Multiscale Methods & Analysis for Nonlinear Klein-Gordon Equation in Nonrelativistic Limit Regime

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Outline

- Nonlinear Klein-Gordon (KG) equation
- Numerical methods and error estimates
  - Finite difference time domain (FDTD) methods
  - Exponential wave integrator (EWI) spectral method
- Nonlinear Schrodinger (NLS) equation with wave operator
  - FDTD methods and uniform error estimates
  - EWI spectral method and optimal error estimate
- Multiscale methods for nonlinear KG equation
- Conclusion & future challenges

Motivation

- The nonlinear Klein-Gordon (KG) equation

$$\varepsilon^2 \partial_{tt} u(\vec{x},t) - \Delta u + \frac{1}{\varepsilon^2} u + f(u) = 0 \qquad \vec{x} \in \mathbb{R}^d, \quad t > 0$$

  - With initial conditions

$$u(\vec{x},0) = \phi(\vec{x}), \quad \partial_t u(\vec{x},0) = \frac{1}{\varepsilon^2}\gamma(\vec{x}), \quad \vec{x} \in \mathbb{R}^d$$

  - $u = u(\vec{x},t)$ real (complex)-valued field (order parameter)
  - $0 < \varepsilon \leq 1$ dimensionless parameter, e.g. $\sim 1/c$
  - $f(u)$ real-valued function (or $f(u) = g(|u|^2)u$ if u is complex)
  - ϕ & γ given dimensionless real (or complex) functions

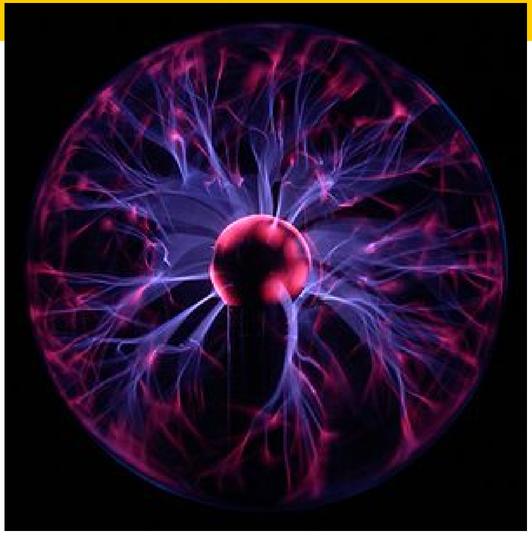
The (linear) Klein-Gordon (KG) equation

$$\frac{1}{c^2}\partial_{tt}u - \Delta u + \frac{m^2c^2}{\hbar^2}u = 0$$

- Proposed in 1927 by physicists Oskar Klein & Walter Gordon
  - To describe relativistic electrons (correct for spinless pion)
  - It is a relativistic version of the Schrodinger equation which suffers from not being relativistically covariant or not take into account Einstein's special relativity
  - An equation of motion of a quantum scalar field for spinless particles
  - With appropriate interpretation, it does describe the quantum amplitude for finding a point particle in various places, but particle propagates both forwards and backwards in time!!

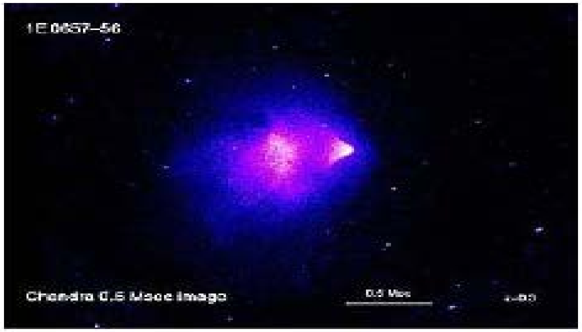
The (nonlinear) Klein-Gordon (KG) equation

- Applications in other areas
  - Plasma, e.g. interaction between langmuir & ion sound waves (Klein-Gordon-Zakharv)
    - P.M. Bellan, Fundamental of Plasma Physics, 2006
    - R. O. Dendy, Plasma Dynamics, 1990

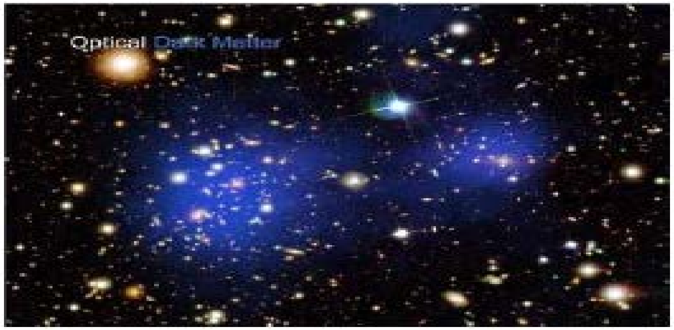


Plasma lamp

  - Universe, e.g. dark matter or black-hole evaporation (Huang, 10')



Overall view



Dark matter

Properties of KG equation

- Time symmetric, i.e. unchanged if $t \rightarrow -t$
- Hamiltonian (or energy) conservation

$$F(u) = 2\int_0^u f(s)\,ds$$

$$E(t) = \int_{\mathbb{R}^d} \left[\varepsilon^2 |\partial_t u|^2 + |\nabla u|^2 + \frac{1}{\varepsilon^2}|u|^2 + F(u) \right] d\vec{x}$$

$$\equiv \int_{\mathbb{R}^d} \left[\frac{1}{\varepsilon^2}|\gamma|^2 + |\nabla \phi|^2 + \frac{1}{\varepsilon^2}|\phi|^2 + F(\phi) \right] d\vec{x} := E(0), \quad t \geq 0$$

- Two different regimes
  - O(1)-wave regime, e.g. $\varepsilon = 1$
  - Nonrelativistic limit regime, $0 < \varepsilon \ll 1$

Existing results in O(1)-wave regime

- Analytical results for Cauchy problem: Browder, 62'; Segal, 63'; Strauss, 68'; Morawetz & Strauss, 72'; Glassey, 73' &82'; Ablowitz, Kruskal & Ladik, 79'; Shatah, 85'; Ginibre & Velo, 85'&89'; Klainerman & Machedon, 93'; Adomian, 96'; Nakmura & Ozawa, 01'; Tao, 01'; Ibrahim, Majdoub & Masmoudi, 06'; ……
  - Existence, uniqueness & regularity for defocusing case $F(u) \geq 0$
  - Finite time blow-up for focusing case $F(u) \leq 0$
- Numerical methods
  - Finite difference time domain (FDTD) methods: Strauss & Vazquez, 78'; Jimenez & Vazquez, 90'; Tourigny, 90'; Li & Vu-Quoc, 95'; Duncan, 97'; Cohen, Hairer & Lubich, 08';……
    - Conservative vs non-conservative
    - Implicit vs explicit
  - Spectral methods: Cao& Guo, 93'; ……..

Existing results in nonrelativistic limit regime

- Nonrelativistic limits: Tsutsumi, 84'; Najman, 89' & 90'; Machiara, 01'; Masmoudi, Nakanishi, 02'; Machihara, Nakanishi & Ozawa, 02'; Bechouche, Mauser & Selberg, 03'; Masmoudi & Nakaishi, Invent. Math. 08'; Y. Lu & Z. Zhang, 14';...

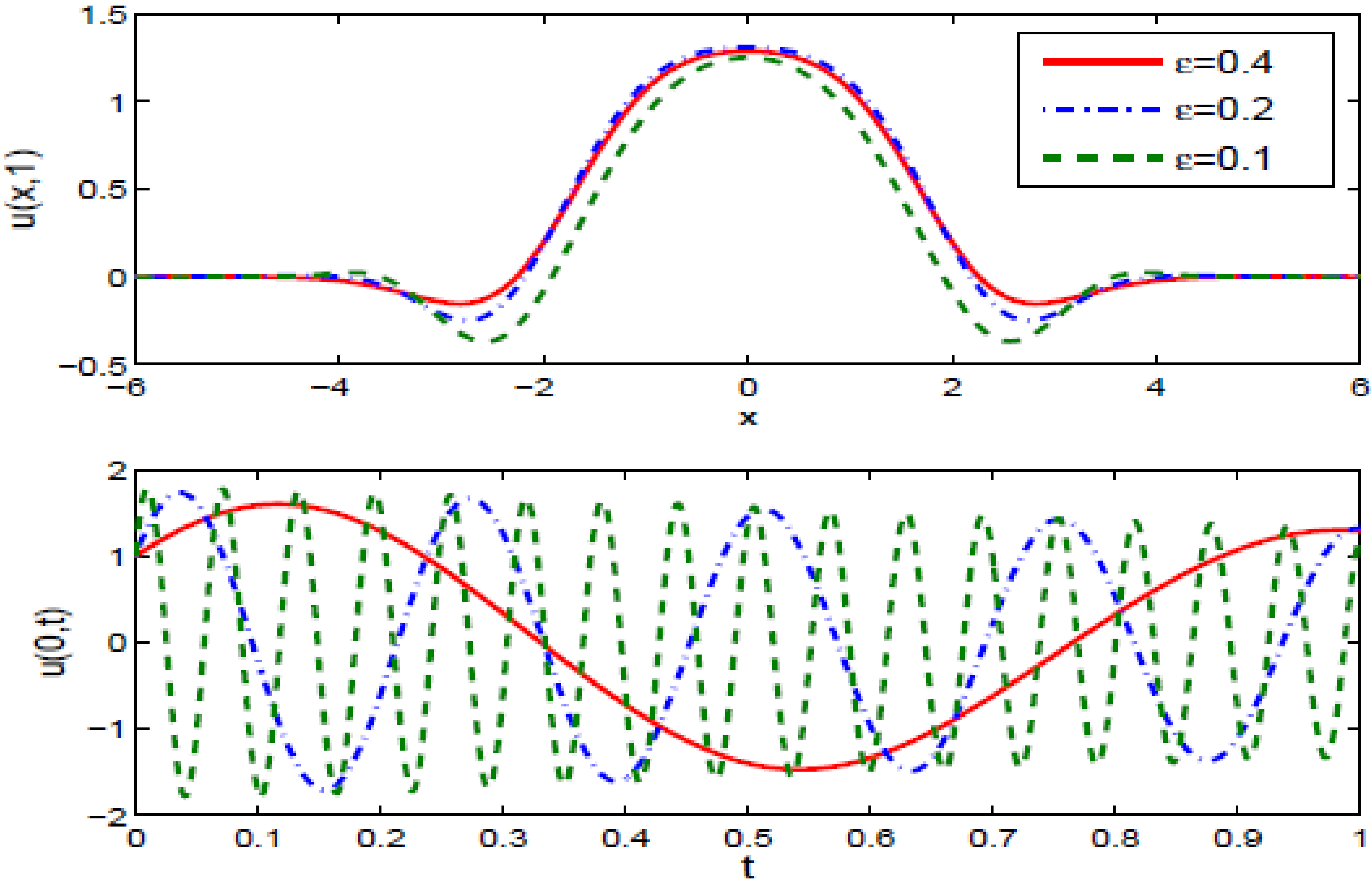
$$u := u^{\varepsilon} \to ??? \quad \text{when} \quad \varepsilon \to 0$$

  – Main difficulty: $E(t)$ is unbounded when $\varepsilon \to 0$!!!

