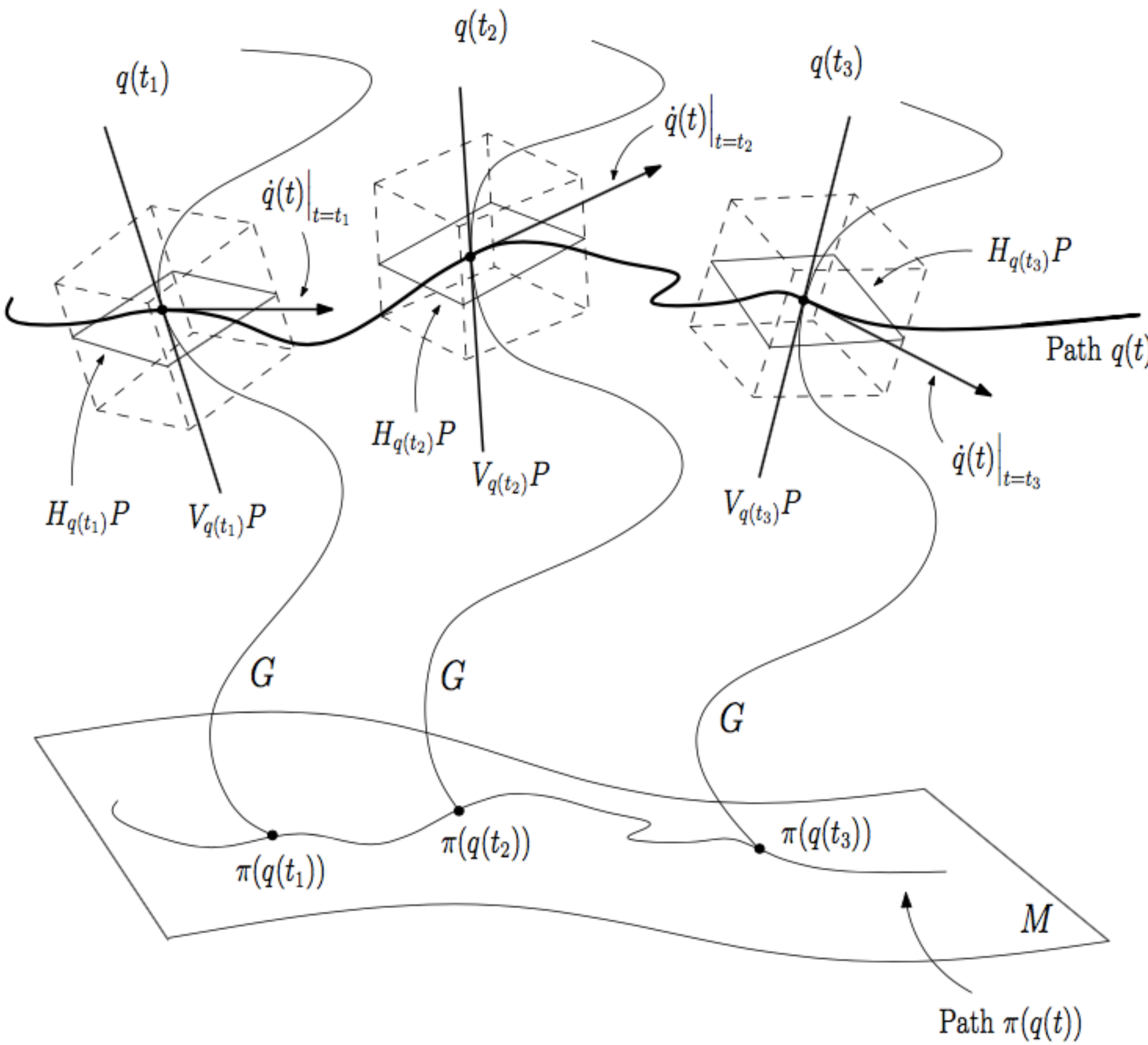
Richard Healey identifies 3 interps:

1. Local gauge properties (Feynman) but A is clearly not gauge-invariant
2. No gauge properties instrumental
3. Holonomy properties

Healey, R. (2007). *Gauging What's Real.*

Fiber bundles

Rupert Way (2010) Introduction to connections on principle fiber bundles.

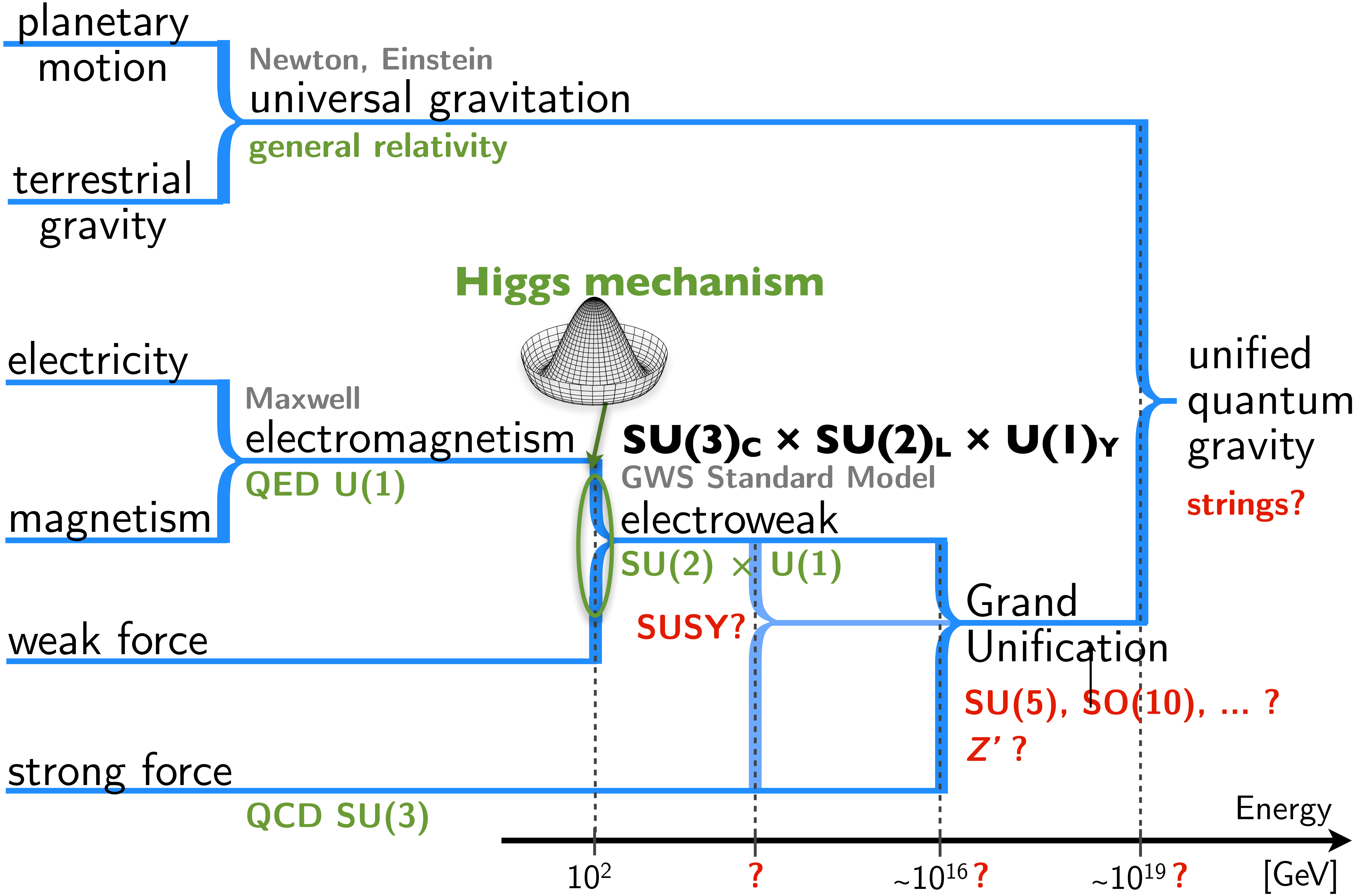


The gauge potential represented by the bundle connection defines a path-dependent similarity relation.

Allows for parallel translation and covariant differentiation.

Geometrically and topologically encodes the locality and gauge invariant constraints we asked of QFT.

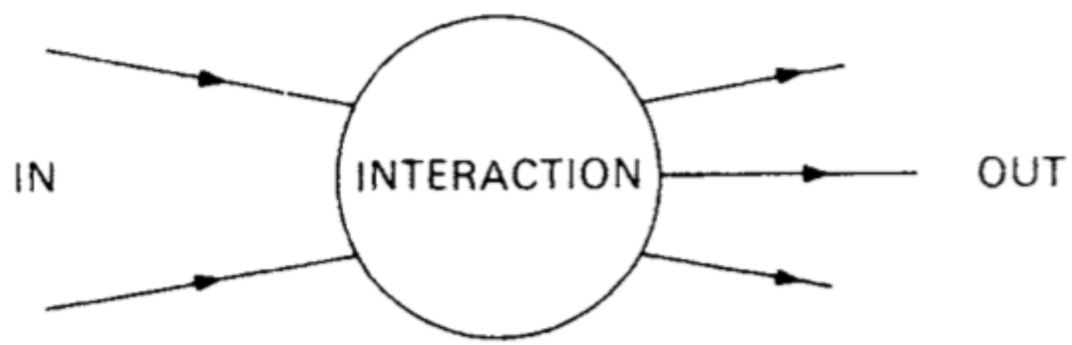
Unification?



Part 2: Interacting QFT

Haag's theorem

Several important theorems in QFT by Haag (1992), Malament (1996), and others, point out the difficulties in decomposing an interacting field theory into what could be called "particle" states.



Unitarily inequivalent representations

$$\phi(\vec{x}, t) \neq U^{\dagger}(t)\, \phi_{\mathrm{in}}(\vec{x}, t)\, U(t)$$

"For a free system, special relativity and the linear field equation conspire to produce a quanta interpretation. For an interacting system, the combination of special relativity and the nonlinear field equation is not so fortuitous; as a result, there is no quanta interpretation and **there are no quanta.**"

--

Fraser, D. (2008). The fate of 'particles' in quantum field theories with interactions.

Paul said it well

"Everyone must agree that as a piece of mathematics Haag's theorem is a valid result that at least appears to call into question the mathematical foundation of interacting quantum field theory, and agree that at the same time the theory has proved astonishingly successful in application to experimental results. What seems less clear is how the assumptions of the theorem should be brought to bear… It may also be possible that there is something deeply wrong with the theory, in spite of its formidable successes. Or there may be only a less exciting difficulty in seeing clearly the use of the assumptions of Haag's theorem in a detailed, consistent development of a very complex theory."

--
Teller, P. (1995). *An Interpretive Introduction to QFT.* p. 115-6.

How to stop worrying

10.5 How to stop worrying about Haag's theorem

We have already indicated on numerous occasions, without providing specific justification, that there are difficulties in the implementation of an interaction picture in the case of continuum field theories, which can be circumvented by a temporary *full regularization* of the theory (i.e., by introduction of both large-distance (IR) and small-distance (UV) cutoffs) which reduces the number of independent dynamical variables to a finite number—for example, the fields, and their time-derivatives (which play the role of conjugate momenta)—on a finite number of spacetime points. The

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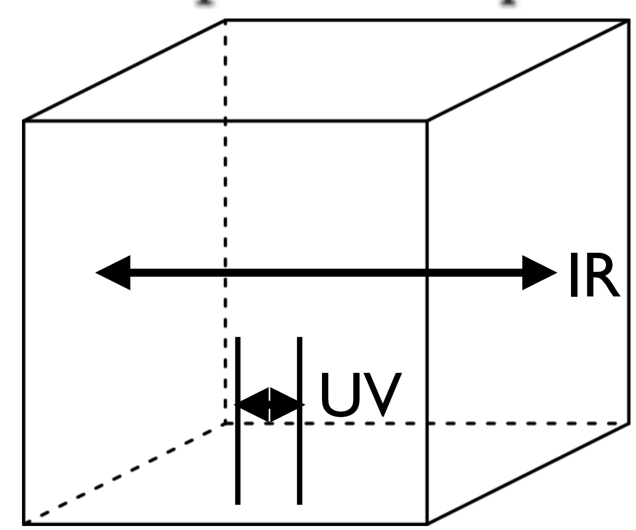
Duncan, A. (2012). *The Conceptual Framework of Quantum Field Theory*.



"Once renormalised, these theories are nontrivial and *unitary inequivalent to the very free theories employed to construct them*. In other words, it is precisely renormalisation that allows us to stay clear of Haag's theorem."

