# Universes as Bigdata:

## from Physics, to Geometry, to Machine-Learning


YANG-HUI HE

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

Merton College, **University of Oxford**

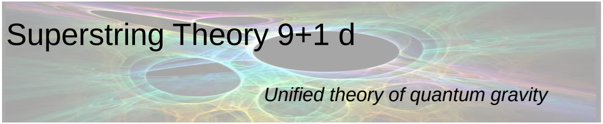
School of Physics, **NanKai University**


Algebraic Geometry in the Summer, (Virtual) Nottingham

# Enriching the Maths/Physics Dialogue

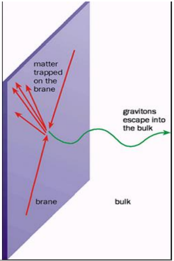
- Alg./diff. Geometry/topology - Rep. Theo : the right language for physics
  - Gravity $\sim$ Ricci 2-form of Tangent bundles;
  - Elementary Particles $\sim$ irreducible representations of the Lorentz group and sections of bundles with Lie structure group;
  - Interactions $\sim$ Tensor products of sections ...
  - **String theory: brain-child of gauge-gravity geometrization tradition**
- A new exciting era for synergy with (pure & computational) geometry, group theory, combinatorics, number theory: *Sage, M2, GAP, LMFDB, GrDB* are becoming indispensible tools for physicists
- Interdisciplinary enterprise: cross-fertilisation of particle/string theory, phenomenology, pure mathematics, computer algorithms, data-bases, ...

# standard string paradigm: $10 = 4 + 3 \times 2$




I. 6 Large Dim

AdS/CFT
Brane World

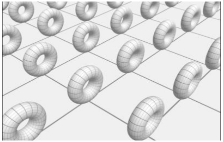


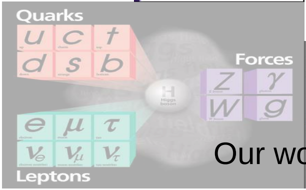

*1. Reduce Dim: 10 = 6+4*

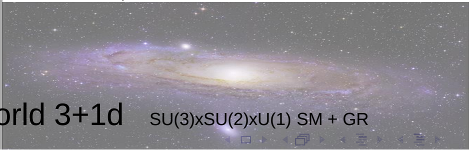
*2. Break SUSY*

II. 6 small dim

Compactification





# 1984: $10 = 4 + 3 \times 2$

- First String Revolution [Green-Schwarz] anomaly cancellation;

  Heterotic string [Gross-Harvey-Martinec-Rohm]: $E_8 \times E_8$ or $SO(32)$, 1984 - 5
- String Phenomenology [Candelas-Horowitz-Strominger-Witten]: 1985
  - $SU(3) \times SU(2) \times U(1) \subset SU(5) \subset SO(10) \subset E_6 \subset E_8$
  - Standard Solution (MANY more since): $\mathbb{R}^{3,1} \times X$, $X$ is not just 6-manifold,

    but a complex 3-fold, and Ricci-flat (vacuum Einstein), Kähler (SUSY)
- *mathematicians were independently thinking of the same problem:*

  Riemann Uniformization Theorem in $\dim_{\mathbb{C}} = 1$: Trichotomy $R < 0, = 0, > 0$

| $g(\Sigma) = 0$ | $g(\Sigma) = 1$ | $g(\Sigma) > 1$ |
|---|---|---|

Calabi-Yau

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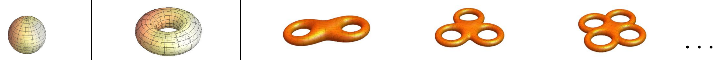


