Superheavy Dark Matter from String Theory

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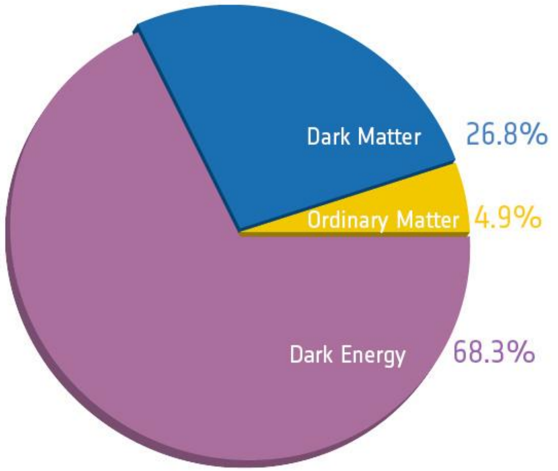
Based on:

R.A., Broeckel, Cicoli, Osinski JHEP 1810, 02, 026 (2021)

Introduction:

The present universe according to observations:



BSM needed to explain 95% of the universe.

Important questions about DM:

What is the identity of DM?

How did it acquire its relic abundance?

Profound consequences for:

Particle Physics (BSM)

Cosmology (thermal history)

String constructions provide a UV complete description of the early universe (inflation to BBN), as well as BSM.

Type IIB flux compactifications typically predict:

$$H_{inf} \lesssim m_{3/2}$$

Obtaining the correct amplitude for density perturbations results in:

$$H_{inf} \sim 10^{10} - 10^{11}\ GeV$$

How to reconcile this with low-energy SUSY $m_{soft} \sim O(TeV)$?

(1) $H_{inf} \gg m_{3/2} \qquad m_{soft} \sim O(TeV)$

KKLT with two exponents (as in the racetrack model). → tuned situation

Kallosh, Linde JHEP 12, 004 (2004)

(2) $H_{inf} \lesssim m_{3/2} \gg m_{soft} \sim O(TeV)$

Sequestered LVS → very specific brane configurations and Kahler metric

Blumenhagen, Conlon, Krippendorf, Moster, Quevedo JHEP 09, 007 (2009)

Lets consider the more natural case:

$$H_{inf} \lesssim m_{3/2} \qquad m_{soft} \gg O(TeV)$$

This will result in thermal overproduction of DM.

Griest, Kamionkowski PRL 64, 615 (1990)

But, string constructions generically result in non-standard thermal histories that involve epoch(s) of EMD driven by string moduli.

Kane, Sinha, Watson IJMPD 24, 1530022 (2015)

The entire DM abundance can be directly produced from decay of a modulus ϕ :

$$\frac{n_\chi}{s} = \frac{3T_{\rm R}}{4m_\varphi}\,{\rm Br}_\chi \qquad\qquad T_R \sim \left(\frac{m_\phi^3}{M_P}\right)^{1/2}$$

"Branching scenario"

Gelmini, Gondolo PRD 74, 023510 (2006)

R.A., B. Dutta, Sinha PRD 83, 083502 (2011)

This scenario can be implemented in sequestered LVS, volume modulus plays the role of ϕ .

R.A., Cicoli, B. Dutta, Sinha PRD 88, 095015 (2013)

However, the simplest realization does not work for superheavy DM:

(1) $Br_\chi \gtrsim O(10^{-3}) \Rightarrow \frac{n_\chi}{s} \gg \left(\frac{n_\chi}{s}\right)_{obs} \simeq 4.2 \times 10^{-10} \left(\frac{1\ GeV}{m_\chi}\right)$

(2) ϕ decay produces an excess of DR.

R.A., Cicoli, B. Dutta, Sinha JCAP 10, 004 (2014)

The "branching scenario" should be modified in this case so that it:

(1) Gives rise to a sufficiently small DM relic density.

(2) Does not produce an excessive amount of DR.

R.A., Broeckel, Cicoli, Osinski JHEP 02, 026 (2021)

The Scenario:

σ: inflaton ϕ: modulus

$m_\sigma > m_\chi > m_\phi$

Post-inflationary thermal history:

(1) $\Gamma_\sigma \lesssim H < H_{inf}$: EMD from inflaton oscillations. Inflaton decay produces DR and a subdominant component of DM.

(2) $H_D \lesssim H < \Gamma_\sigma$: Inflationary reheating completes, transition to RD.

