

Cosmology of long range Yukawa interactions

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Based on arXiv:2606.28246 with
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Outlook

- Long range forces in the Early Universe
- Yukawa interactions in hidden dark sectors
- Solutions for generalised nonlinear Yukawa couplings
- Scaling homogeneous solutions

FLRW Evolution

FLRW metric: $ds^2 = -dt^2 + a^2(t)\delta_{ij}dx^i dx^j$ $H = \frac{\dot{a}}{a}$

fluid with eq. of state: $p = w\rho, \rho \sim a^{-3(1+w)}$

Standard tale:

Inflation

$w \approx -1, \rho \approx \text{constant}$

Not strong
constraints



radiation domination

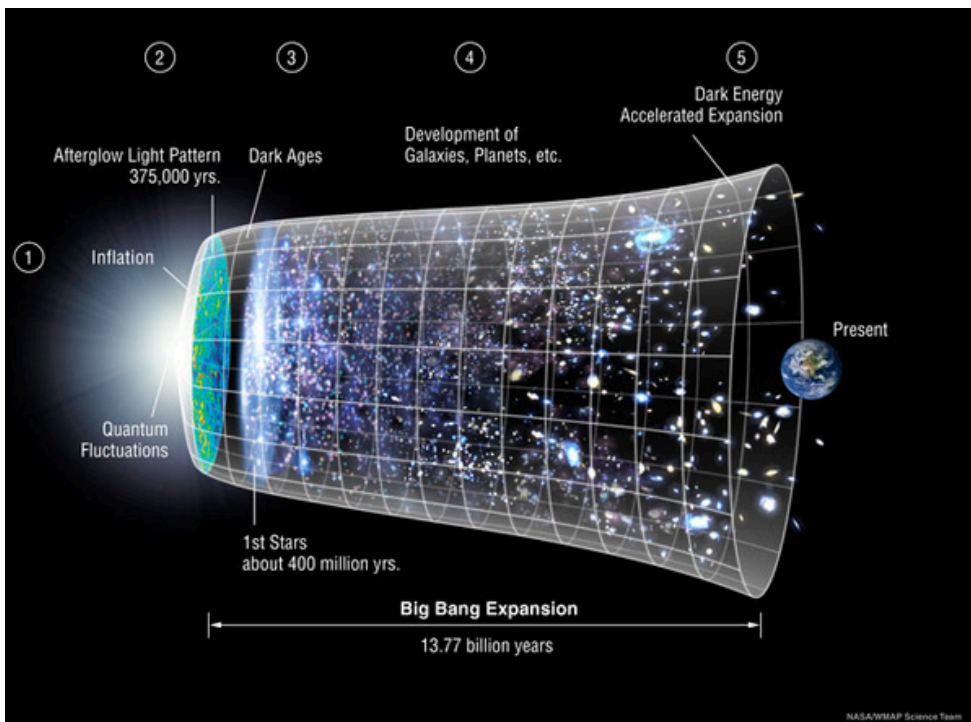
$w = 1/3, \rho \sim a^{-4}$

↓
matter domination

$w = 0, \rho \sim a^{-3}$

↓
late time cosmological constant

$w \approx -1$

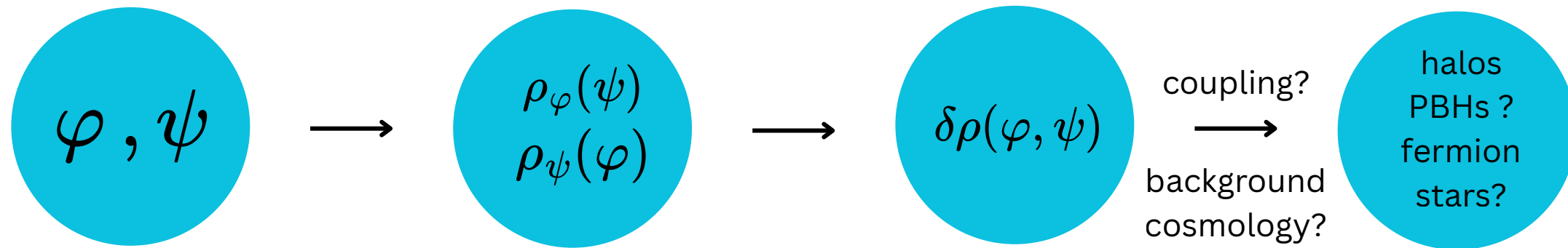


Long range Yukawa forces

Assume a dark hidden sector: scalar coupled to fermion

An attractive long range scalar force mediated by a **scalar** can be stronger than gravity

can significantly change the evolution of structures in the early universe



Scalar forces acting on dark matter

- The early Universe provides very small physical scales.
- A hidden sector can experience a force much stronger than gravity.

$$\beta_5 = M_{\text{pl}} \frac{\partial m(\varphi)}{\partial \varphi} \quad \frac{|F_5|}{|F_G|} \simeq 2\beta_5^2 \quad (r_{\text{phys}} \ll m_s^{-1})$$

Phenomenological interest

Early compact structures

Strong attraction can amplify ordinary primordial fluctuations into bound structures.
Accelerate early structure formation producing dark matter halos

PBHs

Once halos form, scalar radiation can remove energy and drive contraction, potentially leading to PBHs

Other Compact objects and gravitational waves

Previous Work

Development	
Coupled scalar and matter backgrounds	Wetterich (1995), arXiv:hep-th/9408025 Amendola (2000), arXiv:astro-ph/9908023
Early compact objects and primordial halos	Amendola, Rubio & Wetterich (2018), arXiv:1711.09915 Savastano et al. (2019), arXiv:1906.05300
Scalar cooling and PBHs	Flores & Kusenko (2021), arXiv:2008.12456
Relativistic backgrounds and nonlinear halos	Domènech & Sasaki (2021), arXiv:2104.05271 Domènech et al. (2023), arXiv:2304.13053

Relativistic backgrounds: Domènech & Sasaki (2021)

$$\mathcal{L}_{\text{DS}} = -\frac{1}{2}(\partial\varphi)^2 + \bar{\psi}(\Gamma^\mu D_\mu - m_\psi)\psi + y\varphi\bar{\psi}\psi$$

$$m_{\text{eff}} = |m_\psi + y\varphi|, \quad \varphi_s = -m_\psi/y$$

- The scalar is driven to a zero fermion mass point and oscillates around it.
- Both initially relativistic and predominantly nonrelativistic fermion gases (both for degenerate and thermal gases) reach an averaged scaling regime.

$$\langle m_{\text{eff}} \rangle \propto a^{-1}, \quad \langle \rho_\psi \rangle \propto a^{-4}, \quad \langle \rho_\varphi \rangle \propto a^{-4}$$

Effectively massless mediator, radiation background

Halo formation: Domènech et al. (2023)

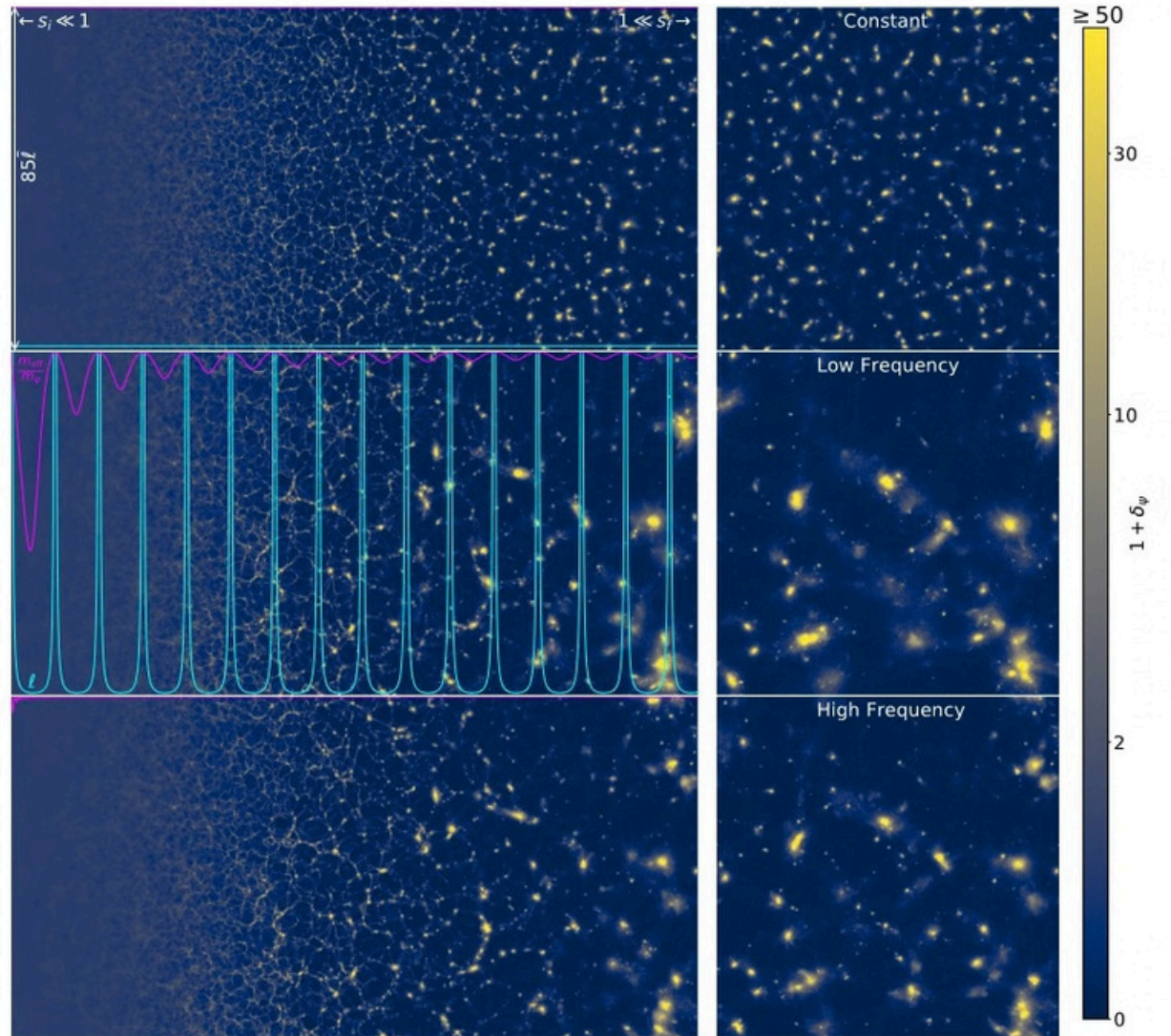
Exponential growth of fermion number density fluctuations for subhorizon perturbations

$$\ddot{\delta}_n + \left(2H + \frac{\dot{m}_{\text{eff}}}{m_{\text{eff}}}\right) \dot{\delta}_n \simeq 4\pi G_{\text{eff}} \rho_\psi \delta_n$$

$$\delta_n \sim e^{\Gamma N} \quad \text{with} \quad \Gamma \sim k^{1/2}$$

Scalar perturbations also grow but remain subdominant

Halo formation: Domènech et al. (2023)



Linear Yukawa coupling

Scalar potentials are included such that they allow a regime where fermions remain nonrelativistic.

