Theory Status and Outlook

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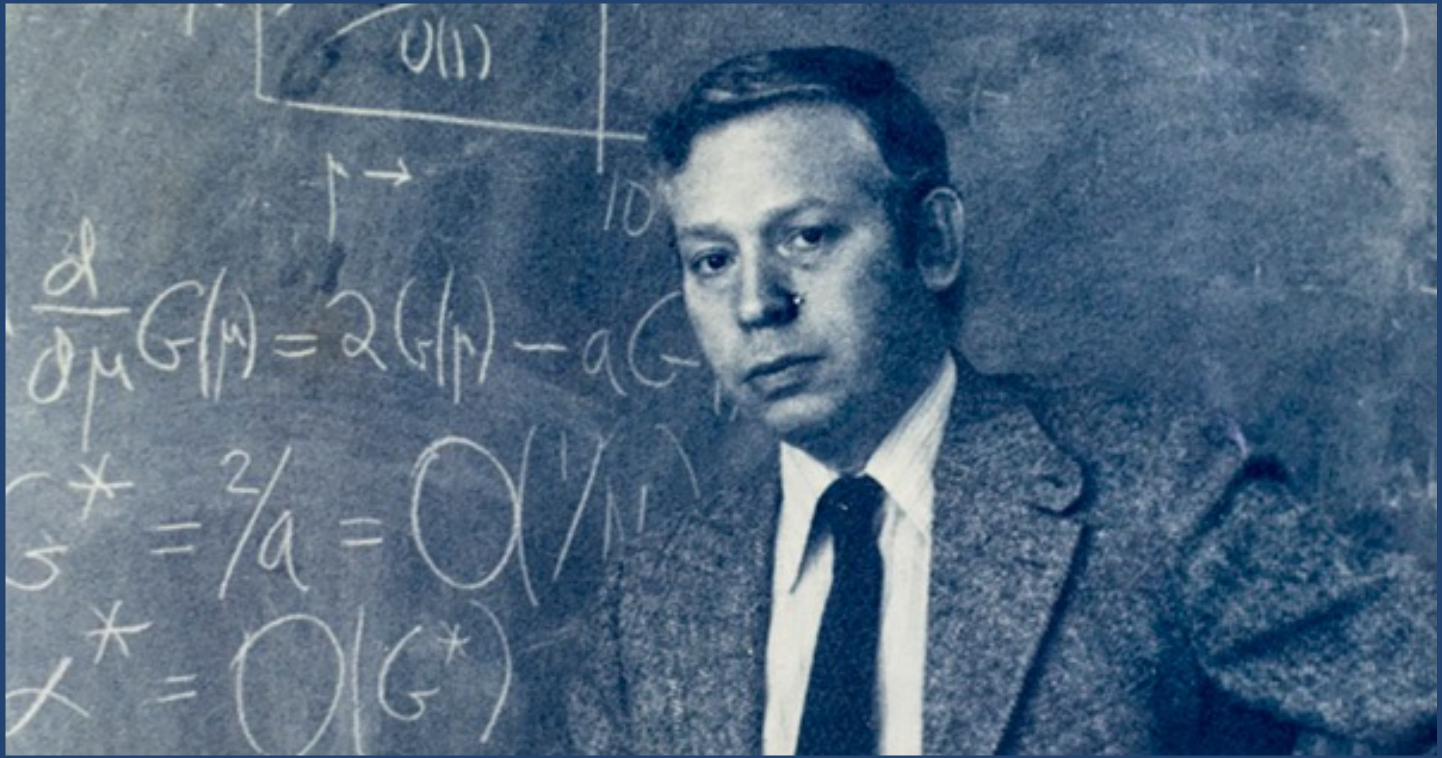
ICHEP 2022
Bologna July 2022

Formal≈ Arxives hep-th

In memoriam



Steven Weinberg 1933-2021

Fundamental open questions in formal HEP

- **Solvable Quantum Field Theories (QFTs)**
  - S-matrix (perturbative and non-perturbative effects,…)
  - Strongly coupled QFTs (e.g. Confinement)
  - Phases of QFTs …

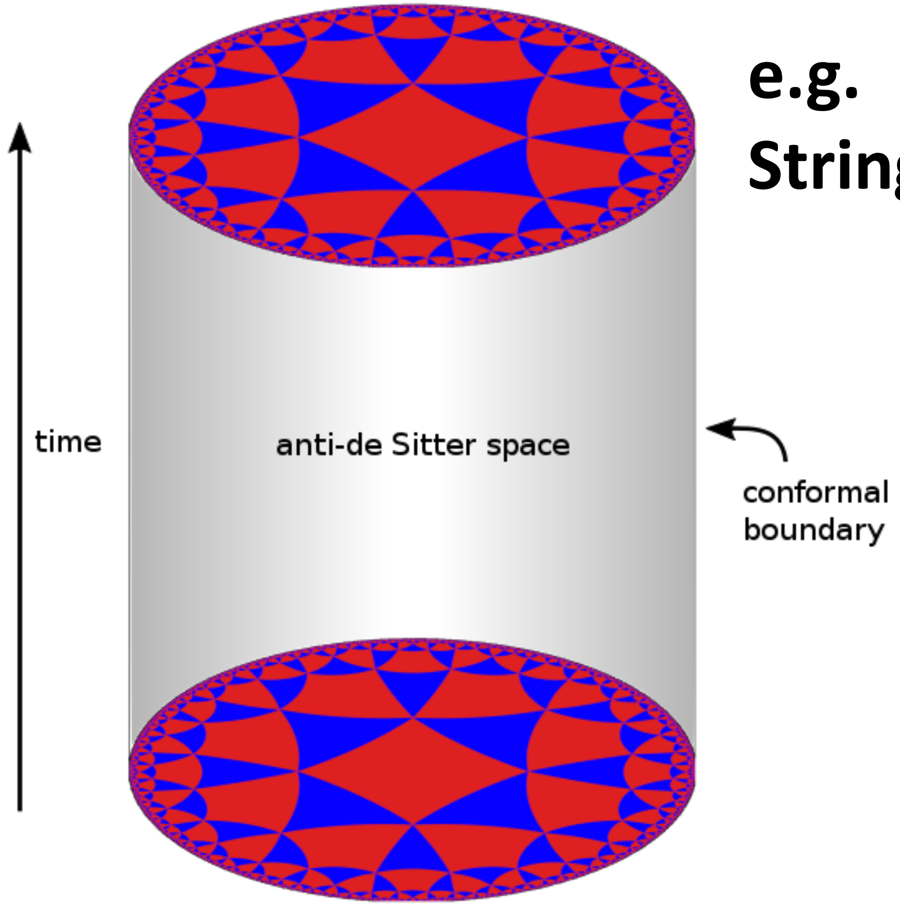
- **Quantum gravity**
  - Mathematical consistency (EFT vs UV completion)
  - Black holes (singularity, information)
  - Big-bang (singularity, wave function of the universe, density perturbations,…)
  - Vacuum energy and transitions (Dark energy, Tunneling in gravity, CDL,…)
  - Unification (BSM and gravity)

e.g. see *all* parallel talks

Black holes & Information

Main progress in past 25 years

AdS/CFT correspondence (Gauge/Gravity duality, Holography)



e.g.

