STRING COSMOLOGY

Strings 2025

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Resources

https://indico.dfa.unipd.it/event/1051/

Recent Reviews

String cosmology:
From from the early universe to today

Cicoli, Conlon, AM, Parameswaran, Quevedo, Zavala

Superstring cosmology —
a complementary review

Brandenberger

Plan

- Focus on a few topics (seven/eight) and in each case discuss a *recent* paper or two.

(Not a status summary)

- Papers part of bigger projects.

Future Observations

High Frequency Gravitational Waves

- Universal nature of gravity implies many sources for stochastic gravitational waves.

  Cosmic strings, Phase transitions, Oscillons …..

  Most of these are model dependent.

- There is one guaranteed by the Hot Big Bang model and is UV sensitive.

High Frequency Gravitational Waves

- At $T < M_{\rm pl}$, gravitons are not in equilibrium with the cosmic plasma.

- Gravitons are constantly emitted due to fluctuations of the plasma stress tensor.

- For an observer today, these emissions sum up to give the

Cosmic Gravitational Wave Background (CGWB)

High Frequency Gravitational Waves

- The theoretical prediction for the background from the SM and BSM models has been computed

Ghiglieri, Laine; 15
Ghiglieri, Jackson, Laine, Zhu; 20
Ringwald, Schutte-Engel, C. Tamarit; 21

$$\frac{d}{d\log a(t)}\left(\frac{d\rho_{\mathrm{GW}}^{(0)}}{d\log f}\right) \sim \frac{T(t)}{M_{\mathrm{pl}}}\rho(t)a^4(t)F\left(\frac{f^{\mathrm{em}}}{T(t)}\right)$$

Contribution to GW wave energy density today per log frequency band during one e-folding of a(t)

F : Property of the gauge theory; peaks at

$$f^{\mathrm{em}}/T \approx 1$$

CGWB : The Peak

$$\frac{d}{d\log a(t)}\left(\frac{d\rho_{\rm GW}^{(0)}}{d\log f}\right) \sim \frac{T(t)}{M_{\rm pl}}\rho(t)a^4(t)F\left(\frac{f^{\rm em}}{T(t)}\right)$$

→ F : Property of the gauge theory; peaks at $f^{\rm em}/T \approx 1$

- For most gravitons:

  Emission Frequency ~ Temperature of plasma at time of emission

- After emission, a graviton's frequency redshifts as $1/a(t)$ .The plasma's temperature also does the same.

Peak freq.of CGWB (today) $\approx$ Peak freq. of CMB (today) $\approx$ **GHz band**

CGWB : The Amplitude

$$\frac{d}{d\log a(t)}\left(\frac{d\rho_{\rm GW}^{(0)}}{d\log f}\right)\sim\frac{T(t)}{M_{\rm pl}}\rho(t)a^4(t)F\left(\frac{f^{\rm em}}{T(t)}\right)$$

- The amplitude is proportional to

$$\mathcal{A}\sim\frac{T_{\rm max}}{M_{\rm pl}}$$

as there are more and more e-folding of the scale factor further back.

- UV sensitive: interesting for high energy physics & quantum gravity

CGWB : The Prospects

- Today's experiments operate far from the GHz band (Ligo: in the 10 Hz to 10 KHz)

Living Reviews in Relativity (2021) 24:4
https://doi.org/10.1007/s41114-021-00032-5

REVIEW ARTICLE

Check for updates

Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

- At the same time, there are many developments in the high frequency range (in both theory and experiments)

CGWB : The Prospects

- To the extent that the first experiments have already received support

HIGHLIGHT

GravNet: A Global Network for the Search for High-Frequency Gravitational Waves Receives ERC Synergy Grant 2024

November 5, 2024

- GravNet is the first dedicated effort to detect high-frequency gravitational waves. Their detection would open a new observational window into previously unseen astrophysical processes.
- Quantum Technologies and Gravitational Wave detection meet in this project, which proposes innovative table-top detectors for high-frequency gravitational waves.

- The proposed sensitivities are orders of magnitude below what is needed to observe the CGWB; we should be optimistic as this is just the start.

Moduli Stabilisation

IIB Flux Compactications & Hierarchies

Chauhan, Cicoli, Krippendorf, AM, Piantadosi Schachner 25

Builds upon
Dubey, Krippendorf, Schachner; 23
Pauschinn, Schlechter 23

- Integer data such as flux quanta and ranks of gauge groups characterise string compactifications

- What hierarchies can be generated from the integers?

  Hierarchy from exponentials well known.

  Report on the possibility from *polynomials.*

IIB Flux Compactications

- Three form flux F, H threading three cycles of CY,

$$G_3 = i * G_3 \qquad G = F - \tau H$$

satisfying the Imaginary Self Dual (ISD) condition.

- ISD condition fixes the complex structure moduli & the dilaton, no potential of Kahler moduli.

Gukov, Vafa, Witten 99
Dasgupta, Rajesh, Sethi 99
Giddings, Kachru, Polchinski 01

IIB Flux Compactications

- 4d EFT description: Gukov-Vafa-Witten superpotential

$$W_{GVW} = \int_X G \wedge \Omega(z_i)$$

$\Omega(z_i)$: holomorphic three form of CY

- Tadpole cancellation:

$$N_{\rm D3} + N_{\rm flux} = Q_{\rm D3}$$

$$N_{\rm flux} = \frac{1}{2}\int_X H_3 \wedge F_3$$

(Flux contribution to D3 charge non -ve)

IIB Flux Compactications: Challenges

- Tadpole condition

$$N_{\text{flux}} = \int_X H_3 \wedge F_3 \quad \leq 2Q_{D3}$$

does not cut out a compact subspace of the flux vector space

- CY periods known as expansions in patches, modding out by discrete symmetries.

IIB Flux Compactications

- Work locally in a region of the the moduli space (even within patches for period expansions)

Validity of EFT

Pheno. considerations

- Variables motivated by special geometry of underlying CY.

