Towards a dark sector model from string theory

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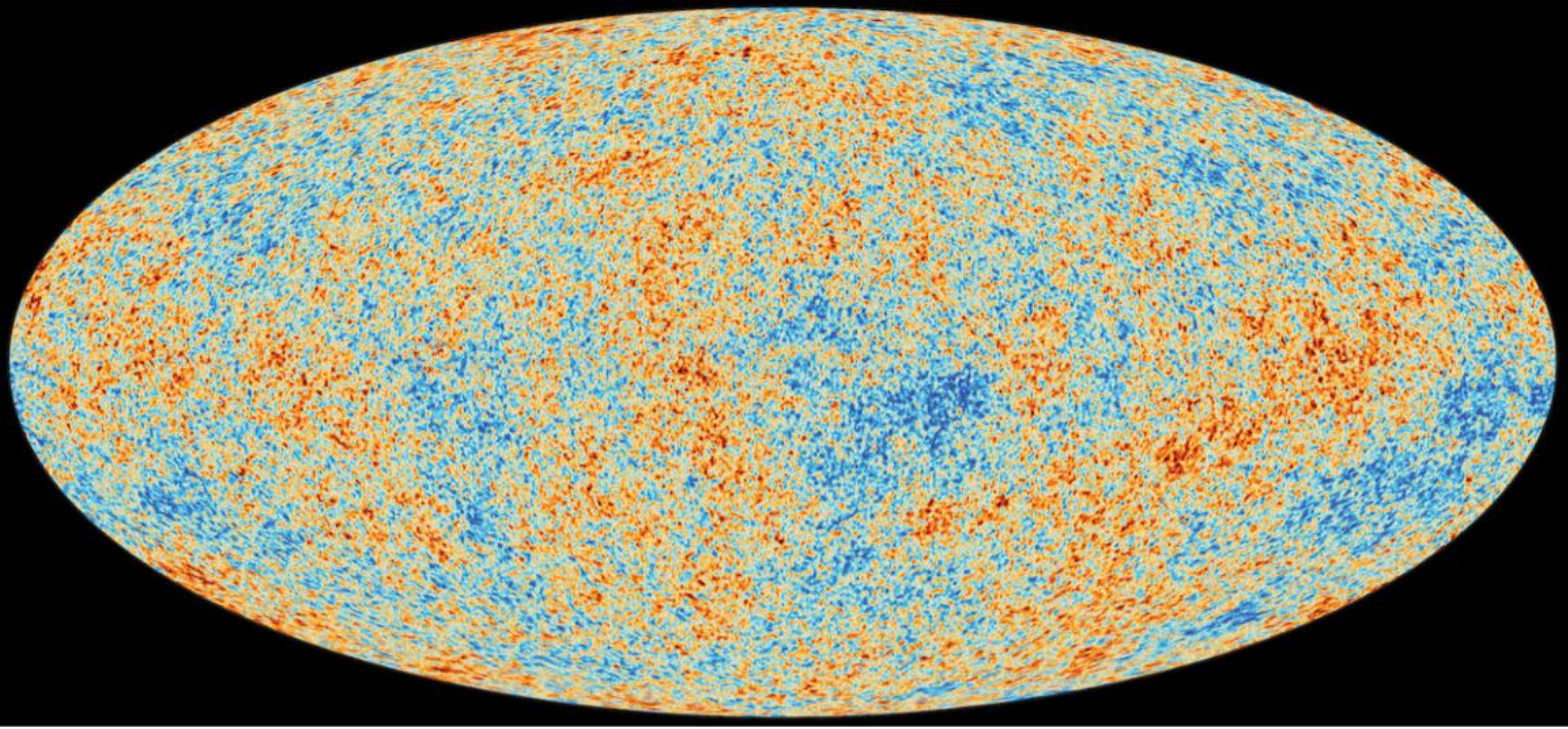
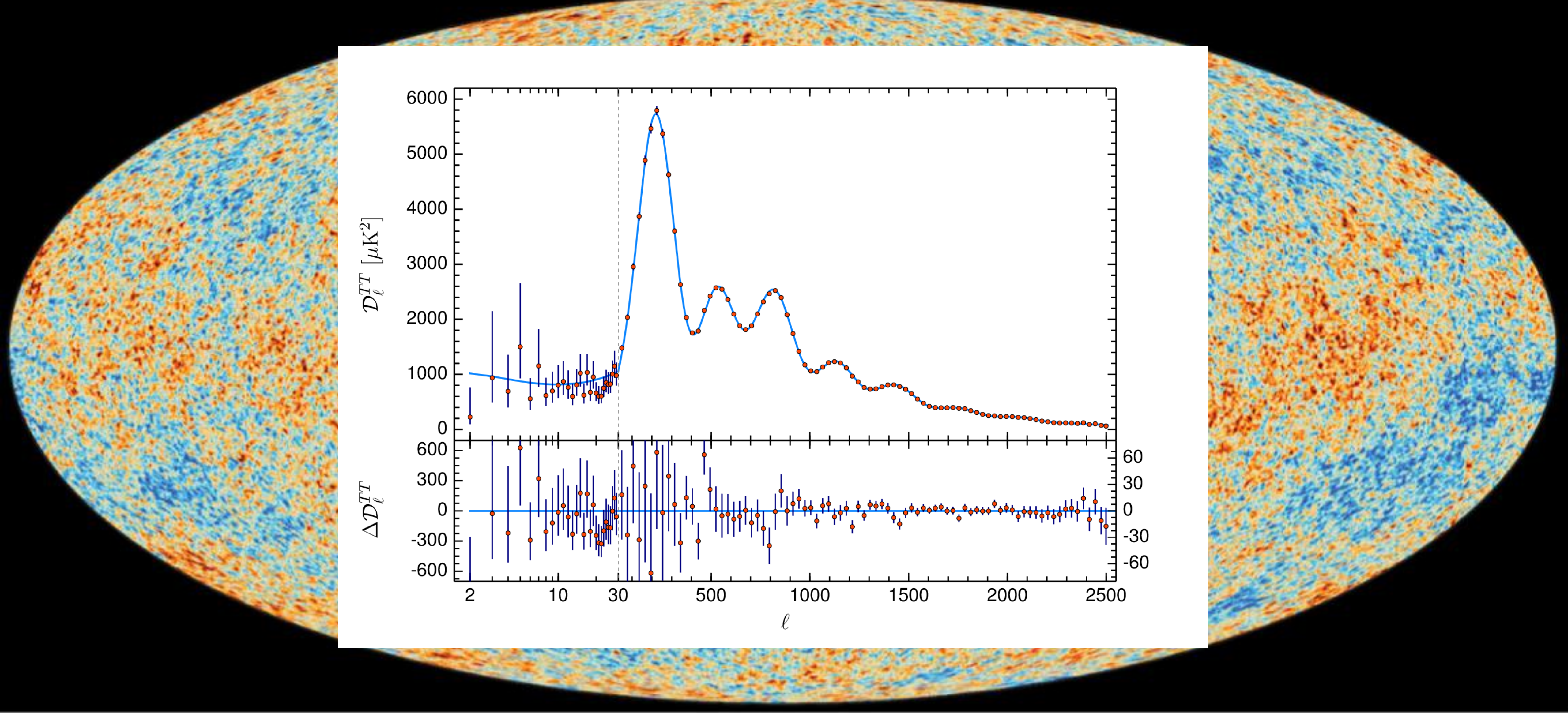
Plan