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Klaczynski, L. (2016) arxiv:1602.00662

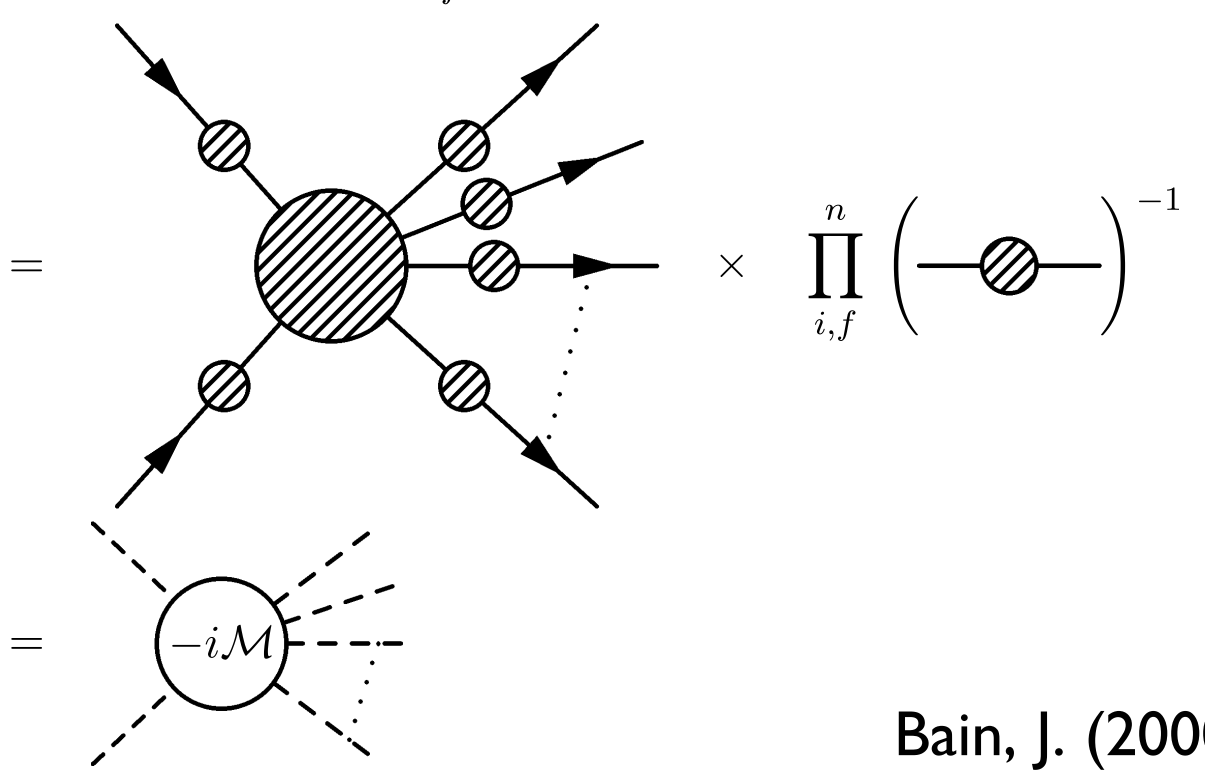
Asymptotic LSZ "particle" states are still ok!

Bain defines "For All Practical Purposes, FAPP-localizable, LSZ particle states"—localized wave-packets.

LSZ reduction formula

$$S_{fi} = \langle f|\hat{S}|i\rangle$$

$$= \tilde{G}^{(n)}(-p_f, \ldots, p_i) \prod_f \left(\tilde{G}^{(2)}(p_f)\right)^{-1} \prod_i \left(\tilde{G}^{(2)}(p_i)\right)^{-1}$$

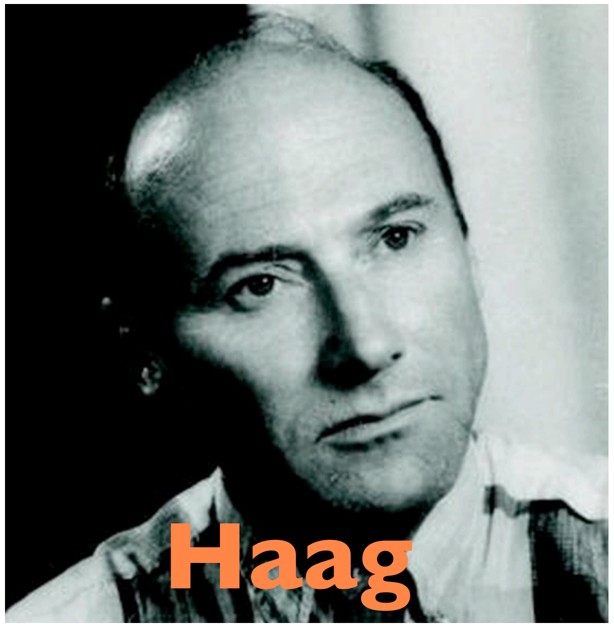


$$= -i\,\mathcal{M}\,(2\,\pi)^4\,\delta^4\left(\sum p_i - \sum p_f\right),$$

Asymptotic particle states that appear in the LSZ formalism of interacting field theory are still definable, and asymptotically related to the free fields, and form a Fock space.

Bain, J. (2000). Against particle/field duality: Asymptotic particle states and interpolating fields in interacting QFT, or Who's afraid of Haag's theorem?

Field-particle duality?



“Yet the belief in field-particle duality as a general principle, the idea that to each particle there is a corresponding field and to each field a corresponding particle has also been misleading and served to veil essential aspects. The role of fields is to implement the principle of locality. The number and the nature of different basic fields needed in the theory is related to the charge structure, *not to the empirical spectrum of particles*. In the presently favoured gauge theories the basic fields are the carriers of charges called colour and flavour but are not directly associated to observed particles like protons.”

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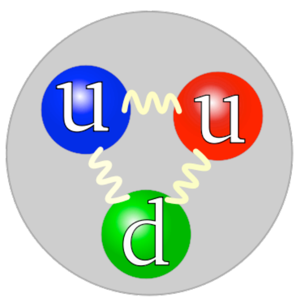
Haag, R. (1992). *Local Quantum Physics: Fields, Particles, Algebras*. p. 46.

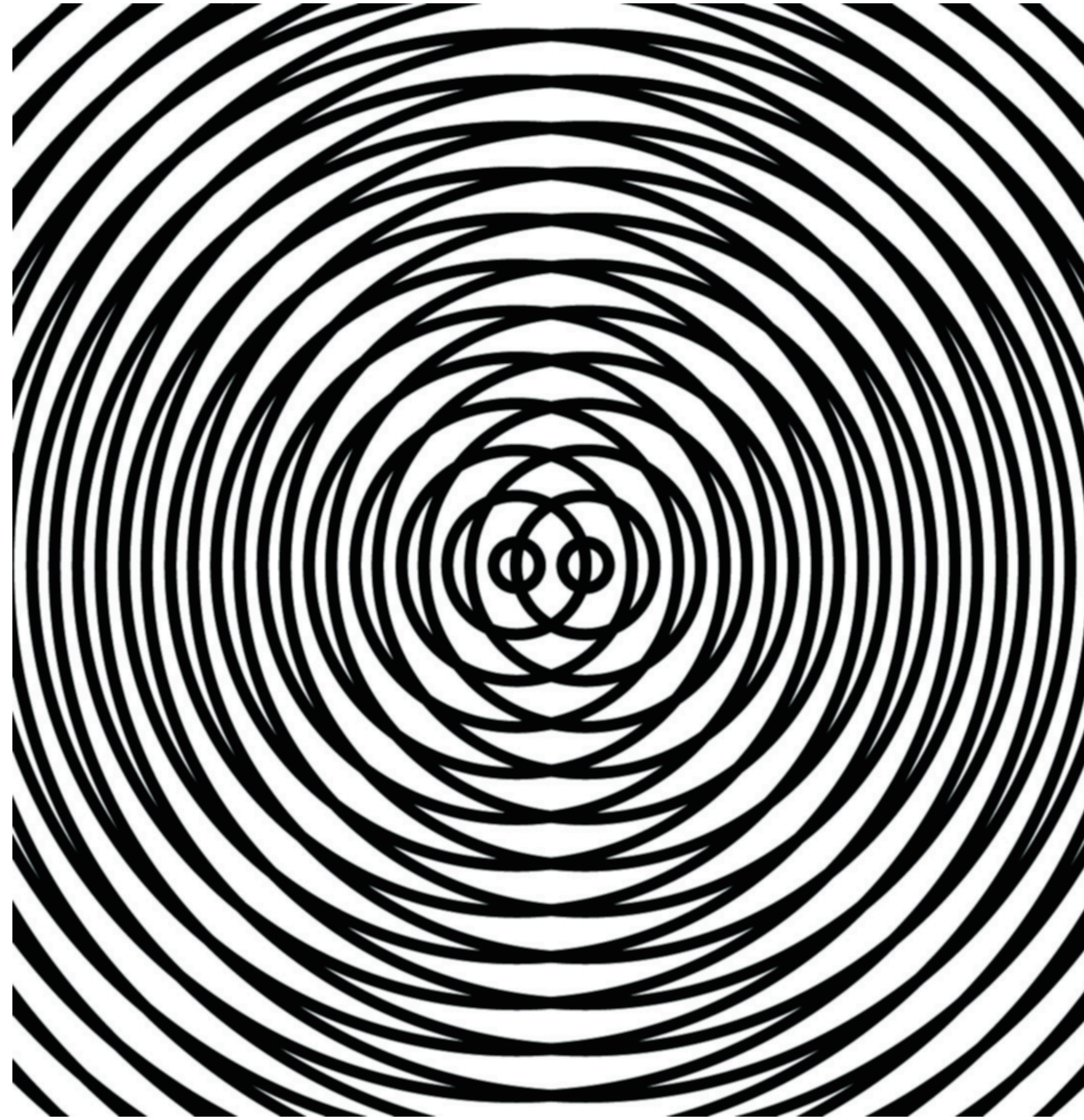


proton

Particle states *emerge* from a QFT depending on the structure and strength of the couplings among its fields. But fields and particles are not dual; not one-to-one.

1. If a particle has a field in the Lagrangian, it is (effectively) *fundamental*.
2. If it is a boundstate of energy in multiple of such fields, it is *composite*.

Part 4: Decoherence



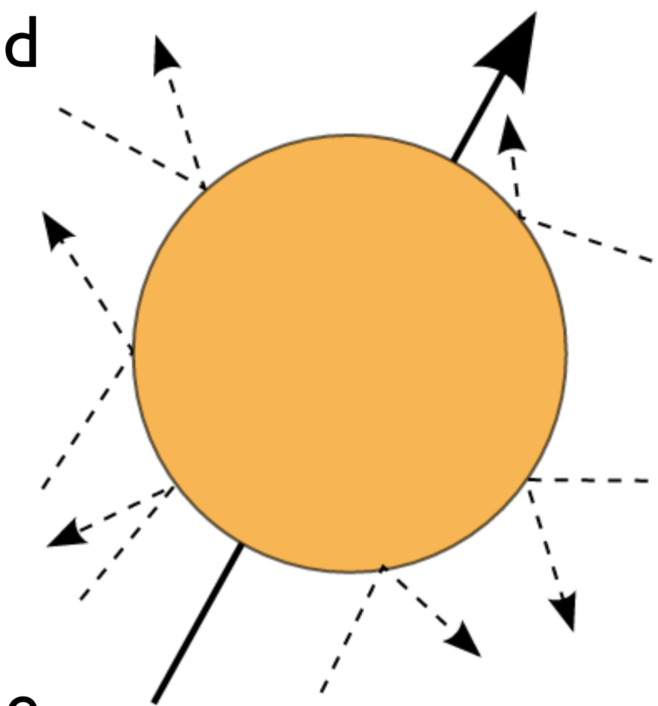
Decoherence

Decoherence is caused by a premeasurement-like process carried out by the environment ε:

system/apparatus/environment

$$|\Psi_{\mathcal{SA}}\rangle|\varepsilon_0\rangle = (\sum_j \alpha_j |s_j\rangle|A_j\rangle)|\varepsilon_0\rangle$$

$$\longrightarrow \sum_j \alpha_j |s_j\rangle|A_j\rangle|\varepsilon_j\rangle \;=\; |\Phi_{\mathcal{SAE}}\rangle$$



Decoherence leads to ***einselection*** when the states of the environment $|\varepsilon_j\rangle$ corresponding to different ***pointer states*** become orthogonal: $\langle\varepsilon_i|\varepsilon_j\rangle = \delta_{ij}$

Decoherence shows how a quantum system interacting with an environment with many degrees of freedom rapidly moves from being in a pure quantum state—in general a coherent superposition—to being in an incoherent mixture of these states, the appearance of collapse!

Zurek, W.H. (2003). Decoherence, einselection, and the quantum origins of the classical. *Rev. Mod. Phys.* 75, 715. http://arxiv.org/abs/quant-ph/0105127

Minimal QM (+Decoherence) → ≈Everett

"Decoherence adherents have typically been inclined towards relative-state interpretations presumably because **the Everett approach takes unitary quantum mechanics essentially "as is" with a minimum of added interpretive elements.** This matches well the spirit of the decoherence program, which attempts to explain the emergence of classicality purely from the formalism of basic quantum mechanics. It may also seem natural to identify the decohering components of the wave function with different Everett branches."

--

Schlosshauer, M. (2004). Decoherence, the measurement problem, and interpretations of quantum mechanics. *Rev.Mod.Phys.*, *76*, 1267–1305.

