# *Machine learning in $Z_2 \times Z_2$ orbifold classification*

## or, *What do we need machine learning for?*

- Classification of $Z_2 \times Z_2$ orbifolds 2003 –

  With: Costas Kounnas, John Rizos, Sander Nooij, Ben Assel,
  Kyriakos Christodoulides, Laura Bernard, Ivan Glazer,
  Hasan Sonmez, Glyn Harries, Ben Percival

- Related results:

  Spinor–Vector duality, Exophobia, stringy Z' models, ...

Machine Learning in the String Landscape, ICTP, Trieste, 11 December 2018

String Phenomenology: An answer in search of a question

The Answer : The Standard Model and its BSM extensions

A question : What is the true string vacuum?

A question : Can we identify signatures of classes of string compactifications in the experimental particle data?

In this talk:

Classification of fermionic $Z_2 \times Z_2$ orbifold compactifications

Where can novel computational tools help?

# PHENOMENA

DATA $\longrightarrow$ STANDARD MODEL

EWX −> PERTUBATIVE

STANDARD MODEL −> UNIFICATION

EVIDENCE: 16 of SO(10), Log running, proton stability, neutrino masses

+ GRAVITY < −− > STRINGS

PRIMARY GUIDES:

3 generations
SO(10) embedding

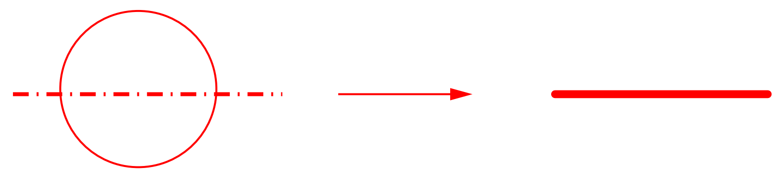
# REALISTIC STRING MODELS :

heterotic 10D –> heterotic 4D

6D compactifications $(T^2 \times T^2 \times T^2)$

Orbifold – twists of flat 6D torus

$Z_2$



FREE FERMIONIC MODELS –

$Z_2 \times Z_2$ Orbifold –> $U(1)_Y \in SO(10)$

$$\frac{6}{2} = 1+1+1$$

# Realistic free fermionic models

‘Phenomenology of the Standard Model and Unification’

- Minimal Superstring Standard Model — NPB 335 (1990) 347 (with Nanopoulos & Yuan)
- Top quark mass $\sim$ 175–180GeV — PLB 274 (1992) 47
- Generation mass hierarchy — NPB 407 (1993) 57
- CKM mixing — NPB 416 (1994) 63 (with Halyo)
- Stringy seesaw mechanism — PLB 307 (1993) 311 (with Halyo)
- Gauge coupling unification — NPB 457 (1995) 409 (with Dienes)
- Proton stability — NPB 428 (1994) 111
- Squark degeneracy — NPB 526 (1998) 21 (with Pati)
- Moduli fixing — NPB 728 (2005) 83
- Classification & Exophobia — 2003 – $\cdots$ (with Nooij, Assel, Christodoulides, Kounnas, Rizos & Sonmez)

## Other approaches

### Geometrical

Greene, Kirklin, Miron, Ross (1987)
Donagi, Ovrut, Pantev, Waldram (1999)
Blumenhagen, Moster, Reinbacher, Weigand (2006)
Heckman, Vafa (2008)
........

