Title: Correlators in integrable models with Separation of Variables

Speakers: Nikolay Gromov

Series: Quantum Fields and Strings

Date: February 02, 2021 - 2:00 PM

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Abstract: I will review recent progress in application of separation of variables method.

In particular I will review the construction for the integrable spin chains with gl(N) symmetry.

By finding, for the first time, the matrix elements of the SoV measure explicitly I will show how to compute various correlation functions and wave function overlaps in a simple determinant form.

General philosophy of application of these methods to the problems related to AdS/CFT, N=4 SYM etc. will be discussed too.

SoV

By N. Gromov

Based on: 2011.08229 1910.13442
1907.03788 1610.08032

With: A.Cavaglia F.Levkovich-Maslyuk
P.Ryan G.Sizov D.Volin

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Problem: $\langle \Psi | \hat{O} | \Phi \rangle = ?$

- In integrable theories

Important examples:

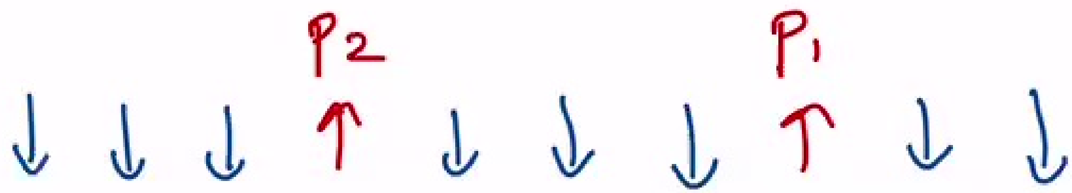
- Spin chains

  ⋮

- $N=4$ SYM

(related)

When a spin-chain is solvable by Bethe Ansatz → can use Bethe roots



$$\Psi = \sum_{perm} \dots e^{i n_1 p_1 + i n_2 p_2}$$

↗ coord BA

↙ in terms of p_i, or u_i

$$\langle \Psi | O | \Phi \rangle = \sum_{perm} \sum_{perm} \dots$$

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Many interesting cases are not solvable by BA

including $N=4$ SYM* ↓ next slide

Universal Language for int. models
Q-functions

$\exists$ BA $\Rightarrow$ Q's are Baxter poly.
$Q = \prod (u - u_i)$

$\nexists$ BA $\Rightarrow$ Q's functions of u
can be computed (e.g. $N=4$ SYM)

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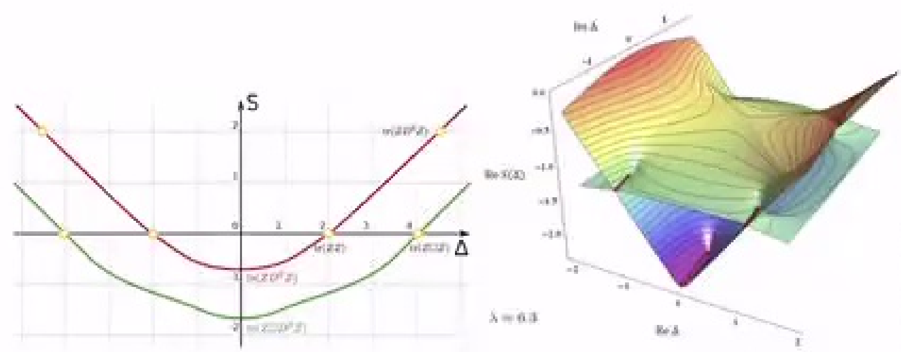
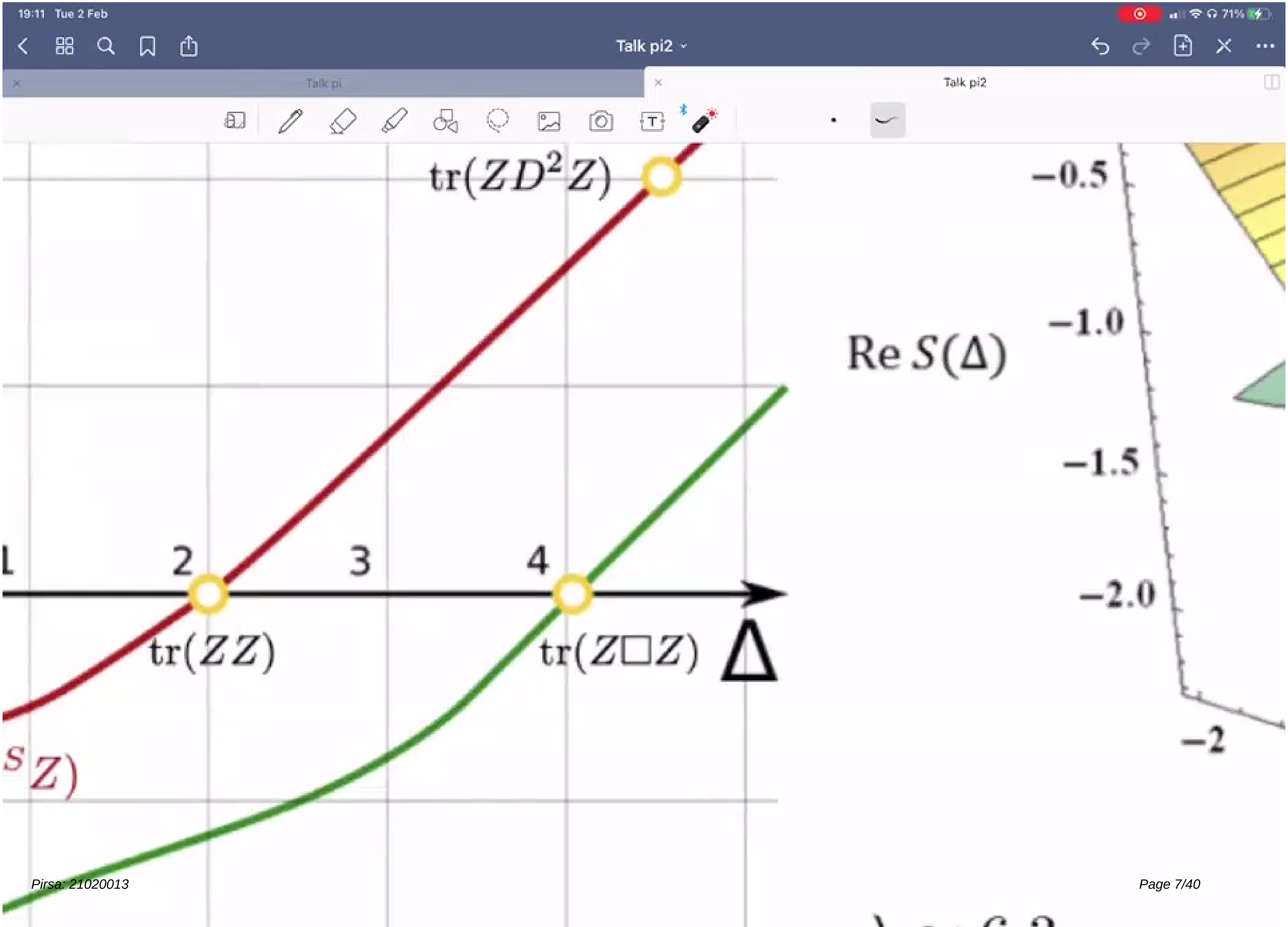
In $\mathcal{N}=4$ SYM at weak coupling one can approximate Q's by z-polynomials

