Non-thermal dark matter and dark radiation from strings

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Based on:

1) Non-thermal dark matter: Allahverdi, MC, Dutta, Sinha, Phys.Rev. D88 (2013) 9, 095015
2) SUSY-breaking from strings: Aparicio, MC, Krippendorf, Maharana, Muia,Quevedo, JHEP 1411 (2014) 071
3) Non-thermal CMSSM: Aparicio, MC,Dutta, Krippendorf,Maharana, Muia,Quevedo, arXiv:1502.05672
4) Axionic dark radiation: MC, Conlon, Quevedo, Phys.Rev. D87 (2013) 4, 043520
5) Dark matter-dark radiation: Allahverdi, MC, Dutta, Sinha, JCAP 1410 (2014) 002
6) Axions and the 3.5 keV line: MC, Conlon, Marsh, Rummel, Phys.Rev. D90 (2014) 023540

Contents

- String theory and 4D physics
- Moduli dynamics in early Universe
- Post-inflationary string cosmology:

  i) Non-thermal dark matter in CMSSM
  ii) Axionic dark radiation
  iii) Cosmic axion background
  iv) Soft X-ray excess and 3.5 keV line in galaxy clusters

Focus on phenomenology more than maths

⟶ Indirect predictions from generic features of string compactifications!

String Theory

- String theory: promising theory of fundamental physics

  i) Quantum gravity
  ii) Unification of matter and interactions

- Key-features of string theory:

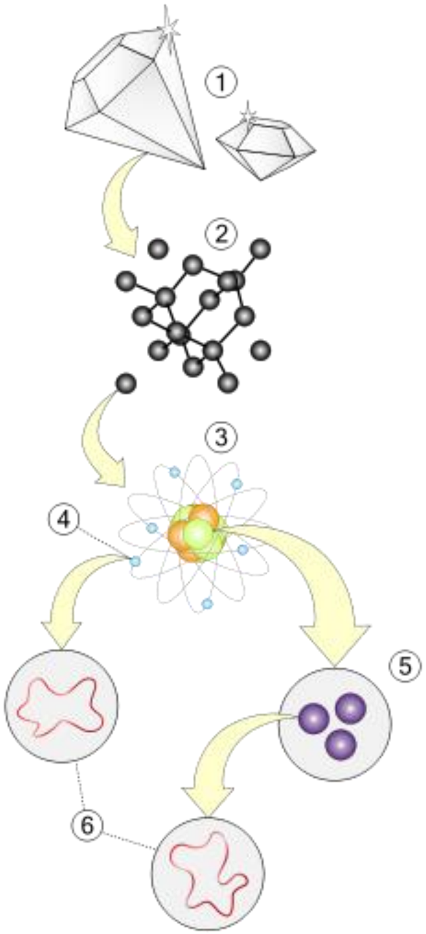
  i) Extended elementary objects (strings)
  ii) Extra dimensions
  iii) 1 parameter: string scale M_s
  iv) Web of dualities ⟶ unique theory in 11D!

- String phenomenology: attempt to test string theory

  i) Directly: detection of strings in colliders for very low M_s
  ii) Indirectly: low-energy implications for ordinary 4D physics

⟶ depend on properties of extra dimensions!

⟶ study string compactifications



String Compactifications

- Perturbative string theory lives in 10D and needs supersymmetry for consistency
- Compactified extra dimensions:

$$X_{10D} = M_{4D} \times Y_{6D} \quad \text{with} \quad \mathrm{Vol}(Y_{6D}) = \mathcal{V} M_s^{-6}$$

- 4D EFT for

$$E << M_{KK} \approx \frac{1}{\mathrm{Vol}(Y_{6D})^{1/6}} = \frac{M_s}{\mathcal{V}^{1/6}}$$

- Geometrical and topological properties of Y_{6D} determine 4D physics
- N > 1 SUSY in 4D for generic Y_{6D} ⟶ non-chiral theory ⟶ non-realistic!
- N=1 SUSY in 4D if Y_{6D} is a Calabi-Yau manifold ⟶ chiral theory ⟶ realistic!
- N=1 SUSY helps to control corrections to EFT
- N=1 SUSY broken at TeV scale gives:

  i) Solution of the hierarchy problem ⟶ Higgs mass naturally around 125 GeV
  ii) Gauge coupling unification
  iii) Radiative EW symmetry breaking
  iv) Dark matter

String Moduli

- Y_{6D} can de deformed in size and shape remaining CY

i) Maths: deformations parameterised by moduli

ii) 4D Physics: moduli are new scalar particles with only gravitational couplings to matter

iii) Technically: moduli from dimensional reduction of 10D metric, dilaton and p-form fields

- Moduli ϕ massless at classical level ⟶ flat potential $V(\phi)=0$ ⟶ $\langle 0|\phi|0\rangle$ unfixed!

- Two big problems:

i) Unobserved long-range forces for $m < 1$ meV
ii) Unpredictability of low-energy theory since:

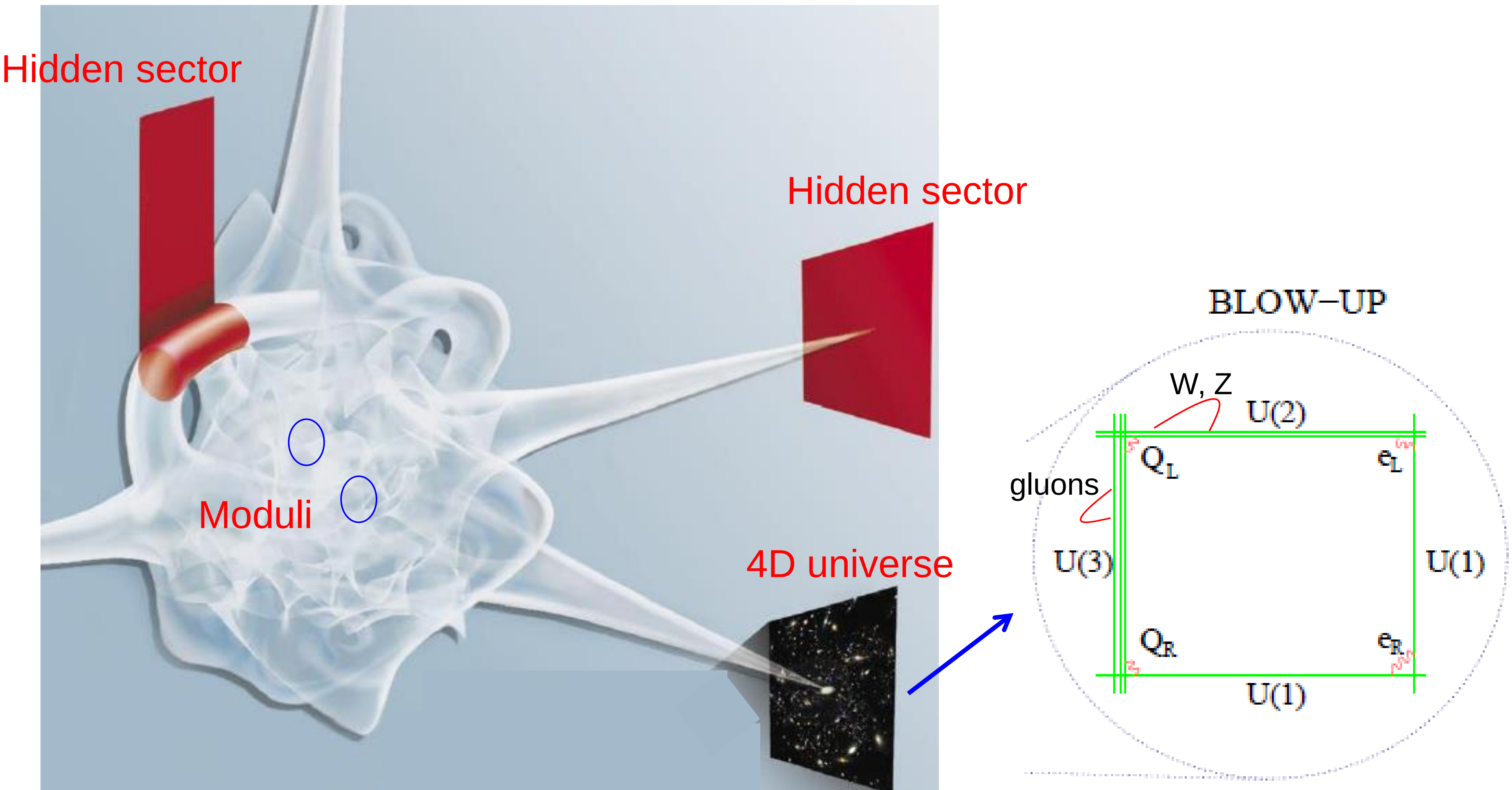
1) String coupling $g_s = g_s(\phi)$
2) Gauge couplings $g_{YM} = g_{YM}(\phi)$
3) Yukawa couplings $Y_{ijk} = Y_{ijk}(\phi)$
4) Low-energy gauge group depends on ϕ