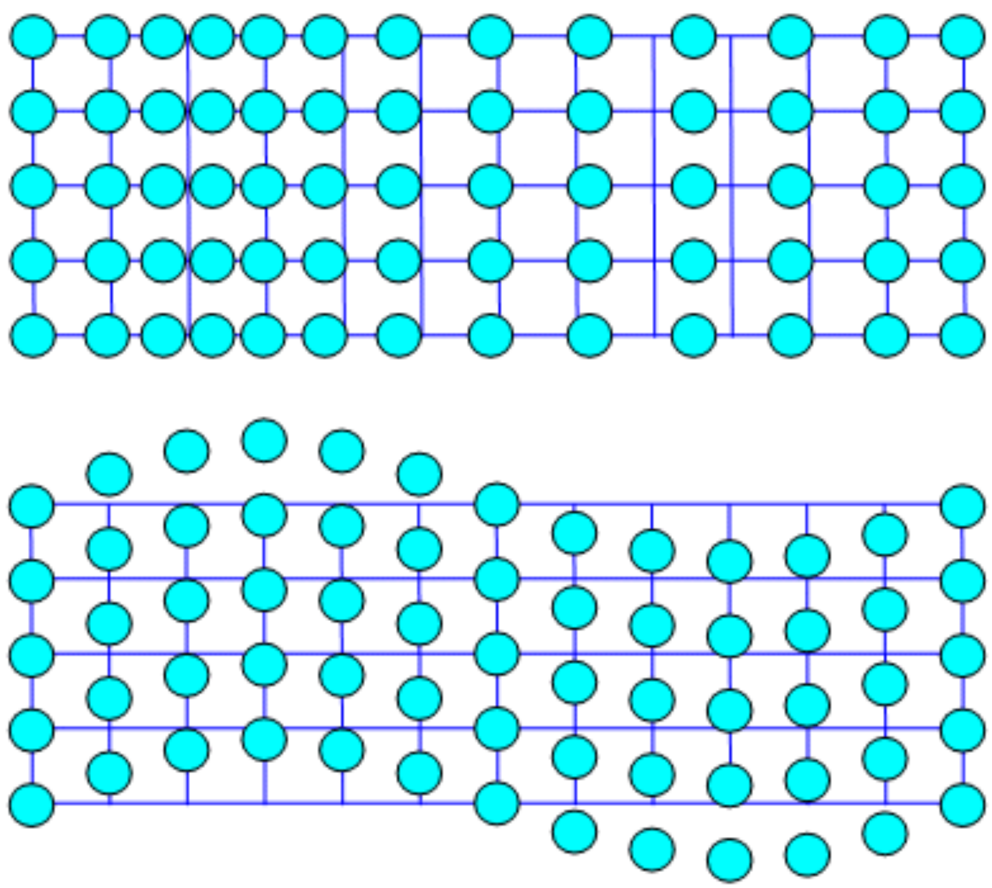
$$\hat{U}(t) = e^{-i\,\hat{H}\,t}$$

⇒ Decoherence, having fully unitary evolution, makes no-collapse interpretations of QM very tenable.

Emergence of particles

Wallace argues that particles in QFT may be thought of as emergent in a way analogous to how quantized *phonon* quasiparticles emerge from the dynamics of an underlying crystaline latice in condensed matter.

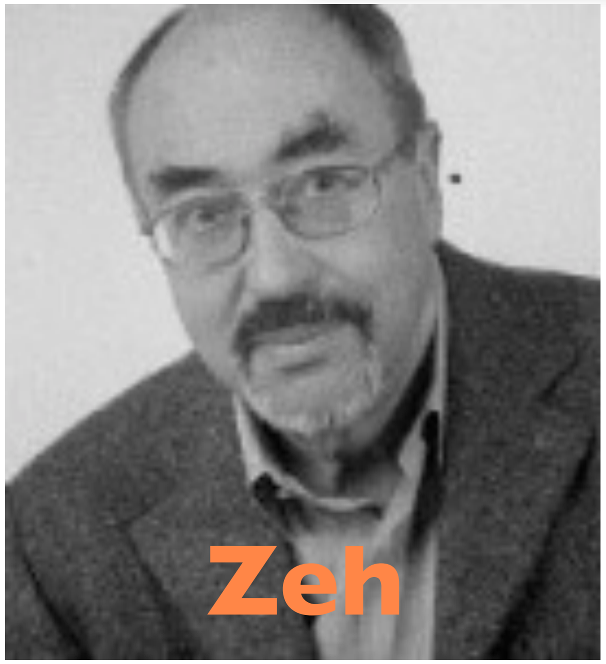
phonon excitation modes



The condensed matter community speaks of particles, uses Feynman diagrams, never considers their particles as fundamental.

Wallace, D. (2001). Emergence of particles from bosonic quantum field theory.

Decoherence → particles



Why do we see particles:

- h is small
- $\mathcal{L}$ is local
- Decoherence is fast

"Time-dependent quantum states *may also describe apparently discontinuous "events" by means of a smooth but rapid process of decoherence.*"
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Zeh, H. (2003). There is no "first" quantization. *Phys.Lett.A, 309*, 329–334.

"*All particle aspects* observed in measurements of quantum fields (like spots on a plate, tracks in a bubble chamber, or clicks of a counter) can be understood by taking into account the decoherence of the relevant local (i.e., subsystem) density matrix."
--
Zeh, H. (1993). There are no quantum jumps, nor are there particles! *Phys.Lett.A, 172*, 189.

Fundamental particles?

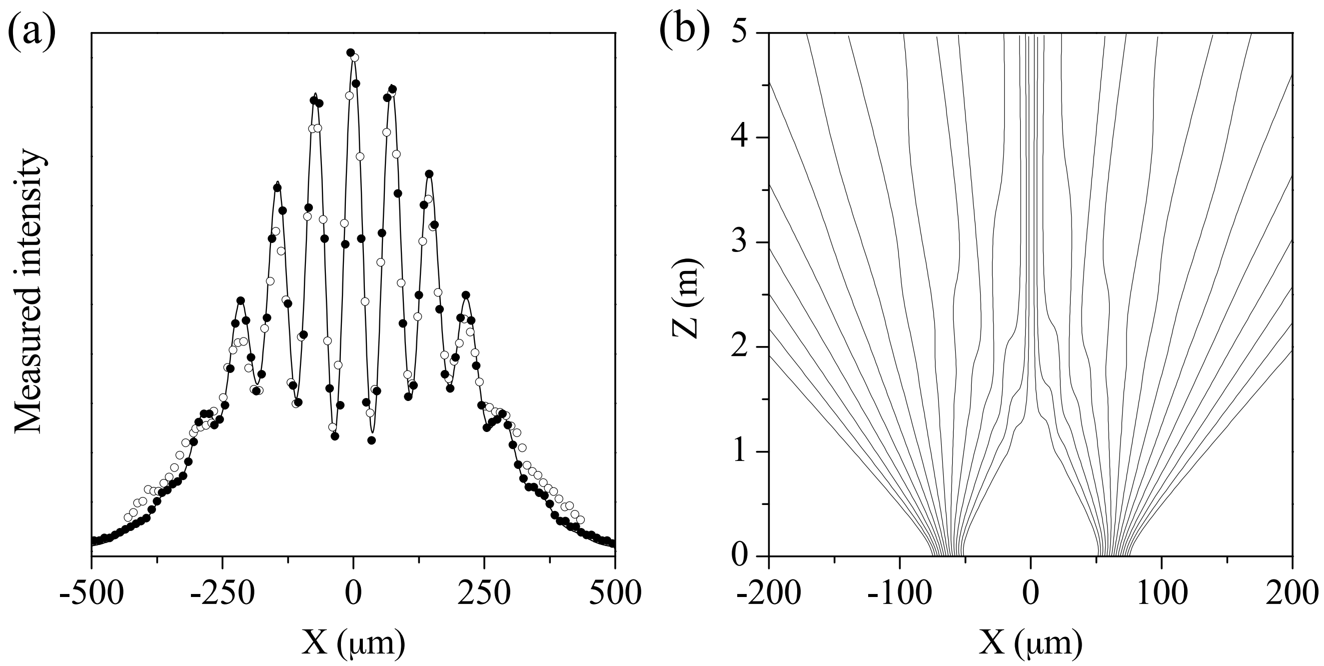
"so decoherence alone does not necessarily make Bohm's particle concept superfluous. But it suggests that the postulate of particles as fundamental entities could be unnecessary, and taken together with the difficulties in reconciling such a particle theory with a relativistic quantum field theory, Bohm's *a priori* assumption of particles at a fundamental level of the theory appears seriously challenged."

--

Schlosshauer, M. (2004). Decoherence, the measurement problem, and interpretations of quantum mechanics. *Rev.Mod.Phys.*, *76*, 1267–1305.

It is not to claim that particles do not exist, but they are reducible to emergent effects of a more fundamental field theory.

Bohmian trajectories



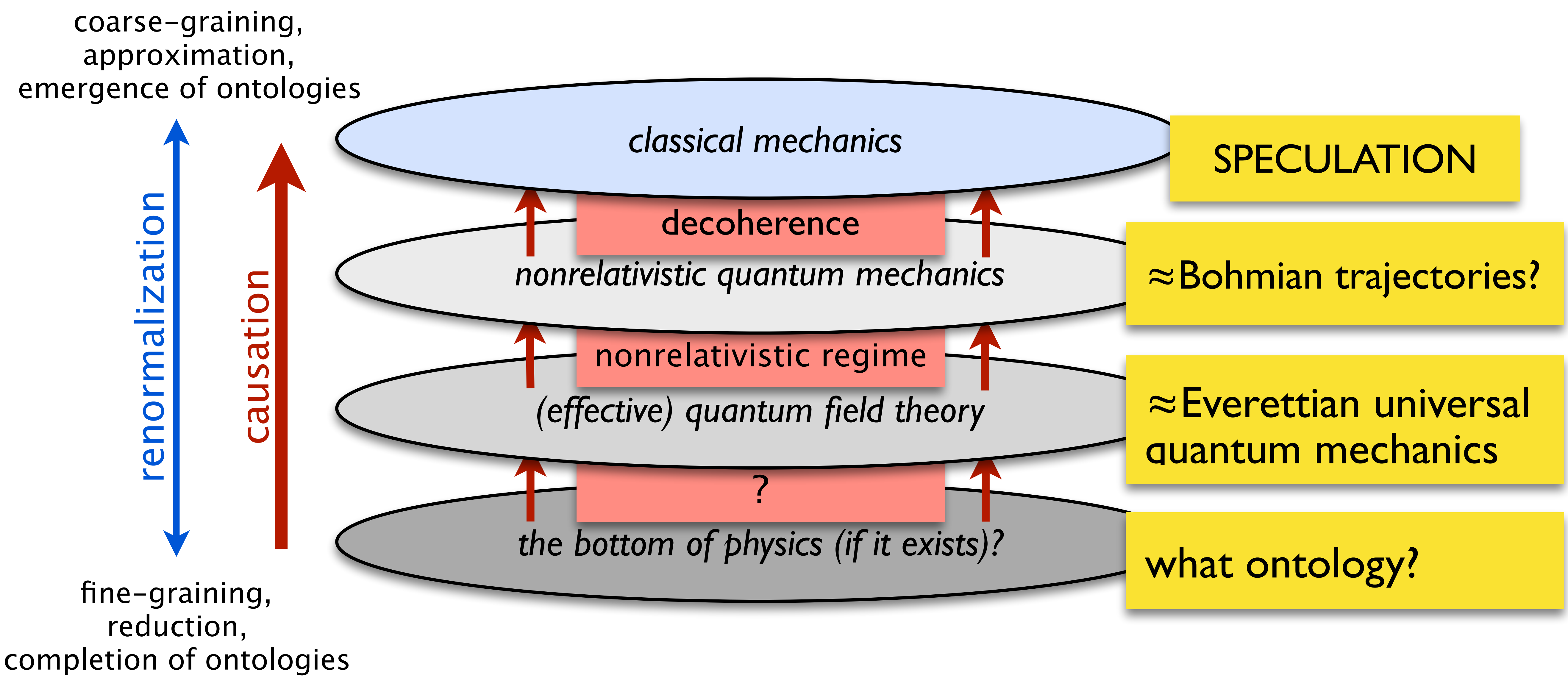
Several recent calculations make arguments supporting the plausibility that Bohmian trajectories could be in some sense the (semi-classical) limiting case of post-decoherence.

Appleby, D. M. (1999). Bohmian trajectories post-decoherence. Foundations of Physics, 29, 1885–1916.

Sanz, A.S., & Borondo, F. (2007). A quantum trajectory description of decoherence. TheEuropean Physical Journal D, 44, 319–326.

