.

THE FUTURE OF FUNDAMENTAL PARTICLE PHYSICS

- And remarks based on historical lessons from facility development in high energy physics

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I am grateful for my collaboration with Stephen Hawking on parts of this **(arxiv:1804.00682)**. The memo was completed and posted on national and international media before Stephen died. We appreciate discussions with Nima Arkani-Hamed, Malcolm Perry, Jianming Qian, Shing-Tung Yau, and Yue Zhao

Hawking bet

Originated in response to earlier public discussion of such issues

PLAN OF TALK

First I want to ovide physics context for discussing future facilities

– Where are we in understanding our world and the las of nature?

– Where do we want to go next?

– To address these topics need to xamine:

The Status of Fundamental Particle Physics

This is fun and ineresting, and tells us why we can expect more discoveries

Then describe some history of colliders, and some information about their non-scientific and economic impact

AFTER 400 YEARS (Galileo and Kepler) WE'VE FINALLY DISCOVERED THE STANDARD MODELS OF PARTICLE PHYSICS AND COSMOLOGY – ACHIEVED THE HISTORICAL GOALS OF PHYSICS – A *DESCRIPTION* OF OUR PHYSICAL WORLD – 1974

The Higgs boson h (2012) was the final brick (bet with Hawking)

- PREDICTED, NECESSARY
- We do know the observed Higgs boson is THE Higgs boson because it has the full strength decay h→Z+Z:

  [but h → Z+Z IS FORBIDDEN IN THE STANDARD MODEL because h is a weak isospin doublet, while Z is in a triplet – cannot combine two triplets to make a doublet – 3x3 does not contain 1/2

  The TRUE VERTEX IS hhZZ, and ONE h GETS A VACUUM VALUE, giving ~~h~~hZZ-- If hZZ effective vertex is full strength, a single Higgs boson has the vacuum value, none left over for other Higgs]
- If no h, electron massless → atoms infinitely large, no universe!

WHAT DO WE NEED TO KNOW TO SAY WE UNDERSTAND OUR PHYSICAL WORLD? AT LEAST:

- **PARTICLES – quarks and leptons –**

THE GOALS AND BOUNDARIES OF PHYSICS HAVE CHANGED SINCE ~ 1974 WHEN THE STANDARD MODEL WAS ESTABLISHED

- **First came ideas of unifying description of forces so only one underlying force, "grand unification", and "supersymmetry" – middle 1970s**
- **Then in mid 1980s came inflation, and string theory**

→ **ALL THE BASIC INGREDIENTS MAY BE PRESENT**

Ernest Rutherford, 1920: "Don't let me catch anyone talking about the universe in my department"

Steven Weinberg, recently: "Scientists of the past were not just like scientists of today who didn't know as much as we do. They had completely different ideas of what there was to know and how to go about learning it."

Level 2

- we want to know what the dark matter is,
- and what the inflaton is,

Level 3 - One can ask “deeper” questions

- black hole information paradox
- are the forces and particles inevitable (equivalent to why is the Standard Model our field theory instead of a different one?)
- are the rules of relativistic quantum field theory inevitable?
- cosmological constant
- why three large dimensions?
- why is there a universe? – multiple universes? Multiverse?
- Asking these questions is new historically

– WE CAN HAVE A PROXIMATE UNDERSTANDING OF OUR WORLD WITHOUT UNDERSTANDING THESE ISSUES

UNDERSTANDING LEVEL 3 QUESTIONS IS UNLIKELY TO HELP EXPLAIN PARITY VIOLATION, OR THE HIGGS BOSON MASS AND DECAY BRANCHING RATIOS, OR THE TOP QUARK MASS, ETC

ẆE DON'T WANT JUST A *DESCRIPTION* OF OUR WORLD,

A. Want *explanations*, "WHY" is the Standard Model what it is?

B. Standard Model description INCOMPLETE – in 4 ways:

- three are theoretical, or cosmological – 4th is particle physics and challenging

Standard Model incomplet

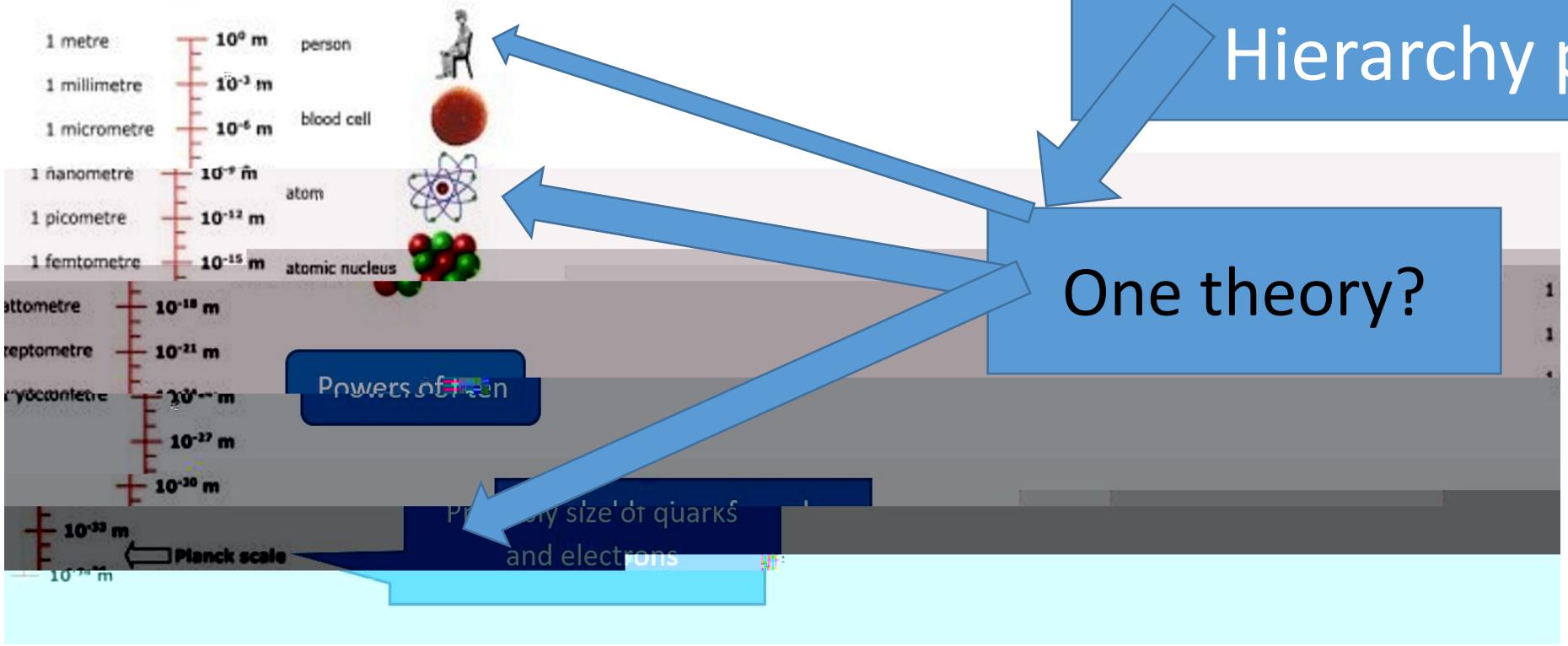
3. Level 3 – nice problems, but work on them later:

- ❑ **Why three large dimensions? – are the forces and particles inevitable? – why universes? – etc**
- ❑ **Don't need these to understand our world**

4. HIERARCHY PROBLEM!!!

- ❑ **UNAVOIDABLE ONCE INCORPORATE GRAVITY – SOLUTIONS GENERICALLY GUARANTEE NEW PHYSICS IS PRESENT AT ACCESSIBLE ENERGIES**


Form the Matter Molecule Atom to the Quark to the Strings
Electron
Proton
Quark
Quark Up


1 metre
10^{0} m
person
1 millimetre
10^{-3} m
1 micrometre
10^{-6} m
blood cell
1 nanometre
10^{-9} m
atom
1 picometre
10^{-12} m
1 femtometre
10^{-15} m
atomic nucleus
10^{-18} m
10^{-21} m
10^{-27} m
10^{-30} m
10^{-33} m
Planck scale
Powers of ten
and electrons
Hierarchy problem
One theory?

Progress can come from data (measurements, facilities) or from ideas

- If only data, hard
- If only theory, people won't be convinced
- Fortunately, data plus string/M-theory framework both arrived in recent two decades
- Contrary to what you may hear and read, string/M-theory is relevant to our world and testable
- STRING/M-THEORY ALLOWS MAKING COMPREHENSIVE THEORIES
- NEED STRING/M-THEORY TO UNDERSTAND HIERARCHY PROBLEM

String theory formulated in 10 (or 11) space-time dimensions, in order to have a mathematically consistent theory of gravity(!) – But we live in 4D!

- **To describe our world: separate 10D (11D) into 4 large dimensions that form our world, plus 6 (7) small Planck-scale size dimensions forming a manifold that we don't directly experience (string or M-theory)**
- **PROJECTING TO 4Dp 0Ct LLol**

Compactified string/M-theories generically contain

- **Yang-Mills forces**
- **Chiral fermions, with quark and lepton charges**

So the ingredients of the Standard Model are present

HIERARCHY PROBLEM (simplified):

In quantum theory the basic Born approximation to calculate a value or transition is

$$M \approx \sum_n \frac{<i|H|n><n|H|f>}{E_n - E_i}$$

- **The sum over n includes all states, and can include heavy states up to the Planck scale – Higgs boson can get large mass from such corrections**
- **In the Standard Model all masses of fermions, and of W and Z bosons, are proportional to the Higgs mass**
- **If the Higgs mass gets contributions from high scales, like unification, or Planck scale states, all masses get huge, orders of magnitude larger than observed**

Supersymmetric Standard Model (1974)

- **Hypothetical extension of Standard Model where the theory is also invariant under interchange of**

  fermions (spin ½) $\leftrightarrow$ bosons (spin 0)

- **Considerable indirect evidence for supersymmetry in nature – properties of observed Higgs boson imply we are on right track to expect discovery of superpartners next at LHC – also unification of forces**

- **If nature supersymmetric, should see superpartners of some of particles (photon, gluon etc) at LHC**

  →(photino, gluino etc)

Logically the Standard Model could hold all the way to the Planck scale, with no new physics – but then we could not explain or understand the electroweak scale, or the hierarchy between the Planck scale and the electroweak scale – would have to give that up

So far no sign we cannot understand the electroweak scale – maybe someday have to give up, but not until forced

(Probably) in any world where we can understand the electroweak scale, and why we have the strong and electromagnetic and weak forces, the hierarchy problem will have a physical solution and lead to new physics

If not superpartners, some other phenomena will show up and be observable not too far above the electroweak scale

A supersymmetric theory connects our scale with ~ the Planck scale

- Can write Planck scale theory and calculate predictions for our scale, collider scale

- Can take low scale data and theories and see what they suggest about the high scale theory

