Moduli Stars and Bubbles of False Vacuum*

Fernando Quevedo
ICTP + Cambridge

String Phenomenology
CERN June 2019

*Only time for ”Moduli Stars”   For False Vacuum bubbles: de Alwis, Muia, Pasquarella, FQ to appear 1907.xxxxx

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.

LatticeEasy

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

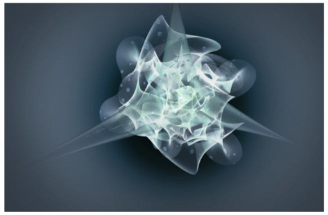
- F. Muia, M. Cicoli, K. Clough, F. Pedro, FQ, G. Vacca
  ``The Fate of Dense Scalar Stars,”
  [arXiv:1906.09346].

GRChombo

* See also talk by Francesco Muia

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 (Λ>0)

Moduli Stabilisation in IIB

- Moduli S, T_i, U_a

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

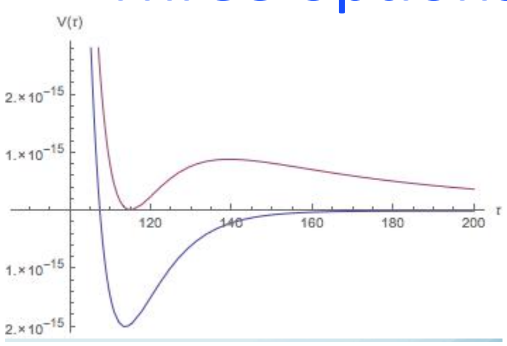
$$W_{\rm tree} = W_{\rm flux}(U,S) \qquad K^{-1}_{i\bar{j}} K_i K_{\bar{j}} = 3$$ No-scale

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

Fix S,U but T arbitrary

- Quantum corrections $\delta V \propto W_0^2 \delta K + W_0 \delta W$
- Three options:

$W_0 \gg \delta W \qquad \delta K \gg \delta W$	Runaway: Dine-Seiberg problem
$W_0 \sim \delta W = W_{\rm np}.$ $W_0 \ll 1$	Fix T-modulus: KKLT
$\delta K \sim W_0 \delta W$ $\delta K \sim 1/\mathcal{V}$ and $\delta W \sim e^{-a\tau}$ $\mathcal{V} \sim e^{a_s \tau_s} \gg 1$ with $\tau_s \sim \frac{\xi^{2/3}}{g_s}$.	Fix T-moduli: LVS



***Warning: Runaway ≠ *Quintessence*!**

de Sitter

- Anti D3 brane
- D+F terms in EFT or T-branes
- Complex structure/Dilaton uplift ($D_U W \neq 0$, $D_S W \neq 0$)
- Non critical strings, negative curvature compactifications, Kahler uplift, nonperturbative effects on D3 branes, ...

Challenges to KKLT, LVS,...

See talks: McCallister, Hebecker, van Riet, Sethi, Grana, Blumenhagen, Tomasiello,…

- Antibranes, fluxes and non-perturbative effects?
- Tuning W_0<<1? in KKLT (W_0 =O(1) in LVS)
- Higher order corrections ?
- T-branes in a controlled region?
- More explicit compact CY (realistic) models of dS
- Populating the landscape (large # of U moduli + vacuum transitions)

See: Cicoli, de Alwis, Maharana, Muia, FQ **arXiv:1808.08967**

Swampland and Bootstrap

J. Conlon, FQ 1811.06276

e.g. LVS/CFT

Mode	Spin	Parity	Conformal dimension
$T_{\mu\nu}$	2	+	3
a	0	-	3
Φ	0	+	$8.038 = \frac{3}{2}\left(1+\sqrt{19}\right)$

All other conformal dimensions *O(V^a)*

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

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

* LVS Satisfies strong and weak AdS distance conjectures (Palti)

Further Conjectures?

- SUSY at KK scale ?
- Standard Model ?
- Quintessence?

Partly full Partly empty

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).

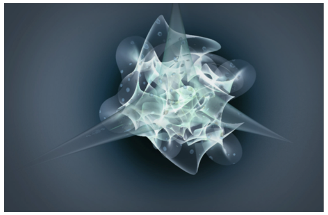
"Generically": If EFT is supersymmetric then the moduli survive at low energies until susy breaks:

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

(but interesting exceptions!)

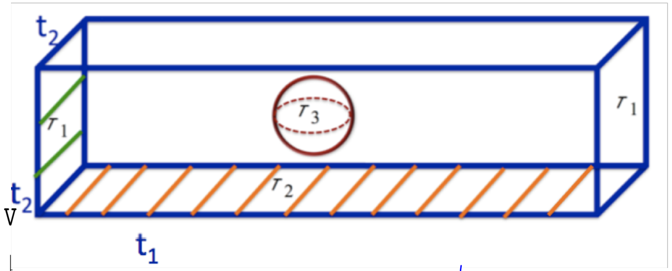
Kahler moduli

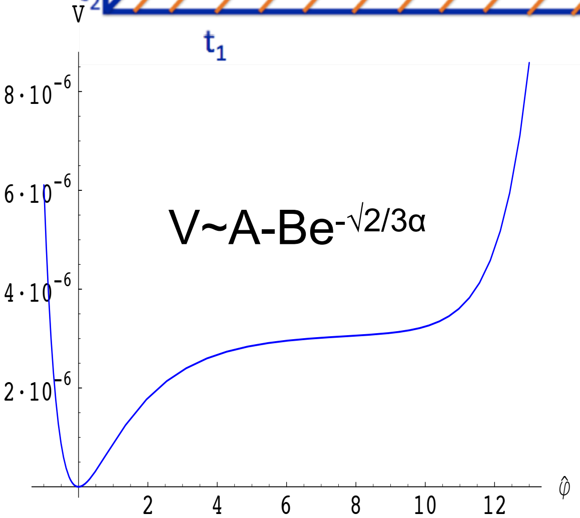
- Overall volume



- Blow-up

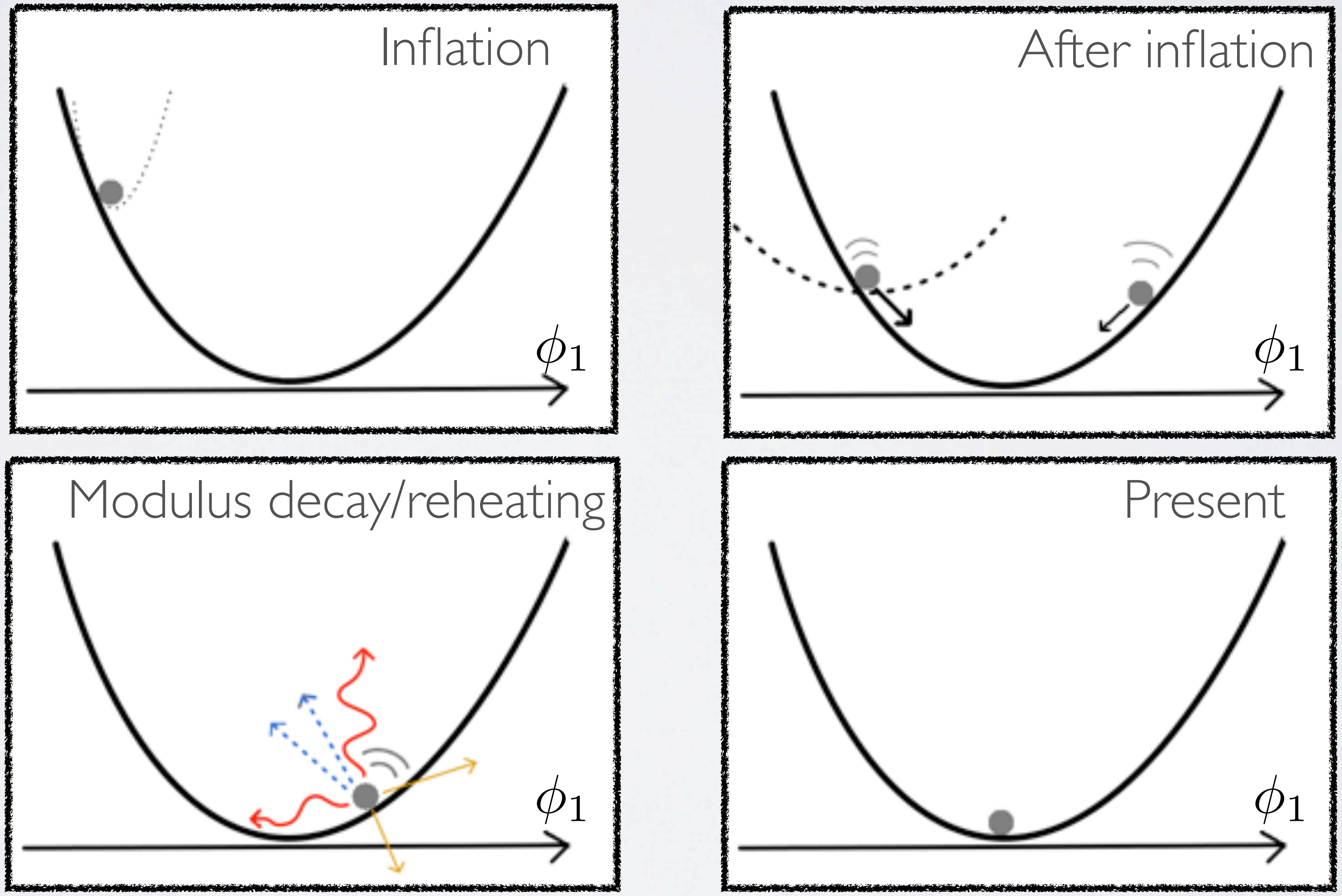
- Fibre moduli





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

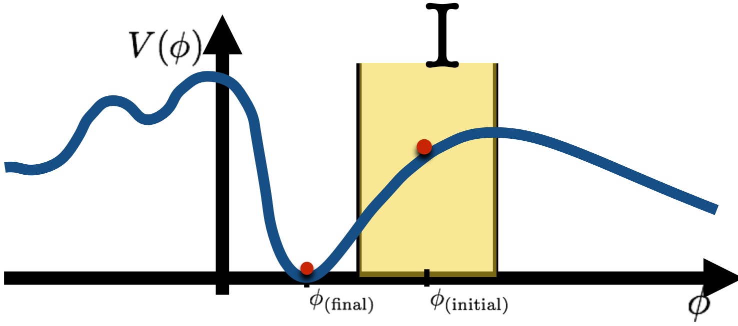
*localised, long-lived, non-linear excitations of the scalar fields.

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)

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

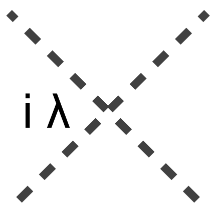
Necessary Conditions for Oscillons production

- 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.

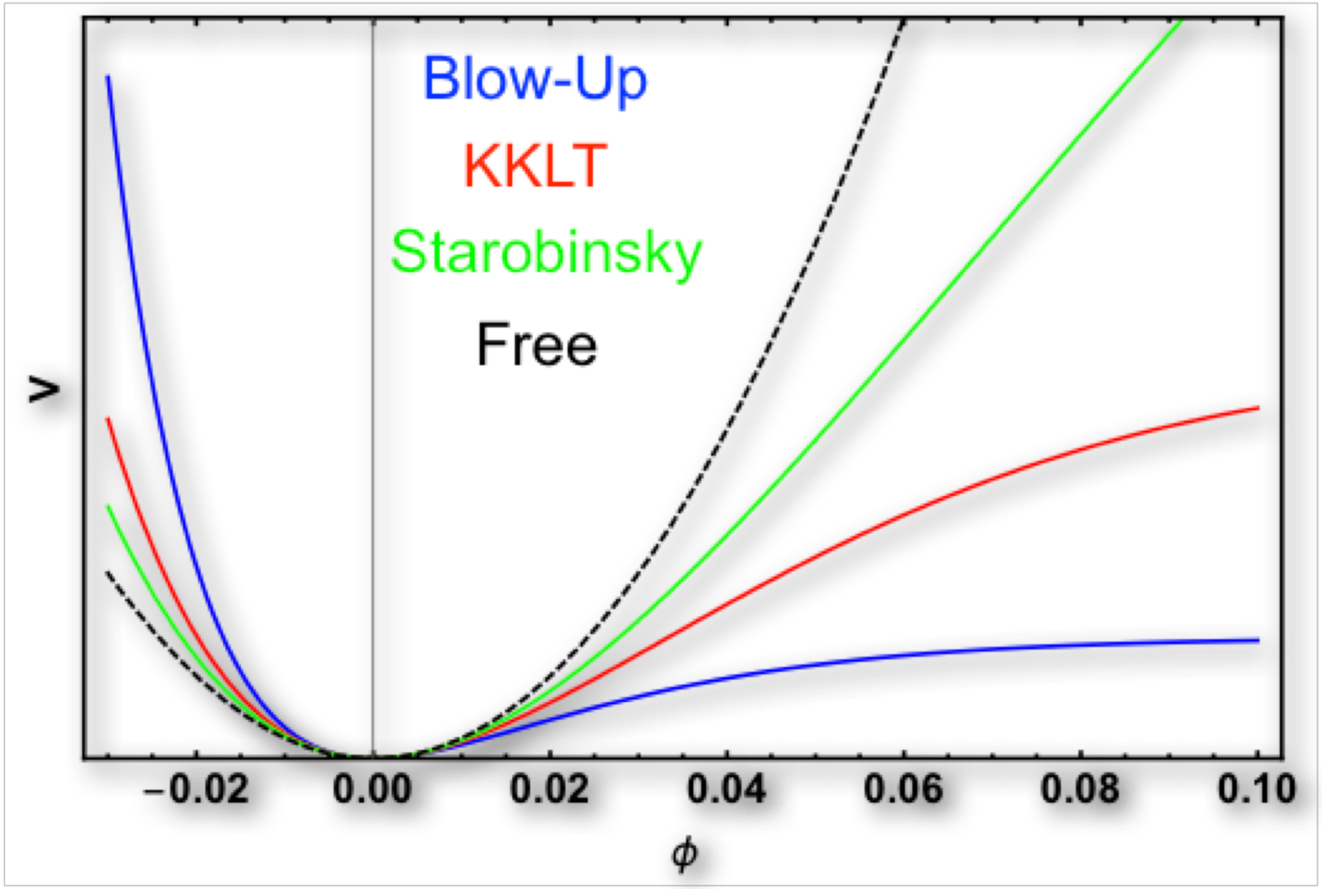
- The potential is shallower than quadratic away from the minimum in some field space region relevant for the dynamics of the field.

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



Attractive ‘force’ for $\lambda > 0$

Moduli Potentials



Lattice simulations*

- LatticeEasy: to analyse strong growth of perturbations.

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

- Modified version to calculate also metric perturbations:

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

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

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

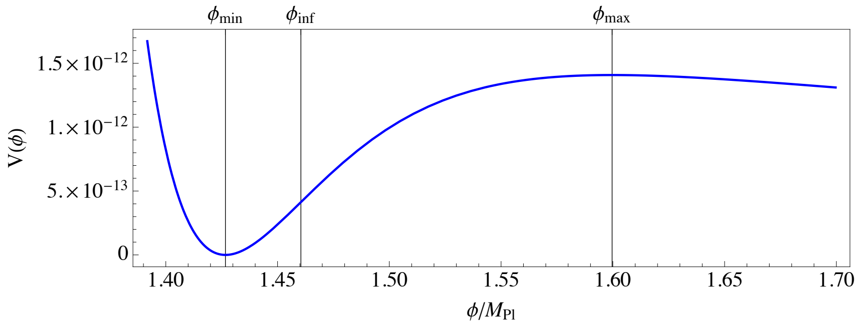
*Plus Floquet analysis

KKLT Oscillons

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

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

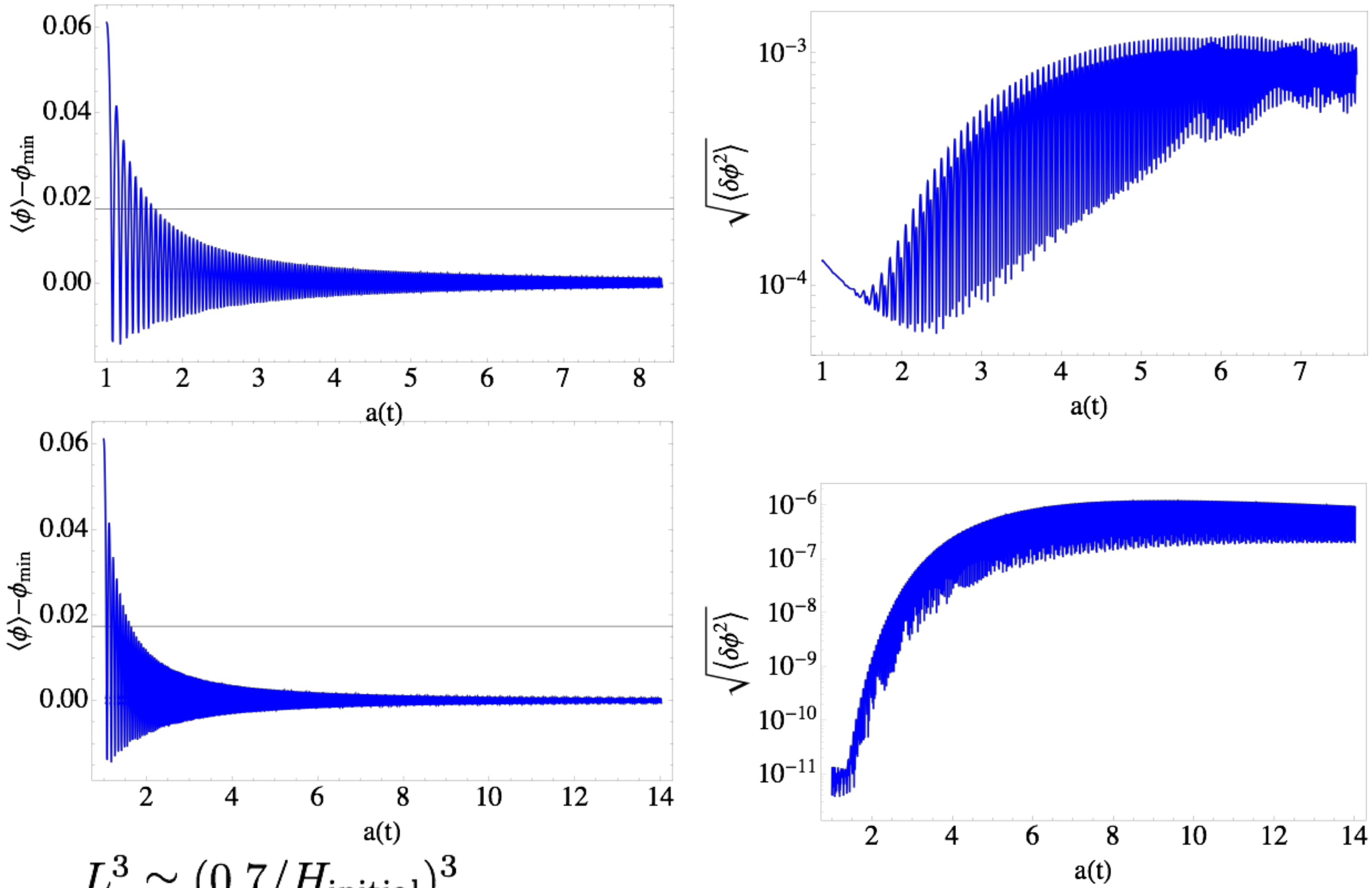
$$10^{-12} \le W_0 \le 10^{-5}\,, \qquad 1 \le A \le 10\,, \qquad 1 \le a \le 2\pi \ .$$



KKLT results

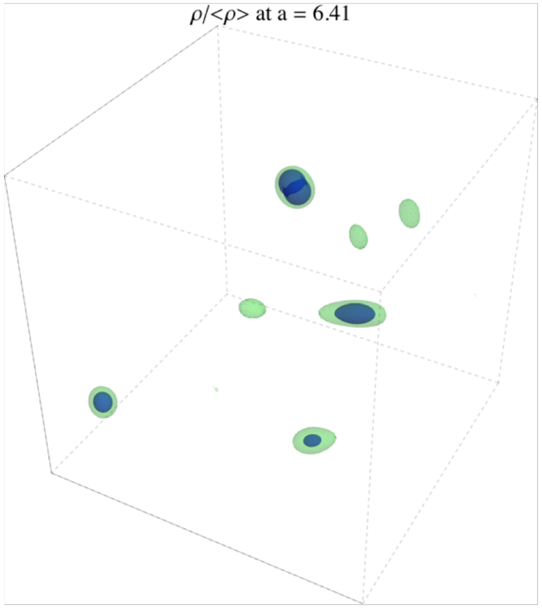
$W_0 = 10^{-12}$
(no oscillons)

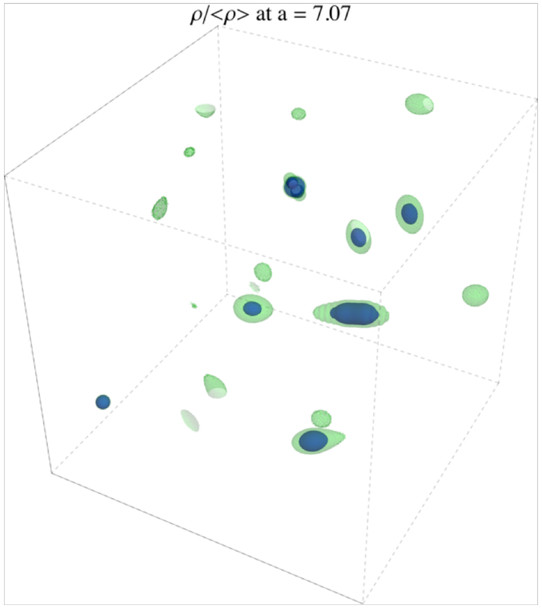
$W_0 = 10^{-5}$
oscillons
generated



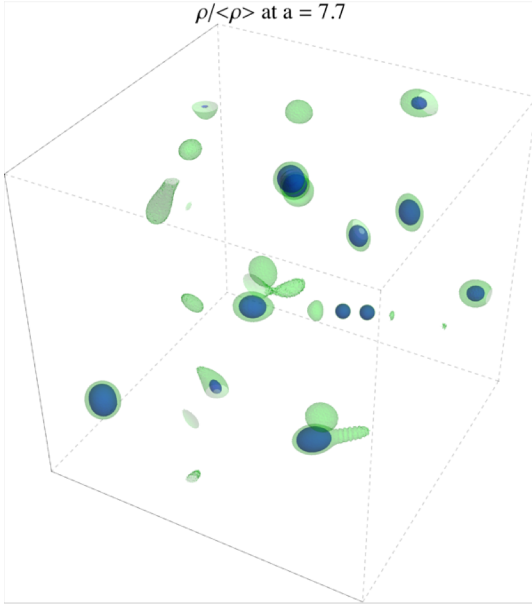
512^3 points $L^3 \simeq (0.7/H_{\text{initial}})^3$

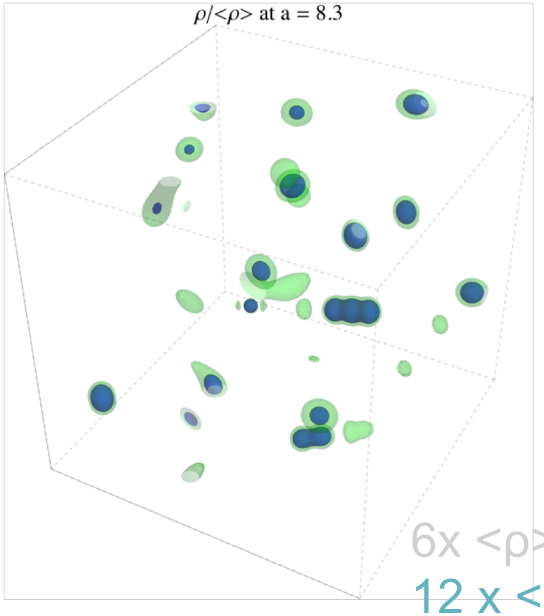
Snapshots





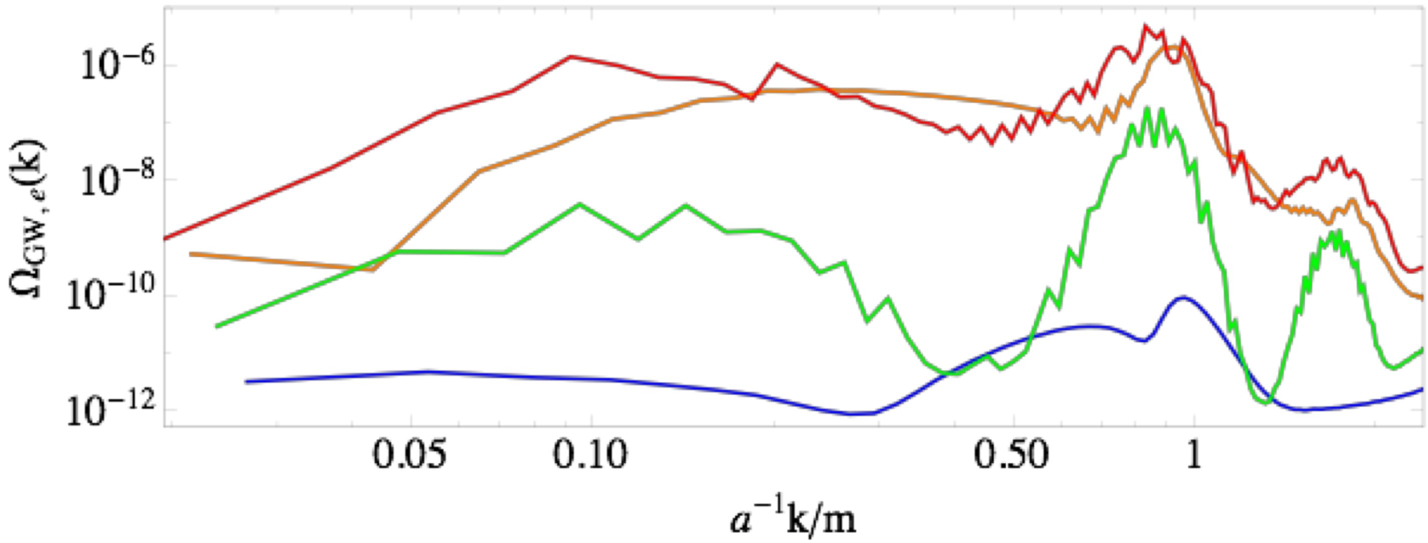
$W_0=10^{-5}$
A=10
a=2π





6x <ρ>
12 x <ρ>

GW spectrum: KKLT

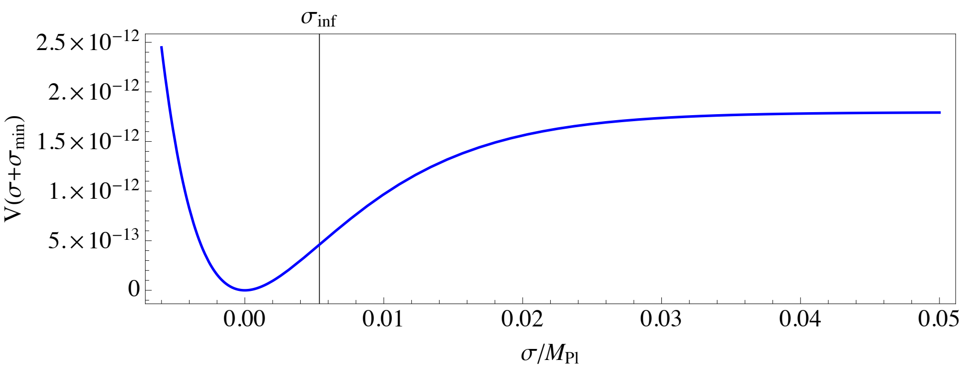


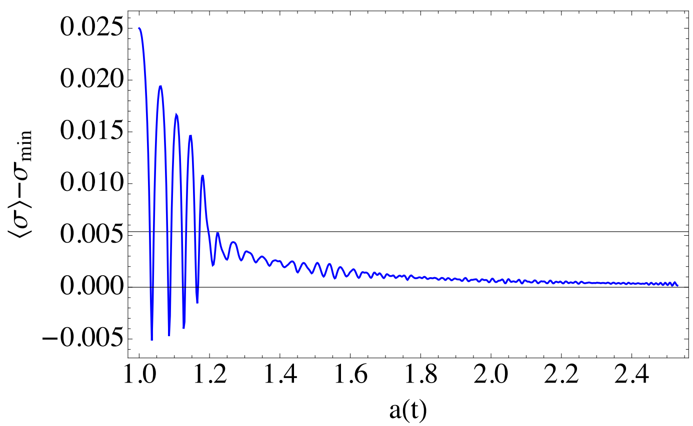
$f_{0,\mathrm{peak}} \sim 10^9\ \mathrm{Hz}$ $\qquad$ $\Omega_{\mathrm{GW},0}(f_{0,\mathrm{peak}}) \sim 3 \times 10^{-11}$

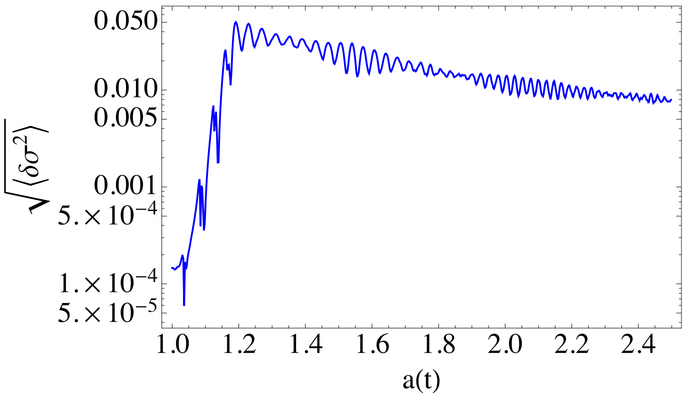
*Overall scaling can lower frequency but also lower the amplitude

Blow-up Potential in LVS

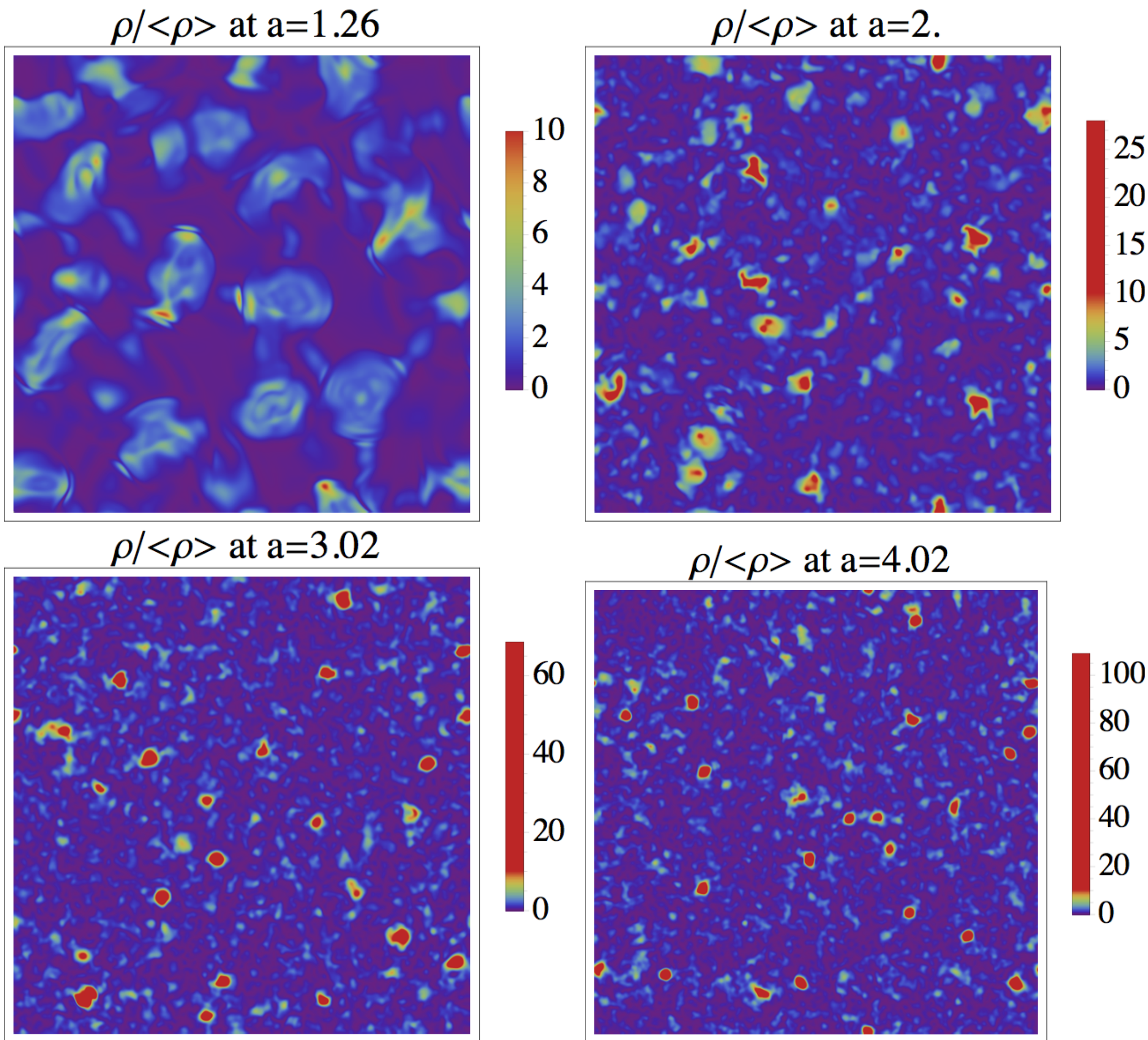
$$V \sim V_0 \left(1 - \kappa(\sigma) e^{-\alpha \sigma^{4/3}}\right)^2 \, ,$$



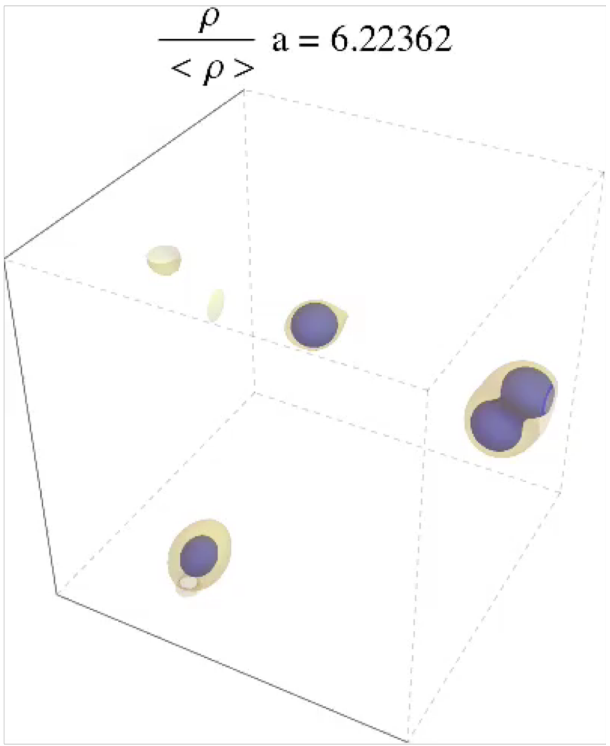


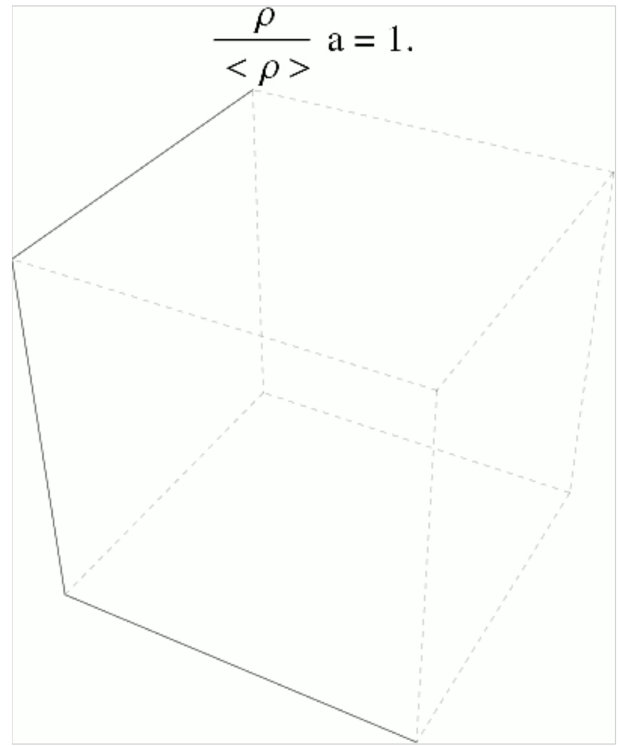


Oscillons from Blow-up mode



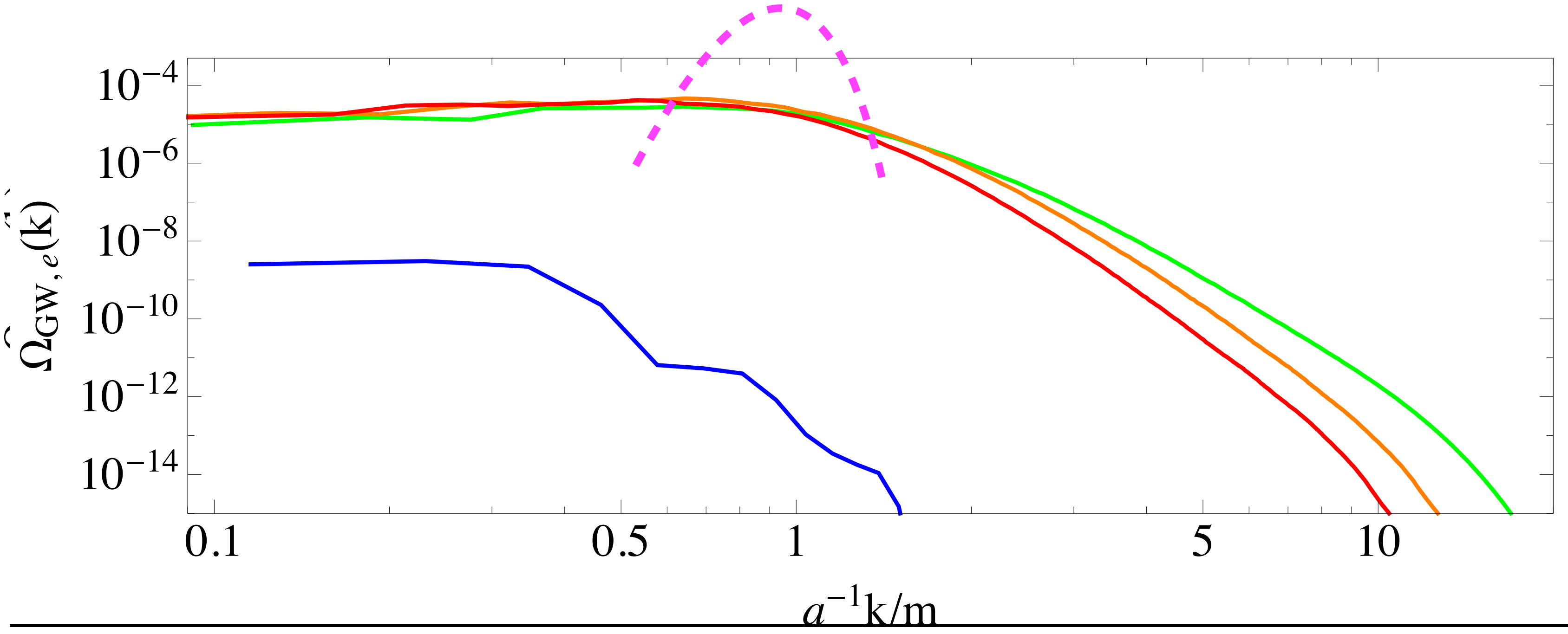
3D lattice simulations (Blow-up vs KKLT)





- $\rho > 6\langle\rho\rangle$ (yellow)
- $\rho > 12\langle\rho\rangle$ (blue)

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 $M_c \sim M_p^3/m^2$

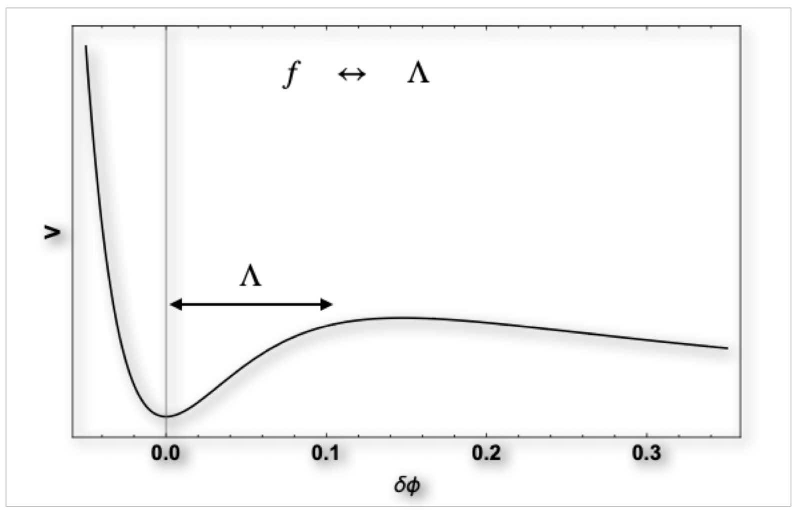
Classification of Scalar Stars

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*** (e.g. Axion and Moduli stars)	

Regimes

- Dilute

- Dense



if $\Lambda/M_p \sim \mathcal{O}(0.1-1)$ gravity is non negligible

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:

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

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

e.g. Volume modulus stars

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

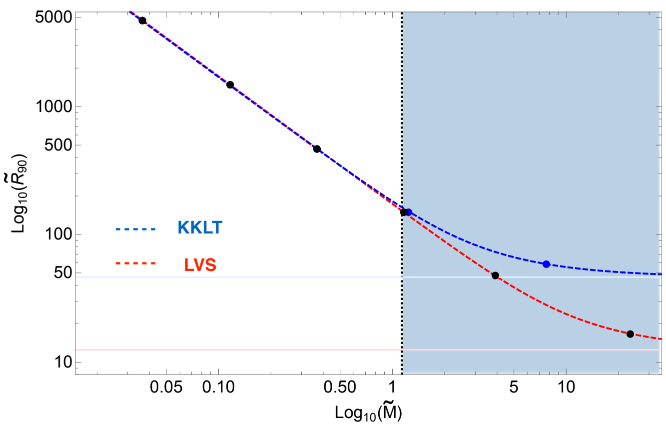
$$\varphi(r,t) = \varphi_0(r)\cos(\omega t)\ ,$$

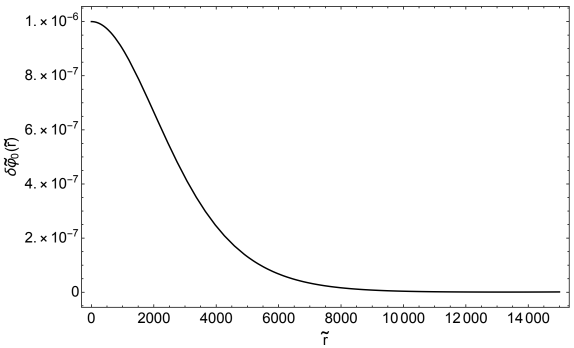
$$ds^2 = -(1+2\phi)dt^2 + (1-2\phi)\,dr^2 + r^2 d\Omega^2\,,$$

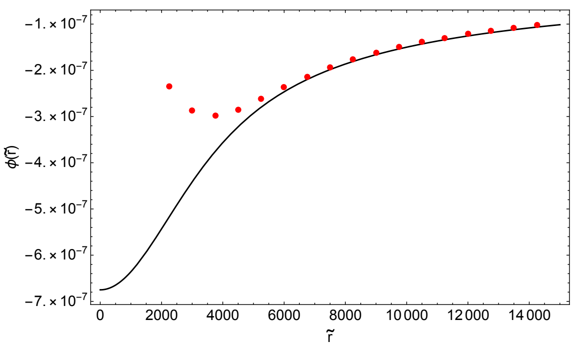
$$\tilde{\varphi}_0''(\tilde{r}) + \frac{2}{\tilde{r}}\tilde{\varphi}_0'(\tilde{r}) = 2\,(\phi(\tilde{r}) - \epsilon)\,\tilde{\varphi}_0(\tilde{r})\,,$$

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

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







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)

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

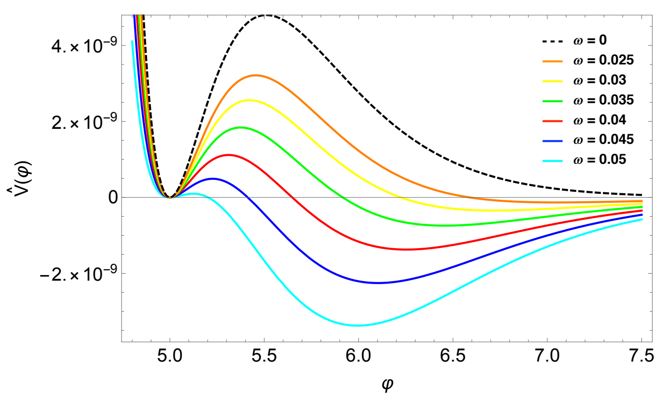
- PQ symmetry almost exact (PQ-balls?)

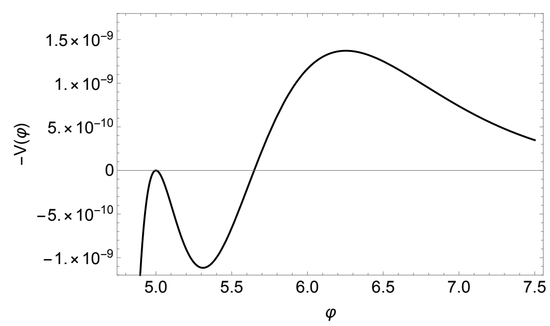
PQ Balls?*

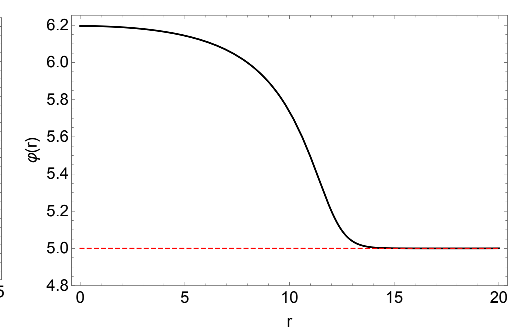
$$S = \int d^4x\, \mathcal{L} = \int d^4x\, \left[-f(\tau)\left[\partial_\mu\tau\partial^\mu\tau + \partial_\mu\theta\partial^\mu\theta\right] - V(\tau)\right]$$

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

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







Formation Mechanisms

I) There is some initial localized overdensity;

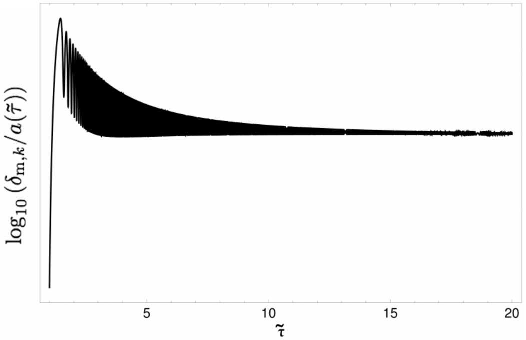
II) The initial overdensity collapses due to the effect of attractive interactions.

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

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

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

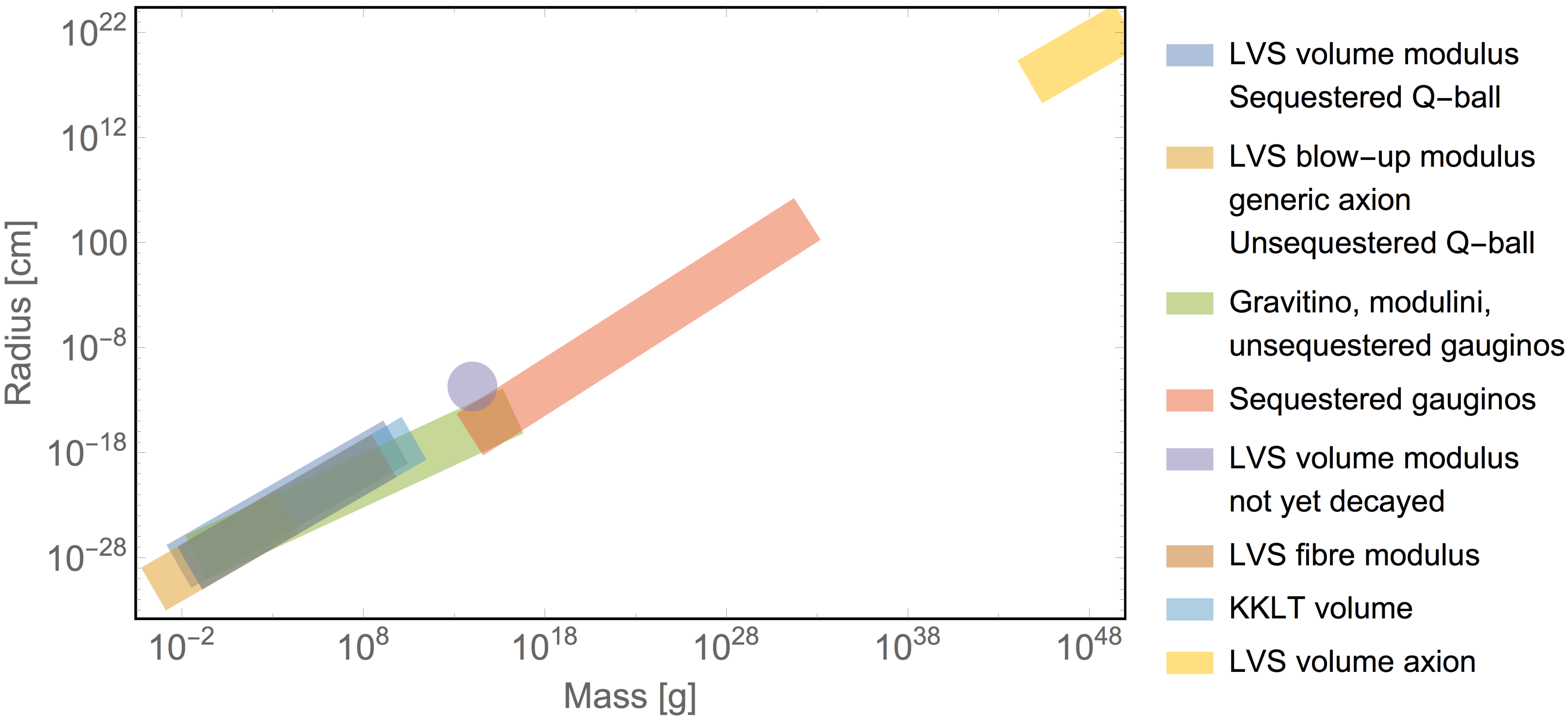
Enhacement factor!



Properties of Moduli Stars

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

Size and Mass of Moduli Stars

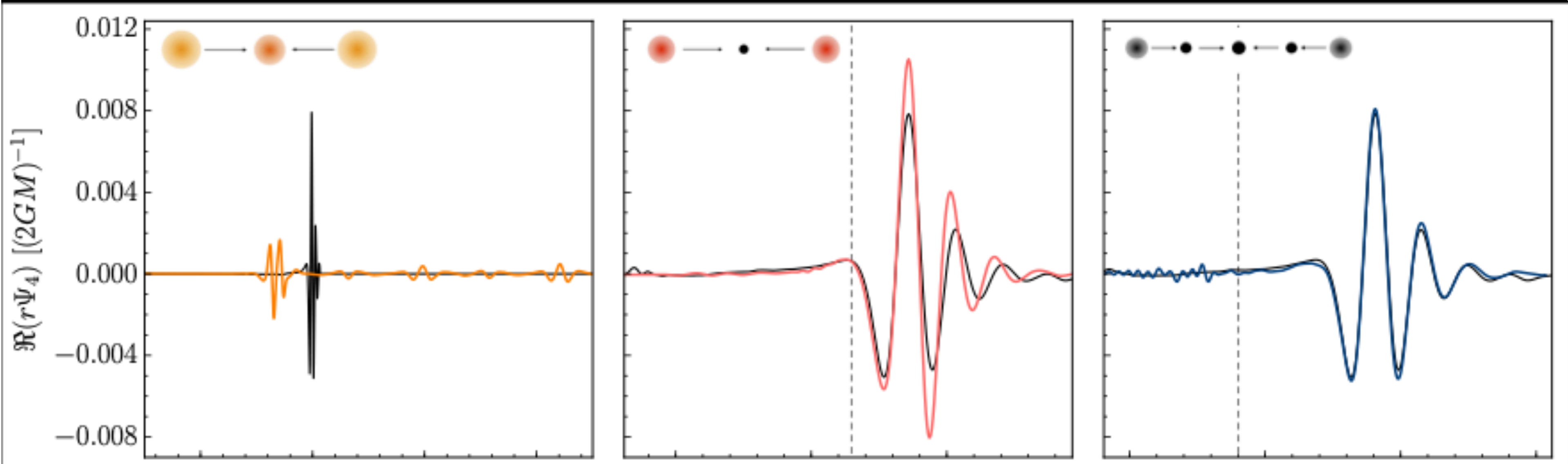


Effects of Gravity :

- Additional attractive force → Easier to have stable solutions?

- Larger compactness: $C \simeq \left(\frac{\Lambda}{M_p}\right)^2$ → Larger GW production from collisions; BH production from collisions

[T. Helfer, E. Lim, Garcia, Amin, 2018]



Effects of Gravity :

- Additional attractive force → Easier to have stable solutions?

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  [T. Helfer, E. Lim, Garcia, Amin, 2018]

  → Larger GW production from collisions

  → BH production from collisions

- Analytical estimates show that $\Omega_{GW} \simeq A^4$

  [S. Antusch, F. Cefalà, 2017]

  → if $\Lambda \simeq M_p$ potentially large GW production

- Possible production of light Primordial Black Holes.

Effects of Gravity 2:

Light Primordial Black Holes??

- Provide initial conditions for Hawking genesis.
  [O. Lennon, J. March-Russell, R. Petrossian-Byrne, H. Tillim, 2017]

- Hawking radiation is democratic → constraints on string model building?

- Longer lifetime: $\tau_{osc} \simeq 10^3 \times m^{-1}$

  $$\frac{\tau_{BH}}{\tau_{osc}} \simeq \left(\frac{M_p}{m}\right)^2 \lesssim 10^{26}$$

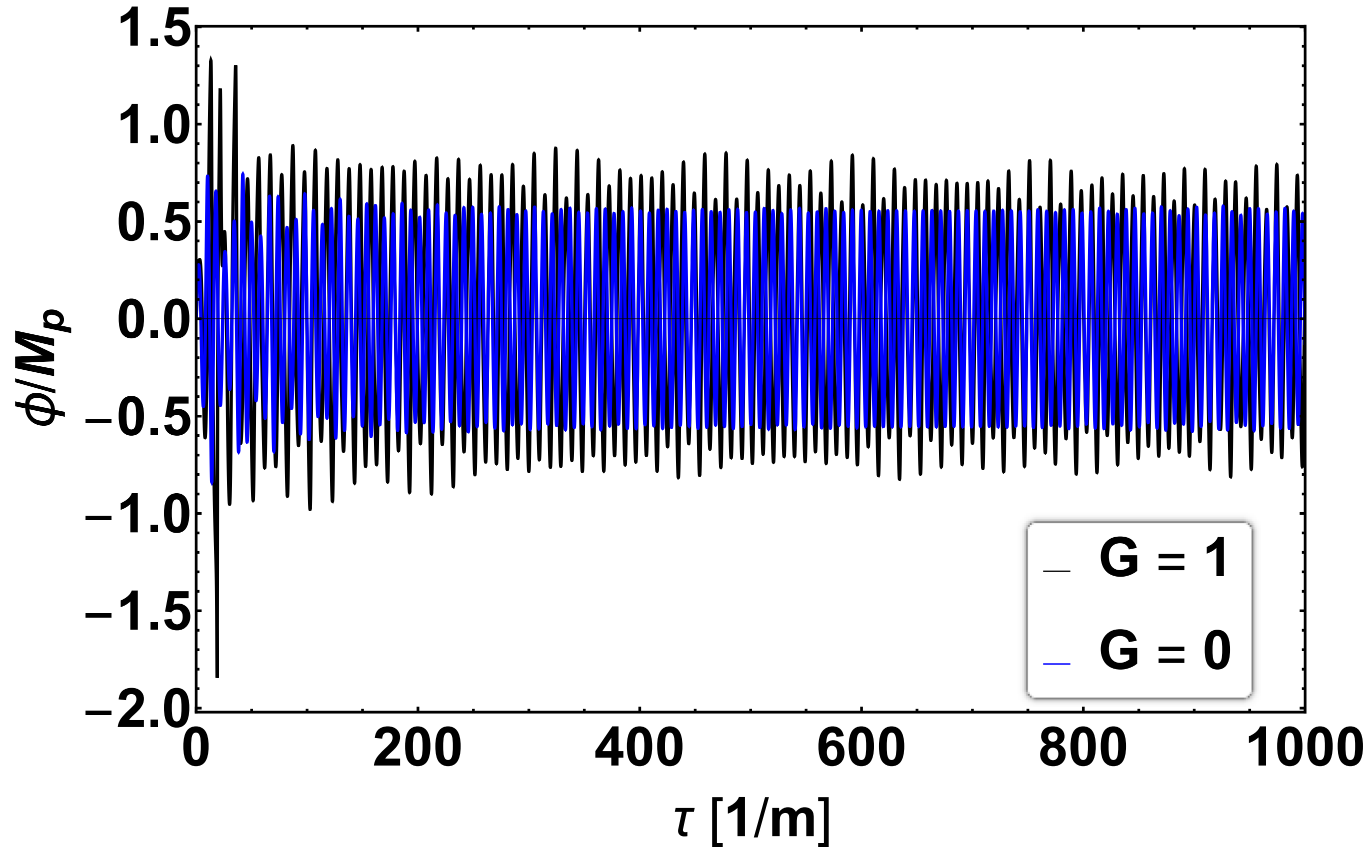
  → more dynamics and GW production?

  [M. Amin, P. Mocz, 2019]

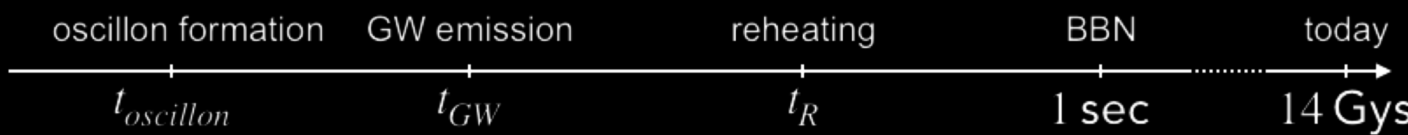
- Matter domination: LPBHs could cluster
  [A. Dolgov, D. Ejlli, 2011]

  → Enhanced GW production from collisions

e.g. Effects of gravity

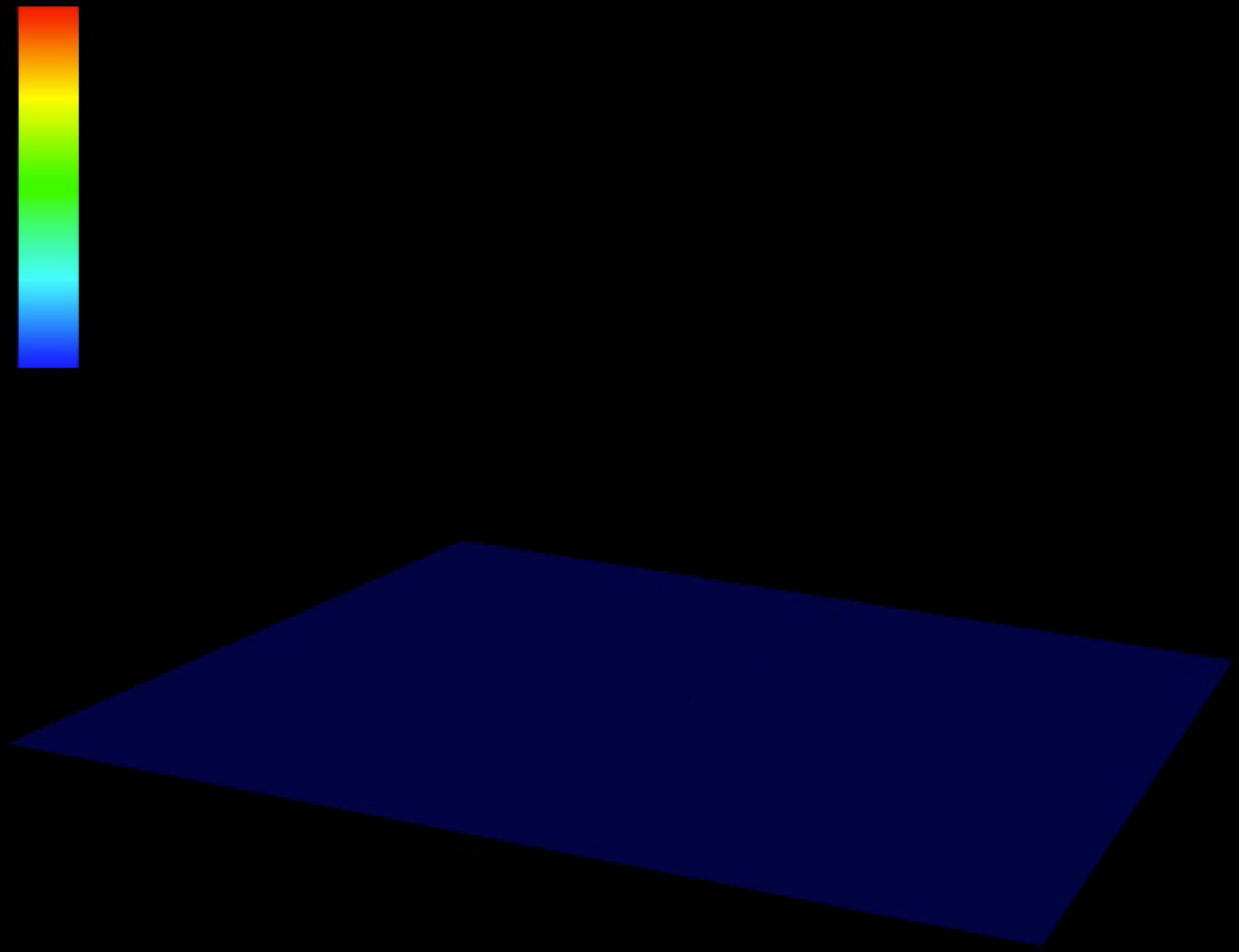


Gravitational wave production

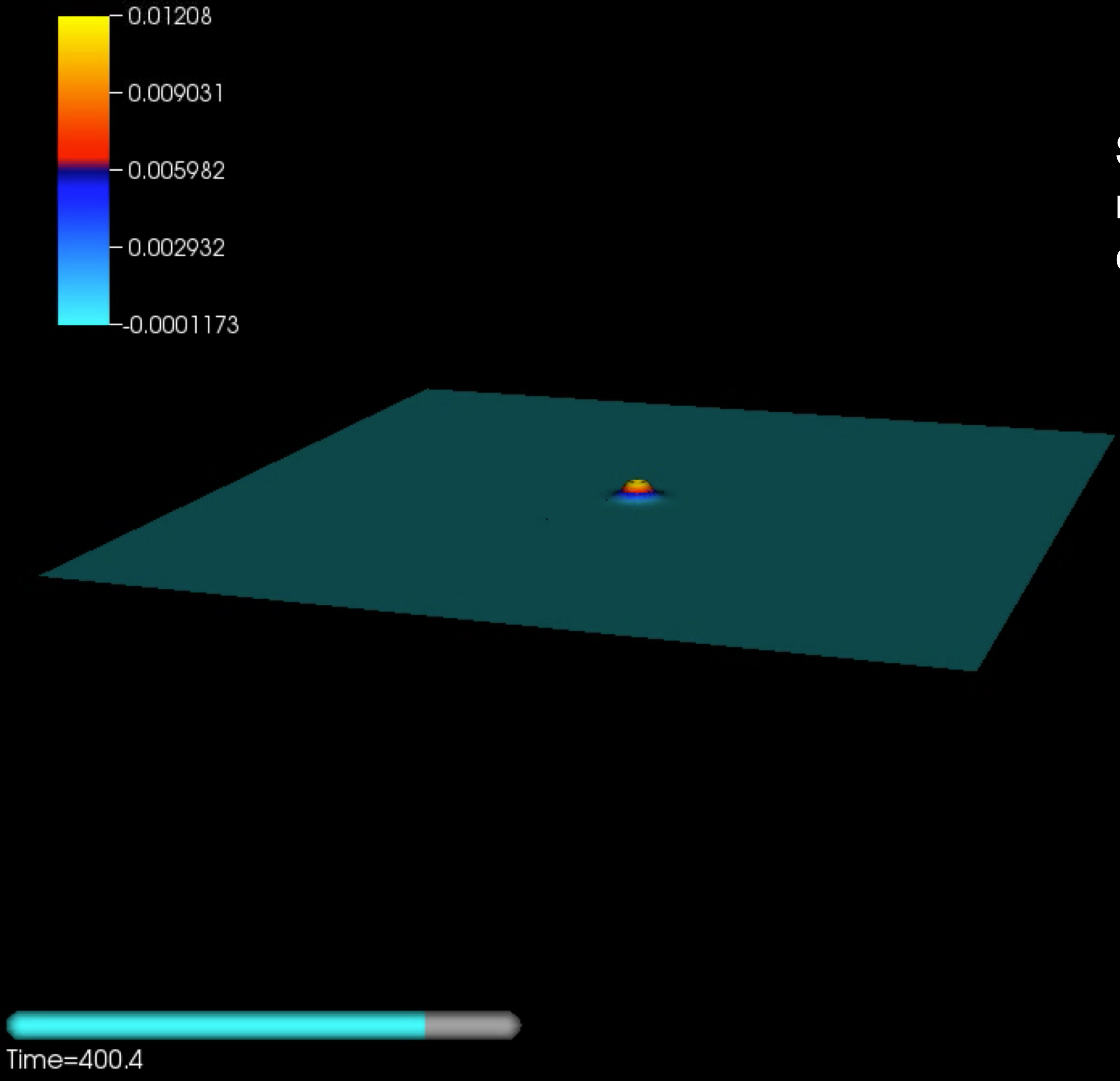


$$f_0 \geq \left(\frac{m}{\text{TeV}} \right)^{5/6} \text{Hz}$$

$m \simeq 400\,\text{GeV}$	$f_0 \geq 10^{-2}\,\text{Hz}$	Lisa
$m \simeq 10^{9}\,\text{GeV}$	$f_0 \geq 10^{2}\,\text{Hz}$	Ligo
$m \simeq 10^{12}\,\text{GeV}$	$f_0 \geq 10^{6}\,\text{Hz}$	
$m \simeq 10^{15}\,\text{GeV}$	$f_0 \geq 10^{9}\,\text{Hz}$	



e.g. Stable oscillatons



Starobinsky / Fibre moduli. Black hole collapse.

Summary Results

- Blow-up: Gravity effects negligible
- KKLT: Metastable, larger amplitudes
- Fibre/attractors: Higher amplitudes, Black hole collapse

Conclusions

- Post-inflation pre-BBN string cosmology interesting
- Rich spectrum of compact objects (stringy oscillons, gravitino, modulini, moduli, oscillatons, axion stars)
- Gravitational waves spectrum ('hear the shape of the extra dimensions?')

See Caprini's talk

- High frequency GWs?

Challenges and Opportunities of High Frequency Gravitational Waves Detection

14-18 October 2019

Organizers:

Valerie Domcke
Francesco Muia
Fernando Quevedo
Jessica Steinlechner
Sebastian Steinlechner