FROM PLANCK SCALE M-THEORY TO PREDICTIONS FOR SUPERPARTNERS AT LHC, SOON

- Dark matter 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

***To make progress also need to extend theories* – compactified string/M theory framework has increasingly emerged as a good approach to an underlying theory - incorporates SM, supersymmetry, supersymmetry breaking (determines parameters), etc – solves hierarchy problem, explains EW symmetry breaking simultaneously, etc – lots of tests – considerable progress in recent years**

Natauralness? 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 – with a theory, get predictions for superpartner masses, etc

OUTLINE

- Introduction
  - Compactified string/M theory as underlying theory – not so familiar, so needs some explanation
  - Progress, testable
  - "Generic"
  - "Gravitino"
  - "Moduli"!
- More about compactified M Theory
- Moduli → non-thermal cosmology for relic density
- Derivation of scales, Planck to Electroweak – Hierarchy problem solved – LHC
- LHC Signatures
- Hidden sector DM – properties – detection
- Final remarks

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

Wrong to claim that string theory is not testable

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

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

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

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

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

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

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

No principle yet to fix those

Try out motivated examples for branch, curled up dimensions – calculate predictions, test – lots of useful, relevant results – many theoretical constraints, limited possibilities, few parameters – lots of examples now

Three new physics aspects:

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

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

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 the theory, 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

-- 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

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 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 – M-theory embedding SU(5)-MSSM, solves doublet-triplet splitting in 4D supersymmetric GUT, discrete symmetry sets $\mu=0$
- Beasley and Witten, hep-th/0203061, generic Kahler form

Particles!

- Friedmann and Witten, 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

Basic framework established – powerful, rather complete

Some Discrete 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, 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 EWSB – Higgs potential stable - precise M_h (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 $\lesssim$ 1/10 M_{pl}, masses multi TeV √
- Calculate gravitino mass approximately, from Planck scale ~ 50 TeV (factor 2 or so)
- Scalars (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 (not finished)
- Axions stabilized, give solution to strong CP problem, spectrum of 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
- tanβ approximately calculable ~ 5-10 PREDICTION
- LHC predictions – gluinos (~ 1.5 TeV, 3rd family decays enhanced)

  -- wino, bino ~ ½ TeV , BR(wino → bino + Higgs) ≈ 100%
- Need future collider for higgsinos, scalars PREDICTION
- Hidden sector DM under study

ALL FOLLOW FROM DISCRETE ASSUMPTIONS – all simultaneous

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 ~ ¼ so regenerate DM → "non-thermal cosmological history"**

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]* *– only qualitative so far*

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

- **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 $M_h << M_{3/2}$, explains Higgs mechanism, EW Symmetry Breaking

GAUGINO MASSES GENERICALLY 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 – $F_{\text{moduli}}/F_{\text{chiral meson}} \sim V_3/V_7 << 1$

Scales

M-THEORY COMPACTIFIED ON G2 MANIFOLD, TO MSSM

Planck scale

GUT~2×10^{16}

String, KK, etc

$\Lambda \approx 10^{14}$ 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

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

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"$/2 \approx -\mu^2 - M_{Hu}^2 + M^2_{3/2}/\tan^2\beta$ →

"M_Z"$\lesssim$ TeV

And maybe ok

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]