(3) $\Gamma_\phi \lesssim H < H_D$: EMD driven by modulus oscillations. Entropy generation at the end of this stage dilutes DR and DM from (1).

(4) $\Gamma_\phi \lesssim H < H_D$: Modulus decay completes. Transition to RD prior to the onset of BBN. by modulus oscillations.

$$\frac{n_\chi}{s} \simeq \frac{3}{4} \times 10^{-3} \, \frac{1}{Y_\phi^2} \, \frac{\Gamma_{\sigma\to\mathrm{vis}}}{\Gamma_\sigma} \, \frac{\Gamma_\phi}{\Gamma_{\phi\to\mathrm{vis}}} \, \frac{T_\mathrm{R}}{m_\sigma}$$

$$T_\mathrm{R} = \left(\frac{90}{\pi^2 g_{*,\mathrm{R}}} \frac{\Gamma_{\phi\to\mathrm{vis}}}{\Gamma_\phi}\right)^{1/4} \sqrt{\Gamma_\phi M_\mathrm{P}}$$: final reheating temperature

$$Y_\phi \equiv \phi_0 / M_\mathrm{P}$$

$$\frac{\rho_\mathrm{DR}}{\rho_\mathrm{R}} \simeq \frac{1}{Y_\phi^{8/3}} \left(\frac{\Gamma_\phi}{\Gamma_\sigma}\right)^{2/3} \frac{\Gamma_{\sigma\to\mathrm{DR}}}{\Gamma_\sigma} \, \frac{\Gamma_\phi}{\Gamma_{\phi\to\mathrm{vis}}} + \frac{\Gamma_{\phi\to\mathrm{DR}}}{\Gamma_{\phi\to\mathrm{vis}}}$$

Note:

$$Y_\phi \uparrow \Rightarrow \frac{n_\chi}{s} \downarrow, \frac{\rho_{DR}}{\rho_R} \downarrow$$

Expected: a longer EMD epoch results in a larger dilution factor.

EMD also affects inflationary observables:

$$N_e \simeq 57 + \frac{1}{4}\ln r - \frac{1}{4}N_{reh} - \frac{1}{4}N_\phi$$

r: tensor-to-scalar ratio

$$N_{reh} \simeq \frac{2}{3}\ln\left(\frac{H_{inf}}{\Gamma_\sigma}\right)$$

$$N_\phi \simeq \frac{2}{3}\ln\left(\frac{H_D}{\Gamma_\phi}\right) \simeq \frac{2}{3}\ln\left(Y_\phi^4 \frac{\Gamma_\sigma}{\Gamma_\phi}\right)$$

$$N_e \simeq 57 + \frac{1}{4}\ln r - \frac{1}{6}\ln\left(Y_\phi^4 \frac{H_{inf}}{\Gamma_\phi}\right)$$

The scalar spectral index follows:

$$n_s = 1 - \frac{a}{N_e}$$

In our model $a = 2$ (also for Starobinsky model & Higgs inflation):

$$N_e \gtrsim \frac{2}{1 - n_{s,min}}$$

$$Y_\phi \uparrow \Rightarrow N_e \downarrow, n_{s,min} \downarrow$$

Opposite constraints from $\frac{n_\chi}{s}$ and n_s on the duration of EMD.

The Model:

Type IIB model with three Kahler moduli:

$$\mathcal{V} = \tau_{\text{big}}^{3/2} - \tau_{\text{vis}}^{3/2} - \tau_{\text{inf}}^{3/2}$$

$$K = -2\ln\left(\mathcal{V} + \frac{\xi}{2g_s^{3/2}}\right) \qquad W = W_0 + A_{\text{vis}}\, e^{-a_{\text{vis}}T_{\text{vis}}} + A_{\text{inf}}\, e^{-a_{\text{inf}}T_{\text{inf}}}$$

$$\epsilon \equiv \frac{W_0}{\mathcal{V}} \ll 1 \qquad \kappa \equiv \frac{g_s}{8\pi} \ll 1$$

Mass spectrum:

$$m_\sigma^2 \simeq \kappa\, \epsilon^2\, (\ln\epsilon)^2\, M_{\text{P}}^2 \qquad m_\phi^2 \simeq \frac{\epsilon\, m_\sigma^2}{g_s^{3/2} W_0\, |\, (\ln\epsilon)^3\, |} \ll m_\sigma^2$$

$$m_{a_{\text{DR}}}^2 \simeq \kappa\, e^{-2\mathcal{V}^{2/3}}\, M_{\text{P}}^2 \sim 0$$

$$m_{3/2} = \sqrt{\kappa}\,\epsilon\, M_{\rm P} \qquad m_0 \simeq M_{1/2} \simeq \frac{m_{3/2}}{|\ln \epsilon|} \qquad m_\chi \simeq m_0 \simeq M_{1/2}$$