String theory on AdS_5 x S^5 $\equiv$ $\mathbf{4d}$ *N*=4 SU(N_c) Yang-Mills

- **Large N_c**
- **Emerging ‘space’!**

Maldacena 1997,…

Main progress in past 3 years

Hawking information loss paradox:

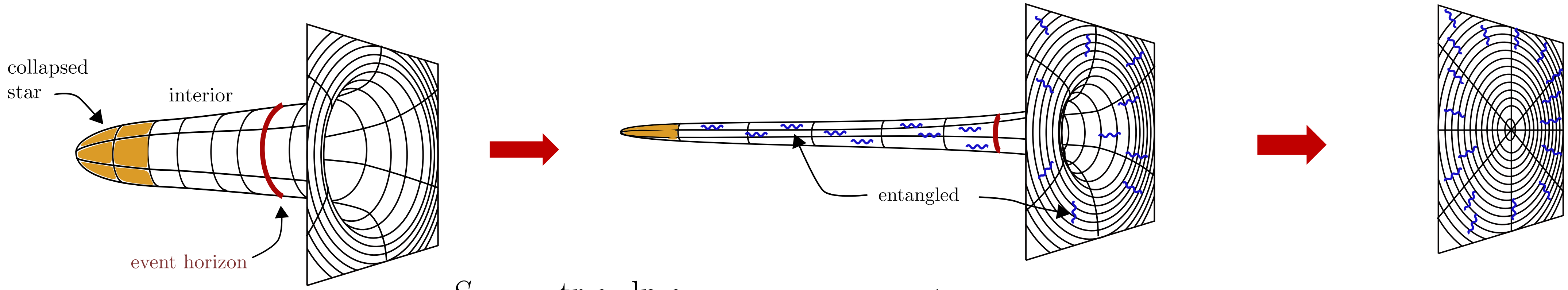
- **We ‘knew’ from AdS/CFT that evolution should be unitary, but why?**
- **Recent progress: Calculations indicate unitarity (not yet full proof but close)**

Penington 2019, Almheiri et al, Maldacena et al….

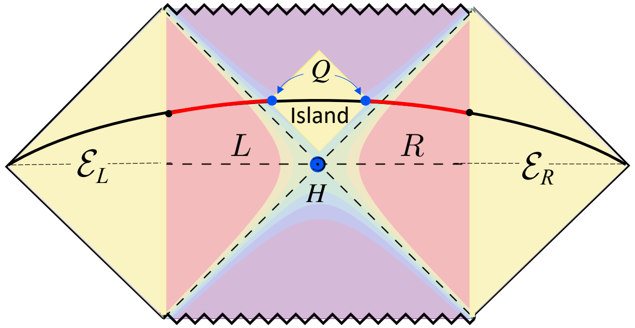
(Earlier work 2005-2020s: Ryu-Takayanagi, Hubeny et al., Wall, …).

Also: number of microscopic states matching the black hole entropy (Strominger&Vafa 1995)
+ recent derivations using AdS/CFT (Benini et al 2015, Pando-Zayas et al 2020)

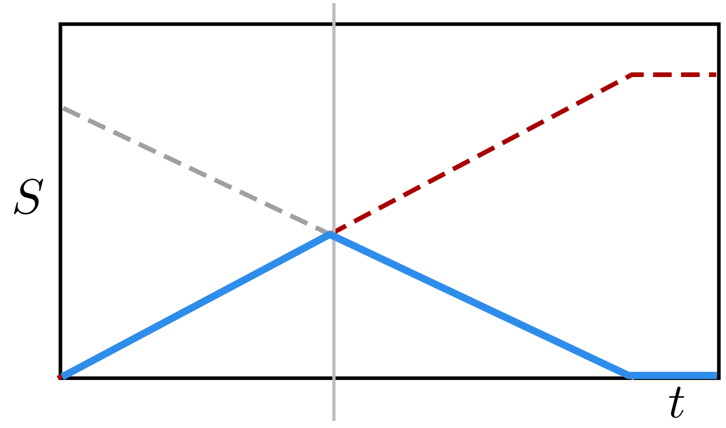
Hawking evaporation



$S_{\mathrm{R}} = -\mathrm{tr}\, \rho_{\mathrm{R}} \ln \rho_{\mathrm{R}}$ $S_{\mathrm{BH}} = \mathrm{Area}/4G$



$$S(\mathcal{E}) = \mathrm{ext}_Q \left[\frac{\mathrm{Area}(Q)}{4G_N} + S_{\mathrm{qft}}(I \cup \mathcal{E}) \right]$$



Page curve!

Good/bad news: only needed semiclassical gravity.

Thanks: V. Pasquarella

Black holes and generalised holography

- Wedge/codimension 2 holography
- T- $\overline{\mathrm{T}}$ deformations, subregions holography and dS to dS duality
- Von Neuman algebras and duality beyond large N
- Minkowski and celestial sphere

Takayanagi et al 2020

Silverstein et al 2021

Witten et al 2021

Strominger et al

Islands, holography and cosmology?

e.g. Hartman, 2019
van Raamsdonk et al 2020-2022,
Gorbenko et al 2021,
Bousso et al 2022.

(Islands and early universe? vacuum transitions? De Sitter entropy?)

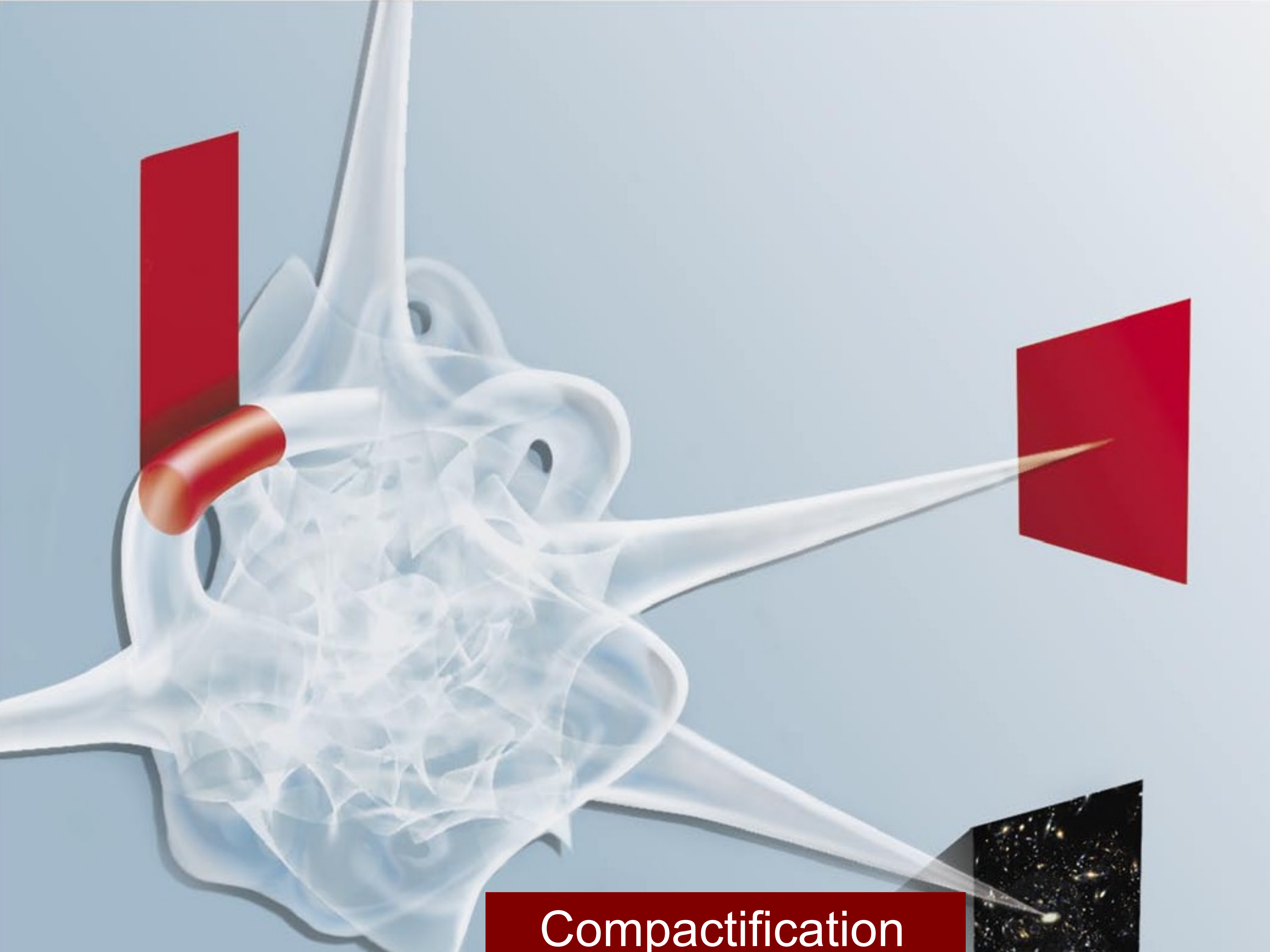
Formal Theory and HEP

Formal$\approx$String, …

Challenges for UV complete Models

- Gravity quantum
- Gauge and matter structure of SM
- Hierarchy of scales + masses (including neutrinos)
- Flavor CKM, PMNS mixing, CP no FCNC
- Hierarchy of gauge couplings (unification?)
- ‘Stable’ proton + baryogenesis
- Inflation or alternative for CMB fluctuations
- Dark matter (+ avoid overclosing)
- Dark radiation (N_{eff}~3.04)
- Dark energy