⟶ need to develop $V(\phi)\neq 0$ via quantum corrections ⟶ fix $\langle 0|\phi|0\rangle$

⟶ moduli get a mass $m > 1$ meV due to moduli stabilisation

Standard Model

- Ordinary particles are open strings living on branes
- Branes provide non-Abelian gauge symmetries and chiral matter
- Standard Model (or MSSM/GUT theories) localised on branes
  - ⟶ model-building is a local issue while moduli stabilisation is a global issue



Global vs Local

Local (brane) issues	Global (bulk) issues
Gauge group	Moduli stabilisation
Chiral spectrum	Cosmological constant
Yukawa couplings	Hierarchies
Gauge coupling unification	Moduli spectrum
Mixing angles	SUSY breaking and soft terms
Proton stability	Inflation
Reheating	Reheating
Dark matter	Dark matter
Dark radiation	Dark radiation

moduli coupling to visible sector

↑ Model dependent

↑ Model independent

Recent progress on combining global with local issues in explicti compact CY models!

Cosmological Moduli Problem

- Moduli potential $V = \frac{1}{2} m^2 \phi^2 \quad \text{with} \quad m \approx m_{3/2} \approx M_{soft} \approx O(1)\,\text{TeV}$
- Extra contribution during inflation

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

→ 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 ≈ 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 cosmology from strings

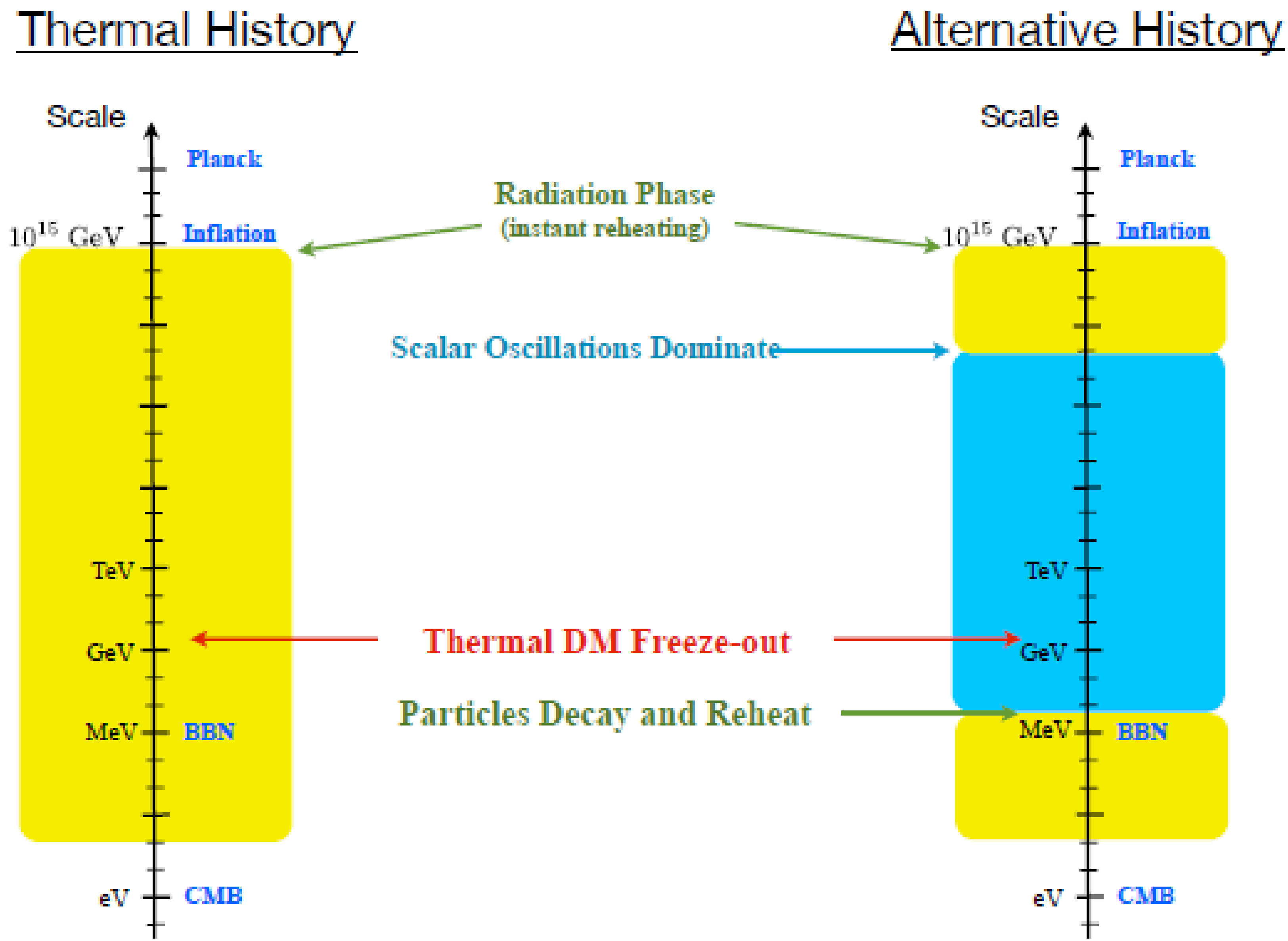
Focus on $m_\phi > 50$ TeV $\Rightarrow$ ϕ decay dilutes any previous relic [Moroi,Randall]:

- 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



Non-thermal dark matter from strings

Q: What is generic value of T_{rh} from strings?