### Orbifolds

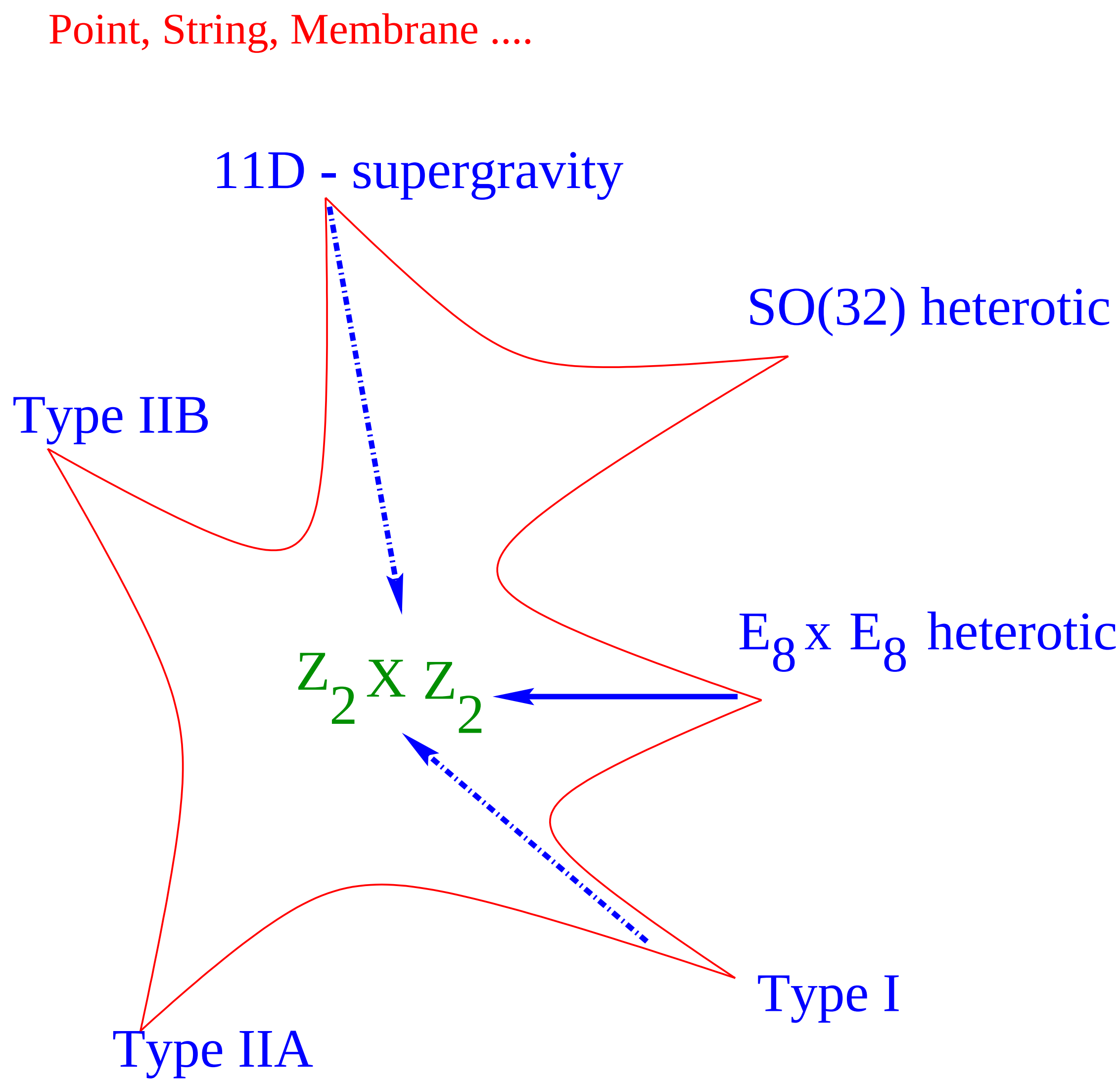
Ibanez, Nilles, Quevedo (1987)
Bailin, Love, Thomas (1987)
Kobayashi, Raby, Zhang (2004)
Lebedev, Nilles, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter (2007)
Blaszczyk, Groot–Nibbelink, Ruehle, Trapletti, Vaudrevange (2010)
.......

### Other CFTs

Gepner (1987)
Schellekens, Yankielowicz (1989)
Gato–Rivera, Schellekens (2009)
.......

### Orientifolds

Cvetic, Shiu, Uranga (2001)
Ibanez, Marchesano, Rabadan (2001)
Kiristis, Schellekens, Tsulaia (2008)
.......



Point, String, Membrane ....
11D - supergravity
SO(32) heterotic
Type IIB
E8 x E8 heterotic
Z2 X Z2
Type I
Type IIA

# String GUT models in the Free Fermionic Construction:

Left-Movers: $\psi^{\mu}_{1,2}$, $\chi_i$, $y_i$, $\omega_i$ $(i = 1, \cdots, 6)$

Right-Movers

$$
\bar{\phi}_{A=1,\cdots,44} = \begin{cases} \bar{y}_i\ ,\ \bar{\omega}_i & i = 1, \cdots, 6 \\ \\ \bar{\eta}_i & U(1)_i \quad i = 1, 2, 3 \\ \bar{\psi}_{1,\cdots,5} & SO(10) \\ \bar{\phi}_{1,\cdots,8} & SO(16) \end{cases}
$$

Models $\longleftrightarrow$ Basis vectors $+$ one–loop phases

Free Fermionic Models: $Z_2 \times Z_2$ orbifolds with discrete Wilson lines

## Old School:

The NAHE set : $\{ \mathbf{1}, S, b_1, b_2, b_3 \}$

$N = 4 \rightarrow 2 \quad 1 \quad 1$ vacua

$Z_2 \times Z_2$ orbifold compactification

$\Longrightarrow$ Gauge group $SO(10) \times SO(6)^{1,2,3} \times E_8$

beyond the NAHE set  Add $\{\alpha, \beta, \gamma\}$  $e.g.$ FNY model

number of generations is reduced to three

$$SO(10) \longrightarrow SU(3) \times SU(2) \times U(1)_{T_{3_R}} \times U(1)_{B-L}$$

$$U(1)_Y = \frac{1}{2}(B-L) + T_{3_R} \in SO(10) \; !$$

$$SO(6)^{1,2,3} \longrightarrow U(1)^{1,2,3} \times U(1)^{1,2,3}$$

## Exotic matter :

### In realistic string models

Unifying gauge group $\Rightarrow$ broken by "Wilson lines".

$\Rightarrow$ non–GUT physical states.