N-body simulations and halo formation

Rapid fragmentation produces halos whose later fate needs further evolution.

Generalised couplings and expansion histories

Do scaling behaviours survive beyond a linear Yukawa coupling?

- Nonlinear monomial coupling functions and both coupling signs.
- Focus on Matter, radiation and stiff-fluid dominated backgrounds.
- Include a bare potential scalar potential.

Homogeneous dynamics as input to subsequent perturbation studies

Scalar–fermion Dark Sector

$$\mathcal{L}_{\text{DS}} = -\frac{1}{2}(\partial\varphi)^2 - V_{\text{bare}}(\varphi) + \bar{\psi}(\Gamma^\mu D_\mu - m_\psi)\psi + yf(\varphi)\bar{\psi}\psi$$

Effective fermion mass: $m_{\text{eff}}(\varphi) = |m_\psi + yf(\varphi)|$

Non-linear Yukawa coupling:

Bare scalar potential:

$$f(\varphi) = \pm M_{\text{Pl}} \left(\frac{\varphi}{M_{\text{Pl}}} \right)^p, \quad V_{\text{bare}}(\varphi) = \frac{\lambda_q}{q} M_{\text{Pl}}^4 \left(\frac{\varphi}{M_{\text{Pl}}} \right)^q$$

$p = 1$ gives the linear Yukawa interaction. Higher powers are EFT operators.

Prescribed cosmological backgrounds

Agnostic Background cosmology:

$$H^2(a) = H_i^2 a^{-3(1+w)}, \quad a_i = 1, \quad w \in \{0, 1/3, 1\}$$

Background	w	Dominant density
Matter	0	a^{-3}
Radiation	1/3	a^{-4}
Stiff fluid	1	a^{-6}

Dark sector spectator if: $\Omega_\varphi \equiv \frac{\rho_\varphi}{3M_{\text{Pl}}^2 H^2} \ll 1, \quad \Omega_\psi \equiv \frac{\rho_\psi}{3M_{\text{Pl}}^2 H^2} \ll 1$

Degenerate Fermi gas

Dark sector is **decoupled** from the background cosmic fluid

Fermion number is conserved and dilute only due to expansion

$$\rho_\psi = \frac{1}{\pi^2} \int_0^{p_F} dk \, k^2 \sqrt{k^2 + m_{\text{eff}}^2},$$

$$p_\psi = \frac{1}{3\pi^2} \int_0^{p_F} dk \, \frac{k^4}{\sqrt{k^2 + m_{\text{eff}}^2}}.$$

$$\rho_{\text{DS}} = \rho_\varphi + \rho_\psi$$

$$\dot{\rho}_\psi + 3H(\rho_\psi + p_\psi) = \mathcal{S}_\varphi \dot{\varphi},$$

$$\dot{\rho}_\varphi + 3H(\rho_\varphi + p_\varphi) = -\mathcal{S}_\varphi \dot{\varphi}.$$

Degenerate Fermi gas

Fermion number density dilutes with volume expansion:

$$n_\psi = n_{\psi,i} a^{-3}, \quad p_F = (3\pi^2 n_\psi)^{1/3} = p_{F,i} a^{-1}$$

$$\rho_\psi = \rho_\psi(n_\psi, m_{\text{eff}}), \quad p_\psi = p_\psi(n_\psi, m_{\text{eff}})$$

Define the ratio:

$$x = \frac{m_{\text{eff}}}{p_F} \geq 0$$

Limiting cases

$$x \ll 1 \quad \text{relativistic fermions}$$

$$x \gg 1 \quad \text{nonrelativistic fermions}$$

T = 0 gives analytic control while retaining degeneracy pressure.

Coupled homogeneous evolution

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{dV_{\text{bare}}(\varphi)}{d\varphi} + \mathcal{S}_{\varphi} = 0 ,$$

$$\mathcal{S}_{\varphi} \equiv \frac{\partial \rho_{\psi}}{\partial \varphi} = y \frac{\partial f(\varphi)}{\partial \varphi} \text{sgn}(m_{\psi} + yf(\varphi)) \frac{\rho_{\psi} - 3p_{\psi}}{m_{\text{eff}}} ,$$

scalar density: $\rho_{\varphi} = \frac{1}{2}\dot{\varphi}^2 + V_{\text{bare}}(\varphi)$

fermion density :

$$\rho_{\psi} = \rho_{\psi,i} a^{-4} \quad x \ll 1$$

$$\rho_{\psi} = n_{\psi} m_{\text{eff}} = \rho_{\psi,i} a^{-3} |m_{\psi} + yf(\varphi)| \quad x \gg 1$$

Density-dependent effective potential

$$V_{\text{eff}}(\varphi, a) = V_{\text{bare}}(\varphi) + \rho_{\psi}[n_{\psi,i}a^{-3}, m_{\text{eff}}(\varphi)]$$

$$x \gg 1 : \quad \rho_{\psi} \simeq n_{\psi}m_{\text{eff}},$$

$$x \ll 1 : \quad \rho_{\psi} \simeq \frac{p_F^4}{4\pi^2} + \frac{m_{\text{eff}}^2 p_F^2}{4\pi^2}.$$

The profile depends on both the coupling function and the diluting fermion density.

One saturation point for odd monomial positive couplings

$$\phi \equiv \left(\frac{y M_{\text{Pl}}}{m_\psi} \right)^{1/p} \frac{\varphi}{M_{\text{Pl}}}, \quad m_{\text{eff}} = m_\psi |1 + \phi^p|$$

$$\phi_s = -1 \quad \text{such that} \quad m_{\text{eff}}(\phi_s) = 0 \quad \text{for} \quad f(\phi) \propto +\phi^p$$

A finite zero of the physical mass selects the local oscillation centre.

Dimensionless limiting equations for $f(\phi) \propto \pm \phi^p$

Define: $\beta \equiv \left(\frac{y M_{\text{pl}}}{m_\psi} \right)^{1/p}$, $\phi \equiv \frac{\beta \varphi}{M_{\text{pl}}}$, $\Lambda_q \equiv \frac{\lambda_q M_{\text{pl}}^2}{H_i^2 \beta^{q-2}}$, $m_{\text{eff}} = m_\psi |1 \pm \phi^p|$, $x = x_i a \frac{|1 \pm \phi^p|}{|1 \pm \phi_i^p|}$

relativistic fermions $x \ll 1$

$$\phi'' + \frac{5-3w}{2a} \phi' + \Lambda_q a^{3w+1} \phi^{q-1} \pm K p a^{3w-1} (1 \pm \phi^p) \phi^{p-1} = 0, \quad K \simeq \frac{6 \beta^2 x_i^2}{|1 \pm \phi_i^p|^2} \Omega_{\psi,i}$$

non-relativistic fermions $x \gg 1$

$$\phi'' + \frac{5-3w}{2a} \phi' + \Lambda_q a^{3w+1} \phi^{q-1} \pm D p a^{3w-2} \text{sgn}(1 \pm \phi^p) \phi^{p-1} = 0, \quad D \simeq \frac{3 \beta^2}{|1 \pm \phi_i^p|} \Omega_{\psi,i}$$

At late times bare potential contribution **always** dominates the evolution

Dynamics in terms of the “effective potential”

Bare term + coupling contribution integrated, give an effective potential for (+) coupling

relativistic fermions $x \ll 1$

$$V_{\text{eff}}^{\text{rel}}(\phi; a) = \frac{1}{q} \Lambda_q a^{3w+1} \phi^q + K \left(\phi^p + \frac{1}{2} \phi^{2p} \right) a^{3w-1}.$$

non-relativistic fermions $x \gg 1$

$$V_{\text{eff}}^{\text{non-rel}}(\phi; a) = \frac{1}{q} \Lambda_q a^{3w+1} \phi^q + D a^{3w-2} \begin{cases} \phi^p, & p \text{ even}, \\ |1 + \phi^p|, & p \text{ odd}. \end{cases}$$

At late times bare potential contribution **always** dominates the evolution

Dynamics in terms of the “effective potential”

