Universes as Bigdata: Geometry, Strings, & AI

YANG-HUI HE

London Institute of Mathematical Sciences, Royal Institution

Merton College, **University of Oxford**

Dept of Mathematics, City, **University of London**

School of Physics, **NanKai University**

Colloquium: Técnico Lisboa, Jan, 2023

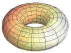
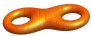
A Classic Problem in Mathematics: Since 1736

- Trichtomy classification of (connected compact orientable) surfaces Σ

Euler: topological classification of $\dim_{\mathbb{R}} = 2$

Gauss: relates topology to metric geometry

Riemann: complexify $\rightsquigarrow$ Riemann surfaces or complex curves: $\dim_{\mathbb{C}} = 1$

		   ...
$g(\Sigma) = 0$	$g(\Sigma) = 1$	$g(\Sigma) > 1$
$\chi(\Sigma) = 2$	$\chi(\Sigma) = 0$	$\chi(\Sigma) < 0$
Spherical	Ricci-Flat	Hyperbolic
$+$ curvature	0 curvature	$-$ curvature

Euler number $\chi(\Sigma)$, genus $g(\Sigma)$

Classical Results for Riemann Surface Σ

$\chi(\Sigma) = 2 - 2g(\Sigma) =$	$= [c_1(\Sigma)] \cdot [\Sigma] =$	$= \frac{1}{2\pi} \int_\Sigma R =$	$= \sum\limits_{i=0}^{2} (-1)^i h^i(\Sigma)$
Topology	Algebraic Geometry	Differential Geometry	Index Theorem (co-)Homology
Invariants	Characteristic classes	Curvature	Betti Numbers

Going up in Complex Dimension

- $\dim_{\mathbb{R}} > 2$ manifolds extremely complicated
- Luckily, for a special class of complex manifolds called **Kähler**

$$g_{\mu\bar{\nu}} = \partial_\mu \partial_{\bar{\nu}} K(z, \bar{z})$$

  all Σ in $\dim_{\mathbb{C}} = 1$ automatically Kähler

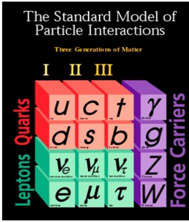
- CONJECTURE [E. Calabi, 1954, 1957]: M compact Kähler manifold (g, ω) and $([R] = [c_1(M)])_{H^{1,1}(M)}$.
  Then $\exists!(\tilde{g}, \tilde{\omega})$ such that $([\omega] = [\tilde{\omega}])_{H^2(M;\mathbb{R})}$ and $Ricci(\tilde{\omega}) = R$.

Rmk: $c_1(M) = 0 \Leftrightarrow$ Ricci-flat (rmk: Ricci-flat familiar to physicists through GR)

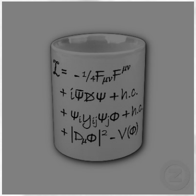
- THEOREM [S-T Yau, 1977-8; Fields 1982] Existence Proof

Two Pillars of Modern Physics

1. MACROSCOPIC (General Relativity)
   - motions of galaxies and stars
   - Gravitational Waves: 2018, new era for cosmology, confidence 99.99994%
2. MICROSCOPIC (Quantum Field Theory)
   - $\sim SU(3)_{str} \times [SU(2) \times U(1)]_{EW}$
   - experimentally verified to 19 digits!
   - Higgs Boson: 2014 at LHC, CERN, last piece to SM!



