String Phenomenology Circa 2014

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Instituto de Física Teórica UAM-CSIC, Madrid

SPLE Advanced Grant

String Pheno 2014, ICTP
July 7-11, 2014

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European Research Council
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Instituto de Física Teórica
EXCELENCIA SEVERO OCHOA

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VISION


Happy 30th
Anniversary
© cupcake huda

Some Properties of O(32) Superstrings

Edward Witten (Princeton U.)

Oct 1984 - 12 pages

Phys.Lett. B149 (1984) 351-356

(He was 32)

- First String Pheno paper
- U(1) bundles, axions....

First decade: Heterotic Monopoly

1985 — CY Het.

Orbifolds, free fermions, Gepner...

T-duality effective actions

1990 — S-duality

Gaugino condensation, moduli fixing

Soft terms

String GUT's

1995

Second decade: Type II resurects

1995 M-theory Revolution

D-branes, F-theory...

ADD large dimensions

Toroidal orientifolds

Randall-Sundrum

2000 D3,D7 at singularities

Intersecting D6-branes

GKP

KKLT

2005 Landscape studies

Third decade: eclectic

2005 — Large Volume Scenario

Heterotic revisited

D-instantons and applications

F-theory GUT's

2010 — Discrete symmetries

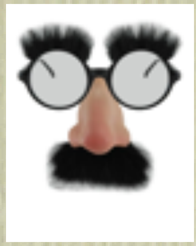
(Higgs found at LHC)

Large field inflation
(Planck, BICEP2)

2015 — ??????????

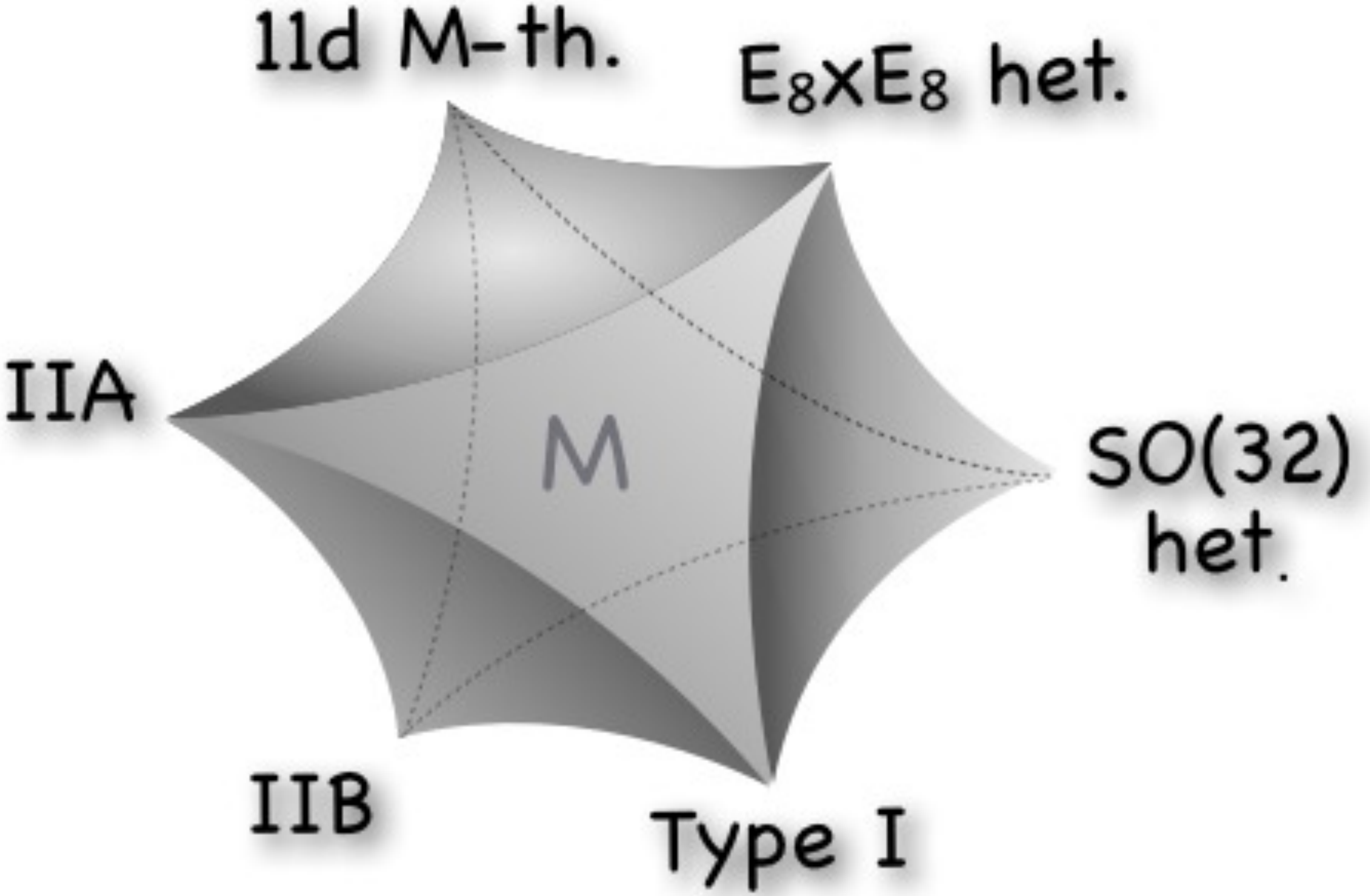
We are exploring terra incognita...

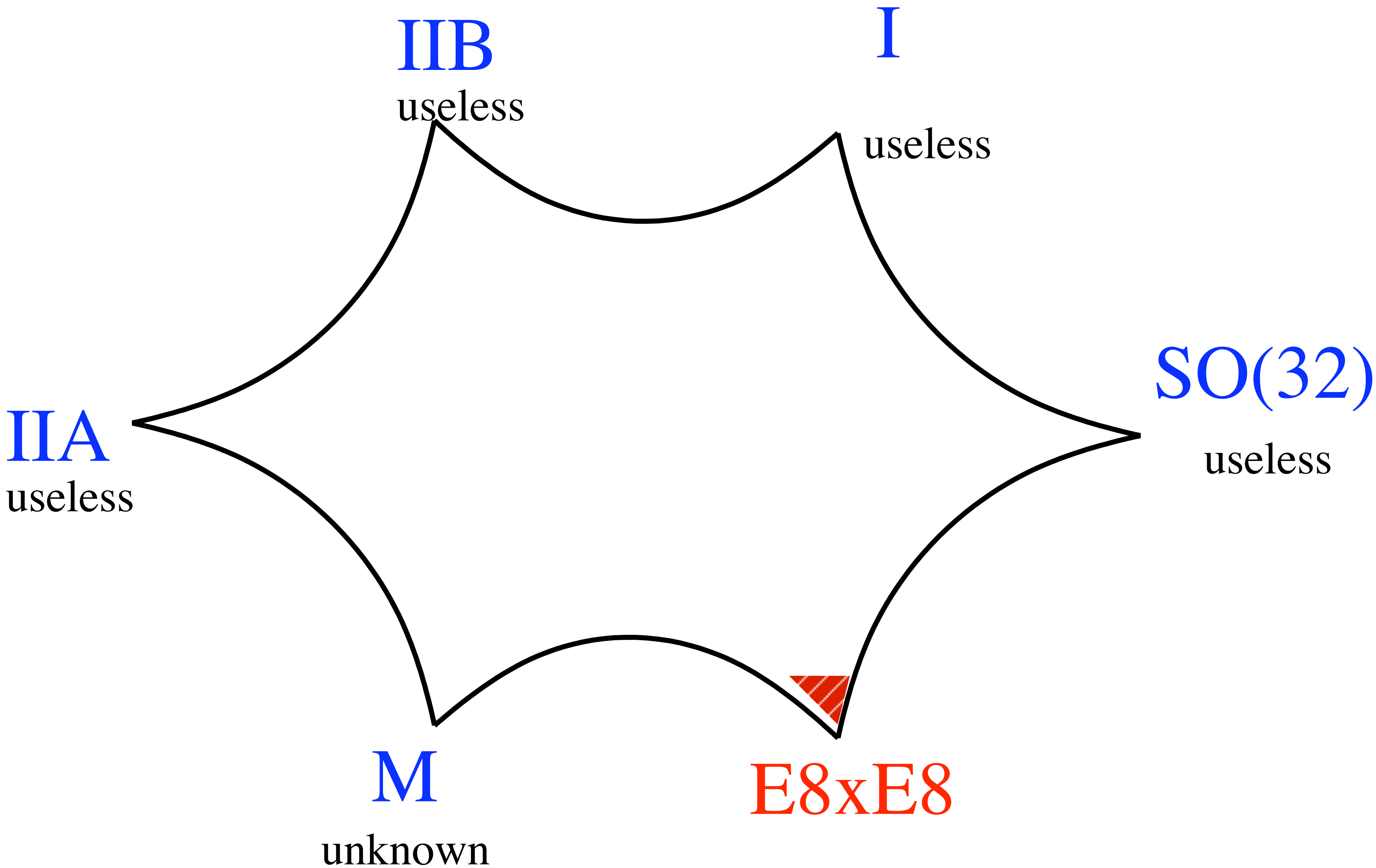
...very much like XVI c. explorations



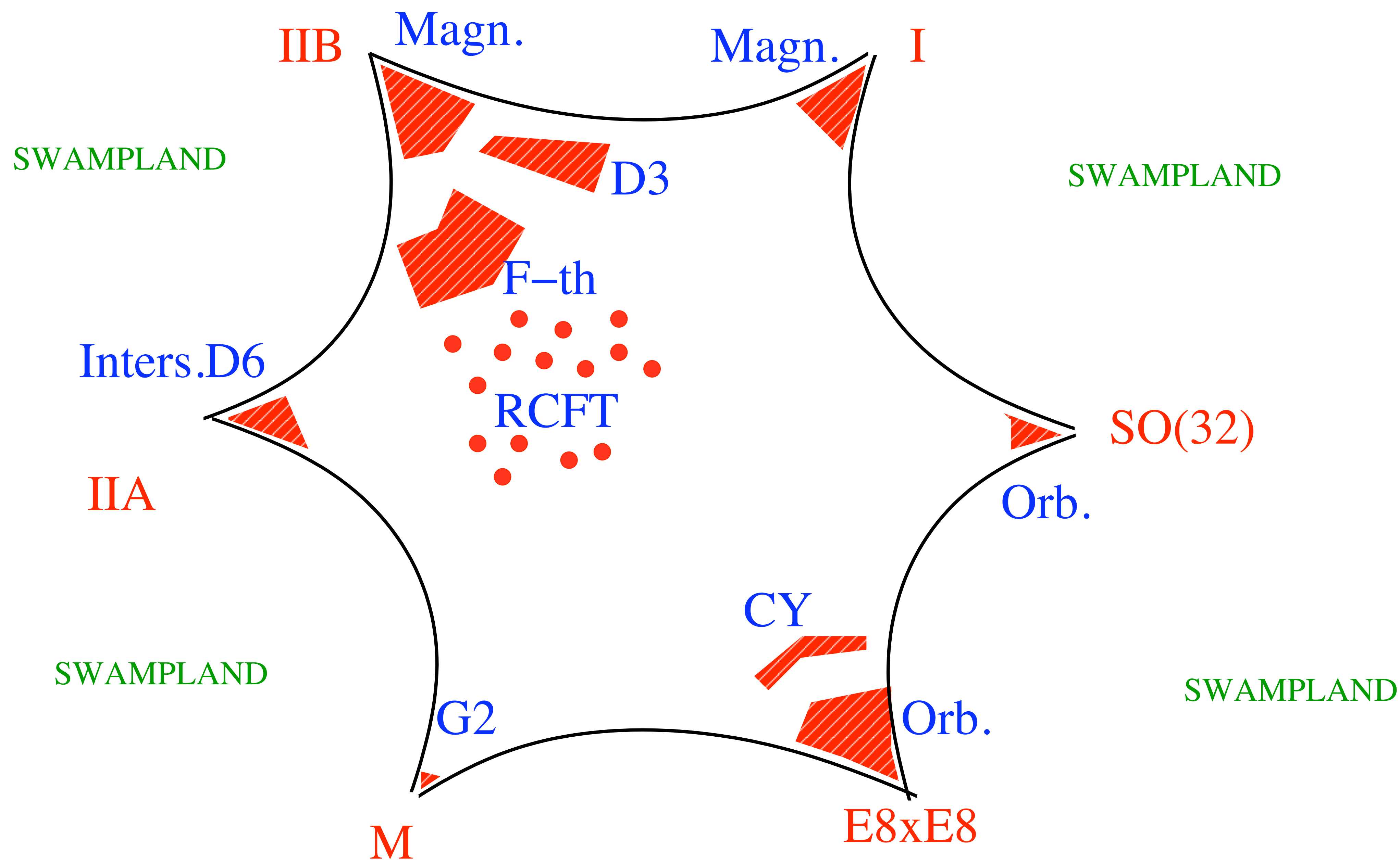
Knowledge of string vacua and effective action accumulates

We are unveiling the rich structure of string theory in its application as a unified theory of all interactions


11d M-th.
E8xE8 het.
IIA
M
SO(32)
het.
IIB
Type I

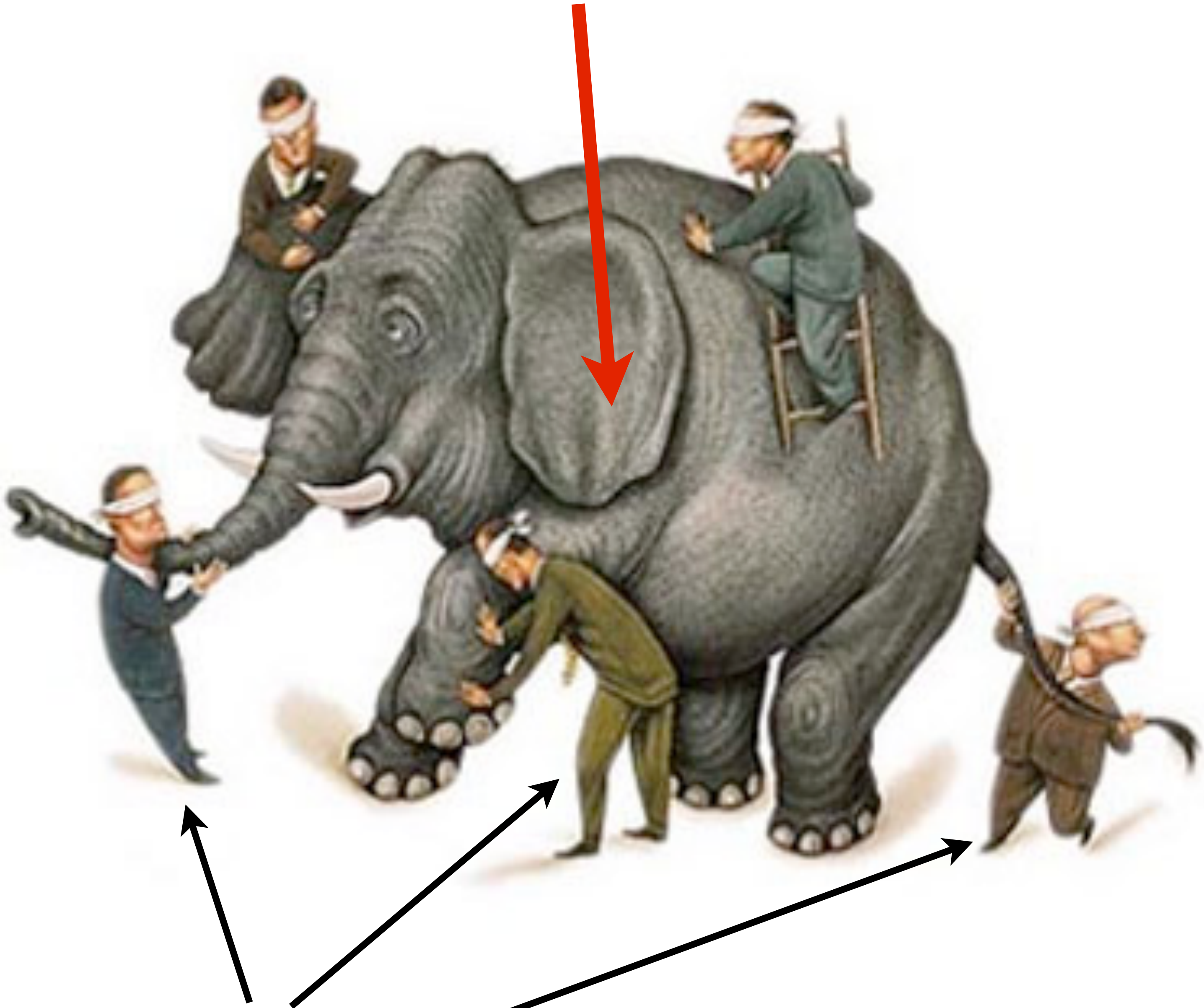

IIB
useless
I
useless
IIA
useless
SO(32)
useless
M
unknown
E8xE8

Circa 1995


IIB
Magn.
Magn.
I
SWAMPLAND
D3
SWAMPLAND
F–th
Inters.D6
RCFT
SO(32)
IIA
Orb.
CY
SWAMPLAND
SWAMPLAND
G2
Orb.
M
E8xE8