$\Rightarrow$ Meta-stable heavy string relics

$\longrightarrow$ Dark Mater NPB 477 (1996) 65

(with Coriano and Chang)

Provided that $N_L^c \in 16, \ \ \overline{N}^c \in \overline{16}$ Exist in the spectrum

Discrete symmetry : $U(1)_{T_{3_R}} \times U(1)_{B-L} \ \longrightarrow \ U(1)_Y$

FNY model (NPB 335 (1990) 347) $\longrightarrow$ no $\overline{N}^c \in \overline{16}$

$\Rightarrow$ Forced to use exotics $\Longleftrightarrow$ No discrete symmetry

## Classification of fermionic $Z_2 \times Z_2$ orbifolds (Modern School )

### Basis vectors:

$$1 = \{\psi^\mu,\ \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} \mid \bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\}$$

$$S = \{\psi^\mu, \chi^{1,\dots,6}\},$$

$$z_1 = \{\bar{\phi}^{1,\dots,4}\},$$

$$z_2 = \{\bar{\phi}^{5,\dots,8}\},$$

$$e_i = \{y^i, \omega^i | \bar{y}^i, \bar{\omega}^i\},\ i = 1, \dots, 6,$$ $N = 4$ Vacua

$$b_1 = \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,\dots,5}\},$$ $N = 4 \rightarrow N = 2$

$$b_2 = \{\chi^{12}, \chi^{56}, y^{12}, y^{56} | \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^2, \bar{\psi}^{1,\dots,5}\},$$ $N = 2 \rightarrow N = 1$

$$\alpha = \{\bar{\psi}^{4,5}, \bar{\phi}^{1,2}\}$$ & $SO(10) \rightarrow SO(6) \times SO(4) \times \cdots$

$$\beta = \{\bar{\psi}^{1,\cdots,5} \equiv \tfrac{1}{2}, \cdots\}$$ & $SO(10) \rightarrow SU(5) \times U(1) \times \cdots$

## Independent phases $c\binom{v_i}{v_j} = \exp[i\pi(v_i|v_j)]$: upper block

$$
\begin{array}{c}
 \\ 1 \\ S \\ e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \\ z_1 \\ z_2 \\ b_1 \\ b_2 \\ \alpha
\end{array}
\begin{array}{c}
\begin{array}{ccccccccccccc}
1 & S & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & z_1 & z_2 & b_1 & b_2 & \alpha
\end{array}
\\
\left(\begin{array}{ccccccccccccc}
-1 & -1 & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 1 & 1 & -1 \\
 & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & & & & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & & & & & \pm & \pm & \pm & \pm & \pm \\
 & & & & & & & & & \pm & \pm & \pm & \pm \\
 & & & & & & & & & & \pm & \pm & \pm \\
 & & & & & & & & & & & \pm & \pm \\
 & & & & & & & & & & & -1 & \pm \\
 & & & & & & & & & & & & 
\end{array}\right)
\end{array}
$$

A priori 66 independent coefficients $\rightarrow$ $2^{66}$ distinct vacua

## The twisted matter spectrum:

$$B^1_{\ell^1_3\ell^1_4\ell^1_5\ell^1_6} = S + b_1 + \ell^1_3 e_3 + \ell^1_4 e_4 + \ell^1_5 e_5 + \ell^1_6 e_6$$
$$B^2_{\ell^2_1\ell^2_2\ell^2_5\ell^2_6} = S + b_2 + \ell^2_1 e_1 + \ell^2_2 e_2 + \ell^2_5 e_5 + \ell^2_6 e_6$$
$$B^3_{\ell^3_1\ell^3_2\ell^3_3\ell^3_4} = S + b_3 + \ell^3_1 e_1 + \ell^3_2 e_2 + \ell^3_3 e_3 + \ell^3_4 e_4 \qquad l^j_i = 0,1$$

sectors $B^i_{pqrs}$ $\rightarrow$ 16 or $\overline{16}$ of $SO(10)$ with multiplicity $(1,0,-1)$

$B^i_{pqrs} + x$ $\rightarrow$ 10 of $SO(10)$ with multiplicity $(1,0)$

$x = \{\bar\psi^{1,\cdots,5}, \bar\eta^1, \bar\eta^2, \bar\eta^3\}$ $\qquad x -$ map $\leftrightarrow$ spinor–vector map

## Counting: for each $B^i_{pqrs}$:

Projectors: $\quad P^{(1)}_{p^1q^1r^1s^1} = \frac{1}{16} \prod \left(1 - c\binom{e_i}{B^{(1)}_{p^1q^1r^1s^1}}\right) \prod \left(1 - c\binom{z_i}{B^{(1)}_{p^1q^1r^1s^1}}\right)$

$S^{(i)}_\pm = \sum_{pqrs} \frac{1 \pm X^{(i)}_{p^iq^ir^is^i}}{2} P^{(i)}_{p^iq^ir^is^i}$ , $i = 1,2,3$ $\quad$ similarly for vectorials

Algebraic formulas for $\quad S = \sum_{i=1}^3 S^{(i)}_+ - S^{(i)}_-$ $\quad$ and $\quad V = \sum_{i=1}^3 V^{(i)}$

