Noncommutative Solitons and Integrable Systems

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Based on

- **MH**, JMP46 (2005) 052701 [hep-th/0311206]
- **MH**, PLB625 (2005) 324 [hep-th/0507112]
- cf. **MH**, ``NC solitons and integrable systems'' Proc. of NCGP2004, [hep-th/0504001]

1. Introduction

Successful points in NC theories

- Appearance of new physical objects
- Description of real physics
- Various successful applications
  to D-brane dynamics etc.

NC Solitons play important roles
(Integrable!)

Final goal: NC extension of all soliton theories

Integrable equations in diverse dimensions

4	Anti-Self-Dual Yang-Mills eq. (instantons) $F_{\mu\nu} = -\tilde{F}_{\mu\nu}$	NC extension (Successful)
3	Bogomol'nyi eq. (monopoles)	NC extension (Successful)
2 (+1)	KP eq. BCS eq. DS eq. …	NC extension (This talk)
1 (+1)	KdV eq. Boussinesq eq. NLS eq. Burgers eq. sine-Gordon eq. (affine) Toda field eq. …	NC extension (This talk)

Dim. of space

Ward's observation: Almost all integrable equations are reductions of the ASDYM eqs.

R.Ward, Phil.Trans.Roy.Soc.Lond.A315('85)451

ASDYM eq.

↓ Reductions

KP eq. BCS eq. Ward's chiral model
KdV eq. Boussinesq eq.
NLS eq. Toda field eq.
sine-Gordon eq. Burgers eq. …
(Almost all !?)

e.g. [The book of Mason&Woodhouse]

NC Ward's observation: Almost all NC integrable equations are reductions of the NC ASDYM eqs.

MH&K.Toda, PLA316('03)77[hep-th/0211148]

NC ASDYM eq.

Successful

↓ NC Reductions

Reductions

NC KP eq. NC BCS eq. NC Ward's chiral model
NC KdV eq. NC Boussinesq eq.
NC NLS eq. NC Toda field eq.
NC sine-Gordon eq. NC Burgers eq. …
(Almost all !?)

Successful!!!

Now it is time to study from more comprehensive framework.

Program of NC extension of soliton theories

MH, PLB625, 324 [hep-th/0507112]

- Confirmation of NC Ward's conjecture — Going well
  - NC twistor theory → geometrical origin — Talk at 13th NBMPS in Duham on Nov.5
  - D-brane interpretations → applications to physics

- Completion of NC Sato's theory
  - Existence of ``hierarchies'' → Solved!
  - Existence of infinite conserved quantities — Successful

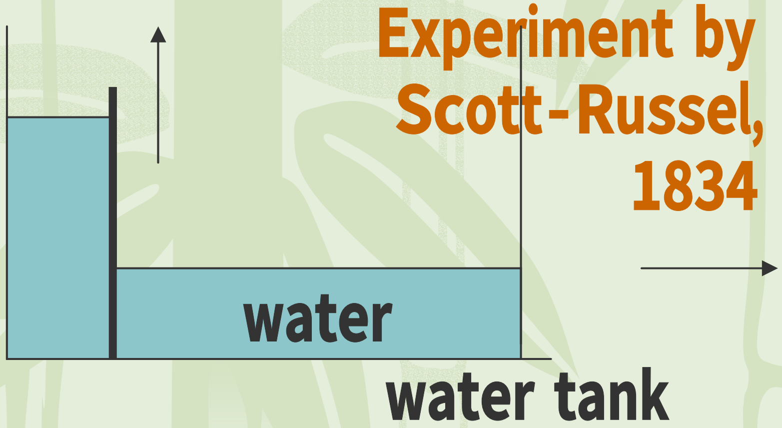
    → infinite-dim. hidden symmetry — MH, JMP46 (2005) [hep-th/0311206]
  - Construction of multi-soliton solutions — Successful
  - Theory of tau-functions → description of the symmetry and the soliton solutions — Work in progress