- Motivation
- The BF model
- Basics of heterotic strings
- Susy breaking and one-loop potential
- Conclusions



CMB: Blackbody spectrum ($T \approx 2.7\ K$) with temperature fluctuations ($\delta T / T \sim 10^{-5}$)



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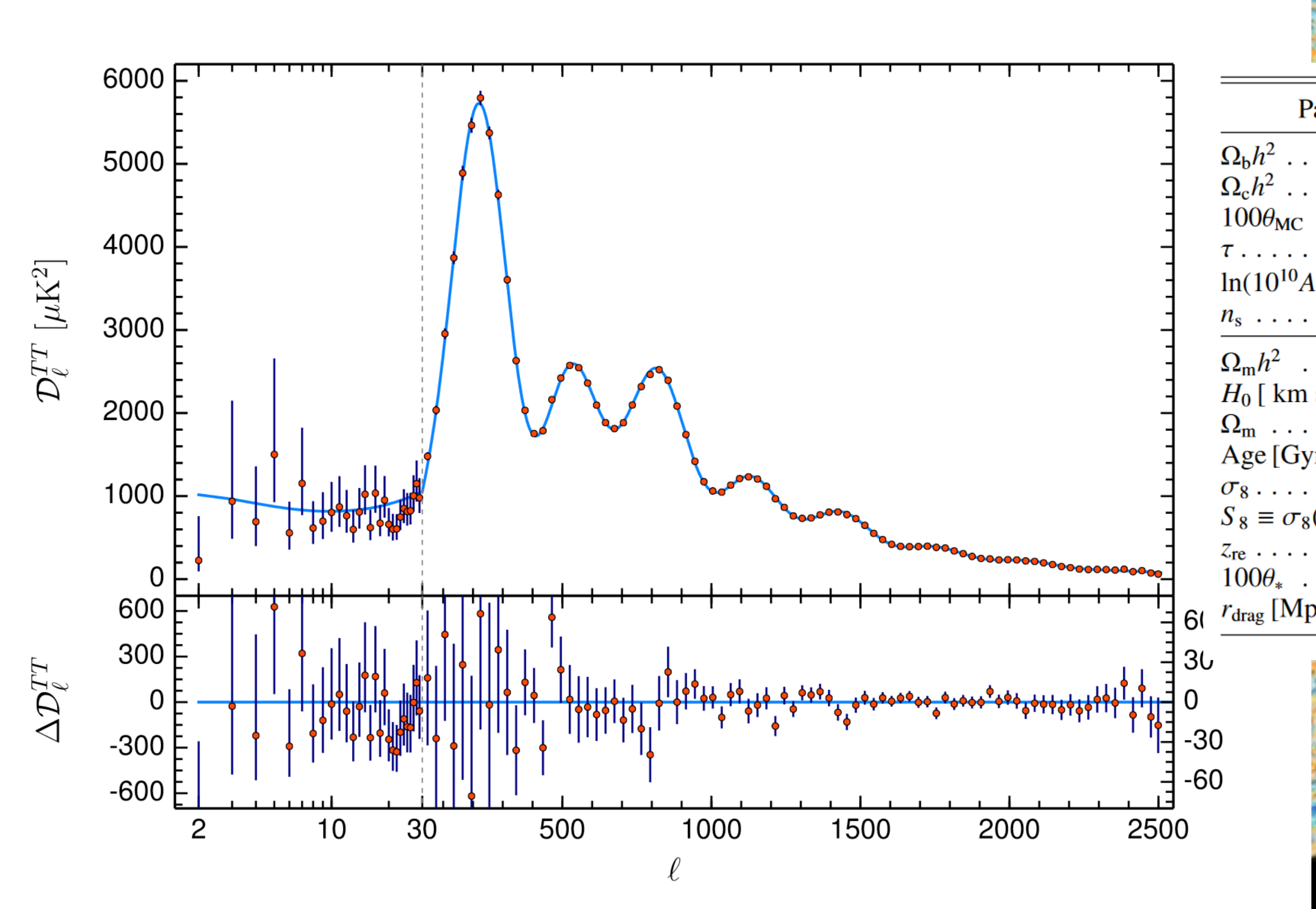

Parameter	
$\Omega_b h^2$	0.02233 ± 0.00015
$\Omega_c h^2$	0.1198 ± 0.0012
$100\theta_{MC}$	1.04089 ± 0.00031
τ	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.043 ± 0.014
n_s	0.9652 ± 0.0042
$\Omega_m h^2$	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}] . . .	67.37 ± 0.54
Ω_m	0.3147 ± 0.0074
Age [Gyr]	13.801 ± 0.024
σ_8	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.830 ± 0.013
z_{re}	7.64 ± 0.74
$100\theta_*$	1.04108 ± 0.00031
r_{drag} [Mpc]	147.18 ± 0.29

CMB: Blackbody spectrum ($T \approx 2.7\ K$) with temperature fluctuations ($\delta T/T \sim 10^{-5}$)

- Observations supports the ΛCDM model (modulo some tensions)

- Our “simple” universe: the model is based on a flat FLRW metric,

$$ds^2 = -dt^2 + a^2(t)[dr^2 + r^2 d\Omega_2^2]$$

- Inflation is often evoked to solve certain puzzles.

- We still don’t know the physics of dark energy and dark matter -> we need theoretical developments.
- What is usually done: construct EFTs that give the correct phenomenology and hope for an embedding into a fundamental theory.
- UV theories motivate us to look for alternatives to the cosmological constant.