IIB Flux Compactications

- ISD condition becomes a matrix relationship between flux vectors:

$$f = (f_1, f_2) \qquad h = (h_1, h_2) \qquad \qquad \dim\ f_i, h_i = h^{2,1}$$

(in a symplectic basis).

- ISD matrix is closely related to the gauge kinetic matrix

$$\mathcal{N}_{IJ} = \overline{F}_{IJ} + 2\mathrm{i}\,\frac{\mathrm{Im}(F_{IL})X^L\,\mathrm{Im}(F_{JK})X^K}{X^M\mathrm{Im}(F_{MN})X^N}\,, \quad F_{IJ} = \partial_{X^I}\,\partial_{X^J}F\,.$$

Bounding the Flux Vectors

- Bounds on flux vectors in terms of local (in moduli space) properties of the gauge kinetic matrix and related matrices

$$\frac{\sqrt{3}}{2}\mu_{\rm min}||h_2||^2 \leq N_{\rm flux}\,, \qquad \mu_{\rm min}\left[||f_2||^2 + \left(c_0^2 + \frac{3}{4}\right)||h_2||^2\right] - 2\mu_{\rm max}\,|c_0|\,||f_2||\,||h_2|| \leq sN_{\rm flux}\,,$$

$$\frac{\sqrt{3}}{2}\tilde{\mu}_{\rm min}||h_1||^2 \leq N_{\rm flux}\,. \qquad \tilde{\mu}_{\rm min}\left[||f_1||^2 + \left(c_0^2 + \frac{3}{4}\right)||h_1||^2\right] - 2\tilde{\mu}_{\rm max}\,|c_0|\,||f_1||\,||h_1|| \leq sN_{\rm flux}\,.$$

- $\mu_{\rm max/min}$ and $\tilde{\mu}_{\rm max/min}$ are max/min eigenvalues of matrices related to the gauge kinetic matrix.

Hierarchy from Polynomials

- Example:

$$\text{Symmetric locus of CY in } \mathbb{P}(1,1,1,6,9)$$

Two moduli, in the large complex structure limit.

- The prepotential is a **polynomial**

negligible

$$F(z) = -\frac{1}{6}\tilde{\kappa}_{ijk} z^i z^j z^k + \frac{1}{2} a_{ij} z^i z^j + b_i z^i + \tilde{\xi} + F_{\text{inst}}(z)$$

implying the same for the superpotential.

Hierarchy from Polynomials

- For the following choice of the flux vectors:

$$f = (4, 12, 2, -1, 0, -1), \quad h = (36, -1, 0, 0, 1, -1)$$

- The expectation of the GVW super potential is

$$W_0 \equiv \sqrt{\frac{2}{\pi}} \langle e^{\frac{K}{2}} \int G \wedge \Omega \rangle \sim 5.5 \times 10^{-5} \ll 1$$

A lowered scale of SUSY breaking

Explicit Solutions: IIB Flux Compactications

- Present approach provides explicit flux quantum numbers for solutions of interest: avenue for top-down studies.

- Explicit access to features such as: mass hierarchies, voids in moduli space …

- Complementary to the statistical approach to study these vacua; broad agreement with some interesting differences.

Ashok, Douglas 03
Denef, Douglas 04

Acceleration

Acceleration

- Observations have established that today's universe is accelerating:

$$\frac{\ddot{a}}{a} > 0$$

- Accelerating solutions in string theory have been a challenge. Due to certain No-gos:

Gibbons 85
De Witt, Hari Dass, Smit 89
Maldacena, Nunez 01

Compactifications of classical (2-derivative) 10d supergravities/ M-theory have no accelerating FRW solutions.

No Gos: Loopholes

$$ds^2 = W(y) g_{\mu\nu}^{\rm FRW} dx^\mu dx^\nu + g_{mn}(y) dy^m dy^n$$

Many loopholes:

- Singularities in $g_{mn}(y)$ or $W(y)$ that have a string interpretation.
- Time dependence in the internal metric: $g_{mn}(y,t)$ (not for dS). Townsend 03, Russo Townsend 21
- Quantum/Classical corrections to the 2 derivative action.
- Localized sources in the 10d/11d action.

No general understanding of when a particular loop hole can evade the no go and if any part of no survives in general (such as dS swampland conjectures)

dS Swampland

Obied, Ooguri, Spodynieko, Vafa 03 .....

de Sitter

Salam Sezgin Solution

Salam Sezgin 84

6d (1,0) Sugra

$$\mathcal{L}_6 = -\sqrt{-g}\left[\frac{1}{2\kappa^2}\, g^{MN}\left(R_{MN} + \partial_M\varphi\,\partial_N\varphi\right) + \frac{1}{4}e^{-\varphi}F_{MN}F^{MN} + \frac{1}{12}e^{-2\varphi}H_{MNP}H^{MNP} + \frac{2\mathfrak{g}^2}{\kappa^4}\, e^{\varphi}\right]$$

- The potential is a runaway: $V(\varphi) = +\dfrac{2\mathfrak{g}^2}{\kappa^2}e^{\varphi}$

  No maximally symmetric solutions in 6d.

φ : tensor multiplet scalar
(hypers integrated out)

- Salam-Sezgin solution: Minkowski solution to 4d

$$M^{3,1} \times S^2$$

A sphere compactification with flux.

Salam Sezgin Solution

- Later, AdS_4 and dS_4 solutions were found; when allowing for localized sources.

- de Sitter came out naturally given the +ve potential

$$V(\varphi) = +\frac{2\mathfrak{g}^2}{\kappa^2} e^{\varphi}$$

Salam-Sezgin in String Compactifications

- Motivated by this

Burgess Quevedo Muia 24

String compactifications to 6d (1,0)

↓

Further compactify to 4d to get de Sitter

- The string compactifications considered

Bonetti Grimm 11
Grimm Pugh 13

M- theory on elliptically fibred CY_3 leading to N=2 theories in 5d

↓

Uplifted to 6d (1,0)

Salam-Sezgin in String Compactifications

- This give large number of 6D theories, simplest one has been studied in detail.