| | | |
|---|---|---|
| $g(\Sigma) = 0$ | $g(\Sigma) = 1$ | $g(\Sigma) > 1$ |

Calabi-Yau

# Calabi-Yau Manifolds as Algebraic Varieties

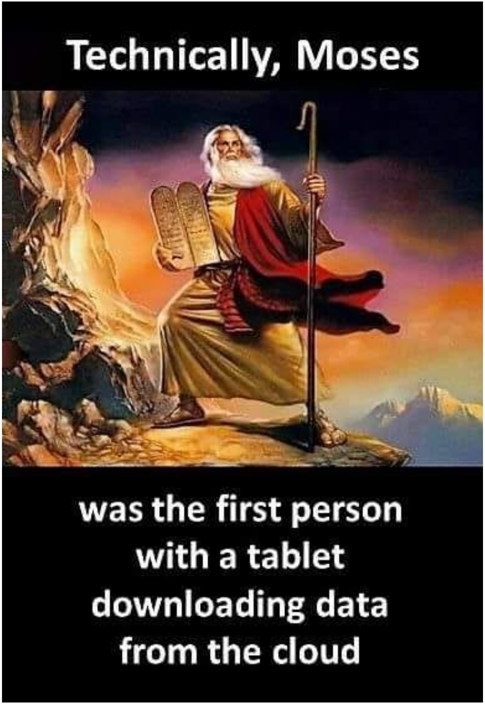
- THM: Homog deg $n+1$ in $\mathbb{P}^n$, is Calabi-Yau $\dim_{\mathbb{C}} = n-1$ (adjunction)
- $\dim_{\mathbb{C}} = 1$: $T^2$ as cubic (elliptic curve) in $\mathbb{P}^2$;

  $\dim_{\mathbb{C}} = 2$: K3 surface as quartic in $\mathbb{P}^3$
- CY3, immediately get 5 (cyclics): Degree 5 in $\mathbb{P}^4$ (The Quintic Q), [3,3] in $\mathbb{P}^5$, [2,4] in $\mathbb{P}^5$, [2,2,3] in $\mathbb{P}^6$, [2,2,2,2] in $\mathbb{P}^7$
- First physics challenge to algebraic geometry:
  - Particle Spectrum: Generation : $n_{27} = h^1(X, TX) = h^{2,1}_{\bar{\partial}}(X)$;

    Anti-Generation : $n_{\overline{27}} = h^1(X, TX^*) = h^{1,1}_{\bar{\partial}}(X)$
  - $\#$ generations of particles $= \chi = 2(h^{1,1} - h^{2,1})$; 1986 Question: Are there Calabi-Yau threefolds with Euler number $\pm 6$? (None of our 5 obvious ones )

# 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 $\mathbb{CP}^{n_i}$ CICYs
  - 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] Reflexive Polytopes
  - 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

of course, experimental physics had been decades ahead in data-science/machine-learning

After 40 years of research by mathematicians and physicists

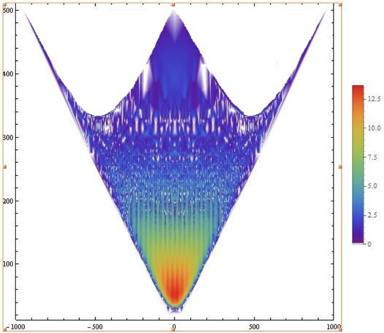
. . . . . .

# The Compact CY3 Landscape

cf. YHH, *The Calabi-Yau Landscape: from Geometry, to Physics, to Machine-Learning,* 1812.02893, [Springer, to appear] $\sim 10^{10}$ data-points (and growing, still mined by many international collabs: Some Recent Advances

Georgia O'Keefe on Kreuzer-Skarke

Vienna (KS, Knapp,. . . ), Penn (Ovrut, Cvetic, Donagi, Pantev . . . ), Oxford/London (Candelas, Constantin, Lukas, Mishra, YHH, . . . ), MIT (Taylor, Johnson, Wang, . . . ), Northeastern/Wits (Halverson, Long, Nelson, Jejjala, YHH), Virginia Tech (Anderson, Gray, SJ Lee, . . . ), Utrecht (Grimm . . . ), CERN (Weigand, . . . ), Cornell (MacAllister, Stillman), Munich (Luest, Vaudravange), Uppsala (Larfors, Seong)



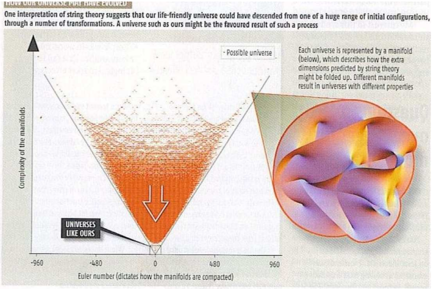

. . .

