Universitat Autònoma de Barcelona

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Cracow School of Theoretical Physics

Oscillons in Cosmology, Particle Physics and beyond

Cracow School of Theoretical Physics, 17th of June 2024

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Overview

Many scalar theories with attractive forces allow for "oscillons"

- Limit of large number of quanta (classical description)
- Non-perturbative solutions with universal properties
- Come with model-dependent observational signatures

Attractiveness leads to a binding energy

$$\Delta\omega^2 \sim m^2 - \frac{V_{nl}}{m^2}$$

Relevance to

- Early Universe (Preheating)
- Dark Matter
- Particle Physics

Oscillons: Motivation

Observational Signatures

As I will show these objects come with interesting phenomenological consequences that are **model-dependent**

High Energy Physics

Many models of UV physics predict a large amount of scalars

Oscillons could be a natural probe of these theories

Typically **multi-field**! (e.g. String Axiverse *arXiv:0905.4720*)

The model: a simple scalar

A scalar minimally coupled to gravity

$$\frac{L}{\sqrt{-g}} = \frac{R}{16\,\pi\,G} + \frac{1}{2}\,\partial_\mu\phi\,\partial^\mu\phi\; - \frac{1}{2}m^2\phi^2 + \frac{1}{4}\,\lambda\,\phi^4$$

Nomenclature very confusing: different limits have different names

Generally controlled by

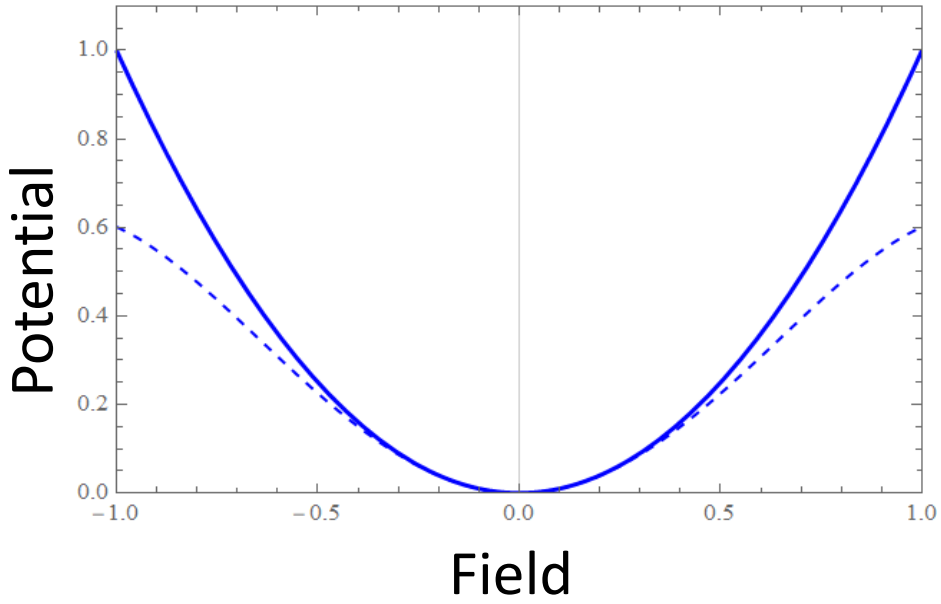
$$f_a/M_{pl}$$

The origin of boundedness can always be understood as an interplay between the dispersion of a free wave and attractive forces

Oscillons

Universal Characteristics:

1. Oscillating Field Configuration
2. Generally Attractors
3. Slowly Decaying (Unstable)

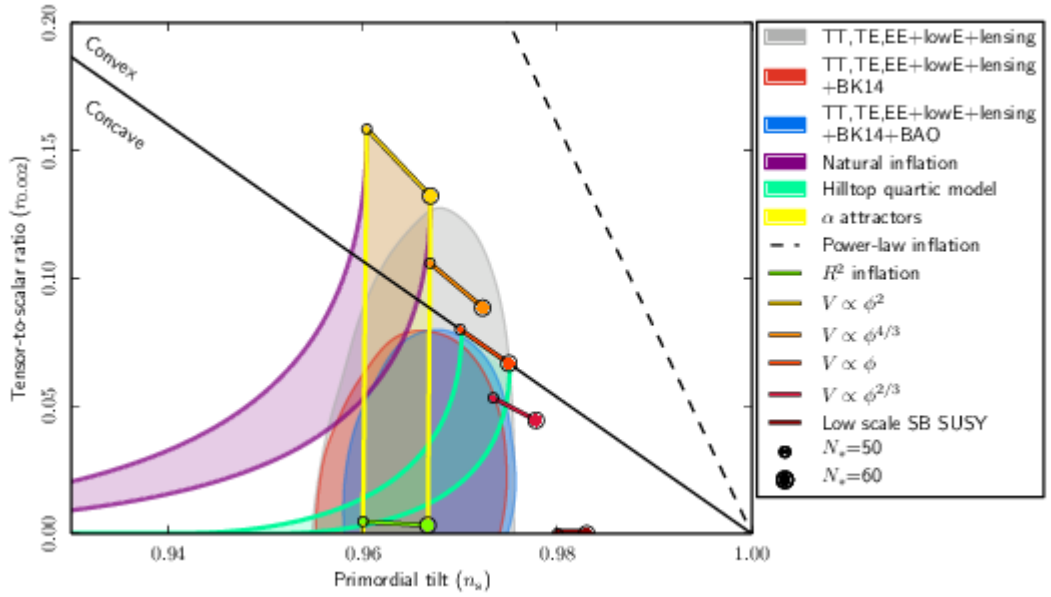


Requirements: Attractive Self-Interactions (“shallower than quadratic”)

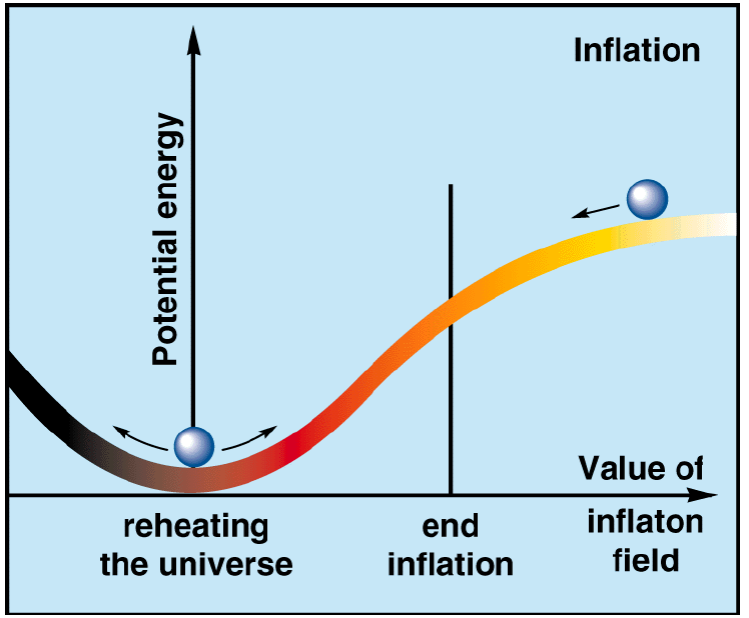
Oscillons in the Early Universe

Preheating

Many preferred models of Inflation support (somewhat) violent phases of particle production