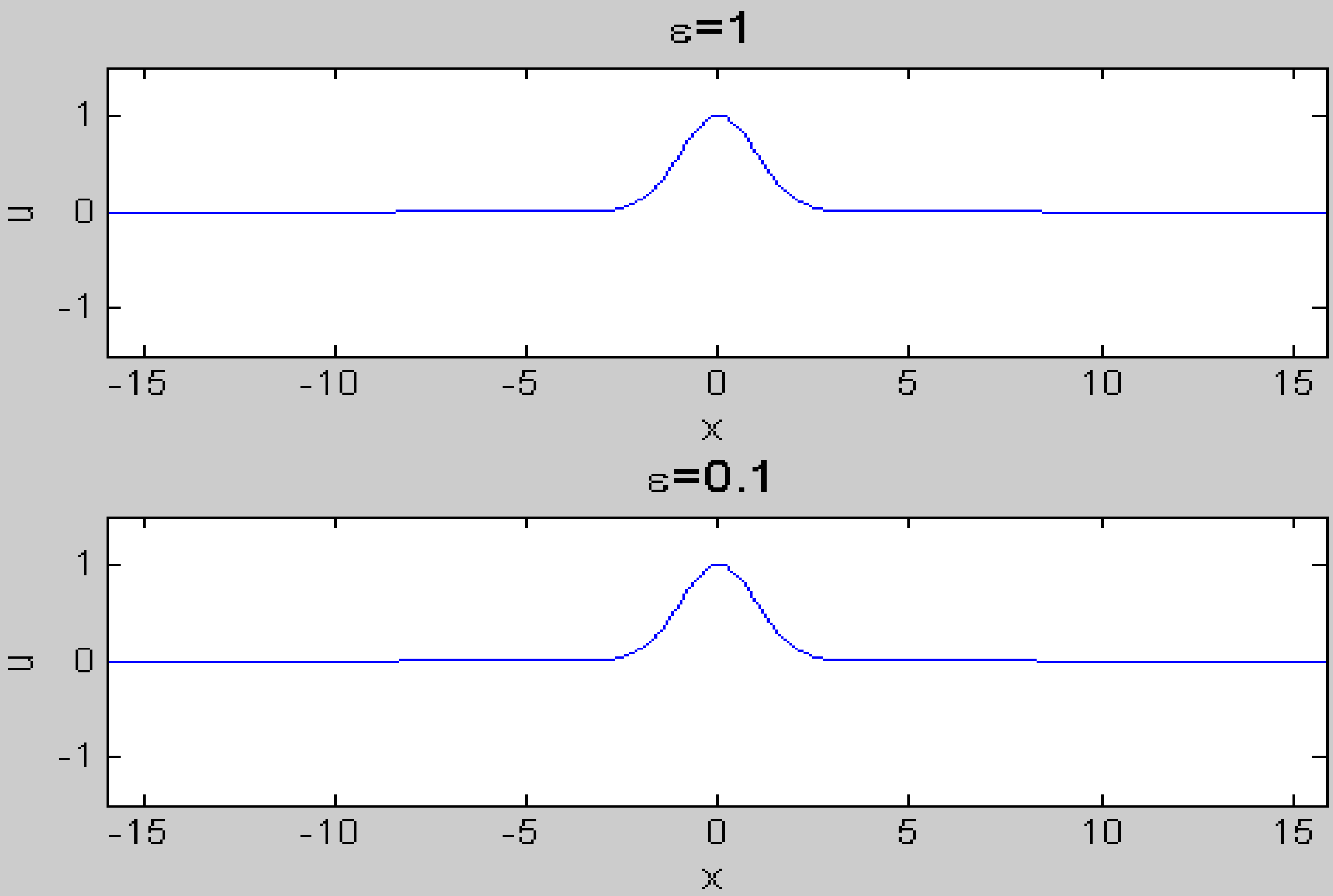
- Solution propagates waves with wavelength $O(\varepsilon^2)$ in time & $O(1)$ in space
  – Plane wave solutions $f(u) = \lambda |u|^p u$

$$u(\vec{x},t) = Ae^{i(\vec{k}\bullet\vec{x}+\omega t)} \quad \text{with} \quad \omega_{\pm} = \frac{\pm 1}{\varepsilon^2}\sqrt{1+\varepsilon^2(|\vec{k}|^2+\lambda A^p)} = O\left(\frac{1}{\varepsilon^2}\right)$$

Numerical results



Numerical results



Existing results in nonrelativistic limit regime

– Asymptotic and rigorous results: Masmoudi, Nakanishi, Math Ann., 02'; Machihara, Nakanishi & Ozawa, Math. Ann., 02'; ….

$$u := u^{\varepsilon} \to e^{it/\varepsilon^2}\psi + e^{-it/\varepsilon^2}\overline{\psi}, \quad \varepsilon \to 0$$

- Nonlinear Schrodinger equation with wave operator (NLSW)

$$2i\partial_t\psi + \varepsilon^2\partial_{tt}\psi - \Delta\psi + F(\psi) = 0$$

- Nonlinear Schrodinger equation (NLSE)

$$2i\partial_t\psi - \Delta\psi + F(\psi) = 0 \qquad F(\psi) := \frac{1}{2\pi}\int_0^{2\pi} f(e^{i\theta}\psi + e^{-i\theta}\overline{\psi})e^{-i\theta}\,d\theta$$

- Highly oscillatory dispersive PDE

Numerical methods in nonrelativistic limit $0 < \varepsilon \ll 1$

- FDTD--Finite difference time domain– methods: Bao& Dong, Numer. Math., 11'
  - CNFD, SIFD or LPFD: $O(h^2 + \tau^2 / \varepsilon^6)$
- EWI–exponential wave integrator– methods: Bao & Dong, Numer. Math., 11'
  - EWI-SP, EWI-FD: $O(h^2 + \tau^2 / \varepsilon^4)$
- MTI–multiscale time integrator– methods: Bao,Cai& Zhao, SINUM, 14'
  - MTI-SP, MTI-FD: $O(h^2 + \tau)$
- AP–Asymptotic preserving –methods: Faou&Schratz, Numer. Math, 14'
  - AP-SP, AP-FD: $O(h^2 + \tau^2 + \varepsilon^2)$
- SAM--Stroboscopic Averaging-- methods: Chartier, Crouseilles, Lemou, Mehats, 14'

Numerical methods for KG equation

- Finite difference time domain (FDTD) methods

$$\varepsilon^2 \partial_{tt} u(x,t) - \partial_{xx} u + \frac{1}{\varepsilon^2} u + f(u) = 0 \qquad \vec{x} \in \Omega = (a,b), \quad t > 0$$

$$u(a,t) = u(b,t) = 0, \qquad t \geq 0$$

$$u(x,0) = \phi(x), \quad \partial_t u(x,0) = \frac{1}{\varepsilon^2} \gamma(x), \qquad a \leq x \leq b$$

  – Mesh size $h := \Delta x = \dfrac{b-a}{M}, \quad x_j = a + jh, \quad j = 0,1,\ldots,M$
  – Time step $\tau := \Delta t > 0, \quad t_n = n\tau, \quad n = 0,1,\ldots$
  – Numerical approximation

$$u(x_j, t_n) \approx u_j^n, \quad j = 0,1,\ldots,M, \quad n = 0,1,\ldots$$

Numerical methods for KG equation

- Finite difference discretization operators

$$\delta_t^+ u_j^n = \frac{u_j^{n+1} - u_j^n}{\tau}, \quad \delta_t^- u_j^n = \frac{u_j^n - u_j^{n-1}}{\tau}, \quad \delta_t^2 u_j^n = \frac{u_j^{n+1} - 2u_j^n + u_j^{n-1}}{\tau^2},$$

$$\delta_x^+ u_j^n = \frac{u_{j+1}^n - u_j^n}{h}, \quad \delta_x^- u_j^n = \frac{u_j^n - u_{j-1}^n}{h}, \quad \delta_x^2 u_j^n = \frac{u_{j+1}^n - 2u_j^n + u_{j-1}^n}{h^2}.$$

- Energy conservative finite difference (CNFD) method

$$\varepsilon^2 \delta_t^2 u_j^n - \frac{1}{2}\delta_x^2 \left(u_j^{n+1} + u_j^{n-1}\right) + \frac{1}{2\varepsilon^2}\left(u_j^{n+1} + u_j^{n-1}\right) + G\left(u_j^{n+1}, u_j^{n-1}\right) = 0;$$

$$G(v,w) = \int_0^1 f\left(\theta v + (1-\theta)w\right)\, d\theta = \frac{F(v) - F(w)}{2(v-w)}, \quad \forall\, v, w \in \mathbb{R},$$

- Semi-implicit finite difference (SIFD) method

$$\varepsilon^2 \delta_t^2 u_j^n - \frac{1}{2}\delta_x^2 \left(u_j^{n+1} + u_j^{n-1}\right) + \frac{1}{2\varepsilon^2}\left(u_j^{n+1} + u_j^{n-1}\right) + f(u_j^n) = 0;$$

Properties of FDTD methods

- Time symmetric, unchanged if $n+1 \leftrightarrow n-1 \quad \& \quad \tau \leftrightarrow -\tau$
- Stability
  - CNFD is unconditionally stable
  - SIFD is unconditionally stable when it is wave type
- Energy conservation: CNFD conserves energy vs SIFD not
- Computational cost
  - CNFD needs solve a nonlinear coupled system per time step!!
  - SIFD needs solve a linear coupled system via fast solver!!
- Resolution in nonrelativistic limit regime

$$h = O(\varepsilon^{?}) \quad \& \quad \tau = O(\varepsilon^{?}), \quad 0 < \varepsilon \ll 1$$

Error estimates for FDTD methods

- Define `error' function $e_j^n = u(x_j, t^n) - u_j^n, \quad j = 0,1,\ldots,M, \quad n \geq 0$
- Assumption
  - For the solution of the nonlinear KG equation

$$\text{(A)} \quad u \in C^4([0,T]; W^{1,\infty}) \cap C^3([0,T]; W^{2,\infty}) \cap C^2([0,T]; W^{3,\infty}) \cap C([0,T]; W_p^{5,\infty}), \quad \left\| \frac{\partial^{r+s}}{\partial t^r \partial x^s} u(x,t) \right\|_{L^\infty(\Omega_T)} \lesssim \frac{1}{\varepsilon^{2r}}, \quad 0 \leq r \leq 4 \ \& \ 0 \leq r+s \leq 5$$

  - For the nonlinear function *f*

$$\text{(B1)} \quad f \in C^2(\mathbb{R}) \qquad \text{(B2)} \quad f \in C^3(\mathbb{R})$$

Error estimates for FDTD methods

- For CNFD (Bao& Dong, Numer. Math., 11')

Theorem 2 *Assume $\tau \lesssim h$ and under assumptions (A) and (B2), there exist constants $\tau_0 > 0$ and $h_0 > 0$ sufficiently small and independent of ε such that, for any $0 < \varepsilon \leq 1$, when $0 < \tau \leq \tau_0$ and $0 < h \leq h_0$, we have the following error estimate for the method Impt-EC-FD (2.2) with (2.7) and (2.8)*

$$\|e^n\|_{l^2} + \|\delta_x^+ e^n\|_{l^2} \lesssim h^2 + \frac{\tau^2}{\varepsilon^6}, \quad 0 \leq n \leq \frac{T}{\tau}. \tag{2.25}$$

- For SIFD (Bao& Dong, Numer. Math., 11')