# 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 $\sim 200$ 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, Jan, 5, 2008 feature]

P. Candelas, X. de la Ossa, YHH, and B. Szendroi

"Triadophilia: A Special Corner of the Landscape" ATMP, 2008

# The Landscape Explosion & Vacuum Degeneracy Problem

meanwhile . . . LANDSCAPE grew rapidly with

- D-branes Polchinski 1995
- M-Theory/$G_2$ Witten, 1995
- F-Theory/4-folds Katz-Morrison-Vafa, 1996
- AdS/CFT Maldacena 1998 Alg Geo of AdS/CFT
- Flux-compactification Kachru-Kallosh-Linde-Trivedi, 2003, Denef-Douglas 2005-6: $10^{\gg 500}$ possibilities . . .

String theory trades one hard-problem [quantization of gravity] by another [looking for the right compactification] (in many ways a richer and more interesting problem, especially for the string/maths community)

# Where we stand . . .

**The Good** Last 10-15 years: large collaborations of physicists, computational mathematicians (cf. SageMATH, GAP, Bertini, MAGMA, Macaulay2, Singular) have bitten the bullet computed many geometrical/physical quantities and compiled them into various databases **Landscape Data** ($10^{9\sim10}$ entries typically) links

**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:

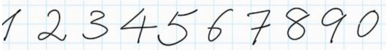
$$\begin{array}{ccc} INPUT & & OUTPUT \\ \boxed{\text{integer tensor}} & \longrightarrow & \boxed{\text{integer}} \end{array}$$

- Q: Can (classes of problems in computational) Algebraic Geometry be "learned" by AI ? , i.e., can we "machine-learn the landscape?"
- [YHH 1706.02714] Deep-Learning the Landscape, *PLB 774, 2017* ( *Science*, feature, Aug, vol 365 issue 6452 ): Experimentally, it seems so for many situations in geometry and beyond.
- 2017

  YHH (1706.02714), Seong-Krefl (1706.03346), Ruehle (1706.07024), Carifio-Halverson-Krioukov-Nelson (1707.00655) Progress in String Theory

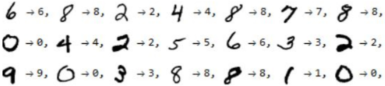
# A Prototypical Question

- Hand-writing Recognition, e.g., my 0 to 9 is different from yours:




- How to set up a bijection that takes these to $\{1, 2, \ldots, 9, 0\}$? Find a clever Morse function? Compute persistent homology? Find topological invariants? ALL are inefficient and too sensitive to variation.

- What does your iPhone/tablet do? What does Google do? Machine-Learn
  - Take large sample, take a few hundred thousand (e.g. NIST database)




$\ldots$

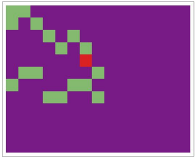
$28 \times 28 \times (RGB)$

Supervised ML in 1 min

# NN Doesn't Care/Know about Alg. Geometry (1706.02714)

- Hodge Number of a Complete Intersection CY is the association rule, e.g.

$$X = \begin{pmatrix} 1&1&0&0&0&0&0&0 \\ 1&0&1&0&0&0&0&0 \\ 0&0&0&1&0&1&0&0 \\ 0&0&0&0&1&0&1&0 \\ 0&0&0&0&0&0&2&0 \\ 0&1&1&0&0&0&0&1 \\ 1&0&0&0&0&1&1&0 \\ 0&0&0&1&1&0&0&1 \end{pmatrix}, \qquad h^{1,1}(X) = 8 \quad \rightsquigarrow$$

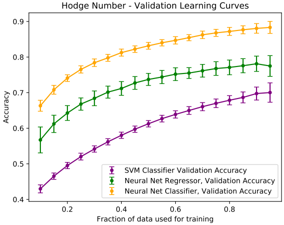


$$\longrightarrow 8$$

CICY is $12 \times 15$ integer matrix with entries $\in [0,5]$ is simply represented as a $12 \times 15$ pixel image of 6 colours Proper Way ; ML in matter of seconds/minutes