~~Bare term~~ + coupling contribution integrated, give an effective potential

relativistic fermions $x \ll 1$

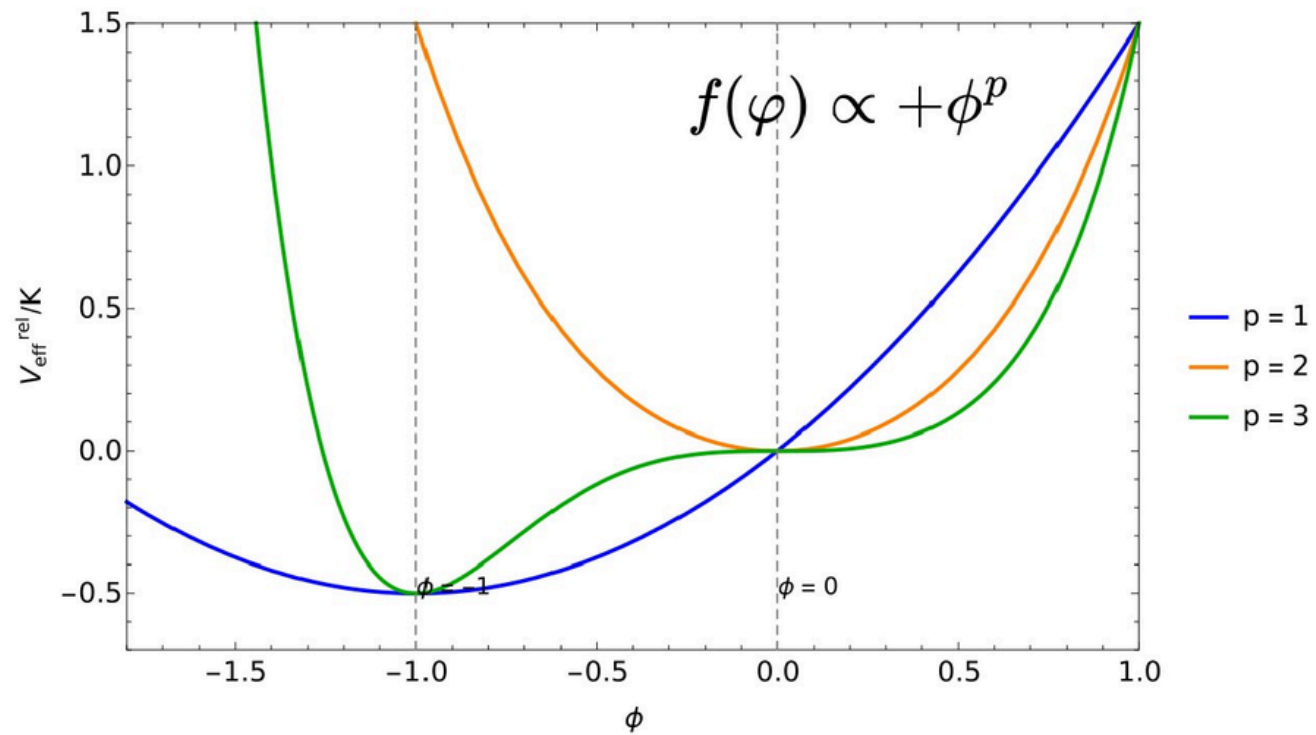
$$V_{\text{eff}}^{\text{rel}}(\phi; a) = \cancel{\frac{1}{q} \Lambda_q a^{3w+1} \phi^q} + K \left(\phi^p + \frac{1}{2} \phi^{2p} \right) a^{3w-1}.$$

non-relativistic fermions $x \gg 1$

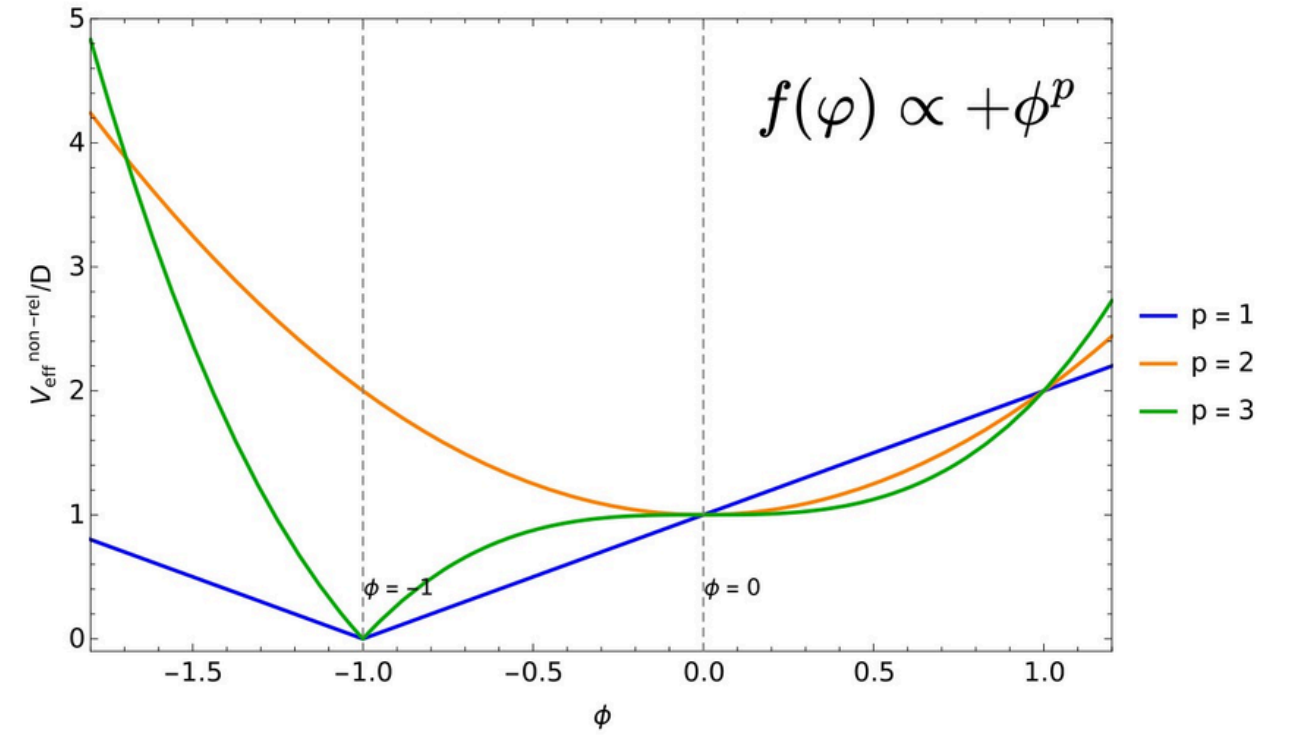
$$V_{\text{eff}}^{\text{non-rel}}(\phi; a) = \cancel{\frac{1}{q} \Lambda_q a^{3w+1} \phi^q} + D a^{3w-2} \begin{cases} \phi^p, & p \text{ even}, \\ |1 + \phi^p|, & p \text{ odd}. \end{cases}$$

Effective-potential profiles for vanishing bare potential

Relativistic limit



Nonrelativistic limit



Odd powers share the zero at $\phi = -1$

Exact solution for linear Yukawa coupling for relativistic fermions

For p=1 linear coupling analytical solution in terms of Bessel functions

Exact solution:

$$\phi = -1 + a^{\frac{3(w-1)}{4}} (c_1 J_\nu(z(a)) + c_2 Y_\nu(z(a))),$$

Late time solution:

$$\phi(a) = -1 + \frac{A}{a} \cos \left(\frac{2\sqrt{K}}{3w+1} a^{\frac{3w+1}{2}} + \theta \right), \quad a \gg 1$$

Late time solution for non-linear Yukawa coupling for relativistic fermions

Late time solutions for $p > 1$ odd:

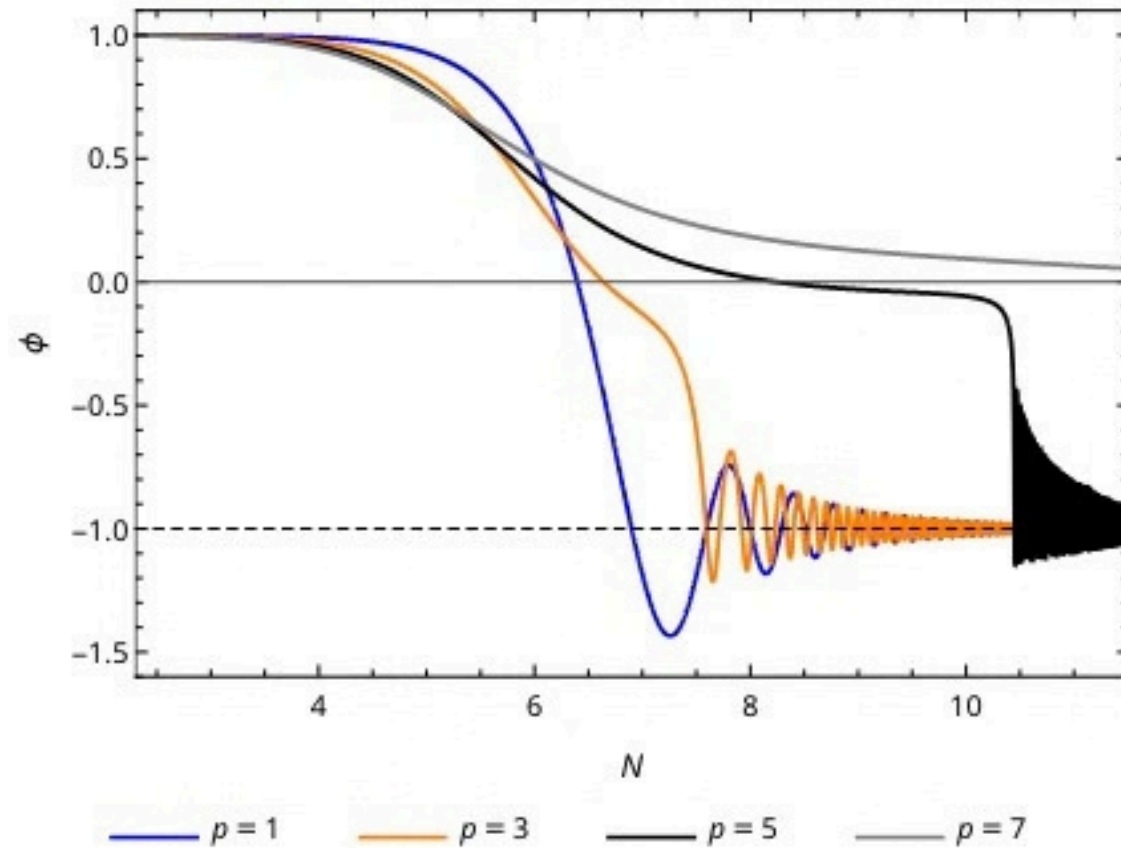
oscillatory solutions:
$$\phi(a) \approx -1 + \frac{A_p}{a} \cos \left(\frac{2p\sqrt{K}}{3w+1} a^{\frac{3w+1}{2}} + \theta_p \right) .$$