- A two field (φ, χ) analogue of the Salam-Sezgin setting.

$$V(\varphi, \chi) = \frac{2g^2}{\kappa^4} e^{\varphi - 2\chi}$$

χ : hypermultiplet multiplet scalar

Salam-Sezgin in String Compactifications

- This 6D effective theory has dS solutions

$$V(\varphi, \chi) = \frac{2g^2}{\kappa^4} e^{\varphi - 2\chi}$$

- The associated metrics are warped and have cylindrical symmetry in the 2-compact directions

$$ds^2 = W^2(\eta) g_{\mu\nu}^{\mathrm{dS}_4} dx^\mu dx^\nu + \underbrace{a^2(\eta) d\theta^2 + a^2(\eta) W(\eta)^8 d\eta^2}_{\text{Cylindrical symmetry}}$$

Cylindrical symmetry

Salam-Sezgin in String Compactifications

- As expected from the no go, there are singularities.
  They show up in the warp factor: $W(\eta)$.

- Properties localised objects associated with the singularities
  (from asymptotic behaviour of fields)

  - +ve tension
  - No D3 or D7 charge

Interpretation in string theory is underway ….

KKLT de Sitter Vacua

Mcallisiter, Moritz, Nally, Schachner 24
Kachru, Kallosh, Linde, Trivedi 03

- Systematic search for KKLT vacua in CYs from the Kreuzer-Skarke list with less than or equal to 8 complex structure moduli

- General methods in computational mirror symmetry have been developed. Wide applicability.

  Demitras Kim McAllister Moritz Rios-Tuscan 19

- Expectation value of the GVW superpotential small, but not very small

  Demitras Kim McAllister Moritz 19

$$W_0 \sim 10^{-2}$$

- Some 2-cycle volumes are small, α' corrections (N=2) have been incorporated (estimates for others indicate they are small)

Candidate deSitter Vacua

Summary Table (so far)

ID	$h^{2,1}$	$h^{1,1}$	M	K'	g_s	W_0	$g_s M$	$\lvert z_{\text{cf}}\rvert$	V_0
1	8	150	16	$\frac{26}{5}$	0.0657	0.0115	1.051	2.822×10^{-8}	$+1.937\times10^{-19}$
2	8	150	16	$\frac{93}{19}$	0.0571	0.00490	0.913	7.934×10^{-9}	$+1.692\times10^{-20}$
3	8	150	18	$\frac{40}{11}$	0.0442	0.0222	0.796	8.730×10^{-8}	$+4.983\times10^{-19}$
4	5	93	20	$\frac{17}{5}$	0.0404	0.0539	0.808	1.965×10^{-6}	$+2.341\times10^{-15}$
5	5	93	16	$\frac{29}{10}$	0.0466	0.0304	0.746	8.703×10^{-7}	$+2.113\times10^{-15}$

- Biggest shortcoming:

$$g_s M \quad \text{sets size of the} \quad S^3 \quad \text{at the bottom of the KS throat is} \quad \mathcal{O}(1)$$

- How does this change as they increase the number of complex structure moduli?

Negatively curved internal geometry

De Luca 25

De Luca, Silverstein, Torroba 22

…………….

- A key physics motivation for CY compactifications is SUSY, there is no evidence for far …

- Negatively curves manifold, SUSY broken at the KK scale

- Rigidity properties imply module stabilisation requires considering just one modulus

De Luca's talk

Acceleration as motivated by the Swampland Program & its implications

Summaries:
Vafa 24
Anchordoqui, Antoniadis, Lust 24

Swampland Program

Vafa 05

Lessons from String Theory

↓

Consistency conditions for any Low Energy EFT compatible with Quantum Gravity

Swampland Distance Conjecture

- As one approaches the boundary of moduli space, there is an exponentially light tower of states

Ooguri Vafa 07

$$m \sim m_0 e^{-\alpha\varphi}$$

$$\varphi \to \text{boundary}$$

$$\alpha \sim \mathcal{O}(1)$$

- Generalised to the emergent string conjecture

Lee Lerche Weigand 19

Tower → KK Tower or String Tower

Towers and the CC

Lust Palti Vafa 19
Montero Vafa Valenzuala 22

- Similar reasoning can be applied to parameters in the theory

AdS string vacua: $m \sim |\Lambda|^a$

- For our universe it has been argued:

(quasi) dS state: $m \sim |\Lambda|^{\frac{1}{d}} = |\Lambda|^{\frac{1}{4}}$

Usual EFT reasoning: $\Lambda \sim \Lambda_0 + m^4$

Burgess, Quevedo 23
Branchina, Branchina, Contino, Pernace 23 & 24
Anchordoqui, Antoniadis, Lust, Lust 24

No contribution to cc above the tower scale

Towers and the CC

- Plugging in the observed value of the CC

$$m \sim 10^{-2}\ \mathrm{eV}$$

- No evidence for strong gravity at such low scales, thus the tower must be a KK tower. At least one radius of size:

$$R \gtrsim \Lambda^{-1/4} \sim 88\ \mu m$$

Dark Dimension

Montero Vafa Valenzuala 22

- SM must be on a brane

Constraints from the cooling of Neutron Stars → One large extra dimension (dark dimension)

- More recently, $m_\nu \to 0$: alternate scenario with 2 large extra dimensions, fundamental scale close to the TeV.