N.B. If ONE of them does not work, rule out the model!!!



e.g. Calabi-Yau Compactifications and the Brane World

New tools: ML

- Machine (supervised and reinforcement) learning

Lukas et al 2018-2019

- Genetic algorithms

Abel et al et al 2021

1. For model selection

2. Computing explicit metrics of Calabi-Yau manifolds

Anderson et al, Douglas et al, Jejjala et al 2020

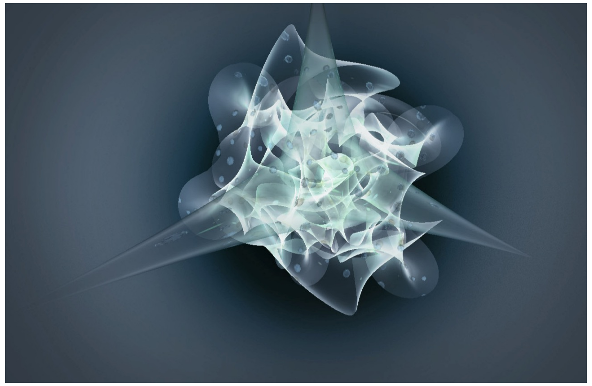
Review Ruehle Phys Rep. 2020

Recent Progress

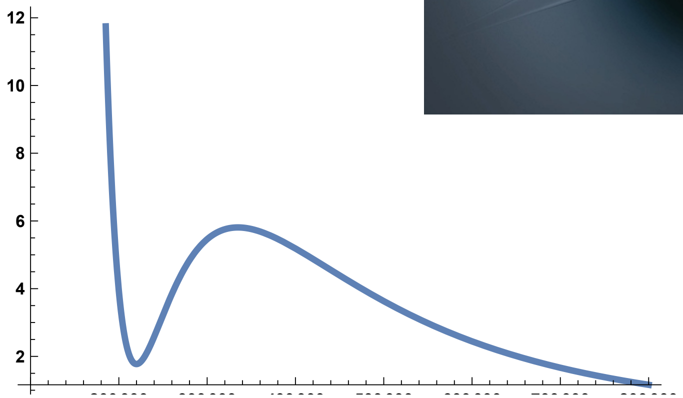
- **N =10^{15} F-theory models with MSSM spectrum** Cvetic et al 2019
- **N>10^{23} heterotic models with MSSM spectrum** Constantin et al 2019
- **Concrete MSSM models with moduli stabilisation** Cicoli et al 2021