qualitatively similar behaviour to $p=1$ case

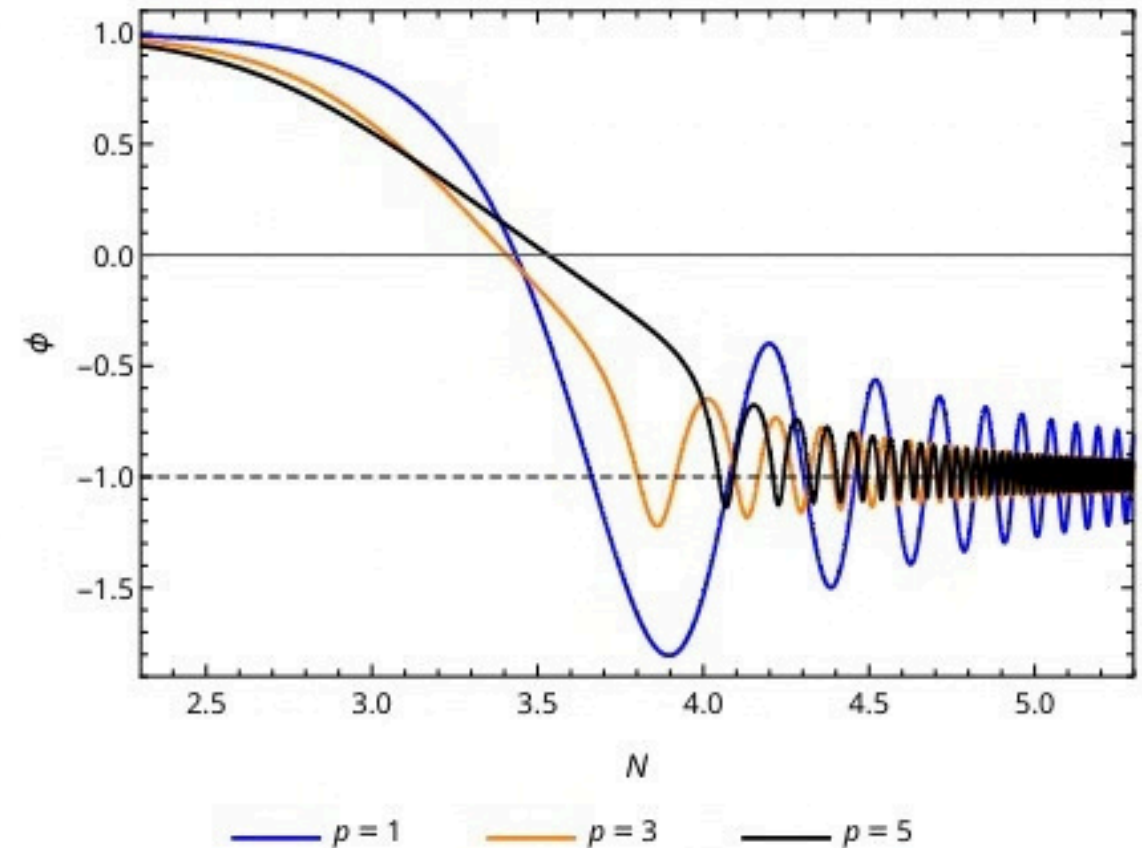
asymptotic solutions:
$$\phi(a) \sim a^{-\frac{3w+1}{p-2}} .$$

Relativistic trajectories near saturation

$w = 1/3$



$w = 1$



$$\phi(a) \simeq -1 + \frac{\mathcal{A}_p}{a} \cos \Theta_p(a), \quad \Theta_p(a) \propto a^{(3w+1)/2}$$

Scaling solutions around the saturation point

Late time solution $a \gg 1$

$$|1 + \phi| = a^{-1} \times \text{oscillations}(a)$$

$$x \approx x_i a |1 + \phi| \sim x_i a^0 \times \text{oscillations}(a) \ll 1$$

relativistic fermions **remain** on average relativistic at scaling regime

$$m_{\text{eff}} \sim |1 + \phi^p| \sim a^{-1}$$

Radiation-like energy scaling

energy densities:

Relativistic fermions decay as radiation

$$\langle \rho_\psi \rangle \sim p_F^4 + m_{\text{eff}}^2 p_F^2 \sim a^{-4}$$

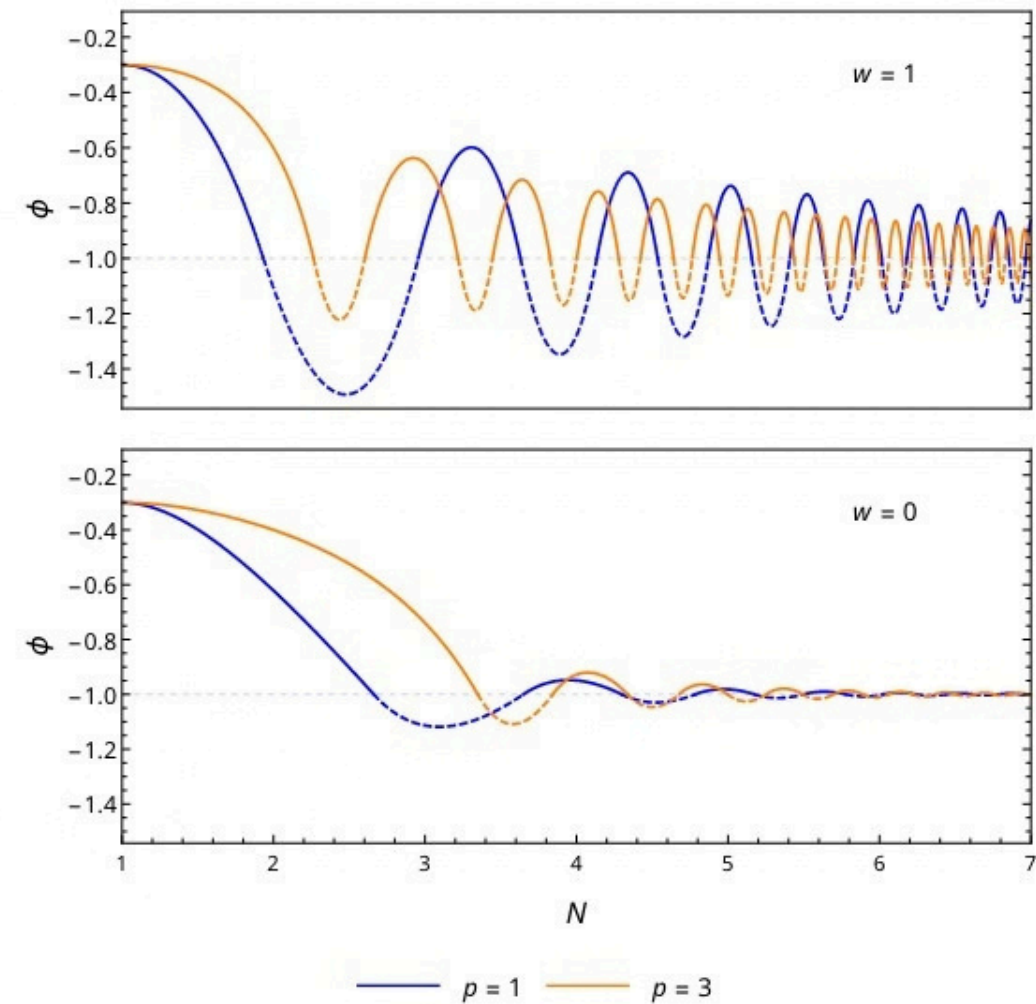
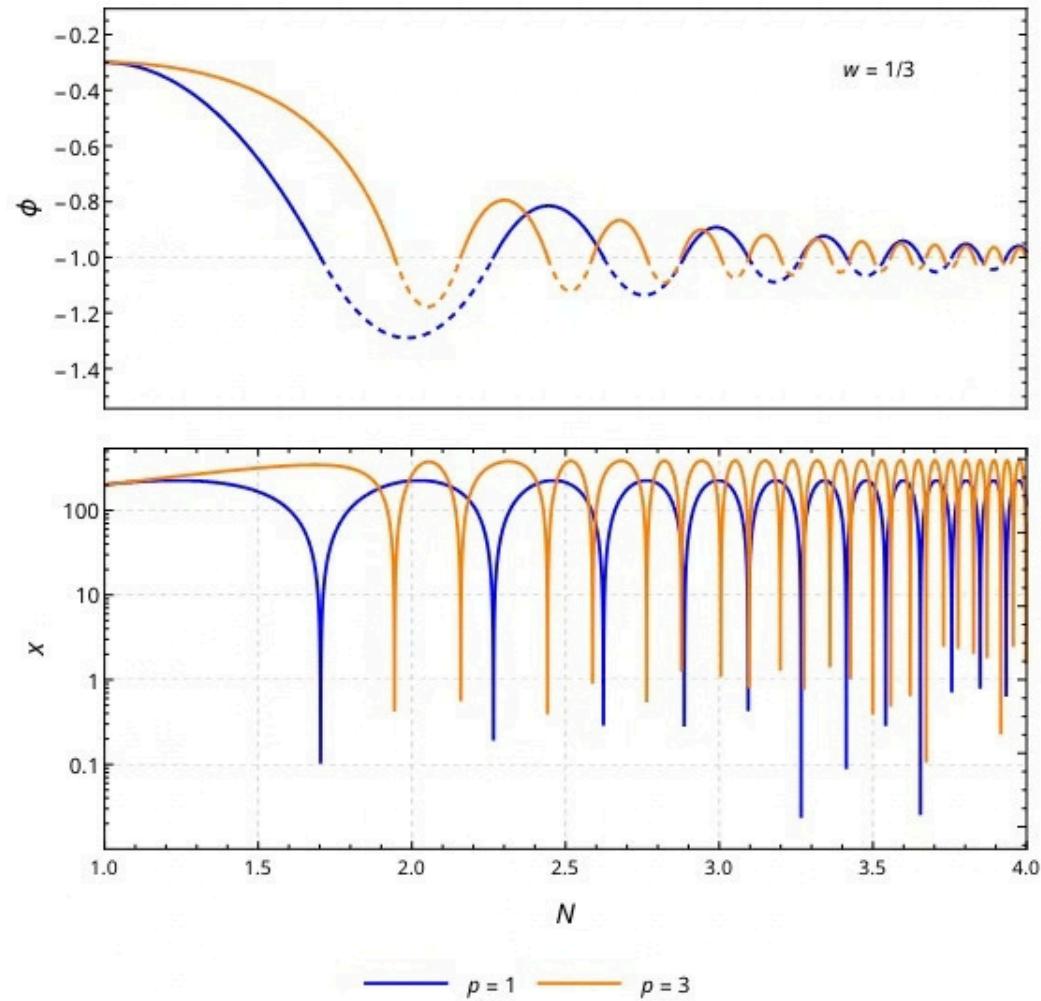
Scalar kinetic energy around the saturation point

