PiTP 2004 lectures:

Scalar Interactions in the Dark Sector

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Scalar interactions have a special property:

$\boxed{\text{Like objects attract. Unlike objects repel.}}$

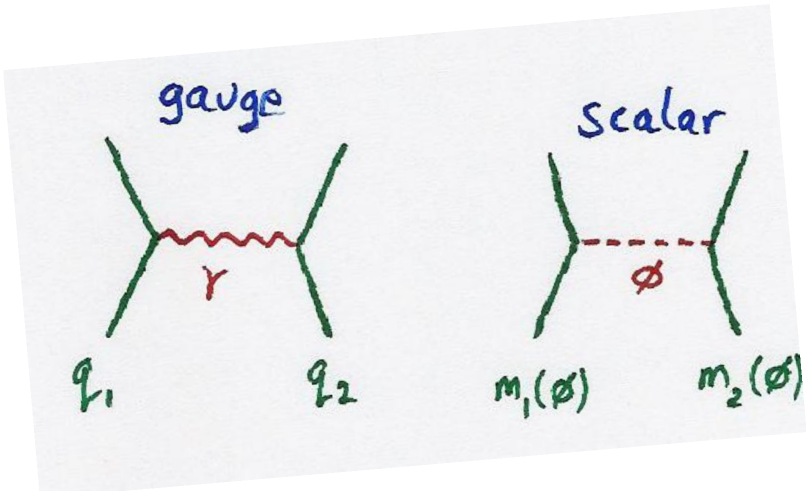
So they're potentially interesting in the dark sector.

String theory provides a multitude of scalars (moduli) as well as heavy objects coupled to them (e.g. wrapped branes).

Generically expect all scalars to get a mass after SUSY breaking. But do we really understand genericity and SUSY breaking?

While the court is still out, propose to consider *very light scalars* ($m_\phi \lesssim 1\,\text{Mpc}^{-1}$) in the dark sector.

Like objects attract. Unlike objects repel.



Scalar exchange is similar to gauge boson exchange:

$$
\begin{aligned}
&\text{gauge:}\quad \mathcal{M} \sim q_1 q_2 \frac{g^{00}}{p^2} = -\frac{q_1 q_2}{p^2} \;\rightarrow\; V_\gamma = \frac{q_1 q_2}{4\pi r} \\
&\text{scalar:}\quad \mathcal{M} \sim \frac{dm_1}{d\phi}\frac{dm_2}{d\phi}\frac{1}{p^2} \;\rightarrow\; V_s = -\frac{\frac{dm_1}{d\phi}\frac{dm_2}{d\phi}}{4\pi r}
\end{aligned} \tag{1}
$$

Compare to the force of gravity:

$$
\begin{aligned}
V_g &= -\frac{G m_1 m_2}{r} \\
\beta_{12} \equiv \frac{V_s}{V_g} &= \frac{\frac{dm_1}{d\phi}\frac{dm_2}{d\phi}}{4\pi G m_1 m_2} = \frac{1}{4\pi G}\frac{Q_1}{m_1}\frac{Q_2}{m_2},
\end{aligned} \tag{2}
$$

where $Q_i = \frac{dm_i}{d\phi}$ is the scalar charge: conserved in non-relativistic processes.

Brandenberger-Vafa scenario as an example

- At early times, universe was $\mathbf{R} \times T^9$, thermally populated with winding & momentum strings.
- As $T^3 \to \mathbf{R}^3$, winding strings generically annihilate. Not true if $T^4 \to \mathbf{R}^4$. Hence $D \leq 4$!
- Other T^6 directions stay close to self-dual radius.

Consider strings on $\mathbf{R}^{3,1} \times S^1$ (times some M_5 if you like):

$$
\begin{aligned}
S &= \frac{1}{2\kappa_5^2} \int d^5x \sqrt{G_5} e^{-2\Phi_5} \left[R_5 + 4(\partial\Phi_5)^2 \right] + \ldots \\
&= \frac{1}{2\kappa_4^2} \int d^4x \sqrt{G_4} e^{-2\Phi_4} [R_4 + 4(\partial\Phi_4)^2 \\
&\qquad\qquad - (\partial\varphi)^2] + \ldots \\
&= \int d^4x \sqrt{g} \left[\frac{1}{16\pi G}(R - 2(\partial\Phi_4)^2) - \frac{1}{2}(\partial\phi)^2 \right]
\end{aligned}
\tag{3}
$$

