News in Type IIB String Phenomenology

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The Abdus Salam
International Centre
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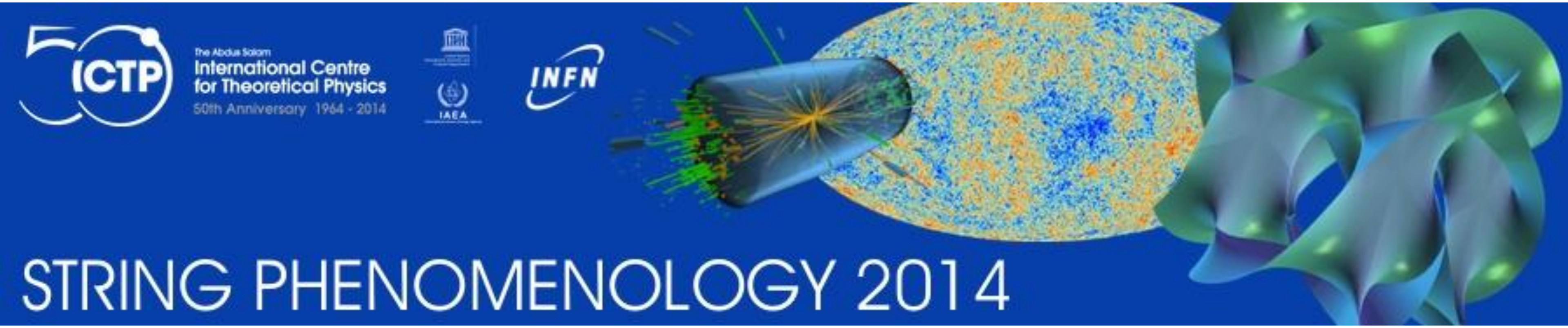
Two reviews:

1) String Inflation after Planck: Burgess, MC, Quevedo, arXiv:1306.3512 [hep-th]

2) Particle physics models: Maharana, Palti, arXiv:1212.0555 [hep-th]

Based on papers written with: Allahverdi, Burgess, Conlon, Downes, B. Dutta, K. Dutta, Goodsell, Klevers, Krippendorf, Maharana, Mayrhofer, Ringwald, Pedro, Quevedo, Sinha, Tasinato, Valandro, Zavala, Westphal

First news!



Venue: ICTP, Trieste

Date: July 7-11

Website: stringpheno2014.ictp.it

Organisers: Aparicio, Acharya, Cicoli, Quevedo, Valandro

Contents

- String inflation, tensor modes and non-gaussianities
- Pre-inflationary string cosmology and power loss at large scales
- Post-inflationary string cosmology

  i) Dark radiation
  ii) Cosmic axion background
  iii) Non-thermal dark matter
  iv) 3.5 keV line

- Particular case: sequestered LVS models

Focus on phenomenology more than maths!

→ Interesting indirect predictions from generic features of string compactifications!

Understanding acceleration

Era of precision cosmology (COBE, WMAP, Planck)

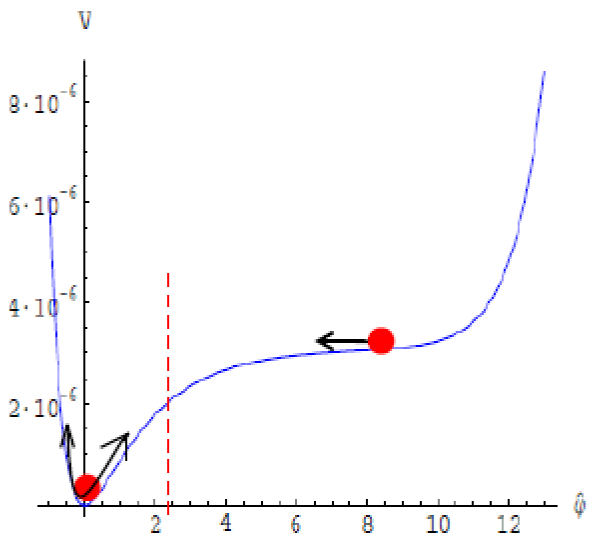
Emerging picture: striking simplicity

i) Gaussian scalar fluctuations

ii) Spectral index close to scale-invariant: $n_s \simeq 0.96$

iii) No evidence for tensor fluctuations: r << 1

→ Early epoch of accelerated expansion driven by a scalar field



Slow-roll inflation:

$$\varepsilon \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 << 1 \qquad \eta \equiv M_P^2 \frac{V''}{V} << 1$$

$$N_e = \frac{1}{M_P}\int_{\varphi_{end}}^{\varphi_{in}} \frac{1}{\sqrt{2\varepsilon}}\, d\varphi \approx 60 \qquad V \approx 3H_{\inf}^2 M_P^2$$

$$P_S(k) \approx A_S^2\, k^{n_s - 1} \qquad A_S \approx \frac{H_{\inf}}{M_P\sqrt{\varepsilon}} \approx \frac{V^{3/2}}{M_P^3 V'} \approx 10^{-5}$$

$$n_s - 1 = 2\eta - 6\varepsilon \approx -0.04 \qquad r \equiv \frac{A_T^2}{A_S^2} = 16\varepsilon < 0.12$$

Why string inflation?

Inflation is UV-sensitive! ⟶ complete theory of quantum gravity as string theory

• Abnormally flat potentials -- η-problem

i) Inflation requires very light scalar fields

ii)Hierarchy problem for Higgs: why $m_H << M_P$? Similarly for the inflaton: why $m_{inf} << H_{inf}$?

Need to control quantum gravity interactions ⟶ string theory

Slow-roll parameters are sensitive to dim 6 Planck suppressed operators:

$$\Delta V \approx V \frac{\varphi^2}{M_P^2} \quad \Rightarrow \quad \Delta m_{\inf}^2 \approx \frac{V}{M_P^2} \approx H_{\inf}^2 \quad \Rightarrow \quad \Delta\eta \approx 1$$

•Trans-Planckian field motion

Observable gravitational waves require trans-Planckian distances

Lyth bound: $\frac{\Delta\varphi}{M_P} \approx \sqrt{\frac{r}{0.01}}$ $\qquad M_{\inf} \approx M_{GUT} r^{1/4}$ ⟶ see GUT-scale physics!

How can you trust the low-energy expansion? ⟶ string theory

$$V(\varphi) = V_0 + \frac{m^2}{2}\varphi^2 + \varphi^4 \sum_{i=0}^{\infty} \lambda_i \left(\frac{\varphi}{M_P}\right)^i$$

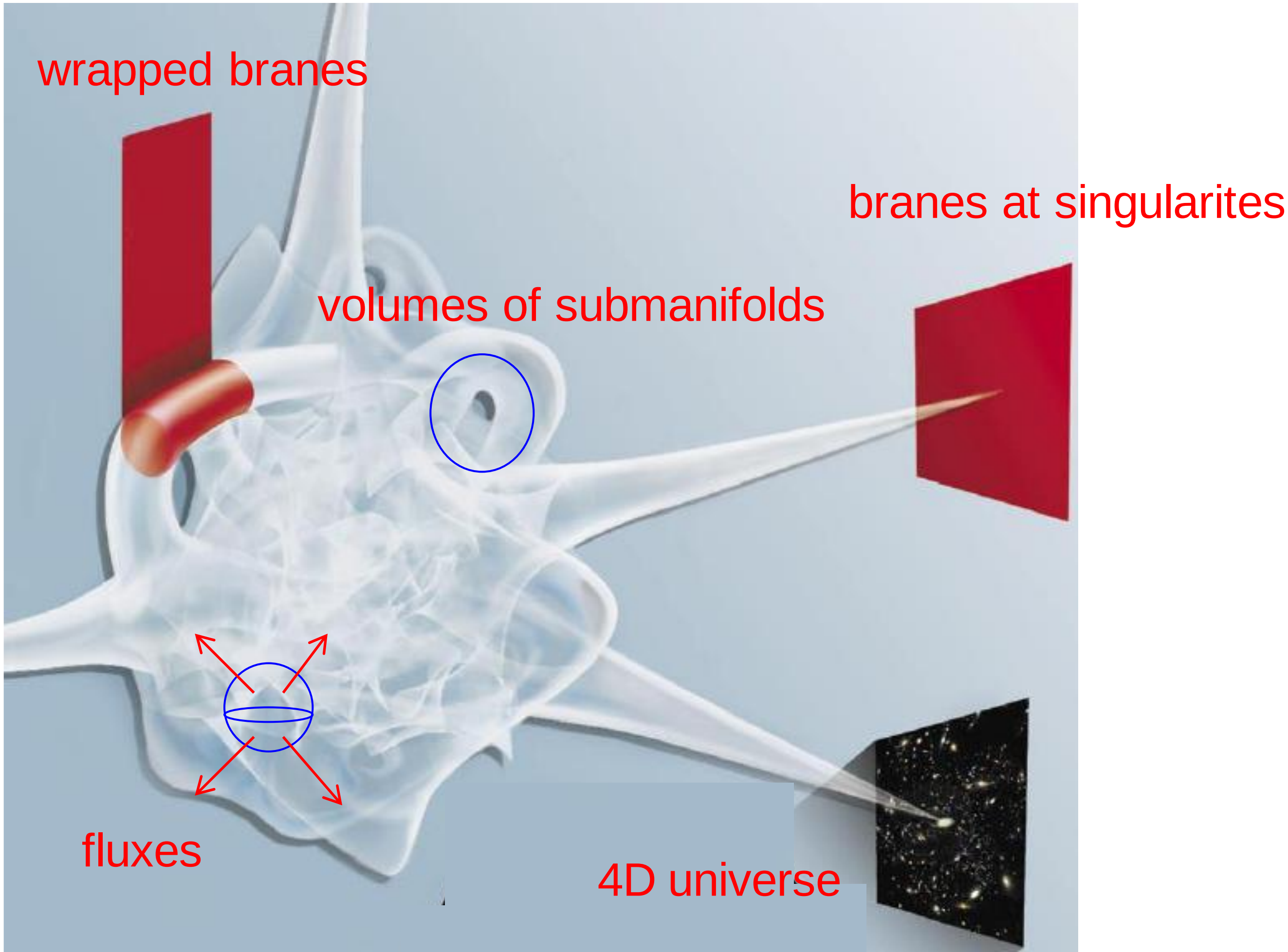
• Initial conditions

Successful inflation depends crucially on initial positions and velocities

Understanding pushed back to earlier epochs with higher energies ⟶ string theory

Scalars from strings

String theory → extra dimensions → 4D scalars (gauge singlets)
Many ingredients: topology, branes, fluxes
Potential landscape: $V(\phi_i)$, ϕ_i moduli from 10D metric,brane positions, form fields (axions)