$$\langle \rho_\phi \rangle \sim \phi'^2 / a^2 \sim a^{-4}$$

This is independent of the background fluid

for radiation background $\rho_f \sim a^{-4} \Rightarrow$ tracking solutions

Nonrelativistic trajectories and brief mass crossings



Zero-mass crossings can occupy only a small fraction of each oscillation.

Non-relativistic scaling solutions for p odd

Late time solutions for odd p, hyperbolic waves for each sign branch

Fourier decomposition first harmonic:

$$\phi(a) \approx -1 + \frac{32A_p}{\pi^3 a} \cos \left(\sqrt{\frac{\pi^2 D p}{2(3w+1)^2 A_p}} a^{\frac{3w+1}{2}} + \Theta_p(a) \right)$$

freq. same dependence as in rel.

$$|1 + \phi| = a^{-1} \times \text{oscillations}(a)$$

$$x \approx x_i a |1 + \phi| \sim x_i a^0 \times \text{oscillations}(a)$$

$$m_{\text{eff}} \sim |1 + \phi^p| \sim a^{-1}$$

nonrelativistic treatment breaks briefly when $x=0$

Radiation-like scaling

Again Radiation-like energy scaling

Predominantly nonrelativistic fermions

$$\langle \rho_\psi \rangle \simeq n_\psi \langle m_{\text{eff}} \rangle \propto a^{-3} a^{-1} = a^{-4}$$

Scalar kinetic energy

$$\langle \rho_\phi \rangle \sim a^{-4}$$

Nonrelativistic fermions have the same radiation-like redshifting.

Scale invariance near the mass zero

Nearby a saturation points, locally linear Yukawa interaction.

$$M(\varphi) = m_\psi + yf(\varphi), \quad M(\varphi_s) = 0,$$
$$\chi = \varphi - \varphi_s, \quad M(\varphi) \simeq g_s \chi, \quad g_s = M_{,\varphi}(\varphi_s) \neq 0.$$

$$\mathcal{L}_{\text{local}} = -\frac{1}{2}(\partial\chi)^2 + i\bar{\psi}\gamma^\mu\partial_\mu\psi - g_s\chi\bar{\psi}\psi$$

The coupling is dimensionless. No fixed mass scale remains.

$$x^\mu \mapsto \lambda x^\mu, \quad \chi \mapsto \lambda^{-1}\chi, \quad \psi \mapsto \lambda^{-3/2}\psi \quad (\lambda = \text{constant})$$

Constant dilations leave the action unchanged.

Small excursions around the zero, negligible bare potential

Conformal variables and the mass scaling

Absorb the expansion into the fields

$$u = a\chi, \quad \tilde{\psi} = a^{3/2}\psi, \quad a m_{\text{eff}} = |g_s u|$$

$$u'' + \mathcal{U}_{,u} - \underbrace{\frac{a''}{a} u}_{\text{expansion correction}} \simeq 0, \quad \mathcal{U}(u) = a^4 \rho_\psi$$

Conserved comoving Fermi momentum makes the potential time independent.

For $\omega \gg H$ the correction is negligible. In radiation domination it vanishes.

$$\mathcal{E} = \frac{1}{2}u'^2 + \mathcal{U}(u) \simeq \text{constant}$$

Constant rescaled energy gives a constant oscillation amplitude.

$$\text{envelope}(m_{\text{eff}}) \propto a^{-1}$$

Primes denote conformal-time derivatives, $dt = a \, d\tau$

Peculiar solutions for positive even couplings

$$f(\phi) \propto +\phi^p, \quad p \text{ even}$$
$$m_{\text{eff}} = m_\psi |1 + \phi^p| > 0$$

Effective potential has min at $\phi = 0$

Oscillatory solutions around zero: $\phi = a^{-4/(p+2)} \times \text{oscillations}(a) \quad x \ll 1$

$$\phi = a^{-3/(p+2)} \times \text{oscillations}(a) \quad x \gg 1$$

Asymptotic solutions: $\phi \sim a^{-\frac{3w+1}{p-2}} \quad x \ll 1$

The asymptotic expression with $p - 2$ excludes $p = 2$.

Consistency checks

Far from the saturation point fermions may get non-relativistic (eg. **asymptotic solutions**)

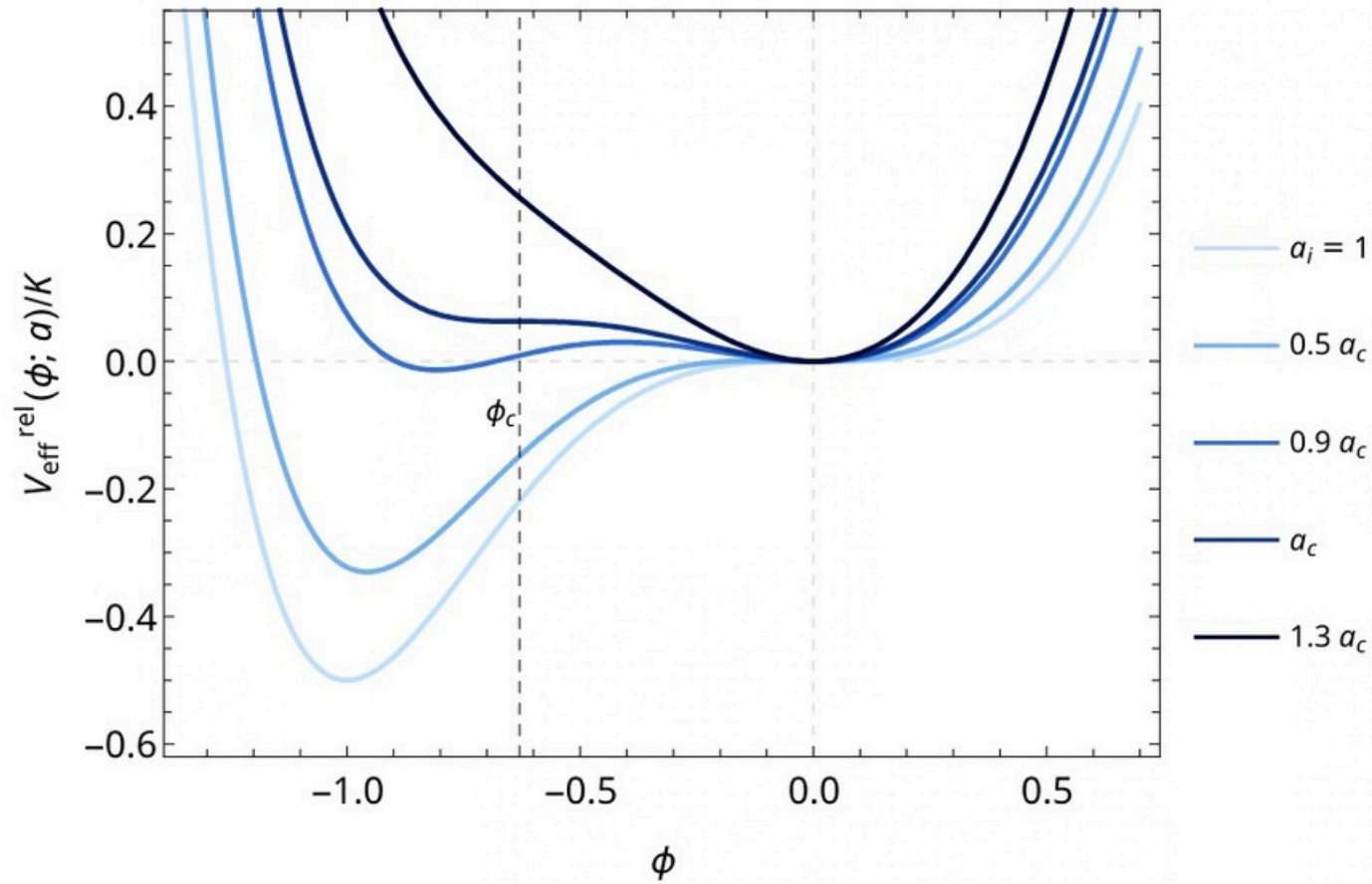
$$x \sim x_i a |1 + \phi^p| \sim a$$

Dark sector **must** remain subdominant

Background	
Matter, $w = 0$	$\Omega_{\text{DS}} \sim a^{-1}$
Radiation, $w = 1/3$	$\Omega_{\text{DS}} \sim \text{constant}$
Stiff fluid, $w = 1$	$\Omega_{\text{DS}} \sim a^2$

The scaling regime must fit inside the spectator window.