$M_{gluino} \approx 1.5$ TeV,

$M_{bino} \approx 450$ GeV,

$M_{wino} \approx 620$ GeV

all consistent with current data

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

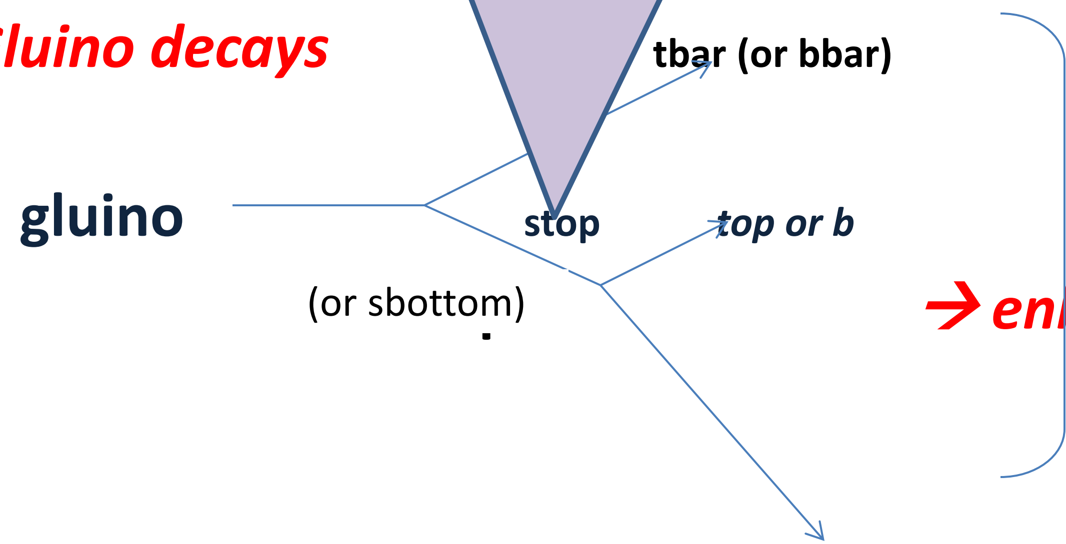
$\sigma_{gluino} \approx 15$ fb, $\sigma_{wino\ pairs} \approx 20$ fb [20fb x 100 fb^{-1} → 2000 events]

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,

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)

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) ≈ 30-45 for 1.5 TeV gluino

HIDDEN SECTOR DARK MATTER – work in progress

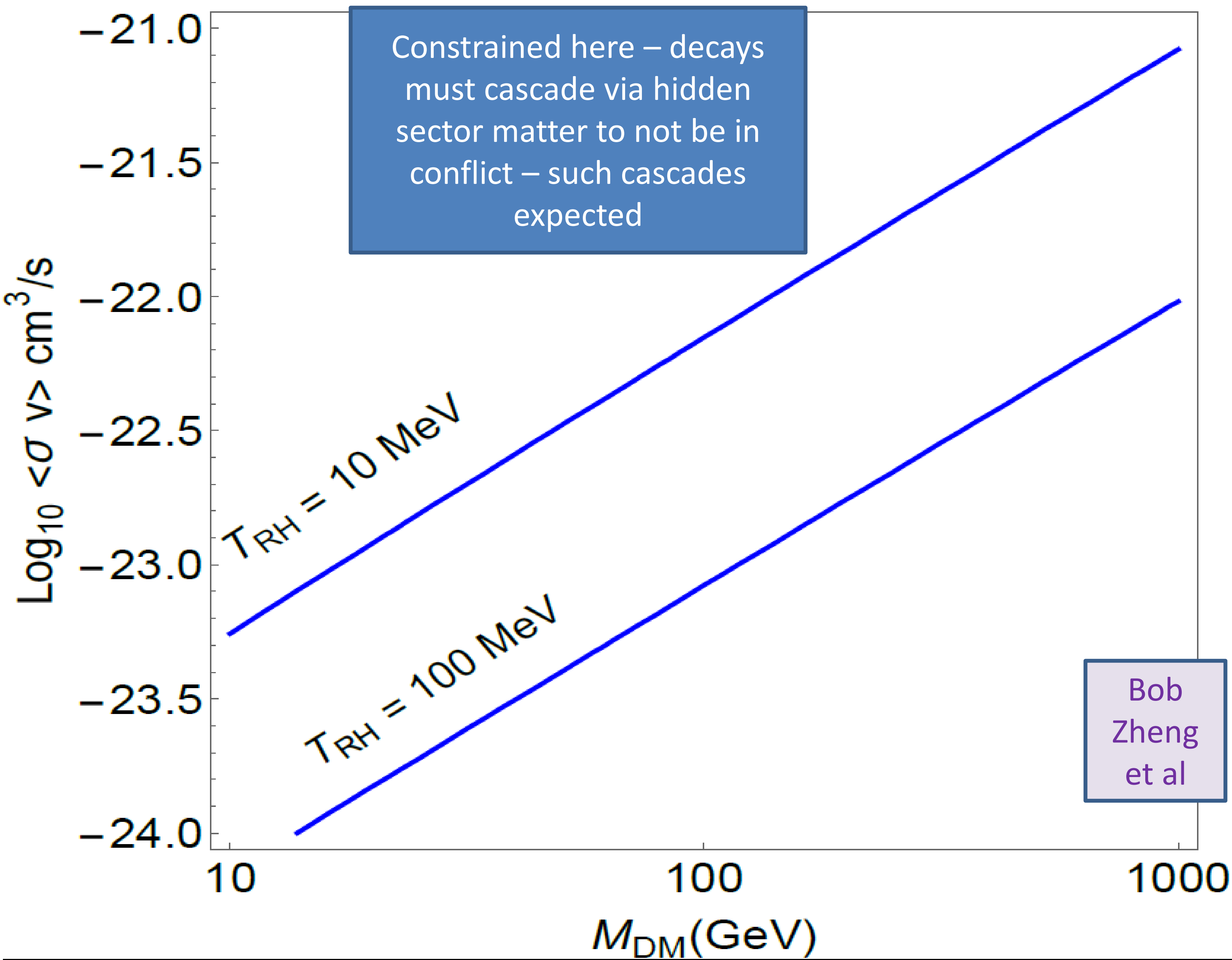
[Acharya, GK, Kumar, Nelson, Zheng]

