

# Quantum Mechanics, vacuum, particles, Gödel-Cohen Incompleteness and the Universe

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**Abstract – What is the origin of Quantum Mechanics (QM)?  
Is it an ultimate principle of Physics or a property of  
standard particles generated at a more fundamental level?**

**In the last case, a spinorial space-time with two complex  
coordinates instead of the standard four real ones can  
play an important role in the foundations of QM.**

**Similarly, if the vacuum is made of preons and the vacuum preons are superluminal just as the speed of light is much larger than that of sound, quantum entanglement appears as a natural property for standard particles and Bell's theorem does not apply to this new situation.**

**A vacuum made of superluminal preons can also influence black hole dynamics, including new quantum effects and new forms of radiation. LIGO and VIRGO data can potentially be sensitive to such an interaction.**

**Can the Gödel-Cohen incompleteness be avoided for a suitable formulation of the Quantum Physics of standard particles, if these particles are actually excitations of a preonic vacuum? After reviewing the present situation for conventional Quantum Mechanics, we attempt to answer this question considering implications for both Particle Physics and Cosmology.**



**John Stewart BELL**

**Belfast 1928**

—

**Geneva 1990**

**John Bell  
taught us  
what is,  
and what is not,  
Quantum  
Mechanics**

# BELL'S THEOREM

**BASIC CONTENT :** Theories with local hidden variables cannot reproduce all the predictions of Quantum Mechanics

In his book *Speakable and Unspeakable in Quantum Mechanics*, Cambridge University Press, 1987, p. 65, commenting on a hidden variable approach to Quantum Mechanics considered by Georges Lochak, John Bell writes explicitly:

*... if his extension is local it will not agree with quantum mechanics, and if it agrees with quantum mechanics it will not be local.*

**John Bell, in *On the Einstein Podolsky Rosen Paradox*, *Physics* 1 (3), 195 (1964) :**

***In a theory in which parameters are added to quantum mechanics to determine the results of individual measurements, without changing the statistical predictions, there must be a mechanism whereby the setting of one measuring device can influence the reading of another instrument, however remote. Moreover, the signal involved must propagate instantaneously, so that such a theory could not be Lorentz invariant.***

**Actually, the signal propagation can also be superluminal.**

# **POSSIBLE INGREDIENTS OF A NEW APPROACH TO QUANTUM MECHANICS**

## **I – VACUUM STRUCTURE AND DYNAMICS**

### **STANDARD PARTICLES AS VACUUM EXCITATIONS**

# THE PHYSICAL VACUUM AND STANDARD QUANTUM FIELD THEORY

In standard quantum field theory (SQFT), standard particles are “elementary” and the associated quantum fields can condense in vacuum. In this way, vacuum acquires an internal structure.

**But SQFT does not describe an intrinsic internal structure of vacuum pre-existent to standard particles and of which such particles would be excitations.**

**BEYOND SQFT =>  
A PREONIC VACUUM STRUCTURE ?**

See, for instance, my previous ICNFP papers

**IF STANDARD PARTICLES ARE VACUUM EXCITATIONS,  
LIKE PHONONS AND SOLITONS IN CONDENSED MATTER,  
THE CONSTITUENTS OF VACUUM CAN NATURALLY HAVE  
A CRITICAL SPEED MUCH LARGER THAN THE SPEED  
OF LIGHT  $c$  JUST AS  $c$  IS MUCH LARGER  
THAN THE SPEED OF SOUND**

**=>THE SUPERBRADYON HYPOTHESIS**

**(L. Gonzalez-Mestres, arXiv:astro-ph/9505117, 1995, and  
subsequent papers)**

**SUPERBRADYONS (SUPERLUMINAL PREONS) WOULD  
BE THE CONSTITUENTS OF THE PHYSICAL VACUUM**

**THEN, STANDARD RELATIVITY AND QUANTUM  
MECHANICS WOULD NO LONGER BE  
ULTIMATE FUNDAMENTAL PRINCIPLES**



# CAN SUPERBRADYONS PROPAGATE AS FREE PARTICLES IN OUR UNIVERSE?

## AN OPEN QUESTION

Assuming this is the case, they are expected (contrary to tachyons) to spontaneously emit Cherenkov-like radiation in vacuum in the form of standard particles until they reach a speed close to  $c$ .