Planck 2018



9906497

Gravitational Wave Signature

<u>Parametric Resonance of Fluctuations leads to GW production</u>

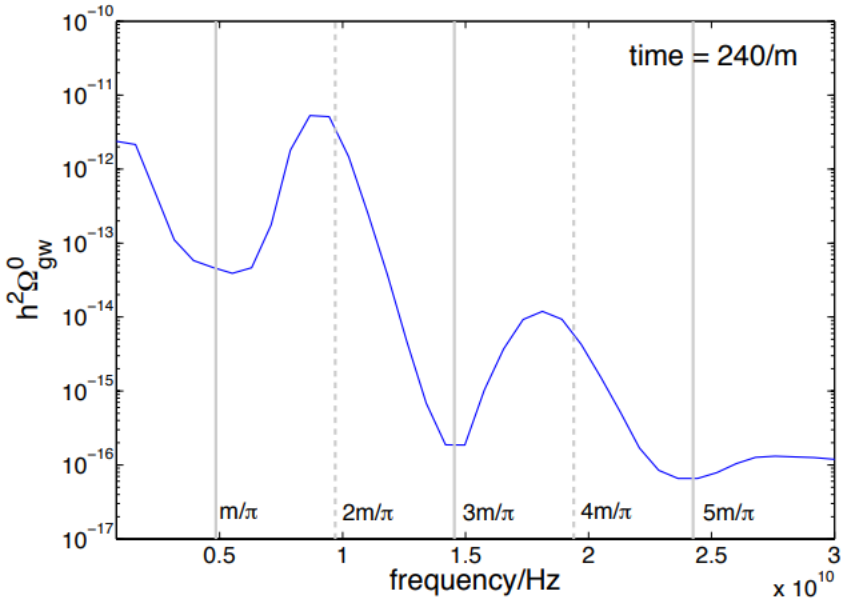
Oscillons "sphericalize" fluctuations of order

$$k \sim m$$

Spectrum knows about nonlinearities

Inflationary Preheating too high frequency

GHz for $H_i \sim 10^{-6}$Mpl

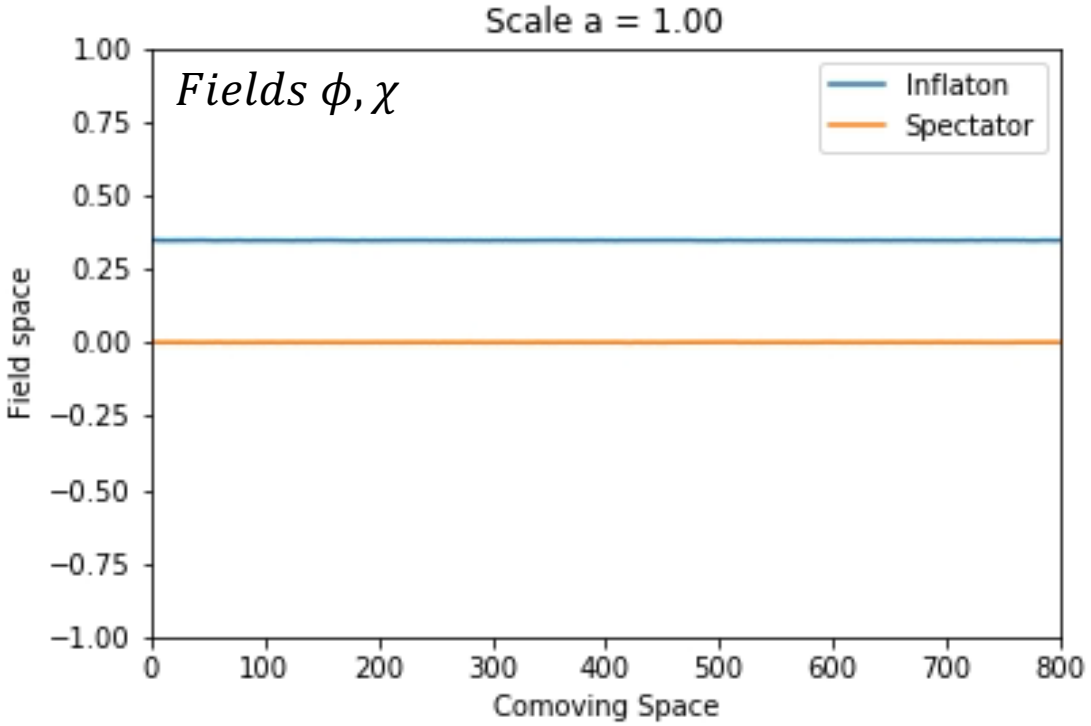


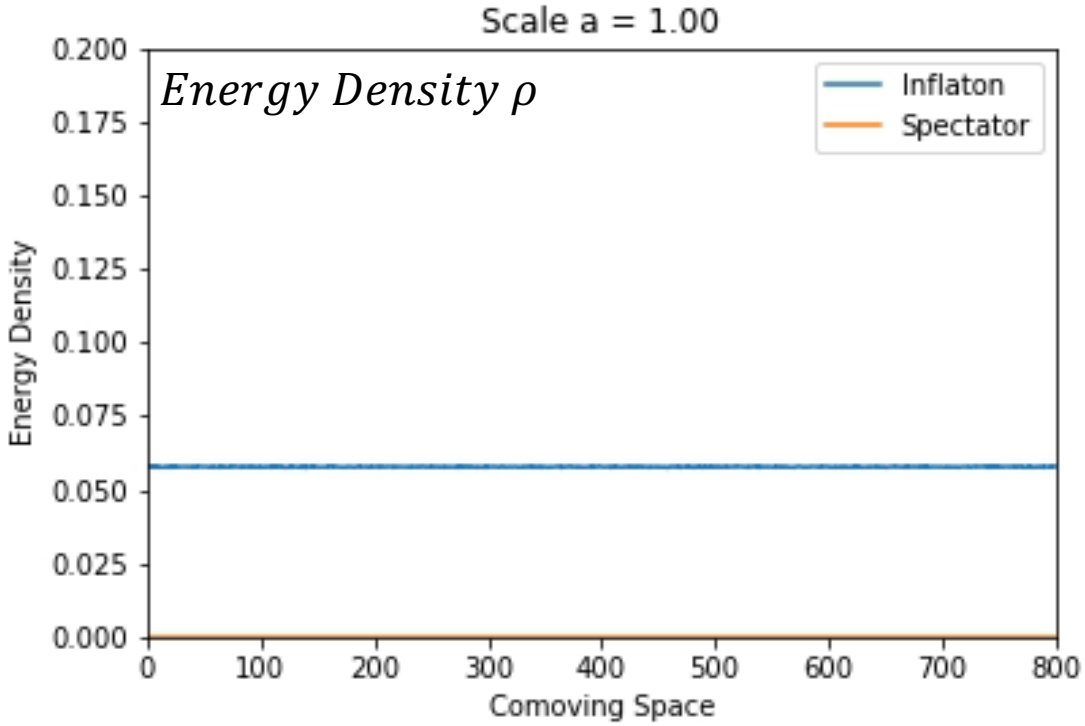
1304.6094 (2013)

Emergence: Preheating

Field Fragmentation in Preheating: New Scenario [FD, Sfakianakis: 2010.07789]

1. **Fragmentation of the Inflaton**
2. **Inflaton settles into Single-Field oscillons**
3. **The Single-Field oscillons (sometimes) excite instabilities in the spectator field**
4. **Composite oscillons are formed**





Oscillons in the Late Universe

Role as Dark Matter

Relativistic oscillons can be (a component of) Dark Matter if long-lived (*1906.06352*)

More general

If the constituent particles of the oscillon become nonrelativistic they can form a coherent BEC described by a collective wavefunction

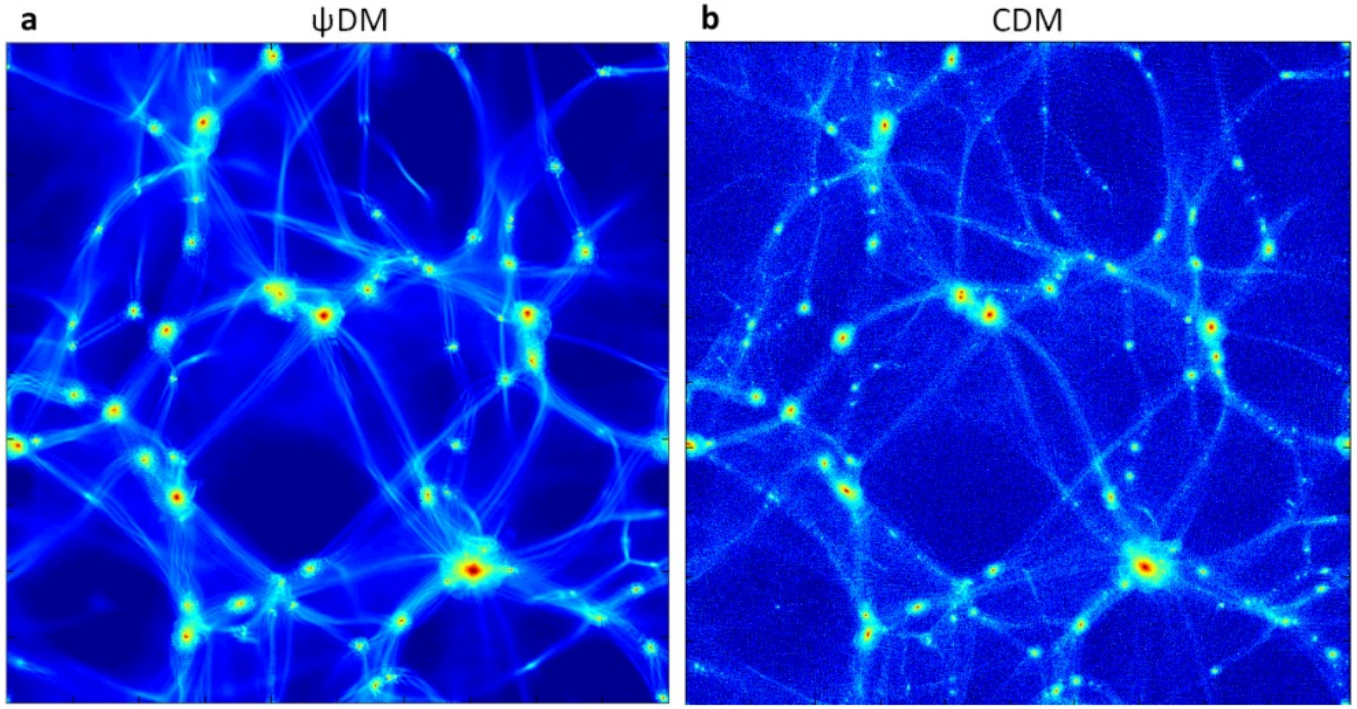
The wavefunction ψ can have oscillon-like bound states (with gravity now becoming important)

Introduction: ULDM

Simulations of light scalars show cored halos, fitting Rotation Curve data.

$$\lambda_c \approx \frac{\hbar}{m\, v_{DM}}$$

To reproduce a typical core of 1 kpc we find $m \approx 10^{-22}$eV for $v_{DM} = 10^{-3}c$



Schive et al. 2014 1406.6586

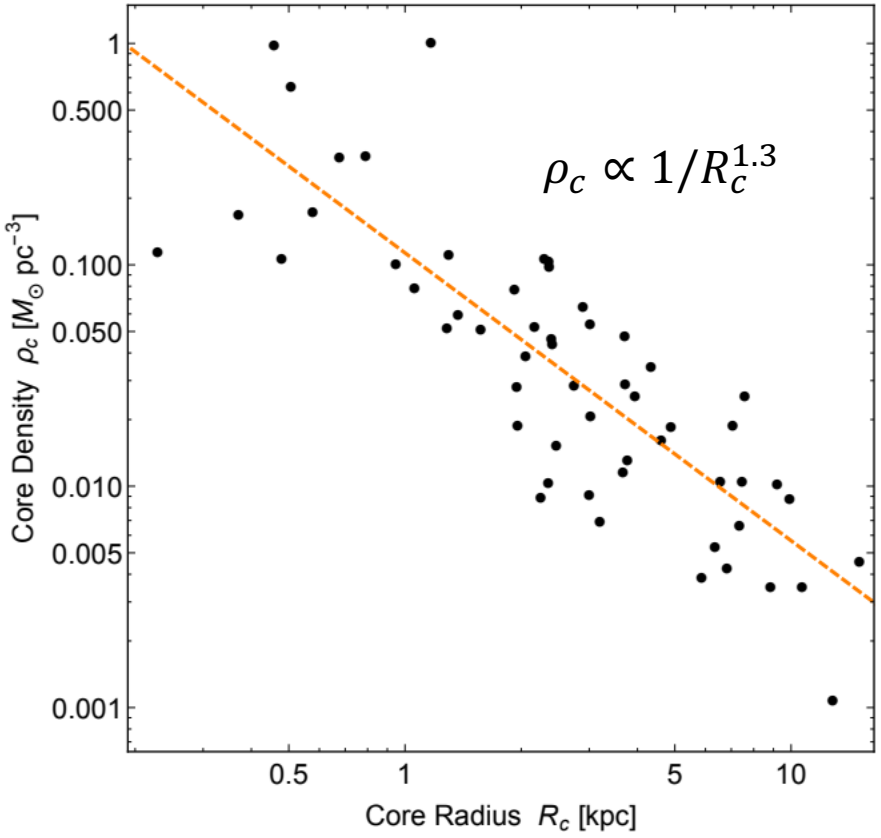
Solitonic problem

The scaling of the solitonic cores from data does not seem to match the observational data

No simple solution in Single Field

$$\boldsymbol{\rho_c \propto 1/R_c^4}$$

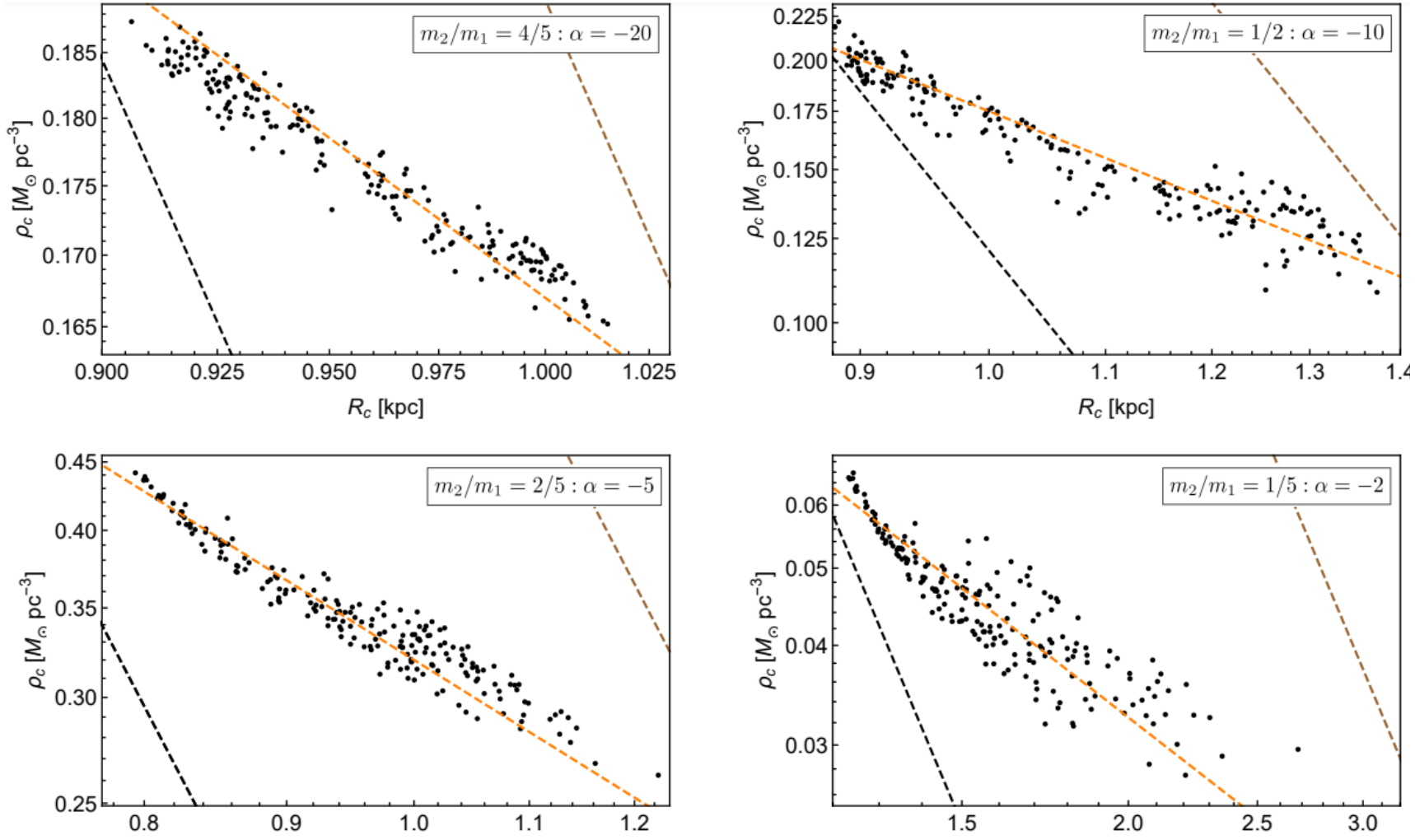
How well can we fit RC's? Other options also excluded (e.g. self-interactions)



Deng et al. 2018 1804.05921

Two light scalars: different solitons

[*FD, Hertzberg, Shapiro: 2310.19762*]



Oscillons in Particle Physics

Role as Resonances

Certain theories contain relativistic oscillons with well-defined

1. Mass
2. Lifetime
3. Decay Width

Potentially interesting signatures in colliders? (*9303281*)

Chiral lagrangian

Soft Pions are described by the Chiral Lagrangian (ignoring EM)

$$L = \frac{F_\pi^2}{4} tr\left(\partial_\mu U \partial^\mu U^+\right) + \frac{F_\pi^2\, m_\pi^2}{2} tr\left(M(U + U^+)\right)$$

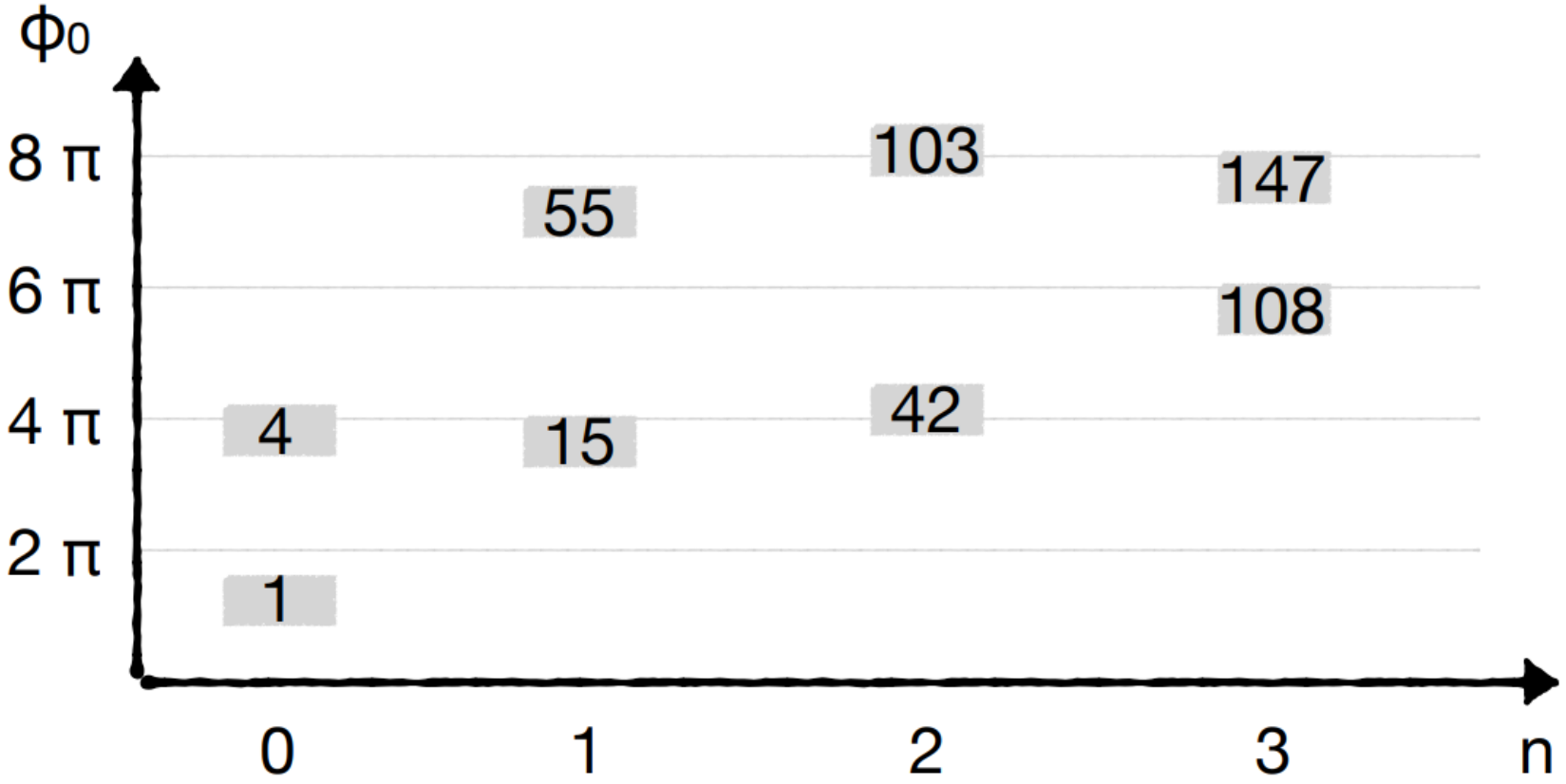
Described by a nonlinear sigma model

If only one pion is present the field is described (classically) by the famous Sine-Gordon equation

$$\ddot{\phi} - \nabla^2\phi + \sin\phi = 0$$