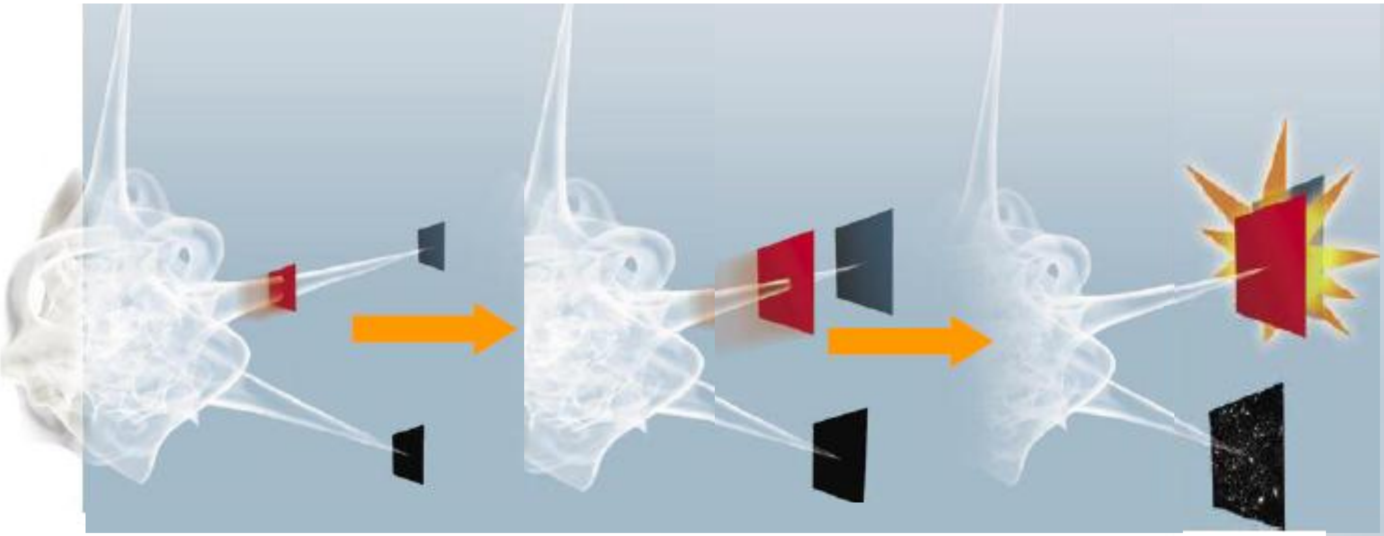
String inflationary scenarios

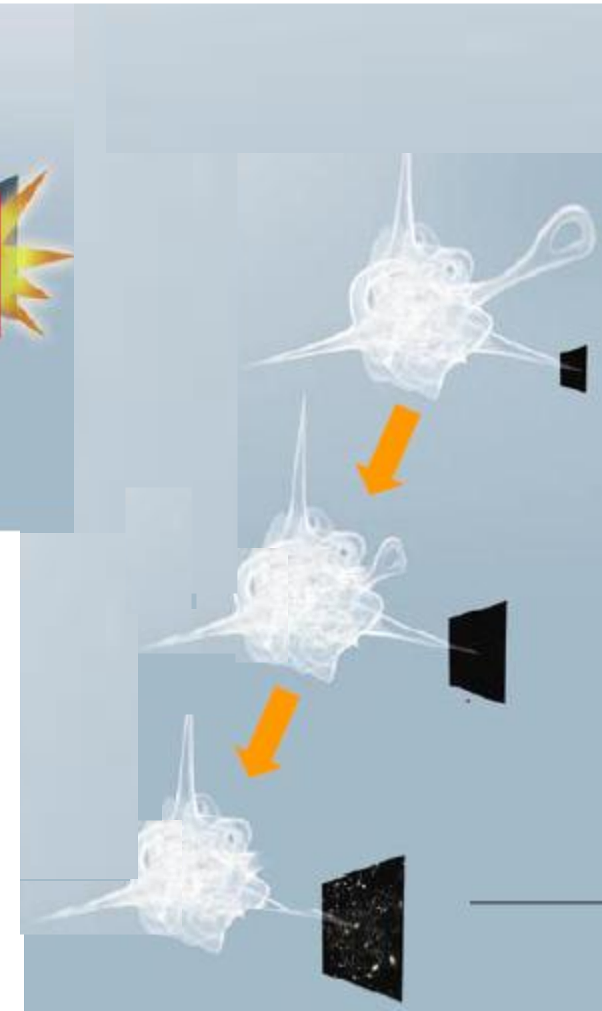
Two classes of models:

• Open string inflation – inflaton is a brane position modulus

i) No symmetry solving the η-problem (except for large cx str limit) ⟶ fine-tuning

ii)Upper bounds on field range from size of EDs ⟶ no detectable tensor modes





• Closed string inflation

i) Approximate symmetries solving the η-problem

ii) Models with detectable tensor modes

Inflaton:

i) volume of an internal submanifold

ii) axion

Closed string inflation: axions

- Approximate symmetries solving the η-problem → suppress higher dim. operators
  - i) Shift-symmetry for axions
  - ii) No-scale structure for volume moduli → accidental shift symmetry
- Inflation using axions:

1) N-flation

   i) One axion: flat potential for $f_a > M_P$
   ii) N>>1 axions: inflation for each $f_a < M_P$
   iii) Typical potential:

$$V = \sum_{i=1}^{N} \Lambda^4 \left(1 - \cos\left(\frac{a_i}{f_{a_i}} \right) \right)$$

   iv) Effectively large field inflation → $r \simeq 0.001$ BUT control issues!

2) Axion monodromy

   i) Monodromy induced by wrapped branes “unwraps” compact axion direction
   ii) Typical potential:

$$V = \mu^3 \varphi + \Lambda^4 \cos\left(\frac{\varphi}{f} \right)$$

   iii) Large field inflation → $0.04 < r < 0.07$ BUT control issues!

Closed string inflation: volume moduli

- Inflation using volume moduli:

  i) No-scale structure broken by perturbative effects only by lifting one direction χ

  → naturally flat potential for fields φ orthogonal to χ!

  ii) Suppressed higher dim. operators due to approximate shift symmetry for φ

  iii) Typical potential:

$$V = V_0\left(1 - \beta\kappa\, e^{-\kappa\varphi} + \delta\, e^{+\mu\varphi}\right) \approx V_0\left(1 - \beta\kappa\, e^{-\kappa\varphi}\right) \qquad \beta \approx O(1), \delta << 1$$

  iv) κ depends on the details of the model: topology of φ and effects to generate V

  v) Implications of V:

$$\varepsilon \approx \frac{\eta^2}{2k^2} \quad \text{and} \quad \eta \approx -\beta\kappa^3 e^{-\kappa\varphi} < 0 \quad \Rightarrow \quad \varepsilon << |\eta| << 1$$

  vi) Typical prediction: $r \approx \frac{2}{\kappa^2}(n_s - 1)^2 \quad \Rightarrow \quad \text{for } n_s \approx 0.96 \quad \Rightarrow \quad r \approx \frac{0.0032}{\kappa^2}$

  vii) Three models:

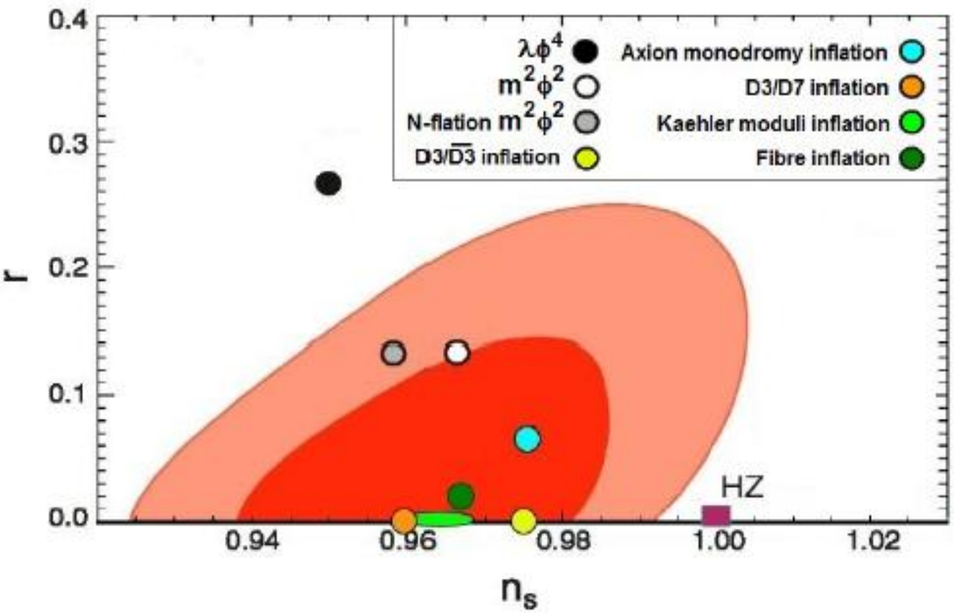
1) Kahler moduli inflation: $\kappa \simeq \mathcal{V}^{1/2} >> 1$ → $r \simeq 10^{-10}$