Plan of this talk

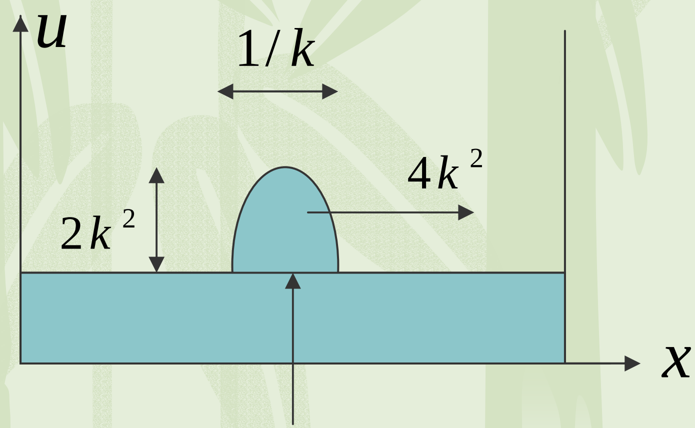
1. Introduction
2. Review of soliton theories (fun)
3. NC Sato's theory
   (derivation of NC soliton eqs.)
4. Conservation Laws
   (infinite conserved quantities)
5. Exact Solutions and Ward's conjecture
   (solvability and physical pictures)
6. Conclusion and Discussion

2. Review of Soliton Theories

- KdV equation : describe shallow water waves



Experiment by Scott-Russel, 1834



solitary wave = soliton

$$u = 2k^2 \cosh^{-2}(kx - 4k^3 t)$$

This configuration satisfies

$$\dot{u} + u''' + 6u'u = 0$$: **KdV eq.** **[Korteweg-de Vries, 1895]**

This is a typical integrable equation.

Let's solve it now !

- Hirota's method [PRL27(1971)1192]

$$\dot{u} + u''' + 6u'u = 0$$: naively hard to solve

$$\downarrow \quad u = 2\partial_x^2 \log \tau$$

$$\tau\dot{\tau}' - \tau'\dot{\tau} + 3\tau''\tau'' - 4\tau'\tau''' + \tau\tau'''' = 0$$

Hirota's bilinear relation : more complicated ?

A solution: $\tau = 1 + e^{2(kx - \omega t)}, \quad \omega = 4k^3$

$$\rightarrow \quad u = 2k^2 \cosh^{-2}(kx - 4k^3 t)$$ **: The solitary wave !**
(1-soliton solution)

❖ 2-soliton solution

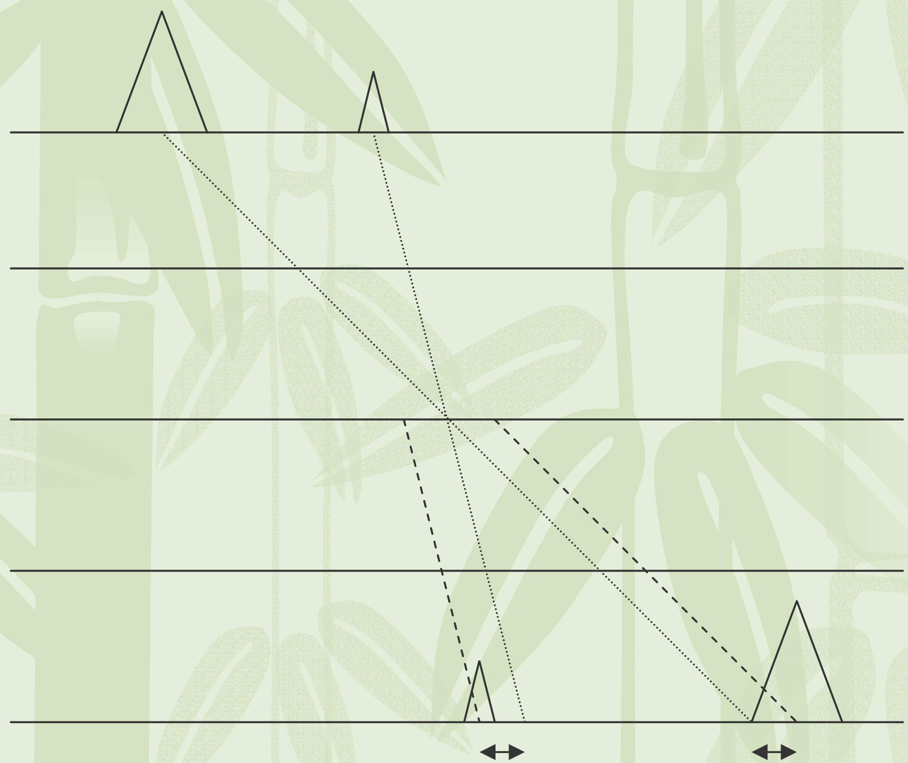
$$\tau = 1 + A_1 e^{2\theta_1} + A_2 e^{2\theta_2} + B A_1 A_2 e^{2(\theta_1+\theta_2)}$$

= A determinant of Wronski matrix (general property of soliton sols.)