↑ DM is the LSP

$$m_\phi^2 \simeq \frac{\epsilon\,|\ln\epsilon|}{g_s^{3/2} W_0}\, m_\chi^2 \ll m_\chi^2 \quad \text{for} \quad \epsilon \ll 1$$

MSSM-like hidden sector:

(1) $\Lambda_{QCD}^{hid} \gg \Lambda_{QCD}$.

(2) R-parity violation.

(3) Very light hidden electrons (similar to visible sector neutrinos).

Couplings:

$$\mathcal{L} \supset -\frac{1}{4}\frac{c_{\rm hid}}{M_{\rm P}}\,\sigma\, F_{\mu\nu}^{\rm hid} F_{\rm hid}^{\mu\nu} - \frac{1}{4}\frac{c_{\rm vis}}{M_{\rm P}}\,\sigma\, F_{\mu\nu}^{\rm vis} F_{\rm vis}^{\mu\nu}$$

$$c_{\rm hid} \simeq g_s^{3/4}\sqrt{\mathcal{V}} \gg 1 \qquad \text{and} \qquad c_{\rm vis} \simeq c_{\rm hid}^{-1}$$

$$\mathcal{L} \supset -\frac{1}{4}\frac{\lambda_{\rm hid}}{M_{\rm P}}\,\phi\, F^{\rm hid}_{\mu\nu} F^{\mu\nu}_{\rm hid}\,, \qquad \lambda_{\rm hid} \simeq \frac{1}{|\ln\epsilon|}$$

$$\mathcal{L} \supset -\frac{1}{4}\frac{\lambda_{\rm vis}}{M_{\rm P}}\,\phi\, F^{\rm vis}_{\mu\nu} F^{\mu\nu}_{\rm vis}\,, \qquad \lambda_{\rm vis} \simeq \frac{1}{|\ln\epsilon|}$$

$$\mathcal{L} \supset \lambda_{\rm DR}\,\frac{m_\phi^2}{M_{\rm P}}\,\phi\, a_{\rm DR}\, a_{\rm DR}\,, \qquad \lambda_{\rm DR} \simeq \frac{1}{\sqrt{6}}$$

Giudice-Masiero contribution:

$$\mathcal{L} \supset c\,\frac{m_\phi^2}{M_{\rm P}}\,\phi\,\left[(h^0)^2 + (G^0)^2 + ({\rm Re}G^+)^2 + ({\rm Im}G^+)^2\right] \qquad c = Z/(2\sqrt{6})$$

$$\Delta N_{\rm eff} \simeq 3\,\frac{\Gamma_{\phi\to{\rm DR}}}{\Gamma_{\phi\to{\rm vis}}} = \frac{3}{Z^2} \lesssim 0.75 \quad \text{for} \quad Z \gtrsim 2$$

$$\boxed{\Gamma_\phi = \frac{1+Z^2}{48\pi}\frac{m_\phi^3}{M_{\rm P}^2}}$$

$$\boxed{\Gamma_\sigma = N_g^{\rm hid}\,\frac{c_{\rm hid}^2}{64\pi}\left(1 + \frac{N_g}{N_g^{\rm hid}}\frac{1}{c_{\rm hid}^4}\right)\frac{m_\sigma^3}{M_{\rm P}^2} \simeq N_g^{\rm hid}\,\frac{c_{\rm hid}^2}{64\pi}\frac{m_\sigma^3}{M_{\rm P}^2}} \qquad N_g^{hid} = 12$$

