Research Article

Qi Li, Shuangjie Peng, and Wei Shuai*

On fractional logarithmic Schrödinger equations

https://doi.org/10.1515/ans-2022-0002
received August 16, 2021; accepted January 14, 2022

Abstract: We study the following fractional logarithmic Schrödinger equation:
\[ (-\Delta)^s u + V(x)u = u \log u^2, \quad x \in \mathbb{R}^N, \]
where \( N \geq 1 \), \((-\Delta)^s\) denotes the fractional Laplace operator, \( 0 < s < 1 \) and \( V(x) \in C(\mathbb{R}^N) \). Under different assumptions on the potential \( V(x) \), we prove the existence of positive ground state solution and least energy sign-changing solution for the equation. It is known that the corresponding variational functional is not well defined in \( H^s(\mathbb{R}^N) \), and inspired by Cazenave (Stable solutions of the logarithmic Schrödinger equation, Nonlinear Anal. 7 (1983), 1127–1140), we first prove that the variational functional is well defined in a subspace of \( H^s(\mathbb{R}^N) \). Then, by using minimization method and Lions’ concentration-compactness principle, we prove that the existence results.

Keywords: fractional logarithmic Schrödinger equations, positive ground state solutions, sign-changing solutions, variational methods

MSC 2020: 35R11 (35B38 35Q55 47J30)

1 Introduction

In this article, we study the following fractional logarithmic Schrödinger equation:
\[ (-\Delta)^s u + V(x)u = u \log u^2, \quad x \in \mathbb{R}^N, \quad (1.1) \]
where \( N \geq 1 \), \( 0 < s < 1 \), \( V(x) \in C(\mathbb{R}^N) \) and \( V_0 = \inf_x V(x) > 0 \). The fractional Laplace operator \((-\Delta)^s\) is defined by
\[ (-\Delta)^s u(x) = C_{N,s} \text{P.V.} \int_{\mathbb{R}^N} \frac{u(x) - u(y)}{|x-y|^{N+2s}} dy, \]
where P.V. stands for the principle value and \( C_{N,s} \) is a normalization constant, see for instance [1] and references therein.

Equation (1.1) arises from looking for standing waves \( \Phi(t, x) = e^{-it}u(x) \) of the following fractional logarithmic Schrödinger equation:
\[
\frac{\partial \Phi}{\partial t} = (-\Delta)^s \Phi + (V(x) + \omega)\Phi - \Phi \log |\Phi|^2, \quad (t, x) \in \mathbb{R}^+ \times \mathbb{R}^N, \quad (1.2)
\]

which is a generalization of the following logarithmic Schrödinger equation:
\[
\frac{\partial \Phi}{\partial t} = -\Delta \Phi + (V(x) + \lambda)\Phi - \Phi \log |\Phi|^2, \quad (t, x) \in \mathbb{R}^+ \times \mathbb{R}^N. \quad (1.3)
\]

For physical and mathematical background of equation (1.3), we refer the reader to [2–8] and references therein.

There are few results on fractional logarithmic Schrödinger equation. For example, Ardila [9] recently studied the existence and stability of standing waves for nonlinear fractional Schrödinger equation (1.2). In [10], d’Avenia et al. employed non-smooth critical point theory and obtained infinitely many standing wave solutions to equation (1.2).

Equation (1.1) formally associated with the energy functional \( I : H^s(\mathbb{R}^N) \to \mathbb{R} \cup \{ +\infty \} \) is defined by
\[
I(u) = \frac{1}{2} \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} |u(x) - u(y)|^2 \, dx \, dy + \frac{1}{2} \int_{\mathbb{R}^N} (V(x) + 1) |u|^2 \, dx - \frac{1}{2} \int_{\mathbb{R}^N} u^2 \log u^2 \, dx,
\]
where
\[
H^s(\mathbb{R}^N) = \left\{ u \in L^2(\mathbb{R}^N) | \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} |u(x) - u(y)|^2 \, dx \, dy < \infty \right\},
\]
with the norm
\[
|u|_{H^s} = \left( |u|_2^2 + |u|_{L^2(\mathbb{R}^N)}^2 \right)^{\frac{1}{2}}, \quad |u|_s = \left( \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{|u(x) - u(y)|^2}{|x-y|^{N+2s}} \, dx \, dy \right)^{\frac{1}{2}}.
\]

By the fractional logarithmic Sobolev inequality (see [11]), for each \( u \in H^s(\mathbb{R}^N) \), then
\[
\int_{\mathbb{R}^N} u^2 \log \left( \frac{u^2}{|u|_{L^2}^2} \right) \, dx + \left( N + \frac{N}{s} \log \alpha + \log \frac{\Gamma \left( \frac{N}{2} \right)}{\Gamma \left( \frac{N + s}{2} \right)} \right) |u|_{L^2}^2 \leq \frac{\alpha^2}{\alpha} |u|_s^2, \quad \text{for any } \alpha > 0. \quad (1.4)
\]

It is easy to see that \( \int_{\mathbb{R}^N} u^2 \log u^2 < +\infty \), but the functional fails to be finite since the logarithm is singular at origin. Indeed, let \( u \) be a smooth function that satisfies
\[
u(x) = \begin{cases} (|x|^{N/2} \log |x|)^{-1}, & |x| \geq 3, \\ 0, & |x| \leq 2. \end{cases} \quad (1.5)
\]

One can verify directly that \( u \in H^s(\mathbb{R}^N) \) but \( \int_{\mathbb{R}^N} u^2 \log u^2 \, dx = -\infty \). Thus, \( I \) fails to be \( C^1 \) on \( H^s(\mathbb{R}^N) \).

Due to loss of smoothness, the classical critical point theory cannot be applied for \( I \). The same difficulty also occurs for \( s = 1 \). In order to investigate the following logarithmic Schrödinger equation:
\[
-\Delta u + V(x)u = u \log u^2, \quad x \in \mathbb{R}^N, \quad (1.6)
\]
several approaches developed so far in the literature. Cazenave [5] worked in a suitable Banach space endowed with a Luxemburg-type norm, in which the corresponding energy functional is well defined. Squassina and Szulkin [12] applied non-smooth critical point theory for lower semi-continuous functionals, see also [13–15]. Tanaka and Zhang [16] used penalization technique. Recently, via direction derivative and constrained minimization method, Shuai [17] proved the existence of ground state solutions and sign-changing solutions for equation (1.6). Recently, Wang and Zhang [18] proved that the positive ground state solution of the power-law equations
\[
\begin{cases}
-\Delta u + Au = |u|^{p-2}u, & x \in \mathbb{R}^N, \\
\lim_{|x| \to \infty} u(x) = 0
\end{cases}
\] (1.7)

converges to the Gaussian

\[ U(x) = e^{\frac{x}{2}}e^{-\frac{1}{2}|x|} \]

up to translations, which is the unique positive solution of the logarithmic equation

\[
\begin{cases}
-\Delta u = u \log |u|^2, & x \in \mathbb{R}^N, \\
\lim_{|x| \to \infty} u(x) = 0.
\end{cases}
\]

They also proved that the same result holds for bound state solutions.

Inspired by [5], we first find a suitable Banach space, in which the energy functional \( I \) is well defined. Then, we study the existence of positive ground state solution and least energy sign-changing solution for equation (1.1).

Throughout this article, we assume \( V(x) \in C^{0,1}(\mathbb{R}^N) \) for some \( \gamma \in (0, 1) \) and bounded from below. The following different types of potential are considered:

(V1) \( \lim_{|x| \to \infty} V(x) = +\infty \).

(V2) \( V(x) \) is radially symmetric, i.e., \( V(x) = V(|x|) \).

(V3) \( V(x) \) is 1-periodic in each variable of \( x_1, x_2, \ldots, x_N \).

(V4) For almost every \( x \in \mathbb{R}^N \), \( V(x) \leq \liminf_{|x| \to \infty} V(x) = V_\infty < +\infty \), and the inequality is strict in a subset of positive Lebesgue measure.

(V5) There exist positive constants \( M, C_0 \) and \( m \in (0, 2s) \) such that

\[ V(x) \leq V_\infty - \frac{C_0}{1 + |x|^m}, \quad \forall |x| \geq M. \]

Next, we denote

\[ H = \left\{ u \in H^s(\mathbb{R}^N) \mid \int_{\mathbb{R}^N} V(x)u^2 \, dx < \infty \right\} \]

with the norm

\[ |u|_H = \left( \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{|u(x) - u(y)|^2}{|x - y|^{N+2s}} \, dx \, dy + \int_{\mathbb{R}^N} V(x)u^2 \, dx \right)^{\frac{1}{2}}. \]

The Orlicz space \( L^A(\mathbb{R}^N) \) is defined by

\[ L^A(\mathbb{R}^N) = \{ u \in L^1_{\text{loc}}(\mathbb{R}^N) \mid A(|u|) \in L^1(\mathbb{R}^N) \} \]

which is equipped with the Luxemburg norm

\[ \|u\|_{L^A} = \inf \left\{ k > 0 \mid \int_{\mathbb{R}^N} A(k^{-1}|u(x)|) \, dx \leq 1 \right\}, \]

where \( A \) is given by

\[ A(s) = \begin{cases} 
-s^2 \log s^2, & 0 \leq s \leq e^{-3}, \\
3s^2 + 4e^{-3}s - e^{-6}, & s \geq e^{-3}.
\end{cases} \]
We also denote
\[ F(s) = s^2 \log s^2, \quad B(s) = F(s) + A(s), \quad \forall s \geq 0. \]

It is easy to check that \( A, B \) are nonnegative convex and increasing function on \([0, +\infty)\), and \( A \in C^2([0, +\infty)) \cap C^2((0, +\infty)) \).

Now, define
\[ W^s(R^N) = H \cap L^A(R^N), \]
which is equipped with the norm
\[ ||u|| = ||u||_H + ||u||_L^A, \]
By Lemma 2.2 in [9], we know that
\[ W^s(R^N) = \left\{ u \in H^s(R^N) : \int_{\mathbb{R}^N} u^2 |\log u^2| < +\infty \right\}. \]

Now, we give the definition of weak solutions for equation (1.1).

**Definition 1.1.** We say \( u \in W^s(R^N) \) is a weak solution to equation (1.1) if \( u \) satisfies
\[ \int_{R^N} (-\Delta)^2 u \Delta^2 \varphi + V(x) u \varphi \, dx = \int_{R^N} u \varphi \log u^2 \, dx, \quad \text{for each } \varphi \in W^s(R^N). \]

It follows from Proposition 2.5 in [9] that the energy functional \( I \) is well defined on \( W^s(R^N) \) and belongs to \( C^1(W^s(R^N), \mathbb{R}) \). Hence, the critical points of \( I \) are corresponding to weak solutions of equation (1.1).

**Remark 1.1.** We remark that, for \( \lambda \neq 0 \), if \( v \) is a solution of
\[ (-\Delta)^2 v + (V(x) - \log \lambda^2) v = v \log v^2, \quad x \in \mathbb{R}^N, \]
then \( \lambda v \) solves equation (1.1). Thus, one can choose \( \lambda > 0 \) small enough such that \( V(x) - \log \lambda^2 > 0 \) for each \( x \in \mathbb{R}^N \). Since \( V(x) \) is bounded from below, we always assume \( V_0 := \inf_{\mathbb{R}^N} V(x) > 0 \) in the sequent.

Before stating our main results, we give some notations. Denote
\[ N = \{ u \in W^s(R^N) \mid \{u\} = 0, \quad M = \{ u^+ \neq 0 \mid \langle I(u), u^+ \rangle = \langle I(u), u^- \rangle = 0 \}, \]
where \( u^+ = \max\{u, 0\} \), \( u^- = \min\{u, 0\} \) and \( J \) is given by
\[ J(u) = \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{|u(x) - u(y)|^2}{|x - y|^{N + 2s}} \, dx \, dy + \int_{\mathbb{R}^N} V(x) u^2 \, dx - \int_{\mathbb{R}^N} u^2 \log u^2 \, dx. \]

By Lemma 2.1, we know that \( N, M \) are nonempty. Then we define
\[ c = \inf_{N} I(u), \quad m = \inf_{M} I(u). \]

Our first result can be stated as follows.

**Theorem 1.1.** If \( u \in N \) with \( I(u) = c \), then \( u \) is a positive solution of equation (1.1). If \( u \in M \) with \( I(u) = m \), then \( u \) is a sign-changing solution to equation (1.1). Moreover, if \( c \) and \( m \) are achieved, then \( m > 2c \).