Theorem 5 *Assume $\tau \lesssim h$ and under assumptions (A) and (B1), there exist constants $\tau_0 > 0$ and $h_0 > 0$ sufficiently small and independent of ε such that, for any $0 < \varepsilon \leq 1$, when $0 < \tau \leq \tau_0$ and $0 < h \leq h_0$, we have the following error estimate for the method SImpt-FD (2.4) with (2.7) and (2.8)*

$$\|e^n\|_{l^2} + \|\delta_x^+ e^n\|_{l^2} \lesssim h^2 + \frac{\tau^2}{\varepsilon^6}, \quad 0 \leq n \leq \frac{T}{\tau}. \tag{2.29}$$

Error estimates for FDTD methods

- Ingredients of the proof
  - Energy method
  - Inverse inequality & either mathematical induction or boots-trap technique to bound numerical solution u^n
  - Asymptotic behavior of the exact solution u
  - Valid in 2D & 3D
- Convergence rates for fixed ε : 2nd order in space & time
- Resolution in nonrelativistic limit regime

$$h = O(1), \quad \tau = O(\varepsilon^3), \quad 0 < \varepsilon \ll 1$$

Numerical results for CNFD

ε-Scalability	τ =1.00E–3	τ =5.00E–4	τ =2.50E–4	τ =1.25E–4	τ =6.25E–5
$\varepsilon = 0.1,\ \tau$	4.6484E–2	1.1063E–2	2.7344E–3	6.8472E–4	1.7533E–4
$\varepsilon/2,\ \tau/2^3$	4.9171E–2	1.2912E–2	3.2712E–3	8.2486E–4	2.1197E–4
$\varepsilon/4,\ \tau/4^3$	4.6831E–2	1.1162E–2	2.7597E–3	6.9083E–4	1.7681E–4
$\varepsilon/8,\ \tau/8^3$	3.6900E–2	9.6406E–3	2.4426E–3	6.1784E–4	1.6129E–4
$\varepsilon = 0.1,\ \tau$	7.5093E–2	1.8650E–2	4.6877E–3	1.2087E–3	2.8179E–4
$\varepsilon/2,\ \tau/2^3$	9.2221E–2	2.3739E–2	6.0030E–3	1.5347E–3	3.8945E–4
$\varepsilon/4,\ \tau/4^3$	7.0780E–2	1.7431E–2	4.3724E–3	1.1292E–3	2.9825E–4
$\varepsilon/8,\ \tau/8^3$	7.7202E–2	1.9840E–2	5.0233E–3	1.2937E–3	3.1687E–4
$\varepsilon = 0.1,\ \tau$	2.9725E–2	7.7927E–3	1.8177E–3	4.5897E–4	1.2252E–4
$\varepsilon/2,\ \tau/2^3$	4.3783E–2	1.1543E–2	2.9273E–3	7.3938E–4	1.9031E–4
$\varepsilon/4,\ \tau/4^3$	2.8754E–2	6.9944E–3	1.7321E–3	4.2850E–4	1.1127E–4
$\varepsilon/8,\ \tau/8^3$	2.9213E–2	7.9193E–3	2.0227E–3	5.1313E–4	1.3350E–4

l^2 – error (top 4 rows); semi-H^1-error (middle 4 rows); l^∞-error (bottom 4 rows)

Exponential wave integrator (EWI) spectral method

- Apply sine spectral method for spatial derivatives

$$\varepsilon^2 \partial_{tt} u_M(x,t) - \Delta u_M + \frac{1}{\varepsilon^2} u_M + P_M f(u_M) = 0, \quad a \le x \le b, \quad t \ge 0.$$

  – with

$$u_M(x,t) = \sum_{l=1}^{M-1} \widehat{u}_l(t) \sin(\mu_l(x-a)), \quad a \le x \le b, \quad \mu_l = \frac{l\pi}{b-a}, \quad l = 1,2,\ldots,M-1$$

- Take sine transform, we get ODEs for *l=1,2,…,M-1*

$$\varepsilon^2 \frac{d^2}{dt^2} \widehat{u}_l(t) + \frac{1+\varepsilon^2 \mu_l^2}{\varepsilon^2} \widehat{u}_l(t) + \widehat{f(u_M)}_l(t) = 0,$$

Exponential wave integrator (EWI) for 2nd ODE

- Second-order wave-type ODE

$$y''(t) + \lambda^2 y(t) + f(y) = 0, \quad t > 0,$$

$$y(0) = y_0, \quad y'(0) = y_1 \qquad \text{with} \quad \lambda > 0 \;\&\; f(0) = 0$$

- Notations $\tau = \Delta t > 0, \quad t_n = n\tau, \quad n = 0,1,2,\ldots \quad y^n \approx y(t_n)$
- Analytical solution near $t = t_n$

$$y(t_n + s) = y(t_n)\cos(\omega s) + y'(t_n)\frac{\sin(\omega s)}{\omega} - \frac{1}{\omega}\int_0^s g(y(t_n + w))\sin(\omega(s - w))dw$$

$$\omega = \sqrt{\lambda^2 + a}, \quad a = f'(0), \quad g(y) = f(y) - a\,y, \quad s \in \mathbb{R}$$

Exponential wave integrator (EWI) for 2nd ODE

- Take $s=\tau$ or $s=-\tau$

$$y(t_n+\tau)=y(t_n)\cos(\omega\tau)+y'(t_n)\frac{\sin(\omega\tau)}{\omega}-\frac{1}{\omega}\int_0^{\tau}g(y(t_n+w))\sin(\omega(\tau-w))dw$$

$$y(t_n-\tau)=y(t_n)\cos(-\omega\tau)+y'(t_n)\frac{\sin(-\omega\tau)}{\omega}-\frac{1}{\omega}\int_0^{-\tau}g(y(t_n+w))\sin(\omega(-\tau-w))dw$$

$$=y(t_n)\cos(\omega\tau)-y'(t_n)\frac{\sin(\omega\tau)}{\omega}-\frac{1}{\omega}\int_0^{\tau}g(y(t_n-w))\sin(\omega(\tau-w))dw$$

- Sum together

$$y(t_{n+1})=2y(t_n)\cos(\omega\tau)-y(t_{n-1})-\frac{1}{\omega}\int_0^{\tau}[g(y(t_n+w))+g(y(t_n-w))]\sin(\omega(\tau-w))dw$$

Approximate integral via quadratures

– Exponential wave integrator (EWI) in Gautschi-type :
  Gautschi, 68'; Hochbruck & Lubich, 99'; Hochbruck & Ostermann, 00'; Hairer, Lubich & Wanner, 02'; Grim, 05' & 06'; ….

$$y^{n+1} = 2\cos(\omega\tau)y^n - y^{n-1} - 2\frac{1-\cos(\omega\tau)}{\omega^2}g(y^n), \quad n \geq 1$$

$$y^0 = y_0, \quad y^1 = y_0\cos(\omega\tau) + y_1\frac{\sin(\omega\tau)}{\omega} - \frac{1-\cos(\omega\tau)}{\omega^2}g(y_0)$$

– Via trapezoidal rule: Deuflhart, 79', ……

$$y^{n+1} = 2\cos(\omega\tau)y^n - y^{n-1} - \frac{\sin(\omega\tau)}{\omega}g(y^n), \quad n \geq 1$$

$$y^0 = y_0, \quad y^1 = y_0\cos(\omega\tau) + y_1\frac{\sin(\omega\tau)}{\omega} - \frac{\sin(\omega\tau)}{2\omega}g(y_0)$$

Approximate first-order derivative

- Take derivative & subtract: Hochbruck & Lubich, Numer. Math., 99'

$$y'(t_n+\tau)-y'(t_n-\tau)=-2\sin(\omega\tau)y(t_n)$$

$$-\int_0^{\tau}[g(y(t_n+w))+g(y(t_n-w))]\cos(\omega(\tau-w))dw$$

  – Approximate by Gautschi-type rule

$$y'(t_{n+1})\approx y'(t_{n-1})-2\sin(\omega\tau)y^n-\frac{2\sin(\omega\tau)}{\omega}g(y^n),\quad n\ge 1$$

Properties of EWI in Gautschi-type

- Explicit
- Unconditionally stable for linear & Conditionally stable for nonlinear $\lambda\tau \le C$
- Give exact results when $f(y) = \alpha y$ is linear!!!
- Error estimate $\max_{0\le n\le T/\tau} |y(t_n) - y^n| \le C\tau^2$
- Essentially conserves the energy when

$$\lambda \gg 1 \quad \& \quad \tau\lambda \approx 1$$

- This is a very good method to discretize the ODEs for KG equation after sine spectral discretization in space!!

EWI-SP method for KG equation

- EWI spectral (EWI-SP) method (Bao & Dong, Numer. Math. 11)
  - Spectral method for spatial derivatives
  - Exponential wave integrators (EWI) for time derivatives
- Properties
  - Explicit –no need to solve any linear system
  - Easy to extend to 2D or 3D
  - Conditionally stable with $\tau\,\varepsilon^2 \le C$, but it can be unconditionally stable by adding a proper linear stabilizing term!!
  - Give exact solutions for linear case, i.e. $f(u)=a\,u$

Error Estimate of EWI-SP (Bao & Dong, Numer. Math., 11')

Theorem 9 *Let $u_M^n(x)$ be the approximation obtained from the Gautschi-FP method* (3.10) *with* (3.16). *Assume $\tau \lesssim \varepsilon^2\sqrt{C_d(h)}$ and $f(\cdot) \in C^3(\mathbb{R})$, under the assumption (C), there exist $h_0 > 0$ and $\tau_0 > 0$ sufficiently small and independent of ε such that, for any $0 < \varepsilon \le 1$, when $0 < h \le h_0$ and $0 < \tau \le \tau_0$ and under the condition* (3.31), *we have the following error estimate*

$$\|u(x,t_n) - u_M^n(x)\|_{L^2} \lesssim \frac{\tau^2}{\varepsilon^4} + h^{m_0}, \quad \|u_M^n(x)\|_{L^\infty} \le 1 + M_1, \tag{3.32a}$$

$$\|\nabla[u(x,t_n) - u_M^n(x)]\|_{L^2} \lesssim \frac{\tau^2}{\varepsilon^4} + h^{m_0-1}, \quad 0 \le n \le \frac{T}{\tau}. \tag{3.32b}$$

– Resolution in nonrelativistic limit regime
  - Linear case $h = O(1) \quad \tau = O(1)$
  - Nonlinear case $h = O(1) \quad \tau = O(\varepsilon^2)$

Numerical results of EWI-SP

ε-Scalability	τ =5.00E–3	τ =2.50E–3	τ =1.25E–3	τ =6.25E–4	τ =3.125E–4
$\varepsilon = 0.1,\ \tau$	2.4902E–3	6.1124E–4	1.5208E–4	3.7957E–5	9.4697E–6
$\varepsilon/2,\ \tau/2^2$	3.1009E–3	7.6212E–4	1.8973E–4	4.7384E–5	1.1845E–5
$\varepsilon/4,\ \tau/4^2$	2.5929E–3	6.3666E–4	1.5846E–4	3.9564E–5	9.8826E–6
$\varepsilon/8,\ \tau/8^2$	2.5965E–3	6.3757E–4	1.5862E–4	3.9563E–5	9.8072E–6
$\varepsilon = 0.1,\ \tau$	6.0409E–3	1.4857E–3	3.6976E–4	9.2230E–5	2.2948E–5
$\varepsilon/2,\ \tau/2^2$	8.6467E–3	2.1232E–3	5.2845E–4	1.3197E–4	3.2989E–5
$\varepsilon/4,\ \tau/4^2$	6.3003E–3	1.5450E–3	3.8453E–4	9.6000E–5	2.3974E–5
$\varepsilon/8,\ \tau/8^2$	7.9670E–3	1.9557E–3	4.8650E–4	1.2126E–4	3.0079E–5
$\varepsilon = 0.1,\ \tau$	1.9268E–3	4.7365E–4	1.1786E–4	2.9447E–5	7.3746E–6
$\varepsilon/2,\ \tau/2^2$	2.4770E–3	6.0895E–4	1.5161E–4	3.7863E–5	9.4650E–6
$\varepsilon/4,\ \tau/4^2$	1.9261E–3	4.7358E–4	1.1797E–4	2.9445E–5	7.3572E–6
$\varepsilon/8,\ \tau/8^2$	1.9103E–3	4.6947E–4	1.1682E–4	2.9120E–5	7.2235E–6

l^2 – error (top 4 rows); semi-H^1-error (middle 4 rows); l^∞-error (bottom 4 rows)

