String/M-theory *IS* Testable As Traditional Physics –

Obviously to test a 10D theory in a 4D world, must "compactify"

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OUTLINE

- **Testing theories in physics – some generalities**

- **Testing 10/11 dimensional string/M-theories as underlying theories of *our* world *requires* compactification to four space-time dimensions!**

- **Testing all theories requires assumptions, eventually removable**

- **Example: compactifying M-theory on "G2 manifolds" to describe/explain/understand *our* vacuum**

  - ➤ **Fluxless sector!**

- **Comments on multiverse issues**

- **Final remarks**

String/M theory a powerful, very promising framework for constructing an underlying theory that incorporates the Standard Models of particle physics and cosmology and probably addresses all the questions we hope to understand about the physical universe – we hope for such a theory!

Don't have to be somewhere to test theory there – e.g. no one at big bang, or dinosaur extinction, but tests fully compelling – don't need experiments at Planck scale – always relics – don't need to travel at speed of light to test that it is a limiting speed

"No superpartners yet" a test of string theory? What if find them in next run – confirms string theory?

"Naturalness" does suggest should have found superpartners at LHC Run 1, but naturalness is what you invoke if you *don't* have a theory – all superpartner predictions before about a decade ago were based on naturalness, not theory

Theories need not be "natural" - Actual compactified string theories imply should *not* have found superpartners at LHC Run 1 (see below)

String/M theory must be formulated in 10 (11) D to be a possible quantum theory of gravity, and obviously must be projected to 4D ("compactified") for predictions, tests

Many string theorists who study black holes, AdS/CFT, amplitudes, gravity etc in general do not know the techniques to study or evaluate compactified string/M-theories in 4 D – their comments may not be useful

Also, if one's impression of string theory came from some popular books and articles and blogs, or from theorists who hadn't actually studied string/M-theory projected onto 4 D, one might be suspicious of taking string theory explanations seriously

Most of what is written on this is very misleading, even by experts(!) – string theorists do not think much about it ("string theorists have temporarily given up trying to make contact with the real world" - 1999)

String theory conferences have few talks about compactified string theories and physics beyond the SM

String theorists seldom read papers about, or have seminars at their universities about, compactified string theories connecting to physics beyond the SM

But string/M-theory's potential to provide a comprehensive underlying theory is too great to ignore it

String/M-theory is too important to be left to string theorists

Before we look at details about testing string theory, ask what it means to test theories?

In what sense is F=ma testable?

-- claim about actual relation between forces and particle behavior

-- might not have been correct

-- can test it for any particular force, but *not in general*

Similar for Schrodinger equation!

-- Insert particular Hamiltonian, calculate ground state and energy levels, make predictions – without a particular Hamiltonian, no test

-- tests are tests of both Schrodinger equation and Hamiltonian

Analogous for string theory!

Currently there is a well defined procedure to "compactify" (procedure for going to 4D)

- **Choose corner of string/M theory, e.g. heterotic, M-theory, etc**
- **Choose manifold of small Planck scale size dimensions**
- **Determine/write "superpotential", essentially Lagrangian**
- **Determine/write "gauge kinetic function", metric for "gauge fields"**
- **Determine/write "Kahler potential", essentially metric for "scalar" fields"**
- **Calculate potential energy, minimize it → 4D ground state**

Eventually theory may determine and allow calculation of all these ["vacuum selection principle"], but not yet

Nevertheless, can address most issues

Now done for some examples – some give compactified theories consistent with being good descriptions of what is known, make more testable predictions (examples below)

Others already give wrong predictions – still testable!

[e.g., compactify heterotic string on Z2 orbifold, can calculate neutrino masses – wrong – hep-th/0502032, Phys.Rev. D71 (2005) 115013 Gleick, Kane, Langacker, Nelson]

Of course, one falsifiable prediction is sufficient to have a theory be testable

COMPACTIFIED STRING THEORIES GIVE 4D TESTABLE RELATIVISTIC SUPERGRAVITY QUANTUM FIELD THEORIES – can calculate lots of predictions

Crucial to recognize that compactified string theory is analogous to Lagrangian of a system

In all areas of physics one specifies the particular "theory" by giving the Lagrangian (Hamiltonian)

Physical systems are described not by the Lagrangian but by *solutions* to the equations

