String Compactifications and low-energy SUSY: The last attempts?

F. Quevedo,
ICTP/Cambridge

Strings 2015,
Bangalore, June 2015

Collaborations with (linear combinations of):
L. Aparicio, M. Cicoli, B Dutta, D. Klevers, S. Krippendorf, A. Maharana, C. Mayrhofer, F. Muia, R. Valandro
arXiv:1312.0014, arXiv:1409.1931, arXiv:1502.05672, + to appear

Low-energy SUSY Bottom-up
Recall:

- **Hierarchy problem**
- **Gauge coupling unification**
- **(Thermal) WIMP Dark matter**
- **REWSB**

Top-down: ~~SUSY~~ in 4D Strings

★ Calabi-Yau compactifications N=1 ✓

CHSW 85

★ Moduli stabilisation ✓?

★ SUSY breaking: ✓?

- Fluxes (GKP),
- Nonperturbative effects (racetrack),
- Antibranes (KKLT)

Strings, MSSM and LHC

- Accept 1/100-1/1000 tuning as ‘natural’
- Extend the MSSM
- Address hierarchy problem differently within SUSY
  - Tuned MSSM
  - Split SUSY (heavy sfermions, TeV fermions)
  - Large SUSY breaking scale
- Non-SUSY approaches to hierarchy problem

Golden opportunity for string scenarios

String Phenomenology:

Long-term goal:

String theory scenarios that satisfy all particle physics and cosmological observations and hopefully lead to measurable predictions

Progress in several ways

- **‘Generic’ model independent results**
- **Explicit constructions of (classes) of models**
- **Explicit computations of EFT**
- **Extract scenarios that can lead to eventually ‘testable’ predictions.**

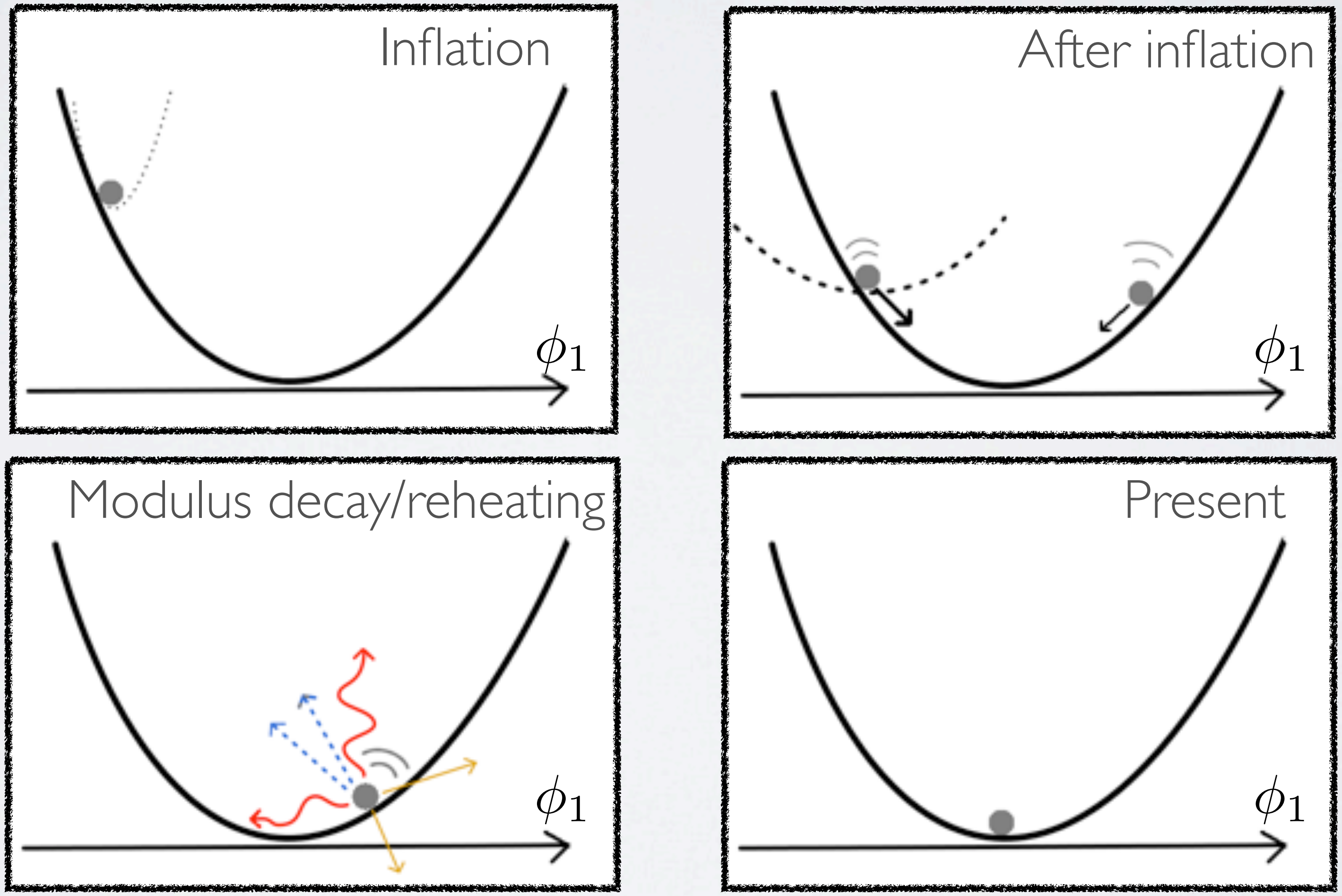
`Generic 4D String Predictions'

- SUSY, small irreps, branes, fluxes, axions, no global symmetries,...

- Cosmological Moduli Problem ⟸

  (unless M_{moduli}>30 TeV)

Cosmological Moduli ‘Problem’