Generically in string compactifications :

i) SUSY breaking generates m_ϕ

ii) Moduli mediate SUSY breaking to MSSM via gravitational interactions ➡ $M_{soft} = k\, m_\phi$

iii) Since $m_\phi > 50$ TeV, can get TeV-scale SUSY only for $k \ll 1$

iv) $k = O(10^{-2})$ from loop suppression or $k = O(10^{-3} - 10^{-4})$ from sequestering

v) For $M_{soft} = O(1)$ TeV, reheating temperature is

$$T_{\rm rh} \approx m\sqrt{m/M_P} \approx k^{-3/2} M_{\rm soft}\sqrt{M_{\rm soft}/M_P} \approx k^{-3/2} O(10^{-2})\ {\rm MeV}$$

$$\text{for } 10^{-4} \leq k \leq 10^{-2} \quad \Longrightarrow \quad 10\ {\rm MeV} \leq T_{\rm rh} \leq 10\ {\rm GeV}$$

Below freeze-out temperature for LSP masses between O(100) GeV and O(1) TeV!

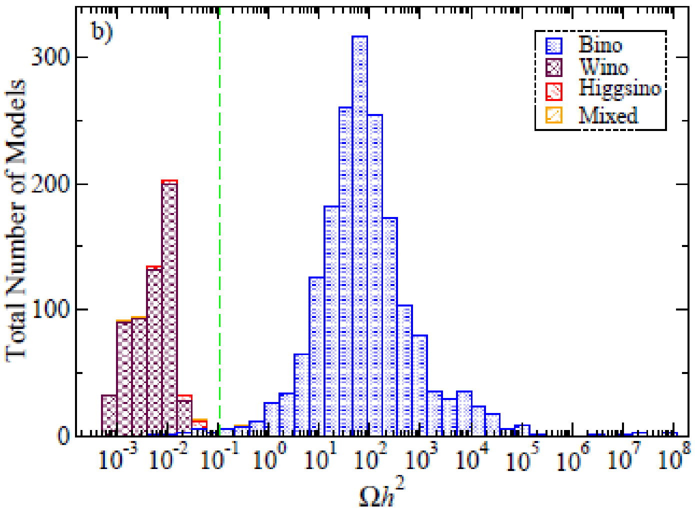
$$10\ {\rm GeV} \leq T_{\rm f} \approx m_{\rm DM}/20 \leq 100\ {\rm GeV}$$

➡ Non-thermal dark matter from strings!

Non-thermal dark matter production

- ϕ decay dilutes thermal DM

  ➡ larger parameter space



[Baer et al]

- Non-thermal DM from ϕ decay:

$$\frac{n_{\rm DM}}{s} = \left(\frac{n_{\rm DM}}{s}\right)_{\rm obs} \frac{\langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}}{\langle\sigma_{\rm ann} v\rangle_{\rm f}} \left(\frac{T_{\rm f}}{T_{\rm rh}}\right)$$

where $\left(\frac{n_{\rm DM}}{s}\right)_{\rm obs} \approx 5\cdot 10^{-10}\left(\frac{1\,{\rm GeV}}{m_{\rm DM}}\right)$ and $\langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th} \approx 3\cdot 10^{-26} cm^3 s^{-1}$

i) Need $\langle\sigma_{\rm ann} v\rangle_{\rm f} = \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th} (T_{\rm f} / T_{\rm rh})$

ii) Since $T_{\rm rh} > T_{\rm f}$ ➡ $\langle\sigma_{\rm ann} v\rangle_{\rm f} > \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}$

➡ Wino/Higgsino-like LSP DM

iii) Bino-like LSP: $\langle\sigma_{\rm ann} v\rangle_{\rm f} < \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}$ ➡ DM overproduction

CMSSM

- SUSY breaking due to moduli stabilisation: $F^{\phi} \sim m_{3/2}\ M_P \neq 0$
- Generate soft terms via gravity mediation: $M_{soft} \sim k\, F^{\phi} / M_P \sim k\, m_{3/2}$
- Soft SUSY breaking Lagrangian:

$$\mathcal{L}_{\text{soft}} = \frac{1}{2} M_a \lambda^a \lambda^a - m_\alpha^2 C^\alpha \overline{C}^{\overline{\alpha}} - \frac{1}{6} A_{\alpha\beta\gamma} Y_{\alpha\beta\gamma} C^\alpha C^\beta C^\gamma - B\mu H_u H_d + \text{h.c.}$$

scalar masses (→ $m_\alpha^2 C^\alpha \overline{C}^{\overline{\alpha}}$); gaugino masses (→ M_a); trilinear couplings (→ $A_{\alpha\beta\gamma}$); Bilinear Higgs mixing (→ $B\mu$)

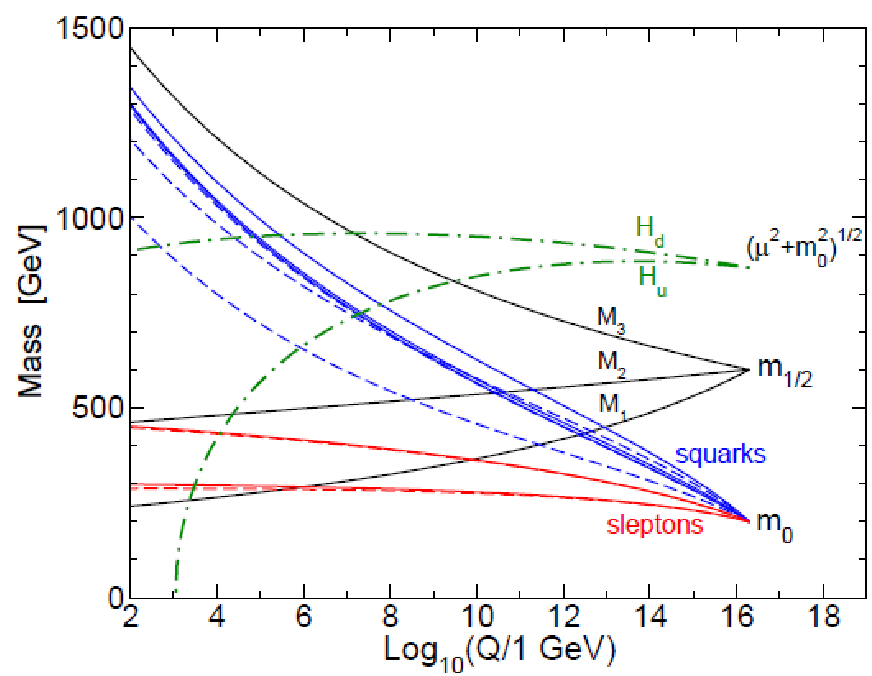
- Supersymmetric μ-term (Higgsino + Higgs mass) forbidden by symmetries
- μ-term generated by Giudice-Masiero mechanism ➡ solution of the μ-problem
- Constrained MSSM: universal conditions at GUT scale

$$M_a = M_{1/2} \quad m_\alpha = m_0 \quad A_{\alpha\beta\gamma} = A$$

➡ 5 parameters at GUT scale: $(M_{1/2}, m_0, A, B, \mu)$

- RG evolution from GUT to EW scale
- Correct radiative EWSB:
  i) fixes $|\mu|$
  ii) can trade B for $\tan\beta = \langle H_u\rangle / \langle H_d\rangle$

