FROM UNDERLYING PLANCK SCALE M-THEORY, TO TEV-SCALE SUPERPARTNERS AT LHC – DETECTABLE SOON

- and further explanations and predictions

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Once the Standard Model was in place in 1970s, could ask about its foundations, ask about an underlying theory covering all scales – Grand Unified Theories, ultraviolet completions, etc

Needed to develop many *experimental facilities*, search for signals beyond SM – LHC, DM detectors, etc – finally in place

***Also need to extend theories* – compactified string/M theory framework has increasingly emerged as an approach to an underlying theory**

-- incorporates SM, supersymmetry, supersymmetry breaking (determines parameters), etc

– solves hierarchy problem, explains EW symmetry breaking, etc – lots of tests – considerable progress in recent years

Naturalness?

Opposite of naturalness is having a theory!

– Naturalness is what you try when you have given up on finding an underlying theory that predicts masses – naturalness doesn't explain anything, theories explain

-- Forget naturalness if you think there is an underlying theory, an ultraviolet completion

– With a theory, get predictions for superpartner masses

OUTLINE

- Introduction
  - Progress on compactified string/M theory as underlying theory – not so familiar, so needs some explanation
  - Testable
  - Define "Generic", "Gravitino", "Moduli"!
- More about compactified M Theory
- Moduli → non-thermal cosmology for relic density
- Scales calculable, Planck to Electroweak – Hierarchy problem solved – LHC
- LHC Signatures
- (Hidden sector DM)
- Final remarks

Is string/M-theory useful to connect to the real world? Testable?

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 so 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 theorists who mainly 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

Simply wrong to claim that string theory is not testable

- don't have to be around during big bang to test it, etc

- lots of testable predictions

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

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

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

Several branches of string/M theory – heterotic, Type IIA, …M-theory – which? – are results different?

Also not yet known what gauge, matter groups to compactify to

No principles known so far that imply branch, gauge groups and matter

→ Try out motivated examples for branch, curled up dimensions – calculate predictions, test – lots of useful, relevant results

Only a few choices – several examples now

In practice, physics provides guidance!

Three new physics aspects:

- **“Generic”**
- **“Gravitino”**
- **“Moduli”**

GENERIC:

- **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 (or very few) adjustable parameters, no tuning***

GRAVITINO

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

– Gravitino mass sets the mass scale for the theory, for all superpartners, for some dark matter – sets the scale for the supersymmetry soft breaking Lagrangian

- Gravitino mass calculable

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

-- To describe sizes and shapes and metrics of small manifolds theory provides a number of scalar fields, called “moduli” fields – matter

-- In compactified M-theory, supersymmetry breaking generates potential for all moduli

-- 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*

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

-- Moduli dominate after inflation, oscillate, stabilize – we begin there

-- Number of phenomenological implications

Important theoretical connection between moduli and gravitino: Lightest eigenvalue of MODULI mass matrix generically ≈ GRAVITINO mass [Douglas, Denef 2004; Scrucca et al 2006; Acharya Kane Kuflik 2010]

(top down simple argument, scalar goldstino generically has gravitino mass, and mixes with moduli, so lightest eigenvalue of moduli mass matrix < lighter eigenvalue of any 2x2 submatrix, i.e. about gravitino mass)

MODULI COSMOLOGY

- **Moduli couple gravitationally to everything**
- **Moduli decay (when width ~ H) – dilutes any previous population of DM by factor $(T_{freezeout}/T_{decay})^3$ if entropy conserved in process**

  [because T~ 1/a and volume ~ a^3]

- **So thermal freezeout occurs, typically at T ~ 20 GeV, *but resulting DM diluted by ~10^9 when moduli decay at T ~20 MeV, shortly before nucleosynthesis***

  [first noticed by Moroi, Randall hep-ph/9906527 – generic in string/M theories]

- **Moduli have BR to superpartners, axions, hidden sector DM so regenerate DM → "non-thermal cosmological history"**

THREE DECADES OF COMPACTIFIED M-THEORY

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

And superpartners

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 (derived)
- 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 G2 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 – shows embedding SU(5)-MSSM ok, solves doublet-triplet splitting in 4D supersymmetric GUT, discrete symmetry sets μ=0
- Beasley and Witten, hep-th/0203061, generic Kahler form

  [gave set of Kahler potentials, consistent with G2 holonomy, known to describe explicit examples]
- Friedmann and Witten, th/0211269, SU(5) MSSM, scales – Newton's constant, GUT scale, proton decay – no stabilization or susy breaking
- Lukas, Morris hep-th/0305078, generic gauge kinetic function

Particles!