Casas Ibanez Marchesano 24

KK Gravitons as DM

Gonzalo, Montero, Obied, Vafa 22
Law-Smith, Obied, Prabhu, Vafa 23
Obied, Dvorkin, Gonzalo, Vafa 23

- Dark matter is KK gravitons produced from the decay of SM plasma. Dark matter abundance:

$$y_{\rm dm} \sim T_{\rm max}^3 R \sim T_{\rm max}^3 \Lambda^{-1/4} \qquad (y_{\rm dm} = \rho_{\rm dm}/T^3)$$

- Furthermore:

$T_{\rm max}$ —related to→ Lifetime of modulus that decays to reheat the SM —related to (by TCC)→ Λ

→ $T_{\rm max} \sim \Lambda^{1/6}$ → $y_{\rm dm} = \Lambda^{1/4}$

TCC: Berdoya, Vafa 19

KK Gravitons as DM

- Dark matter is mass is dynamical due to decay between KK towers

$$m_{\text{initial}} \sim T_{\text{max}} \sim \Lambda^{1/6} \xrightarrow{\text{decays}} m_{\text{dm}}^{\text{now}} \sim \Lambda^{5/28}$$

- Overall, unification of scales in terms of the cc

$$R \sim \Lambda^{-1/4},\ M_{\text{pl}}^{\text{higher}} \sim \Lambda^{1/12},\ T_{\text{max}} \sim \Lambda^{1/6},$$

$$H_{\text{today}} \sim \Lambda^{1/12},\ m_{\text{dm}} \sim \Lambda^{5/28}$$

5D Primordial Blackholes as dark matter

Anchordoqui, Antoniadis, Lust 23 & 24

- Two important differences from the 4d case:

  5 dimensional blackholes live longer than 4d black of the same mass.

  Size of extra dimensions ~ Wavelength of visible light (microlensing)

- Leads to an enhanced range for all PBH interpretation of dark matter (for BH on the brane)

$$10^{15} \lesssim M_{\rm BH}/{\rm grams} \lesssim 10^{21}$$

Lower mass region extended by two orders of magnitude compared to 4d

Quintessence

Quintessence

- The dark energy equation of state will be probed minutely by various upcoming experiments in the next decade. (DESI, Euclid …)

- For dynamical dark energy, slowly rolling scalars are natural candidates

$$w_{\rm DE} = w_\varphi = \frac{\frac{1}{2}\dot{\varphi}^2 - V(\varphi)}{\frac{1}{2}\dot{\varphi}^2 + V(\varphi)}$$

- Runaway potentials:

A class of explicit examples from string theory.

Confront the models with precision cosmological data.

Quintessence: Challenges

- Many challenges in addition to the magnitude of the vacuum energy:

  - UV stability of light mass (& susy breaking)
  - Time varying fundamental constants
  - Fifth forces

First, one has to find the runway solutions …..

- Candidate runaways in the asymptotic of field space just too steep:

$$\frac{|\nabla V|}{V} \geq \sqrt{2}$$

Obied, Ooguri, Spodyneiko, Vafa 18;
Garg Krishnan18;
Ooguri, Palti, Shiu, Vafa 18;
Bedroya, Vafa 20; Rudelius ’21

Quintessence: Runaway Solutions

- Explicit runaway solutions in type IIA / massive IIA

Marconnet, Tsimpis 23

Chen, Ho, Neupane, Ohta & Wang 03

Andersson, Heinzle 06

- Consistent truncations to 2-field systems with exponential potential

$$V = \begin{cases} 72 b_0^2 e^{-\phi-12A} + \frac{3}{2} c_0^2 e^{\phi/2-14A} & \text{CY with internal three- and four-form fluxes} \\ \frac{1}{2} c_\varphi^2 e^{-\phi/2-18A} + \frac{1}{2} m^2 e^{5\phi/2-6A} - 6\lambda e^{-8A} & \text{E with external four-form flux} \\ \frac{3}{2} c_0^2 e^{\phi/2-14A} + \frac{1}{2} m^2 e^{5\phi/2-6A} - 6\lambda e^{-8A} & \text{EK with internal four-form flux} \\ \frac{1}{2} c_\varphi^2 e^{-\phi/2-18A} + \frac{3}{2} c_f^2 e^{3\phi/2-10A} - 6\lambda e^{-8A} & \text{EK with internal two-form, external four-form.} \end{cases}$$

FRW metrics with negative spatial curvature (k = -1)

Quintessence: Runaway Solutions

Features:

- FRW metrics with negative spatial curvature (k = -1)
- Time dependence in the internal metric and fluxes
- Einstein case: the internal manifold is negatively curved
- 4d picture, asymptotically a single exponential, $e^{-\lambda\varphi} : \lambda > \sqrt{2}$

Further analysis:

Androit, Tsimpis, Wrase 23

- String loop and curvature corrections
- No cosmological horizons (in general for $\lambda > \sqrt{2}$)

Hellerman, Kaloper & Susskind 01
Fischler, Kashani-Poor, McNees & Paban 01

Runaways: A full Cosmology

Androit, Parameswaran, Tsimpis, Wrase, Zavala 24

Dynamical system analysis of k=-1 universes

An exponential potential: $e^{-\lambda\varphi}$
(instead of cc)