Three related questions

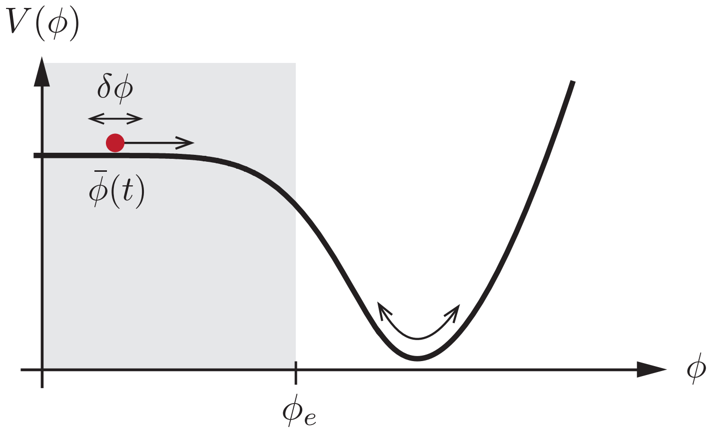
- Moduli stabilization



- De Sitter

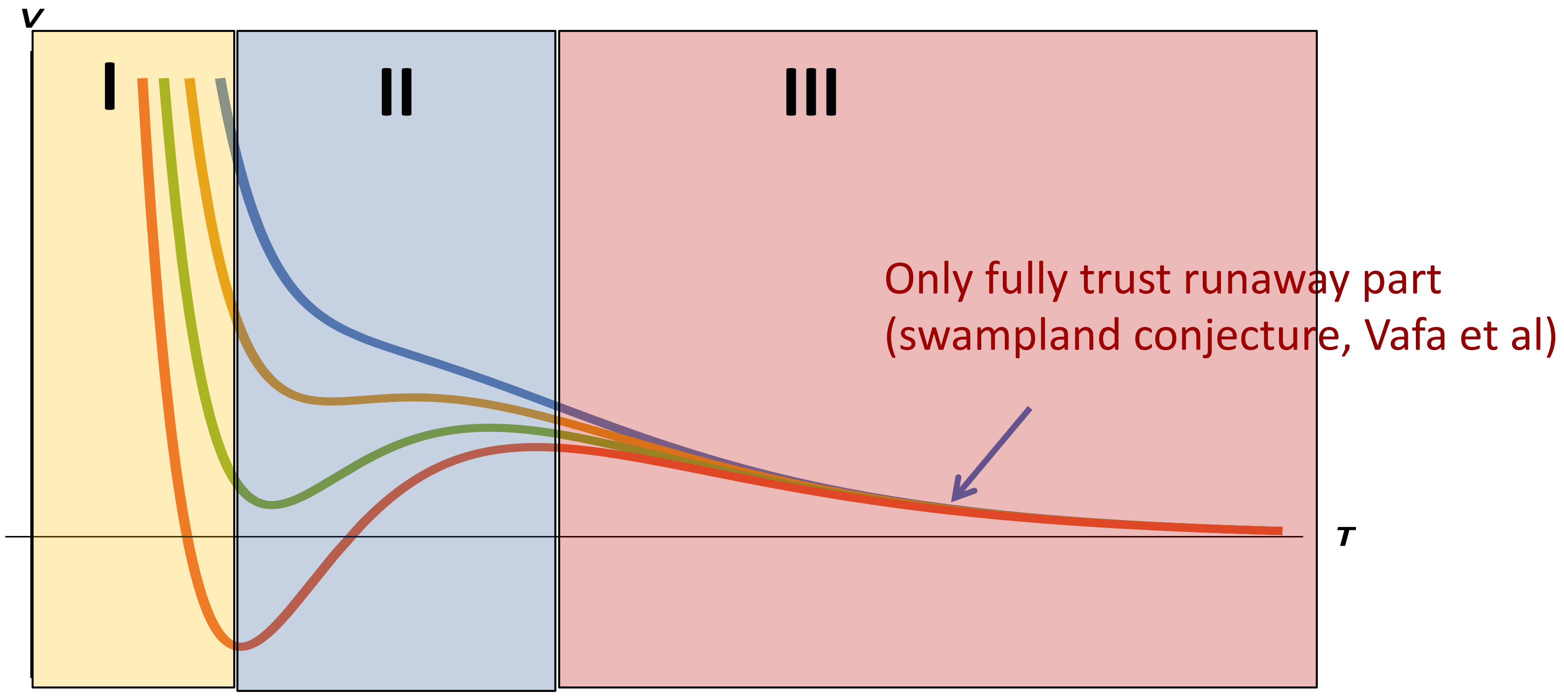


- Inflation



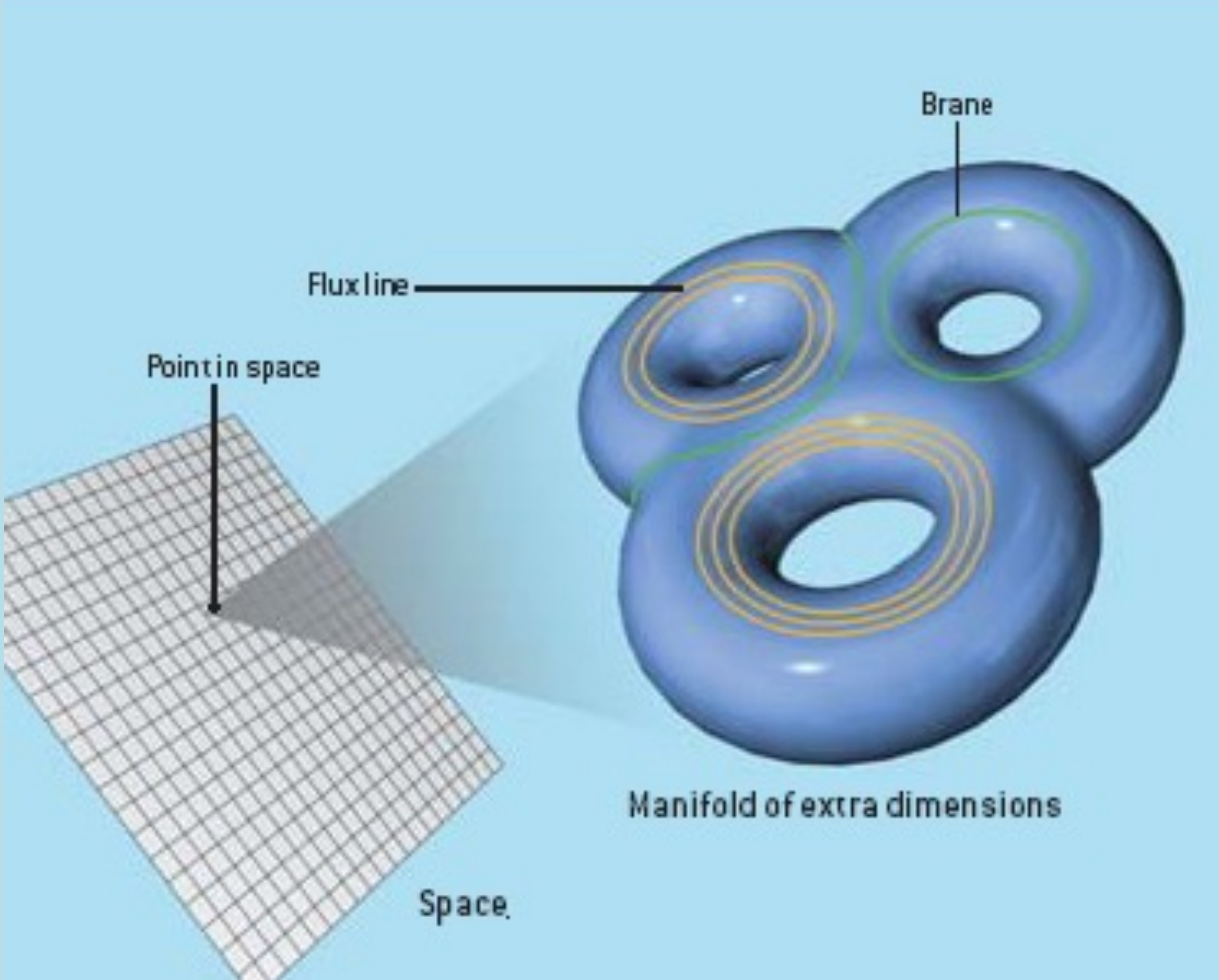
Dine-Seiberg Problem

Dine, Seiberg 1985



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

e.g. String Landscape from Flux compactifications



Two leading scenarios

- **Non-perturbative vs tree level (KKLT)**

$$W_0 \ll 1$$

Kachru et al 2003

- **Perturbative vs non-perturbative (LVS)**

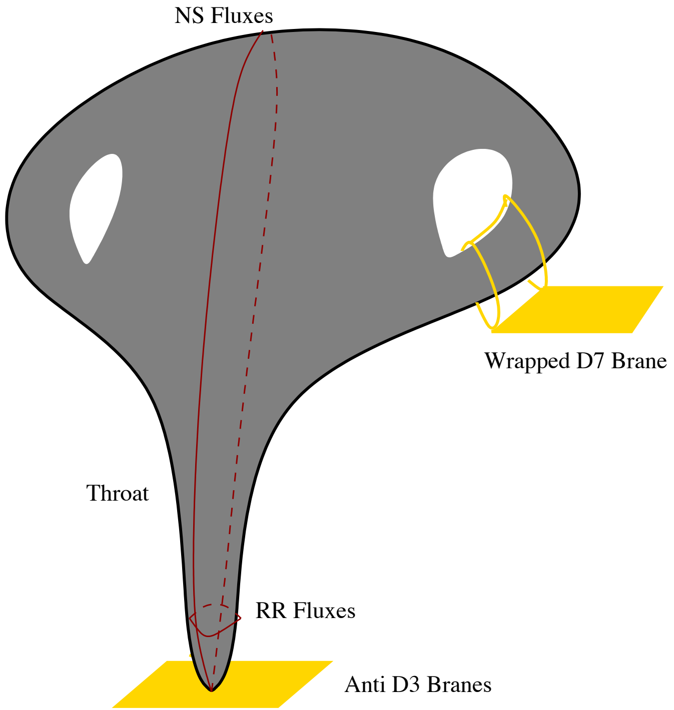
Conlon et al 2003

$$\delta K \sim 1/\mathcal{V} \text{ and } \delta W \sim e^{-a\tau}$$

$$\mathcal{V} \sim e^{a\tau}$$

- **Alternative? Perturbative**

Antoniadis et al 2021
Burgess et al 2022



e.g. Naturalness ?

$$\mathcal{L}_{SM} = \sum_i c_i \mathcal{O}_i \,, \quad [c_i] + [\mathcal{O}_i] = 4 \,.$$

- $[\mathcal{O}_i] = 0$: $c_0 = \Lambda$ $\quad \boxed{\frac{\Lambda}{M_P^4} \sim 10^{-123} \ll 1 \quad \Lambda/\langle H \rangle^4 \sim 10^{-60}}$ **Cosmological constant problem**
- $[\mathcal{O}_i] = 2$: $c_2 = m^2 \quad H^2 = \mathcal{O}_2$ $\quad \boxed{\frac{m_h}{M_P} \sim 10^{-15}}$ **Hierarchy problem**
- $[\mathcal{O}_i] = 3$: $c_3 = M^{\nu} \quad \nu_R \nu_R = \mathcal{O}_3$.

  Right handed neutrino mass term ?
- $[\mathcal{O}_i] = 4$: **All other terms in SM**

.

.

. **Higher order operators SMEFT**

Can we address both problems at once?

- **String landscape** (Weinberg-Bousso-Polchinski+…)

Worst solution to the cc problem with the exception of all the others!

But: not yet a full solution (de Sitter, populating the landscape, measure problem,…)

- **Alternatives?**

Quintessence at least as difficult as dS!

