Baryogenesis from Strings

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Based on:

Allahverdi, MC, Muia, arXiv:1603.xxxxx

LARGE Volume Scenario

- Volume, Kahler potential and superpotential

$$\mathcal{V} = \tau_b^{3/2} - \sum_{i=1}^{n} \tau_i^{3/2} \qquad K = -2\ln\mathcal{V} - \frac{\xi}{g_s^{3/2}\mathcal{V}} \qquad W = W_0 + \sum_{i=1}^{n} A_i\, e^{-a_i T_i}$$

- Scalar potential

axion minimisation

$$V = \sum_{i=1}^{n}\left(\frac{8}{3}\sqrt{\tau_i}\,(a_i A_i)^2\,\frac{e^{-2a_i\tau_i}}{\mathcal{V}} - 4a_i A_i W_0 \tau_i\,\frac{e^{-a_i\tau_i}}{\mathcal{V}^2}\right) + \frac{3\xi W_0^2}{4g_s^{3/2}\mathcal{V}^3}$$

- AdS minimum at

$$\tau_i \approx \left(\frac{\xi}{2n}\right)^{2/3} g_s^{-1} \approx g_s^{-1} \approx O(10) \quad \text{for } g_s \approx 0.1$$

$$\mathcal{V} \approx W_0\, e^{a_i\tau_i} \approx e^{1/g_s} >> 1$$

trust approximations

- dS vacua without anti-branes

dS_1 case: non-zero hidden matter F-terms induced by D-terms (T-branes) [MC, Quevedo, Valandro]

dS_2 case: non-perturbative effects at singularities [MC, Maharana, Quevedo, Burgess]

- Generate hierarchies naturally: $m_{3/2} \approx \dfrac{W_0 M_p}{\mathcal{V}} \approx M_p\, e^{-1/g_s} << M_p$ TeV-scale SUSY

- Spontaneous SUSY breaking: $F^{T_b} \approx \dfrac{M_p^2}{\mathcal{V}^{1/3}} \neq 0 \qquad F^{T_i} \approx \dfrac{M_p^2}{\mathcal{V}} \neq 0$

Visible sector

- D7s in geometric regime:

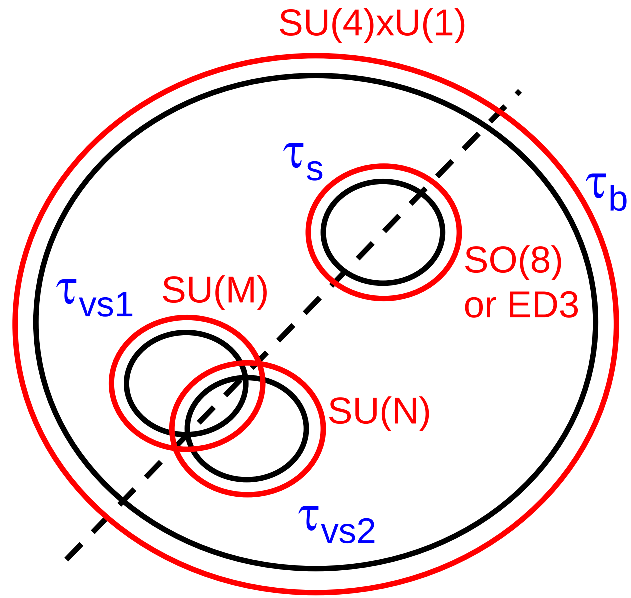
$$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2} - \left(\alpha \tau_{vs1} + \beta \tau_{vs2}\right)^{3/2}$$

i) D-terms fix $\tau_{vs1} \sim \tau_{vs2} \sim \tau_{vs}$

ii) NP + α' effects fix τ_b and τ_s at

$$\tau_b^{3/2} \approx e^{\tau_s} \qquad \tau_s \approx g_s^{-1}$$

iii) g_s effects fix τ_{vs}



- D3s at singularities:

$$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2} - \tau_{vs1}^{3/2} - \tau_{vs2}^{3/2}$$

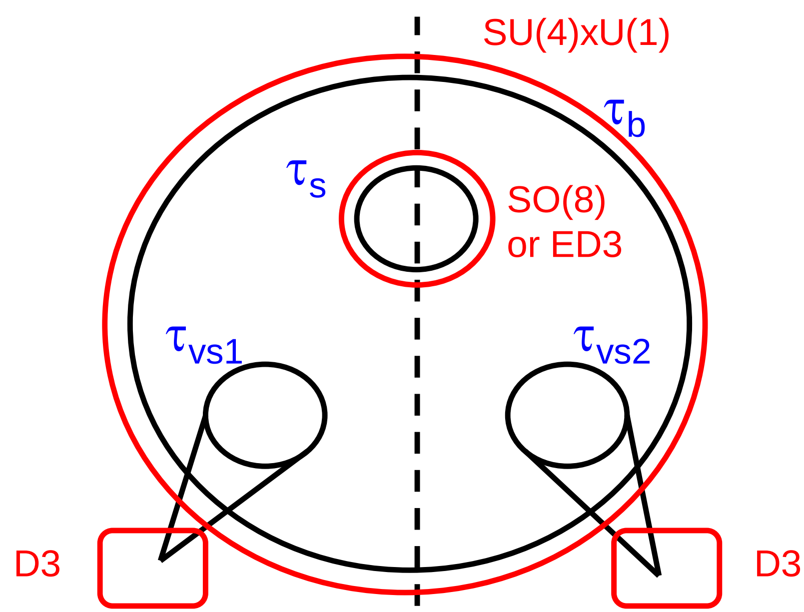
i) $\tau_{vs1} \longleftrightarrow \tau_{vs2}$ orientifold projection

→ get U(N) groups

ii) D-terms fix $\tau_{vs1} \sim \tau_{vs2} \longrightarrow 0$

iii) NP + α' effects fix τ_b and τ_s at

$$\tau_b^{3/2} \approx e^{\tau_s} \qquad \tau_s \approx g_s^{-1}$$



NB1 Non-perturbative effects for rigid cycles!

NB2 τ_{vs} fixed by D-terms or g_s effects

→ compatible with chirality!

Mass scales in sequestered models

- D3s at singularties → F-term of τ_{vs} is zero: $F^{vs} \propto \xi_{FI} \propto \tau_{vs} \to 0$
- Soft-terms (depending on matter Kahler metric and dS mechanism):

$$M_{1/2} \approx \frac{M_p}{\mathcal{V}^2} << m_{3/2} \approx \frac{M_p}{\mathcal{V}} \qquad m_0 \approx \begin{cases} \frac{M_p}{\mathcal{V}^{3/2}} \approx m_{\tau_b} \\ \frac{M_p}{\mathcal{V}^2} \end{cases}$$

- Set $\mathcal{V} \sim 10^7$ to get $M_{1/2} \sim O(1)$ TeV :

$$M_P \approx 10^{18}\,\text{GeV}$$

$$M_{GUT} \approx M_s \mathcal{V}^{1/6} \approx 10^{16}\,\text{GeV}$$

$$M_s \approx m_{\tau_{vs}} \approx m_{a_{vs}} \approx 10^{15}\,\text{GeV}$$

$$M_{KK} \approx 10^{14}\,\text{GeV}$$

$$m_{\tau_s} \approx m_{a_s} \approx 10^{12}\,\text{GeV}$$

$$m_{3/2} \approx 10^{11}\,\text{GeV}$$

1) TeV scale SUSY
2) Standard GUTs
3) Right inflationary scale
4) No CMP for τ_b and no gravitino problem
5) QCD axion from open string modes
6) Reheating driven by the decay of τ_b
7) $T_{rh} \sim 1$ GeV
8) Non-thermal dark matter
9) Axionic dark radiation

MSSM:

$$m_{\tau_b} \approx 10^7\,\text{GeV}$$

$$M_{1/2} \approx m_0 \approx M_P \mathcal{V}^{-2} \approx 1\,\text{TeV}$$

↔

Split SUSY:

$$m_{\tau_b} \approx m_0 \approx 10^7\,\text{GeV}$$

$$M_{1/2} \approx 1\,\text{TeV}$$

$$m_{a_{open}} \approx 1\,\text{meV} \quad \text{for} \quad f_{a_{open}} \approx M_s \sqrt{\tau_{vs}} << M_s$$

$$m_{a_b} \approx 0$$

How is baryogenesis realised?