➡ CMSSM parameters: $(M_{1/2}, m_0, A, \tan\beta, \text{sign}\ \mu)$

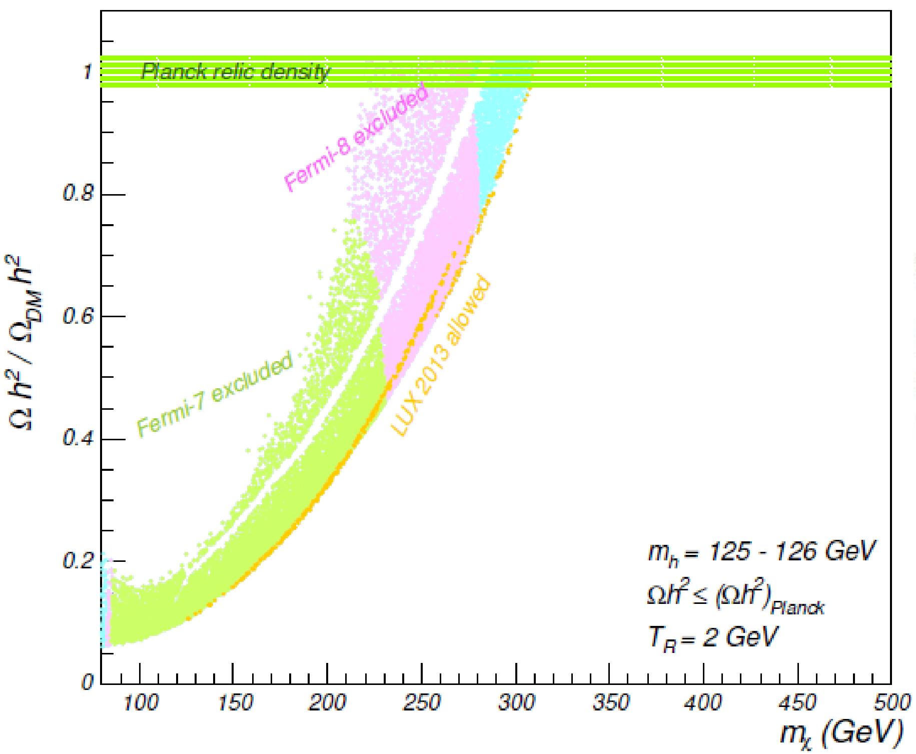


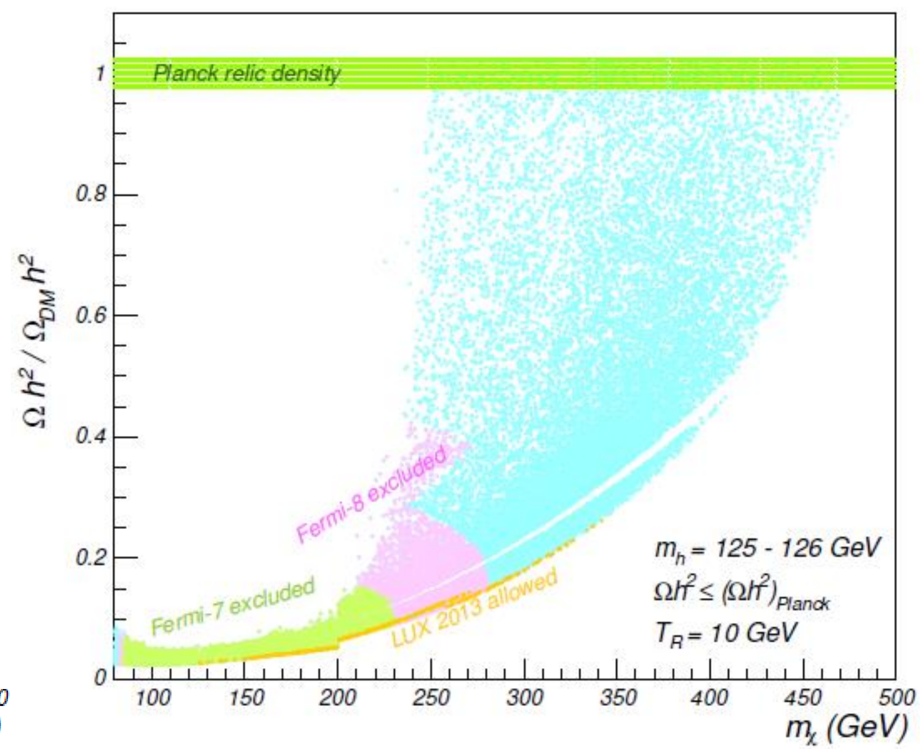
Non-thermal CMSSM

- 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 $T_R = 2$ GeV and 300 GeV Higgsino-like LSP
→ b) sfermion and gluino masses in the few TeV region
c) realised in string models with sequestered SUSY breaking





Sequestered string models

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

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: $M_s \simeq \mathcal{O}(10^{16})$ GeV
   $\Rightarrow$ good for GUTs and inflation

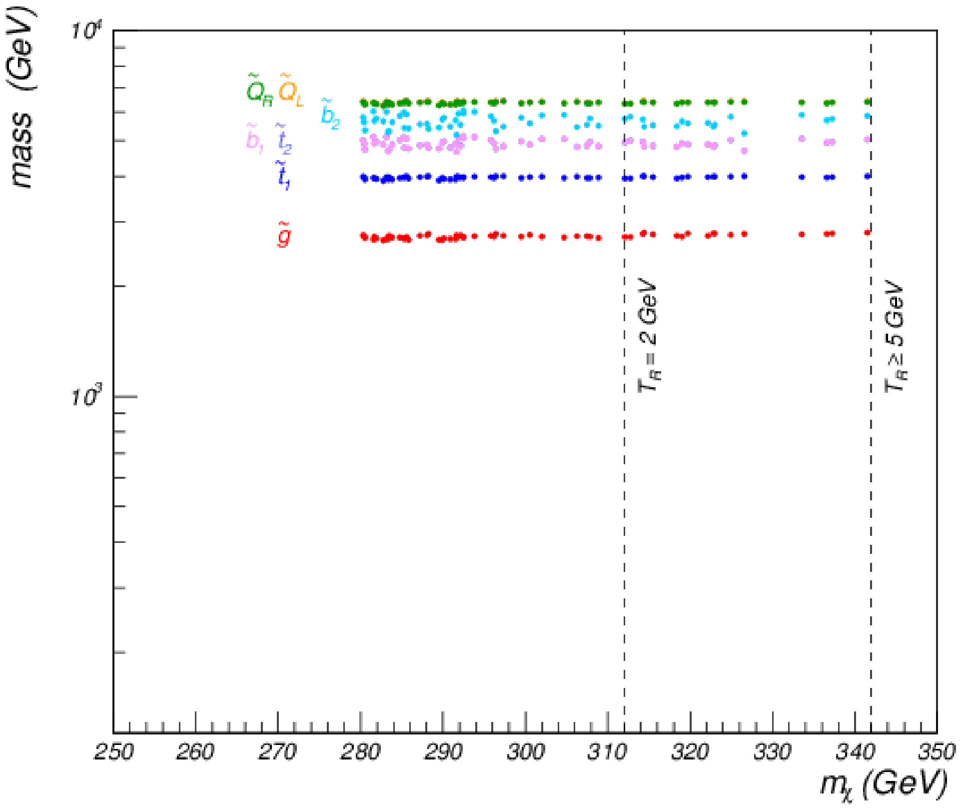
[MC,Burgess,Quevedo]