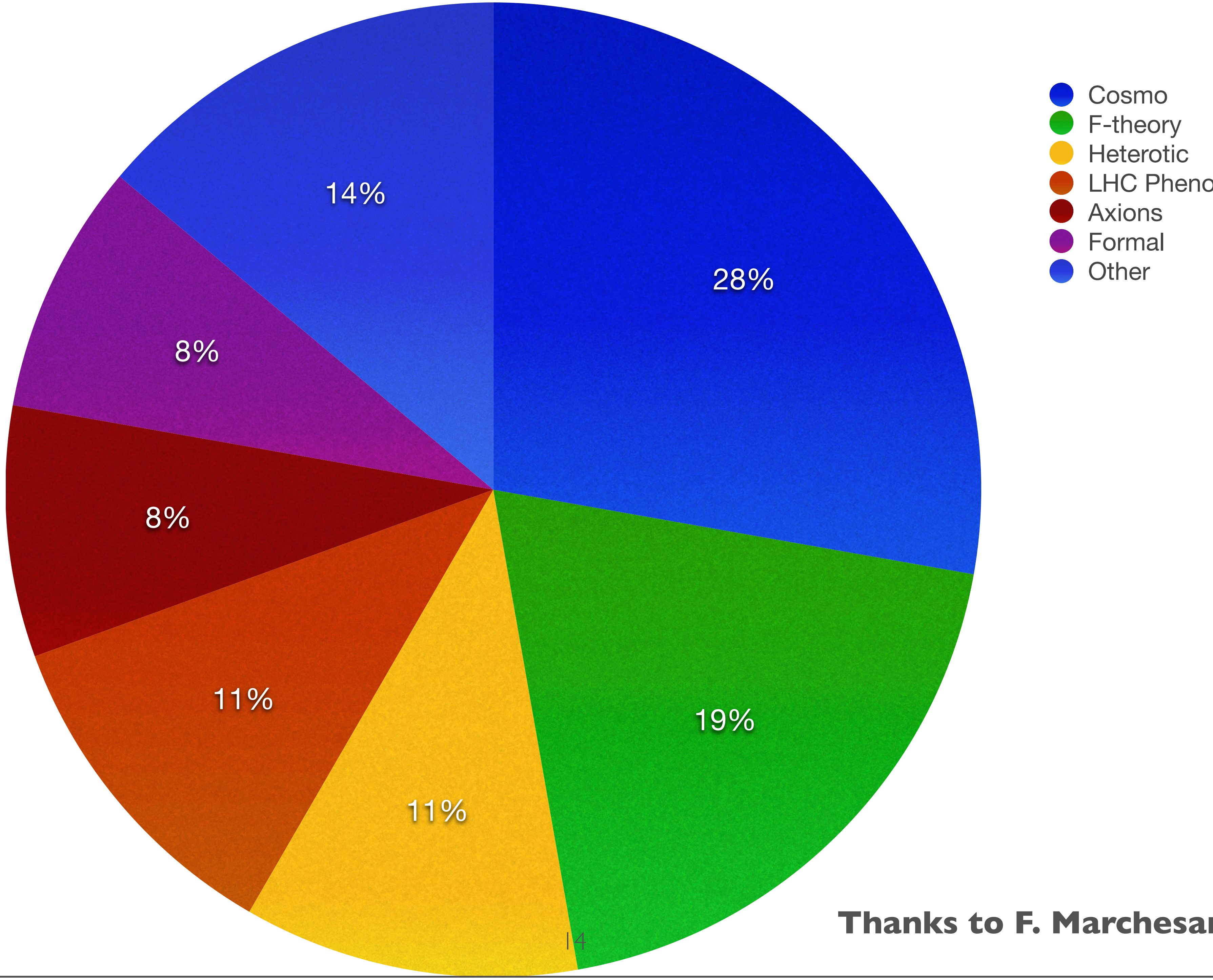
Circa 2014

String/M-theory



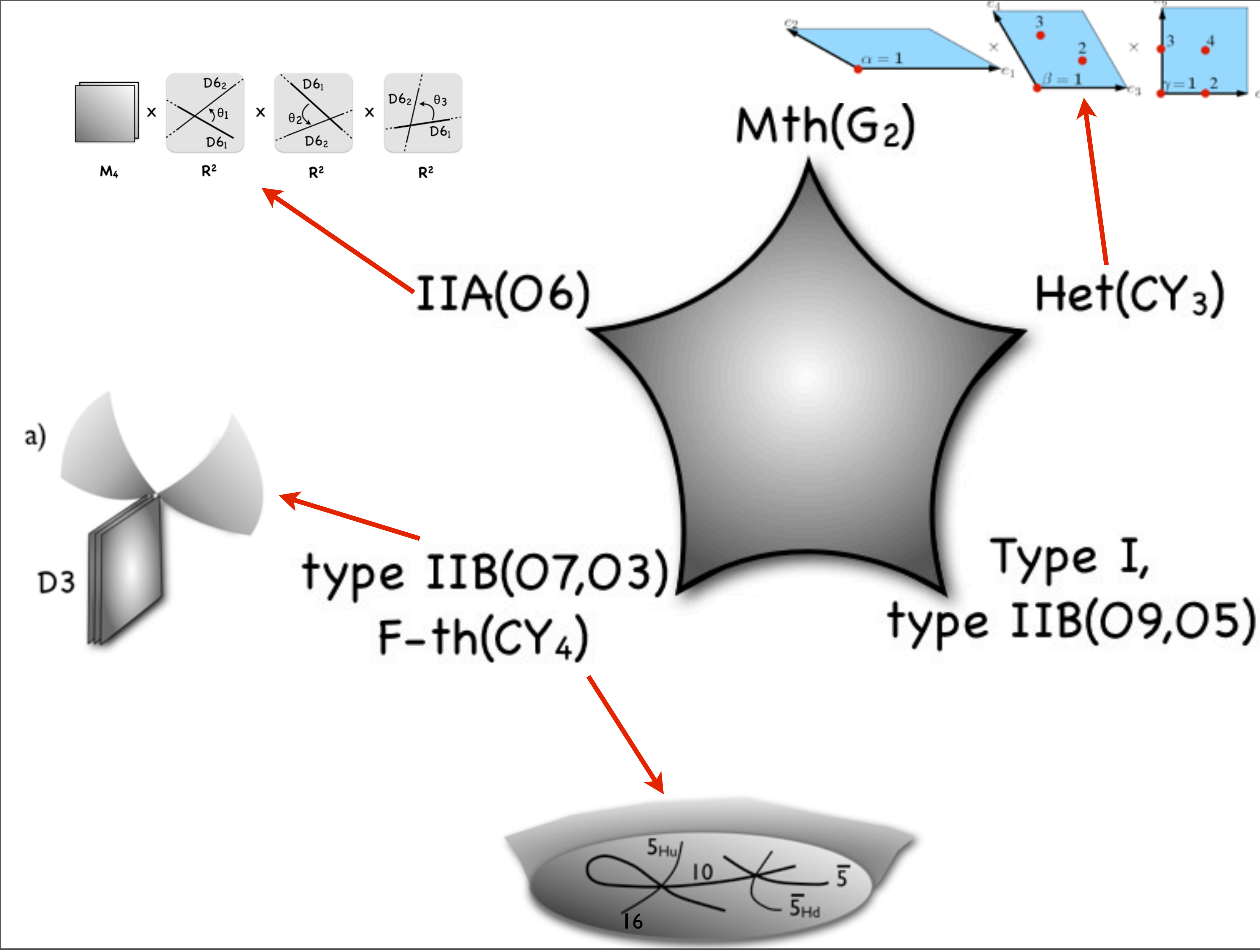
String phenomenologists

Topics plenary talks at String Pheno 2014



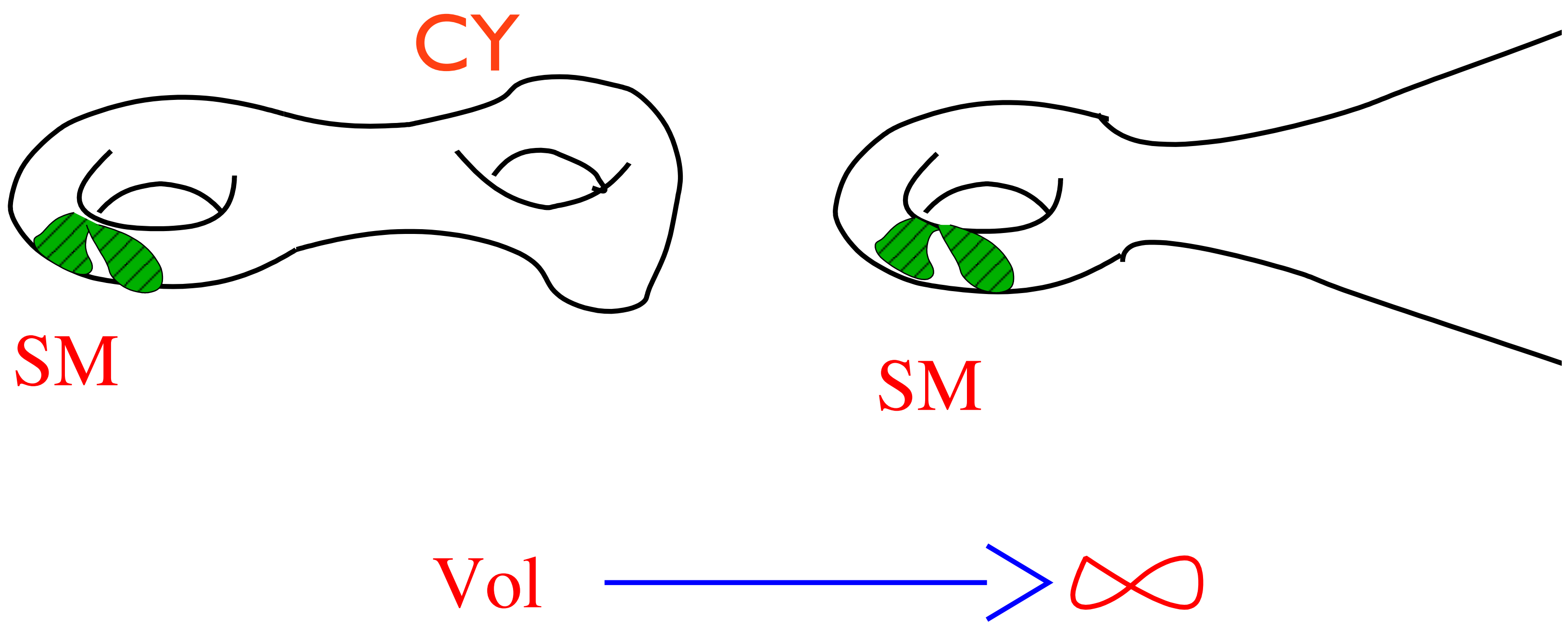
Thanks to F. Marchesano

Charting the vacua



Mth(G₂)
IIA(O6)
Het(CY₃)
type IIB(O7,O3)
F-th(CY₄)
Type I,
type IIB(O9,O5)
M₄
R²
R²
R²
D6₂
θ₁
D6₁
D6₁
θ₂
D6₂
D6₂
θ₃
D6₁
α = 1
β = 1
γ = 1
a)
D3
5Hu
10
5̄
5̄Hd
16

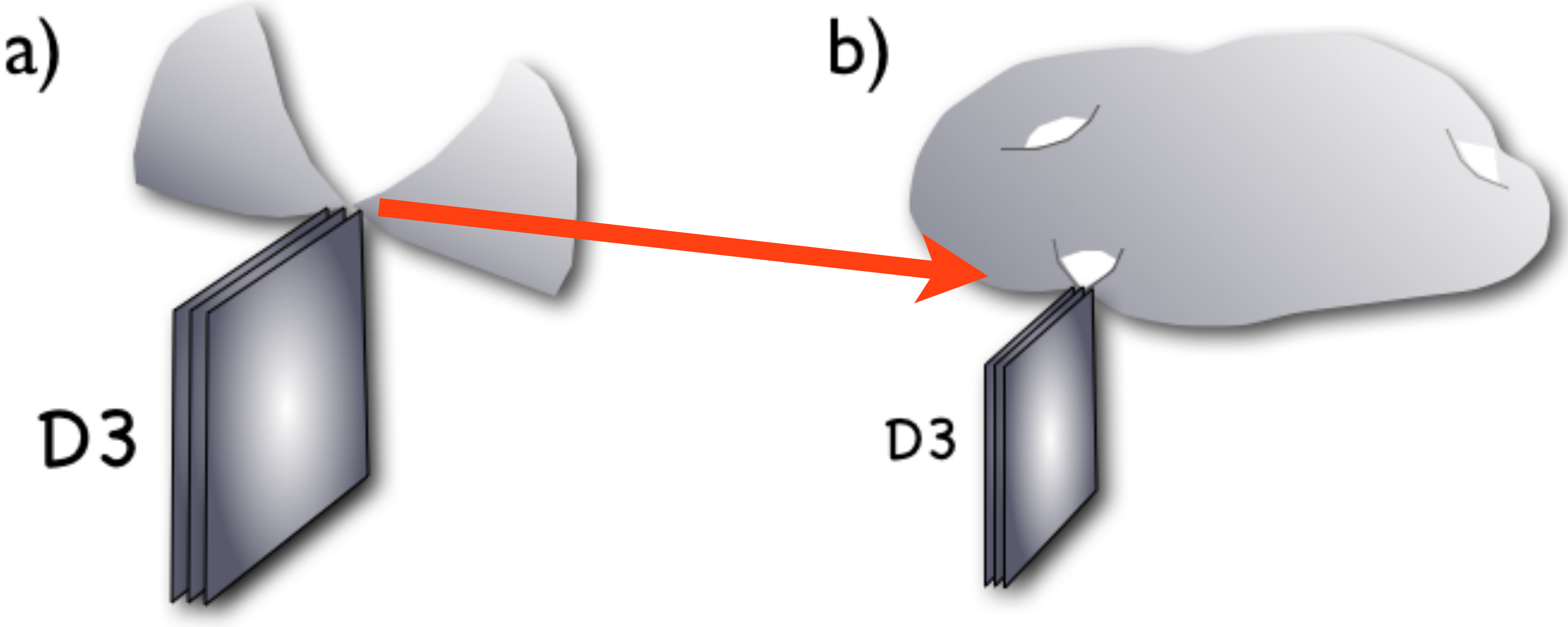
D-branes allow for localized SM



Bottom-up local approach

(Sure, a global solution better, but....)

Example:

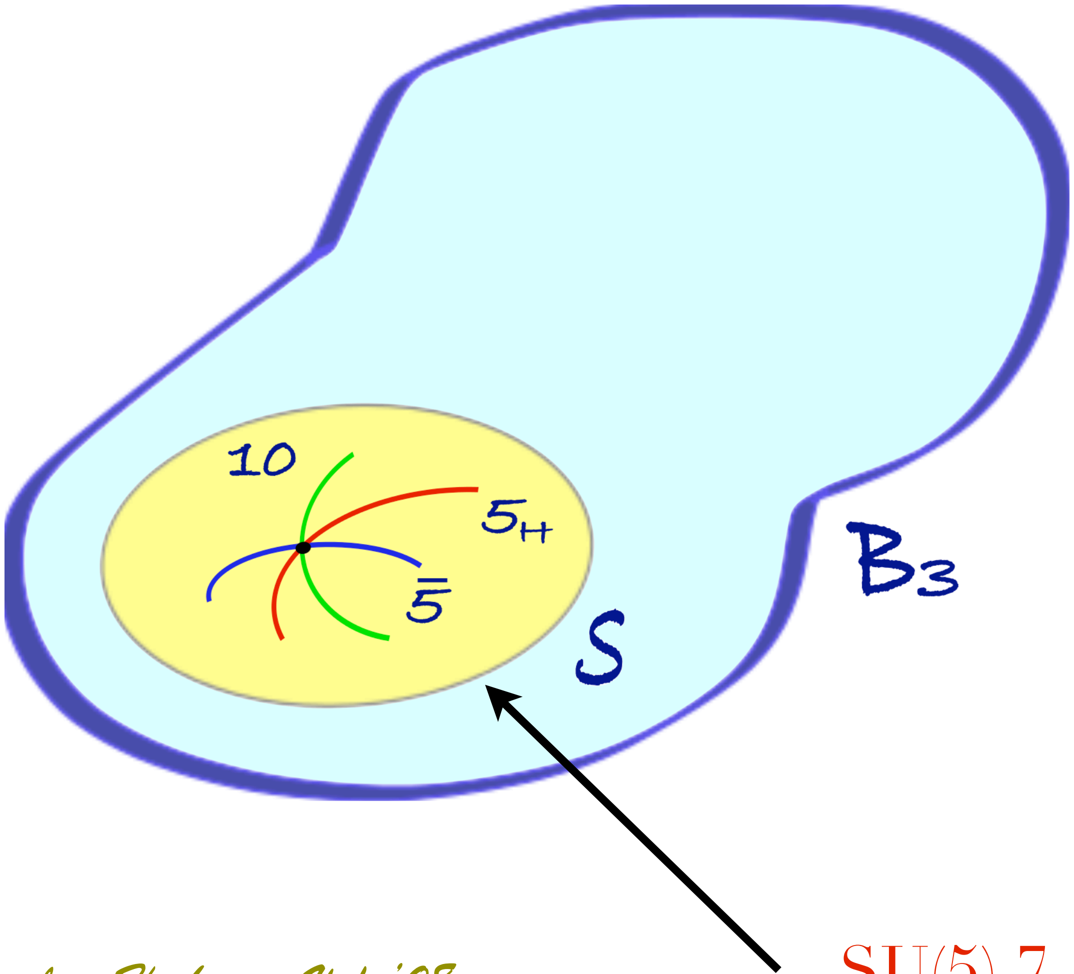


Also : F-theory local GUT's

F-theory SU(5)

Vafa '96

- F-theory may be considered as a non-perturbative version of Type IIB orientifolds.



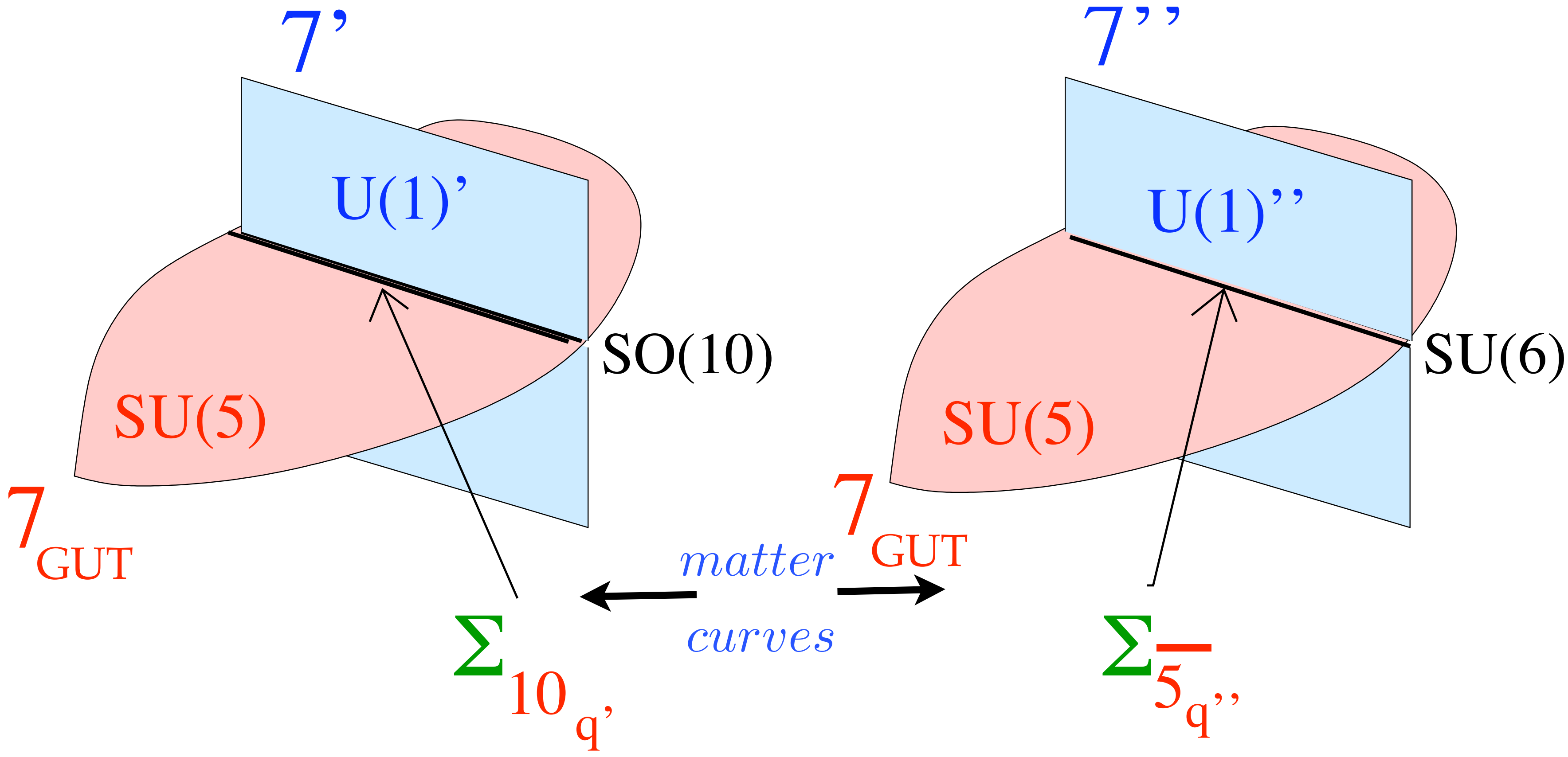
$$X_4 \sim T^2 \times B_3$$

The c.s. modulus of 2-torus is identified with complex dilaton $(varying\ over \mathcal{B}_3)$

SU(5) 7-branes wrap a 4-cycle S
(singularities in the fibration)

Beasley, Heckman, Vafa '08
Donagi & Wijnholt '08

Matter curves:



- At matter curves there are U(1)' fluxes $F_{U(1)'}$ needed for chirality.

- SU(5) is broken by an additional hypercharge flux F_Y

- F-theory: Interesting in its own right: possibly one of the most general class of compactifications.

- New phenomena could be uncovered

- Phenomenological virtues (compared to IIB orientifolds): 1) Allow for top quark Yukawa, 2) Aproximate unification of coupling constants

Talks: Collinucci, Cvetic, Schafer-Nameki, Grimm, Weigand, Garcia-Etxebarria, Mayrhofer,....

F-theory developments

- 1) U(1)'s in F-theory.

Important:

- May be required to forbid dim 4, 5 proton decay operators, as well as a mu-term.

- Give rise to chirality on the matter curves

- Hypercharge flux: SU(5) breaking and doublet triplet splitting

- The U(1) structure given by elliptic fibrations with extra sections (beyond the zero one): Mordell-Weil group

$$SU(5) \times U(1)^n$$

$$Each\ extra\ section\ comes\ with\ a\ \omega_{(1,1)}\ form$$

$$Reduction\ of\ C_3 = A \wedge \omega_{(1,1)}\ gives\ a\ U(1)$$

- Construction of G_4 fluxes

A lot of progress:

Cvetic, Schafer-Nameki, Grimm, Weigand, Garcia-Etxebarria, Mayrhofer, ...

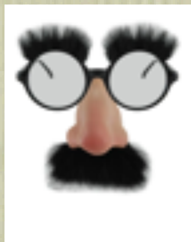
- Direct SU(3)xSU(2)xU(1)xU(1) (local) F-theory models (rank M-W=2) *Weigand talk*

The two phenomenological motivations lost (unification and t-quark Yukawa). Still interesting. May be better suited for large SUSY breaking scale > 10^11 GeV

- Fibrations without a section *Garcia-Etxebarria talk*

- Model building. Global F-theory compactifications

Comment:



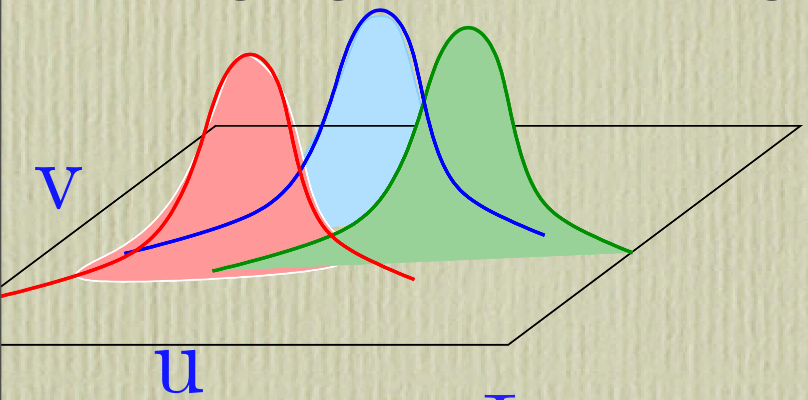
- U(1)'s phenomenologically motivated in F-theory by p-stability, mu-term....

- U(1) technology is slightly painful....

- If SUSY breaking scale above 10^11 GeV, no such U(1)'s would be required, easier model-building

Ultra-local modelling

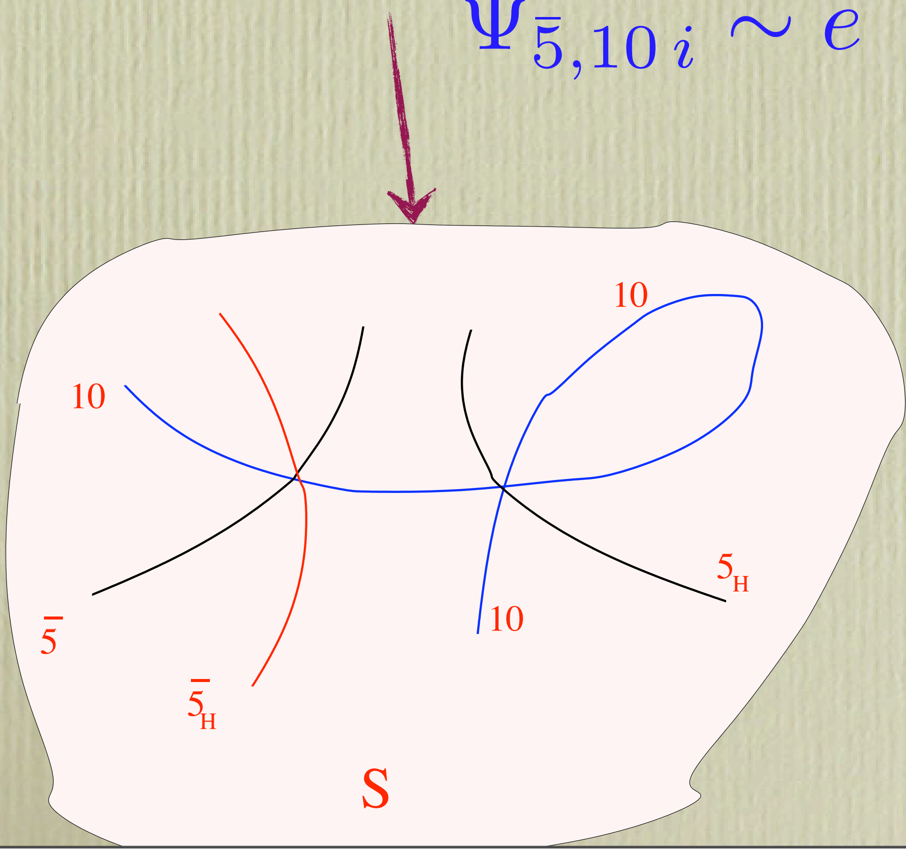
- Chiral fields appear from 8d 7-brane action compactified on S: from 8d gauge bosons and geometric moduli A_M, Φ



$$W = \int_S \mathrm{Tr}(A \wedge A \wedge \Phi)$$

$$\Psi_{\bar{5},10\,i} \sim e^{-\sqrt{\left(\frac{M}{2}\right)^2 + m_s^4}\,|u|^2} e^{-\frac{|M|}{2}|v|^2} f_i(v)$$

localized on matter curves



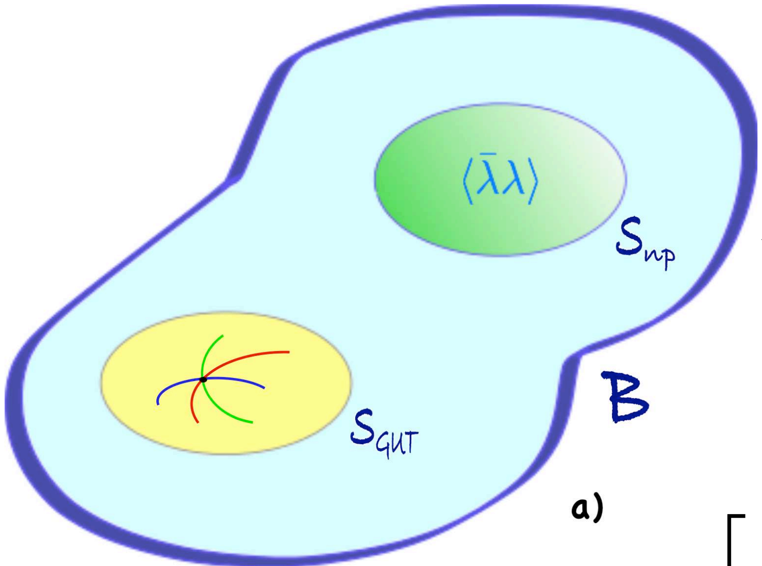
Beasley, Heckman, Vafa '08; Font, L.I '08; Dudas, Palti '09; Leontaris, Ross 2010

$$Y^{ij} = \int_S d\mu\, \psi_{\frac{i}{1}} \psi_{\frac{j}{2}} \varphi$$

- Yukawa couplings are typically rank=1: (good starting point)

- Non-pert. effects give mass to first two generations.