- Cross-Validation:
  - Take samples of $X \to h^{1,1}$
  - train a NN, or SVM
  - Validation on *unseen* $X \to h^{1,1}$

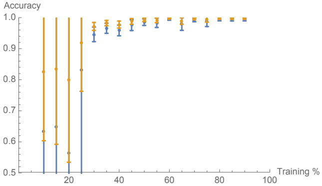
- YHH (1706.02714) Bull-YHH-Jejjala-Mishra (1806.03121, 1903.03113), Erbin-Finotello (2007.13379; Google Inception NN)




Learning Hodge Number $h^{1,1} \in [0, 19]$ so can set up 20-channel NN classifer, regressor, as well as SVM,

bypass exact sequences

- YHH-SJ Lee (1904.08530): Distinguishing Elliptic Fibrations in CY3




bypass Oguiso-Kollar-Wilson Theorem/Conjecture

learning curves for precision and Matthews $\phi$

# More Success Stories in Algebraic Geometry

- Ruehle '17: genetic algorithm for bundle cohomology
- Halverson, Nelson, Long et al '17- programme of ML of KS data
- Brodie-Constantin-Lukas '19: EXACT formulae for line-bundle coho / complex surfaces Interpolation vs Extrapolation $\rightsquigarrow$ Conjecture Formulation
- Ashmore-YHH-Ovrut '19: ML Calabi-Yau metric: improves Donaldson alg. for numerical CY metric by 10-100 times
- Deen-YHH-Lee-Lukas '20: Distinguishing Heterotic SMs from the sum-line-bundle database and extrapolating beyond
- q.v. K. Hashimoto '18: AdS/CFT = Boltzmann Machine !
- . . . *ML now a standard programme in string community since 2017*

# Machine Learning Mathematical Structures

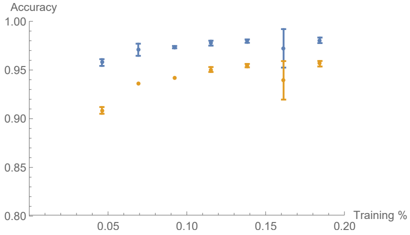
Why stop at string/geometry?

# Representation/Group Theory

[YHH-MH. Kim 1905.02263] Machine-Learning Algebraic Structures

(GAP finite groups/ring DB)

- When is a Latin Square (Sudoku) the Cayley (multiplication) table of a finite group? (rmk: there is a known quadrangle-thm to test this) NN/SVM find to 94.9% ($\phi = 0.90$) at 25-75 cross-validation.
- Can one look at the Cayley table and recognize a finite simple group?




- bypass Sylow and Noether Thm
- SVM: space of finite-groups (point-cloud of Cayley tables), ?$\exists$ hypersurface separating simple/non-simple?

# Combinatorics, Graph/Quivers, Symmetries

- [YHH-ST. Yau 2006.16619] (Wolfram Finite simple graphs DB)
  - ML standard graph properties: acyclic? (0.95); planar? (0.8); genus $>, =, < 0$? (0.8); ?∃ Hamilton/Euler cycles ($\sim 0.8$)
  - spectral bounds ($R^2 \sim 0.9$) ...
  - Recognition of Ricci-Flatness (0.9) (todo: find new Ricci-flat graphs);
- [Bao-Franco-YHH-Hirst-Musiker-Xiao 2006.10783]: categorizing different quiver mutation (Seiberg-dual) classes (0.9 - 1.0)
- [Chen-YHH-Lal-Zas 2006.16114]: even/odd/reflection sym (>0.99); distinguishing CFT 3pt functions (>0.99); Fourier coefficients / conformal block presence (>0.97) ... (q.v. [Krippendorf-Syvaeri 2003.13679])
- NB. Only "solving" the likes of traveling salesman (similarly Groebner bases in geom) stochastically