Origin of chiral fermions, parity violation

Basic framework established – powerful, rather complete

Some Discrete Assumptions - input

- **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 mathematical manifolds exist – considerable progress recently – Simons Center workshops, 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, etc

[**Acharya**, Bobkov, GK, Piyush Kumar, Kuflik, Shao, Watson, Lu, **Zheng**, Ellis, Perry – 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 – gravity mediated
- Simultaneously moduli stabilized, in unique de Sitter vacuum for a given manifold – no "uplifting" needed
- μ included in theory – suppressed ~ factor 10 from $M_{3/2}$
- Calculated the supersymmetry soft-breaking Lagrangian → radiative EWSB – Higgs potential stable - precise M_h (in decoupling sector) – EW scale calculable, not tuned or anthropic as in split susy
- Gravitino mass (tens of) Tev even though Planck scale is only dimensionful parameter in the theory
- Calculate approximate gluino, wino, bino, higgsino 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

N=1 supersymmetry a theorem, broken by gaugino and chiral fermion condensation generically

NO free parameters

(Kahler potential term K_{mod} K_{vis} has approximately calculable coefficient)

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

ALL ONE THEORY

- Moduli stabilized – vevs $\lesssim$ 1/10 M_{pl}, masses multi TeV ☺
- Calculate gravitino mass approximately ~ 40 TeV (factor 2 or so)
- Scalars (squarks, higgs sector, sleptons) ~ gravitino mass ~ 40 TeV (2006) T
- Gaugino masses suppressed (by volume ratios), ~ factor 40 T
- Hierarchy problem solved ☺☺☺
- Non-thermal cosmological history via moduli decay at late time (but still before BBN)
- Moduli decay provides baryogenesis *and* DM, maybe ratio (not finished) ☺
- Axions stabilized, give solution to strong CP problem
- EW scale and EWSB emerge, anticipated Higgs boson mass *and* BR (SM-like) T ☺☺☺
- SM quark and lepton charges, Yang-Mills 3-2-1 forces, parity violation, generic
- Gauge coupling unification, proton decay all right
- No flavor problem, weak CPV ok – ($\mu \rightarrow e\gamma$ Ellis, Geidt, in progress)
- EDMs calculable, smallness explained (could have been wrong) T ☺
- $\mu \approx$ few TeV – included in theory, approximately calculable T
- $\tan\beta$ approximately calculable ~ 5-10
- LHC predictions – gluinos (~ 1.5 TeV, 3rd family decays enhanced) T

  -- wino, bino ~ ½ TeV , BR(wino → bino + Higgs) ≈ 100% T
- Need future collider ~ 100 TeV for higgsinos, scalars – gluino+scalar associated production ok
- Hidden sector DM under study [Acharya, Ellis, GK, Nelson, Perry, Zheng arxiv:1510.xxxxx]

Possible bonus – Since moduli decay suppresses initial baryon asymmetry (~ 1) to give actual baryon asymmetry (10^{-9}), *and moduli decay also* gives DM, perhaps can explain both *and ratio* *[important – highest dimension of non-renormalizable operators for Affleck-Dine known to be 9]*

[GK, Shao, Watson, Yu arXiv: 1108.5178]

SCALES

- **Solve hierarchy problem fully!** – input Planck scale and derive physics at TeV scale(s)

- Two basic physics scales – supersymmetry broken (F terms generated) at about 10^{14} GeV, and gravitino mass ($M_{3/2}$) is ~ 50 TeV – IMPORTANT TO DISTINGUISH

- Three suppressions from gravitino mass to smaller scales (scalars, trilinears not suppressed):

  * Theory predicts gaugino masses (gluino, wino, bino, LSP) suppressed to ~ TeV because no contribution from F_{chi}

  * "μ" incorporated into theory, not a parameter, suppressed order of magnitude from gravitino mass by moduli vevs