T. Brennan, F. Carta and C. Vafa, 2017;
P. Agrawal, G. Obied, P. Steinhardt and C. Vafa, 2018;
E. Palti, 2019;
L. Heisenberg, M. Bartelmann, R. Brandenberger and A. Refregier, 2018; R. Brandenberger, 2021.

dS conjecture

- Controlled examples of flux compactification support the following constraint on effective potentials:

$$|V'| \geq c_1 M_{pl}^{-1} V \qquad \text{or} \qquad V'' \leq -c_2 M_{pl}^{-2} V$$

- This is can also be derived assuming the “distance conjecture” and the covariant entropy bound.

G. Obied, H. Ooguri, L. Spodyneiko and C. Vafa, 2018;
H. Ooguri, E. Palti, G. Shiu and C. Vafa, 2018;

Quintessence + axion dark matter

- In 2004.10025, Brandenberger&Froehlich considered the following dark-sector model:

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa^2} R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}(\partial\theta)^2 - \left(\Lambda + \frac{1}{2}\mu^4 \left(\frac{\theta}{f}\right)^2 \right) e^{-2\phi/f} \right]$$

- We can tune the parameters to reproduce cosmological evolution: for $\mu = 10^4 eV, m_\theta \approx 10^{-21} eV$

- In the BF model, the DE domination era is modelled by the slow-roll solution of the quintessence potential, while the DM phase is described by oscillations of the axion field.

- We get a phenomenological model describing the cosmological evolution.

- What is the origin of those fields? How can we justify the potential used theoretically?

We need to derive cosmological models from a fundamental theory to answer such questions

Some theoretical challenges:

1. Find a potential with the correct parametric form for both fields (quintessence+axion)

2. How to obtain the DE scale from some fundamental scale?

3. How to get a potential which is flat enough to admit accelerated solutions?

Basics of heterotic strings

- At low-energies, the action describing the massless bosonic fields of the theory is

$$S = \frac{1}{2\kappa_{10}^2} \int d^{10}x \sqrt{-G^{(E)}} \left[R^{(E)} - \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{e^{-\phi}}{2} |\tilde{H}_3|^2_{(E)} - \frac{e^{-\phi/2}\kappa_{10}^2}{30 g^2} \mathrm{tr} |F_2|^2_{(E)} \right]$$

- This is a 10d action, we need to dimensionally reduce.

Bas… rings

- At low-ener… sless bosonic fields of the theor…

$$S = \frac{1}{2\kappa_{10}^2} \int d^{10} \ldots - \frac{e^{-\phi/2}\kappa_{10}^2}{30g^2} \mathrm{tr}|F_2|^2_{(E)} \Big]$$

- This is a 10d… educe.

Compactification ansatz:

$$ds_{10}^2 = G_{ab}^{(E)} dx^a dx^b = e^{-6\sigma(x)} g_{\mu\nu}(x) dx^\mu dx^\nu + e^{2\sigma(x)} h_{mn}(y) dy^m dy^n$$

At energies much smaller than the compactification scale, we find

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa^2} R - \frac{1}{4\kappa^2} (\partial\Phi)^2 - \frac{3}{4\kappa^2} (\partial\Psi)^2 - \frac{1}{4\kappa^2} e^{2\Phi} (\partial a)^2 + \cdots \right]$$

where

$$\Phi = \frac{\phi}{2} - 6\sigma, \quad \Psi = \frac{\phi}{2} + 2\sigma, \quad (*_E da)_{\mu\nu\rho} = e^{-2\Phi} (H_3)_{\mu\nu\rho}$$

- For more general compactifications, the 4D theory can be quite more involved.

- In the heterotic case, its complexity is fixed by the internal space: CY compactification, special-Hermitean, non-Kaehler manifolds.

- From a phenomenological perspective, since we also want to describe particle physics, we shall assume a N=1 supergravity + chiral and vector multiplets.

