Correlations and quenches in integrable systems

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P. Calabrese, N. Slavnov, A. Faribault

Plan of the talk

Correlation dynamics

Systems which can be treated using ‘exact’ methods

Short overview of the methods used

Example 1: quantum spin chains

3 approaches: lattice, q group, field theory

Example 2: one-d Bose gas

repulsive, attractive

Example 3: the Richardson model

Quantum quenches

General comments

... quenches in the Richardson model

The contract: calculate dynamical correlation functions of local operators in interacting models

General form:

$$\langle \mathcal{O}(1)\mathcal{O}^\dagger(2) \rangle$$

some local operator

Ground state, prepared state, thermal average, ...

- Difficulty: multiparticle eigenstates are not obtained as simple products of single-particle states (alt., not created using simple products of local ops)
- Exact methods (integrability): traditionally restricted to equilibrium thermodynamics

Correlation functions: elements

$$S^{a,\bar{a}}(q,\omega) = 2\pi \sum_{\mu} |\langle 0|\mathcal{O}_q^a|\mu\rangle|^2 \delta(\omega - E_\mu + E_0)$$

1) Eigenstates basis: energies, states (+ norms)

→ ***Bethe Ansatz; quantum groups***

2) We need to be able to compute the matrix elements of the operators we're interested in

→ ***Algebraic Bethe Ansatz; q. groups***

3) We need to be able to perform the sum over intermediate states

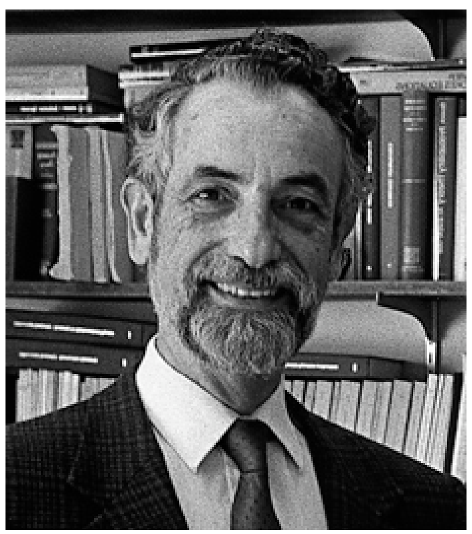
→ ***Numerics, analytics***

Models which we can treat:

- Heisenberg spin-1/2 chain

$$H = \sum_{j=1}^{N} \left[J\left(S_j^x S_{j+1}^x + S_j^y S_{j+1}^y + \Delta S_j^z S_{j+1}^z\right) - H_z S_j^z \right]$$

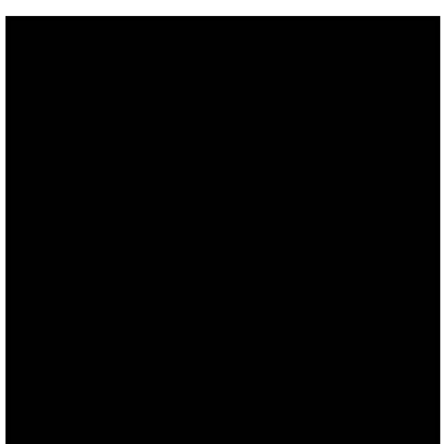
(finite lattice BA; quantum groups)



- Interacting Bose gas (Lieb-Liniger)

$$\mathcal{H}_N = -\sum_{j=1}^{N} \frac{\partial^2}{\partial x_j^2} + 2c \sum_{1\leq j<l\leq N} \delta(x_j - x_l)$$

(BA for finite particle numbers)



- Richardson model (+ Gaudin magnets)

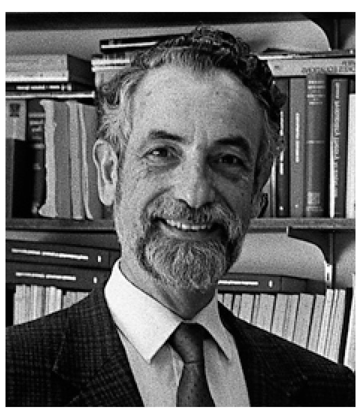
$$H_{BCS} = \sum_{\substack{\alpha=1 \\ \sigma=+,-}}^{N} \frac{\varepsilon_\alpha}{2} c_{\alpha\sigma}^\dagger c_{\alpha\sigma} - g \sum_{\alpha,\beta=1}^{N} c_{\alpha+}^\dagger c_{\alpha-}^\dagger c_{\beta-} c_{\beta+}$$

What we can calculate:

- DYNAMICAL STRUCTURE FACTOR

$$S^{a\bar{a}}(q,\omega) = \frac{1}{N}\sum_{j,j'=1}^{N} e^{iq(j-j')}\int_{-\infty}^{\infty} dt e^{i\omega t}\langle S^a_j(t) S^{\bar{a}}_{j'}(0)\rangle_c$$

→ ***inelastic neutron scattering***



- DENSITY-DENSITY FUNCTION

$$S(k,\omega) = \int dx \int dt e^{-ikx+i\omega t}\langle\rho(x,t)\rho(0,0)\rangle$$

- ONE-BODY FN

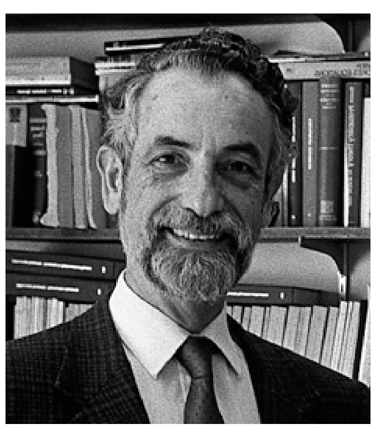
$$G_2(x,t) = \langle\Psi^\dagger(x,t)\Psi(0,0)\rangle$$

→ ***Bragg spectroscopy, interference experiments, ...***

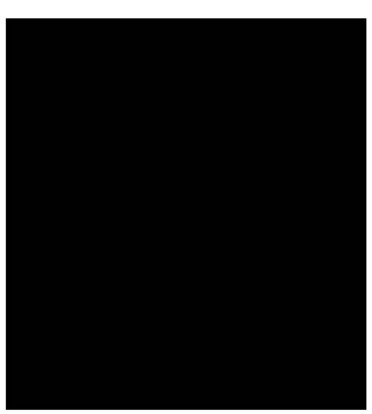
(zero temperature only (for now !))

Specific cases treated:

	Finite BA numerics	Analytics (q groups)
General XXZ AFM, Hz	done	no go
XXX gapless AFM, Hz=0		done: (2)+4 sp
XXZ gapped AFM, Hz=0		done: 2 sp
XXZ gapless AFM, Hz=0		done: 2 sp (t.b.p.)



	Finite BA numerics	Analytics (brute force)
Repulsive	done	no go
Attractive		done



	Finite BA numerics	*Quenches*
Richardson	done	done (t.b.p.)

Method 1: Bethe Ansatz

July 2, 1906 – March 6, 2005

Hans Bethe, 1931

$$H = \sum_{j=1}^{N} \left[J (S_j^x S_{j+1}^x + S_j^y S_{j+1}^y + \Delta S_j^z S_{j+1}^z) - H_z S_j^z \right]$$

Exact solution through Bethe Ansatz:

Eigenstate with M down spins fully characterized by set of rapidities $\{\lambda_j\}, \quad j = 1, ..., M$

$$\Psi(j_1, ..., j_M | \lambda_1, ..., \lambda_M) = \sum_P^{M!} A(P|\{\lambda\}) e^{i \sum_{a=1}^{M} k(\lambda_{P_a}) j_a}$$

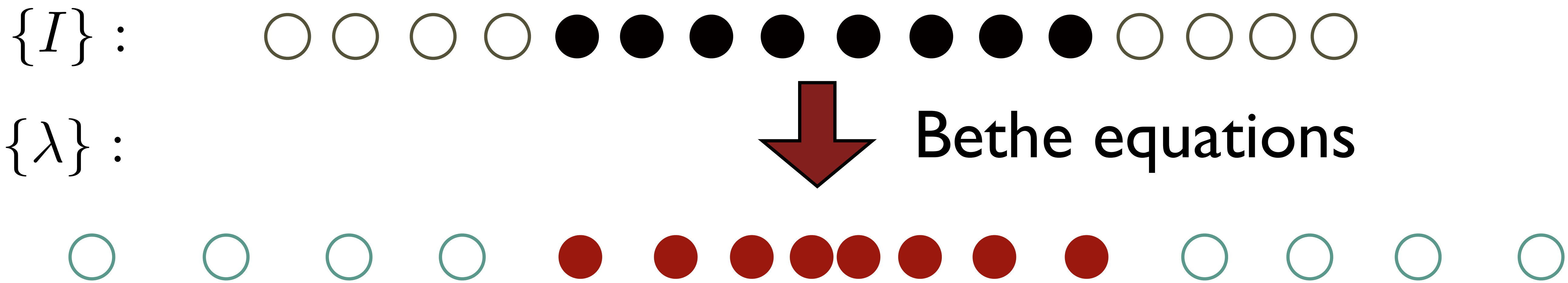
Known amplitudes ↑

The M rapidities are solutions of the Bethe equations

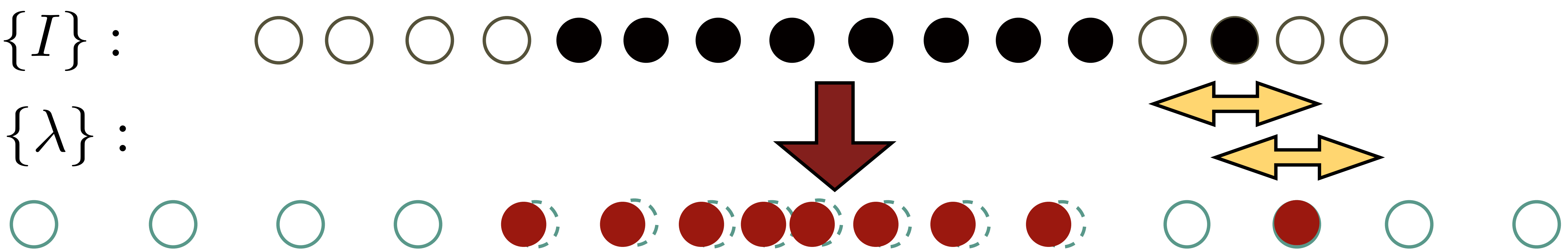
$$\theta_1(\lambda_j) - \frac{1}{N}\sum_{l=1}^{M}\theta_2(\lambda_j - \lambda_l) = 2\pi\frac{I_j}{N}, \qquad j = 1, ..., M$$

Eigenstates: labeled by set of quantum numbers

Ground state:



Simple excitations:



Solving the BE: nontrivial in general, still: it's feasible

Deformed strings (XXX)