If \( u \) is a sign-changing solution to equation (1.1), then \( u \in N \), and we can easily check that
\[
I(u) = I(u^+) + I(u^-) - \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u^+(x)u^-(y) + u^-(x)u^+(y)}{|x - y|^{N + 2s}} \, dx \, dy, \tag{1.8}
\]
\[ \langle I'(u), u' \rangle = \langle I'(u'), u' \rangle - \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u'(x)u'(y) + u'(x)u'(y)}{|x - y|^{N+2s}} \, dx \, dy. \]  

(1.9)

\[ \langle I'(u), u' \rangle = \langle I'(u'), u' \rangle - \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u'(x)u'(y) + u'(x)u'(y)}{|x - y|^{N+2s}} \, dx \, dy. \]  

(1.10)

Note that

\[ \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u'(x)u'(y) + u'(x)u'(y)}{|x - y|^{N+2s}} \, dx \, dy < 0. \]

Hence, by (1.8)–(1.10), one obtains

\[ I(u) > I(u') + I(u'), \quad \text{and } u', u \notin \mathcal{N}, \]

which is totally different from the case \( s = 1 \), because equation (1.1) is a nonlocal problem. And we cannot directly infer that \( I(u) > 2c \). This property is called energy doubling by Weth [19], which is crucial in overcoming the difficulty of lack of compactness.

Now, we focus on whether \( c \) or \( m \) is achieved.

**Theorem 1.2.** If one of the following four conditions hold: \( (V_1); (V_2) \) and \( N \geq 2; (V_3); (V_4) \), then \( c \) is achieved. If one of the following three conditions hold: \( (V_1); (V_2) \) and \( N \geq 2; (V_3) \) and \( (V_5) \), then \( m \) is achieved. In particular, if \( m \) is not achieved provided \( (V_3) \) holds.

The proof of Theorem 1.2 is based on the concentration-compactness principle [20]. However, as we will see, the nonlocal operator \((-\Delta)^s\) and the logarithmic nonlinearity cause some obstacles, which need some new technique and subtle analysis.

**Remark 1.2.** We point out that (i) the variational framework also works for equation (1.6), while the analogous results for equation (1.6) are obtained by using direction derivative and constrained minimization method; (ii) Theorems 1.1 and 1.2 also hold for the following fractional Schrödinger equation:

\[ (-\Delta)^s u + V(x)u = |u|^{p-2}u, \quad x \in \mathbb{R}^N, \]  

(1.11)

where \( 2 < p < 2^*_s \). Even for equation (1.11), the results on the existence of sign-changing solutions are new.

In the rest of the article, we shall first prove some preliminary results and prove Theorem 1.1 in Section 2, and then we prove Theorem 1.2 in Section 3. We will use \( C \) to denote different positive constants from line to line.

## 2 Proof of Theorem 1.1

In this section, we first prove some technical lemmas, which is crucial for proving our main results.

**Lemma 2.1.**

(i) Let \( u \in W^s(\mathbb{R}^N) \setminus \{0\} \), then there exists a unique \( t_u > 0 \) such that \( t_u u \in \mathcal{N} \);

(ii) Let \( u \in W^s(\mathbb{R}^N) \) with \( u^+ \neq 0 \), then there exists a unique pair \((a_u, \beta_u) \in \mathbb{R}^+ \times \mathbb{R}^+ \) such that \( a_u u^+ + \beta_u u^- \in M \).

**Proof.** Note that, by (1.14) in [21], we know that \( u^+ \in H'(\mathbb{R}^N) \) if \( u \in H'(\mathbb{R}^N) \), thus, \( u^+ \in W^s(\mathbb{R}^N) \) if \( u \in W^s(\mathbb{R}^N) \). We only prove (ii), and (i) can be proved by a similar argument. First, we prove the existence of \((a_u, \beta_u) \). By a direct calculation, we have
\[
\langle I'(au' + \beta u'), au' \rangle = a^2 [u']^2 - a \beta \int_{\mathbb{R}^N} u'(x)u'(y) + u'(x)u'(y) \frac{1}{|x-y|^{N+2s}} \, dx \, dy \\
+ \alpha^2 \int_{\mathbb{R}^N} V(x)(u')^2 \, dx - \alpha^2 \int_{\mathbb{R}^N} |u'|^2 \log|u'|^2 \, dx - \alpha^2 \log \beta^2 \int_{\mathbb{R}^N} |u'|^2 \, dx
\]

(2.1)

and

\[
\langle I'(au' + \beta u'), \beta u' \rangle = \beta^2 [u']^2 - a \beta \int_{\mathbb{R}^N} u'(x)u'(y) + u'(x)u'(y) \frac{1}{|x-y|^{N+2s}} \, dx \, dy \\
+ \beta^2 \int_{\mathbb{R}^N} V(x)(u')^2 \, dx - \beta^2 \int_{\mathbb{R}^N} |u'|^2 \log|u'|^2 \, dx - \beta^2 \log \beta^2 \int_{\mathbb{R}^N} |u'|^2 \, dx.
\]

(2.2)

Define

\[
F(a, \beta) = (\langle I'(au' + \beta u'), au' \rangle, \langle I'(au' + \beta u'), \beta u' \rangle).
\]

It follows from (2.1) and (2.2) that there exists \( R > r > 0 \) such that

\[
\langle I'(ru' + \beta u'), ru' \rangle > 0 \quad \text{and} \quad \langle I'(Ru' + \beta u'), Ru' \rangle < 0, \quad \forall \beta \in [r, R],
\]

\[
\langle I'(au' + ru'), ru' \rangle > 0 \quad \text{and} \quad \langle I'(au' + Ru'), Ru' \rangle < 0, \quad \forall \alpha \in [r, R].
\]

By Miranda theorem, there exists \((a \alpha, \beta) \in (r, R) \times (r, R)\) such that \(F(a \alpha, \beta) = 0\), that is, \(a \alpha u' + \beta \beta u' \in M\).

Next, we prove the uniqueness of \((a \alpha, \beta)\) on \( \mathbb{R}^* \times \mathbb{R}^* \). If \( u \in M \), then

\[
[u']^2 = \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u'(x)u'(y) + u'(x)u'(y)}{|x-y|^{N+2s}} \, dx \, dy + \int_{\mathbb{R}^N} V(x)(u')^2 \, dx = \int_{\mathbb{R}^N} |u'|^2 \log|u'|^2 \, dx
\]

(2.3)

and

\[
[u']^2 = \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u'(x)u'(y) + u'(x)u'(y)}{|x-y|^{N+2s}} \, dx \, dy + \int_{\mathbb{R}^N} V(x)(u')^2 \, dx = \int_{\mathbb{R}^N} |u'|^2 \log|u'|^2 \, dx.
\]

(2.4)

We claim that \((a \alpha, \beta) = (1, 1)\) is the unique pair of positive numbers such that \(a \alpha u' + \beta \beta u' \in M\).

Indeed, let \((a \alpha, \beta)\) satisfy \(a \alpha u' + \beta \beta u' \in M\). By direct computation, we have

\[
a^2 [u']^2 = a \beta \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u'(x)u'(y) + u'(x)u'(y)}{|x-y|^{N+2s}} \, dx \, dy + a^2 \int_{\mathbb{R}^N} V(x)(u')^2 \, dx
\]

\[
= a^2 \int_{\mathbb{R}^N} |u'|^2 \log|u'|^2 \, dx + a^2 \log \beta^2 \int_{\mathbb{R}^N} |u'|^2 \, dx.
\]

(2.5)

and

\[
\beta^2 [u']^2 = a \beta \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u'(x)u'(y) + u'(x)u'(y)}{|x-y|^{N+2s}} \, dx \, dy + \beta^2 \int_{\mathbb{R}^N} V(x)(u')^2 \, dx
\]

\[
= \beta^2 \int_{\mathbb{R}^N} |u'|^2 \log|u'|^2 \, dx + \beta^2 \log \beta^2 \int_{\mathbb{R}^N} |u'|^2 \, dx.
\]

(2.6)

Without loss of generality, we assume that \(0 < a \alpha \leq \beta \). Then by (2.5),

\[
a^2 [u']^2 = a^2 \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u'(x)u'(y) + u'(x)u'(y)}{|x-y|^{N+2s}} \, dx \, dy + a^2 \int_{\mathbb{R}^N} V(x)(u')^2 \, dx
\]

\[
\leq a^2 \int_{\mathbb{R}^N} |u'|^2 \log|u'|^2 \, dx + a^2 \log a^2 \int_{\mathbb{R}^N} |u'|^2 \, dx.
\]

(2.7)
Combining (2.3) and (2.7), we deduce that
\[ a_u^2 \log a_u^2 \int_{\mathbb{R}^N} |u^+|^2 \, dx \geq 0, \]
which implies that \( a_u \geq 1 \). Thus, \( 1 \leq a_u \leq \beta_u \). On the other hand, by using a similar argument to (2.4) and (2.6), we obtain that
\[ \beta_u^2 \log \beta_u^2 \int_{\mathbb{R}^N} |u^-|^2 \, dx \leq 0, \]
which implies \( \beta_u \leq 1 \). Therefore, \( a_u = \beta_u = 1 \).

If \( u \notin \mathcal{M} \), then there exists \( (a_u, \beta_u) \in \mathbb{R}^+ \times \mathbb{R}^+ \) such that \( a_u u^+ + \beta_u u^- \in \mathcal{M} \). If there exists another pair \( (\tilde{a}_u, \tilde{\beta}_u) \in \mathbb{R}^+ \times \mathbb{R}^+ \) such that \( \tilde{a}_u u^+ + \tilde{\beta}_u u^- \in \mathcal{M} \). Denote \( v = a_u u^+ + \beta_u u^- \) and \( \tilde{v} = \tilde{a}_u u^+ + \tilde{\beta}_u u^- \), then we have
\[ \frac{a_u}{a_u} v^+ + \frac{\beta_u}{\beta_u} v^- = \tilde{v} \in \mathcal{M}. \]

Hence, by the above analysis, we conclude that
\[ \frac{a_u}{a_u} = \frac{\beta_u}{\beta_u} = 1. \]

Therefore, \( (a_u, \beta_u) \) is unique. \( \square \)

**Lemma 2.2.** Let \( u \in W^\alpha(\mathbb{R}^N) \) with \( u^+ \neq 0 \) such that \( \langle I'(u), u^+ \rangle \leq 0 \) and \( \langle I'(u), u^- \rangle \leq 0 \). Then the unique pair \( (a_u, \beta_u) \) obtained in Lemma 2.1 satisfies \( 0 < a_u \leq 1 \) and \( 0 < \beta_u \leq 1 \).

**Proof.** Without loss of generality, we assume that \( 0 < \beta_u \leq a_u \). Since \( a_u u^+ + \beta_u u^- \in \mathcal{M} \), then
\[ a_u^2 |u^+|^2 - a_u \beta_u \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{\partial^\alpha u^+(x) u^-(y) + \partial^\alpha u^-(x) u^+(y)}{|x-y|^{N+2\alpha}} \, dx \, dy + a_u^2 \int_{\mathbb{R}^N} V(x) |u^+|^2 \, dx \]
\[ = a_u^2 \int_{\mathbb{R}^N} |u^+|^2 \log |u^+|^2 \, dx + a_u^2 \log a_u \int_{\mathbb{R}^N} |u^+|^2 \, dx \]  
(2.8)

and
\[ \beta_u^2 |u^-|^2 - a_u \beta_u \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{\partial^\alpha u^-(x) u^-(y) + \partial^\alpha u^+(x) u^+(y)}{|x-y|^{N+2\alpha}} \, dx \, dy + \beta_u^2 \int_{\mathbb{R}^N} V(x) |u^-|^2 \, dx \]
\[ = \beta_u^2 \int_{\mathbb{R}^N} |u^-|^2 \log |u^-|^2 \, dx + \beta_u^2 \log \beta_u \int_{\mathbb{R}^N} |u^-|^2 \, dx. \]  
(2.9)

Note that
\[ \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{\partial^\alpha u^+(x) u^-(y) + \partial^\alpha u^-(x) u^+(y)}{|x-y|^{N+2\alpha}} \, dx \, dy < 0. \]

Thus, it follows from (2.8) that
\[ a_u^2 |u^+|^2 = a_u^2 \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{\partial^\alpha u^+(x) u^-(y) + \partial^\alpha u^-(x) u^+(y)}{|x-y|^{N+2\alpha}} \, dx \, dy + a_u^2 \int_{\mathbb{R}^N} V(x) |u^+|^2 \, dx \]
\[ \geq a_u^2 \int_{\mathbb{R}^N} |u^+|^2 \log |u^+|^2 \, dx + a_u^2 \log a_u \int_{\mathbb{R}^N} |u^+|^2 \, dx. \]  
(2.10)
By using the fact \( I'(u) u^* \leq 0 \), we have
\[
[u^*]^2 - \int \int \frac{u^*(x) u^*(y) + u^*(x) u^*(y)}{|x - y|^{N + 2s}} dxdy + \int \int V(x) |u^*|^2 dx \leq \int |u^*|^2 \log |u^*|^2 dx.
\] (2.11)

Combining (2.10) with (2.11), we deduce that
\[
\alpha_0^2 \log \alpha_0 \int |u^*|^2 dx \leq 0,
\]
which implies that \( 0 < \alpha_0 \leq 1 \). Therefore, \( 0 < \beta_0 < \alpha_0 \leq 1 \). \( \Box \)

**Lemma 2.3.** For fixed \( u \in W^s(\mathbb{R}^N) \) with \( u^* \neq 0 \), define \( \Phi(\alpha, \beta) = I(u^* + \beta u^*) \). Then \( (\alpha_0, \beta_0) \) obtained in Lemma 2.1 is the unique maximum point of \( \Phi(\alpha, \beta) \) on \( \mathbb{R}^+ \times \mathbb{R}^+ \).