Inflationary observables:

$$N_{\rm reh} \simeq \frac{2}{3}\ln\left(\sqrt{\frac{3}{2}\frac{512^2\pi^4}{(2\pi)^{3/2}}}\frac{\mathcal{V}^{1/2}}{N_g^{\rm hid} W_0^2 g_s^{5/2}\,|\ln\epsilon|^{9/4}}\right)$$

$$N_\phi \simeq \frac{2}{3}\ln\left(Y_\phi^4\frac{\Gamma_\sigma}{\Gamma_\phi}\right) \simeq \frac{2}{3}\ln\left(\frac{3}{4}\frac{N_g^{\rm hid}}{1+Z^2}Y_\phi^4\, g_s^{15/4}\,\mathcal{V}^{5/2}\,|\ln\epsilon|^{9/2}\right)$$

$$r \simeq 16\times 3.7\times 10^6\left(\frac{3}{2}\frac{|\ln\epsilon|^{3/2}}{(2\pi)^{3/2}}\right)\frac{g_s}{16\pi}\frac{W_0^2}{\mathcal{V}^3}$$

$$N_{\rm e} \simeq 60.1 - \frac{1}{6}\ln\left(\frac{Y_\phi^4\,\mathcal{V}^{15/2}}{5 g_s^{1/4} W_0^5\,|\ln\epsilon|^{9/4}}\right)$$

Obtaining the right density perturbations gives the following relation:

$$\boxed{\mathcal{V}^{2/3} \simeq \lambda\left(\frac{\alpha^{1/4}\mathcal{V}}{g_s^{1/2} W_0\,|\ln\epsilon|^{3/4}\,N_{\rm e}}\right)^4}$$

$$\mathcal{V}^{2/3} \simeq \lambda\,\tau_{\rm inf} \qquad \lambda \gg 1$$

Results:

We impose the requirement from density perturbations, and find the DM mass that corresponds to the observed abundance.

We perform this over the expected range of parameters (1444 points):

$W_0 \in [1, 10^3]$ $g_s \in [10^{-3}, 0.1]$ $\lambda \in [10, 10^4]$

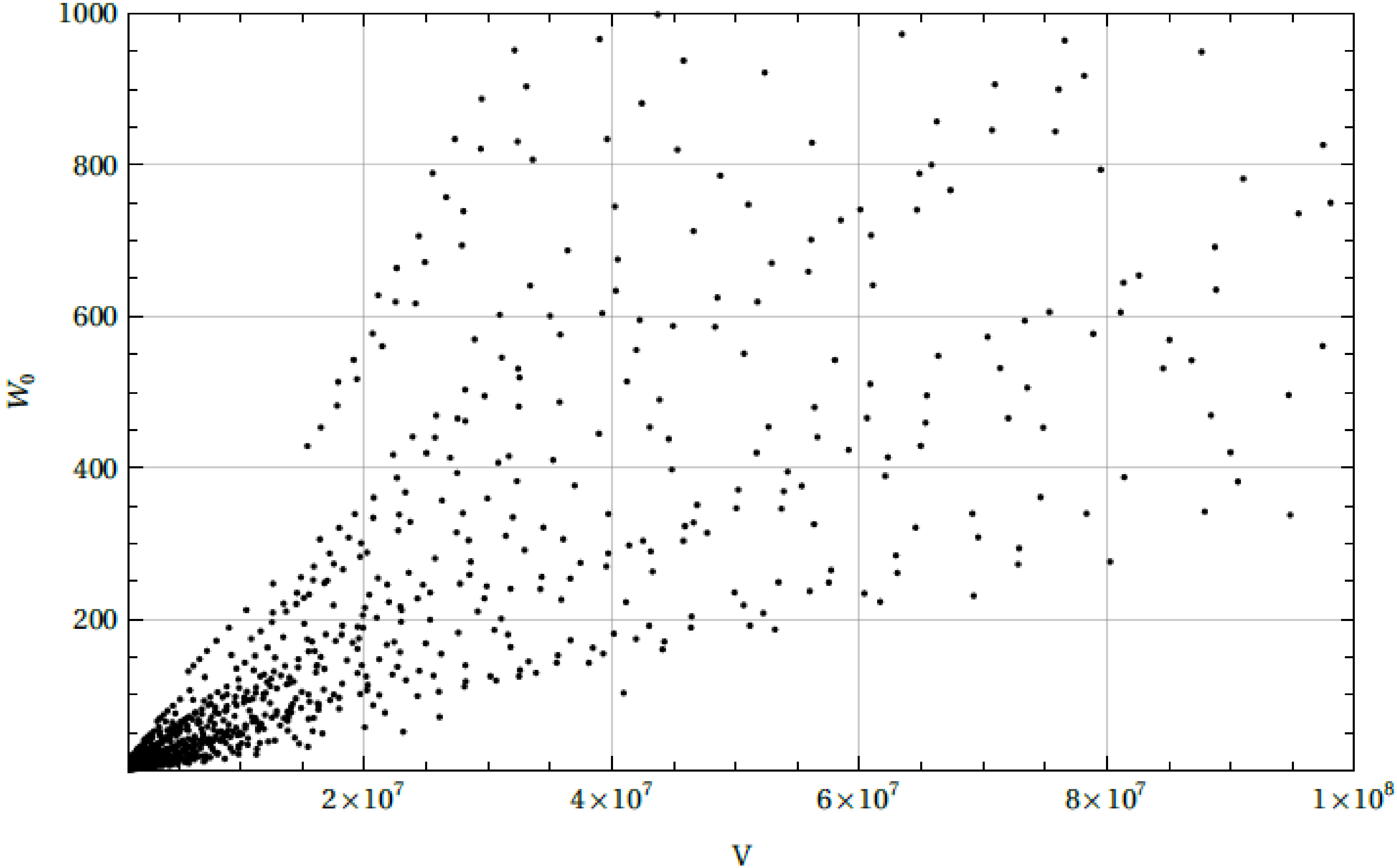
$Y_\phi \in [0.01,1]$ Cicoli, K. Dutta, Maharana, Quevedo JCAP 08, 006 (2016)