Cecotti, Cheng, Heckman, Vafa '09
Marchesano, Martuci '10
Aparicio, Font, L.I, Marchesano '11
Font, L.I, Marchesano, Regalado '12
Font, Marchesano, Regalado, Zocarrato '13



a)

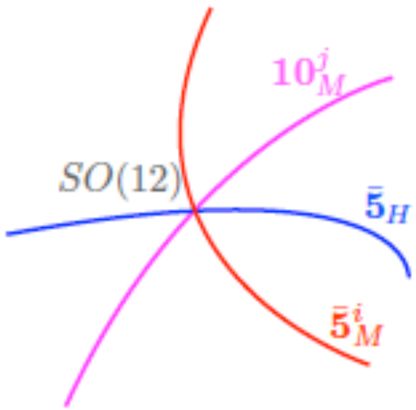
$$W = m_*^4\left[\int_S \mathrm{Tr}(\Phi_{xy}F)\wedge dx\wedge dy + \frac{\epsilon}{2}\sum_n \int_S \theta_n\, \mathrm{STr}\left(\Phi_{xy}^n F\wedge F\right)\right]$$

$$\textit{One obtains fermion mass hierarchies} \simeq 1\,,\ \epsilon\,,\ \epsilon^2$$

T-branes and Up-type Yukawas

Down-type

$$Y_D^{ij} : \bar{\mathbf{5}}_H \, \bar{\mathbf{5}}_M^i \, \mathbf{10}_M^j$$



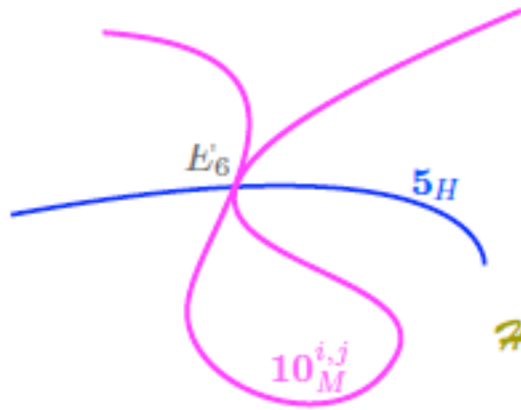
Intersecting branes, $[\langle\Phi\rangle, \langle\bar{\Phi}\rangle] = 0$

$$\langle\Phi\rangle \sim \begin{pmatrix} -x & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & x-y \end{pmatrix} dx \wedge dy$$

$$\omega \wedge F = 0$$

Up-type

$$Y_U^{ij} : \mathbf{5}_H \, \mathbf{10}_M^i \, \mathbf{10}_M^j$$



Hayashi et al. '09
Cecotti et al. '10

T-branes, $[\langle\Phi\rangle, \langle\bar{\Phi}\rangle] \neq 0$

$$\langle\Phi\rangle \sim \begin{pmatrix} 0 & 1 & 0 \\ x & 0 & 0 \\ 0 & 0 & y \end{pmatrix} dx \wedge dy$$

$$\omega \wedge F + \frac{1}{2}[\Phi, \bar{\Phi}] = 0$$

Analogous hierarchies in both D and U Yukawas

Font, Marchesano, Regalado, Zocaratto 2013

Soft terms from fluxes on mat. curves

$$m^2_{\bar{\mathbf{5}}} = \frac{M^2}{2}\left(1 - \frac{\tilde{M}}{2}\right) + \frac{q_Y}{4}\tilde{N}_Y M^2$$

$$m^2_{\mathbf{10}} = \frac{M^2}{2}\left(1 - \frac{\tilde{M}}{2}\right) - \frac{q_Y}{4}\tilde{N}_Y M^2$$

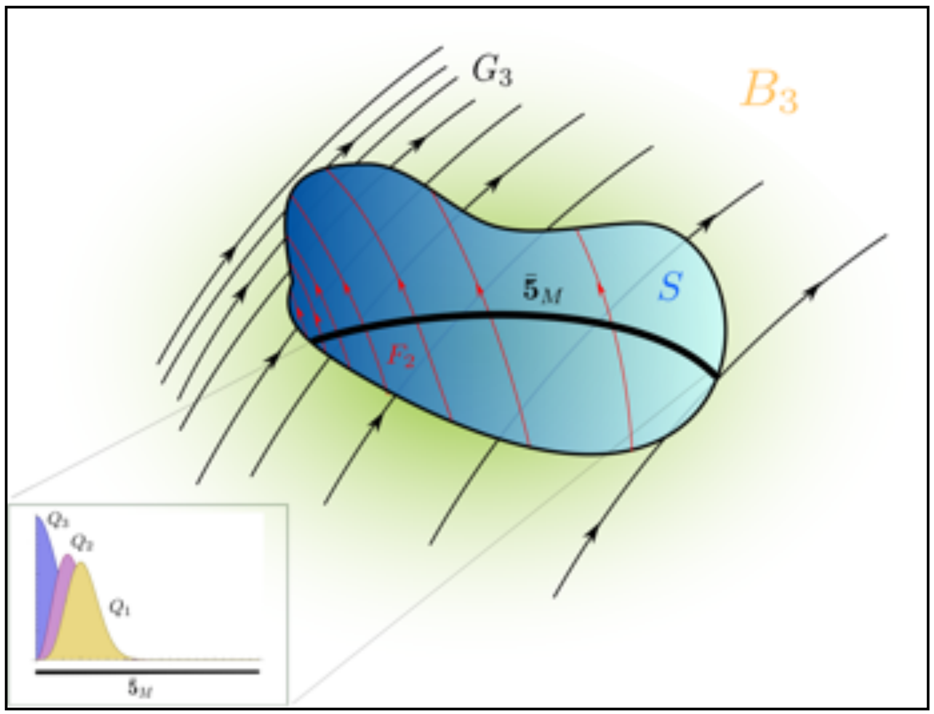
Hypercharge dependent soft terms

$$m^2_{ij} = \frac{g_s}{4\mathrm{Vol}(S)} \int_S d^2z d^2\bar{z}\sqrt{g_4}|G|^2 \left(1 - \left|\frac{F_-}{m}\right|\right) \varphi_i^+ (\varphi_j^+)^*$$

magnetic 2-form flux

3-form flux

localized w.f.



FCNC constraints:

$$m^2_{\tilde{f}} \geq (10\ \mathrm{TeV})^2$$

(Not very good for LHC...)

Camara, L.I., Valenzuela

But there IS life beyond F-theory:

Heterotic:

Lukas, Vaudrevange, Rizos talks..

- Large class of SU(5) models from Heterotic with U(1) bundles (instead of SU(N),N=3,4,5):

35,000 SU(5) models in CICY's (with a Higgs and no anti-10). May be broken to MSSM with discrete W.L.

Quite impresive...

Anderson, Constantin, Gray, Lukas, Palti 2013

Heterotic Orbifolds

The OrbifoldLandscape

orbifold		# MSSM	max. # of indep. WLs	# models with 0 indep. vanishing WLs	1	2	3	≥ 4	# MSSM without $U(1)_{anom}$
$\mathbb{Z}_3$	(1,1)	0	3	0	0	0	0	0	0
$\mathbb{Z}_4$	(1,1)	0	4	0	0	0	0	0	0
	(2,1)	128	3	128	0	0	0	0	0
	(3,1)	25	2	25	0	0	0	0	0
$\mathbb{Z}_6$-I	(1,1)	31	1	31	0	0	0	0	0
	(2,1)	31	1	31	0	0	0	0	0
$\mathbb{Z}_6$-II	(1,1)	348	3	13	335	0	0	0	1
	(2,1)	338	3	10	328	0	0	0	2
	(3,1)	350	3	18	332	0	0	0	2
	(4,1)	334	2	39	295	0	0	0	3
$\mathbb{Z}_7$	(1,1)	0	1	0	0	0	0	0	0
$\mathbb{Z}_8$-I	(1,1)	263	2	221	42	0	0	0	7
	(2,1)	164	2	123	41	0	0	0	5
	(3,1)	387	1	387	0	0	0	0	27
$\mathbb{Z}_8$-II	(1,1)	638	3	212	404	22	0	0	7
	(2,1)	260	2	92	168	0	0	0	3
$\mathbb{Z}_{12}$-I	(1,1)	365	1	365	0	0	0	0	8
	(2,1)	385	1	385	0	0	0	0	9

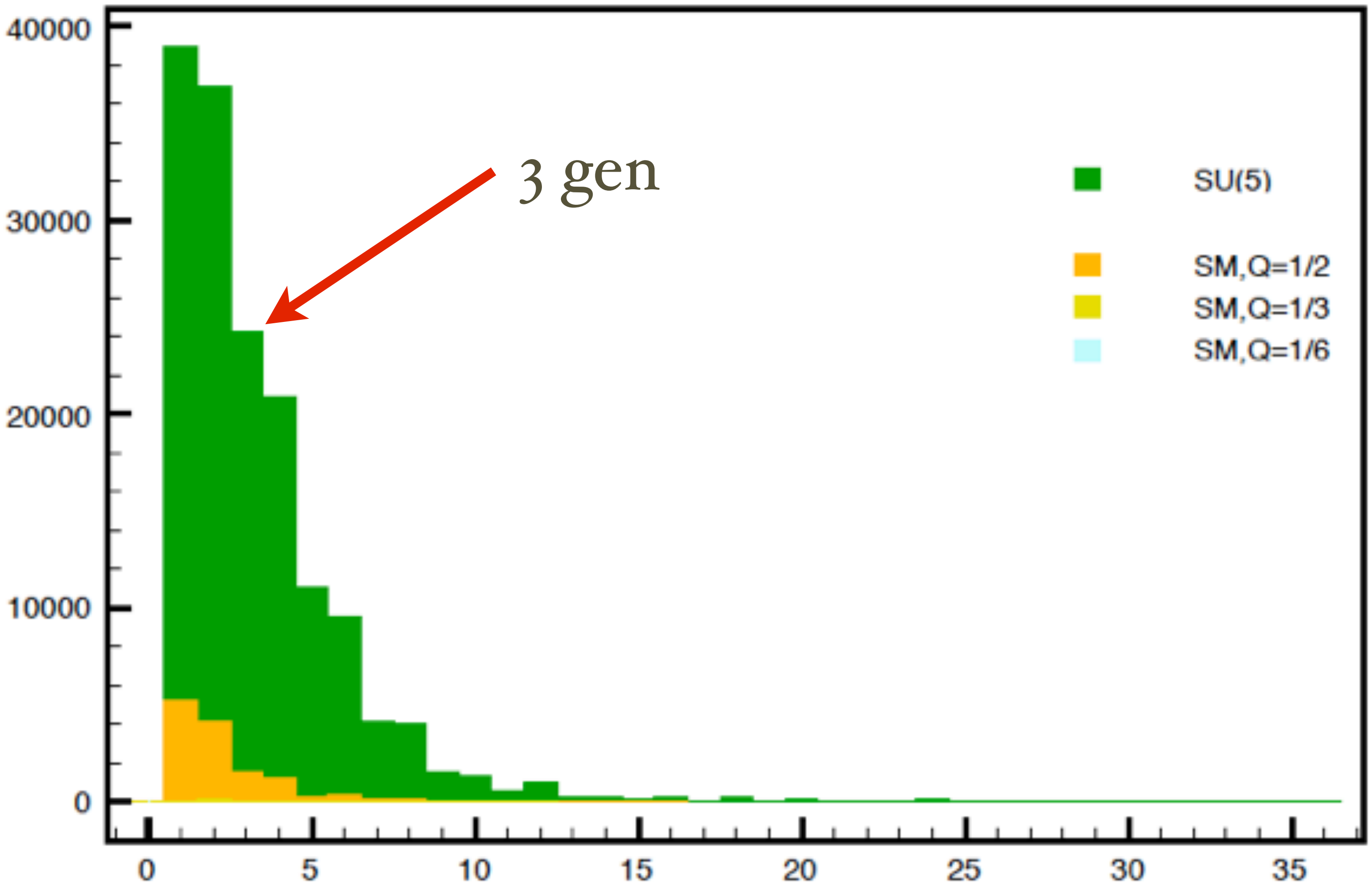
Vaudrevange talk

The OrbifoldLandscape

orbifold		# MSSM	max. # of indep. WLs	# models with 0 indep. vanishing WLs	1	2	3	≥ 4	# MSSM without $U(1)_{anom}$
$\mathbb{Z}_{12}$-II	(1,1)	211	2	135	76	0	0	0	3
$\mathbb{Z}_2 \times \mathbb{Z}_2$	(1,1)	101	6	0	59	42	0	0	0
$\mathbb{Z}_2 \times \mathbb{Z}_4$	(1,1)	3632	4	67	2336	1199	30	0	10
$\mathbb{Z}_2 \times \mathbb{Z}_6$-I	(1,1)	445	2	332	113	0	0	0	5
$\mathbb{Z}_2 \times \mathbb{Z}_6$-II	(1,1)	0	0	0	0	0	0	0	0
$\mathbb{Z}_3 \times \mathbb{Z}_3$	(1,1)	445	3	1	369	75	0	0	9
$\mathbb{Z}_3 \times \mathbb{Z}_6$	(1,1)	465	1	441	24	0	0	0	0
$\mathbb{Z}_4 \times \mathbb{Z}_4$	(1,1)	1466	3	11	529	921	5	0	1
$\mathbb{Z}_6 \times \mathbb{Z}_6$	(1,1)	1128	0	1128	0	0	0	0	0
total		11940							102

12,000 MSSM's

100 MSSM models without anomalous U(1)



Heterotic Gepner MSSM-like models

Figure 1: Distribution of the number of families for all tensor products combined.

(Schellekens et al. 2010)

Rizos: Free fermion PS models

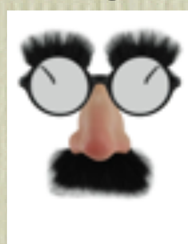
Discrete gauge symmetries

Uranga, Ratz,....

- Appear both in Heterotic and Type II orientifolds:

$$\mathcal{L}_{4d} \sim n(B \wedge F) \quad \xleftrightarrow{dB = *da} \quad (da - nA) \wedge *(da - nA)$$

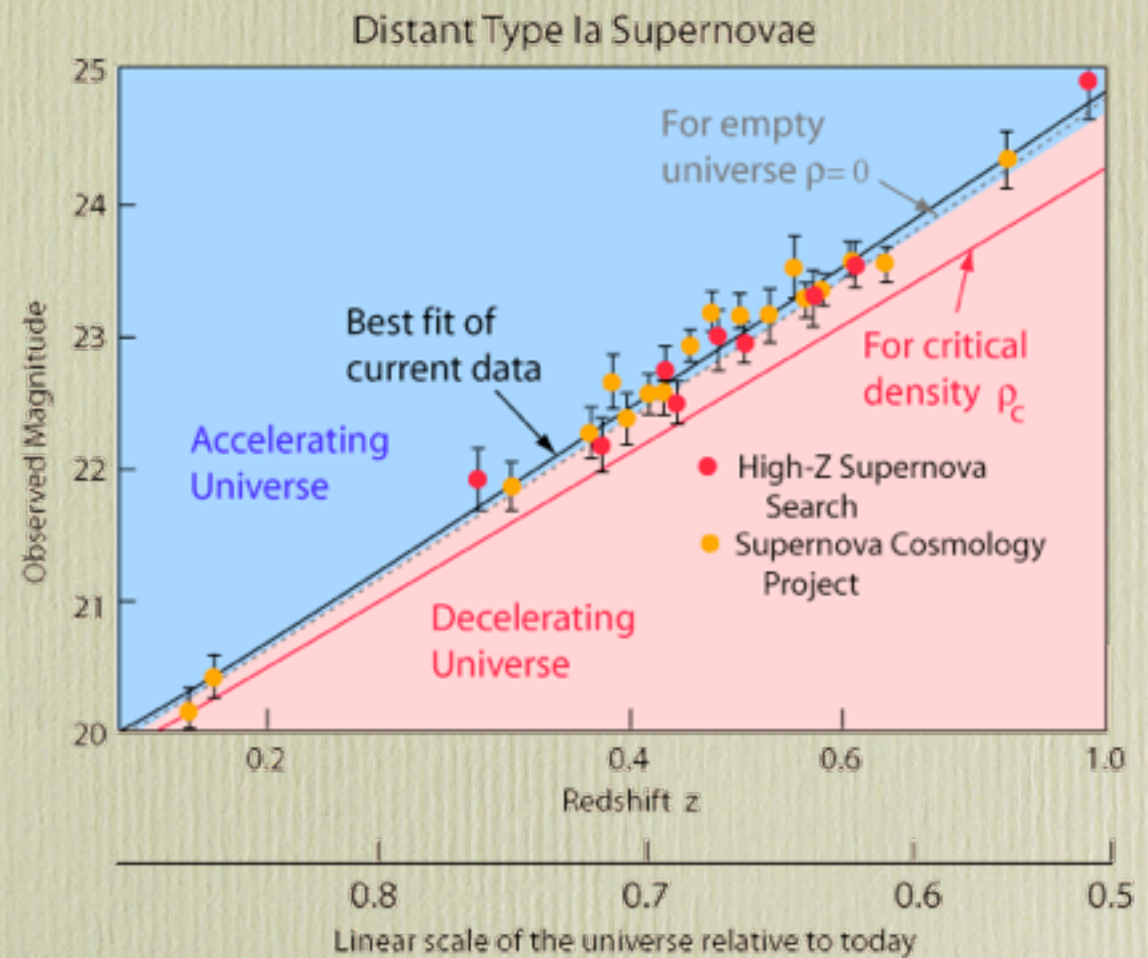
Also non-Abelian, which could be relevant for fermion structure.



- R-parity or B-triality not terribly frequent in MSSM-like Type II vacua

2(+1) Crucial Experimental inputs

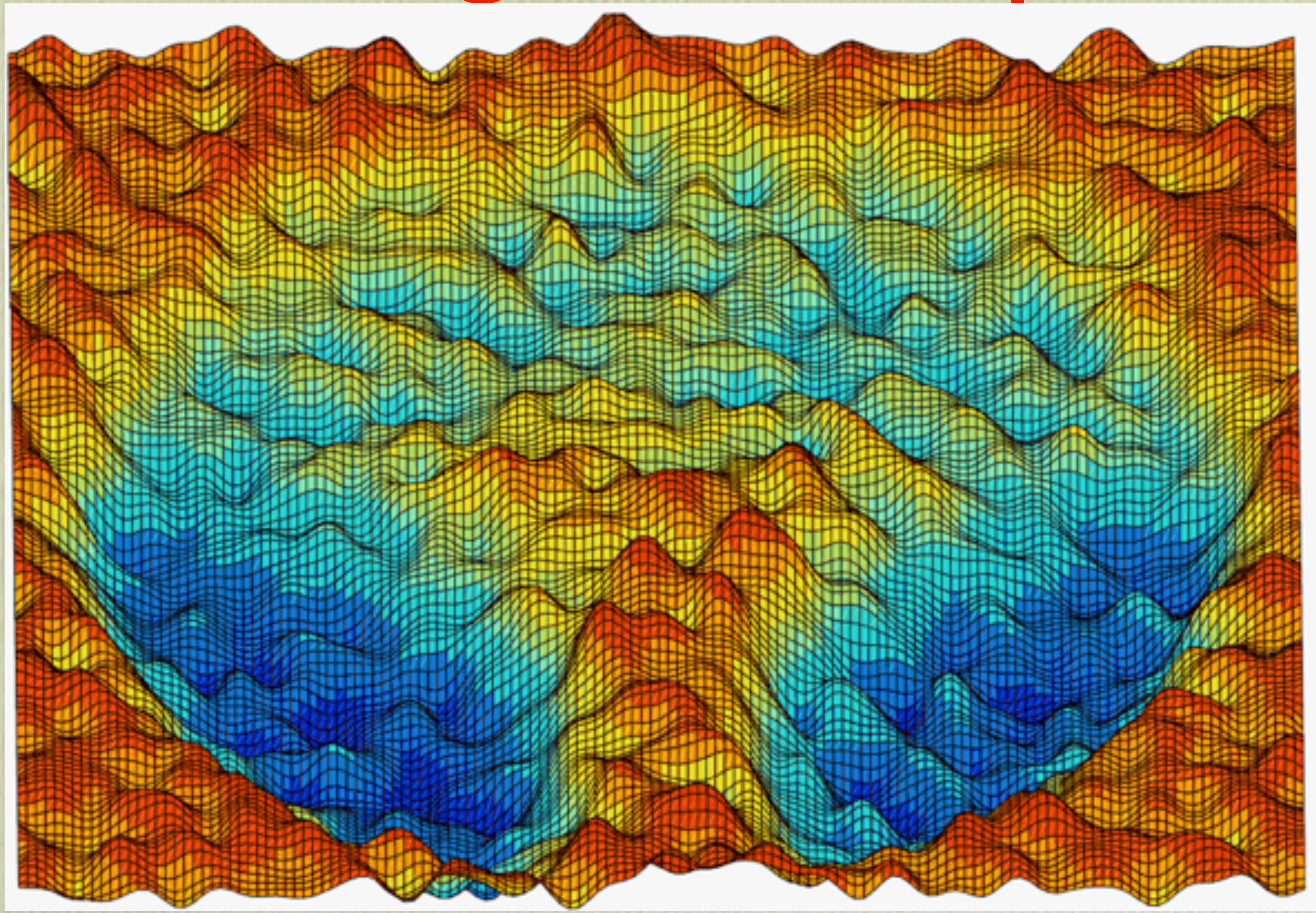
1) The Universe is accelerating



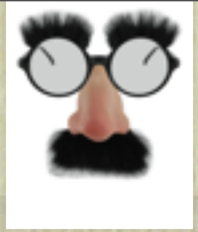
Dark energy = cosmological cons.

$$\Lambda_{c.c.} \simeq (10^{-3}\ eV)^4$$

The rich flux structure leads to a huge String Landscape



Small, positive c.c. may be environmentally selected



- A large landscape of vacua may be argued to be a virtue rather than a shortcoming

- It allows for an anthropic understanding of the c.c.