Introducing the notation $\quad c\binom{a_i}{a_j} = e^{i\pi(a_i|a_j)}\ ,\ (a_i\,|a_j) = 0,1$

the projectors can be written as system of equations

$$\Delta^{(I)}\,U_{16}^{(I)} = Y_{16}^{(I)} \quad , \quad \Delta^{(I)}\,U_{10}^{(I)} = Y_{10}^{(I)}\ ,\ I = 1,2,3$$

where the unknowns are the fixed point labels

$$U_{16}^{(I)} = \begin{bmatrix} p_{16}^I \\ q_{16}^I \\ r_{16}^I \\ s_{16}^I \end{bmatrix} \ , \qquad U_{10}^{(I)} = \begin{bmatrix} p_{10}^I \\ q_{10}^I \\ r_{10}^I \\ s_{10}^I \end{bmatrix}$$

and

$$\Delta^{(1)} = \begin{bmatrix} (e_1\,|e_3) & (e_1\,|e_4) & (e_1\,|e_5) & (e_1\,|e_6) \\ (e_2\,|e_3) & (e_2\,|e_4) & (e_2\,|e_5) & (e_2\,|e_6) \\ (z_1\,|e_3) & (z_1\,|e_4) & (z_1\,|e_5) & (z_1\,|e_6) \\ (z_2\,|e_3) & (z_2\,|e_4) & (z_2\,|e_5) & (z_2\,|e_6) \end{bmatrix} \quad ; \quad \Delta^{(2)}\ldots$$

$$Y_{16}^{(1)} = \begin{bmatrix} (e_1\,|b_1) \\ (e_2\,|b_1) \\ (z_1\,|b_1) \\ (z_2\,|b_2) \end{bmatrix} \quad , \quad Y_{16}^{(2)} = \ldots$$

$$Y_{10}^{(1)} = \begin{bmatrix} (e_1\,|b_1 + x) \\ (e_2\,|b_1 + x) \\ (z_1\,|b_1 + x) \\ (z_2\,|b_2 + x) \end{bmatrix} \quad , \quad Y_{10}^{(2)} = \ldots$$

## The number of solutions per plane

$$S^{(I)} = \begin{cases} 2^{4-\text{rank}\left(\Delta^{(I)}\right)} & \text{rank}\left(\Delta^{(I)}\right) = \text{rank}\left[\Delta^{(I)}, Y_{16}^{(I)}\right] \\ 0 & \text{rank}\left(\Delta^{(I)}\right) < \text{rank}\left[\Delta^{(I)}, Y_{16}^{(I)}\right] \end{cases}$$

$$V^{(I)} = \begin{cases} 2^{4-\text{rank}\left(\Delta^{(I)}\right)} & \text{rank}\left(\Delta^{(I)}\right) = \text{rank}\left[\Delta^{(I)}, Y_{10}^{(I)}\right] \\ 0 & \text{rank}\left(\Delta^{(I)}\right) < \text{rank}\left[\Delta^{(I)}, Y_{10}^{(I)}\right] \end{cases}$$

## Spinor–vector duality:

Duality under exchange of spinors and vectors.

| First Plane | | | Second plane | | | Third Plane | | | |
|---|---|---|---|---|---|---|---|---|---|
| $s$ | $\bar{s}$ | $v$ | $s$ | $\bar{s}$ | $v$ | $s$ | $\bar{s}$ | $v$ | # of models |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1325963712 |
| 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1340075584 |
| 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3718991872 |
| 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 6385031168 |

$\#$ of models with $\#(16+\overline{16}) = \#$ of models with $\#(10)$

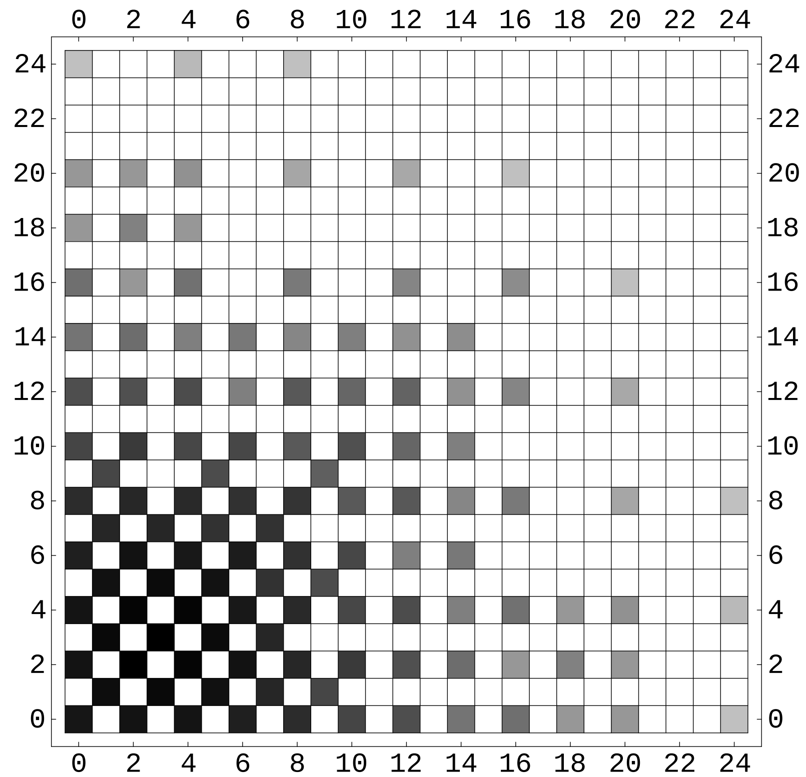
For every model with $\#(16+\overline{16})$ & $\#(10)$