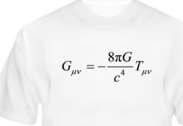
The Greatest Challenge to Science



Standard Model

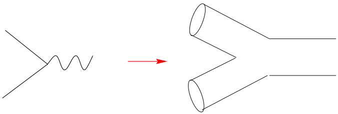
- Problem: the two are incompatible, unrenormalisability of gravity uncancellable infinities in QFT approach to GR
- Albert Einstein spent the last years of his life on this TOE [theory of everything] in vain *"The only thing incomprehensible about our world is that it is comprehensible."*
- Should there exist a single equation unifying the Laws of Nature?
- The universe gives a hint:

$$L_{Planck} = \sqrt{\frac{\hbar G_{Newton}}{c^3}} \sim 10^{-35} m$$



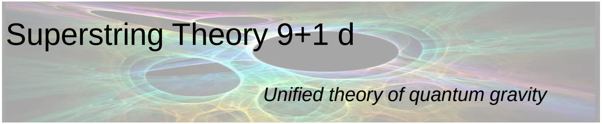
General Relativity

Paradigm Shift: Points $\rightsquigarrow$ Strings $\rightsquigarrow$ ToE

- Fund constituents 1-dim, NOT points (0-dim)? $\rightsquigarrow$ strings, size L_{Planck}
- Smear out interactions: 
- PREMISE: All particles, all of space-time, all of reality are vibration modes of an OPEN or CLOSED string
  - Heterotic string [Gross-Harvey-Martinec-Rohm]: $E_8 \times E_8$ or $SO(32)$, 1984
  - E_8 accommodates Standard Model

$$SU(3) \times SU(2) \times U(1) \subset SU(5) \subset SO(10) \subset E_6 \subset E_8$$

  - WORKS only in 10 dimensions

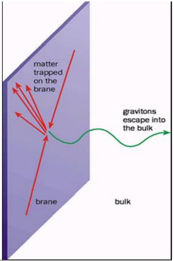


Superstring Theory 9+1 d

Unified theory of quantum gravity

I. 6 Large Dim

AdS/CFT
Brane World

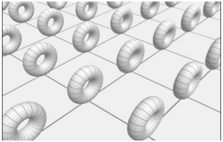


1. Reduce Dim: 10 = 6+4

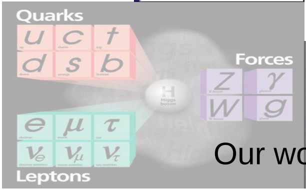
2. Break SUSY

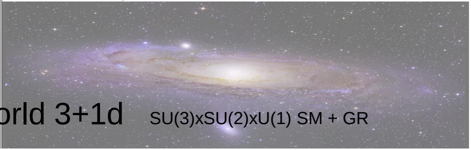
II. 6 small dim

Compactification



String





Our world 3+1d   SU(3)xSU(2)xU(1) SM + GR

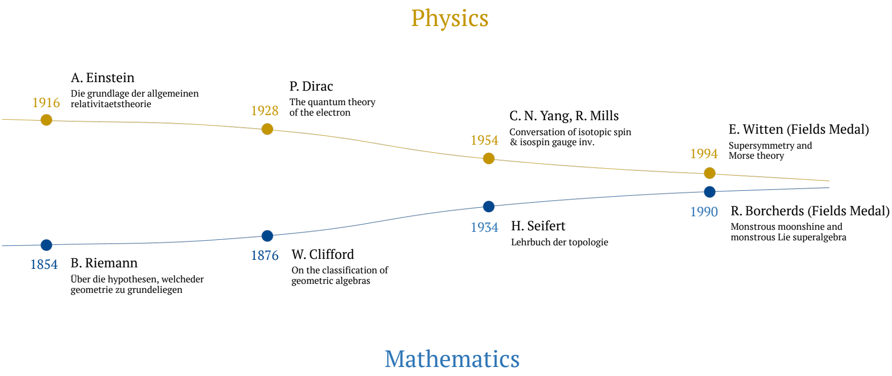
Phenomenology [Candelas-Horowitz-Strominger-Witten]: 1985

simplest solution of 6 extra dimensions: Ricci-Flat, Kähler $\dim_{\mathbb{C}} = 3$