Interesting:

- The idea of the landscape an anthropics has permeated the comunity. More respectable.
- Still not much recent work on pure landscape issues...

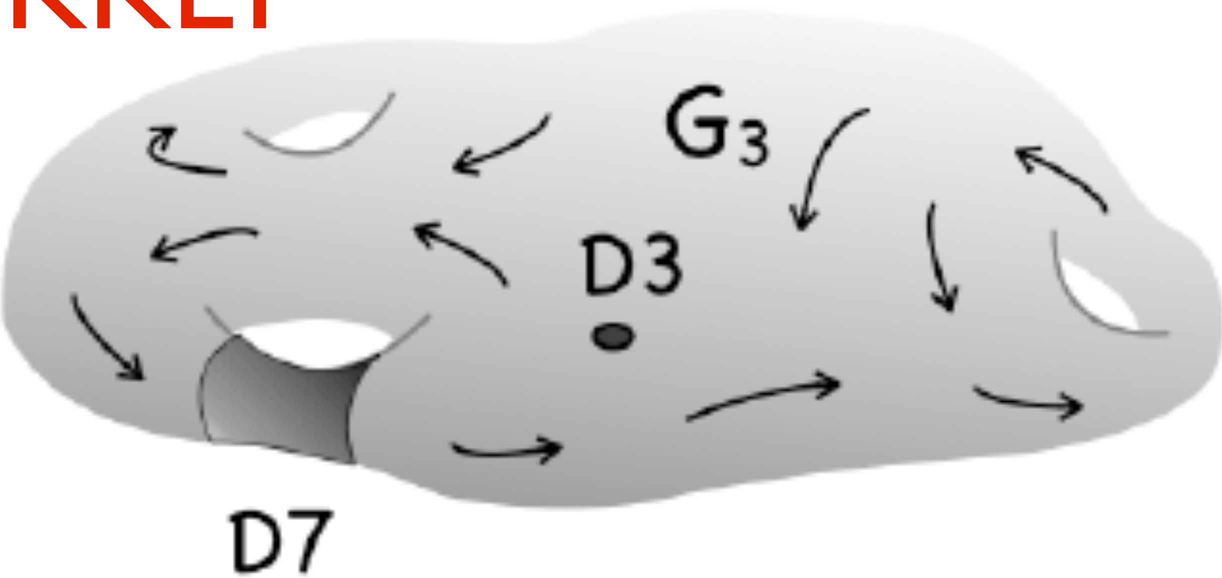
Moduli Fixing

Conlon, Zavala,...

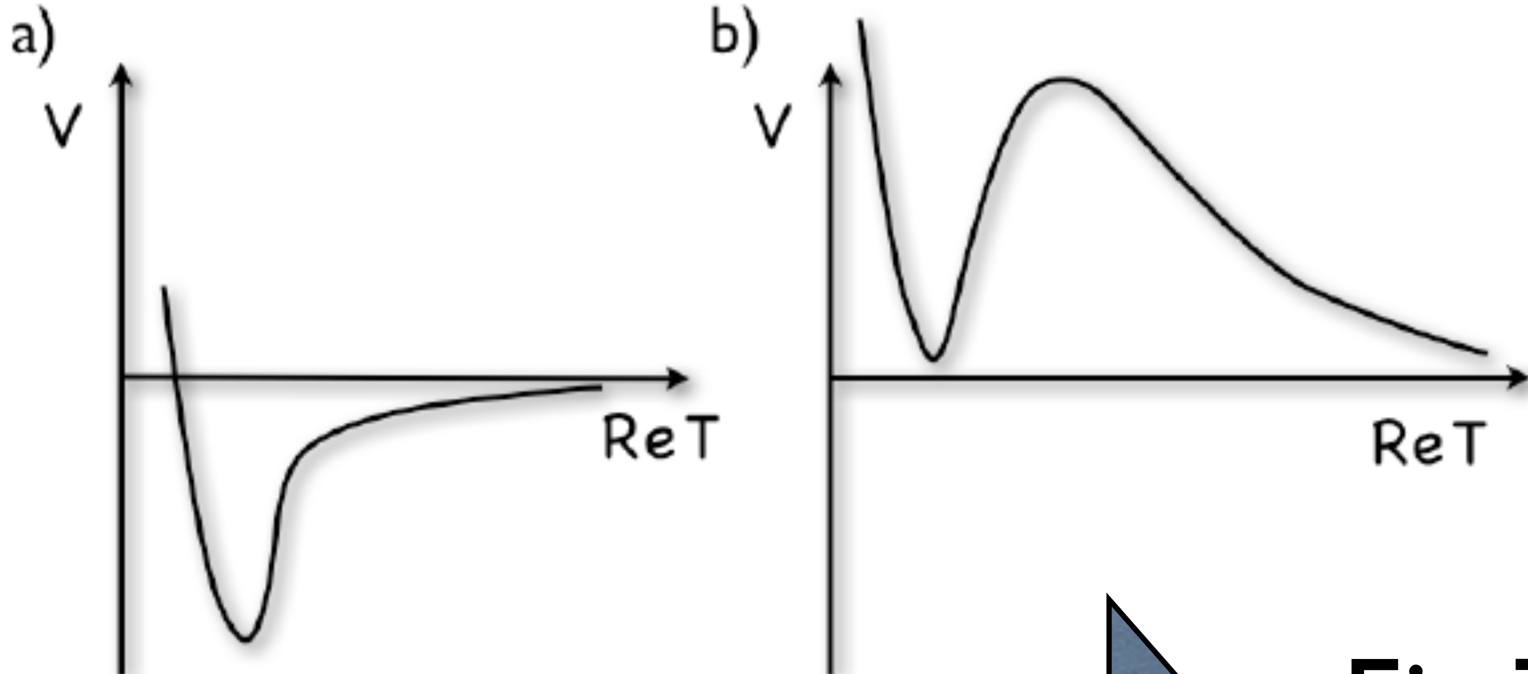
Landscape of vacua intimately connected to moduli stabilization

- First examples of moduli stabilization still the paradigms in Type IIB: KKLT, LVS

KKLT



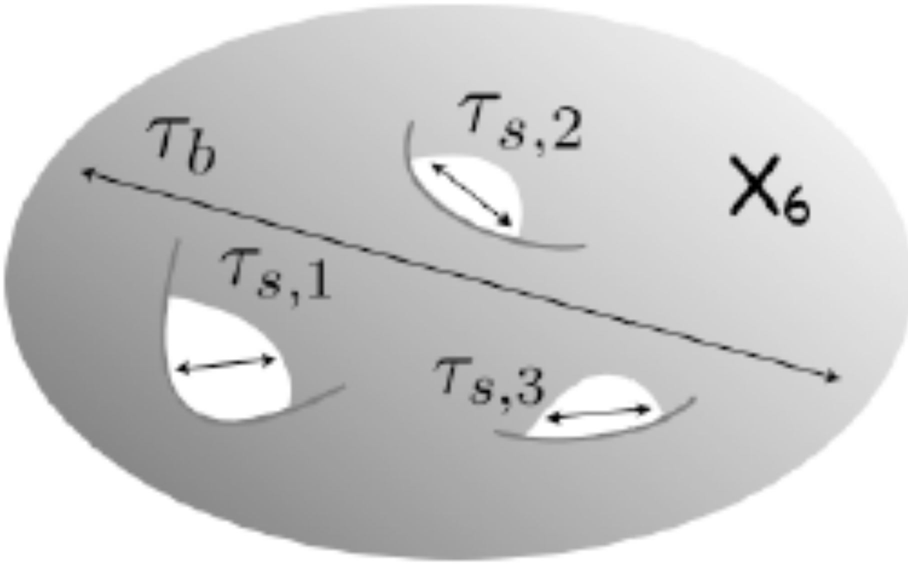
Fix S,U



Instantons/Gaugino condensates

Fix T

Large Volume Scenario



- $\tau_b \gg \tau_{s_i}$

- Hierarchy of volumes and scales, parametrically controlled. Up-lifting less clear...

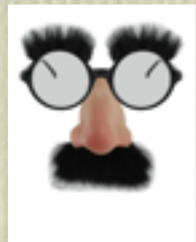
- SM on D3's (D7 also possible)

- A lot of work on low energy effective action, cosmology, ALP's,

- Progress towards first examples of models with both moduli stabilization and a MSSM-like sector (from D3-branes at singularities).

Cicoli et al. . . .

- Possible lamp-post effect:

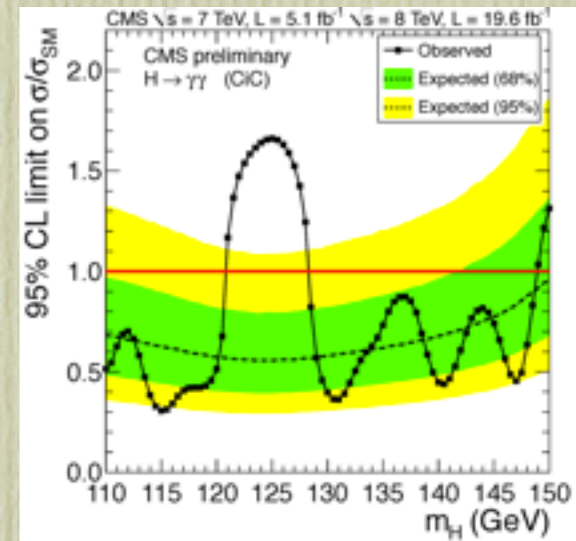


Present technology does not make use of ingredients like e.g non-geometric fluxes (which are mirror to IIA fluxes)....could play an important role...

No example as yet able to reproduce the smallness of the c.c.

Conlon: further caveats.....

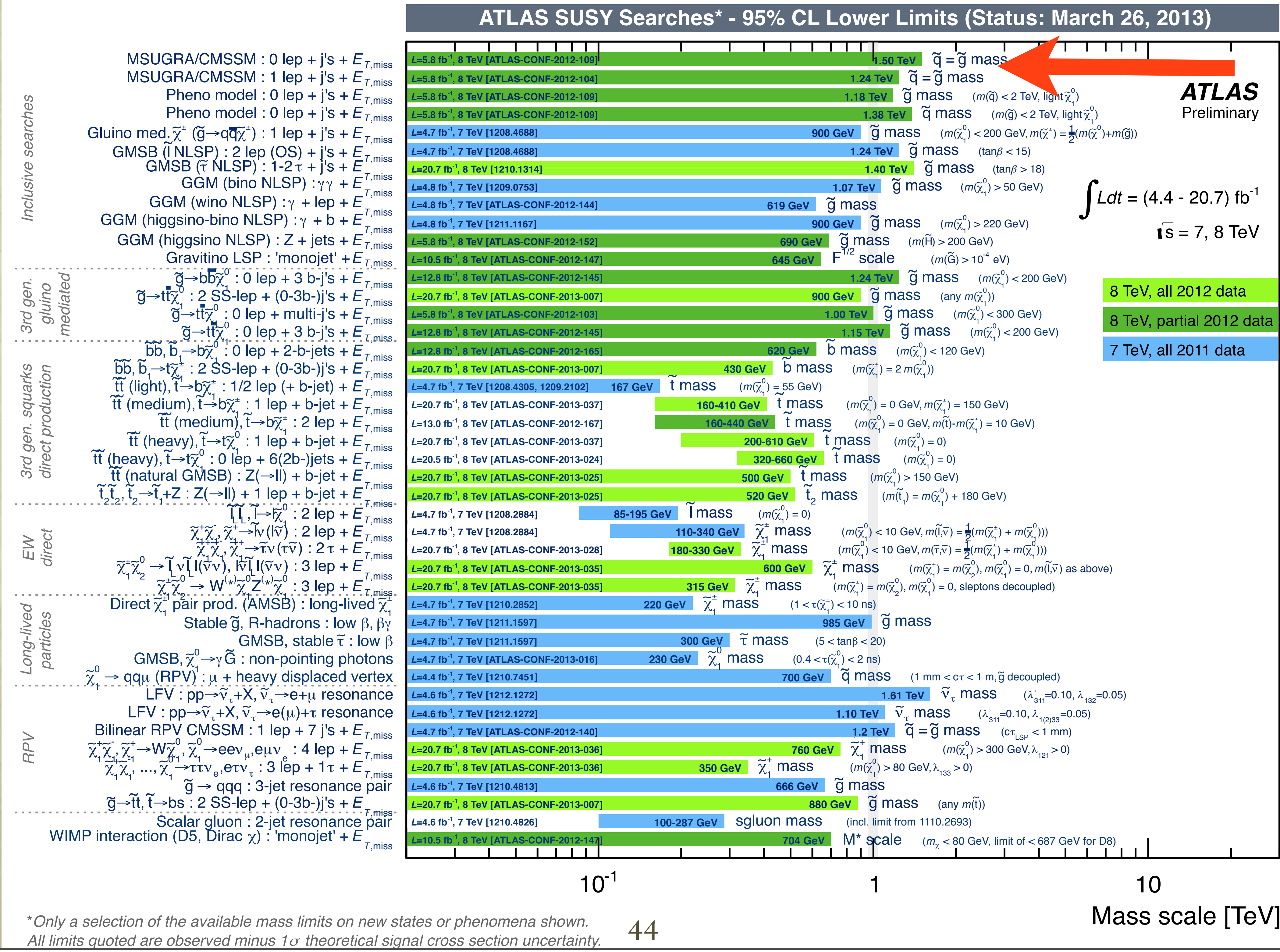
The second crucial experimental input comes from LHC and it is two-fold:

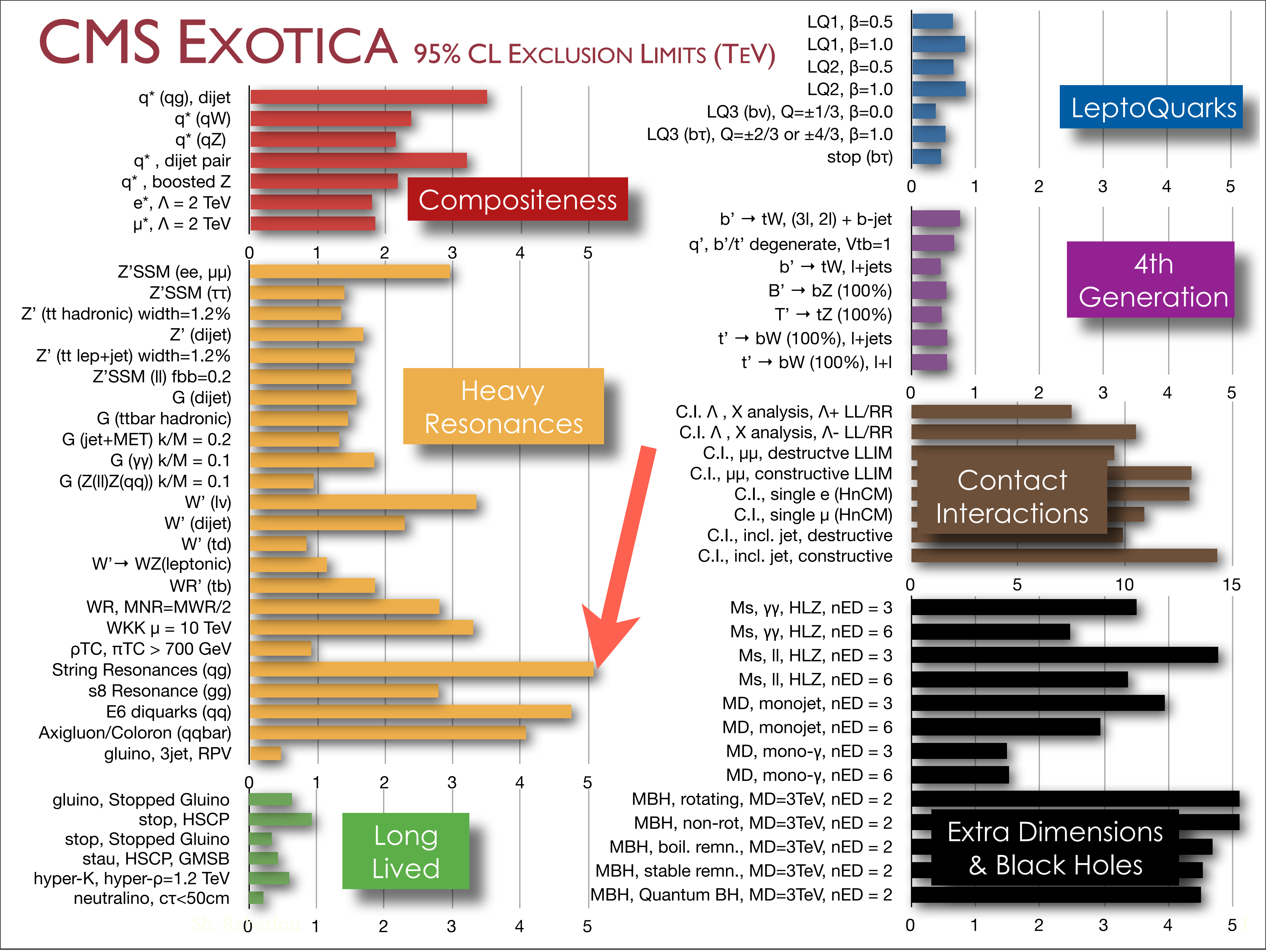


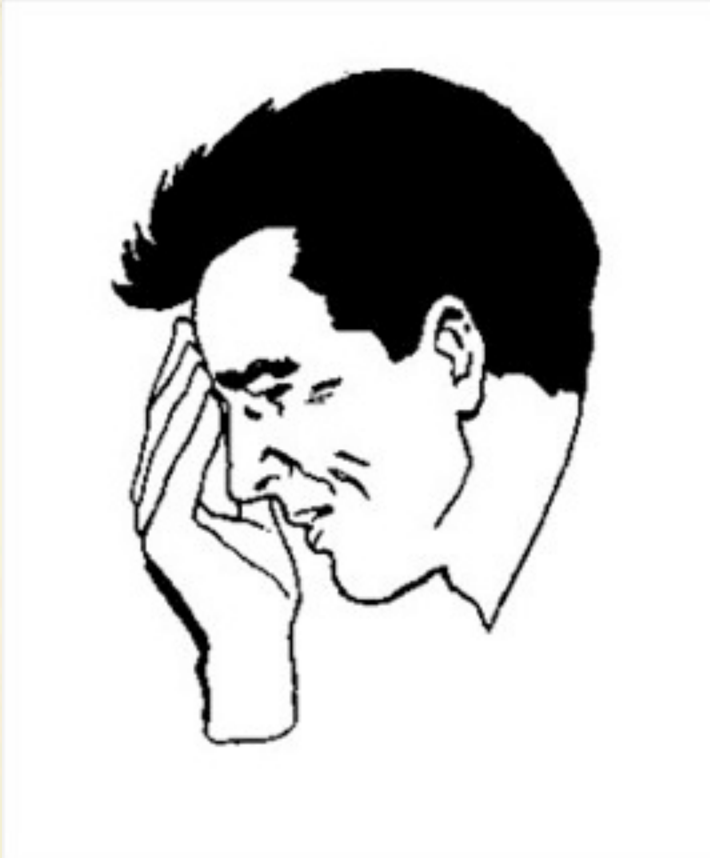
** The Higgs

** Nothing else!

Talks: Antoniadis, Ovrut, Kumar, Kripendorf,...