$+$

Cosmological fluids
for matter and radiation

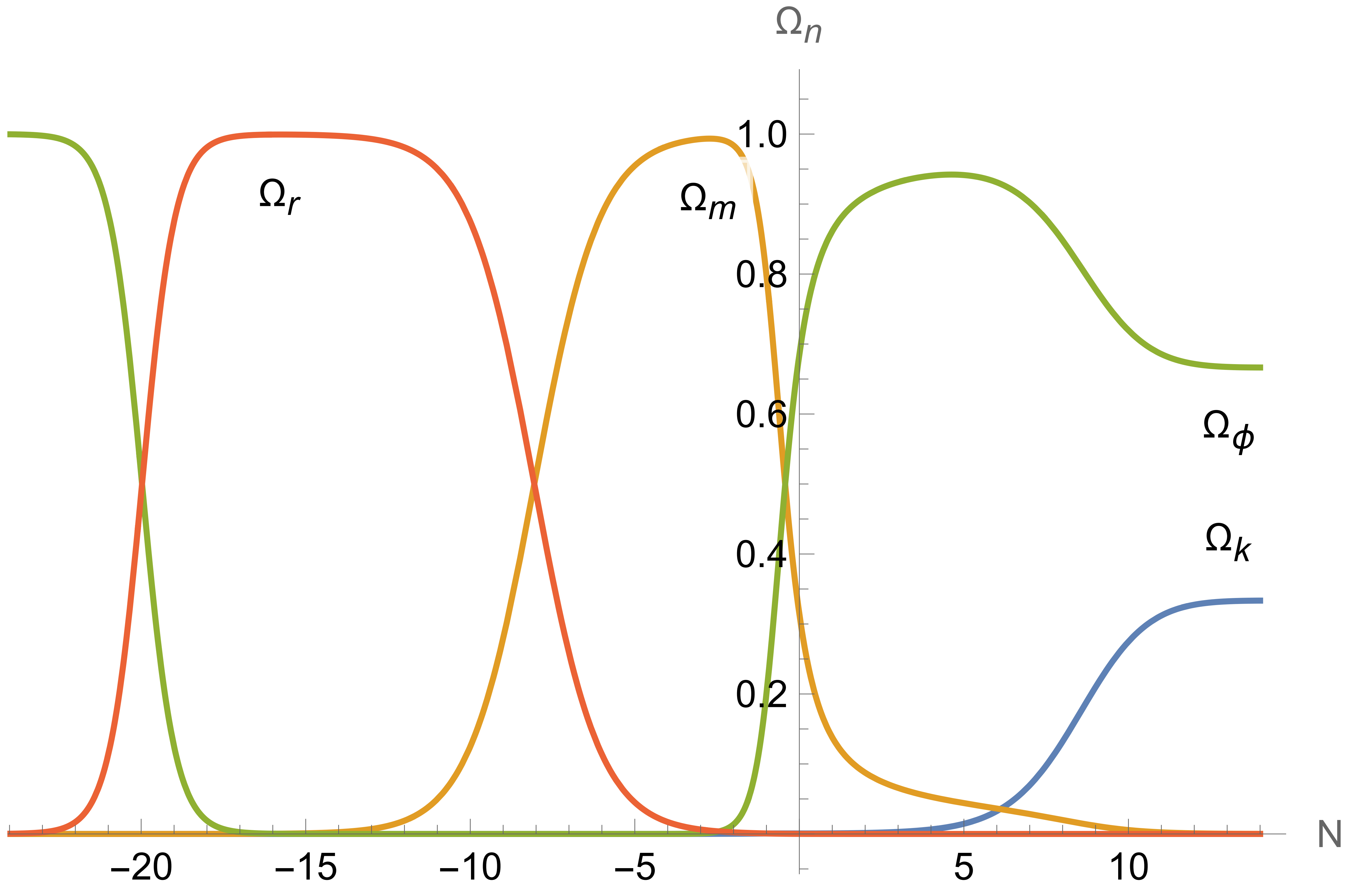
Summary of Results:

- A `` future" fixed point solution with $\ddot{a} = 0$.
- All solutions approach this fixed point, and accelerate while doing so.
- Having an epoch of radiation domination requires $\lambda < \sqrt{3}$

Following: Copeland, Liddle, Wands 93 & 98; Wetterich 98

A Background Cosmology

Sample background cosmology:



Fractional energy densities as a function of e-foldings

Precision Cosmology

Bhattacharya , Borghetto , Malhotra, Parameswaran, Tasinato, Zavala 24
Alestas, Delgado, Ruiz, Akrami, Montero, Nesseris 24

- Confront the model with precision cosmological data:

Parameter	CMB+DESI	+Pantheon+	+Union3+	+DESY5
$\boldsymbol{\lambda}$	< 0.537	$0.48^{+0.28}_{-0.21}$	$0.68^{+0.31}_{-0.20}$	$0.77^{+0.18}_{-0.15}$
$\boldsymbol{\Omega_k}$	0.0026 ± 0.0015	0.0025 ± 0.0015	$0.0028^{+0.0016}_{-0.0019}$	0.0027 ± 0.0016

- Unfortunately analysis puts:

Exponent in the exponential (λ) at less than one.

well away from the range our theory model put it ($\lambda > \sqrt{2}$)

- Clearly exhibits the kind of for interesting interplay that can take place between theory constraints and precision cosmology

Similar to earlier results for k=0 Agrawal, Obied, Steinhardt & Vafa 18; Akrami, Kallosh, Linde & Vardanyan 18; Raveri, Hu & Sethi 18;

Alternate Histories
&
Cosmic Strings

Alternate Histories

- The history of the Universe before big bang nucleosynthesis is almost unconstrained.

- String theory provides various well motivated possibilities for this era

    Moduli domination

    Kination

    Cosmological stasis

- Each of these has a rich phenomenology and could well have left its imprint on today's universe.

Kination & Cosmic Strings

Colon Copeland Hardy Gonzalez 24

Epoch where the energy density of the universe is dominated by the kinetic energy of a scalar field:

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{\partial V}{\partial \phi} \to 0 \qquad \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3}\left(\frac{1}{2}(\dot{\phi})^2 + V(\phi)\right), \quad V(\phi) \to 0$$

Leading to :

$$\phi = \phi_0 + \sqrt{\frac{2}{3}}\ln\left(\frac{t}{t_0}\right) \qquad \rho(t) \propto \frac{1}{a^6} \qquad \frac{\dot{a}}{a} = \frac{1}{3t}$$

More on kination and strings: Apers, Conlon, Copeland, Monsy, Revello 24

Kination is Generic

- Dynamical system analysis of

Steep exponentials
(Typical for Moduli) + Matter & Radiation fluids

gives a kination epoch as the global past repeller (is generic).

- This give good motivation to study its implications in detail.

Kination and Couplings

- Kinating moduli can lead to rapid variation of couplings. Our focus:

Variation of the string tension: $\mu(t)$

$$m_s \sim \frac{M_{\rm pl}}{\sqrt{\mathcal{V}}}$$

(in the context of cosmic strings)

- Example: in the Large Volume Scenario in IIB, the canonically normalised volume modulus has a exponential potential.