When Physics meets Maths

- Strominger was next door to Yau in 1986 at the IAS, physicists called Ricci-Flat, Kähler manifolds, CHSW called these Calabi-Yau manifolds
- GEOMETRIZATION PROGRAMME: Historically, the right language of physics is increasingly geometrical: Buy my Books :)
  - Gravity/Space-time $\rightsquigarrow$ GR $\rightsquigarrow$ Differential geometry;
  - Particle physics/Standard Model $\rightsquigarrow$ Gauge Theory/Yang-Mills $\rightsquigarrow$ Algebraic geometry (bundles/connections) + group theory (Lie and Finite groups);
  - Condensed matter physics of topological insulators $\rightsquigarrow$ algebraic topology; ...
  - String theory is a brain-child of this tradition
- TAKE-HOME MESSAGE: Whenever physics and maths converge and generate new ideas, the right things are happening

The Confluence of Maths and Physics



The Confluence of Maths and Physics

1959

2010

The Unreasonable Effectiveness of Mathematics in the Natural Sciences

Richard Courant Lecture in Mathematical Sciences delivered at New York University, May 11, 1959

EUGENE P. WIGNER
Princeton University

Phil. Trans. R. Soc. A (2010) **368**, 913–926

Geometry and physics

BY MICHAEL ATIYAH[1], ROBBERT DIJKGRAAF[2,*] AND NIGEL HITCHIN[3]

[1]*School of Mathematics, University of Edinburgh, Edinburgh EH9 3JZ, UK*
[2]*Institute for Theoretical Physics, University of Amsterdam, Valckenierstraat 65, 1018 Amsterdam, The Netherlands*
[3]*Mathematical Institute, University of Oxford, 24–29 St Giles, Oxford OX1 3LB, UK*

"One may be tempted to invert Wigner's comment and marvel at 'the unreasonable effectiveness of physics in mathematics.'"

Back to Calabi-Yau: Explicit Examples

An interesting sequence: 1,2, ??? ...

$\dim_{\mathbb{C}} = 1$

Torus $T^2 = S^1 \times S^1$

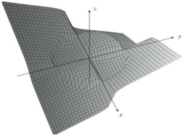
QFT in $10 - 2 = 8d$

$\dim_{\mathbb{C}} = 2$

(1) 4-Torus $T^4 = S^1 \times S^1 \times S^1 \times S^1$

(2) K3 surface

QFT in $10 - 4 = 6d$

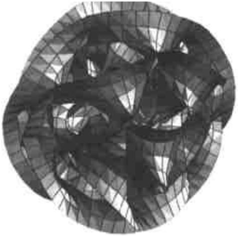


$\dim_{\mathbb{C}} = 3$

Unclassified ???

(Yau's Conjecture: Finite Number)