72% of the parameter set gives rise to the correct DM abundance.

The resulting DM mass is always in the following range:

$$m_\chi \sim 10^{10} - 10^{11}\ GeV$$

Points that yield the correct density perturbations and DM abundance:

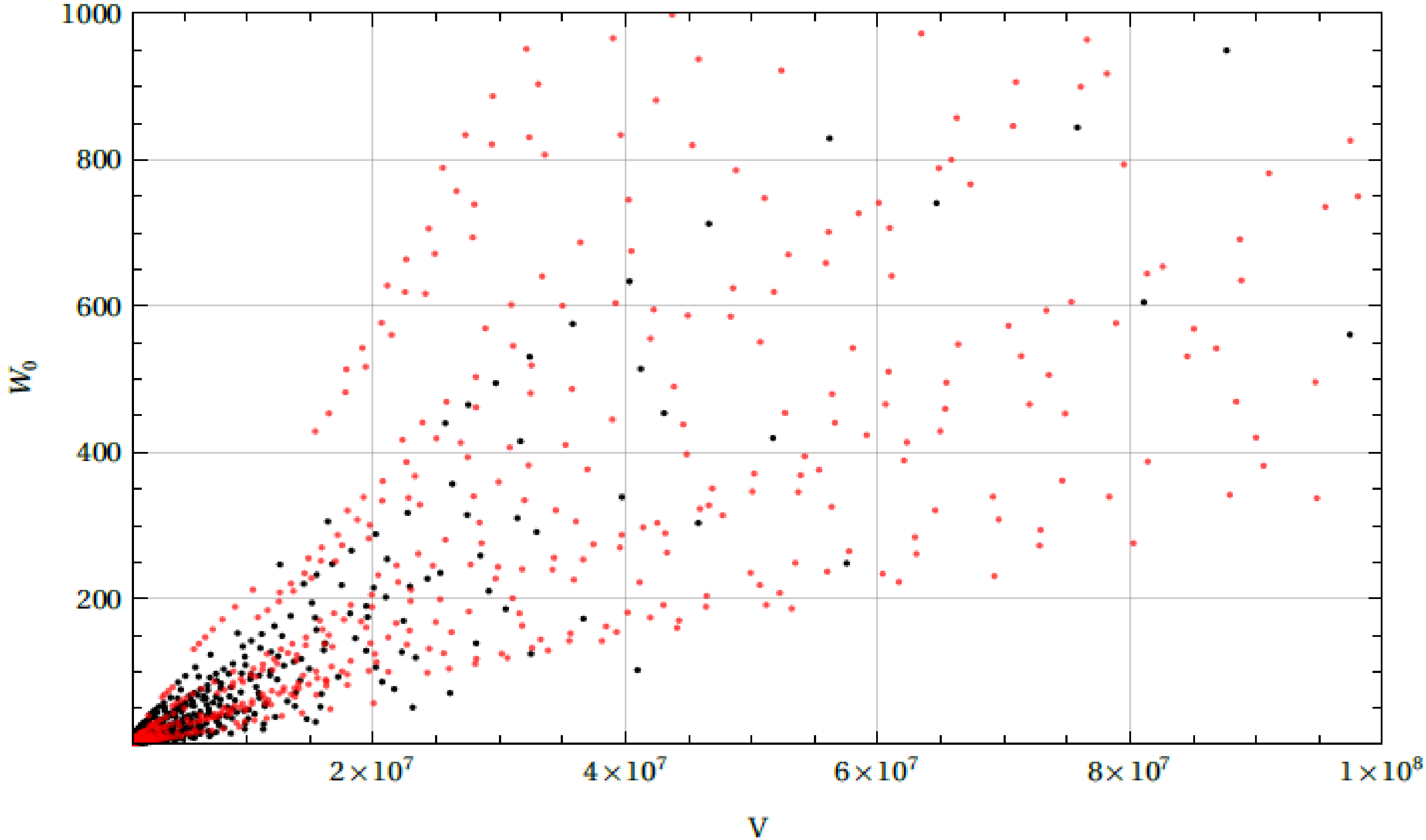


$$\frac{n_\chi}{s} \propto Y_\phi^{-2} V^{-13/4}$$

Black: n_s *in the* 2σ *range* $0.9565 < n_s < 0.9733$

