Dilute and dense axion stars

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Based on:

LV, Baum, Redondo, Freese, Wilczek, PLB **777**, 64 (2018)
ArXiv:1710.08910

Solitons made out of bosons

A bosonic field can arrange into a self-gravitating, compact, solitonic equilibrium configuration

These solutions have finite mass, are compact, and occupy a defined region of space

Bosonic matter can collapse to high densities (large occupation numbers), attaining hydrostatic equilibrium

Solitons made out of bosons

Examples:

I) Q-balls [Coleman Nucl. Phys. B **262** 263 (1985)];

II) Scalar soliton stars [Lee PRD **35** 3637 (1987)];

III) Boson stars [Colpi *et al.* PRL **57** 2485 (1986)];

IV) Oscillating soliton stars [Seidel&Suen PRL **66** 1659 (1991)];

I) II) III) are described by complex fields (Noether)

Solitons made out of bosons

Option IV) (oscillating soliton stars):

I) Beats Derrick theorem (prevents static solutions of non-linear KGE) [G.H.Derrick, J. Math. Phys. **5** 1252 (1964)]

II) Applies to scalar bosons (no Noether current)

Motivations

Axions are viable, well-motivated DM candidates

Signatures from axion stars include:

- Effects on local axion density (haloscopes)
- MicroLensing
- Effects on structure formation?
- Tidal disruption of axion stars?
- What happens when they collide?
- What happens near a large magnetic field?

Solitons made out of bosons

Massive real scalar field $\phi = \phi(x)$

Self-gravitating $G^{\mu\nu} = 8\pi T^{\mu\nu}(\phi)$

Lagrangian: $\mathcal{L} = \frac{1}{2}(\partial^\mu \phi)(\partial_\mu \phi) - V(\phi)$

Metric: $ds^2 = N^2(t,r)dt^2 - g^2(t,r)dr^2 - r^2 d\Omega^2$

Oscillons out of the axion field

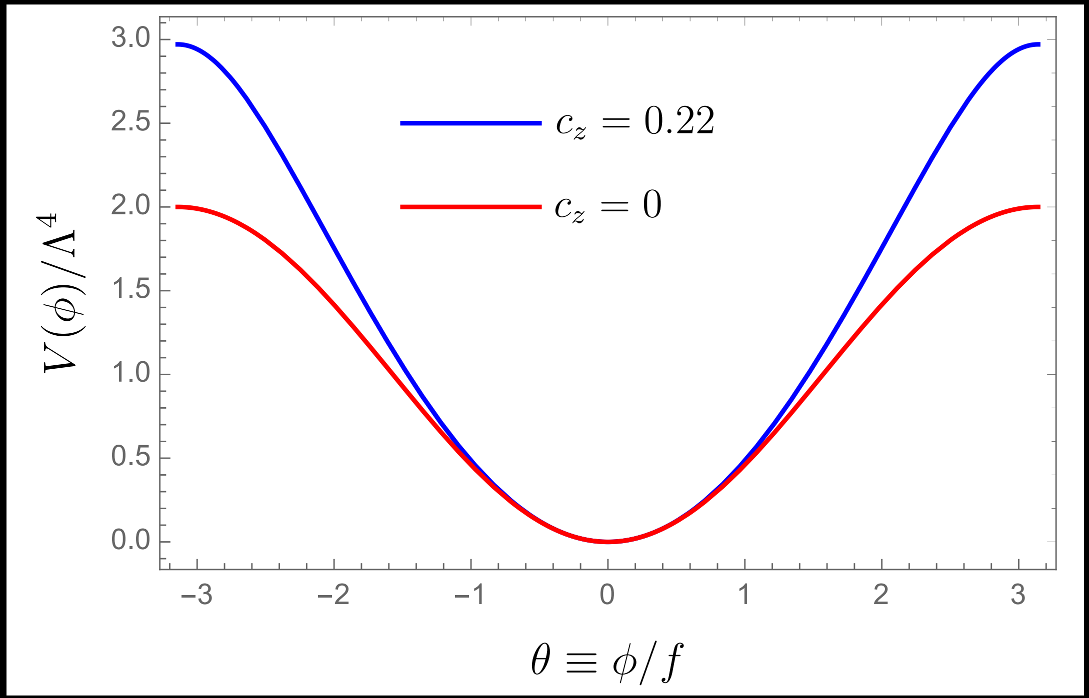
$$V(\phi) = \frac{\Lambda^4}{c_z}\left(1 - \sqrt{1 - 4c_z \sin^2\frac{\phi}{2f}}\right)$$