**BUT THEY WOULD IN ANY CASE BE ABLE TRAVEL AT SUPERLUMINAL SPEED INSIDE THE VACUUM STRUCTURE => SUPERLUMINAL SIGNALS WOULD BE ABLE TO PROPAGATE**

**AS SUPERBRADYONS WOULD NOT BE  
STANDARD PARTICLES,**

**WE EXPECT THE DIRECT COUPLING  
OF A SINGLE SUPERBRADYON  
TO STANDARD INTERACTIONS TO BE WEAKER  
THAN THAT OF STANDARD MATTER**

**BUT IF THE PHYSICAL VACUUM  
IS MADE OF SUPERBRADYONS,**

**THE TRANSMISSION OF SIGNALS  
AND INFORMATION FROM STANDARD MATTER  
WILL BE A COLLECTIVE EFFECT  
AND CAN BE AMPLIFIED AS SUCH**

# **SUPERLUMINAL SIGNALS PROPAGATING IN A SUPERBRADYONIC VACUUM**

**=> A NATURAL EXPLANATION FOR  
QUANTUM ENTANGLEMENT**

**Assume that the critical speed of  
superbradyons inside vacuum is  $c_s \sim 10^6 c$   
just as  $c$  is  $\sim 10^6$  times larger than the  
speed of sound => can explain data from  
Bernien, Hensen et al.**

$$1.3 \text{ Km} / c_s \sim 4 \times 10^{-12} \text{ s}$$

**Experiments on entanglement can lead to  
bounds on  $c_s$  and even, possibly, determine it.**

<http://arxiv.org/abs/1508.05949>

## **Experimental loophole-free violation of a Bell inequality using entangled electron spins separated by 1.3 km**

[B. Hensen](#), [H. Bernien](#), [A.E. Dréau](#), [A. Reiserer](#), [N. Kalb](#), [M.S. Blok](#), [J. Ruitenberg](#), [R.F.L. Vermeulen](#), [R.N. Schouten](#), [C. Abellán](#), [W. Amaya](#), [V. Pruneri](#), [M. W. Mitchell](#), [M. Markham](#), [D.J. Twitchen](#), [D. Elkouss](#), [S. Wehner](#), [T.H. Taminiau](#), [R. Hanson](#) (Submitted on 24 Aug 2015)

For more than 80 years, the counterintuitive predictions of quantum theory have stimulated debate about the nature of reality. In his seminal work, John Bell proved that no theory of nature that obeys locality and realism can reproduce all the predictions of quantum theory. Bell showed that in any local realist theory the correlations between distant measurements satisfy an inequality and, moreover, that this inequality can be violated according to quantum theory.

This provided a recipe for experimental tests of the fundamental principles underlying the laws of nature. In the past decades, numerous ingenious Bell inequality tests have been reported. However, because of experimental limitations, all experiments to date required additional assumptions to obtain a contradiction with local realism, resulting in loopholes. Here we report on a Bell experiment that is free of any such additional assumption and thus directly tests the principles underlying Bell's inequality. We employ an event-ready scheme that enables the generation of high-fidelity entanglement between distant electron spins. Efficient spin readout avoids the fair sampling assumption (detection loophole), while the use of fast random basis selection and readout combined with **a spatial separation of 1.3 km** ensure the required locality conditions. We perform 245 trials testing the CHSH-Bell inequality  $S \leq 2$  and find  $S = 2.42 \pm 0.20$ . A null hypothesis test yields a probability of  $p = 0.0039$  that a local-realist model for space-like separated sites produces data with a violation at least as large as observed, even when allowing for memory in the devices. This result rules out large classes of local realist theories, and paves the way for implementing device-independent quantum-secure communication and randomness certification.