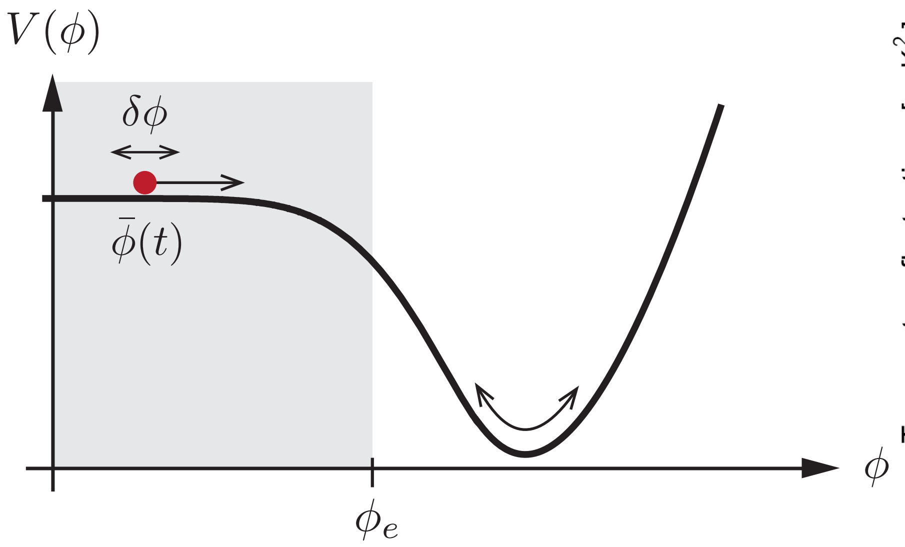
Cicoli et al 2021

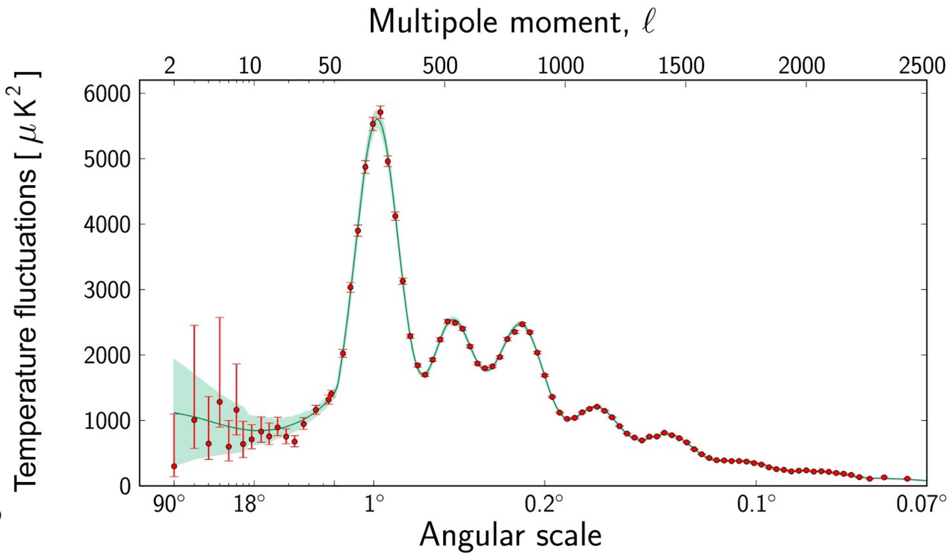
Challenges to KKLT, LVS,...

- **Fluxes under control only in SUSY 10D?** (Sethi, Kachru-Trivedi, de Alwis et al…)
- **All SUSY breaking part is 4D EFT. Trust EFT?**(Carta, et al, Moritz et al, Kallosh, Gautason et al, Hamada et al, Kachru et al.)
- **Higher corrections in LVS?** (Cicoli et al.)
- **Antibranes (non susy, singularity?)** (Bena et al, Moritz et al, Cohen-Maldonado et al, Gao et al)
- **Tadpole problem** (Bena et al., Crino et al, Junghans, Xin Gao et al, Vafa et al…)
- **Consistency with AdS/CFT** (de Alwis et al, Conlon et al, Vafa et al…)
- **Tuning W_0<<1? in KKLT** (Demirtas et al, Alvarez-Garcia et al, Blumenhagen et al)

e.g. String Theory and Cosmology

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

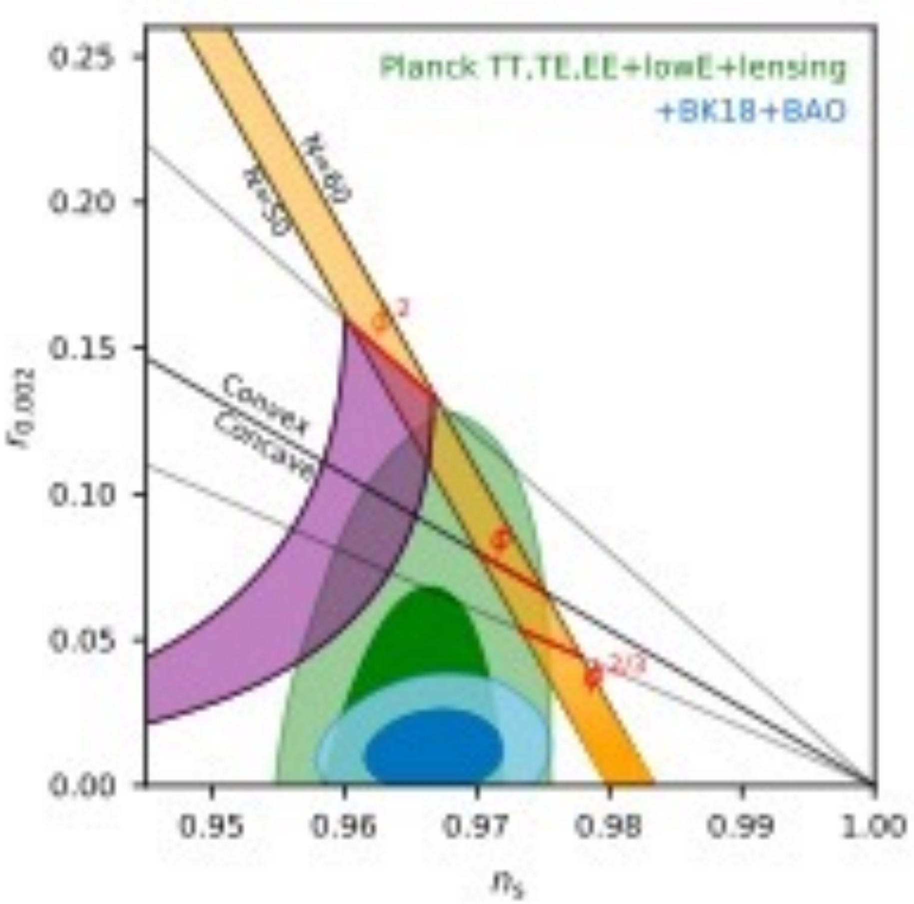
String Scenario	n_s	r
$\mathrm{D3}/\overline{\mathrm{D3}}$ Inflation	$0.966 \leq n_s \leq 0.972$	$r \leq 10^{-5}$
Inflection Point Inflation	$0.92 \leq n_s \leq 0.93$	$r \leq 10^{-6}$
DBI Inflation	$0.93 \leq n_s \leq 0.93$	$r \leq 10^{-7}$
Wilson Line Inflation	$0.96 \leq n_s \leq 0.97$	$r \leq 10^{-10}$
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	$0.95 \leq n_s \leq 0.97$	$r \leq 10^{-5}$

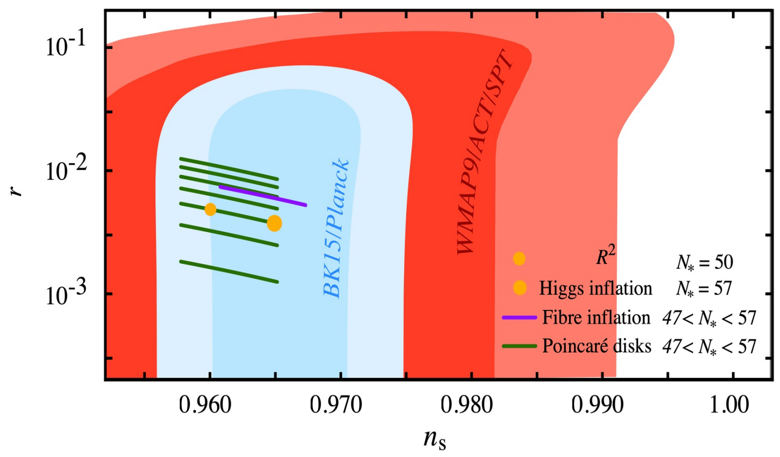
Burgess, Cicoli, FQ 2013

Challenges: **eta problem, scales (KL problem), moduli stabilisation, observations?**