There exist another model in which they are interchanged

Reflects discrete exchange of phases

# Spinor–vector duality:

Invariance under exchange of $\#(16+\overline{16})$ $<->$ $\#(10)$



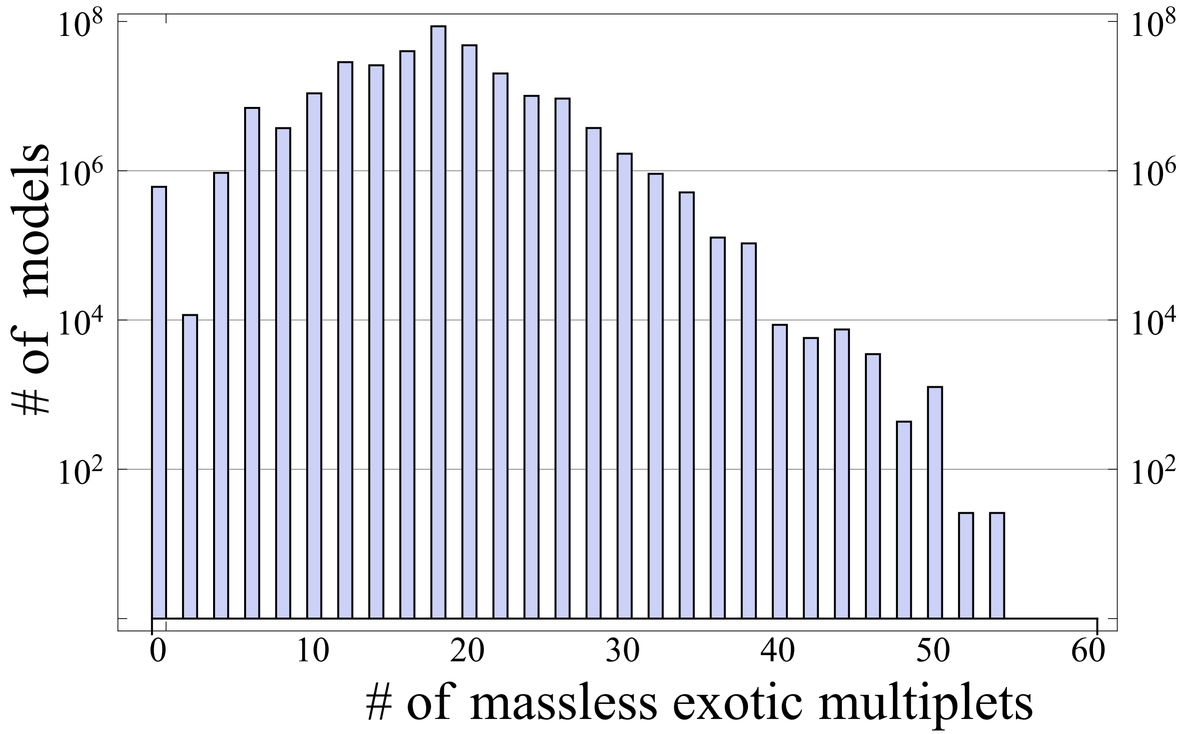

Symmetric under exchange of rows and columns

$$E_6 \; : \qquad 27 = 16 + 10 + 1 \qquad \overline{27} = \overline{16} + 10 + 1$$

Self-dual: $\#(16+\overline{16}) \; = \; \#(10)$ without $E_6$ symmetry

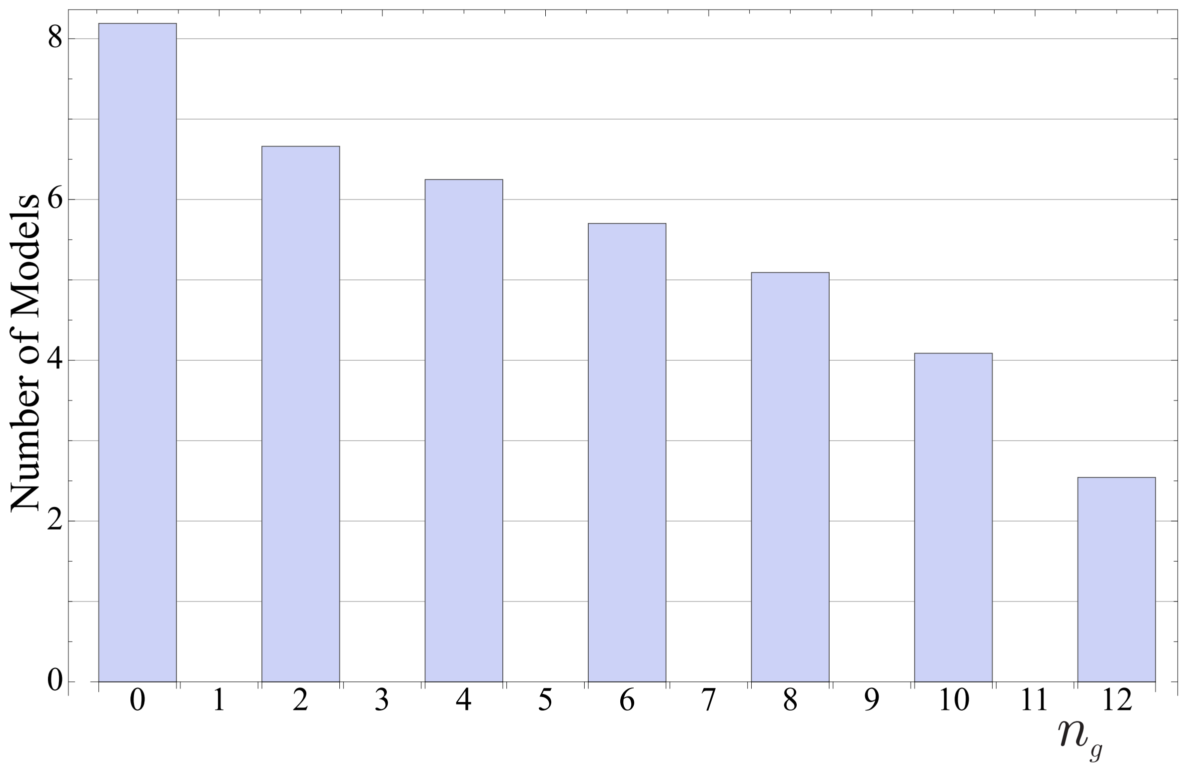
## Pati–Salam class: with Assel, Christodoulides, Kounnas, Rizos