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 26, 2013)
ATLAS
Preliminary
∫Ldt = (4.4 - 20.7) fb^-1
√s = 7, 8 TeV
8 TeV, all 2012 data
8 TeV, partial 2012 data
7 TeV, all 2011 data
Inclusive searches
MSUGRA/CMSSM : 0 lep + j's + E_T,miss | L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-109] | 1.50 TeV | q̃ = g̃ mass
MSUGRA/CMSSM : 1 lep + j's + E_T,miss | L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-104] | 1.24 TeV | q̃ = g̃ mass
Pheno model : 0 lep + j's + E_T,miss | L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-109] | 1.18 TeV | g̃ mass | (m(q̃) < 2 TeV, light χ̃⁰₁)
Pheno model : 0 lep + j's + E_T,miss | L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-109] | 1.38 TeV | q̃ mass | (m(g̃) < 2 TeV, light χ̃⁰₁)
Gluino med. χ̃± (g̃→qq̄χ̃±) : 1 lep + j's + E_T,miss | L=4.7 fb^-1, 7 TeV [1208.4688] | 900 GeV | g̃ mass | (m(χ̃⁰₁) < 200 GeV, m(χ̃±) = ½(m(χ̃⁰)+m(g̃))
GMSB (l̃ NLSP) : 2 lep (OS) + j's + E_T,miss | L=4.7 fb^-1, 7 TeV [1208.4688] | 1.24 TeV | g̃ mass | (tanβ < 15)
GMSB (τ̃ NLSP) : 1-2 τ + j's + E_T,miss | L=20.7 fb^-1, 8 TeV [1210.1314] | 1.40 TeV | g̃ mass | (tanβ > 18)
GGM (bino NLSP) : γγ + E_T,miss | L=4.8 fb^-1, 7 TeV [1209.0753] | 1.07 TeV | g̃ mass | (m(χ̃⁰₁) > 50 GeV)
GGM (wino NLSP) : γ + lep + E_T,miss | L=4.8 fb^-1, 7 TeV [ATLAS-CONF-2012-144] | 619 GeV | g̃ mass
GGM (higgsino-bino NLSP) : γ + b + E_T,miss | L=4.8 fb^-1, 7 TeV [1211.1167] | 900 GeV | g̃ mass | (m(χ̃⁰₁) > 220 GeV)
GGM (higgsino NLSP) : Z + jets + E_T,miss | L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-152] | 690 GeV | g̃ mass | (m(H̃) > 200 GeV)
Gravitino LSP : 'monojet' + E_T,miss | L=10.5 fb^-1, 8 TeV [ATLAS-CONF-2012-147] | 645 GeV | F^1/2 scale | (m(G̃) > 10^-4 eV)
3rd gen. g̃ mediated
g̃→bb̄χ̃⁰₁ : 0 lep + 3 b-j's + E_T,miss | L=12.8 fb^-1, 8 TeV [ATLAS-CONF-2012-145] | 1.24 TeV | g̃ mass | (m(χ̃⁰₁) < 200 GeV)
g̃→tt̄χ̃⁰₁ : 2 SS-lep + (0-3b-)j's + E_T,miss | L=20.7 fb^-1, 8 TeV [ATLAS-CONF-2013-007] | 900 GeV | g̃ mass | (any m(χ̃⁰₁))
g̃→tt̄χ̃⁰₁ : 0 lep + multi-j's + E_T,miss | L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-103] | 1.00 TeV | g̃ mass | (m(χ̃⁰₁) < 300 GeV)
g̃→tt̄χ̃⁰₁ : 0 lep + 3 b-j's + E_T,miss | L=12.8 fb^-1, 8 TeV [ATLAS-CONF-2012-145] | 1.15 TeV | g̃ mass | (m(χ̃⁰₁) < 200 GeV)
3rd gen. squarks direct production
b̃b̃, b̃₁→bχ̃⁰₁ : 0 lep + 2-b-jets + E_T,miss | L=12.8 fb^-1, 8 TeV [ATLAS-CONF-2012-165] | 620 GeV | b̃ mass | (m(χ̃⁰₁) < 120 GeV)
b̃b̃, b̃₁→tχ̃±₁ : 2 SS-lep + (0-3b-)j's + E_T,miss | L=20.7 fb^-1, 8 TeV [ATLAS-CONF-2013-007] | 430 GeV | b̃ mass | (m(χ̃±₁) = 2 m(χ̃⁰₁))
t̃t̃ (light), t̃→bχ̃±₁ : 1/2 lep (+ b-jet) + E_T,miss | L=4.7 fb^-1, 7 TeV [1208.4305, 1209.2102] | 167 GeV | t̃ mass | (m(χ̃⁰₁) = 55 GeV)
t̃t̃ (medium), t̃→bχ̃±₁ : 1 lep + b-jet + E_T,miss | L=20.7 fb^-1, 8 TeV [ATLAS-CONF-2013-037] | 160-410 GeV | t̃ mass | (m(χ̃⁰₁) = 0 GeV, m(χ̃±₁) = 150 GeV)
t̃t̃ (medium), t̃→bχ̃±₁ : 2 lep + E_T,miss | L=13.0 fb^-1, 8 TeV [ATLAS-CONF-2012-167] | 160-440 GeV | t̃ mass | (m(χ̃⁰₁) = 0 GeV, m(t̃)-m(χ̃±₁) = 10 GeV)
t̃t̃ (heavy), t̃→tχ̃⁰₁ : 1 lep + b-jet + E_T,miss | L=20.7 fb^-1, 8 TeV [ATLAS-CONF-2013-037] | 200-610 GeV | t̃ mass | (m(χ̃⁰₁) = 0)
t̃t̃ (heavy), t̃→tχ̃⁰₁ : 0 lep + 6(2b-)jets + E_T,miss | L=20.5 fb^-1, 8 TeV [ATLAS-CONF-2013-024] | 320-660 GeV | t̃ mass | (m(χ̃⁰₁) = 0)
t̃t̃ (natural GMSB) : Z(→ll) + b-jet + E_T,miss | L=20.7 fb^-1, 8 TeV [ATLAS-CONF-2013-025] | 500 GeV | t̃ mass | (m(χ̃⁰₁) > 150 GeV)
t̃₂t̃₂, t̃₂→t̃₁+Z : Z(→ll) + 1 lep + b-jet + E_T,miss | L=20.7 fb^-1, 8 TeV [ATLAS-CONF-2013-025] | 520 GeV | t̃₂ mass | (m(t̃₁) = m(χ̃⁰₁) + 180 GeV)
EW direct
l̃_L l̃_L, l̃→lχ̃⁰₁ : 2 lep + E_T,miss | L=4.7 fb^-1, 7 TeV [1208.2884] | 85-195 GeV | l̃ mass | (m(χ̃⁰₁) = 0)
χ̃⁺₁χ̃⁻₁, χ̃⁺₁→l̃ν(lν̃) : 2 lep + E_T,miss | L=4.7 fb^-1, 7 TeV [1208.2884] | 110-340 GeV | χ̃±₁ mass | (m(χ̃⁰₁) < 10 GeV, m(l̃,ν̃) = ½(m(χ̃±₁) + m(χ̃⁰₁)))
χ̃⁺₁χ̃⁻₁, χ̃⁺₁→τ̃ν(τν̃) : 2 τ + E_T,miss | L=20.7 fb^-1, 8 TeV [ATLAS-CONF-2013-028] | 180-330 GeV | χ̃±₁ mass | (m(χ̃⁰₁) < 10 GeV, m(τ̃,ν̃) = ½(m(χ̃±₁) + m(χ̃⁰₁)))
χ̃±₁χ̃⁰₂ → l̃_Lνl̃_Ll(ν̃ν), lν̃l̃_Ll(ν̃ν) : 3 lep + E_T,miss | L=20.7 fb^-1, 8 TeV [ATLAS-CONF-2013-035] | 600 GeV | χ̃±₁ mass | (m(χ̃±₁) = m(χ̃⁰₂), m(χ̃⁰₁) = 0, m(l̃,ν̃) as above)
χ̃±₁χ̃⁰₂ → W(*)χ̃⁰₁Z(*)χ̃⁰₁ : 3 lep + E_T,miss | L=20.7 fb^-1, 8 TeV [ATLAS-CONF-2013-035] | 315 GeV | χ̃±₁ mass | (m(χ̃±₁) = m(χ̃⁰₂), m(χ̃⁰₁) = 0, sleptons decoupled)
Long-lived particles
Direct χ̃±₁ pair prod. (AMSB) : long-lived χ̃±₁ | L=4.7 fb^-1, 7 TeV [1210.2852] | 220 GeV | χ̃±₁ mass | (1 < τ(χ̃±₁) < 10 ns)
Stable g̃, R-hadrons : low β, βγ | L=4.7 fb^-1, 7 TeV [1211.1597] | 985 GeV | g̃ mass
GMSB, stable τ̃ : low β | L=4.7 fb^-1, 7 TeV [1211.1597] | 300 GeV | τ̃ mass | (5 < tanβ < 20)
GMSB, χ̃⁰₁→γG̃ : non-pointing photons | L=4.7 fb^-1, 7 TeV [ATLAS-CONF-2013-016] | 230 GeV | χ̃⁰₁ mass | (0.4 < τ(χ̃⁰₁) < 2 ns)
χ̃⁰₁ → qqμ (RPV) : μ + heavy displaced vertex | L=4.4 fb^-1, 7 TeV [1210.7451] | 700 GeV | q̃ mass | (1 mm < cτ < 1 m, g̃ decoupled)
RPV
LFV : pp→ν̃_τ+X, ν̃_τ→e+μ resonance | L=4.6 fb^-1, 7 TeV [1212.1272] | 1.61 TeV | ν̃_τ mass | (λ'311=0.10, λ132=0.05)
LFV : pp→ν̃_τ+X, ν̃_τ→e(μ)+τ resonance | L=4.6 fb^-1, 7 TeV [1212.1272] | 1.10 TeV | ν̃_τ mass | (λ'311=0.10, λ1(2)33=0.05)
Bilinear RPV CMSSM : 1 lep + 7 j's + E_T,miss | L=4.7 fb^-1, 7 TeV [ATLAS-CONF-2012-140] | 1.2 TeV | q̃ = g̃ mass | (cτ_LSP < 1 mm)
χ̃⁺₁χ̃⁻₁, χ̃⁺₁→Wχ̃⁰₁, χ̃⁰₁→eeν_μ, eμν_e : 4 lep + E_T,miss | L=20.7 fb^-1, 8 TeV [ATLAS-CONF-2013-036] | 760 GeV | χ̃±₁ mass | (m(χ̃⁰₁) > 300 GeV, λ121 > 0)
χ̃⁺₁χ̃⁻₁, χ̃⁺₁→Wχ̃⁰₁, χ̃⁰₁→ττν_e, eτν_τ : 3 lep + 1τ + E_T,miss | L=20.7 fb^-1, 8 TeV [ATLAS-CONF-2013-036] | 350 GeV | χ̃±₁ mass | (m(χ̃⁰₁) > 80 GeV, λ133 > 0)
g̃ → qqq : 3-jet resonance pair | L=4.6 fb^-1, 7 TeV [1210.4813] | 666 GeV | g̃ mass
g̃→t̃t, t̃→bs : 2 SS-lep + (0-3b-)j's + E_T,miss | L=20.7 fb^-1, 8 TeV [ATLAS-CONF-2013-007] | 880 GeV | g̃ mass | (any m(t̃))
Scalar gluon : 2-jet resonance pair | L=4.6 fb^-1, 7 TeV [1210.4826] | 100-287 GeV | sgluon mass | (incl. limit from 1110.2693)
WIMP interaction (D5, Dirac χ) : 'monojet' + E_T,miss | L=10.5 fb^-1, 8 TeV [ATLAS-CONF-2012-147] | 704 GeV | M* scale | (m_χ < 80 GeV, limit of < 687 GeV for D8)
10^-1
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

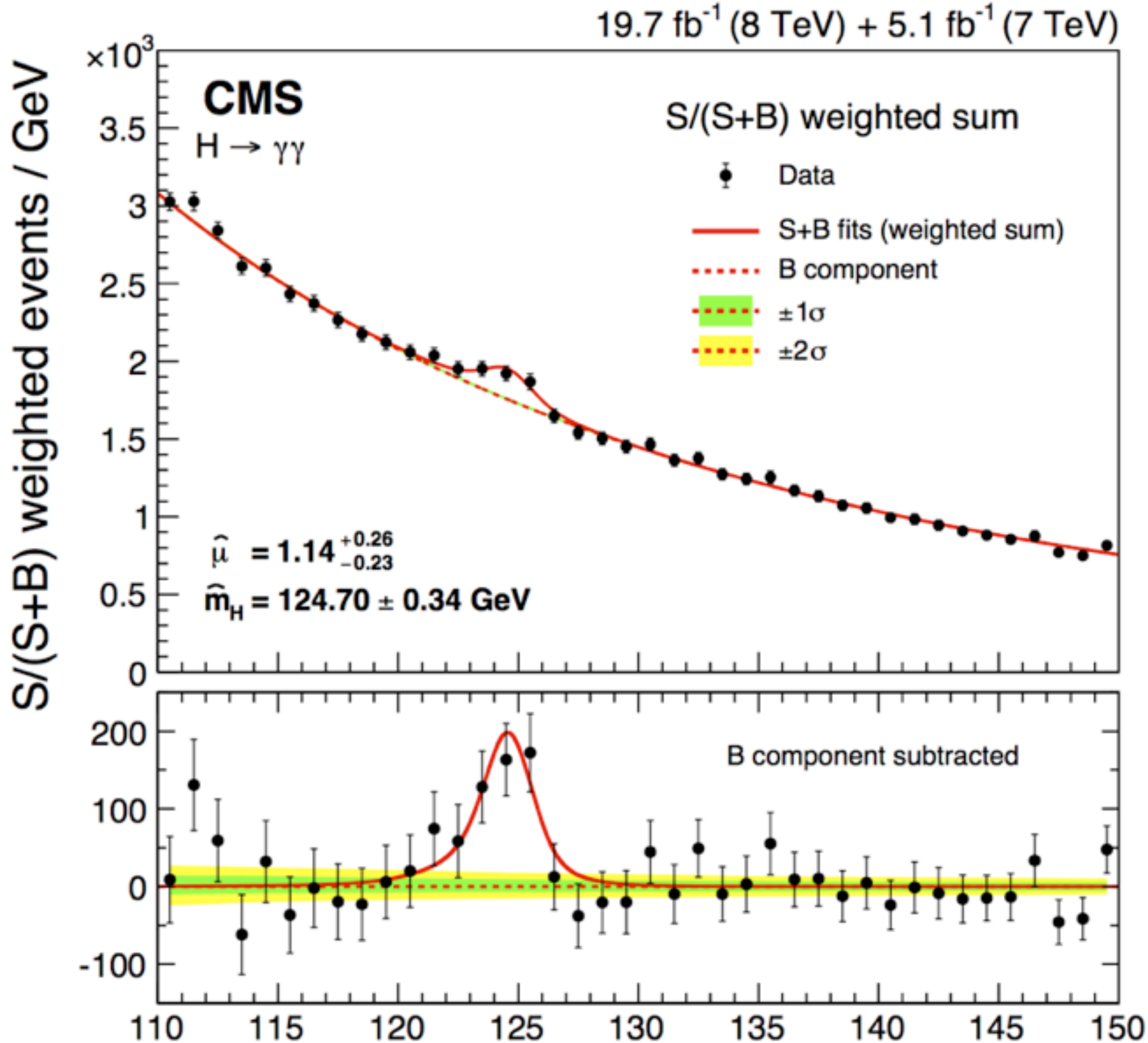

CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Heavy Resonances
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lν)
W' (dijet)
W' (td)
W'→ WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
4th Generation
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
Contact Interactions
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
Extra Dimensions & Black Holes
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
0 1 2 3 4 5
0 5 10 15

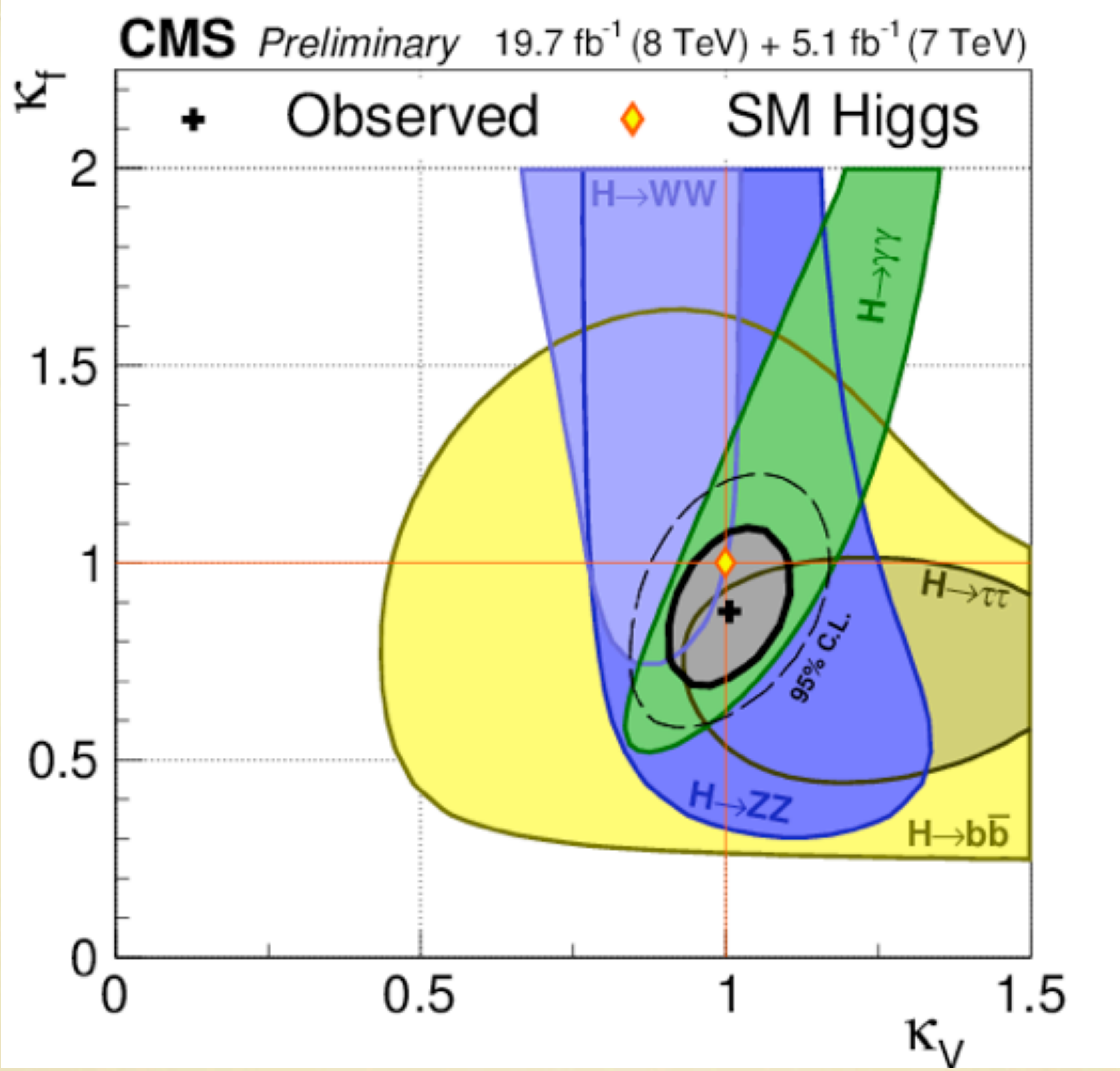


No sign so far of SUSY nor anything BSM !!

Perhaps new physics will arise at LHC-13 !!!

(perhaps WW excess?)

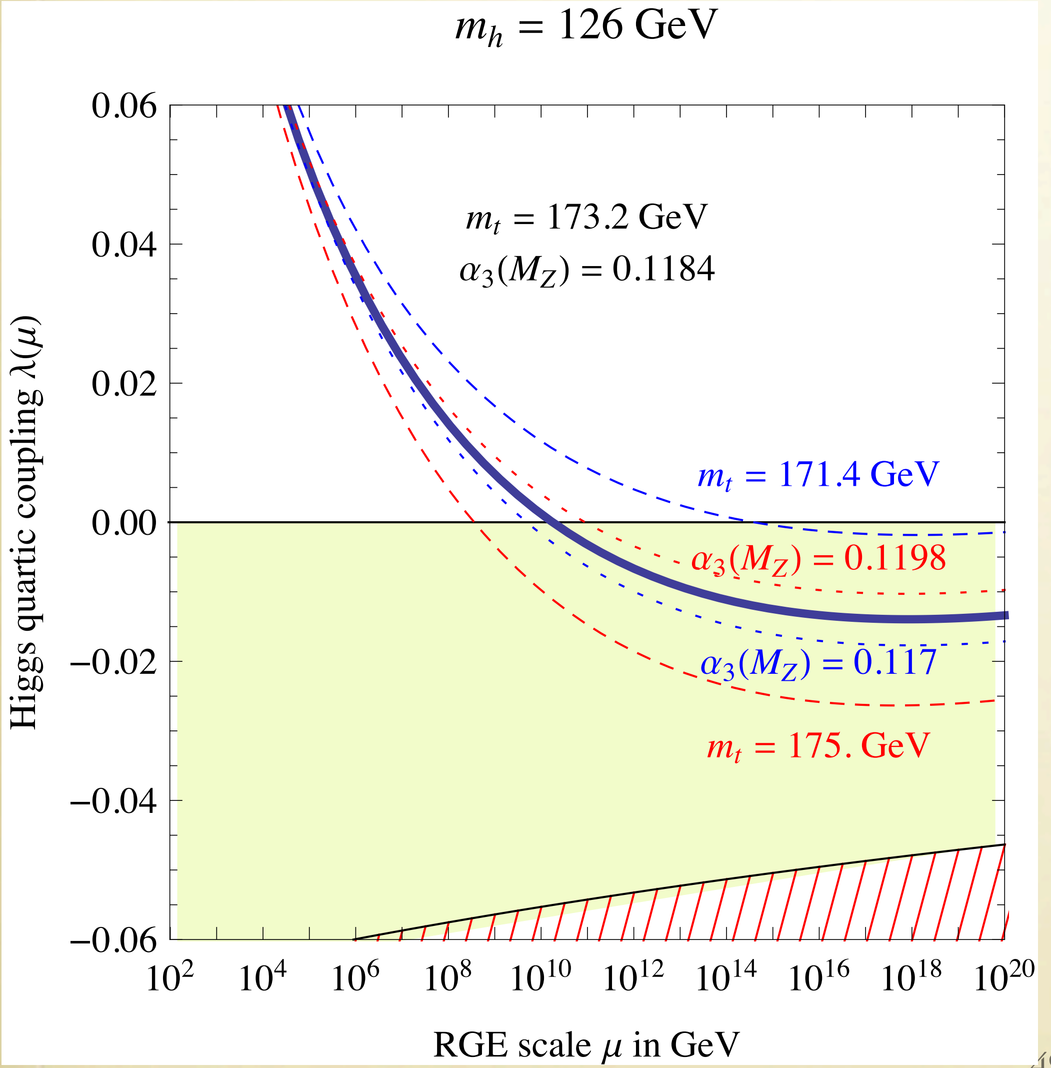

19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
H → γγ
S/(S+B) weighted sum
Data
S+B fits (weighted sum)
B component
±1σ
±2σ
μ̂ = 1.14 +0.26 −0.23
m̂H = 124.70 ± 0.34 GeV
S/(S+B) weighted events / GeV
×10³
B component subtracted
110 115 120 125 130 135 140 145 150



No sign of new physics in the Higgs couplings either...

STILL..

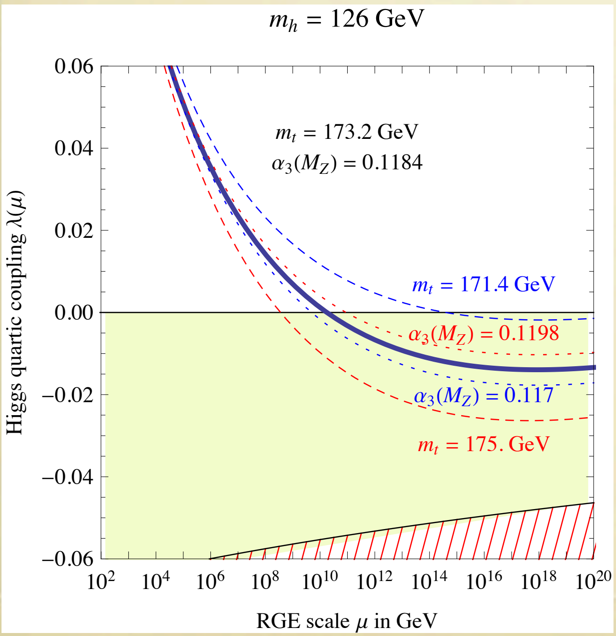
Just-SM unlikely to survive all the way to Planck scale:



- `Stability Problem´: the Higgs potential unbounded well below the Planck scale....