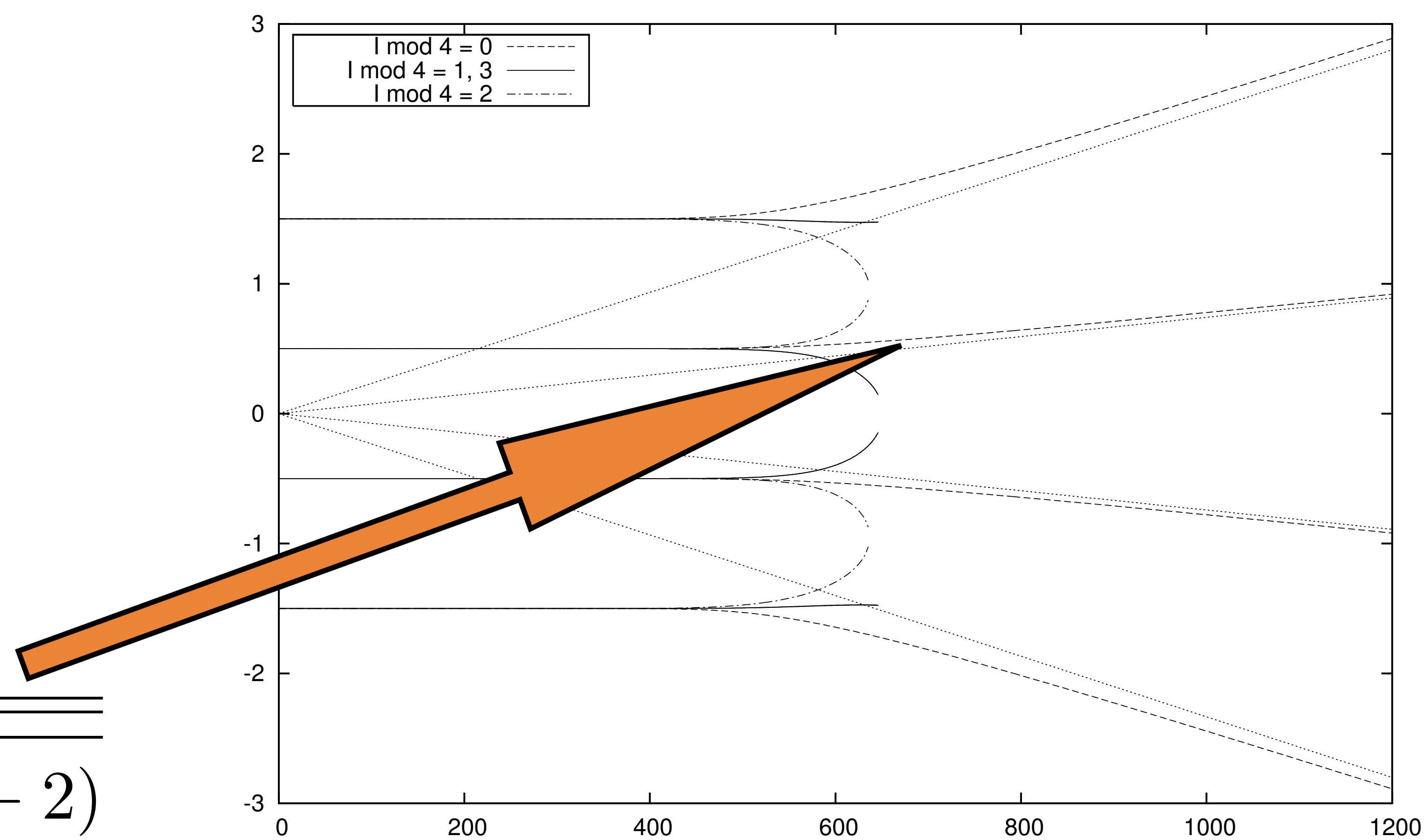
M = 2: Bethe, Vladimirov, Essler Korepin Schoutens, ...

Wide pairs, narrow pairs, extra real solutions for N > 22

Higher M

(R. Hagemans & JSC, JPA 2007)

Here: 4-strings on a chain of 1M sites



Asymptotes:

$$\Im\lambda = \frac{\Re\lambda}{\sqrt{N-3 \pm \sqrt{\frac{2}{3}(N-3)(N-2)}}}$$

Beyond strings: important for completeness, finite size, ...

Full understanding of solutions to BE remains to be obtained

Algebraic Bethe Ansatz

Like '2nd quantization' for Bethe Ansatz

Introduce family $A(\lambda), B(\lambda), C(\lambda), D(\lambda)$ of nonlocal operators which act in Hilbert space of model

$B(\lambda)$ creation operator, increasing particle number by 1

Wavefunctions: $|\Psi(\{\lambda\})\rangle = \prod_j B(\lambda_j)|0\rangle$

provided the rapidities satisfy Bethe equations

Mapping ABA ops to local ops: quantum inverse problem (Maillet 1999)

For spin chains: $A(\lambda), B(\lambda), C(\lambda), D(\lambda) \longleftrightarrow S_j^a$

State norms: Gaudin-Korepin formula

Form factors: Slavnov's theorem

Det representation of form factors from the Algebraic Bethe Ansatz

$$|\langle\{\mu\}|S^z_q|\{\lambda\}\rangle|^2 = \frac{|F^z_M(\{\mu\},\{\lambda\})|^2}{|N_M(\{\mu\})N_M(\{\lambda\})|} = \prod_{j=1}^{M}\left|\frac{\sinh(\mu_j - i\zeta/2)}{\sinh(\lambda_j - i\zeta/2)}\right|^2 \prod_{j>k=1}^{M}\left|\sinh^2(\mu_j-\mu_k)+\sin^2\zeta\right|^{-1} \times$$

$$\times \prod_{j>k=1}^{M}\left|\sinh^2(\lambda_j-\lambda_k)+\sin^2\zeta\right|^{-1} \frac{|\det[\mathbf{H}(\{\mu\},\{\lambda\}) - 2\mathbf{P}(\{\mu\},\{\lambda\})]|^2}{|\det\mathbf{\Phi}(\{\mu\})\det\mathbf{\Phi}(\{\lambda\})|}$$

All matrices are given explicitly as functions of the rapidities of the eigenstates involved:

$$\mathbf{H}_{ab}(\{\mu\},\{\lambda\}) = \frac{1}{\sinh(\mu_a-\lambda_b)}\left[\prod_{j\neq a}\sinh(\mu_j-\lambda_b-i\zeta) - \left[\frac{\sinh(\lambda_b+i\zeta/2)}{\sinh(\lambda_b-i\zeta/2)}\right]^N \prod_{j\neq a}\sinh(\mu_j-\lambda_b+i\zeta)\right],$$

(Kitanine, Maillet, Slavnov, Terras 1999 & 2000)

String states: need modified determinants

(Caux, Hagemans, Maillet 2005)

Integrability for correlations: generic features

- Exact realization of ground state, taking all 'entanglement' into account

- Exact realization of excited states (spinons, Lieb types I, II, Gaudinos,...), *irrespective of their energy*

- Action of local operators: accurately captured by using only a handful of BA excitations

→ ***incredibly efficient basis for many physically relevant correlations***

Correlation functions: elements

$$S^{a,\bar{a}}(q,\omega) = 2\pi \sum_{\mu} |\langle 0|\mathcal{O}_q^a|\mu\rangle|^2 \delta(\omega - E_\mu + E_0)$$

1) Eigenstates basis: energies, states (+ norms)

→ ***Bethe Ansatz; quantum groups*** ✓

2) We need to be able to compute the matrix elements of the operators we're interested in ✓

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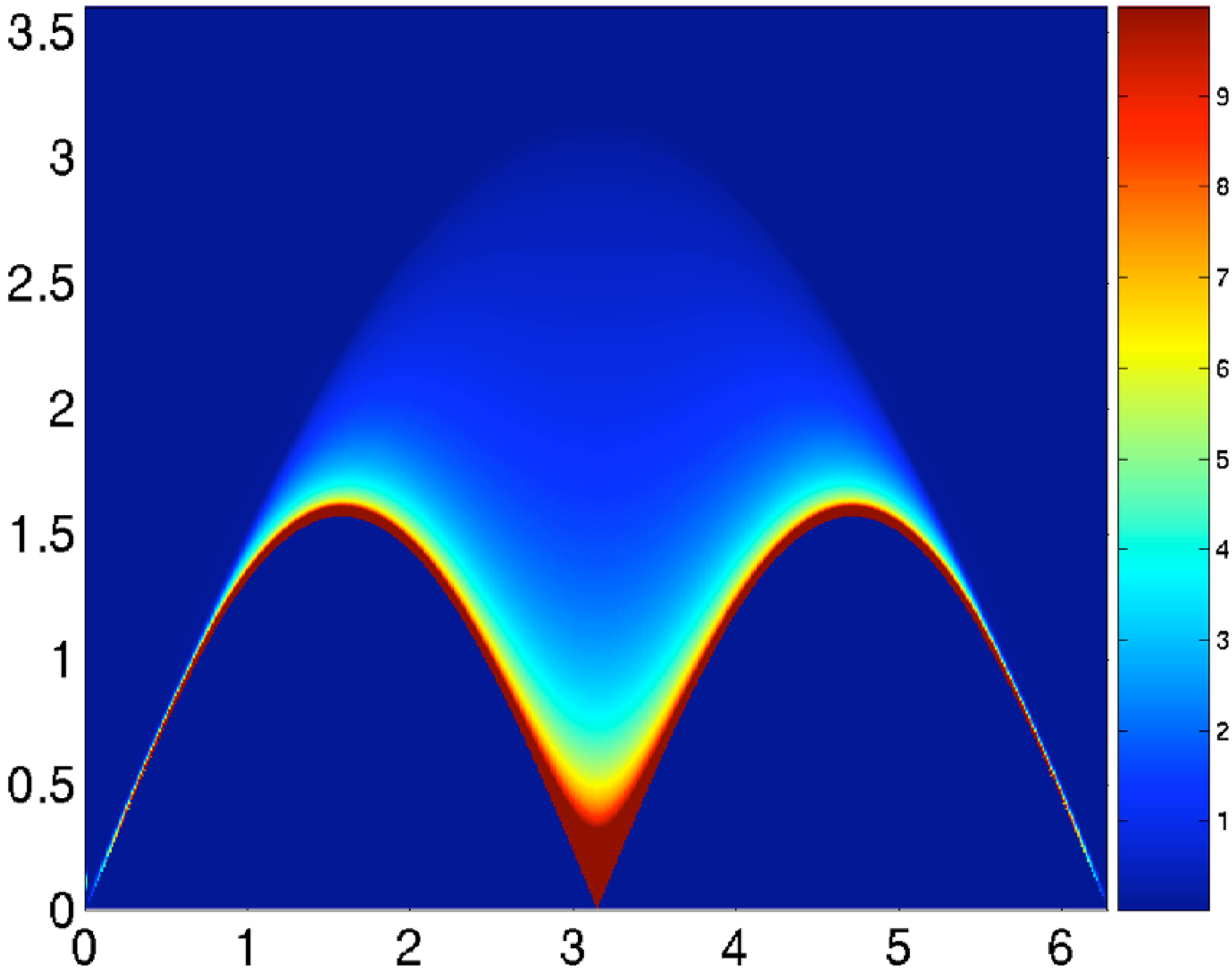
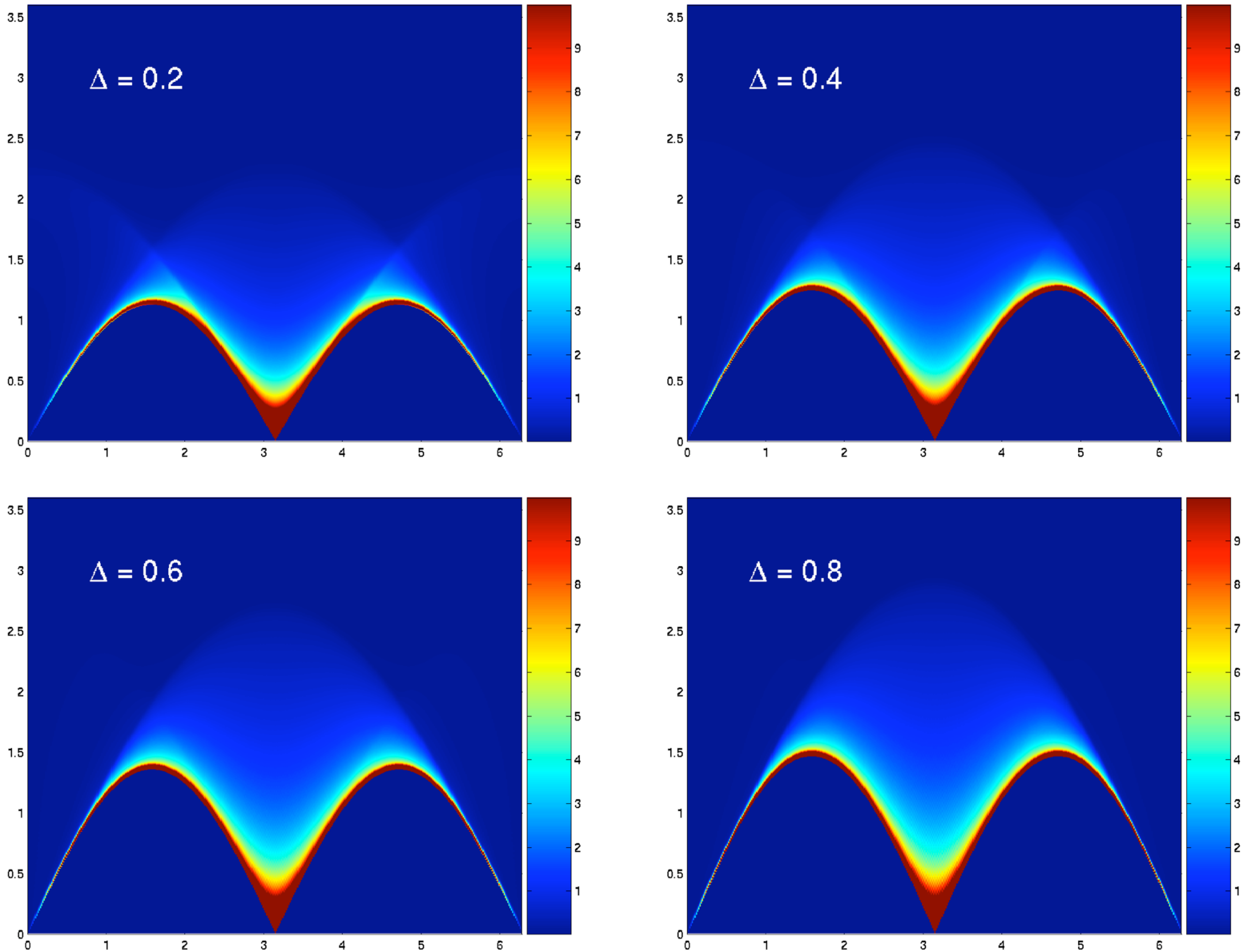
→ ***Numerics, analytics***

Method 1: ABACUS

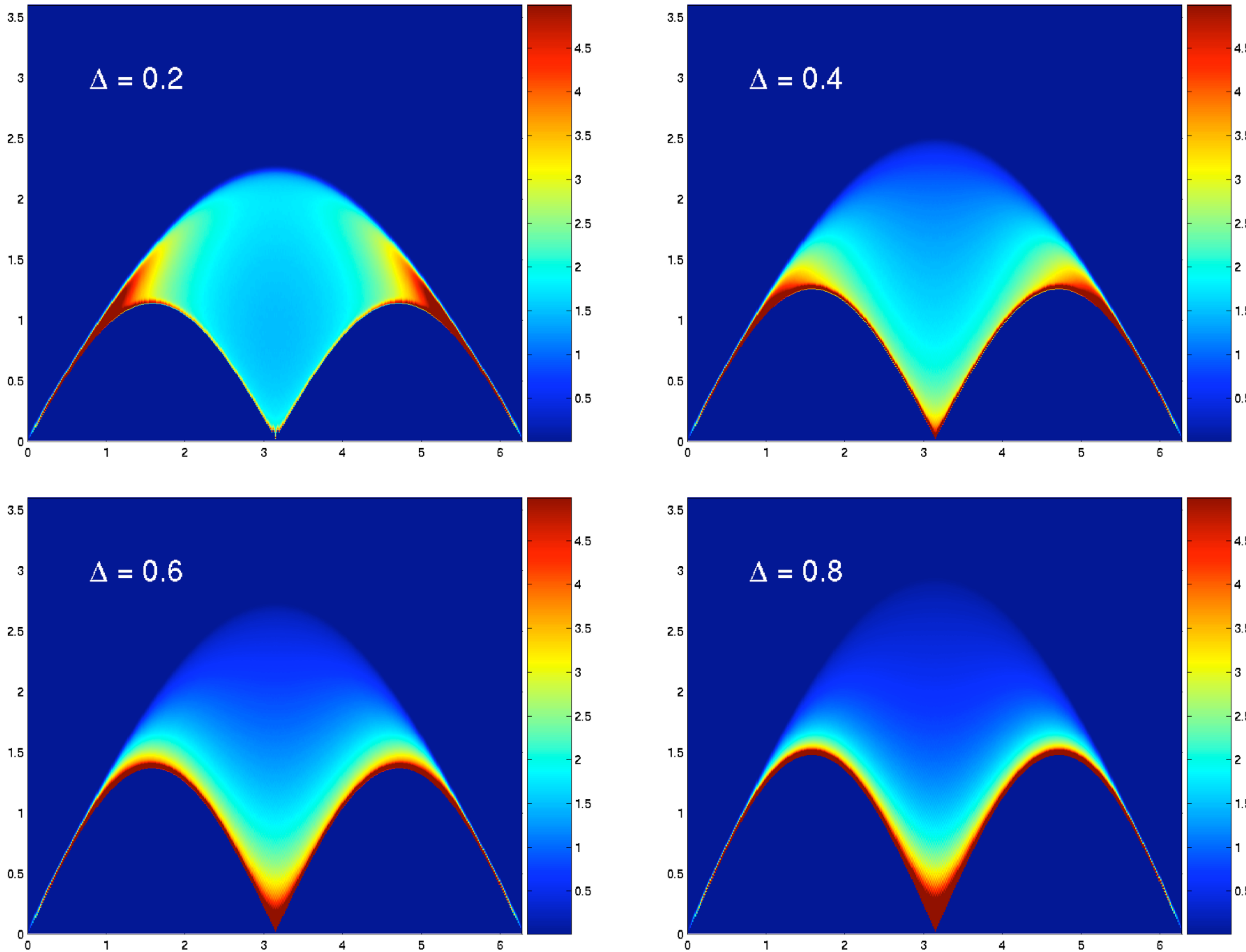
$$S(k, \omega), \quad \Delta = 1, \quad h = 0$$

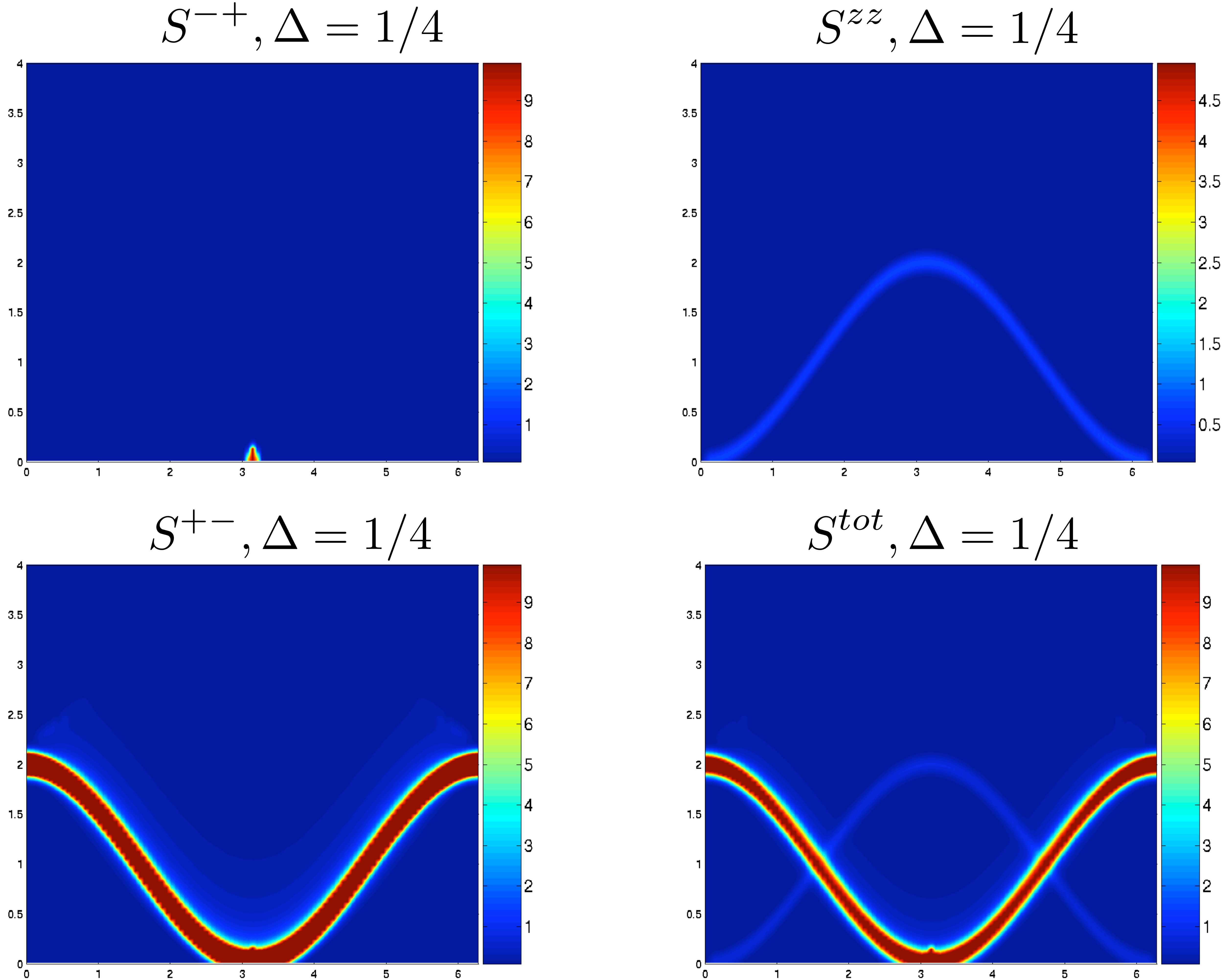


Zero field chain: transverse SF



Zero field chain: longitudinal SF

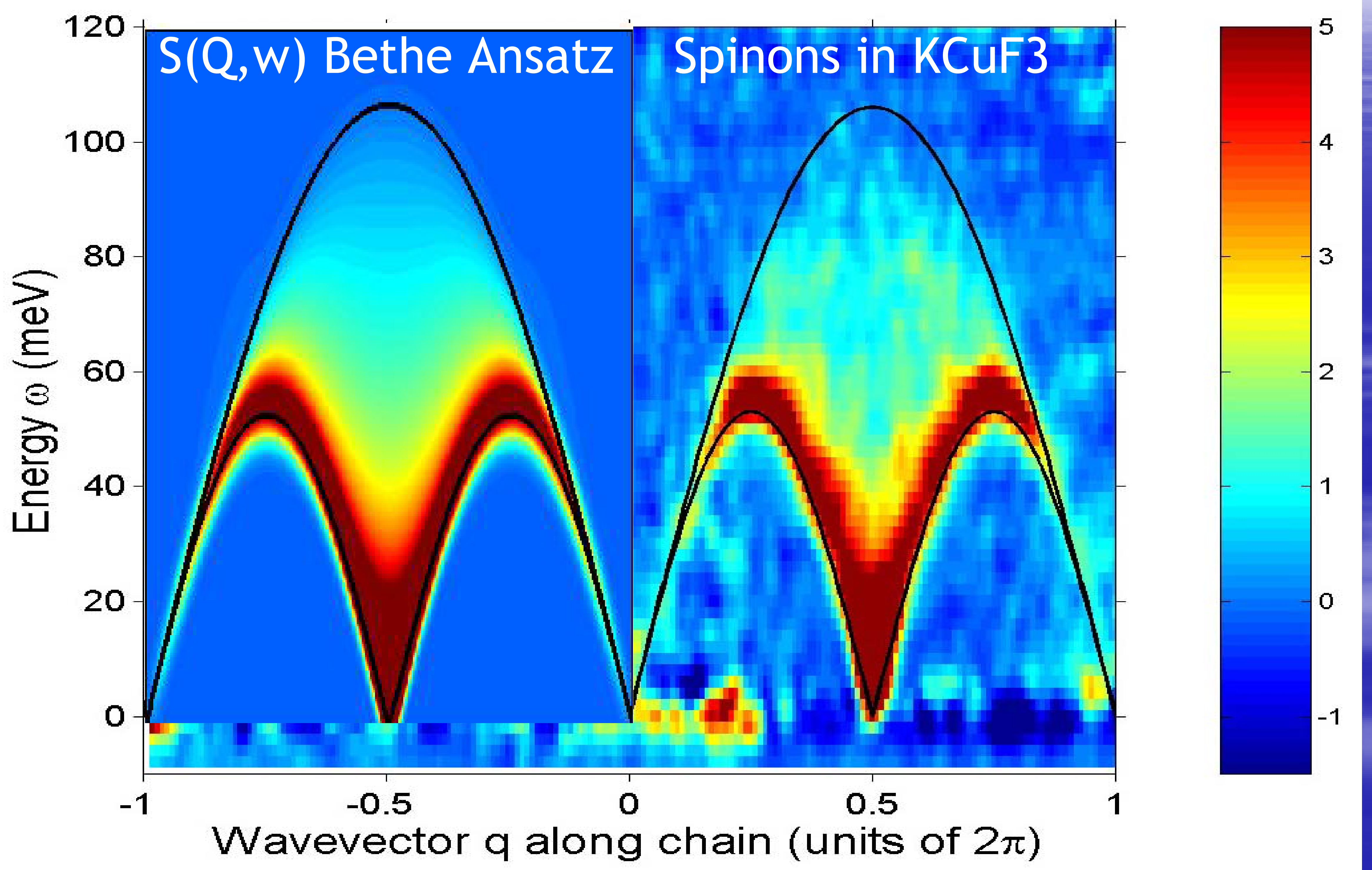




$S^{-+}, \Delta = 1/4$
$S^{zz}, \Delta = 1/4$
$S^{+-}, \Delta = 1/4$
$S^{tot}, \Delta = 1/4$

Hahn-Meitner-Institut Berlin
in der Helmholtz-Gemeinschaft

BENSC



Method 2: analytics (XXX, h = 0)

- Infinite model, zero field: possesses $U_q(\hat{sl}_2)$ quantum group symmetry
- Representation theory of q group

→ eigenstates and form factors (Jimbo, Miwa, ...)

Excitations: built up of even numbers of spinons

Two spinon part of the structure factor:

Bougourzi, Couture, Kacir 1996; Karbach, Müller, B., Fledderjohann, Mütter 1997

→ Two spinon states carry 72.89% of integrated intensity (71.30% of first frequency moment)

Remarkable: measure 0 set in Hilbert space carries majority of correlation weight !

Missing part: higher spinon numbers

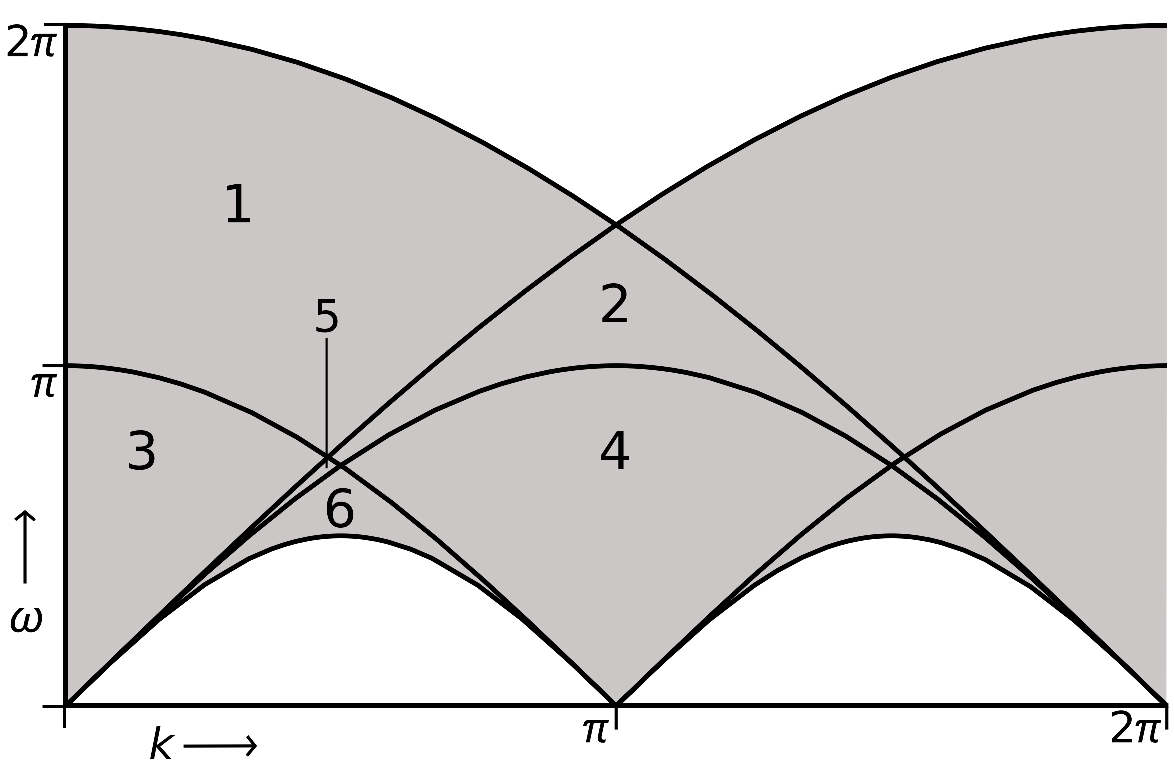
Four spinon part of zero-field structure factor in the thermodynamic limit

(Abada, Bougourzi, Si-Lakhal 1997, revised in JSC & R. Hagemans JSTAT 2006)

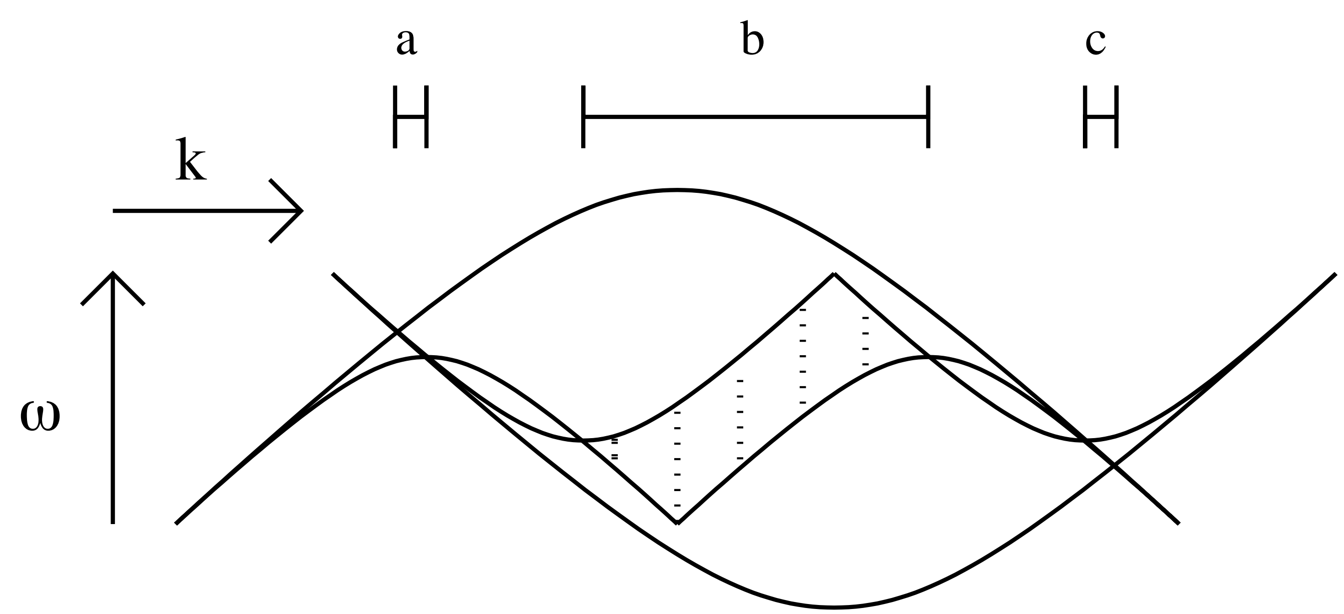
At each point, 4 spinon SF is two-fold integral:

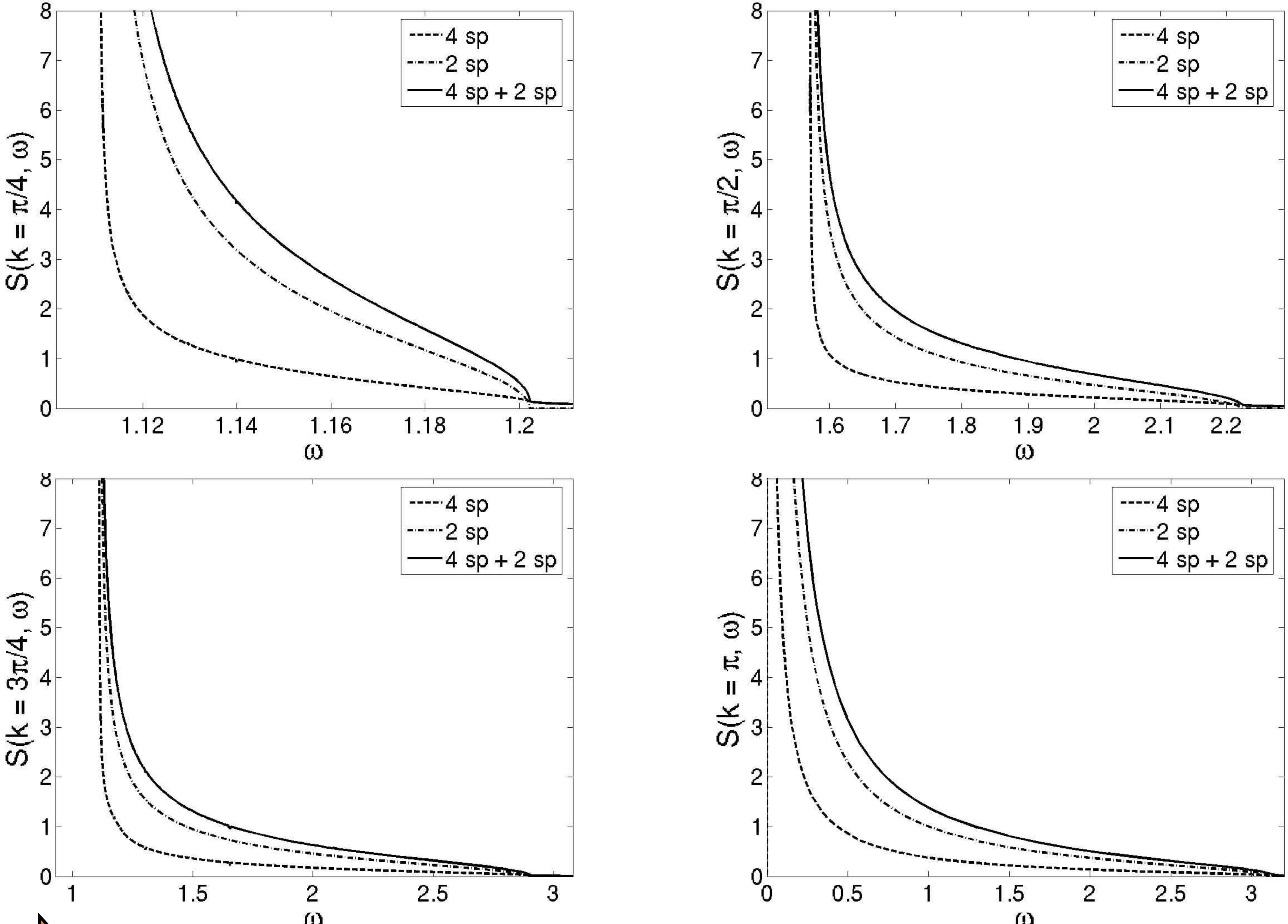
$$S_4(k,\omega) = C_4 \int_{\mathcal{D}_K} dK \int_{\Omega_l(k,\omega,K)}^{\Omega_u(k,\omega,K)} d\Omega \; \frac{J(k,\omega,K,\Omega)}{\left\{\left[\omega_{2,u}^2(K) - \Omega^2\right]\left[\omega_{2,u}^2(k-K) - (\omega-\Omega)^2\right]\right\}^{1/2}}$$

4-spinon continuum:



Integration regions: intersection of two 2-spinon continua





4-spinon states carry about 27% of full intensity

2 + 4 spinons: approx 98% of correlations !

Analytics (II): gapped XXZ, h = 0

(Bougourzi, Karbach, Müller 1998, revisited in JSC, Mossel & Pérez Castillo, JSTAT 2008)

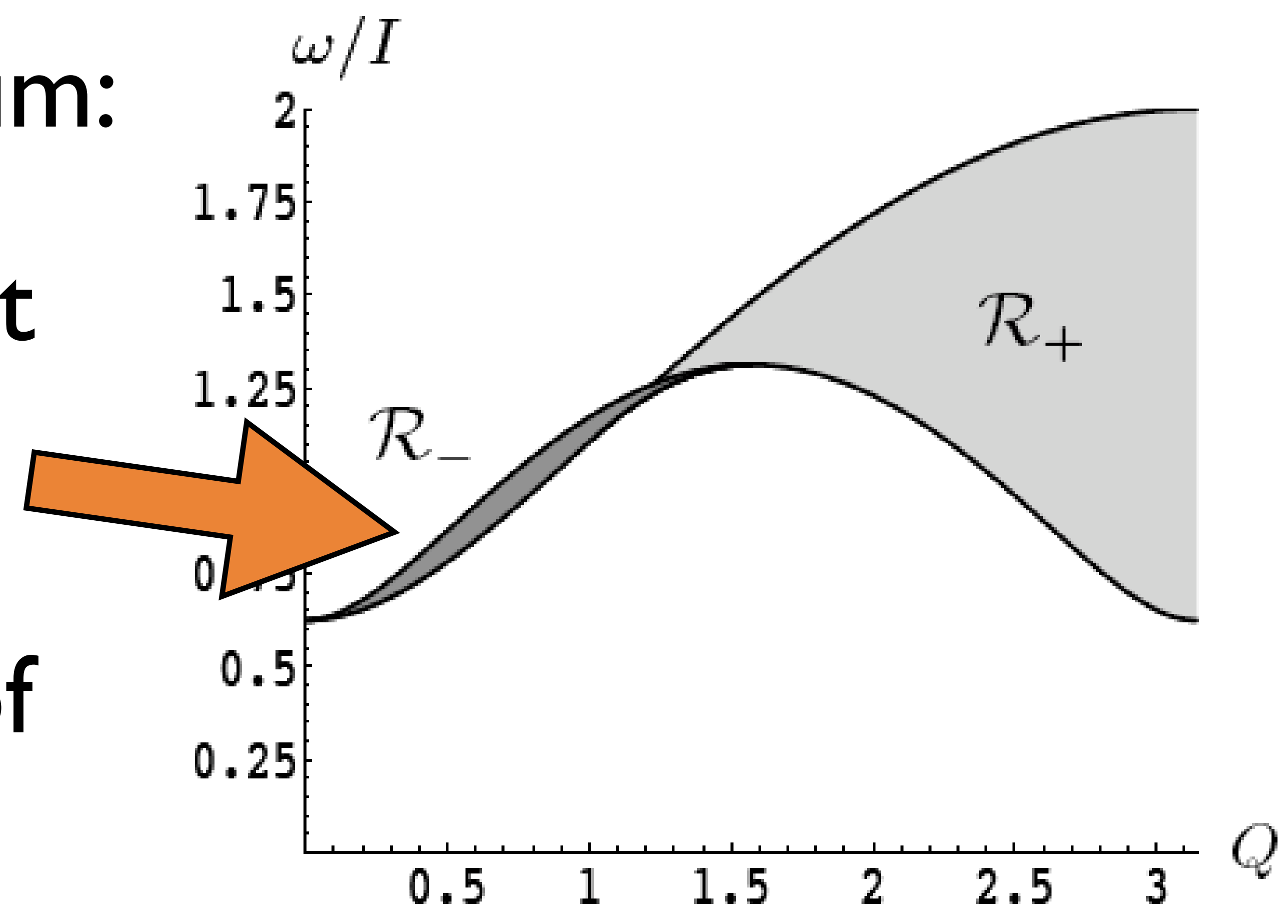
Spinon excitations:

$$e(\beta) = I\,\mathrm{dn}(\beta), \quad p(\beta) = \mathrm{am}(\beta) + \frac{\pi}{2}, \quad I \equiv \frac{JK}{\pi}\sinh\left(\frac{\pi K'}{K}\right)$$

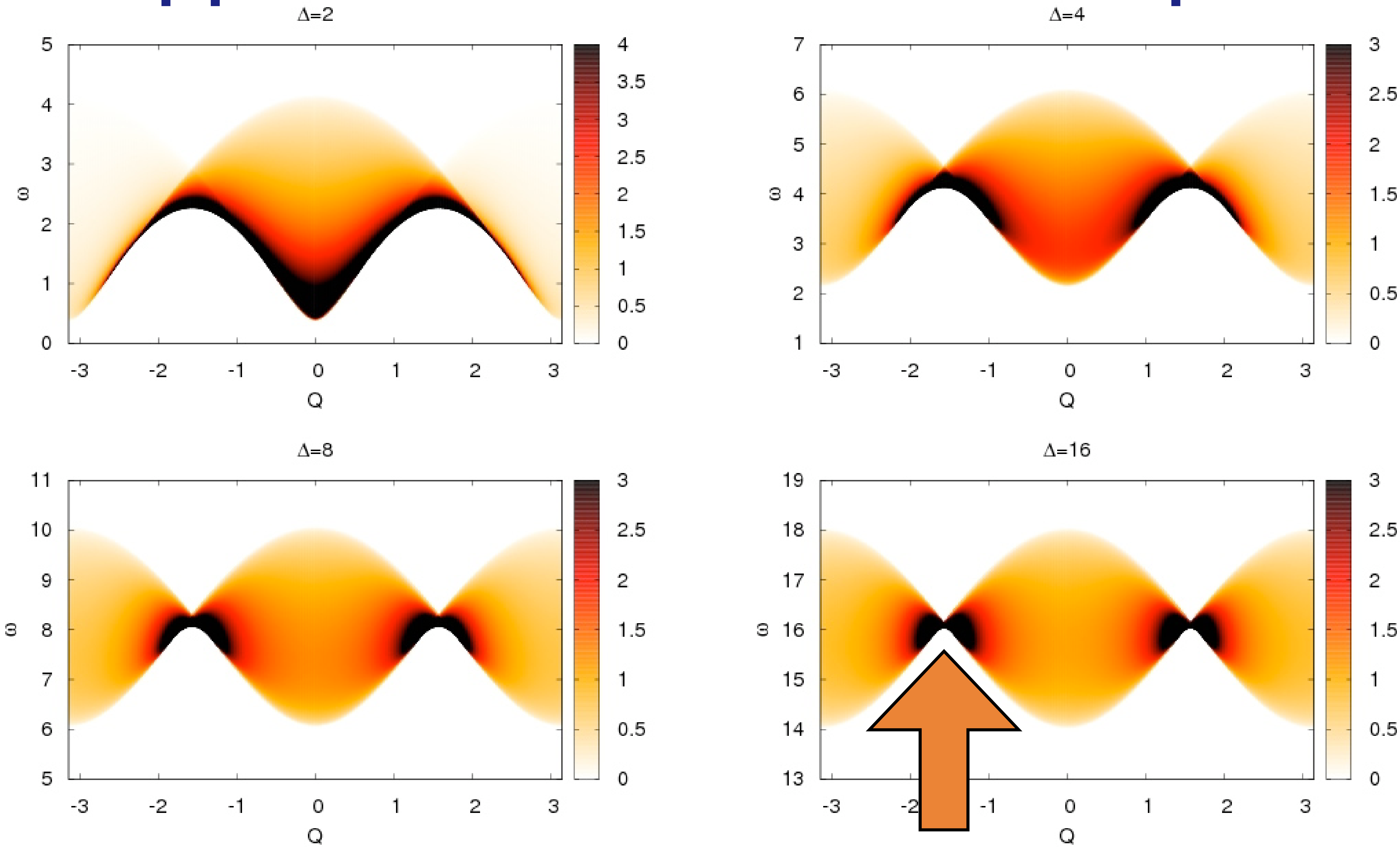
Dispersion relation: $e_1(p) = I\sqrt{1 - k^2\cos^2(p)}, \quad 0 \leq p \leq \pi$

Nontrivial 2-spinon continuum:

‘Folding up’ of continuum at small momentum transfer (curvature of dispersion relation changes sign as fn of momentum)



Gapped XXZ AFM, h = 0, 2spinons



EXACT correlation function in thermodynamic limit for energies below twice the gap

π periodicity only recovered in true Ising limit

Method 3: Field theory approach (small-q limit) / DMRG / BA for longitudinal structure factor

(Pereira, Sirker, Caux, Hagemans, Maillet, Affleck, White: PRL 2006, JSTAT 2007)

Straight free boson: $\mathcal{H}_{LL} = \frac{v}{2}\left[\Pi^2 + (\partial_x \phi)^2\right]$

simply gives $S^{zz}(q,\omega) = K|q|\,\delta(\omega - v|q|)$

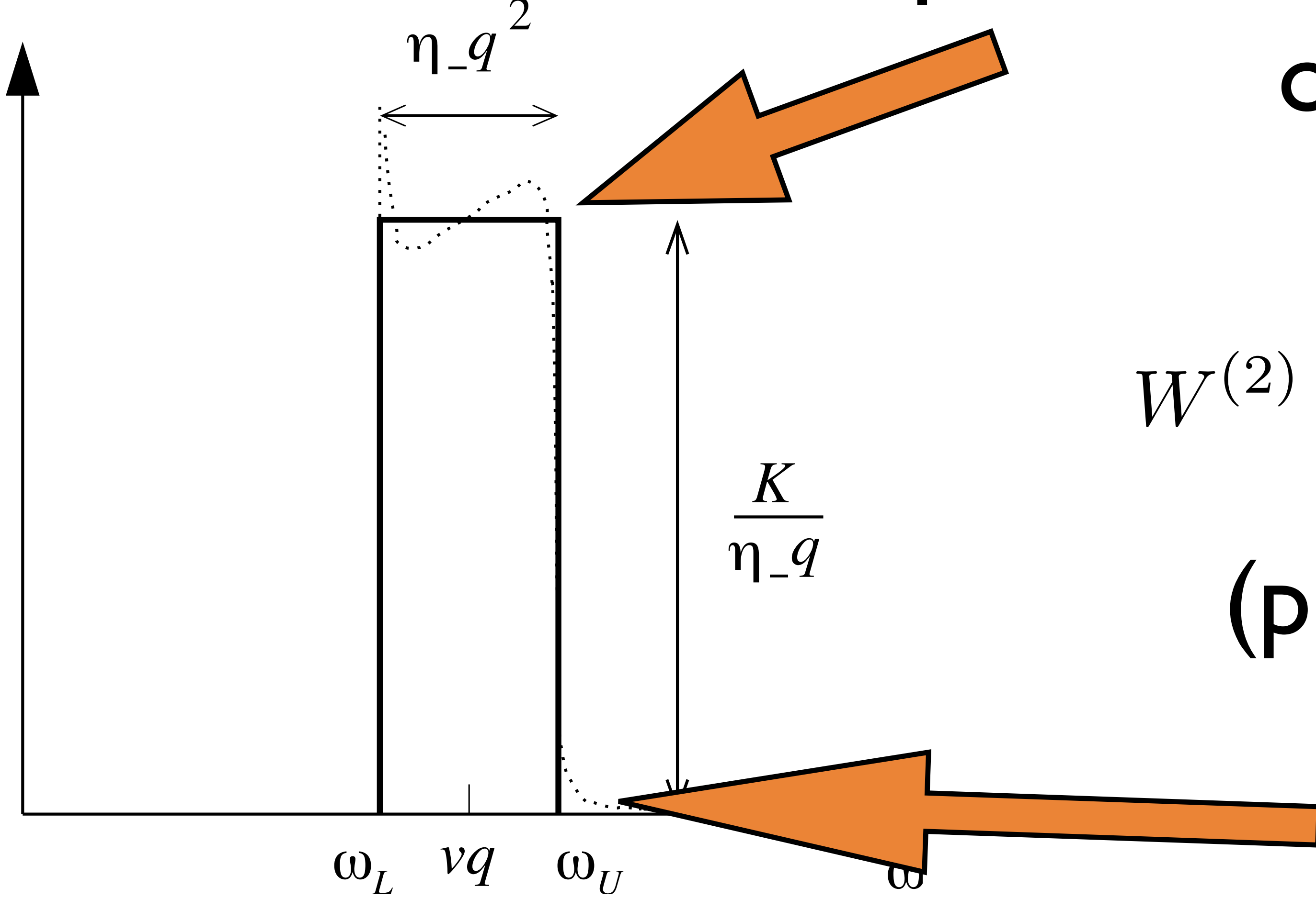
nonzero field

$$\delta\mathcal{H}(x) = \eta_-\left[(\partial_x\phi_L)^3 - (\partial_x\phi_R)^3\right] + \eta_+\left[(\partial_x\phi_L)^2\partial_x\phi_R - (\partial_x\phi_R)^2\partial_x\phi_L\right]$$
$$+\zeta_-\left[(\partial_x\phi_L)^4 + (\partial_x\phi_R)^4\right] + \zeta_+(\partial_x\phi_L)^2(\partial_x\phi_R)^2$$
$$+\zeta_3\left[\partial_x\phi_L(\partial_x\phi_R)^3 + \partial_x\phi_R(\partial_x\phi_L)^3\right] + \lambda\cos\left(4\sqrt{\pi K}\phi + 4k_F x\right)$$

non-integrable

zero field

General appearance of the small q lineshape:



Field theory: resummation of series in η_- leads to box-like lineshape of width

$$W^{(2)} = \eta_- = \sqrt{\frac{v}{\pi\chi}}\left[\frac{3}{2}\frac{\partial v}{\partial h} + \frac{1}{2}\frac{v}{\chi}\frac{\partial \chi}{\partial h}\right]$$

(proof from BA: 2p width)

high-energy tail carrying much lower weight

As for interacting fermions (Pustilnik, Glazman & al.)

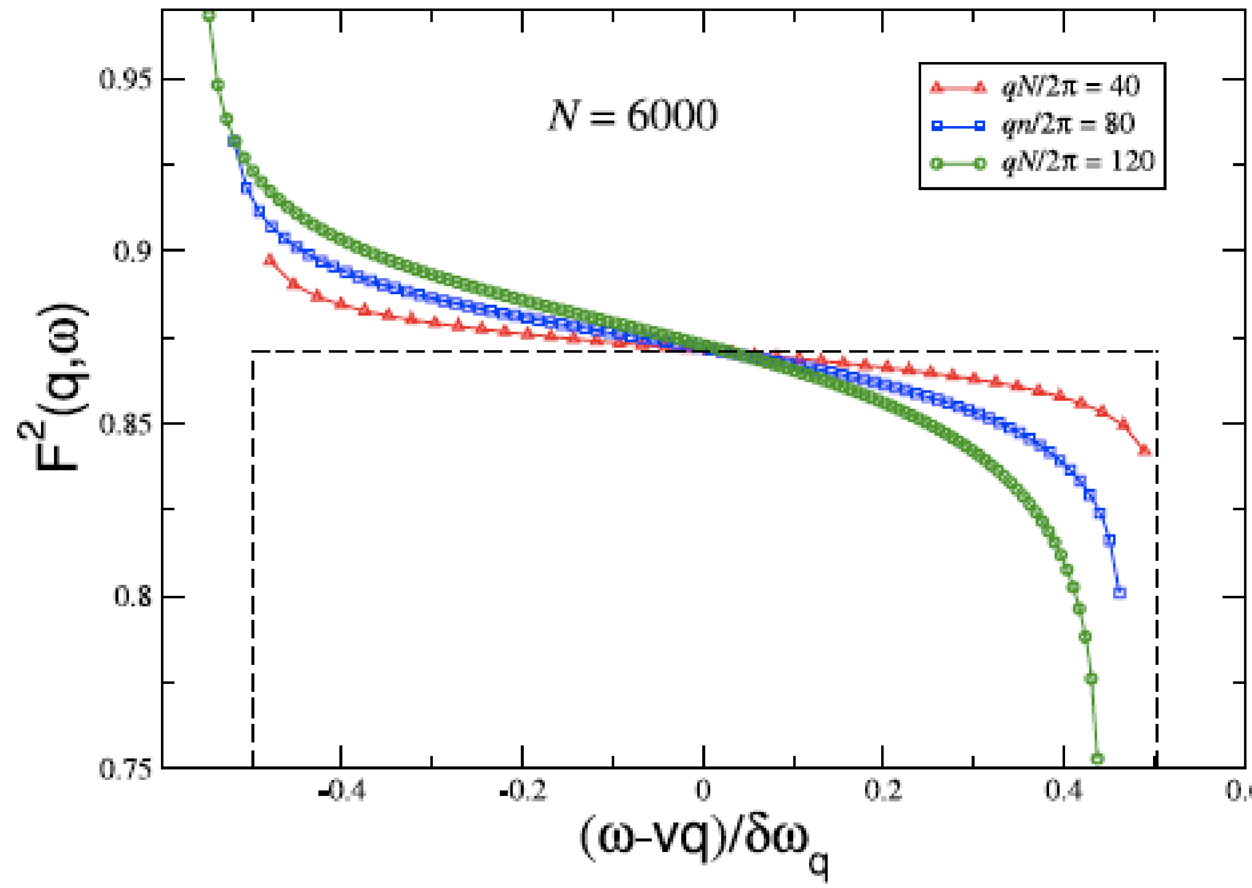
Finer structure for XXZ: can be investigated using BA