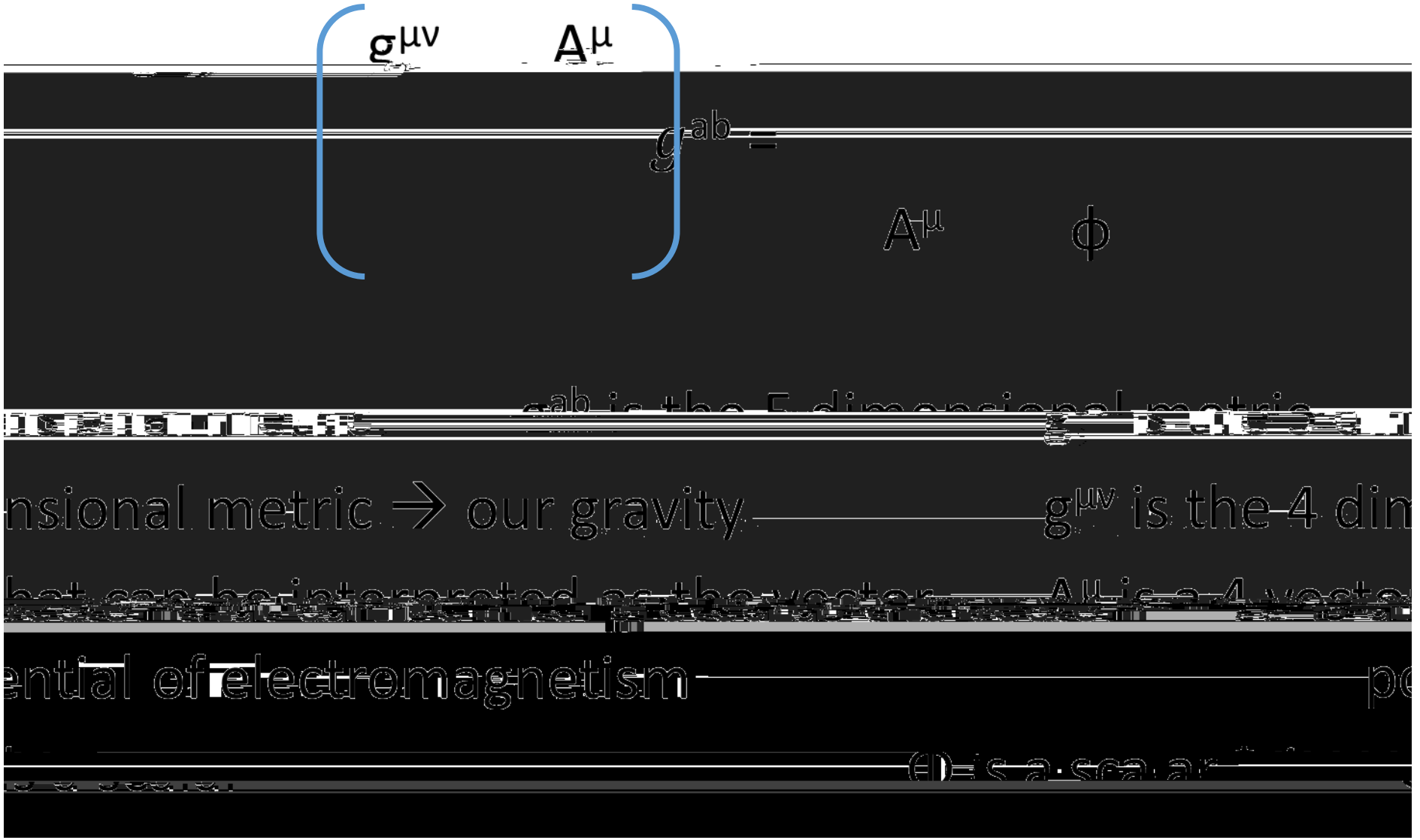
Without discovering that new physics we are barred from connecting to the Planck scale region, and grasping the fundamental underlying physics connecting to quantum gravity

WHY 10 DIMENSIONS?

- ***Can show that a MATHEMATICALLY CONSISTENT RELATIVISTIC QUANTUM THEORY WHICH INCLUDES GRAVITY WILL HAVE 10D! – a fact! – the 4D we know plus 6 extra ones***
- ***We expect the extra dimensions to be curled up at Planck scale sizes, the only natural size***
- **Actually 10 good! – six extra dimensions "become" the forces – need 10 dimensons to get all the SM forces (and only those)**

Extra dimensions weird – but so is the fact that the earth orbits the sun! - counterintuitive

KK:


$g^{\mu\nu}$ A^μ
g^{ab} =
A^μ ϕ
nsional metric → our gravity
$g^{\mu\nu}$ is the 4 dim
ential of electromagnetism

As an example, I have worked (with Bobby Acharya et al) on **M-THEORY COMPACTIFIED ON A "G_2" MANIFOLD TO A 4D THEORY** – well motivated (briefly describe it)

Resulting 4D theory AUTOMATICALLY has

- **Softly-broken SUPERSYMMETRY (gravity mediated), with ALL MODULI STABILIZED IN A DE SITTER VACUUM – supersymmetry not added assumption**
- **Forces and particles like those of the Standard Model – probably three families**
- **SOLVES HIERARCHY PROBLEM**
- **Generic electroweak symmetry breaking, HIGGS MECHANISM, Higgs boson, predicted M_h/M_z**
- **Solves strong CP problem, axions**

❑**AND: dark matter candidates (axions, stable hidden sector matter, allows ok relic density)**

❑**Has scales: Planck, string, susy breaking, gravitino mass, gluino mass, electroweak derived**