# **II – SPACE-TIME STRUCTURE**

**SPACE-TIME, THE UNIVERSE AND  
PARTICLE PROPERTIES**

**=> THE SPINORIAL SPACE-TIME**

# FIRST INGREDIENT OF A NEW FORMULATION OF QUANTUM MECHANICS : SUPERLUMINAL SIGNALS IN THE SUPERBRADYONIC VACUUM

**BUT WHAT ABOUT SPACE-TIME ?**

**IS THERE A LINK BETWEEN QUANTUM  
MECHANICS AND THE SPACE-TIME STRUCTURE ?**

**IS THERE A RELATION BETWEEN COMPLEX  
QUANTUM WAVE FUNCTIONS AND POSSIBLE  
COMPLEX SPACE-TIME COORDINATES ?**

**ARE COMPLEX QUANTUM WAVE FUNCTIONS  
NATURAL EXPRESSIONS OF A COMPLEX  
SPACE-TIME LEADING VACUUM DYNAMICS?**

**HOW ARE FERMIONIC SPINORS GENERATED ?**

# AN EXAMPLE OF NEW SPACE-TIME : THE SPINORIAL SPACE-TIME (SST)

L. Gonzalez-Mestres, 1996-97

FERMIONS ARE NOT REPRESENTATIONS OF THE  
CONVENTIONAL SPACE ROTATION GROUP  $SO(3)$   
BUT OF ITS COVERING GROUP  $SU(2)$

=> Replace the standard four-dimensional space-time by a  $SU(2)$  spinorial one, so that spin-1/2 particles become representations of the actual group of space transformations.

=> Associate to each point of space-time in our Universe a cosmic spinor  $\xi$  (two components, two complex numbers) with a  $SU(2)$  group that contains the space rotations group  $SO(3)$ .



**SEE, FOR INSTANCE, MY PREVIOUS ICNFP PAPERS**

**=> Extracting from a cosmic spinor  $\xi$  the scalar  $|\xi|^2 = \xi^\dagger \xi$  where the dagger stands for hermitic conjugate, a positive cosmic time  $t = |\xi|$  can be defined which leads in particular to a naturally expanding universe, with an arrow of time.**

**=> The conventional space at cosmic time  $t_0$  corresponds to the  $|\xi| = t_0 \mathbf{S}^3$  hypersphere from the four real numbers contained in the two SU(2) spinor components**

**PURELY GEOMETRIC EFFECTS => No matter, no critical speed, involved yet.**

**The definition of cosmic time is not unique :**  
 **$t$  can also be a different function of the spinor modulus  $|\xi| \Rightarrow$  f.i.  $t = |\xi|^2$**

**This does not change the analysis that follows, and has no practical consequences**

**In such a spinorial space-time, comoving frames correspond to **straight lines through the origin**  $\xi = 0$  that corresponds to the origin of cosmic time**

**Spatial distances at a given cosmic time must be measured on the constant time  $S^3$  hypersphere.**

**THE LUNDMARK- LEMAITRE – HUBBLE LAW**  
**CAN THEN EMERGE FROM PURE GEOMETRY**

**The SST automatically Leads to the Lemaître – Hubble law :  $v / d = t_0^{-1}$  where :  $v =$  relative speed,  $d =$  spatial distance at constant  $t$  .**

**The Lundmark - Lemaître – Hubble constant turns out to be equal to the inverse of the age of the Universe. This “automatic” value obtained with such a simple, purely geometric, spinorial pattern is quite reasonable from a phenomenological point of view.**

**No gravitation, standard interactions... has yet been introduced => could the apparent acceleration of the expansion of our Universe be just a fluctuation due to the history of these “local” parameters that initially opposed to the expansion? (See my previous papers)**

# SST AND RELATIVITY

**EVEN IF RELATIVITY WILL REMAIN AN ESSENTIAL PROPERTY OF STANDARD MATTER, IT IS NOT EXPECTED TO BE AN EXACT SYMMETRY IN THE SST**

**=> NOT REALLY PART OF THE BASIC GEOMETRY**

**RELATIVITY WILL IN PRINCIPLE BE VIOLATED AT VERY LOW DISTANCES AND ULTRA-HIGH ENERGIES (f.i. by preon dynamics)**

**SIMILARLY, GENERAL RELATIVITY IS NOT EXPECTED TO BE A DOMINANT FEATURE OF THE UNIVERSE AT THE LARGEST DISTANCE SCALES (IMPLICATIONS OF A POSSIBLE PRE-BIG BANG COSMOLOGY)**

# SST AND A POSSIBLE ORIGIN OF QUANTUM MECHANICS (MY ICNEP 2015 PAPER)

HAVING DEFINED THE COSMIC TIME IN THE SST AS  $t = |\xi|$  , HOW TO DEFINE, IN THE LIMIT OF VERY SMALL TIME AND DISTANCE SCALES, THE LOCAL TIME AND SPACE AROUND A POINT  $\xi_0$  DIFFERENT FROM THE COSMIC ORIGIN ?