Candelas, Horowitz, Strominger and Witten, 1985;
Strominger, 1986;
Becker, Dasgupta and Green, 2003

- Focusing on the chiral multiplet sector, the action is fixed by two functions: $K(A^I, \bar{A}^I)$, $W(A^I)$

$$\int d^4x\sqrt{-g}\left[\frac{1}{2}R - K_{I\bar{J}}\partial_\mu A^I \partial^\mu \bar{A}^{\bar{J}} - e^K\left(K^{I\bar{J}}D_I W \overline{D_J W} - 3|W|^2\right)\right]$$

$$K_{I\bar{J}} = \frac{\partial^2 K}{\partial A^I \partial A^{\bar{J}}}, \quad D_I W = \frac{\partial W}{\partial A^I} + \frac{\partial K}{\partial A^I} W$$

- For the compactification ansatz shown before,

$$K = -\ln(S + \bar{S}) - 3\ln(T + \bar{T})$$
$$S = e^{-\Phi} + ia, \quad \mathrm{Re}\, T = e^{\Psi}$$

- In string literature, there is a trend to find stabilization mechanisms for all moduli fields.

- We will consider the full time-evolution of the “universal” moduli fields instead.

- The goal is to let the theory tell us which class of cosmological solutions one might get (and then compare with the data).

M. Grana, 2006;
R. Blumenhagen, B. Kors, D. Lust and S. Stieberger, 2007
D. Baumann and L. McAllister, 2014

- Typical string effects generate a potential for the dilaton, axion and the size field:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{e^{2\sqrt{2}\phi/m_{pl}}}{4}m_{pl}^2\partial_\mu a\partial^\mu a - V(\phi,\sigma,a)\right]$$

where

$$V(\phi,\sigma,a) = \frac{e^{-\sqrt{6}(\sigma/m_{pl})}}{8}e^{-\sqrt{2}(\phi/m_{pl})}\kappa^2\left[A^2 e^{-2a_0 e^{-\sqrt{2}(\phi/m_{pl})}}\left(a_0 + \frac{1}{2}e^{\sqrt{2}(\phi/m_{pl})}\right)^2 + \right.$$
$$\left. + \frac{W_0^2}{4}e^{2\sqrt{2}(\phi/m_{pl})} - AW_0\left(a_0 + \frac{1}{2}e^{\sqrt{2}(\phi/m_{pl})}\right)e^{\sqrt{2}(\phi/m_{pl})}e^{-a_0 e^{-\sqrt{2}(\phi/m_{pl})}}\cos(a_0 a)\right]$$

S. Gukov, S. Kachru, X. Liu and L. McAllister, 2004

$$V(\phi,\sigma,a) = \frac{e^{-\sqrt{6}(\sigma/m_{pl})}}{8} e^{-\sqrt{2}(\phi/m_{pl})} \kappa^2 \Big[A^2 e^{-2a_0 e^{-\sqrt{2}(\phi/m_{pl})}} \left(a_0 + \frac{1}{2} e^{\sqrt{2}(\phi/m_{pl})}\right)^2 + \\ + \frac{W_0^2}{4} e^{2\sqrt{2}(\phi/m_{pl})} - AW_0 \left(a_0 + \frac{1}{2} e^{\sqrt{2}(\phi/m_{pl})}\right) e^{\sqrt{2}(\phi/m_{pl})} e^{-a_0 e^{-\sqrt{2}(\phi/m_{pl})}} \cos(a_0 a) \Big]$$

Origin of this potential: don't forget the fermions!

$$W = W_0 - Ae^{-a_0 S}$$

where $\mathrm{A} \sim C_H m_s^3,\ a_0 = 8\pi^2/C_H$

Comments on the potential:

- It has a minimum at $\phi = \phi_0$ and $a = 0$ such that $V|_{min} = 0$

$$V(\phi = \phi_0, \sigma, a) \approx e^{-\sqrt{6}\sigma/m_{pl}} \bar{A}(1 - \cos(a_0 a))$$

- The size moduli σ is left unstabilized and without potential

How to obtain the quintessence field?

The axio-dilaton minimum breaks susy -> corrections to the potential are needed.

Have they been fully explored?

M. Cicoli, S. de Alwis and A. Westphal, 2013

- Supersymmetric vacua are such that $\langle D_I W \rangle = 0$. For the previous potential, $\langle D_S W \rangle = 0$ but $\langle D_T W \rangle \neq 0$: susy breaking minimum.