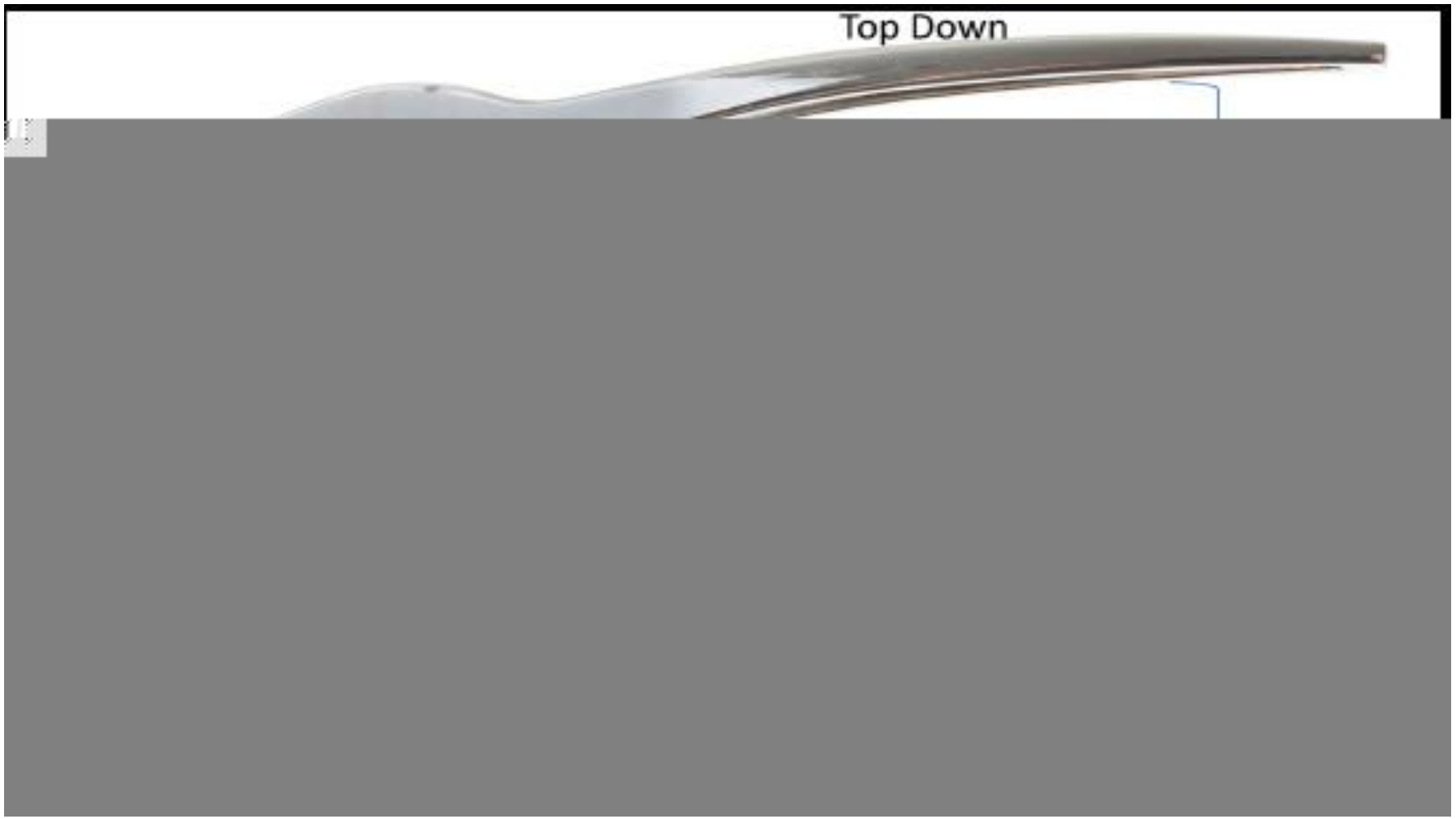
❑**Here and in similar compactified theories EXPECT GLUINOS TO BE 1.5 TEV TO A FEW TEV → DETECTABLE AT COLLIDERS**

❑**Compactified string/M-theories all imply GLUINOS HEAVIER THAN ABOUT 1.5 TEV – should not expect to find them below that**

➢**ONE THEORY, NO FREE PARAMETERS**

Surprisingly, can show that in compactified string/M-theories, Even with R-parity, THE LIGHTEST SUPERPARTNER (LSP) OF SM PARTICLES WILL BE UNSTABLE, AND NOT A CANDIDATE FOR DARK MATTER, contrary to long-standing arguments!(Acharya, S.Ellis, Kane, B. Nelson, Perry – arxiv, PRL)

- **Compactified string/M-theories have hidden sectors – we live on the visible sector, and supersymmetry is broken in some other sector (theorem)**
- **Hidden sectors have matter, which generically may be light (dark photons, chiral fermions)**
- **There is a portal connecting the visible sector $U(1)_Y$ with a U(1)' that generically occurs in hidden sectors, via the kinetic mixing operator $F'_{\mu\nu} F^{\mu\nu}$**
- **Such an operator is dimension 4, like the Lagrangian, so it is not suppressed by a power of masses**
- **Thus the LSP will generically decay to lighter hidden sector matter – the LSP is not a candidate for the dark matter**
- **→ different signatures**


Top Down

Surprisingly some people have claimed that because string theories are naturally formulated at Planck scale high energies or small distances they cannot be tested!

Obviously collisions will never probe energy scales such as the Planck energy 10^{16} TeV (about 10^{15} times LHC), or see distances as small as 10^{-33} cm (atom about 10^{-8}cm)

But DON'T HAVE TO BE SOMEWHERE TO TEST SOMETHING THERE!

-- STARS elsewhere are made of same chemical elements as ours

-- BIG BANG – evidence includes [1] expanding universe, [2] Helium abundance and nucleosynthesis, [3] Cosmic microwave background radiation

-- Don't have to be present 65 million years ago to test whether asteroid impact was a major cause of dinosaur extinction