Normally find the ground state of a system, calculate energy levels and transitions

Analogous for string theory – our world corresponds to a metastable (or stable) ground state – called "vacuum"

Studying such predictions to test theories is how physics has always proceeded

All tests of theories have always depended on assumptions – from Galileo's using inclined plane to slow falling ball, to assuming air resistance could be neglected – to Silk et al "   " - to choice of corner of string theory and compactification manifold

Tests of the string theory are of the compactified theory, but they do *depend on the full 10/11D theory in a number of ways* – there are predicted relations between observables that depend on the full theory, 10 or 11D, the stringy characteristics of the CY or G2 (or even different) manifolds – have to calculate them in each case

Curled up dimensions contain information on our world – particles and their masses, symmetries, forces, dark matter, superpartners, more

Could there be more general tests of string theory?

Relativistic quantum field theory has some general tests:

-- CPT

-- spin and statistics

-- all electrons are identical

-- superposition

Maybe for string theory?

○ **General tests of 10/11 D theory?**

○ **Black hole entropy?**

○ **Otherwise not yet – and string/M theory is a theory with rules of relativistic field theory, AND ALSO particles and forces → general tests unlikely**

○ **Compactified theories? Yes! Gravity, Yang-Mills theories and gauge fields, supersymmetry, moduli, generic chiral fermions, etc –** *all are predictions of and evidence for string/M-theories*

- Landscape? Maybe, maybe not – but if yes, there is no obstruction to finding and testing compactifications that might describe our world – examples such as compactified M-theory show *It is not premature to look for our vacuum*

- In each vacuum perhaps all important observables calculable (except CC?)

- What would we need to understand and calculate to say we had an underlying theory ("final theory") of our world?

UNDERSTAND OUR WORLD? Pretty good list

- ➢ What are we made of? Why quarks and leptons?
- ✓ **What is light?**
- ➢ Why are there protons and nuclei and atoms? Why 3-2-1?
- ➢ **What is the origin of mass for fundamental particles (q, l, W and Z)?**
- ➢ Are the forces unified in form and strength?
- ➢ **Why are quark and charged lepton masses hierarchical?**
- ➢ Why are neutrino masses small and not hierarchical?
- ➢ **Is nature supersymmetric near the weak scale?**
- ➢ How is supersymmetry broken
- ➢ **How is the hierarchy problem solved – stabilize hierarchy? – size of hierarchy? - μ?**
- ➢ Why matter asymmetry?
- ➢ **Quantum theory of gravity**
- ➢ What is an electron?
- ❑ **Why families? Why 3?**
- ❑ What is the inflaton? Why is the universe old and cold and dark?
- ❑ **What is dark matter? Ratio of DM to baryons?**
- ❖ **Which corner of string/M-theory? Are several equivalent?**
- ❖ Why three large dimensions?
- ❖ **Why is there a universe? More populated universes?**
- ❖ Are the rules of quantum theory inevitable?
- ❖ **Are the underlying laws of nature (forces, particles, etc) inevitable?**
- ❖ CC problems?

> ➢ Answered in compactified M-theory - simultaneously

> ❑ Addressed in compactified M-theory

Several branches of string/M theory – heterotic, Type IIA, …M-theory – few choices

Also not yet known what gauge, matter groups to compactify to – few choices

No principle yet to fix those

Try out motivated examples for branch, curled up dimensions – calculate predictions, test – many theoretical constraints, limited possibilities, few parameters – lots of examples no

Three new physics aspects:

o **"Generic" – crucial to be predictive**

o **"Gravitino"- sets scale of superpartner masses**

o **"Moduli" – dominate energy density of universe after inflation; cosmological history; decays give DM and baryons and ratio**

GENERIC methods, results:

- **Probably not a theorem (or at least not yet proved), might be avoided in special cases**

- **One has to work at constructing non-generic cases**

- *No adjustable parameters, no tuning*

- *Predictions NOT subject to qualitative changes from small input changes*

GRAVITINO

-- **In theories with supersymmetry the graviton has a superpartner, gravitino – if supersymmetry broken, gravitino mass ($M_{3/2}$) splitting from the massless graviton is determined by the form of supersymmetry breaking**

– **Gravitino mass sets the mass scale for all superpartners, for some dark matter**