## RESULTS: of random search of over $10^{11}$ vacua




Number of 3-generation models versus total number of exotic multiplets flipped $SU(5)$ class: with Sonmez, Rizos

RESULTS: of random search of over $10^{12}$ vacua




Number of exophobic models versus the number of generations

## Low scale $Z'$ in free fermionic models:

- $\frac{3}{2}U(1)_{B-L} - 2U(1)_R \in SO(10)$ @ $1TeV$ MPL A6 (1991) 61

  (with Nanopoulos)

- But $m_t = m_{\nu_\tau}$ & $1TeV\ Z' \Rightarrow\ m_{\nu_\tau} \approx 10MeV$ PLB 245 (1990) 435

  $E_6 \to SO(10) \times U(1)_A \implies U(1)_A$ is anomalous!

  $\implies U(1)_A \notin$ low scale $U(1)_{Z'}$

- 1996-2013, Pati, AEF, Guzzi, Mehta, Athanasopoulos, $U(1) \notin E_6$

- On the other hand ....(AEF, Viraf Mehta, PRD88 (2013) 025006)

$$\sin^2\theta_W(M_Z)\ ,\ \alpha_s(M_Z) \implies U(1)_{Z'} \in E_6$$

- $Z'$ string derived model, (with Rizos) NPB 895 (2015) 233

## light $Z'$ heterotic–string model $c\left[{v_i \atop v_j}\right] = \exp[i\pi(v_i|v_j)]$:

$$
(v_i|v_j) \;=\; \begin{array}{c} \\ 1 \\ S \\ e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \\ b_1 \\ b_2 \\ z_1 \\ z_2 \\ \alpha \end{array}
\begin{array}{c}
\begin{array}{ccccccccccccc} 1 & S & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & b_1 & b_2 & z_1 & z_2 & \alpha \end{array} \\
\left(\begin{array}{ccccccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\
1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\
1 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 \\
1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1
\end{array}\right)
\end{array}
$$