$$\Gamma_\phi \sim \frac{1}{8\pi}\frac{m_\phi^3}{M_{\rm Pl}^2}$$

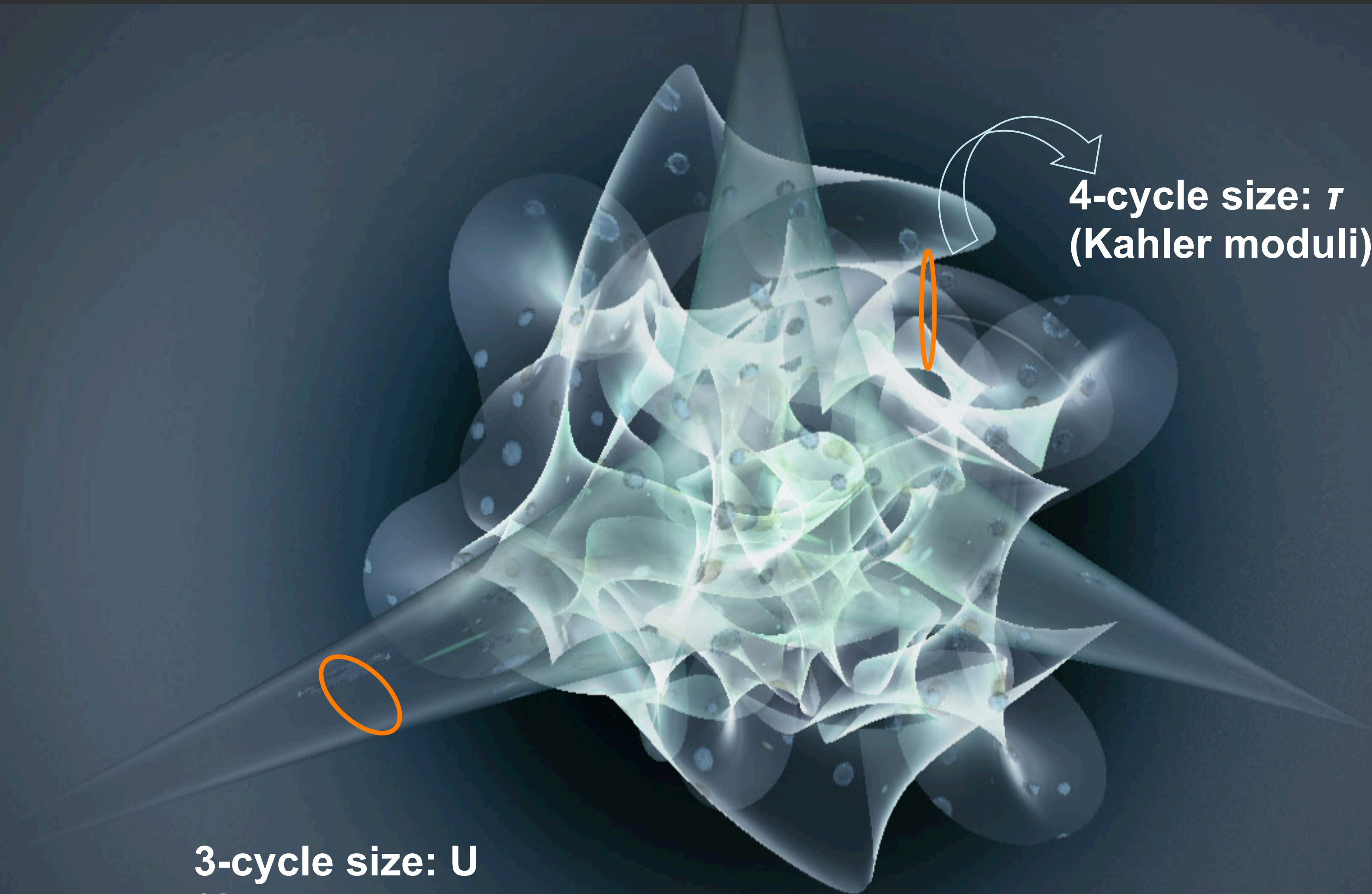
T > O(1 MeV), so $m_\phi \gtrsim 3 \cdot 10^4\ \mathrm{GeV}$

Coughlan et al 1983, Banks et al, de Carlos et al 1993

SUSY Challenges for String Scenarios

- **Explicit $\mathcal{N}$=1 Compactification**
- **Concrete SUSY breaking mechanism**
- **Moduli Stabilisation (small cc)**
  (+ avoid CMP (plus gravitino+ dark radiation excess,etc!)
- **Chiral visible sector**
- **Computable soft terms**

IIB MODULI STABILISATION



Concrete Scenarios

- IIB (F-theory)

  KKLT
  LVS ⬅

- IIA

- Heterotic

- G2 manifolds

LARGE Volume Scenario

Fluxes determine superpotential W_0 (U,S) (GKP 2003)

Perturbative corrections to K: $K = -2\ln\left(\mathcal{V} + \frac{\hat{\xi}}{2}\right)$

Nonperturbative contributions to W: $W_{np} = \sum_i A_i e^{-a_i T_i}$

$$V_F \propto \left(\frac{K^{S\bar{S}}|D_S W|^2 + K^{a\bar{b}} D_a W \bar{D}_{\bar{b}} \bar{W}}{\mathcal{V}^2}\right) + \left(\frac{A e^{-2a\tau}}{\mathcal{V}} - \frac{B e^{-a\tau} W_0}{\mathcal{V}^2} + \frac{C|W_0|^2}{\mathcal{V}^3}\right)$$

$$\mathcal{V} \sim e^{a\tau} \quad \text{with} \quad \tau \sim \mathrm{Re}\, S \sim 1/g_s > 1.$$

Exponentially large volume for weak coupling !

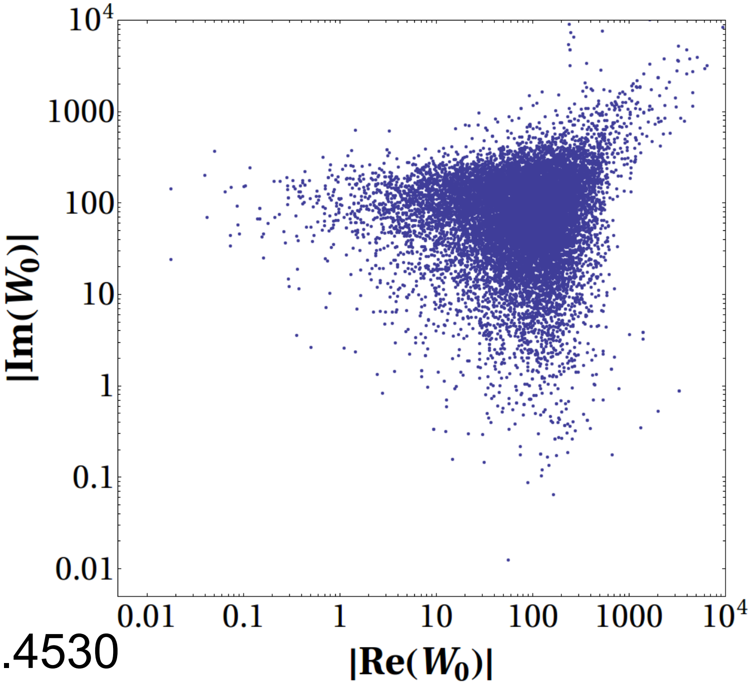
(SUSY broken by Fluxes, AdS) BBCQ, CQS 2005

LVS Conditions

- **Need $1<h_{11}<h_{12}$** (~half Calabi-Yau's)

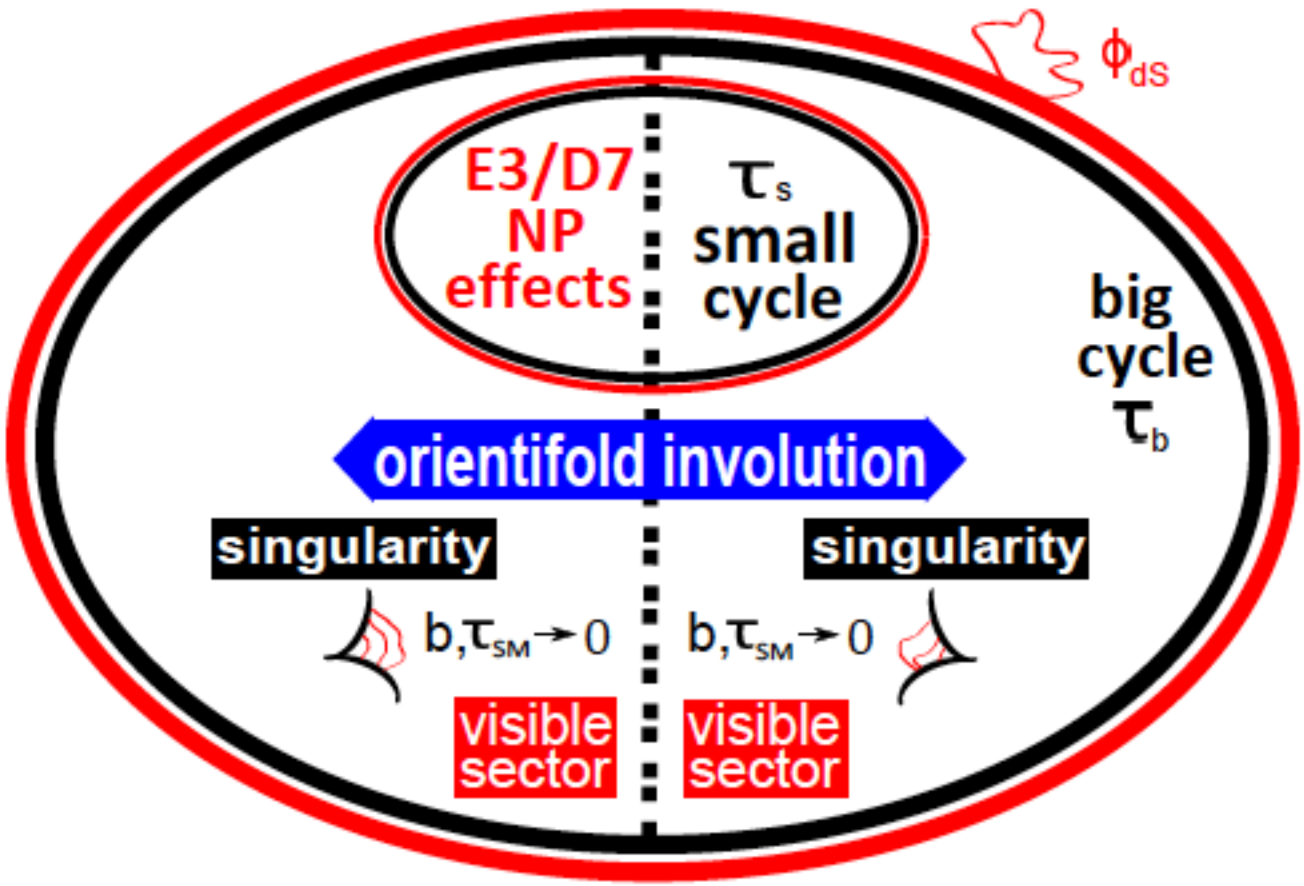
- **Generic values of W_{flux}** ($.1<W_{flux}<1000$)

e.g. $\mathbb{P}^4_{[1,1,1,6,9]}$,



Martinez-Pedrera, Mehta, Rummel, Wesphal 1212.4530

Explicit Chiral Models



Concrete Compactifications

- **From explicit compact Calabi-Yau + Chiral matter**

Cicoli, Klevers, Krippendorf,Mayrhofer, FQ, Valandro arXiv:1312.0014

- **Fully supersymmetric EFT**
- **All geometric moduli stabilised**
- **Volume only moderately large $V\sim 10^6-10^7$**
- **Sequestered scenario: $\langle T_{SM}\rangle=0$, $\langle F_{TSM}\rangle=0$**

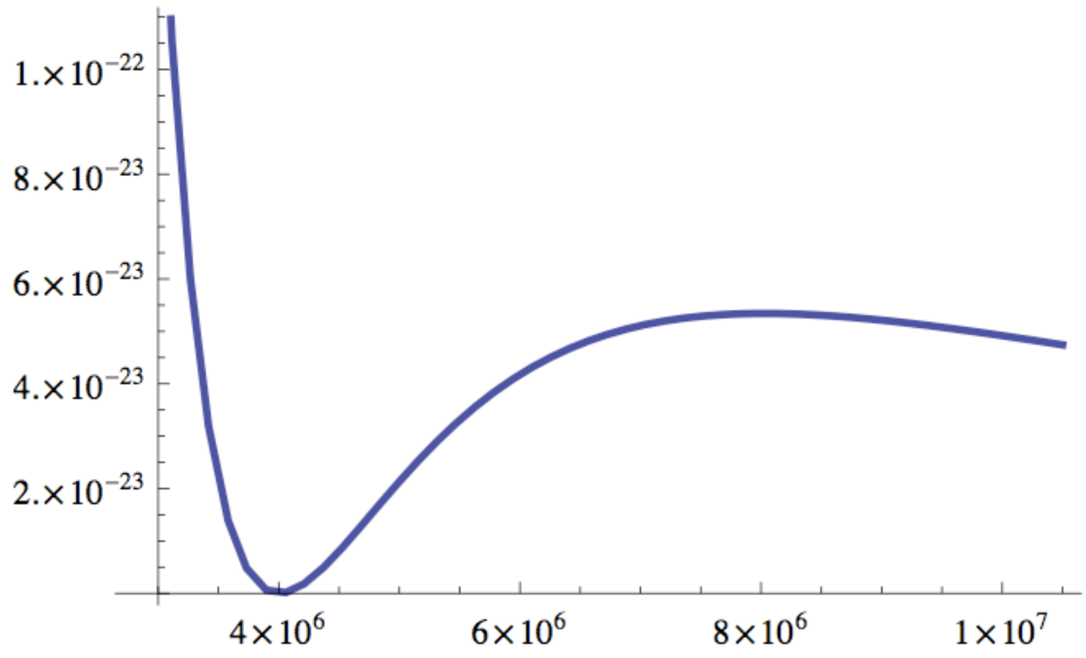
dS Kahler Moduli Stabilisation

$$V_F^{\rm tot} = V_{\rm np} + V_{\alpha'} + V_{\rm soft}$$

$$V_{\rm np} = \frac{8}{3\lambda}(a_s A_s)^2 \sqrt{\tau_s}\,\frac{e^{-2\,a_s\tau_s}}{\mathcal{V}} - 4\,a_s A_s |W_0| \tau_s \frac{e^{-a_s\tau_s}}{\mathcal{V}^2}$$

$$V_{\alpha'} = \frac{3}{4}\frac{\zeta |W_0|^2}{g_s^{3/2}\mathcal{V}^3}$$

$$V_{\rm soft} = p\,\frac{|W_0|^2}{\mathcal{V}^{8/3}\left[\ln\left(\mathcal{V}/|W_0|\right)\right]^2}$$



Relevant Scales

String Scale

$$M_s = \frac{g_s^{1/4} M_P}{\sqrt{4\pi\mathcal{V}}},$$

Kaluza Klein Scale

$$M_{KK} \simeq \frac{M_P}{\sqrt{4\pi}\mathcal{V}^{2/3}},$$

Gravitino mass

$$m_{3/2} \simeq \left(\frac{g_s^2}{2\sqrt{2\pi}}\right)\frac{W_0 M_P}{\mathcal{V}}.$$

Volume modulus mass

$$m_{\mathcal{V}} \simeq m_{3/2}/\sqrt{\mathcal{V}}.$$

Non-generic Implications

- Usually moduli masses = $m_{3/2}$
- And assume soft terms = $m_{3/2}$
- Identify $m_{3/2}$=1 TeV

But LVS is nongeneric scenario

- Volume modulus mass$<<m_{3/2}$
- So CMP more acute than expected!
- Soft terms?

SUSY EFT

$$W_{\text{matter}} = \mu(M) H_u H_d + \frac{1}{6} Y_{\alpha\beta\gamma}(M) C^\alpha C^\beta C^\gamma + \cdots$$

$$K_{\text{matter}} = \tilde{K}_\alpha(M, \overline{M}) \overline{C}^{\overline{\alpha}} C^\alpha + [Z(M, \overline{M}) H_u H_d + \text{h.c.}] \,.$$

Yukawas

$$\hat{Y}_{\alpha\beta\gamma} = e^{K/2} \frac{Y_{\alpha\beta\gamma}(U, S)}{\sqrt{\tilde{K}_\alpha \tilde{K}_\beta \tilde{K}_\gamma}}$$

Conlon, Cremades, FQ
+ Conlon, Witkowski

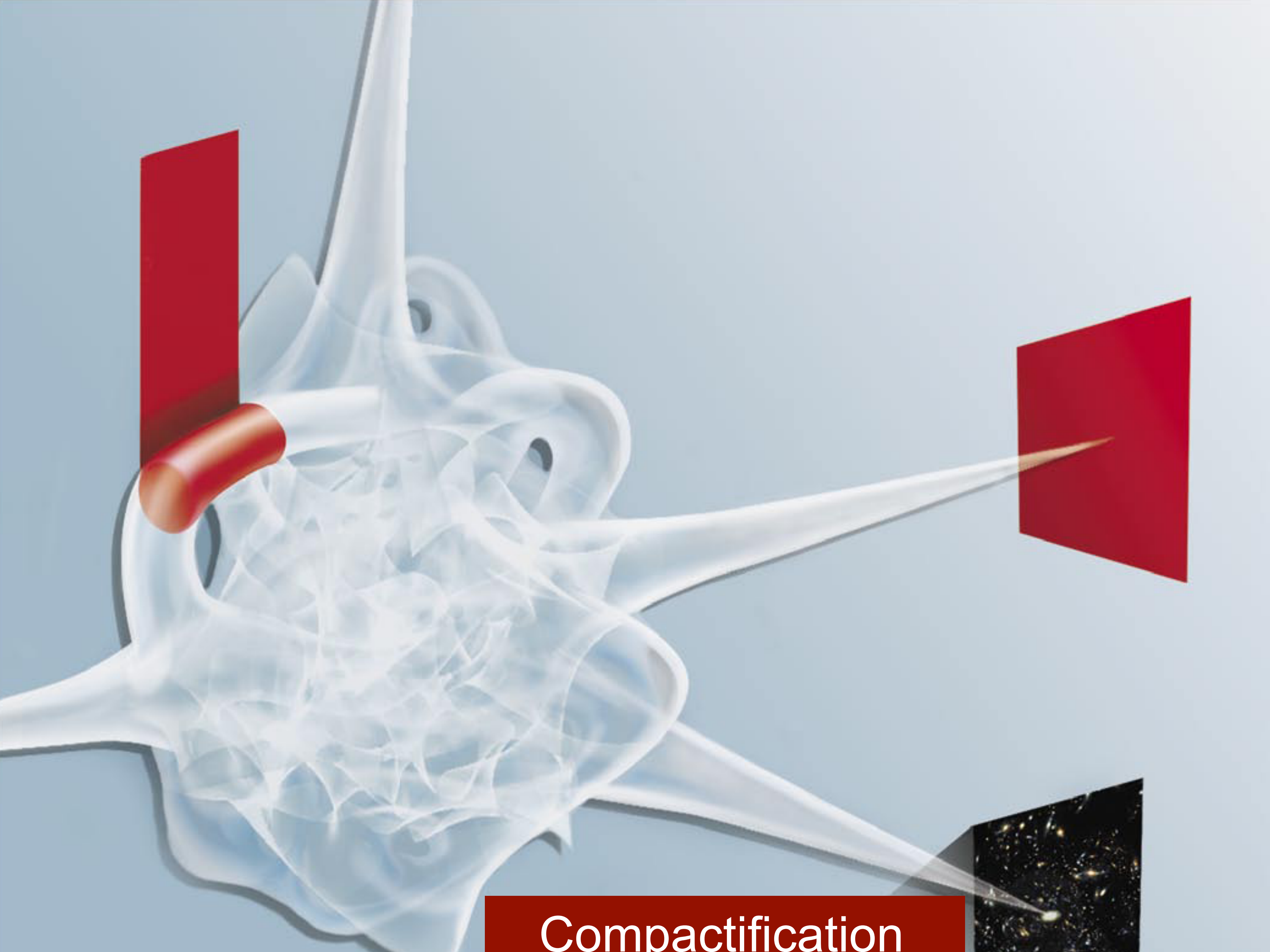
$$\tilde{K}_\alpha = h_\alpha(S, U)\, e^{K/3}$$

- **Approximate: 'Local'**
- **Exact: 'Ultralocal'**

SUSY Breaking

SUSY Breaking

- Fluxes break SUSY
- In EFT: F-terms of Kahler moduli (plus subdominant F_S, F_U)
- Standard Model on a D3 or D7 brane
- Several scenarios


Compactification

Different SUSY Scenarios

Scenario	String Scale	W_0	$m_{3/2}$	Soft masses	CMP
Intermediate Scale	10^{11} GeV	$\mathcal{O}(1)$	1 TeV	$M_{soft} \sim 1$ TeV	Yes
Tuned GUT Scale	10^{15} GeV	10^{-10}	1 TeV	$M_{soft} \sim 1$ TeV	Yes
Generic GUT Scale	10^{15} GeV	$\mathcal{O}(1)$	10^{10} GeV	$M_{soft} \sim 10^{10}$ GeV	No
Sequestered Unsplit	10^{15} GeV	$\mathcal{O}(1)$	10^{10} GeV	$M_{soft} \sim \frac{m_{3/2}}{\mathcal{V}} \sim 1$ TeV	No
Sequestered Split	10^{15} GeV	$\mathcal{O}(1)$	10^{10} GeV	$M_{1/2} \sim \frac{m_0}{\mathcal{V}^{1/2}} \sim \frac{m_{3/2}}{\mathcal{V}} \sim 1$ TeV	No

- First two not yet obtained from compact CY+ chiral matter
- 3rd: high scale SUSY breaking (e.g. Ibanez et al.)
- 4^{th} $+5^{th}$ SUSY 'solve' hierarchy small 'tuning' by flux dependence of GUT soft terms.

Sequestered Soft Terms

Soft term	Local Models	Ultra Local 1	Ultra Local 2
$M_{1/2}$	$c_{1/2}\, m_{3/2} \frac{m_{3/2}}{M_P} \left[\ln\left(\frac{M_P}{m_{3/2}}\right)\right]^{3/2}$		
m_α^2	$c_0\, m_{3/2} M_{1/2}$	$c_0 \frac{m_{3/2} M_{1/2}}{\ln(M_P/m_{3/2})}$	$(c_0)_\alpha\, M_{1/2}^2$
$A_{\alpha\beta\gamma}$	$(c_A)_{\alpha\beta\gamma}\, M_{1/2}$		
$\hat{\mu}$	$c_\mu\, M_{1/2}$		
$B\hat{\mu}$	$c_B\, m_0^2$		

Coefficients c: functions of fluxes

Cosmology:

Use CMP as a guide for low energy physics

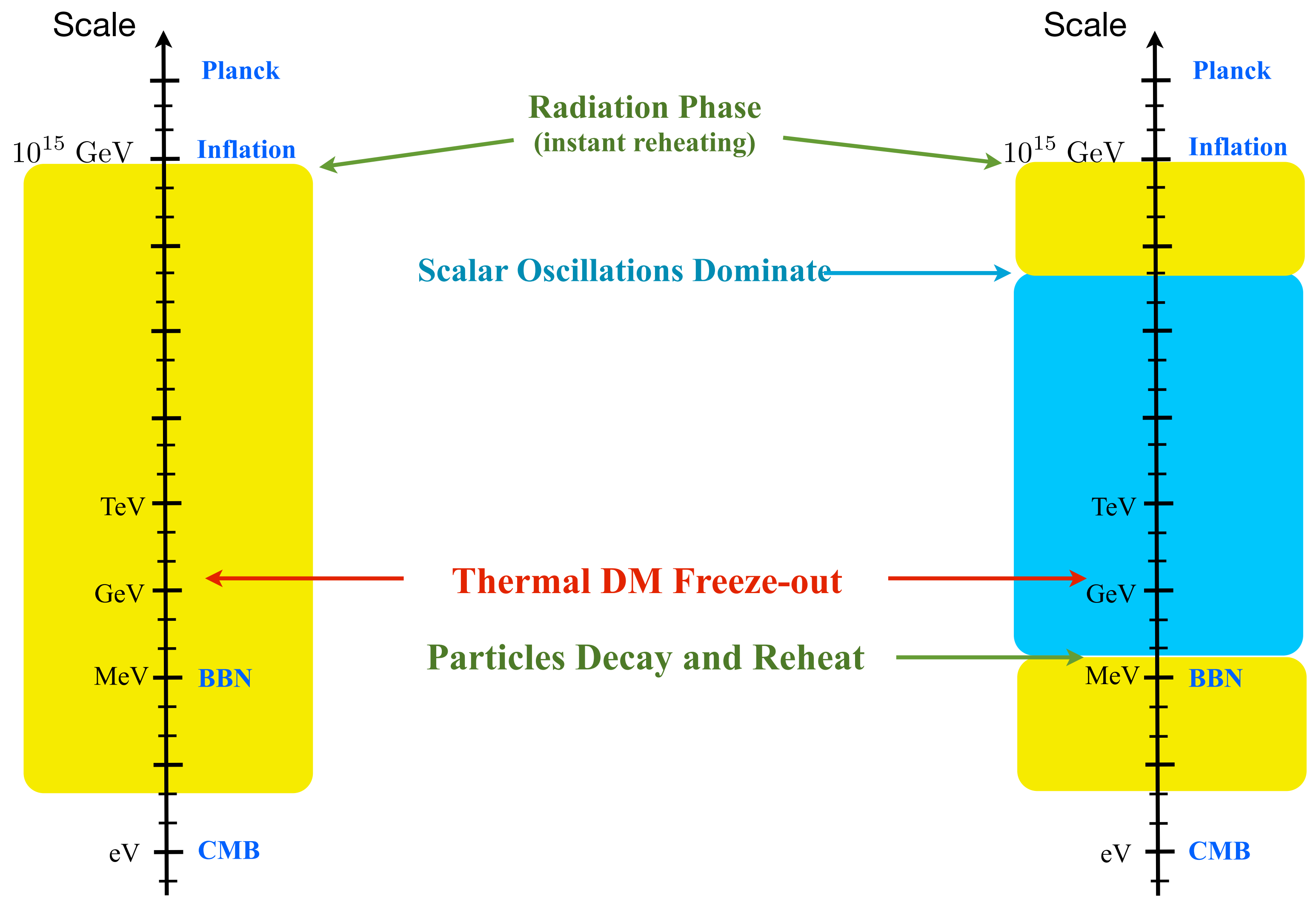
Constraints on the volume

- **Validity of EFT** ($m_{3/2} << M_{kk}$) : **$V >> 10^3$**
- CMP ($m_{volume} > 30$ TeV): **$V < 10^9$**

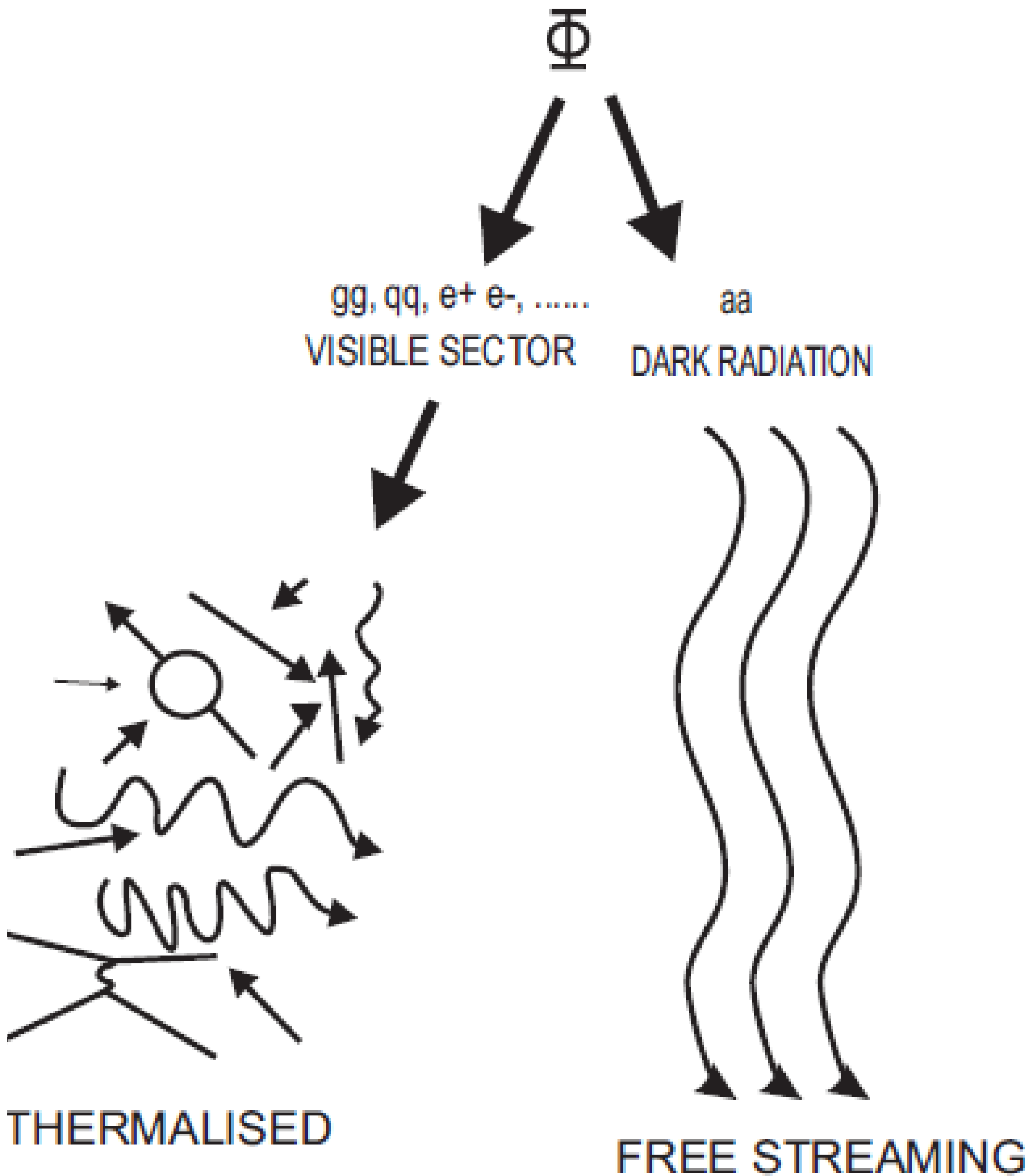
Ranges of relevant scales (GeV)

$$10^{17} > M_s > 10^{14}$$
$$10^{15} > m_{3/2} > 10^{10}$$
$$10^{12} > M_{1/2} > 10^2$$
$$10^7 > T_{RH} > 1$$

Thermal History / Alternative History



From S. Watson, SUSY 2013



Φ
gg, qq, e+ e-, ...
VISIBLE SECTOR
aa
DARK RADIATION
THERMALISED
FREE STREAMING

Volume Reheating*

*Sequestered scenarios

M.Cicoli, J.P. Conlon, FQ arXiv:1208.3562
T. Higaki, F.Takahashi arXiv:1208.3563

$$\Gamma_{\Phi\to a_b a_b} = \frac{1}{48\pi}\frac{m_\Phi^3}{M_P^2}.$$

Volume axion a_b

$$\Gamma_{\Phi\to H_u H_d} = \frac{2Z^2}{48\pi}\frac{m_\Phi^3}{M_P^2}.$$

Higgses

$$\Gamma_{\Phi\to BB} = \left(\frac{\lambda}{3/2}\right)^2\frac{9}{16}\frac{1}{48\pi}\frac{m_\Phi^3}{M_P^2}$$

Closed string axions

$$\Gamma_{\Phi\to C\bar{C}} \sim \frac{m_0^2 m_\Phi}{M_P^2} \ll \frac{m_\Phi^3}{M_P^2}$$

Matter scalars C

$$T_{reheat} \sim \frac{m_\Phi^{3/2}}{M_{Pl}^{1/2}} \sim 0.6\ \mathrm{GeV}\left(\frac{m_\Phi}{10^6\mathrm{GeV}}\right)^{3/2}.$$

Dark Radiation

Energy density:

$$\rho_{total} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right).$$

Standard Model N_{eff}=3.04

At CMB: WMAP, ACT, SPT

Planck 2015: N_{eff} = 3.13 ± 0.32 (68% CL)

$$3.12\,\kappa \le \Delta N_{eff} \le 3.48\,\kappa$$
$$\kappa = (1 + 9n_a/16)/n_H Z^2$$

Simplest Z=1:

$$1.56 \le \Delta N_{eff} \le 1.74$$

General: Strong constraints on matter and couplings!

Phenomenology

Nonthermal CMSSM*

$T_{rh} < T_f = m/20$

- Assume: CMSSM parameters ($M, m, A, \tan\beta$, signμ plus T_R)
- REWSB with ≈125 GeV Higgs
- Constraints:

Colliders (LEP, LHC)

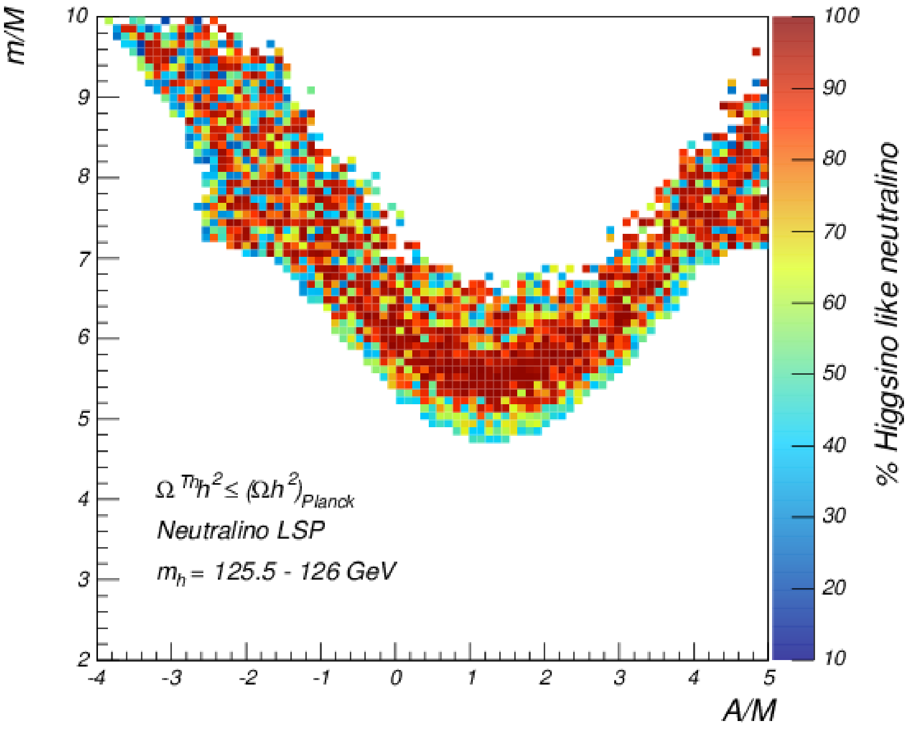
CMB (Planck)

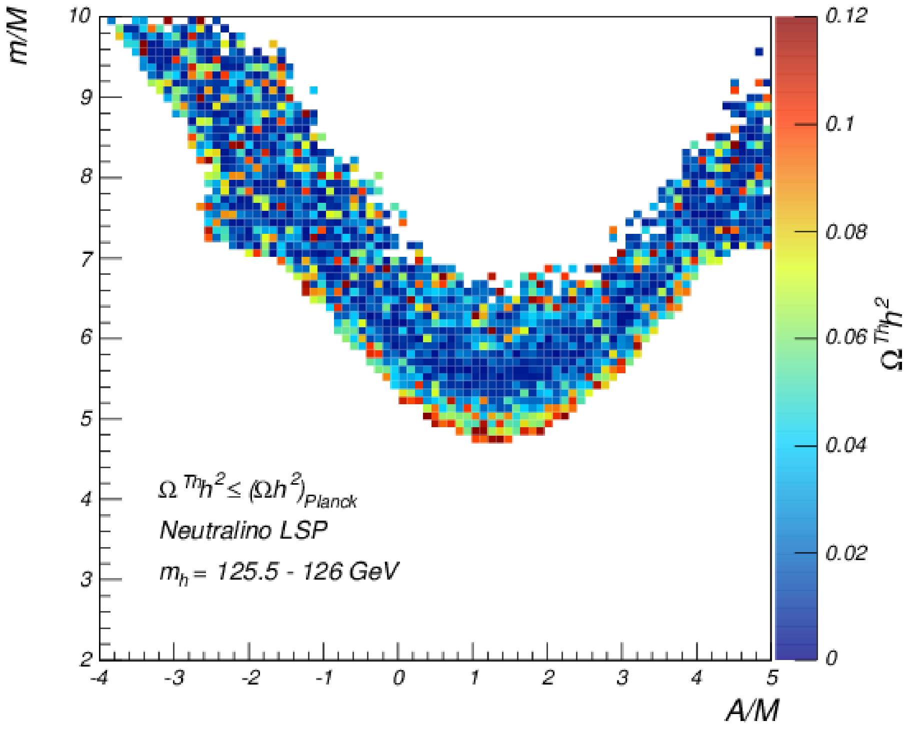
Direct DM dtection (LUX, XENON100, CDMS, IceCube)

Indirect DM detection (Fermi)

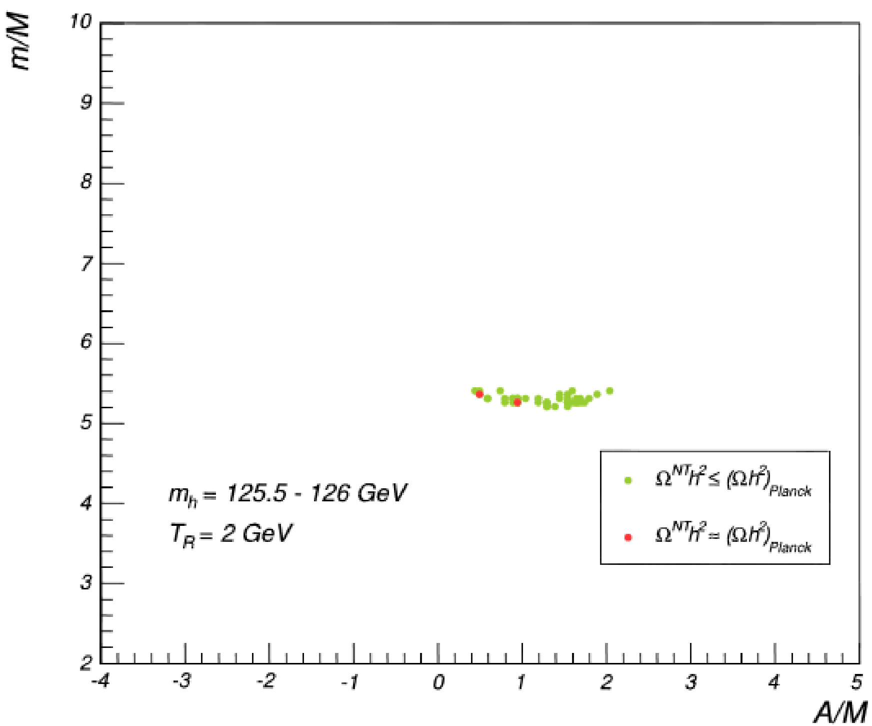
* Warning: at this stage is purely phenomenological not stringy!

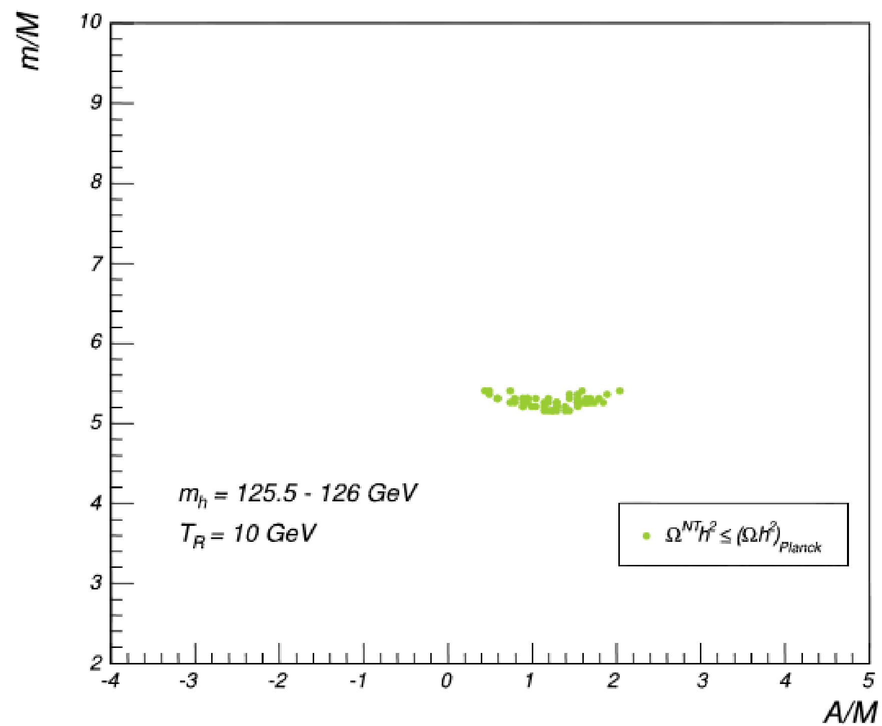
Collider and CMB constraints



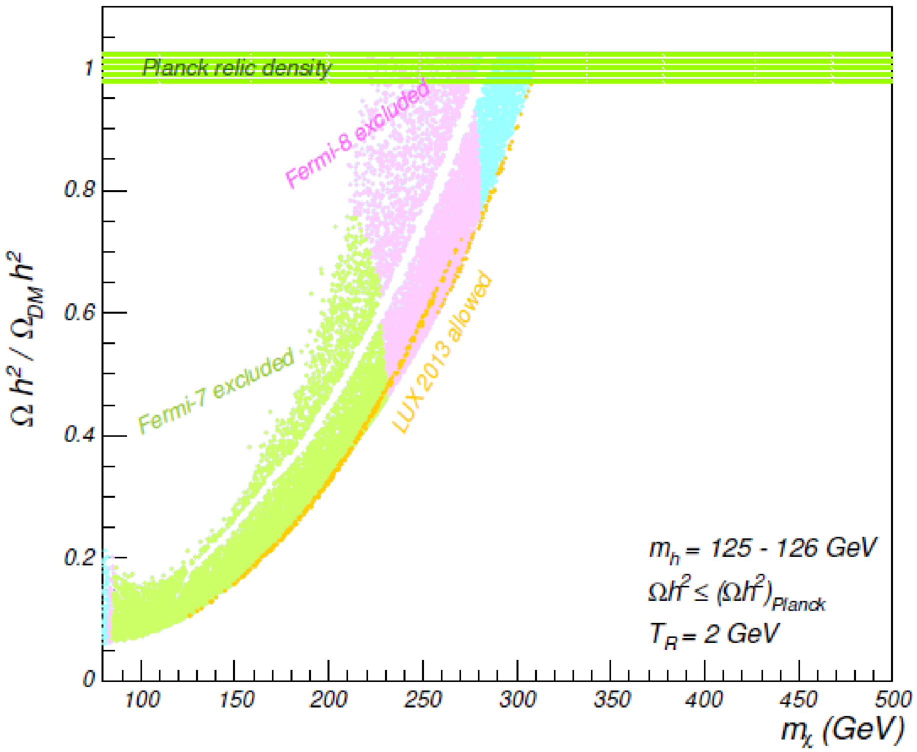


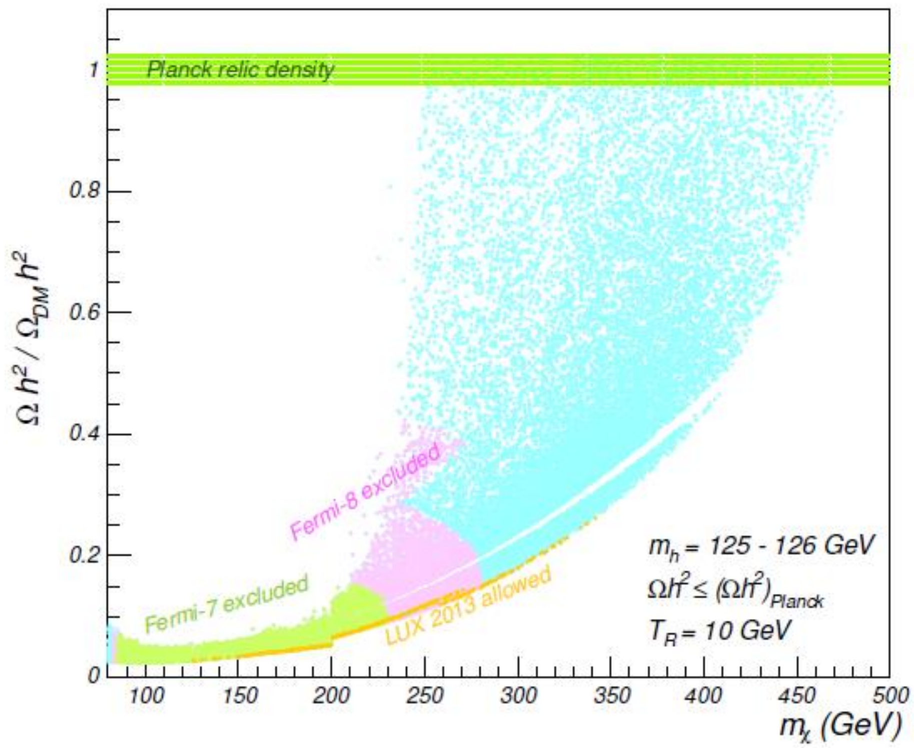
Direct and Indirect DM Constraints





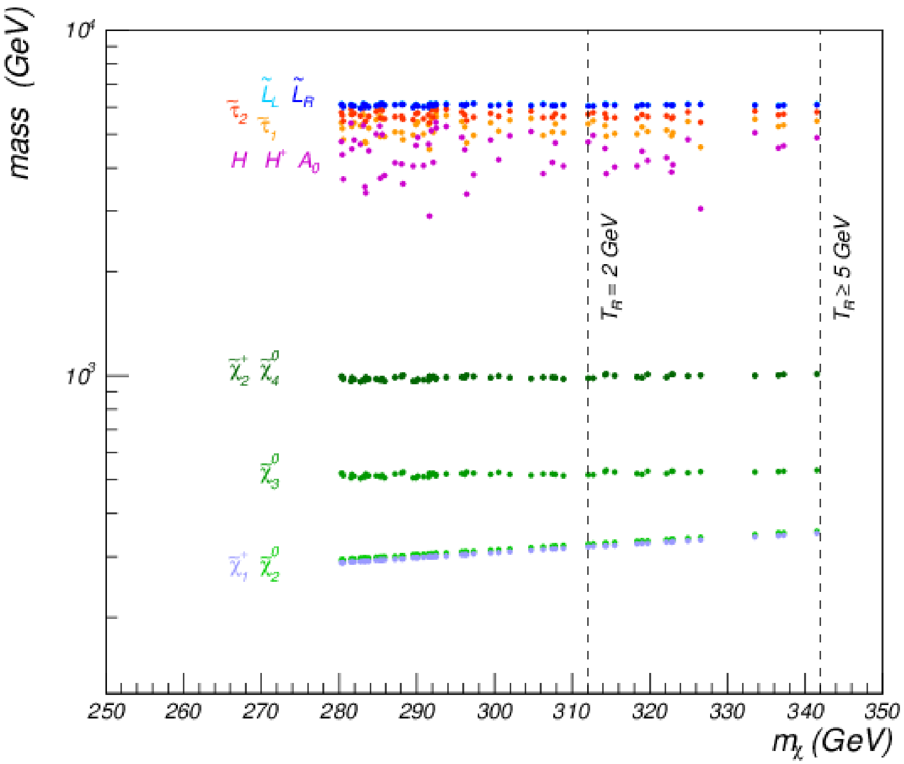
Survivors

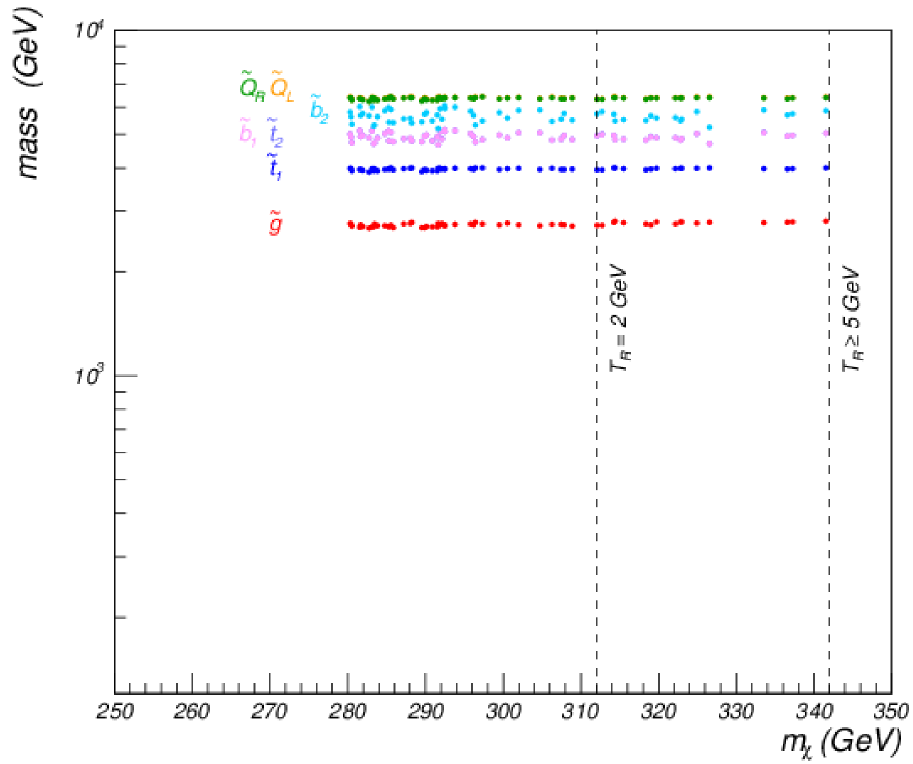




Neutralino Higgsino-like saturates Planck's density for m=300 GeV, T_R=2 GeV

Spectrum

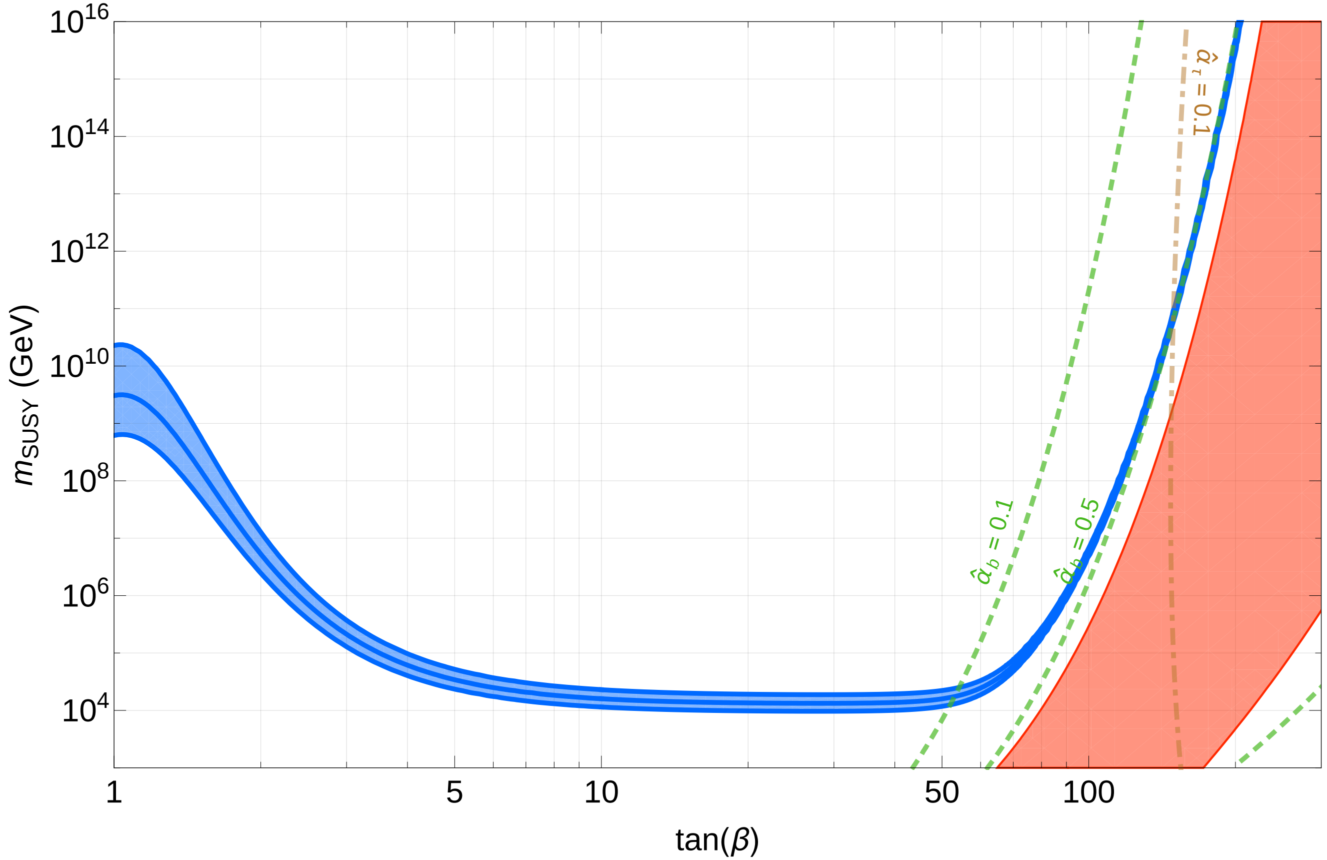




LHC signatures:
Monojets + soft leptons + ME
Vector boson fusion jets + large ME

Large scale and split SUSY?

In progress:
strong Higgs mass constraints,
explicit determination of splitting m~V$^{1/2}$ M



Pardo+Villadoro 2015

CONCLUSIONS

- Global embedding CY and Moduli Stabilisation

  Several SUSY breaking scenarios

  (tuning at UV, low T_R)
- Most known ingredients used: geometry, fluxes, branes, perturbative, non-perturbative effects
- Cosmology-Phenomenology interplay
- Complicated models (but recall SM is ugly)
- Many open questions (MSSM, large scales, etc. + formal aspects)