MODULI – from *compactified* string/M theories get not only quantum field theories, but new physics

-- **To describe sizes and shapes and metrics of small manifolds the theory provides a number of fields, called "moduli" fields**

-- **Moduli fields have definite values in the ground state (vacuum) – jargon is "stabilized" – then measurable quantities such as masses, coupling strengths, etc, are determined in that ground state –** *if not stabilized, laws of nature time and space dependent*

-- **In compactified M-theory, supersymmetry breaking generates potential for all moduli and stabilizes them**

-- **Moduli fields (like all fields) have quanta (also called moduli), with masses fixed by fluctuations around minimum of moduli potential**

Moduli dominate energy density of universe after inflation ends oscillate after inflation ends – we begin M-theory compactification then – stabilize

Moduli decay before nucleosynthesis – decay introduces lots of entropy and washes out all earlier dark matter, matter asymmetry, etc – decays into dark matter and stabilizes matter asymmetry, so determines ratio of matter to dark matter

Example – M-theory compactified on G2 manifold

PAPERS ABOUT M-THEORY COMPACTIFICATIONS ON G_2 MANIFOLDS (11-7=4)

Earlier work 1995-2004 (stringy, mathematical) ;   Witten 1995

- Papadopoulos, Townsend th/9506150, compactification on 7D manifold with G_2 holonomy → **resulting quantum field theory has** N=1 supersymmetry!!!
- Acharya, hep-th/9812205, **non-abelian gauge fields localized on singular 3 cycles**
- Atiyah and Witten, hep-th/0107177, **analyze dynamics of M-theory on manifold of G_2 holonomy with conical singularity and relations to 4D gauge theory**
- Acharya and Witten, hep-th/0109152, **chiral fermions supported at points with conical singularities**
- Witten, hep-ph/0201018 – **M-theory embedding SU(5)-MSSM, solves doublet-triplet splitting in 4D supersymmetric GUT, discrete symmetry sets μ=0**
- Beasley and Witten, hep-th/0203061, **generic Kahler form**

Particles and forces!

- Friedmann and Witten, hep-th/0211269, **SU(5) MSSM, scales – Newton's constant, GUT scale, proton decay – no susy breaking**
- Lukas, Morris hep-th/0305078, **generic gauge kinetic function**
- **Acharya and Gukov, Physics Reports**

Basic framework established – powerful, rather complete

➢ Acharya and I (and students, postdocs) began there

Few Discrete Assumptions (recall all tests have assumptions)

○ Compactify **M-Theory** on manifold with **G$_2$** holonomy **in fluxless sector** – well motivated and technically robust

○ **Compactify to gauge matter group SU(5)-MSSM – can try others, one at a time**

○ Use generic Kahler potential and generic gauge kinetic function

○ Assume needed singular mathematical manifolds exist – considerable progress recently – Simons Center workshops, Acharya, Simon Donaldson et al, etc

○ **CC issues not relevant** - solving it doesn't help learn our vacuum, and not solving it doesn't stop learning our vacuum

We started in 2005 – since LHC coming, focused on moduli stabilization, supersymmetry breaking, etc → LHC physics, Higgs physics, dark matter etc

[**Acharya**, Bobkov, GK, **Piyush Kumar**, Kuflik, Shao, Watson, Lu, Zheng, Ellis – over 20 papers, over 500 arXiv pages]

- **Indeed we showed that in M theory supersymmetry automatically was spontaneously broken via gaugino and chiral fermion condensation**

- **Simultaneously moduli stabilized, in de Sitter vacuum**

- **Calculated the supersymmetry soft-breaking Lagrangian → radiative electroweak symmetry breaking, Higgs boson – precise M_h and decays (in decoupling sector) – approximate gluino and wino masses, etc**

Get 4D effective supersymmetric field theory – in usual case coefficients of all operators are independent, so many coefficients – here all coefficients calculable and connected

NO adjustable parameters

MAIN RESULTS, PREDICTIONS FOR M-THEORY SO FAR, and in progress – ONE THEORY

- Moduli stabilized – vevs calculable and $\lesssim$ 1/10 M_{pl}, masses multi TeV √

- Calculate gravitino mass approximately, from Planck scale ~ 50 TeV (factor 2 or so)