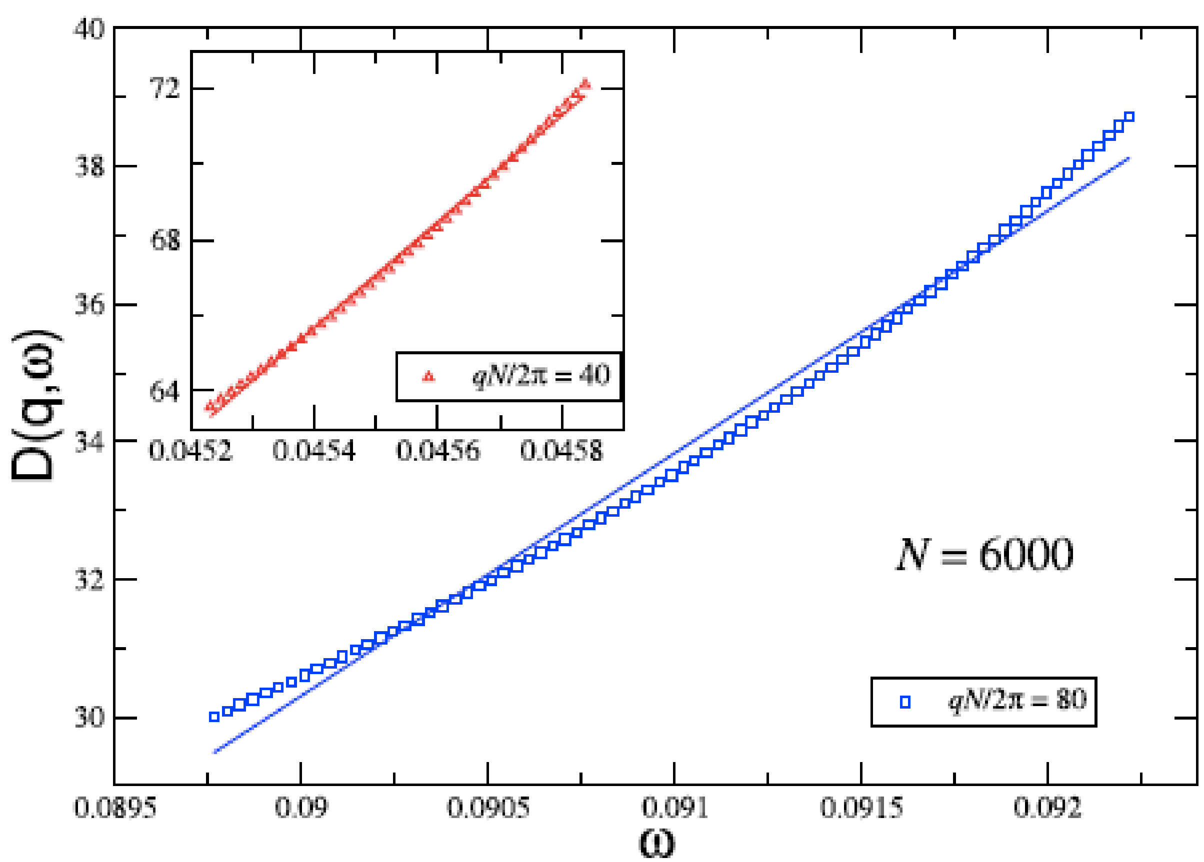
Peak region: 2p

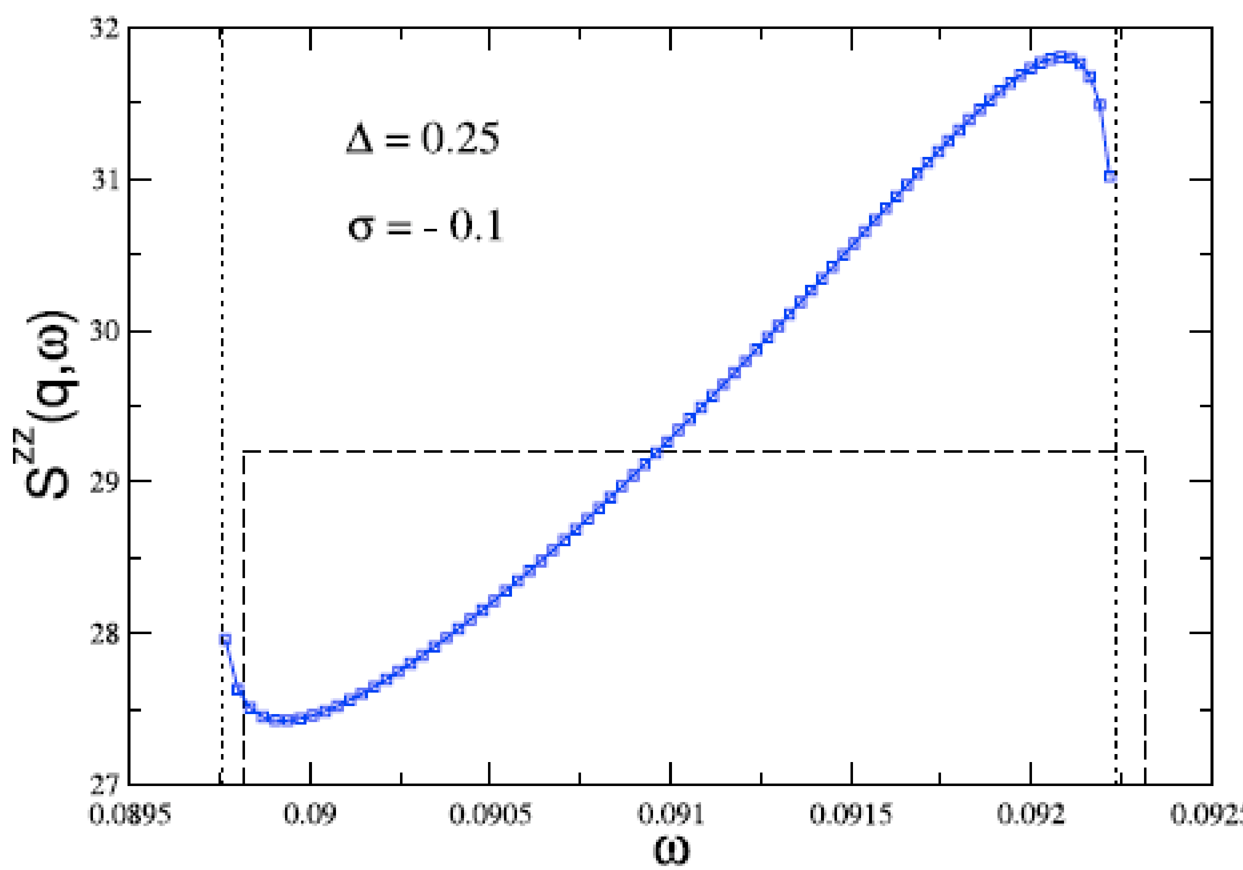
Combining:
frequency-dependent form factors