ASSUME THAT, HAVING A PREONIC VACUUM, WE INTRODUCE LOCAL SPINORIAL COORDINATES SIMILAR TO THE COSMIC ONES THROUGH THE LOCAL SPINOR  $\xi - \xi_0$  LEADING TO A LOCAL TIME

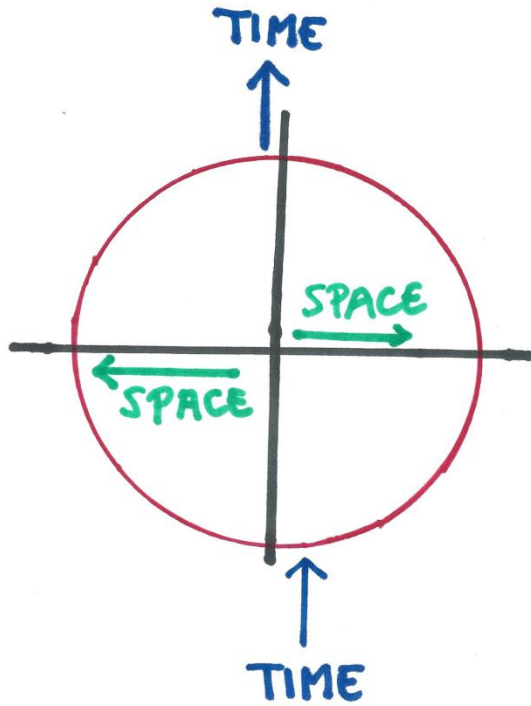
$|\xi - \xi_0| \Rightarrow$  A CONTRADICTION ARISES AT VERY SMALL DISTANCES BETWEEN LOCAL AND COSMIC TIME  $\Rightarrow$  CONSEQUENCES FOR MATTER<sup>21</sup> ?

If  $\Psi (\xi - \xi_0)$  is the spinorial wave function from preon dynamics, centered at  $\xi = \xi_0$ , of a fermion in the local spinorial space-time, it may happen that  $\Psi (\xi - \xi_0)$  is a solution of the basic equations leading preon dynamics, but its continuous propagation is not and is forbidden by dynamics.

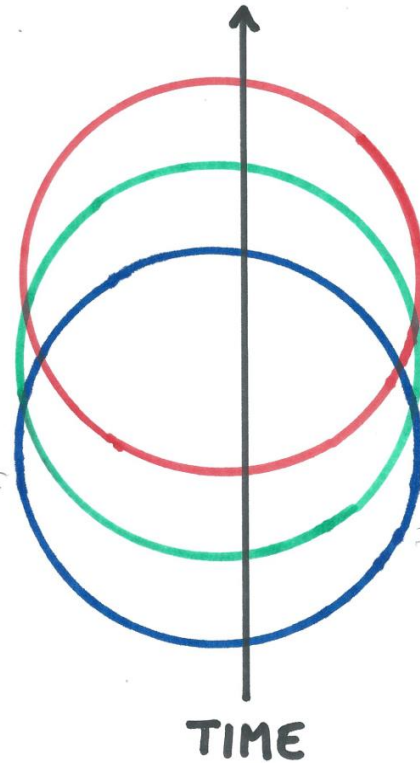
Taking for the cosmic time associated to the fermion space-time position  $t_0 = |\xi_0|$ , the spinor  $\xi - \xi_0$  spans over a continuous set of values of the cosmic time  $\Rightarrow$  In the SST with a preonic vacuum, particles are extended objects in both space and time

$\Rightarrow$  THIS CAN FORBID CONTINUOUS MOTION

FROM MY  
ICNEP 2015  
POSTER  
ON QM



AN "EXTENDED"  
SPIN-1/2 PARTICLE  
IN THE SST  $\Rightarrow$   
A WHOLE CONTINUUM  
OF VALUES OF TIME  
IS SIMULTANEOUSLY  
CONCERNED



CONTINUOUS MOTION  
FORBIDDEN BY  
VACUUM DYNAMICS  
BECAUSE OF  
OVERLAP IN TIME?