NLS equation with wave operator (NLSW)

$$\begin{cases} i\partial_t u^\varepsilon(\mathbf{x},t) - \varepsilon^2 \partial_{tt} u^\varepsilon(\mathbf{x},t) + \nabla^2 u^\varepsilon(\mathbf{x},t) + f(|u^\varepsilon|^2) u^\varepsilon(\mathbf{x},t) = 0, & \mathbf{x} \in \mathbb{R}^d, \ t > 0, \\ u^\varepsilon(\mathbf{x},0) = u_0(\mathbf{x}), \qquad \partial_t u^\varepsilon(\mathbf{x},0) = u_1^\varepsilon(\mathbf{x}), & \mathbf{x} \in \mathbb{R}^d, \end{cases}$$

- Arising in many applications
  - Nonrelativistic limits of nonlinear KG equation: Masmoudi, Nakanishi, Math Ann., 02'; Machihara, Nakanishi & Ozawa, Math. Ann., 02'; ….
  - Langmuir wave envelope approximation in plasma: Berge & Colin, 95'; Colin & Fabrie, 98'; ….
  - Modulated pulse approximation of sine-Gordon equation for light bullets: Xin, 00'; Bao, Dong & Xin, 10'; ….

Properties of NLSW

- Time symmetric
- Mass conservation

$$N^\varepsilon(t) := \int_{\mathbb{R}^d} |u^\varepsilon(\mathbf{x},t)|^2\, d\mathbf{x} - 2\varepsilon^2 \int_{\mathbb{R}^d} \mathrm{Im}\left(\overline{u^\varepsilon(\mathbf{x},t)}\partial_t u^\varepsilon(\mathbf{x},t)\right)\, d\mathbf{x} \equiv N^\varepsilon(0), \quad t \geq 0,$$

- Energy conservation $F(s) = \int_0^s f(\rho)\, d\rho, \qquad s \geq 0.$

$$E^\varepsilon(t) := \int_{\mathbb{R}^d} \left[\varepsilon^2|\partial_t u^\varepsilon(\mathbf{x},t)|^2 + |\nabla u^\varepsilon(\mathbf{x},t)|^2 - F(|u^\varepsilon(\mathbf{x},t)|^2)\right]\, d\mathbf{x} \equiv E^\varepsilon(0), \quad t \geq 0,$$

- Limits when $\varepsilon \to 0$:

$$\begin{cases} i\partial_t u(\mathbf{x},t) + \nabla^2 u(\mathbf{x},t) + f(|u|^2)u(\mathbf{x},t) = 0, & \mathbf{x} \in \mathbb{R}^d,\ t > 0, \\ u(\mathbf{x},0) = u_0(\mathbf{x}), & \mathbf{x} \in \mathbb{R}^d, \end{cases}$$

Properties of NLSW

$$\|u^\varepsilon - u\|_{L^\infty([0,T];H^2)} \le C\varepsilon^2.$$

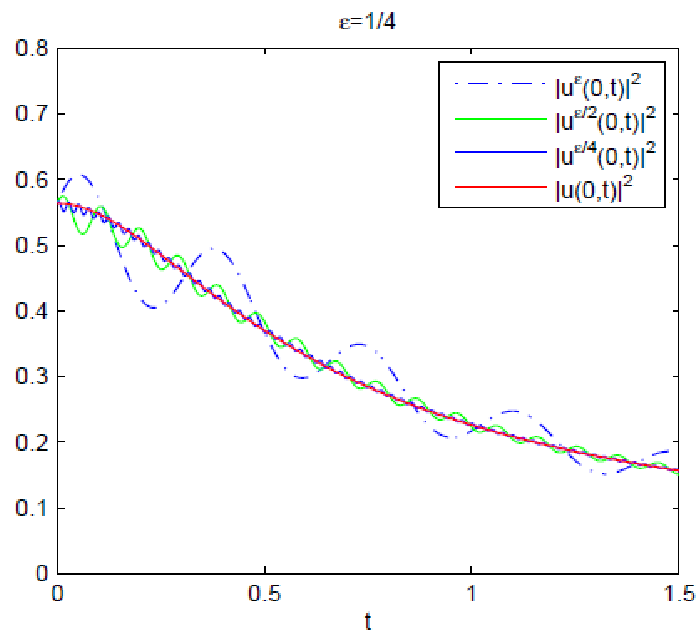
- Convergence rate: Berge & Colin, 95
- Initial data $u_1^\varepsilon(\mathbf{x}) = i\,(\nabla^2 u_0(\mathbf{x}) + f(|u_0(\mathbf{x})|^2)u_0(\mathbf{x})) + \varepsilon^\alpha w(\mathbf{x}), \quad \mathbf{x} \in \mathbb{R}^d, \qquad \alpha \ge 0,$
  - Well-prepared $\alpha \ge 2$
  - ill-prepared $0 \le \alpha < 2$
- Plane wave solution $f(\rho) = -\lambda\,\rho^p$

$$u^\varepsilon(\vec{x},t) = Ae^{i(\vec{k}\cdot\vec{x}+\omega t)} \text{ with } \omega_\pm = \frac{1 \pm \sqrt{1+4\varepsilon^2(|\vec{k}|^2 + \lambda A^{2p})}}{2\varepsilon^2} = O(1) \quad \& \quad O\left(\frac{1}{\varepsilon^2}\right)$$

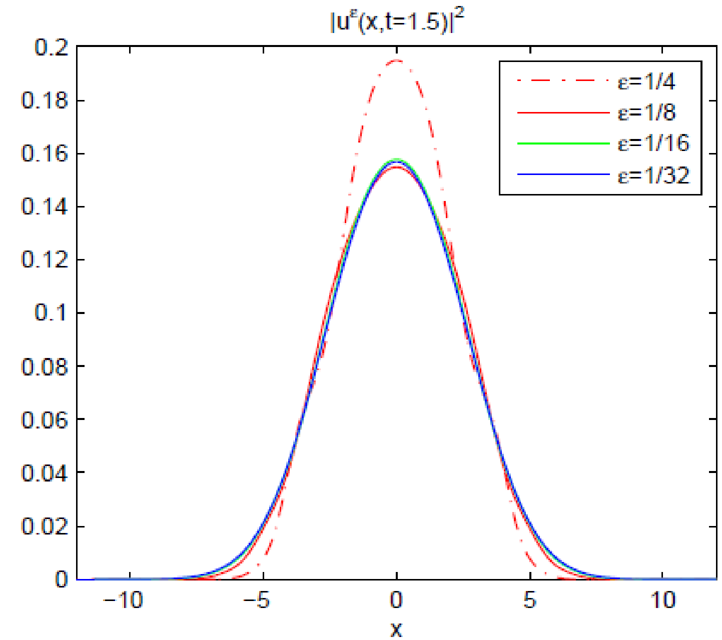
- Fast-slow wave decomposition

$$u^\varepsilon(\mathbf{x},t) = u(\mathbf{x},t) + \varepsilon^2\{\text{terms without oscillation}\}$$
$$+\varepsilon^{2+\min\{\alpha,2\}}v(\mathbf{x},t/\varepsilon^2) + \text{higher order terms with oscillation},$$

Oscillatory structure of NLSW $0 < \varepsilon \ll 1$



Time dynamics for ε



Spatial dynamics for ε

- **Observations:** Solution propagates waves with wavelength
  - In space at *O(1)*; in time at $O(\varepsilon^2)$ with amplitude $O(\varepsilon^4)$ for well-prepared initial data & $O(\varepsilon^{2+\alpha})$ for ill-prepared initial data

FDTD methods for NLSW

- NLSW in 1D

$$\begin{cases} i\partial_t u^\varepsilon(x,t) - \varepsilon^2\partial_{tt}u^\varepsilon(x,t) + \partial_{xx}u^\varepsilon(x,t) + f(|u^\varepsilon|^2)u^\varepsilon(x,t) = 0, & x \in \Omega = (a,b) \subset \mathbb{R},\ t > 0, \\ u^\varepsilon(x,0) = u_0(x), \qquad \partial_t u^\varepsilon(x,0) = u_1^\varepsilon(x), & x \in \overline{\Omega} = [a,b], \\ u^\varepsilon(x,t)\big|_{\partial\Omega} = 0, & t > 0. \end{cases}$$

- Crank-Nicolson finite difference (CNFD) method

$$(i\delta_t - \varepsilon^2\delta_t^2)u_j^{\varepsilon,n} = -\frac{1}{2}\left[\delta_x^2 u_j^{\varepsilon,n+1} + \delta_x^2 u_j^{\varepsilon,n-1}\right] - G(u_j^{\varepsilon,n+1}, u_j^{\varepsilon,n-1}), \quad j \in \mathcal{T}_M,\ n \geq 1,$$

$$G(z_1,z_2) := \int_0^1 f(\theta|z_1|^2 + (1-\theta)|z_2|^2)\,d\theta \cdot \frac{z_1+z_2}{2} = \frac{F(|z_1|^2) - F(|z_2|^2)}{|z_1|^2 - |z_2|^2} \cdot \frac{z_1+z_2}{2}.$$

- Semi-implicit finite difference (SIFD) method

$$i\delta_t u_j^{\varepsilon,n} = \varepsilon^2\delta_t^2 u_j^{\varepsilon,n} - \frac{1}{2}\left[\delta_x^2 u_j^{\varepsilon,n+1} + \delta_x^2 u_j^{\varepsilon,n-1}\right] - f(|u_j^{\varepsilon,n}|^2)u_j^{\varepsilon,n}, \quad j \in \mathcal{T}_M,\ n \geq 1.$$

Error estimates

- Define `error' function $e_j^{\varepsilon,n} = u^\varepsilon(x_j, t_n) - u_j^{\varepsilon,n}, \quad j \in \mathcal{T}_M,$
- For CNFD (Bao & Cai, SINUM, 11') $\alpha^* = \min\{\alpha, 2\}.$

THEOREM 2.1. *(Convergence of CNFD) Assume $f(s) \in C^3([0, +\infty))$, under assumptions (A) and (B), there exist $h_0 > 0$ and $\tau_0 > 0$ sufficiently small, when $0 < h \le h_0$ and $0 < \tau \le \tau_0$, CNFD method (2.6) with (2.7) and (2.13) admits a solution such that the following optimal error estimates hold*

$$\|e^{\varepsilon,n}\|_2 + \|\delta_x^+ e^{\varepsilon,n}\|_2 \lesssim h^2 + \frac{\tau^2}{\varepsilon^{4-\alpha^*}}, \quad 0 \le n \le \frac{T}{\tau}, \tag{2.19}$$

$$\|e^{\varepsilon,n}\|_2 + \|\delta_x^+ e^{\varepsilon,n}\|_2 \lesssim h^2 + \tau^2 + \varepsilon^2, \quad 0 \le n \le \frac{T}{\tau}. \tag{2.20}$$