A bare potential moves the minimum



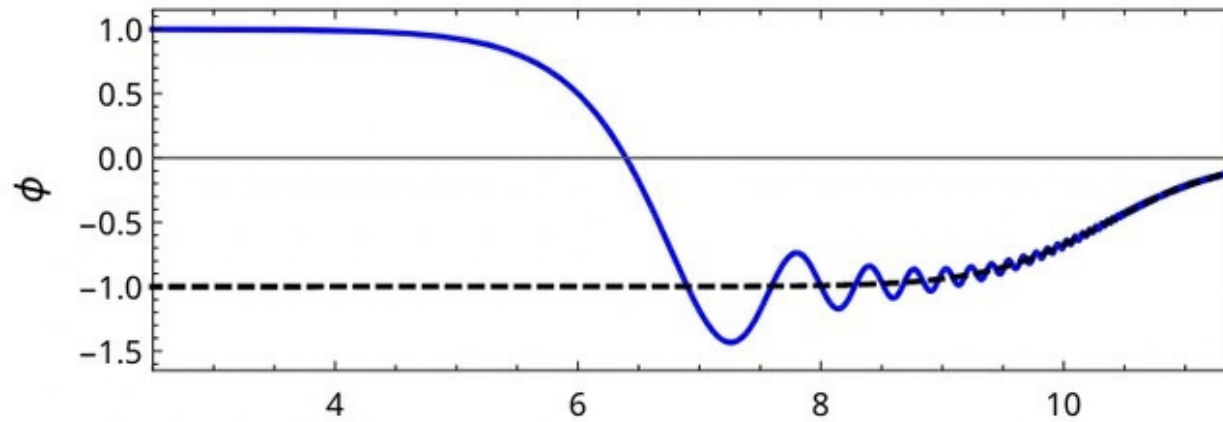
- The fermion-induced contribution dilutes.
- The effective minimum moves away from saturation.
- The scalar increasingly responds to its bare potential.

The effective minimum drifts towards the origin.

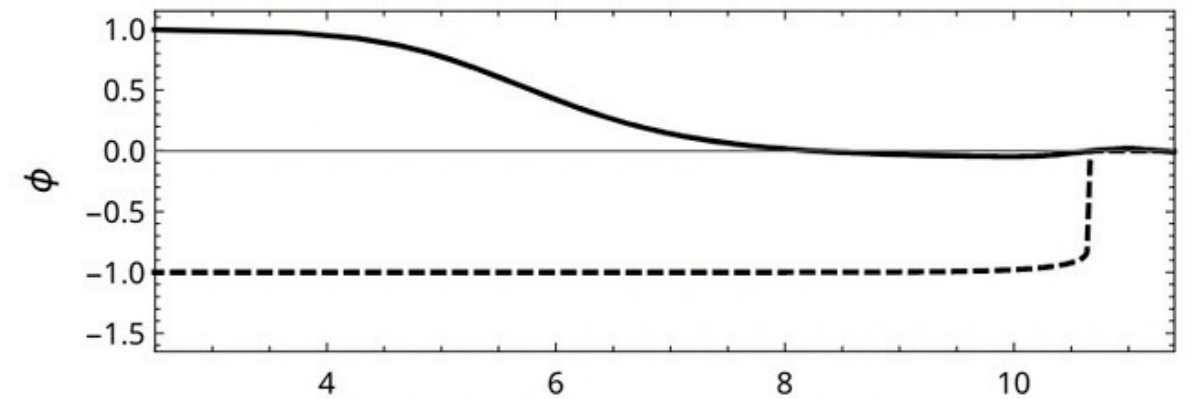
Quadratic bare potential

$$V_{\text{bare}} = \frac{1}{2}m_{\varphi}^2\varphi^2, \quad m_{\text{eff}} \longrightarrow m_{\psi} \quad (\varphi \longrightarrow 0)$$

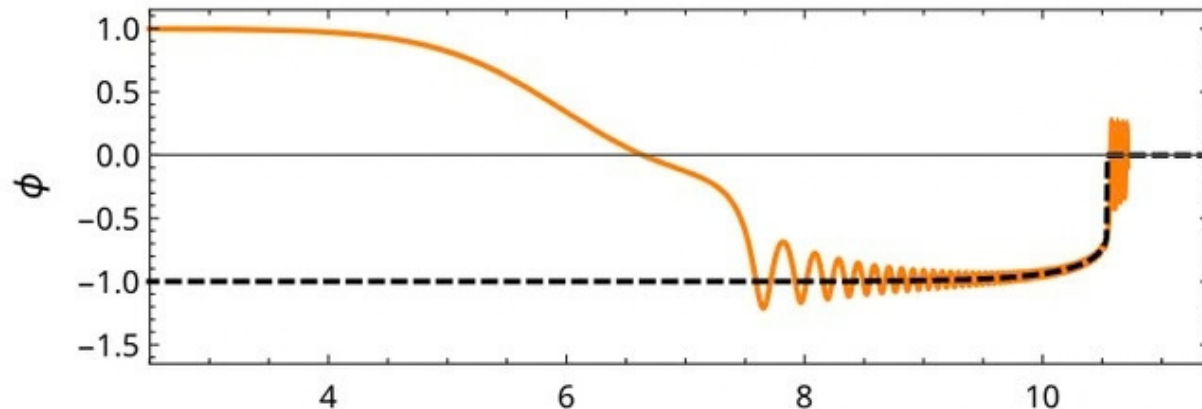
p = 1



p = 5



p = 3



Solid: scalar trajectory
Dashed: effective minimum

$N = \ln a$

Linear coupling: continuous drift.
Higher powers: the saturation branch ends at a finite time.

Energy evolution after departure from saturation

Separate dynamical regimes

- Scaling around the saturation point.
- Motion around the drifting minimum.
- Oscillations about the bare minimum.

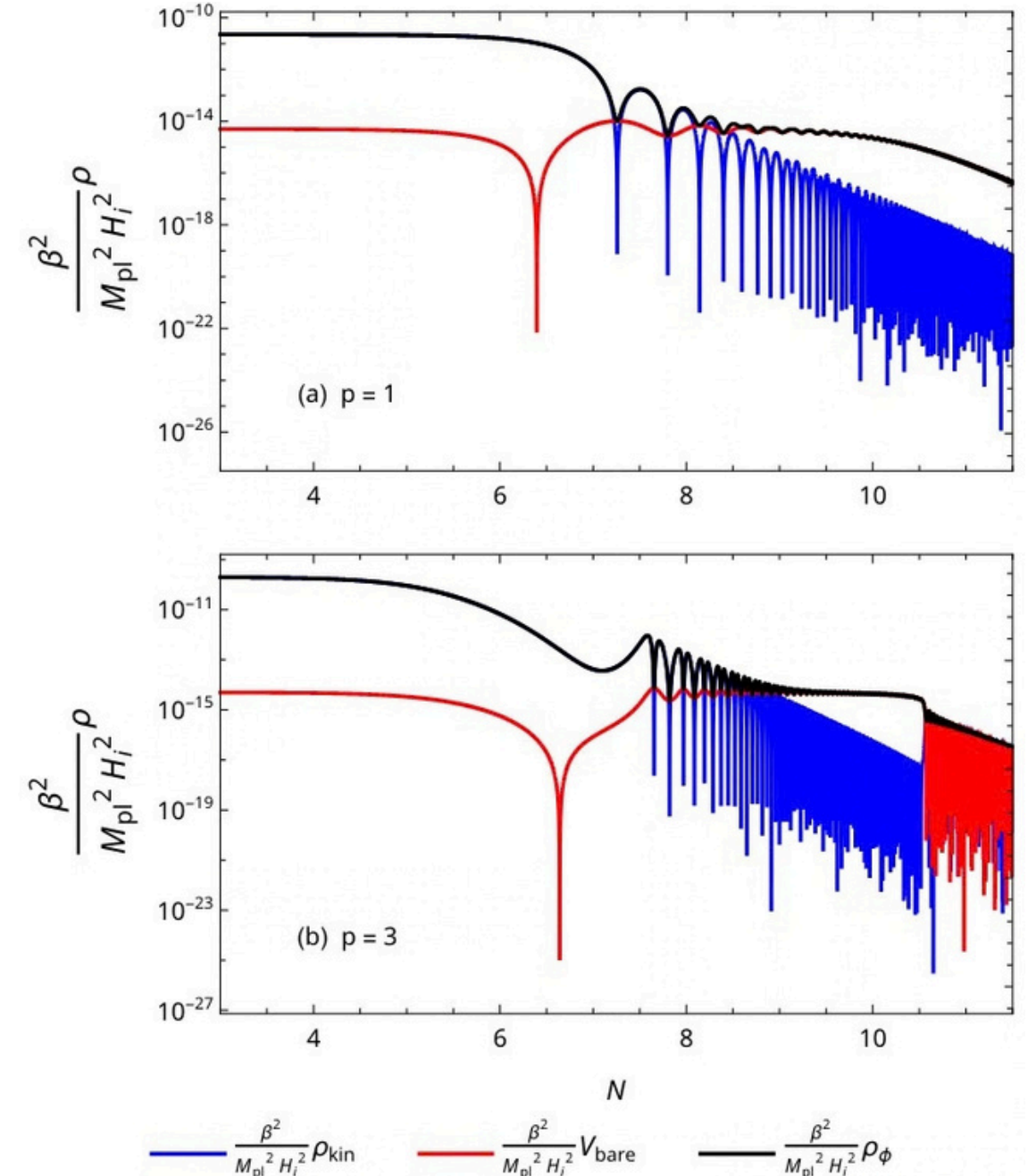
For linear Yukawa:

$$\rho_\phi \sim V(\phi) \sim \phi_{\min}^2 \sim a^{-4} \quad a \gg 1$$

$$\rho_{\phi \text{ kin}} \sim a^{-4}$$

For $p > 1$:

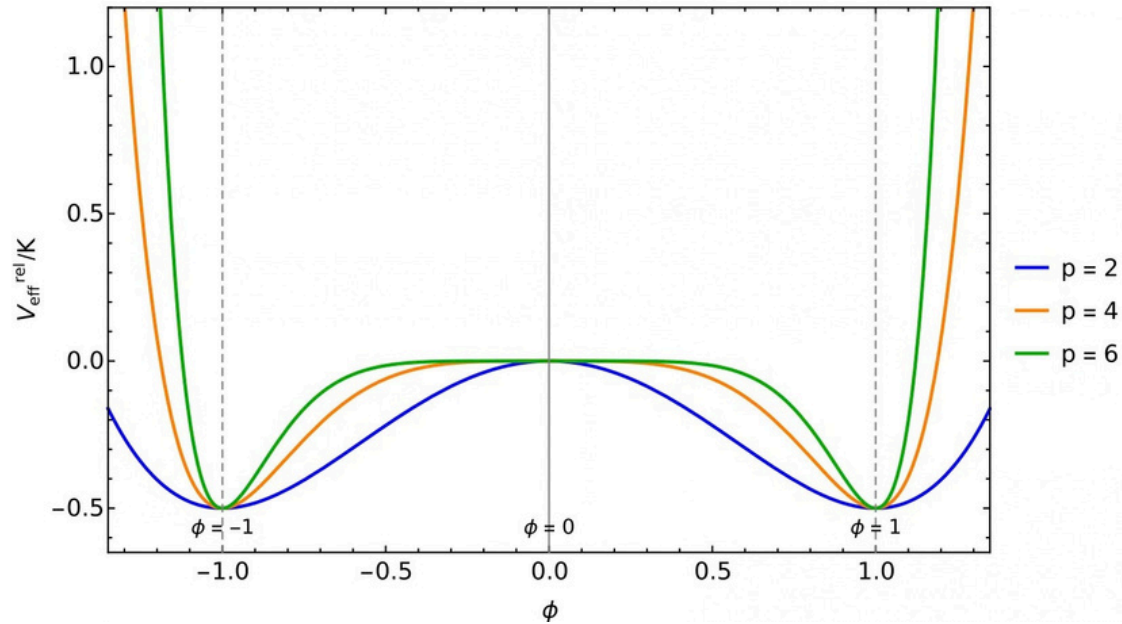
$$\rho_\phi \sim a^{-3} \quad a \gg 1$$



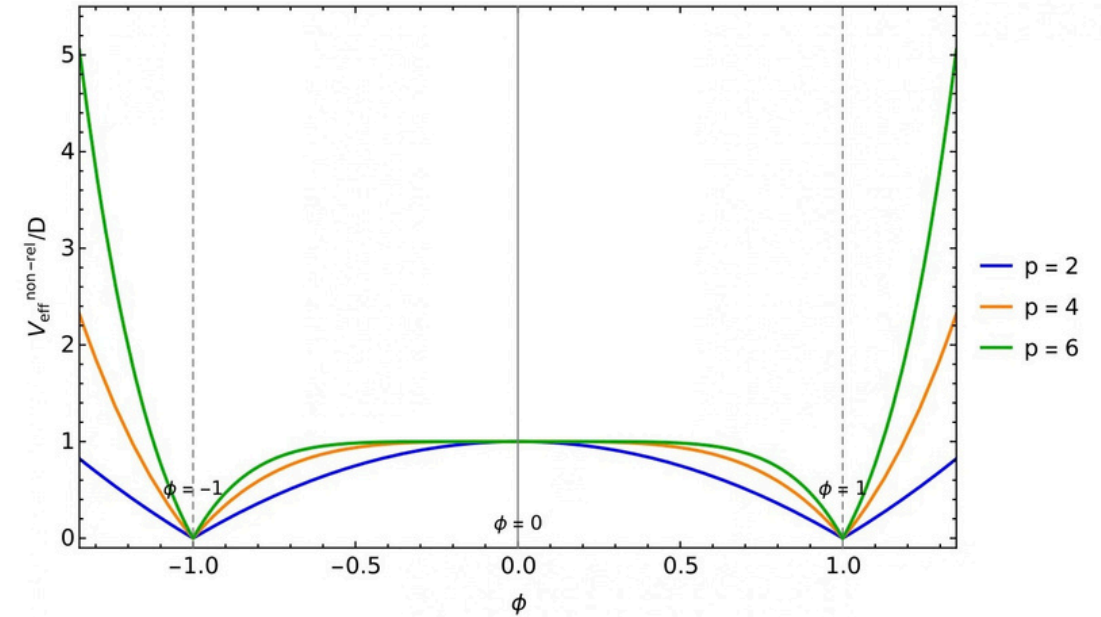
Even powers can give two such saturation points

$$m_{\text{eff}} = m_{\psi}|1 - \phi^p|, \quad \phi_s = \pm 1 \quad (p \text{ even})$$

Relativistic limit

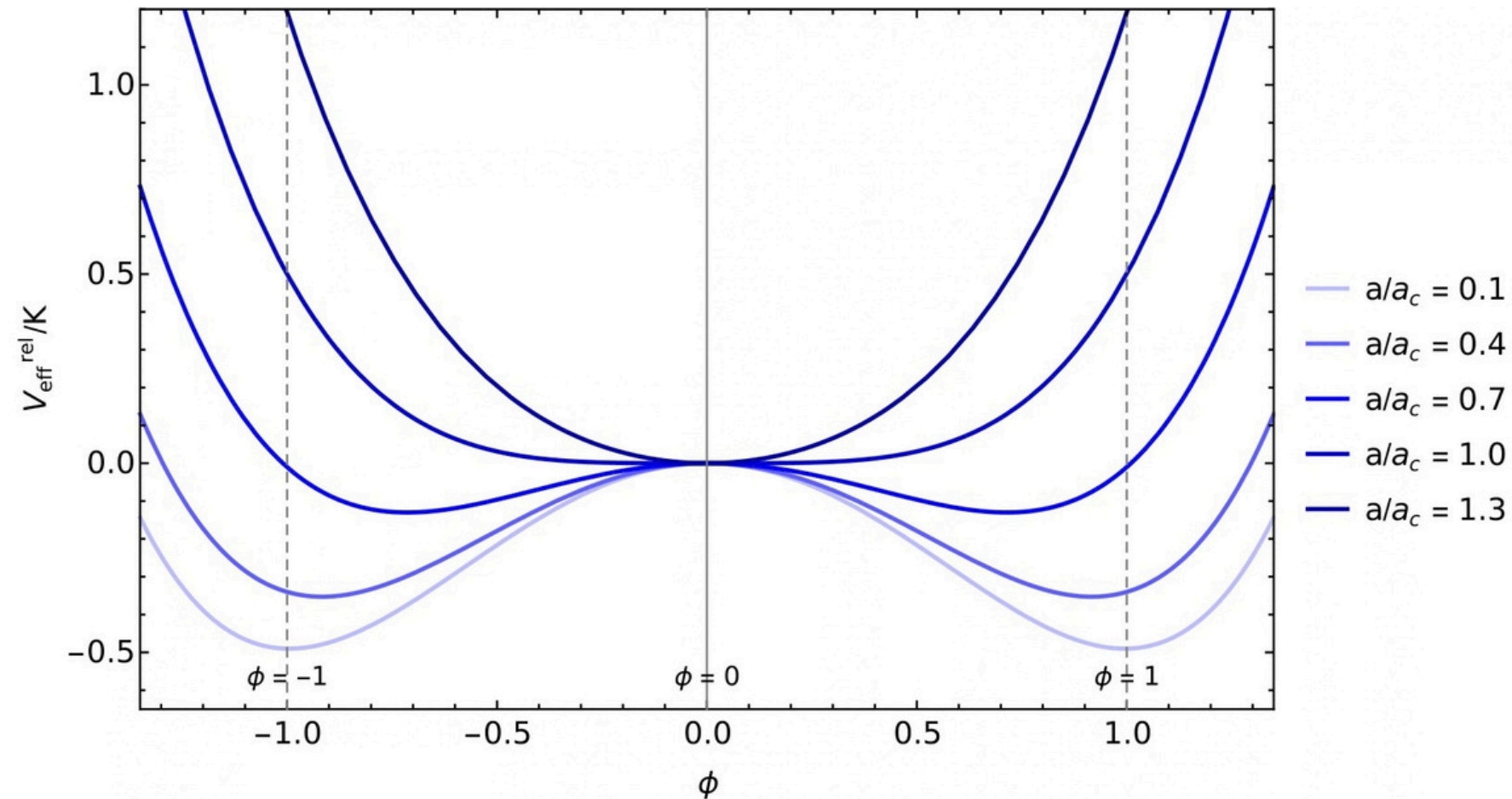


Nonrelativistic limit



Coupling sign and parity change the number of accessible mass-zero points.