**Proof.** By the proof of Lemma 2.1, we deduce that \( (\alpha_0, \beta_0) \) is the unique critical point of \( \Phi(\alpha, \beta) \) on \( \mathbb{R}^+ \times \mathbb{R}^+ \). By direct calculation, we conclude that the maximum is not achieved on the boundary of \( \mathbb{R}^+ \times \mathbb{R}^+ \). Without loss of generality, we may suppose by contradiction that \( 0, 0 \) is a maximum point of \( \Phi \). Then we can deduce that this is impossible, since
\[
h(\alpha) = \frac{\alpha^2}{2} |u^*|^2 - \alpha \beta_0 \int \int \frac{u^*(x) u^*(y) + u^*(x) u^*(y)}{|x - y|^{N + 2s}} dxdy + \int \int \frac{u^2}{2} |u^*|^2 dx
\]
\[
+ \frac{\alpha^2}{2} \int (V(x) + 1)|u^*|^2 dx + \frac{\beta_0^2}{2} \int (V(x) + 1)|u^*|^2 dx
\]
\[
- \frac{\alpha^2}{2} \int |u^*|^2 \log |u^*|^2 dx - \frac{1}{2} \alpha^2 \log \alpha^2 \int |u^*|^2 dx
\]
\[
- \frac{\beta_0^2}{2} \int |u^*|^2 \log |u^*|^2 dx - \frac{1}{2} \beta_0^2 \log \beta_0^2 \int |u^*|^2 dx
\]
is strictly increasing in \( \alpha \) for \( \alpha > 0 \) small enough. \( \Box \)

**Lemma 2.4.** Let \( u \in W^s(\mathbb{R}^N) \) be a non-negative solution of (1.1), then \( u \in L^\infty(\mathbb{R}^N) \).

**Proof.** The proof is inspired by Proposition 2.2 in [22]. Let us define, for \( \beta \geq 1 \) and \( T > 0 \) large enough,
\[
\varphi(s) = \varphi_{\beta, T}(s) = \begin{cases} 0, & s \leq 0, \\ s^\beta, & 0 < s < T, \\ \beta T^{\beta - 1}(s - T) + T^\beta, & s \geq T. \end{cases}
\]
Obviously, \( \varphi \) is convex and differential function. Then, for \( u \in W^s(\mathbb{R}^N) \), one has
\[
(-\Delta)^s \varphi(u) \leq \varphi'(u)(-\Delta)^s u.
\] (2.13)

Since \( \varphi(u) \) grows linearly and \( \varphi \) is Lipschitz with constant \( K = \beta T^{\beta - 1} \), therefore,
\[
|\varphi(u)|_H = \left( \int \int \frac{|\varphi(u(x))| - \varphi(u(y))|^2}{|x - y|^{N + 2s}} dxdy + \int \int V(x)|\varphi(u(x))|^2 dx \right)^{1/2} \leq C|u|_H
\]
and
\[
\int \int |\varphi(u(x))|^2 \log |\varphi(u(x))|^2 |dx \leq C_1 \int u^2 dx + C_2 \int |u^2 \log u|^2 dx.
\]
Thus, \( \varphi(u(x)) \in W^s(\mathbb{R}^N) \) if \( u \in W^s(\mathbb{R}^N) \). Observe that by the Sobolev embedding theorem, we have the following inequality:

\[
\| \varphi(u) \|^2_{L^2(\mathbb{R}^N)} = \left\| (-\Delta)^s \varphi(u) \right\|^2_{L^2(\mathbb{R}^N)} \geq S(N, s) \| \varphi(u) \|^2_{S(N, s)} ,
\]

where \( S(N, s) \) is the best fractional Sobolev constant defined by

\[
S(N, s) = \inf \{ \| u \|^2_{S(N, s)} \mid u \in H^s(\mathbb{R}^N) \quad \text{and} \quad \| u \|^2_{S(N, s)} = 1 \}.
\]

On the other hand, since \( \varphi(u) \varphi'(u) \in W^s(\mathbb{R}^N) \), thus

\[
\int_{\mathbb{R}^N} \varphi(u)(-\Delta)^s \varphi(u) \, dx \leq \int_{\mathbb{R}^N} \varphi(u) \varphi'(u)(-\Delta)^s u \, dx \leq C \int_{\mathbb{R}^N} \varphi(u) \varphi'(u) |u|^{2s-1} \, dx.
\]

Since \( u \varphi'(u) \leq \beta \varphi(u) \), the above estimate (2.14)–(2.15) becomes

\[
\left( \int_{\mathbb{R}^N} (\varphi(u(x)))^{2s} \, dx \right)^{\frac{1}{2s}} \leq C \beta \int_{\mathbb{R}^N} (\varphi(u(x)))^{2s} |u|^{2s-2} \, dx.
\]

We point out that since \( \varphi(u) \) grows linearly, both sides of (2.16) are finite.

**Claim:** Let \( \beta_1 \) be such that \( 2\beta_1 = \frac{s}{s^*} \), then \( u \in L^{\beta_1 s^*}(\mathbb{R}^N) \).

To prove this, we take \( R \) large to be determined later. Then, Hölder’s inequality gives

\[
\int_{\mathbb{R}^N} (\varphi(u(x)))^{2s} |u|^{2s-2} \, dx = \int_{|u| \leq R} (\varphi(u(x)))^{2s} |u|^{2s-2} \, dx + \int_{|u| > R} (\varphi(u(x)))^{2s} |u|^{2s-2} \, dx \leq \int_{|u| \leq R} |\varphi(u(x))|^{2s} R^{2s-2} \, dx + \left( \int_{|u| \leq R} |\varphi(u(x))|^{\frac{2s}{s^*}} \, dx \right)^{\frac{s^*}{2s}} \int_{|u| > R} |u(x)|^{2s} \, dx \leq \int_{|u| > R} |u(x)|^{2s} \, dx.
\]

By the Monotone convergence theorem, we may take \( R \) so that

\[
\left( \int_{|u| \leq R} |u(x)|^{2s} \, dx \right)^{\frac{2s}{s^*}} \leq \frac{1}{2C\beta_1}.
\]

In this way, the second term above is absorbed by the left-hand side of (2.16) to obtain

\[
\left( \int_{\mathbb{R}^N} (\varphi(u(x)))^{2s} \, dx \right)^{\frac{1}{2s}} \leq 2C\beta_1 \int_{|u| \leq R} |\varphi(u(x))|^{2s} R^{2s-2} \, dx.
\]

Using that \( \varphi_{\beta_1, T}(u) \leq u^{\beta_1} \) in the right-hand side of (2.17) and letting \( T \to +\infty \) in the left-hand side, since \( 2\beta_1 = \frac{s}{s^*} \), we obtain

\[
\left( \int_{\mathbb{R}^N} |u(x)|^{2\beta_1} \, dx \right)^{\frac{1}{2\beta_1}} \leq 2C\beta_1 \int_{\mathbb{R}^N} |u(x)|^{2s} R^{2s-2} \, dx < +\infty.
\]

This proves the claim.

We now go back to inequality (2.16) and we use as before \( \varphi_{\beta_1, T}(u) \leq u^{\beta_1} \) in the right-hand side and then we take \( T \to +\infty \) in the left-hand side.
\[
\left( \int_{\mathbb{R}^N} |u(x)|^{2s} \, dx \right)^{\frac{1}{2s}} \leq C_\beta \int_{\mathbb{R}^N} |u(x)|^{\beta+2s-2} \, dx.
\]

(2.18)

Then, by standard bootstrap technique, one can prove that \( u \in L^\infty(\mathbb{R}^N) \). We omit the details here.

\[\square\]

Proposition 2.5. Let \( u \in W^s(\mathbb{R}^N) \) be a non-negative solution of equation (1.1), then \( u \) is a classical solution of equation (1.1), i.e., \((-\Delta)^s u\) can be written as

\[(-\Delta)^s u = C_{N,s} \int_{\mathbb{R}^N} \frac{u(x) - u(y)}{|x - y|^{N+2s}} \, dy,
\]

and equation (1.1) is satisfied pointwise in all \( \mathbb{R}^N \).

Proof. Let \( u \in W^s(\mathbb{R}^N) \) be a non-negative solution of (1.1), we prove the conclusion by two cases.

Case 1. If \( V(x) \) is bounded, by Theorem 3.4 in [23], we can deduce that \( u \in C^{0,\mu}(\mathbb{R}^N) \) for some \( \mu \in (0,1) \). The function \( h(x) = u(x) - V(x)u(x) + |u(x)|^2 \log |u(x)|^2 \) belongs to \( C^{0,\sigma}(\mathbb{R}^N) \) for certain \( \sigma > 0 \). Let \( \eta_1 \) be a non-negative, smooth function with support in \( B_1(0) \) such that \( \eta_1 = 1 \) in \( B_{1/2}(0) \). Let \( u_1 \in H^s(\mathbb{R}^N) \) be the solution of the equation

\[(-\Delta)^s u_1 + u_1 = \eta_1 h(x), \quad x \in \mathbb{R}^N.
\]

It follows from Lemma 2.4 that \( \eta_1 h(x) \in L^q(\mathbb{R}^N) \) for all \( q > 2 \), then \( u_1 \in W^{2s,q}(\mathbb{R}^N) \) and thus \( u_1 \in C^{0,\sigma}(\mathbb{R}^N) \) for some \( \sigma_0 \in (0,\sigma) \).

Now we look at the equation

\[-\Delta w = -u_1 + \eta_1 h \in C^{0,\sigma_0}(\mathbb{R}^N).
\]

By Hölder’s regularity theory for the Laplacian, we find \( w \in C^{2,\sigma_0}(\mathbb{R}^N) \), so that if \( 2s + \sigma_0 > 1 \), then \((-\Delta)^{1-s} w \in C^{1,2s+\sigma_0-1}(\mathbb{R}^N) \), while if \( 2s + \sigma_0 \leq 1 \), then \((-\Delta)^{1-s} w \in C^{0,2s+\sigma_0}(\mathbb{R}^N) \). Then, since

\[(-\Delta)^s(u_1 - (-\Delta)^{1-s} w) = 0,
\]

the function \( u_1 - (-\Delta)^{1-s} w \) is \( s \)-harmonic, we find that \( u_1 \) has the same regularity as \((-\Delta)^{1-s} w \). By the similar arguments as the proof of Theorems 1.3 and 3.4 in [23], one obtains that \( u \) has the same regularity as \( u_1 \).

Thus, we conclude that \( u \in C^{1,2s+\sigma_0-1}(\mathbb{R}^N) \) if \( 2s + \sigma_0 > 1 \), while \( u \in C^{0,2s+\sigma_0}(\mathbb{R}^N) \) if \( 2s + \sigma_0 \leq 1 \). Note that the conclusion holds locally, but the corresponding Hölder norms depend only on \( \eta_1 \), \( s \), \( N \), \( \|u\|_{H^s} \) and \( \|V(x)\|_{C^{0,\sigma}(\mathbb{R}^N)} \), so these estimates are global in \( \mathbb{R}^N \).

Case 2. If \( V(x) \) is coercive, i.e., \( \lim_{|x| \to +\infty} V(x) = +\infty \). Similar to the proof of Case 1, we can deduce that \( u \in C^{1,2s+\sigma_0-1}_{\text{loc}}(\mathbb{R}^N) \) if \( 2s + \sigma_0 > 1 \), while \( u \in C^{0,2s+\sigma_0}_{\text{loc}}(\mathbb{R}^N) \) if \( 2s + \sigma_0 \leq 1 \).