Thus, by taking the minimum, we have the ε-independent convergence rate as

$$\|e^{\varepsilon,n}\|_2 + \|\delta_x^+ e^{\varepsilon,n}\|_2 \lesssim h^2 + \tau^{4/(6-\alpha^*)}, \quad 0 \le n \le \frac{T}{\tau}. \tag{2.21}$$

Error estimates

- For SIFD (Bao & Cai, SINUM, 11')

THEOREM 2.2. *(Convergence of SIFD) Assume $f(s) \in C^2([0,+\infty))$, under assumptions (A) and (B), there exists $h_0 > 0$ and $\tau_0 > 0$ sufficiently small, when $0 < h \le h_0$ and $0 < \tau \le \tau_0$, the SIFD discretization (2.6) with (2.7) and (2.13) admits a unique solution and the following optimal error estimates hold,*

$$\|e^{\varepsilon,n}\|_2 + \|\delta_x^+ e^{\varepsilon,n}\|_2 \lesssim h^2 + \frac{\tau^2}{\varepsilon^{4-\alpha^*}}, \qquad 0 \le n \le \frac{T}{\tau}, \tag{2.22}$$

$$\|e^{\varepsilon,n}\|_2 + \|\delta_x^+ e^{\varepsilon,n}\|_2 \lesssim h^2 + \tau^2 + \varepsilon^2, \qquad 0 \le n \le \frac{T}{\tau}. \tag{2.23}$$

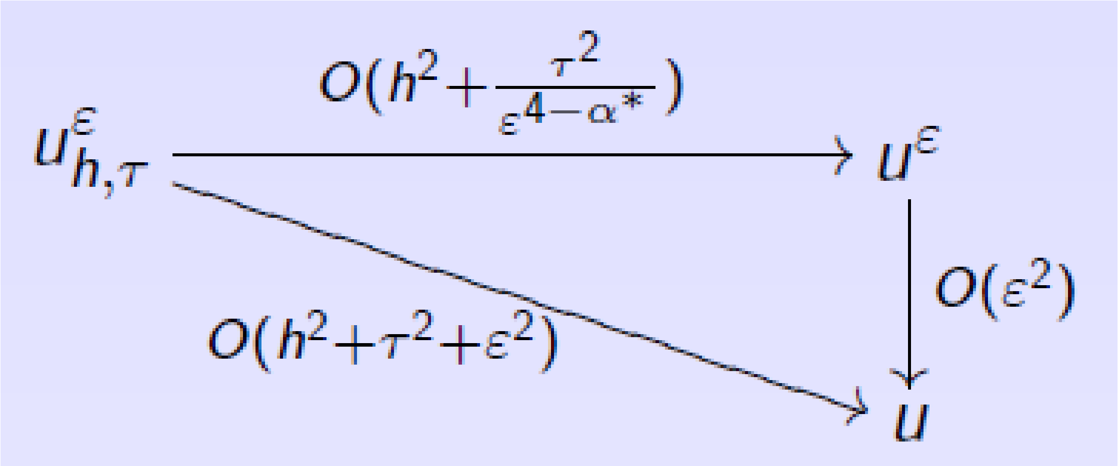
Thus, by taking the minimum, we have the ε-independent convergence rate as

$$\|e^{\varepsilon,n}\|_2 + \|\delta_x^+ e^{\varepsilon,n}\|_2 \lesssim h^2 + \tau^{4/(6-\alpha^*)}, \quad 0 \le n \le \frac{T}{\tau}. \tag{2.24}$$

- Uniform for $0 \le \varepsilon \le 1$; optimal when $\varepsilon = O(1)$ or $\varepsilon \le \tau$

Ingredients of the proof

- Energy method
- Inverse inequality & either mathematical induction or bots-trap technique to bound numerical solution u^n
- Asymptotic behavior of the exact solution u
- Use the limit equation: Jin, SISC, 99'; Degond, Liu & Vignal, 08', ….



Numerical results for SIFD

$\alpha = 2$	$h = 1/2$	$h = 1/2^2$	$h = 1/2^3$	$h = 1/2^4$	$h = 1/2^5$	$h = 1/2^6$	$h = 1/2^7$
$\varepsilon = 1/2^2$	1.51E-1	4.05E-2	1.03E-2	2.57E-3	6.45E-4	1.60E-4	3.90E-5
		1.90	1.98	2.00	1.99	2.01	2.04
$\varepsilon = 1/2^3$	1.94E-1	5.35E-2	1.36E-2	3.41E-3	8.51E-4	2.10E-4	4.92E-5
		1.89	1.98	2.00	2.00	2.02	2.09
$\varepsilon = 1/2^4$	2.15E-1	6.05E-2	1.55E-2	3.88E-3	9.67E-4	2.39E-4	5.68E-5
		1.83	1.96	2.00	2.00	2.02	2.07
$\varepsilon = 1/2^5$	2.22E-1	6.29E-2	1.61E-2	4.04E-3	1.01E-3	2.49E-4	5.93E-5
		1.82	1.97	1.99	2.00	2.02	2.07
$\varepsilon = 1/2^6$	2.23E-1	6.36E-2	1.63E-2	4.08E-3	1.02E-3	2.52E-4	6.00E-5
		1.81	1.96	2.00	2.00	2.02	2.07
$\varepsilon = 1/2^7$	2.24E-1	6.37E-2	1.63E-2	4.10E-3	1.02E-3	2.52E-4	6.01E-5
		1.81	1.97	1.99	2.01	2.02	2.07
$\varepsilon = 1/2^{10}$	2.24E-1	6.38E-2	1.63E-2	4.10E-3	1.02E-3	2.53E-4	6.02E-5
		1.81	1.97	1.99	2.01	2.01	2.07
$\varepsilon = 1/2^{20}$	2.24E-1	6.38E-2	1.63E-2	4.10E-3	1.02E-3	2.53E-4	6.02E-5
		1.81	1.97	1.99	2.01	2.01	2.07

TABLE 4.1

Spatial error analysis for SIFD scheme (2.6) with different ε *and* h *for Case I, i.e.* $\alpha = 2$, *with norm* $\|e\|_{H^1} = \|e\|_2 + \|\delta_x^+ e\|_2$. *The convergence rate is calculated as* $\log_2(\|e(2h)\|_{H^1}/\|e(h)\|_{H^1})$.

Numerical results for SIFD

$\alpha = 2$	$\tau = 0.1$	$\tau = \frac{0.1}{2}$	$\tau = \frac{0.1}{2^2}$	$\tau = \frac{0.1}{2^3}$	$\tau = \frac{0.1}{2^4}$	$\tau = \frac{0.1}{2^5}$	$\tau = \frac{0.1}{2^6}$	$\tau = \frac{0.1}{2^7}$	$\tau = \frac{0.1}{2^8}$
$\varepsilon = \frac{1}{2^2}$	1.10E-1	4.75E-2	1.49E-2	3.86E-3	9.70E-4	2.43E-4	6.10E-5	1.56E-5	4.47E-6
		1.21	1.67	1.95	1.99	2.00	1.99	1.97	1.80
$\varepsilon = \frac{1}{2^3}$	1.60E-1	5.06E-2	1.46E-2	5.45E-3	3.07E-3	8.27E-4	2.08E-4	5.21E-5	1.32E-5
		1.66	1.79	1.42	0.83	1.89	1.99	2.00	1.98
$\varepsilon = \frac{1}{2^4}$	1.98E-1	6.02E-2	1.85E-2	4.78E-3	1.25E-3	4.14E-4	3.74E-4	1.81E-4	4.70E-5
		1.72	1.70	1.95	1.94	1.59	0.15	1.05	1.95
$\varepsilon = \frac{1}{2^5}$	1.90E-1	7.30E-2	1.92E-2	5.00E-3	1.39E-3	3.49E-4	8.75E-5	2.74E-5	1.65E-5
		1.38	1.93	1.94	1.85	1.99	2.00	1.68	0.73
$\varepsilon = \frac{1}{2^6}$	1.89E-1	6.87E-2	2.18E-2	5.28E-3	1.32E-3	3.34E-4	9.09E-5	2.17E-5	5.72E-6
		1.46	1.66	2.06	2.00	1.98	1.88	2.07	1.92
$\varepsilon = \frac{1}{2^7}$	1.89E-1	6.79E-2	2.06E-2	5.81E-3	1.36E-3	3.38E-4	8.26E-5	2.20E-5	5.54E-6
		1.48	1.72	1.83	2.09	2.01	2.03	1.91	1.98
$\varepsilon = \frac{1}{2^{10}}$	1.89E-1	6.76E-2	2.01E-2	5.37E-3	1.37E-3	3.50E-4	9.27E-5	2.14E-5	5.31E-6
		1.48	1.75	1.90	1.97	1.97	1.92	2.11	2.01
$\varepsilon = \frac{1}{2^{20}}$	1.89E-1	6.76E-2	2.01E-2	5.37E-3	1.36E-3	3.42E-4	8.56E-5	2.14E-5	5.35E-6
		1.48	1.75	1.90	1.98	1.99	2.00	2.00	2.00

TABLE 4.2

Temporal error analysis for SIFD scheme (2.6) with different ε and τ for Case I, i.e. $\alpha = 2$, with norm $\|e\|_{H^1}$.

Numerical results for SIFD

$\alpha=2$	$\varepsilon=1$ $\tau=0.2$	$\varepsilon=1/2$ $\tau=0.2/2^2$	$\varepsilon=1/2^2$ $\tau=0.2/2^4$	$\varepsilon=1/2^3$ $\tau=0.2/2^6$	$\varepsilon=1/2^4$ $\tau=0.2/2^8$
$\|e\|_{H^1}$	1.07E-1	1.77E-2 1.30	3.86E-3 1.10	8.27E-4 1.11	1.81E-4 1.10
$\alpha=0$	$\varepsilon=1/2^2$ $\tau=0.1$	$\varepsilon=1/2^3$ $\tau=0.1/2^3$	$\varepsilon=1/2^4$ $\tau=0.1/2^6$	$\varepsilon=1/2^5$ $\tau=0.1/2^9$	$\varepsilon=1/2^6$ $\tau=0.1/2^{12}$
$\|e\|_{H^1}$	2.91E-1	7.35E-2 1.99/3	1.92E-2 1.94/3	4.83E-3 1.99/3	1.21E-3 2.00/3

TABLE 4.3

Degeneracy of convergence rates for SIFD with $h=1/512$, Case I and Case II. The convergence rate is calculated as $\log_2(e(2^2\tau,2\varepsilon)/e(\tau,\varepsilon))/2$ for $\alpha=2$ (Case I), and $\log_2(e(2^3\tau,2\varepsilon)/e(\tau,\varepsilon))/3$ for $\alpha=0$ (Case II).