- Quantum corrections are given in terms of the mass matrix:

$$V_{1l} = \frac{1}{16\pi^2} \sum_j (-1)^{2j} n_j \left(\Lambda_c^4 - \frac{m_j^2 \Lambda_c^2}{2} - \frac{m_j^4}{4} \ln \left(\frac{m_j^2}{2e^{\gamma_{\mathrm{E}}} \Lambda_c^2} \right) \right)$$
$$= \frac{1}{16\pi^2} \left(\Lambda_c^4 \mathrm{Str}\, \mathbf{1} - \frac{\Lambda_c^2}{2} \mathrm{Str} M^2 - \frac{1}{4} \mathrm{Str} M^4 \ln \left(\frac{M^2}{\bar{\Lambda}^2} \right) \right)$$

Affleck, Dine and Seinberg, 1983;
Dine, Rohm, Seinberg and Witten, 1985.

- To leading order, we need the supertrace of the mass matrix squared.

- Due to the Kaehler geometry of the moduli space, we have

$$\mathrm{Str} M^2 = 2((n-1) - R_{k\bar{l}} G^k G^{\bar{l}}) e^G$$

$$G = K + \ln W + \ln \bar{W}$$

- The leading correction to the potential is of the quintessential form:

$$V_{1l} = \frac{1}{64\pi^2}\frac{A^2}{m_{pl}^2}\left(\frac{m_s}{m_{pl}}\right)^{8/3} a_0^2 e^{-2a_0 e^{-\phi_0/m_{pl}}} e^{-4\sqrt{2/3}\sigma/m_{pl}} := V_0 e^{-c\sigma/m_{pl}}$$

- Recall that $\mathrm{A} \sim C_H m_s^3,\ a_0 = 8\pi^2/C_H$. Moreover, the value of ϕ_0 depends on W_0.

Theoretical challenges:

1. Find a potential with the correct parametric form for both fields (quintessence+axion) ✓

2. How to obtain the DE scale from some fundamental scale?

3. How to get a potential which is flat enough to admit accelerated solutions?

$$V_{1l} = \frac{1}{64\pi^2}\frac{A^2}{m_{pl}^2}\left(\frac{m_s}{m_{pl}}\right)^{8/3} a_0^2 e^{-2a_0 e^{-\phi_0/m_{pl}}} e^{-4\sqrt{2/3}\sigma/m_{pl}} := V_0 e^{-c\sigma/m_{pl}}$$

- If $\frac{\sigma}{m_{pl}} \lesssim 1$, we need $a_0 S_0 = a_0 e^{-\phi_0} \sim 10^2$ to reproduce the Dark Energy scale.

- If $C_H = 5$, we get $a_0 \sim 10$ and $S_0 \sim 10$ -> this gives a realistic value for $g_{YM}^2 = 1/S_0$ close to the GUT scale!

Theoretical challenges:

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- Now that the parameters are fixed to reproduce DE, the mass of the axion $\theta = \frac{e^{\Phi}}{\sqrt{2}} m_{pl}\, a$

$$m_\theta^2 \simeq (8\pi^2)^4 C_H^{-2} S_0^3 \left(\frac{m_s}{m_{pl}}\right)^6 m_{pl}^2 e^{-2a_0 S_0} e^{-3\sqrt{2/3}\psi}$$

is predicted to be $m_\theta \sim 10^{-23} eV$.

$$V_{1l} = \frac{1}{64\pi^2}\frac{A^2}{m_{pl}^2}\left(\frac{m_s}{m_{pl}}\right)^{8/3} a_0^2 e^{-2a_0 e^{-\phi_0/m_{pl}}} e^{-4\sqrt{2/3}\sigma/m_{pl}} := V_0 e^{-c\sigma/m_{pl}}$$

- Unfortunately, isotropic compactifications gives $w > -\frac{1}{3}$
- If only one direction in the internal space is dynamical, we get $c = 1$ and $w = -\frac{2}{3}$, which corresponds to acceleration but not close to a cosmological constant.

Theoretical challenges:

1. Find a potential with the correct parametric form for both fields (quintessence+axion) ✓
2. How to obtain the DE scale from some fundamental scale? ✓
3. How to get a potential which is flat enough to admit accelerated solutions?

Conclusions/Outlook

- I have described a possible model for the Dark Sector constructed in heterotic strings from fluxes, gaugino condensation and loop effects.
- The dark-sector fields are the size moduli of the internal space and the universal axion
- The parameter choice that “fits” the DE scale fixes the axion to be ultralight
- Unfortunately, the only accelerated solutions are far from $w \approx -1$.