Romano, D. (2016). Bohmian Classical Limit in Bounded Regions. http://arxiv.org/abs/1603.03060

Reductionism



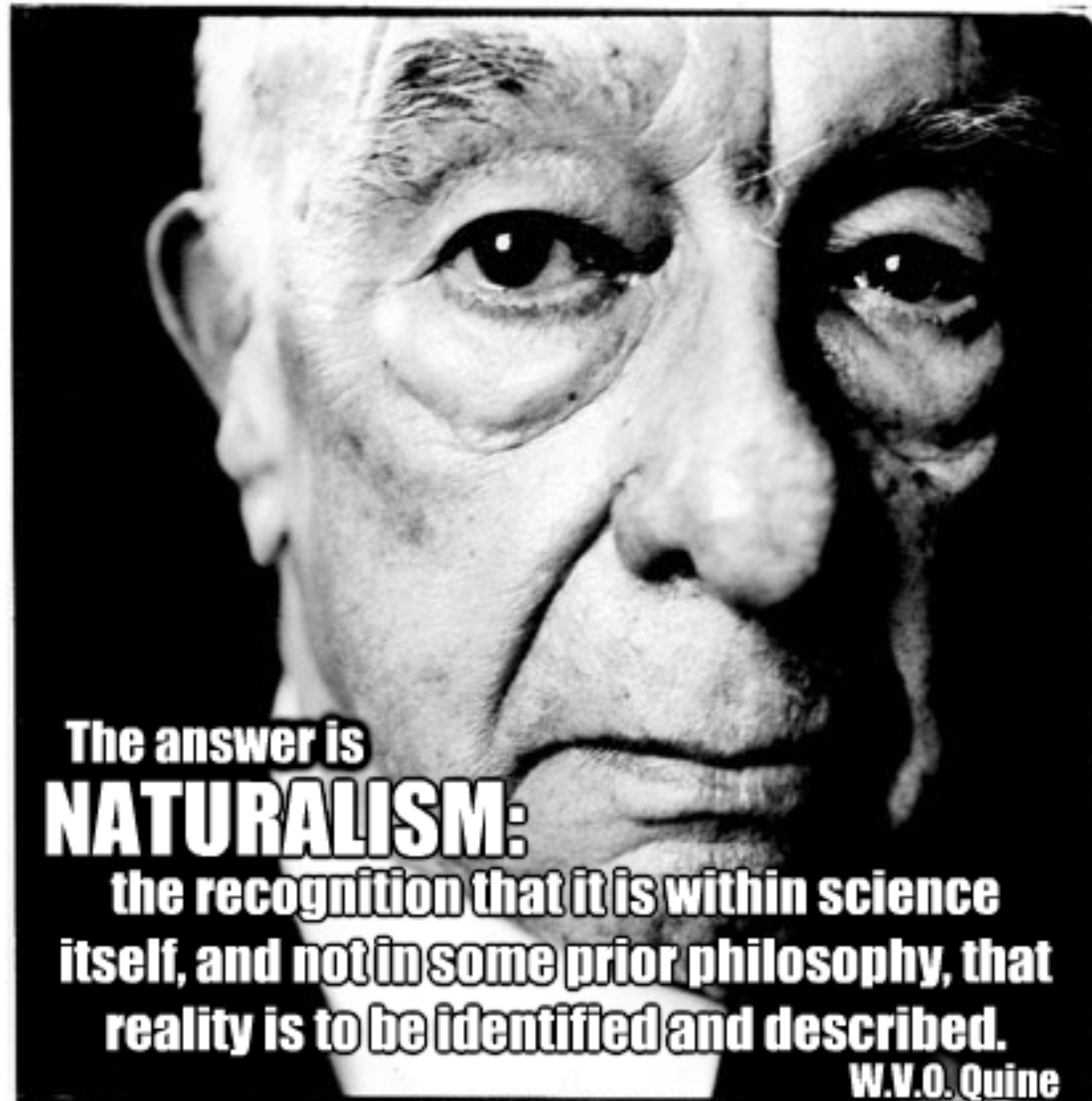
Is Bohmian mechanics an emergent nonrelativistic property of an underlying effective field theory obeying universal, unitary quantum mechanics?

adapted from my figure here: http://philosophy-in-figures.tumblr.com/post/93712656521/reductionism

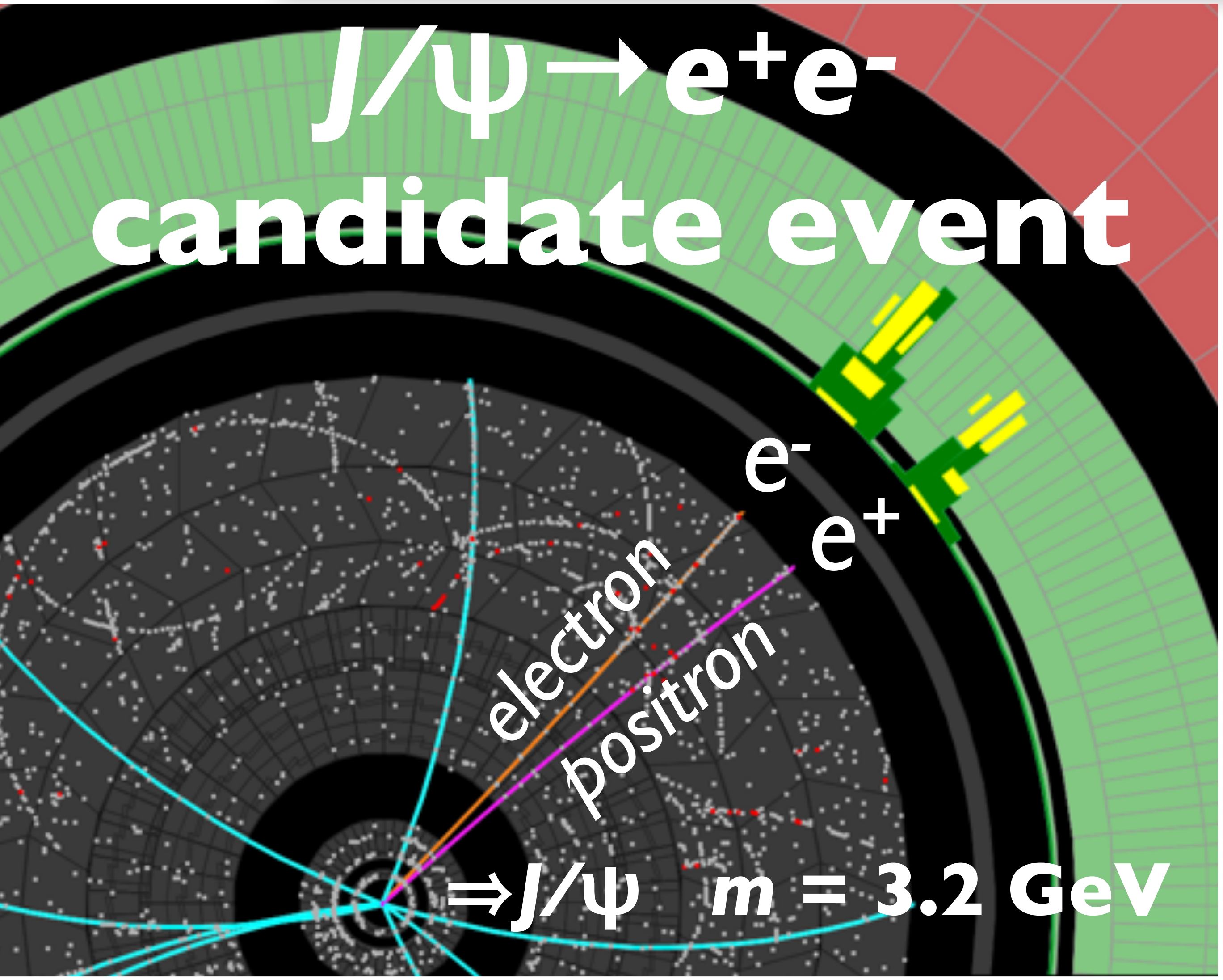
Summary

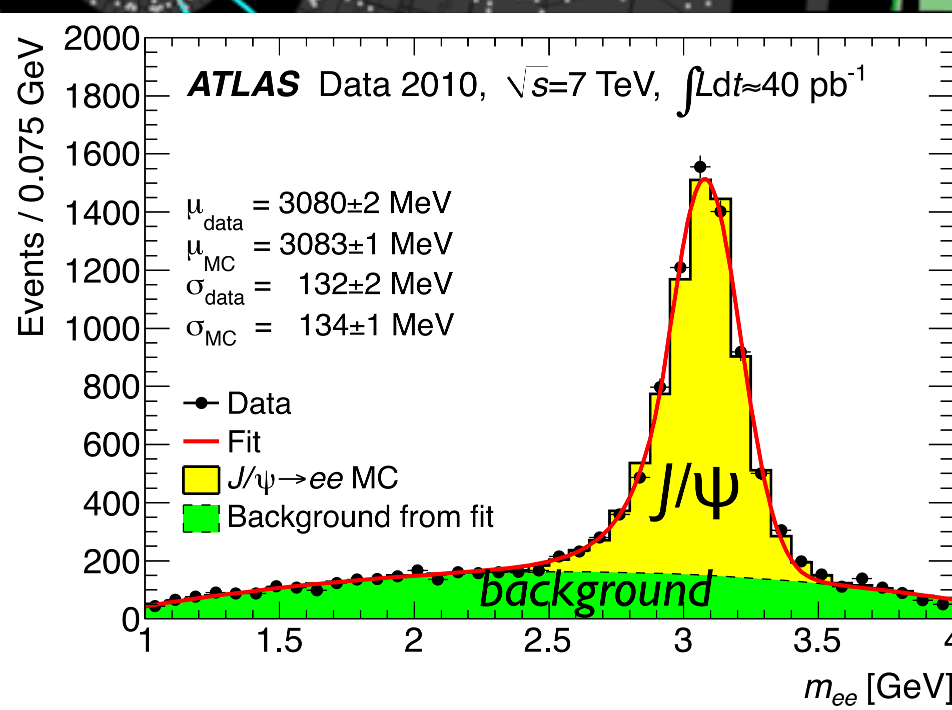
- Reviewed orthodox quantum mechanics
- Emphasized a symmetry-first approach, with Wigner's theorem as a cornerstone.
- Despite the several concerns about the formal apparatus of QFT, the LSZ formalism has enabled remarkably precise and experimentally verified predictions of scattering theory, g-2, etc.
- But fields are effective, not fundamental; they are approximations insofar as special relativity, locality / cluster decomposition, and gauge invariance continue through regimes.
- Decoherence naturally produces particle-like states through interactions of a system with the environment.
- *Fields are ~~conceptually~~ prior to particles in our best theories of physics.*
  mechanistically/causally

Back up slides



Real Patterns

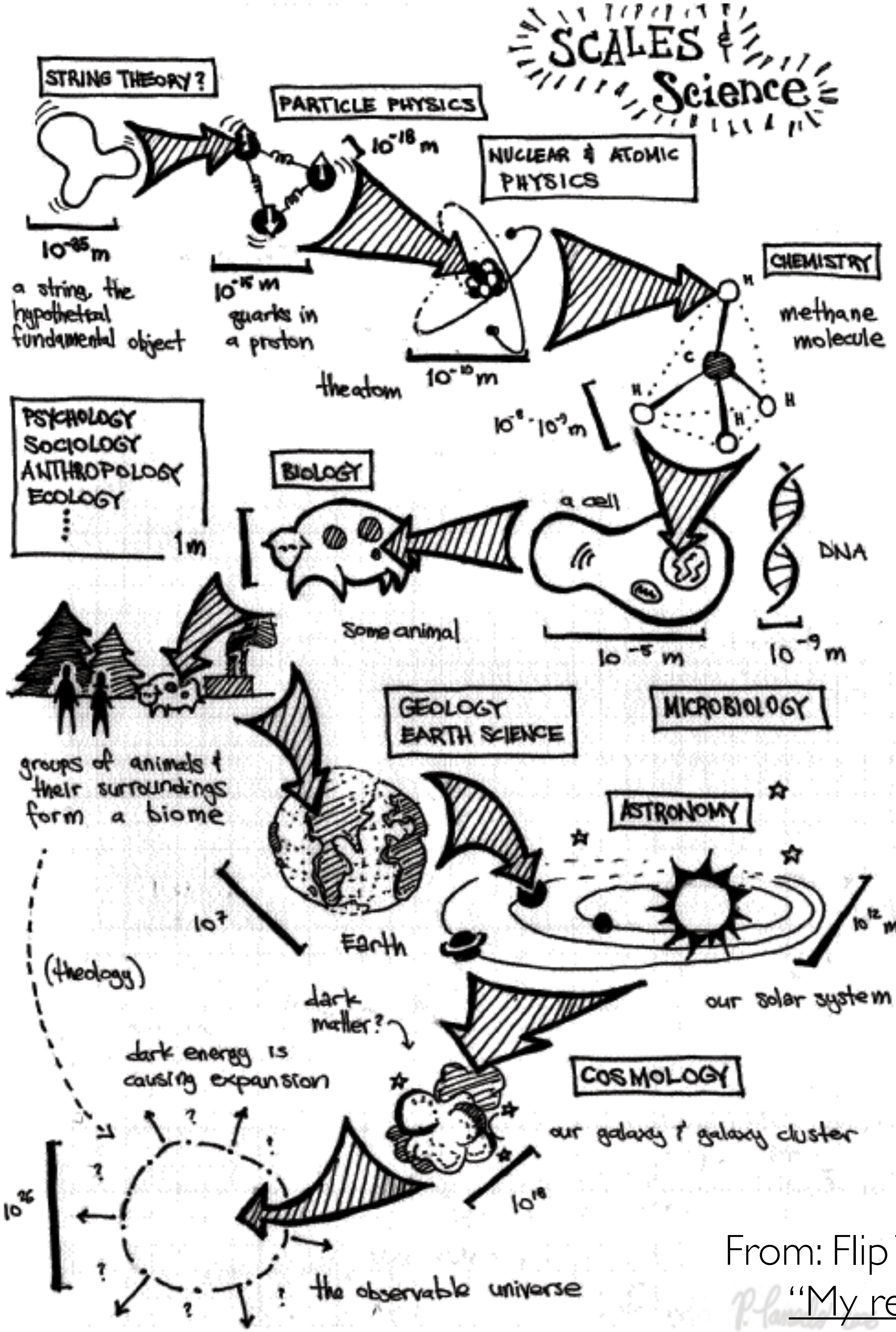




What is an electron?

- An excitation in a ***Dirac spinor field*** representation of SU(2)xU(1) — more fundamental.
- ***A particle-like track***, *a software object* with a reconstructed track and calorimeter deposit, passing some selection cuts, the *"pragmatist electron"*.
- ***A set of voltages*** and timings read-out from the detector, the *"Ramsified electron"*.