**IF CONTINUOUS MOTION IS FORBIDDEN AT VERY SMALL DISTANCE SCALES, DISCRETE MOTION WILL PRESENT RANDOM FEATURES POTENTIALLY LEADING TO A FEYNMAN-LIKE PATH INTEGRAL AT MACROSCOPIC SCALES**

**=> A SUPERBRADYONIC VACUUM WITH SST SPACE-TIME GEOMETRY CAN NATURALLY BE AT THE ORIGIN OF QUANTUM MECHANICS**

**THE SITUATION DESCRIBED CAN POTENTIALLY BE GENERATED WITH ANY DYNAMICAL PATTERN IMPLYING A DEFINITION OF TIME AT VERY SMALL DISTANCES IN CONTRADICTION WITH THE MACROSCOPIC ONE OR NATURALLY INTRODUCING AN INTRINSIC TIME UNCERTAINTY => DESERVES FURTHER INVESTIGATION**



**THE SCENARIO JUST CONSIDERED VIOLATES CONVENTIONAL RELATIVITY AND QUANTUM MECHANICS AT VERY SMALL DISTANCES AND VERY HIGH ENERGY FOR STANDARD PARTICLES**

**=> HOW TO TEST SUCH VIOLATIONS ?**

**- Ultra-high energy cosmic rays (e.g. GZK ?, see my previous ICNFP papers) : the situation remains unclear**

**=> AUGER is preparing an upgrade**

**- SST predicts a privileged space direction for each comoving observer (see my previous ICNFP papers) : Planck may have seen a signature of this phenomenon, but its final results are not yet known.**

<http://arxiv.org/abs/1604.03637>

# **The Pierre Auger Observatory Upgrade - Preliminary Design Report**

The [Pierre Auger Collaboration](#):

(Submitted on 13 Apr 2016)

The Pierre Auger Observatory has begun a major Upgrade of its already impressive capabilities, with an emphasis on improved mass composition determination using the surface detectors of the Observatory. Known as AugerPrime, the upgrade will include new 4 m<sup>2</sup> plastic scintillator detectors on top of all 1660 water-Cherenkov detectors, updated and more flexible surface detector electronics, a large array of buried muon detectors, and an extended duty cycle for operations of the fluorescence detectors. This Preliminary Design Report was produced by the Collaboration in April 2015 as an internal document and information for funding agencies. It outlines the scientific and technical case for AugerPrime. (...)

# **III – HOW TO TEST THE SUPERBRADYONIC VACUUM ?**

**(INCLUDING QUANTUM-MECHANICAL  
EFFECTS IN THIS CONTEXT)**

**A POSSIBLE NEW WAY AFTER LIGO –  
VIRGO RESULTS :**

**BLACK HOLES, GRAVITATIONAL  
WAVES, OTHER POSSIBLE WAVES...**

## Schwarzschild black hole of mass $M$ :

$$ds^2 = - c^2 (1 - 2GM / c^2 r) dt^2 - (1 - 2GM / c^2 r)^{-1} dr^2 + r^2 (d\theta^2 + \sin^2 \theta d\varphi^2)$$

$G$  = gravitational constant,  $r$  = spatial radius,  
 $c$  = speed of light,  $t$  = time,  $\theta$  and  $\varphi$  = standard  
angular variables.