N=1 4D Kahler potential

- Kahler potential

$$K = -2\ln\left(\mathcal{V} + \frac{\hat{\xi}}{2}\right) - \ln(S+\overline{S}) + \frac{\tau_{\rm SM}^2}{\mathcal{V}} + \frac{b^2}{\mathcal{V}} + K_{\rm cs}(U) + K_{\rm matter}$$

$$K_{\rm matter} = \tilde{K}_\alpha(U,S,T) C^\alpha \overline{C}^{\overline{\alpha}} + Z(U,S,T)\,(H_u H_d + {\rm h.c.})$$

- Kahler matter metric from Yukawas

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

- Locality implies:

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

- Two limits:

  i) Ultra-local limit: (*) holds exactly

  ii) Local limit: (*) holds only at leading order in $\mathcal{V}$-expansion

$$e^{K/3} = \frac{e^{K_{\rm cs}/3}}{(2\,s)^{1/3}} \frac{1}{\left(\mathcal{V}+\frac{\hat{\xi}}{2}\right)^{2/3}} = \frac{e^{K_{\rm cs}/3}}{(2\,s)^{1/3}} \frac{1}{\hat{\mathcal{V}}^{2/3}} \left(1 + \frac{2}{3}\frac{\tau_n^{3/2}}{\hat{\mathcal{V}}} - \frac{\hat{\xi}}{3\hat{\mathcal{V}}} + \cdots\right) \qquad \hat{\mathcal{V}} = \tau_b^{3/2} - \sum_{j=1}^{n-1} \tau_j^{3/2}$$

- Parametrisation of Kahler matter metric: $\tilde{K}_\alpha = \frac{f_\alpha(U,S)}{\hat{\mathcal{V}}^{2/3}} \left(1 - 2c_n \frac{\tau_n^{3/2}}{\hat{\mathcal{V}}} - c_\xi \frac{\hat{\xi}}{\hat{\mathcal{V}}} + \cdots\right)$

- Ultra-local limit for $c_\xi = -c_n = 1/3$

F-terms

- SUSY broken by background fluxes

  → non-zero F-terms and gravitino mass

$$F^i = e^{K/2} K^{i\bar{j}} D_{\bar{j}} \overline{W} \qquad\qquad m_{3/2} = e^{K/2}|W| \simeq \frac{g_s^{1/2}}{2\sqrt{2\pi}} \frac{W_0 M_p}{\mathcal{V}}$$

- F-term of big cycle: $F^{T_b} = F^{T_b}_{\text{tree}} + F^{T_b}_{\alpha'} + F^{T_b}_{\text{np}}$

$$\frac{F^{T_b}_{\text{tree}}}{m_{3/2}} = -2\tau_b\,, \qquad \frac{F^{T_b}_{\alpha'}}{m_{3/2}} = -\frac{3\tau_b}{2}\frac{\hat{\xi}}{\mathcal{V}}\,, \qquad \frac{F^{T_b}_{\text{np}}}{m_{3/2}} = \sum_{i=1}^{n} \frac{4A_i a_i \tau_i}{\sqrt{\tau_b}} \frac{\mathcal{V}}{W_0} e^{-a_i\tau_i}$$

- At the minimum

$$\langle F^{T_b}_{\text{np}} \rangle = -\langle F^{T_b}_{\alpha'} \rangle + \mathcal{O}\left(\frac{\tau_b \hat{\xi}\, m_{3/2}}{\mathcal{V}\ln\mathcal{V}}\right) \quad \longrightarrow \quad \langle F^{T_b} \rangle = -2\tau_b m_{3/2}\left[1 + \mathcal{O}\left(\frac{\hat{\xi}}{\mathcal{V}\ln\mathcal{V}}\right)\right]$$

- F-term of small cycles: $F^{T_i} = F^{T_i}_{\text{tree}} + F^{T_i}_{\alpha'} + F^{T_i}_{\text{np}}$

$$\frac{F^{T_i}_{\text{tree}}}{m_{3/2}} = -2\tau_i\,, \qquad \frac{F^{T_i}_{\alpha'}}{m_{3/2}} = -\frac{3\tau_i}{2}\frac{\hat{\xi}}{\mathcal{V}}\,, \qquad \frac{F^{T_i}_{\text{np}}}{m_{3/2}} = \frac{8A_i a_i \sqrt{\tau_i}}{3} \frac{\mathcal{V}}{W_0} e^{-a_i\tau_i}$$

- At the minimum

$$\langle F^{T_i}_{\text{np}} \rangle = -\langle F^{T_i}_{\text{tree}} \rangle + \mathcal{O}\left(\frac{\tau_i m_{3/2}}{\ln\mathcal{V}}\right) \quad \longrightarrow \quad \langle F^{T_i} \rangle \simeq -\frac{3m_{3/2}}{2a_i}$$

- F-terms of dilaton and complex str. moduli

$$F^S = s\,\omega(U,S)\frac{\tau_i^{3/2} m_{3/2}}{\mathcal{V}} \qquad \text{and} \qquad F^{U^\alpha} = \beta^\alpha(U,S) F^S$$

Soft terms

[Aparicio, MC, Krippendorf, Maharana, Muia,Quevedo]

- Gaugino masses

$$f_a = \kappa_a S + \lambda_a T_{\rm SM} \to \kappa_a S \quad \longrightarrow \quad M_{1/2} = \frac{F^S}{2s} \simeq \lambda(U,S) \frac{\hat{\xi}\, m_{3/2}}{\mathcal{V}}$$

- Scalar masses:

$$m_\alpha^2 = m_{3/2}^2 + V_0 - F^{T_i} F^{\overline{T}_{\bar{j}}} \partial_{T_i} \partial_{\overline{T}_{\bar{j}}} \ln \tilde{K}_\alpha + \tilde{K}_\alpha^{-1} \sum_a g_a^2 D_a \partial_\alpha \partial_{\bar{\alpha}} D_a \qquad D_a = \sum_j Q_{ja} \phi_j \frac{\partial K}{\partial \phi_j} + \sum_i q_{ia} \partial_{T_i} K$$

- Ultra-local limit:

dS$_1$ case: generated by D-terms at O($\mathcal{V}^{-3}$) $\quad m_0^2 \simeq \frac{9}{64} \frac{\hat{\xi}\, m_{3/2}^2}{\mathcal{V} \ln \mathcal{V}}$

dS$_2$ case: generated by F-terms of U and S at O($\mathcal{V}^{-4}$) $\quad m_\alpha^2 \simeq Q_\alpha(U,S) M_{1/2}^2$

- Local limit: D-terms are negligible

(a) $c_n = -1/3$: $\quad m_0^2 \simeq \frac{15}{4} \left(c_\xi - \frac{1}{3} \right) \frac{\hat{\xi}\, m_{3/2}^2}{\mathcal{V}} \qquad c_\xi > 1/3$

(b) $c_\xi = 0$: $\quad m_0^2 \simeq \frac{15}{4\,n} \left[c_n - \frac{1}{3}(n-1) \right] \frac{\hat{\xi}\, m_{3/2}^2}{\mathcal{V}} \qquad c_n > (n-1)/3$