# Number Theory: A Reprobate

- [YHH 1706.02714, 1812.02893:] Predicting primes tried supervised ML on $2 \to 3,\ 2,3 \to 5,\ 2,3,5 \to 7$; fixed window of $(\text{yes/no})_{1,2,\ldots,k}$ to $(\text{yes/no})_{k+1}$, no breaking banks yet (expect same for Riemann zeroes)
- [Hirst-YHH-Peterken 2004.05218]: adjacency of dessin d'enfants (Grothendieck's Esquisse for Abs. Galois) $\to$ transcendental degree (<0.3)
- [Alessandretti-Baronchelli-YHH 1911.02008] (LMFdb/Cremona Database) ML/TDA@Birch-Swinnerton-Dyer *New Scientist* feature Dec 9 (BSD: $L$-function $L(s,\mathcal{E})$ of elliptic curve $\mathcal{E}$ has $L(s \to 1, \mathcal{E})$ given in terms of precise quantities: rank $r$, torsion $T$, period $\Omega$, Tate-Shaferevich group Ш, conductor $N$, regulator $R$, Tamagawa number $c$ ); Ш and $\Omega$ ok with regression and boosted decision trees: RMS $< 0.1$; Weierstrass $\to$ rank: random

# Meta-mathematics/physics?

[YHH-Jejjala-Nelson ] "hep-th" 1807.00735

- Word2Vec: [Mikolov et al., '13] NN which maps words in sentences to a vector space **by context** (much better than word-frequency, quickly adopted by Google); maximize (partition function) over all words with sliding window ($W_{1,2}$ weights of 2 layers, $C_\alpha$ window size, $D$ # windows )

$$Z(W_1, W_2) := \frac{1}{|D|} \sum_{\alpha=1}^{|D|} \log \prod_{c=1}^{C_\alpha} \frac{\exp([\vec{x}_c]^T \cdot W_1 \cdot W_2)}{\sum\limits_{j=1}^{V} \exp([\vec{x}_c]^T \cdot W_1 \cdot W_2)}$$

- We downloaded all $\sim 10^6$ titles of hep-th, hep-ph, gr-qc, math-ph, hep-lat from ArXiv since the beginning (1989) till end of 2017 Word Cloud (rmk: Ginzparg has been doing a version of linguistic ML on ArXiv) (rmk: abs and full texts in future)

# Subfields on ArXiv has own linguistic particulars

- Linear Syntactical Identities

  *bosonic + string-theory = open-string*

  *holography + quantum + string + ads = extremal-black-hole*

  *string-theory + calabi-yau = m-theory + g2*

  *space + black-hole = geometry + gravity . . .*

- binary classification (Word2Vec + SVM) of formal (hep-th, math-ph, gr-qc) vs phenomenological (hep-ph, hep-lat) : 87.1% accuracy (5-fold classification 65.1% accuracy). ArXiv classifications

- Cf. **Tshitoyan et al.**, "Unsupervised word embeddings capture latent knowledge from materials science literature", **Nature** July, 2019: 3.3. million materials-science abstracts; uncovers structure of periodic table, predicts discoveries of new thermoelectric materials years in advance, and suggests as-yet unknown materials

# Summary and Outlook

PHYSICS

- Use AI (Neural Networks, SVMs, Regressor . . . ) as
  1. Classifier deep-learn and categorize landscape data
  2. Predictor estimate results beyond computational power

MATHS

- how is AI doing maths w/o knowing any maths? (Alg Geo/$\mathbb{C}$, combinatorics, RT = integer matrices, NT ??)
  1. Predictor form new conjectures/formulae
  2. Classifier stochastically do NP-hard problems
- Hierarchy of Difficulty ML struggles with:

  **numerical** $<$ **algebraic geometry over** $\mathbb{C}$ $<$ **combinatorics/algebra** $<$ **number theory**

# Semantics vs Syntax

- Boris Zilber [Merton Professor of Logic, Oxford]: "you've managed syntax without semantics. . ."
-

| | | |
|---|---|---|
| Alpha Go | $\to$ | Alpha Zero |
| ML | $\to$ | Voevodsky's Dream; Automated Thm Pf |