- Scalars heavy (squarks, higgs sector, sleptons) ~ gravitino mass (2006) PREDICTION, LHC

- Gaugino masses suppressed (by volume ratios), ~ factor 40 PREDICTION, LHC

- Hierarchy problem solved √

- Non-thermal cosmological history via moduli decay at late time (but still before BBN) PREDICTION

- Moduli decay provides baryogenesis *and* DM, ratio PREDICTION

- Axions stabilized, give solution to strong CP problem, spectrum of axion masses √

- Anticipated Higgs boson mass *and* BR (SM-like) before data PREDICTION √

- SM quark and lepton charges, Yang-Mills 3-2-1 forces, parity violation, accommodated

- Gauge coupling unification, proton decay all right

- No flavor problem, weak CPV ok

- EDMs calculable, smallness explained (could have been wrong) PREDICTION √

- $\mu \approx$ few TeV – included in theory, approximately calculable

- $\tan\beta$ approximately calculable ~ 5-8 PREDICTION

- LHC predictions – gluinos (~ 1.5 TeV, 3rd family decays enhanced)

  -- wino, bino ~ ½ TeV numbers predicted , BR(wino $\rightarrow$ bino + Higgs) ≈ 100%

- Need future collider for higgsinos, scalars – not at LHC PREDICTION

- Hidden sector DM under study

ALL FOLLOW FROM DISCRETE ASSUMPTIONS – all SIMULTANEOUS

Scales

M-THEORY COMPACTIFIED ON G2 MANIFOLD, TO MSSM

Planck scale

$GUT \sim 2 \times 10^{16}$

String, KK, etc

$\Lambda \approx 10^{14}$ GeV — **gaugino, chiral fermion condensation, F-terms ≠ 0** (susy broken)

$\Lambda \approx \exp\{-2\pi V_3/3Q\}\, M_{Pl}/V_7^{1/2}$

$(V_3 \sim Q$ so not sensitive)

Supersymmetry breaking dynamical, automatic!

Hierarchy problem solved

Top-down, gravitino ~ factor 2

$M_{3/2} \sim 50$ TeV — **Gravitino mass** (so squarks heavy) $M_{3/2} = e^{K/2} W/M_{Pl}^2$, $W \sim \Lambda^3$

μ

TeV

Gaugino mass suppression

$M_{1/2} \sim F_{mod} \partial f_{vis}/\partial F_{mod}$

$+ F_{ChiFerm} \partial f_{vis}/\partial F_{ChiFerm}$

and $F_{mod}/F_{ChiFerm} \sim V_3/V_7 \ll 1$

gluino ~ 1.5 TeV, wino, bino 0.5 TeV

REWSB

$\mu \approx <mod> M_{3/2}$ (Witten+mod stabilization) ~ few TeV

$M_{Hu} \sim f_{M0}(t)\, M_0^2 - f_{A0}(t)\, A_0^2 \ll M_{3/2}$ $(f_{M0} \approx f_{A0};\ A_0 \gtrsim M_0)$

EWSB condition "M_Z^2"$/2 \approx -\mu^2 - M_{Hu}^2 + M_{3/2}^2/\tan^2\beta$ →

HIGGS MASS, DECAYS

Two Higgs doublets in supersymmetry – large scalar terms in soft-breaking Lagrangian plus radiative electroweak symmetry breaking imply one light Higgs boson and four heavy ones, "decoupling sector"

Calculate ratio of M_{higgs}/M_Z – technically, determined by "λ" of Higgs potential – write theory at string scale – do "renormalization group running" down to electroweak scale, known through three loops with heavy scalars

Compactified M-theory (with generic gauge kinetic function and kahler potential) anticipated M_{higgs}=126.4 GeV summer 2011, before data – predicted all decay branching ratios within few per cent of Standard Model ones (as observed)

Electroweak scale spread of about $\pm$1.2 GeV purely because top quark yukawa and α_s enter RGE running from high scale

Higgs data exactly as expected from compactified M-theory MSSM decoupling sector and electroweak symmetry breaking

Gluino, wino, bino mass predictions are generic and robust – not just "a little above current limits" – clear to any knowledgeable person who goes through derivation

Qualitatively:

- **Compactification, RGE running down**
- F-terms $\neq 0$ from hidden sector gaugino and chiral fermion condensation, so supersymmetry broken – largest gauge groups on 3-cycles run fastest –> scale $\approx 10^{14}$ GeV $[\Lambda \approx (M_{pl}/V_7) \exp(-2\pi V_3/3Q) \approx 10^{14} \text{GeV}]$
- **Then calculate gravitino mass ≈ 50 TeV** $[W \sim \Lambda^3/M_{pl}^3 , M_{3/2} \approx e^{K/2} W/M_{pl}^2]$
- Gaugino masses automatically suppressed to $\sim$ TeV since largest susy-breaking source of mass absent, $V_3/V_7 \sim 1/40$
    - $\rightarrow$ gluino mass ~ 1.5 TeV ($\pm 10\text{-}15\%$)

Gaugino mass suppression
$M_{1/2} \sim F_{mod} \partial f_{vis}/\partial F_{mod}$
$+ F_{ChiFerm} \partial f_{vis}/\partial F_{ChiFerm}$
and $F_{mod}/F_{ChiFerm} \sim V_3/V_7 << 1$

Production at LHC is **cross section x integrated luminosity = number of events** – cross section ≈ 12 fb, currently luminosity about 4 fb^{-1} per detector – expect (say) 20 fb^{-1} summer 2016, but top pair background large – note limits weaker for heavy squarks

LHC

Squark masses ~ gravitino mass ~ few tens of TeV

GAUGINO MASSES ~ TeV

arXiv:1408.1961 [Sebastian Ellis, GK, Bob Zheng]

$M_{gluino} \approx 1.5$ TeV,

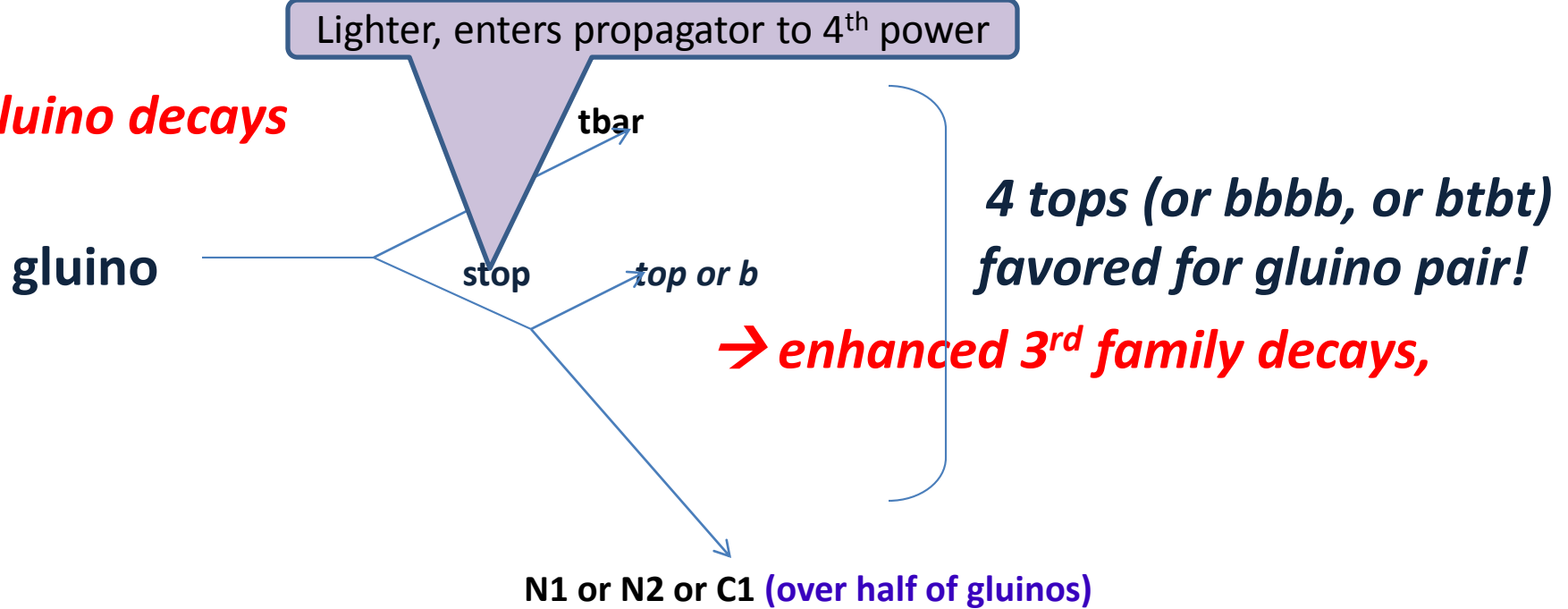$M_{bino} \approx 450$ GeV,

$M_{wino} \approx 620$ GeV

all consistent with current data

Lesson from (compactified M-)theory: should not have expected superpartners at LHC Run 1