SIMPLY WRONG TO STATE STRING THEORY NOT TESTABLE

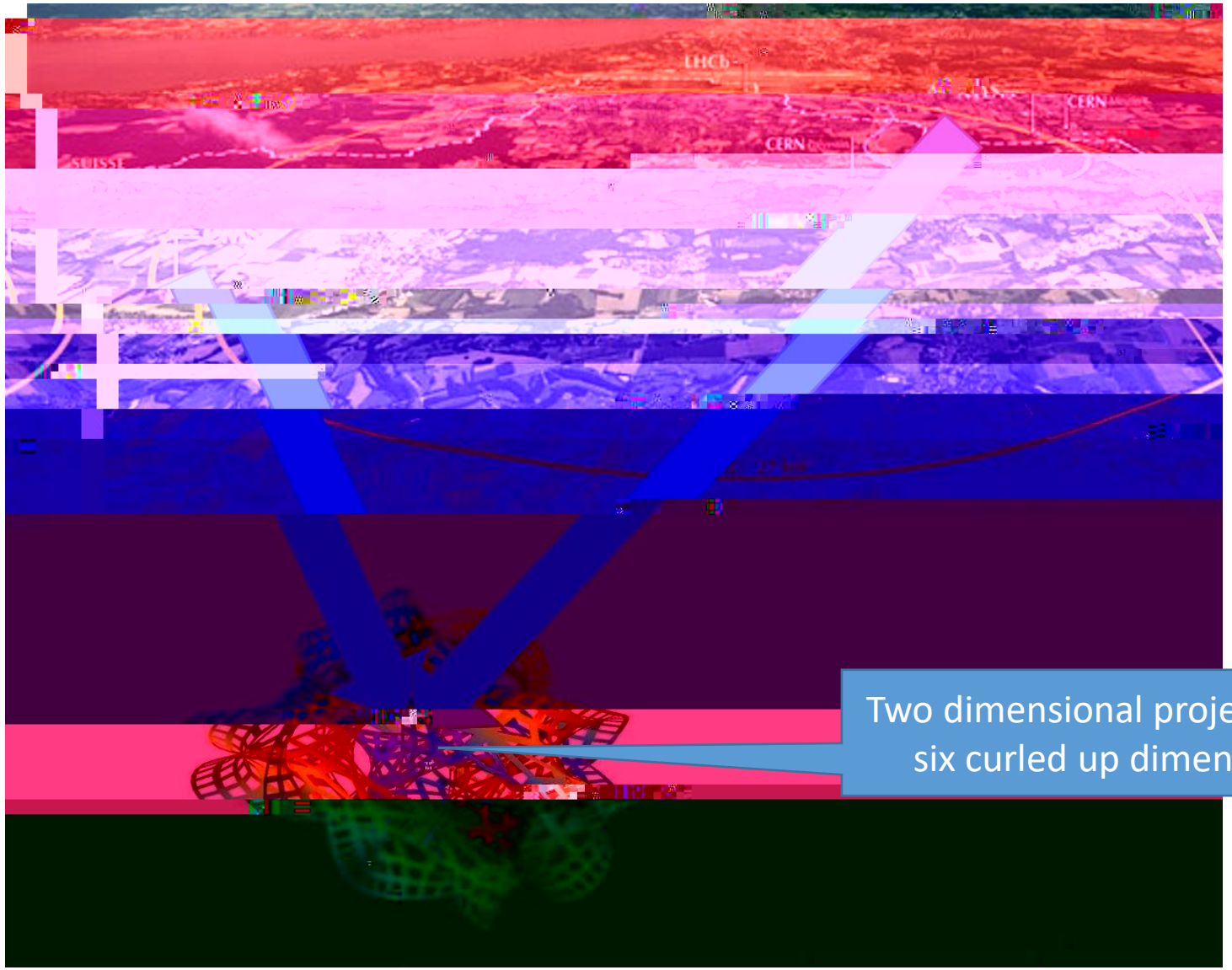
Simons foundation has funded a 4-year, $10 million, study of "$G_2$ " MANIFOLDS of interest, that arise in the M-theory compactification

– "Manifolds of Special Holonomy"

--Many top mathematicians and some physicists actively involved including my collaborator Acharya

– Soon we will understand the small, curled-up manifolds well – they are where the physics is

A COLLIDER IS A BIG indirect MICROSCOPE



Two dimensional projection of six curled up dimensions

Some e^+ e^- colliders can focus on learning more Higgs physics–
Give two examples here:

1.

2. The Higgs boson should have partners, which can be searched for at future colliders

- There are other programs for electron-positron colliders
  - ILC in Japan, initial energy allows studying Higgs boson, requires international funding
  - -- CLIC at CERN being studied – could be built with long term CERN budget, only after LHC luminosity upgrade, maybe energy upgrade
- In the past, several countries/regions have had overlapping machines
- A great advantage of future circular $e^+ e^-$ colliders over other proposals is that they can have a second phase with proton-proton collisions – tunnel would already be in place
- *Like LHC after LEP at CERN, same tunnel*
- *Can also have tera-Z*

- LHC, OR A NEW e^+ e^- COLLIDER, COULD FIND THE FIRST CLUE TO NEW PHYSICS – then need to study the whole spectrum and interactions, like Standard Model at LEP studied over a decade
- History again provides a guide
  - W and Z bosons were discovered at lower energy facilities
  - Then CERN built and ran the LEP electron-positron collider, studying the Standard Model and alternatives, and establishing the Standard Model
  - Then in the same tunnel, LHC collided protons on protons at higher energies, and discovered the Higgs boson
- May need later hadron collider with energy few x LHC
- Be sure that decisions allow going to colliding protons at higher energy if needed – e.g. tunnel length and diameter

Now discuss several issues relevant to future facilities – issues often raised in discussions – go fast, give general impression

Several issues relevant to future collider in China – Hawking & Kane (arxiv:1804.00682)

- **Great Scientific programs have been successful in China.**
  - **BESS, Daya Bay, PandaX, CDEX, DAMPE, etc**

- **CEPC or other colliders can do great physics**
  - **Test if the Higgs boson is close to the Standard Model one.**
  - **Search for partners of the Higgs boson.**
  - **Opportunities to convert to SPPC with higher energy (historically LEP -> LHC)**

A great advantage of CEPC over other proposals is that it can have a second phase, called SPPC with higher energy and proton-proton collisions – tunnel would already be in place

To understand economic impact, the essential point to grasp:

- When one is at the frontier of knowledge and understanding, progress *requires new techniques and developments* – otherwise discoveries would have already been made – requires technology at levels and in areas where no one has gone before – requires innovation

- To store and process the huge amount of DATA PRODUCED in LHC experiments, grid and cloud computing were developed, linking many computers – now these technologies are crucial for many internet business applications – services – shopping – entertainment – social media – multibillion dollar industried

- MAGNET TECHNOLOGY AND SUPERCONDUCTING WIRE TECHNOLOGY more multibillion dollar industries

- Multibillion dollar IMAGING INDUSTRY owes existence to development of particle physics detectors → smartphones …

- Multibillion dollar ACCELERATOR INDUSTRY – synchrotron light sources – proton accelerators that treat cancer – medical isotope production –

- **Scientific Linux operating system – developed at Fermilab in 2004 for accelerator**
  -

- A major effect comes because innovations can lead to START-UP COMPANIES – start-ups are risky – with LHC to PROVIDE AN INITIAL MARKET for the products of the start-ups they have been far more likely to succeed – that would be true for any future facility too

- Economists say OVER HALF OF ALL NEW JOBS COME IN SCIENCE AND TECHNOLOGY sector – Solow – Romer – Salter ang Martin – Owen-Smith et al, Science vol 344, p41, April 2014:

  "many small businesses leverag u v ys leve 2

- **Possibly the largest benefit for China of new ambitious facilities would be ATTRACTING MANY BRIGHT YOUNG CHINESE TO SCIENCE and its goals – the attraction of curiosity-driven research – these young people would get excited about many areas of science along the way, and decide to work in those areas, greatly strengthening the entire scientific enterprise in China**

- **About half of all PhD's earned at CERN go to people who move into industries and areas outside of particle physics, and enrich those areas –about half the grad students go on to postdocs in particle physics, and ABOUT A QUARTER OF ALL END UP PERMANENTLY IN PARTICLE PHYSICS**

- **Gain for society is not only economic, but QUALITY OF LIFE is improved for many people, and QUALITY LIFE-SPAN LONGER for many people**

- **For the first decades of the THIRD INDUSTRIAL REVOLUTION High Energy Physics was a leader - Requirements for data acquisition and storage and access, and the materials and technologies needed for the next facilities could help lead to the FOURTH INDUSTRIAL REVOLUTION**

➢Could there be any ALTERNATIVES to a higher energy facility to discover or exclude new particles, and address the hierarchy problem? - NO

- People have invented clever methods to accelerate protons and/or electrons to higher energies
- But unfortunately all approaches have led to luminosities far too small to discover new physics – a few events per decade
  - Seeing Higgs boson signal at LHC above backgrounds that could fake it took over 200,000 events per detector

➢In the SSC era of 1980s opponents claimed that new magnet technologies (e.g. high T superconductivity based) would emerge that would replace the well-established superconducting magnets – four decades later such new magnet technologies still have not arrived, and are unlikely to exist

- **Could NEW THEORETICAL CONCEPTS OR TOOLS emerge that would move science forward without new facilities – NO**

  - **Of course new ideas might lead to new insights – BUT WITHOUT DATA WE WILL NOT KNOW IF A THEORY REALLY DESCRIBES OR EXPLAINS NATURE – without discovery of the Higgs boson most physicists would still doubt about the Higgs mechanism giving mass, or the Higgs field describing our vacuum**

  - **Results from ASTROPHYSICS AND COSMOLOGY AND THE COSMIC MICROWAVE BACKGROUND provide information about exciting questions, but**

- **China has several MEDIUM-SIZE SCIENTIFIC PROJECTS (e.g the China Spallation Neutron Source just successfully turned on, operated by the Institute of High Energy Physics and the Institute of Physics, one of four such facilities in the world)**
- **China is starting construction on FOUR ADDITIONAL MEDIUM SIZE projects (soft x-ray free electron laser, High-Energy Photon Source, Accelerator Driven System, High Intensity Heavy Ion Accelerator Facility)**
- **but there is so far no area where it has the unique WORLD'S LEADING FACILITY**

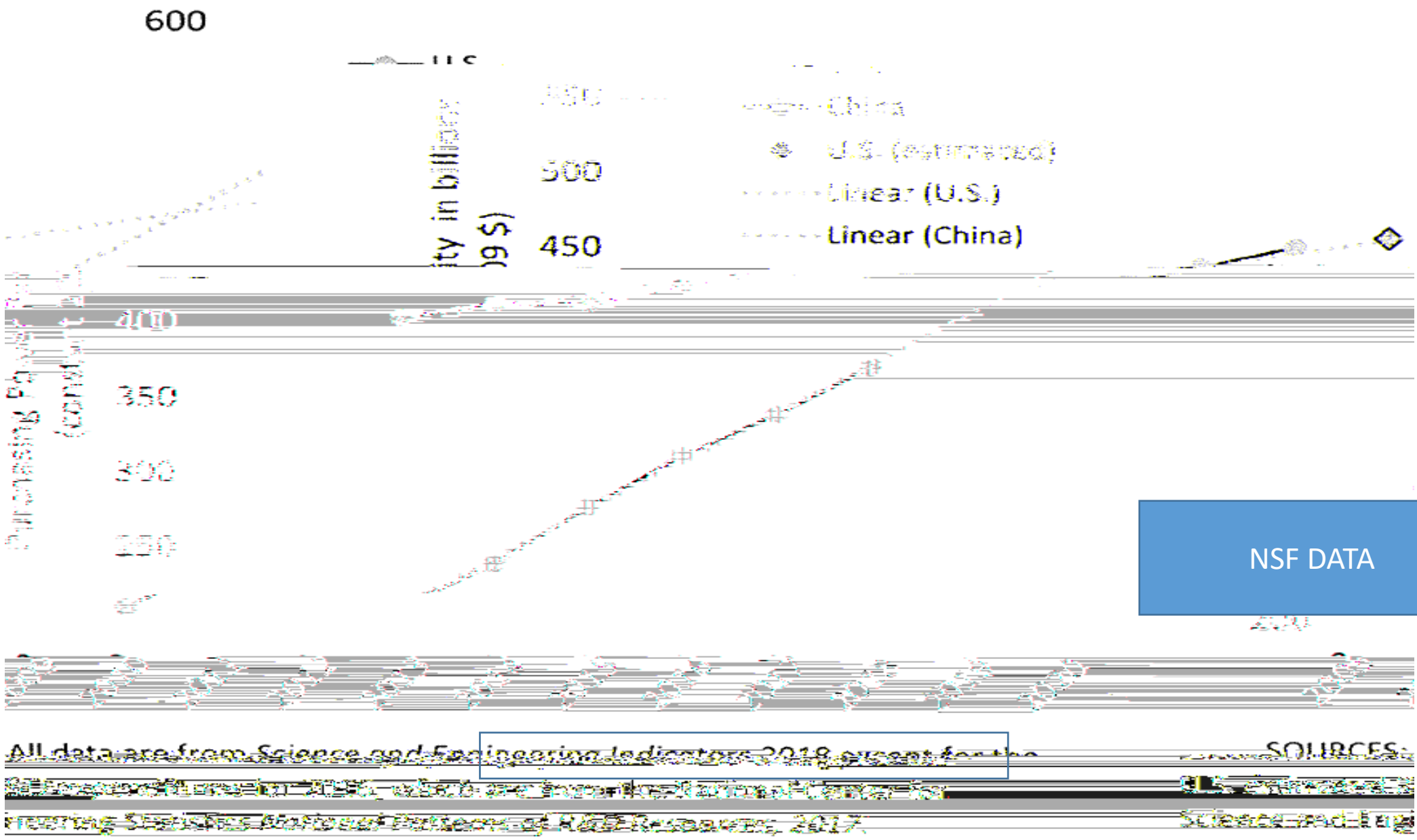
- **Today COLLIDER CONSTRUCTION IS A MATURE TECHNOLOGY. Cost and time estimates will be examined by experts, and are likely to be basically accurate.**

- **THE CHINESE PARTICLE PHYSICS COMMUNITY HAS MATURED - has mastered the low energy collider technology with the Beijing collider BEPC - Many Chinese physicists have worked at collider laboratories such as CERN and Fermilab**

- **China's GDP per capita is not yet as high as that of the wealthiest nations, but its total GDP is now among the largest in the world, and can afford a future collider – see slide**

- **If frontier activities are underway in China, foreign physicists would come to where the action is, and help make any effort maximally successful**

Gross Expenditures on R&D



NSF DATA

All data are from Science and Engineering Indicators 2018 except for the

SOURCES:

- **There is tradition in particle physics for group leaders, and for those who made colliders happen, to get Nobel Prizes**

--for the CERN collider the prizes for W, Z discovery went to Carlo Rubbia and Simon van der Meer

– for the discovery of the charmed quark it was the group leaders Samuel Ting and Burton Richter

- **The Chinese have so far taken a wise approach to financing a number of medium size science facilities – Insisting on INTERNATIONAL COLLABORATION FOR FACILITIES CAN LEAD TO COMPLICATIONS, DELAYS – Once China is proceeding, other countries may join in.**

- **NO NEED FOR COLLIDER FUNDING TO COMPETE WITH NOR ADVERSELY AFFECT OTHER SCIENCE FUNDING – each area should have its funding at a level that is healthy for its development**

- **Proponents should first argue for funding for science in general, then for funding for high energy physics, and only then for funding for their own favorite facility**

- **Description of scientific and cultural case for a future collider program has been presented in "From the Great Wall to the Great Collider: China and the Quest to Uncover the Inner Workings of the Universe", by Steve Nadis and Shing-Tung Yau, International Press of Boston, 2015**

- **I hope there will be NEW STUDIES by economists + physicists to document impact on economy and innovation based on Fermilab and CERN – some limited studies by physicists about CERN already exist**