Desired QFT in $10 - 6 = 4d$

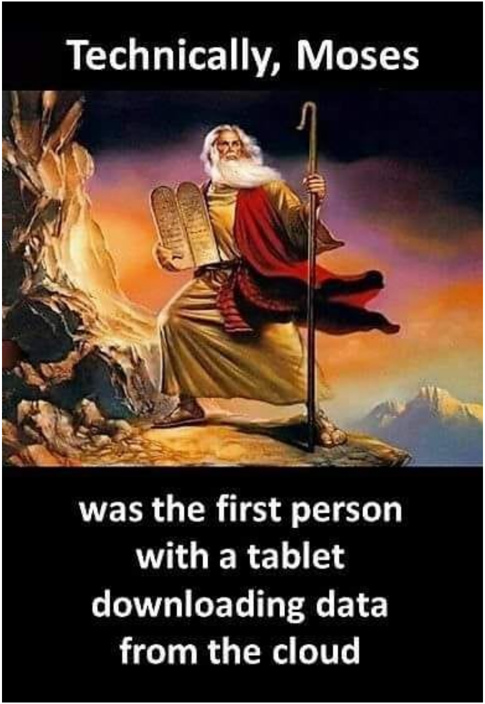


The Inevitability of Algebraic Geometry

- How to construct CY3? Realize as vanishing locus of polynomials, **Algebraic Geometry** e.g., $\{(p,q)|p^2+q^2-1=0\} \subset \mathbb{R}^2$ is a circle (1-real dimension)
- Complexify and Projectivize (Projective algebraic variety)
  - Cubic equation in $\mathbb{CP}^2$: e.g. CY1 $= T^2$ $\{(x,y,z)|x^3+y^3+z^3=0\} \subset \mathbb{CP}^2$ (elliptic curve); $\dim_{\mathbb{C}} = 2-1=1$
  - TMH: Homogeneous Eq in $\mathbb{CP}^n$, degree $= n+1$ is Calabi-Yau of $\dim_{\mathbb{C}} = n-1$
- **An Early Physical Challenge to Algebraic Geometry**
  - Particle content in [CHSW] $\#$ gens of SM particles $= \pm\frac{1}{2}$ Euler number
  - 1986 Question: Are there Calabi-Yau-3 with $\chi = \pm 6$?

The First Data-sets in Mathematical Physics/Geometry

- [Candelas-A. He-Hübsch-Lutken-Schimmrigk-Berglund] (1986-1990)
  - CICYs (complete intersection CYs) multi-deg polys in products of $\mathbb{CP}^{n_i}$
  - Problem: *classify all configuration matrices*; employed the best computers at the time (**CERN supercomputer**); q.v. magnetic tape and dot-matrix printout in Philip's office
  - 7890 matrices, 266 Hodge pairs $(h^{1,1}, h^{2,1})$, 70 Euler $\chi \in [-200, 0]$
- [Candelas-Lynker-Schimmrigk, 1990]
  - Hypersurfaces in Weighted P4
  - 7555 inequivalent 5-vectors w_i, 2780 Hodge pairs, $\chi \in [-960, 960]$
- [Kreuzer-Skarke, mid-1990s - 2000]
  - Hypersurfaces in (Reflexive, Gorenstein Fano) Toric 4-folds
  - 6-month running time on dual Pentium SGI machine
  - at least 473,800,776, with 30,108 distinct Hodge pairs, $\chi \in [-960, 960]$

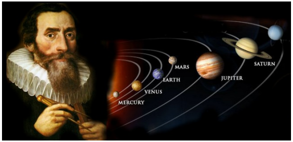


The age of data science in mathematical physics/string theory not as recent as you might think

After 40 years of research by mathematicians and physicists

. . . . . .

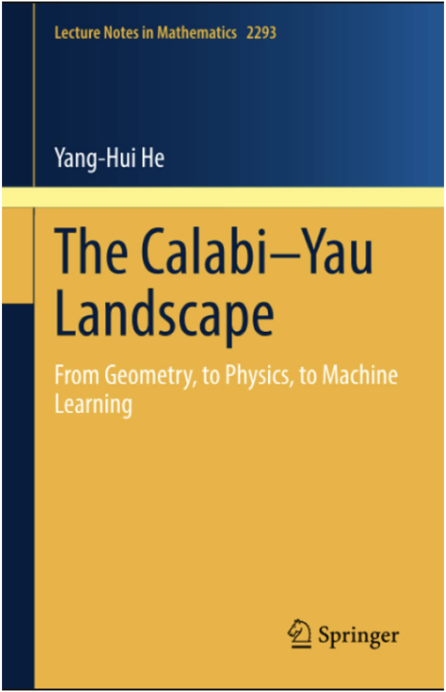
Geometric Origin of our Universe

- Each CY3 (+ bundles, discrete symmetries) X gives a 4-D universe
  - The geometry (algebraic/differential geometry/topology etc.) of X determines the physical properties of the 4-D world
  - particles and interactions $\sim$ cohomology theory; masses $\sim$ metric; Yukawa $\sim$ Triple intersections/integral of forms over X
- 

  Ubi materia, ibi geometria

  – Johannes Kepler (1571-1630)
- Our Universe: $\begin{cases} \text{(1) probabilistic/anthropic?} \\ \text{(2) Sui generis/selection rule?} \\ \text{(3) one of multi-verse ?} \end{cases}$ Triadophilia

  cf. *Exo-planet/Habitable Zone search* (so far $\sim 10^3$ in 10^{21})



YH He

Springer-Nature, 2021

Lecture Notes in Maths

A playful intro for Masters to PhD students

An even more playful intro

Vacuum Degeneracy

Perhaps the biggest theoretical challenge to string theory:

selection criterion??? metric on the landscape???

- Douglas (2003): Statistics of String vacua
- Kachru-Kallosh-Linde-Trivedi (2003): type II/CY estimates of 10^{500}
- Taylor-YN Wang (2015-7): F-theory estimates 10^{3000} to 10^{10^5}
- Basic Reason:

Algebraic Geometry $\rightsquigarrow$ Combinatorial Geometry $\rightsquigarrow$ Exponential Growth in dim

Where we stand ...

The Good: Last 10-15 years: several international groups have bitten the bullet Oxford, London, Vienna, Blacksburg, Boston, Johannesburg, Munich, ... computed many geometrical/physical quantities and compiled them into various databases **Landscape Data** ($10^{9\sim10}$ entries typically)

The Bad: Generic computation HARD: dual cone algorithm (exponential), triangulation (exponential), Gröbner basis (double-exponential) ...e.g., how to construct stable bundles over the $\gg 473$ million KS CY3? Sifting through for SM computationally impossible ...

The ???: **Borrow new techniques from "Big Data" revolution**

A Wild Question

- Typical Problem in String Theory/Algebraic Geometry:

$$\begin{array}{ccc} INPUT & & OUTPUT \\ \boxed{\text{integer tensor}} & \longrightarrow & \boxed{\text{integer}} \end{array}$$

- Q: Can problems in computational geometry and theoretical physics be "learned" by AI ? implications:
  - can we "machine-learn the landscape?"
  - can we do mathematics with ML?
- [YHH 1706.02714] Deep-Learning the Landscape, PLB 774, 2017

  Science feature article, Aug, vol 365 issue 6452 :

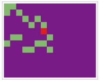
  Experimentally, it seems to be the case for many situations in geometry and beyond in a matter of seconds on ordinary laptop.

Algebraic Geometry is an Image Processing Problem

- *Every manifold can be represented as a numerical tensor*
- A typical calculation:

$$h^{2,1}\left(\begin{pmatrix} 1&1&0&0&0&0&0&0\\ 1&0&1&0&0&0&0&0\\ 0&0&0&1&0&1&0&0\\ 0&0&0&0&1&0&1&0\\ 0&0&0&0&0&0&2&0\\ 0&1&1&0&0&0&0&1\\ 1&0&0&0&0&1&1&0\\ 0&0&0&1&1&0&0&1 \end{pmatrix}\right) = 22$$

think of as



$\longrightarrow 22$

- NN doesn't know/care about the maths Proper Way
- Feed to some Neural Network:
  - Take samples of $X \to h$ (compiled over 40 years)
  - train a NN, or SVM, etc.,
  - Validation on *unseen* $X \to h$
- can reach reaches 99.9% quickly (cf. YHH, Bull-YHH-Jejjala-Mishra, Erbin-Finotello, Constantin-Lukas, ...)

2017: String Theory enters the ML Era

YHH (1706.02714);

(see also: Krefl-Seong (1706.03346); Ruehle (1706.07024) Carifio-Halverson-Krioukov-Nelson (1707.00655))

Sophia: Hanson Robotics, HongKong

- Beginning of `String_Data` annual conference series
- How can ML and modern data-science help with the vacuum degeneracy problem & string phenomenology??
- Meanwhile . . . Sophia becomes a "human" citizen (in Saudi Arabia)

Machine Learning Mathematics

Why stop at string/geometry?