``tau-functions''

$$\theta_i = k_i x - 4k_i^3 t, \quad B = \left(\frac{k_1 - k_2}{k_1 + k_2}\right)^2$$

Scattering process



The shape and velocity is preserved ! (stable)

The positions are shifted ! (Phase shift)

3. NC Sato's Theory

- Sato's Theory : one of the most beautiful theory of solitons
  - Based on the exsitence of

hierarchies and tau-functions

A set of infinite soliton equations (in terms of u)	$\xrightarrow{\quad u = 2\partial_x^2 \log \tau \quad}$	A set of infinite bilinear equations (in terms of τ)

Infinite evolution eqs. whose flows are all commuting

$\downarrow$

Infinite conserved quantities

Pluecker embedding maps which define an infinite-dim. Grassmann manifold. (=the solution space)

$\downarrow$

Infinite dimensional symmetry

Derivation of soliton equations

- Prepare a Lax operator which is a pseudo-differential operator

$$L := \partial_x + u_2 \partial_x^{-1} + u_3 \partial_x^{-2} + u_4 \partial_x^{-3} + \cdots \qquad u_k = u_k(\underline{x^1, x^2, x^3, \cdots})$$

- Introduce a differential operator

$$B_m := (\underbrace{L * \cdots * L}_{m\ times})_{\geq 0}$$

Noncommutativity is introduced here:

$$[x^i, x^j] = i\theta^{ij}$$

- Define NC (KP) hierarchy:

$$\boxed{\frac{\partial L}{\partial x^m} = [B_m, L]_*}$$

Here all products are star product:

$$\partial_m u_2 \partial_x^{-1} + \partial_m u_3 \partial_x^{-2} + \partial_m u_4 \partial_x^{-3} + \cdots$$

$$f_{m2}(u)\partial_x^{-1} + f_{m3}(u)\partial_x^{-2} + f_{m4}(u)\partial_x^{-3} + \cdots$$

$\longrightarrow$ **Each coefficient yields a differential equation.**

Negative powers of differential operators

$$\partial_x^n \circ f := \sum_{j=0}^{\infty} \binom{n}{j} (\partial_x^j f) \partial_x^{n-j}$$

$$\binom{n}{j} \equiv \frac{n(n-1)(n-2)\cdots(n-(j-1))}{j(j-1)(j-2)\cdots 1}$$

: **binomial coefficient which can be extended to negative n → negative power of differential operator (well-defined !)**

$$\partial_x^3 \circ f = f\partial_x^3 + 3f'\partial_x^2 + 3f''\partial_x^1 + f'''$$
$$\partial_x^2 \circ f = f\partial_x^2 + 2f'\partial_x + f''$$

$$\partial_x^{-1} \circ f = f\partial_x^{-1} - f'\partial_x^{-2} + f''\partial_x^{-3} - \cdots$$
$$\partial_x^{-2} \circ f = f\partial_x^{-2} - 2f'\partial_x^{-3} + 3f''\partial_x^{-4} - \cdots$$

Star product:

$$f(x) * g(x) := f(x)\exp\left(\frac{i}{2}\theta^{ij}\overleftarrow{\partial}_i\overrightarrow{\partial}_j\right)g(x)$$

which makes theories ``noncommutative'':

$$[x^i, x^j]_* := x^i * x^j - x^j * x^i = i\theta^{ij}$$

Closer look at NC KP hierarchy

For m=2

$$\partial_x^{-1})\quad \partial_2 u_2 = \underline{2u_3'} + u_2''$$

$$\partial_x^{-2})\quad \partial_2 u_3 = \underline{2u_4'} + u_3'' + 2u_2 * u_2' + 2[u_2, u_3]_*$$

$$\partial_x^{-3})\quad \partial_2 u_4 = \underline{2u_5'} + u_4'' + 4u_3 * u_2' - 2u_2 * u_2'' + 2[u_2, u_4]_*$$

$$\vdots$$

Infinite kind of fields are represented in terms of one kind of field $u_2 \equiv u$

MH&K.Toda, [hep-th/0309265]

$$u_x := \frac{\partial u}{\partial x}$$

$$\partial_x^{-1} := \int^x dx'$$

For m=3

$$\partial_x^{-1})\quad \partial_3 u_2 = u_2''' + 3u_3'' + 3u_4'' + 3u_2' * u_2 + 3u_2 * u_2'$$

etc.

$$\vdots$$

$$\downarrow$$

$$u_t = \frac{1}{4}u_{xxx} + \frac{3}{4}(u_x * u + u * u_x) + \frac{3}{4}\partial_x^{-1}u_{yy} + \frac{3}{4}[u, \partial_x^{-1}u_{yy}]_*$$

(2+1)-dim. NC KP equation

and other NC equations (NC KP hierarchy equations)

$$u = u(x^1, x^2, x^3, \cdots)$$

$$\updownarrow \quad \updownarrow \quad \updownarrow$$

$$x \quad y \quad t$$

(KP hierarchy) $\xrightarrow{\text{reductions}}$ (various hierarchies.)

- (Ex.) KdV hierarchy

Reduction condition

$$L^2 = B_2 (=: \partial_x^2 + u)$$: 2-reduction

gives rise to NC KdV hierarchy

which includes (1+1)-dim. NC KdV eq.:

$$u_t = \frac{1}{4} u_{xxx} + \frac{3}{4}(u_x * u + u * u_x)$$

Note $\frac{\partial u}{\partial x_{2N}} = 0$: dimensional reduction in x_{2N} directions

$$\begin{array}{llr} \textbf{KP :} & u(\underset{x}{x^1}, \underset{y}{x^2}, \underset{t}{x^3}, x^4, x^5, \ldots) & \textbf{: (2+1)-dim.} \\ \downarrow & & \downarrow \\ \textbf{KdV :} & u(\underset{x}{x^1}, \underset{t}{x^3}, x^5, \ldots) & \textbf{: (1+1)-dim.} \end{array}$$

l-reduction of NC KP hierarchy yields wide class of other NC (GD) hierarchies

- No-reduction → NC KP $\quad (x, y, t) = (x^1, x^2, x^3)$
- 2-reduction → NC KdV $\quad (x, t) = (x^1, x^3)$
- 3-reduction → NC Boussinesq $\quad (x, t) = (x^1, x^2)$
- 4-reduction → NC Coupled KdV $\quad \ldots$
- 5-reduction → ...
- 3-reduction of BKP → NC Sawada-Kotera
- 2-reduction of mKP → NC mKdV
- Special 1-reduction of mKP → NC Burgers
- … **Noncommutativity should be introduced into space-time coords**

4. Conservation Laws

- Conservation laws: $\partial_t \sigma = \partial_i J^i$ σ : Conserved density

time **space**

Then $Q := \int_{space} dx\,\sigma$ is a conserved quantity.

$$\because \partial_t Q = \int_{space} dx \partial_t \sigma = \int_{\substack{spatial \\ \inf inity}} dS_i J^i = 0$$

Conservation laws for the hierarchies

$$\partial_m res_{-1} L^n = \partial_x J + \underline{\theta^{ij} \partial_j \Xi_i}$$

time **space**

I have succeeded in the evaluation explicitly !

$res_{-r} L^n$: coefficient of ∂_x^{-r} in L^n

Noncommutativity should be introduced in space-time directions only. →

$t \equiv x^m$

∂_j **should be space or time derivative**

→ **ordinary conservation laws !**

Infinite conserved densities for the NC soliton eqs. (n=1,2,..., ∞)

$$\sigma_n = res_{-1}L^n + \theta^{im}\sum_{k=0}^{m-1}\sum_{l=0}^{k}\binom{k}{l}(\partial_x^{k-l}res_{-(l+1)}L^n)\Diamond(\partial_i res_k L^m)$$

$t \equiv x^m$ $\qquad$ $res_r L^n$: coefficient of ∂_x^r in L^n

$\Diamond$: Strachan's product (commutative and non-associative)

$$f(x)\Diamond g(x) := f(x)\left(\sum_{s=0}^{\infty}\frac{(-1)^s}{(2s+1)!}\left(\frac{1}{2}\theta^{ij}\overleftarrow{\partial}_i\overrightarrow{\partial}_j\right)^{2s}\right)g(x)$$

MH, JMP46 (2005) [hep-th/0311206]

This suggests infinite-dimensional symmetries would be hidden.