- cf. Renner et al., PRL/Nature News, 2019: ML (*SciNet*, *autoencoder*) finds heliocentrism from Mars positions alone.
- cf. Lample-Charton, 2019: ML Symolic manipulations in mathematics

Sophia (Hanson Robotics, HK)

1st non-human citizen (2017, Saudi Arabia)

1st non-human with UN title (2017)

1st String Data Conference (2017)

# THANK YOU

- Paolo Di Vecchia: *String theory is a piece of 21st century physics that happened to fall into the 20th century ...*
- Edward Witten: *piece of 21st century mathematics that happened to begin in the 20th century ...*
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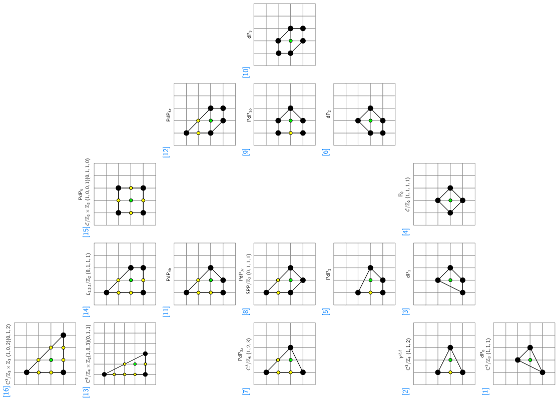
# Digressions

- | $\chi(\Sigma) = 2$ | $\chi(\Sigma) = 0$ | $\chi(\Sigma) < 0$ |
  |---|---|---|
  | Spherical | Ricci-Flat | Hyperbolic |
  | $+$ curvature | $0$ curvature | $-$ curvature |
  | Fano | Calabi-Yau | General Type |

- Euler, Gauss, Riemann, Bourbaki, Atiyah-Singer $\ldots \rightsquigarrow$ generalize

$$\chi(\Sigma) = 2 - 2g(\Sigma) = [c_1(\Sigma)] \cdot [\Sigma] = \frac{1}{2\pi} \int_\Sigma R = \sum_{i=0}^{2} (-1)^i h^i(\Sigma)$$

- CONJECTURE [E. Calabi, 1954, 1957] / Thm [ST. Yau, 1977-8] $M$ compact Kähler manifold $(g, \omega)$ 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 $Ricci(\tilde{\omega}) = R$.
- Strominger & Yau were neighbours at IAS in 1985: CHSW named Ricci-Flat Kähler as Calabi-Yau Back



classify convex lattice polytopes with single interior point and all faces are distance 1 therefrom (up to $SL(n;\mathbb{Z})$)

Kreuzer-Skarke: 4319 reflexive polyhedra, 473,800,776 reflexive 4-polytopes,

Skarke: next number is at least 185,269,499,015.

# Heterotic Comp: Recent Development

- $E_6$ GUTs a toy, $SU(5)$ and $SO(10)$ GUTs and SM: general embedding
  - Instead of $TX$, use (poly-)stable holomorphic vector bundle $V$
  - Gauge group$(V) = G = SU(n)$, $n = 3, 4, 5$, gives $H =$ Commutant$(G, E_8)$:

| $E_8 \to G \times H$ | Breaking Pattern | | |
|---|---|---|---|
| $SU(3) \times E_6$ | $248$ | $\to$ | $(1, 78) \oplus (3, 27) \oplus (\overline{3}, \overline{27}) \oplus (8, 1)$ |
| $SU(4) \times SO(10)$ | $248$ | $\to$ | $(1, 45) \oplus (4, 16) \oplus (\overline{4}, \overline{16}) \oplus (6, 10) \oplus (15, 1)$ |
| $SU(5) \times SU(5)$ | $248$ | $\to$ | $(1, 24) \oplus (5, \overline{10}) \oplus (\overline{5}, 10) \oplus (10, 5) \oplus (\overline{10}, \overline{5}) \oplus (24, 1)$ |