How do different branches of mathematics respond to ML?

Review Paper: YHH 2101.06317 “Machine-Learning Mathematical Structures”, IJDSMS 2022

How does one *DO* mathematics, I ?

- Russell-Whitehead *Principia Mathematica* [1910s] (Leibniz, Frege, ...) axiomatize maths, but . . . Gödel [1931] Incompleteness ; Church-Turing [1930s] Undecidability
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  - Newell-Simon-Shaw [1956] Logical Theory Machine: subset of *Principia*
  - Type Theory [1970s] Martin-Löf, Coquand, . . . Coq: 4-color (2005); Feit-Thompson Thm (2012); Lean (2013); Univalent Foundation / Homotopy Type Theory [2006-] Voevodsky

Buzzard: "Future of Maths" 2019, ICM 2022 Davenport: ICM 2018 "Computer Assisted Proofs" Szegedy: more extreme view, computers > humans @ chess (1990s); @ Go (2018); @ Proving theorems (2030)

We can call this Bottom-up Mathematics

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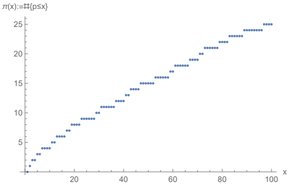
How does one *DO* mathematics, II ?

- Historically, Maths perhaps more Top-Down: practice before foundation
  - Countless examples: calculus before analysis; algebraic geometry before Bourbaki, permutation groups / Galois theory before abstract algebra . . .
  - A lot of mathematics starts with intuition, experience, and experimentation
- The best neural network of C18-19th? brain of Gauß ; e.g., age 16



(w/o computer and before complex analysis [50 years before Hadamard-de la Vallée-Poussin's proof]): PNT $\pi(x) \sim x/\log(x)$

- BSD computer experiment of Birch & Swinnerton-Dyer [1960's] on plots of rank r & N_p on elliptic curves

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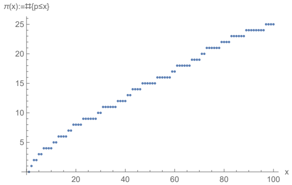

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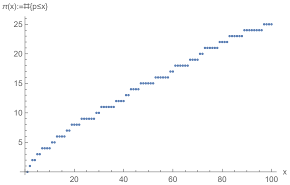

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Mathematical Data

- NOISELESS Data: different from real-world data to which ML is usually applied; If I gave you 100,000 cases of

$$\text{e.g.}\ \begin{pmatrix} 5&3&4&3&5&1&4&4&1&2\\ 5&0&4&5&2&4&4&2&2&4\\ 1&1&2&2&0&4&1&4&5&0\\ 5&0&1&1&0&2&0&5&0&1\\ 2&5&0&1&1&3&2&3&0&3\\ 3&2&2&3&0&0&2&2&1&0\\ 2&2&5&1&4&4&0&0&1&2\\ 5&0&0&0&4&5&0&4&1&1\\ 4&3&4&3&3&1&0&0&2&5\\ 2&0&5&0&3&0&4&4&1&5 \end{pmatrix}, \quad \text{or, labeled data e.g.}\ \begin{pmatrix} 5&3&4&3&5&1&4&4&1&2\\ 5&0&4&5&2&4&4&2&2&4\\ 1&1&2&2&0&4&1&4&5&0\\ 5&0&1&1&0&2&0&5&0&1\\ 2&5&0&1&1&3&2&3&0&3\\ 3&2&2&3&0&0&2&2&1&0\\ 2&2&5&1&4&4&0&0&1&2\\ 5&0&0&0&4&5&0&4&1&1\\ 4&3&4&3&3&1&0&0&2&5\\ 2&0&5&0&3&0&4&4&1&5 \end{pmatrix} \longrightarrow 3$$

- Q: Is there a pattern? Can one conjecture & then prove a formula?
- Q: What branch of mathematics does it come from?