- A-terms generated at O($\mathcal{V}^{-2}$)
- Two scenarios:

i) MSSM-like: ultra-local dS$_2$ case $\quad M_{1/2} \sim m_\alpha \sim A_{\alpha\beta\gamma} \sim \frac{M_p}{\mathcal{V}^2}$

ii) Split SUSY: other cases $\quad M_{1/2} \sim A_{\alpha\beta\gamma} \sim \frac{M_p}{\mathcal{V}^2} \quad$ while $\quad m_0 \sim \frac{M_p}{\mathcal{V}^{3/2}}$

Inflation from Kahler moduli

- Non-compact Abelian pseudo NG bosons: rescaling and Kahler moduli [Burgess, MC, Quevedo, Williams]

$$\Phi \to e^{\alpha}\Phi \qquad \Phi = \rho\, e^{i\vartheta} \qquad \rho \to e^{\alpha}\rho$$ realised for T-moduli because of extended no-scale

- Canonical normalisation: $\rho = e^{\varphi/f}$ $\qquad \varphi \to \varphi + \alpha f$ $\qquad$ non periodic
- EFT under control when $\rho >> 1 \;\Leftrightarrow\; \varphi >> f \;\Leftrightarrow\; \varphi >> M_P \quad \text{for} \quad f \approx M_P$
- Decoupling m_{mod} >> m_{infl} relatively easy due to no-scale cancellation
- Breaking to generate inflaton potential: $V_0\, e^{\pm\varphi/f}$ ⟶ $V = V_0\left(1 - e^{-\varphi/f}\right)$

i) Implications:

$$\varepsilon \approx \frac{1}{2}\left(\frac{f}{M_P}\right)^2 \eta^2 \quad \text{and} \quad \eta \approx -\left(\frac{M_P}{f}\right)^2 e^{-\varphi/f} < 0 \quad \Rightarrow \quad \varepsilon << |\eta| << 1$$

$$r \approx 2\left(\frac{f}{M_P}\right)^2 (n_s - 1)^2 \quad \Rightarrow \quad \text{for} \quad n_s \approx 0.96 \quad \Rightarrow \quad r \approx 0.003\left(\frac{f}{M_P}\right)^2$$

ii) 3 models:

1) Kahler moduli inflation: $f \approx M_P/\sqrt{\mathcal{V}} << M_P$ $\qquad$ r $\simeq 10^{-10}$ [Conlon,Quevedo]

2) Fibre inflation: $f \approx M_P$ $\qquad$ r $\simeq$ 0.005 [MC,Burgess,Quevedo]

3) Poly-instanton inflation: $f \approx M_P/\ln \mathcal{V} < M_P$ $\qquad$ r $\simeq 10^{-5}$ [MC,Pedro,Tasinato]

Inflationary dynamics

- Focus on Kahler moduli inflation → inflation driven by τ_n displaced from its minimum

$$V=\frac{g_s}{8\pi}\left[\sum_{j=1}^{n-1}\left(\frac{8}{3}(a_jA_j)^2\sqrt{\tau_j}\,\frac{e^{-2a_j\tau_j}}{\mathcal{V}}-4a_jA_jW_0\tau_j\,\frac{e^{-a_j\tau_j}}{\mathcal{V}^2}\right)+\frac{3\hat{\xi}|W_0|^2}{4\mathcal{V}^3}\right]+V_{\rm ds}+\delta V(\tau_n)$$

- All τ_j j=1,…,n-1 and $\mathcal{V}$ fixed at their minima:

$$V_{\rm inf}=V_0-\frac{g_s}{2\pi}a_nA_nW_0\tau_n\frac{e^{-a_n\tau_n}}{\mathcal{V}^2}\qquad V_0=\frac{3}{4\,n}\frac{\hat{\xi}\,m_{3/2}^2}{\mathcal{V}}$$

- The minimum for τ_j j=1,…,n-1 and $\mathcal{V}$ slightly shifted during inflation

$$\ln\mathcal{V}|_{\rm inf}\underset{n\gg1}{\simeq}\ln\mathcal{V}\left(1+\frac{2}{n}\right)\qquad \tau_j^{3/2}\Big|_{\rm inf}\underset{n\gg1}{\simeq}\tau_j^{3/2}\left(1+\frac{3}{n}\right)$$

- Canonically normalised potential:

$$\phi=\sqrt{\frac{4}{3\mathcal{V}}}\,\tau_n^{3/4}\qquad V_{\rm inf}=V_0-\frac{g_s}{2\pi}\frac{a_nA_nW_0}{\mathcal{V}^2}\left(\frac{3\mathcal{V}}{4}\right)^{2/3}\phi^{4/3}e^{-a_n\left(\frac{3\mathcal{V}}{4}\right)^{2/3}\phi^{4/3}}$$

- Slow-roll parameters

$$\epsilon\simeq\frac{2048}{27}\frac{a_n^3A_n\tau_n^{5/2}}{\hat{\xi}^2W_0^2}\mathcal{V}^3\,e^{-2a_n\tau_n}$$

$$\eta\simeq-\frac{128}{9}\frac{a_n^3A_n\tau_n^{3/2}}{\hat{\xi}W_0}\mathcal{V}^2\,e^{-a_n\tau_n}$$

→ $a_n\tau_n\gtrsim 2\ln\mathcal{V}$

- Predictions for $N_e\sim 60$: $n_s\simeq 0.967$ and $r\lesssim 10^{-10}$ match COBE for $\mathcal{V}\sim10^7$

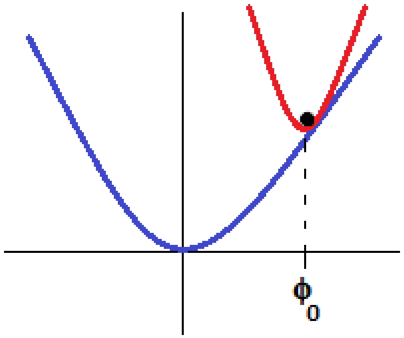
Reheating via lightest modulus decay

- Lightest modulus potential: $$V = \frac{1}{2} m^2 \phi^2 \quad \text{with} \quad m^2 \approx \frac{\hat{\xi}\, m_{3/2}^2}{\mathcal{V} \ln \mathcal{V}}$$
- Extra contribution during inflation

$$V = \frac{1}{2} m^2 \phi^2 + c H_{\inf}^2 (\phi - \phi_0)^2 \approx c H_{\inf}^2 (\phi - \phi_0)^2 \quad \text{for} \quad m << H_{\inf}$$

⟶ ϕ displaced from $\phi = 0$ during inflation

- ϕ behaves as harmonic oscillator with friction $\ddot{\phi} + 3H\dot{\phi} + m^2 \phi = 0$



- End of inflation: friction wins ⟶ ϕ frozen at $\phi = \phi_0$
- Reheating ⟶ thermal bath with temperature T and $H \approx T^2 / M_P$
- Universe expands and cools down ⟶ H decreases
- ϕ starts oscillating when $H \approx m$ ⟶ ϕ stores energy $\rho_\phi \approx m^2 \phi_0^2 \approx H^2 M_p^2 \approx T^4 \approx \rho_{\text{rad}}$
- ϕ redshifts as $\rho_\phi \propto T^3$ while thermal bath redshifts $\rho_{\text{rad}} \propto T^4$

⟶ ϕ dominates energy density of the Universe ⟶ dilutes everything when it decays!