The two minima of the effective potential merge as fermions dilute



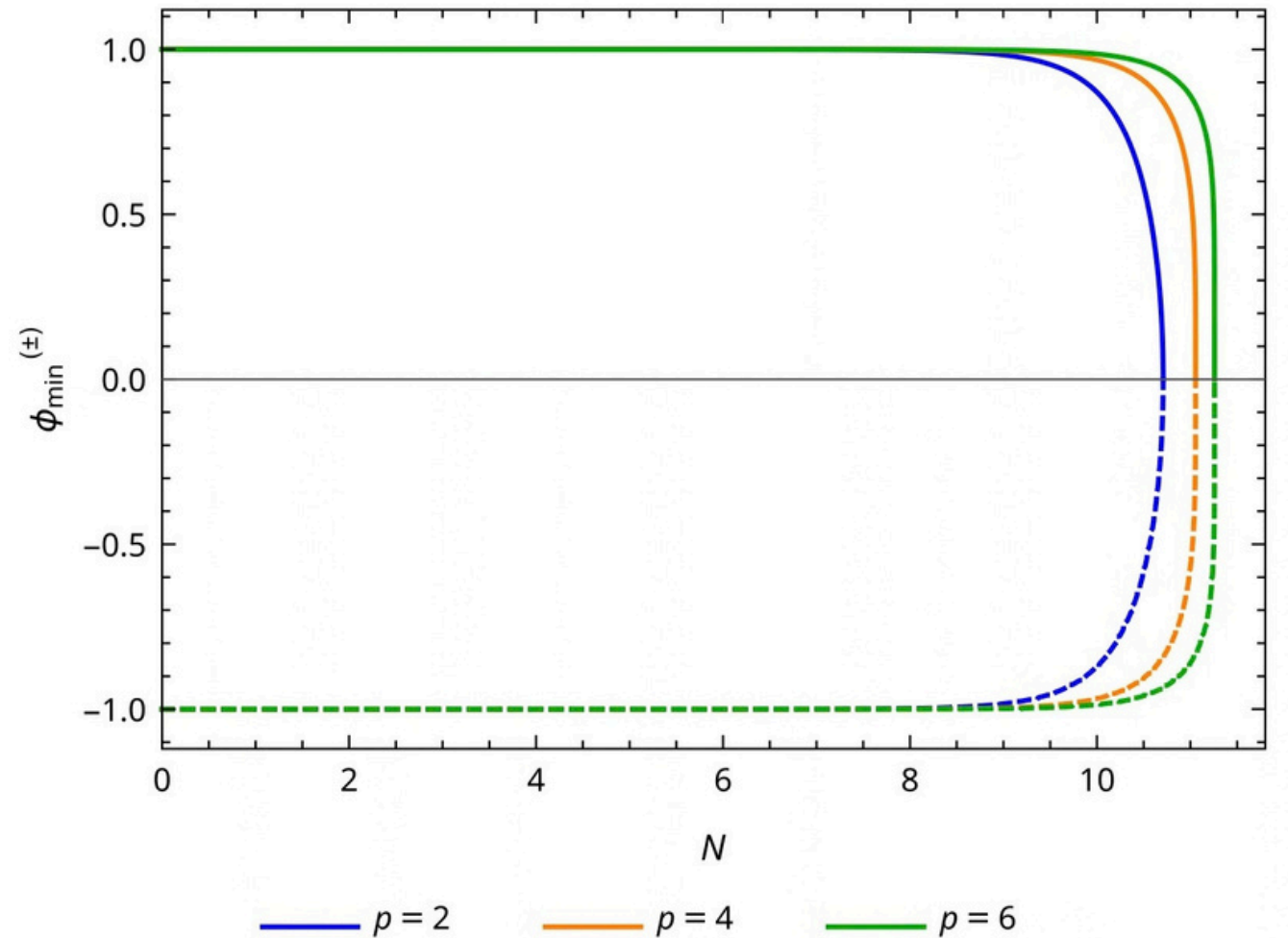
$$f(\phi) \sim -\phi^2$$

$$V_{\text{bare}} \sim \phi^2$$

At finite time the two minima merge

Even-p minima: the two branches converge

Relativistic regime, $q = p = 2, 4, 6$



$$\phi_{\min}^{(\pm)}(a) = \pm \left[1 - \left(\frac{a}{a_c} \right)^2 \right]^{1/p},$$

$$a_c^2 = \frac{Kp}{\Lambda_p}, \quad a \leq a_c.$$

Solid: positive minimum

Dashed: negative minimum

Different patches could occupy opposite effective minima.

Domain-wall formation and disappearance require spatial evolution.

Dilatonic coupling

$$f(\varphi) = \pm M_{\text{pl}} e^{c\varphi/M_{\text{pl}}}$$
$$m_{\text{eff}} = m_{\psi} \left| 1 \pm \frac{y M_{\text{pl}}}{m_{\psi}} e^{c\varphi/M_{\text{pl}}} \right|$$

For (+) coupling: runaway solution

$$\phi \sim -c(w) \ln a$$

scalar density tracks the background

For (-) coupling:

$$\phi \sim a^{-1} \times \text{oscillations}(a)$$

same behaviour as monomial

Future directions

Linear perturbations on the general scaling backgrounds

Work in progress with G. Domènech and Hanqiong Jia

$$\phi \rightarrow \bar{\phi} + \delta\phi$$

$$n_\psi \rightarrow \bar{n}_\psi + \delta n_\psi$$

$$g_{\mu\nu} \rightarrow \bar{g}_{\mu\nu} + \delta g_{\mu\nu}$$

What is the fate of linear perturbations for both subhorizon and superhorizon limits?

Gravitational waves signatures from melting domain walls

Work in progress with G. Domènech and Alexander Vikman

Summary

- Generalised Yukawa couplings admit **scaling solutions** when there exist saturation points in both relativistic and non-relativistic limit. regardless of background w .
- In scaling regime the non-relativistic fermions remain non-relativistic save for a small transition time
- Dilaton couplings that can yield saturation points admit scaling solutions which behave in a similar way as monomial
- Couplings with multiple degenerate saturation points hint towards domain wall formation channel, GW wave background

Thank you!!

Force strength and local scalar response

$$\beta_5 \equiv M_{\text{Pl}} \frac{\partial \ln m_{\text{eff}}}{\partial \varphi}, \quad \frac{|F_5|}{|F_G|} \simeq 2\beta_5^2 \quad (r \ll \ell_{\text{phys}})$$

$$G_{\text{eff}}(k, a) \simeq G \left[1 + 2\beta_5^2 \frac{k^2/a^2}{k^2/a^2 + m_s^2} \right]$$

$$m_s^2 \simeq V_{\text{bare},\varphi\varphi} + n_\psi m_{\text{eff},\varphi\varphi} \quad (x \gg 1, \ m_{\text{eff}} > 0)$$

Local, stable response away from a mass-zero crossing

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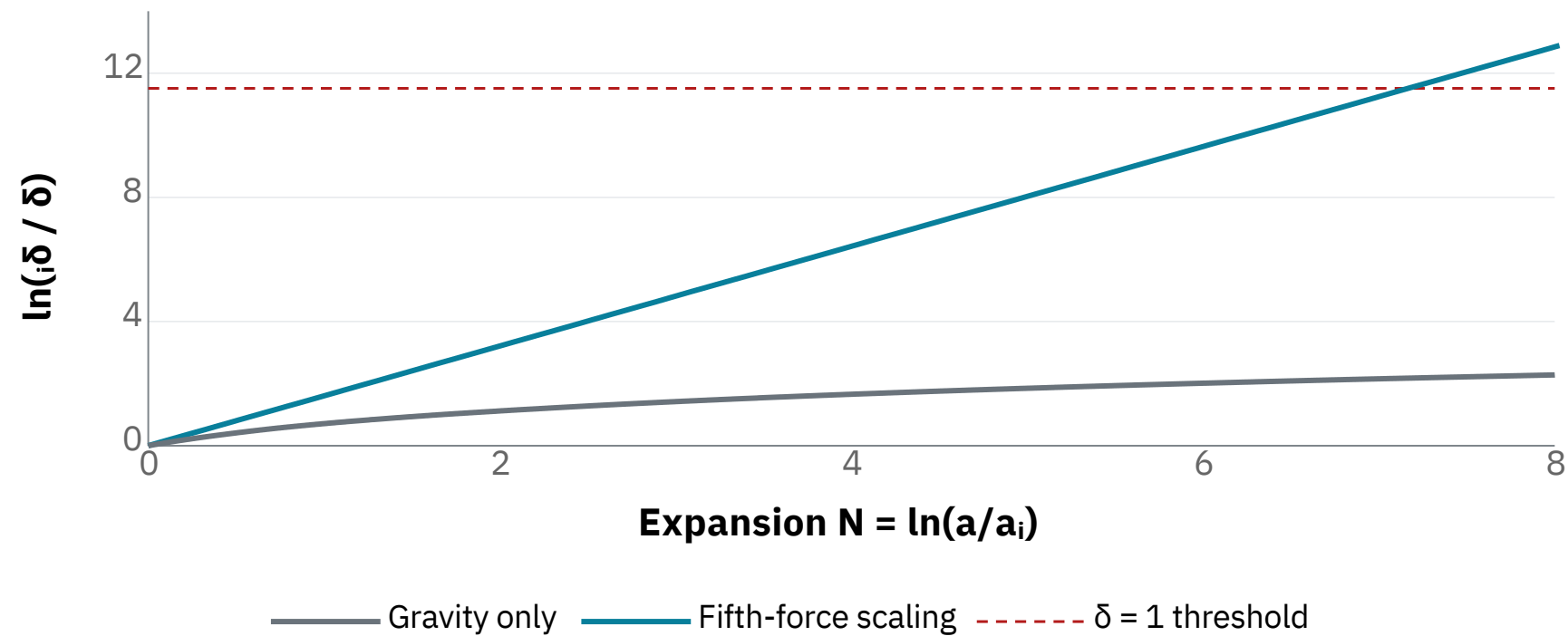
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Illustrative amplification



Illustrative: $\delta_i = 10^{-5}$. Gravity: $\delta/\delta_i = 1 + N$.
Constant- β_5 radiation scaling: $\delta/\delta_i = \exp(1.62 N)$.

Strong attraction can overcome the slow growth of the standard radiation era.