- MSSM: $H \xrightarrow{\text{Wilson Line}} SU(3) \times SU(2) \times U(1)$
- Issues in low-energy physics $\sim$ Precise questions in Alg Geo of $(X, V)$
  - Particle Content $\sim$ (tensor powers) $V$ Bundle Cohomology on $X$
  - LE SUSY $\sim$ Hermitian Yang-Mills connection $\sim$ Bundle Stability
  - Yukawa $\sim$ Trilinear (Yoneda) composition
  - Doublet-Triplet splitting $\sim$ representation of fundamental group of $X$

Back to Landscape

# Various Databases

- Kreuzer-Skarke: `http://hep.itp.tuwien.ac.at/~kreuzer/CY/`
  - new PALP: Braun-Walliser: ArXiv 1106.4529
  - Triang: Altmann-YHH-Jejjala-Nelson: `http://www.rossealtman.com/`
- CICYs: resurrected Anderson-Gray-YHH-Lukas, `http://www-thphys.physics.ox.ac.uk/projects/CalabiYau/cicylist/index.html`
- q.v. other databases of interesting to the math/physics community:

  Graded Rings/Varieties: Brown, Kasprzyk, et al. `http://www.grdb.co.uk/`

  Finite Groups/Rings: GAP `https://www.gap-system.org/`

  Modular Forms: Sutherland, Cremona et al. `https://www.lmfdb.org/`

  Knots & Invariants: KnotAtlas `http://katlas.org/` Return

  . . .

# Progress in String Theory

Back to ML/Maths

Major International Annual Conference Series

- 1986- First "Strings" Conference
- 2002- First "StringPheno" Conference
- 2006 - 2010 String Vacuum Project (NSF)
- 2011- First "String-Math" Conference
- 2014- First String/Theoretical Physics Session in SIAM Conference
- 2017- First "String-Data" Conference

# CICYs

$$M = \left[ \begin{array}{c|cccc} n_1 & q_1^1 & q_1^2 & \dots & q_1^K \\ n_2 & q_2^1 & q_2^2 & \dots & q_2^K \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ n_m & q_m^1 & q_m^2 & \dots & q_m^K \end{array} \right]_{m \times K}$$

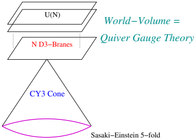
– Complete Intersection Calabi-Yau (CICY) 3-folds
– $K$ eqns of multi-degree $q_j^i \in \mathbb{Z}_{\geq 0}$ embedded in $\mathbb{P}^{n_1} \times \ldots \times \mathbb{P}^{n_m}$
– $c_1(X) = 0 \rightsquigarrow \sum_{j=1}^{K} q_r^j = n_r + 1$
– $M^T$ also CICY

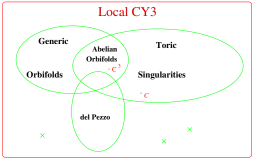
- The Quintic $Q = [4|5]^{1,101}_{-200}$ (or simply $[5]$);
- CICYs Central to string pheno in the 1st decade [Distler, Greene, Ross, et al.]
  $E_6$ GUTS unfavoured; Many exotics: e.g. 6 entire anti-generations

Back to CICYs

# AdS/CFT as a Quiver Rep/Moduli Variety Corr.

a 20-year prog. joint with **A. Hanany**, S. Franco, B. Feng, et al.



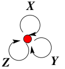




D-Brane Gauge Theory

(SCFT encoded as quiver)

$\longleftrightarrow$

Vacuum Space as affine Variety

- $(\mathcal{N} = 4$ SYM$)$ $\Bigg($   $, W = \text{Tr}([x, y], z) \Bigg) \longleftrightarrow \mathbb{C}^3 = \text{Cone}(S^5)$ [Maldacena]
- THM [(P) Feng, Franco, Hanany, YHH, Kennaway, Martelli, Mekareeya, Seong, Sparks, Vafa, Vegh, Yamazaki, Zaffaroni ... (M) R. Böckland, N. Broomhead, A. Craw, A. King, G. Musiker, K. Ueda ...] (coherent component of) representation variety of a quiver is toric CY3 iff quiver + superpotential graph dual to a bipartite graph on $T^2$ Back to Landscape

combinatorial data/lattice polytopes $\longleftrightarrow$ gauge thy data as quivers/graphs