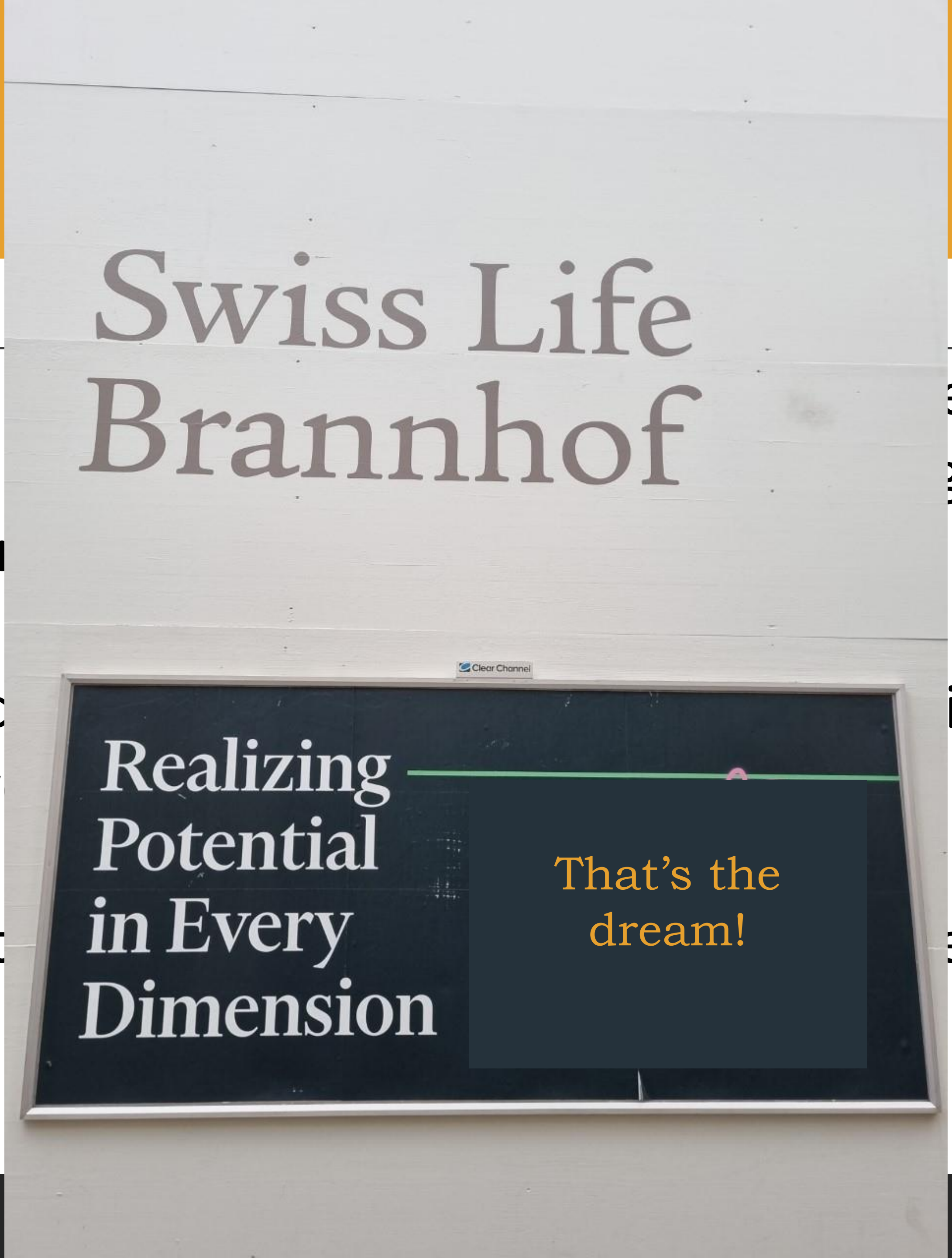
Conclusions/Outlook

- Controlled susy breaking mechanism?
- There are attempts to construct quintessence models from type IIB strings
- The parameter choice that "fits" the DE scale fixes the axion to be ultralight
- Unfortunately, the only accelerated solutions are far from $w \approx -1$.

- I have descri ... ector constructed ... gino condensatio ...

- The dark-sec ... internal space and the univ ...

- The paramet ... es the axion to be ultralight ...



Thank you for your attention!

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