$\sigma_{gluino} \approx 12$ fb, $\sigma_{wino\ pairs} \approx 15$ fb   **For 1.5 Tev, 3σ signal needs ~ 50 fb^{-1}**

Any bets?

Lighter, enters propagator to 4th power

Gluino decays

gluino

stop

tbar

top or b

4 tops (or bbbb, or btbt) favored for gluino pair!

→ *enhanced 3rd family decays,*

N1 or N2 or C1 (over half of gluinos)

Gluino lifetime ~ 10^{-19} sec, decays in beam pipe

Gluino decays flavor-violating: 3rd family/(1st + 2nd) ≈ 1.2 (naively 0.5)

For heavy squarks, σ(gluinos, 13 TeV)/ σ(gluinos, 8 TeV)≈ 30-45 for 1.5 TeV gluino

HIDDEN SECTOR DARK MATTER – in progress – predictions and tests

[Acharya, Ellis, GK, Nelson, Perry, Zheng]

- In M-theory, curled up 7D space has 3D submanifolds ("3-cycles") that generically have (orbifold) singularities and therefore have particles in gauge groups – tens of submanifolds (3rd Betti number)

- We live on one, "visible sector"

- Supersymmetry breaking due to ones with large gauge groups

- Gravitational interactions, same gravitino and moduli for all

- Other hidden sectors have their own matter, some stable and DM candidates – can calculate spectra, relic densities

- Calculations underway: already published general relic density calculations with a non-thermal cosmological history, arXiv:1502.05406 (Acharya, GK, Nelson, Zheng)

- Now analyzing actual hidden sectors systematically for M-Theory

- Examples of stable relics exist, with relic density of order what is observed – e.g. M-theory case $U(1)^3$, DM mass ~ MeV

Our compactified M-theory is good candidate for underlying theory beyond SM – my point not to push it, but to argue it is obviously a testable string theory by traditional physics methods

Lots to do to complete it – lots of work, more tests, could go wrong

FINAL REMARKS (1)

➤ **String/M-theory too important to be left to string theorists**

➤ **10/11 D String/M-theory with curled up small dimensions may seem complicated – but probably it is the SIMPLEST FRAMEWORK THAT COULD SIMULTANEOUSLY INCORPORATE AND *EXPLAIN* ALL THE PHENOMENA WE WANT TO UNDERSTAND – 10/11D needed**

➤ **Compactified M-theory promising candidate for our vacuum – at least shows not premature to study such compactifications**

FINAL REMARKS (2)

- **Moduli generically present – inevitable in M Theory – implies non-thermal cosmological history**

- **Higgs boson mass and decay branching ratios anticipated**

- **LHC: gluino $\sim$ 1.5 TeV, wino, bino $\sim$ 0.5 TeV ($\pm \sim$ 10%) – good signatures – requires $\gtrsim$ 50 fb^{-1}**

- **Hidden sector dark matter candidates generic, probably inevitable**

FINAL REMARKS (3)

➢ **Landscape? – Obviously many solutions**

➢ **If so, examples already show not an obstacle to finding candidate descriptions of our world – then study properties of compactifications to see implications for multiverse populations**

➢ **Crucial question is are the many solutions populated? – several papers argue maybe not [Perry et al; Greene et al, Shiu et al]**

➢ **Analogy: periodic table – imagine don't understand nuclei - keep increasing charge of nuclei – add electrons – get indefinitely large number of chemical elements – but nuclei unstable above 92, so number of elements cuts off**

FINAL REMARKS (4)

- Dawid emphasizes that theories imply much that is not yet tested – if many tests work then other consequences of the theory must be true

- E.g. entanglement in quantum theory – many decades before testable