Observable gauge group: $SO(6) \times SO(4) \times U(1)_{1,2,3}$

$U(1)_\zeta = U(1)_1 + U(1)_2 + U(1)_3$ is anomaly free

| sector | field | $SU(4)\times SU(2)_L\times SU(2)_R$ | $U(1)_1$ | $U(1)_2$ | $U(1)_3$ | $U(1)_\zeta$ |
|---|---|---|---|---|---|---|
| $S+b_1$ | $\bar F_{1R}$ | $(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$ | 1/2 | 0 | 0 | 1/2 |
| $S+b_1+e_3+e_5$ | $F_{1R}$ | $(\mathbf{4},\mathbf{1},\mathbf{2})$ | 1/2 | 0 | 0 | 1/2 |
| $S+b_2$ | $F_{1L}$ | $(\mathbf{4},\mathbf{2},\mathbf{1})$ | 0 | 1/2 | 0 | 1/2 |
| $S+b_2+e_1+e_2+e_5$ | $F_{2L}$ | $(\mathbf{4},\mathbf{2},\mathbf{1})$ | 0 | 1/2 | 0 | 1/2 |
| $S+b_2+e_1$ | $\bar F_{2R}$ | $(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$ | 0 | 1/2 | 0 | 1/2 |
| $S+b_2+e_2+e_5$ | $\bar F_{3R}$ | $(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$ | 0 | 1/2 | 0 | 1/2 |
| $S+b_3+e_1+e_2$ | $F_{3L}$ | $(\mathbf{4},\mathbf{2},\mathbf{1})$ | 0 | 0 | 1/2 | 1/2 |
| $S+b_3+e_2$ | $\bar F_{4R}$ | $(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$ | 0 | 0 | 1/2 | 1/2 |
| $S+b_3+x$ | $h_1$ | $(\mathbf{1},\mathbf{2},\mathbf{2})$ | −1/2 | −1/2 | 0 | −1 |
| $S+b_2+x+e_5$ | $h_2$ | $(\mathbf{1},\mathbf{2},\mathbf{2})$ | −1/2 | 0 | −1/2 | −1 |
| $S+b_2+x+e_1+e_2$ | $h_3$ | $(\mathbf{1},\mathbf{2},\mathbf{2})$ | −1/2 | 0 | −1/2 | −1 |
| $S+b_3+x+e_1$ | $D_4$ | $(\mathbf{6},\mathbf{1},\mathbf{1})$ | −1/2 | −1/2 | 0 | −1 |
| | $\chi_1^+$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 1/2 | 1/2 | 1 | +2 |
| | $\chi_1^-$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 1/2 | 1/2 | −1 | 0 |
| | $\zeta_a, a=2,3$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 1/2 | −1/2 | 0 | 0 |
| | $\bar\zeta_a, a=2,3$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | −1/2 | 1/2 | 0 | 0 |
| $S+b_2+x+e_1+e_5$ | $D_5$ | $(\mathbf{6},\mathbf{1},\mathbf{1})$ | −1/2 | 0 | −1/2 | −1 |
| | $\chi_2^+$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 1/2 | 1 | 1/2 | +2 |
| | $\chi_2^-$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 1/2 | −1 | 1/2 | 0 |
| | $\zeta_a, a=4,5$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 1/2 | 0 | −1/2 | 0 |
| | $\bar\zeta_a, a=4,5$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | −1/2 | 0 | 1/2 | 0 |
| $S+b_2+x+e_2$ | $D_6$ | $(\mathbf{6},\mathbf{1},\mathbf{1})$ | −1/2 | 0 | −1/2 | −1 |
| | $\chi_3^+$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 1/2 | 1 | 1/2 | +2 |
| | $\chi_3^-$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 1/2 | −1 | 1/2 | 0 |
| | $\zeta_a, a=6,7$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 1/2 | 0 | −1/2 | 0 |
| | $\bar\zeta_a, a=6,7$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | −1/2 | 0 | 1/2 | 0 |
| $S+b_1+x+e_3$ | $\bar D_6$ | $(\mathbf{6},\mathbf{1},\mathbf{1})$ | 0 | 1/2 | 1/2 | +1 |
| | $\bar\chi_4^+$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | −1 | −1/2 | −1/2 | −2 |
| | $\bar\chi_4^-$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 1 | −1/2 | −1/2 | 0 |
| | $\zeta_a, a=8,9$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 0 | 1/2 | −1/2 | 0 |
| | $\bar\zeta_a, a=8,9$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 0 | −1/2 | 1/2 | 0 |
| $S+b_1+x+e_5$ | $D_7$ | $(\mathbf{6},\mathbf{1},\mathbf{1})$ | 0 | −1/2 | −1/2 | −1 |
| | $\chi_5^+$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 1 | 1/2 | 1/2 | +2 |
| | $\chi_5^-$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | −1 | 1/2 | 1/2 | 0 |
| | $\zeta_a, a=10,11$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 0 | 1/2 | −1/2 | 0 |
| | $\bar\zeta_a, a=10,11$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 0 | −1/2 | 1/2 | 0 |
| $S+b_3+x+e_2+e_3$ | $\zeta_1$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 1/2 | −1/2 | 0 | 0 |
| | $\bar\zeta_1$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | −1/2 | 1/2 | 0 | 0 |
| $S+b_1+x+e_3+e_4+e_6$ | $\phi_1$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 0 | 1/2 | 1/2 | +1 |
| | $\bar\phi_1$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 0 | −1/2 | −1/2 | −1 |
| $S+b_1+x+e_4+e_5+e_6$ | $\phi_2$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 0 | 1/2 | 1/2 | +1 |
| | $\bar\phi_2$ | $(\mathbf{1},\mathbf{1},\mathbf{1})$ | 0 | −1/2 | −1/2 | −1 |

Table 1: *Observable twisted matter spectrum and* $SU(4)\times SU(2)_L\times SU(2)_R\times U(1)^3$ *quantum numbers.*

The chiral spectrum is self–dual under spinor–vector duality

maintains the $E_6$ embedding $\Rightarrow$ $U(1)_\zeta$ is anomaly free

Exophobic, three generations + heavy and light higgs + $\lambda_t \sim 1$

$$U(1)_{Z'} = \frac{1}{5}\,U(1)_C - \frac{1}{5}\,U(1)_L - U_\zeta$$

$Z' \Rightarrow$ Additional matter at the $Z'$ breaking scale

Exotic $SO(10)$ singlets with non–standard $U(1)_\zeta$ charges

$\Rightarrow$ Natural Wilsonian dark–matter candidates

# SLM random classifcation 1z: with Sonmez, Rizos

| | | |
|---|---|---|
| Total Models | | 1E+11<br>1276526169 |
| Total Realistic Models | | 3 |
| States | | Total |
| | -8 | 37 |
| | -6 | 1047 |
| | -5 | 756 |
| | -4 | 34765 |
| | -3 | 163225 |
| | -2 | 3036744 |
| | -1 | 76330452 |
| | 0 | 4505764853 |
| | 1 | 51148185 |
| | 2 | 1357446 |
| | 3 | 28878 |
| | 4 | 5046 |
| | 6 | 22 |
| 3 Generation Models | | Total |
| Total Models | | 1E+11<br>1276526169 |
| Constraint | | 3 |
| Number of 3 Generations | | 28878 |
| SLM Heavy Higgs Breaking | | 0 |
| SM Light Higgs Breaking | | 0 |
| SLM Heavy Higgs Breaking & SM Light Higgs Breaking | | 0 |
| Triplet Higgs | | 0 |
| Minimal SLM Heavy Higgs Breaking | | 0 |
| Minimal SMLight Higgs Breaking | | 0 |
| Minimal SLM Heavy Higgs & SMLight Higgs Breaking | | 0 |
| Minimal Higgs Triplet | | 0 |