  * Radiative Electroweak Symmetry Breaking solutions common, lightest higgs boson $M_h \ll M_{3/2}$, explains Higgs mechanism, EW Symmetry Breaking

GAUGINO MASSES ALWAYS SUPRESSED!

$$M_{1/2} = K_{mn}\, F_m\, \partial_n\, f_{SM}$$

Visible sector gauge kinetic function

f_{SM} doesn't depend on hidden sector chiral fermions, so term proportional to $F_{\text{chiral meson}}$ simply absent – $F_{\text{moduli}}/F_{\text{chiral meson}} \sim V_3/V_7 << 1$

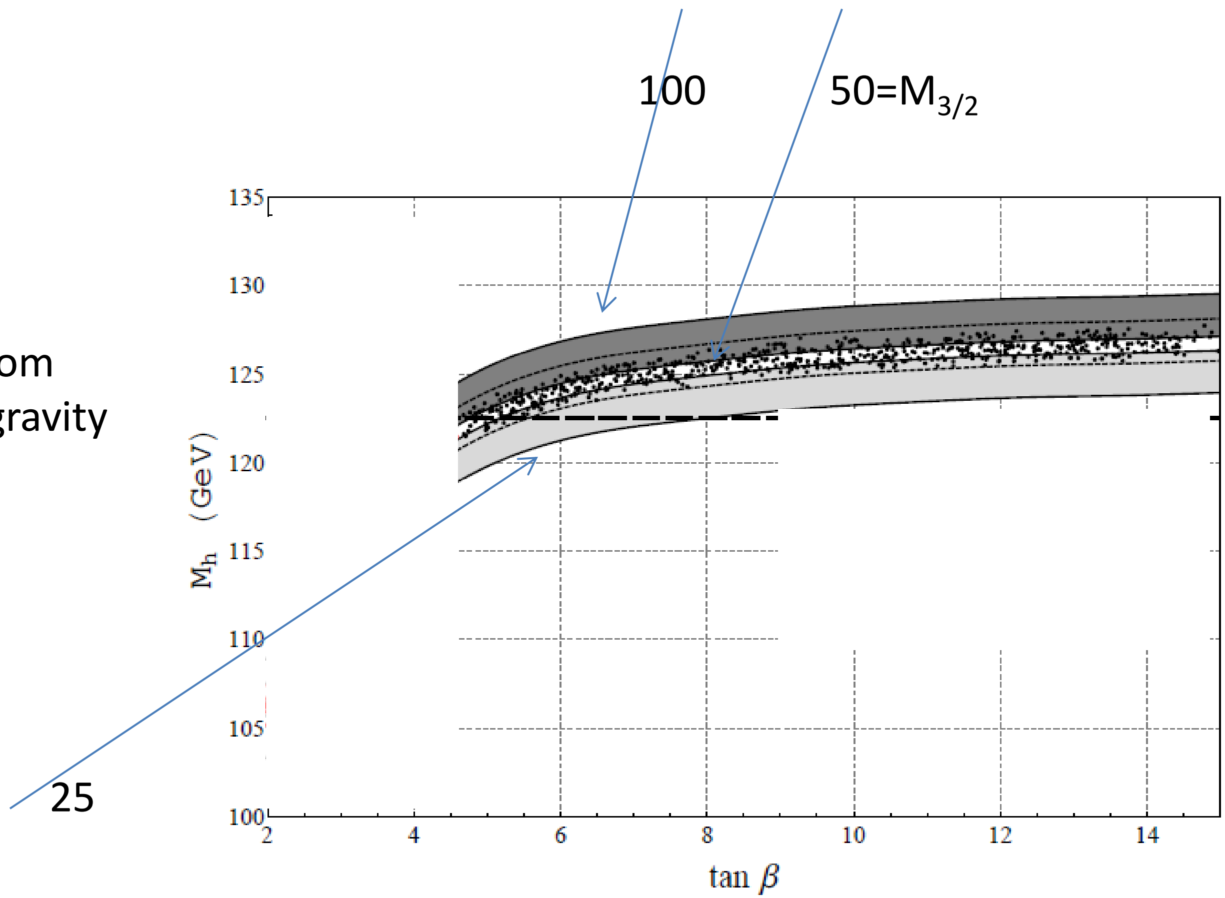
HIGGS MASS (1112.1059)