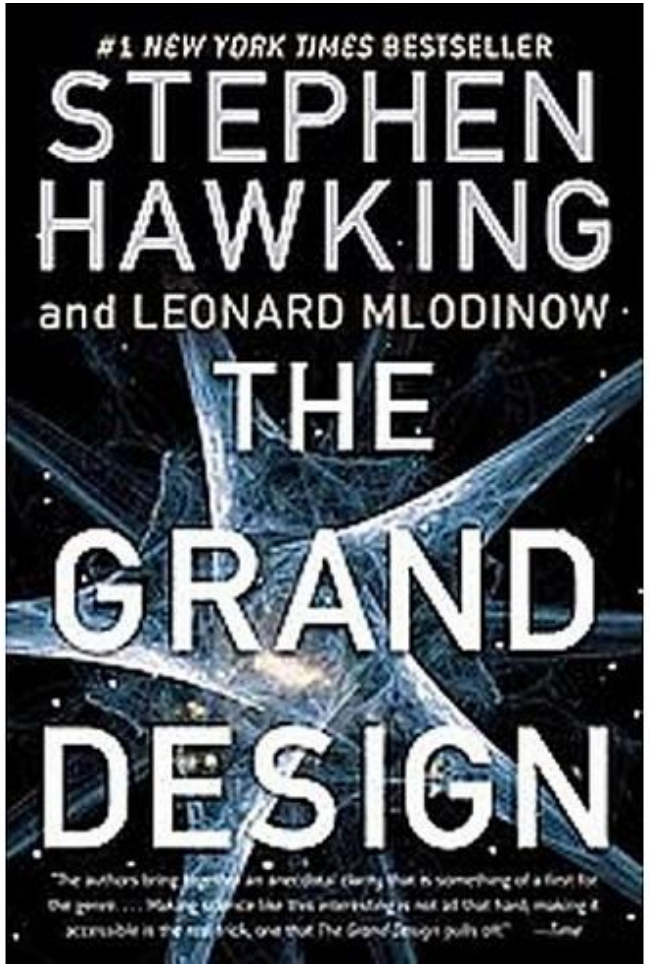
FINAL REMARKS - 1

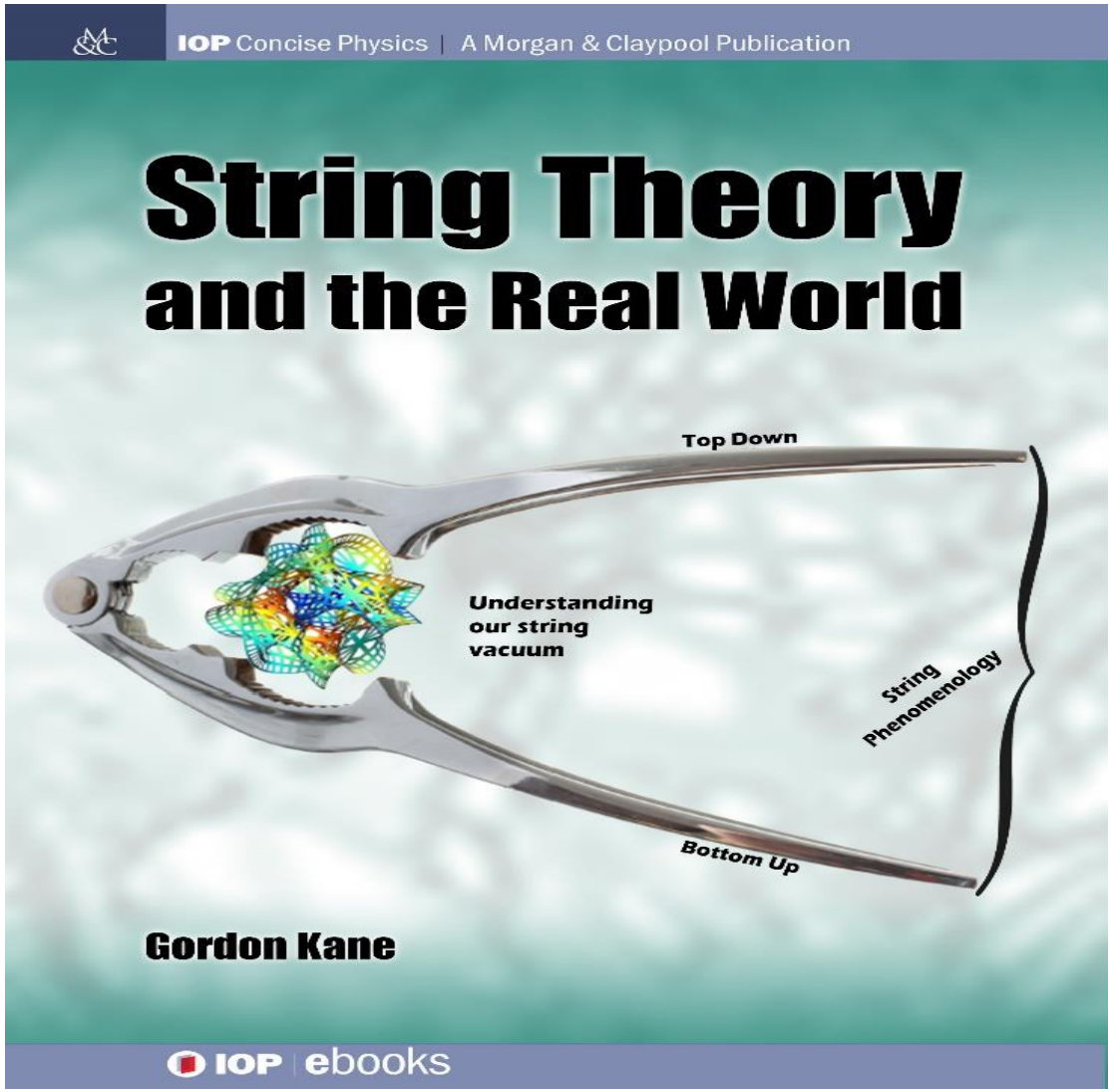
- **Having quantum theory of gravity changes how we think about our world (even if don't care so much about quantum gravity)– DON'T IGNORE UV (ULTRAVIOLET) COMPLETION**
- **INCLUDING GRAVITY FORCES US TO DEAL WITH THE HIERARCHY PROBLEM, and we need to include gravity**
- **Solving the Hierarchy Problem is essential to comprehend our world, and to define our goals – reqires finding the new physics experimentally**
- **There has been PROGRESS IN COMPACTIFIED STRING/M-THEORIES**

FINAL REMARKS -2

- **Future facilities that could take us to the next deeper level are an ECONOMIC AND CULTURAL INVESTMENT THAT FAR MORE THAN PAYS FOR ITSELF REGARDLESS OF THE PHYSICS RESULTS**

- **The country that makes the greatest advances in discovering the workings of nature itself, via the science of particle physics, will be permanently remembered for its achievements.**





BOTH BOOKS EMPHASIZE M-THEORY

Cosmological constant/dark energy

- Important, very interesting problem
- No solution yet in particular string vacuum
- Expect solution decoupled from all the particle physics issues – this holds in all known approaches
- Solving CC/DE unlikely to help answer questions
- Not solving CC/DE unlikely to prevent answering questions
- In practice, set CC to zero for calculations, and ensure can do that and have deSitter minimum for vacuum – requires two contributions to breaking supersymmetry

In control room of Atlas detector:

“To advance human knowledge, to continue an endless quest to learn where we come from and why the Universe is as we see it today”

Some theorists today think the boundaries have changed, and perhaps the quest is not endless

Minister of Science and Technology Wan Gang:

- **“Creativity doesn’t thrive under orders. It depends on scientists’ imagination and free thinking”**
- **“We will create a more relaxed environment for scientists – only when they feel free will they be able to think freely”**

14 March, 2018

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)

Supersymmetry breaking dynamical, automatic!

Hierarchy problem solved

Top-down, gravitino ~ factor 2

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

Squarks, 11-20 Tev (3rd family), 25 TeV (1st + 2nd family)

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

EWSB

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

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

E' ... β →

Note - Produce two gluinos

- **Suppose consider search where both decay into 3rd family particles, top and bottom quarks**
- **Then detector sees 3rd families 1/2x1/2 = ¼ of the time**
- **Also, production diagrams with t-channel squark negligible since squarks heavy, so cross section smaller by 2/3**
- **So finally effective cross section smaller by 2/3x1/4 =1/6**
- **Limit reduced accordingly**
- **Currently gluino mass of 1.7 TeV and less excluded, soon 1.8 TeV**
- **2 TeV allowed for next few years, 1.9 or 2 TeV gluino could be discovered**

People have said that the absence of superpartners at LHC so far makes discovery of superpartners unlikely - using "naturalness" – but opposite of naturalness is having a theory, and they don't have any theory for what the superpartner masses should be – naturalness is a misleading argument – NOT A THEORY – History implies "naturalness" not useful for masses:

*When b quark was found in 1979 people argued that the top quark mass would be only a few times the b quark mass, since they are in same SU(2) doublet

*Converted SLAC collider (to PEP) to look for top up to $3M_b$ →nothing

*Japan built new collider (Tristan) to look for M_{top} up to $6M_b$→nothing
In fact top quark is 41 times the b quark mass, and only found nearly twenty years later, at Fermilab*

[*Fermilab, in U.S. outside Chicago, had the Tevatron collider, with final energy 1.96 TeV – it ran for about 2 decades, shut down in 2011 – collided protons and antiprotons, circumference 6.3 km – discovered b quark and top quark – could have found Higgs boson before LHC if its luminosity and running time were optimized]