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Mathematical Data

- NOISELESS Data: different from real-world data to which ML is usually applied; If I gave you 100,000 cases of

$$\text{e.g.} \quad \begin{pmatrix} 5&3&4&3&5&1&4&4&1&2\\ 5&0&4&5&2&4&4&2&2&4\\ 1&1&2&2&0&4&1&4&5&0\\ 5&0&1&1&0&2&0&5&0&1\\ 2&5&0&1&1&3&2&3&0&3\\ 3&2&2&3&0&0&2&2&1&0\\ 2&2&5&1&4&4&0&0&1&2\\ 5&0&0&0&4&5&0&4&1&1\\ 4&3&4&3&3&1&0&0&2&5\\ 2&0&5&0&3&0&4&4&1&5 \end{pmatrix}, \quad \text{or, labeled data e.g.} \quad \begin{pmatrix} 5&3&4&3&5&1&4&4&1&2\\ 5&0&4&5&2&4&4&2&2&4\\ 1&1&2&2&0&4&1&4&5&0\\ 5&0&1&1&0&2&0&5&0&1\\ 2&5&0&1&1&3&2&3&0&3\\ 3&2&2&3&0&0&2&2&1&0\\ 2&2&5&1&4&4&0&0&1&2\\ 5&0&0&0&4&5&0&4&1&1\\ 4&3&4&3&3&1&0&0&2&5\\ 2&0&5&0&3&0&4&4&1&5 \end{pmatrix} \longrightarrow 3$$

- Q: Is there a pattern? Can one conjecture & then prove a formula?
- Q: What branch of mathematics does it come from?

Thank you! Hundreds of Experiments since 2017-

my fantastic students Jiakang Bao, Elli Heyes, Ed Hirst Tejas Acharya, Daatta Aggrawal, Malik Amir, Kieran Bull, Lucille Calmon, Siqi Chen, Suvajit Majumder, Maks Manko, Toby Peterken, Juan Pérez-Ipiña, Max Sharnoff, Yan Xiao

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Representation Theory: Mandy Cheung, Pierre Dechant, Minhyong Kim, Jianrong Li, Gregg Musiker

Combinatorics: Johannes Hofscheier, Alexander Kasprzyk, Shiing-Tung Yau

Clearly useful for maths and physics

- conjecture formulation: e.g.
  - '19 YHH-Kim: separating hyperplane - simple/non-simple groups; open
  - '19 Brodie-Constantin-Lukas: exact formulae for cohomo surf.; proved.
  - '20 YHH-Lee-Oliver: L-coefs and integer pt./torsion on ell; Known.
  - '20 Craven-Jejjala-Par: Jones poly best-fit function; open
  - '22 DeepMind-Oxford-Sydney, Nature: Volume bounds for knots; proved
- speed-ups & accuracies: e.g.,
  - computing/estimating (top.inv., charges, etc) MUCH FASTER
  - '19 Ashmore-YHH-Ovrut: speed up Donaldson alg@CY metric 10-100
  - '20 Douglas et al., Anderson et al. improves Donaldson 10-100 times

Please submit

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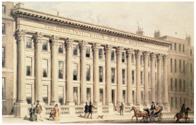
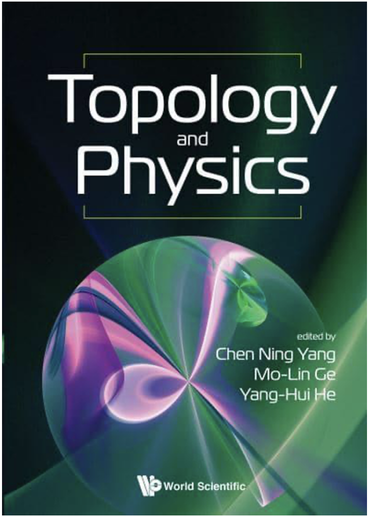
  Arnold Felowships