Red: n_s *in the* 3σ *range (but outside* 2σ*)* $0.9523 < n_s < 0.9775$

Planck 2018 Astron. Astrophys. 641, A10 (2020)



Conclusions:

- Superheavy DM can arise typically within string theory

- Epoch(s) of EMD from moduli can yield the observed DM abundance

- Presented a type IIB LVS model with an epoch of modulus domination

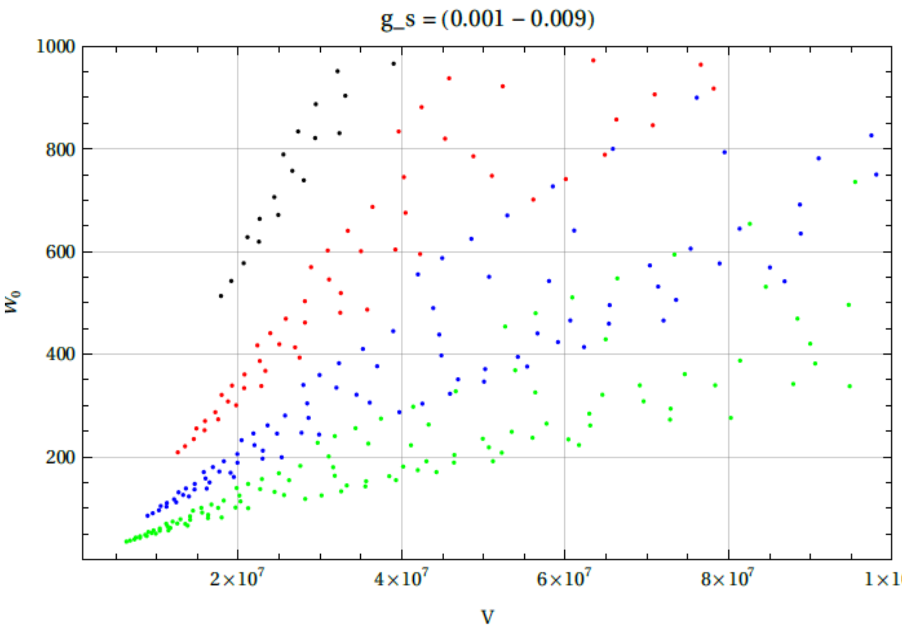
- Successful inflation & right DM content for $m_\chi \sim 10^{10} - 10^{11}\ GeV$