But only up to the „wrapping order" in λ



$\mathrm{tr}\, Z D^5 Z$

Riemann surface of „twist-2" ops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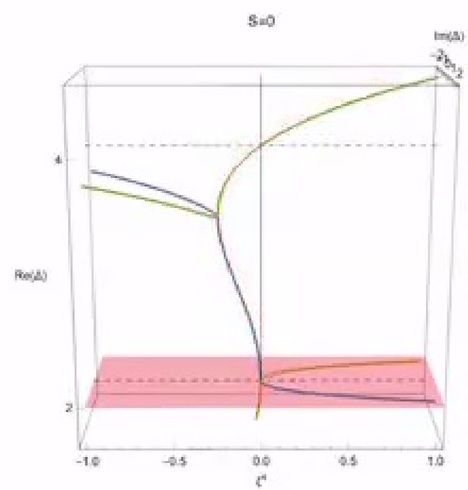
tr(ZD²Z)
2
3
4
tr(ZZ)
tr(Z□Z)
Δ
Re S(Δ)
−0.5
−1.0
−1.5
−2.0
−2

example from Fishnet



no magnons

many magnons

$\mathrm{tr}(\varphi_1^2)$ and $\mathrm{tr}(\varphi_1^2 \varphi_2 \varphi_2^\dagger)$

non-perturbative „mixing"

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Goal: develop tools for computing $\langle \Psi | \hat{O} | \Phi \rangle$ in terms of Q-functions

- SoV — „Sep. of Variables"

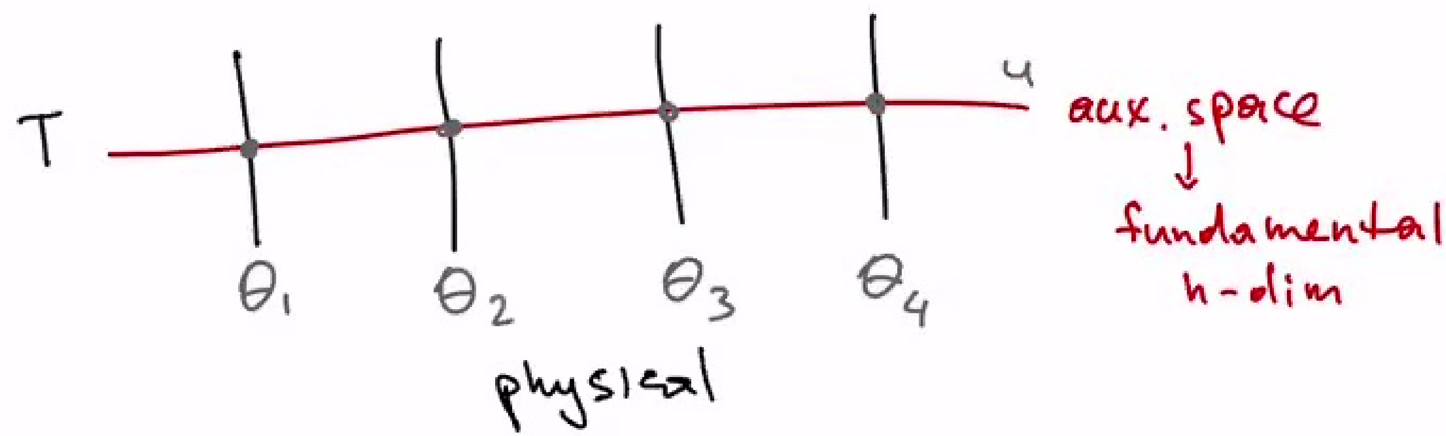
  r, φ, θ

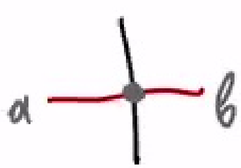
  $$\Psi(r,\varphi,\theta) = R(r)\,\Phi(\varphi)\,\Theta(\theta)$$