- Observations
  - 2nd order in space & uniform for $0 \le \varepsilon \le 1$
  - CNFD performs the same

EWI-SP method for NLSW

- EWI spectral (EWI-SP) method (Bao & Cai, SINUM, 13')
  - Spectral method for spatial derivatives
  - Exponential wave integrators (EWI) for time derivatives
- Properties
  - Explicit –no need to solve any linear system
  - Easy to extend to 2D or 3D
  - Unconditionally stable
  - Give exact solutions for linear case, i.e. $f(v)=a\,v$

Error Estimates of EWI-SP (Bao & Cai, SINUM, 13')

- For well-prepared initial data (Bao & Cai, SINUM, 13')

THEOREM 2.1. *(Well-prepared initial data) Let $\psi^n \in Y_M$ and $\psi_I^n(x) = I_M(\psi^n)$ $(n \geq 0)$ be the numerical approximation obtained from (2.27)-(2.28). Assume $f(s) \in C^k([0,+\infty))$ $(k \geq 3)$, under assumptions (A) and (B), there exist constants $0 < \tau_0, h_0 \leq 1$ independent of ε, if $h \leq h_0$ and $\tau \leq \tau_0$, we have for $\alpha \geq 2$, i.e. the well-prepared initial data case,*

$$\begin{aligned} &\|\psi(x,t_n) - \psi_I^n(x)\|_{L^2} \lesssim h^m + \tau^2, \qquad \|\psi^n\|_{l^\infty} \leq M_1 + 1, \\ &\|\nabla(\psi(x,t_n) - \psi_I^n(x))\|_{L^2} \lesssim h^{m-1} + \tau^2, \qquad 0 \leq n \leq \frac{T}{\tau}, \end{aligned} \tag{2.34}$$

- Observations
  - Spectral accuracy in space
  - 2nd order accuracy in time: uniform & optimal for $0 \leq \varepsilon \leq 1$

For ill-prepared initial data (Bao & Cai, SINUM, 13')

THEOREM 2.2. *(Ill-prepared initial data) Under the same condition of Theorem 2.1, we have for* $\alpha \in [0,2]$*, i.e. the ill-prepared initial data case,*

$$\|\psi(x,t_n) - \psi_I^n(x)\|_{L^2} \lesssim h^m + \frac{\tau^2}{\varepsilon^{2-\alpha}}, \quad \|\nabla(\psi(x,t_n) - \psi_I^n(x))\|_{L^2} \lesssim h^{m-1} + \frac{\tau^2}{\varepsilon^{2-\alpha}}, \tag{2.35}$$

$$\|\psi(x,t_n) - \psi_I^n(x)\|_{L^2} \lesssim h^m + \tau^2 + \varepsilon^2, \quad \|\nabla(\psi(x,t_n) - \psi_I^n(x))\|_{L^2} \lesssim h^{m-1} + \tau^2 + \varepsilon^2, \tag{2.36}$$

$$\|\psi^n\|_{l^\infty} \le M_1 + 1, \quad 0 \le n \le \frac{T}{\tau}, \tag{2.37}$$

where $m = \min\{m_0, k\}$ *and* M_1 *defined in (2.33). Thus, by taking the minimum of* $\varepsilon^2 + \frac{\tau^2}{\varepsilon^{2-\alpha}}$*, we could obtain uniform error bounds as*

$$\|\psi(x,t_n) - \psi_I^n(x)\|_{L^2} \le h^m + \tau^{4/(4-\alpha)}, \quad \|\nabla[\psi(x,t_n) - \psi_I^n(x)]\|_{L^2} \lesssim h^{m-1} + \tau^{4/(4-\alpha)}, \quad 0 \le n \le \frac{T}{\tau}.$$

Observations

- Spectral accuracy in space
- Uniform convergence in time: optimal for $\varepsilon = O(1)$ or $\varepsilon \le \tau$

Numerical results for EWI-SP method

	$\alpha = 0$				$\alpha = 2$			
	$h = 2$	$h = 1$	$h = 1/2$	$h = 1/4$	$h = 2$	$h = 1$	$h = 1/2$	$h = 1/4$
$\varepsilon = 1/2$	1.03E00	9.59E-2	6.76E-4	4.15E-8	9.45E-1	8.85E-2	6.39E-4	3.90E-8
$\varepsilon = 1/2^2$	8.85E-1	6.85E-2	2.36E-4	2.47E-9	8.55E-1	6.96E-2	2.45E-4	2.43E-9
$\varepsilon = 1/2^3$	8.62E-1	6.71E-2	1.57E-4	1.30E-10	8.55E-1	6.72E-2	1.57E-4	1.39E-10
$\varepsilon = 1/2^4$	8.57E-1	6.71E-2	1.40E-4	7.00E-11	8.60E-1	6.72E-2	1.40E-4	6.99E-11
$\varepsilon = 1/2^5$	8.61E-1	6.73E-2	1.37E-4	5.44E-11	8.62E-1	6.72E-2	1.37E-4	5.45E-11
$\varepsilon = 1/2^6$	8.62E-1	6.73E-2	1.36E-4	5.14E-11	8.62E-1	6.73E-2	1.36E-4	5.15E-11
$\varepsilon = 1/2^{10}$	8.62E-1	6.73E-2	1.36E-4	5.06E-11	8.62E-1	6.73E-2	1.36E-4	5.06E-11
$\varepsilon = 1/2^{20}$	8.62E-1	6.73E-2	1.36E-4	5.06E-11	8.62E-1	6.73E-2	1.36E-4	5.06E-11

TABLE 5.1

Spatial error analysis for scheme (2.27)-(2.28), with different ε *for Case I* ($\alpha = 2$) *and Case II* $\alpha = 0$, *for the* $\|e^n(x)\|_{H^1}$.

Numerical results for EWI-SP method

$\alpha = 2$	$\tau = 0.2$	$\tau = \frac{0.2}{4}$	$\tau = \frac{0.2}{4^2}$	$\tau = \frac{0.2}{4^3}$	$\tau = \frac{0.2}{4^4}$	$\tau = \frac{0.2}{4^5}$	$\tau = \frac{0.2}{4^6}$	$\tau = \frac{0.2}{4^7}$
$\varepsilon = 1/2$	4.63E-2	2.97E-3	1.87E-4	1.17E-5	7.34E-7	4.59E-8	2.87E-9	1.87E-10
		1.98	1.99	2.00	2.00	2.00	2.00	1.97
$\varepsilon = 1/2^2$	4.22E-2	4.52E-3	2.83E-4	1.77E-5	1.11E-6	6.91E-8	4.32E-9	2.77E-10
		1.61	2.00	2.00	2.00	2.00	2.00	1.98
$\varepsilon = 1/2^3$	5.01E-2	3.99E-3	3.76E-4	2.37E-5	1.48E-6	9.27E-8	5.78E-9	3.53E-10
		1.83	1.70	2.00	2.00	2.00	2.00	2.02
$\varepsilon = 1/2^4$	5.50E-2	3.73E-3	3.09E-4	2.45E-5	1.53E-6	9.61E-8	6.01E-9	3.74E-10
		1.94	1.80	1.83	2.00	2.00	2.00	2.00
$\varepsilon = 1/2^5$	5.65E-2	3.85E-3	2.43E-4	1.95E-5	1.61E-6	1.02E-7	6.38E-9	4.04E-10
		1.94	1.99	1.82	1.80	1.99	2.00	1.99
$\varepsilon = 1/2^6$	5.69E-2	3.88E-3	2.45E-4	1.54E-5	1.25E-6	1.00E-7	6.30E-9	3.82E-10
		1.94	1.99	2.00	1.81	1.82	1.99	2.02
$\varepsilon = 1/2^{10}$	5.70E-2	3.89E-3	2.46E-4	1.54E-5	9.62E-7	6.01E-8	3.76E-9	2.48E-10
		1.94	1.99	2.00	2.00	2.00	2.00	1.96
$\varepsilon = 1/2^{20}$	5.70E-2	3.89E-3	2.46E-10	1.54E-5	9.62E-7	6.01E-8	3.76E-9	2.46E-10
		1.94	1.99	2.00	2.00	2.00	2.00	1.97

TABLE 5.2

Temporal error analysis for scheme (2.27)-(2.28), with different ε *for Case I* ($\alpha = 2$), *with* $\|e^n(x)\|_{H^1}$. T
nvergence rates are calculated as $\log_2(\|e^n(x,4\tau)\|_{H^1}/\|e^n(x,\tau)\|_{H^1})/2$

A multiscale method for KG equation

$$\varepsilon^2\partial_{tt}u(\vec{x},t)-\Delta u+\frac{1}{\varepsilon^2}u+f(u)=0,\qquad \vec{x}\in\mathbb{R}^d,\quad t>0$$

$$u(\vec{x},0)=\phi(\vec{x}),\quad \partial_t u(\vec{x},0)=\frac{1}{\varepsilon^2}\gamma(\vec{x}),\quad \vec{x}\in\mathbb{R}^d$$

- For time interval $[t_n,t_{n+1}]$: (Bao, Cai & Zhao, SINUM, 14')
  - Given initial data

$$u(\vec{x},t_n)=\phi_n(\vec{x})\quad \&\quad \partial_t u(\vec{x},t_n)=\frac{1}{\varepsilon^2}\gamma_n(\vec{x}),\quad \vec{x}\in\Omega$$

  - Multiscale decomposition in frequency (MDF)

$$u(\vec{x},t_n+s)=e^{is/\varepsilon^2}\,z^n(\vec{x},s)+e^{-is/\varepsilon^2}\,\overline{z}^n(\vec{x},s)+r^n(\vec{x},s),\quad \vec{x}\in\Omega,\quad 0\le s\le\tau$$

Multiscale decomposion of KG

– NLSW for z^n with well-prepared initial data ($\varepsilon^2 -$)

$$2i\partial_s z^n(\vec{x},s)+\varepsilon^2\partial_{ss}z^n-\Delta z^n+F(z^n)=0,\quad \vec{x}\in\Omega, 0\le s\le\tau$$

– Nonlinear KG-type equation for r^n with small data (rest)

$$\varepsilon^2\partial_{ss}r^n(\vec{x},s)-\Delta r^n+\frac{1}{\varepsilon^2}r^n+G(r^n,s;z^n)=0,\quad \vec{x}\in\Omega,\quad 0\le s\le\tau$$

- with

$$G(r,s;z):=f(ze^{is/\varepsilon^2}+\overline{z}e^{-is/\varepsilon^2}+r)-F(z)e^{is/\varepsilon^2}-F(\overline{z})e^{-is/\varepsilon^2},\quad 0\le s\le\tau$$

Multiscale decomposion of initial data

$$t = t_n \Leftrightarrow s = 0$$

$$u(\vec{x}, t_n) = z^n(\vec{x}, 0) + \overline{z}^n(\vec{x}, 0) + r^n(\vec{x}, 0) = \phi_n(\vec{x})$$

$$\partial_t u(\vec{x}, t_n) = \frac{i}{\varepsilon^2}\left[z^n(\vec{x}, 0) - \overline{z}^n(\vec{x}, 0)\right] + \partial_s z^n(\vec{x}, 0) + \partial_s \overline{z}^n(\vec{x}, 0) + \partial_s r^n(\vec{x}, 0) = \frac{1}{\varepsilon^2}\gamma_n(\vec{x})$$

– Small data for r^n :

$$r^n(\vec{x}, 0) = 0 \quad \& \quad z^n(\vec{x}, 0) + \overline{z}^n(\vec{x}, 0) = \phi_n(\vec{x})$$

– Well-prepared data for z^n

$$\partial_s z^n(\vec{x}, 0) = \frac{-i}{2}[\Delta z^n - F(z^n)]_{s=0}$$

– Equate *O(1)* and $O(1/\varepsilon^2)$

$$z^n(\vec{x}, 0) - \overline{z}^n(\vec{x}, 0) = -i\gamma_n(\vec{x}) \quad \& \quad \partial_s r^n(\vec{x}, 0) = -\partial_s z^n(\vec{x}, 0) - \partial_s \overline{z}^n(\vec{x}, 0), \quad \vec{x} \in \overline{\Omega}$$

– Solve and get

$$z^n(\vec{x}, 0) = \frac{1}{2}[\phi_n(\vec{x}) - i\gamma_n(\vec{x})], \quad \vec{x} \in \overline{\Omega}$$