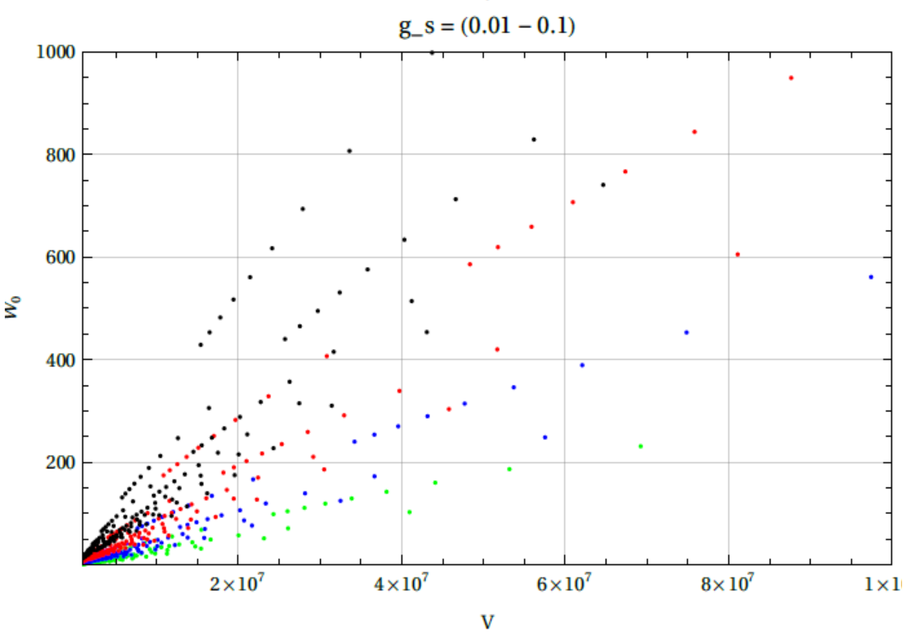
- Multiple epochs of modulus domination possible, not advantageous

- Possible indirect detection signal from decaying superheavy DM

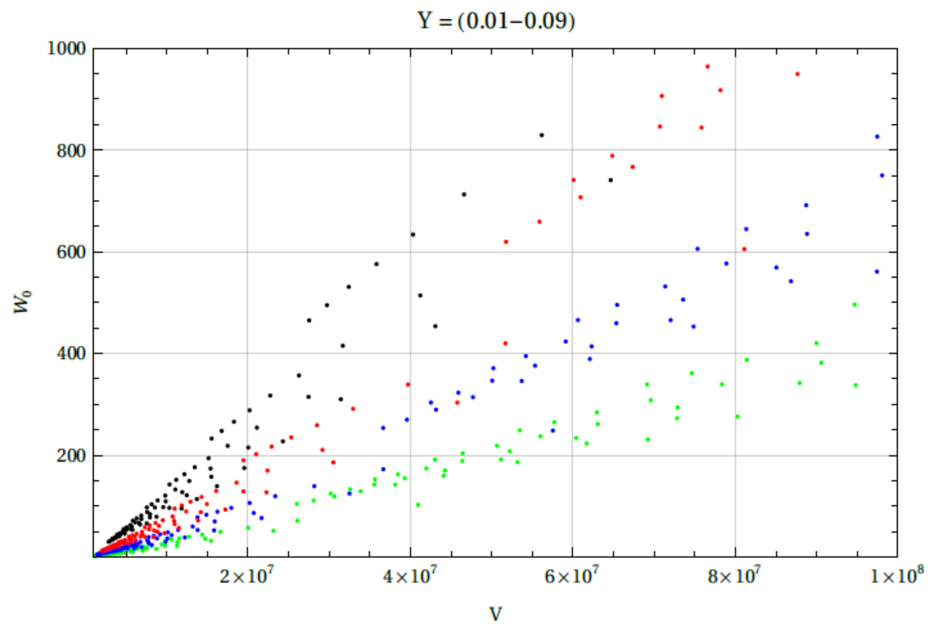
  Work in progress

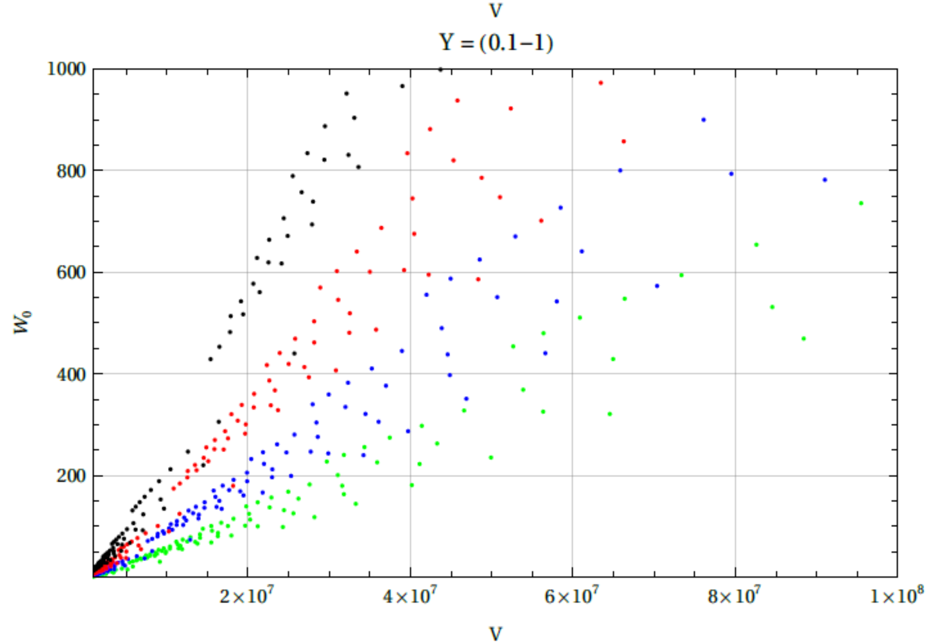
Subsets according to g_s:





Subsets according to Y_ϕ:





Numerical Analysis:

System of Boltzmann equations governing various species:

$$\frac{d\rho_\sigma}{dt} + 3H\rho_\sigma = -\Gamma_\sigma\,\rho_\sigma\,,$$

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi\,\rho_\phi\,,$$

$$\frac{d\rho_{\rm DR}}{dt} + 4H\rho_{\rm DR} = \Gamma_{\sigma\to{\rm DR}}\rho_\sigma + \Gamma_{\phi\to{\rm DR}}\rho_\phi\,,$$

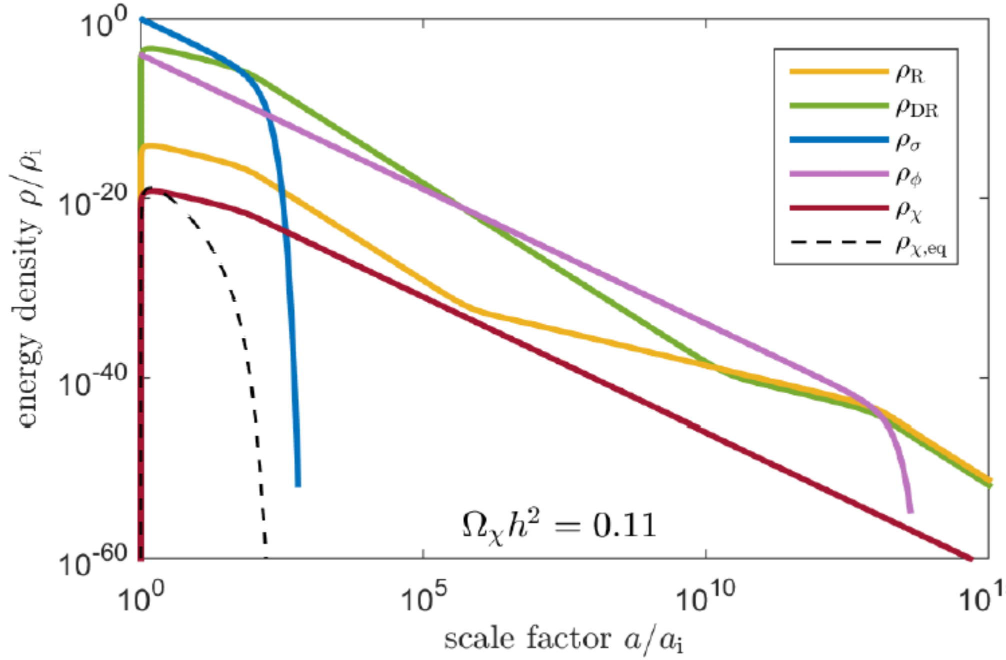
$$\frac{d\rho_{\rm R}}{dt} + 4H\rho_{\rm R} = \Gamma_{\sigma\to{\rm vis}}\rho_\sigma + \Gamma_{\phi\to{\rm vis}}\rho_\phi\,,$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = {\rm Br}_\chi\Gamma_\sigma\left(\frac{\rho_\sigma}{m_\sigma}\right) + \langle\sigma_{\rm ann}v\rangle\left(n^2_{\chi,{\rm eq}} - n^2_\chi\right),$$

Benchmark point to numerically solve this system:

W_0	39.1
$\mathcal{V}$	8.4×10^6
N_e	47.4
$N_{\rm reh}$	3.7
N_ϕ	16.4
$n_{\rm s}$	0.9578
m_σ	8.7×10^{12}GeV
m_ϕ	3.9×10^{8}GeV
$m_{3/2}$	7.1×10^{11}GeV
m_χ	5.8×10^{10}GeV
$c_{\rm hid}$	514.7

Evolution of the various energy densities:



Evolution of the visible sector temperature: