Cosmology of String Moduli and the Swampland

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SILAFAE 2018
Lima, Peru, 2018

Based on Articles

- S. Antusch, F. Cefala, S. Krippendorf, F. Muia, S. Orani and FQ:
  "Oscillons from String Moduli,''
  JHEP {1801} (2018) 083, [arXiv:1708.08922.

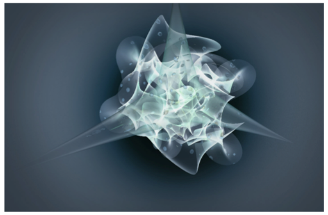
- S. Krippendorf, F. Muia and FQ,
  ``Moduli Stars,''
  JHEP {1808} (2018) 070, [arXiv:1806.04690].

- M Cicoli, S. de Alwis, A. Maharana, F. Muia and FQ
  "de Sitter vs Quintessence in String Theory,"
  [arXiv:1808.08967].

- J.P. Conlon and FQ
  "Putting the Boot into the Swampland,"
  [arXiv:1811.06276].

Strings and Moduli

- String theory predicts (6 or 7) extra dimensions
- Major problem: Fixing size and shape of extra dimensions (moduli)



- Progress to fix all moduli: only this century (GKP, KKLT, LVS,...)
- In some cases the 4D space = de Sitter space ($\Lambda>0$)

Physics of Moduli

- Moduli: scalar particles in 4D: candidates for inflatons
- Gravitational strength couplings
- Mass of moduli ~ gravitino mass
- Each modulus equivalent to saxion+axion
- Number of moduli order 100-1000

Moduli Stabilisation in IIB

- Moduli S, T_i, U_a

$$V_F = e^K \left(K^{-1}_{M\bar{N}} D_M W \overline{D}_{\overline{M}} \overline{W} - 3|W|^2 \right)$$

$$W_{\rm tree} = W_{\rm flux}(U,S) \qquad K^{-1}_{i\bar{\jmath}} K_i K_{\bar{\jmath}} = 3$$

No-scale

$$V_F = e^K \left(K^{-1}_{a\bar{b}} D_a W D_{\bar{b}} W \right) \geq 0$$

Fix S,U but T arbitrary

- Quantum corrections $\delta V \propto W_0^2 \delta K + W_0 \delta W$
- Three options: $W_0 \gg \delta W$ $\quad \delta K \gg \delta W$ Runaway: Dine-Seiberg problem

$$W_0 \sim \delta W = W_{\rm np}.$$
$$W_0 \ll 1$$

Fix T-modulus: KKLT

$$\delta K \sim W_0 \delta W$$
$$\delta K \sim 1/\mathcal{V} \text{ and } \delta W \sim e^{-a\tau}$$

Fix T-moduli: LVS

String Cosmology

- Epochs: Pre-inflation, inflation, post-inflation (pre-BBN)
- Chiral spectrum implies N=0,1 in 4D (work with N=1)
- Strings relevant in postinflation? (yes: moduli).

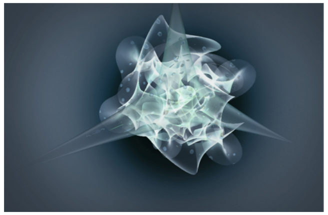
“Generically”: If EFT is suspersymmetric then the moduli survive at low energies until susy breaks:

$$\text{mass}_{\text{moduli}} \approx m_{\text{gravitino.}}$$

(but interesting exceptions!)

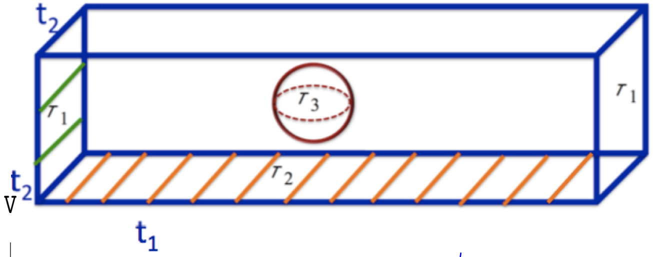
Kahler moduli

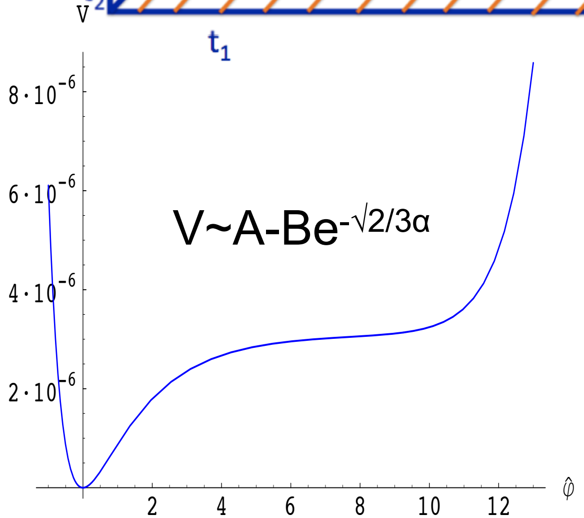
- Overall volume



- Blow-up

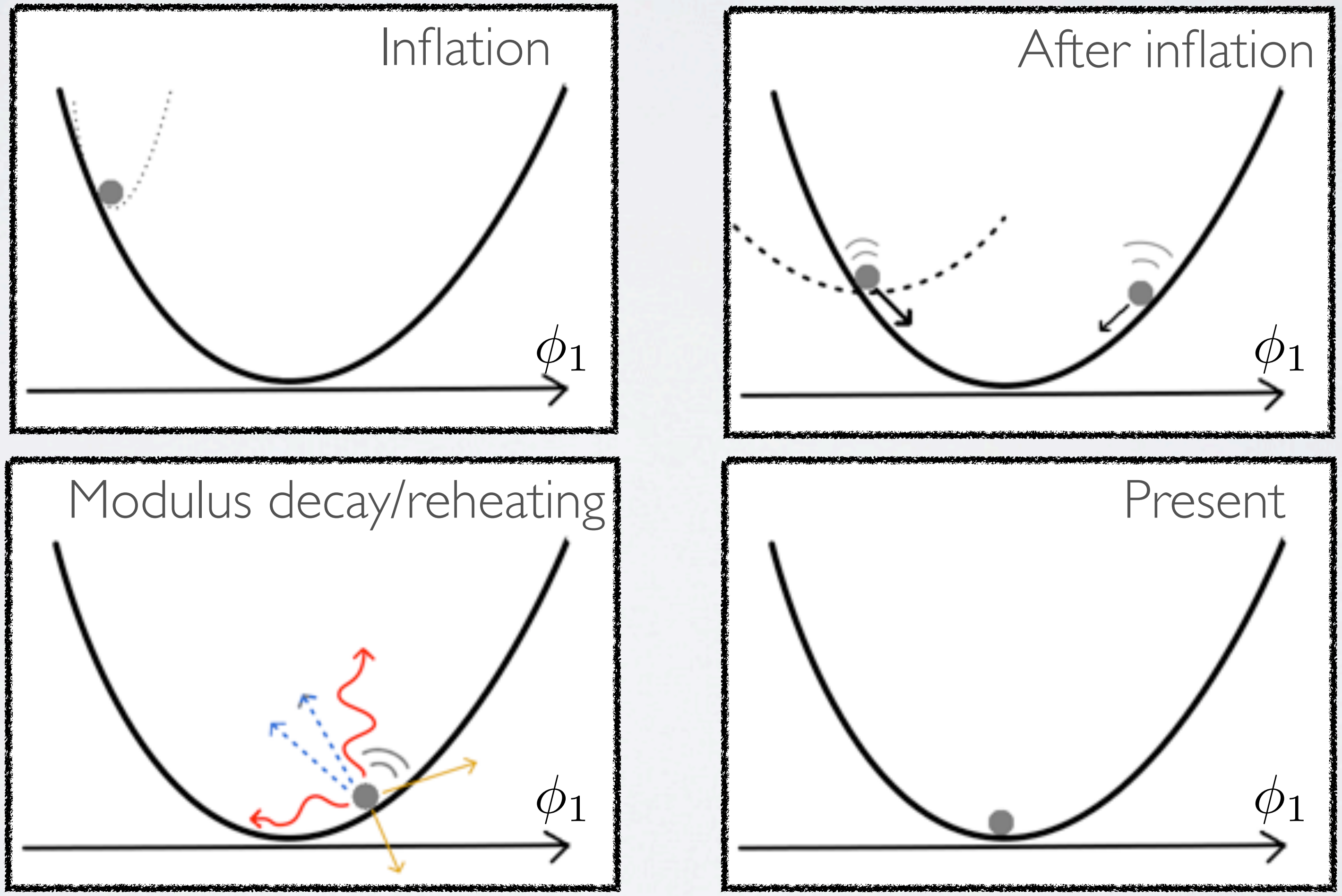
- Fibre moduli





Post Inflation

Moduli Domination



$$\Gamma_\phi \sim \frac{1}{8\pi}\frac{m_\phi^3}{M_{\rm Pl}^2}$$

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

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

Oscillons* from String Moduli

Antusch, Cefalá, Krippendorf, Muia, Orani, FQ

arXiv:1708.08922

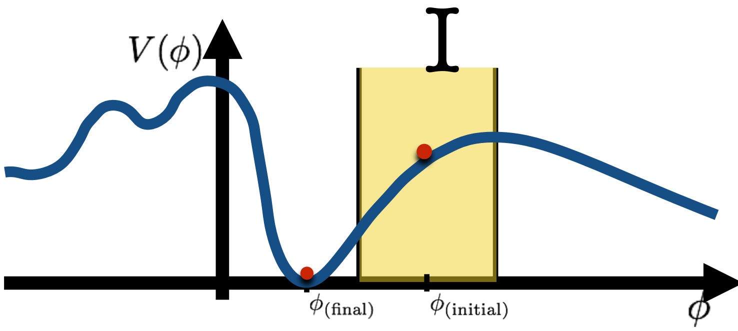
*localised, long-lived, non-linear excitations of the scalar fields.

Generalities

- Exponentially growing solutions:

$$\ddot{\phi}(t) + 3H\dot{\phi}(t) + V'(\phi(t)) = 0$$

$$\delta\ddot{\phi}_k + 3H\delta\dot{\phi}_k + \left(\frac{k^2}{a^2(t)} + V''(\phi(t))\right)\delta\phi_k = 0$$



- Conditions for unstable solutions:
  i. parametric resonance
  ii. tachyonic preheating (modulus displaced in I)

$$k^2/a^2 + \partial^2 V/\partial\phi^2 < 0$$

  iii. tachyonic oscillations (oscillations reach I)

$$k_p \sim \sqrt{\partial^2 V/\partial\phi^2|_{\min}} \equiv m$$

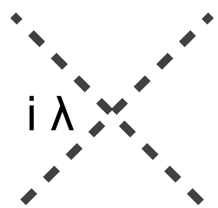
Necessary Conditions for Oscillons production

- Quantum fluctuations of the field grow as it oscillates around the minimum.

- The growth of fluctuations is sufficiently strong for non-linear interactions to become important.

- The potential is shallower than quadratic away from the minimum in some field space region relevant for the dynamics of the field.

$$V = \frac{m^2}{2}\phi^2 - \frac{\lambda}{4!}\phi^4 + \ldots$$



Attractive 'force' for $\lambda > 0$

Lattice simulations*

- LatticeEasy: to analyse strong growth of perturbations.

$$\ddot{\phi} + 3H\dot{\phi} - \frac{1}{a^2}\nabla^2\phi + \frac{\partial V}{\partial \phi} = 0 \qquad H^2 = \frac{1}{3M_{\mathrm{Pl}}^2}\left(V + \frac{1}{2}\dot{\phi}^2 + \frac{1}{2a^2}|\nabla\phi|^2\right)$$

- Modified version to calculate also metric perturbations:

$$ds^2 = -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j$$

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = \frac{2}{M_{\mathrm{Pl}}^2}\Pi_{ij}^{\mathrm{TT}} \qquad \Pi_{ij}^{\mathrm{TT}} = \frac{1}{a^2}\left[\partial_i\phi\partial_j\phi\right]^{\mathrm{TT}}$$

$$\Omega_{\mathrm{GW}}(k) = \frac{1}{\rho_{\mathrm{c}}}\,k\,\frac{d\,\rho_{\mathrm{GW}}}{dk} \qquad \rho_{\mathrm{GW}}(t) = \frac{M_{\mathrm{Pl}}^2}{4}\left\langle \dot{h}_{ij}(\mathbf{x},t)\dot{h}_{ij}(\mathbf{x},t)\right\rangle_{\mathrm{V}}$$

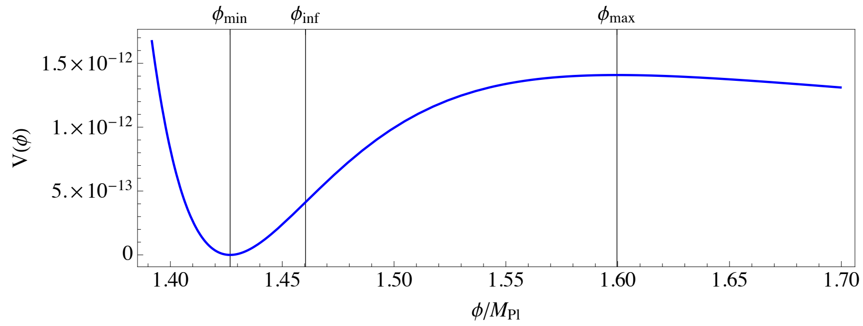
*Plus Floquet analysis

KKLT Oscillons

$$V/M_{\rm Pl}^4 = \frac{e^{K_{\rm cs}}}{6\tau^2}\left(aA^2(3+a\tau)e^{-2a\tau} - 3aAe^{-a\tau}W_0\right) \ .$$

$$\phi/M_{\rm Pl} = \frac{\sqrt{3}}{2}\log\left(T+\bar{T}\right).$$

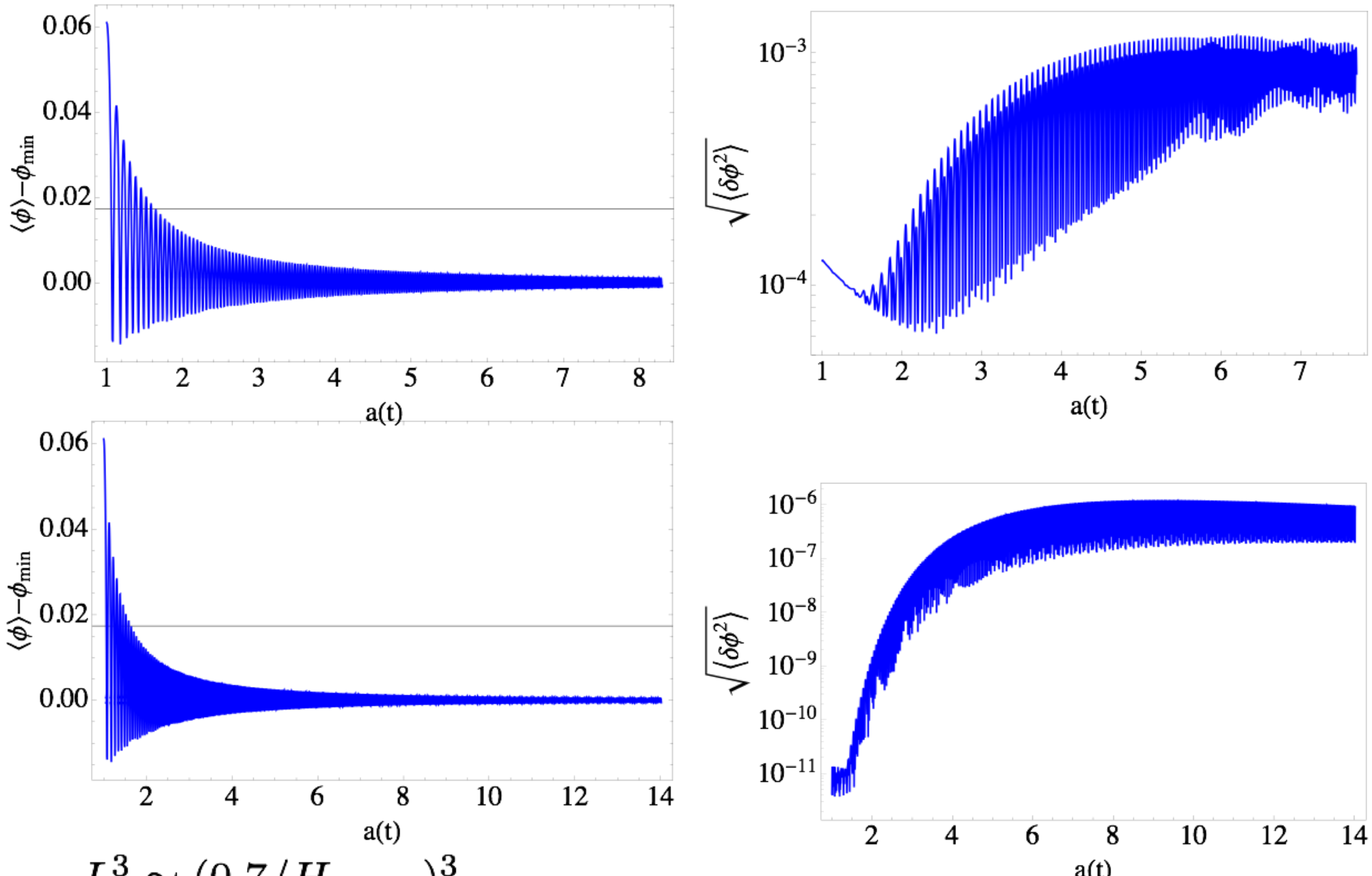
$$10^{-12} \leq W_0 \leq 10^{-5}\,, \qquad 1 \leq A \leq 10\,, \qquad 1 \leq a \leq 2\pi \ .$$



KKLT results

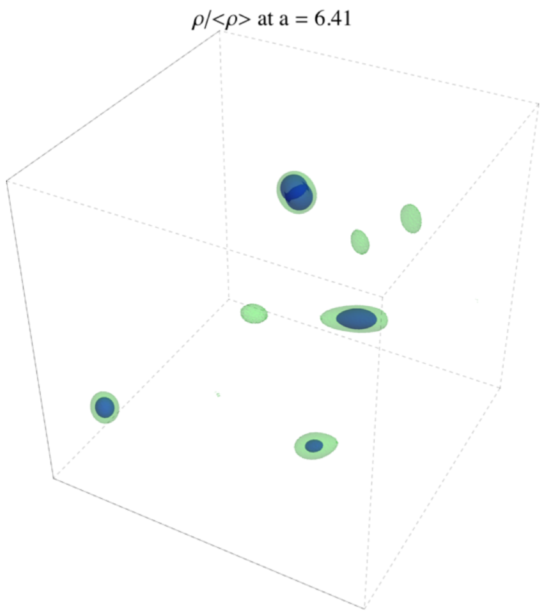
$W_0 = 10^{-12}$
(no oscillons)

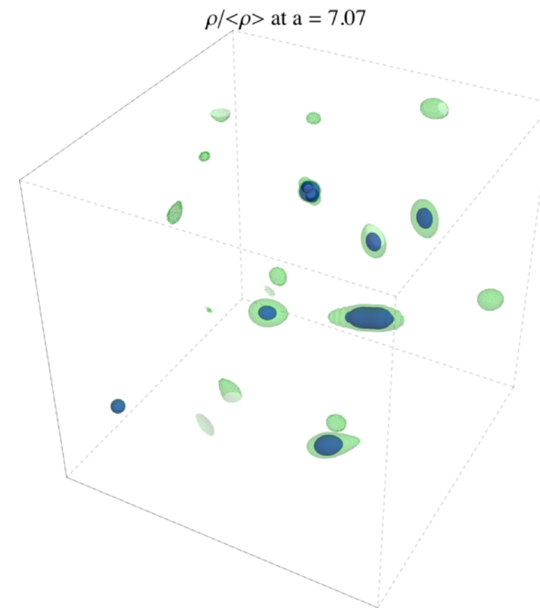
$W_0 = 10^{-5}$
oscillons
generated



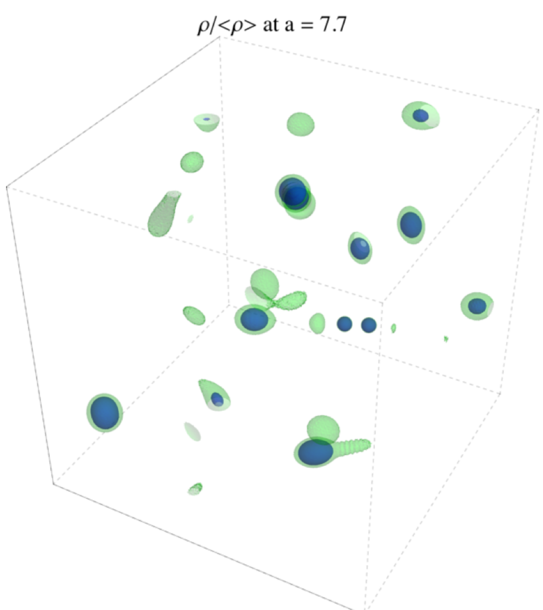
512^3 points $L^3 \simeq (0.7/H_{\mathrm{initial}})^3$

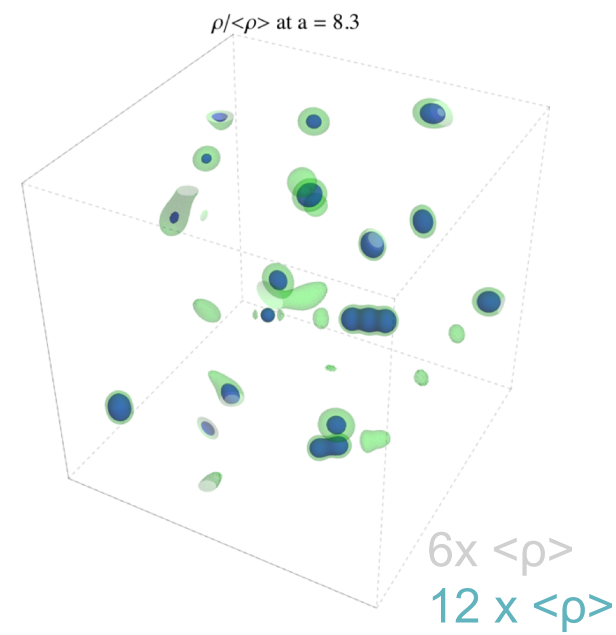
Snapshots



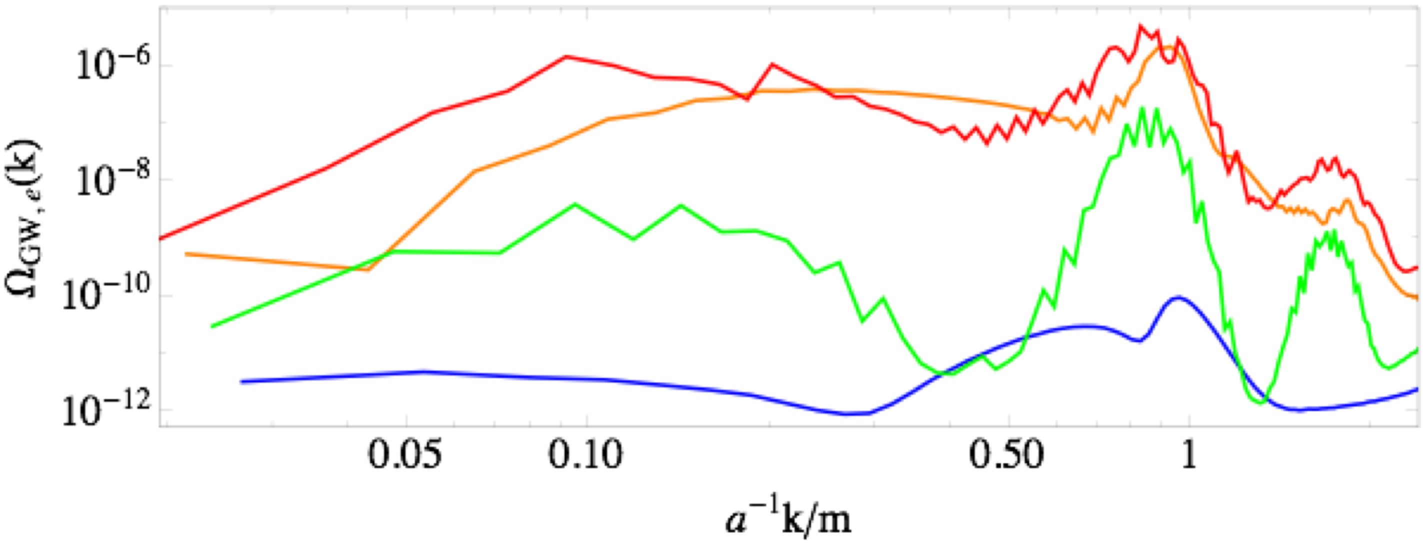


$W_0=10^{-5}$
A=10
a=2π





GW spectrum: KKLT

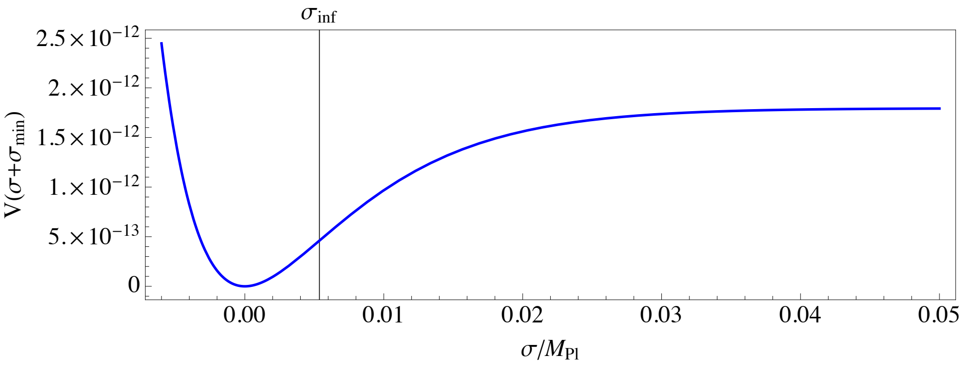


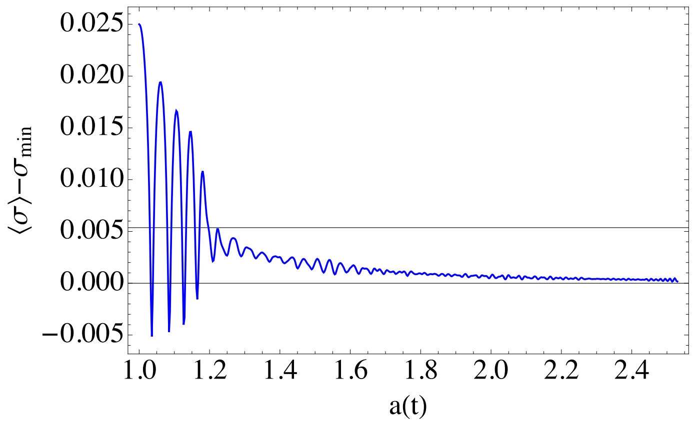
$f_{0,\mathrm{peak}} \sim 10^9\ \mathrm{Hz}$ $\Omega_{\mathrm{GW},0}(f_{0,\mathrm{peak}}) \sim 3 \times 10^{-11}$

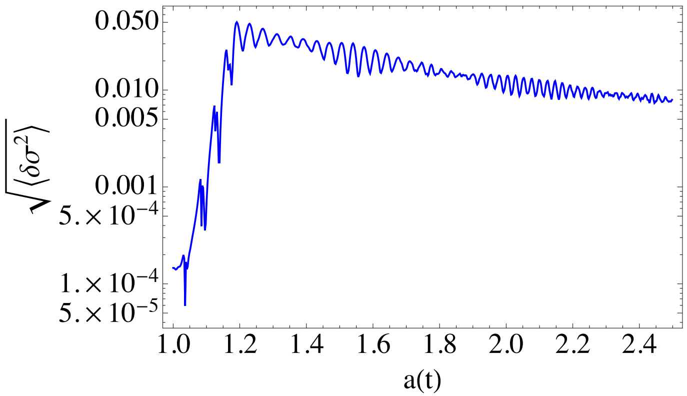
*Overall scaling can lower frequency but also lower the amplitude

Blow-up Potential in LVS

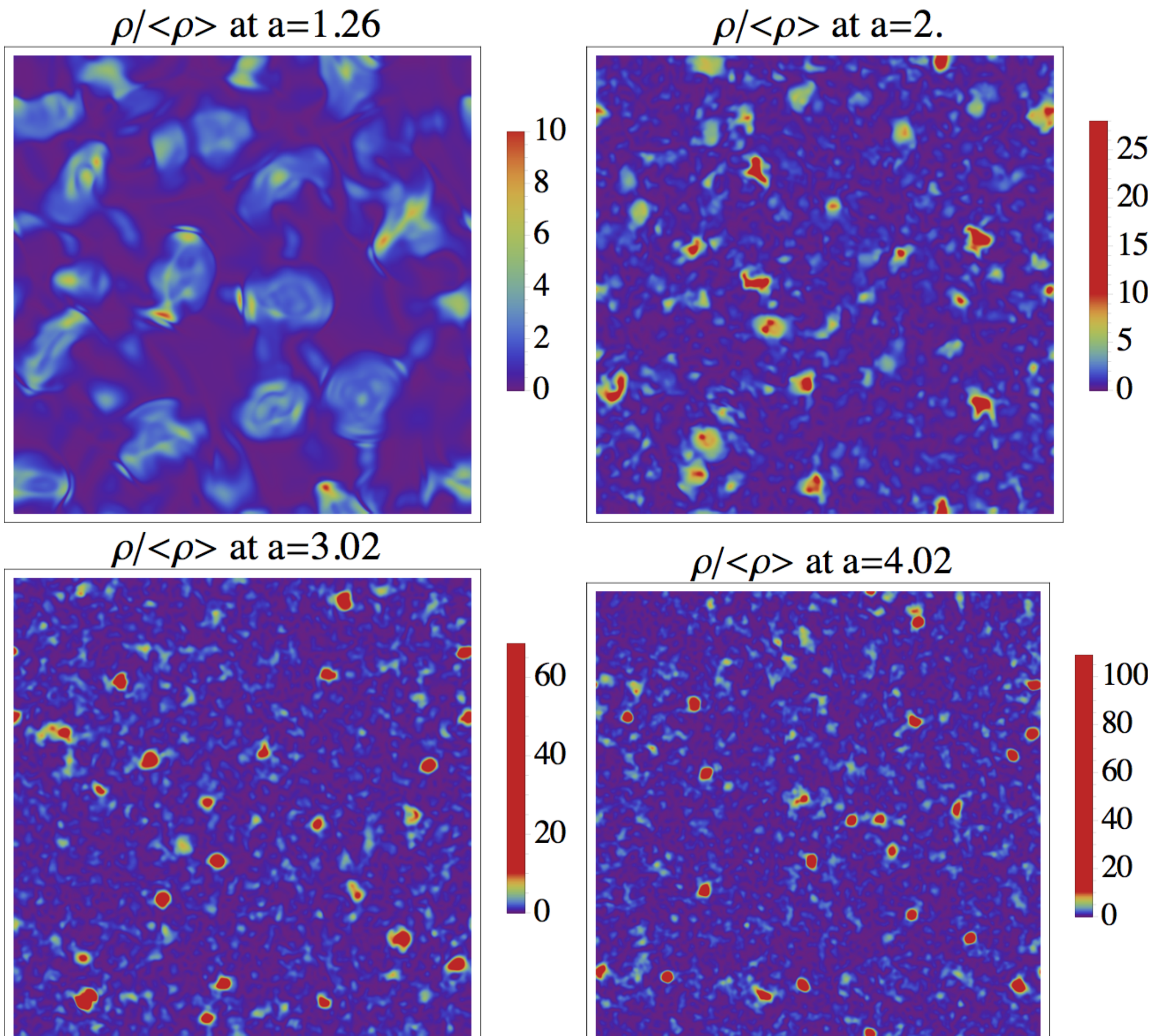
$$V \sim V_0 \left(1 - \kappa(\sigma) e^{-\alpha \sigma^{4/3}}\right)^2 ,$$



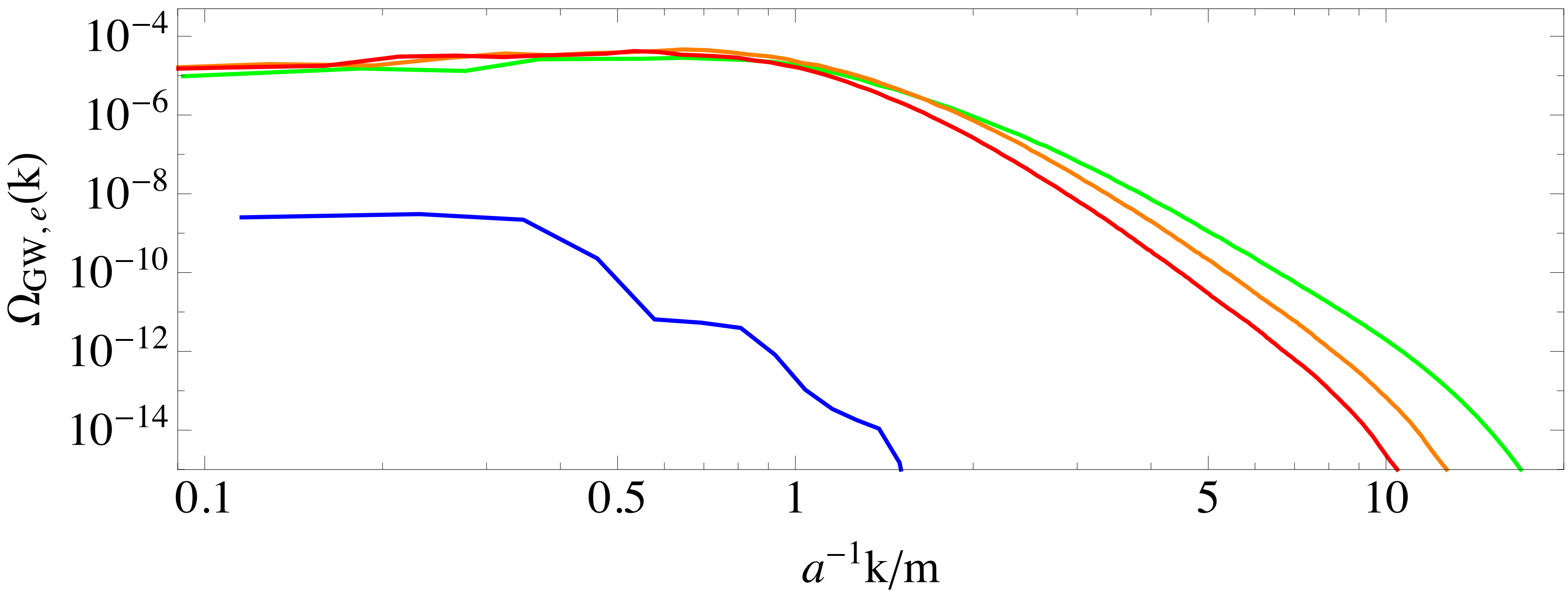




Oscillons from Blow-up mode



Gravitational Waves



$$f_0 \sim 10^8\,\mathrm{Hz} - 10^9\,\mathrm{Hz}\,, \qquad \text{with} \qquad \Omega_{\mathrm{GW},0} \sim 10^{-10} - 5\times 10^{-10}\,.$$

*No oscillons for volume nor fibre moduli but also no overshooting!

Moduli Stars

Krippendorf, Muia + FQ
JHEP {1808} (2018) 070, [arXiv:1806.04690].

Boson and Fermion Stars

- Fermion stars: Gravity vs fermion pressure

$$GM^2/R \sim N^{4/3}/R\,, \qquad N = M/m$$

$$M_{\max} \sim \frac{M_{\rm P}^3}{m_f^2} \qquad R_{\min} \sim \frac{M_{\rm P}}{m_f^2}.$$

(e.g. $M \sim M_\odot$ for $m \sim 1\ \mathrm{GeV}$ neutron star)

- Boson stars: Gravitational BEC

Heisenberg R>1/m
Schwarschild R ~ 2GM

$$R_{\min} \sim \frac{1}{m}\,. \qquad M_{\max} \sim \frac{M_{\rm P}^2}{m}\,.$$

But adding interactions $M_c \sim M_p^3/m^2$

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)
  (+ axion miniclusters)

Are there stringy boson/fermion stars?

Candidates:
Long-lived (stable) gravitationally coupled fields:

- hidden sector fermions/bosons,
- moduli,
- modulini,
- gravitini

Stringy Fermion Stars

Gravitino and modulini:

$$M_{\max} \sim \frac{M_{\mathrm{P}}^3}{m_f^2} \qquad\qquad m_f = m_{3/2} = \frac{W_0}{\mathcal{V}}$$

Validity of EFT and Cosmological moduli problem: $10^3 \leq \mathcal{V} \leq 10^9$

$$1\,\mathrm{g} \lesssim M \lesssim 10^{15}\,\mathrm{g}\,, \qquad 10^{-27}\,\mathrm{cm} \lesssim R \lesssim 10^{-15}\,\mathrm{cm}$$

Recall: $M_\odot \simeq 2 \times 10^{33}\,\mathrm{g} \simeq 10^{57}\,\mathrm{GeV}\,.$ $\quad 1\,\mathrm{GeV} \simeq 1.8 \times 10^{-24}\,\mathrm{g}$

Volume modulus stars

$$S = \int d^4x \sqrt{-g} \left[-\frac{g^{\mu\nu}}{2} \partial_\mu \varphi \partial_\nu \varphi - V(\varphi) \right]$$

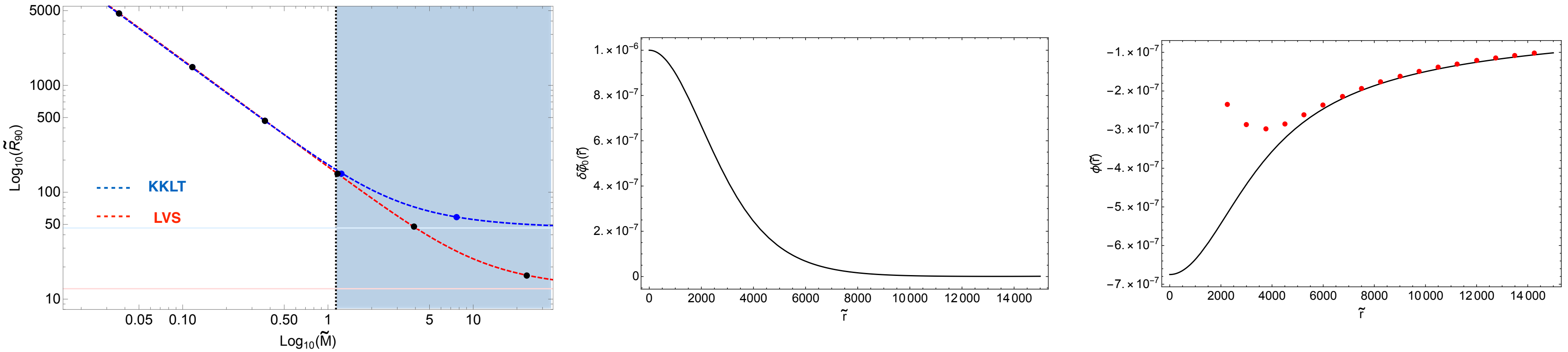
$$\varphi(r,t) = \varphi_0(r) \cos(\omega t) \ ,$$

$$ds^2 = -(1+2\phi)dt^2 + (1-2\phi)\, dr^2 + r^2 d\Omega^2 \, ,$$

$$\tilde{\varphi}_0''(\tilde{r}) + \frac{2}{\tilde{r}} \tilde{\varphi}_0'(\tilde{r}) = 2\left(\phi(\tilde{r}) - \epsilon\right) \tilde{\varphi}_0(\tilde{r}) \, ,$$

$$\phi''(\tilde{r}) + \frac{2}{\tilde{r}} \phi'(\tilde{r}) = \frac{\tilde{\varphi}_0^2(\tilde{r})}{4} \, ,$$

$$M(r) = \left(\frac{\Lambda^2}{m}\right) \tilde{M}(\tilde{r}) \, , \qquad \tilde{M}(\tilde{r}) = 4\pi \int_0^{\tilde{r}} d\tilde{r}' \, \tilde{r}'^2 \tilde{\rho}(\tilde{r}') \, .$$



Q-Balls*

...Coleman (1985)...

Complex scalar, U(1) global symmetry

$$\mathcal{L} = \int d^3x \left(\frac{1}{2} \partial^\mu \Phi \partial_\mu \Phi^* \; - \; U(|\Phi|) \right)$$

U minimum at Φ=0

Noether current and conserved charge

$$J_\mu = \frac{1}{2i} \left(\Phi^* \partial_\mu \Phi - \Phi \partial_\mu \Phi^* \right); \qquad Q = \int d^3x J^0 = \frac{1}{2i} \int d^3x \left(\Phi^* \dot{\Phi} - h.c. \right)$$

Extrema of energy

$$E_\omega = \int d^3x \left(\frac{1}{2} |\dot{\Phi}|^2 + \frac{1}{2} |\nabla \Phi|^2 + U(|\Phi|) \right) + \omega \left(Q - \frac{1}{2i} \int d^3x \left(\Phi^* \dot{\Phi} - h.c. \right) \right)$$

$$= \int d^3x \left(\frac{1}{2} |\dot{\Phi} - i\omega \Phi|^2 + \frac{1}{2} |\nabla \Phi|^2 + \hat{U}(|\Phi|) \right) + \omega Q \qquad \hat{U}_\omega(|\Phi|) = U(|\Phi|) - \frac{1}{2} \omega^2 |\Phi|^2.$$

$$\Phi(x,t) = \varphi(x) e^{i\omega t}$$

Thin wall approximation (large Q)

$$E = Q \sqrt{\frac{2U(\varphi_0)}{\varphi_0^2}}$$

Q-balls in string theory?*

Global symmetries?

1. From (non) anomalous U(1)
2. From Peccei-Quinn symmetries

***Open strings:**

$$U_{\rm D} = g^2 \left(\xi - \sum_i q_i |\Phi_i|^2 \right)^2$$

$$U_{\rm soft} = \sum_i m_i^2 \, |\Phi_i|^2 + \left(\sum_{ijk} A_{ijk} \, \Phi_i \Phi_j \Phi_k + \sum_{ij} B_{ij} \, \Phi_i \Phi_j + h.c. \right)$$

$$E^2 = \frac{2U}{\sum_i q_i |\Phi_i|^2} = \frac{2(U_D + U_{soft})}{\sum_i q_i |\Phi_i|^2}$$

MInimum for novanishing: $\rho^2 = \sum_i q_i \rho_i^2 = \sum_i q_i |\Phi_i|^2$

e.g. Kusenko (1997) for MSSM

Closed string sector*

- Massive moduli + axion
  (generalised axion stars, m> 1 TeV)

- Axion much lighter
  (Ultra-light axion)

$$V_\psi = \frac{g_s}{2\pi} a_b A_b \frac{e^{-a_b \tau_b}}{\tau_b^2} \left[1 + \cos\left(a_b \psi_b\right)\right] \, ,$$

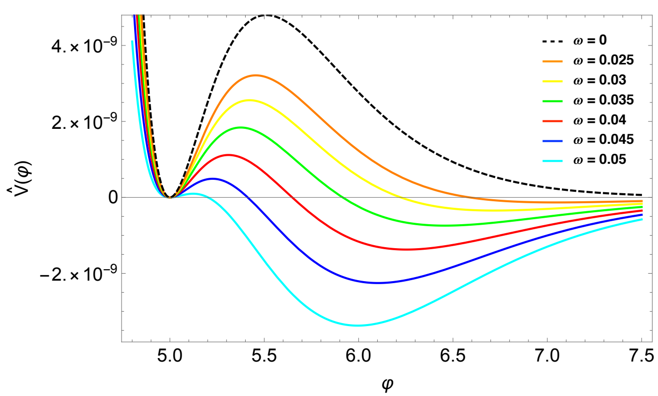
- PQ symmetry almost exact (PQ-balls?)

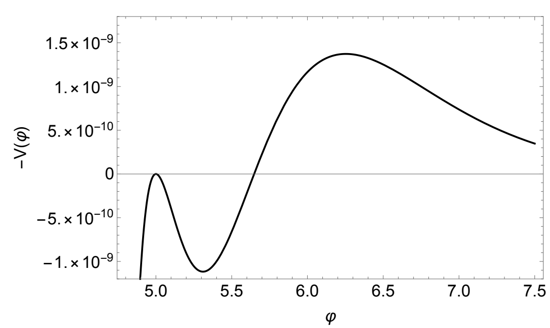
PQ Balls?*

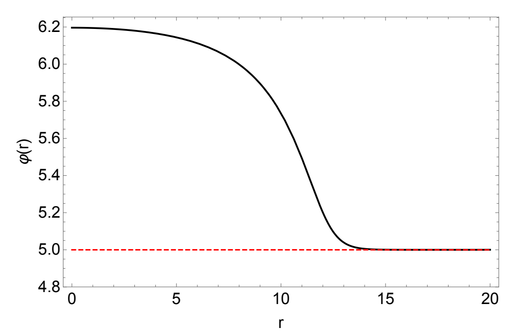
$$S = \int d^4x \, \mathcal{L} = \int d^4x \, [-f(\tau) \, [\partial_\mu \tau \partial^\mu \tau + \partial_\mu \theta \partial^\mu \theta] - V(\tau)]$$

$$\dot{\theta} = \omega \, , \qquad \nabla \theta = 0 \, . \qquad \hat{V}(\tau) = V(\tau) - \omega^2 f(\tau)$$

$$Q = \omega \int d^3x f(\tau) \propto \int 4\pi r^2 dr \frac{\omega}{r^2} \to \infty \, .$$







Spinning Axions?*

$$\mathcal{S} = \int d^4x\,\sqrt{-g}\,[-g^{\mu\nu}\left(\partial_\mu\varphi\partial_\nu\varphi + f(\varphi)\partial_\mu\theta\partial_\nu\theta\right) - V]$$

$$f = \alpha/\tau^2 = \alpha e^{-\sqrt{2/\alpha}\varphi}\,.$$

$$\ddot{\varphi} + 3H\dot{\varphi} + \partial_\varphi V = \frac{q^2\partial_\varphi f}{4a^6 f^2}\,.$$

$$V = V_0\,e^{-\kappa_1\varphi}\,, \qquad f = \alpha\,e^{-\kappa_2\varphi}\,,$$

$$\varphi(t) = B\,\ln t - C\,, \qquad a(t) = t^{\frac{\kappa_1+\kappa_2}{3\kappa_1}} \qquad w(\varphi) = \frac{\kappa_1-\kappa_2}{\kappa_1+\kappa_2}\,.$$

Similar to spintessence

Formation Mechanisms?

I) There is some initial localized overdensity;

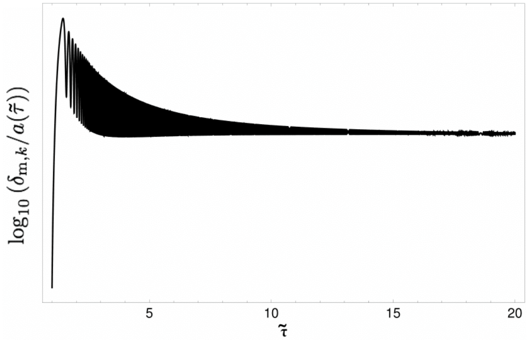
II) The initial overdensity collapses due to the effect of attractive interactions.

$$\delta_{\rm m,k} \equiv \frac{\delta\rho_{\rm m,k}}{\langle\rho\rangle} \propto a(t) \sim t^{2/3}\,, \qquad k \gg aH\,.$$

$$\Psi = \frac{\delta_{\rm m,k}(t_{\rm dec})}{\delta_{\rm m,k}(t_{\rm mat})} \approx \left(\frac{t_{\rm dec}}{t_{\rm mat}}\right)^{2/3} \approx \left(\frac{H_{\rm mat}}{H_{\rm dec}}\right)^{2/3} \approx \left(\frac{m}{\Gamma}\right)^{2/3} \approx \left(\frac{M_{\rm P}}{m}\right)^{4/3}\,,$$

$$\Psi = \left.\frac{\delta_{\rm m,k}(\tau_{\rm dec})}{\delta_{\rm m,k}(\tau_{\rm mat})}\right|_{\mathcal{V}} \approx \left(\frac{M_{\rm P}}{M_{\rm P}/\mathcal{V}^{3/2}}\right)^{4/3} = \mathcal{V}^2\,,$$

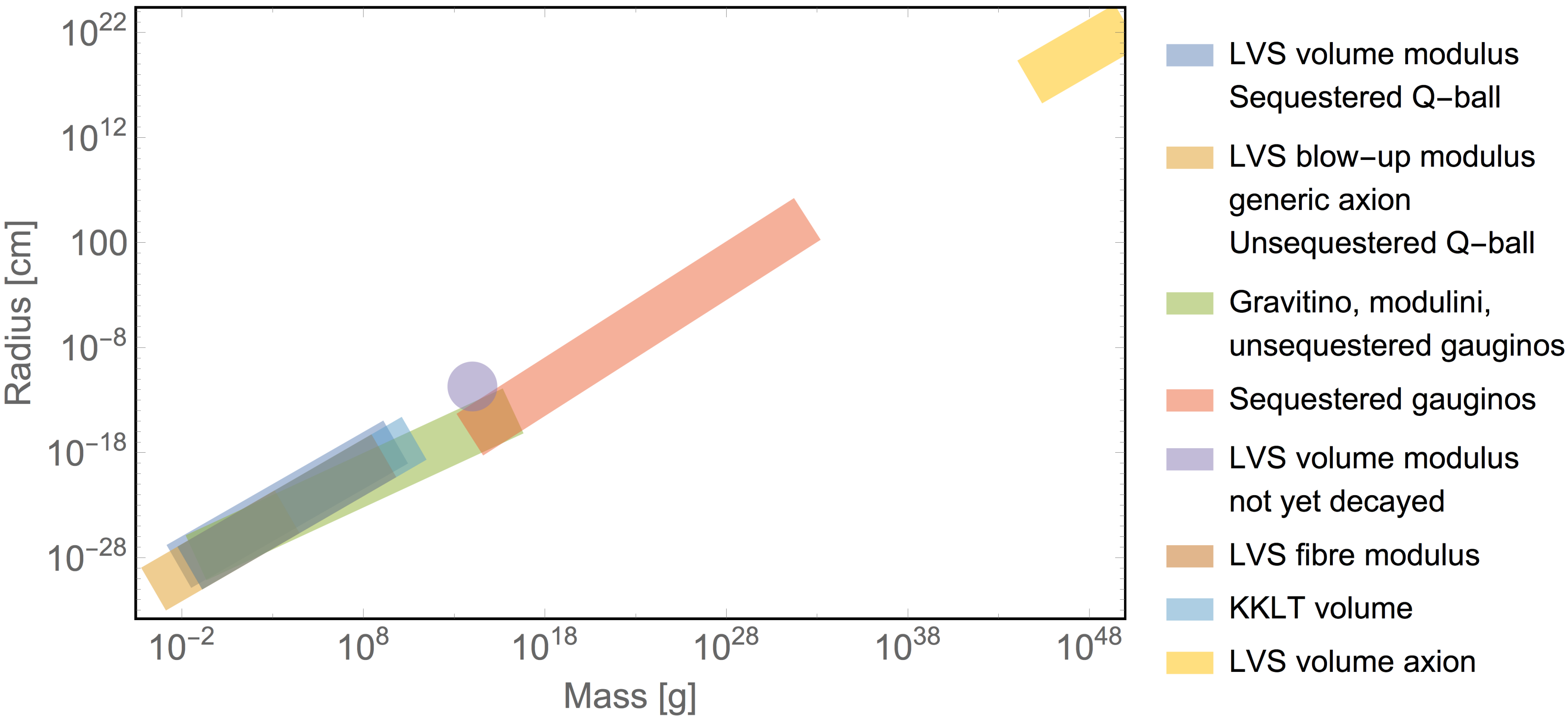
Enhacement factor!



Properties of Moduli Stars

Particle	State mass	Star mass	Star radius	Enhancement
LVS volume modulus	$M_{\rm P}/\mathcal{V}^{3/2}$	$M_{\rm P}\mathcal{V}^{3/2}$	$l_{\rm P}\mathcal{V}^{3/2}$	$\mathcal{V}^{2}$
LVS blow-up modulus Generic axion	$M_{\rm P}/\mathcal{V}$	$M_{\rm P}\mathcal{V}$	$l_{\rm P}\mathcal{V}^{5/3}$	$\mathcal{V}^{4/3}$
LVS fibre moduli	$M_{\rm P}/\mathcal{V}^{5/3}$	$M_{\rm P}\mathcal{V}^{5/3}$	$l_{\rm P}\mathcal{V}^{5/3}$	$\mathcal{V}^{20/9}$
LVS volume axion	$M_{\rm P}e^{-\alpha\mathcal{V}^{2/3}}$	$M_{\rm P}e^{\alpha\mathcal{V}^{2/3}}$	$l_{\rm P}e^{\alpha\mathcal{V}^{2/3}}$	$e^{4/3\alpha\mathcal{V}^{2/3}}$
KKLT volume modulus	$M_{\rm P}\lvert W_0\rvert/\mathcal{V}$	$M_{\rm P}\lvert W_0\rvert^{-1}\mathcal{V}$	$l_{\rm P}\lvert W_0\rvert^{-1}\mathcal{V}$	$(\lvert W_0\rvert^{-1}\mathcal{V})^{4/3}$
Gravitino, modulini, unsequestered gauginos	$M_{\rm P}\lvert W_0\rvert/\mathcal{V}$	$M_{\rm P}\mathcal{V}^2/\lvert W_0\rvert^2$	$l_{\rm P}\mathcal{V}^2/\lvert W_0\rvert^2$	$\mathcal{V}^{4/3}/\lvert W_0\rvert^{4/3}$
Sequestered gauginos	$M_{\rm P}/\mathcal{V}^{2}$	$M_{\rm P}\mathcal{V}^{4}$	$l_{\rm P}\mathcal{V}^{4}$	$\mathcal{V}^{8/3}$
Unsequestered Q-balls	$M_{\rm P}/\mathcal{V}$	$M_{\rm P}\mathcal{V}$	$l_{\rm P}\mathcal{V}$	$\mathcal{V}^{4/3}$
Sequestered Q-balls	$M_{\rm P}/\mathcal{V}^{3/2}$	$M_{\rm P}\mathcal{V}^{3/2}$	$l_{\rm P}\mathcal{V}^{3/2}$	$\mathcal{V}^{2}$

Size and Mass of Moduli Stars



de Sitter vs Quintessence

de Sitter Challenges

- Define S-matrix (resonance?)
- Classical no-go theorems (atoms are unstable classically!)
- No dS solution of string theory under full calculational control* (KKLT, LVS,...?)

* de Sitter solutions so far EFT “not under full control” ≠ “no control at all”!

Swampland conjectures

- Swampland: Quantum gravity vs EFT ! Vafa et al.
- Weak gravity conjecture
- Distance conjecture
- New (non) de Sitter conjecture: $M_p \frac{|\nabla V|}{V} \gtrsim c \,,$

(It would imply quintessence and no de Sitter Obied et al

and difficult to have inflation!).

Challenges for the new conjecture

- Higgs potential with quintessence field? (at the <H>=0 point.

Denef et al.

- If V asymptotes to infinite from above even supersymmetric AdS forbidden.

Conlon

- Both addressed if modify conjecture (allow saddle points for V>0).

see e.g. Andriot
Ooguri et al

Quintessence from Strings?

- Need stabilise all moduli except for quintessence field: as difficult as getting de Sitter
- Or have many fields rolling but slower than quintessence. Difficult.
- Fifth force and varying couplings constraints (e.g. volume modulus or dilaton problematic)

Quintessence Candidates

- Modulus (fibre, blow-up) that does not couple directly to SM. It also would require a very small string scale (e.g. Ms~TeV)

Cicoli, et al

- Axions

$$\mathcal{L} = -\frac{1}{2}\partial^\mu\theta\partial_\mu\theta - \mu^4\left(1 - \cos\left(\frac{\theta}{f}\right)\right) ,$$

K. Choi
Panda et al
Kaloper et al.

Axion Quintessence 1

$$m_a \simeq \sqrt{\frac{g_s}{8\pi}} \frac{M_p}{\mathcal{V}^{2/3}} e^{-\frac{\pi}{N}\mathcal{V}^{2/3}} M_p \,,$$

Naturally very small!

$$V = \Lambda^4 - \sum_{i=1}^{N_{\rm ULA}} \Lambda_i^4 \cos\left(\frac{a_i}{f_i}\right) + \cdots \,,$$

Minimum not necessarily at zero

$$\epsilon = \frac{1}{2}\left[\left(\frac{\Lambda_\ell}{\Lambda}\right)^4 \frac{M_p}{f_\ell}\right]^2 \frac{\sin^2(a_\ell/f_\ell)}{\left(1-(\Lambda_\ell/\Lambda)^4\cos(a_\ell/f_\ell)\right)^2} < 1 \,.$$

Slow-roll

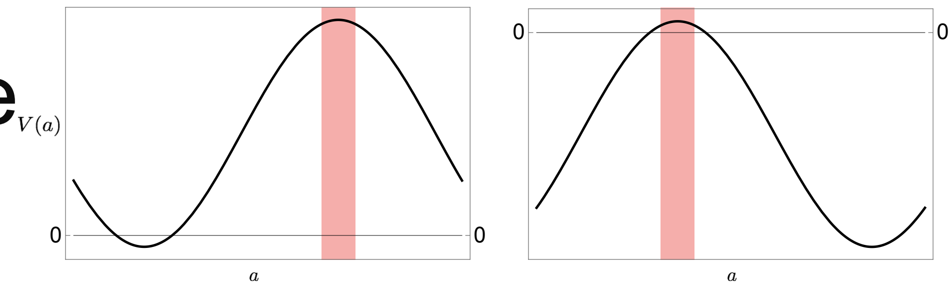
$$f_\ell \gtrsim M_p.$$

Not necessarily

Axion Quintessence 2

- Hilltop Quintessence

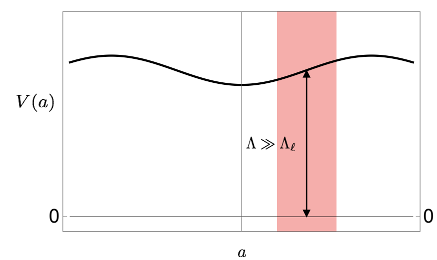
$$\Lambda^4 + \Lambda_i^4 > 0$$



- Quasi-natural quintessence

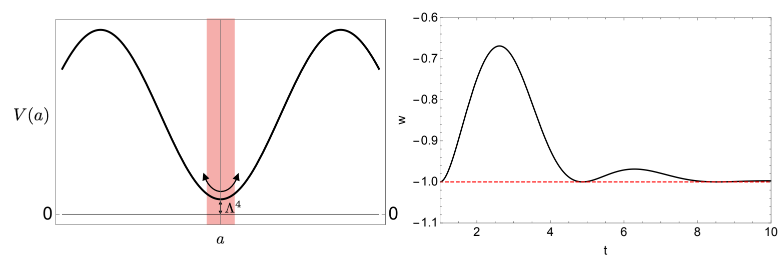
$$f_\ell \gtrsim \left(\frac{\Lambda_\ell}{\Lambda}\right)^4 M_p$$

$$f_\ell < M_p \qquad \Lambda \gg \Lambda_\ell.$$



$$w = \frac{p}{\rho} = \frac{\frac{\dot{a}^2}{2} - V}{\frac{\dot{a}^2}{2} + V} \sim -\frac{1 - \frac{1}{3}\epsilon}{1 + \frac{1}{3}\epsilon} \sim -1 + \frac{2}{3}\epsilon\,.$$