2) Fibre inflation: $\kappa \simeq O(1)$ → $0.005 < r < 0.007$

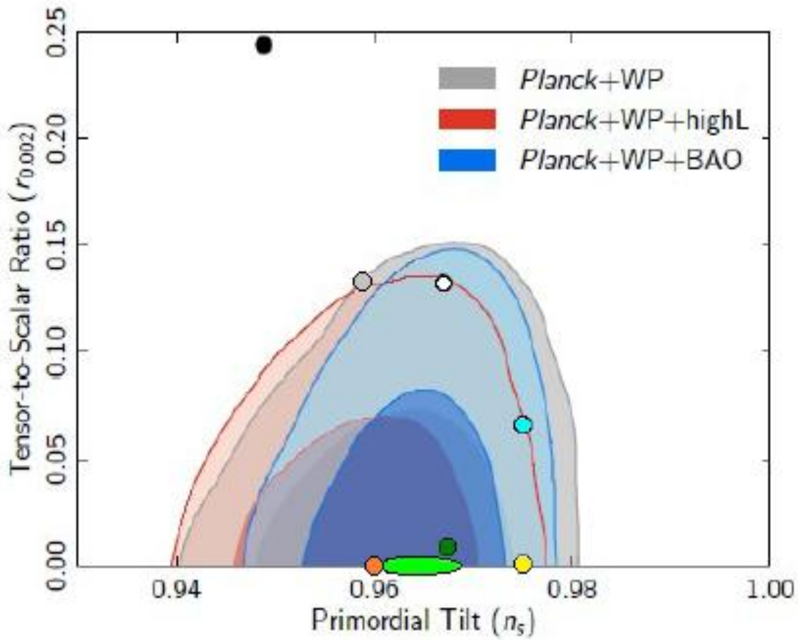
3) Poly-instanton inflation: $\kappa \simeq \ln\mathcal{V} > 1$ → $r \simeq 10^{-5}$

(n_s,r)-plane

2008



2013



- Almost unanimous prediction of small r
- Well agreement with observations
- Is there a reason for this agreement?

Prospects for measuring r

- Observations more sensitive to r in near future: what might be found?
- Two theoretical points of view:

1) Flat prior: ε and η similar in size: $\varepsilon \simeq \eta$

$$n_s - 1 \approx 2\eta - 6\varepsilon \approx -4\varepsilon \approx -0.04 \quad \Rightarrow \quad \varepsilon \approx 0.01 \quad \Rightarrow \quad r \approx 16\varepsilon \approx 0.16$$

⟶ tensor modes should soon be observed!

2) Flat log prior: size of tensor perturbations set by inflationary energy scale

$$r \approx \left(\frac{M_{\inf}}{M_{GUT}} \right)^4$$

i) M_{inf} could be anywhere between 100 GeV and 10^{15} GeV

ii) No intrinsic reason to prefer any scale

⟶ no preference for observable or unobservable r

Stringy point of view: Trans-Planckian fields to obtain large r

i) Consistent EFT? Answer in string theory

ii) Difficulty to find large r -- no-go theorems

iii) Majority of known string models do not predict large r

⟶ expect r to be too small to be visible

Non-Gaussianities

Two main mechanisms for non-Gaussianity in string inflation:

1) Non-canonical kinetic terms (DBI inflation)

   i) Large NG due to departure from slow-roll
   ii) Tension with the data due to prediction of large equilateral and orthogonal NG

2) Multi-field dynamics

   i) Large NG due to large self-interaction of fields which generate NG
   ii) A generic compactification has many moduli
   → some of them heavier and some lighter than H_{inf}
   iii) During inflation light fields get large quantum fluctuations
   iv) Non-standard generation of density perturbations + large local NG
   v) Examples: curvaton or modulated reheating

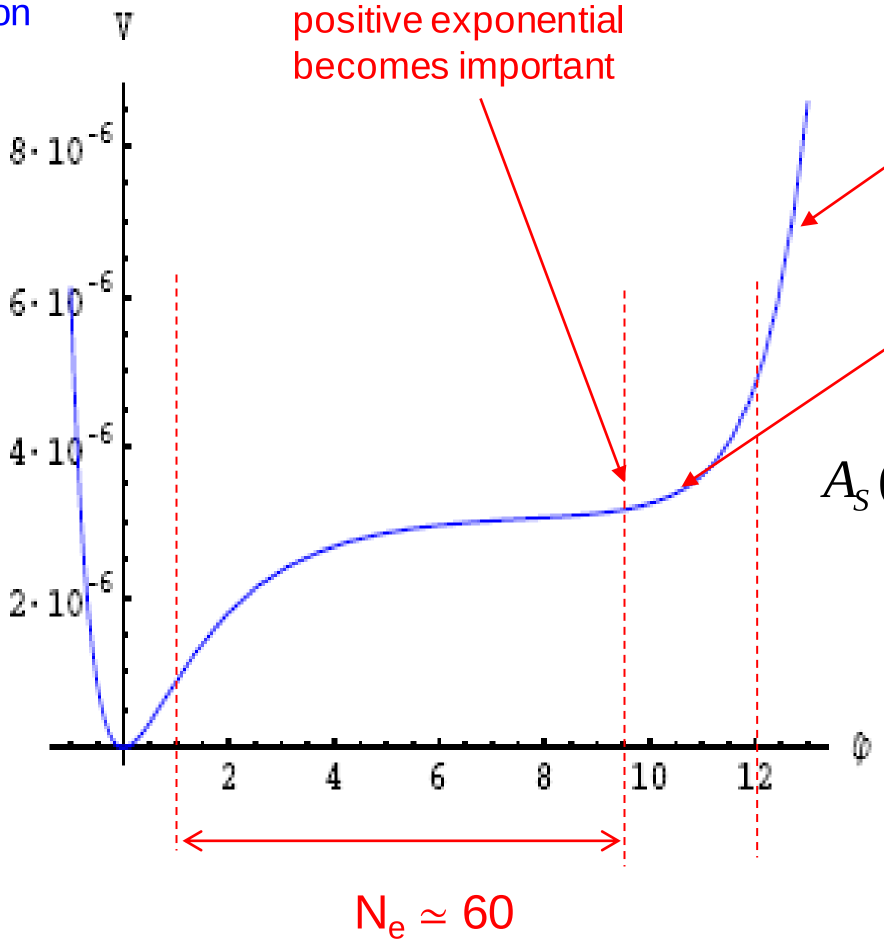
BUT in most cases multi-field models do NOT generate isocurvature perturbations due to an effective single-field dynamics -- motion is along a trough!
→ partial explanation of why inflationary models describe the data so well
→ observational evidence for single-field models is not against multi-field models

Strings and power loss at large scales

- Qualitative behaviour of closed string inflation with volume moduli

see Pedro's talk

Fit Planck high-precision data at ℓ >50, predict power at ℓ <50: TOO LOW power at low-ℓ! 10% deficit at 2.5 σ



$$A_S\,(\text{large scales}) \approx \frac{V^{3/2}}{M_P^3 V'} << 10^{-5}$$

Power loss at low-ℓ!

[MC, Dutta, Downes, Pedro, Westphal]

In Fibre Inflation:

$$N_e \approx g_s^{-4/3} >> 1$$

$$\delta \approx g_s^{4} << 1$$

- Typical potential: $V = V_0\left(1 - \beta\kappa\, e^{-\kappa\varphi} + \delta\, e^{+\mu\varphi}\right) \qquad \beta \approx O(1),\ \delta << 1$

Post-inflationary string cosmology

Two ubiquitous problems of string compactifications:

- Cosmological moduli problem [Coughlan et al][Banks et al][de Carlos et al]:
  1. ϕ starts oscillating at $H_{\rm osc} \sim m_\phi$ with $\phi_0 \sim M_P$
  2. ϕ redshifts as matter $\Rightarrow$ dominates the energy density
  3. ϕ decays at $H_{\rm dec} \sim \Gamma \sim \epsilon^2 m_\phi$ where $\epsilon \equiv m_\phi/M_P \ll 1$
  4. Reheat temperature $T_{\rm rh} \sim \epsilon^{1/2} m_\phi > T_{\rm BBN} \simeq 3$ MeV $\Rightarrow m_\phi > 50$ TeV
- Axionic dark matter overproduction [Preskill et al] [Abbott,Sikivie]:
  1. $\mathcal{O}(100)$ axions in string compactifications
  2. Some projected out, eaten up by anomalous $U(1)$s or heavy from NP effects
  3. Some remain light $\Rightarrow$ one can be the QCD axion with $f_a \sim M_s$
  4. Overproduction of axionic cold DM for $f_a > 10^{12}$ GeV

Tension between these two problems:

ϕ heavier/lighter than 50 TeV $\Leftrightarrow$ high/low string scale $\Leftrightarrow$ too much/right axion DM

Non-standard cosmology from strings

Focus on $m_\phi > 50$ TeV $\Rightarrow \phi$ decay dilutes any previous relic [Moroi,Randall]:

- Axionic DM diluted if $T_{\rm rh} < \Lambda_{\rm QCD} \simeq 200$ MeV [Fox,Pierce,Thomas]
  $\Rightarrow$ if $T_{\rm rh} \gtrsim T_{\rm BBN}$ can have $f_a \sim 10^{14}$ GeV without tuning
- Standard thermal LSP DM diluted if $T_{\rm rh} < T_{\rm f} \simeq m_{\rm DM}/20 \sim \mathcal{O}(10)$ GeV
- Baryon asymmetry diluted if produced before ϕ decay
  $\Rightarrow$ good for Affleck-Dine baryogenesis which can be too efficient [Kane,Shao,Watson,Yu]