Recent BICEP/KECK 2021 results

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

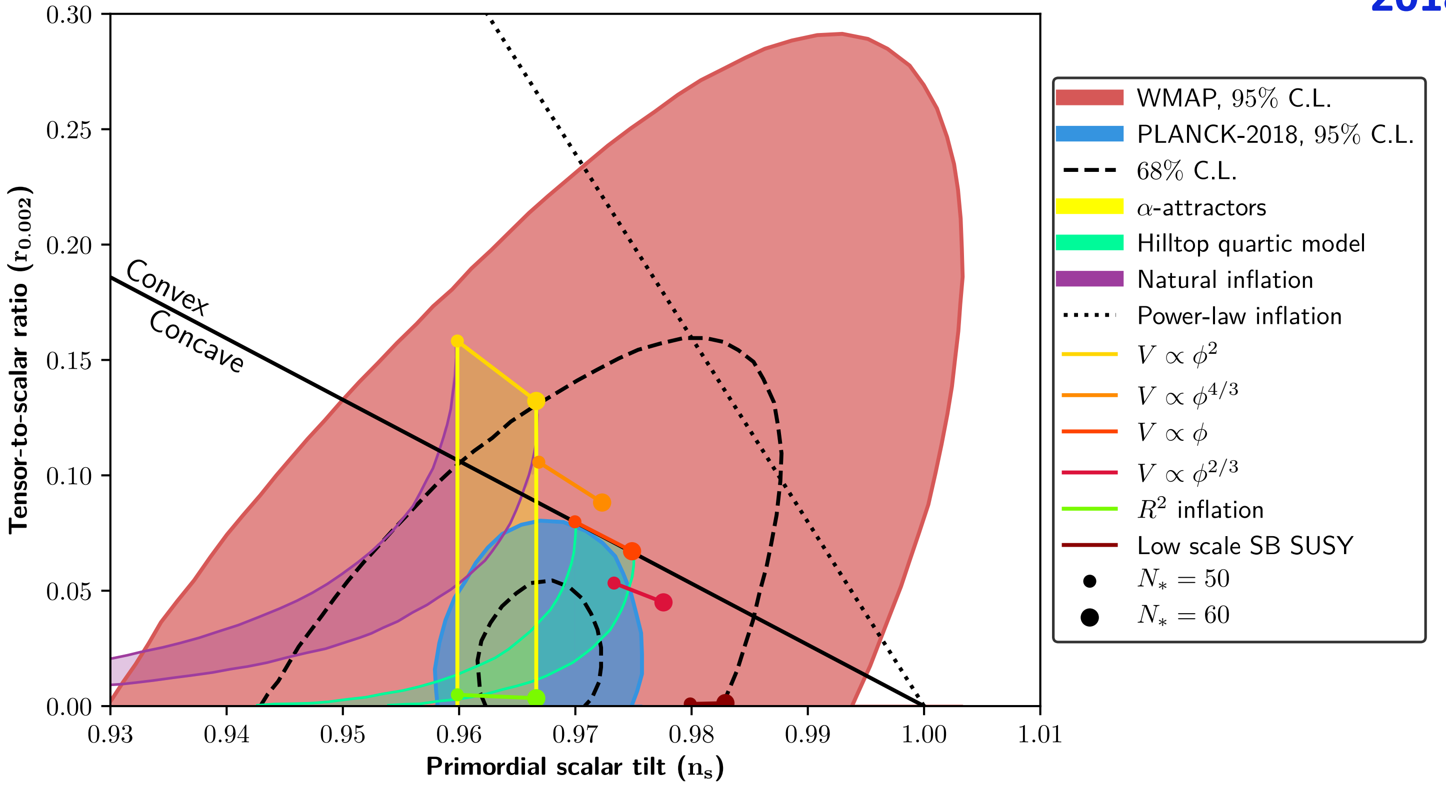




From Flauger 2021 (see Kallosh-Linde)

Early Universe, CMB: PLANCK 2018 versus WMAP 2010

2018



2004 Racetrack
Inflation in String theory
$n_s \leq 0.95$

1994 F-term, 1996 D-term Inflation
In supergravity, D3/D7 model in String theory, 2007
$n_s \approx 0.98$

?

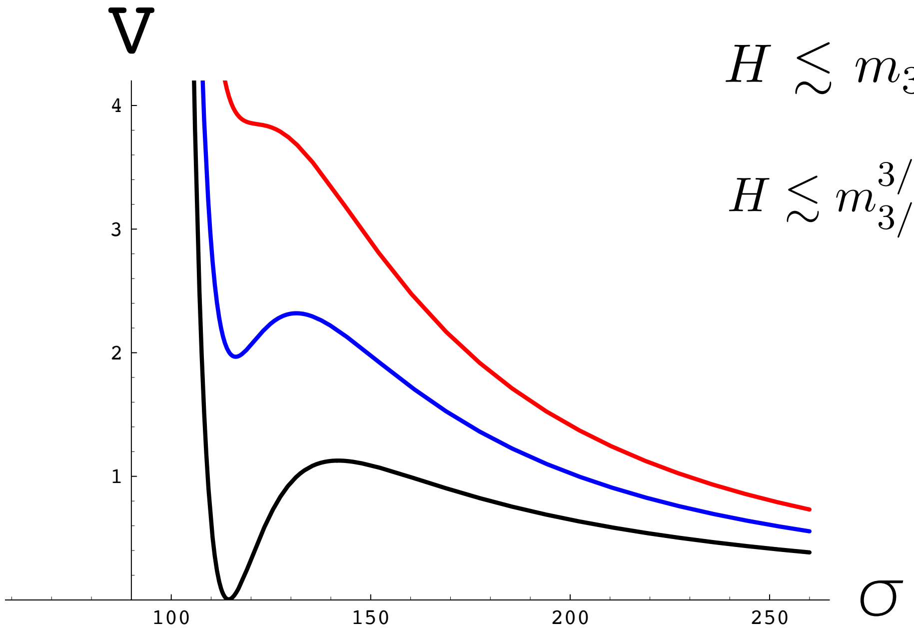
H_0 tension?

2003 KKLMMT
2010 inflection model
$n_s \leq 0.93$

2005 N-flation
r=0.13

From Kallosh, Linde 2022

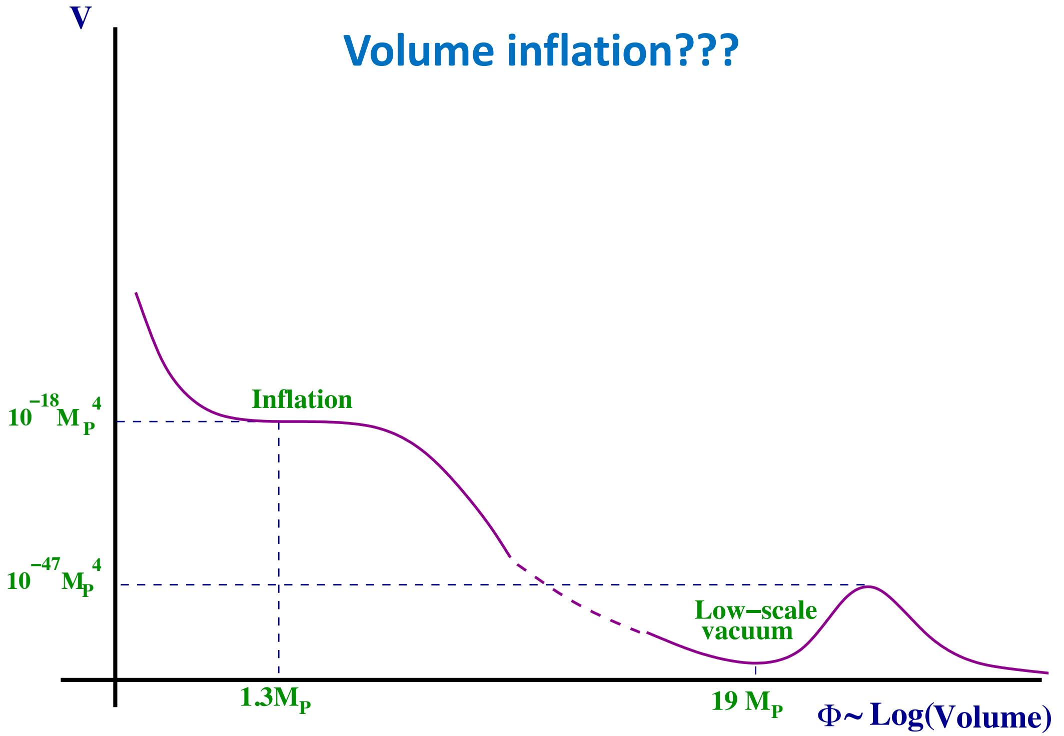
Correlations: e.g. Kallosh-Linde problem