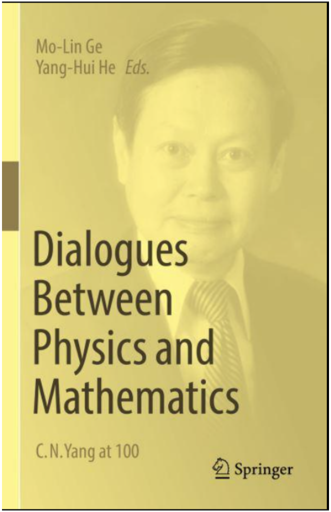
  Landau Fellowships



Obrigada!



CN Yang, ML Ge & YH He, ed, World Scientific, 2019 contributions: Atiyah, Dijkgraaf, Kim, Penrose, Witten, et al.



ML Ge & YH He, ed, Springer-Nature, 2022 contributions: Drinfeld, Leggett, Manin, Penrose, Polyakov, Wilczek, Witten, et al.

Back to Language of Physics

Just came out in 2020 ...

CalabiYau the Game

游戏介绍 （from https://www.9k9k.com/shouyou/klbq/）
《卡拉比丘》是一款宏大世界观的动作游戏。采用5V5的战斗模式，玩家需要选择自己的阵营，操控英雄探索地图，与队友密切协作，战胜敌人玩家即可获得比赛的胜利，更有上百位美少女英雄等待你的召唤！

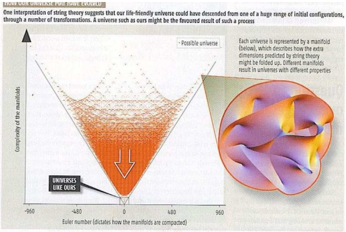
Back to Serious Geometry

Triadophilia

Exact (MS)SM Particle Content from String Compactification

- [Braun-YHH-Ovrut-Pantev, Bouchard-Cvetic-Donagi 2005] first exact MSSM
- [Anderson-Gray-YHH-Lukas, 2007-] use alg./comp. algebraic geo & sift
- Anderson-Gray-Lukas-Ovrut-Palti ~ 200 in 10^{10} MSSM Stable Sum of Line Bundles over CICYs (Oxford-Penn-Virginia 2012-)

  Constantin-YHH-Lukas '19: 10^{23} exact MSSMs (by extrapolation on above set)?



A Special Corner [New Scientist, 5/1/2008 feature]

Candelas-de la Ossa-YHH-Szendroi "Triadophilia: A Special Corner of the Landscape" ATMP, 2008

Back to String Landscape

Computing Geometrical Invariants

- Recall Hodge decomposition $H^{p,q}(X) \simeq H^q(X, \wedge^p T^\star X) \rightsquigarrow$

$$H^{1,1}(X) = H^1(X, T_X^\star), \qquad H^{2,1}(X) \simeq H^{1,2} = H^2(X, T_X^\star) \simeq H^1(X, T_X)$$

- Euler Sequence for subvariety $X \subset A$ is short exact:

$$0 \to T_X \to T_M|_X \to N_X \to 0$$

- Induces long exact sequence in cohomology :

$$\begin{array}{cccccccc}
0 & \to & \cancel{H^0(X, T_X)} \nearrow 0 & \to & H^0(X, T_A|_X) & \to & H^0(X, N_X) & \to \\
 & \to & \boxed{H^1(X, T_X)} & \stackrel{d}{\to} & H^1(X, T_A|_X) & \to & H^1(X, N_X) & \to \\
 & \to & H^2(X, T_X) & \to & \ldots & & &
\end{array}$$

- Need to compute Rk(d), cohomology and $H^i(X, T_A|_X)$ (Cf. Hübsch)

Back to ML