The volume kinates $\longrightarrow$ $\frac{\dot{\mu}}{\mu} = -\frac{1}{t}$

A single cosmic string

- Consider the dynamics of single cosmic closed string

$$S_{\rm NG} = -\int d^2\xi\, \mu(t)\sqrt{-\gamma} \qquad\qquad \xi^0 = x^0, \quad (\gamma_{ab}) = \begin{pmatrix} 1 - a^2\dot{\vec{x}}^2 & 0 \\ 0 & -a^2\vec{x}'^2 \end{pmatrix}.$$

- The quantity

$$\varepsilon(t,\sigma) \equiv \sqrt{\frac{-x'^2}{\dot{x}^2}} = \sqrt{\frac{a^2\vec{x}'^2}{1 - a^2\dot{\vec{x}}^2}}.$$

(on the world sheet) naturally appears in the EOM.

- It is directly related to the physical size of strings.

Single string: constant tension

- It satisfies

$$\frac{\dot{\varepsilon}}{\varepsilon} = \frac{\dot{a}}{a}(1 - 2a^2\dot{\vec{x}}^2) - \frac{\dot{\mu}}{\mu}a^2\dot{\vec{x}}^2 = \frac{\dot{a}}{a} - a^2\dot{\vec{x}}^2\left(2\frac{\dot{a}}{a} + \frac{\dot{\mu}}{\mu}\right)$$

- With constant tension

$$\frac{\dot{\varepsilon}}{\varepsilon} \approx 0$$

it is time independent (for sub-horizon strings).

- Strings remain of fixed physical size (as in Minkowski) and shrink in comoving coordinates.

Single string: varying tension

- Now, to varying tension .....

$$\frac{\dot{\epsilon}}{\epsilon} = \frac{\dot{a}}{a} - a^2 \dot{\vec{x}}^2 \left(2\frac{\dot{a}}{a} + \frac{\dot{\mu}}{\mu} \right)$$

- Recall, we had

$$\frac{\dot{a}}{a} = \frac{1}{3t}, \qquad \frac{\dot{\mu}}{\mu} = -\frac{1}{t} \qquad \Longrightarrow \qquad \left(2\frac{\dot{a}}{a} + \frac{\dot{\mu}}{\mu} \right) = -\frac{1}{3t}$$

- Thus

$$\frac{\dot{\epsilon}}{\epsilon} > \frac{\dot{a}}{a}$$

→ strings grow in comoving coordinates

Cosmic string networks

$$\frac{\dot{\epsilon}}{\epsilon} > \frac{\dot{a}}{a}$$ → strings grow in comoving coordinates

Leads to a novel mechanism to get string networks.

- In a kinating universe, a small number of strings can: grow, find each other, percolate and form networks.

- Detailed study of various aspects of this mechanism (such evolution of networks in a kinating epoch) has started.

Revello and Villa 24

Inflation

Inflation

- Various features of the fluctuations in the CMB:
  - Correlation on superhorizon scales
  - Approximately scale invariant
  - Nearly Gaussian

All provide support to the inflationary paradigm

- Inflationary paradigm is tied to quantum gravity

Brane Inflation

Dvali, Tye 98; Alexander 01;
Burgess, Majumdar, Nolte, Quevedo, Rajesh, Zhang 01

- I will give an update on recent developments in brane inflation.

Inflationary model building ⟷ UV complete setting

Brane Inflation

Brane inflation :

Inflation driven by brane dynamics

Our focus:

Space-filling D3 and anti-D3 branes; point like in the compact dimensions.

$$V_{\inf}(r) = C_0 \left(1 - \frac{D_0}{r^4}\right)$$

r : Inter-brane separation (inflaton)

C_0, D_0 : constants (related to the D3 brane tension)

Slow roll model.

Brane dynamics can be far more general: DBI inflation: non slow roll, pheno: large non-gaussianities …

Alishahiha, Silverstein, Tong 04

Brane Inflation

To sustain inflation, slow roll conditions: $\epsilon = \frac{M_{\rm pl}^2}{2}\left(\frac{V_\varphi}{V}\right)^2 \ll 1; \quad \eta = M_{\rm pl}^2\left(\frac{V_{\varphi\varphi}}{V}\right) \ll 1$

$$\eta = M_p^2 \frac{V_{\varphi\varphi}}{V} \simeq -\frac{10}{\pi^3}\frac{\mathcal{V}}{(rM_s)^6},$$

← Compactification volume

In an isotropic compactification, the maximum brane separation is bounded

$$r_{\rm max}^6 \lesssim \mathcal{V}$$

→ No slow roll

Gravitational Redshifting

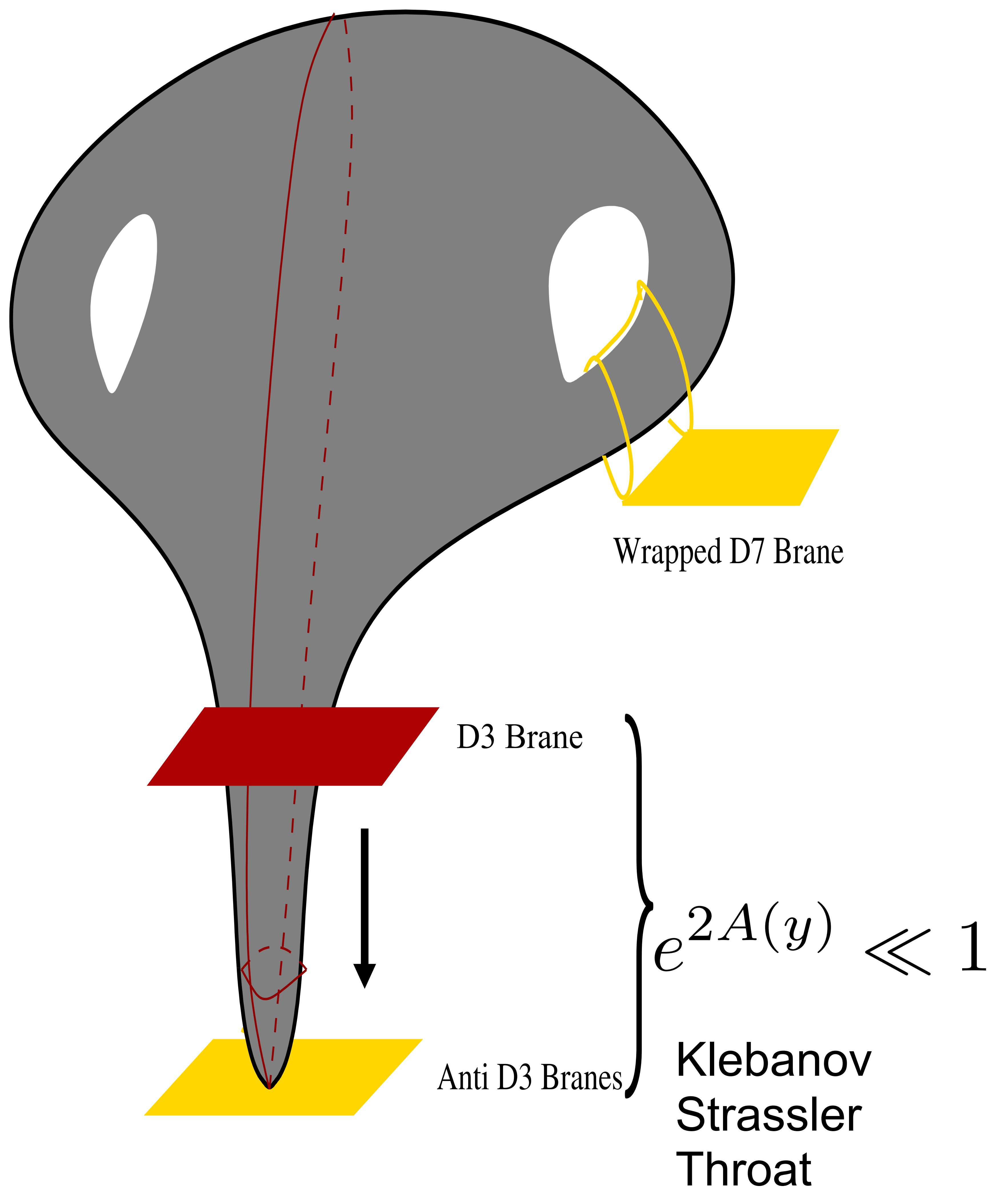
Kachru, Kallosh, Linde, Maldacena, Mc Allister, Trivedi 03

- Consider brane inflation in a highly warped region of the compactification

$$ds^2 = e^{2A(y)} g_{\mu\nu} dx^\mu dx^\nu + g_{mn}(y) dy^m dy^n$$

- Effective brane tensions are redshifted and one indeed finds

$$\eta \equiv M_{\rm pl}^2 \left(\frac{V_{\varphi\varphi}}{V} \right) \ll 1$$



UV sensitivity & other fields

- The potential has dependence on the volume

$$V_{\rm inf}(r) = \frac{\mathcal{C}_0}{\mathcal{V}^{4/3}}\left[1 - \frac{\mathcal{D}_0}{r^4}\right]$$

- A controlled single field inflationary trajectory requires directions other than the inflaton are heavy

$V_{\rm total}(r, \mathcal{V})$ → Integrate out heavy direction → Compute η for the light direction

UV sensitivity & other fields

- A generic contribution to $V_{\rm total}(r, \mathcal{V})$ arises from non-perturbative effects associated with the universal Kahler modulus.

- This is constrained by: holomorphy & structure of the two field moduli space.

- Signature: a uniiversal contribution to η:

$$\eta = \frac{2}{3} + \text{ contributions from } V_{\rm inf} + \text{non-universal contributions}$$

Universal → No slow-roll

UV sensitivity & other fields

- Tune

$$\eta = \frac{2}{3} + \text{ contributions from } V_{\text{inf}} + \text{non-universal contributions}$$

is to tune the non-universal contributions to cancel the $\mathbf{\frac{2}{3}}$

Baumann, Dymarsky, Klebanov, Maldacena, McAllister, Murugan 06
Baumann, Dymarsky, Klebanov, and McAllister 06

- Shape of the potential is altered, more like inflating at an inflection point.

Brane Inflation

Cicoli, Hughes, Kamal, Marino, Quevedo. Ramos-Humud, Villa 24

- Brane inflation, in warped throat — concrete realisation of the idea to use perturbative corrections to the Kahler potential to stabilise the volume

$$\mathcal{O}(g_s\alpha'^2), \quad \mathcal{O}(\alpha'^3) \text{ and log enhanced terms at } \mathcal{O}(g_s\alpha'^3)$$

(regime where non-perturbative effects not relevant)

- In this case, the high scale potential depends only on the volume and essentially independent of the inflation direction

$$V_{\text{total}}(r, \mathcal{V}) = V_{\text{inf}}(r) + V_{\text{high}}(\mathcal{V})$$

- Integrating out volume, inflation can be realised using the original concave form of the potential.

$$V_{\text{inf}}(r) = C_0\left(1 - \frac{D_0}{r^4}\right)$$

Inflation

String model	n_s	r
Fibre Inflation	0.967	0.007
Blow-up Inflation	0.961	10^{-10}
Poly-instanton Inflation	0.958	10^{-5}
Aligned Natural Inflation	0.960	0.098
N-Flation	0.960	0.13
Axion Monodromy	0.971	0.083
D7 Fluxbrane Inflation	0.981	5×10^{-6}
Wilson line Inflation	0.971	10^{-8}
D3-$\overline{\text{D3}}$ Inflation	0.968	10^{-7}
Inflection Point Inflation	0.923	10^{-6}
D3-D7 Inflation	0.981	10^{-6}
Racetrack Inflation	0.942	10^{-8}
Volume Inflation	0.965	10^{-9}
DBI Inflation	0.923	10^{-7}

Summary of Models

High Frequency
Gravitational Waves

High Frequency Gravitational Waves

- Recall that the amplitude of the background in case of SM/BSM

$$\mathcal{A} \propto \frac{T_{\rm max}}{M_{\rm pl}}$$

was proportional to the maximum temperature of the plasma in the hot big bang.