- Oscillating quintessence



AdS/CFT and Bootland Conjectures

Bootland Conjecture

- LVS/CFT correspondence?

$$\Delta = \frac{3(1+\sqrt{19})}{2}\left(1 - \sqrt{\frac{2}{27}}\frac{1}{\langle\Phi\rangle} + \mathcal{O}\left(\frac{1}{\langle\Phi\rangle}\right)^2\right).$$

For Volume mode

$$\Delta_a = 3.$$

For volume axion mode

- n-point functions

$$\mathcal{L}_{(\delta\Phi)^n} = (-1)^{n-1}\lambda^n(n-1)\left(-3\frac{M_P^2}{R_{AdS}^2}\right)\frac{1}{n!}\left(\frac{\delta\Phi}{M_P}\right)^n\left(1+\mathcal{O}\left(\frac{1}{\lambda\langle\Phi\rangle}\right)\right),$$

$$\mathcal{L}_{(\delta\Phi)^{n-2}aa} = \left(-\sqrt{\frac{8}{3}}\right)^{(n-2)}\frac{1}{2(n-2)!}\left(\frac{\delta\Phi}{M_P}\right)^{n-2}\partial_\mu a\partial^\mu a,$$

- Bootland: bootstrap constraints in CFT side=Swampland constraints on AdS side.

Conclusions

- Rich spectrum of compact objects (stringy oscillons, gravitino, modulini, moduli, oscillatons, axion stars) Gravitational waves spectrum ('hear the shape of the extra dimensions?')

- de Sitter vs Quintessence: Many achievements, challenges, open questions (*experiments??)

The report of my death was an exaggeration.

Mark Twain

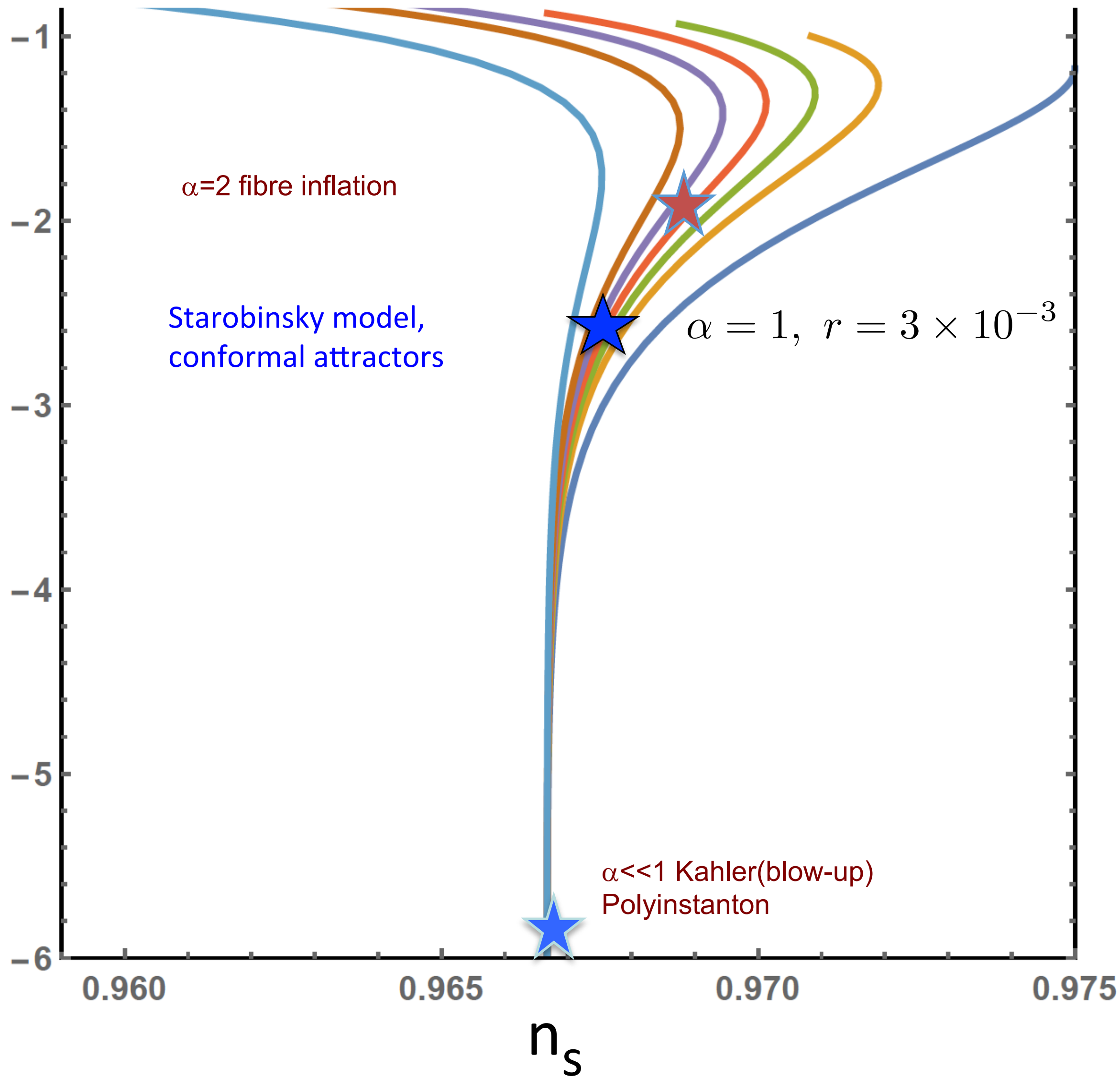
- Swampland conjectures: interesting new perspective, e.g. "bootland" and LVS/CFT, KKLT/CFT

- More? "Standard Model Swampland Conjecture"??..

de Sitter Achievements

- Remarkable: well defined prescription exists that includes all stringy ingredients: branes, orientifolds, warping, anti (T)-branes, perturbative, non-perturbative effects, etc.
- IIB with fluxes~ Calabi-Yau (moduli space understood).
- W_0<<1 is plausible (not achieved yet) due to the large number of fluxes.
- Perturbative effects in LVS in better control as the volume is exponentially large. All computed so far harmless.
- Antibrane: nonlinearly realised SUSY (nilpotent superfield)
- Hierarchies: $E \ll M_{\mathrm{KK}} = \frac{M_s}{\mathcal{V}^{1/6}} \ll M_s \equiv \frac{1}{\ell_s} \equiv \frac{1}{2\pi\sqrt{\alpha'}} = g_s^{1/4}\frac{M_p}{\sqrt{4\pi\mathcal{V}}}\,.$

Inflation: Fibre+Blow-up



Adapted from
Kallosh, Linde
α-attractors

Conclusions 2

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Challenges to KKLT, LVS,...

- Fluxes under full control only in SUSY 10D   Sethi
- All SUSY breaking part is 4D EFT (with string inputs). Trust EFT?
- Tuning $W_0 << 1$? in KKLT
- Higher correction in LVS?
- Antibranes (by hand, non susy, singularity?)
- T-branes in a control region?   Bena et al.
- Antibranes and non-perturbative effects?

Moritz et al.

String Cosmology

- Some inflationary EFTs describe CMB + other data very well.
- Inflation needs an UV completion.
- Some EFTs of string compactification can describe inflation
- Challenges: Moduli stabilisation and

$$M_{planck} > M_{string} > M_{kk} > M_{inf} \,.$$