- ϕ decays when $H \approx \Gamma \approx m^3 / M_p^2$ ⟶ Reheating temperature $T_{\text{rh}} \approx \sqrt{\Gamma M_p} \approx m \sqrt{m / M_p}$
- Need $T_{rh} > T_{BBN} \approx$ 3 MeV ⟶ $m > 50$ TeV

Non-standard post-inflationary cosmology

- Volume mode mass: $m_\phi \sim 10^7$ GeV >> 50 TeV ⟶ $T_{rh} \sim 1 - 10$ GeV
- ϕ decay dilutes any previous relic [Moroi,Randall]:

i) Baryon asymmetry ⟶ good if AD baryogenesis is too efficient [Kane,Shao,Watson,Yu]

ii) Standard thermal WIMP DM since $T_{rh} < T_f \sim m_{DM}/20 \sim 10$ GeV - 100 GeV

[Allahverdi, Acharya, MC, Dutta, Kane,Kumar,Sinha,Watson,…]

- Products from ϕ decay:

i) Non-thermal DM

$$\frac{n_{DM}}{s} = \left(\frac{n_{DM}}{s}\right)_{obs} \frac{\langle\sigma_{ann} v\rangle_f^{th}}{\langle\sigma_{ann} v\rangle_f}\left(\frac{T_f}{T_{rh}}\right) \quad \text{where} \quad \left(\frac{n_{DM}}{s}\right)_{obs} \approx 5\cdot 10^{-10}\left(\frac{1\,\text{GeV}}{m_{DM}}\right) \quad \text{and} \quad \langle\sigma_{ann} v\rangle_f^{th} \approx 3\cdot 10^{-26} cm^3 s^{-1}$$

a) Need $\langle\sigma_{ann} v\rangle_f = \langle\sigma_{ann} v\rangle_f^{th} (T_f / T_{rh})$

b) Since $T_{rh} < T_f$ ⟶ $\langle\sigma_{ann} v\rangle_f > \langle\sigma_{ann} v\rangle_f^{th}$ ⟶ Higgsino-like DM

c) Bino-like LSP: $\langle\sigma_{ann} v\rangle_f < \langle\sigma_{ann} v\rangle_f^{th}$ ⟶ DM overproduction

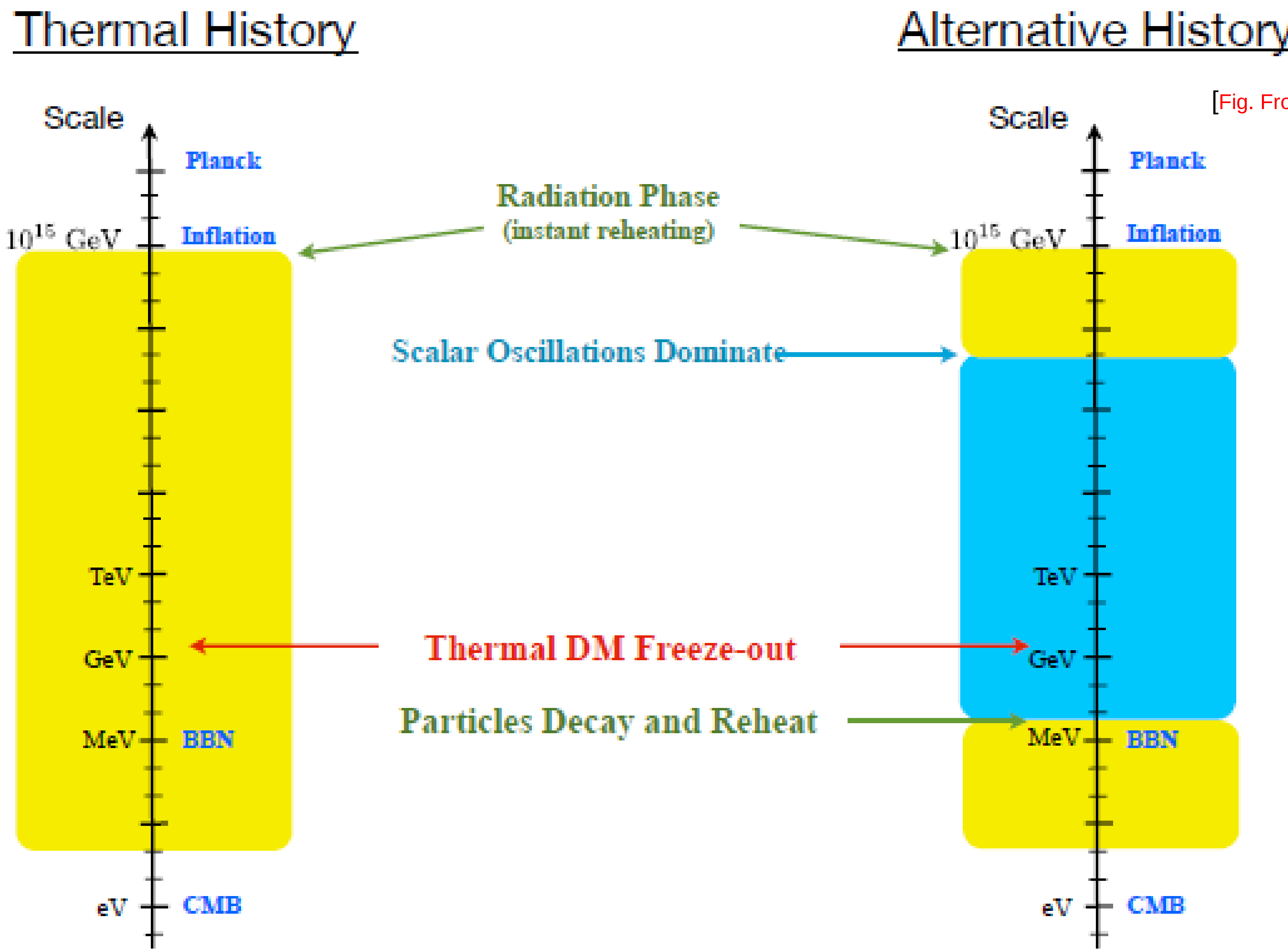
ii) Axionic dark radiation

a) Moduli are gauge singlets ⟶ non-zero branching ratio into hidden fields

b) Light axions unavoidable in models with perturbative moduli stabilisation [Allahverdi, MC, Dutta,Sinha]

⟶ $\Delta N_{eff} > 0$ unavoidable $\Delta N_{eff} \leq 1$ within 2 σ

Thermal vs Non-thermal cosmology



[Fig. From S. Watson]

Non-thermal MSSM

- Consider CMSSM with non-thermal LSP dark matter
- Impose: [Aparicio, MC, Dutta, Krippendorf, Maharana, Muia, Quevedo]

i) radiative EW symmetry breaking + Higgs mass around 125 GeV

ii) no dark matter overproduction

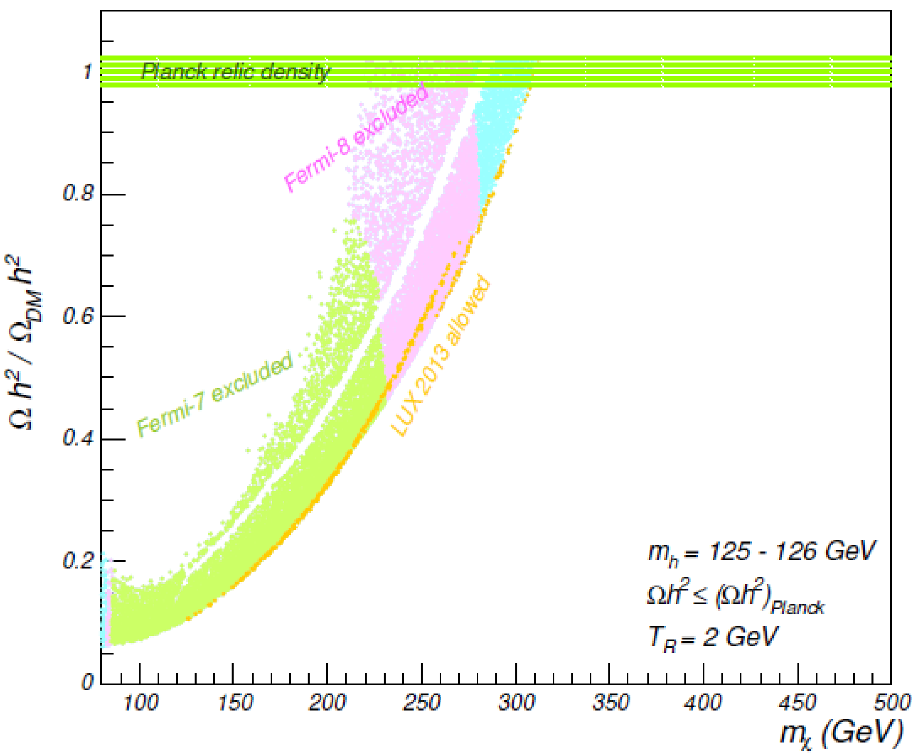
iii) bounds from colliders (LHC), CMB (Planck), direct (LUX) and indirect (Fermi) DM searches