- The background can serve as a probe for much more

Two areas:

Gravitons produced from a gauge theory plasma at strong coupling

Gravitons produced from the decay of highly excited strings

Strongly Coupled Plasma

Castells-Tiestos, Casalderrey-Solana 22

- The early universe could have had a strongly coupled gauge sector

- The gravitational wave production using holographic methods for a toy universe with N=4 super Yang Mills as its constituent

- Comparison of weak and strong ’t Hooft coupling results; change by roughly a factor of five of the amplitude, with no major changes in the spectral shape

Gravitational Waves from High Temperature Strings

Frey Mahanta AM Villa Quevedo 24

- The Standard Model is realised by open strings degrees of freedom on D3 branes

- The early universe was at very high temperatures, massive open strings on the brane were in thermal equilibrium.

- As the universe cooled the massive strings primarily decayed to the Standard Model degrees of freedom producing the SM plasma.

- A fraction of the decays to gravitons: What background does this lead to today ?

- Villa's poster

GW Spectrum: Features

Plugging in fiducial values, spectral density

$$h^2\Omega_{GW}(\omega) = 6 \times 10^{-11} \left(\frac{M_s}{10^{15}\text{GeV}}\right) \left(\frac{\omega}{100\text{GHz}}\right)^{5/2} I\left(\frac{\omega}{100\text{GHz}}\right)$$

I(x) : exponentially damped for large arguments

The Peak:

- Frequency is close to the CMB peak.

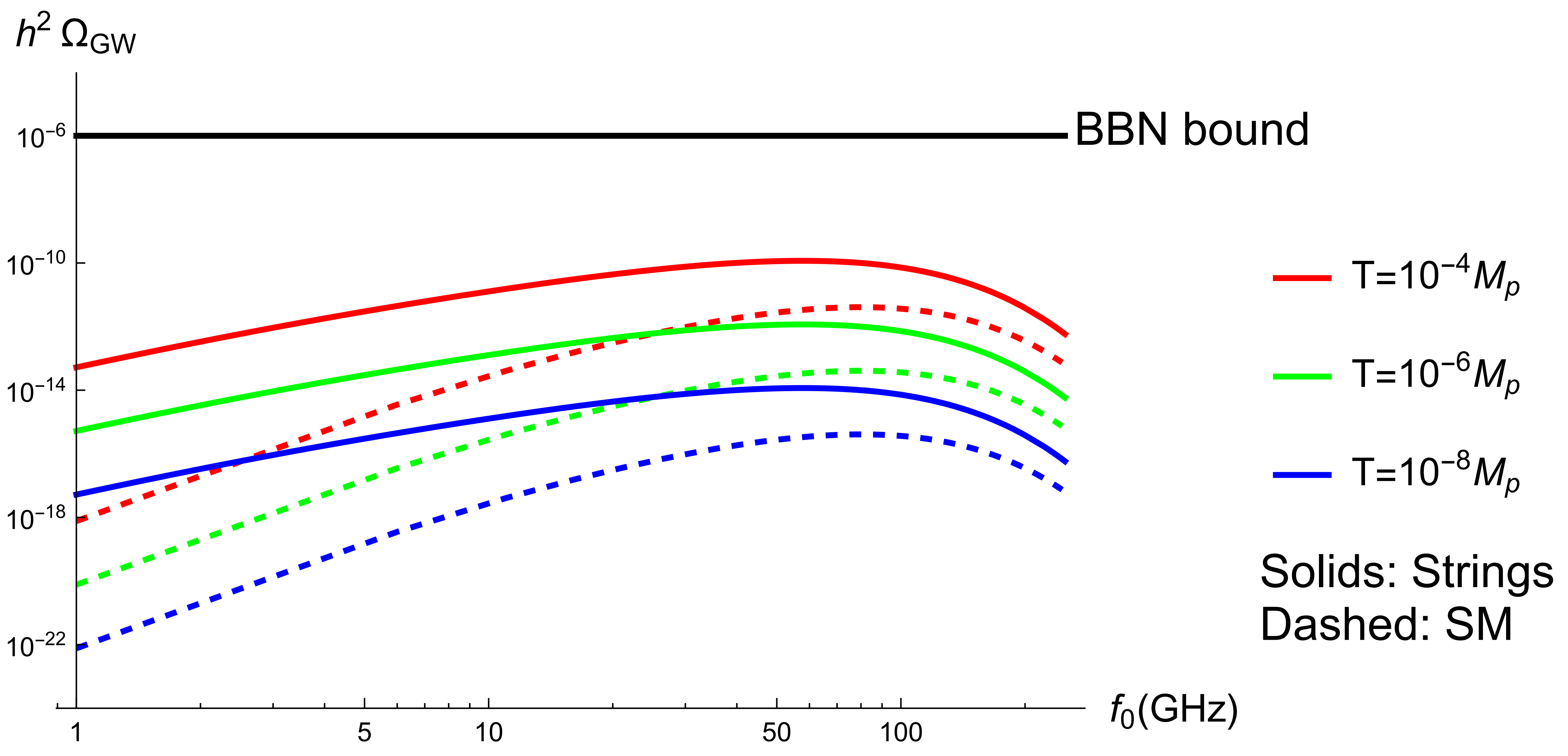
The Amplitude:

- Proportional to the string scale (UV sensitivity)

- Large: Is orders of magnitude than what the SM (or BSM) would give if it were at the same temperature

GW spectrum

Comparative plot:



Amplitude proportional to the string scale

Interesting differences in the shape

High frequency gravitational waves can directly probe the string scale

High Frequency Gravitational Waves ⟷ String Cosmology in the early Universe

Conclusions

- Moduli Stabilisation
- De Sitter Constructions
- Cosmology as motivated by the Swampland program
- Quintessence
- Alternative histories (cosmic strings)
- Inflation
- High Frequency Gravitational Waves

Conclusions

- We discussed of collection topics
- Focusing on a few papers.
- Rich connection between strings and cosmology

  Various cosmological epochs and string theory played a role.

  Each also raise various questions related to our understanding of string theory: both at the technical and conceptual level.

- We can expect a lot of observational inputs.

Thank You