String Theory Suggests SUSY is present at some scale

- 1) It is a fundamental symmetry of string theory
- 2) To avoid the presence of tachyons in string compactifications
- 3) Additional reason: to stabilize the Higgs potential:



$$V = D^2 + F^2 \geq 0$$

Potential positive definite automatically

$SUSY\ could\ be\ realized\ at\ a\ scale \gg\ 1\ TeV$

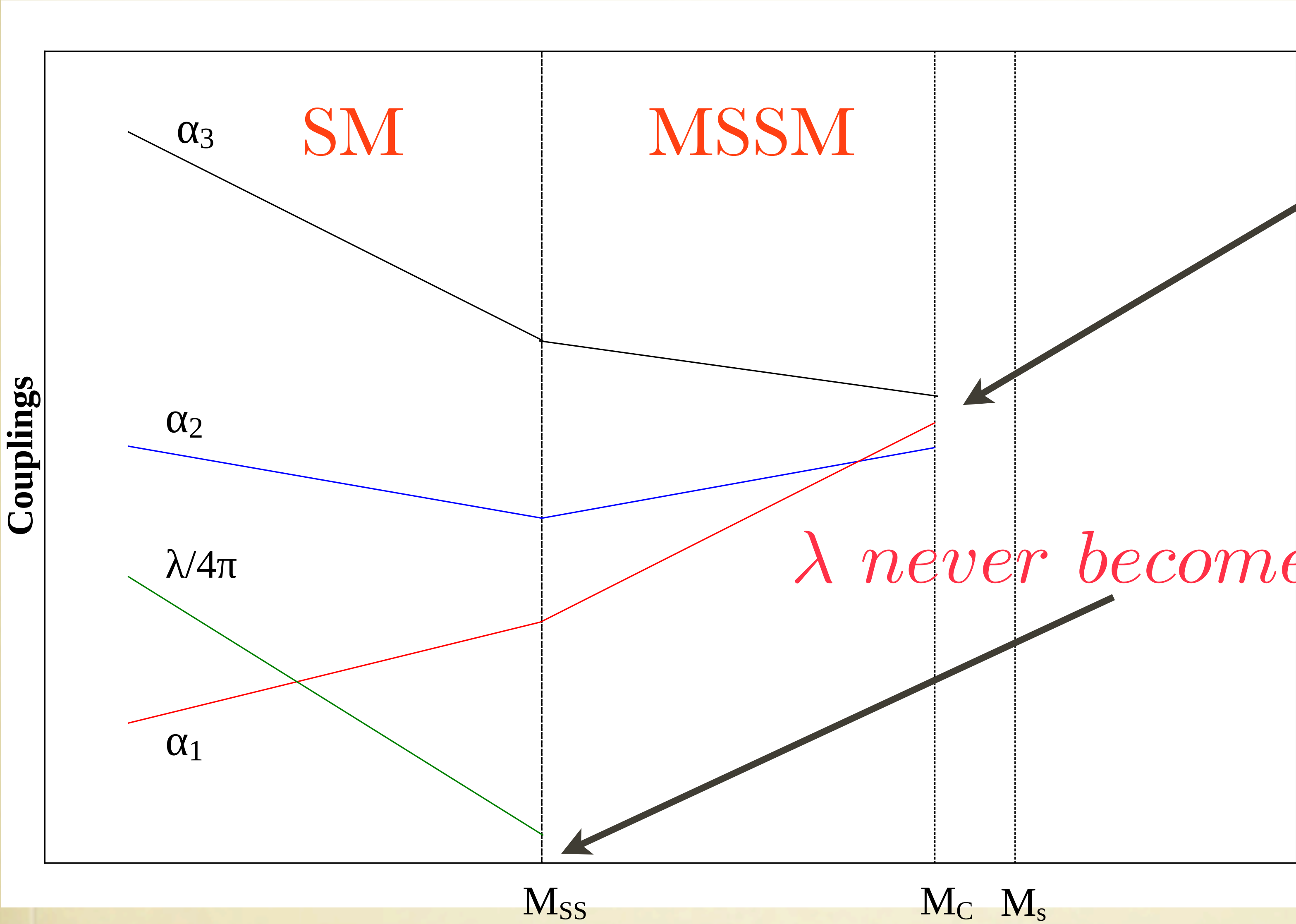
SUSY would be needed NOT to stabilize the hierarchy but to stabilize the SM vacuum

$This\ would\ require\ M_{SS}\ \leq\ 10^{11} - 10^{13}\ GeV$

$(before\ \lambda\ becomes\ negative)$

The solution of the hierachy problem would be then anthropic again...

Hebecker, and Weigand '12, '13 L.I, Marchesano, Regalado, Valenzuela arXiv:12, L.I. and Valenzuela 2013



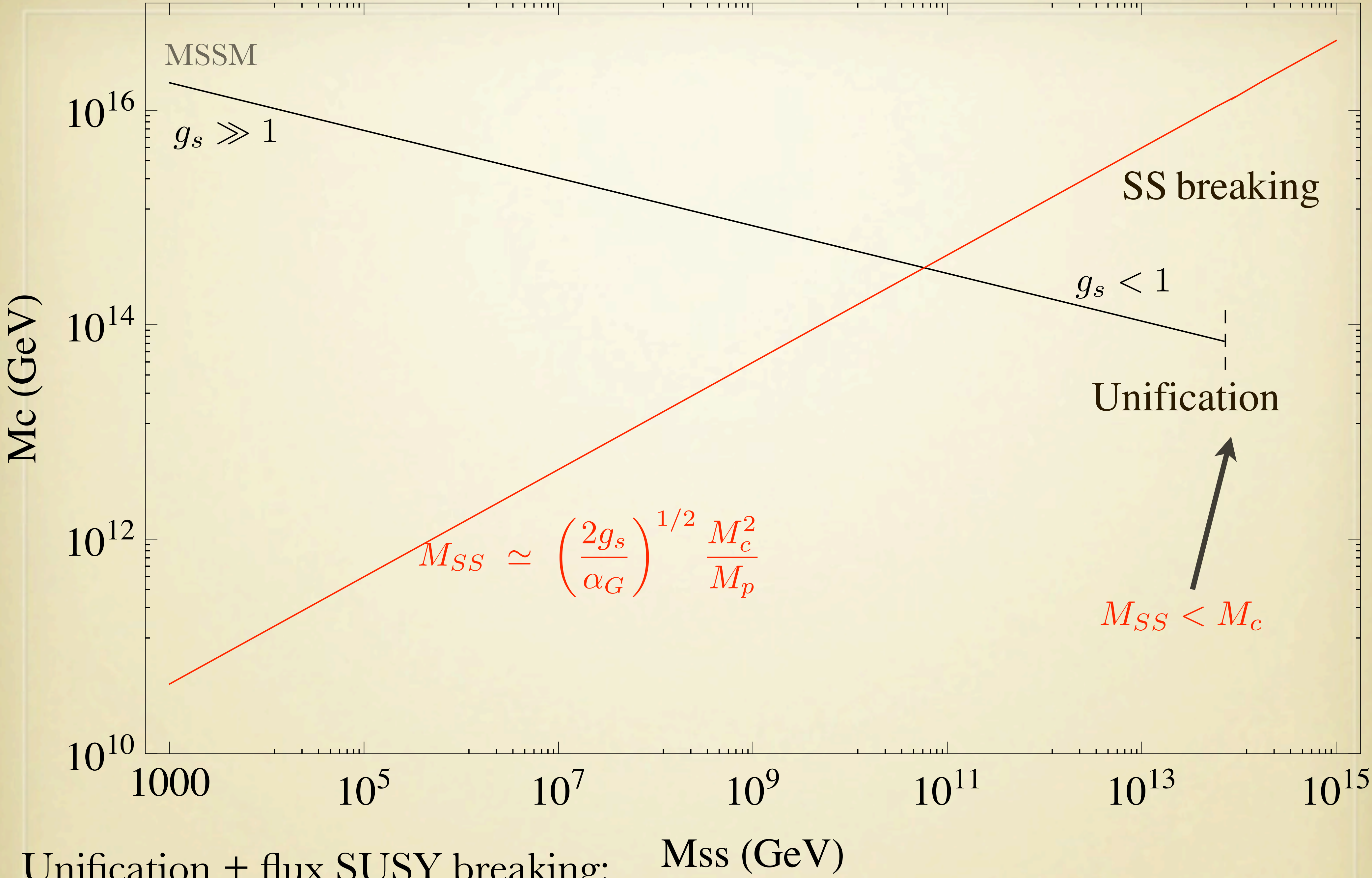
Threshold corrections

Blumenhagen'08

λ *never becomes negative* !!

Intermediate Scale SUSY Breaking

$$m_H \simeq 125\ GeV\ \ for\ M_{ss} \simeq 10^{10} - 10^{13}\ GeV$$



Unification + flux SUSY breaking:

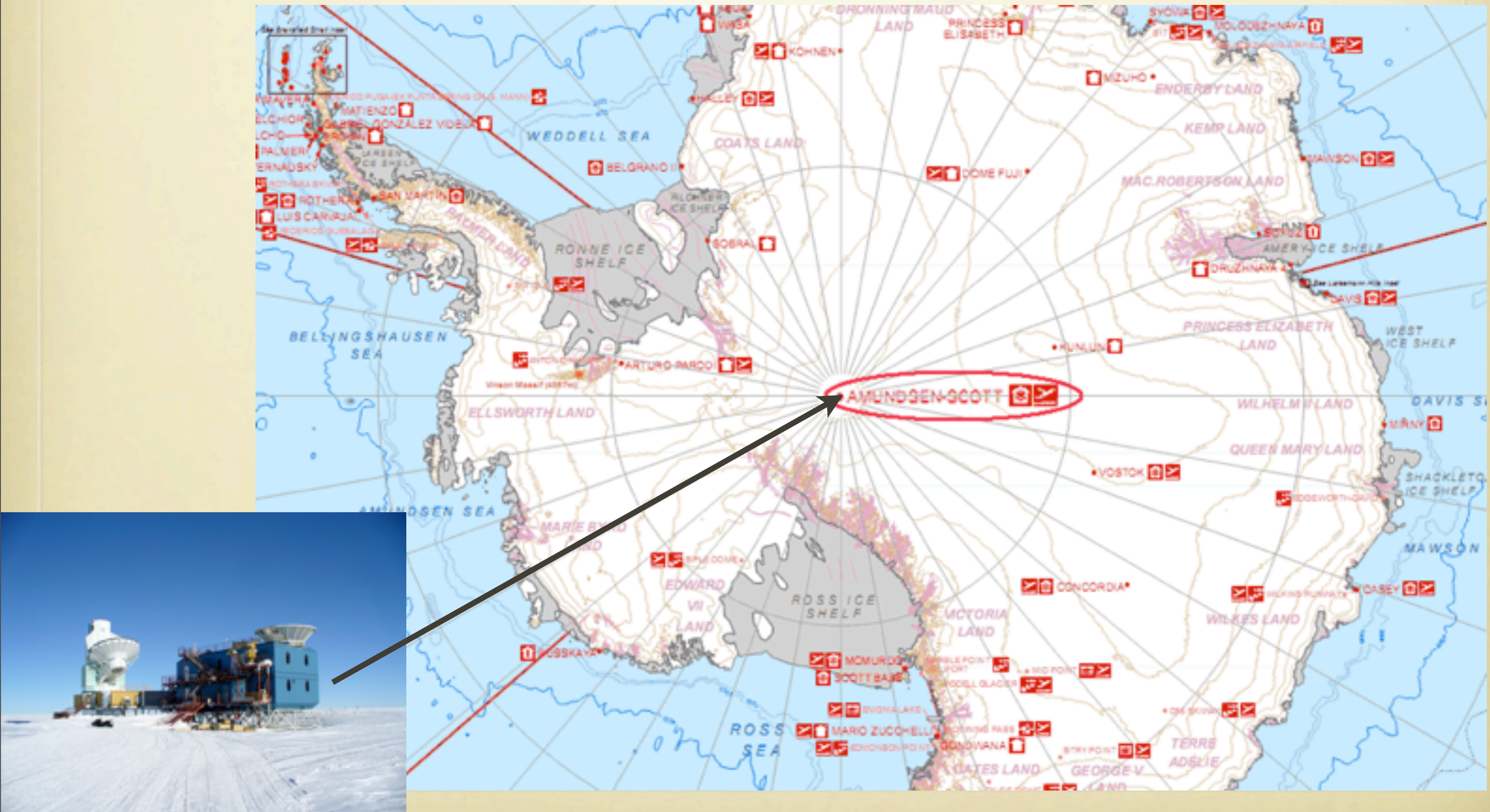
$$M_{SS} = 5 \times 10^{10}\ GeV\ ;\ M_c = 3 \times 10^{14}\ GeV$$

- SUSY breaking scale could be in the range $10^{10} - 10^{13}\ GeV.\ Consistent\ with\ m_H = 125\ GeV$

- Such scales arise if SUSY broken by isotropic bulk fluxes in Type IIB+ gauge coupling unification

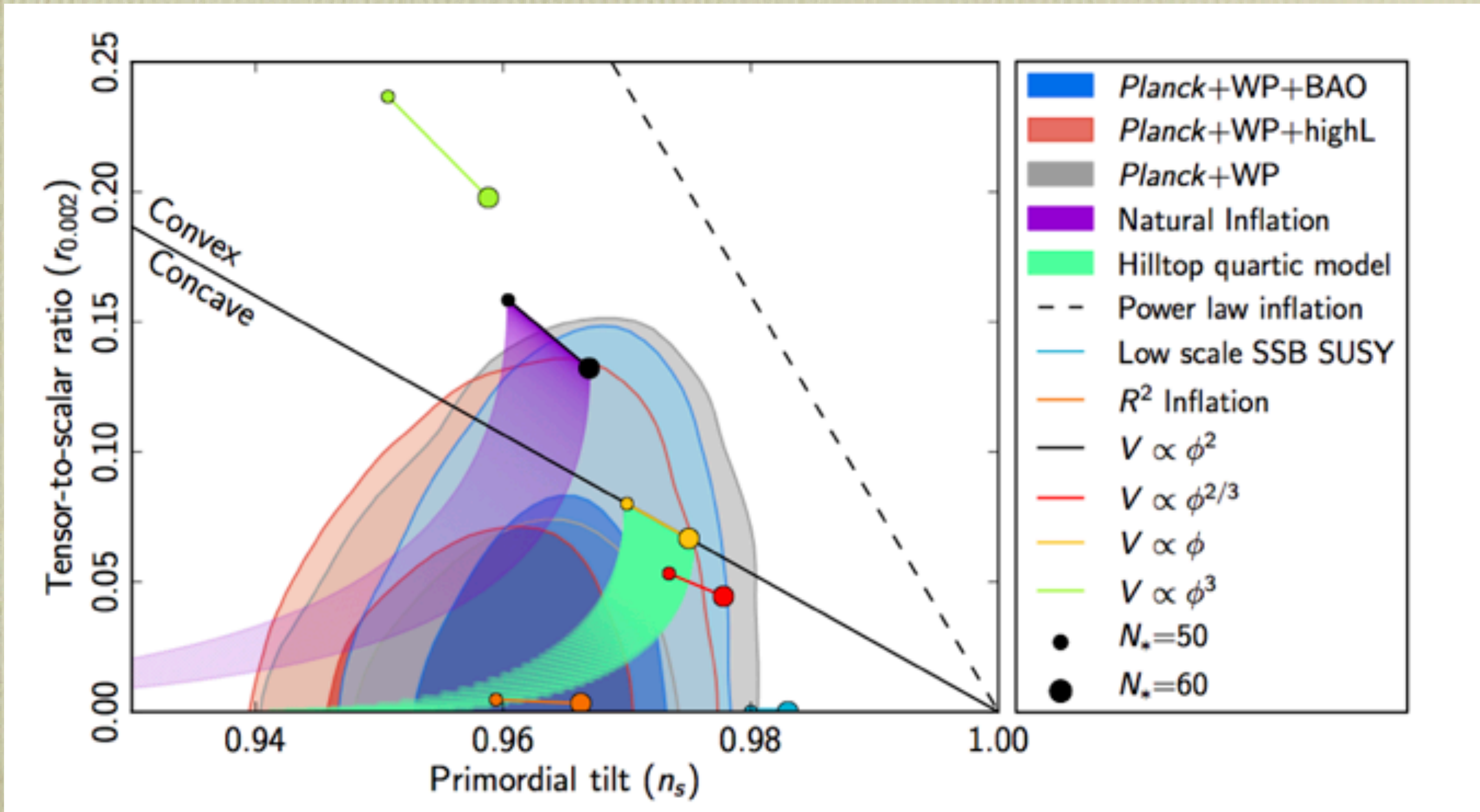
- No symmetries needed to suppress p-decay dim 4,5 operators nor doublet triplet splitting!!

The third crucial experimental input came (??) from the South Pole

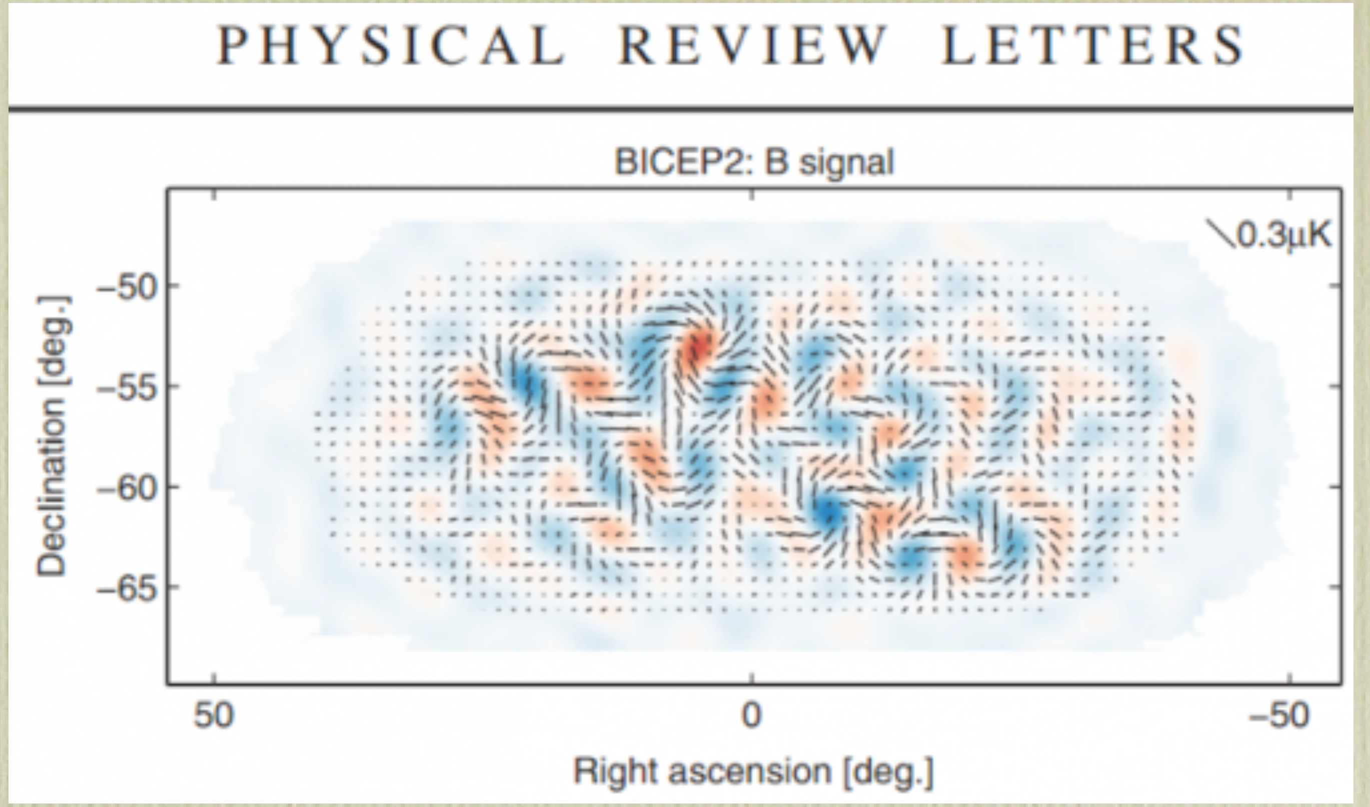


Inflation before March 17-th 2014

Planck:



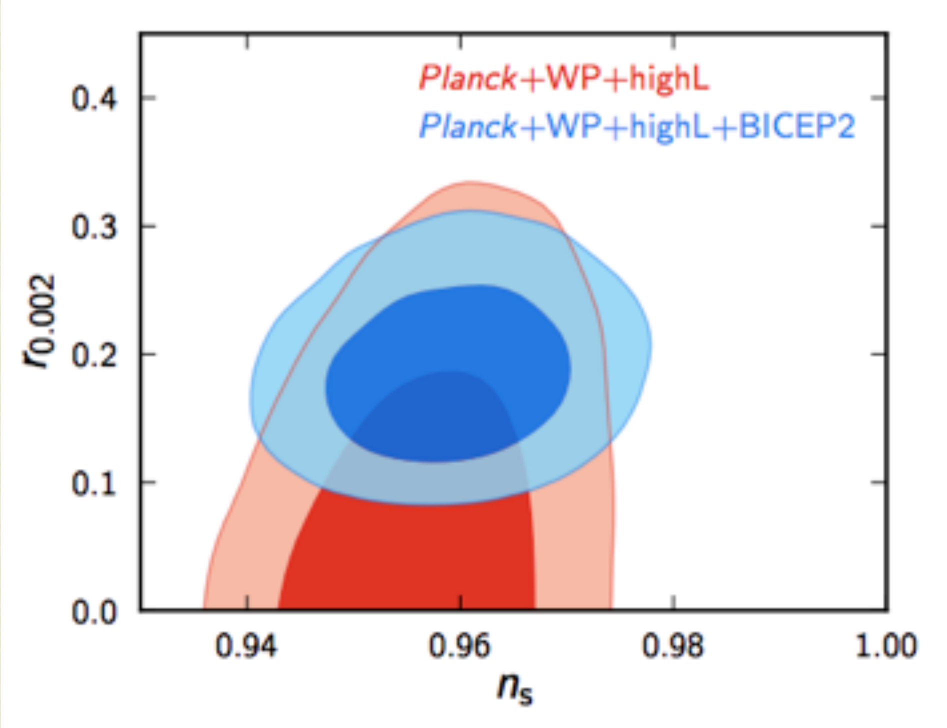
$$\phi^n \ , \ n \geq 2 \ close \ to \ exclusion\ldots$$



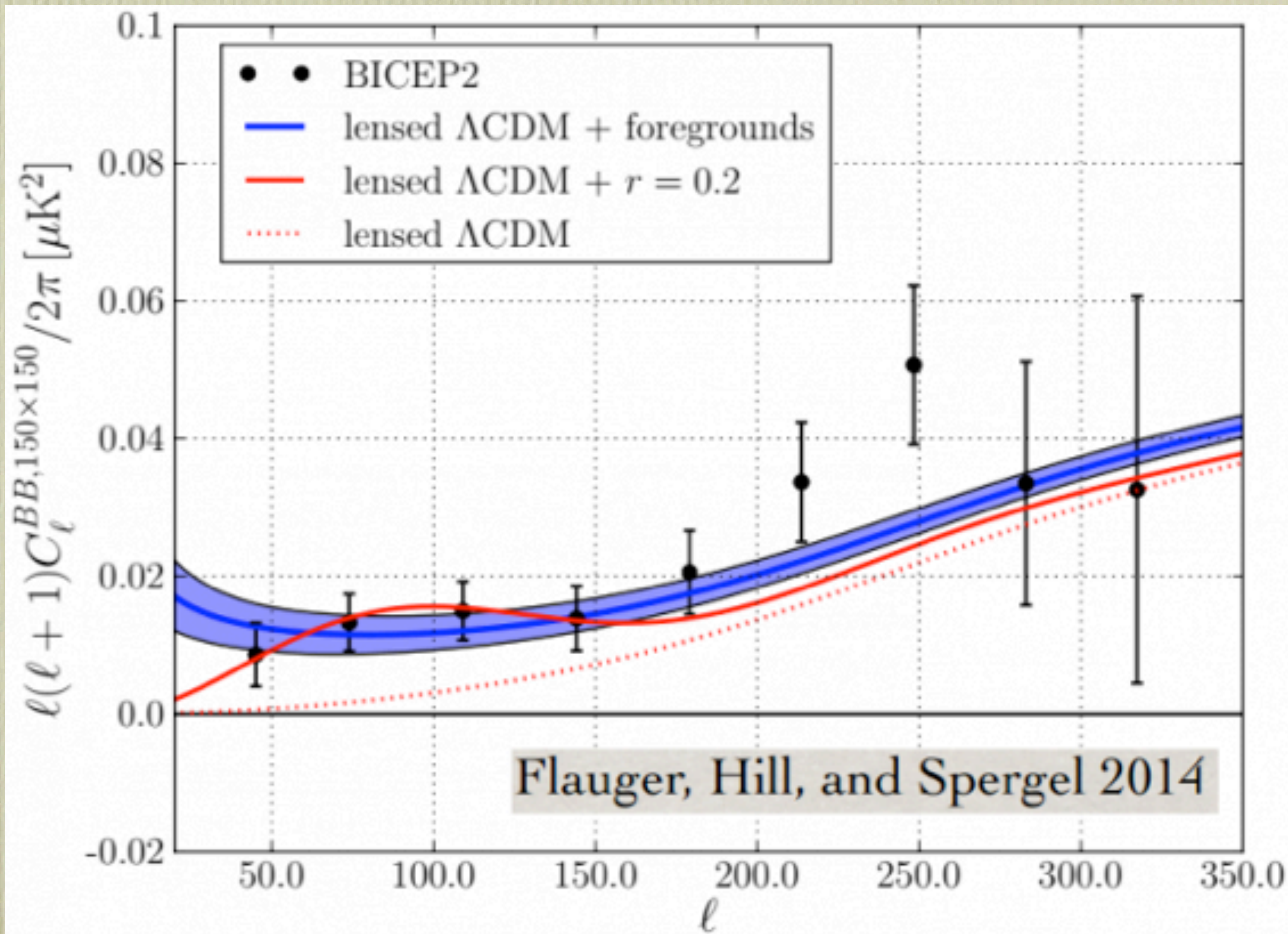
BICEP2

Primordial B-modes

$$r = 0.1 - 0.2$$



But the dust still has to settle....