We can calculate the explicit forms of conserved densities for the wide class of NC soliton equations.

- Space-Space noncommutativity:

  NC deformation is slight: $\sigma_n = res_{-1} L^n$

  involutive (integrable in Liouville's sense)

- Space-time noncommutativity

  NC deformation is drastical:

  - Example: NC KP and KdV equations $([t, x] = i\theta)$

$$\sigma_n = res_{-1} L^n - 3\theta((res_{-1} L^n) \Diamond u_3' + (res_{-2} L^n) \Diamond u_2')$$

meaningful ?

5. Exact Solutions and Ward's conjecture

- We have found exact N-soliton solutions for the wide class of NC hierarchies.
- 1-soliton solutions are all the same as commutative ones because of

$$f(x-vt) * g(x-vt) = f(x-vt)g(x-vt)$$

- Multi-soliton solutions behave in almost the same way as commutative ones except for phase shifts.
- Noncommutativity affects the phase shifts

Exact multi-soliton solutions of the NC soliton eqs.

$L = \Phi \partial_x \Phi^{-1}$ **solves the NC Lax hierarchy !**

$\Phi f := \left| W(y_1, \ldots, y_N, f) \right|_{N+1,N+1}$ **quasi-determinant of Wronski matrix**

$y_i = \exp \xi(x, \alpha_i) + a_i \exp \xi(x, \beta_i)$

$\xi(x, \alpha) = x_1 \alpha + x_2 \alpha^2 + x_3 \alpha^3 + \cdots$

Etingof-Gelfand-Retakh, [q-alg/9701008]

The exact solutions are actually N-soliton solutions !

Noncommutativity might affect the phase shift by $\theta^{ij} \omega_i k_j$

[MH, work in progress]

$\because) \exp i(\omega_i t - k_i x) * \exp i(\omega_j t - k_j x)$

$\cong \underline{\exp(-i\theta^{ij} \omega_i k_j)} \exp i((\omega_i + \omega_j)t - (k_i + k_j)x)$

Exactly solvable!

Quasi-determinants

❖ Defined inductively as follows

[For a review, see Gelfand et al., math.QA/0208146]

$$|X|_{ij} = x_{ij} - \sum_{i',j'} x_{ii'} \left(|X^{ij}|_{i'j'}\right)^{-1} x_{j'j}$$

$$n=1: \quad |X|_{ij} = x_{ij}$$

$$n=2: \quad |X|_{11} = x_{11} - x_{12}\cdot x_{22}^{-1}\cdot x_{21}, \ |X|_{12} = x_{12} - x_{11}\cdot x_{21}^{-1}\cdot x_{22},$$

$$|X|_{21} = x_{21} - x_{22}\cdot x_{12}^{-1}\cdot x_{11}, \ |X|_{22} = x_{22} - x_{21}\cdot x_{11}^{-1}\cdot x_{12},$$

$$n=3: \quad |X|_{11} = x_{11} - x_{12}\cdot(x_{22} - x_{23}\cdot x_{33}^{-1}\cdot x_{32})^{-1}\cdot x_{21} - x_{13}\cdot(x_{32} - x_{33}\cdot x_{23}^{-1}\cdot x_{22})^{-1}\cdot x_{21}$$

$$- x_{12}\cdot(x_{23} - x_{22}\cdot x_{32}^{-1}\cdot x_{33})^{-1}\cdot x_{31} - x_{13}\cdot(x_{33} - x_{32}\cdot x_{22}^{-1}\cdot x_{23})^{-1}\cdot x_{31}$$

$$\cdots$$

Wronski matrix:

$$W(f_1, f_2, \cdots, f_m) = \begin{bmatrix} f_1 & f_2 & \cdots & f_m \\ \partial_x f_1 & \partial_x f_2 & \cdots & \partial_x f_m \\ \vdots & \vdots & \ddots & \vdots \\ \partial_x^{m-1} f_1 & \partial_x^{m-1} f_2 & \cdots & \partial_x^{m-1} f_m \end{bmatrix}$$

NC Ward's conjecture (NC NLS eq.)