SUSY spectra: coloured particles

- Heavy coloured particles
- 1-loop correction to Higgs mass

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

- Need large loop correction ➡ heavy squarks
- Stops lighter than 1st and 2nd generation squarks due to RG running
- Probably beyond LHC reach

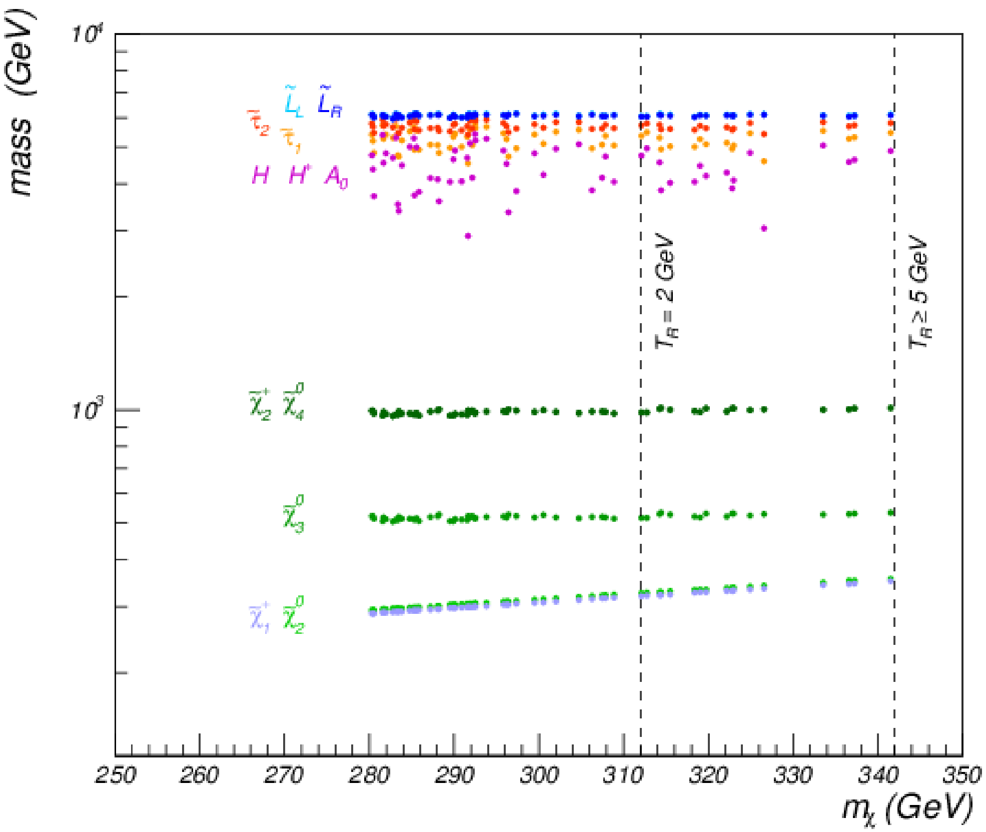


SUSY spectra: uncoloured particles

- Sparticle spectra typical of Natural SUSY
- Condition for REWSB

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

- Need small μ to avoid fine-tuning ➡ Higgsino-like LSP
- Almost degenerate lightest and second to lightest neutralino and lightest chargino



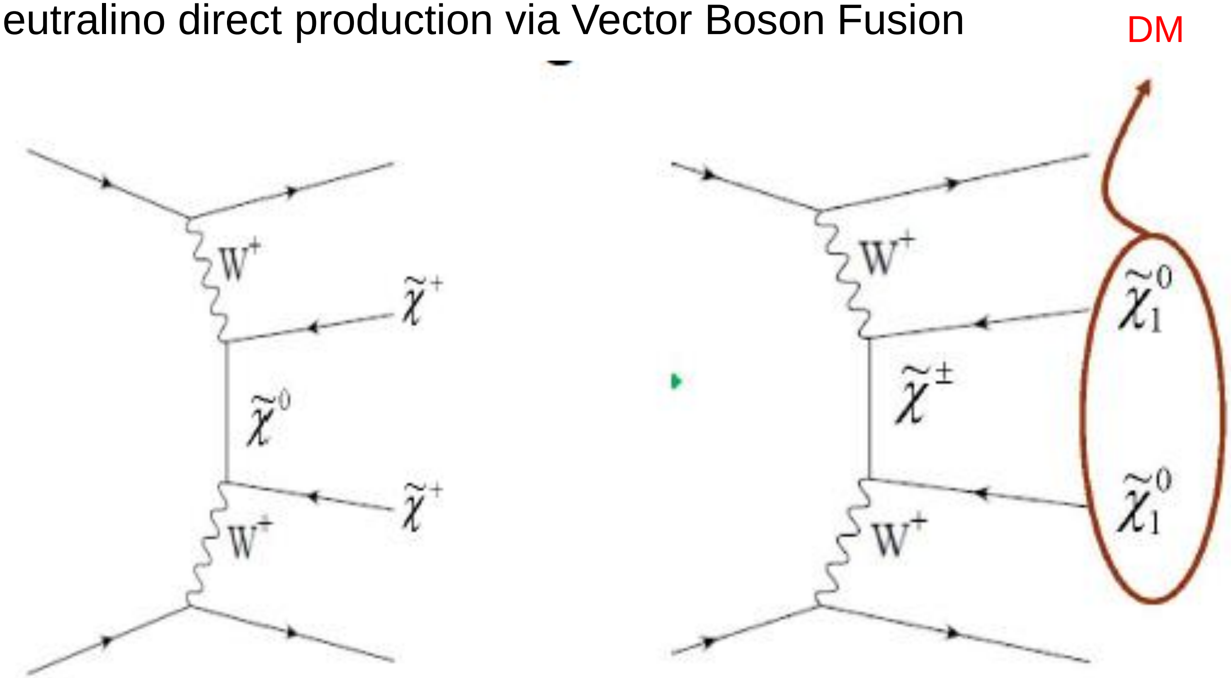
LHC signatures

- Neutralinos have only EW interactions

  ➡ small production rate ➡ weak bounds from LHC

- All other particles are too heavy

  ➡ cannot have standard LSP production from gluino cascade decay
  ➡ focus on neutralino direct production via Vector Boson Fusion