- 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 (3^{rd} Betti number)
- We live on one, "visible sector"
- Supersymetry 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 (GK, Kumar, Nelson, Zheng)
- Now analyzing actual hidden sectors systematically for M-Theory

M-theory hidden sector model (analysis not complete):

- QCD-like, hidden sector SU(3) gauge group, 3 flavors of quark (superfields)
- Λ'_{QCD} < gravitino mass, so integrate out heavy dark squark fields
- → low energy gauge theory with 3 quark flavors, like QCD
- Generically "dark" baryons, $M_{baryon} \sim \Lambda'_{QCD}$ and lightest dark baryon stable
- Generically lighter dark pions, dark proton will annihilate to them
- **If dark proton gives full relic abundance then $M_{DM} \approx M_{baryon} \sim 1$ TeV** (scales like $(\Lambda'_{QCD})^3$)
- Large annihilation cross sections, probably cascade via dark sector matter, finally to visible sector particles
- (T_{reheat} is radiation temperature after moduli decay)

- **Such hidden sectors must have "strong dynamics", like QCD, if the DM mass is of order few GeV or more – otherwise mass scales generated by radiative breaking will be $\sim M_{3/2}$ so annihilation rates will be suppressed and universe overclosed**



Constrained here – decays must cascade via hidden sector matter to not be in conflict – such cascades expected
Bob Zheng et al
T_{RH} = 10 MeV
T_{RH} = 100 MeV
−21.0
−21.5
−22.0
−22.5
−23.0
−23.5
−24.0
10
100
1000
Log_{10} <σ v> cm^3/s
M_{DM}(GeV)

- **Expect many different hidden sectors with different gauge groups**
- **Λ' scales exponentially sensitive to values of gauge couplings at compactification scale, which are determined by volumes of 3-cycles on which the hidden sector lives**
- **Expect gauge couplings to be uniformly distributed on linear scale**
- **Then Λ' scales uniformly ~ distributed on log scale, so exponentially separated**
- **The hidden sector with Λ' ~ TeV will provide dark matter, while other hidden sectors decay to DM hidden sector, or give small contributions to DM abundance – typically several hidden sectors involved**

For example,

$<\sigma v> \approx 4\pi/M^2_{DM}$ "SU(3) strong dynamics"

$$\Omega_{DM} h^2 \sim 0.1 \times \left(\frac{T_{RH}}{100\,\mathrm{MeV}}\right)\left(\frac{M_{DM}}{1.5\,\mathrm{TeV}}\right)^3$$

DM includes stable baryon-like particle of G_2 3-cycle hidden sector – could provide full relic density, or less – annihilates to several visible and hidden sector particles – M ~ 1 TeV

Don't lose predictive power – relic abundance still depends only on mass and σv (non-thermal "wimp miracle" but at moduli reheat temperature), plus moduli mass ↔ reheat temp

[Some earlier work – "hidden valleys", not really string/M theory sectors -- *Major differences* – (1)always non-thermal history for M Theory – (2)gravitino and scalars and trilinears ~ 50 TeV for M Theory – (3)will have gravitino mass suppressed annihilation unless strong dynamics, Goldberger-Trieman size coupling]

DM SIGNATURES

- **Indirect – yes, analysis underway**

  -- annihilation into hidden sector matter, cascade to visible sector matter

- **Direct? Maybe not from strong dynamics sector**
- **LHC**
  - **Gluino or winos produced – all decays in beam pipe**
  - **If decays prompt, perhaps signatures with SM particles and dark light escaping stuff**
  - **If decays slower, then look like escaping usual LSPs.**
  - **No hidden sector production from vector boson fusion**

FINAL REMARKS (1)