B-mode power spectrum

Slow roll inflation

$$\epsilon = \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \quad , \quad \eta = M_p^2 \frac{|V''|}{V} \ll 1$$

Perturbations:

$$Scalar\ spectral\ index: \quad n_s - 1 = 2\eta - 6\epsilon$$

$$tensor/scalar\ ratio: \ r = 16\epsilon$$

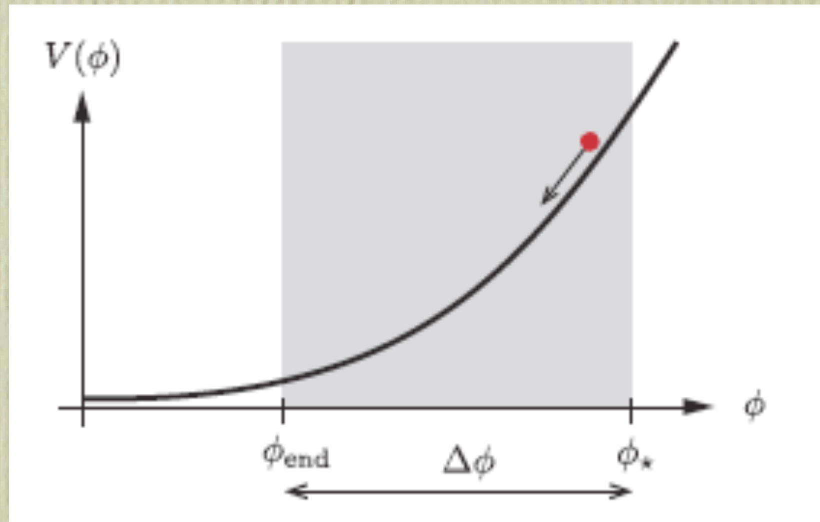
$$Number\ e-folds: \quad N_* = \frac{1}{M_p}\int_{\phi_{end}}^{\phi_*} \frac{d\phi}{\sqrt{2\epsilon}}$$

Lyth bound: $$\frac{\Delta\phi}{M_p} \geq \ 0.25 \ \left(\frac{r}{0.01}\right)^{1/2}$$

Large r requires trans-Planckian inflaton excursions

Chaotic Inflation

Linde 88

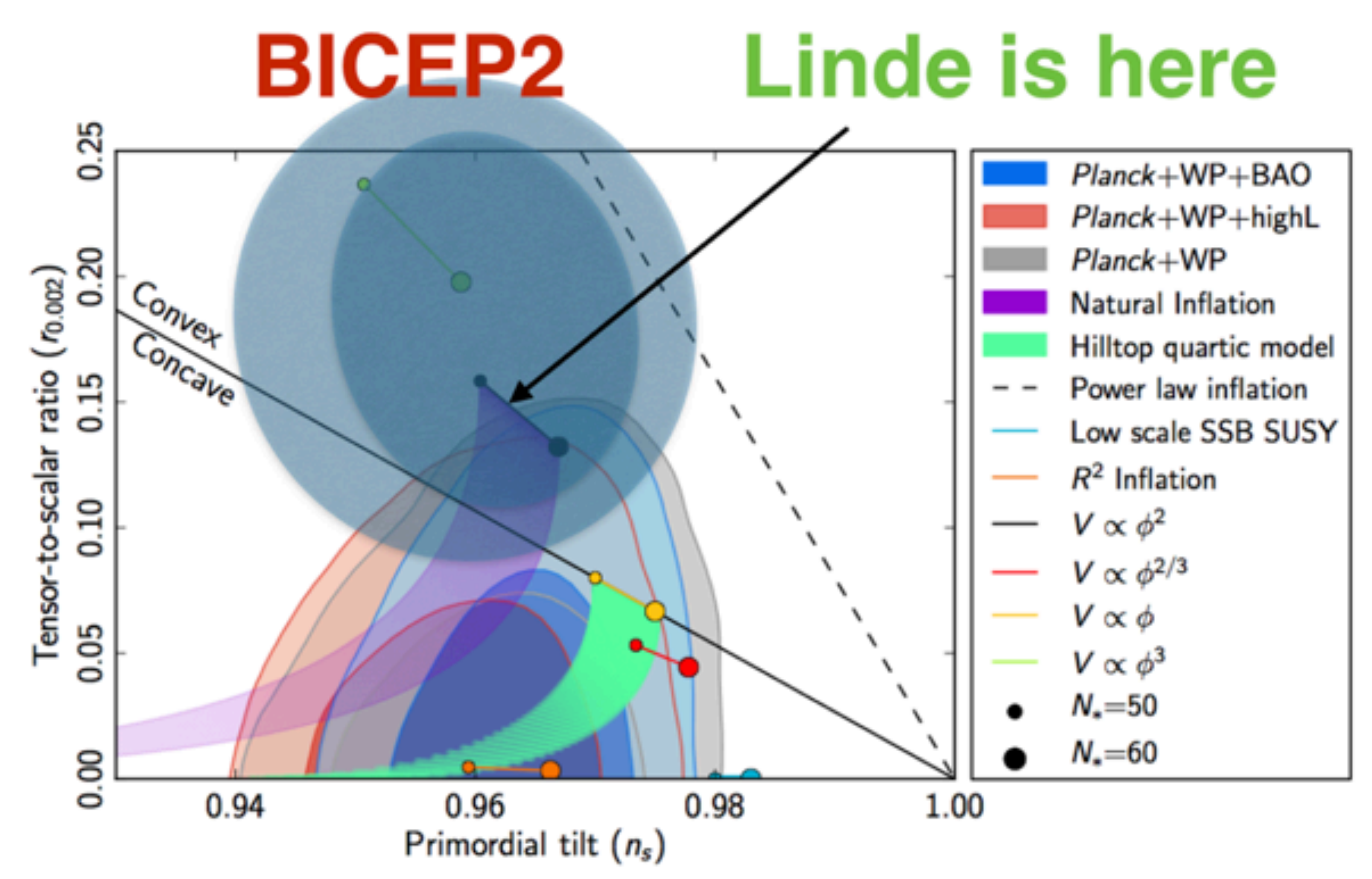


(Bauman McAllister book)

$$V(\phi) \;=\; \mu^{4-p}\phi^p$$

$$N_* \simeq \frac{1}{2p}\left(\frac{\phi_*}{M_p}\right)^2 \to trans - Planckian$$

$$n_s - 1 \;=\; -\;\frac{(2+p)}{2N_*} \quad , \quad r = \frac{4p}{N_*}$$



$p = 1:$	$n_s \approx 0.975\,,$	$r \approx 0.07\,,$	$\phi_\star \approx 11 M_{\rm pl}\,,$
$p = 2:$	$n_s \approx 0.967\,,$	$r \approx 0.13\,,$	$\phi_\star \approx 15 M_{\rm pl}\,,$
$p = 3:$	$n_s \approx 0.958\,,$	$r \approx 0.20\,,$	$\phi_\star \approx 19 M_{\rm pl}\,,$
$p = 4:$	$n_s \approx 0.950\,,$	$r \approx 0.27\,,$	$\phi_\star \approx 22 M_{\rm pl}\,.$

$$\phi_* \geq 10\ M_p$$

If BICEP2 correct:

$$V^{1/4} \simeq \left(\frac{r}{0.01}\right)^{1/4} \times 10^{16}\ GeV \simeq 10^{16} GeV$$

$$H_I \simeq \left(\frac{r}{0.20}\right)^{1/2} \times 10^{14}\ GeV$$

$$m_I \simeq 10^{13}\ GeV$$

String theory and large field inflation

Talks:

Nilles, Westphal, Burgess, Takahashi, Maharana, Hebecker, Sagnotti, Uranga, Shiu, Kaloper, Lust. . .

Scales in string large inflaton

10^{13} 10^{14} 10^{16} 10^{18} 10^{19}

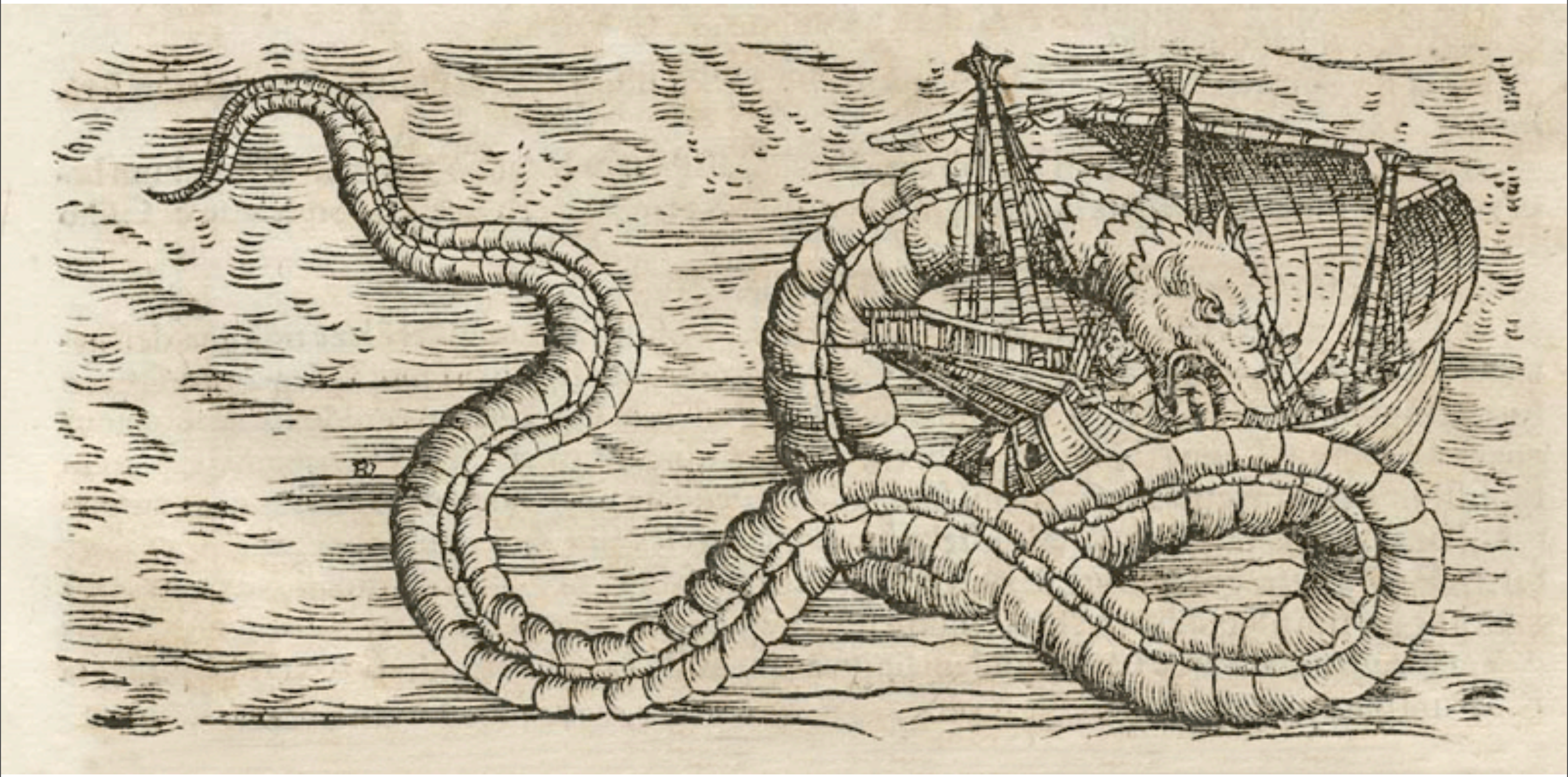
m_I H_I $V^{1/4}$ M_p ϕ_*

m_{moduli} M_c, M_{str}

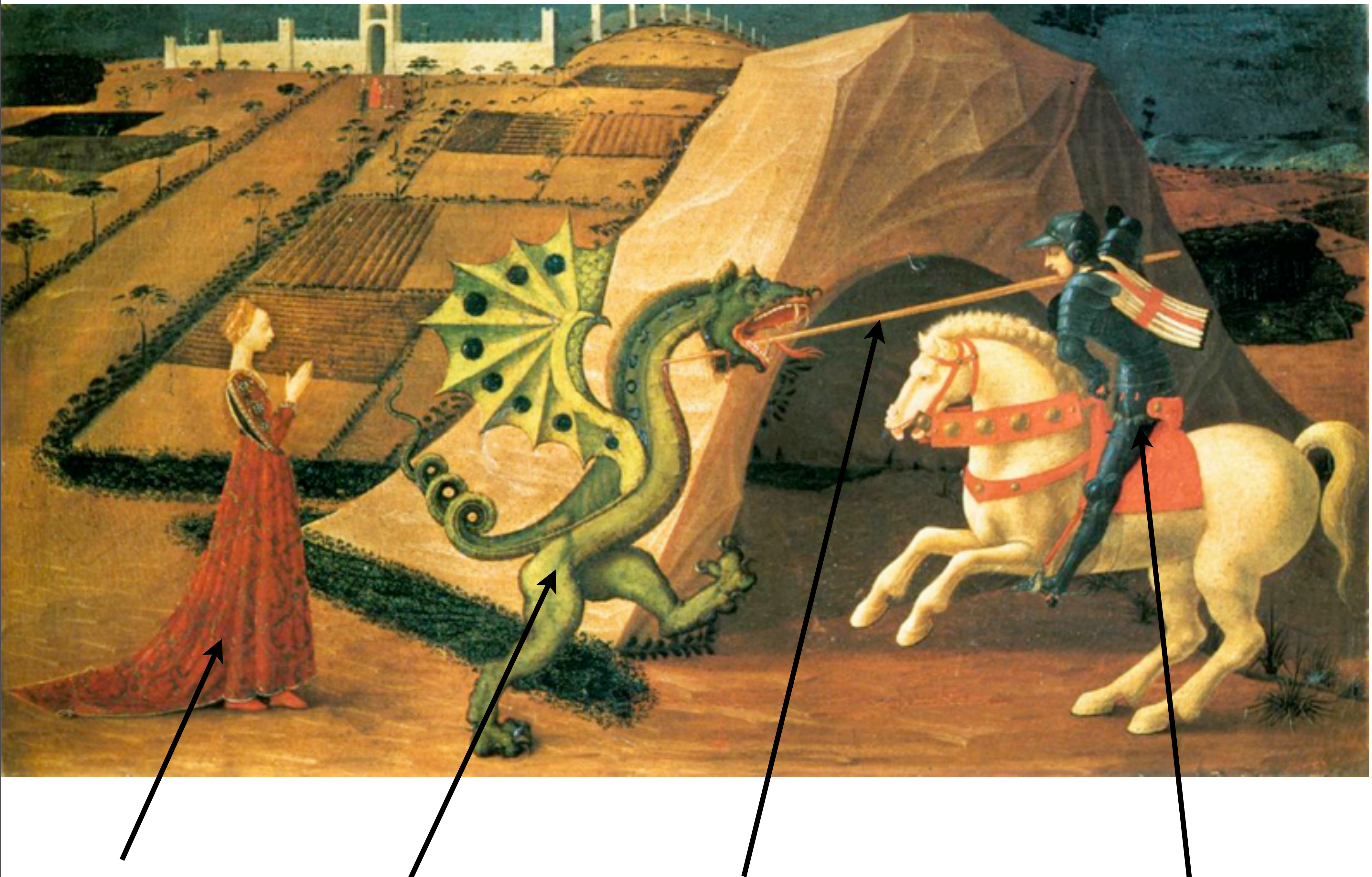
$D = 4$ *field theory ok*

$$\phi_* \simeq 10 M_p \; ok, \;\; as \; long \; as V(\phi)^{1/4} \leq M_c, M_{str}$$

But in the large field seas....



people say there are dragons....


Inocent Inflaton
Uncontrolled corrections
A shift symmetry
String Phenomenologist

$$10^{13} \quad 10^{14} \quad 10^{16} \quad 10^{18} \quad 10^{19}$$

$$m_I \quad H_I \quad V^{1/4} \quad M_p \quad \phi_*$$

NEED:

1) $Stable\ m_I \ll M_p\ (m_I \ll H_I\ if\ SUSY) : \eta\ problem$

2) $Large\ \phi_* \gg M_p\ possible$

3) $Corrections\ under\ control\ for\ \phi_* \gg M_p$

$$1), 3) \longrightarrow shift\ symmetry :$$

$$\phi \longrightarrow \phi + c$$

$$2) \rightarrow periodic\ moduli\ fields$$

$$\longrightarrow \phi = RR\ or\ NS\ axions; D - brane\ moduli$$

Non-trans-Planckian axion inflation

1) $One\ axion$ $\quad Requires\ f \geq 10\ M_p$

$$V\ =\ \lambda^4 \left(1 - cos\left(\frac{\phi}{f}\right)\right)$$

$\ldots problematic\ in\ string\ theory$

$see\ however$ Grimm, 14

2) $Two\ axions,\ two\ confining\ gauge\ groups$

KNP 2004

$$\sum_{i=1}^{2} \frac{\phi_i}{f_i} \left(c_a^i (F_a \wedge F_a) + c_b^i (F_b \wedge F_b)\right)$$

$$\rightarrow\ V = \Lambda_a^4 \left(1 - cos(c_a^1 \frac{\phi_1}{f_1} + c_a^2 \frac{\phi_2}{f_2})\right) + \Lambda_b^4 \left(1 - cos(c_b^1 \frac{\phi_1}{f_1} + c_b^2 \frac{\phi_2}{f_2})\right)$$

$For\ c_a^1 c_b^2 = c_b^1 c_a^2\ one\ effective\ f_{eff}\ can\ be\ very\ large$

$Embedded\ in\ string\ theory?$ Ben-Dayan, Pedro, Westphal

3) $N\ axions:\ \ N - flation$

$N \simeq 10 - 1000,\ renormalize\ G_{Newton}$

Dimopoulos et al 2008

Maharana talk

Monodromy inflation

$V(\phi)$

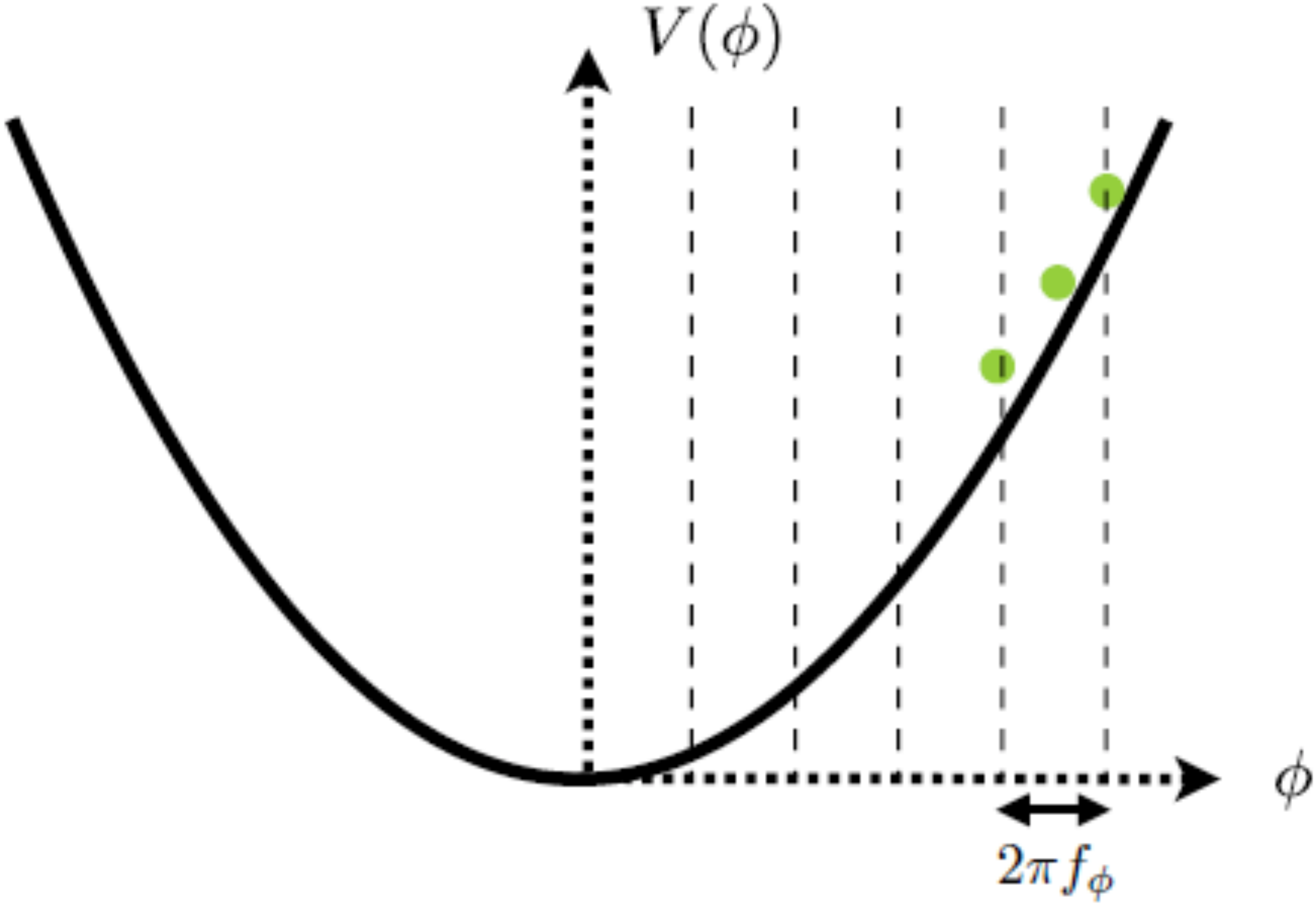
$B_2, C_2, \phi_{brane}, \ldots$

Silverstein, Westphal 08;
McAllister, Silverstein, Westphal
Kaloper, Sorbo 08

Gur-Ari, 13

Marchesano, Shiu, Uranga , 14

Talks:
Westphal, Hebecker,
Uranga, Shiu, Kaloper,...