Sine-Gordon Spectrum

[*FD, Pùjolas, Sfaianakis: 2303.16072*]



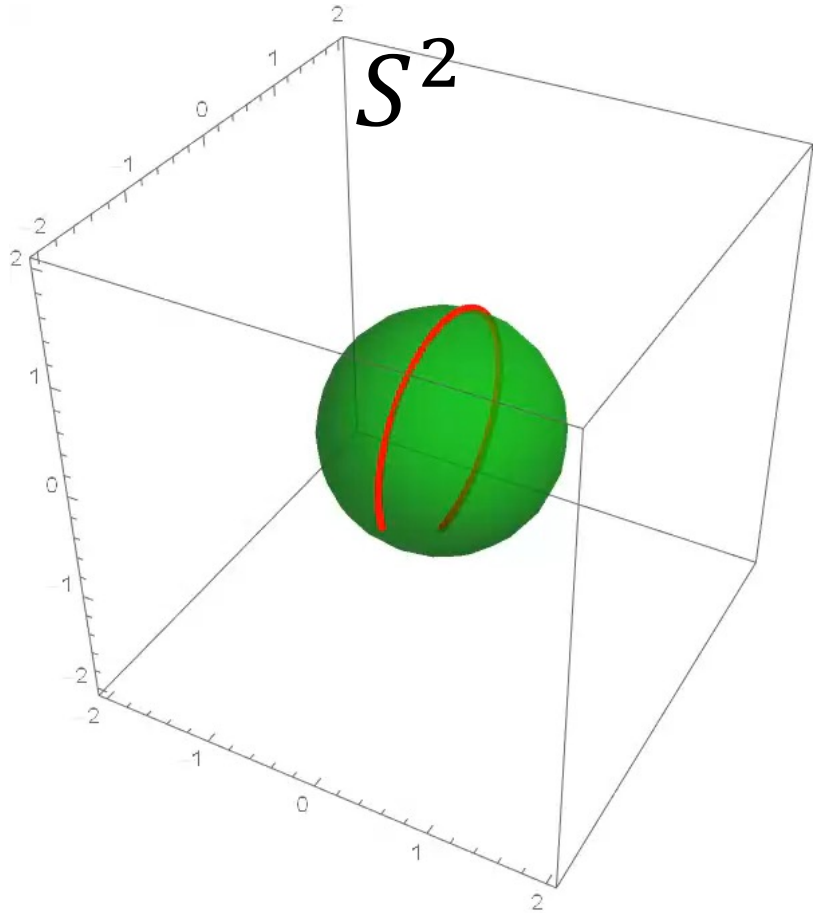
2303.16072 (2023)

The Chiral Lagrangian: the full story

These Oscillons are unstable to the “perpendicular” Pion directions

The Sine-Gordon spectrum is greatly reduced

Solutions only exist in 1D



Conclusions

Bound states of many particles show up in many models of real scalars that contain self interactions

1. Early Universe (Preheating) **[FD, Sfakianakis: 2010.07789]**
2. Late Universe (Dark Matter) **[FD, Hertzberg, Shapiro: 2310.19762]**
3. Particle Physics (Resonances in colliders) [***FD, Pùjolas, Sfaianakis: 2303.16072***]

Many of their characteristics are universal while also carrying model-dependent signatures!