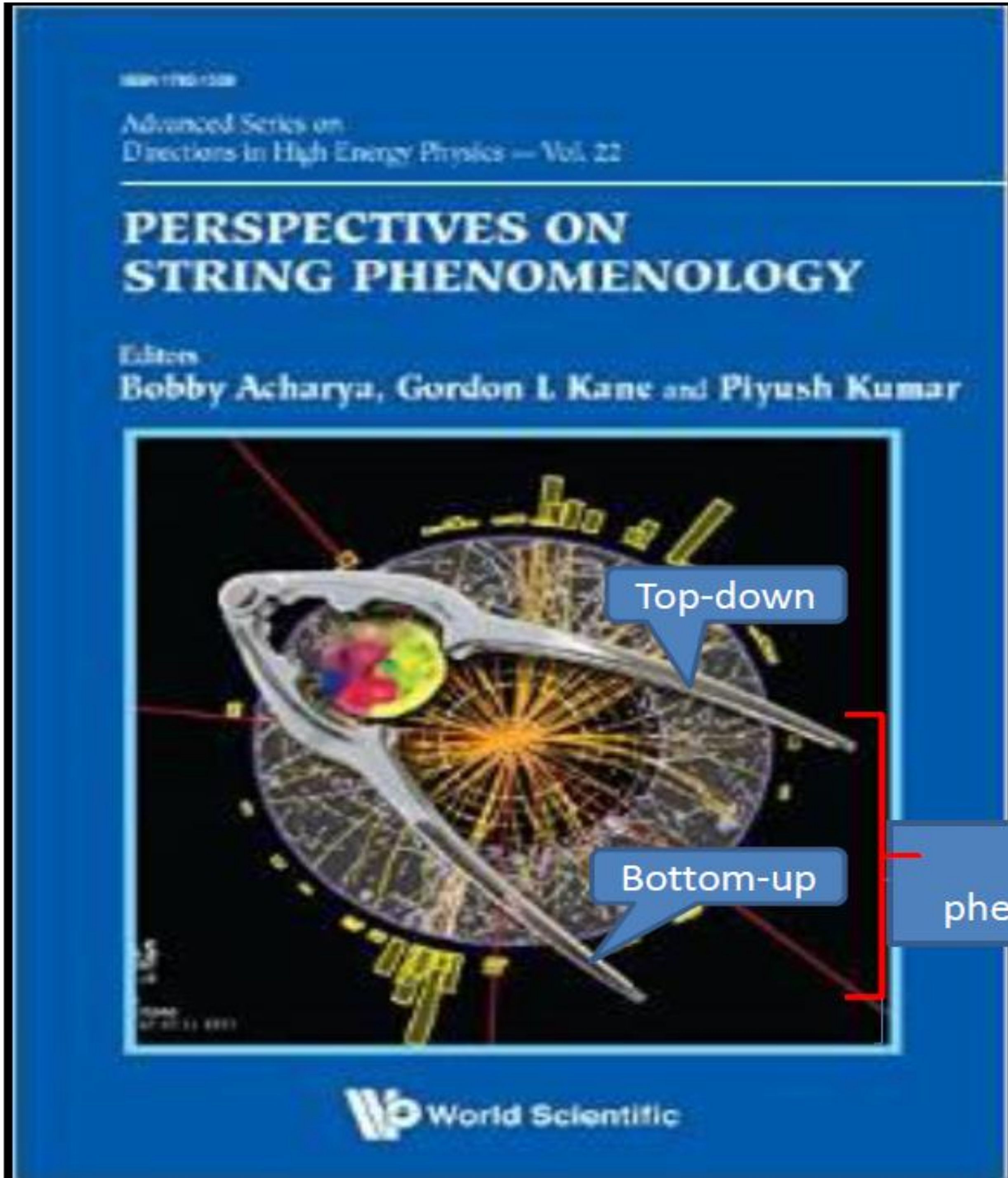
- **String/M-theory too important to be left to string theorists**

- **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**
- **Compactified M-theory promising candidate**

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

FINAL REMARKS (2)

- Moduli generically present – inevitable in M Theory – implies non-thermal cosmological history
- LHC: gluino ~ 1.5 TeV, wino, bino ~ 0.5 TeV ($\pm$ ~ 10%) – good signatures
- Hidden sector dark matter candidates generic, probably inevitable – can be up to few TeV, or light – relic densities calculable – signatures calculable
  - Indirect detection – yes
  - Direct detection, maybe
  - LHC for DM – yes, maybe subtle – gluino → LSP → hidden sector matter + SM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PERSPECTIVES ON
STRING PHENOMENOLOGY
Editors
Bobby Acharya, Gordon L Kane and Piyush Kumar
Top-down
Bottom-up
String
phenomenology
World Scientific

