Discussion on String Cosmology

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Cambridge
BIRS Workshop
Oaxaca, Mexico November 2021
(together with Shamit Kachru)

In memoriam

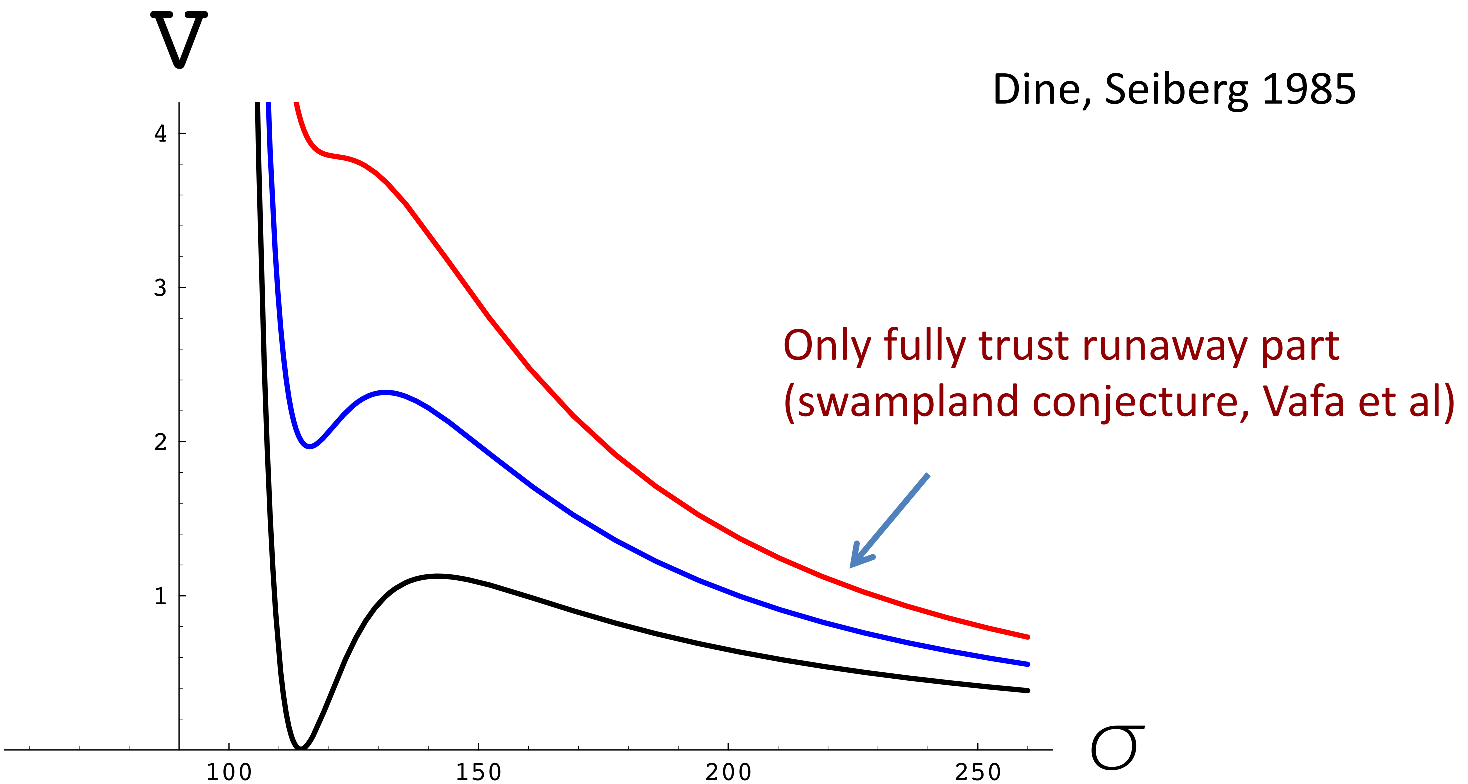
Graham Ross (1944-2021)

Strings and Cosmology

- Big Bang? (before inflation?)
- Inflation or alternatives
- After Inflation ((P)Reheating, dark matter, baryogenesis,…)
- Today (dark energy)
- Future?

Moduli Stabilisation e.g. KKLT, LVS

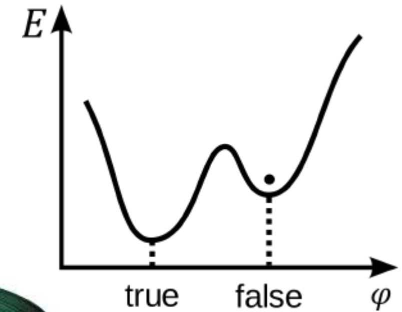
(Dine-Seiberg Problem)



$\mathbf{V} \longrightarrow \mathbf{0}$ at weak coupling and large volume.

Fluxes can be adjusted in KKLT and LVS to get weak coupling de Sitter minima

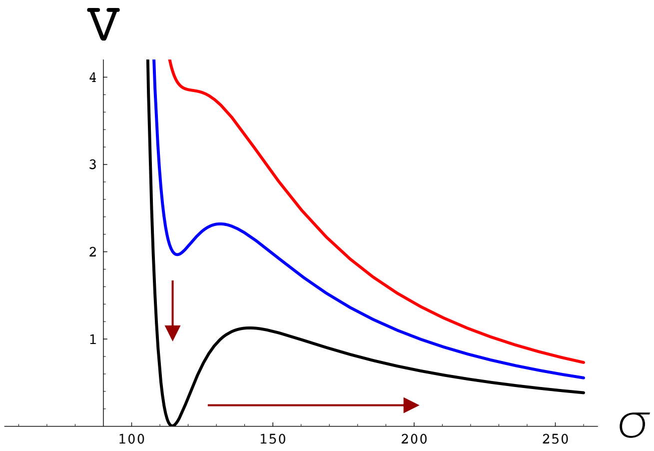
Vacuum Transitions
(beginning and end of our universe?)

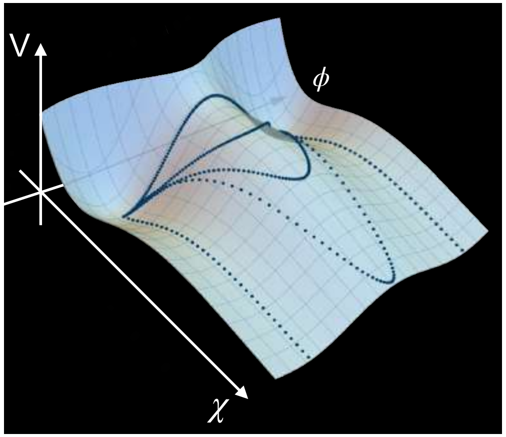


1. **Transition between two minima of scalar potential**
   Coleman-De Luccia 1980

2. **Brane nucleation: M_1 to M_1+Wall+M_2**
   Brown-Teitelboim 87

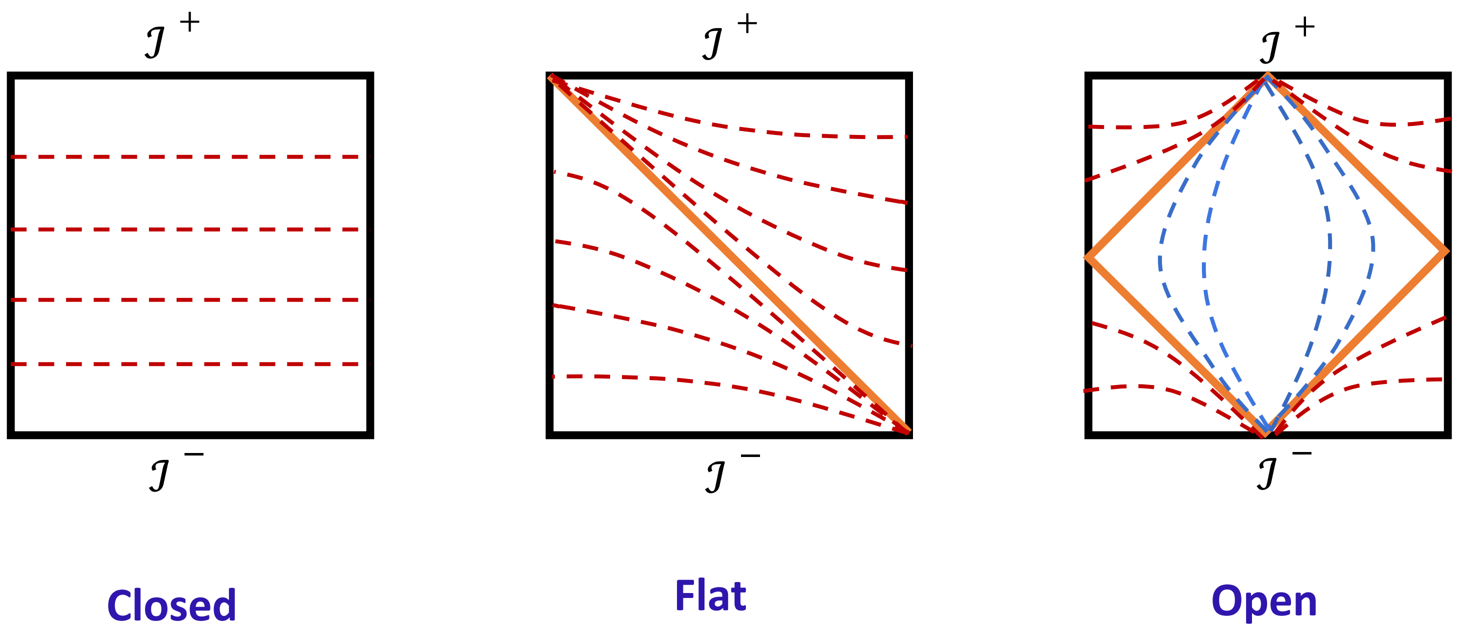
Both realized in string landscape !





Approximate picture

Open or Closed Universes?



From Euclidean approach the bubble leads to an open universe.
From Hamiltonian approach: Spherical symmetry, closed slicing.
Universe inside the bubble is closed. But other slicings possible

Vacuum Transitions

Standard

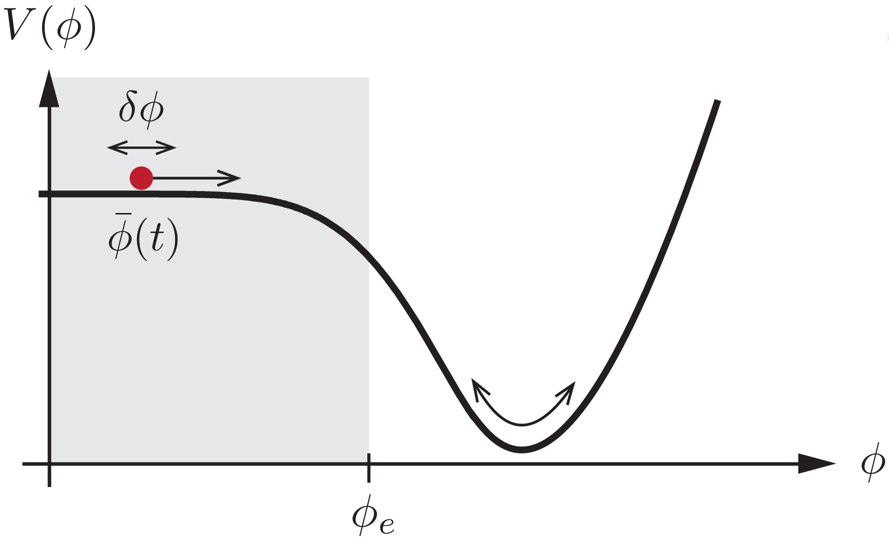
- Euclidean
- No Minkowski to dS
- Open Universe
- Bounce, HM, Flyover

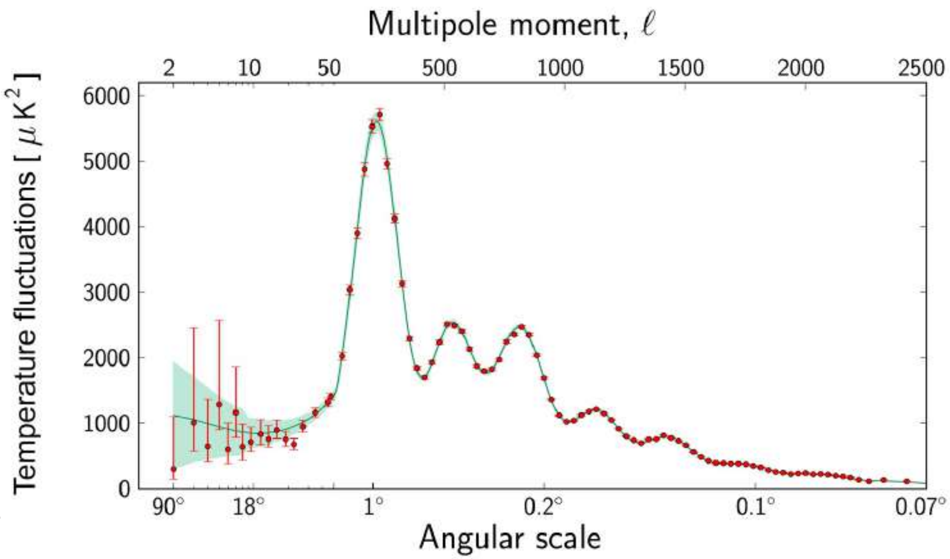
Non-Standard

- Hamiltonian
- Minkowski to dS
- Closed Universe
- New classical trajectories

* Hamiltonian approach only available in mini-superspace or transitions without scalar potential

Inflation





ΛCDM + inflation
(source of almost scale invariant, gaussian, adiabatic density perturbations)

Note: There is no theory behind (origin of dark matter, dark energy, inflation, etc.)

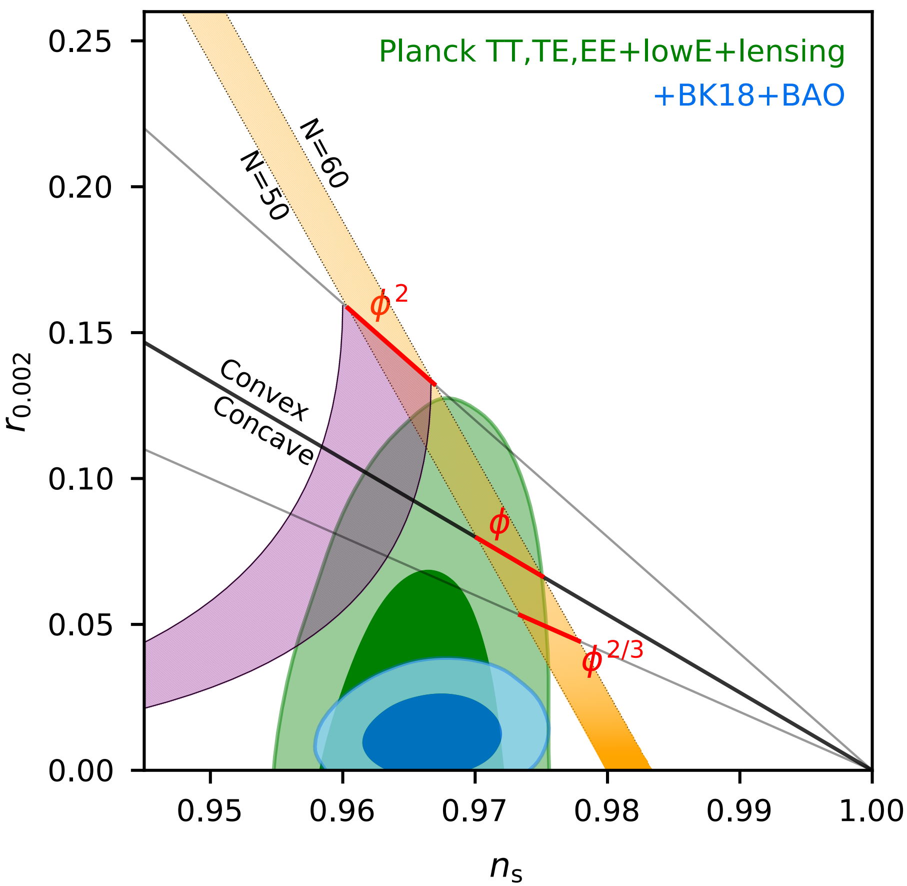
Concrete Models of String Inflation

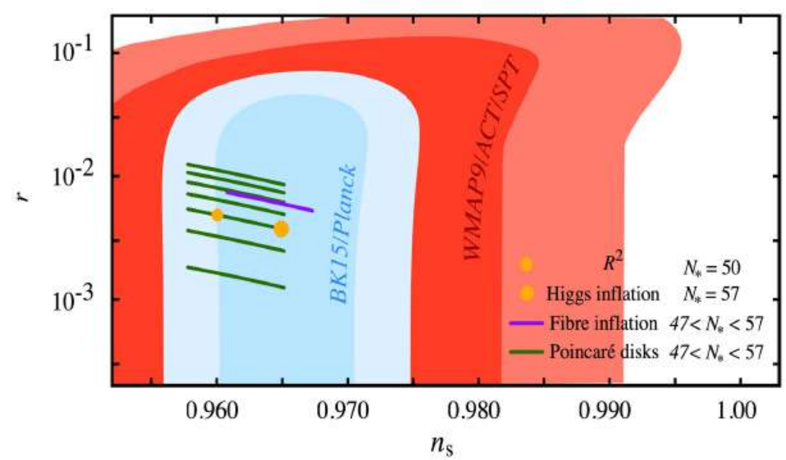
String Scenario	n_s	r
$\mathrm{D3}/\overline{\mathrm{D3}}$ Inflation	$0.966 \leq n_s \leq 0.972$	$r \leq 10^{-5}$
Inflection Point Inflation	$0.92 \leq n_s \leq 0.93$	$r \leq 10^{-6}$
DBI Inflation	$0.93 \leq n_s \leq 0.93$	$r \leq 10^{-7}$
Wilson Line Inflation	$0.96 \leq n_s \leq 0.97$	$r \leq 10^{-10}$
D3/D7 Inflation	$0.95 \leq n_s \leq 0.97$	$10^{-12} \leq r \leq 10^{-5}$
Racetrack Inflation	$0.95 \leq n_s \leq 0.96$	$r \leq 10^{-8}$
N − flation	$0.93 \leq n_s \leq 0.95$	$r \leq 10^{-3}$
Axion Monodromy	$0.97 \leq n_s \leq 0.98$	$0.04 \leq r \leq 0.07$
Kahler Moduli Inflation	$0.96 \leq n_s \leq 0.967$	$r \leq 10^{-10}$
Fibre Inflation	$0.965 \leq n_s \leq 0.97$	$0.0057 \leq r \leq 0.007$
Poly − instanton Inflation	$0.95 \leq n_s \leq 0.97$	$r \leq 10^{-5}$

Burgess, Cicoli, Quevedo 2013

Recent BICEP/KECK results

$$r_{0.05} = 0.014^{+0.010}_{-0.011} \; (r_{0.05} < 0.036 \text{ at } 95\% \text{ confidence})$$

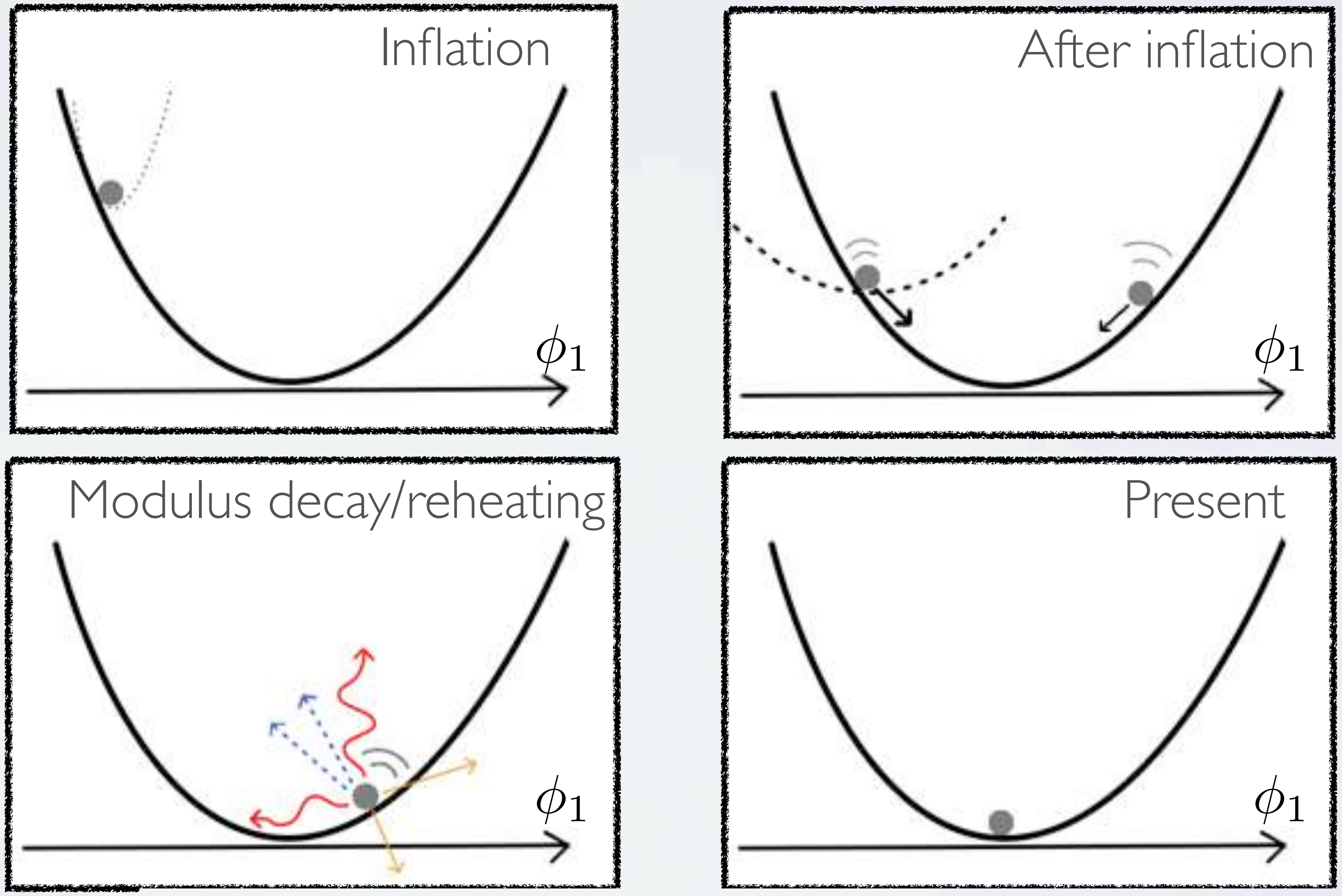




From Flauger (see Kallosh-Linde)

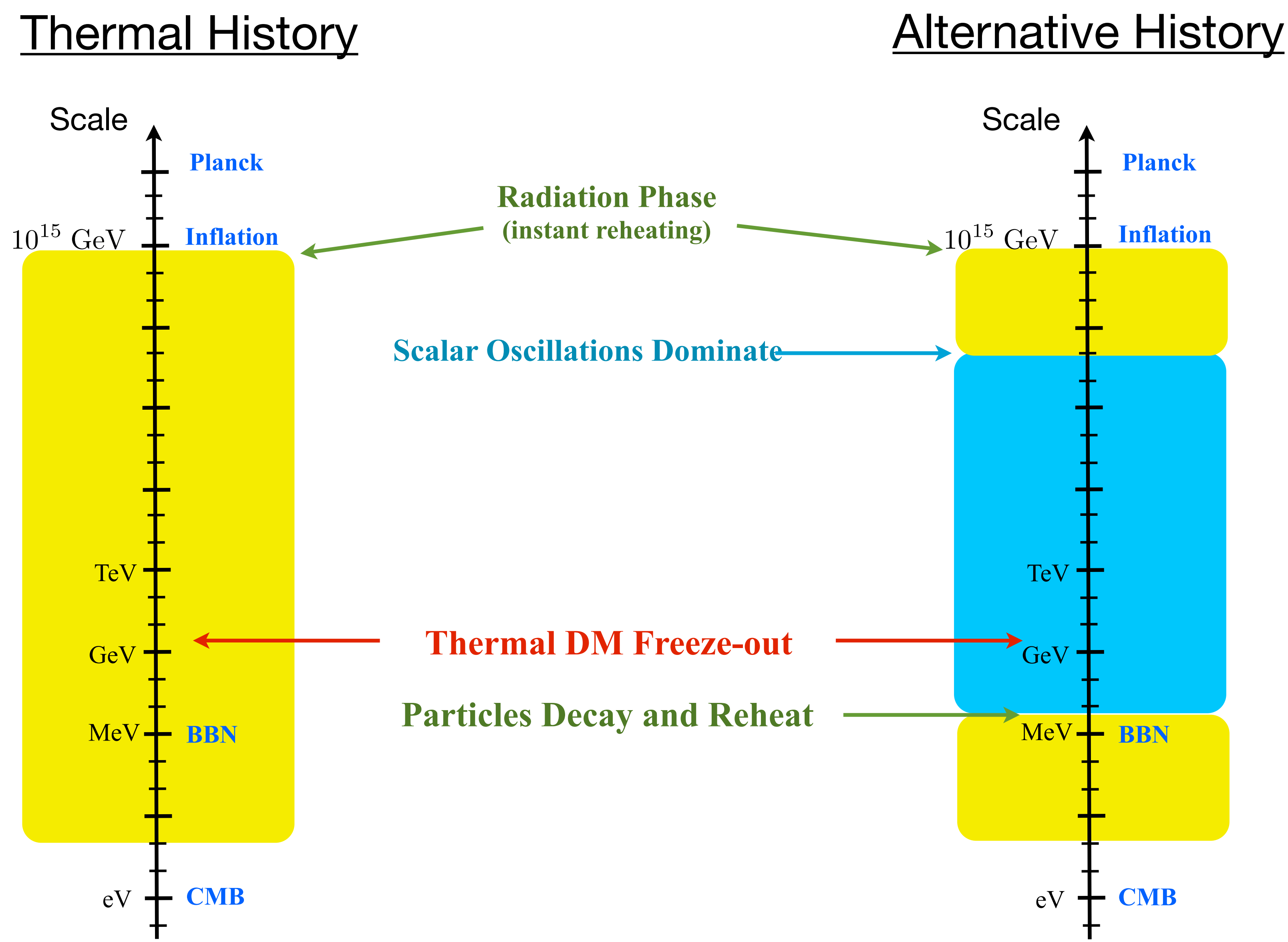
Post-Inflation

(Moduli Domination)



$T > O(1\ \mathrm{MeV})$, so $m_\phi \gtrsim 3 \cdot 10^4\ \mathrm{GeV}$.

Coughlan et al 1983, Banks et al, de Carlos et al 1993



From S. Watson

Bosonic Compact Objects

- Q-balls
- Oscillons

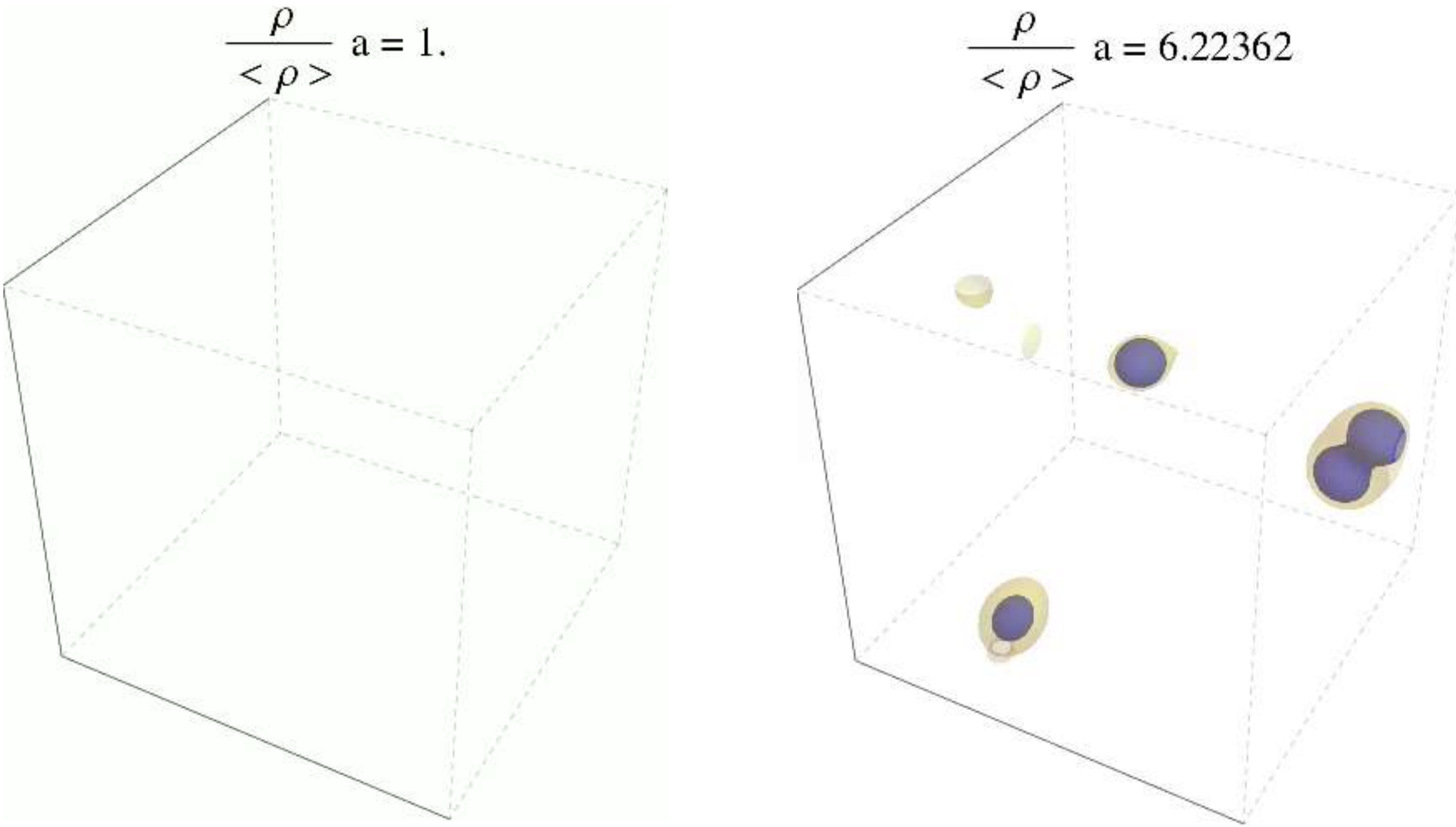
Repulsive pressure vs attractive interaction

Gravity vs Repulsive pressure

- Boson stars
- Mini-boson stars
- Oscillatons (e.g. axion stars, moduli stars)

Scalar	$G = 0$	$G = 1$	
Complex	***Q-Balls*** Global $U(1)$	***Mini-Boson Stars*** weak self-interactions	***Boson Stars*** strong self-interactions
Real	***Oscillons*** attractive self-interactions	***Oscillatons***	

3D lattice simulations (Blow-up LVS vs KKLT)

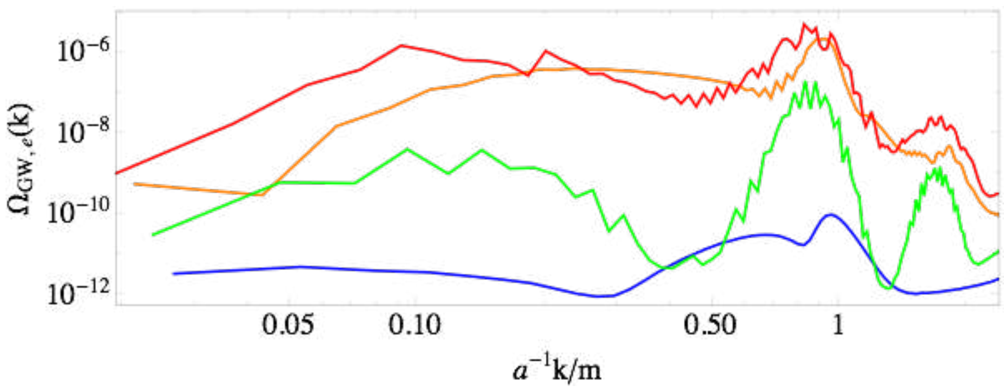


● $\rho > 6\langle\rho\rangle$

● $\rho > 12\langle\rho\rangle$

*No oscillons for volume or fibre moduli

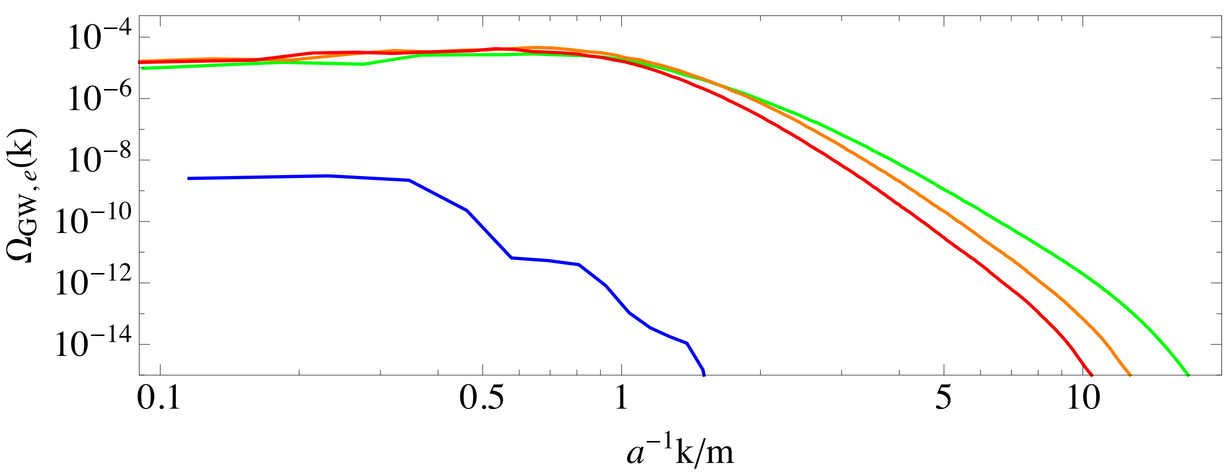
GW spectrum: KKLT



$$f_{0,\text{peak}} \sim 10^9\,\text{Hz}$$

$$\Omega_{\text{GW},0}(f_{0,\text{peak}}) \sim 3 \times 10^{-11}$$

GW spectrum: Blow-up LVS



$$f_0 \sim 10^8\,\text{Hz} - 10^9\,\text{Hz}\,,$$

$$\Omega_{\text{GW},0} \sim 10^{-10} - 5 \times 10^{-10}\,.$$

Ultra High Frequency Gravitational Waves

CERN-TH-2020-185
HIP-2020-28/TH
DESY 20-195

arXiv:2011.12414v1 [gr-qc] 24 Nov 2020

Challenges and Opportunities of Gravitational Wave Searches at MHz to GHz Frequencies

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Abstract

The first direct measurement of gravitational waves by the LIGO and Virgo collaborations has opened up new avenues to explore our Universe. This white paper outlines the challenges and gains expected in gravitational wave searches at frequencies above the LIGO/Virgo band, with a particular focus on the MHz and GHz range. The absence of known astrophysical sources in this frequency range provides a unique opportunity to discover physics beyond the Standard Model operating both in the early and late Universe, and we highlight some of the most promising gravitational sources. We review several detector concepts which have been proposed to take up this challenge, and compare their expected sensitivity with the signal strength predicted in various models. This report is the summary of the workshop *Challenges and opportunities of high-frequency gravitational wave detection* held at ICTP Trieste, Italy in October 2019.

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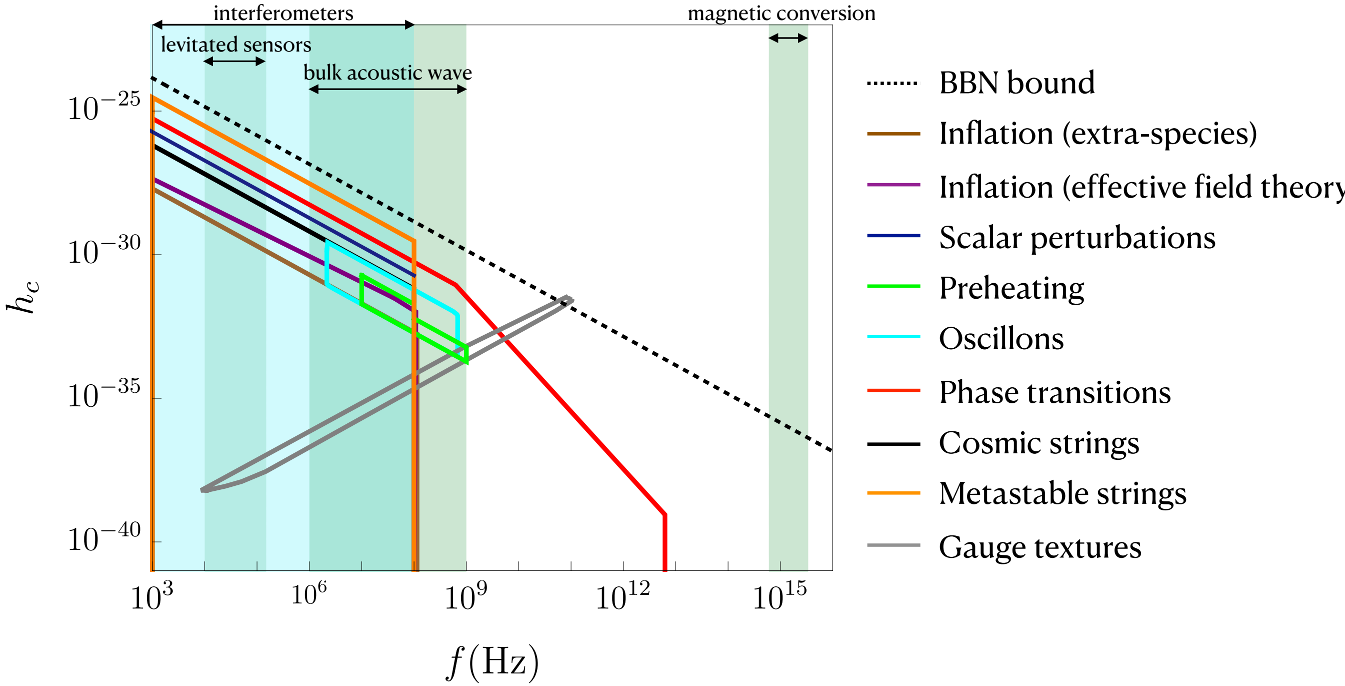
See also:

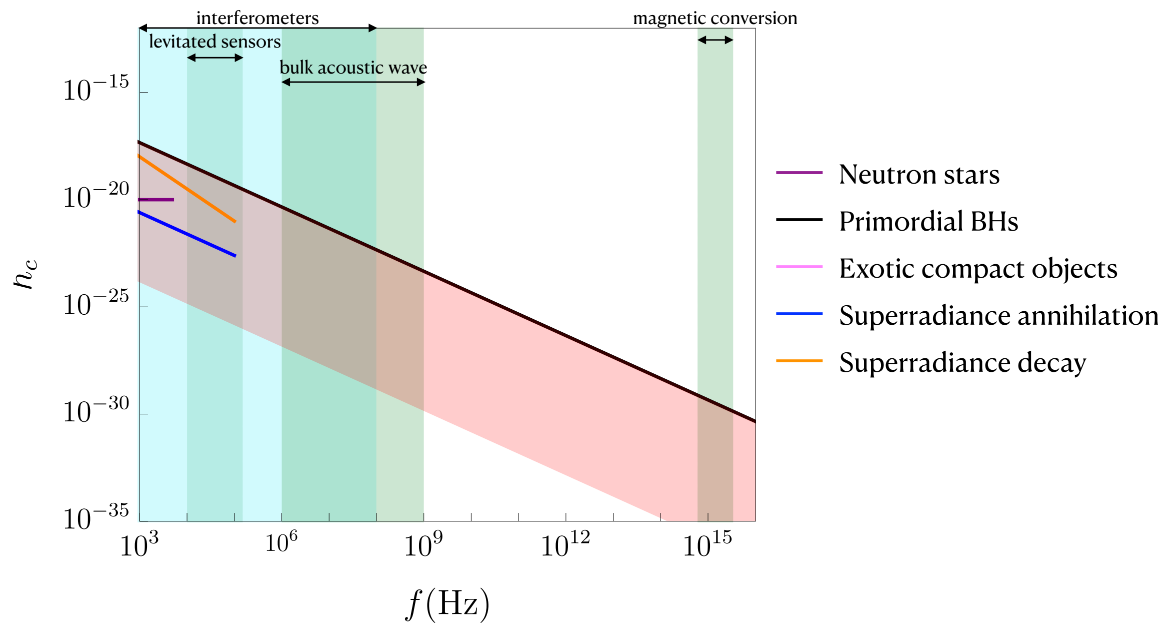
http://www.ctc.cam.ac.uk/activities/UHF-GW.php

https://indico.cern.ch/event/1074510/

Cosmological sources of stochastic High Frequency Gravitational Waves



Sources of Coherent Gravitational Waves



Some Open Questions

- **De Sitter** **(resonance?, islands?...)**
- **Landscape population** **(transitions to runaway; M to (A)dS…)**
- **Inflation** **(axion monodromy with moduli stabilization; inflation scale against gravitino mass; Inflation, dS+Standard Model,…)**
- **After Inflation** **((p)reheating, dark matter, baryogenesis,…)**
- **Today** **(dark energy: cosmological constant vs quintessence?)**
- **Future?** **(GWs to test string theory?)**