In the presence of a superbradyonic vacuum, we  
expect the  $r = 0$  singularity of the black hole to  
interact with vacuum structure and be replaced by  
a new dynamical configuration, including quantum  
effects => **Can modify black hole dynamics and  
radiation => Observable by LIGO and VIRGO ?**

<http://arxiv.org/abs/1602.03840>

## Properties of the Binary Black Hole Merger GW150914

The [LIGO Scientific Collaboration](#), the [Virgo Collaboration](#)

On September 14, 2015, the Laser Interferometer Gravitational-wave Observatory (LIGO) detected a gravitational-wave transient (GW150914); we characterize the properties of the source and its parameters. The data around the time of the event were analyzed coherently across the LIGO network using a suite of accurate waveform models that describe gravitational waves from a compact binary system in general relativity. GW150914 was produced by a nearly equal mass binary black hole of  $36^{+5}_{-4} M_{\odot}$  and  $29^{+4}_{-4} M_{\odot}$ ; for each parameter we report the median value and the range of the 90% credible interval. The dimensionless spin magnitude of the more massive black hole is bound to be  $<0.7$  (at 90% probability). The luminosity distance to the source is  $410^{+160}_{-180}$  Mpc, corresponding to a redshift  $0.09^{+0.03}_{-0.04}$  assuming standard cosmology. The source location is constrained to an annulus section of  $610 \text{ deg}^2$ , primarily in the southern hemisphere. The binary merges into a black hole of  $62^{+4}_{-4} M_{\odot}$  and spin  $0.67^{+0.05}_{-0.07}$ . This black hole is significantly more massive than any other inferred from electromagnetic observations in the stellar-mass regime.

<http://arxiv.org/abs/1606.04855>

## **GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence**

The [LIGO Scientific Collaboration](#), the [Virgo Collaboration](#)

We report the observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC. The signal was initially identified within 70 s by an online matched-filter search targeting binary coalescences. Subsequent off-line analyses recovered GW151226 with a network signal-to-noise ratio of 13 and a significance greater than  $5\sigma$ . The signal persisted in the LIGO frequency band for approximately 1 s, increasing in frequency and amplitude over about 55 cycles from 35 to 450 Hz, and reached a peak gravitational strain of  $3.4^{+0.7}_{-0.9} \times 10^{-22}$ . The inferred source-frame initial black hole masses are  $14.2^{+8.3}_{-3.7} M_{\odot}$  and  $7.5^{+2.3}_{-2.3} M_{\odot}$  and the final black hole mass is  $20.8^{+6.1}_{-1.7} M_{\odot}$ . We find that at least one of the component black holes has spin greater than 0.2. This source is located at a luminosity distance of  $440^{+180}_{-190}$  Mpc corresponding to a redshift  $0.09^{+0.03}_{-0.04}$ . All uncertainties define a 90 % credible interval. This second gravitational-wave observation provides improved constraints on stellar populations and on deviations from general relativity.

<http://arxiv.org/abs/1407.0989>

# Black hole fireworks: quantum-gravity effects outside the horizon spark black to white hole tunneling

[Hal M. Haggard](#), [Carlo Rovelli](#)

We show that there is a classical metric satisfying the Einstein equations outside a finite spacetime region where matter collapses into a black hole and then emerges from a white hole. We compute this metric explicitly. We show how **quantum theory determines** the (long) time for the process to happen. **A black hole can thus quantum-tunnel into a white hole.** For this to happen, quantum gravity should affect the metric also in a small region outside the horizon: we show that contrary to what is commonly assumed, this is not forbidden by causality or by the semiclassical approximation, because quantum effects can pile up over a long time. This scenario alters radically the discussion on the black hole information puzzle.

**NEW PHYSICS CAN INDEED  
MODIFY BLACK HOLE DYNAMICS  
AND PRODUCE OBSERVABLE EFFECTS**

**THE EFFECT CAN BE EVEN STRONGER  
FOR A BLACK HOLE MERGER**

**STANDARD QUANTUM EFFECTS  
ARE ALREADY KNOWN TO PRODUCE  
HAWKING RADIATION,**

**BUT WHAT CAN HAPPEN  
IN THE PRESENCE  
OF A SUPERBRADYONIC VACUUM?**



# A SIMPLE EXAMPLE OF A POSSIBLE SIGNATURE

Assume that, as a result of the interaction between the superbradyonic vacuum and the black hole (or black hole merger), some superbradyons can penetrate inside the black hole (or black hole merger) and leave it as free particles  
**=> a new form of black hole radiation**

The Schwarzschild radius  $R = 2GMc^{-2}$  associated to the observed black holes and black hole mergers is in all cases less than 200 Km => **A superbradyon with speed  $\sim 10^6 c$  would possibly be able to leave the black hole in less than 1ns => No time to interact gravitationally ?**

Then, assuming Cherenkov decay in vacuum, superbradyons emitted by the observed black hole mergers should be able to reach Earth with a speed close to  $c$

Energy ? Interaction with detectors ?