- Signal: 2 high E_T forward jets in opposite hemispheres + 2 leptons + missing energy
- Can probe m_{LSP} (at 5σ) up to 400 GeV at LHC14 TeV and 1000 fb^{-1} luminosity

[Dutta, Gurrola, Kamon, John, Sinha, Sheldon]

A challenge for moduli decays

GENERIC feature of string compactifications: presence of light axionic degrees of freedom UNAVOIDABLE in most string models [Allahverdi, MC, Dutta,Sinha]

- Axionic dark radiation overproduction:
  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 $N_{\rm eff}$

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

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

GENERIC PREDICTION of string compactifications: axionic dark radiation production from ϕ decay is UNAVOIDABLE in most string models!

Planck 2015: $N_{\rm eff}$ = 3.13 ± 0.32 (68% CL)
reduced evidence for dark radiation BUT……

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)

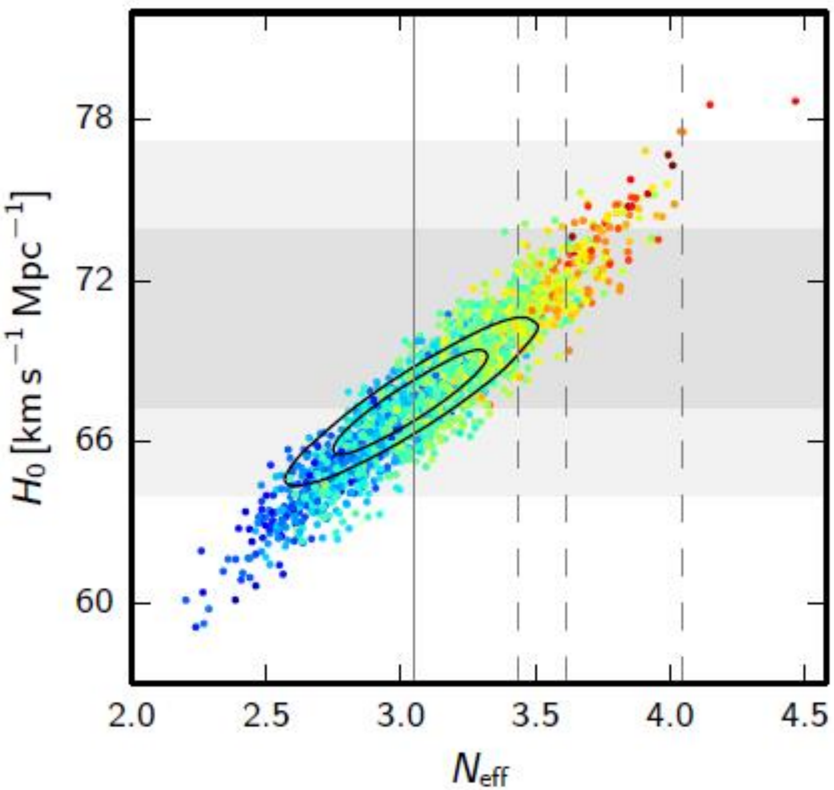
- HST direct value of H_0 :

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

2.4 σ tension ➡ need new physics: ΔN_{eff} >0

BUT HST data reanalysed by Planck:

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



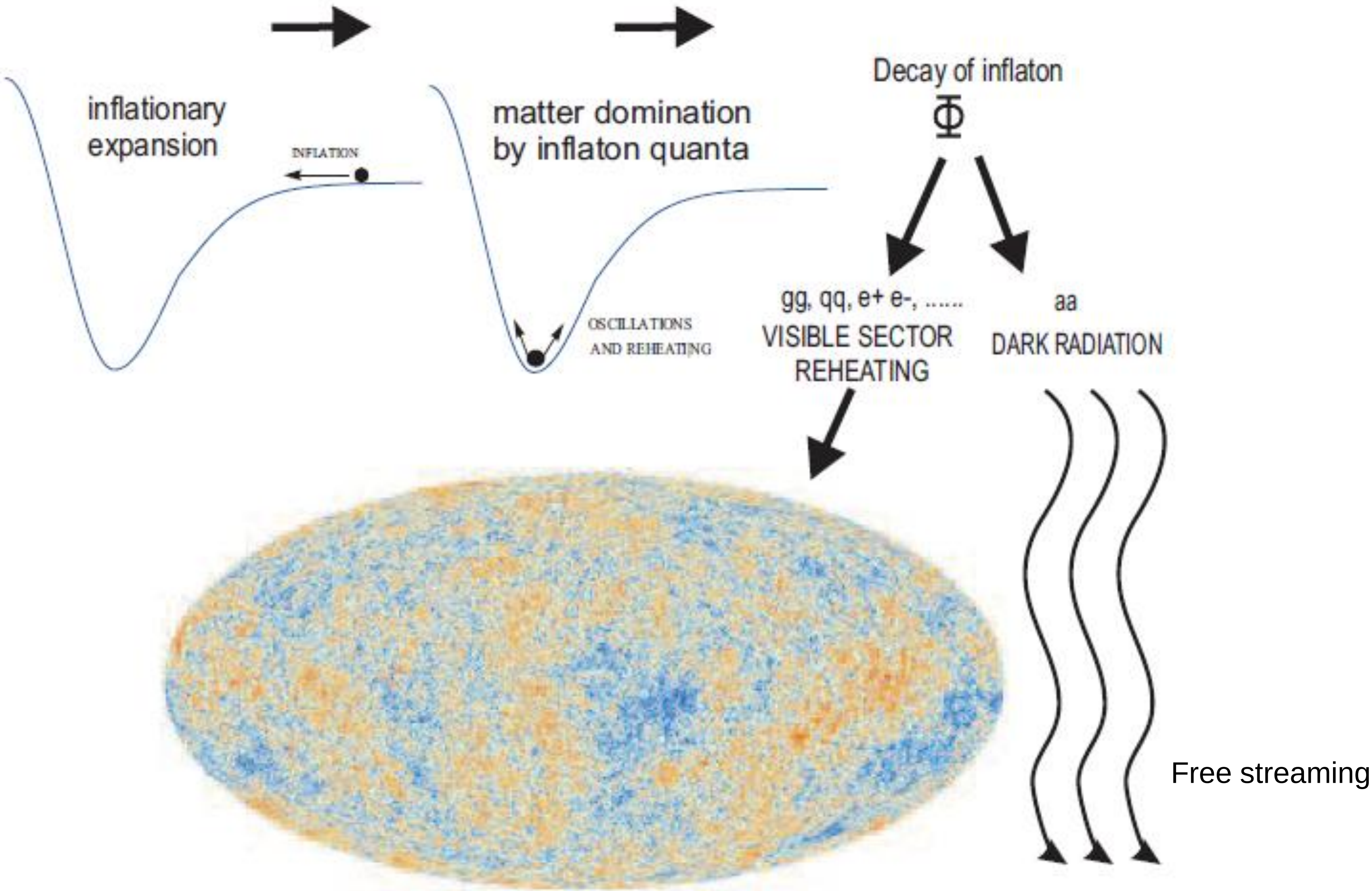
only 1 σ away from Planck value ➡ no need new physics: $\Delta N_{eff} \to 0$

BUT ΔN_{eff} >0 still allowed by Planck! (HST value of H_0 still controversial)

E.g.: for ΔN_{eff} =0.39 Planck data give (68% CL):
H_0 = 70.6 ± 1.0 km s^{-1} Mpc^{-1} ➡ better agreement with HST!
$n_s \simeq 0.983 \pm 0.006$ ➡ larger central value!