Two subproblems

– NLSW for z^n with well-prepared initial data

$$2i\partial_s z^n(\vec{x},s)+\varepsilon^2\partial_{ss}z^n-\Delta z^n+F(z^n)=0,\quad \vec{x}\in\Omega, 0\le s\le\tau$$

- with

$$z^n(\vec{x},0)=\frac{1}{2}[\phi_n(\vec{x})-i\gamma_n(\vec{x})],\quad \partial_s z^n(\vec{x},0)=\frac{-i}{2}[\Delta z^n-F(z^n)]_{s=0},\qquad \vec{x}\in\overline{\Omega}$$

– Nonlinear KG-type equation for *w* with small data

$$\varepsilon^2\partial_{ss}r^n(\vec{x},s)-\Delta r^n+\frac{1}{\varepsilon^2}r^n+G(r^n,s;z^n)=0,\quad \vec{x}\in\Omega,\quad 0\le s\le\tau$$

$$r^n(\vec{x},0)=0,\quad \partial_s r^n(\vec{x},0)=-\partial_s z^n(\vec{x},0)-\partial_s\overline{z}^n(\vec{x},0),\quad \vec{x}\in\overline{\Omega}$$

Reconstruction at $t = t_{n+1}$

- Solve the NLSW for z^n by EWI-SP method to obtain

$$z^n(x,\tau), \quad \partial_s z^n(x,\tau), \quad \vec{x} \in \Omega$$

- Solve the KG-type equation for *w* by EWI-SP to obtain

$$r^n(x,\tau), \quad \partial_s r^n(x,\tau), \quad \vec{x} \in \Omega$$

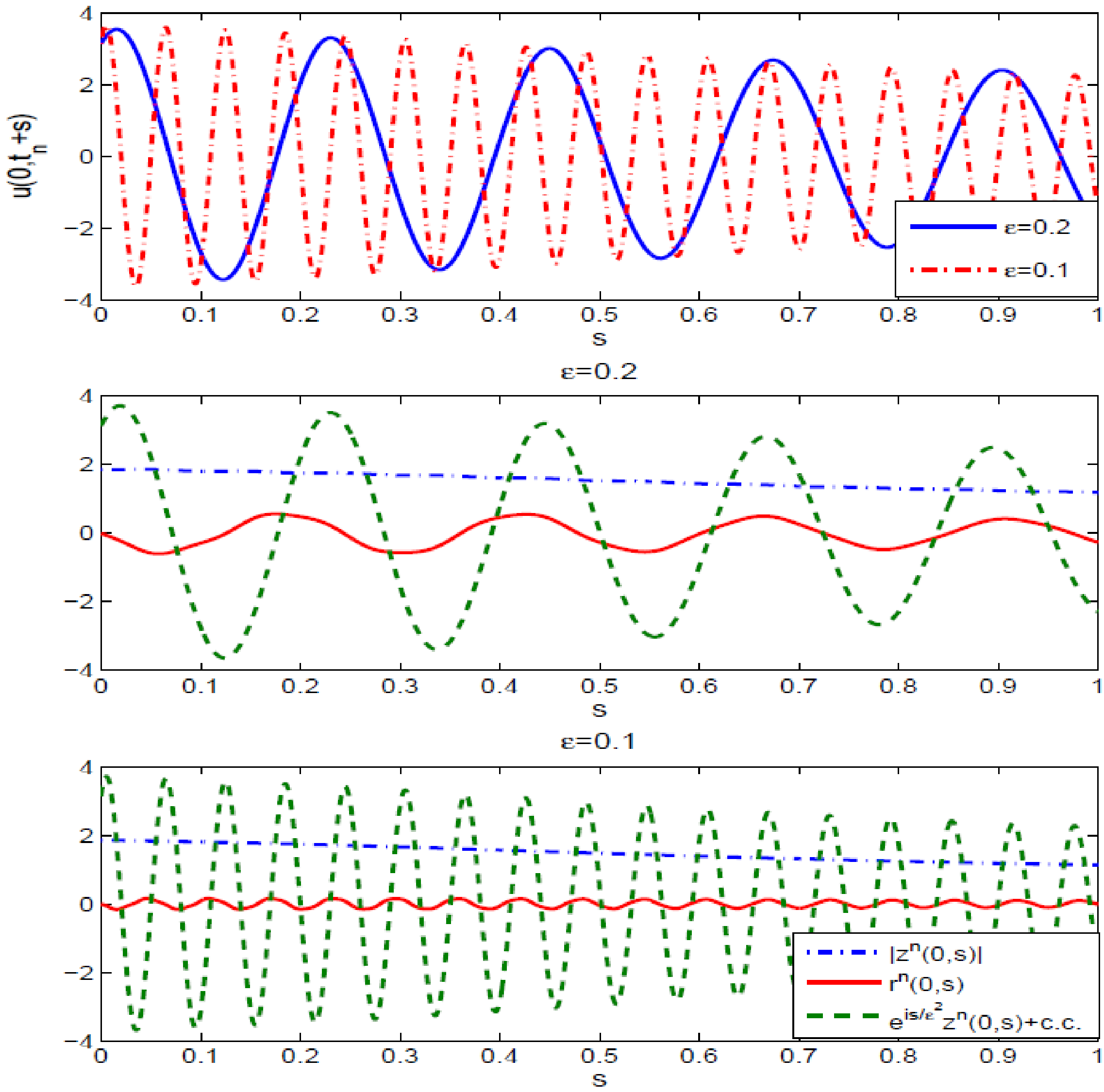
- Construct solution at $t = t_{n+1}$ based on the decomposition

$$u(x,t_{n+1}) := e^{i\tau/\varepsilon^2}\, z^n(\vec{x},\tau) + e^{-i\tau/\varepsilon^2}\, \overline{z}^n(\vec{x},\tau) + r^n(\vec{x},\tau) := \phi_{n+1}(\vec{x}), \quad \vec{x} \in \Omega$$

$$\partial_t u(x,t_{n+1}) := e^{i\tau/\varepsilon^2}\, \partial_s z^n(\vec{x},\tau) + e^{-i\tau/\varepsilon^2}\, \partial_s \overline{z}^n(\vec{x},\tau) + \partial_s r^n(\vec{x},\tau) + \frac{i}{\varepsilon^2}[z^n(\vec{x},\tau) - \overline{z}^n(\vec{x},\tau)]$$

$$\Rightarrow \gamma_{n+1}(\vec{x}) = i[z^n(\vec{x},\tau) - \overline{z}^n(\vec{x},\tau)] + \varepsilon^2[e^{i\tau/\varepsilon^2}\, \partial_s z^n(\vec{x},\tau) + e^{-i\tau/\varepsilon^2}\, \partial_s \overline{z}^n(\vec{x},\tau) + \partial_s r^n(\vec{x},\tau)]$$

$$u(\vec{x}, t_n + s) = e^{is/\varepsilon^2} z^n(\vec{x}, s) + \text{c.c.} + r^n(\vec{x}, s)$$



z^n is smooth & no oscillation!

r^n is oscillating, but its amplitude is small! Also, r^n(.,0)=0!!, no numerical error be accumulated between different time interval

Properties of the multiscale method

- Explicit & unconditionally stable
- Easy to extend to 2D & 3D
- Accuracy
  - Spectral accuracy in space
  - Uniform convergence in time for $0 < \varepsilon \leq 1$
- Resolution in nonrelativistic limit regime

$$h = O(1) \quad \& \quad \tau = O(1)$$

Error bounds for the multiscale method

- Theorem (Bao, Cai &Zhao, SINUM 14') Under some reasonable and proper assumptions, for $0<\varepsilon\le 1$, we can establish the following two independent error estimates for

$$\left\|u(x,t_n)-u_M^n(x)\right\|_{L^2}\le\frac{\tau^2}{\varepsilon^2}+h^{m_0},\quad \left\|\nabla(u(x,t_n)-u_M^n(x))\right\|_{L^2}\le\frac{\tau^2}{\varepsilon^2}+h^{m_0-1},\quad 0\le n\le\frac{T}{\tau},$$

$$\left\|u(x,t_n)-u_M^n(x)\right\|_{L^2}\le\tau^2+\varepsilon^2+h^{m_0},\quad \left\|\nabla(u(x,t_n)-u_M^n(x))\right\|_{L^2}\le\tau^2+\varepsilon^2+h^{m_0-1}.$$

By taking the minimum, we get error bound uniformly for $0<\varepsilon\le 1$ as:

$$\left\|u(x,t_n)-u_M^n(x)\right\|_{L^2}\le\tau+h^{m_0},\quad \left\|\nabla(u(x,t_n)-u_M^n(x))\right\|_{L^2}\le\tau+h^{m_0-1},\quad 0\le n\le\frac{T}{\tau}.$$

Numerical results (Bao,Cai & Zhao, SINUM, 14')

$$\varepsilon^2\partial_{tt}u(x,t)-\partial_{xx}u+\frac{1}{\varepsilon^2}u+|u|^2u=0\qquad x\in\mathbb{R},\quad t>0$$

$$u(x,0)=\phi(x)=(1+i)e^{-x^2/2},\quad \partial_t u(x,0)=\frac{3\phi(x)}{2\varepsilon^2},\quad \vec{x}\in\mathbb{R}$$

$e_\varepsilon^{\tau,h}(T)$	$h_0=1$	$h_0/2$	$h_0/4$	$h_0/8$
$\varepsilon_0=0.5$	1.65E−1	3.60E−3	1.03E−6	7.34E−11
$\varepsilon_0/2^1$	2.65E−1	9.70E−3	9.07E−7	5.03E−11
$\varepsilon_0/2^2$	9.02E−1	1.34E−2	1.73E−7	4.60E−11
$\varepsilon_0/2^3$	1.13E+0	2.98E−2	2.25E−7	4.10E−11
$\varepsilon_0/2^4$	4.67E−1	3.14E−2	1.79E−7	4.78E−11
$\varepsilon_0/2^5$	7.41E−1	2.73E−2	2.50E−7	5.49E−11
$\varepsilon_0/2^7$	7.41E−1	2.62E−2	2.12E−7	4.96E−11
$\varepsilon_0/2^9$	6.33E−1	3.57E−2	1.92E−7	5.04E−11
$\varepsilon_0/2^{11}$	9.19E−1	2.44E−2	2.19E−7	6.18E−11
$\varepsilon_0/2^{13}$	1.18E+0	2.38E−2	2.59E−7	5.86E−11

Observation: spectral order in time & uniform convergence in ε !!!!