$V(\phi)$
ϕ
$2\pi f_\phi$

1) Monodromy inflation from DBI

Silverstein, Westphal 08;
McAllister, Silverstein, Westphal

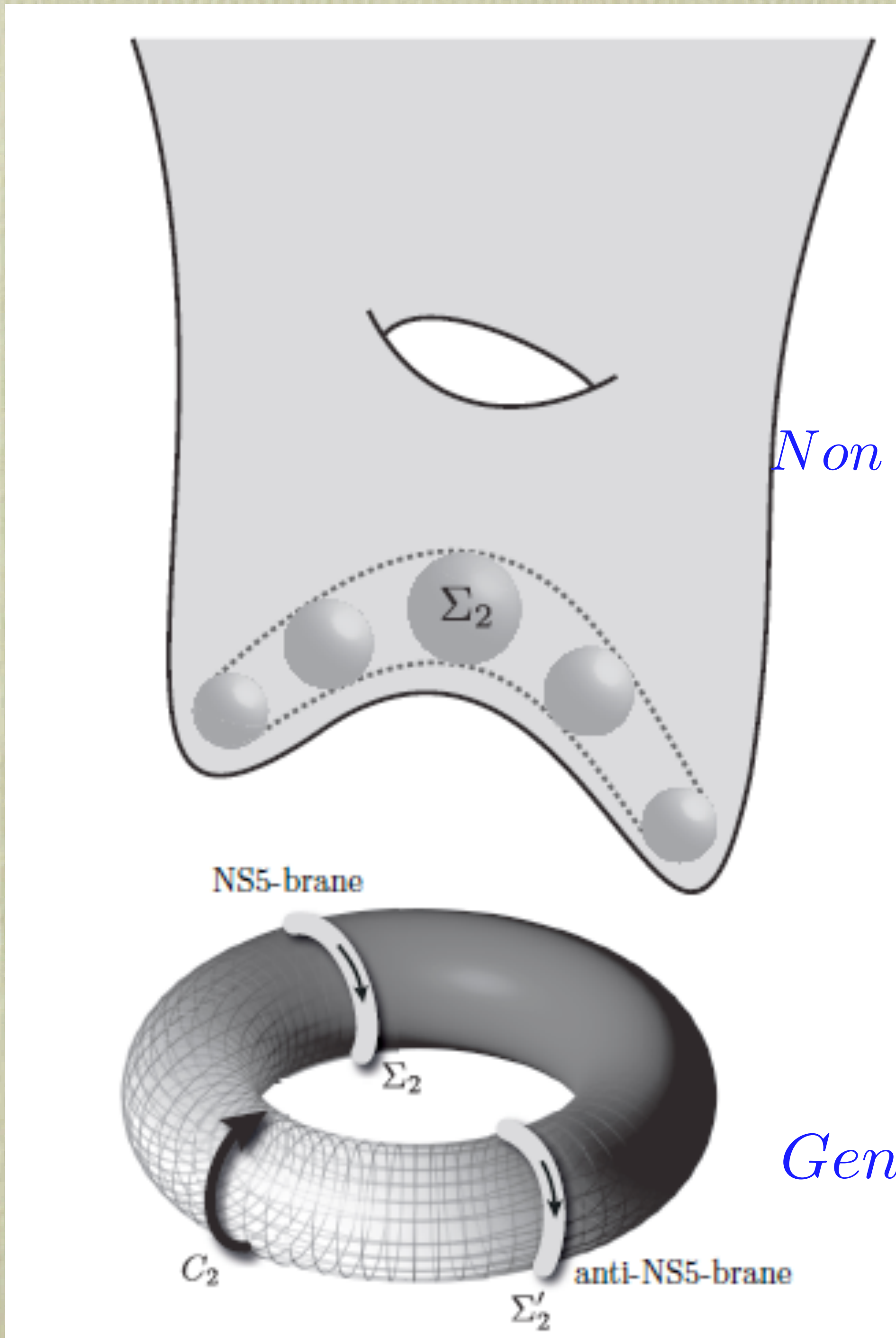
$Consider\ a\ O(3)/O(7)\ IIB\ orientifold.\ Can\ have\ axionic\ moduli:$

$$b = \int_{\Sigma_2^-} B_2 \quad , \quad c = \int_{\Sigma_2^-} C_2 \qquad (shift\ symmetry)$$

$Consider\ a\ D5-brane\ wrapping\ \Sigma_2^-$

$$V_{DBI} \propto \int_{M_4 \times \Sigma_2^-} \sqrt{-det(G+B)} \propto \sqrt{L^4 + b^2}$$

$Breaks\ shift\ symmetry:\ linear\ potential\ for\ large\ b$



(from Baumann+McAllister book 14)

$D3$ *tadpole cancellation and preservation of shift symmetry....*

Non − SUSY configuration.Back − reaction could be strong

$$V \simeq \mu^3 \phi + \Lambda^4 cos(\frac{\phi}{f_a})$$

subleading modulations

Generalization with $(p, q) - 7 -$ *branes*

(Palti, Weigand 14)

2) Monodromy with no D-branes

- Monodromy induced on axions via Fluxes:

Kaloper, Sorbo 08; Marchesano, Shiu, Uranga, 14

$$\int dx^4 \ |db_2 - C_3|^2 \ + \ |F_4|^2$$

$$C_3 \ \rightarrow \ C_3 \ + \ d\Lambda \ , \ b_2 \ \rightarrow \ b_2 \ + \ \Lambda$$

$d\phi = *db_2$

$$\phi F_4 \ + \ |F_4|^2 \ \longrightarrow \ (|F_4|^2)\phi^2$$

$$F - term\ monodromy\ from\ fluxes$$

$$shift\ symmetry\ has\ a\ gauge\ origin$$

$$may\ be\ embedded\ in\ string\ theory:\ \phi\ = massive\ W.L.$$

Marchesano, Shiu, Uranga, 14

McAllister, Silverstein, Westphal, Wrase 14

- Many examples:

$$1)\ Type\ II-A\ ,\ T=\int_{\Sigma_2}(J+iB_2)\ :$$

$$W\ =\ eT-qT^2+mT^3\ ,\ m=F_0\ ,\ q=\int_{\Sigma_2}F_2\ ,\ e=\int_{\Sigma_2}F_4$$

$quartic\ scalar\ potential$

$$2)\ See\ directly\ from\ D=10\ action:$$

$$L=-\int dx^{10}\left(\frac{1}{g_s^2}|H_3|^2+\sum_p|\tilde{F}_p|^2\right)$$

$$e.g.\ \tilde{F}_4=dC_3+C_1\wedge H_3+mB\wedge B,\ \rightarrow\ \ V\simeq m^2|B|^4$$

$$(expected\ to\ flatten\ at\ large\ B\ldots)$$

3) Monodromy with D-branes+fluxes

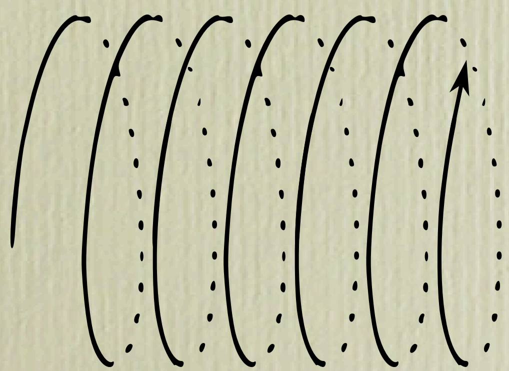
- Inflatons are W.L. or position moduli from branes

Silverstein, Westphal 08; Gur-Ari 14; Marchesano et al 14

$$1)\ D - branes\ wrapping\ twisted\ tori$$

$$Inflaton\ =\ D - brane\ position\ on S^1.$$
$$Monodromy\ from\ DBI\ +\ geometric\ flux$$

$$V(\phi)\ \simeq\ \phi^{2/3}, \phi, \phi^{6/5}, \phi^{4/3}, \phi^2\ \ (for\ large\ \phi)$$

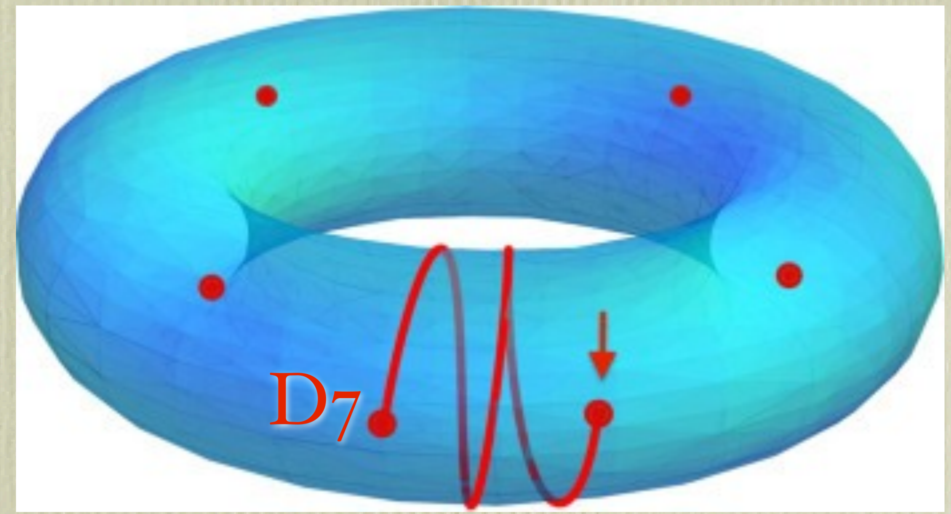


$2)\ D7 - branes\ in\ IIB\ orientifolds\ with\ fluxes$

$$Large\ c.s.\ limit\ features\ shift\ symmetry$$

$$Inflaton = position\ modulus$$

Hebecker, Kraus, Witkowwski 14



$$Monodromy:\ superpotential\ from\ fluxes$$

$$Quadratic\ potential\ (for\ small\ field)$$

$$(also\ D3's\ wrapping\ 1 - cycles)$$

Shlaer 12

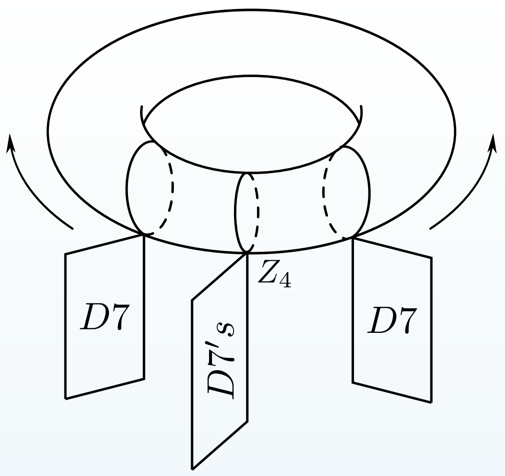
3) *Inflaton as a SUSY partner of the Higgs*

6 D7-branes at $(\mathbf{C^2} \times \mathbf{T^2})/Z_4$ *L. I. Valenzuela 14*

Gauge group: $U(3) \times U(2) \times U(1)$

Matter fields: $2(3,\overline{2}) \; + \; 2(1,\overline{3}) \; + \; (1,2) + (1,\overline{2})$

vector pair: H_u , H_d



$U(2) \times U(1) \to U(1) \times U(1)$

One U(2)-brane + U(1)-brane can leave the singularity in opposite directions.

- Relative position:

$\langle H \rangle \equiv \langle H_u + H_d^* \rangle \neq 0$

↳ Inflaton

Open string modulus monodromy inflation:

✦ Periodic behaviour around 1-cycle of T^2.

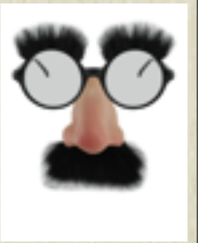
✦ Addition of closed string fluxes: generate monodromy and the potential.

Potential linear at large field from DBI.

• Chaotic inflation naturally arises in string models where inflaton=axion,W-L,D-moduli, may have a large field range

• Stability at large field provided by continuous/discrete shift symmetries and periodicity of spectrum

•Generic: flattening of potential for large inflaton: N=1 SUGRA leading effective action may be not sufficient....



That's all very nice. But you have first to fix all moduli before talking about inflation!!

Yep. But advances are done step by step. It is not unreasonable to assume that moduli are fixed at a somewhat larger scale and study the consequences.....

BICEP2 announcement has been very positive for the field. If the results are confirmed, most string inflationary models ruled out. This shows explicitly that experimental data can test the theory

Even if eventually not confirmed, it has forced us to test the theory in a challenging regime, giving rise to brand new ideas and scenarios.

Axions and axion-like particles

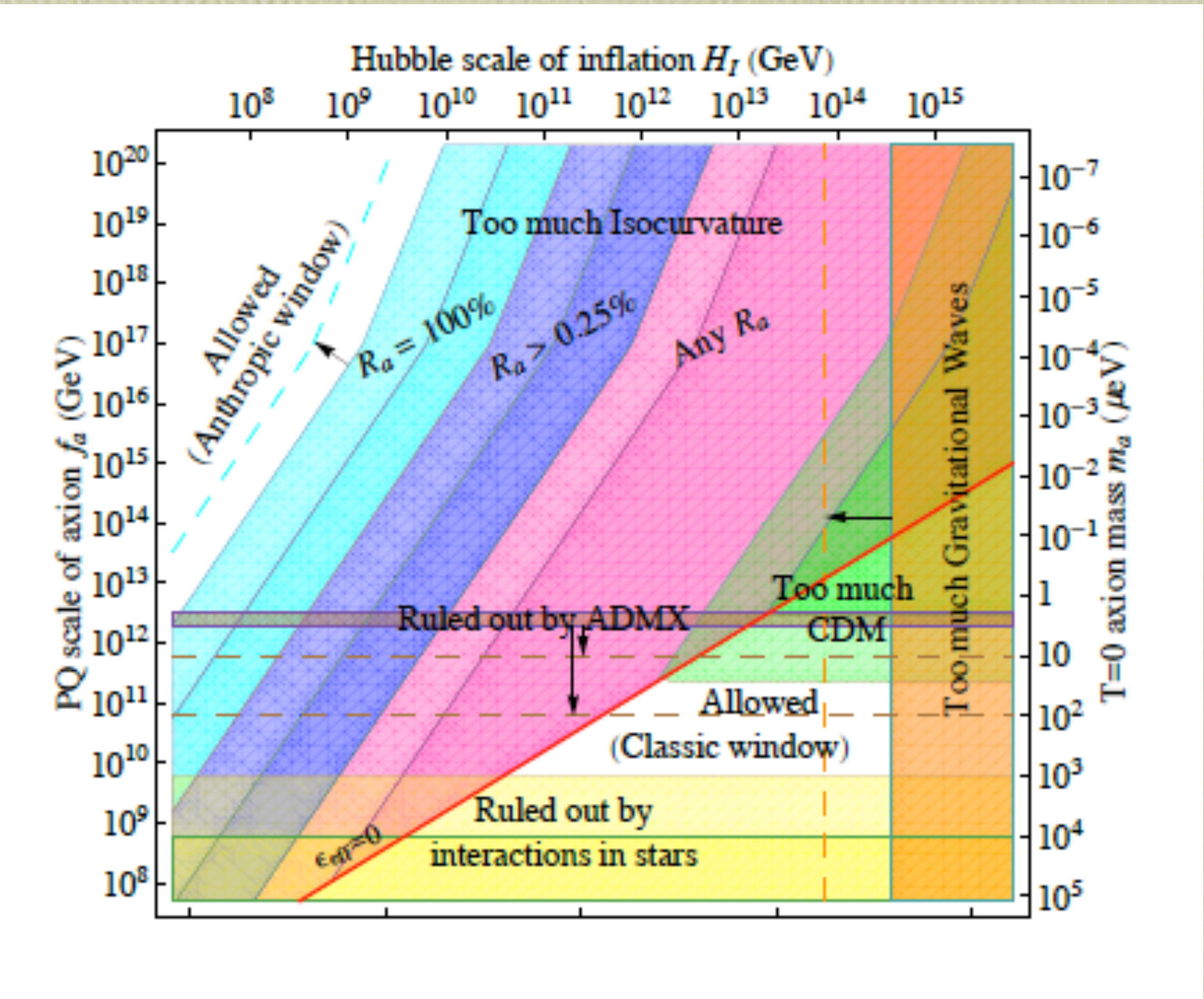
- Axion-like particles are abundant in string theory ($from\ B_2,\ C_n, ...$)

- One linear combination of these could remain massless and act as a QCD axion

- Others could also remain light and give rise to cosmological and/or astrophysical signatures.

Talks by Marsh, Conlon,....parallels

QCD axions after BICEP2 (??)



Ringwald 14

$$f_a < 10^{12}\ GeV$$

To avoid too much isocurvature perturbations..

Axion-like states in cosmo/astro

EXAMPLE: Pseudo-scalar partner of lightest modulus in LVS

Talks by Marsh, Conlon,....parallels

- Dark radiation

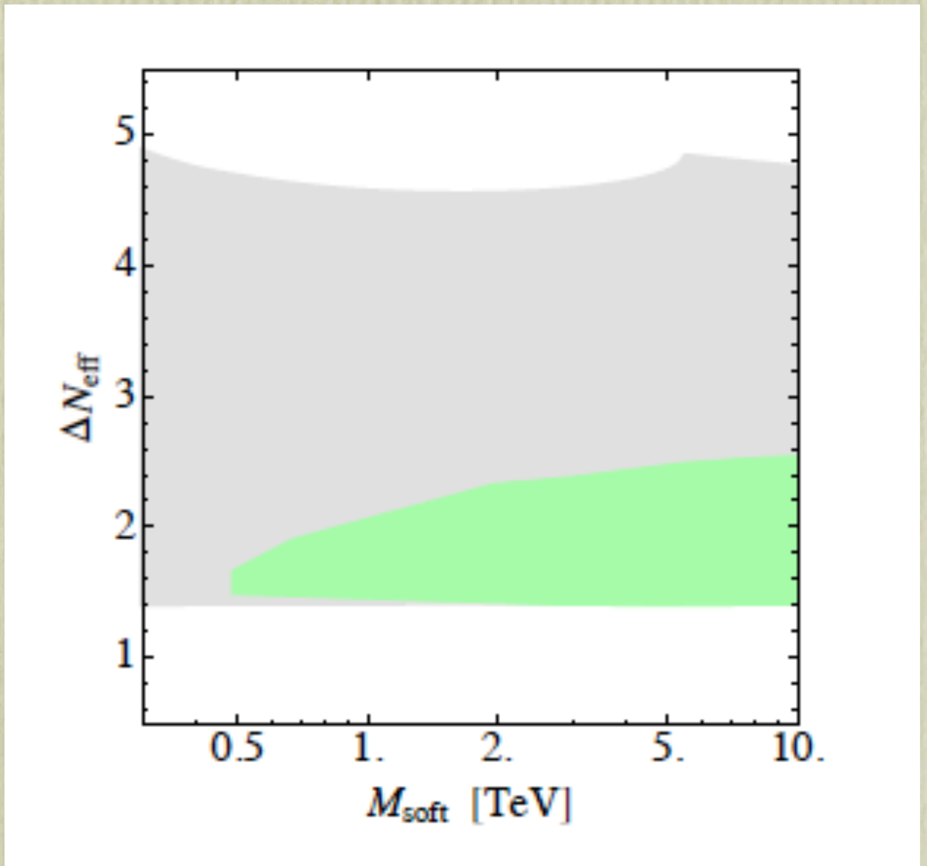
- Difusse gamma rays in clusters of galaxies (axion-photon conversion)

- 3.55 KeV gamma ray line in Andromeda and clusters

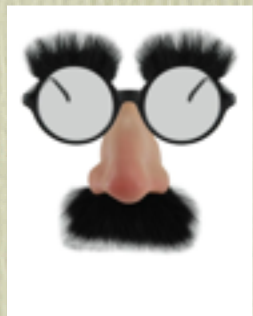
Dark radiation in minimal LVS:

Conlon, Marsh, Angus,....,parallels

$$N_{eff} = 3.52^{+0.48}_{-0.45}\ ,\ with\ H_0 = 67.3 \pm 1.2\ Km\ s^{-1} Mpc^{-1}$$



- Shows how data can rule out specific string models!



COMMENT:

- Axion-like particles in string theory tend to get masses easily: GS mechanism, bulk fluxes, instantons......

- It is probably too optimistic considering scenarios like N-flation or an ‘axiverse” with hundreds of light ALP’s

Other data can give us important info

- Proton decay. Could be sizable in large SUSY-breaking *Talks by Hebecker, Kumar, Valenzuela*
- U(1)'s: milicharged particles *Marchesano*
- SUSY at LHC. If found, specific models provide patterns for soft terms

Talks by Antoniadis, Ovrut, Kumar, Kripendorf,...

Formal versus less formal

- One historical characteristic of SP is that has always been eager to explore possible phenomenological applications of new formal developments (and viceversa, recall dualities).

- E.g., Double field theory, Gauged supergravity, Instantons, Matrix models, Topological field theory,.... could perhaps be crucial in future developments...

Talks by Jockers, Martucci, Lust, Triendl..

Next decade:

2015 — BICEP2 confirmed

SUSY found at LHC

M-theory/Geometry phenomenology

2020 — Unified flux techniques developed

Axions detected

First complete stable SM vacua

2025 — ....

THANK YOU!!!!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SEE YOU ALL IN MADRID !!!!