# SLM random classifcation 2z: with Sonmez, Rizos

| | | |
|---|---|---|
| Total Models | | 1E+11 |
| | | 1276526169 |
| Total Realistic Models | | 3 |
| States | | Total |
| | -8 | 37 |
| | -6 | 1047 |
| | -5 | 756 |
| | -4 | 34765 |
| | -3 | 163225 |
| | -2 | 3036744 |
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| 3 Generation Models | | Total |
| Total Models | | 1E+11 |
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| Triplet Higgs | | 0 |
| Minimal SLM Heavy Higgs Breaking | | 0 |
| Minimal SMLight Higgs Breaking | | 0 |
| Minimal SLM Heavy Higgs & SMLight Higgs Breaking | | 0 |
| Minimal Higgs Triplet | | 0 |

Standard-like Model class: with Sonmez, Rizos NPB 927 (2018) 1

RESULTS: of random search of over $10^{11}$ vacua

- Adaptation of the methodology:

- Two stage process;

- Random fertile $SO(10)$ models; Fertility conditions

- Complete SLM classification of fertile cores.

$10^7$ Three generation SLMs with standard light and heavy Higgs spectrum

# Fertile 3 generations Standard-like Model classification $10^9$ sample

| | $n(Q)$ | $n(L)$ | $n(d^c)$; $n(\nu^c)$ | $n(u^c)$;$n(e^c)$ | $n(\overline{Q})$ | $n(\overline{L})$ | $n(\overline{d^c})$; $\mathbf{n}(\overline{\nu^c})$ | $n(\overline{u^c})$; $n(\overline{e^c})$ | $n(H_u)$; $n(H_d)$ | $n(d^{c\prime})$ ; $n(\overline{d^{c\prime}})$ | Multiplicity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 | 1 | 1 | 27264 |
| 2 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 | 3 | 3 | 16896 |
| 3 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 | 2 | 0 | 7296 |
| 4 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 | 2 | 2 | 2304 |
| 5 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 | 5 | 1 | 1536 |
| 6 | 4 | 3 | 3 | 4 | 1 | 0 | 0 | 1 | 2 | 2 | 768 |
| 7 | 3 | 4 | 3 | 4 | 0 | 1 | 0 | 1 | 2 | 2 | 768 |
| 8 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 | 1 | 5 | 640 |
| 9 | 4 | 4 | 3 | 3 | 1 | 1 | 0 | 0 | 5 | 3 | 512 |
| 10 | 3 | 3 | 4 | 4 | 0 | 0 | 1 | 1 | 3 | 1 | 384 |
| 11 | 3 | 3 | 4 | 4 | 0 | 0 | 1 | 1 | 1 | 3 | 384 |
| 12 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 | 3 | 1 | 256 |
| 13 | 4 | 4 | 3 | 3 | 1 | 1 | 0 | 0 | 3 | 5 | 256 |
| **14** | **3** | **3** | **4** | **4** | **0** | **0** | 1 | **1** | **7** | **1** | **192** |
| 15 | 4 | 4 | 3 | 3 | 1 | 1 | 0 | 0 | 3 | 1 | 192 |
| 16 | 3 | 3 | 3 | 5 | 0 | 0 | 0 | 2 | 3 | 1 | 192 |
| 17 | 3 | 3 | 3 | 5 | 0 | 0 | 0 | 2 | 1 | 3 | 192 |
| 18 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 | 1 | 3 | 128 |
| 19 | 3 | 4 | 3 | 4 | 0 | 1 | 0 | 1 | 4 | 4 | 128 |
| 20 | 3 | 4 | 4 | 3 | 0 | 1 | 1 | 0 | 4 | 4 | 128 |
| 21 | 4 | 3 | 4 | 3 | 1 | 0 | 1 | 0 | 4 | 4 | 128 |
| 22 | 4 | 3 | 3 | 4 | 1 | 0 | 0 | 1 | 4 | 4 | 128 |
| 23 | 3 | 3 | 4 | 4 | 0 | 0 | 1 | 1 | 5 | 3 | 64 |
| 24 | 3 | 3 | 4 | 4 | 0 | 0 | 1 | 1 | 3 | 5 | 64 |
| 25 | 3 | 3 | 4 | 4 | 0 | 0 | 1 | 1 | 1 | 7 | 64 |

## Conclusions

- DATA $\longrightarrow$ UNIFICATION
- STRINGS $\longrightarrow$ GAUGE & GRAVITY UNIFICATION
- Free fermionic models $\longleftrightarrow$ $Z_2 \times Z_2$ orbifolds $\longrightarrow$ A Fertile Crescent
- From exemplary models $\longrightarrow$ Large classes $\longrightarrow$ too large classes
- Question: Can ML tools be used to identify fertility conditions ?
- Glyn Harries, Ben Percival, ( John Rizos )