For each point \( x \in \mathbb{R}^N \), since \( u \in L^\infty(\mathbb{R}^N) \) and \( u \in C^{1,2s+\sigma_0-1}(B_1(x)) \) if \( 2s + \sigma_0 > 1 \), while \( u \in C^{0,2s+\sigma_0}(B_1(x)) \) if \( 2s + \sigma_0 \leq 1 \), thus

\[
\int_{B_1(x)} \frac{u(x) - u(y)}{|x - y|^{N+2s}} \, dy < +\infty,
\]

\[
\int_{\mathbb{R}^N \setminus B_1(x)} \frac{u(x) - u(y)}{|x - y|^{N+2s}} \, dy < +\infty.
\]

Therefore,

\[(-\Delta)^s u = C_{N,s} \int_{\mathbb{R}^N} \frac{u(x) - u(y)}{|x - y|^{N+2s}} \, dy,
\]

and thus equation (1.1) is satisfied pointwise in all \( \mathbb{R}^N \).

\[\square\]

Now, we prove the minimizers of \( c \) or \( m \) are indeed solutions to equation (1.1) by quantitative deformation lemma and degree theory.
Proof of Theorem 1.1. (i) Suppose that \( u \in \mathcal{N} \) and \( I(u) = c \), by Lagrange multiplier theorem, there exists \( \mu \in \mathbb{R} \) such that

\[
I'(u) = \mu J'(u).
\]

Thus, we have

\[
0 = \langle I'(u), u \rangle = \mu \langle J'(u), u \rangle
\]

Noting that

\[
\langle J'(u), u \rangle = -2 \int_{\mathbb{R}^N} u^2 \, dx < 0.
\]

Hence, \( \mu = 0 \), that is, \( I'(u) = 0 \). By standard arguments, \( u \geq 0 \) or \( u \leq 0 \). Without loss of generality, assume \( u \geq 0 \). If there exists \( x_0 \in \mathbb{R}^N \) such that \( u(x_0) = 0 \), then

\[
(-\Delta)^s u(x_0) = C_{N,s} \int_{\mathbb{R}^N} \frac{u(x_0) - u(y)}{|x - y|^{N+2s}} \, dy = -C_{N,s} \int_{\mathbb{R}^N} \frac{u(y)}{|x - y|^{N+2s}} \, dy < 0.
\]

On the other hand, it holds

\[
(-\Delta)^s u(x_0) = -\nabla u \cdot u(x_0) + u(x_0) \log |u(x_0)|^2 = 0,
\]

which contradicts with (2.19). Therefore, \( u(x) > 0 \) for each \( x \in \mathbb{R}^N \). Consequently, \( u \) is a positive ground state solution to equation (1.1).

(ii) Now, suppose that \( u \in \mathcal{M} \) and \( I(u) = m \), then \( u^+, u^- \neq 0 \) and

\[
\langle I'(u), u^\pm \rangle = \langle I'(u), u^- \rangle = 0.
\]

It follows from Lemma 2.3 that, for any \((\alpha, \beta) \in \mathbb{R}^+ \times \mathbb{R}^\times \{1, 1\}\),

\[
I(au^+ + \beta u^-) < I(u^+ + u^-) = m.
\]

If \( I'(u) \neq 0 \), then there exist \( \delta > 0 \) and \( \theta > 0 \) such that

\[
\|I'(v)\| \geq \theta, \quad \text{for all } \|v - u\| \leq 3\delta.
\]

Define \( D = \left( \frac{1}{2}, \frac{3}{2} \right) \times \left( \frac{1}{2}, \frac{3}{2} \right) \) and \( g(\alpha, \beta) = au^+ + \beta u^- \). Then

\[
\bar{m} = \max_{\partial D} I(g(\alpha, \beta)) < m.
\]

For \( S_\delta = B_\delta(u) \) and \( \varepsilon = \min \left\{ \frac{1}{2} - m - \frac{\delta^2}{4}, \frac{3}{2} - m - \frac{\delta^2}{4} \right\} \), it follows from deformation lemma (see Lemma 2.3, [24]) that there exists a deformation \( \eta \in C[0, 1] \times W^{2,s}(\mathbb{R}^N), W^2(\mathbb{R}^N) \) such that

(a) \( \eta(1, u) = u \) if \( u \notin I^{-1}([m - 2\varepsilon, m + 2\varepsilon]) \cap S_\delta \),

(b) \( \eta(1, I^{m-\varepsilon} \cap S_\delta) \subset I^{m-\varepsilon} \),

(c) \( \eta(1, u) \leq I(u) \) for all \( u \in W^2(\mathbb{R}^N) \),

where \( S_\delta = \{ w : \|w - v\| \leq 2\delta, v \in S \} \) and \( I^c = \{ u : I(u) \leq c \} \).

It is easy to check that

\[
\max_{(\alpha, \beta) \in D} I(\eta(1, g(\alpha, \beta))) < m.
\]

Now, we prove that

\[
\eta(1, g(D)) \cap \mathcal{M} \neq \emptyset,
\]

which is contradiction to the definition of \( m \). Setting \( h(\alpha, \beta) = \eta(1, g(\alpha, \beta)) \) and

\[
\Psi_\delta(\alpha, \beta) = (\langle I'(g(\alpha, \beta), u^+), \langle I'(g(\alpha, \beta), u^-) \rangle, \Psi_\delta(\alpha, \beta) = \left\{ \frac{1}{\alpha} \langle I'(h(\alpha, \beta), h^+(\alpha, \beta)), \frac{1}{\beta} \langle I'(h(\alpha, \beta), h^-(\alpha, \beta)) \right\}.
\]
By Lemma 2.1 and topological degree theory, we know that \( \deg(\Psi_0, D, 0) = 1 \). Moreover, (2.20) and (a) imply that \( h = g \) on \( \partial D \). It follows from the property of homotopy invariance of topological degree that
\[
\deg(\Psi_1, D, 0) = \deg(\Psi_0, D, 0) = 1.
\]
Therefore, there exists \((a_0, \beta_0) \in D\) such that
\[
\eta(1, g(a_0, \beta_0)) = h(a_0, \beta_0) \in M,
\]
which yields a contradiction with (2.20). Hence, \( I'(u) = 0 \). As a direct result, \( u \) is a least energy sign-changing solution to equation (1.1).

(iii) Suppose \( u \in M \) such that \( I(u) = m \), then \( u, u \neq 0 \), similar to the proof of Lemmas 2.1–2.2, we conclude that there exists a unique \( \alpha_u \in (0, 1) \) such that \( \alpha_u u \in \mathcal{N} \), and a unique \( \beta_u \in (0, 1) \) such that \( \beta_u u \in \mathcal{N} \).

On the other hand, one has
\[
I(\alpha_u u^* + \beta_u u^*) = I(\alpha_u u^*) + I(\beta_u u^*) - \alpha_u \beta_u \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u^*(x)u^*(y) + u^*(x)u^*(y)}{|x-y|^{N+2s}} \, dx \, dy
\]
and
\[
\int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u^*(x)u^*(y) + u^*(x)u^*(y)}{|x-y|^{N+2s}} \, dx \, dy < 0.
\]
Thus, by Lemma 2.3, we conclude that
\[
m = I(u^* + u^*) > I(\alpha_u u^* + \beta_u u^*) > I(\alpha_u u^*) + I(\beta_u u^*) \geq 2c.
\]

3 Existence and nonexistence of minimizer

In this section, we study whether \( c \) or \( m \) is achieved under different types of potential. The following Brézis-Lieb-type lemma for \( u^* \log u^2 \) is crucial.

Lemma 3.1. (Lemma 2.3, [9]) Let \( \{u_n\} \) be a bounded sequence in \( W^s(\mathbb{R}^N) \) such that \( u_n \rightharpoonup u \) a.e. in \( \mathbb{R}^N \). Then \( u \in W^s(\mathbb{R}^N) \) and
\[
\lim_{n \to \infty} \int_{\mathbb{R}^N} [u_n^2 \log u_n^2 - (u_n - u)^2 \log(u_n - u)^2] \, dx = \int_{\mathbb{R}^N} u^2 \log u^2 \, dx.
\]

3.1 Compact potential

Lemma 3.2. Assume \((V_1)\) or \((V_2)\), then both \( c > 0 \) and \( m > 0 \) are achieved.

Proof. We only prove the case for \( m \), one can argue similarly to verify that \( c > 0 \) is achieved. Noting that \( \mathcal{M} \subset \mathcal{N} \), we have \( J(\nu) = 0 \) for any \( \nu \in \mathcal{M} \). Take \( \alpha = \pi^2 \) in the logarithm Sobolev inequality (1.4), then
\[
\int_{\mathbb{R}^N} v^2 \log \frac{v^2}{\|v\|^2_{L^2}} \, dx + \left( N + N \log \sqrt{\pi} + \log \frac{s \Omega(N/2)}{\Gamma(N/2)} \right) \|v\|^2_{L^2} \leq \|v\|^2_{L^2}.
\]
Combining $J(v) = 0$ with (3.1), we deduce that
\[
\int_{\mathbb{R}^n} V(x)v^2 \, dx + \left( N + N \log \sqrt{n} + \log \frac{s \Gamma \left( \frac{N}{2} \right)}{\Gamma \left( \frac{N}{2s} \right)} \right) \|v\|_{L^2}^2 \leq \|v\|_{L^2}^2 \log \|v\|_{L^2}^2,
\]
which implies that
\[
\|v\|_{L^2}^2 \geq e^{N \pi^2} \frac{s \Gamma \left( \frac{N}{2} \right)}{\Gamma \left( \frac{N}{2s} \right)} > 0.
\]
Therefore, we can derive
\[
I(v) = I(v) - \frac{1}{2} J(v) = \frac{1}{2} \|v\|_{L^2}^2 \geq \frac{1}{2} e^{N \pi^2} \frac{s \Gamma \left( \frac{N}{2} \right)}{\Gamma \left( \frac{N}{2s} \right)} > 0,
\]
which implies that $m > 0$.

Let $\{u_n\} \subset M$ be a minimizing sequence of $m$, then
\[
\lim_{n \to \infty} I(u_n) = \lim_{n \to \infty} \left( \frac{1}{2} J(u_n) \right) = \lim_{n \to \infty} \frac{1}{2} \int_{\mathbb{R}^n} u_n^2 \, dx = m.
\]
Hence, $\{u_n\}$ is bounded in $L^2(\mathbb{R}^N)$. By (1.4) and $J(u_n) = 0$, we can derive
\[
\left( 1 - \frac{\alpha^2}{\pi^s} \right) \|u_n\|_{L^2}^2 + \int_{\mathbb{R}^n} V(x)u_n^2 \, dx \leq \|u_n\|_{L^2}^2 \log \left( \|u_n\|_{L^2}^2 \left( \frac{e^{-N \Gamma \left( \frac{N}{2s} \right)}}{sa^2 \Gamma \left( \frac{N}{2} \right)} \right) \right).
\]
(3.2)

Taking $\alpha > 0$ is small enough in (3.2), we deduce that $\{u_n\}$ is bounded in $H$. Thus, up to a subsequence, there exists $u \in H$ such that
\[
\begin{align*}
\{u_n\} & \to u \quad \text{in } H, \\
{u_n} & \to u \quad \text{in } L^p(\mathbb{R}^N), \quad 2 < p < 2^*_s, \\
{u_n} & \to u \quad \text{a.e. on } \mathbb{R}^N.
\end{align*}
\]
(3.3)

For any $2 < p < 2^*_s$, we have
\[
0 < C \leq \|u\|_{H^p}^2 \leq \int_{\mathbb{R}^n} (|u_n|^2 \log |u_n|^2)^+ \, dx \leq C_P \int_{\mathbb{R}^n} |u_n|^p \, dx
\]
and
\[
0 < C \leq \|u\|_{H^p}^2 \leq \int_{\mathbb{R}^n} (|u_n|^2 \log |u_n|^2)^+ \, dx \leq C_P \int_{\mathbb{R}^n} |u_n|^p \, dx.
\]
Hence, by using (3.3), we obtain
\[
\int_{\mathbb{R}^n} (|u|^2 \log |u|^2)^+ \, dx = \lim_{n \to \infty} \int_{\mathbb{R}^n} (|u_n|^2 \log |u_n|^2)^+ \, dx \geq C > 0
\]
(3.4)

and
\[
\int_{\mathbb{R}^n} (|u|^2 \log |u|^2)^+ \, dx = \lim_{n \to \infty} \int_{\mathbb{R}^n} (|u_n|^2 \log |u_n|^2)^+ \, dx \geq C > 0.
\]
(3.5)
Now, by the fact that $I'(u_n) = 0$, (3.4) and Fatou lemma, one has

$$
\|u^*\|_H^2 - \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u^*(x)u^*(y) + u^*(x)u^*(y)}{|x-y|^{N+2s}} \, dx \, dy - \int_{\mathbb{R}^N} (|\nabla u|^2 \log |\nabla u|^2)^* \, dx
\leq \liminf_{n \to \infty} \left[ \|u_n^*\|^2_H - \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u_n^*(x)u_n^*(y) + u_n^*(x)u_n^*(y)}{|x-y|^{N+2s}} \, dx \, dy - \int_{\mathbb{R}^N} (|\nabla u_n|^2 \log |\nabla u_n|^2)^* \, dx \right]
= \liminf_{n \to \infty} \int_{\mathbb{R}^N} (|u_n^*|^2 \log |u_n^*|^2)^* \, dx = \int_{\mathbb{R}^N} (|u|^2 \log |u|^2)^* \, dx,
$$

which implies

$$
\|u^*\|_H^2 - \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u^*(x)u^*(y) + u^*(x)u^*(y)}{|x-y|^{N+2s}} \, dx \, dy - \int_{\mathbb{R}^N} |\nabla u|^2 \log |\nabla u|^2 \, dx \leq 0. \quad (3.6)
$$

Similarly, one can prove

$$
\|u^-\|_H^2 - \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u^-(x)u^-(y) + u^-(x)u^-(y)}{|x-y|^{N+2s}} \, dx \, dy - \int_{\mathbb{R}^N} |\nabla u^-|^2 \log |\nabla u^-|^2 \, dx \leq 0. \quad (3.7)
$$

Thus, Lemma 2.1 yields a unique $(\alpha_u, \beta_u) \in \mathbb{R}^+ \times \mathbb{R}^+$ such that $\bar{\alpha} = \alpha_u u^* + \beta_u u^- \in M$. It follows from Lemma 2.2, (3.6) and (3.7) that $0 < \alpha_u \leq 1$ and $0 < \beta_u \leq 1$. Thus, by direct computation, we have

$$
m \leq I(\bar{\alpha}) = I(\bar{\alpha}) - \frac{1}{2} I(\bar{\alpha}) = \frac{1}{2} \int_{\mathbb{R}^N} \bar{\alpha}^2 \, dx
\leq \frac{\alpha_u}{2} \int_{\mathbb{R}^N} |u|^2 \, dx + \frac{\beta_u}{2} \int_{\mathbb{R}^N} |u^-|^2 \, dx
\leq \frac{1}{2} \int_{\mathbb{R}^N} |u|^2 \, dx \leq \liminf_{n \to \infty} \frac{1}{2} \int_{\mathbb{R}^N} |u_n|^2 \, dx = m,
$$

which implies $\alpha_u = \beta_u = 1$. As a result, $\bar{\alpha} = u$ and $I(u) = m$. \qed

### 3.2 Periodic potential

**Lemma 3.3.** If potential $V(x)$ satisfies $(V_3)$, then $c$ can be achieved.

**Proof.** Let $\{u_n\}$ be a minimizer sequence of $c$, then

$$
\lim_{n \to \infty} I(u_n) = \lim_{n \to \infty} \left[ I(u_n) - \frac{1}{2} I(u_n) \right] = \lim_{n \to \infty} \frac{1}{2} \int_{\mathbb{R}^N} u_n^2 \, dx = c,
$$

which implies that $\{u_n\}$ is bounded in $L^2(\mathbb{R}^N)$. By the logarithm Sobolev inequality (1.4), we can obtain that $\{u_n\}$ is bounded in $H$. One can check that for any $\varepsilon > 0$, there exists $C_\varepsilon > 0$ such that $B(|u|) \leq C\|u\|^{2+\varepsilon}$. Using $u_n \in \mathcal{N}$, we have

$$
\int_{\mathbb{R}^N} A(|u_n|) \, dx = \int_{\mathbb{R}^N} B(|u_n|) \, dx - \|u_n\|^2_2 \leq C \varepsilon \int_{\mathbb{R}^N} |u_n|^{2+\varepsilon} \, dx \leq C.
$$

It follows from Lemma 2.1 in [5] that $\{u_n\}$ is bounded in $L^4(\mathbb{R}^N)$. Therefore, $\{u_n\}$ is bounded in $W^s(\mathbb{R}^N)$. 

We claim that there exists \( \{y_n\} \) such that
\[
\liminf_{n \to \infty} \int_{B_d(y_n)} u_n^2 \, dx > 0.
\]
If not, then we have
\[
\limsup_{n \to \infty} \int_{B_d(y_n)} u_n^2 \, dx = 0,
\]
which implies that \( u_n \to 0 \) in \( L^p(\mathbb{R}^N) \) for \( 2 < p < \infty \). Using \( u_n \in \mathcal{N} \) again, we have
\[
\|u_n\|_p^2 = \int_{\mathbb{R}^N} u_n^2 \log u_n^2 \, dx \leq \int_{\mathbb{R}^N} (u_n^2 \log u_n^2)^p \, dx \leq C_p \int_{\mathbb{R}^N} |u_n|^p \, dx,
\]
which implies that \( \|u_n\|_p \geq C > 0 \). This is a contradiction.

Let \( v_n(x) = u_n(x + y_n) \). Noting that for any \( y_n \in \mathbb{R}^N, \{v_n\} \) is still a bounded minimizing sequence of \( c \), we may assume that, up to a subsequence, there exists \( v \in H[0] \) such that
\[
\begin{align*}
&v_n \to v \quad \text{in} \; H, \\
v_n \to v \quad \text{in} \; L^p(\mathbb{R}^N), \quad 2 \leq p < \infty, \\
v_n \to v \quad \text{a.e. on} \; \mathbb{R}^N.
\end{align*}
\]
By Lemma 3.1, we can know that \( v \in W^p(\mathbb{R}^N) \).

Now, we intend to show that \( J(v) = 0 \) and \( I(v) = c \). If \( J(v) < 0 \), then there exists \( 0 < \lambda < 1 \) such that \( J(\lambda v) = 0 \). Direct computation yields that
\[
c \leq I(\lambda v) = \frac{\lambda^2}{2} \int_{\mathbb{R}^N} v^2 \, dx < \lim_{m \to \infty} \frac{1}{2} \int_{\mathbb{R}^N} v_m^2 \, dx = c,
\]
which leads to a contradiction. If \( J(v) > 0 \), then we claim that \( J(v_n - v) < 0 \) for sufficiently large \( n \).

Indeed, by Lemma 3.1, we have
\[
\lim_{n \to \infty} J(v_n - v) = \lim_{n \to \infty} J(v_n) - J(v) = -J(v) < 0.
\]
Thus, by a similar argument above, we also have
\[
c \leq \lim_{m \to \infty} \frac{1}{2} \int_{\mathbb{R}^N} |v_n - v|^2 \, dx = c - \frac{1}{2} \int_{\mathbb{R}^N} v^2 \, dx < c,
\]
which is a contradiction.

As a result, we have \( J(v) = 0 \). Consequently, we have
\[
c \leq J(v) \leq \lim_{m \to \infty} \frac{1}{2} \int_{\mathbb{R}^N} v_m^2 \, dx = c.
\]
Thus, we complete the proof. \( \square \)

**Lemma 3.4.** If potential \( V(x) \) satisfies \( (V_i) \), then \( m \) cannot be achieved.

**Proof.** If \( u \in \mathcal{N} \), then \( J(|u|) \leq J(u) = 0 \). Thus, there exists \( t \in (0, 1) \) such that \( J(t|u|) = 0 \) and \( I(t|u|) \leq I(u) \).

Hence, we have
\[
c = \inf \{ I(u) : u \in \mathcal{N} \quad \text{and} \quad u \geq 0 \quad \text{in} \quad \mathbb{R}^N \}.
\]
By density argument, one obtains
\[ c = \inf \{ I(u) : u \in \mathcal{N} \cap C_0^\infty(\mathbb{R}^N) \text{ and } u \geq 0 \text{ in } \mathbb{R}^N \}. \]
Therefore, for any \( \varepsilon > 0 \), we can choose a nonnegative function \( u \in \mathcal{N} \) such that
\[ I(u) < c + \varepsilon. \]
Without loss of generality, we may assume that \( \text{supp}(u) \subset B_\varepsilon(0) \). Define
\[ \tilde{u} = u(x + \varepsilon e_1) - u(x - \varepsilon e_1), \]
where \( e_1 = (1, 0, \ldots, 0) \in \mathbb{R}^N \). By Lemma 2.1, there exists \( (\alpha, \beta) \in \mathbb{R}^+ \times \mathbb{R}^+ \) such that
\[ a\alpha(x + \varepsilon e_1) - \beta\alpha(x - \varepsilon e_1) = a\tilde{u}^+ + \beta\tilde{u}^- \in \mathcal{M}. \]
Combining this with \( u \in \mathcal{N} \), direct computation yields that
\begin{equation}
\alpha^2 \log \alpha^2 \int_{\mathbb{R}^N} u^2 \, dx = -a \beta \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \tilde{u}'(x) \tilde{u}'(y) + \tilde{u}'(x) \tilde{u}'(y) \, |x - y|^{N+2s} \, dx \, dy > 0 \tag{3.8}
\end{equation}
and
\begin{equation}
\beta^2 \log \beta^2 \int_{\mathbb{R}^N} u^2 \, dx = -a \beta \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \tilde{u}'(x) \tilde{u}'(y) + \tilde{u}'(x) \tilde{u}'(y) \, |x - y|^{N+2s} \, dx \, dy > 0. \tag{3.9}
\end{equation}
Hence, \( \alpha = \beta > 1 \). On the other hand, it follows from \( \text{supp}(u) \subset B_\varepsilon(0) \) that
\[ \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{\tilde{u}'(x) \tilde{u}'(y)}{|x - y|^{N+2s}} \, dx \, dy = \int_{B_\varepsilon(-2\varepsilon e_1)} \int_{B_\varepsilon(2\varepsilon e_1)} \frac{\tilde{u}'(x) \tilde{u}'(y)}{|x - y|^{N+2s}} \, dx \, dy = \mathcal{O}\left( \frac{1}{|k - R|^{N+2s}} \right). \]
Let \( k \to \infty \), by (3.8) and (3.9), we have
\[ \log \alpha^2 \int_{\mathbb{R}^N} u^2 \, dx = o_k(1) = \log \beta^2 \int_{\mathbb{R}^N} u^2 \, dx, \]
where \( o_k(1) \to 0 \) as \( k \to +\infty \). Therefore, \( \alpha \to 1 \) and \( \beta \to 1 \) as \( k \to \infty \). It follows from Lemma 2.3 that
\[ m \leq I(\alpha\tilde{u}^+ + \beta\tilde{u}^-) = 2I(u) + o_k(1) \leq 2c + \varepsilon + o_k(1). \]
Since \( \varepsilon \) is arbitrary, we deduce that
\[ m \leq 2c, \]
which is contradiction to Theorem 1.1. Thus, we complete the proof. \( \square \)

### 3.3 \((V)_\alpha\) potential

In this subsection, we prove \( c \) and \( m \) are achieved under conditions \((V)_\alpha\) and \((V)_\beta\). In order to overcome the difficulties caused by the loss of compactness, we first study the following problem in bounded domain, the solutions will be used as minimizing sequences.

\[
\begin{cases}
(-\Delta)^s u + V(x)u = u \log u^2, & x \in B_R, \\
u = 0, & x \in \mathbb{R}^N \setminus B_R,
\end{cases}
\tag{3.10}
\]
where \( B_R = \{ x \in \mathbb{R}^N \mid |x| < R \} \). We now define
\[ c_R = \inf_{u \in \mathcal{N}_R} I(u), \quad m_R = \inf_{u \in \mathcal{M}_R} I(u), \]
where
\[ \mathcal{N}_R = \mathcal{N} \cap X^0_0(B_R), \quad \mathcal{M}_R = \mathcal{M} \cap X^0_0(B_R) \]
and
\[ X^0_0(\Omega) = \{ u \in H^s(\mathbb{R}^N) \mid u = 0 \text{ a.e. on } \mathbb{R}^N \setminus \Omega \}. \]

Obviously, \( I \) is well defined on \( X^0_0(B_R) \) and \( I \in C(X^0_0(B_R), \mathbb{R}) \). Therefore, one can easily verify the following result.

**Lemma 3.5.** \( c_R, m_R \) are achieved. Assume that \( u \in \mathcal{N}_R \) and \( I(u) = c_R \), or \( u \in \mathcal{M}_R \) and \( I(u) = m_R \), then \( u \) is a solution of equation (3.10).