  $r^2 \cos\theta$

- how to build those nice coords
- building blocks
- me

Set-up: $sl(n)$ spin-chain

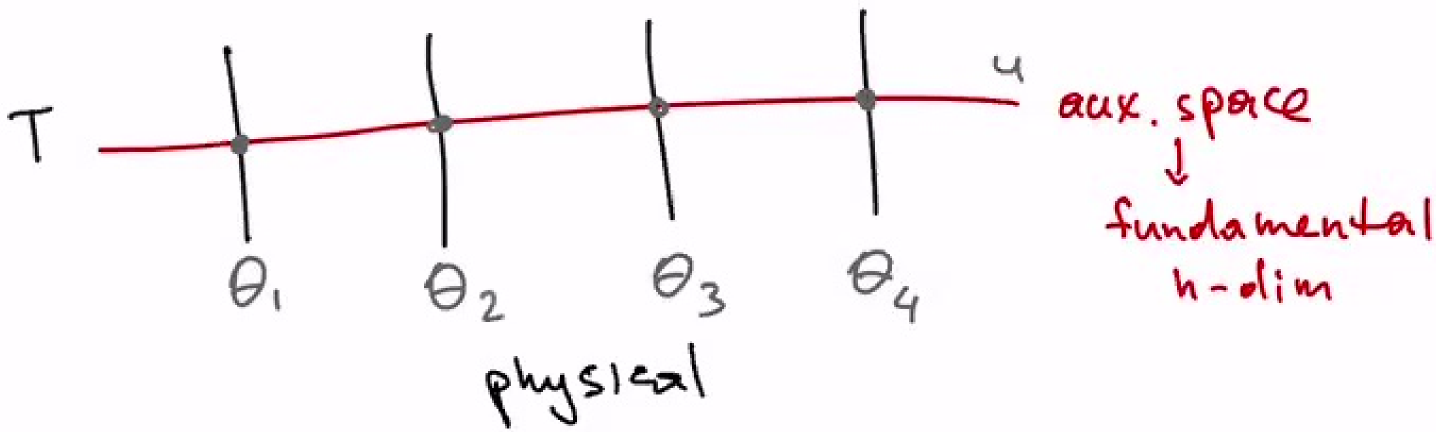


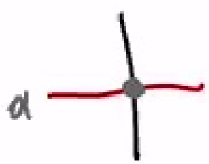


$$= u\,\delta_{ab} + i\,E_{ba}$$

← sl_n generator in some rep

Set-up: $sl(n)$ spin-chain

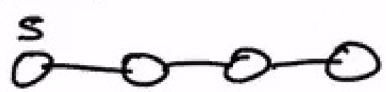




$$= u\,\delta_{ab} + i\,E_{ba}$$

← sl_n generator in some rep

representation: spin-s reps



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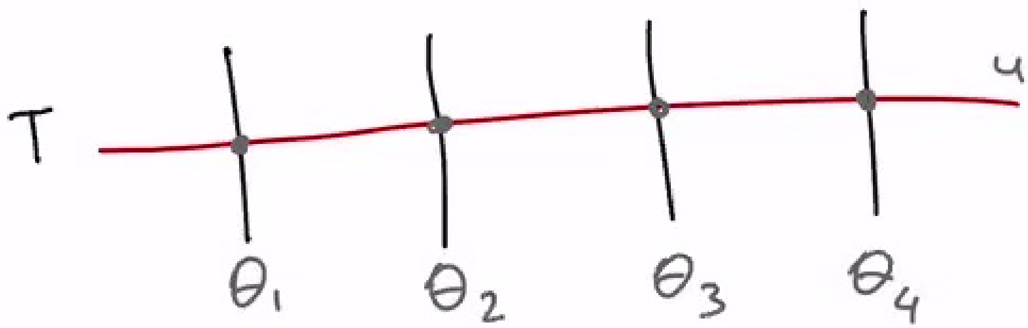
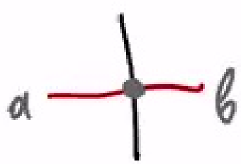
Set-up: $sl(n)$ spin-chain



aux. space
↓
fundamental
n-dim

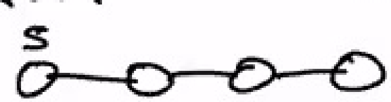
physical

← sl_n generator in some rep



$$= u\,\delta_{ab} + i\,E_{ba}$$

representation — spin-s reps



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Sklyanin SOV

$sl(2)$

$$T = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$$ ← poly deg-n

- construct p_α, x_β ?
  ⟷ simple comb. of A, B, C, D
- classically p ← quasimom
  i.e. e^p ← eigenvalue of T

if $B = 0 \Rightarrow A$ and D are $e^{\pm p}$

$$A(x_\alpha) = e^{p_\alpha} \qquad B(x_\alpha) = 0$$

$$[p_\alpha, x_\beta] = -i\,\delta_{\alpha\beta}$$

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Algebraic BAE : $|\Psi\rangle = B(u_1) \dots B(u_M)|\Omega\rangle$ ← all up

$$\langle \vec{x}| \hat{B}(u) = \prod_{\alpha=1}^{L} (u - x_\alpha) \langle \vec{x}|$$

$$\langle \vec{x}|\Psi\rangle = \prod_{\alpha=1}^{L} \prod_{i=1}^{M} (u_i - x_\alpha) \langle \vec{x}|\Omega\rangle$$

$\langle \vec{x}|\Omega\rangle = 1$ ← norm. of $\langle \vec{x}|$

$$= \pm \prod_{\alpha=1}^{L} Q(x_\alpha)$$

↑ wave function is factorized

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Algebraic BAE : $|\Psi\rangle = B(u_1) \ldots B(u_M) |\Omega\rangle$ ← all up

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$$\langle \vec{x} | \Psi \rangle = \prod_{\alpha=1}^{L} \prod_{i=1}^{M} (u_i - x_\alpha) \langle \vec{x} | \Omega \rangle$$

$$= \pm \prod_{\alpha=1}^{L} Q(x_\alpha)$$

$\langle \vec{x} | \Omega \rangle = 1$ ← norm. of $\langle \vec{x} |$

wave function is factorized

$$\Psi = R\, \Theta\, \Phi$$

Sklyonin's magic recipy

$$T = \begin{pmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{23} & T_{34} \\ T_{31} & T_{32} & T_{33} \end{pmatrix}$$

can try the same

$T_{12} = 0 \quad T_{13} = 0 \quad e^{P} = T_{11}$

too constraining

$$T' = K^{-1} T K \qquad K = \begin{pmatrix} 1 & \alpha & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

find α: $T'_{13} = 0$

$u+i \qquad u-i$

$$T'_{12} = 0 \iff B(u) = T_{23}^2 T_{12} - T_{23} T_{22} T_{13} + T_{13} T_{11} T_{23} - T_{13} T_{21} T_{13}$$

$$B(x_\alpha) = 0 \qquad T'_{11} = e^{P_\alpha}$$

Algebraic BAE : $|\Psi\rangle = B(u_1) \dots B(u_M)|\Omega\rangle$

all up

$$\langle \vec{x}| \hat{B}(u) = \prod_{\alpha=1}^{L}(u - x_\alpha)\langle \vec{x}|$$

$$\langle \vec{x}|\Psi\rangle = \prod_{\alpha=1}^{L}\prod_{i=1}^{M}(u_i - x_\alpha)\langle \vec{x}|\Omega\rangle$$

$$= \pm \prod_{\alpha=1}^{L} Q(x_\alpha)$$

$\langle \vec{x}|\Omega\rangle = 1$ ← norm. of $\langle \vec{x}|$

wave function is factorized

$$\Psi = R\,\Theta\,\Phi$$

$$K T K^{-1} = T \qquad B^{good} = B + \alpha A + \alpha C$$

States in SOV

in algebraic nested BAE

$$\Psi = \sum_{\text{permutations}} \dots\dots T_{12}(u_i)\, T_{13}(v_j)\, |\Omega\rangle$$

not clear SOV works!

But if you beleive in magic then

$$\Psi = B^{8}(u_1) \dots\dots B^{8}(u_M)\, |\Omega\rangle$$

mom carrying

$$\langle x|\, B = \prod_{\alpha=1}^{L} (u - x_{\alpha,a})\, \langle x| \qquad a = 0,1,2$$

$$\langle x|\Psi\rangle = \prod_{\alpha} Q(x_{\alpha,a})$$

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$$\langle x | \Psi \rangle = \prod_{\alpha, a} Q(x_{\alpha, a})$$

$$E = \frac{1}{u_i^2 + 1/u_i}$$

$$\langle x | \Psi \rangle = \prod Q(x_{\alpha, a})$$

are we happy?

NOT (yet) happy

- $\langle \Phi | y \rangle = \prod \ldots\ldots$ ← smile ?
- $\mu^{-1} = \langle x | y \rangle$ ← nice

- $|y\rangle$ is right eigenstate of B?
  - $\langle x|y\rangle = \Gamma_{xy}$ ← smile
  - $\langle \phi|y\rangle$ is not a product
- $|y\rangle$ is $\langle x|^{\dagger}$

  $\langle \phi|y\rangle$ works $= \Gamma$

  $\langle x|y\rangle =$ ugly ☹

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Functional SoV

Idea: assuming SoV work, consider

$\langle \psi^A | \psi^B \rangle = N_A \delta_{AB}$ eigenstates of T

$$\sum_{x,y} \langle \psi^A | y \rangle \mu \langle x | \psi^B \rangle = \sum_{x,y} \prod Q^A \mu \prod Q^B = \delta_{AB}$$

$N^L \times N^L - N^L$ ident.

so we would have $N^2 - N$ orthogonality relations on Q's

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Sl(2) case

$$E_{12} = \partial_x \qquad E_{21} = -x^2\partial_x - 2sx$$

$$E_{11} = -x\partial_x - s \qquad E_{22} = x\partial_x + s$$

scalar product: monomials are $\perp$, but

$$e_n = x^n \sqrt{\frac{\Gamma(n+2s)}{\Gamma(n+1)\Gamma(2s)}} \qquad \|e_n\| = 1$$

BAE

$$\prod_{i=1}^{L}(u-\theta_i) \qquad \prod(u-u_j)$$

$$\frac{Q_\theta(u_k - is)}{Q_\theta(u_k+is)} = -\frac{Q(u_k+i)}{Q(u_k-i)} \qquad k = 1 \ldots M$$

$$T(u) = Q_\theta^{[-2s]}\frac{Q^{--}}{Q} + Q_\theta^{[+2s]}\frac{Q^{++}}{Q}$$

$$Q_\theta(u_k + is) \qquad Q(u_k - i)$$

$$T(u) = Q_\theta^{[-2s]} \frac{Q^{--}}{Q} + Q_\theta^{[+2s]} \frac{Q^{++}}{Q}$$

$$\hat{O}^A = Q_\theta^{[2s]} D^2 - T^A + Q_\theta^{[-2s]} D^{-2}$$

$$\hat{O} Q = 0$$

$$((f g)) \text{ s.t. } ((f \hat{O} g)) = ((g \hat{O} f))$$

$$\| \quad \int_{-\infty}^{+\infty} \mu_\alpha(u) f(u) g(u)$$

$$\mu_\alpha = \text{periodic} \cdot \prod_{\beta=} \frac{\Gamma(s - iu + i\theta_\beta)}{\Gamma(s \ldots)}$$

$$\text{periodic} = \frac{1}{1 - e^{2\pi(u - \theta_\alpha - is)}} \qquad \alpha = 1 \ldots L$$

$$\langle\!\langle Q^A (\hat{O}^A - \hat{O}^B) Q^B \rangle\!\rangle_\alpha = 0$$

$$\|$$

$$\langle\!\langle Q^A (T^A - T^B) Q^B \rangle\!\rangle_\alpha \qquad T^A = I^A_\beta u^\beta$$

(e.v. of cons. ∫)

$$\|$$

$$\langle\!\langle Q^A u^\beta Q^B \rangle\!\rangle_\alpha (I^A_\beta - I^B_\beta) = 0$$

L equations

$$\Downarrow$$

$$\det_{\alpha,\beta} \langle\!\langle Q^A u^\beta Q^B \rangle\!\rangle_\alpha = 0 \quad \text{if } A \neq B$$

$L \times L$

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$$\det_{\substack{\alpha,\beta \\ L\times L}} \left(\left(Q^A u^\beta Q^B \right) \right)_\alpha = 0 \quad \text{if } A \neq B$$

$x_\alpha = \theta_\alpha + is + in_\alpha \qquad n_\alpha \geq 0$

$$M_{n_1 \ldots n_L} = \frac{\Delta(\{x^\alpha\})}{\Delta(\{\theta_\alpha\})} \prod_{\alpha=1}^{L} \frac{r_{\alpha,n_\alpha}}{r_{\alpha,0}}$$

Pochhammer

$$r_{\alpha,n} = -\frac{1}{2\pi} \prod_{\beta=1}^{L} \left(n+1-i\theta_\alpha + i\theta_\beta\right)_{2s-1}$$

SoV int.

$$\sum_{n_1 \ldots n_L} \prod_\alpha Q^A(x_\alpha) \prod_\beta Q^B(x_\beta) \, \mu_{SoV} = 0$$

? ||

$\langle x | y \rangle$

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α, β

$L \times L$

$x_\alpha = \theta_\alpha + is + in_\alpha \qquad n_\alpha \geq 0$

$$M_{n_1 \ldots n_L} = \frac{\Delta(\{x^\alpha\})}{\Delta(\{\theta_\alpha\})} \prod_{\alpha=1}^{L} \frac{r_{\alpha, n_\alpha}}{r_{\alpha, 0}}$$

Pochhammer

$$r_{\alpha, n} = -\frac{1}{2\pi} \prod_{\beta=1}^{L} (n+1-i\theta_\alpha + i\theta_\beta)_{2s-1}$$

SoV int.

$$\sum_{n_1 \ldots n_L} \underbrace{\prod_\alpha Q^A(x_\alpha)}_{\langle x|\Psi\rangle} \underbrace{\prod_\beta Q^B(x_\beta)}_{\langle \Phi|y\rangle} \underbrace{\mu_{SoV}}_{\langle x|y\rangle} = 0$$

that works!

$$\det_{L \times L}\left(Q^A Q^B u^\beta \right)_\alpha = \langle \Phi | \Psi \rangle$$

$|\Psi\rangle = \prod B(v_i)|0\rangle$

$$\langle \Phi|\Psi\rangle = \sum \mu \prod Q^A \prod Q^B$$

SL(n) - new features

TQ - relation

Q_θ's

$$\hat{O} Q_1 = \ldots D^3 Q_1 + \tau_2 D Q_1 + \tau_1 D^{-1} Q_1 + \ldots D^{-3} Q_1$$

$$\hat{O}^+ = \ldots D^{-3} + \tau_2 D^{-1} + \tau_1 D + \ldots D^3$$

$$\hat{O}^+ Q_1 \neq 0 \qquad \hat{O}^+ Q_{12} = 0$$

$$\hat{O}^+ Q_{13} = 0$$

← aux. roots Q

(( )) same as sl_2

$$\det_{2L\times 2L} \left(\left(Q_1^A \, u_{\alpha}^{\beta-1} \, D^{\pm} \, Q_{1,2 \text{ or } 3} \right)\right)_\alpha$$

$\alpha = 1\ldots L$

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$((\quad))$ same as sl_2

$$\det_{2L\times 2L} \left(\left(Q_1^A \; u_{1\ldots L}^{\beta-1} \; D^{\pm} \; Q_{1,2 \text{ or } 3} \right)\right)_\alpha = 0$$

sl_n orthogonality

$$\det_{(a,\alpha)(b,\beta)} \left(\left(Q_1^A \; u^{\beta-1} \; D^{3-2b} \; Q^B_{1,a+1} \right)\right)_\alpha = 0$$

$2L\times 2L$ det

$\int \to \Sigma$

$$\underbrace{\Sigma \, M}_{\text{measure}} \; \underbrace{\Pi \, Q_1^A}_{\langle x|\Psi\rangle} \; \underbrace{\Pi \begin{pmatrix} Q_{12}^{B+} & Q_{13}^{B+} \\ Q_{12}^{B-} & Q_{13}^{B-} \end{pmatrix}}_{\langle}$$

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$$Q_{13} = 0$$

(( )) same as sl_2

$$\det_{2L\times 2L} \left(\left(Q_1^A \, u_{\substack{\| \\ 1\ldots L}}^{\beta-1} \, D^{\pm} \, Q_{1,2 \text{ or } 3} \right)\right)_\alpha = 0$$

sl_n orthogonality

$$\det_{(a,\alpha)(b,\beta)} \left(\left(Q_1^A \, u^{\beta-1} \, D^{3-2b} \, Q^B_{1,a+1} \right)\right)_\alpha = 0$$

$2L \times 2L$ det

$$\int \to \sum$$

$$\underbrace{\sum M}_{\text{measure}} \; \underbrace{\prod Q_1^A}_{\langle x|\Psi\rangle} \; \underbrace{\prod \begin{pmatrix} Q^{B+}_{12} & Q^{B+}_{13} \\ Q^{B-}_{12} & Q^{B-}_{13} \end{pmatrix}}_{\langle \Phi|y\rangle}$$

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extracting $\langle x|y\rangle^{-1}$

$$M_{\mathrm{y,x}}\big|_{m_{\alpha,a}=n_{\alpha,a}-\sigma_{\alpha,a}+\sigma^0_{\alpha,a}} = (-1)^{|\sigma|}\frac{\Delta_1\Delta_2}{\Delta_0^2}\prod\frac{r_{\alpha,n_{\alpha,1}}r_{\alpha,n_{\alpha,2}}}{r^2_{\alpha,0}}$$

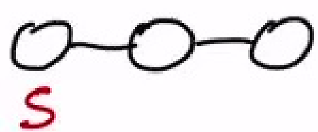
For example $sl(3)$ $L=2$:

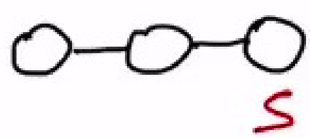
$$M^{1100}_{2000} = \frac{\theta_{12}+2i}{\theta_{12}}\frac{r_{12}}{r_{10}} = +\frac{\mathrm{s}(2\mathrm{s}+1)\,(2\mathrm{s}-i\theta_{12})\,(-i\theta_{12}+2\mathrm{s}+1)}{\theta_{12}\,(\theta_{12}+i)}$$

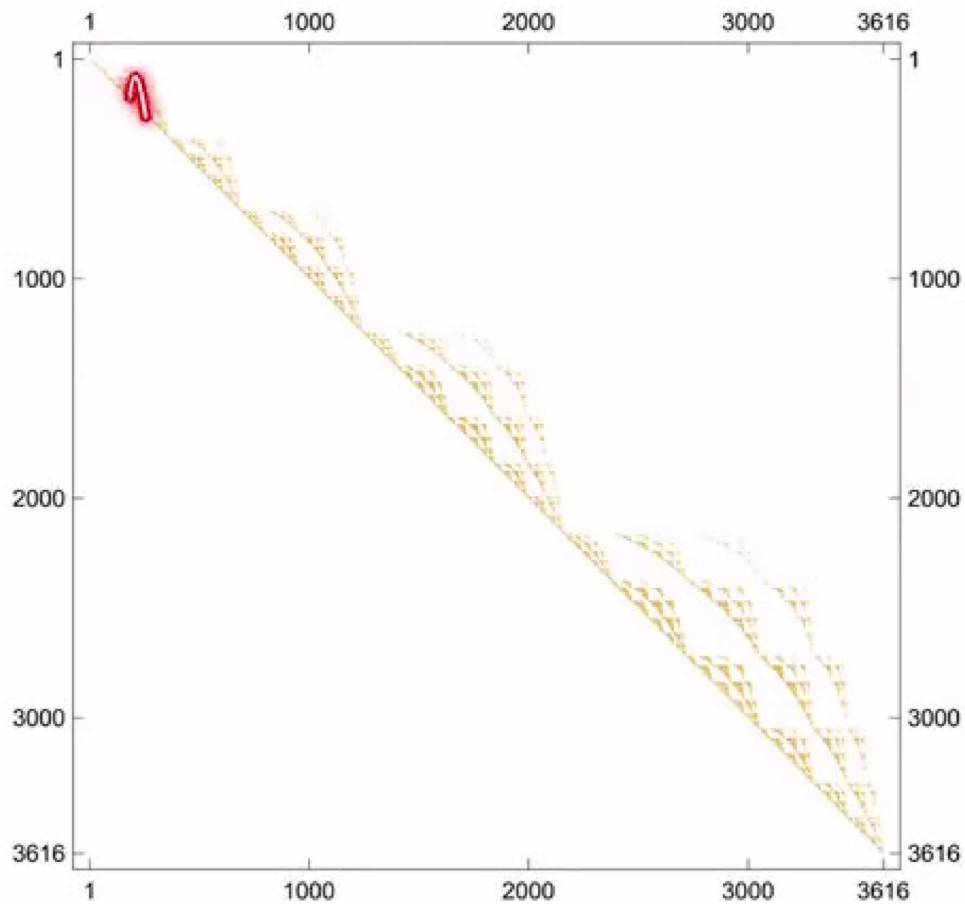
$$\theta_{12} = \theta_1 - \theta_2$$

Dual SoV states

$$\underbrace{\prod_{\alpha} \begin{vmatrix} Q^{+}_{12}(x_{\alpha 1}) & Q^{+}_{13}(x_{\alpha 1}) \\ Q^{-}_{12}(x_{\alpha 2}) & Q^{-}_{13}(x_{\alpha 2}) \end{vmatrix}}_{\langle \Psi | y \rangle}$$

x :  "fundamental"

 : y "anti-fundamental"



sl(4) L = 3

$$B = T_{23}\, T_{12}^{--}\, T_{23} - T_{23}\, T_{22}^{--}\, T_{13} + \dots$$

$$\langle x | \hat{B} = B \langle x |$$

$$C = T_{23}\, T_{12}\, T_{23}^{++} - T_{23}\, T_{22}\, T_{13}^{++} + \dots$$

$$\hat{C} | y \rangle = | y \rangle C$$

$$\langle x | \psi \rangle = \prod Q_1 \qquad \langle \psi | y \rangle = \prod \begin{vmatrix} Q_{12} & Q_{13} \\ Q_{12} & Q_{13} \end{vmatrix}$$

examples $L=2$ $sl(3)$

$\langle x|$

$$\langle 0,0;1,1| = -\frac{i x_1 x_2}{2is-\theta_{12}} + \frac{(2s+1)x_2^2}{2s} + \frac{\theta_{12} y_2}{2s(\theta_{12}-2is)}$$

$$\langle 1,1;0,0| = \frac{1}{(\theta_{12}+2is)^2}\left(x_1 x_2 \left(i\theta_{12}(4s+1)+2s\right) + \frac{\theta_{12}^2(2s+1)x_1^2}{2s} - 2s(2s+1)x_2^2 + \frac{\theta_{12}^2 y_1}{2s} + i\theta_{12} y_2 \right)$$

$$\langle 0,0;2,0| = x_2^2$$

$$\langle 1,0;1,0| = \frac{1}{\theta_{12}+2is}\left(i(2s+1)x_2^2 + (\theta_{12}-i)\, x_1 x_2 \right)$$

$$\langle 2,0;0,0| = i(2s+1)x_2^2 + (\theta_{12}-i)\, x_1 x_2 \,.$$

$|y\rangle$

$$|0,0;1,1\rangle = \frac{\theta_{12} y_2 - 2is\, y_1}{\theta_{12}-2is}$$

$$|1,1;0,0\rangle = y_1$$

$$|0,0;2,0\rangle = \frac{1}{\theta_{12}-2is}\left(\frac{\theta_{12}(\theta_{12}-i)\, x_2^2}{\theta_{12}-i(2s+1)} + \frac{4\theta_{12} s\, x_1 x_2}{i\theta_{12}+2s+1} + \frac{2s(2s+1)x_1^2}{2is+i-\theta_{12}} + 2is\, y_1 - \theta_{12} y_2 \right)$$

$$|1,0;1,0\rangle = \frac{-i(2s+1)x_1^2 + (\theta_{12}+i)\, x_1 x_2 + i y_1 - i y_2}{\theta_{12}-2is}$$

$$|2,0;0,0\rangle = x_1^2 - y_1 \,.$$

$\langle x|y\rangle^{-1}$

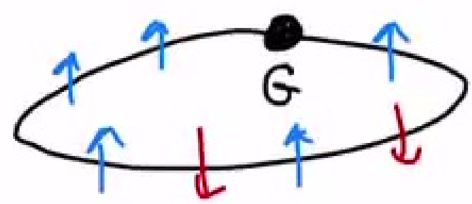
$$\begin{pmatrix}
-\frac{4s^2(2s+i\theta_{12})^2}{\theta_{12}^2} & 0 & \frac{s(2s+1)(2s+i\theta_{12})(i\theta_{12}+2s+1)}{\theta_{12}(\theta_{12}-i)} & \frac{4s^2(\theta_{12}^2+4s^2)}{\theta_{12}^2(\theta_{12}^2+1)} & 0 \\
0 & -\frac{4s^2(2s-i\theta_{12})^2}{\theta_{12}^2} & 0 & \frac{4s^2(\theta_{12}^2+4s^2)}{\theta_{12}^2(\theta_{12}^2+1)} & \frac{s(2s+1)(2s-i\theta_{12})(-i\theta_{12}+2s+1)}{\theta_{12}(\theta_{12}+i)} \\
0 & 0 & -\frac{s(2s+1)(2s+i\theta_{12})(i\theta_{12}+2s+1)}{\theta_{12}(\theta_{12}-i)} & 0 & 0 \\
0 & 0 & 0 & \frac{4s^2(\theta_{12}^2+4s^2)}{\theta_{12}^2+1} & 0 \\
0 & 0 & 0 & 0 & -\frac{s(2s+1)(2s-i\theta_{12})(-i\theta_{12}+2s+1)}{\theta_{12}(\theta_{12}+i)}
\end{pmatrix}$$

coinsides with the prediction!

Observation

$\langle x|$ and $|y\rangle$ do not depend on twist

for quasi-periodic case



Can express a large number of correlators in det form!

$$\langle \Phi_{G'} | C(u) B(v) | \Psi_G \rangle \qquad Q \to Q(u-v)$$

Another class

$$\langle \Phi | \delta I | \Phi \rangle$$

$$((Q\, \delta \hat{O}\, Q))_\alpha = 0$$

$$\Downarrow$$

$$\delta I = \frac{\det}{\det}$$

for δ_{θ_i} can get local spin vars!

20:01 Tue 2 Feb

Talk pi2

Can express a large number of correlators in det form!

$$\langle \Phi_{G'} | C(u) B(v) | \Psi_G \rangle$$

$Q \to Q(u-v)$

$Q_{12} \to \ldots$

Another class

$$\langle \Phi | \delta I | \Phi \rangle$$

$$((Q\ \delta \hat{O}\ Q))_\theta = 0$$

$$\Downarrow$$

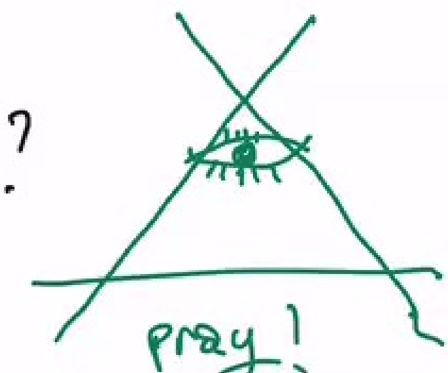
$$\delta I = \frac{\det}{\det}$$

for δ_{θ_i}

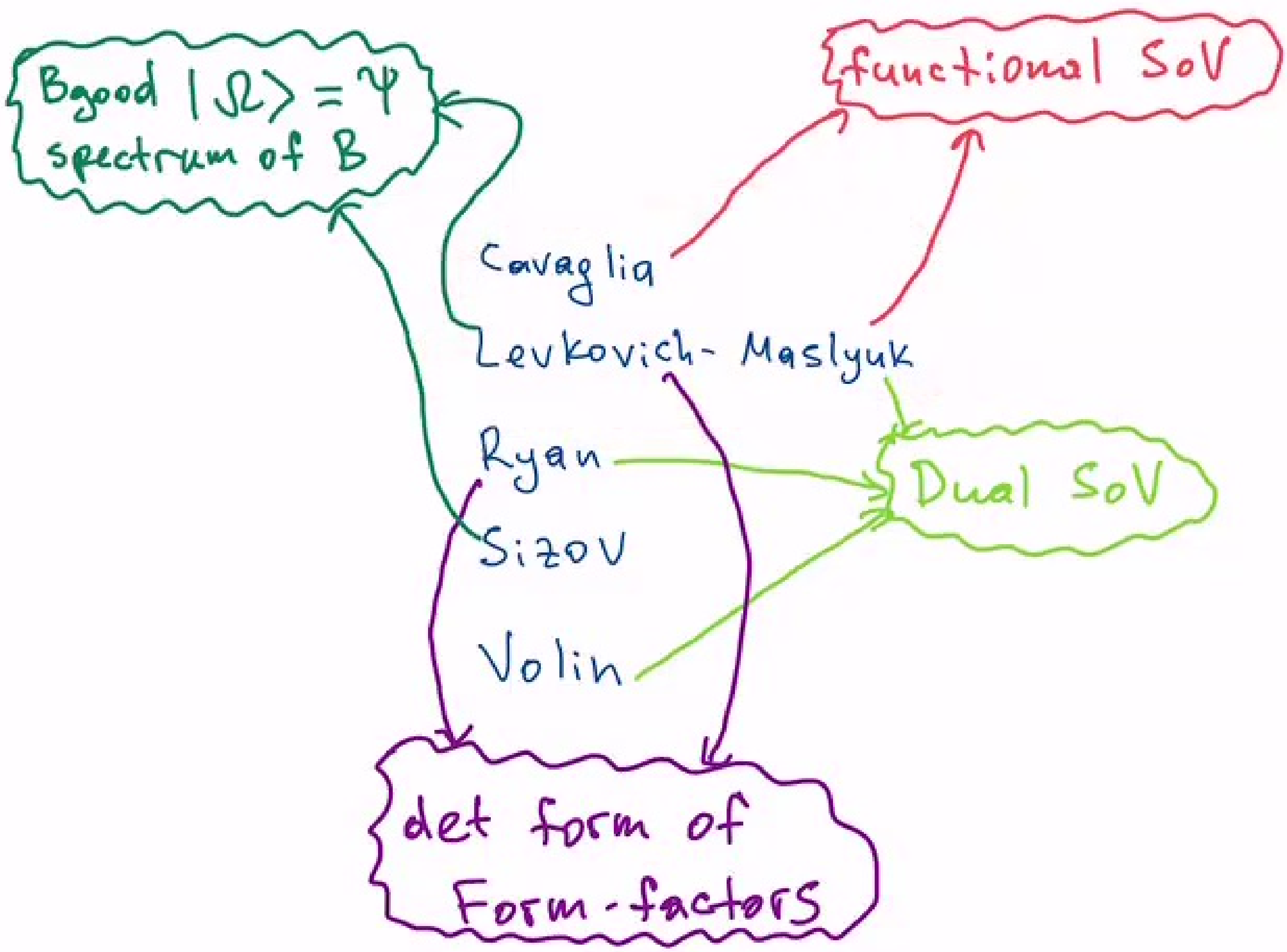
can get local spin vars!

Conclusions

- SoV basis and dual SoV basis
- Measure simple and explicit
- Can compute nontrivial overlaps and form factors
- Can we compute any $\hat{O}$?



Credits


Bgood |Ω⟩ = Ψ
spectrum of B
functional SoV
Cavaglia
Levkovich-Maslyuk
Ryan
Sizov
Volin
Dual SoV
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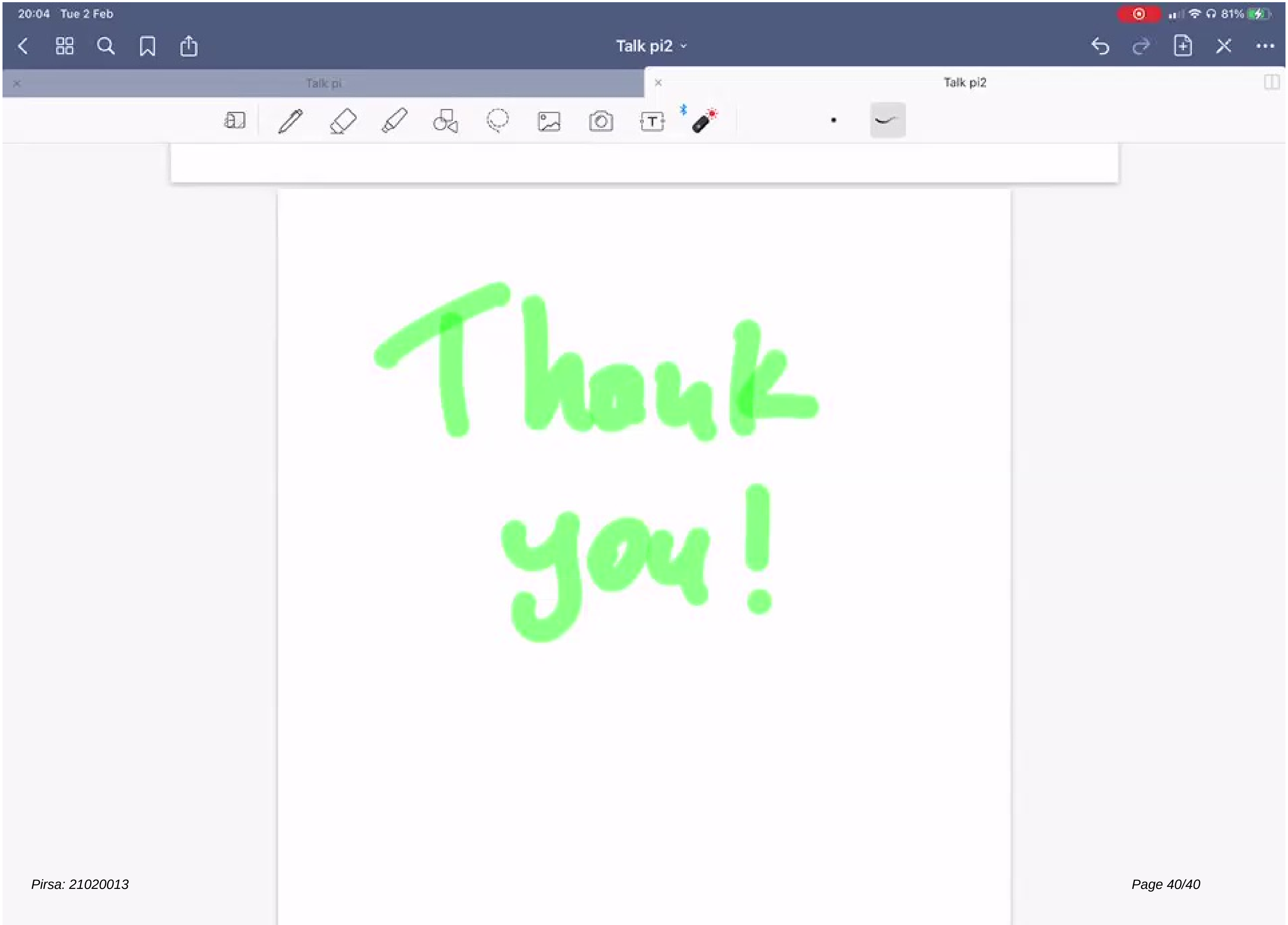
Form-factors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81%
Talk pi2
Talk pi
Talk pi2
Thank
you!