with background

$$
\begin{aligned}
ds^2_{5,str} &= ds^2_{4,str} + e^{2\varphi} dx_5^2 \,, \quad x_5 \sim x_5 + 2\pi\sqrt{\alpha'} \\
e^{-2\Phi_4} &= \frac{\mathrm{Vol}\, S^1}{2\pi\sqrt{\alpha'}} e^{-2\Phi_5} \,, \quad g_{ij} = e^{-2\Phi_4} G_{ij} \\
\frac{1}{2\kappa_4^2} &= \frac{1}{16\pi G} = \frac{M_{Pl}^2}{2} = \frac{2\pi\sqrt{\alpha'}}{2\kappa_5^2} \,, \quad \varphi = M_{Pl}\phi \,.
\end{aligned}
$$

Assume Φ_4 gets fixed but ϕ remains massless. For a string sitting at $\vec{x}=0$ but winding x_5,

$$
\begin{aligned}
S &= -\frac{1}{2\pi\alpha'}\int d^2\sigma\,\sqrt{g} = -\frac{1}{2\pi\alpha'}\int dt dx_5\, e^{\varphi} \\
&= -\int dt\,\frac{1}{\sqrt{\alpha'}} e^{\phi/M_{Pl}} \equiv -\int dt\, m_W(\phi)\,.
\end{aligned}
\tag{4}
$$

Thus we have heavy states,

$$
\begin{aligned}
\text{winding :} \qquad & \sqrt{\alpha'} m_W(\phi) = e^{\phi/M_{Pl}} \\
\text{momentum :} \qquad & \sqrt{\alpha'} m_M(\phi) = e^{-\phi/M_{Pl}}\,.
\end{aligned}
\tag{5}
$$

where the radius of the S^1 is $\sqrt{\alpha'}e^{\phi/M_{Pl}}$ and $M_{Pl}^2 = 1/8\pi G_4$. Let's have these be the dark matter!

Force between two particles is

$$
F_{pq} = B_{pq}\frac{G m_p m_q}{r^2} \qquad p,q \text{ are either M or W.}
$$

$$
B_{pq} = 1 + \beta_{pq} = \begin{pmatrix} 3 & -1 \\ -1 & 3 \end{pmatrix} \begin{matrix} \leftarrow \textit{net repulsion} \\ \leftarrow \textit{triple attraction} \end{matrix}
\tag{6}
$$

(Gauge interactions can be ignored—intuitively, think Debye screening).

Winding strings prefer to clump up away from momentum strings: *different* from CDM. (Too different? See later).

Linear perturbation theory

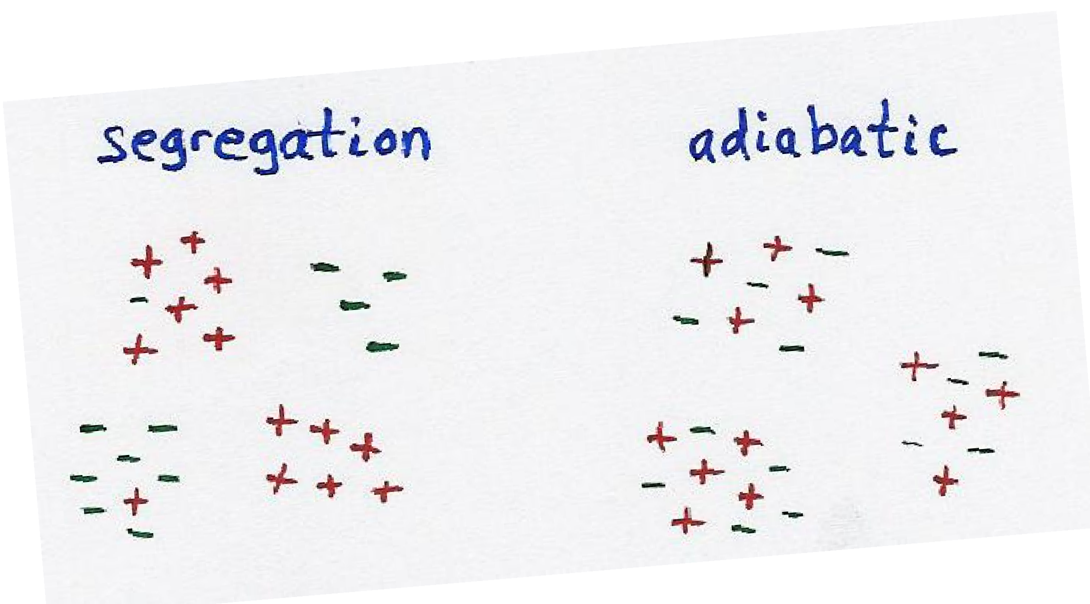
During matter-dominated epoch, number densities $n_p = \bar{n}_p(1+\delta_p)$ and $\phi = 0$, while $a(t) \sim t^{2/3}$. Perturbations evolve according to