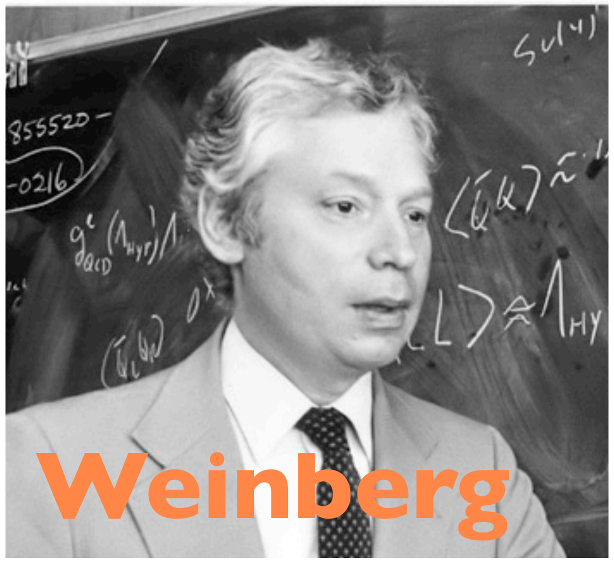
➡ Reality has a hierarchy of onion layers, but it has ***real patterns*** (Dennett 1991).



Effective ↔ emergent theories have some autonomy. Physics breaks into different regimes that have different scales.

From: Flip Tanado (2009). Quantum Diaries blog: "My research [Part 2] effective theories."

Effective Field Theories



"it is very likely that ***any quantum theory*** that at sufficiently low energy and large distances looks Lorentz invariant and satisfies the cluster decomposition principle will also at sufficiently low energy ***look like a quantum field theory. ...***

This leads us to the idea of **effective field theories.** When you use quantum field theory to study low-energy phenomena, then according to the folk theorem you're not really making any assumption that could be wrong, unless of course Lorentz invariance or quantum mechanics or cluster decomposition is wrong, provided you don't say specifically what the Lagrangian is. As long as you let it be the most general possible Lagrangian consistent with the symmetries of the theory, you're simply writing down the most general theory you could possibly write down."

--

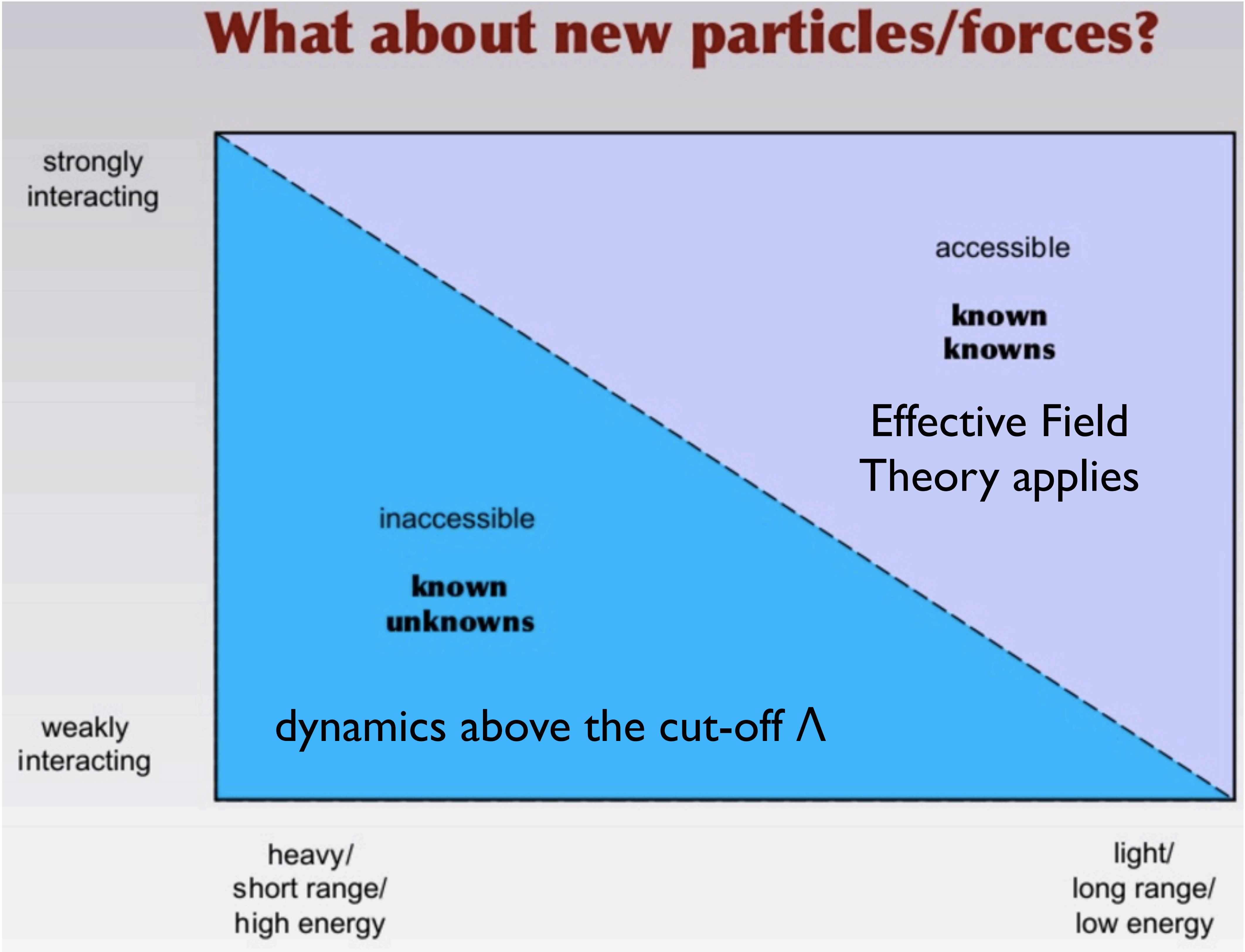
Weinberg, S. (1996). What is quantum field theory, and what did we think it is?

⇒ QFT is a way of parametrizing effective, local degrees of freedom.

Donald Rumsfeld's

- known knowns
- known unknowns
- unknown unknowns

Unknown unknowns
=
violations of QFT itself

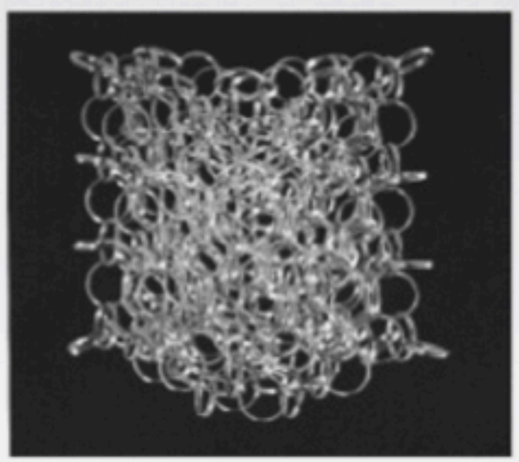


Slide from Sean Carroll:
"Quantum Field Theory and the Limits of Knowledge"

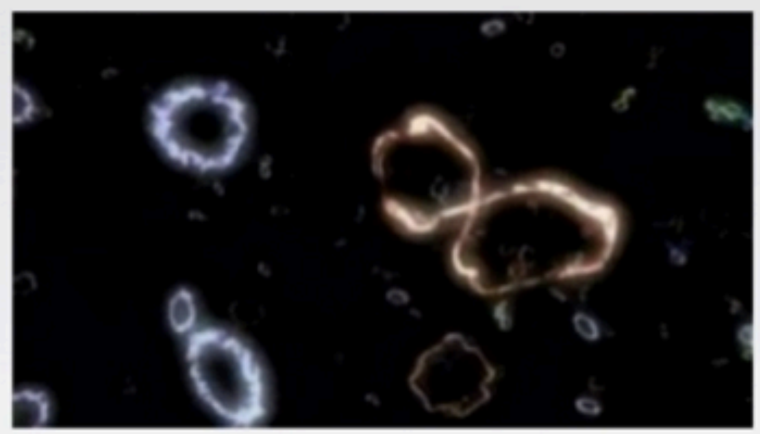
Multiple realizability

A given effective field theory with cutoff Λ could have many "ultraviolet completions" at higher energies.

That's why it's hard to do experiments relevant to quantum gravity: we expect $\Lambda \sim E_{\text{planck}} \sim 10^{15}\, E_{\text{LHC}}$.



loop quantum gravity



string theory

dynamical triangulations

Accepting the empirical adequacy or structural realism of QFT in a regime does not commit one to any "fundamental" ontology.

Slide from Sean Carroll:
"Quantum Field Theory and the Limits of Knowledge"

Against Bohr's classical-quantum duality

"As it is well known, Bohr has repeatedly insisted on the fundamental role of classical concepts. The experimental evidence for superpositions of macroscopically distinct states on increasingly large length scales counters such a dictum. Superpositions appear to be novel and individually existing states, often without any classical counterparts. Only the physical interactions between systems then determine a particular decomposition into classical states from the view of each particular system. ***Thus classical concepts are to be understood as locally emergent in a relative-state sense and should no longer claim a fundamental role in the physical theory."***

--

Schlosshauer, M. (2006). Experimental motivation and empirical consistency in minimal no-collapse quantum mechanics. *Annals of Physics, 321*, 112–149.

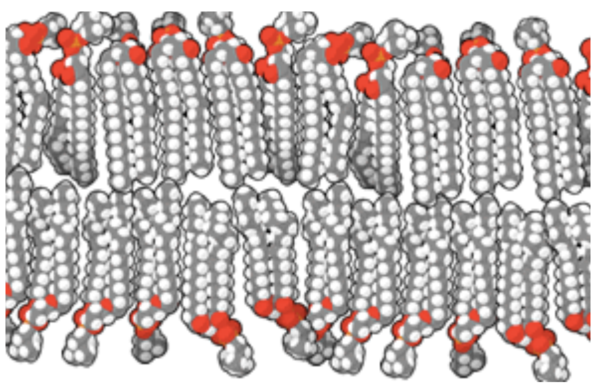
The classical world emerges through decoherence, not an ill-defined measurement bridge between a quantum-classical dualism. Everything is always quantum.

QM of everything

“[Quantum mechanics] has been nevertheless convincingly verified in experiments stimulated by the EPR paradox. Furthermore, **if one denies any special role to consciousness, there is seemingly nothing that could keep one from describing an arbitrary system, no matter how large, by a state vector and Schrödinger equation.** After all, there is nothing in the laws of physics that would make quantum mechanics applicable to a few-body system but render it invalid for a truly many-body system, even if it contains 10^{25} or more atoms as long as it remains isolated.”

--

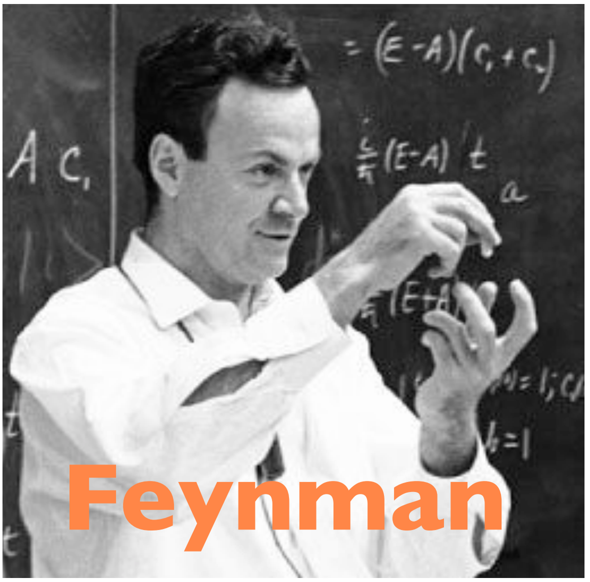
Zurek, W. (1981). Pointer basis of quantum apparatus: Into what mixture does the wave packet collapse? *Phys.Rev. D, 24*, 1516.



Lipid bilayer

⇒ Even the largest systems are, in principle, quantum systems.

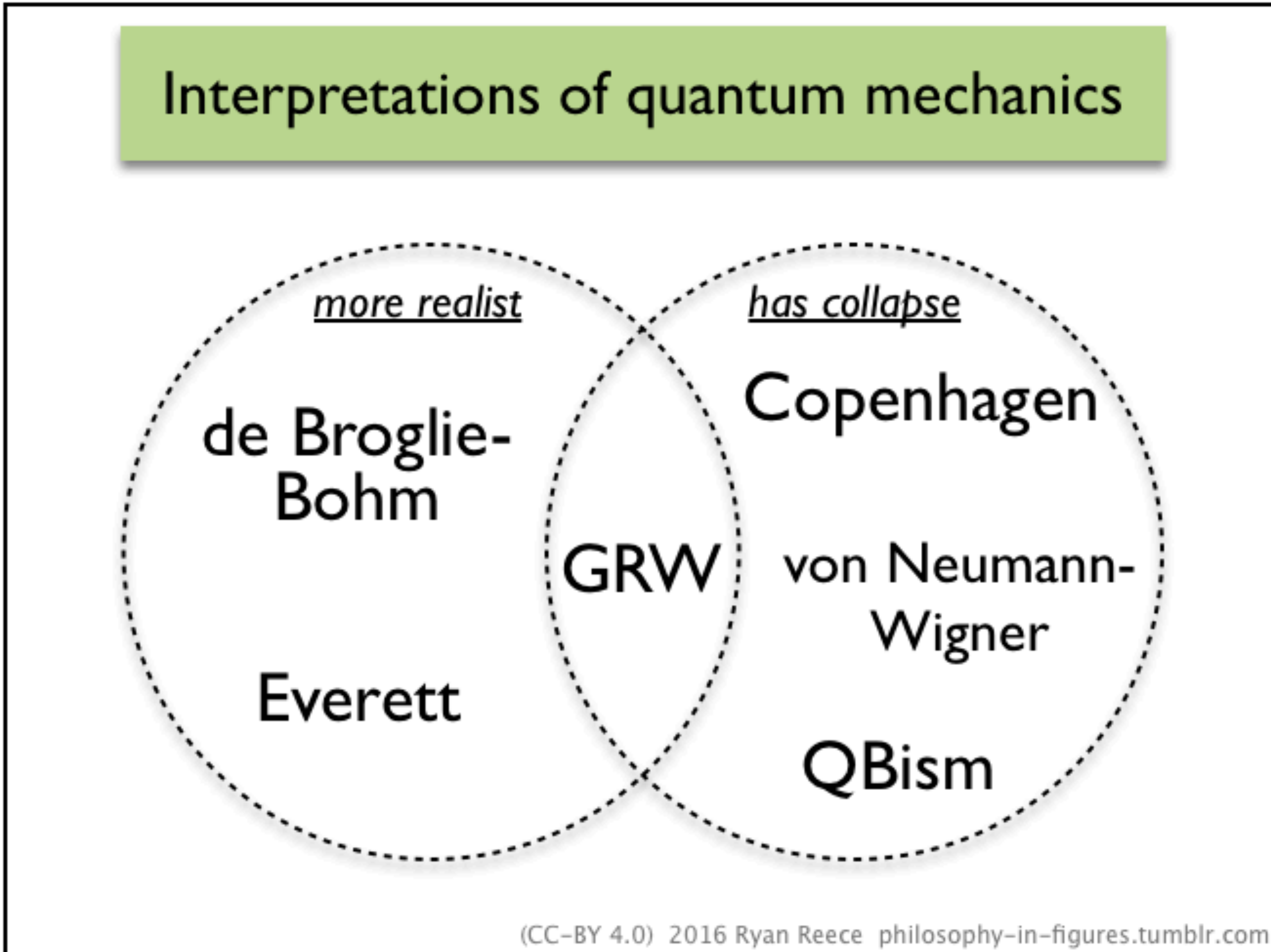
On pluralism in physics



"Theories of the known, which are described by different physical ideas may be equivalent in all their predictions and are hence scientifically indistinguishable. However, they are not psychologically identical when trying to move from that base into the unknown. **For different views suggest different kinds of modifications which might be made and hence are not equivalent in the hypotheses one generates** from them in one's attempt to understand what is not yet understood. I, therefore, think that **a good theoretical physicist today might find it useful to have a wide range of physical viewpoints** and mathematical expressions of the same theory available to him."

--

Feynman, R. (1965). "The Development of the Space-Time View of Quantum Electrodynamics." Nobel Lecture. December 11, 1965.



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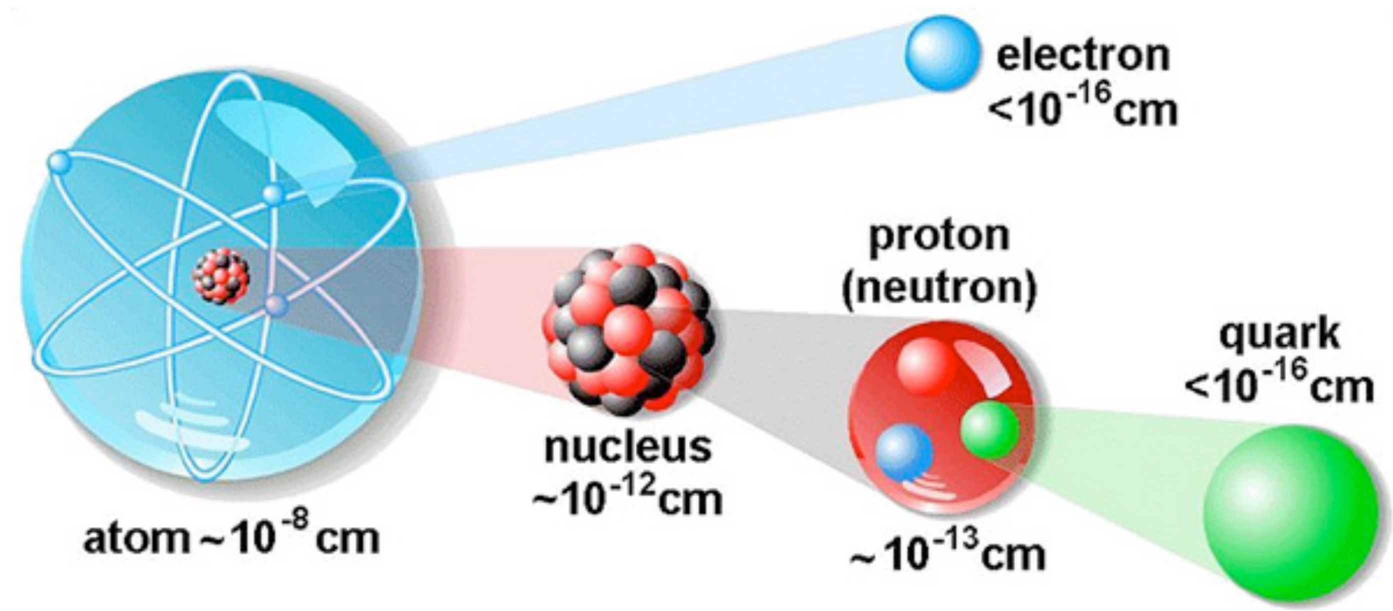
my philosophy blog in figures: http://philosophy-in-figures.tumblr.com

Particle Physics

Fundamental questions of particle physics:

1. ***What is matter?***
2. ***How does it interact?***



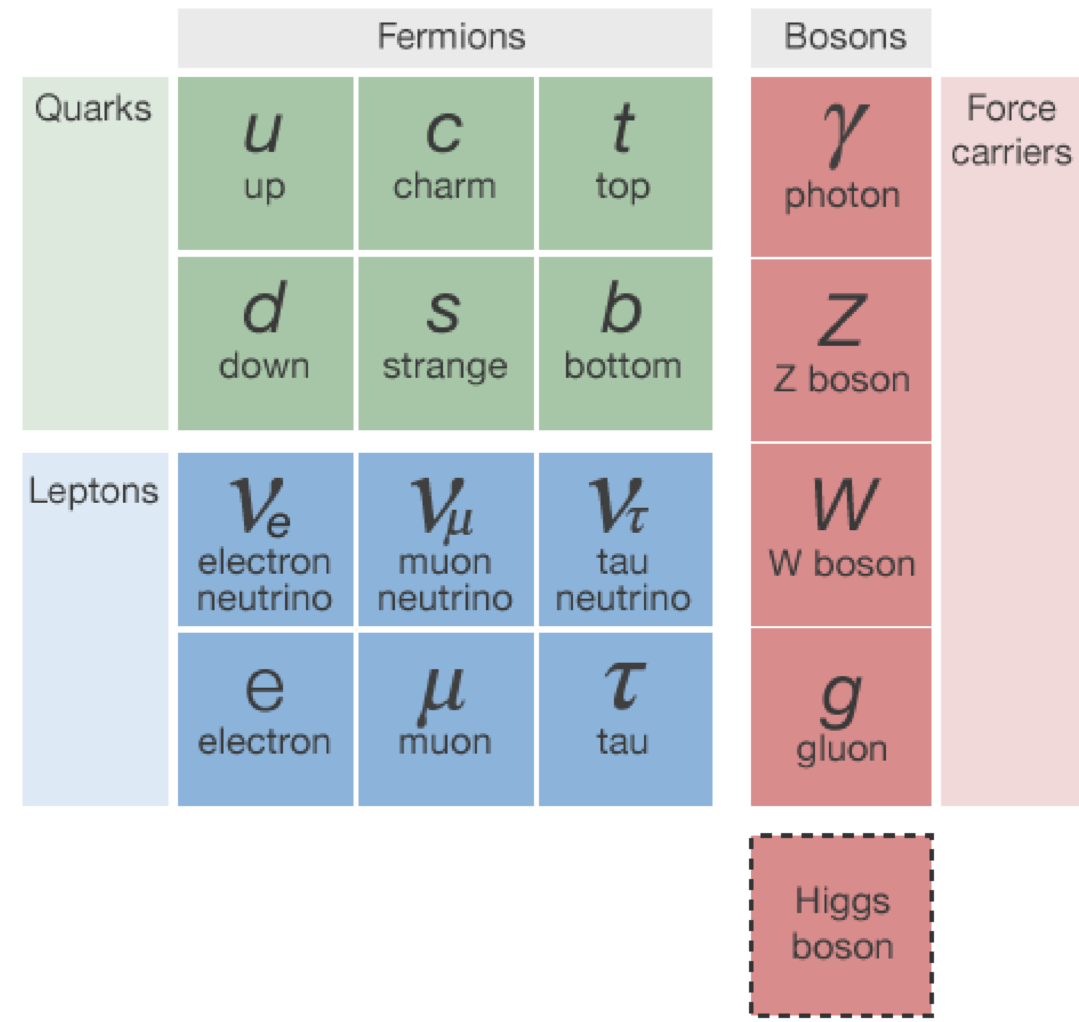
Four fundamental forces at low energies:

1. **Gravity** - very weak, no complete quantum theory
2. **Electromagnetism** - binds atoms, chemistry
3. **Strong force** - nuclear range, binds nuclei
4. **Weak force** - nuclear range, radioactivity, solar fusion

The Standard Model

- In QFT, ***fields*** are actually what is fundamental, and particles are quantized and often localized excitations in the fields.
- ***Gauge symmetries*** determine the character of the forces between fermion fields through exchanging gauge bosons.
- Bosons and chiral fermions develop mass terms that still preserve the gauge symmetries of the Lagrangian through the ***Higgs mechanism***.
- The SM gauge group is

field content of the SM



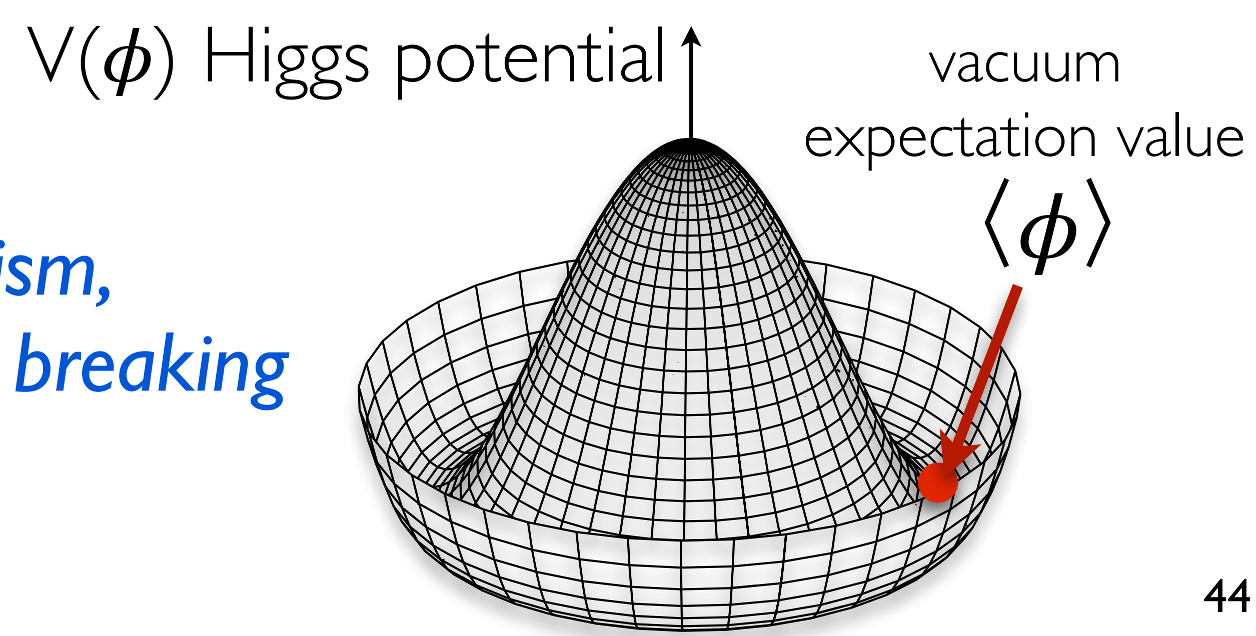
$SU(3)_C \times SU(2)_L \times U(1)_Y$

Electroweak force

$\Downarrow$ **Strong force**

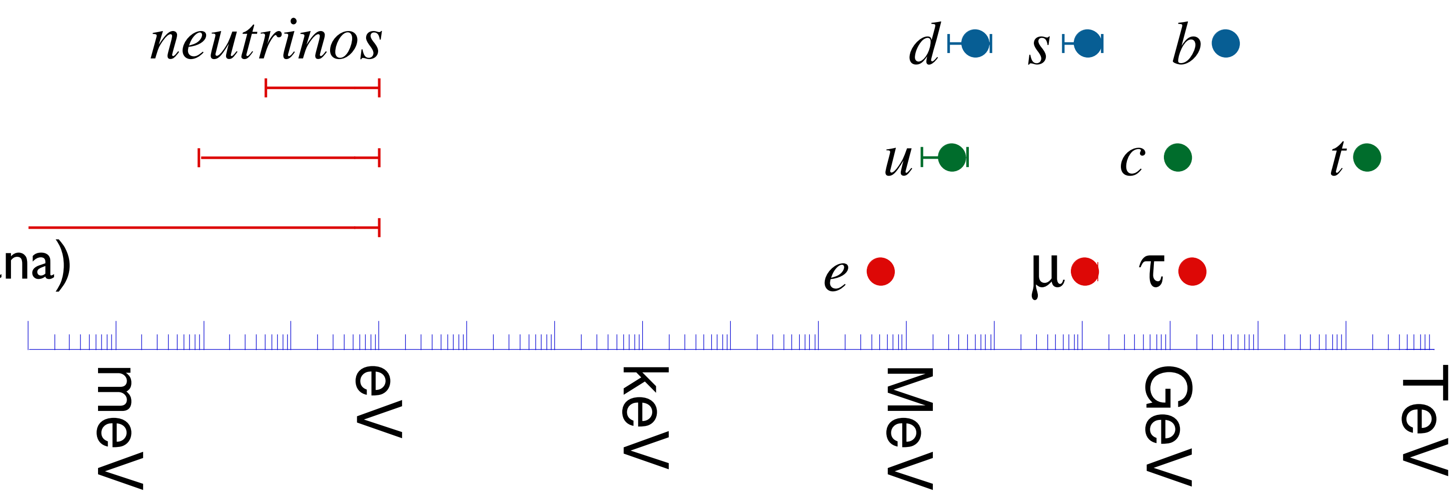
$\Downarrow$ *Higgs mechanism, EW symmetry breaking*

Electromagnetic + weak forces

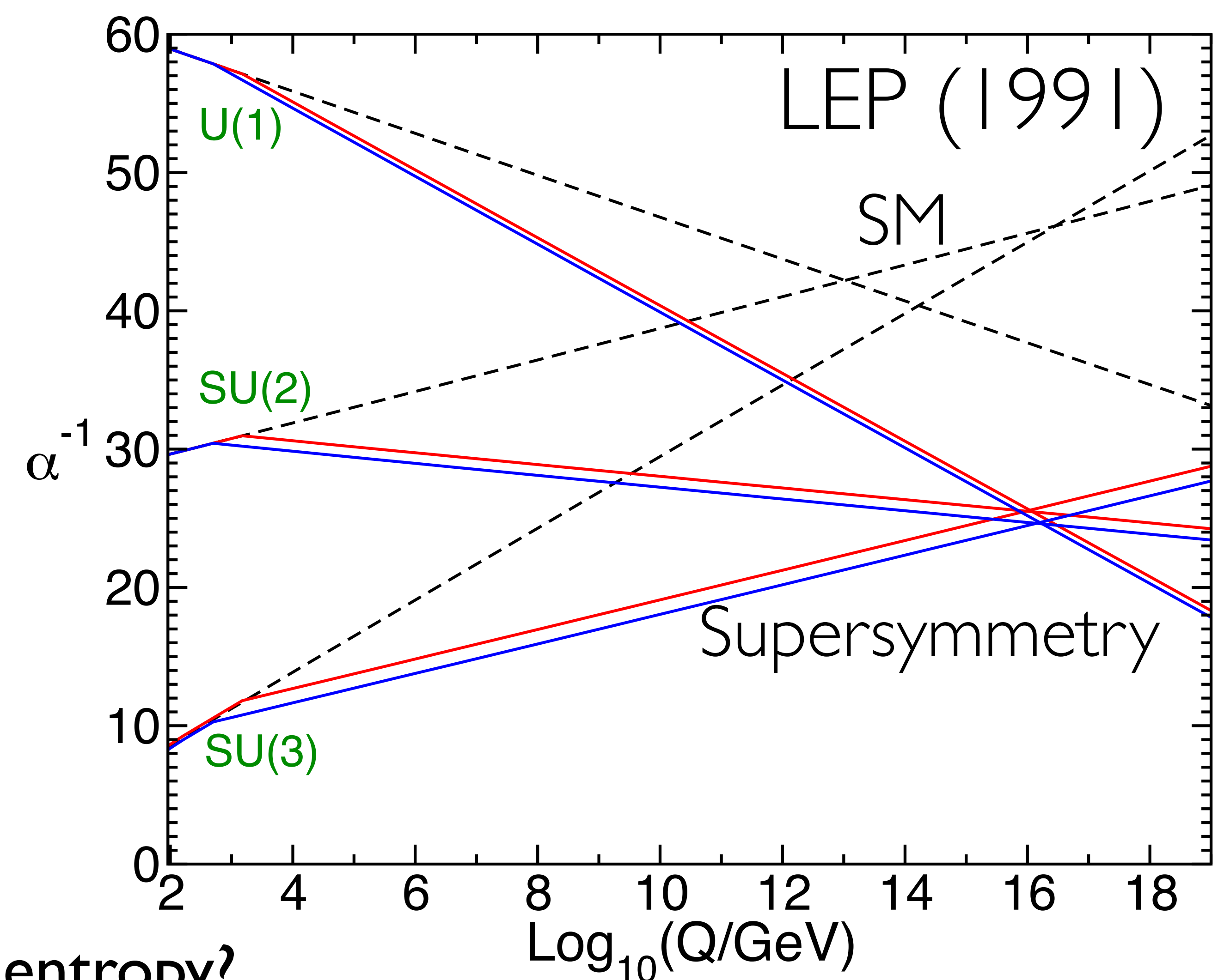


Unanswered problems in particle physics

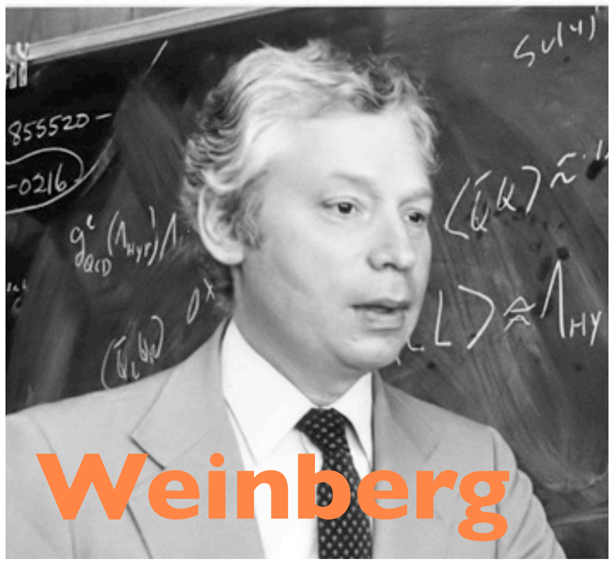
- Ad hoc features
  - Why SU(3)xSU(2)xU(1) ?
  - Neutrino mixing and masses (Dirac or Majorana)
  - Matter-antimatter asymmetry
  - Strong CP-problem



- Dark matter and dark energy
  - 5% SM, 27% dark matter, 68% dark energy
- Hierarchy problem(s)
  - m_{Higgs} vs m_{Planck},
  - quark masses range: 10^5, leptons: 10^9
- Fine-tuning:
  - EW-scale, flatness problem, vacuum stability, etc.
- Unification? Supersymmetry?
- Why did the early universe have such low entropy?



Symmetry-first physics



"Why do we enumerate possible theories by giving their Lagrangians rather than by writing down Hamiltonians? ... that **symmetries** imply the existence of Lie algebras of suitable quantum operators, and you need these Lie algebras to make sensible quantum theories. ... **if you start with a Lorentz invariant Lagrangian density then because of Noether's theorem the Lorentz invariance of the S-matrix is automatic."**

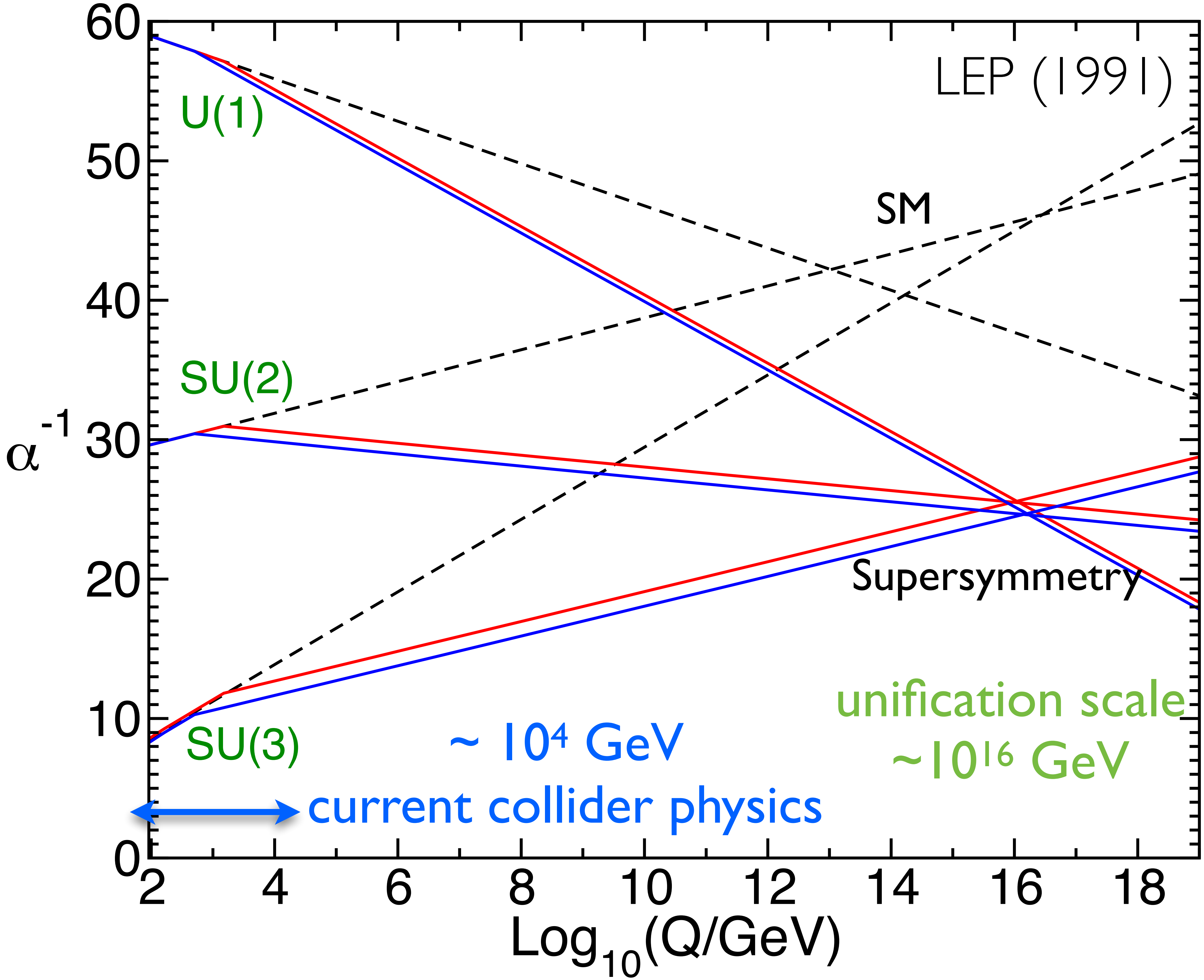
--

Weinberg, S. (1996). What is quantum field theory, and what did we think it is?

⇒ QFT is naturally relativistic if one requires that the Poincaré algebra be satisfied.

Nice for effective model building

Unification = SUSY+GUTs?

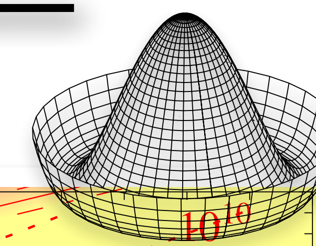


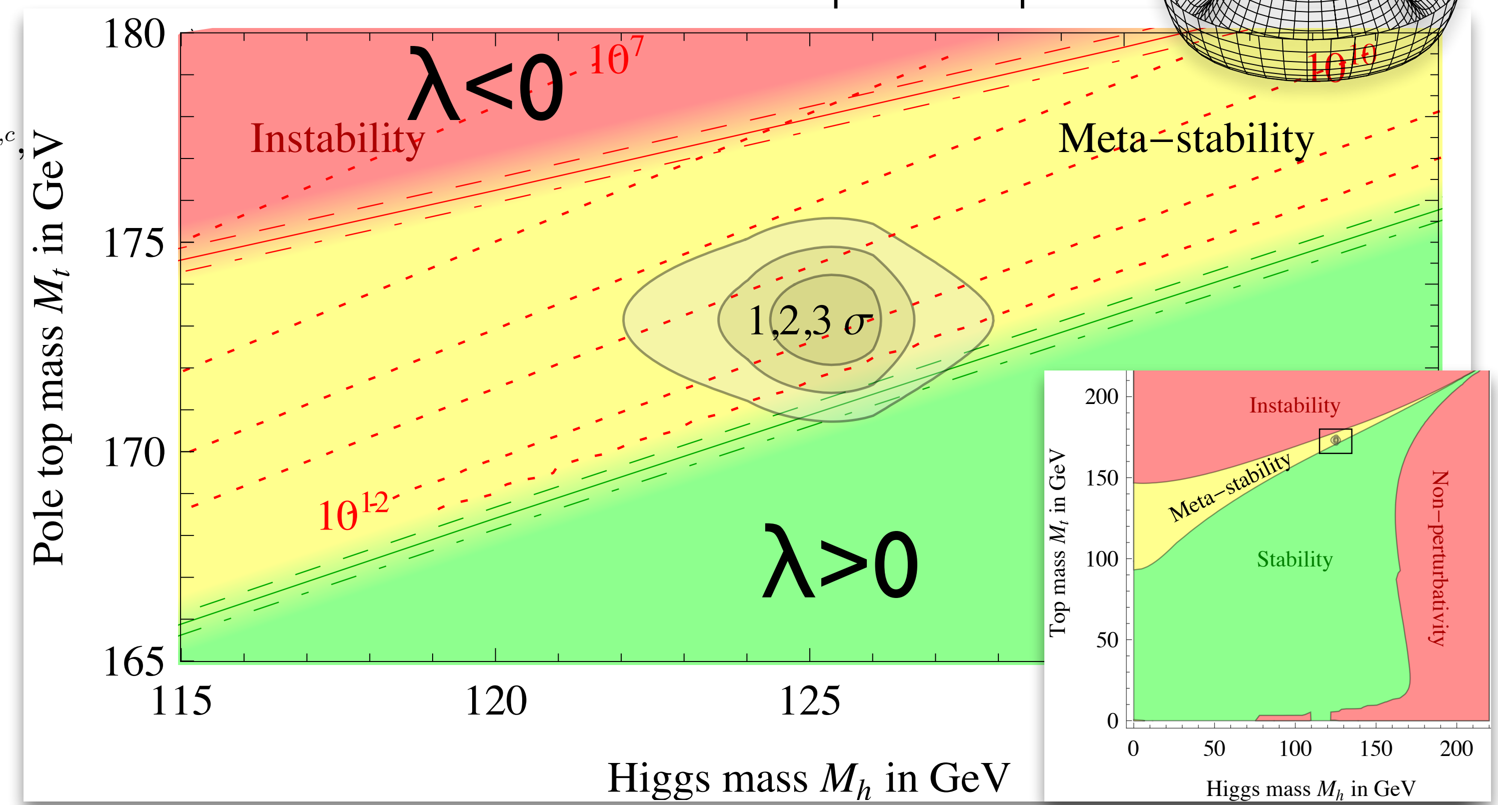
Naturalness or multiverse?

$$V(\Phi) = \mu^2\, \Phi^\dagger\, \Phi + \lambda\, \left|\Phi^\dagger\, \Phi\right|^2$$

Higgs mass and vacuum stability in the Standard Model at NNLO

Giuseppe Degrassi[a], Stefano Di Vita[a], Joan Elias-Miró[b], José R. Espinosa[b,c], Gian F. Giudice[d], Gino Isidori[d,e], Alessandro Strumia[g,h]

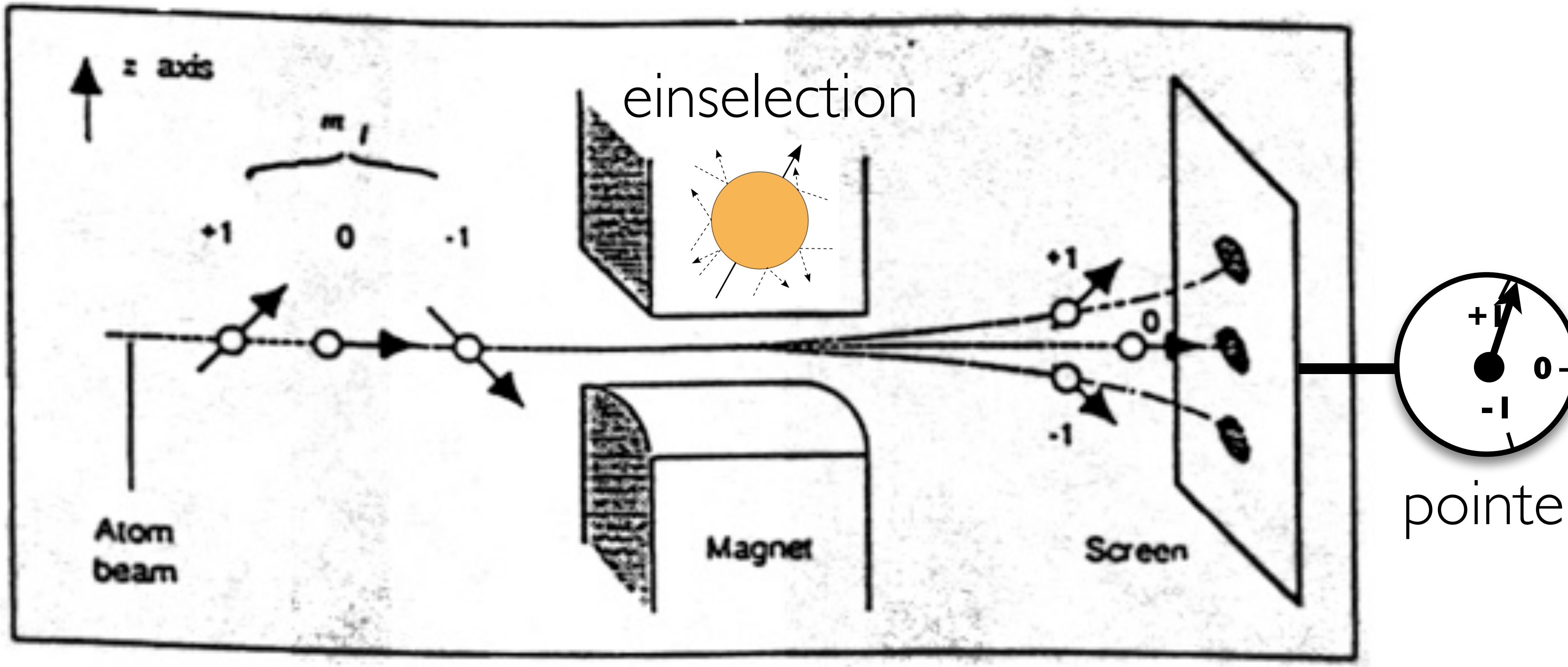




"If the LHC finds Higgs couplings deviating from the SM prediction and new degrees of freedom at the TeV scale, then the most important question will be to see if a consistent and natural (in the technical sense) explanation of EW breaking emerges from experimental data. But if the LHC discovers that the Higgs boson is not accompanied by any new physics, then it will be much harder for theorists to unveil the underlying organizing principles of nature. The multiverse, although being a stimulating physical concept, is discouragingly difficult to test from an empirical point of view. The measurement of the Higgs mass may provide a precious handle to gather some indirect information."

[arxiv: 1205.6497]

Pointers

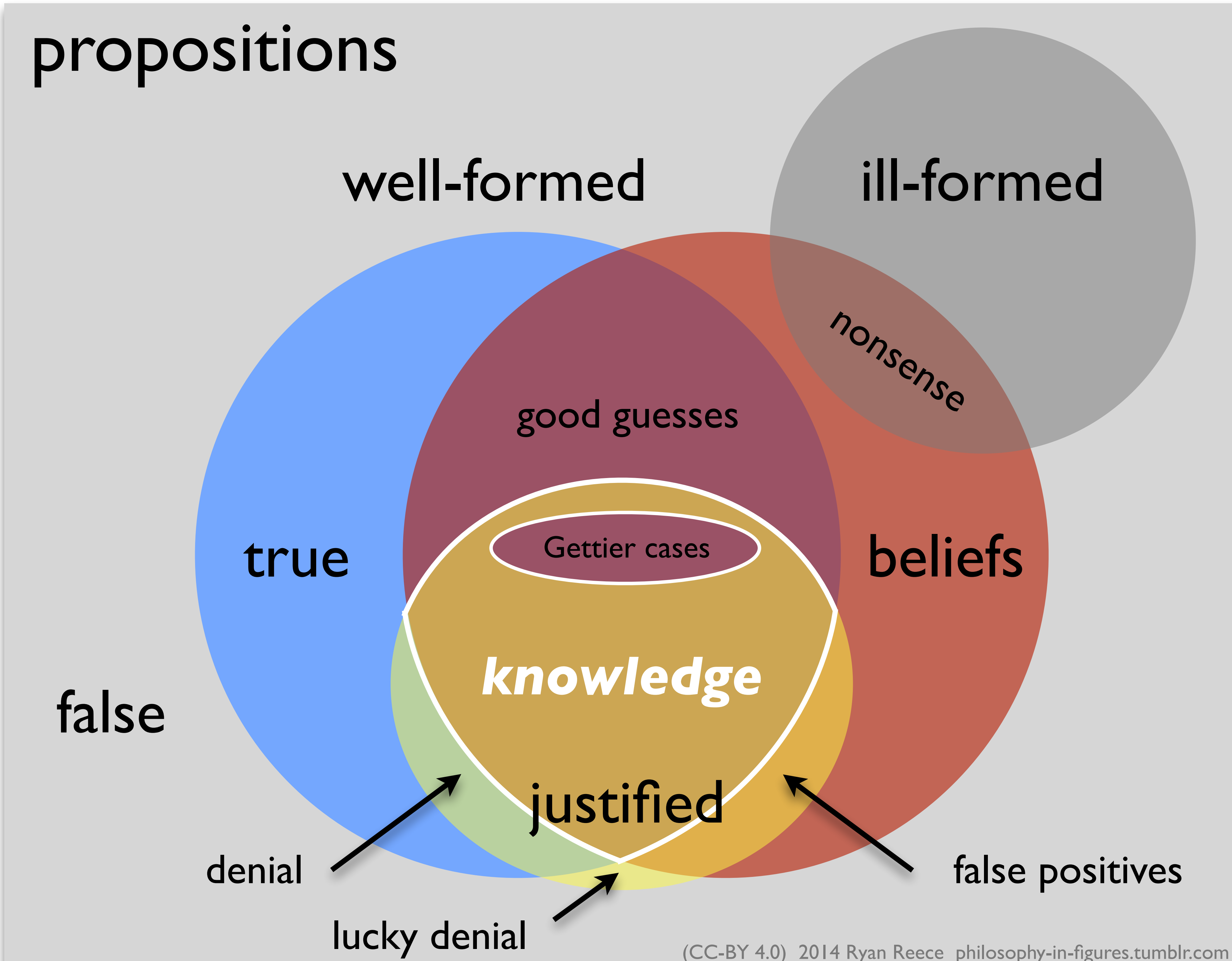


"in physics the only observations we must consider are position observations, if only the positions of instrument pointers."

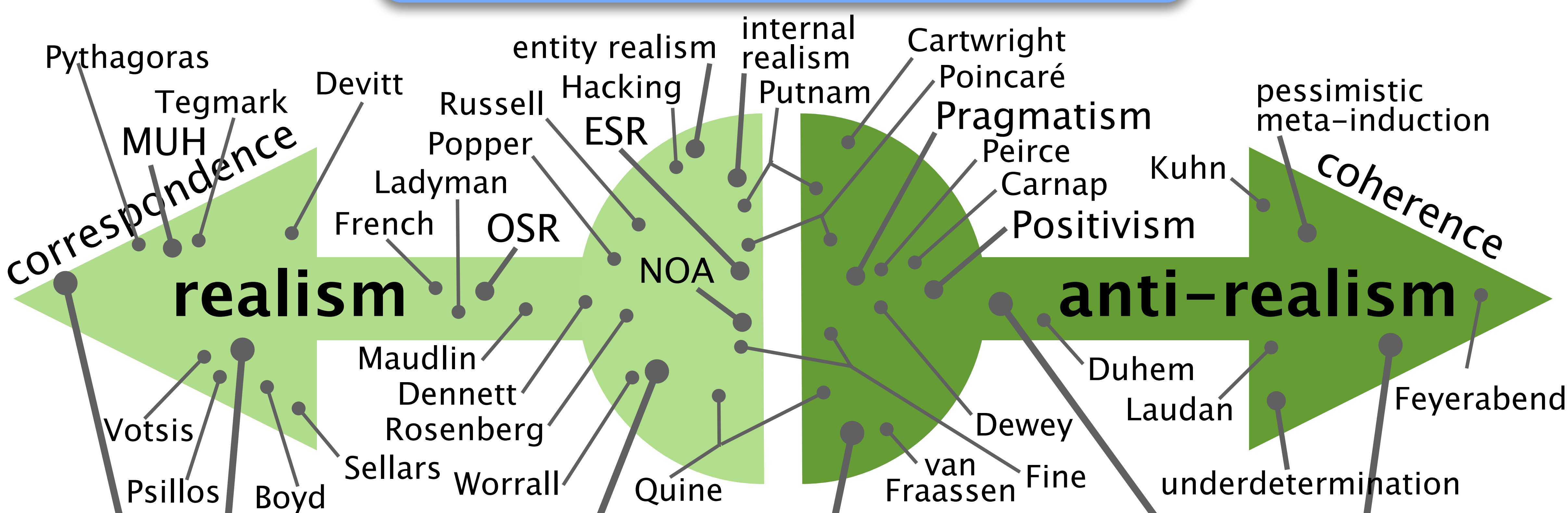
--

Bell, J. (1982). On the Impossible Pilot Wave. *Foundations of Physics*, *12*, 989.

Knowledge = JTB-G



philosophy of science



Naive Realism
The world I see is real. What are you all arguing about?

Structural Realism
Science has identified real patterns, relationships, and structures (at least within a regime) in nature.

Instrumentalism
Theoretical concepts may have use in predicting observations, but we have no ontological commitments to them.

Scientific Realism
Science makes real progress in describing real features of the world.

Constructive Empiricism
Science aims to give us theories which are empirically adequate, but does not justify metaphysical claims about reality.

Relativism
Social constructivism. Epistemological anarchism.