Kallosh, Linde 2004

$H \lesssim m_{3/2}$ **KKLT**

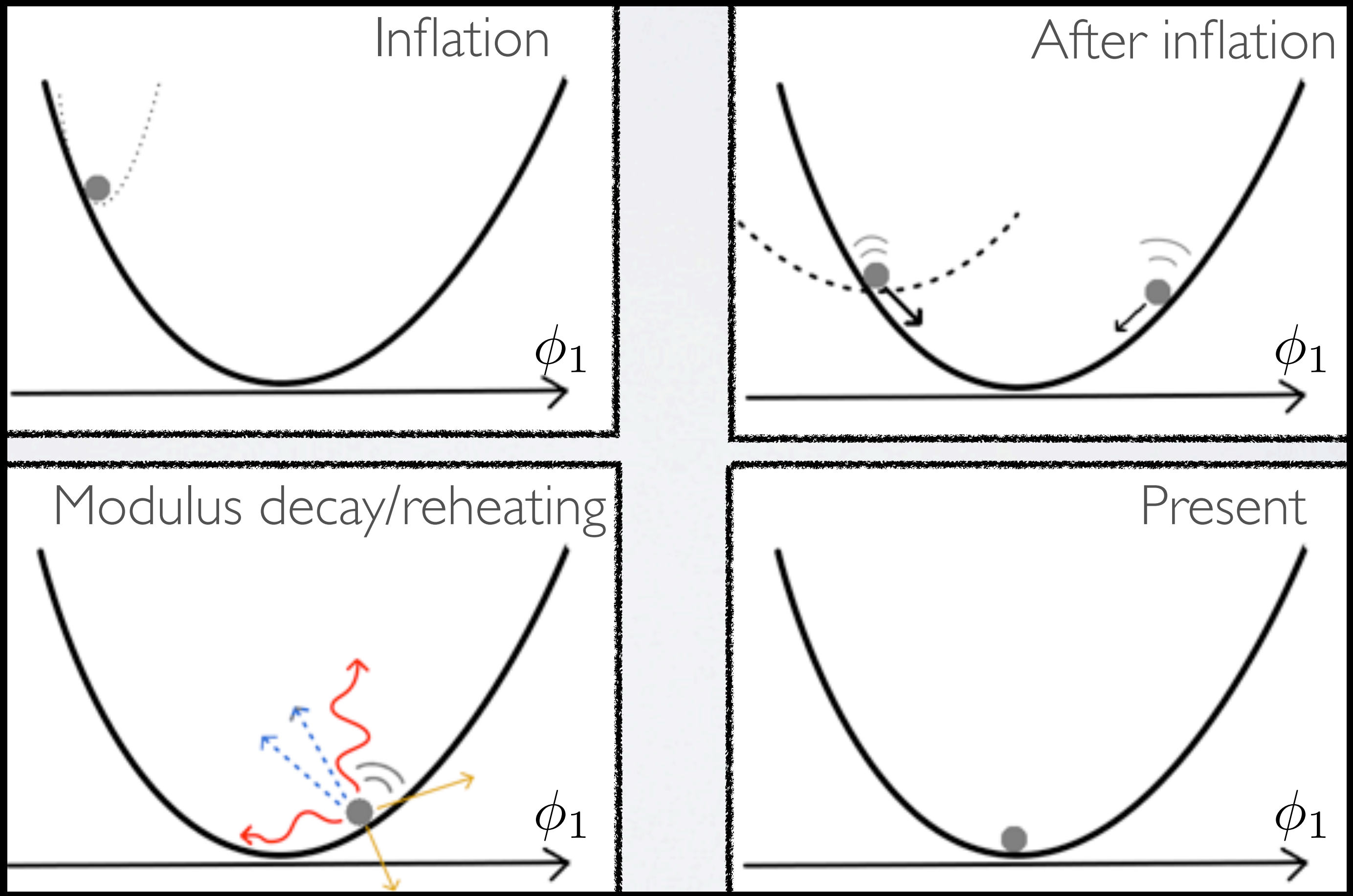
$H \lesssim m_{3/2}^{3/2}$ **LVS**



Conlon, Kallosh, Linde, FQ 2008
Burgess, FQ 2022, Conlon et al 2022

Post-Inflation

(Moduli Domination)

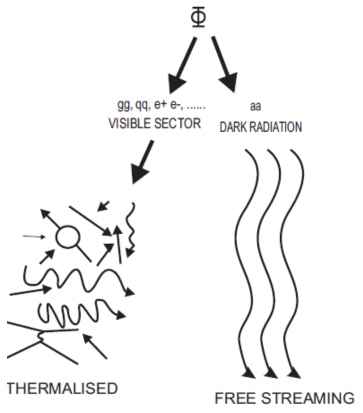


M>30 TeV

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

After Inflation

- Period of Moduli (matter) domination
- Or Kination + matter domination+radiation domination
- Oscillons or Oscillatons (boson stars)
- Reheating=moduli decay
- General constrain: dark radiation!
- Axiverse
- Potential signatures: High frequency Gravitational waves!!!



Ultra High Frequency Gravitational Waves

See also:

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

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

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

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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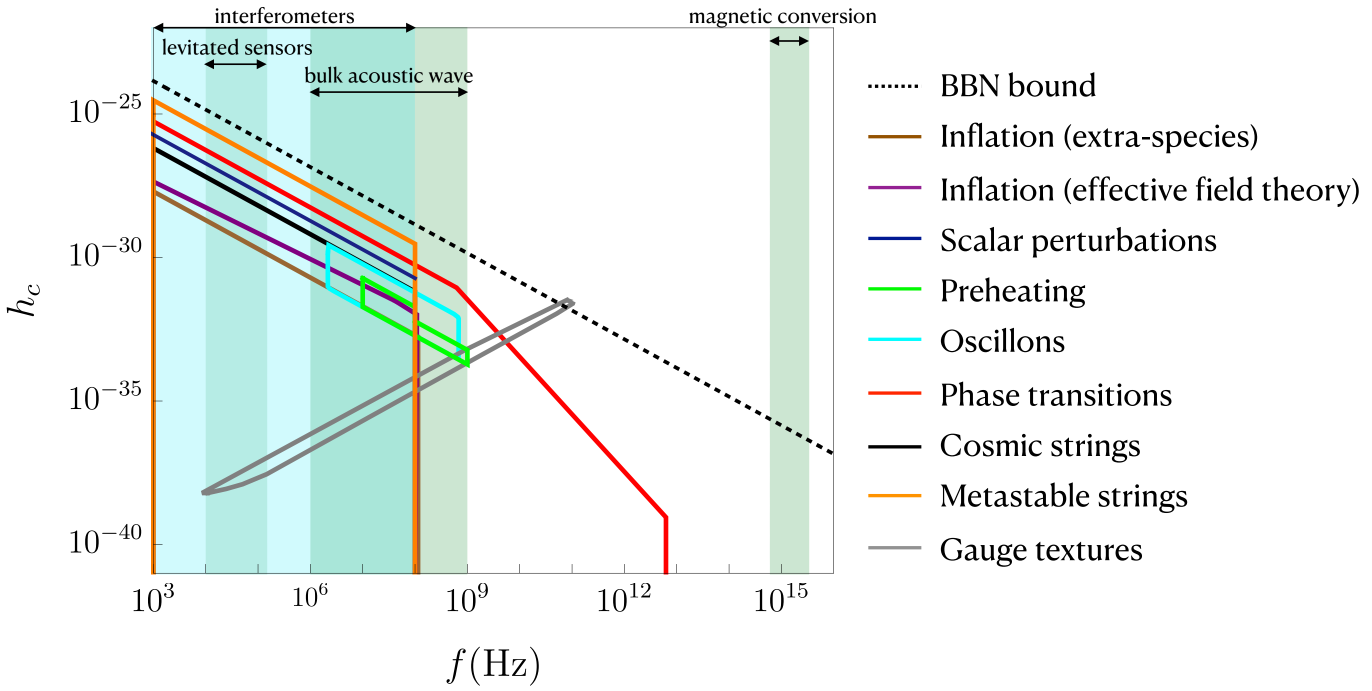
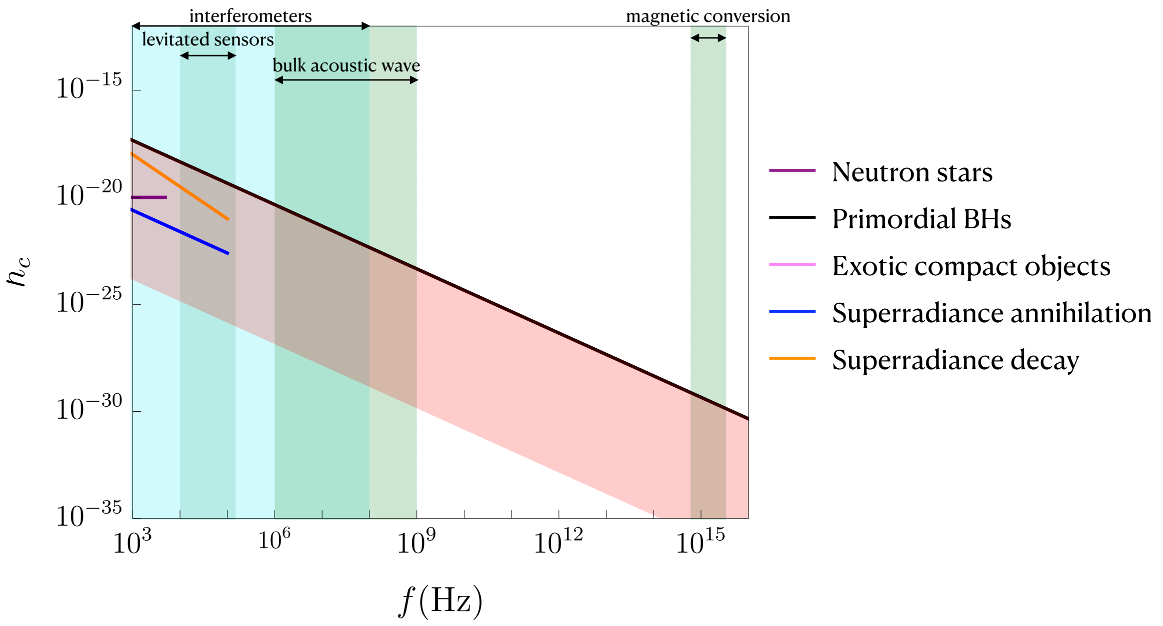
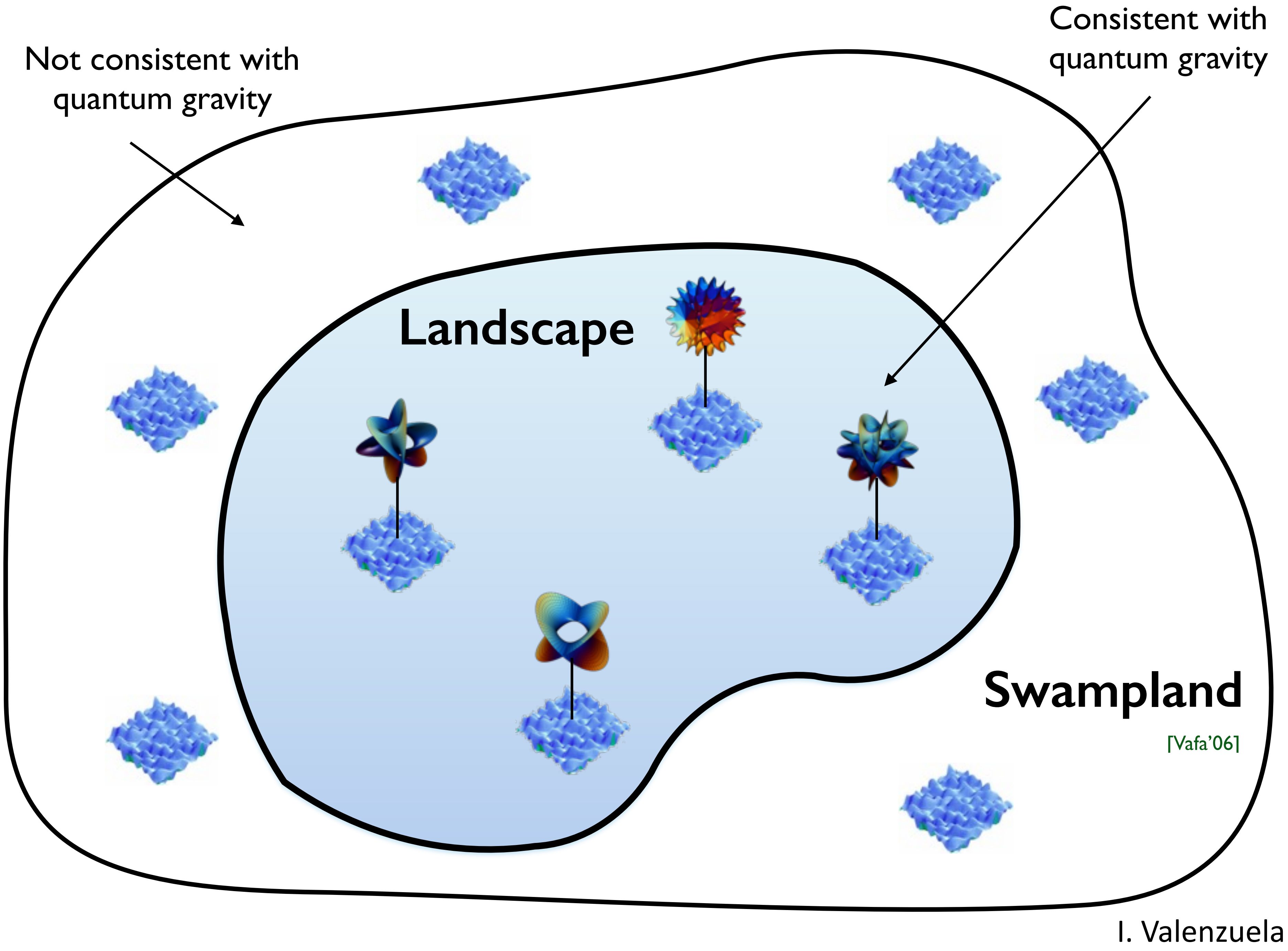
Cosmological sources of stochastic High Frequency Gravitational Waves



Sources of Coherent Gravitational Waves



The Swampland?


Not consistent with quantum gravity
Consistent with quantum gravity
Landscape
Swampland
[Vafa'06]
I. Valenzuela

Swampland conjectures

Vafa et al.

- Swampland: Quantum gravity vs EFT !
- No global symmetries
- Weak gravity conjecture
- Distance conjecture
- ‘anti’- de Sitter conjecture:

(It would imply quintessence and no de Sitter and hard to have inflation!?).

$$M_p \frac{|\nabla V|}{V} \gtrsim c\,,$$

Obied et al

- TransPlanckian Conjecture
- Cobordism conjecture…

Reviews:
Palti 1903.06239
Valenzuela 2102.01111

Amplitudes/Bootstrap

- **SAGEX** https://sagex.org/
- **Bootstrap constraints (Unitarity, locality, causality,…)**
  Review: 2202.11012
- **Bootstrap and cosmology** e.g. Baumann et al 2020, Pajer et al 2021-22, Cespedes et al 2021
  Review: 2203.08121
- **Amplitudehedron,…** e.g. Arkani-Hamed et al 2012.15849
- **Bootstrap and swampland?**

Conclusions

- Continuous steady progress
- Different avenues (black holes, holography, fluxes, dS, swampland, amplitudes, bootstrap, generalized symmetries,etc.)
- Potential contact with phenomenology/experiment (Gravitational waves, axions, cmb, …)
- Many open questions