**Lemma 3.6.** Both \( c_R \) and \( m_R \) are decreasing with respect to \( R \) and converge to \( c, m \), respectively, as \( R \to \infty \).

**Proof.** Obviously, both \( c_R \) and \( m_R \) are decreasing with respect to \( R \), and \( c_R \geq c, m_R \geq m \). Now, we check that \( m_R \to m \) as \( R \to \infty \). By the definition of \( m \), for any \( \varepsilon > 0 \), there exists \( u \in \mathcal{M} \) such that \( I(u) \leq m + \varepsilon \). Choose a cutoff function \( \xi_R \) satisfying
\[ \left\{ \begin{array}{l}
\xi_R = 1 \quad \text{on } B_2, \quad \text{supp}(\xi_R) \subset B_R, \\
0 \leq \xi_R \leq 1, |\nabla \xi_R| \leq \frac{C}{R}.
\end{array} \right. \]

Define \( \xi_R = \xi_R \), then we have
\[ \int_{\mathbb{R}^N} |u_R|^2 \log |u_R|^2 \, dx \to \int_{\mathbb{R}^N} |u|^2 \log |u|^2 \, dx, \quad \text{as } n \to \infty \] (3.11)
and
\[ \int_{\mathbb{R}^N} |u_R|^2 \log |u_R|^2 \, dx \to \int_{\mathbb{R}^N} |u|^2 \log |u|^2 \, dx, \quad \text{as } n \to \infty. \] (3.12)

Now, we calculate that
\[ [u_R]^2 = \int_{|x| \leq \frac{R}{2}} \int_{|y| \leq \frac{R}{2}} \frac{|u(x) - u(y)|^2}{|x - y|^{N+2s}} \, dx \, dy + 2 \int_{|x| \leq \frac{R}{2}} \int_{|y| \leq \frac{R}{2}} \frac{|u_R(x) - u_R(y)|^2}{|x - y|^{N+2s}} \, dx \, dy \]
\[ + \int_{|x| \leq \frac{R}{2}} \int_{|y| \leq \frac{R}{2}} \frac{|u_R(x) - u_R(y)|^2}{|x - y|^{N+2s}} \, dx \, dy \]
\[ = I_1 + I_2 + I_3. \]

By a direct computation, we have
\[ I_2 \leq 4 \left( \int_{|x| \leq \frac{R}{2}} \int_{|y| \leq \frac{R}{2}} \frac{|\xi_R(x) - \xi_R(y)| |u(x)|^2}{|x - y|^{N+2s}} \, dx \, dy + \int_{|x| \leq \frac{R}{2}} \int_{|y| \leq \frac{R}{2}} \frac{|u(x) - u(y)|^2 |\xi_R(y)|^2}{|x - y|^{N+2s}} \, dx \, dy \right) \]
\[ \leq C \left( \int_{|x| \leq \frac{R}{2}} |u(x)|^2 \min(1, |x - y|^{N+2s}/R^2) \, dx \, dy + \int_{|y| \leq \frac{R}{2}} |u(x) - u(y)|^2 \, dx \, dy \right) \]
\[ \leq C \left( O(R^{-2s}) + \int_{|y| \leq \frac{R}{2}} \int_{|x| \leq \frac{R}{2}} \frac{|u(x) - u(y)|^2}{|x - y|^{N+2s}} \, dx \, dy \right) \]
\[ = O(R^{-2s}) + o_R(1), \]
where \( o_R(1) \to 0 \) as \( R \to \infty \). The last equality is because of

\[
\int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{|u(x) - u(y)|^2}{|x - y|^{N+2s}} \, dx \, dy < \infty.
\]

Similarly, we can deduce that

\[
I_3 = o_R(1), \quad \text{as } R \to +\infty.
\]  \hfill (3.15)

It follows from (3.13)–(3.15) that

\[
\int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{|u_R(x) - u_R(y)|^2}{|x - y|^{N+2s}} \, dx \, dy \to \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{|u(x) - u(y)|^2}{|x - y|^{N+2s}} \, dx \, dy, \quad \text{as } R \to +\infty.
\]  \hfill (3.16)

Moreover, it also holds that

\[
\int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u_R(x)u_R(y) + u_R(x)u_R(y)}{|x - y|^{N+2s}} \, dx \, dy \to \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{u(x)u(y) + u(x)u(y)}{|x - y|^{N+2s}} \, dx \, dy.
\]  \hfill (3.17)

Therefore,

\[
\langle I'(u_R), u_R \rangle \to \langle I'(u), u' \rangle = 0, \quad \langle I'(u_R), u_R \rangle \to \langle I'(u), u' \rangle = 0, \quad \text{as } R \to +\infty.
\]

By using Lemma 2.1, there exists \( a_{u_R}, \beta_{u_R} > 0 \) such that \( a_{u_R}u_R + \beta_{u_R}u_R \in M_R \) and \( a_{u_R} \to 1, \beta_{u_R} \to 1 \) as \( R \to +\infty \). Thus,

\[
m_R \leq I(a_{u_R}u_R + \beta_{u_R}u_R)
\]

\[
\leq I(a_{u_R}u' + \beta_{u_R}u') + C \left( \int_{|x| \leq R/2} \int_{|y| \leq R/2} \frac{|u_R(x) - u_R(y)|^2}{|x - y|^{N+2s}} \, dx \, dy \right.
\]

\[
+ \left. \int_{|x| > R/2} \int_{|y| > R/2} \frac{|u_R(x) - u_R(y)|^2}{|x - y|^{N+2s}} \, dx \, dy + \int_{|x| > R/2} V(x)u^2 + |u|^2 \log u^2 \, dx \right)
\]

\[
\leq I(u' + u') + o_R(1)
\]

\[
\leq m + \varepsilon + o_R(1),
\]

which implies \( \lim_{R \to +\infty} m_R \leq m \). Considering \( m_R \geq m \), we then conclude that \( \lim_{R \to +\infty} m_R = m \).

Similarly, we can prove \( \lim_{R \to +\infty} c_R = c \).

Next, we need to study the following limiting functional:

\[
F^\infty(u) = \frac{1}{2} \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{|u(x) - u(y)|^2}{|x - y|^{N+2s}} \, dx \, dy + \frac{1}{2} \int V(x) + 1)u^2 \, dx - \frac{1}{2} \int u^2 \log u^2 \, dx, \quad u \in W^s(\mathbb{R}^N).
\]

Define

\[
F^\infty(u) = \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{|u(x) - u(y)|^2}{|x - y|^{N+2s}} \, dx \, dy + \int_{\mathbb{R}^N} V_{\infty}u^2 \, dx - \int_{\mathbb{R}^N} u^2 \log u^2 \, dx, \quad u \in W^s(\mathbb{R}^N),
\]

and

\[
N^\infty = \{ u \in W^s(\mathbb{R}^N) \setminus \{0\} \mid F^\infty(u) = 0 \}, \quad c^\infty = \inf_{u \in N^\infty} F^\infty(u).
\]

It follows from Lemma 3.3 that \( c^\infty > 0 \) is achieved.
Lemma 3.7. Let $u_R$ be a solution of equation (3.10). Suppose that $u_R$ is bounded in $W^s(\mathbb{R}^N)$ with respect to $R,$ and up to a subsequence $R_n \to \infty,$ that
\[ \int_{B_R} |u_n|^p dx \to \lambda \in (0, \infty), \]
where $u_n := u_{R_n}$ and $2 < p < 2^*_s.$ Then there exist $\beta \in (0, 1]$ and $\{x_n\}$ satisfying that for any $\varepsilon > 0,$ there exists $r_\varepsilon > 0$ such that, for any $r' \geq r \geq r_\varepsilon > 0,$
\[ \liminf_{n \to \infty} \int_{B_{r}(x_n)} |u_n|^p dx \geq \beta \lambda - \varepsilon \]
and
\[ \liminf_{n \to \infty} \int_{R^N\setminus B_{r}(x_n)} |u_n|^p dx \geq (1 - \beta) \lambda - \varepsilon. \]
Moreover, if $\beta < 1,$ then $\liminf_{n \to \infty} I(u_n) \geq c + e^{\varepsilon_0}.$

Proof. Since $\{u_n\}$ is bounded in $H^s(\mathbb{R}^N)$ and $\int_{B_R} |u_n|^p dx$ is bounded away from zero, then the existence of such a number $\beta \in (0, 1]$ follows from a result of P.-L. Lions (see Lemma I.1. [20] or Lemma 4.3 [25]).

Now, we assume that $\beta < 1.$ Choose $\varepsilon_n \to 0$ and $r'_n \geq r_n \to +\infty$ such that, up to a subsequence, we may assume
\[ \liminf_{n \to \infty} \int_{B_{r_n}(x_n)} |u_n|^p dx \geq \beta \lambda - \varepsilon_n, \quad \liminf_{n \to \infty} \int_{R^N\setminus B_{r_n}(x_n)} |u_n|^p dx \geq (1 - \beta) \lambda - \varepsilon_n. \]

Choose a cutoff function $\xi(x)$ satisfying
\[
\begin{cases}
\xi \equiv 1 & \text{on } B_1(0) \setminus B_{1/2}(0), \\
0 \leq \xi \leq 1, & \text{supp}(\xi) \subset B_1(0) \setminus B_{1/2}(0), \\
|\nabla \xi| \leq 2.
\end{cases}
\]
Define $\xi_n(x) := \xi(|x - x_n|/r_n),$ then $\xi_n u_n \in W^s(\mathbb{R}^N).$ Direct computation yields
\[
\int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{|u_n(x) - u_n(y)|^2 \xi_n^2(x)}{|x - y|^{N + 2s}} \, dx \, dy + \int_{\mathbb{R}^N} V(x) u_n^2 \xi_n \, dx - \int_{\mathbb{R}^N} \xi_n (u_n^2 \log u_n^2) \, dx
\]
\[
= \int_{\mathbb{R}^N} \xi_n (u_n^2 \log u_n^2) \, dx + \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{(u_n(x) - u_n(y))(\xi_n(x) - \xi_n(y)) u_n(y) \, dx \, dy}{|x - y|^{N + 2s}}
\]
\[
\leq C \int_{\mathbb{R}^N} \xi_n |u_n|^p \, dx + \int_{\mathbb{R}^N} \left( \int_{\mathbb{R}^N} \frac{|\xi_n(x) - \xi_n(y)|^2 |u_n(y)|^2}{|x - y|^{N + 2s}} \, dx \, dy \right) \frac{1}{2} \int_{\mathbb{R}^N} |u_n(y)|^2 \, dy
\]
\[
\leq C \int_{\mathbb{R}^N} \xi_n |u_n|^p \, dx + C |u_n| \left( \int_{\mathbb{R}^N} |u_n(y)|^2 \, dy \int_{\mathbb{R}^N} \frac{|x - y|^2/r_n^2}{|x - y|^{N + 2s}} \, dx \, dy \right)^{\frac{1}{2}}
\]
\[
+ C \int_{\mathbb{R}^N} \frac{|u_n(y)|^2}{|x - y|^{N + 2s}} \, dx \, dy \right)^{\frac{1}{2}}
\]
\[
\leq C \int_{\mathbb{R}^N} \xi_n |u_n|^p \, dx + O(r_n^{-s}).
\]
Thus,
\[
\int_{2r_n \leq |x-x_n| \leq 3r_n} \int_{\mathbb{R}^N} \frac{|u_n(x) - u_n(y)|^2}{|x-y|^{N+2s}} \, dx \, dy + \int_{2r_n \leq |x-x_n| \leq 3r_n} V(x) u_n^2 \xi_n + |u_n^* \log u_n| \, dx = o_n(1). \tag{3.22}
\]

Take another cutoff function \( \eta(x) \) satisfying
\[
\begin{cases}
\eta \equiv 1 & \text{on } B_2(0), \quad \text{supp}(\eta) \subset B_2(0), \\
0 \leq \eta \leq 1, |\nabla \eta| \leq 2.
\end{cases}
\]

Define
\[
w_n(x) = \eta \left( \frac{|x-x_n|}{r_n} \right) u_n(x), \quad v_n(x) = \left[ 1 - \eta \left( \frac{|x-x_n|}{r_n} \right) \right] u_n(x).
\]

Using (3.20), we can infer
\[
\int_{\mathbb{R}^N} |w_n|^p \, dx \geq \int_{B_{2r_n}(x_n)} |u_n|^p \, dx \geq \beta \lambda - \epsilon_n
\]
and
\[
\int_{\mathbb{R}^N} |v_n|^p \, dx \geq \int_{\mathbb{R}^N \setminus B_{3r_n}(x_n)} |v_n|^p \, dx \geq (1-\beta) \lambda - \epsilon_n.
\]

On the other hand, since \( \text{supp}(v_n) \subset \mathbb{R}^N \setminus B_{2r_n}(x_n) \), one can deduce that
\[
\begin{align*}
\int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{(w_n(x) - w_n(y))(v_n(x) - v_n(y))}{|x-y|^{N+2s}} \, dx \, dy &= \int_{|x-x_n| \geq 2r_n} \int_{|y-x_n| \geq 2r_n} \frac{(w_n(x) - w_n(y))(v_n(x) - v_n(y))}{|x-y|^{N+2s}} \, dx \, dy \\
&= \int_{|x-x_n| \geq 2r_n} \int_{|y-x_n| \geq 2r_n} \frac{(w_n(x) - w_n(y))(v_n(x) - v_n(y))}{|x-y|^{N+2s}} \, dx \, dy \\
&\quad + \int_{|x-x_n| \geq 2r_n} \int_{|y-x_n| < 2r_n} \frac{(w_n(x) - w_n(y))(v_n(x) - v_n(y))}{|x-y|^{N+2s}} \, dx \, dy \\
&\quad + \int_{|x-x_n| < 2r_n} \int_{|y-x_n| \geq 2r_n} \frac{(w_n(x) - w_n(y))(v_n(x) - v_n(y))}{|x-y|^{N+2s}} \, dx \, dy \\
&= o_n(1). \tag{3.25}
\end{align*}
\]

It follows from (3.22)–(3.25) that
\[
I(u_n) = I(w_n) + I(v_n) + o_n(1). \tag{3.26}
\]

Moreover, by using (3.25) again, we derive that
\[
J(w_n) = \langle \Gamma(u_n), w_n \rangle + o_n(1) = o_n(1)
\]
and
\[
J(v_n) = \langle \Gamma(u_n), v_n \rangle + o_n(1) = o_n(1).
\]

Therefore, there exist two sequences \( \{a_n\}, \{\beta_n\} \) such that \( a_n w_n \in \mathcal{N}, \beta_n v_n \in \mathcal{N}, \) and \( a_n \to 1, \beta_n \to 1 \) as \( n \to \infty. \)

If \( \{x_n\} \) is bounded, then
\[
\lim_{n \to \infty} \inf \{I(\beta_n v_n) \} = \lim_{n \to \infty} \inf \{F(\beta_n v_n) \} \geq c^{\infty}, \tag{3.27}
\]
Furthermore, it follows from (3.26) and (3.27) that
\[
\lim_{n \to \infty} \inf \{I(u_n) \} = \lim_{n \to \infty} \inf \{I(a_n w_n) \} + \lim_{n \to \infty} \inf \{I(\beta_n v_n) \} \geq c + c^{\infty}.
\]
If \( \{x_n\} \) is unbounded, then
\[
\liminf_{n \to \infty} I(\alpha_n w) = \liminf_{n \to \infty} J^c(\alpha_n w) \geq c^\infty, \tag{3.28}
\]
which upon combining with (3.26) also yields \( \liminf_{n \to \infty} J(u_n) \geq c + c^\infty. \)

**Lemma 3.8.** Assume \((V_0)\) holds, then \(c\) is achieved.

**Proof.** First, we claim that \( c < c^\infty \). It follows from Lemma 3.3 that there exists \( w \in N^\infty \) such that \( J^c(w) = c^\infty \) and \( J^c(w) > 0 \). Moreover, by a similar argument of the proof of Theorem 1.1, we conclude that \( w(x) > 0 \) for each \( x \in \mathbb{R}^N \).

It follows from \((V_0)\) that
\[
c \leq \max_{a \geq 0} I(aw) = I(a_0 w) < I^c(aw) = \max_{a \geq 0} J^c(aw) = J^c(w) = c^\infty,
\]
where \( a_0 \) is the constant such that \( \max_{x \in \Omega} I(x) = I(a_0 w) \).

Now, it follows from Lemmas 3.5 and 3.6 that there exists a sequence \( \{u_n\} \subset N_{R^N} \) such that \( J(u_n) = c_n \to c \) as \( n \to \infty \). Since \( J(u_n) = 0 \), we can deduce that \( \{u_n\} \) is uniformly bounded in \( W^s(\mathbb{R}^N) \). Thus, for any \( \epsilon > 0 \), by Lemma 3.7 there exist \( r > 0 \) and a sequence \( \{x_n\} \subset \mathbb{R}^N \) such that
\[
\liminf_{n \to \infty} \int_{B_r(x_n)} |u_n|^p dx \geq \lambda - \epsilon,
\]
where
\[
\lambda := \lim_{n \to \infty} \int_{\mathbb{R}^N} |u_n|^p dx > 0.
\]

Now, we claim that \( \{x_n\} \) is bounded in \( \mathbb{R}^N \). If not, then we have
\[
J^c(u_n) = J(u_n) + o_n(1),
\]
which implies the existence of \( a_n > 0 \) such that \( a_n \to 1 \) and \( J^c(a_n u_n) = 0 \). Thus, we have
\[
c^\infty \leq \limsup_{n \to \infty} J^c(a_n u_n) = \liminf_{n \to \infty} J^c(u_n) = \liminf_{n \to \infty} J(u_n) = c,
\]
which leads to a contradiction. Therefore, \( \{x_n\} \) is bounded and thus \( u_n \to u \) in \( L^p(\mathbb{R}^N) \) for \( 2 < p < 2^*_s \). Proceeding as the arguments in the proof of Lemma 3.2, we can prove that \( c \) is achieved. \( \square \)

**Lemma 3.9.** Assume \((V_0)\) holds, and let \( u(x) \) be a positive ground state solution of equation (1.1), then
\[
u(x) \leq \frac{C}{1 + |x|^{N + 2s}}.
\]

**Proof.** By Lemma 2.4 and Proposition 2.5, we know that \( u \in C^{1,2s+\alpha_0}(\mathbb{R}^N) \cap L^\infty(\mathbb{R}^N) \) if \( 2s + \alpha_0 > 1 \), while \( u \in C^{0,2s+\alpha_0}(\mathbb{R}^N) \cap L^\infty(\mathbb{R}^N) \) if \( 2s + \alpha_0 \leq 1 \). Then, by a similar argument to the proof of Lemma 2.6 in [26], one can derive
\[
\lim_{|x| \to \infty} u(x) = 0.
\]

Thus, there exists \( R > 0 \) such that
\[
(-\Delta)^s u + \nu u \leq (-\Delta)^s u + V(x)u = u \log u^2 \leq 0, \quad x \in \mathbb{R}^N \setminus B_R.
\]

It follows from Lemma C.1 in [27] that the fundamental solution \( G_{\delta,16} \) satisfies
\[
((-\Delta)^s + \nu)G_{\delta,16} = 0, \quad x \in \mathbb{R}^N.
\]
Furthermore, \( G_{s, \alpha} \) is radial, positive, strictly decreasing in \( |x| \) and satisfies
\[
\lim_{|x| \to \infty} |x|^{N+2s} G_{s, \alpha} = V_0^{-2} C_{N,s}
\] (3.29)
with some positive constant \( C_{N,s} \). Hence, there exists a constant \( c_0 > 0 \) such that \( G_{s, \alpha} \geq c_0 > 0 \) in \( B_R \). Let \( C_0 = c_0 \|u\|_{L^\infty} \), then we have
\[
w(x) = C_0 G_{s, \alpha} - u \geq 0, \quad x \in B_R
\]
and
\[
(\Delta)^s w + V_0 w = ((\Delta)^s + V_0) \left( C_0 G_{s, \alpha} - u \right) \geq 0, \quad x \in \mathbb{R}^N \setminus B_R.
\]
Note that the function \( w \) is continuous away from the origin and \( w(x) > 0 \) on \( B_R \) holds. We claim that \( w(x) \geq 0 \) on \( B_{2R} \) as well. Suppose on the contrary that \( w \) is strictly negative somewhere in \( B_{2R} \). Since \( w(x) \to 0 \) as \( |x| \to +\infty \) and \( w(x) > 0 \) on \( B_R \), this implies that \( w \) attains a strict global minimum at some point \( x_0 \in B_{2R} \) with \( w(x_0) < 0 \). By using the singular integral expression for \( (\Delta)^s \), it is easy to see that \( w \) is continuous away from the origin and \( w(x) > 0 \) on \( B_R \). We claim that \( w(x) \geq 0 \) on \( B_{2R} \) as well. Suppose on the contrary that \( w \) is strictly negative somewhere in \( B_{2R} \). Since \( w(x) \to 0 \) as \( |x| \to +\infty \) and \( w(x) > 0 \) on \( B_R \), this implies that \( w \) attains a strict global minimum at some point \( x_0 \in B_{2R} \) with \( w(x_0) < 0 \). By using the singular integral expression for \( (\Delta)^s \), it is easy to see that \( (\Delta)^s w(x_0) < 0 \). On the other hand, we have \( (\Delta)^s w + V_0 w \geq 0 \) on \( B_{2R} \), which implies that \( (\Delta)^s w(x_0) > 0 \). This is a contradiction, and we conclude that \( w(x) \geq 0 \). Thus, we conclude
\[
w(x) \geq C_0 G_{s, \alpha}.
\] (3.30)
Therefore, the result is directly from (3.29) and (3.30).

From Lemma 3.8, there exists \( u \in N, w \in N^{\infty} \) such that \( I(u) = c \) and \( I^{\infty}(w) = c^{\infty} \). Furthermore, with the same argument as that in proving Theorem 1.1, we may assume \( u > 0 \) and \( w > 0 \). Similar to Lemma 3.9, one obtains
\[
w(x) \leq \frac{C}{1 + |x|^{N+2s}}, \quad \text{for some constant } C > 0.
\]
Denote \( w_R(x) = w(x + 2R, x') \) with \( x, x' \in \mathbb{R}^N \). We have the following estimate.

**Lemma 3.10.** Suppose that \( V(x) \) satisfies (\( V_4 \))–(\( V_5 \)), then \( m < c + c^{\infty} \).

**Proof.** Direct computation yields
\[
I(au + \beta w_R) = \frac{\alpha^2}{2} \left[ |u|^2_R + \int_{\mathbb{R}^N} (V(x) + 1)|u|^2dx \right] + \frac{\beta^2}{2} \left[ |w_R|^2_R + \int_{\mathbb{R}^N} (V(x) + 1)|w_R|^2dx \right]
+ a\beta \int_{\mathbb{R}^N} (V(x) + 1)uw_R dx - \frac{1}{2} \int_{\mathbb{R}^N} (au + \beta w_R)^2 \log(au + \beta w_R)^2 dx
+ a\beta \int_{\mathbb{R}^N} \int_{\mathbb{R}^N} \frac{(u(x) - u(y))(w_R(x) - w_R(y))}{|x - y|^{N+2s}} dx dy.
\] (3.31)

To prove this lemma, it is sufficient to show that
\[
\sup_{(a,\beta) \in \mathbb{R}^2} I(au + \beta w_R) < c + c^{\infty}.
\] (3.32)

In fact, by Miranda theorem, there exist \( \bar{a} > 0 \) and \( \bar{\beta} < 0 \) such that \( \bar{a}u + \bar{\beta}w_R \in M \). Thus, \( m < c + c^{\infty} \).

**Claim 1.** There exists \( R_0, \rho_0 > 0 \) such that for all \( R \geq R_0, a^2 + \beta^2 = r^2 > r_0^2 \),
\[
\sup_{(a,\beta) \in \mathbb{R}^2} I(au + \beta w_R) \leq 0.
\]
Indeed, let $\alpha = \alpha r$ and $\beta = \beta r$ and $\varphi = \tilde{\alpha}u + \tilde{\beta}w_r$. We first find $R' > 0$ such that for all $R > R'$, $\|\varphi\|_s$ and $\int_{R^N} \varphi^2 \log \varphi^2 \, dx$ are bounded from above and below by two positive constants. Thus, we have

$$I(u\alpha + \beta w_d) = I(rp) = r^2 I(\varphi) - \frac{1}{2} r^2 \log r^2 \int_{R^N} \varphi^2 \, dx,$$

which implies the conclusion if $r > 0$ is large enough.