Numerical results (Bao,Cai & Zhao, SINUM, 14')

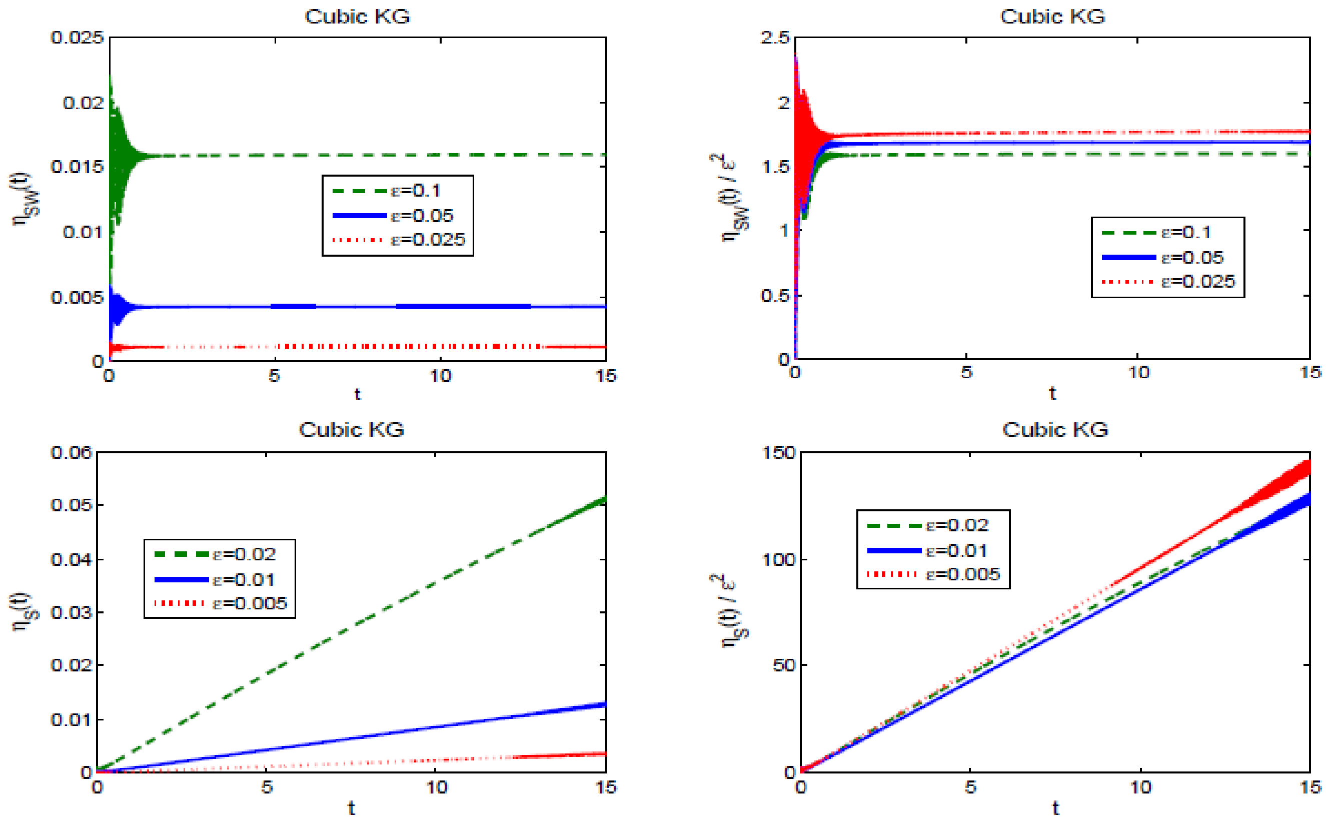
$e_{\varepsilon}^{\tau,h}(T)$	$\tau_0=0.2$	$\tau_0/2^2$	$\tau_0/2^4$	$\tau_0/2^6$	$\tau_0/2^8$	$\tau_0/2^{10}$	$\tau_0/2^{12}$
$\varepsilon_0=0.5$	7.04E-1	5.73E-2	3.50E-3	2.14E-4	1.33E-5	8.14E-7	3.67E-8
rate	—	1.81	2.02	2.01	2.00	2.01	2.20
$\varepsilon_0/2^1$	4.92E-1	1.58E-1	1.12E-2	6.74E-4	4.15E-5	2.54E-6	1.18E-7
rate	—	0.82	1.91	2.02	2.01	2.01	2.21
$\varepsilon_0/2^2$	4.55E-1	1.47E-1	3.70E-2	2.70E-3	1.62E-4	9.87E-6	4.62E-7
rate	—	0.82	0.99	1.90	2.02	2.01	2.20
$\varepsilon_0/2^3$	5.46E-1	6.11E-2	4.13E-2	8.90E-3	6.51E-4	3.92E-5	1.82E-6
rate	—	1.58	0.28	1.11	1.89	2.02	2.21
$\varepsilon_0/2^4$	5.20E-1	2.83E-2	1.16E-2	1.05E-2	2.20E-3	1.60E-4	7.41E-6
rate	—	2.09	0.64	0.07	1.13	1.89	2.21
$\varepsilon_0/2^5$	5.23E-1	2.83E-2	2.50E-3	2.70E-3	2.60E-3	5.26E-4	2.98E-5
rate	—	2.10	1.75	-0.06	0.01	1.17	2.07
$\varepsilon_0/2^7$	5.21E-1	2.74E-2	1.76E-3	2.37E-4	1.37E-4	1.96E-4	1.91E-4
rate	—	2.12	1.98	1.45	0.40	-0.26	0.02
$\varepsilon_0/2^9$	5.21E-1	2.73E-2	1.69E-3	1.12E-4	1.09E-5	5.51E-6	1.69E-6
rate	—	2.12	2.00	1.96	1.68	0.49	0.85
$\varepsilon_0/2^{11}$	5.21E-1	2.73E-2	1.69E-3	1.05E-4	6.95E-6	9.97E-7	3.38E-7
rate	—	2.12	2.00	2.00	1.96	1.40	0.78
$\varepsilon_0/2^{13}$	5.25E-1	2.76E-2	1.70E-3	1.06E-4	6.61E-6	3.94E-7	2.38E-8
rate	—	2.12	2.00	2.00	2.00	2.03	2.02
$e_{\infty}^{\tau,h}(T)$	7.04E-1	1.58E-1	4.13E-2	1.05E-2	2.60E-3	5.26E-4	1.91E-4
rate	—	1.07	0.97	0.99	1.00	1.15	0.74

Observation: 2nd order in time & uniform convergence in ε !!!!

Convergence rates from NKG to NLSW & NLSE

$$u_{sw} = e^{it/\varepsilon^2}\psi_{sw} + e^{-it/\varepsilon^2}\overline{\psi}_{sw}$$

$$u_s = e^{it/\varepsilon^2}\psi_s + e^{-it/\varepsilon^2}\overline{\psi}_s$$

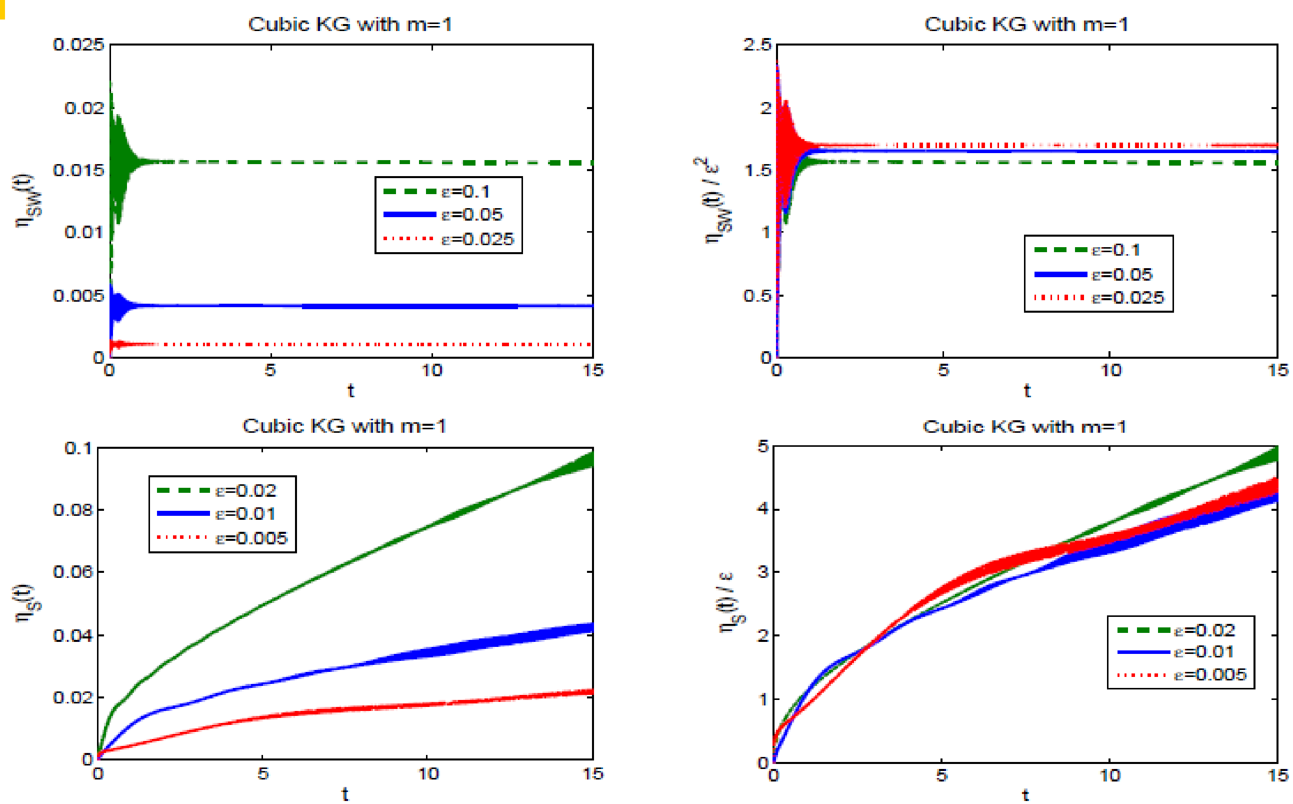


$$\phi(\vec{x}) \in H^3$$

$$\gamma(\vec{x}) \in H^3 \Rightarrow \quad \eta_{sw}(t) = \|u(\cdot,t) - u_{sw}(\cdot,t)\|_{H^1} \le C_0\varepsilon^2, \quad 0 \le t < T^*$$

$$\eta_s(t) = \|u(\cdot,t) - u_s(\cdot,t)\|_{H^1} \le (C_1 + C_2 T)\varepsilon^2, \quad 0 \le t \le T$$

Convergence rates from NKG to NLSW & NLSE



$$\phi(\vec{x}) \in H^2$$
$$\gamma(\vec{x}) \in H^2 \Rightarrow$$

$$\eta_{\mathrm{sw}}(t) = \left\| u(\cdot,t) - u_{\mathrm{sw}}(\cdot,t) \right\|_{H^1} \le C_0 \varepsilon^2, \quad 0 \le t < T^*$$

$$\eta_{\mathrm{s}}(t) = \left\| u(\cdot,t) - u_{\mathrm{s}}(\cdot,t) \right\|_{H^1} \le (C_1 + C_2 T)\varepsilon, \quad 0 \le t \le T$$

Conclusion & future challenges

- Conclusion
  - For nonlinear KG equation in nonrelativistic limit regime
    - FDTD methods $O\left(h^2+\tau^2/\varepsilon^6\right) \Rightarrow h=O(1)\ \&\ \tau=O(\varepsilon^3)$
    - An EWI spectral method $O\left(h^m+\tau^2/\varepsilon^4\right) \Rightarrow h=O(1)\ \&\ \tau=O(\varepsilon^2)$
    - Multiscale methods $O\left(h^m+\min(\varepsilon^2,\frac{\tau^2}{\varepsilon^2})\right)\le O\left(h^m+\tau\right)\Rightarrow h=O(1)\ \&\ \tau=O(1)$
  - For NLS perturbed by wave operator
    - FDTD methods $O\left(h^2+\tau\right) \Rightarrow h=O(1)\ \&\ \tau=O(1)$
    - An EWI spectral method $O\left(h^m+\tau^2\right) \Rightarrow h=O(1)\ \&\ \tau=O(1)$
- Future challenges
  - Applications to high oscillatory dispersive PDEs
  - Simulation of wave in plasma physics