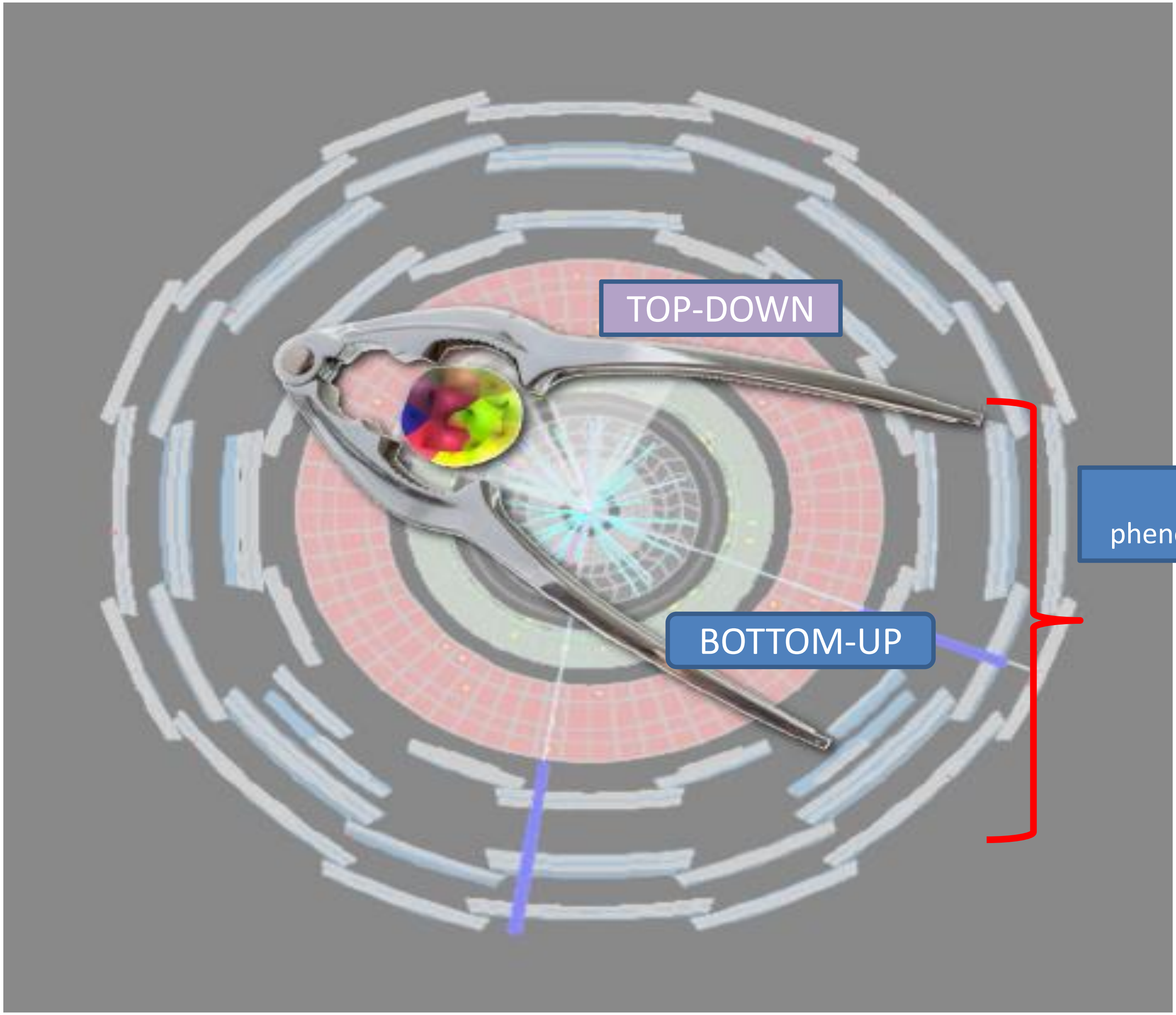
Nutcracker!

COMPACTIFIED M-THEORY (2007)

- **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, decay 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
- **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**



String phenomenology

The parts of science that use a few assumptions to explain a lot about the world are the most impressive and important

-- Frank Wilczek