➡ Need reliable direct measurements of H_0 !

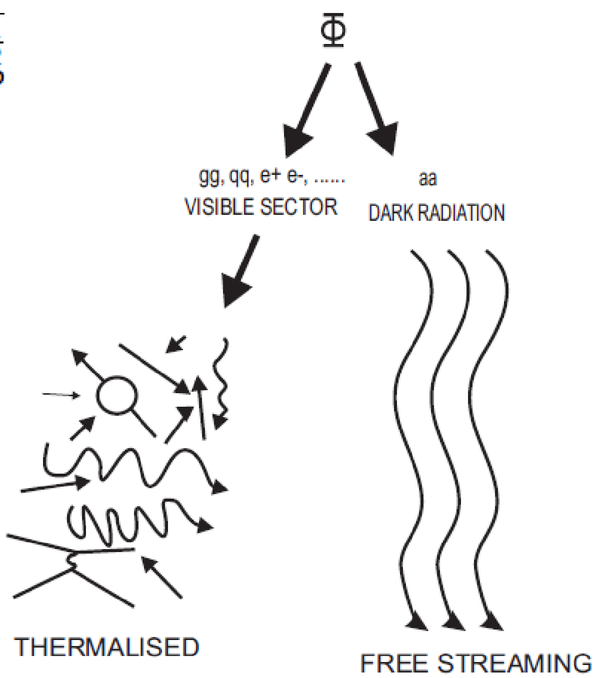
Dark radiation production



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!

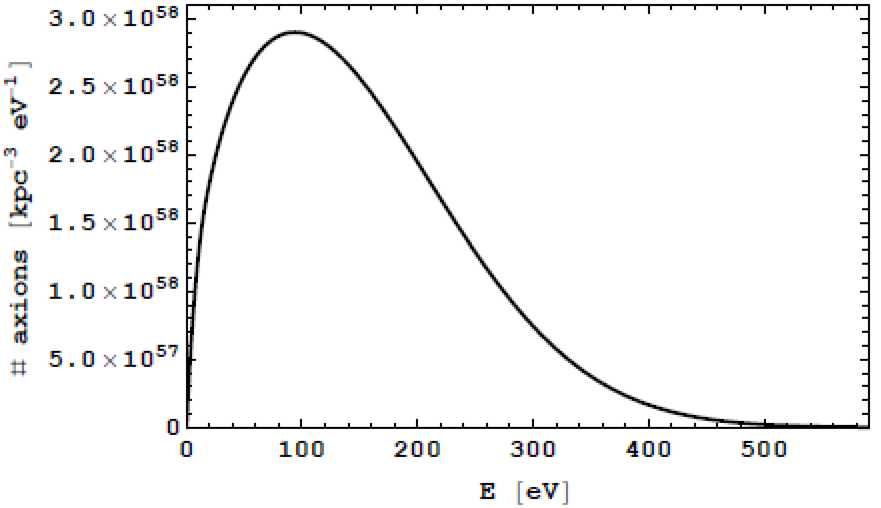
No absolute prediction, but a lightest modulus mass $m \sim 10^6$GeV arises in many string models - often correlated with SUSY approaches to the weak hierarchy problem.

- KKLT hep-th/0503216 Choi et al
- Sequestered LVS 0906.3297 Blumenhagen et al + 1409. 1931 Aparicio, MC, Krippendorf, Maharana, Muia, Quevedo
- 'G2 MSSM' 0804.0863 Acharya et al

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

Axion-photon conversion

- Axion-photon conversion in coherent magnetic fields

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{a}{4M} F^{\mu\nu} \tilde{F}_{\mu\nu} + \frac{1}{2} \partial_\mu a \, \partial^\mu a - \frac{1}{2} m_a^2 a^2$$

$M \geq 10^{11}$ GeV from supernovae cooling

- Axion-photon conversion probability in plasma with frequency ω_{pl}

i) for $m_a < \omega_{pl}$

$$P_{a\to\gamma} \approx \frac{1}{4}\left(\frac{B\,L}{M}\right)^2$$

ii) for $m_a >> \omega_{pl}$

$$P'_{a\to\gamma} \approx P_{a\to\gamma}\left(\frac{\omega_{\rm pl}}{m_a}\right)^4 << P_{a\to\gamma}$$

negligible

- Need large B and L to have large conversion probability ➡ galaxy clusters

i) typical size $R_{cluster} \sim 1$ Mpc
ii) ICM plasma frequency $\omega_{pl} \sim 10^{-12}$ eV
➡ axions with $m_a >> 10^{-12}$ eV (QCD axion) give negligible conversion
iii) B ~ 1 ÷ 10 μG
iv) L ~ 1 ÷ 10 kpc

CAB evidence in the sky

- Soft X-ray excess in galaxy clusters above thermal emission from ICM observed since 1996 by several missions (EUVE, ROSAT, XMM-Newton, Suzaku and Chandra)

- Statistical significance around 100σ!

- No good astrophysical explanation

- Typical excess luminosity

$$\mathcal{L}_{\rm excess} \approx 10^{43}\ \mathrm{erg\ s^{-1}}$$

- CAB energy density

$$\rho_{\rm CAB} = 1.6\times 10^{60}\ \mathrm{erg\ Mpc^{-3}} \left(\frac{\Delta N_{\rm eff}}{0.57}\right)$$

- Soft X-ray luminosity from axion-photon conversion

$$\mathcal{L}_{a\to\gamma} = \rho_{\rm CAB} P^{\rm cluster}_{a\to\gamma} = 3.16\times 10^{43}\ \mathrm{erg\ s^{-1}} \left(\frac{\Delta N_{\rm eff}}{0.5}\right)\left(\frac{B}{\sqrt{2}\,\mu\mathrm{G}}\frac{10^{12}\,\mathrm{GeV}}{M}\right)^2\left(\frac{L}{1\,\mathrm{kpc}}\right)$$

- Match data for

$$\Delta N_{\rm eff} \approx 0.5 \qquad m_a < 10^{-12}\,\mathrm{eV} \qquad M \approx 10^{12}\ \mathrm{GeV}$$

[Conlon, Marsh]

3.5 keV line

- Detection of a 3.5 keV line from:

i) Stacked galaxy clusters (XMM-Newton) and Perseus (Chandra) [Bulbul et al. 1402.2301]

ii) Perseus and Andromeda (XMM-Newton) [Boyarsky et al. 1402.4119]

iii) Perseus (Suzaku) [Urban et al. 1411.0050]

- Non-detection of a 3.5 keV line from:

i) Dwarf spheroidal galaxies (XMM-Newton) [Malyshev et al. 1408.3531]

ii) stacked galaxies (XMM-Newton and Chandra) [Anderson et al. 1408.4115]

- Simplest explanation: DM with m_{DM} ~ 7 keV (sterile neutrinos, axions, axinos,…..) decaying into photons [Higaki, Jeong, Takahashi] [Jaeckel,Redondo, Ringwald]

- Astrophysical explanation: new atomic transition line from ICM plasma – less plausible: line seen in Andromeda where there is no plasma!