Preonic waves together with gravitational

waves ?  $\Rightarrow$  Can one detect such superbradyons and preonic waves ?

Can gravitational waves propagating on very large distances interact with the preonic vacuum ?

**FURTHER WORK IS NEEDED**

# IV - GODEL-COHEN INCOMPLETENESS, THE LAWS OF PHYSICS AND THE REAL WORLD

<http://plato.stanford.edu/entries/goedel-incompleteness/>

## Stanford Encyclopedia of Philosophy Gödel's Incompleteness Theorems

(...) The first incompleteness theorem states that in any consistent formal system  $F$  within which a certain amount of arithmetic can be carried out, there are statements of the language of  $F$  which can neither be proved nor disproved in  $F$ . According to the second incompleteness theorem, such a formal system cannot prove that the system itself is consistent (assuming it is indeed consistent). (...) (end of quote)

**Cohen completed this work for the continuum hypothesis**

<https://arxiv.org/abs/physics/0612253>

## Goedel and Physics

[John D. Barrow](#)

We introduce some early considerations of physical and mathematical impossibility as preludes to the Goedel incompleteness theorems. We consider some informal aspects of these theorems and their underlying assumptions and discuss some the responses to these theorems by those seeking to draw conclusions from them about the completability of theories of physics. **We argue that there is no reason to expect Goedel incompleteness to handicap the search for a description of the laws of Nature, but we do expect it to limit what we can predict about the outcomes of those laws, and examples are given.** We discuss the Goedel universe and the role it played in exposing the full spectrum of possibilities that a global understanding of space-time would reveal. Finally, we show how recent studies of supertasks have shown how global space-time structure determines the ultimate capability of computational devices within them.

**Stephen HAWKING** : Gödel's theorems suggest that there is not an ultimate theory that can be formulated as a finite number of principles

<http://www.hawking.org.uk/godel-and-the-end-of-physics.html>

<http://www.damtp.cam.ac.uk/events/strings02/dirac/hawking/>

**Godel and the End of the Universe**  
**(Cambridge lecture)**

<http://www.nature.com/news/paradox-at-the-heart-of-mathematics-makes-physics-problem-unanswerable-1.18983>

*Nature News*, 09 December 2015

## **Paradox at the heart of mathematics makes physics problem unanswerable**

Gödel's incompleteness theorems are connected to unsolvable calculations in quantum physics.

Daive Castelvechi

A logical paradox at the heart of mathematics and computer science turns out to have implications for the real world, making a basic question about matter fundamentally unanswerable. (...)

<http://arxiv.org/abs/1502.04135>

*Nature* **528**, 207-211 (2015)

[Toby Cubitt](#), [David Perez-Garcia](#), [Michael M. Wolf](#)

## Undecidability of the Spectral Gap (short version)

The spectral gap - the energy difference between the ground state and first excited state - is central to quantum many-body physics. Many challenging open problems, such as the Haldane conjecture, existence of gapped topological spin liquid phases, or the Yang-Mills gap conjecture, concern spectral gaps. These and other problems are particular cases of the general spectral gap problem: **given a quantum many-body Hamiltonian, is it gapped or gapless? Here we prove that this is an undecidable problem.** We construct families of quantum spin systems on a 2D lattice with translationally-invariant, nearest-neighbour interactions for which the spectral gap problem is undecidable. This result extends to undecidability of other low energy properties, such as existence of algebraically decaying ground-state correlations.

The proof combines Hamiltonian complexity techniques with aperiodic tilings, to construct a Hamiltonian whose ground state encodes the evolution of a quantum phase-estimation algorithm followed by a universal Turing Machine. The spectral gap depends on the outcome of the corresponding Halting Problem. Our result implies that there exists no algorithm to determine whether an arbitrary model is gapped or gapless. It also implies that there exist models for which the presence or absence of a spectral gap is independent of the axioms of mathematics.