Higgs boson is lightest eigenvalue of 2x2 CP even sector of two doublet higgs sector,
Decoupling in old fashioned was (Gunion and Haber) – rest of higgs states at gravitino mass

$M_h = v\sqrt{(2\lambda)}$ $\lambda_{tree} = ((g^2 + g'^2)\cos^2 2\beta)/8$

Proceed to calculate full radiative corrections to λ as described in detail in Slavich talk Tuesday, including 3-loop heavy squarks, etc – before LHC

Spread of dots due to error in Top yukawa, and α_3 - $\tan\beta$ range from EWSB plus supergravity constraints



Scales

M-THEORY COMPACTIFIED ON G2 MANIFOLD, TO MSSM

Planck scale

GUT~2×10^{16}

String, KK, etc

$\Lambda\approx10^{14}$**GeV** — **gaugino, chiral fermion condensation, F-terms $\neq$ 0** (susy broken)

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

($V_3 \sim Q$ so not sensitive)

Hierarchy problem solved

Top-down, gravitino ~ factor 2

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

μ

1TeV

Gaugino mass suppression

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

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

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

gluino~1.5 TeV, wino, bino 0.5 TeV

REWSB

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

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

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

"M_Z"$\lesssim$ TeV

LHC

Here is where supersymmetry is “hiding” at LHC

Squark masses ~ gravitino mass ~ few tens of TeV

GAUGINO MASSES ~ TeV

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

arXiv:1506.xxxxx [Sebastian Ellis, Bob Zheng w/backgrounds, etc]

“guidance from theorists”

$M_{gluino} \approx 1.5$ TeV,

$M_{bino} \approx 450$ GeV,

$M_{wino} \approx 620$ GeV

all consistent with current data

lesson from compactified M theory is should not have expected superpartner signal at LHC so far

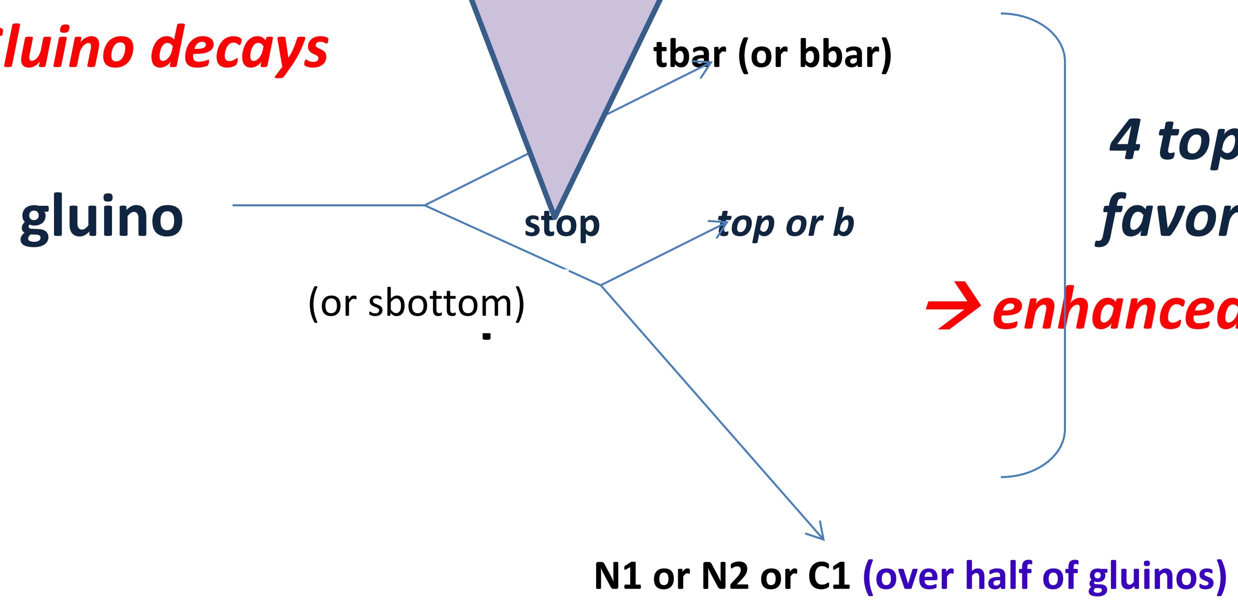
$\sigma_{gluino} \approx 20$ fb, $\sigma_{wino\ pairs} \approx 20$ fb [20fb x 100 fb^{-1} → 2000 events]

Any bets?