Problems with DM decay

- Problems with simplest explanation DM $\longrightarrow \gamma$:

i) Inconsistent inferred signal strength

Line traces only DM quantity in each cluster ➡ clear prediction

$$F^{i}_{\mathrm{DM}\to\gamma} \propto \Gamma_{\mathrm{DM}\to\gamma}\, \rho^{i}_{\mathrm{DM}} \quad \Rightarrow \quad \frac{F^{i}_{\mathrm{DM}\to\gamma}}{F^{j}_{\mathrm{DM}\to\gamma}} \propto \frac{\rho^{i}_{\mathrm{DM}}}{\rho^{j}_{\mathrm{DM}}} \quad \text{fixed}$$

BUT signal strength from Perseus larger than for other stacked galaxy clusters (XMM-Newton and Chandra) and Coma, Virgo and Ophiuchus (Suzaku)

ii) Inconsistent morphology of the signal

Non-zero signal from everywhere in DM halo

BUT stronger signal from central cool core of Perseus (XMM-Newton, Chandra and Suzaku) and Ophiucus + Centaurus (XMM-Newton)

iii) Non-observation in dwarf spheroidal galaxies

Dwarf galaxies are dominated by DM ➡ they should give cleanest DM decay line

BUT the line has not been observed + non-observation in stacked galaxies

Alternative explanation: DM $\rightarrow$ ALP $\rightarrow \gamma$

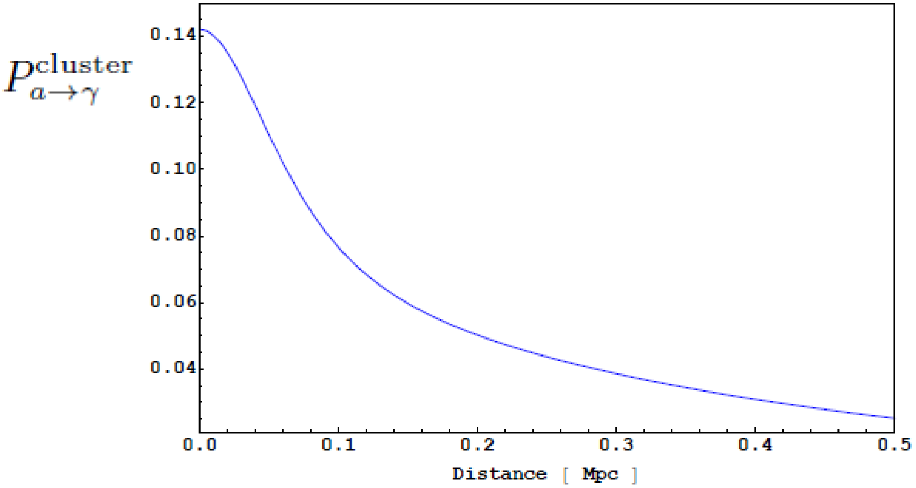
- Monochromatic 3.5 keV axion line from DM decay with m_{DM} ~ 7 keV

a) $\frac{\Phi}{\Lambda}\partial_\mu a \partial^\mu a \;\longrightarrow\; \Gamma_\Phi = \frac{1}{32\pi}\frac{m_\Phi^3}{\Lambda^2}$ b) $\frac{\partial_\mu a}{\Lambda}\bar{\psi}\gamma^\mu\gamma^5\chi \;\longrightarrow\; \Gamma_{\psi\to\chi a} = \frac{1}{16\pi}\frac{(m_\psi^2 - m_\chi^2)^3}{m_\psi^3\Lambda^2}$

- Axion-photon conversion in cluster magnetic field [MC, Conlon, Marsh, Rummel 1403.2370]

$$F^i_{\mathrm{DM}\to\gamma} \propto \Gamma_{\mathrm{DM}\to a} P^i_{a\to\gamma}\rho^i_{\mathrm{DM}} \quad \Rightarrow \quad \frac{F^i_{\mathrm{DM}\to\gamma}}{F^j_{\mathrm{DM}\to\gamma}} \propto \frac{\rho^i_{\mathrm{DM}} P^i_{a\to\gamma}}{\rho^j_{\mathrm{DM}} P^j_{a\to\gamma}} \propto \left(\frac{B^i}{B^j}\right)^2$$

- Morphology of the signal: B-field peakes at centre



$$B(r) = B_0\sqrt{\frac{n_e(r)}{n_e(0)}}$$

- Match data for same values which give soft X-ray excess: $m_a < 10^{-12}\,\mathrm{eV}$ $\quad M \approx 10^{12}\,\mathrm{GeV}$

DM $\rightarrow$ ALP $\rightarrow$ γ: advantages and predictions

- B-dependent line strength can explain:

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

ii) Stronger signal from cool core:
B-field peaks in central cool core in galaxy clusters

iii) Non-observation in dwarf galaxies:
Dwarf galaxies have L and B-field smaller than galaxy clusters
Predicted in MC, Conlon, Marsh, Rummel 1403.2370 ⟹ confirmed in Malyshev et al. 1408.3531

iv) Non-observation in galaxies:
Galaxies have L and B-field smaller than galaxy clusters
Predicted in MC, Conlon, Marsh, Rummel 1403.2370 ⟹ confirmed in Anderson et al. 1408.4115

v) Observation in Andromeda:
it is almost edge on to us
⟹ axions have significant passage through its disk and enhance conversion probability

Conclusions

- Connection between string theory and 4D physics ⟶ string compactifications
- Extra dimensions ⟶ Moduli ϕ: new scalars with gravitational couplings
- Moduli stabilisation: give mass to moduli and break SUSY
- Cosmological moduli problem: $m_\phi > 50$ TeV
- Reheating driven by lightest modulus decay
- Non-standard cosmology: dilution of thermal DM
- Non-thermal dark matter: CMSSM with a 300 GeV Higgsino LSP saturating DM for $T_R = 2$ GeV
- Generic production of axionic dark radiation
- Cosmic axion background with $E_a \sim 200$ eV
- CAB detectable via axion-photon conversion in B
- Explain soft X-ray excess in galaxy clusters
- Explain 3.5 keV line from galaxy clusters improving simplest decaying DM interpretation