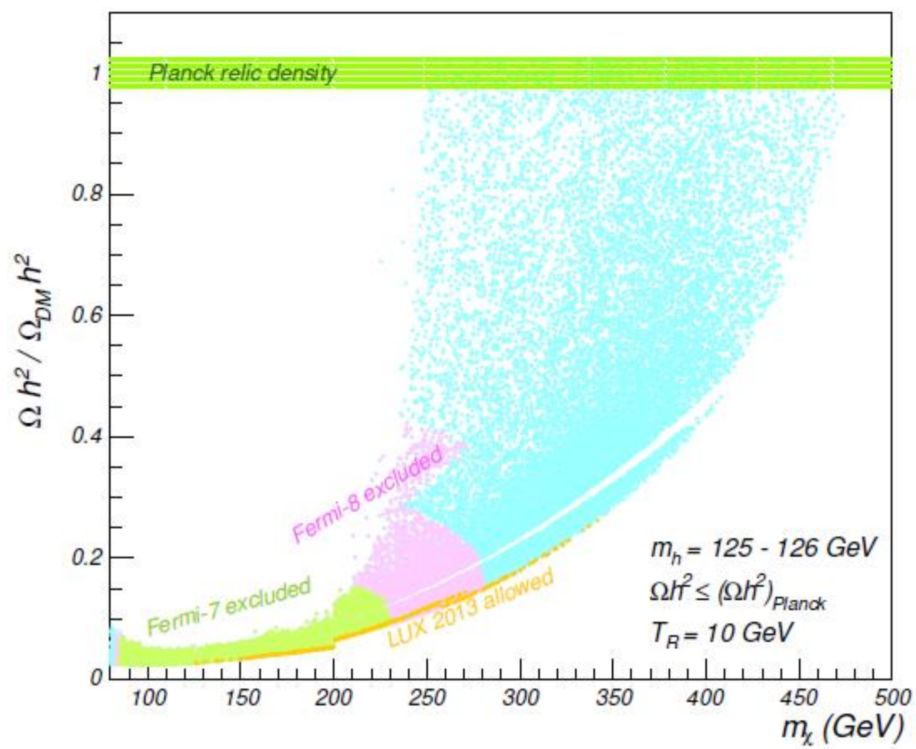
a) observed DM content saturated for T_{rh} = 2 GeV and 300 GeV Higgsino-like LSP

b) MSSM case: 300-1000 GeV Higgsino LSP saturating DM for T_{rh} = 2-10 GeV

c) stops around 4-5 TeV, gluinos around 2-3 TeV + light degenerate neutralinos

d) realised in string models with sequestered SUSY breaking





Reheating from $\mathcal{V}$ decay

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

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

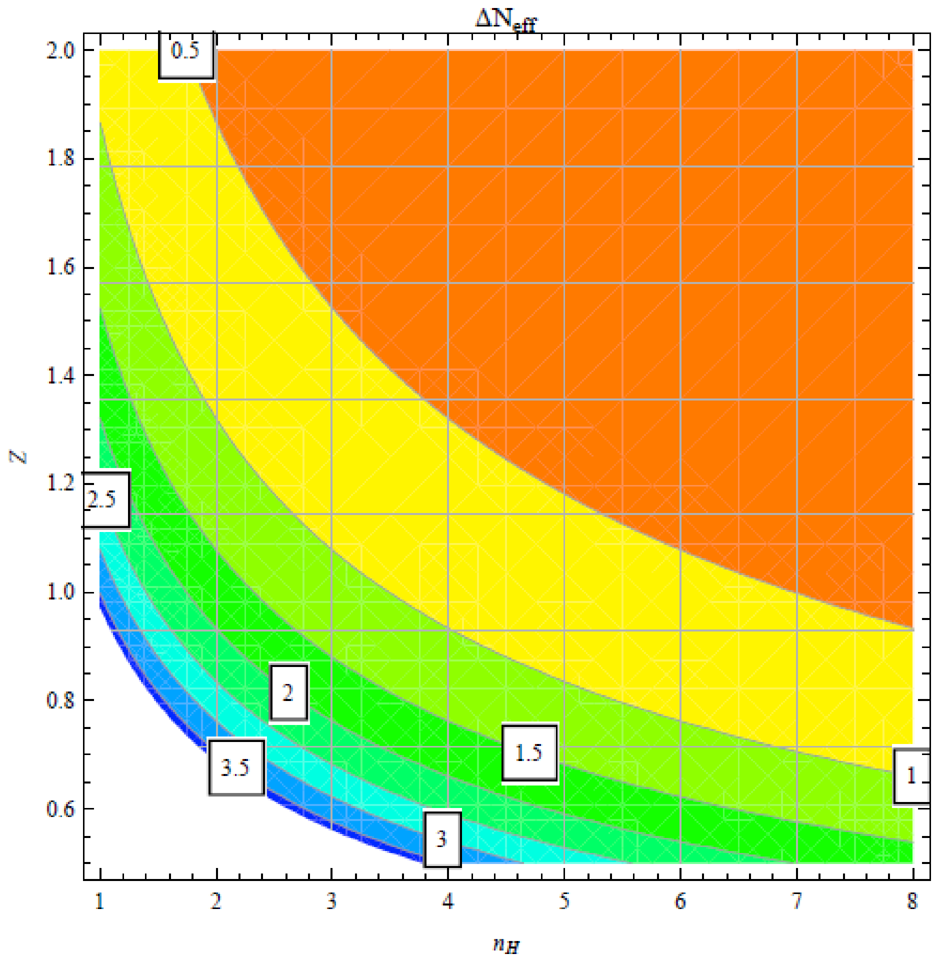
- Leading decay channels:
  - **Higgses:** $c_{\phi\to H_u H_d} = Z^2/12$ from GM term $K \supset Z\,\frac{H_u H_d}{2\mathcal{V}^{2/3}}$
  - **Bulk closed string axions:** $c_{\phi\to a_b a_b} = 1/24$
- Subleading decay channels:
  - **Gauge bosons:** $c_{\phi\to A^\mu A^\mu} = \lambda\frac{\alpha_{\rm vs}^2}{8\pi} \ll 1$
  - **Other visible sector fields:** $c_{\phi\to\psi\psi} \simeq \left(\frac{M_{\rm soft}}{m_\phi}\right)^2 \simeq \frac{1}{\mathcal{V}} \ll 1$ Only for MSSM case!
  - **Local open string axions:** $c_{\phi\to a_b\theta} \simeq \left(\frac{M_s}{M_P}\right)^4 \tau_{\rm sing}^2 \simeq \left(\frac{\tau_{\rm sing}}{\mathcal{V}}\right)^2 \ll 1$

MSSM predictions for dark radiation

Prediction for $\Delta N_{\rm eff}$ for n_H Higgs doublets:

[MC, Conlon, Quevedo] [Higaki, Takahashi]

$$\Delta N_{\rm eff} = \frac{3.48}{n_H Z^2}$$



$\Delta N_{eff} \leq 1$ for $n_H = 2$

if $Z \geq 1.22$

Split SUSY predictions for dark radiation

- In split SUSY $m_0 = c m_\phi$ and $\mu = \tilde{c} m_\phi$ with $c \approx \tilde{c} \approx O(1)$ [MC, Muia]

  → ϕ can decay to squarks, sleptons and Higgsinos if $c \leq 1/2$ and $\tilde{c} \leq 1/2$

- Kinematic condition satisfied due to string loop corrections to K
- Interaction Lagrangian:

$$\mathcal{L}_{\rm cubic} \simeq \frac{7c^2}{2\sqrt{6}} \frac{m_\Phi^2}{M_P} \hat{\Phi} \left[\sigma^\alpha \sigma_\alpha + \chi^\alpha \chi_\alpha + \left(1 + \frac{6\tilde{c}^2}{7c^2}\right) h_i h^i + 2Z \left(c_{B,K} - \frac{1}{7c^2}\right) \sum_{i=1}^{4} (-1)^{i+1} h_{2i-1} h_{2i} \right]$$
$$+ \tilde{c} \sqrt{\frac{2}{3}} \frac{m_\Phi}{M_p} \hat{\Phi} \left(\tilde{H}_u^+ \tilde{H}_d^- - \tilde{H}_u^0 \tilde{H}_d^0 \right) + \text{h.c.}.$$

- New contributions to visible sector branching ratio:

  i) Decays to squarks and sleptons
  ii) Mass term contribution to decays to (heavy) Higgses
  iii) Bμ-term contribution to decays to Higgses
  iv) Decays to Higgsinos

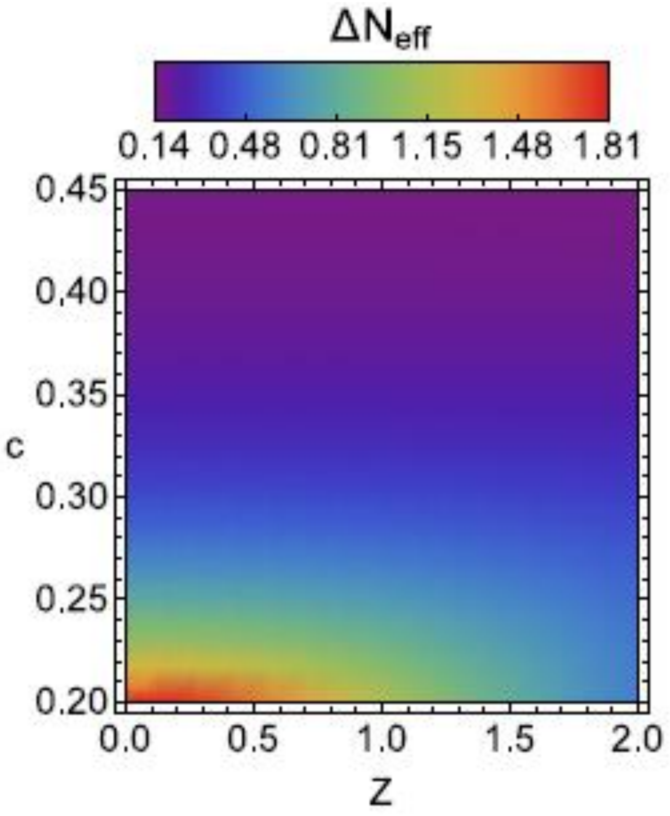
- Significant reduction of extra dark radiation!

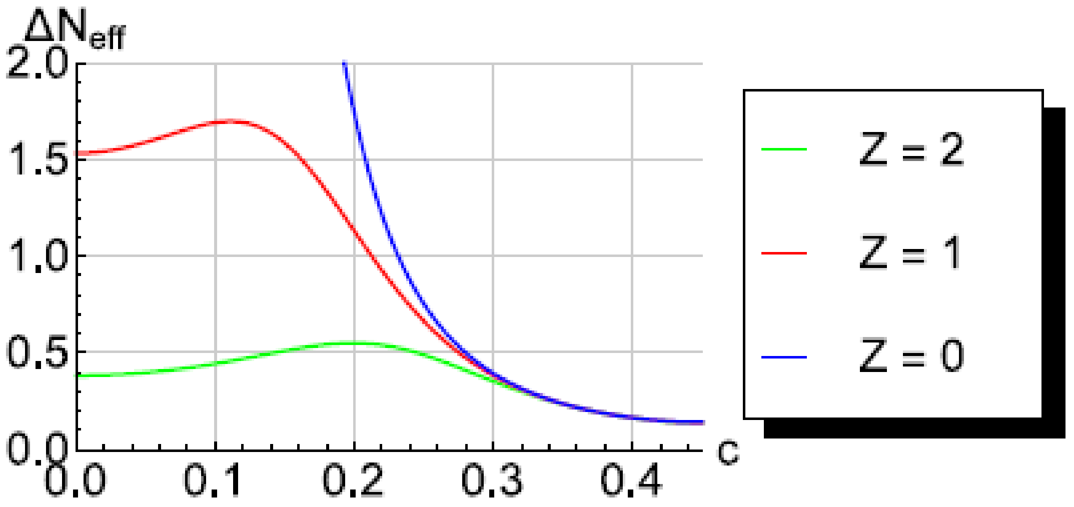
$$0.14 \leq \Delta N_{eff} \leq 1.60 \quad \text{for} \quad Z = 1$$

Split SUSY predictions for dark radiation

- Conservative predictions for $\tilde{c} = 0$

[MC, Muia]





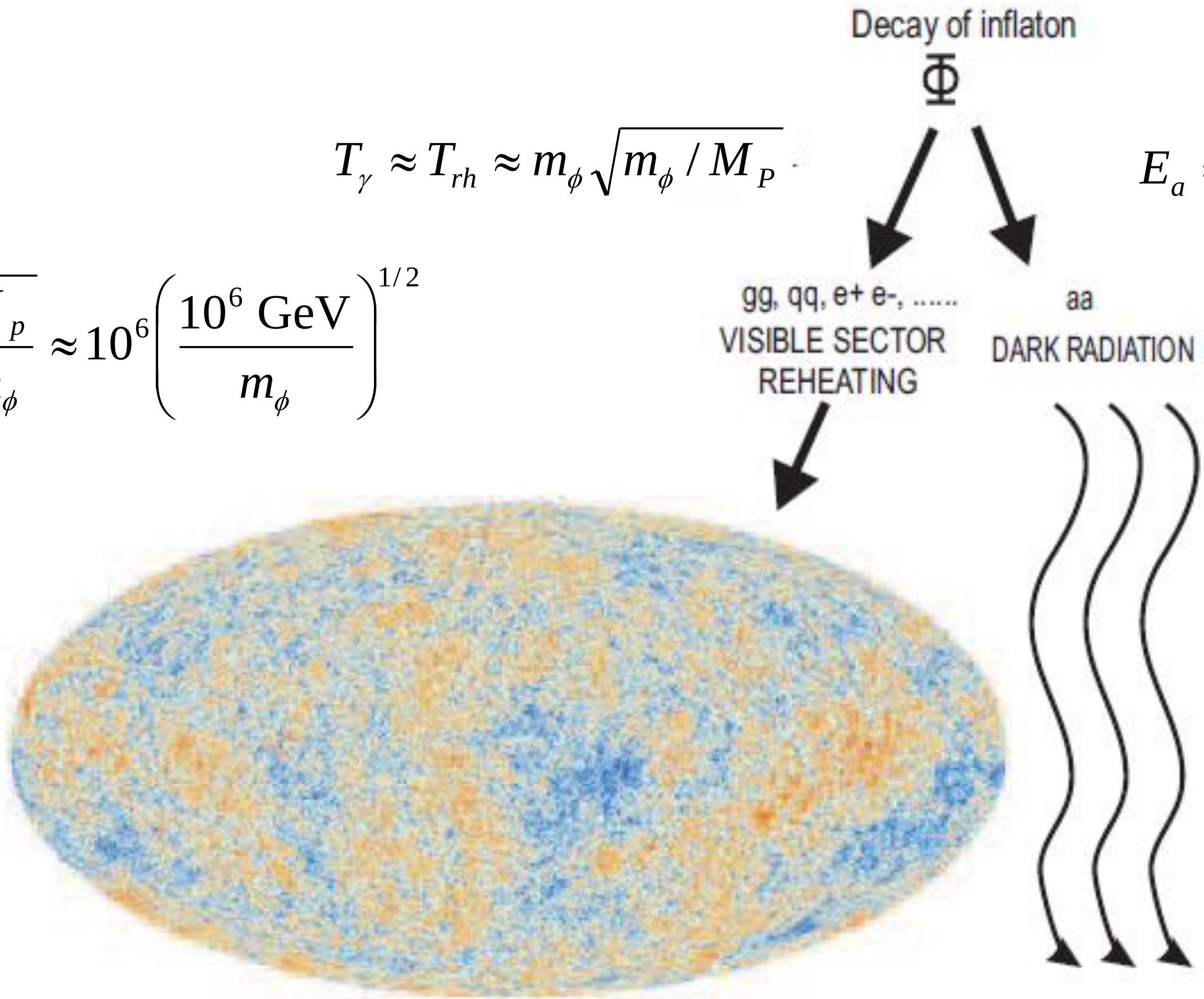
$$\Delta N_{eff} \leq 1 \quad \text{for} \quad Z = 0 \quad \text{if} \quad c \geq 0.23$$