- Reduced ASDYM eq.: $x^\mu \to (t,x)$

Legare, [hep-th/0012077]

$$(i) \quad B' = 0$$

$$(ii) \quad C' - \dot{A} + [A, C]_* = 0$$

$$(iii) \quad A' - \dot{B} + [C, B]_* = 0$$

A, B, C: 2 times 2 matrices (gauge fields)

Further Reduction:

$$A = \begin{pmatrix} 0 & q \\ -\overline{q} & 0 \end{pmatrix}, \ B = \frac{i}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \ C = i\begin{pmatrix} q * \overline{q} & \overline{q}' \\ q' & -\overline{q} * q \end{pmatrix}$$

NOT traceless

$$(ii) \Rightarrow \begin{pmatrix} 0 & i\dot{q} - q'' - 2q * \overline{q} * q \\ i\dot{\overline{q}} + \overline{q}'' - 2\overline{q} * q * \overline{q} & 0 \end{pmatrix} = 0$$

$$i\dot{q} = q'' + 2q * \overline{q} * q$$

: NC NLS eq. !!!

[MH, PLB625,324]

Note: $A, B, C \in u(2) \xrightarrow{\theta \to 0} su(2)$

U(1) part is necessary !

NC Ward's conjecture (NC Burgers eq.)

- Reduced ASDYM eq.: $x^{\mu} \to (t, x)$

MH & K.Toda, JPA36 [hep-th/0301213]

$$(i) \quad \dot{A} + \underline{[B, A]}_{*} = 0$$

$$(ii) \quad \dot{C} - B' + \underline{[B, C]}_{*} = 0, \qquad A, B, C \in \underline{u(1)}$$

should remain

$$\cong u(\infty)$$

Further Reduction: $A = 0,\ B = u' - u^2,\ C = u$

$$(ii) \Rightarrow \quad \dot{u} = u'' + 2u * u'$$

: NC Burgers eq. !!!

Note: Without the commutators [,], (ii) yields:

$$\dot{u} = u'' + \underbrace{u' * u + u * u'}_{\text{Symmetric}}$$

: neither linearizable nor Lax form

NC Ward's conjecture (NC KdV eq.)

- Reduced ASDYM eq.: $x^{\mu} \to (t, x)$

MH, PLB625, 324 [hep-th/0507112]

$$(i) \quad B' = 0$$

$$(ii) \quad C' + \dot{A} + [A, C]_* = 0$$

$$(iii) \quad A' - \dot{B} + [C, B]_* = 0$$

A, B, C: 2 times 2 matrices (gauge fields)

Further Reduction:

$$A = \begin{pmatrix} q & -1 \\ q' + q^2 & -q \end{pmatrix}, \ B = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix},$$

$$C = \begin{pmatrix} \frac{1}{2} q'' + q' * q & -q' \\ f(q, q', q'', q''') & -\frac{1}{2} q'' - q * q' \end{pmatrix}$$

NOT Traceless !

$$(ii) \Rightarrow \begin{pmatrix} \oplus & 0 \\ \otimes & -\oplus \end{pmatrix} = 0 \quad \Rightarrow \dot{q} = \frac{1}{4} q''' + \frac{3}{4} q' * q'$$

: NC pKdV eq. !!!

$u = q'$ → **NC KdV**

Note: $A, B, C \in gl(2) \xrightarrow{\theta \to 0} sl(2)$ **U(1) part is necessary !**

6. Conclusion and Discussion

- We derived very wide class of NC soliton eqs. in the frame work of NC KP or GD hierarchies.
- We proved the existence of infinite conserved quantities and exact multi-soliton sols. for them.
- We also gave some examples of NC Ward's conjecture, which guarantees physical pictures.
- The results shows that they still have very special properties though they include infinite (time!) derivatives.
- Of course there are still many things to be seen

Further directions

- Completion of NC Sato's theory
  - Theory of tau-functions

    → hidden symmetry (deformed affine Lie algebras?)

    Quasi-determinants play crutial roles ?
  - Geometrical descriptions from NC extension of the theories of Krichever, Mulase and Segal-Wilson and so on.
- Confirmation of NC Ward's conjecture
  - NC twistor theory

    e.g. Kapustin&Kuznetsov&Orlov, Hannabuss, Hannover group,…
  - D-brane interpretations → application to physics
- Foundation of Hamiltonian formalism for space-time noncommutativity
  - Liouville's theorem, Noether's theorem, etc.