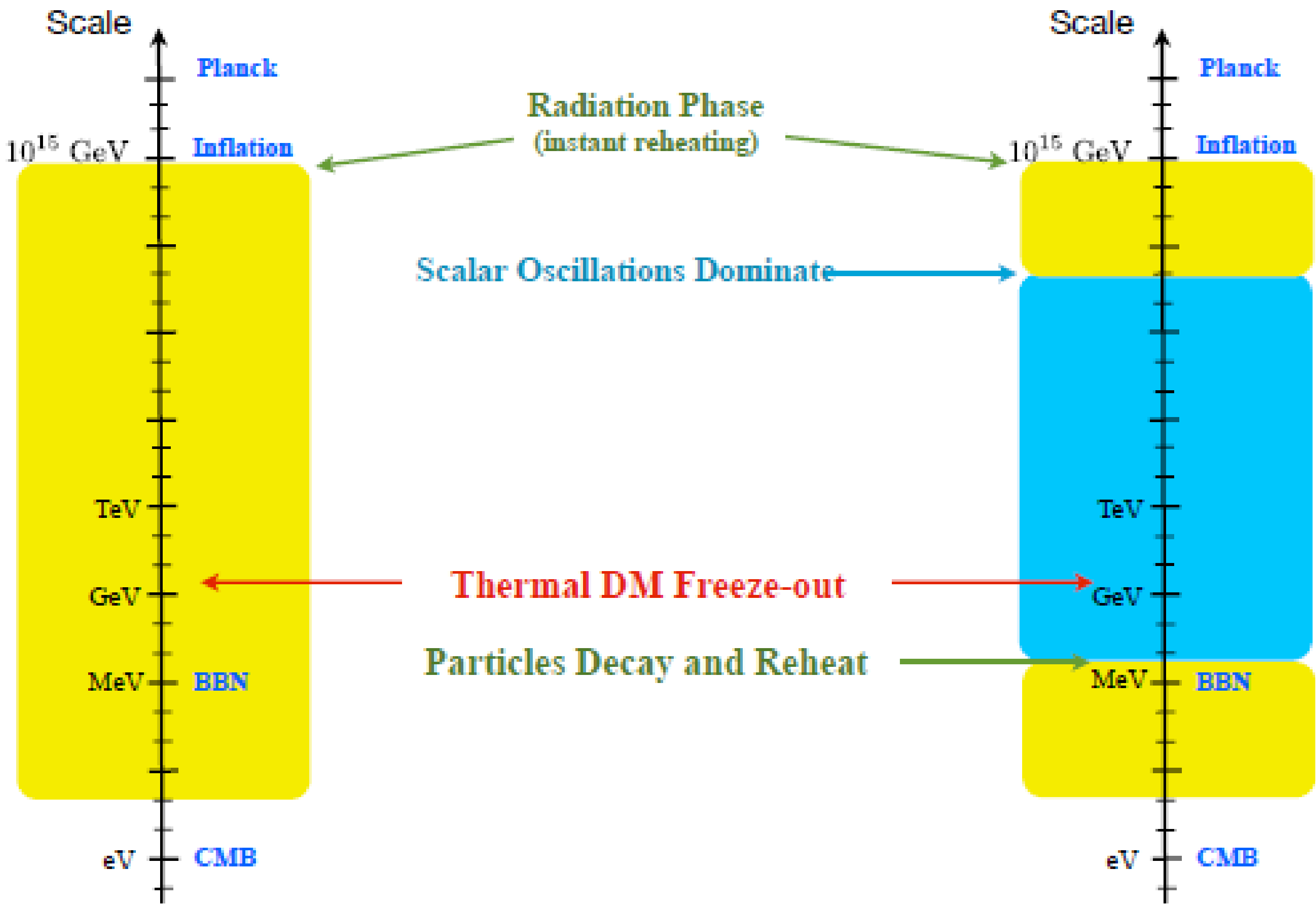
Decay products:

- Non-thermal LSP DM from ϕ decay [Acharya et al][Allahverdi,MC,Dutta,Sinha]
  - Annihilation scenario for high $T_{\rm rh}$ (close to $T_{\rm f}$)
    1. abundant initial production of DM
    2. subsequent efficient annihilation $\Rightarrow$ Wino/Higgsino-like DM
  - Branching scenario for low $T_{\rm rh}$ (close to $T_{\rm BBN}$)
    1. smaller initial production of DM
    2. subsequent inefficient annihilation $\Rightarrow$ Bino-like DM
- Baryon asymmetry from ϕ decay $\Rightarrow$ Co-genesis of DM and baryogenesis due to new $O(\rm TeV)$ coulored particles with B- and CP-violating couplings [Allahverdi,Dutta,Sinha]

Thermal vs Non-thermal cosmology

Thermal History

Alternative History



Challenges for moduli decays

Two problems for moduli decays:

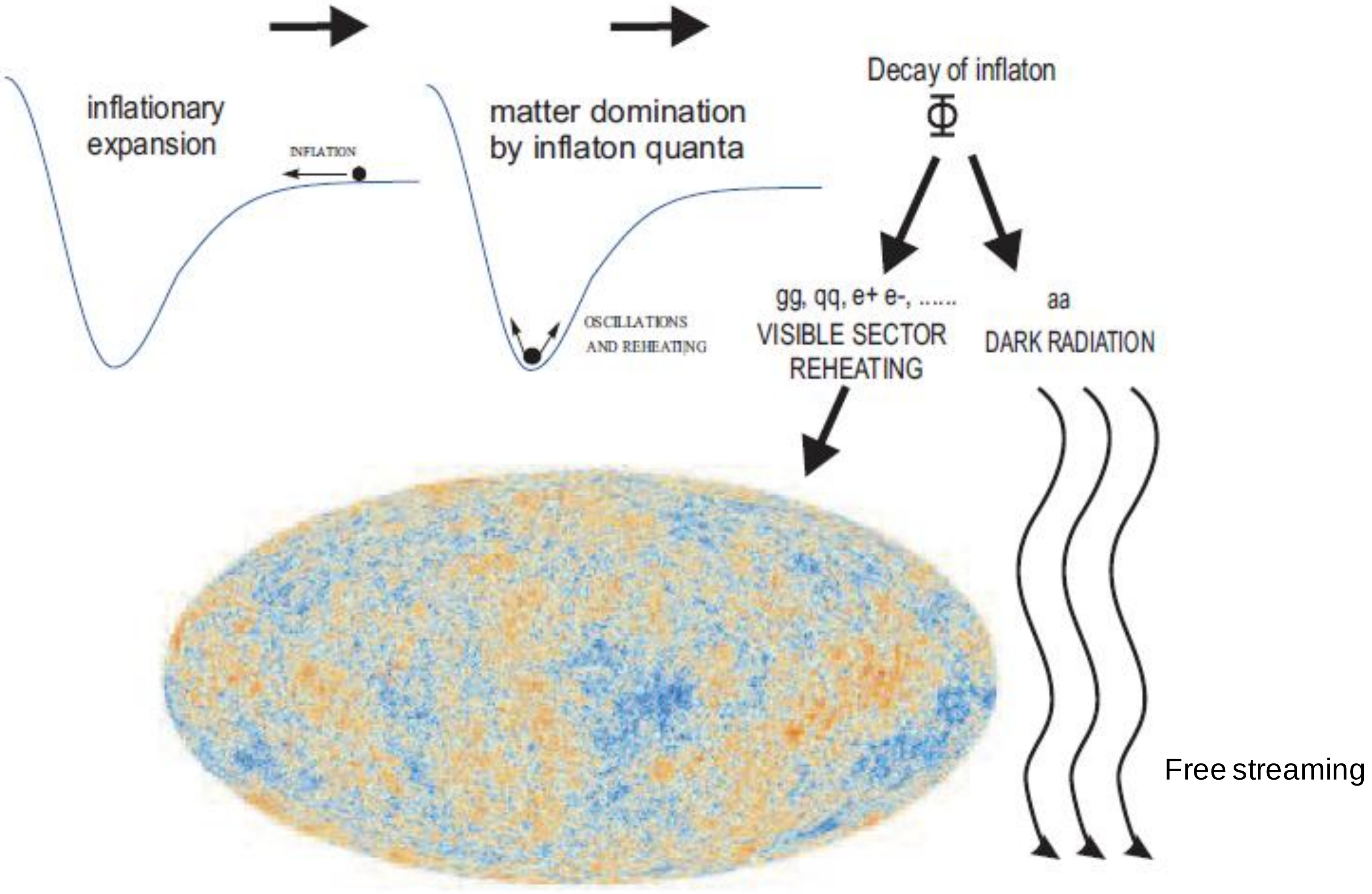
- Gravitino problem [Endo,Hamaguchi,Takahashi] [Nakamura,Yamaguchi]:
  1. if $m_{3/2} < m_\phi$ the gravitino is produced from ϕ decay
  2. if $m_{3/2} < 50$ TeV $\Rightarrow$ gravitino decays after BBN
  3. if $m_{3/2} > 50$ TeV $\Rightarrow$ gravitini could annihilate into DM $\Rightarrow$ DM overproduction
- Axionic dark radiation overproduction [MC,Conlon,Quevedo][Higaki,Takahashi]:
  1. moduli are gauge singlets $\Rightarrow$ they do not prefer to decay into visible sector fields
  2. large branching ratio into light axions $\Rightarrow$ large $N_{\rm eff}$

see Hebecker's talk

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

  3. Tight bounds from observations (Planck+WMAP9+ACT+SPT+BAO+HST):
     $N_{\rm eff} = 3.52^{+0.48}_{-0.45}$ 95% CL $\Rightarrow \Delta N_{\rm eff} \simeq 0.5$

Dark radiation production



Cosmological evolution of dark radiation

$\Phi \to gg, \ldots$: Decays thermalise $T_\gamma \sim T_{reheat} \sim \frac{m_\Phi^{3/2}}{M_P^{\frac{1}{2}}}$

$\Phi \to aa$: Axions never thermalise $E_a = \frac{m_\Phi}{2}$

Thermal bath cools into the CMB while axions never thermalise and freestream to the present day:

Ratio of axion energy to photon temperature is

$$\frac{E_a}{T_\gamma} \sim \left(\frac{M_P}{m_\Phi}\right)^{\frac{1}{2}} \sim 10^6 \left(\frac{10^6 \text{GeV}}{m_\Phi}\right)^{\frac{1}{2}}$$

Retained through cosmic history!

No absolute prediction, but a lightest modulus mass $m \sim 10^6$GeV arises in many string models - often correlated with SUSY approaches to the weak hierarchy problem.

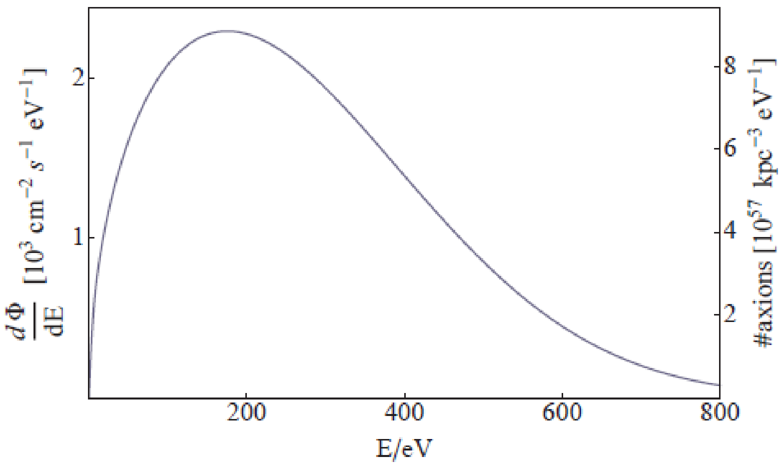
- KKLT hep-th/0503216 Choi et al
- Sequestered LVS 0906.3297 Blumenhagen et al
- 'G2 MSSM' 0804.0863 Acharya et al

No CMP requires m>$10^{4\text{-}5}$ GeV!

Cosmic Axion Background

PREDICTION: Cosmic Axion Background

$$E_a \sim 200\text{eV}\left(\frac{10^6\ \text{GeV}}{m_\Phi}\right)^{\frac{1}{2}}$$



The expectation that there is a dark analogue of the CMB at $E \gg T_{CMB}$ comes from very simple and general properties of moduli.

It is not tied to precise models of moduli stabilisation or choice of string theory etc.

It just requires the existence of massive particles only interacting gravitationally.

For 10^5GeV $\lesssim m_\Phi \lesssim 10^8$GeV CAB lies today in EUV/soft X-ray wavebands.

Observed soft X-ray excess in galaxy clusters via axion-photon conversion!

$$\mathcal{L} \supset g_{a\gamma\gamma} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$

Need $m_a \leq 10^{-12}$ eV
$g_{a\gamma\gamma} \sim (10^{12})^{-1}$ [Conlon, Marsh]

LARGE Volume Scenario

Type IIB LVS models: moduli masses and couplings can be computed explicitly
$\Rightarrow$ can study cosmological history of the universe

- Lightest modulus mass:

$$m_\phi \simeq m_{3/2}\sqrt{\epsilon} \ll m_{3/2} \qquad \text{where} \qquad \epsilon \equiv \frac{m_{3/2}}{M_P} \simeq \frac{W_0}{\mathcal{V}} \simeq e^{-\frac{2\pi}{N g_s}} \ll 1$$

1. NO gravitino problem
2. CMP if $m_{3/2} \simeq \mathcal{O}(M_{\rm soft}) \simeq \mathcal{O}(1)$ TeV $\Rightarrow m_\phi \simeq \mathcal{O}(1)$ MeV

- Way-out: focus on sequestered models [Blumenhagen et al]:

1. Visible sector in the singular regime (fractional D3-branes at singularities)

$$M_{\rm soft} \simeq m_{3/2}\epsilon \ll m_\phi \simeq m_{3/2}\sqrt{\epsilon} \ll m_{3/2}$$

2. NO CMP for $\epsilon \simeq 10^{-7}$
   $\Rightarrow M_{\rm soft} \simeq \mathcal{O}(1)\,\text{TeV} \ll m_\phi \simeq \mathcal{O}(5\cdot 10^6)\,\text{GeV} \ll m_{3/2} \simeq \mathcal{O}(10^{11})\,\text{GeV}$
3. High string scale: $M_s \simeq M_P\sqrt{\epsilon} \simeq \mathcal{O}(10^{15})$ GeV
   $\Rightarrow$ good for GUTs and inflation

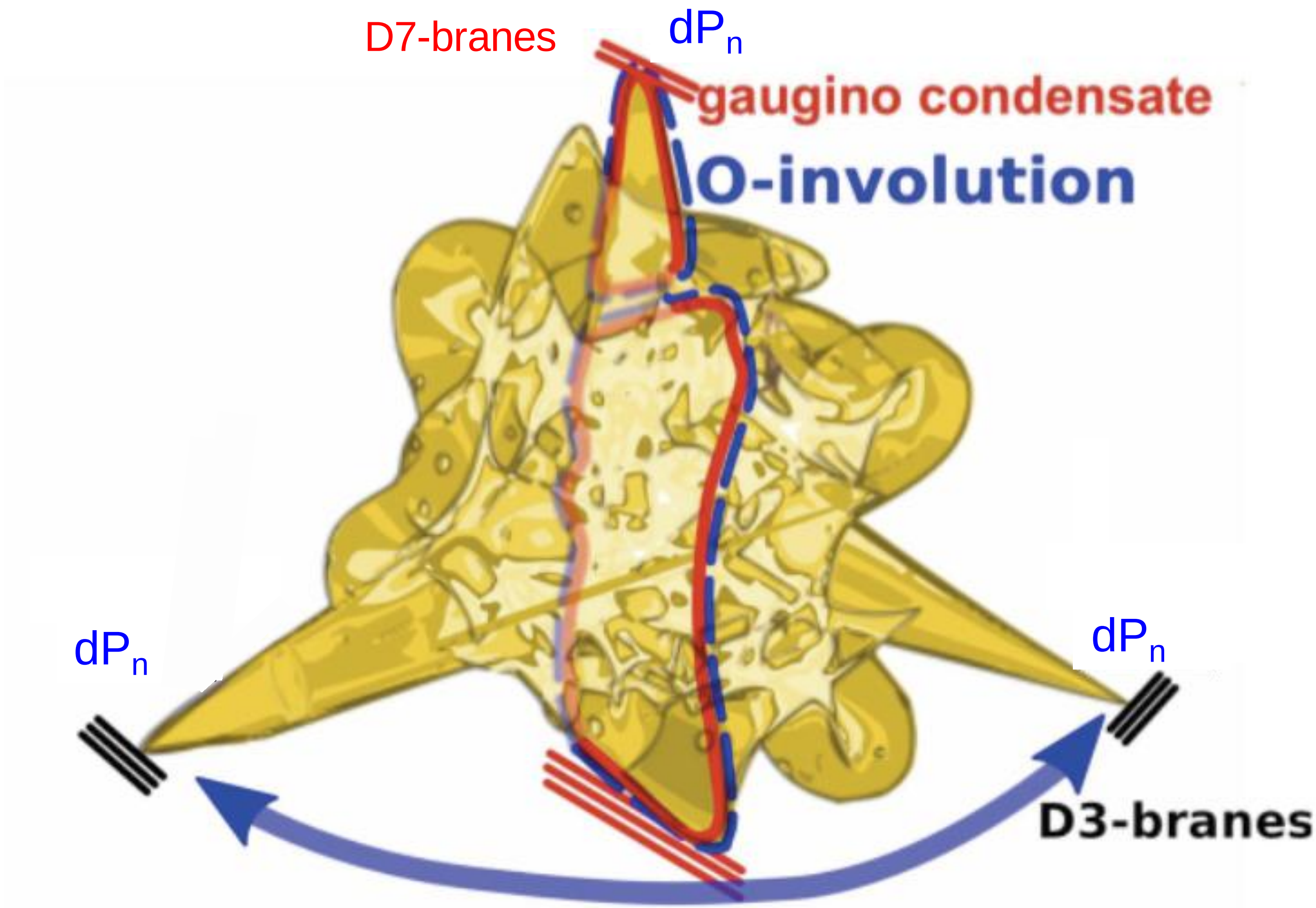
Sequestered LVS models

- Explicit LVS compactifications with fluxes, D3/D7-branes and O3/O7-planes
- Description of the compact CY by toric geometry [MC,Kreuzer,Mayrhofer]
- Global consistency: D5- & D7-tadpole, torsion charges and FW anomaly cancellation + D3-tadpole
- Moduli fixing compatible with chirality within the regime of validity of EFT + explicit fixing of dilaton and cx str moduli using GP method
- D-term induced shrinking of the cycles supporting the visible sector
- Visible sector D3s at del Pezzo singularities [MC,Krippendorf,Mayrhofer,Quevedo,Valandro]
- Minkowski vacua from D-terms or E(-1) instantons [MC,Maharana,Quevedo,Burgess]
- Study of SUSY breaking with running down to TeV scale [Aparicio et al in progress]
- Study of axion phenomenology with explicit QCD axion candidates [MC,Goodsell,Ringwald]
- Interesting cosmology:
  - Inflation using Kähler moduli fits Planck data very well [Burgess,MC,Quevedo]
  - Axion dilution and non-thermal dark matter from moduli decays [Allahverdi,MC,Dutta,Sinha]
  - Dark radiation from light axions [MC,Conlon,Quevedo][Higaki,Takahashi]
  - $\mathcal{O}(200\,\mathrm{eV})$ cosmic axion background [Conlon,Marsh]

Global embedding of D-branes at singularities

- 'Diagonal' dPs crucial to embed quiver theories [MC,Krippendorf,Mayrhofer,Quevedo,Valandro]:
- Consider them to support the visible sector and turn on a non-zero flux:
  $\xi_{\rm dP} \propto \int_{D_{\rm dP}} J \wedge \mathcal{F}_{\rm dP} = k_{{\rm dP}jk}\mathcal{F}^k_{\rm dP} t^j \propto t_{\rm dP} = 0 \Rightarrow t_{\rm dP} \to 0$
- Need 2 dP divisors exchanged by the orientifold involution $\Rightarrow h^{1,1}_- \geq 1$
- 2 dPs do not intersect each other $\Rightarrow$ they do not touch the O7 $\Rightarrow U(N)$ groups
- Involution-invariant 'diagonal' dP for non-pert. effects (generation of $W_{\rm np}$ guaranteed)
- Minimal set-up involves $h^{1,1} = 4$:
  1. $h^{1,1}_- = 1$ G-modulus (reduction of B_2 and C_2)
  2. $h^{1,1}_+ = 3$ T-moduli (1 local blow-up + 1 NP cycle + volume mode)
- A dP divisor has 2 anomalous $U(1)$s
  $\Rightarrow d = 2$ moduli fixed by D-terms (G-modulus and local blow-up)
  $\Rightarrow$ local axions eaten up ⟵ closed string axions
- Other 'diagonal' dP and volume mode fixed by NP + α' effects

Pictorial View



Simplest sequestered LVS model

- Volume form: $\mathcal{V} = \tau_b^{3/2} - \tau_{\rm np}^{3/2} - \tau_{\rm vs}^{3/2} \simeq \tau_b^{3/2}$
- Visible sector cycle shrinks to zero size due to D-terms: $\xi \propto \tau_{\rm vs} \Rightarrow \tau_{\rm vs} \to 0$
- Corresponding axion gets eaten up
- Sources for Kähler moduli stabilisation:

$$K = -2\ln\left(\mathcal{V} + \frac{\xi}{g_s^{3/2}}\right) \qquad \text{and} \qquad W = W_0 + A\, e^{-\frac{2\pi}{N} T_{\rm np}}$$

- Leading F-term potential from α' + non-pert. corrections:

$$V \sim \frac{\sqrt{\tau_{\rm np}}}{\mathcal{V}}\, e^{-\frac{4\pi\tau_{\rm np}}{N}} - W_0\, \frac{\tau_{\rm np}}{\mathcal{V}^2}\, e^{-\frac{2\pi\tau_{\rm np}}{N}} + \frac{W_0^2 \xi}{g_s^{3/2}\mathcal{V}^3}$$

- Fix $\mathcal{V}$ and $\tau_{\rm np}$ at $\tau_{\rm np} \sim g_s^{-1}$ and $\mathcal{V} \sim W_0\, e^{\frac{2\pi}{N g_s}}$
- a_b is a light axion whereas $a_{\rm np}$ is heavy
- AdS minimum with spontaneous SUSY breaking
- Minkowski vacua via D-term uplifting or instantons at sing. [MC,Maharana,Quevedo,Burgess]

Mass spectrum

- Main difference with geometric case: no local SUSY breaking since $F^{\rm vs} \propto \xi = 0$
- Sequestered soft terms: $M_{\rm soft} \sim m_{3/2}/\mathcal{V} \sim M_P/\mathcal{V}^2 \ll m_{3/2}$
- Get TeV-scale SUSY for $\mathcal{V} \sim 10^7 \Rightarrow$ high string scale $M_s \sim M_P/\sqrt{\mathcal{V}} \sim 10^{15}$ GeV
- Right GUT scale: $M_{\rm GUT} \sim M_s \mathcal{V}^{1/6} \sim 10^{16}$ GeV [Conlon,Palti]
- Mass spectrum:
  - $m_{\tau_{\rm vs}} \sim m_{a_{\rm vs}} \sim M_s \sim M_P/\sqrt{\mathcal{V}} \sim 10^{15}$ GeV
  - $m_{\tau_{\rm np}} \sim m_{a_{\rm np}} \sim M_P \ln \mathcal{V}/\mathcal{V} \sim 10^{12}$ GeV
  - $m_{3/2} \sim M_P/\mathcal{V} \sim 10^{11}$ GeV
  - $m_{\tau_b} \sim M_P/\mathcal{V}^{2/3} \sim 5 \times 10^6$ GeV
  - $M_{\rm soft} \sim M_P/\mathcal{V}^2 \sim 1$ TeV
  - $m_{a_b} \sim M_P e^{-2\pi \mathcal{V}^{2/3}} \sim 0$
- No CMP since $m_{\tau_b} \gg 50\,{\rm TeV}$ + No gravitino problem since $m_{3/2} \gg m_{\tau_b}$
- Successful inflation with $N_e \simeq 60$, $n_s \simeq 0.96$, $r \ll 1$, right amount of density perturbations and possibly power loss at large scales [Burgess,MC,Conlon,Pedro,Quevedo,Tasinato]
- Reheating driven by decay of lightest modulus τ_b

Reheating

- Reheating driven by ϕ decays when $H \sim \Gamma_\phi = \frac{c}{2\pi}\frac{m_\phi^3}{M_P^2}$

$$T_{\rm rh} = c^{1/2}\left(\frac{m_\phi}{5\cdot 10^6\,{\rm GeV}}\right)^{3/2}\mathcal{O}(1)\,{\rm GeV}$$

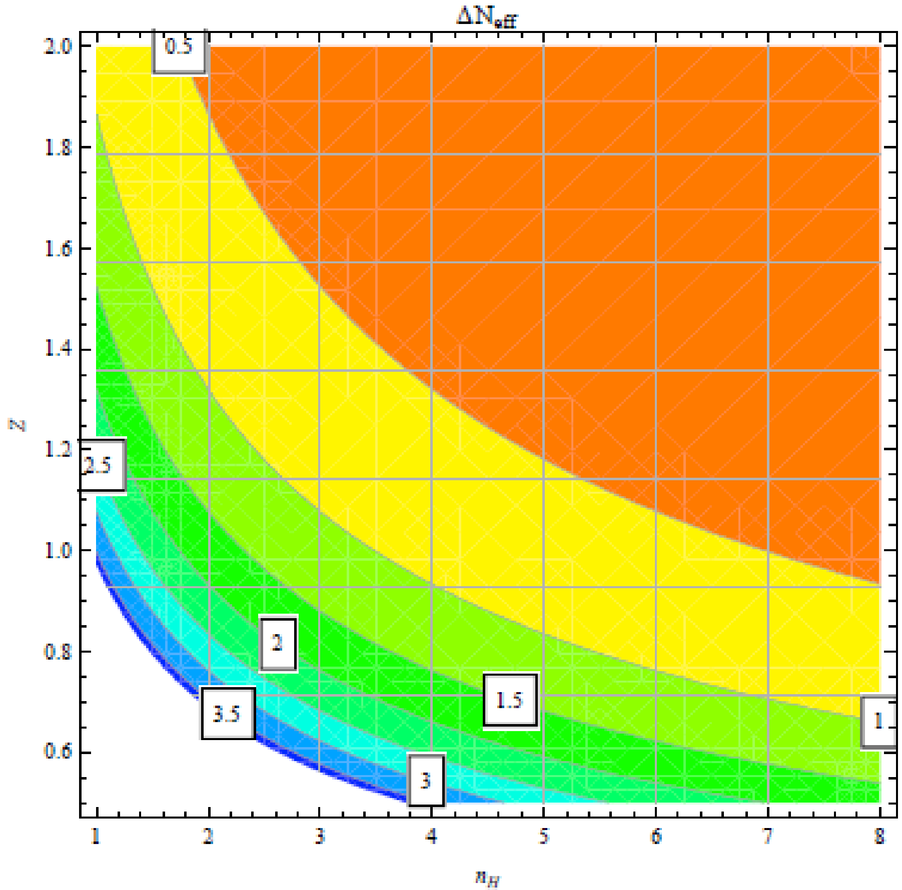
- Leading decay channels:
  - **Higgses:** $c_{\phi\to H_u H_d} = Z^2/12$ from GM term $K \supset Z\,\frac{H_u H_d}{2\mathcal{V}^{2/3}}$
  - **Bulk closed string axions:** $c_{\phi\to a_b a_b} = 1/24$
  - **Local closed string axions** (if not eaten by $U(1)$s): $c_{\phi\to a_{\rm loc}a_{\rm loc}} = 9/384$
- Subleading decay channels:
  - **Gauge bosons:** $c_{\phi\to A^\mu A^\mu} = \lambda\frac{\alpha_{\rm vs}^2}{8\pi} \ll 1$
  - **Other visible sector fields:** $c_{\phi\to\psi\psi} \simeq \left(\frac{M_{\rm soft}}{m_\phi}\right)^2 \simeq \frac{1}{\mathcal{V}} \ll 1$
  - **Local open string axions:** $c_{\phi\to a_b\theta} \simeq \left(\frac{M_s}{M_P}\right)^4\tau_{\rm sing}^2 \simeq \left(\frac{\tau_{\rm sing}}{\mathcal{V}}\right)^2 \ll 1$

Predictions for dark radiation

Prediction for $\Delta N_{\rm eff}$ for n_H Higgs doublets and n_a local closed string axions:

$$\Delta N_{\rm eff} = \frac{3.48}{n_H Z^2}\left(1 + \frac{9 n_a}{16}\right) \underset{n_a = 0}{\longrightarrow} \frac{3.48}{n_H Z^2}$$

[MC, Conlon, Quevedo; Higaki, Takahashi]



Axions from strings

- Low-energy spectrum contains many closed string axions of order $h^{1,1} \simeq O(100)$ for a generic CY ⟶ expect many axions
  - i) closed string axions (KK zero modes of antisymmetric forms)
  - ii) open string axions (phase θ of a matter field $\phi = |\phi|\, e^{i\theta}$)
- BUT:
  - i) axions can be removed from the spectrum by orientifold projection
  - ii) axions can be eaten up by anomalous U(1)s
    - a) open string axions eaten up on cycles in the geometric regime
    - b) closed string axions eaten up for branes at singularities
  - iii) axions can become too heavy if they are fixed supersymmetrically (saxion has to get a mass larger than O(50) TeV!)
- Moduli stabilisation
  - i) axions are light if saxions are fixed perturbatively because of shift symmetry
  - ii) axions are heavy if saxions are fixed non-perturbatively

NB Non-perturbative stabilisation hard because of tuning, deformation zero-modes, chirality and non-vanishing gauge fluxes (Freed-Witten anomaly cancellation)

⟶ GENERIC PREDICTION: dark radiation production is UNAVOIDABLE in models with perturbative moduli stabilisation!!! [Allahverdi, MC, Dutta,Sinha]

Axions in sequestered models

- In LVS $\mathcal{V}$ fixed by perturbative effects $\Rightarrow$ light a_b because of shift symmetry
- Open string axions eaten up by anomalous $U(1)$s on bulk cycles
  $\Rightarrow$ light bulk closed string axions are a model-independent feature of LVS
  $\Rightarrow$ dark radiation is a model-independent prediction of LVS!
- $\mathcal{O}(200)\,\mathrm{eV}$ cosmic axion background + X-ray excess in galaxy cluster [Conlon,Marsh]
- Two options for QCD axion [MC,Goodsell,Ringwald]:
  - **Open string QCD axion** θ: $C = \rho\, e^{i\theta}$
    1. Subleading ϕ decay to $\theta \Rightarrow$ No DR overproduction
    2. D-terms: $V_D \simeq g^2 \left(\rho^2 - \xi\right)^2 \Rightarrow f_a = \langle\rho\rangle = \sqrt{\xi} \simeq \sqrt{\langle\tau_{\rm sing}\rangle}\, M_s$
    3. Subleading F-terms: $\langle\tau_{\rm sing}\rangle = 1/\mathcal{V} \ll 1$
       $\Rightarrow f_a \simeq M_s/\sqrt{\mathcal{V}} \simeq \mathcal{O}(10^{11-12})\,\mathrm{GeV} \Rightarrow$ No DM overproduction
  - **Closed string QCD axion** $a_{\rm sing}$: $T_{\rm sing} = \tau_{\rm sing} + i a_{\rm sing}$
    1. All local closed string axions eaten up by anomalous $U(1)$ in dP singularities
    2. $a_{\rm sing}$ could be left over for more complicated singularities
    3. $f_{a_{\rm sing}} \simeq M_s/\sqrt{4\pi} \simeq 10^{14}$ GeV
    4. Needs to be diluted by ϕ decay or tune initial misalignment angle
    5. $a_{\rm sing}$ could give DR overproduction

Non-thermal dark matter

- Non-thermal DM produced from ϕ decay [Allahverdi,MC,Dutta,Sinha]
- ϕ decay dilutes thermal DM by a factor of order $(T_{\rm f}/T_{\rm rh})^3 \gtrsim 10^6$
- Parameter space larger than the one for thermal DM
- DM production from ϕ decay:

$$\frac{n_{\rm DM}}{s} = \min\left[\left(\frac{n_{\rm DM}}{s}\right)_{\rm obs} \frac{\langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}}{\langle\sigma_{\rm ann} v\rangle_{\rm f}} \left(\frac{T_{\rm f}}{T_{\rm rh}}\right), Y_\phi {\rm Br}_{\phi\to{\rm DM}}\right]$$

where:

- $\left(\frac{n_{\rm DM}}{s}\right)_{\rm obs} \simeq 5\times 10^{-10}\left(\frac{1\ {\rm GeV}}{m_{\rm DM}}\right)$
- $\langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th} \simeq 3\times 10^{-26}{\rm cm}^3\,{\rm s}^{-1}$ is the thermal value
- $Y_\phi \equiv \frac{3T_{\rm rh}}{4m_\phi} = \frac{0.9}{\pi}\sqrt{\frac{c\,m_\phi}{M_P}}$
- ${\rm Br}_{\phi\to{\rm DM}}$ is the branching ratio for ϕ decays into R-parity odd particles

Non-thermal DM scenarios

- DM abundance:

$$\frac{n_{\rm DM}}{s} = \min\left[\left(\frac{n_{\rm DM}}{s}\right)_{\rm obs} \frac{\langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}}{\langle\sigma_{\rm ann} v\rangle_{\rm f}} \left(\frac{T_{\rm f}}{T_{\rm rh}}\right), Y_\phi {\rm Br}_{\phi\to{\rm DM}}\right]$$

- First term on RHS side $\Rightarrow$ Annihilation Scenario
  1. DM produced from ϕ decay undergo some annihilation
  2. Need $\langle\sigma_{\rm ann} v\rangle_{\rm f} = \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th} (T_{\rm f}/T_{\rm rh})$
  3. Since $T_{\rm rh} < T_{\rm f}$, need $\langle\sigma_{\rm ann} v\rangle_{\rm f} > \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}$ $\Rightarrow$ Wino/Higgsino DM
- Second term on RHS side $\Rightarrow$ Branching Scenario
  1. DM annihilation is inefficient and DM is produced directly from ϕ decay
  2. Need $\langle\sigma_{\rm ann} v\rangle_{\rm f} < \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th} (T_{\rm f}/T_{\rm rh})$
  3. Always the case for $\langle\sigma_{\rm ann} v\rangle_{\rm f} < \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}$ $\Rightarrow$ Bino DM
  4. Can also happen for $\langle\sigma_{\rm ann} v\rangle_{\rm f} > \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}$ if $T_{\rm rh}/T_{\rm f}$ is too small $\Rightarrow$ can accommodate also Wino/Higgsino DM

Annihilation scenario

- FERMI bounds from dwarf spheroidal galaxies [Geringer-Sameth, Koushiappas]:
  - For $m_{\rm DM} < 40\,{\rm GeV}$, $\langle \sigma_{\rm ann} v \rangle_{\rm f} < \langle \sigma_{\rm ann} v \rangle_{\rm f}^{\rm th}$ $\Rightarrow$ No 'annihilation scenario'
  - For $m_{\rm DM} > 40\,{\rm GeV}$, $T_{\rm f}/30 \lesssim T_{\rm rh} < T_{\rm f}$ $\Rightarrow$ $T_{\rm rh} \gtrsim 70\,{\rm MeV}$
- $T_{\rm rh} \simeq 0.8\,Z$ GeV for $m_\phi \simeq 5 \times 10^6$ GeV $\Leftrightarrow$ TeV-scale SUSY
- Two cases:

1. QCD axion is an open string mode θ with $f_a \simeq 10^{11-12}$ GeV
   - Subleading ϕ decays to $\theta \Rightarrow$ No DR is produced
   - DR from ϕ decays to bulk closed string axions $\Rightarrow$ suppress $\Delta N_{\rm eff} \simeq 1.74/Z^2$
   - $\Delta N_{\rm eff} \simeq 0.5 \Rightarrow Z \simeq 1.8 \Rightarrow T_{\rm rh} \simeq \mathcal{O}(1)$ GeV
   - $T_{\rm rh} > \Lambda_{\rm QCD} \Rightarrow$ axion DM is not diluted
   - Multicomponent DM (Wino/Higgsino + open string axions)
2. QCD axion is a local closed string mode $a_{\rm loc}$ with $f_a \simeq 10^{14}$ GeV
   - $\phi \to a_{\rm loc} a_{\rm loc}$ is a leading decay channel $\Rightarrow$ suppress $\Delta N_{\rm eff} \simeq 2.72/Z^2$
   - $\Delta N_{\rm eff} \simeq 0.5 \Rightarrow Z \simeq \sqrt{5} \simeq 2.2 \Rightarrow T_{\rm rh} \simeq \mathcal{O}(1)$ GeV
   - Axion DM is not diluted $\Rightarrow$ tune initial misalignment angle
   - Multicomponent DM (Wino/Higgsino + closed string axions)

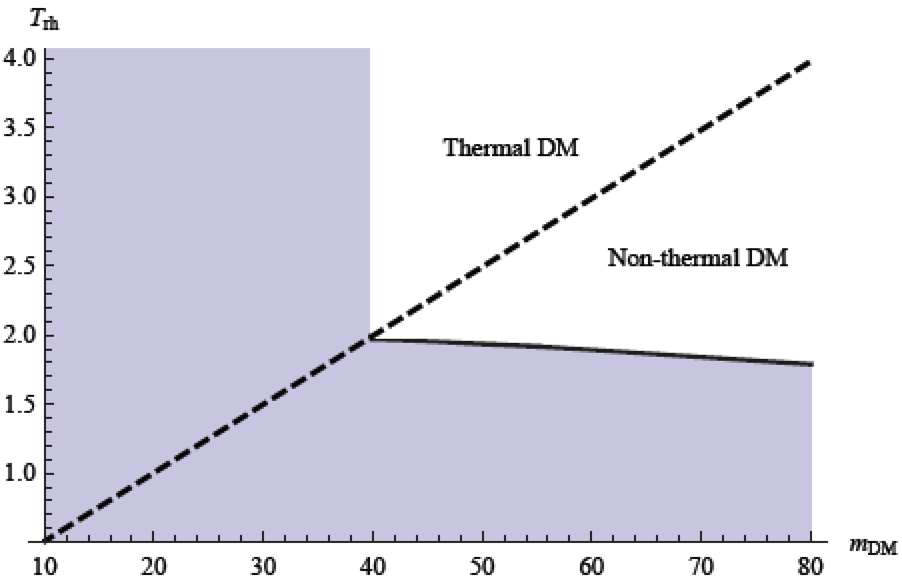
Branching scenario

- Low $T_{\rm rh}$ regime: $3\,{\rm MeV} \lesssim T_{\rm rh} \lesssim 70\,{\rm MeV}$
- Need very small ϕ decay width
- $Z \simeq 2$ to avoid DR problems $\Rightarrow T_{\rm rh} \simeq \mathcal{O}(1)\,{\rm GeV}$
- Cannot lower $T_{\rm rh}$ if $Z = 0$ from loop-suppressed ϕ decays to gauge bosons
- Lower $T_{\rm rh}$ for smaller values of $m_\phi \Rightarrow M_{\rm soft} \ll \mathcal{O}(1)\,{\rm TeV}$
- No DR overproduction + TeV-scale SUSY forbid branching scenario
- Rule out models with Bino LSP $\Rightarrow$ non-thermal DM overproduction
- Way-out: focus on cases where the LSP is unstable
- DM is QCD axion