$$\ddot{\delta}_p + 2\frac{\dot{a}}{a}\dot{\delta}_p = 4\pi G\rho \sum_q \beta_{pq} f_q \delta_q \,. \tag{7}$$

Two independent perturbations:

$$\begin{array}{rl} \text{adiabatic} & \delta_W = \delta_M \sim t^{2/3} \\ \text{isocurvature} & \delta_W = -\delta_M \sim t \end{array} \tag{8}$$

Scalar force is stronger than gravity, so segregation is faster than adiabatic structure formation.

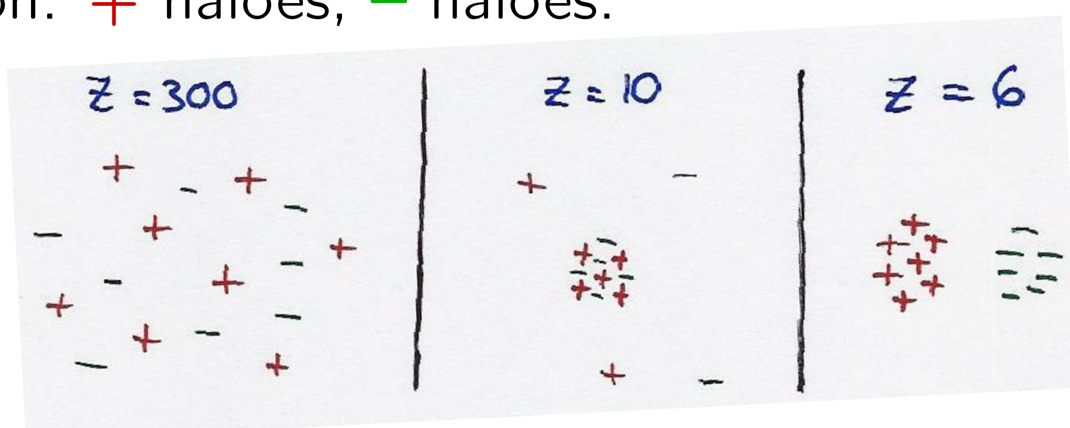


BUT $\delta_{\text{isocurvature}} \ll \delta_{\text{adiabatic}}$ naturally at $z_{\text{eq}} \approx 3000$, e.g. from inflation.

Departing from the linear regime

If $\delta_{\text{isocurvature}} \lesssim \frac{1}{55}\delta_{\text{adiabatic}}$, at $z_{eq} = 3000$, then $\delta_{\text{isocurvature}} \lesssim \delta_{\text{adiabatic}}$ today.

- Haloes exit the linear regime as nearly adiabatic perturbations at perhaps $z_{nl} = 10$.
- Today they're perhaps $300\,\text{kpc}$ across.
- A typical DM particle moves with $v = 200\,\text{km/s}$.
- So a test particle traverses halo in $10^9\,\text{yr}$.
- Galaxies have had at least 10 such "dynamical times" to relax.
- Part of relaxation is probably charge separation: $+$ haloes, $-$ haloes.



In the interests of allowing further tweaking of CDM at scales $\lesssim 1\,\text{Mpc}$ where its correctness is less clear, consider screening of scalar forces.

Screening of scalar forces

Setting $m_\phi = 1\,\mathrm{Mpc}^{-1}$ is one option. Or, consider

$$L = \frac{1}{2}(\partial\phi)^2 + \Psi_s i \nabla\!\!\!/\, \Psi_s - y_s \phi \bar{\Psi}_s \Psi_s \,. \qquad (9)$$

$m_s = |y_s \phi|$. If their energy is $\epsilon_s = m_s/\sqrt{1-v^2}$, then

$$\begin{aligned} \Box\phi &= -y_s \bar{\Psi}_s \Psi_s = -y_s n_s \sqrt{1-v^2}\,\mathrm{sgn}\,\phi \\ &= -\frac{y_s^2 n_s}{\epsilon_s}\phi \equiv -\frac{1}{r_s^2}\phi \,. \end{aligned} \qquad (10)$$

The main trick: $\langle \bar{\Psi}_s \Psi_s \rangle = n_s$ in rest frame. Note

$$r_s = \sqrt{\frac{\epsilon_s}{y_s^2 n_s}} \propto a(t)\,. \qquad (11)$$

Thus we screen at *fixed wavenumber*, not fixed physical length.