Dark radiation production

$$T_\gamma \approx T_{rh} \approx m_\phi \sqrt{m_\phi / M_P}$$

$$E_a = m_\phi / 2$$

$$\frac{E_a}{T_\gamma} \approx \sqrt{\frac{M_p}{m_\phi}} \approx 10^6 \left(\frac{10^6\ \mathrm{GeV}}{m_\phi} \right)^{1/2}$$

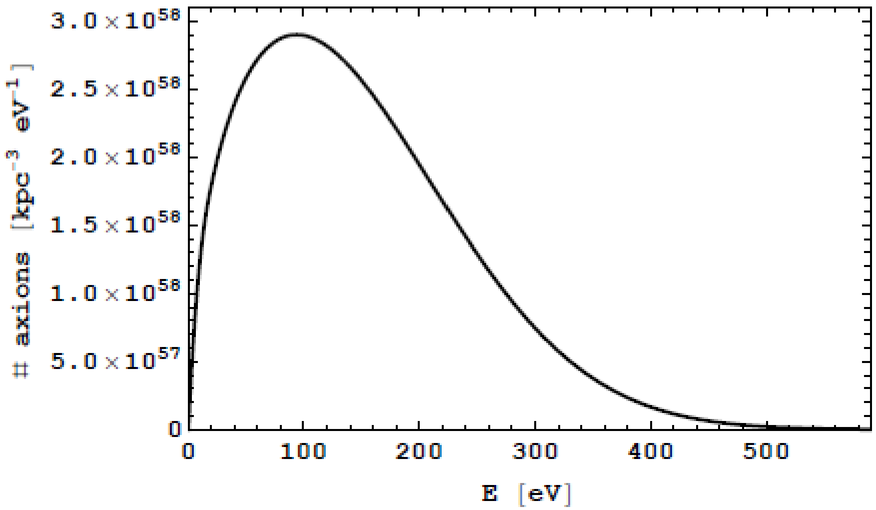


Ratio of energies retained through cosmic history → still valid today!

Cosmic axion background and 3.5 keV line

PREDICTION: Cosmic Axion Background

$$E_a \approx 200\,\text{eV}\left(\frac{10^6\ \text{GeV}}{m_\phi}\right)^{1/2}$$



- For 10^5 GeV ≤ m_φ ≤ 10^7 GeV, CAB lies today in soft X-ray wavebands
- Detectable via axion-photon conversion in astrophysical B-fields

$$\mathcal{L} \supset -\frac{a}{4M} F^{\mu\nu}\tilde{F}_{\mu\nu}$$

- Soft X-ray excess in clusters observed since 1996 (EUVE, ROSAT, XMM-Newton, Suzaku, Chandra)
- Match data for

$$\Delta N_{\text{eff}} \approx 0.5 \qquad m_a < 10^{-12}\text{eV} \qquad M \approx 10^{12}\ \text{GeV}$$ [Conlon, Marsh]

- 3.5 keV line from galaxy clusters (XMM-Newton, Suzaku ,Chandra) due to DM → aa convert to γ
- Better than simplest explanation: DM → $\gamma\gamma$ for m_{DM} ~ 7 keV due to:

i) Inferred signal strength: flux depends on both DM density and B-field

ii) Morphology: stronger signal from cool core where B-field peaks

iii) Non-observation in dwarf galaxies and galaxies: small size and B-field

iv) Match data for same values which give soft X-ray excess

[MC, Conlon, Marsh, Rummel]

Baryogenesis

- How is baryogenesis realised?
- $T_{rh} \sim 1$ GeV ⟶ cannot have standard thermal scenarios (leptogenesis, EW baryogenesis)
- Try to realise Affleck-Dine baryogenesis
- MSSM D-flat directions φ (e.q. LLe, udd,…) that carry a net B or L number
- Lifted by SUSY-breaking effects and higher contributions to W

$$V(\phi) = (m_\phi^2 + c_H H^2)\,|\phi|^2 + |\lambda_n|^2 \frac{|\phi|^{2(n-1)}}{M^{2(n-3)}} + \left[(A_n + a_n H)\frac{\lambda_n \phi^n}{n M^{n-3}} + \text{h.c.}\right]$$

- Role of φ during inflation depends on c_H:

i) $c_H \geq 1$: φ settles down to $\varphi=0$ during inflation and has no interesting consequence

ii) $0 < c_H << 1$: quantum jumps of order $H_I/2\pi$ superimpose in random walk fashion giving

$$\phi_{\max} = \sqrt{\frac{3}{8\pi^2}\frac{H_I^2}{m_\phi}}$$

iii) $c_H < 0$: φ is driven away from $\varphi=0$ during inflation

$$\phi_I = \left(\frac{H_I M^{n-3}}{\sqrt{n-1}\,c_H \lambda_n}\right)^{1/(n-2)}$$

- After inflation, when $H \sim m_\varphi$, φ starts oscillating with initial amplitude

$$\phi_0 \sim \left(\frac{m_\phi M^{n-3}}{\sqrt{n-1}\,\lambda_n}\right)^{1/(n-2)}$$

- Baryon asymmetry transferred to fermions when φ decays

Can the AD mechanism be explicitly realised in our models?

AD field dynamics

[Allahverdi, MC, Muia]

- Compute soft mass of φ during inflation with τ_n away from the minimum

i) MSSM-like case: using ultra-local condition $\tilde{K}_\alpha = f_\alpha(U,S)\, e^{K/3}$

$$\tilde{m}_\phi^2 = m_{3/2}^2 + V_0 - \frac{1}{3}K_{i\bar{j}}F^i\bar{F}^{\bar{j}} - F^i\bar{F}^{\bar{j}}\partial_i\partial_{\bar{j}} \ln f_\alpha(U,S) = \frac{2}{3}V_0 + Q_\alpha(U,S)M_{1/2}^2$$

→ $$\tilde{m}_\phi^2 \simeq \frac{2}{3}V_0 = \frac{1}{2n}\frac{\hat{\xi}m_{3/2}^2}{\mathcal{V}} \simeq 2H_{\rm inf}^2 > 0$$ AD mechanism does not work

ii) Split SUSY: τ_n-dependent contributions to F-terms of τ_n and $\mathcal{V}$ can be neglected during inflation

