Bert and the Multiverse

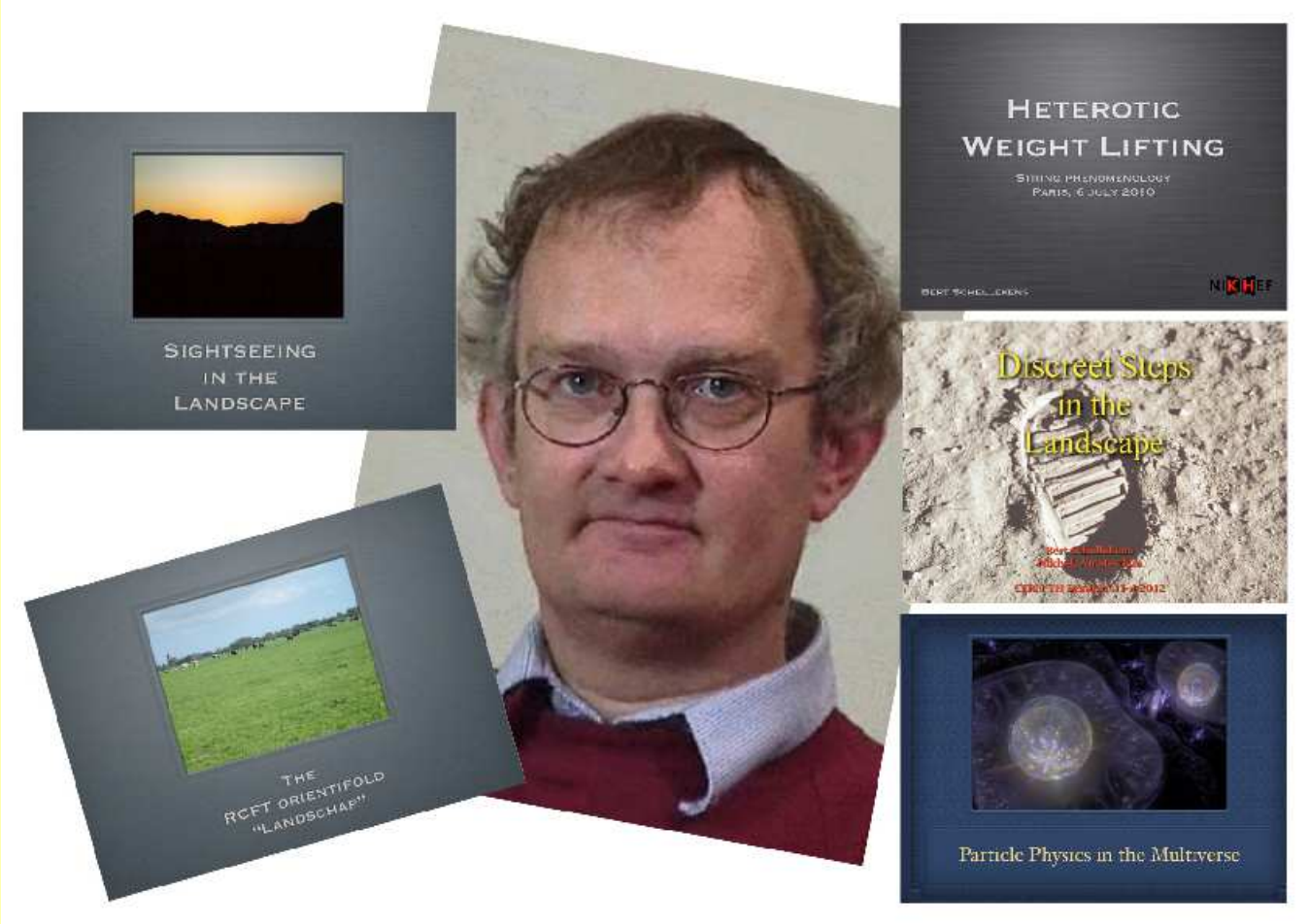
or:

How many choices did God have when creating the world?

BertFest, NIKHEF, Amsterdam, 13 May 2022

Hermann Nicolai
MPI für Gravitationsphysik, Potsdam
(Albert-Einstein-Institut)

Surveying the landscape...



First encounters at CERN in early 80ies where I learned about Bert's early work

- **monopole catalysis of proton decay, composite models, fermion masses, CP violation (1982)**
- **KK theory and KK spectra (bosons and fermions), Yukawa couplings (1984)**

After our collaboration in 1986 contacts became less frequent, but I continued to follow Bert's activities and some remarkable highlights, such as

- **Anomalies, Characters and Strings**

  [A.Schellekens and N.Warner, NPB287(1987)317]

In this talk: retrace a small part of Bert's worldline from my own (a bystander's) perspective, highlighting some of Bert's important insights.

The Heterotic String (1985)

"... Although much work remains to be done there seem to be no insuperable obstacles to deriving all of known physics from the $E_8 \times E_8$ heterotic string."

[Gross,Harvey,Martinec,Rohm, Nucl.Phys.B256(1985)253]

"We study candidate vacuum configurations in ten-dimensional O(32) and $E_8 \times E_8$ supergravity and superstring theory that have unbroken $N = 1$ supersymmetry in four dimensions. This condition *permits only a few possibilities*, all of which have vanishing cosmological constant..."

[Candelas,Horowitz,Strominger,Witten, NPB258(1985)46]

So the hope for an (almost) *unique* path from the $E_8 \times E_8$ heterotic string to the Standard Models of particle physics and cosmology, and thus to our four-dimensional real world, was clearly there....

Our only joint work

Bosonic string as the 'Ur-Theory'? [Casher,Englert,HN,Taormina(1985)]

More details (and a crazy proposal of an 18-dim. string):

Superstrings from 26 dimensions [Englert,HN,Schellekens,NPB274 1986)315]

Bert's subsequent visit in Karlsruhe (1986): fermions from bosons via solitons, superghosts from (physical) target space coordinates?

→ ***Topics in String Theory*** [HN, Schellekens, in: 5th Adriatic Meeting on Particle Physics: Superstrings, Anomalies and Unification, 195-238 (1986)]

"We show how modular and conformally invariant truncations produce the old and new heterotic strings in a practically unique way, using the classification of Niemeyer lattices. These results suggest a natural realization of superconformal field theory in the bosonic string."

With hindsight, one can say that this idea works at the kinematical level, but a dynamical mechanism realizing it was never found (and probably does not exist).

A huge step away from uniqueness

Following [Narain(1985)]: ***Chiral Four-Dimensional Heterotic Strings from Selfdual Lattices*** [Lerche,Lüst,Schellekens, NPB287(1987)477]

$\rightarrow$ **Proliferation of string vacua via lattice compactifications!**

... all of which lead to different physics (gauge groups, particle multiplets, *etc.*) in 4D low energy world. $\rightarrow$

First appearance of a large number 10^{1500} (corrected to 10^{1030} later: "huge but inconsequential error" [Bert]**)**

Meanwhile this number has gotten even larger: flux compactifications, orbi- and orientifolds, brane constructions, F theory,...

- ***Big Numbers in String Theory*** [A.Schellekens,1601.02462 [hep-th]]
- ***Scanning the skeleton of the 4D F-theory landscape*** [W.Taylor,Y.N.Wang, JHEP 01 (2018) 111] $\rightarrow$ 10^{272000} **vacua?**

... and there could well be many more (there is lots of room here for huge inconsequential errors!).

$\rightarrow$ **a blow to expectations of a unique outcome!**

Conclusion: vacuum proliferation is an unavoidable feature of string theory that MUST be dealt with if string theory is the right theory.

Caveat: **most of these constructions are *perturbative* in the sense that the string coupling g_s does not appear to play a role. Maybe 'true' vacuum requires $g_s \neq 0$? But then we may be talking about a different problem and a different theory (M theory?)...**
($g_s \propto R_{11}^{3/2}$ [Witten] **$\rightarrow$ supermembrane?** [cf. JHEP02(2022)114]**)**

Cf. **QCD and Yang-Mills theory: true vacuum is very different from the kinematical (Fock space) vacuum – this is one of the Millenium problems of the Clay Foundation! And there is absolutely no reason to expect the groundstate of the world to be any less complicated than the one of QCD...**

What does this mean?

- **Is string theory a unique theory with one defining fundamental equation that admits (perhaps infinitely) many solutions ('vacua'), in analogy with Einstein's equations which also admit (infinitely) many solutions?**
- **Or is it that there is no defining equation, but merely some self-consistent 'framework', with many subtheories ('vacua') connected by a web of dualities, describing different universes with very different physics?**

For instance, abstractly, the space of all $2D$ CFTs with $c_{tot} = 0$?

- **And where are the Standard Models of particle physics and cosmology in all this, together with the four-dimensionality of our world?**

Even in the string community, opinions differ on whether this proliferation is a good or a bad feature...

A switch of paradigm (1998)

The Landscape 'avant la lettre' [A.Schellekens,physics/0604134]

... the first serious and carefully argued discussion, based on Bert's 1998 inaugural lecture (given in Dutch), suggesting that we should view the proliferation of vacua as a *virtue* of the theory, and not as a drawback – *long before* the idea of the string landscape was picked up and advertized on the US West Coast!

- *"....we are only in an intermediate stage of a very slow shift of opinions regarding the objectives of our field."*
- *"....concluded that a unique theory with a huge number of vacua and anthropic raison d'etre of our universe was the most attractive outcome, and that this was precisely what String Theory was suggesting."*
- *"I expect that the String Theory Landscape will acquire an important place in science history. Of course its ultimate fate depends on the correctness of String Theory, and the unexpectedly huge size of the landscape is making it a lot harder to convince ourselves of that. But String Theory won't be correct without the landscape being correct. And if that is true, it would be one of the most fundamental discoveries one can make."*

The Multiverse

"Bert believes in multiple universes – all of them lousy."

[https://www.cartoonstock.com]

The Multiverse according to Wikipedia

The multiverse is a hypothetical group of multiple universes. Together, these universes comprise everything that exists: the entirety of space, time, matter, energy, information, and the physical laws and constants that describe them. The different universes within the multiverse are called 'parallel universes', 'other universes', 'alternate universes', or 'many worlds'.

... as you can see, there are several different meanings that can be attached to the term 'multiverse', and the string landscape is not even properly mentioned in the above description.

Can string theory (jointly with eternal inflation) provide a mathematically sound basis for this otherwise speculative idea?

Practical Questions

- **How are we to validate the landscape proposal?**
- **Although it appears impossible to survey the string landscape in its totality, can one identify preferred subregions 'close' to the Standard Model?**

More immediately, there are practical questions for actual superstring model building, *cf.* [IJMPA30(2015)03,1530016]**:**

- **Role and importance of low energy ($N = 1$) SUSY ?**
- **SUSY breaking (if SUSY is there at all)?**
- **Vacuum stability, absence of tachyons?**
- **Moduli stabilization (*e.g.* no runaway dilaton)?**
- **Cosmological issues: quintessence *vs.* dS?**

Conceptual Questions

- **What does it mean to say that all these vacua 'exist' simultaneously: actual coexistence or virtual coexistence (parallel universes *vs.* potentialities in a quantum mechanical sense)?**
- **Is there a (weighted) probability distribution over the space of vacua, with peaks near 'realistic' vacua?**
- **... or a huge *'wave function of the multiverse'* providing a probability amplitude on this space?**
- **But then what determines this wave function, and what principle governs the dynamics on this space?**

$\rightarrow$ **may require a 'super-Wheeler-DeWitt equation'!**

The status quo (as of May 2022)

- **Low energy (N=1) SUSY is basically off the table, modulo epicyclical constructions and (to me) implausible scenarios**
- **We still have no idea what Dark Matter is: no WIMPs, no axions,...? Doubts even linger whether it is there at all.**
- $\Lambda > 0$ **difficult to reconcile with string theory**
- **Modifications to SM, if any, are tiny effects (violation of lepton flavor universality,** $(g-2)_\mu$ **, W boson mass, ...??)**
- $\rightarrow$ **It is by no means excluded that SM survives essentially *as is* all the way to the Planck scale. What have string theory and the string landscape to say about this possibility?**

Now playing devil's advocate: there are other ansätze that purport to explain precisely this scenario, *e.g.* with just the SM embedded into asymptotically safe quantum gravity, whose UV completeness is ensured by UV fixed point above the Planck scale.

Question: How do you rule out such alternative ideas if you think string theory is the right theory??

David Gross (23.2.2022): *"...other UV completions than string theory may exist and we should be open to this possibility".*

Here is Bert's advice: [Rev.Mod.Phys.85(2013)4]

- **Derive string theory from a principle of nature.**
- **Establish its consistency.**
- **Prove that it has a landscape.**
- **Prove that the Standard Model is in that landscape.**
- **Show that all quantities are sufficiently densely distributed to explain all anthropic fine-tunings.**
- **Confirm that these vacua are connected by some physical process, so that they can all be sampled.**

In lieu of a conclusion

As skeptical as I am, I think the contemplation of the multiverse is an excellent opportunity to reflect on the nature of science and on the ultimate nature of existence: why we are here.... In looking at this concept, we need an open mind, though not too open. It is a delicate path to tread. Parallel universes may or may not exist; the case is unproved. We are going to have to live with that uncertainty.

(G.F.R. Ellis, 2011)

Also: *some* unmistakable hint from experiment and observation would greatly help....

Happy Retirement!