Add massive species with $m_\pm = m \pm y_\pm \phi$. Galactic haloes are mostly m_+'s or mostly m_-'s.

$$(Hr_s)^2 = \frac{8\pi G}{3}\rho_m \frac{\epsilon_s}{y_s^2 n_s} = \frac{4}{3\beta_{++}}\left(\frac{y_+ n_+}{y_s n_s}\right)^2 \frac{\rho_s}{\rho_m} \qquad (12)$$

$$\rho_s < \rho_\gamma \quad \rightarrow \quad \boxed{r_s \lesssim 1\,\mathrm{Mpc}}$$

But Ψ_s loops will generate $V(\phi)$!

A supersymmetric version

Consider supersymmetric generalizations, e.g. $SU(2)$ gauge thy with an adjoint chiral $X^a{}_b$ and several $\mathbf{2}$ and $\bar{\mathbf{2}}$'s, q_i^a and $\tilde{q}_{ia}$, and

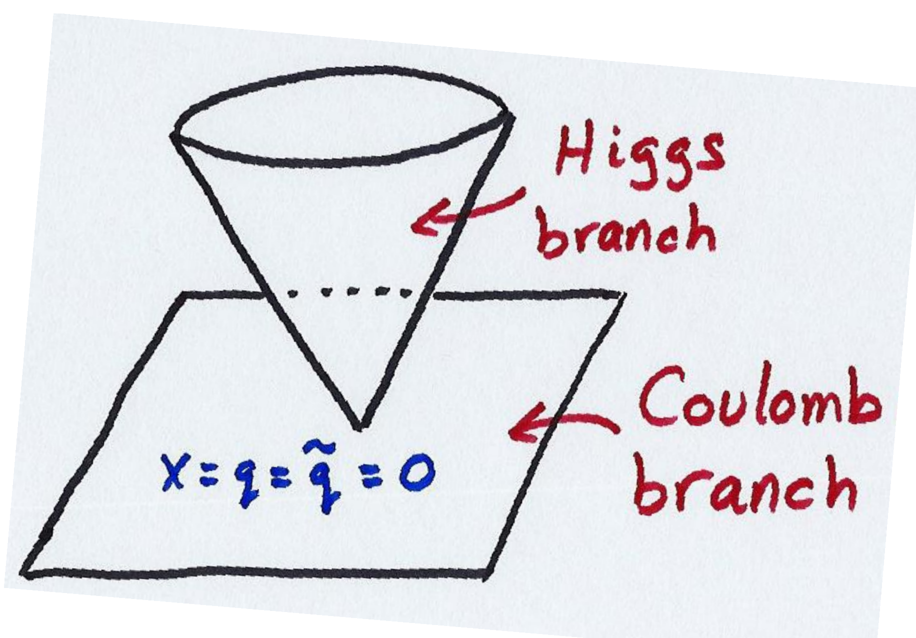
$$W = y_s \tilde{q}_{ia} X^a{}_b q_i^b \,. \tag{13}$$

The analog of ϕ is the moduli space of SUSY vacua. F-flatness

$$y_s X^a{}_b q_i^b = 0\,, \quad y_s \tilde{q}_{ia} X^a{}_b = 0\,, \quad y_s \tilde{q}_{ia} q_i^b = 0\,, \tag{14}$$

has solns with $X = 0$ and $\tilde{q}_{ia} q_i^b = 0$ (Higgs branch, $SU(2) \to$ nothing) and where $q = \tilde{q} = 0$ but $X \neq 0$ (Coulomb branch, $SU(2) \to U(1)$).

D-flatness leaves some flat dir's: on Coulomb branch, $V_D \propto \mathrm{tr}[X, X^\dagger]^2$, leaves $1_{\mathbf{C}}$-dim'l moduli space. At $X = 0$, extra massless degrees of freedom play role of Ψ_s particles.



SUSY protects flat directions... That was the point.