LHC 1-2 years

Lighter, enters propagator to 4th power

Gluino decays



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

→ enhanced 3rd family decays,

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

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

BR (neutral wino → bino + higgs) ≈ 100%

BR (charged wino → bino + $W^{\pm}$) ≈ 100%

$$g \rightarrow bino + \bar{t}t......20\%$$

$$g \rightarrow bino + W^{\pm} + b\bar{t}, t\bar{b}........23\%$$

For heavy squarks, σ(gluinos, 13 TeV)/ σ(gluinos, 8 TeV) ≈ 40 for 1.5 TeV gluino

HIDDEN SECTORS DM (Acharya, S.Ellis, GK, Nelson, Perry, Zheng)

- String theories have hidden sectors
- Generically have gauge groups and associated gauge bosons and superpartners
- Number known (3^{rd} Betti number)
- Largest ranks run fastest, lead to gaugino condensation and supersymmetry breaking
- Smaller ones have spectra, particles stable by symmetries
- Can calculate their relic densities, find order unity (1502.05406)
- Example $U(1)^3$
- Kinetic mixing operator exists, can show bino decays before BBN
- Generically LSP decays to hidden sector matter
- Important to use actual stringy/M-theory hidden sectors – important to use non-thermal cosmological history since freeze-out DM washed out by moduli decay

- Work in progress – arXiv: 1510.xxxxx

COMPACTIFIED M-THEORY (2006)

- **Derive** solution to large hierarchy problem
- Generic solutions with **EWSB derived**
- main F term drops out of **gaugino masses** so **dynamically suppressed**
- **Trilinears > $M_{3/2}$** necessarily
- **μ incorporated in theory**
- Little hierarchy significantly reduced
- **Scalars = $M_{3/2}$ ~ 40 TeV necessarily** , scalars not very heavy
- Gluino lifetime $\lesssim 10^{-19}$ sec, decays in beam pipe
- **$M_h \approx$126 GeV unavoidable**, predicted

SPLIT SUSY (ETC) MODELS

- Assumes **no solution (possible) for large hierarchy problem**
- **EWSB assumed**, not derived, anthropic
- **Gauginos suppressed by assumed** R-symmetry, suppression arbitrary
- Trilinears small, suppressed compared to scalars
- **μ not in theory** at all; guessed μ ~$M_{3/2}$
- No solution to little hierarchy
- Scalars **assumed** very heavy, whatever you want, e.g. 10^{10} GeV
- Long lived gluino, perhaps meters or more
- **Any M_h allowed**

FINAL REMARKS (1)

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

- **String/M-theory may seem complicated – but probably it is the simplest framework that could incorporate and explain all the phenomena we want to understand – compactified M-theory promising candidate**

- **Landscape? – if so, examples already show not an obstacle to finding descriptions of our world – then study implications for multiverse populations**

FINAL REMARKS (2)

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

- **LHC: gluino ~ 1.5 TeV, wino, bino ~ 0.5 TeV   good signatures**

- **Hidden sector dark matter candidates generic, inevitable – can be up to few TeV, or light – relic densities calculable – signatures calculable**

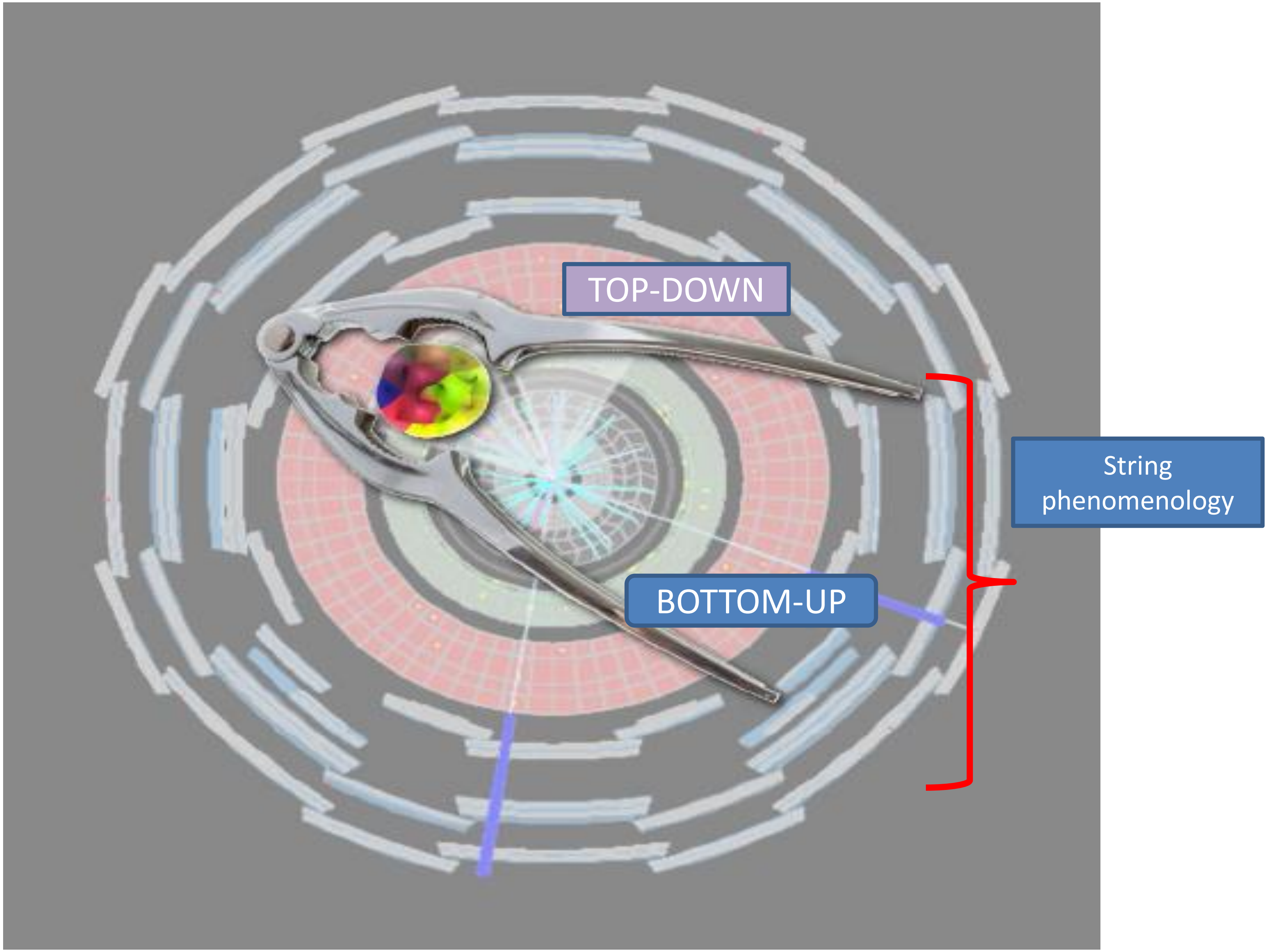

Advanced Series on
Directions in High Energy Physics — Vol. 22
PERSPECTIVES ON
STRING PHENOMENOLOGY
Editors
Bobby Acharya, Gordon L Kane and Piyush Kumar
Top-down
Bottom-up
String phenomenology
World Scientific

Nutcracker!

Surprising result – set value of potential to zero at tree level – get condition on solutions – impose condition on $M_{3/2}$ – for generic G2 manifolds, resulting values of $M_{3/2}$ all in (tens of) Tev region- do not need to independently set V_0 =0 *and* set $M_{3/2}$ to TeV region as in other approaches

$M_{1/2}$ suppression coefficient independent of number of moduli, and of integers N_i in either visible or hidden sectors gauge kinetic function

- all detailed dependence on individual moduli is in V_x , so result universal for any relevant G2 manifold
- Many microscopic parameters, but tree level gaugino masses depend on very few
- Suppression coefficient fixed for set of solutions with Q-P=3 and CC tuned to zero (such solutions have hierarchy problem solved, etc)


TOP-DOWN
String phenomenology
BOTTOM-UP