→ $$\frac{\tilde{F}^{T_b}_{\rm np}}{m_{3/2}} = \sum_{j=1}^{n-1}\frac{4A_j a_j \tau_j}{\sqrt{\tau_b}}\frac{\mathcal{V}}{W_0}e^{-a_j\tau_j}$$ and $$\frac{\tilde{F}^{T_n}_{\rm np}}{m_{3/2}} = \frac{8A_n a_n\sqrt{\tau_n}}{3}\frac{\mathcal{V}}{W_0}e^{-a_n\tau_n} \to 0$$

→ different F-terms during inflation:

$$\tilde{F}^{T_b} = -2\tau_b m_{3/2}\left(1 + \frac{3}{4n}\frac{\hat{\xi}}{\mathcal{V}}\right) \qquad \tilde{F}^{T_n} = \tilde{F}^{T_n}_{\rm tree} = -2\tau_n m_{3/2}$$

Two cases:

(a) $c_n = -1/3$: $$\tilde{m}_\phi^2 = \frac{15}{4}\frac{\hat{\xi}m_{3/2}^2}{\mathcal{V}}\left(c_\xi - \frac{1}{3} + \frac{2}{15n}\right)$$ AD mechanism does not work

(b) $c_\xi = 0$: $$\tilde{m}_\phi^2 = -\frac{5}{4}\frac{\hat{\xi}m_{3/2}^2}{\mathcal{V}}\left(1 - \frac{2}{5n}\right)$$ < 0 for n>1 for all c_n !

$m_\phi^2 > 0$ after the end of inflation if $c_n > (n-1)/3$ → AD mechanism works!

Generation of baryon asymmetry

- Baryon asymmetry generated by φ decay followed by dilution due to $\mathcal{V}$ decay

$$\frac{n_B}{s} \approx \frac{A}{m_\phi}\frac{T_{rh}}{m_\phi}\left(\frac{\phi_0}{M_p}\right)^2 \approx 10^{-10}$$

- Using the previous results

$$A \approx \mathcal{V}\,\frac{m_\phi^2}{M_p} \approx \frac{M_p}{g_s^{3/2}\mathcal{V}^2} \qquad T_{rh} \approx 0.1\, m_\phi \sqrt{\frac{m_\phi}{M_P}}$$

$$\longrightarrow \quad \frac{n_B}{s} \approx 0.1\,\mathcal{V}\left(\frac{m_\phi}{M_p}\right)^{3/2}\left(\frac{\phi_0}{M_p}\right)^2 \approx \frac{0.1}{g_s^{9/8}\mathcal{V}^{5/4}}\left(\frac{\phi_0}{M_p}\right)^2$$

- Use numbers which give inflation with correct COBE normalisation and TeV-scale gauginos
- $\mathcal{V} \sim 10^7$ and $g_s \sim 0.1$

$$\longrightarrow \quad \frac{n_B}{s} \approx 10^{-8}\left(\frac{\phi_0}{M_p}\right)^2 \approx 10^{-10} \quad \text{for} \quad \phi_0 \approx 0.1\, M_p$$

Get correct baryon-to-entropy ratio for natural displacements of AD field!

Conclusions

- Globally consistent chiral models with full closed string moduli stabilisation
- dS vacua with chirality due to consistency
- Pheno: SUSY breaking, TeV soft terms, Inflation, Dark matter, Dark radiation, Baryogenesis
- Good inflaton candidates: Kahler moduli (effective shift symmetry from extended no-scale)
- Expect values of tensor-to-scalar ratio $r \leq 0.01$
- Reheating driven by lightest modulus decay
- Non-standard cosmology: dilution of thermal DM
- Non-thermal dark matter:
  i) CMSSM with a 300 GeV Higgsino LSP saturating DM for $T_{rh} = 2$ GeV
  ii) MSSM with a 300-1000 GeV Higgsino LSP saturating DM for $T_{rh} = 2\text{-}10$ GeV
- Generic production of axionic dark radiation $\longrightarrow$ $\Delta N_{eff} \neq 0$
- Cosmic axion background with $E_a \sim 200$ eV
- CAB detectable via axion-photon conversion in B
- Explain soft X-ray excess and 3.5 keV line in galaxy clusters
- Explicit realisation of AD baryogenesis in split SUSY case
- Correct generation of observed baryon-to-entropy ratio for $\varphi_0 \sim 0.1\, M_p$

Dark radiation and Planck 2015 data

- Positive correlation between N_{eff} and H_0
- Planck indirect value of H_0 :

H_0 = 67.3 ± 1.0 km s^{-1} Mpc^{-1} (68% CL)

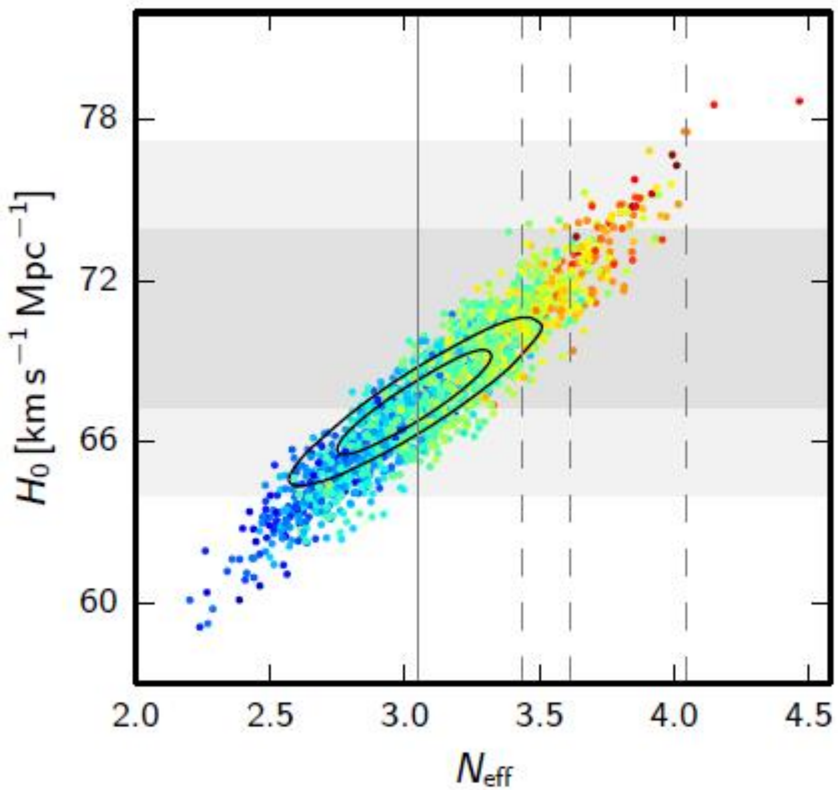
- HST direct value of H_0 :

H_0 = 73.8 ± 2.4 km s^{-1} Mpc^{-1} (68% CL)

2.4 σ tension → need new physics: $\Delta N_{eff} > 0$

BUT HST data reanalysed by Efstathiou:

H_0 = 70.6 ± 3.3 km s^{-1} Mpc^{-1} (68% CL)



only 1 σ away from Planck value → no need new physics: $\Delta N_{eff} \to 0$

BUT $\Delta N_{eff} > 0$ still allowed by Planck! (HST value of H_0 still controversial)

E.g.: for $\Delta N_{eff} = 0.39$ Planck data give (68% CL):
H_0 = 70.6 ± 1.0 km s^{-1} Mpc^{-1} → better agreement with HST!
$n_s \simeq 0.983 \pm 0.006$ → different predictions for tensor modes!

→ Need reliable direct measurements of H_0 !

Axionic dark radiation from strings

- Low-energy theory: many closed string axions of order $h^{1,1} \simeq O(100)$

  → 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 axions can be:

  i) removed from the spectrum by orientifold projection

  ii) eaten up by anomalous U(1)s

  a) open string axions eaten up on cycles in geometric regime

  b) closed string axions eaten up for branes at singularities

  iii) too heavy if 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

Note: 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]