After SUSY breaking, standard wisdom is that $m_\phi \gtrsim m_{3/2}$ for all scalars: comes from gravitational mediation. If $\Lambda_{\mathrm{SUSY}} \sim 10\,\mathrm{TeV}$, then

$$m_{3/2} \sim \frac{\Lambda^2_{\mathrm{SUSY}}}{M_{Pl}} \approx 0.1\,\mathrm{eV} \ggg 1\,\mathrm{Mpc}^{-1}\,.$$

- Standard arguments occasionally fail in ways we don't understand: e.g. cosm. const.
- If SUSY breaking is the only theoretical obstacle, let's press on.

Problems can arise even before SUSY breaking: recall that SUGRA sends

$$\begin{gathered} y_u q H_u u \to e^{K/2} y_u q H_u u \\ m_u \to e^{K/2} m_u\,. \end{gathered} \tag{15}$$

This is clearly a problem if ϕ rolls: generic dimension 5 couplings, $\frac{\phi}{M_{Pl}} y_u q H_u u$, violate Equivalence Principle measurably.

So suppose we start at dimension 6, $\propto (\phi/M_{Pl})^2$.

Proton mass depends on $K(\Phi, \Phi^\dagger)$: fifth force?

Gauge couplings *don't* depend on K, so *if* $K = \Phi^\dagger\Phi/M_{Pl}^2 + \ldots$, then

$$m_p = \bar{m}_p + \epsilon_p \frac{\phi^2}{M_{Pl}^2} \qquad \epsilon_p \sim m_{u,d} \sim 10\,\mathrm{MeV}\,. \quad (16)$$

- Suppose $X = \frac{\Phi}{M_{Pl}}\frac{\sigma_3}{2}$.
- Then $K(\Phi) = \Phi^\dagger\Phi/M_{Pl}^2 + \ldots$
- Gauge invariance forbids a linear term in Φ.

So $dm_p/d\phi = 0$ at $\phi = 0$, just where the screening particles appear!

- In a galactic halo, $\phi \neq 0$, so $dm_p/d\phi = 2\epsilon_p\phi/M_{Pl}^2$.
- Current bounds translate to $\langle\phi\rangle \lesssim 10^{-4} M_{Pl}$.
- Estimate $\phi \sim 10^{-6} M_{Pl}$ in a galaxy.

Conclusion / Perspective

The idea of stabilizing extra dim's with wrapped strings / branes has been around since 1988:

$$\Box\phi = \frac{dV_{\text{eff}}}{d\phi}, \quad V_{\text{eff}} = n_+ m_+(\phi) + n_- m_-(\phi) \tag{17}$$

stabilizes $\phi(t)$ to the minimum of V_{eff}. For this mechanism to be operative today, need bare m_ϕ *very* small.

- Several groups have extended this picture to "brane gas cosmology," usually focusing on the early universe.

- Recent work suggests that quantum effects may draw universe to a point where fields become massless: Ψ_s particles pair-created at $m_s = 0$.

- $\delta\phi(t, \vec{x})$ is at least as interesting: scalar forces on late-time inhomogeities *may* fit observations better than ΛCDM.

- There is room for the requisite light scalars in string / M-theory compactifications, provided we ignore SUSY breaking in dark sector.

References

This talk primarily based on

S.S. Gubser and P.J.E. Peebles, "Structure formation in a string-inspired modification of the cold dark matter model", hep-th/0402225, and "Cosmology with a dynamically screened scalar interaction in the dark sector," hep-th/0407097.

Builds on earlier work, especially

G. Farrar and P.J.E. Peebles, "Interacting dark matter and dark energy," astro-ph/0307316.

also of interest:

T. Damour and A.M. Polyakov, "The string dilaton and a least coupling principle," hep-th/9401069.

Moduli stabilization with wrapped strings first discussed in

J. Kripfganz, H. Perlt, "Cosmological impact of winding strings," Class. Quant. Grav. 5 (1988).

R.H. Brandenberger and C. Vafa, "Superstrings in the early universe," Nucl. Phys. B316 (1989) 391.

Brane gas literature includes

S. Watson and R. Brandenberger, "Stabilization of extra dimensions at tree level," hep-th/0307044.

R. Easther, B.R. Greene, M.G. Jackson, and D. Kabat, "Brane gas cosmology in M-theory: Late time behavior," hep-th/0211124.

Briefly mentioned quantum production:

L. Kofman, A. Linde, X. Liu, A. Maloney, L. McAllister, E. Silverstein, "Beauty is attractive: moduli trapping at enhanced symmetry points," hep-th/0403001.