DM-DR correlation

- Fermi bounds from dwarf spheroidal galaxies constrain T_{rh} as a function of m_{DM}

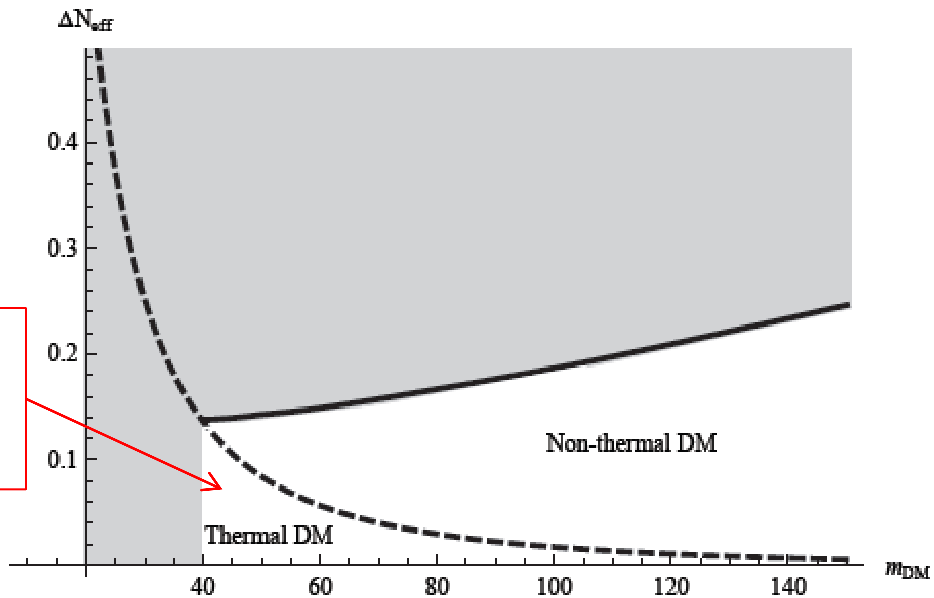
[Allahverdi, MC, Dutta,Sinha]



$$T_{\rm rh} \simeq \frac{\kappa}{\sqrt{\Delta N_{\rm eff}}} \left(\frac{68.5}{g_*}\right)^{1/4} \left(\frac{M_{1/2}}{1\,{\rm TeV}}\right)^{9/8} 1.19\,{\rm GeV}$$

$$M_{1/2} \simeq m_\phi \left(\frac{m_\phi}{M_P}\right)^{1/3} \qquad \kappa \approx O(1)$$

$$T_{rh} \propto \frac{1}{\sqrt{\Delta N_{eff}}}$$



Thermal DM ruled out in LVS since it requires Z>>1

→ large μ-term → Heavy higgsinos

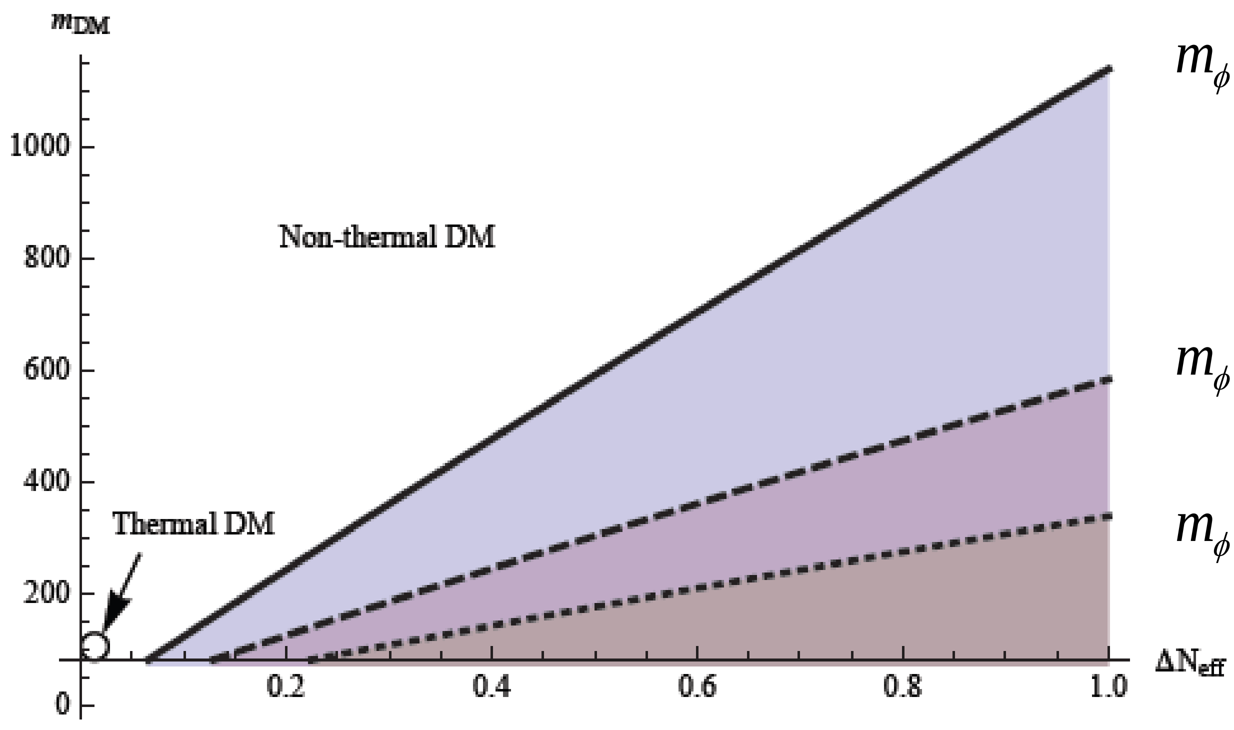
→ LSP is Bino → thermal overproduction!

→ Generic prediction:
Non-thermal Higgsino-like DM!

Lower bound on DM mass from DR

- Lower bound on DM mass as a function of ΔN_{eff}

$$m_{\rm DM} \gtrsim \Delta N_{\rm eff} \sqrt{\frac{g_*}{68.5}} \left(\frac{1\,{\rm TeV}}{M_{1/2}} \right)^{9/4} \frac{230\,{\rm GeV}}{\kappa^2} \qquad \kappa \approx O(1)$$



$m_\phi = 4 \cdot 10^6$ GeV

$m_\phi = 5 \cdot 10^6$ GeV

$m_\phi = 6 \cdot 10^6$ GeV

3.55 keV line

- Unidentified 3.55 keV line from galaxy clusters and from Andromeda recently found! Statistical significance $\sim$ 4 σ [Bulbul at al, Boyarsky et al] see Payez's talk

3.55 keV line may be identified with line from two photon decay of 7.1 keV mass ALP CDM
[Higaki, Jeong, Takahashi; Jaeckel, Redondo, Ringwald]

- For $x_\phi = \rho_\phi / \rho_{\rm DM}$, required life-time

$$\tau_\phi = \frac{64\pi}{g_{\phi\gamma\gamma}^2 m_\phi^3} = x_\phi \times (4\times 10^{27} - 4\times 10^{28})\,{\rm s}$$

- Thus required coupling and scale

$$g_{\phi\gamma\gamma} \sim (3\times 10^{-18} - 10^{-12})\,{\rm GeV}^{-1}$$

$$f_\phi \sim (10^9 - 4\times 10^{14})\,{\rm GeV}$$

if one allows x_ϕ to be in the range

$$x_\phi \sim 10^{-10} - 1$$

Alternative explanation:
1) DM decay into axions
   ➡ Narrower CAB spectrum
   ➡ Good for a line
2) Axion-photon conversion in B

Advantages:
1) Need just 1 ALP to explain soft X-ray excess and 3.5 keV line!
2) Get a prediction:

Each galaxy cluster emits a line at 3.5 keV but with different strength due to different B and electron density

i) Perseus anomaly: its line is too bright!

Hard to explain it with decaying DM!

ii) $P(a \to \gamma) \approx (BLg_{a\gamma\gamma})^2$

[MC, Conlon, Marsh, Rummel, in progress]

Conclusions

- Sequestered LVS models
- Superpartner spectrum in the TeV range

Explicit semi-realistic compact models with full moduli stabilisation and dS vacua!

- High string scale $M_s \simeq 10^{15}\,\mathrm{GeV} \Rightarrow$ Good inflationary scenarios

Power loss at large scales! No observable tensor modes

- No CMP and no gravitino problem since $m_{3/2} \simeq 10^{11}\,\mathrm{GeV} \gg m_\phi \simeq 5 \times 10^6\,\mathrm{GeV}$
- Reheating driven from ϕ decay with $T_{\rm rh} \simeq \mathcal{O}(1)\,\mathrm{GeV}$
- Generic dark radiation production from ϕ decay to light bulk closed string axions
- Non-thermal DM from ϕ decay which increases DM parameter space

CAB and soft X-ray excess!

- 'Annihilation scenario' with multicomponent DM: Wino/Higgsino + QCD axion
- Two options for QCD axion:
  - Open string QCD axion with $f_a \simeq 10^{11-12}\,\mathrm{GeV}$
    $\Rightarrow$ No extra DR contribution + no DM overproduction
  - Closed string QCD axion with $f_a \simeq 10^{14}\,\mathrm{GeV}$
    $\Rightarrow$ Extra DR contribution + tune initial misalignment angle
- No 'Branching scenario' with $T_{\rm rh} \simeq 10\,\mathrm{MeV}$ due to DR + TeV-scale SUSY constraints
  $\Rightarrow$ rule out models with stable Bino-like LSP

3.5 keV line from decaying axion DM or CAB!