# A Single Neuron: The Perceptron

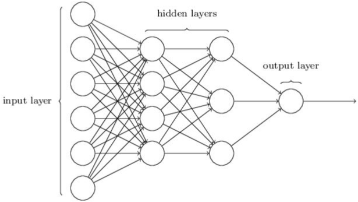
- began in 1957 (!!) in early AI experiments (using CdS photo-cells)
- DEF: Imitates a neuron: activates upon certain inputs, so define
  - Activation Function $f(z_i)$ for input tensor $z_i$ for some multi-index $i$;
  - consider: $f(w_i z_i + b)$ with $w_i$ weights and $b$ bias/off-set;
  - typically, $f(z)$ is sigmoid, Tanh, etc.
- Given training data: $D = \{(x_i^{(j)}, d^{(j)}\}$ with input $x_i$ and **known output** $d^{(j)}$, minimize

$$SD = \sum_j \left( f(\sum_i w_i x_i^{(j)} + b) - d^{(j)} \right)^2$$

  to find optimal $w_i$ and $b \rightsquigarrow$ "learning", then check against Validation Data
- Essentially (non-linear) regression

# The Neural Network: network of neurons $\rightsquigarrow$ the "brain"

- DEF: a connected graph, each node is a perceptron (*Implemented on Mathematica 11.1 + / TensorFlow-Keras on Python*)
  1. adjustable weights/bias;
  2. distinguished nodes: 1 set for input and 1 for output;
  3. iterated training rounds.




Simple case: forward directed only, called multilayer perceptron

- others: e.g., decision trees, support-vector machines (SVM), etc
- Essentially how brain learns complex tasks; **apply to our Landscape Data**

Back to Landscape

# Computing Hodge Numbers $\mathcal{O}(e^{e^d})$

- 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:

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

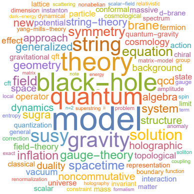
- Induces long exact sequence in cohomology:

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

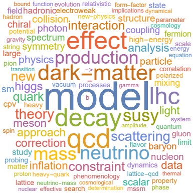
- Need to compute Rk$(d)$, cohomology and $H^i(X, T_A|_X)$ (Cf. Hübsch)

Back to ML

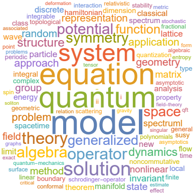
# ArXiv Word-Clouds



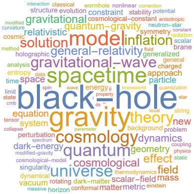

hep-th



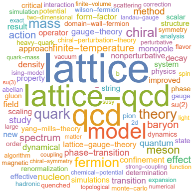

hep-ph




math-ph




gr-qc




hep-lat

Back to Word2Vec

# Classifying Titles

Compare, + non-physics sections, non-science (Times), pseudo-science (viXra)

| Actual \ Word2Vec + SVM | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 40.2 | 6.5 | 8.7 | 24.0 | 20.6 |
| 2 | 7.8 | 65.8 | 12.9 | 9.1 | 4.4 |
| 3 | 7.5 | 11.3 | 72.4 | 1.5 | 7.4 |
| 4 | 12.4 | 4.4 | 1.0 | 72.1 | 10.2 |
| 5 | 10.9 | 2.2 | 4.0 | 7.8 | 75.1 |

1 : hep-th
2 : hep-ph
3 : hep-lat
4 : gr-qc
5 : math-ph

| Actual \ NN | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| viXra-hep | 11.5 | 47.4 | 6.8 | 13. | 11. | 4.5 | 0.2 | 0.3 | 2.2 | 3.1 |
| viXra-qgst | 13.3 | 14.5 | 1.5 | 54. | 8.4 | 1.8 | 0.1 | 1.1 | 2.8 | 3. |

6: cond-mat, 7: q-fin, 8: stat, 9: q-bio, 10: Times of India

Back to Main