Di Vecchia & Veneziano,
Nucl. Phys. B **171 253** (1980);
Grilli di Cortona *et al.*
JHEP **01** 034 (2016)

f Axion decay constant

$$\Lambda = 75.5\,\mathrm{MeV}$$

$$c_z \approx \frac{z}{(1+z)^2} \approx 0.22$$



Solitons made out of bosons

Oscillating solution $\phi = f\,\Theta(r)\cos(\omega t)$

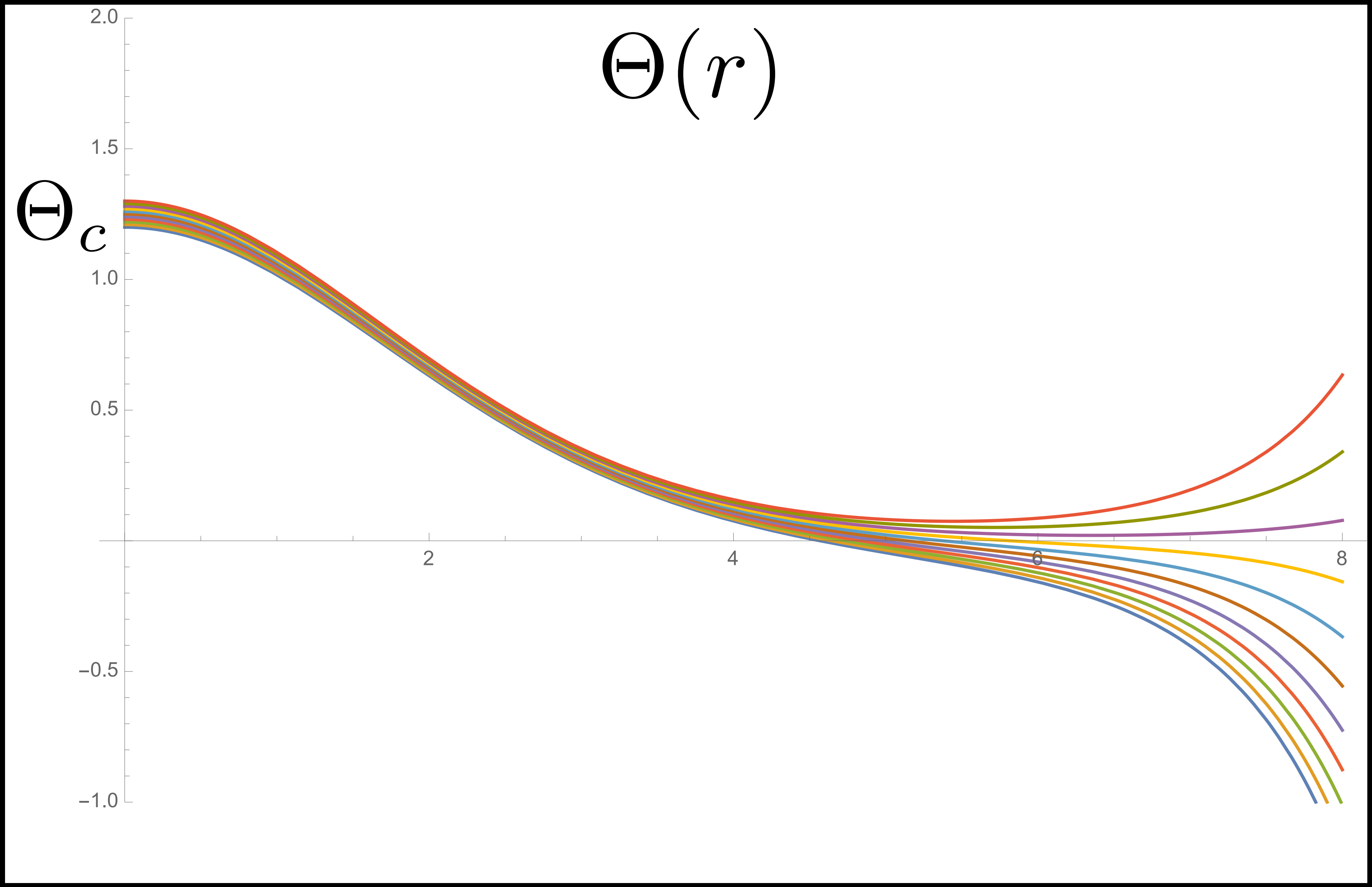
Non-relativistic regime when $|\phi| \ll f$ (or $|\theta| \ll 1$)

Also, $\omega \approx m \,(= \Lambda^2/f)$

Poisson equation + Schrödinger equation

(From Einsten eq.) (From Klein-Gordon eq.)

Solving by shooting method



$$M = 4\pi \int_0^{+\infty} r^2 \phi^2(r) dr \qquad 0.9M = 4\pi \int_0^{R_{90}} r^2 \phi^2(r) dr$$

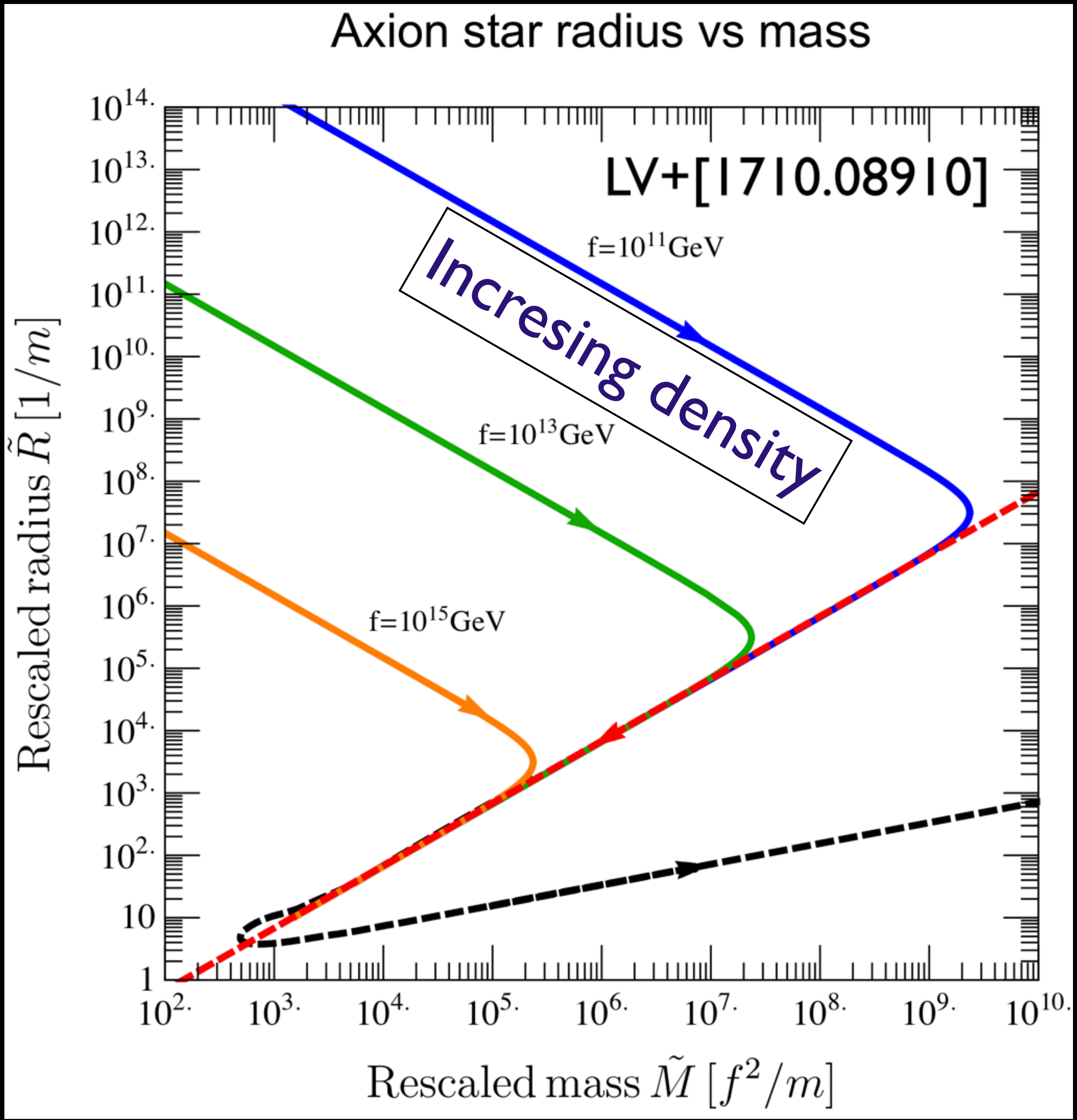
Mass-radius of an axion star

Natural mass and radius scales:

$$\frac{f^2}{m} = 3 \times 10^{-20} M_\odot \left(\frac{10^{-5}\,\mathrm{eV}}{m}\right)^3$$

$$\frac{1}{m} = 3 \times 10^{-11} R_\odot \left(\frac{10^{-5}\,\mathrm{eV}}{m}\right)$$

Three ‘branches’



Mass-radius of an axion star

"Dilute" branch

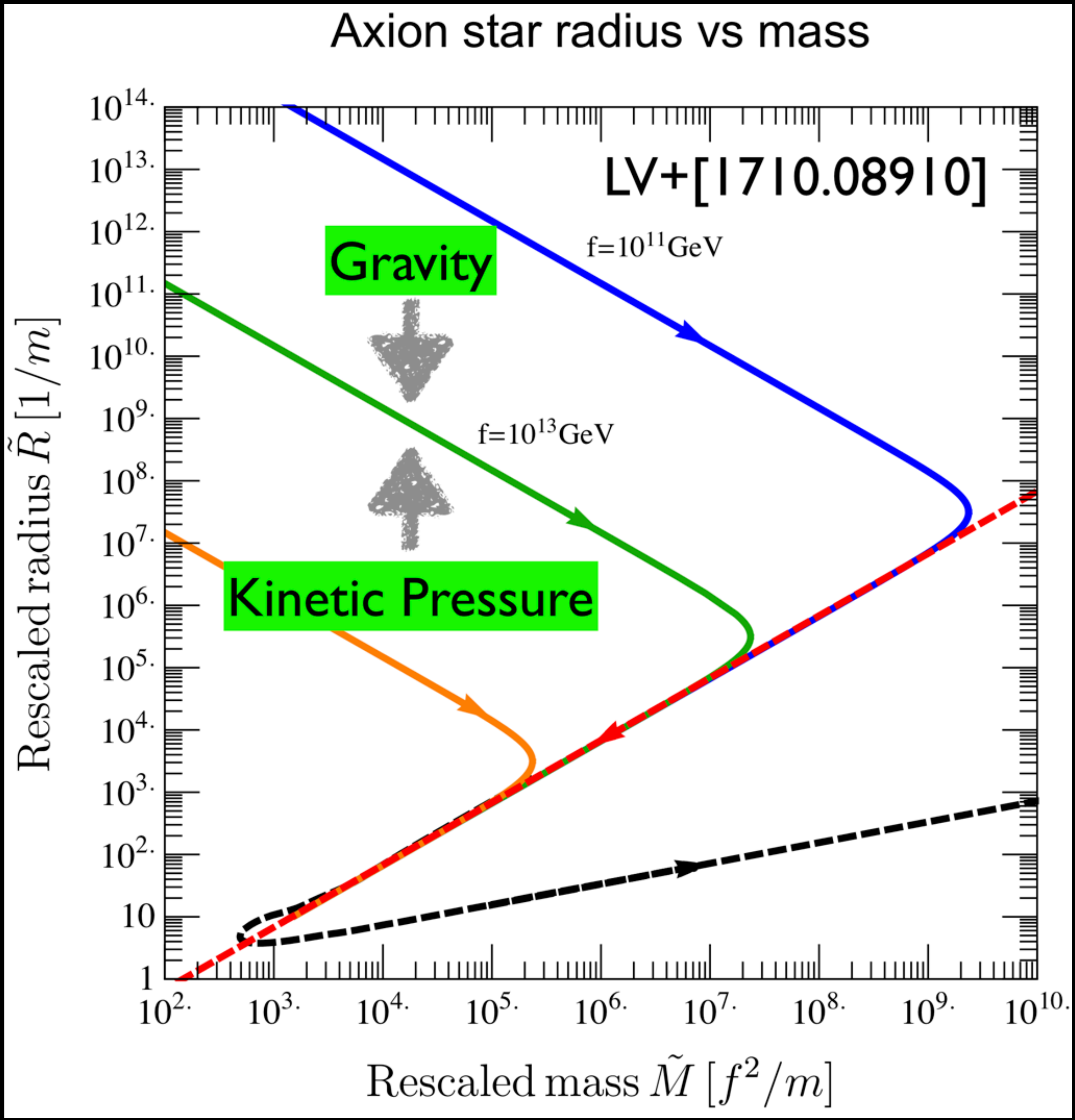
Relevant contributions:

- Kinetic pressure
- Gravity

$$U \sim \frac{M}{2}v^2 - \frac{GM^2}{R}$$

$$R \propto 1/M$$

Stable against perturbations



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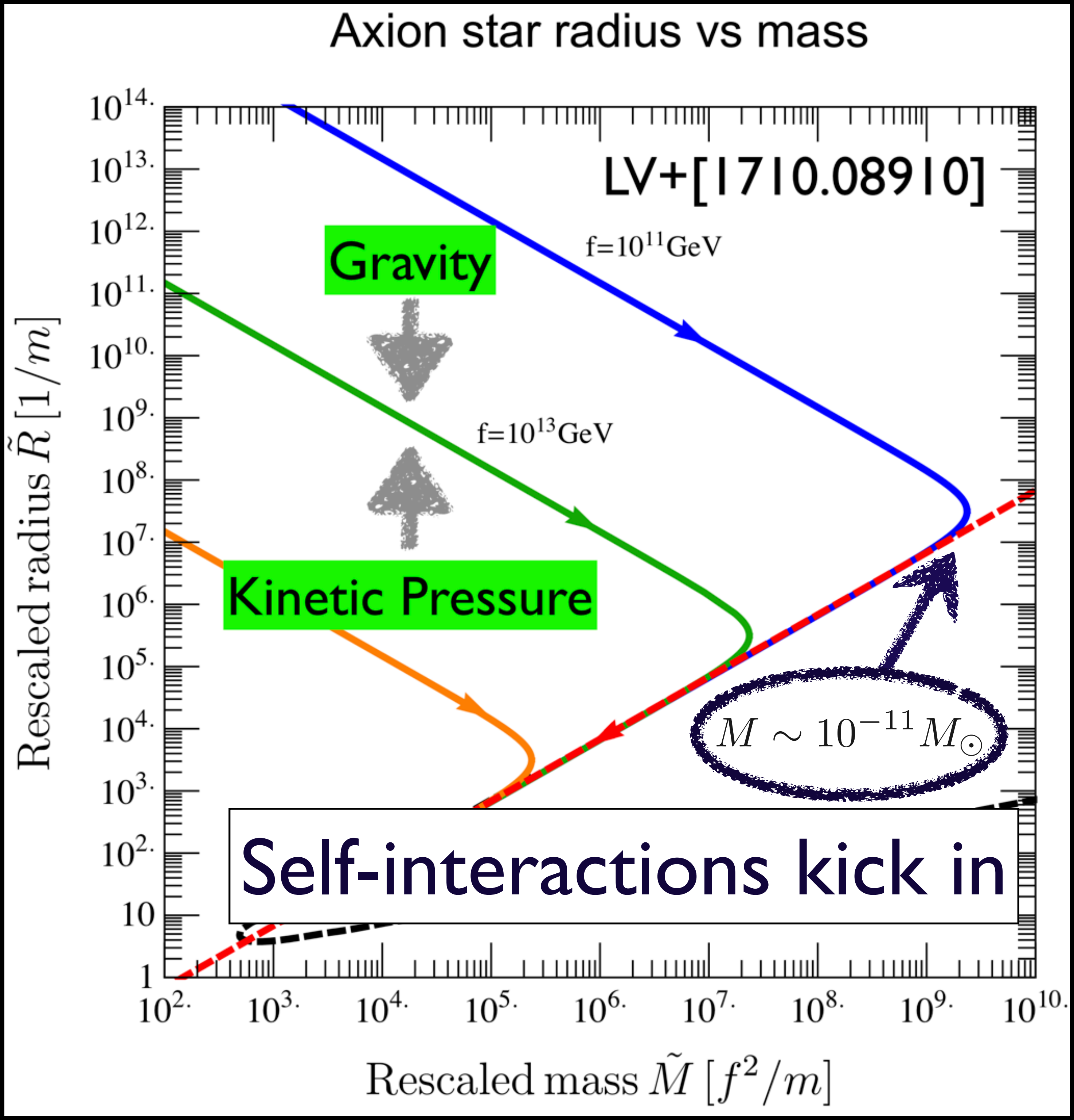


Mass-radius of an axion star

"Critical" branch

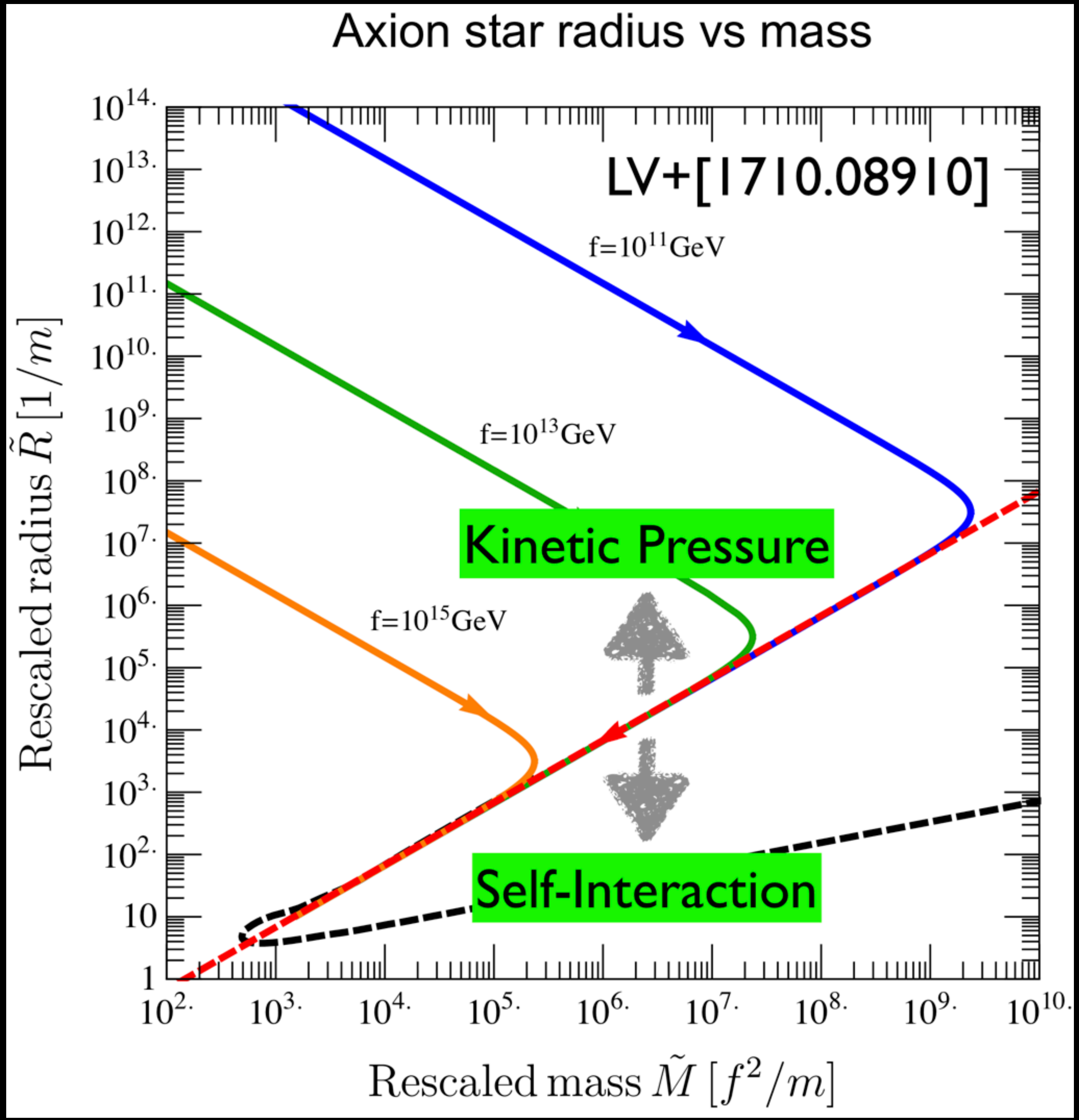
Relevant contributions:

- Kinetic pressure
- Quartic interaction

$$U \sim \frac{M}{2} v^2 - \Lambda^4 \Theta_c^4 R^3$$

$$R \propto M$$

Not stable against perturbations



Mass-radius of an axion star

"Dense" branch

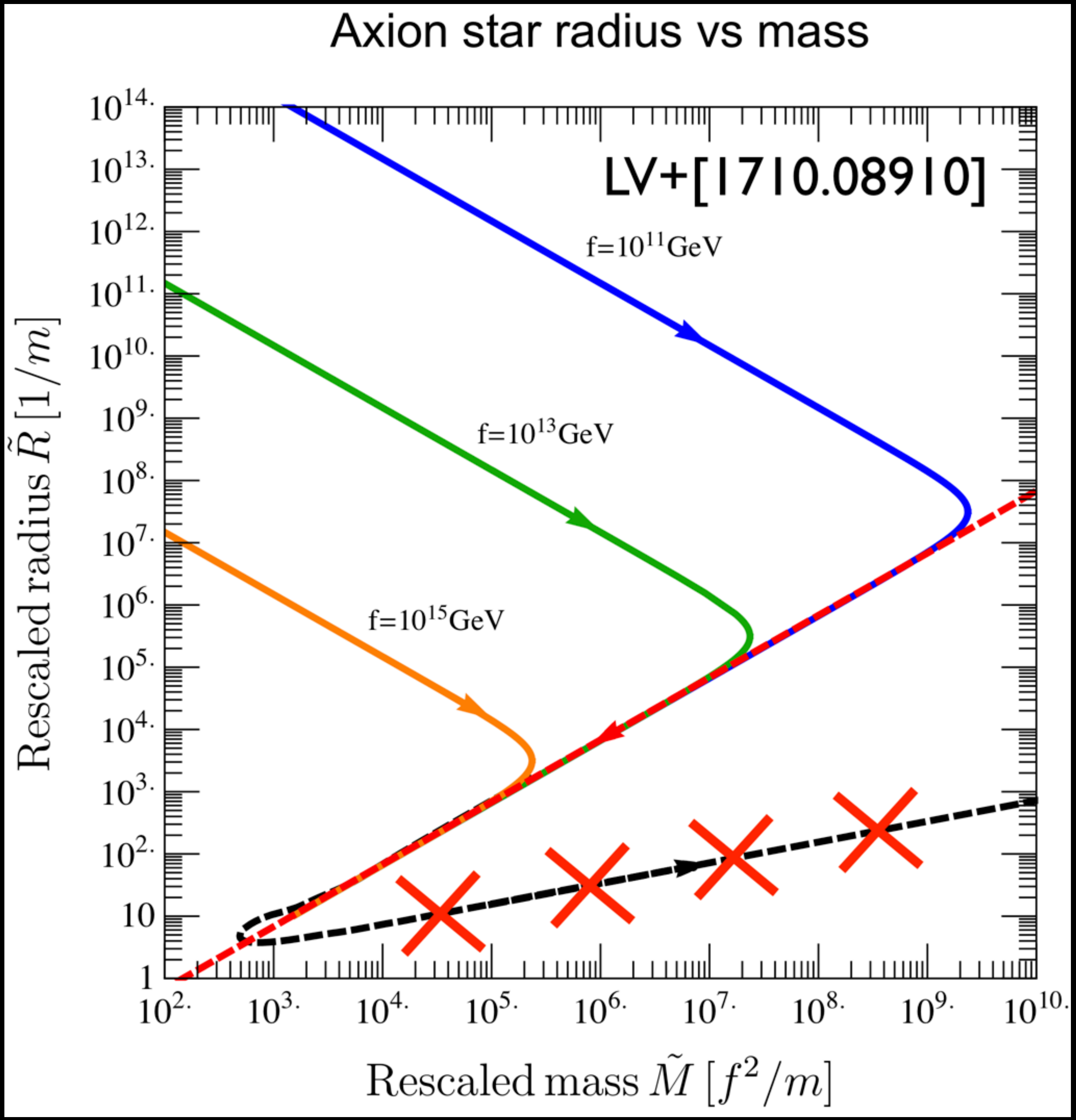
Relevant contributions:

- Kinetic pressure
- Gradient energy
- All orders in the potential

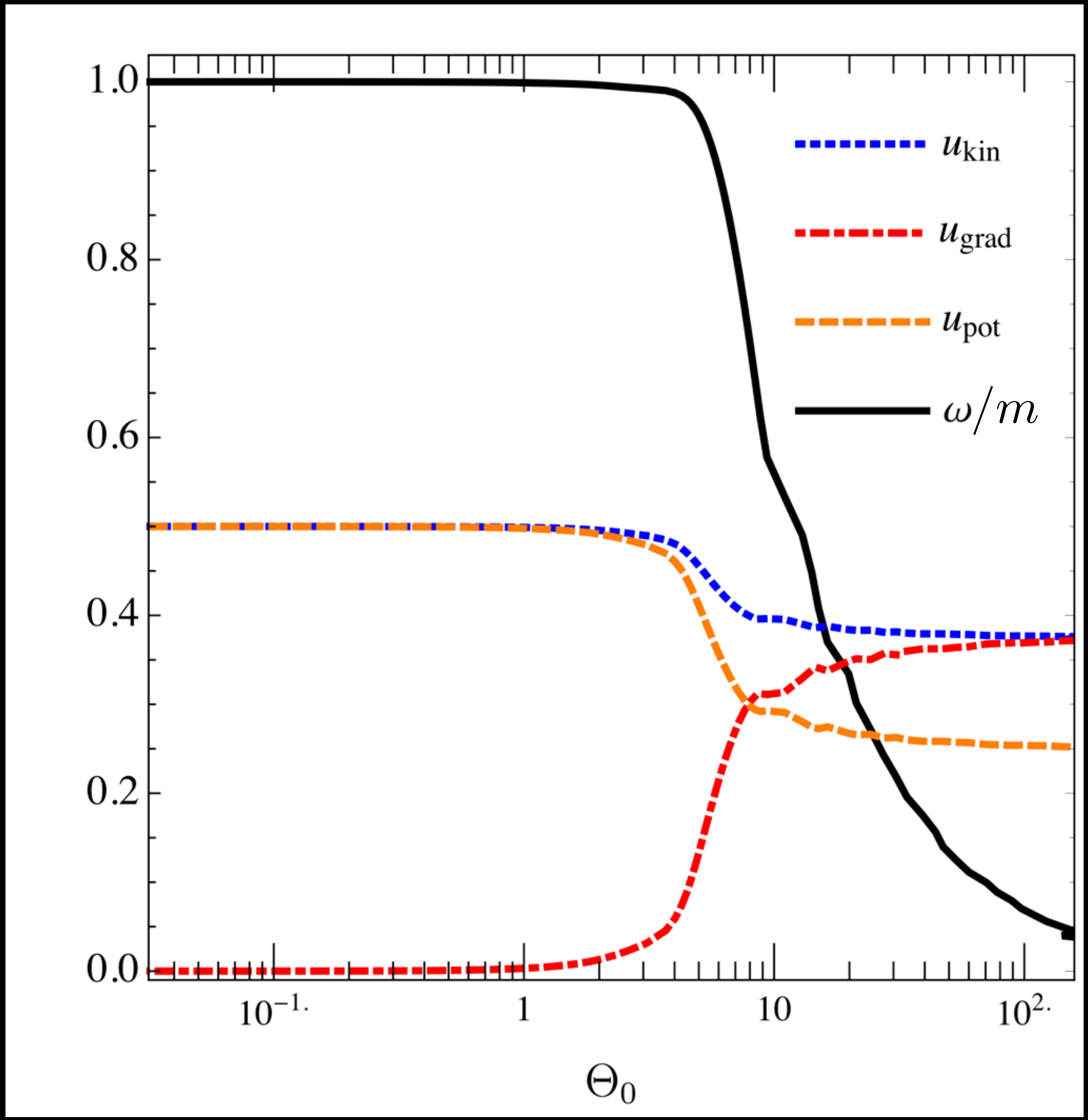
$\rho \sim \Lambda^4 \quad \text{or} \quad R \propto M^{1/3}$

Solutions are pseudo-oscillons of KGE with finite lifetime

$\tau_{\text{life}} = \mathcal{O}\left(\frac{10^3}{m}\right) \sim 10^{-7}\,\text{s}$



Transition from “critical” to “dense” branch



Conclusions

• Only axion stars in the "dilute" branch solution might have survived to date (provided tidal stripping).

Maximum mass $M_{\rm max} \sim 10^{-11} M_\odot \left(\frac{10^{-5}\,{\rm eV}}{m}\right)^2$

• Denser stars either radiate relativistic axions and puff out or they further collapse.

• Similar work: Schiappacasse&Hertzberg [1710.04729]
Chavanis [1710.06268]
Eby *et al.* [1712.04941]