**Claim 2.** There exists $\varepsilon > 0$ small and $R_0 > 0$ large such that for $R > R_0$, it holds

$$\int \int_{R^N \times R^N} \frac{(u(x) - u(y))(w_R(x) - w_R(y))}{|x - y|^{N+2s}} \, dx \, dy + \int_{R^N} (V(x) + 1)uw_R \, dx = O(R^{-2s+\varepsilon(N+2s)}). \quad (3.33)$$

In fact, $w_R > 0$ solves the equation

$$(-\Delta)^s w_R + V_0 w_R = R \log w_R^2, \quad x \in R^N.$$

Thus,

$$\int \int_{R^N \times R^N} \frac{(u(x) - u(y))(w_R(x) - w_R(y))}{|x - y|^{N+2s}} \, dx \, dy + \int_{R^N} V_0 u w_R \, dx = \int_{R^N} u w_R \log w_R^2 \, dx.$$

For arbitrarily $\varepsilon$ small, there exists $C_\varepsilon > 0$ such that $|t \log t^2| \leq C_\varepsilon t^{1-\varepsilon}$ for all $0 < t < 1$. Thus, applying Lemma 3.9, we derive

$$\left| \int_{R^N} u w_R \log w_R^2 \, dx \right| \leq \int_{R^N \setminus B_\varepsilon} |u| w_R \log w_R^2 \, dx + \int_{B_\varepsilon} |u| w_R \log w_R^2 \, dx$$

$$\leq C \left( \int_{R^N \setminus B_\varepsilon} |u| \, dx + \int_{R^N \setminus B_\varepsilon} |w \log w| \, dx \right)$$

$$\leq C R^{-2s} + \int_{R^N \setminus B_\varepsilon} |x|^{-(1-\varepsilon)(N+2s)} \, dx$$

$$\leq CR^{-2s+\varepsilon(N+2s)}.$$

Therefore, Claim 2 follows.

**Claim 3.** For $\alpha$ and $\beta$ bounded, there exists $R_2 > 0$ such that, for $R > R_2$, it holds

$$\int_{R^N} (au + \beta w_d)^2 \log(au + \beta w_d) \, dx = \int_{R^N} (au)^2 \log(au)^2 \, dx + \int_{R^N} (\beta w_d)^2 \log(\beta w_d)^2 \, dx + O(R^{-2s}).$$

In fact, applying Lemma 3.9, one can obtain

$$\int_{R^N \setminus B_0(0)} (au)^2 \log(au)^2 \, dx = O(R^{-2s+\varepsilon(N+2s)}),$$

$$\int_{R^N \setminus B_0(0)} (\beta w_d)^2 \log(\beta w_d)^2 \, dx = O(R^{-2s+\varepsilon(N+2s)}),$$

and

$$\int_{R^N \setminus (B_0(0) \cup B_0(2R_2))} (au + \beta w_d)^2 \log(au + \beta w_d)^2 \, dx = O(R^{-2s+\varepsilon(N+2s)}).$$
Furthermore, direct computation yields
\[
\begin{align*}
&\int_{B_R(0)} (au + \beta w)^2 \log(au + \beta w)^2 \, dx - \int_{B_R(0)} (au)^2 \log(au)^2 \, dx \\
&\leq \int_{B_R(0)} (au)^2 \log(au + \beta w)^2 - \log(au)^2 \, dx + \int_{B_R(0)} (2\alpha \beta \mu w + \beta^2 w)^2 \log(au + \beta w)^2 \, dx \\
&= O(R^{-2\epsilon}).
\end{align*}
\]
Hence, Claim 3 follows.

Now, we prove (3.32). From Claim 1, we may suppose that both \(\alpha\) and \(\beta\) are bounded. Combining Claim 2, Claim 3 with (3.31), we can deduce that for \(R > \max\{R_0, R_1, R_2\}\),
\[
I(au + \beta w_R) = I(au) + I(\beta w_R) + O(R^{-2\epsilon + \epsilon(N+2\epsilon)}).
\]
It is easy to check that \(J(w_R) \to 0\) as \(R \to \infty\). Thus, there exists \(\beta_R\) satisfying \(\beta_R \to 1\) as \(R \to +\infty\) and \(J(\beta_R w_R) = 0\). Moreover, for \(R\) is large enough, by (\(V_3\)) and (\(V_4\)), we deduce that
\[
I(au + \beta w_R) = I(au) + I(\beta w_R) + O(R^{-2\epsilon + \epsilon(N+2\epsilon)}).
\]
\[
\begin{align*}
&\leq I(u) + I^\alpha(\beta w_R) + \frac{1}{2} \beta_R^2 \int_{R^N} (V(x) - V_{\infty})w_R^2 \, dx + O(R^{-2\epsilon + \epsilon(N+2\epsilon)}) \\
&\leq c + c^{\infty} - \frac{1}{2} \int_{B_R(0)} (V_{\infty} - V(x - 2Re_1))w_R^2 \, dx + O(R^{-2\epsilon + \epsilon(N+2\epsilon)}) \\
&\leq c + c^{\infty} - C \int_{B_R(0)} \frac{w^2}{|x - 2Re_1|^m} \, dx + O(R^{-2\epsilon + \epsilon(N+2\epsilon)}) \\
&< c + c^{\infty}.
\end{align*}
\]
Therefore, we complete the proof. \(\square\)

**Proposition 3.11.** Assume (\(V_4\))–(\(V_5\)) hold, then \(m\) is achieved.

**Proof.** It follows from Lemmas 3.5 and 3.6 that there exists a sequence \(\{u_n\}\) such that \(u_n \in M_{R_n}\) and 
\[
I(u_n) = m_{R_n} \to m \quad \text{as} \quad n \to \infty.
\]
Since \(J(u_n) = 0\), we deduce that \(\{u_n\}\) is bounded in \(W^\alpha(R^N)\). Thus, by Lemma 3.7, we find a sequence \(\{x_n\} \subset R^N\) such that for any \(\epsilon > 0\), there exists \(r > 0\) such that
\[
\liminf_{n \to \infty} \int_{B_r(x_n)} |u_n|^p \, dx \geq \lambda - \epsilon,
\]
where
\[
\lambda = \lim_{n \to \infty} \int_{R^N} |u_n|^p \, dx > 0.
\]
Now, we claim that \(\{x_n\}\) is bounded. If not, then
\[
\langle I'(u_n), (u_n)^\ast \rangle = \langle I^{cof}(u_n), (u_n)^\ast \rangle + o_n(1)
\]
and
\[
\langle I'(u_n), (u_n)^\ast \rangle = \langle I^{cof}(u_n), (u_n)^\ast \rangle + o_n(1).
\]
Thus, there exist $a_n, \beta_n > 0$ with $a_n \to 1$, $\beta_n \to 1$ such that
\[
\langle I^\alpha (a_n(u_n)^+) + \beta_n(u_n)^-), a_n(u_n)^+ \rangle = 0
\]
and
\[
\langle I^\alpha (a_n(u_n)^+) + \beta_n(u_n)^-), \beta_n(u_n)^- \rangle = 0.
\]
This implies $a_n(u_n)^+ + \beta_n(u_n)^- \in \mathcal{M}$. Arguing as we prove Theorem 1.1, we infer $2c^{\alpha} \leq m^{\alpha}$. Therefore,
\[
c + c^{\alpha} \leq 2c^{\alpha} \leq \liminf_{n \to \infty} \langle I^\alpha (a_n(u_n)^+) + \beta_n(u_n)^-) \rangle \leq \liminf_{n \to \infty} I^\alpha (u_n) = \liminf_{n \to \infty} I(u_n) = m,
\]
which leads to a contradiction. This implies that $\{x_n\}$ is bounded. Therefore, $u_n \rightharpoonup u$ in $L^p(\mathbb{R}^N)$ for $2 < p < 2^*_s$. Proceeding as the proof of Lemma 3.2, we can verify that $m$ is achieved. 

\[\Box\]

**Acknowledgements:** The research was supported by the Natural Science Foundation of China (11831009, 12071170).

**Conflict of interest:** The authors declare that there is no conflict of interest.

**References**

[1] E. D. Nezza, G. Palatucci, and E. Valdinoci, *Hitchhiker’s guide to the fractional Sobolev spaces*, Bull. Sci. Math. 136 (2012), 521–573.

[2] I. Białynicki-Birula and J. Mycielski, *Nonlinear wave mechanics*, Ann. Phys. 100 (1976), 62–93.

[3] I. Białynicki-Birula and J. Mycielski, *Wave equations with logarithmic nonlinearities*, Bull. Acad. Polon. Sci. 23 (1975), 461–466.

[4] R. Carles and I. Gallagher, *Universal dynamics for the defocusing logarithmic Schrödinger equation*, Duke Math. J. 167 (2018), 1761–1801.

[5] T. Cazenave, *Stable solutions of the logarithmic Schrödinger equation*, Nonlinear Anal. 7 (1983), 1127–1140.

[6] T. Cazenave, *Semilinear Schrödinger equations*, Courant Lecture Notes in Mathematics, 10. New York University, Courant Institute of Mathematical Sciences, American Mathematical Society, New York, 2003.

[7] T. Cazenave and A. Haraux, *Équations daévolution avec non linéarité logarithmique*, Ann. Fac. Sci. Toulouse Math. 2 (1980), 21–51.

[8] T. Cazenave and P.-L. Lions, *Orbital stability of standing waves for some nonlinear Schrödinger equations*, Comm. Math. Phys. 85 (1982), 549–561.

[9] A. H. Ardila, *Existence and stability of standing waves for nonlinear fractional Schrödinger equation with logarithmic nonlinearity*, Nonlinear Anal. 155 (2017), 52–64.

[10] P. d’Avenia, M. Squassina, and M. Zenari, *Fractional logarithmic Schrödinger equations*, Math. Methods Appl. Sci. 38 (2015), 5207–5216.

[11] A. Cotioliis and N. K. Tavoularis, *On logarithmic Sobolev inequalities for higher order fractional derivatives*, C. R. Math. Acad. Sci. Paris. 340 (2005), 205–208.

[12] M. Squassina and A. Szulkin, *Multiple solutions to logarithmic Schrödinger equations with periodic potential*, Calc. Var. Partial Differ. Equ. 54 (2015), 585–597.

[13] C. O. Alves and C. D. de Morais Filho, *Existence and concentration of positive solutions for a Schrödinger logarithmic equation*, Z. Angew. Math. Phys. 69 (2018), 22.

[14] P. d’Avenia, E. Montefusco, and M. Squassina, *On the logarithmic Schrödinger equation*, Commun. Contemp. Math. 16 (2014), 35.

[15] C. Ji and A. Szulkin, *A logarithmic Schrödinger equation with asymptotic conditions on the potential*, J. Math. Anal. Appl. 437 (2016), 241–254.

[16] K. Tanaka and C. Zhang, *Multi-bump solutions for logarithmic Schrödinger equations*, Calc. Var. Partial Differ. Equ. 56 (2017), 35p.

[17] W. Shuai, *Multiple solutions for logarithmic Schrödinger equations*, Nonlinearity 32 (2019), 2201–2225.

[18] Z. Wang and C. Zhang, *Convergence from power-law to logarithm-law in nonlinear scalar field equations*, Arch. Ration. Mech. Anal. 231 (2019), 45–61.

[19] T. Weth, *Energy bounds for entire nodal solutions of autonomous superlinear equations*, Calc. Var. Partial Differ. Equ. 27 (2006), 421–437.
[20] P.-L. Lions, *The concentration-compactness principle in the calculus of variations. The locally compact case. I*, Ann. Inst. H. Poincaré Anal. Non Linéaire. 1 (1984), 109–145.

[21] Y. Deng and W. Shuai, *Sign-changing solutions for non-local elliptic equations involving the fractional Laplacian*, Adv. Differ. Equ. 23 (2018), 109–134.

[22] B. Barrios, E. Colorado, R. Servadei, and F. Soria, *A critical fractional equation with concave-convex power nonlinearities*, Ann. Inst. H. Poincaré Anal. Non Linéaire, 32 (2015), 875–900.

[23] P. Felmer, A. Quass, and J. Tan, *Positive solutions of the nonlinear Schrödinger equation with the fractional Laplacian*, Proc. Royal Edinburgh 142A (2012), 1237–1262.

[24] M. Willem, *Minimax Theorems*, Birkhäuser, Basel, 1996.

[25] M. Struwe, *Variational Methods. Applications to Nonlinear Partial Differential Equations and Hamiltonian Systems*, Springer-Verlag, Berlin, 1990.

[26] C. O. Alves and O. H. Miyagaki, *Existence and concentration of positive solutions for a Schrödinger logarithmic equation*, Z. Angew. Math. Phys. 55 (2016), Art. 47, 19 p.

[27] R. L. Frank, E. Lenzmann and L. Silvestre, *Uniqueness of radial solutions for the fractional Laplacian*, Comm. Pure Appl. Math. 69 (2016), 1671–1726.