**Longer version:**

<http://arxiv.org/abs/1502.04573>

## **Undecidability of the Spectral Gap (full version)**

We show that the spectral gap problem is undecidable. Specifically, we construct families of translationally-invariant, nearest-neighbour Hamiltonians on a 2D square lattice of  $d$ -level quantum systems ( $d$  constant), for which determining whether the system is gapped or gapless is an undecidable problem. (...)



**John Barrow writes (page 10) :**

*Another possible way of evading Gödel's theorem is if the physical world only makes use of the decidable part of mathematics.*

**But this does not seem to be possible in standard Physics if one considers the example provided by Cubitt, Pérez-Garcia and Wolf where it is impossible to decide if a many-body quantum system has a spectral energy gap.**

**AND WHAT ABOUT PARTICLE PHYSICS,  
QUANTUM FIELD THEORY,  
COSMOLOGY... ?**

# **WHAT IN THE PRESENCE OF A PREONIC VACUUM ?**

**If standard particles are excitations of a preonic vacuum, the actual laws of Physics are expected to be exact only at the level of this vacuum.**

**The standard laws of Physics would then be only low-energy approximations and be deformed as the energy scale increases.**

**How exact can they be at low energy ?**

**ACTUALLY, EVEN AT LOW ENERGY, STANDARD PARTICLE PHYSICS CONTAINS BASIC INFORMATION THAT WOULD BE DIRECTLY GENERATED AT THE PREONIC LEVEL (PARTICLE MASSES AND COUPLINGS...)**

**=> CAN ONE TOTALLY ELIMINATE THE PREONIC VACUUM FROM THE EQUATIONS OF PARTICLE PHYSICS, EVEN AT LOW ENERGY ? IF NOT, THE STANDARD EQUATIONS SHOULD ACTUALLY INVOLVE ERRORS BARS**

**SIMULTANEOUSLY, GÖDEL'S THEOREMS SHOULD BE APPLIED TO THE DYNAMICS OF THE PREONIC VACUUM INCLUDING STANDARD PARTICLES AS VACUUM EXCITATIONS**

**ONE MAY EXPECT THAT A FORMULATION OF  
STANDARD PHYSICS WITH SUITABLE  
ERROR BARS REPLACES INCOMPLETENESS  
BY NATURAL UNCERTAINTIES**

**BUT IT MAY ALSO HAPPEN THAT  
THE ROLE OF PREONS CANNOT BE IGNORED  
(QUANTUM FIELDS IN VACUUM...  
SEE MY PREVIOUS ICNFP PAPERS)**

**BY NOW, THE PHYSICAL LAWS LEADING  
THE STRUCTURE AND DYNAMICS OF THE  
PHYSICAL VACUUM REMAIN UNKNOWN**

**AGAIN, FURTHER WORK IS REQUIRED**

# CONCLUSION

**A REAL UNDERSTANDING  
OF QUANTUM MECHANICS  
REQUIRES UNDERSTANDING  
THE PHYSICAL VACUUM**

**=> THIS IS NOT A SIMPLE TASK  
AND CAN TAKE A LONG TIME**

**IF THE VACUUM HAS A NONTRIVIAL  
INTERNAL STRUCTURE, ITS CONSTITUENTS  
WILL NATURALLY BE SUPERLUMINAL**

**=> QUANTUM ENTANGLEMENT**

**THE SST CAN BE AT THE ORIGIN OF THE  
COMPLEX WAVE FUNCTIONS AND GENERATE  
A SPACE-TIME CONTRADICTION LEADING TO  
THE FEYNMAN PATH INTEGRAL**

**BLACK HOLES, GRAVITATIONAL WAVES,  
LIGO, VIRGO... CAN CONTRIBUTE TO UNVEIL  
THE VACUUM STRUCTURE**

**GÖDEL-COHEN INCOMPLETENESS SHOULD  
BASICALLY APPLY TO THE (YET UNKNOWN)  
VACUUM DYNAMICS INCLUDING STANDARD  
PARTICLES AS VACUUM EXCITATIONS**

**DIFFICULT, BUT PROMISING**