& density of states,

a nontrivial lineshape is obtained







Advantages/ disadvantages of the 3 approaches presented here

- ABACUS

Any integrable chain

Any field

Accurate at any energy

Finite N

Finite T

- Quantum group

Exact result

Zero field only

2 & 4 sp only

Finite T

- FIELD THEORY

Not only for integrable cases

Small window of q

Fine structure in w: tough

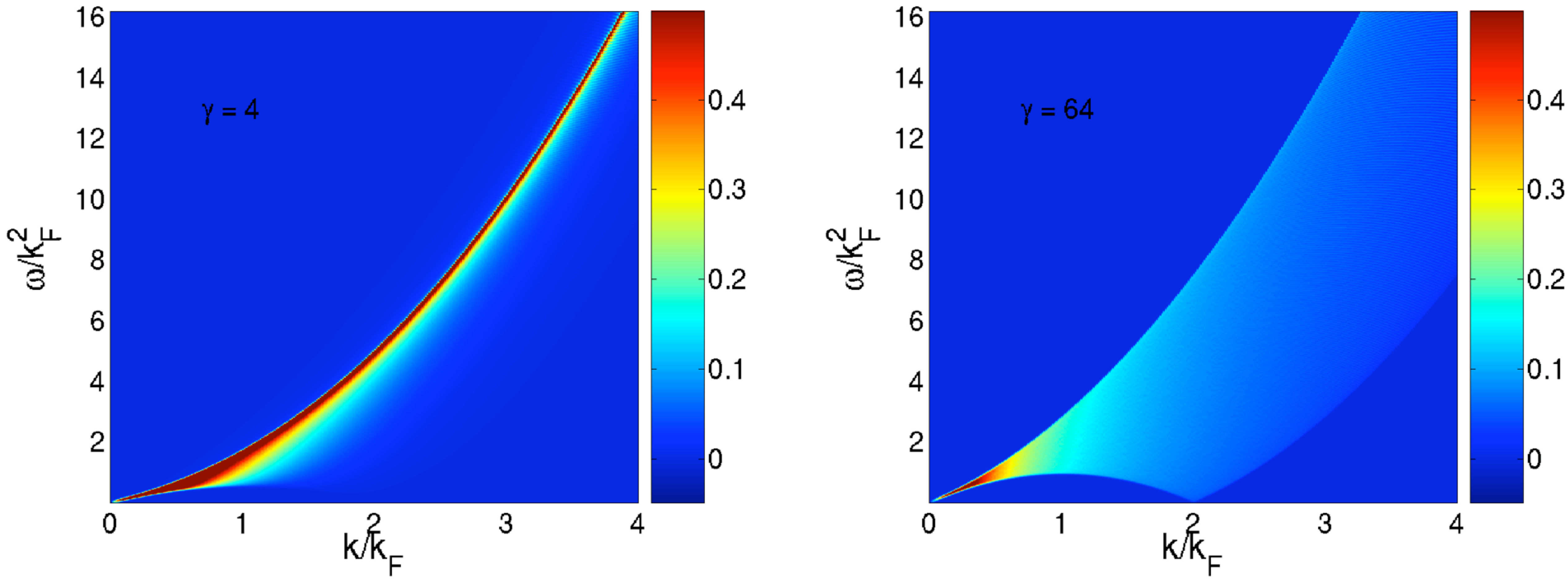
Finite T

Lieb-Liniger Bose gas

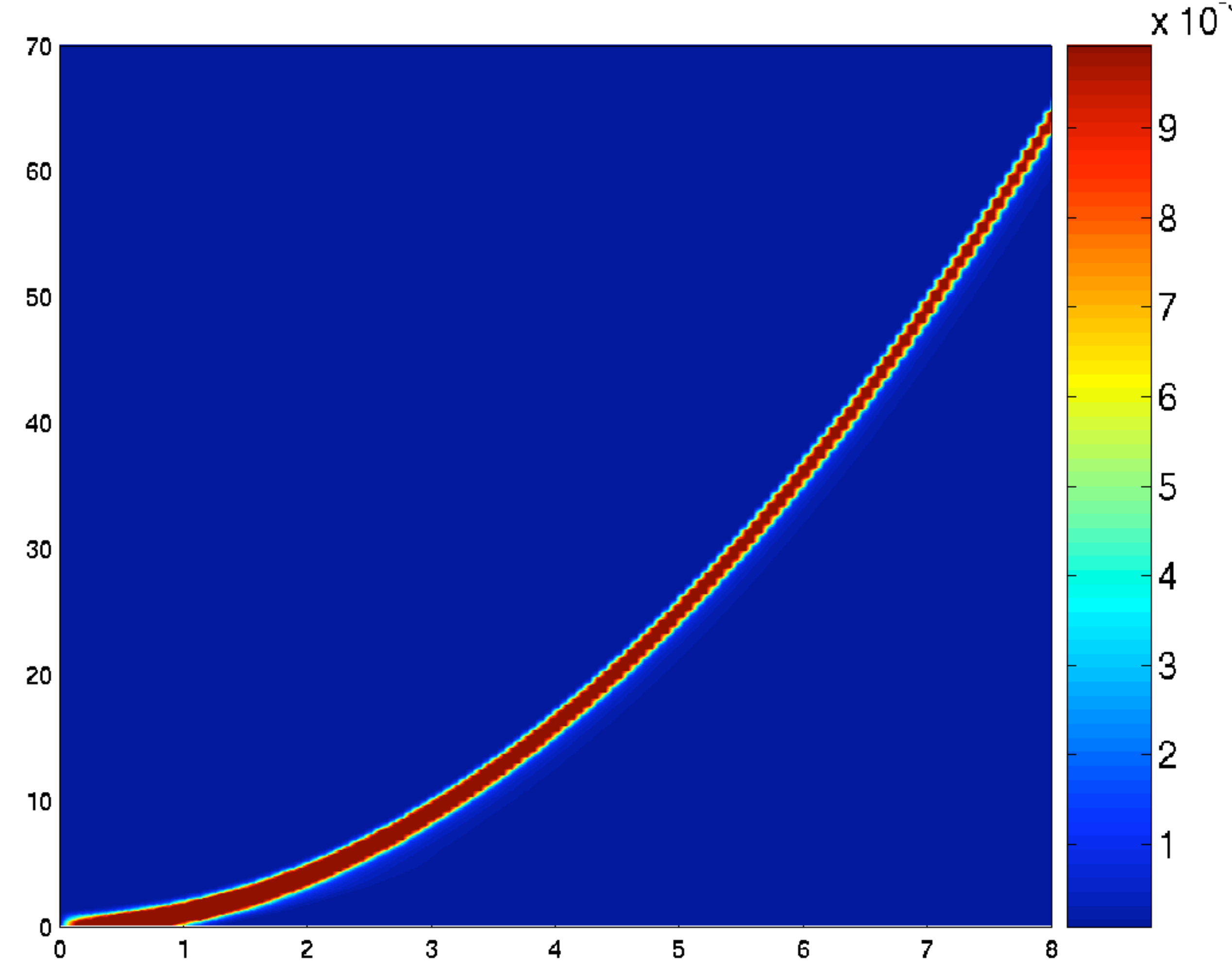
Density-density (dynamical SF)

(J-S C & P Calabrese, PRA 2006)

$$S(k,\omega) = \frac{2\pi}{L} \sum_{\alpha} |\langle 0|\rho_k|\alpha\rangle|^2 \delta(\omega - E_\alpha + E_0)$$

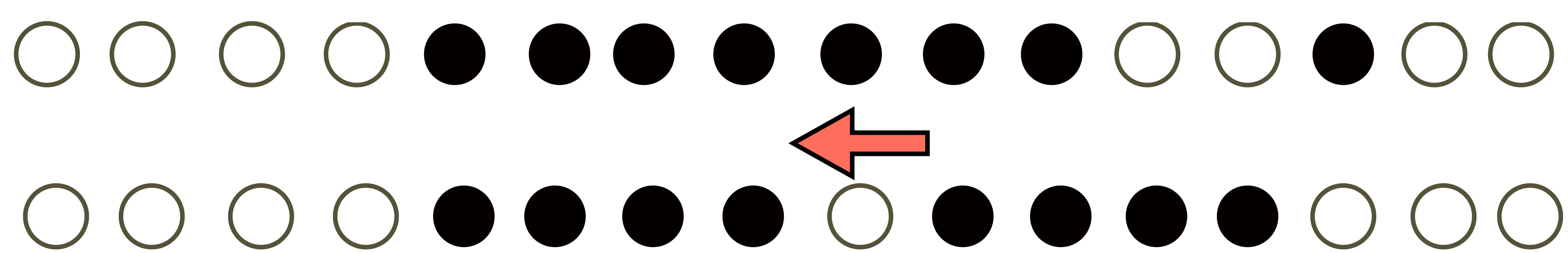


Correspondence with excitations

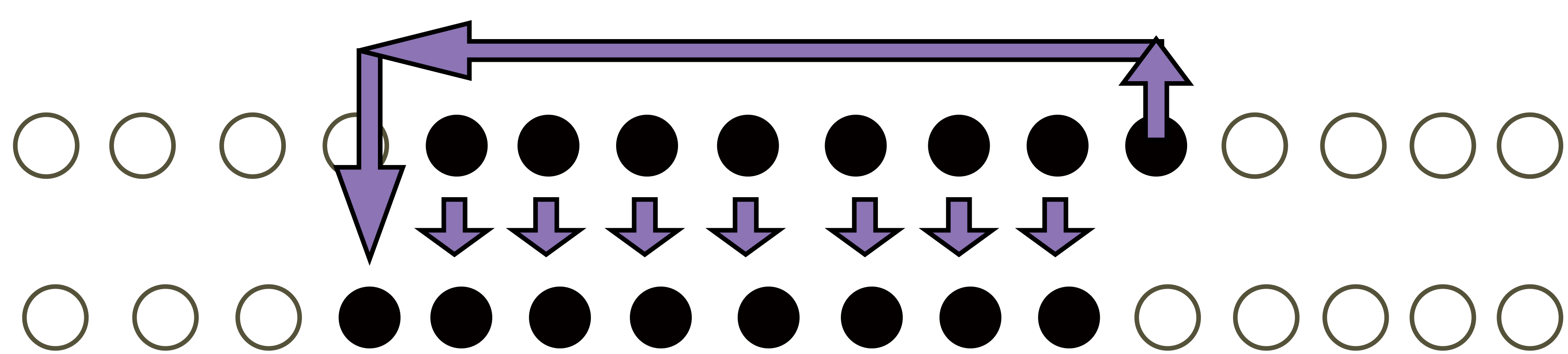


Particle-like

Hole-like



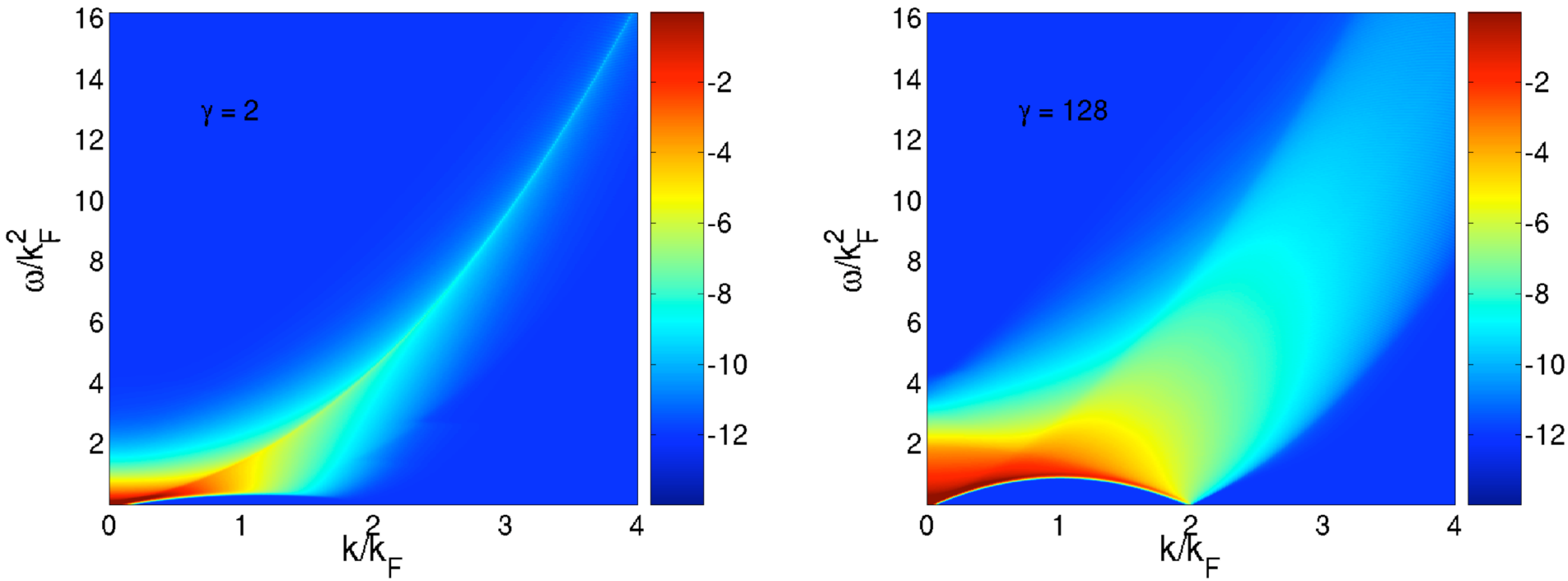
Umklapp



One-particle dynamical function

$$G_2(x,t) = \langle \Psi^\dagger(x,t)\Psi(0,0)\rangle_N$$

(J-S C, P Calabrese & N Slavnov, JSTAT 2007)



The attractive Lieb-Liniger model: analytical solution

$$H = -\frac{\hbar^2}{2m}\sum_{j=1}^{N}\frac{\partial^2}{\partial x_j^2} - 2\bar{c}\sum_{\langle i,j\rangle}\delta(x_i - x_j)$$

!!!

Bethe eqns: $$e^{i\lambda_a L} = \prod_{a\neq b}\frac{\lambda_a - \lambda_b - i\bar{c}}{\lambda_a - \lambda_b + i\bar{c}}, \quad a = 1, ..., N$$

bound state solutions: strings

$$\lambda_\alpha^{j,a} = \lambda_\alpha^j + \frac{i\bar{c}}{2}(j + 1 - 2a) + i\delta_\alpha^{j,a}.$$

(J. B. McGuire, 1964; F. Calogero & A. DeGasperis, 1975; Y. Castin & C. Herzog, 2001)

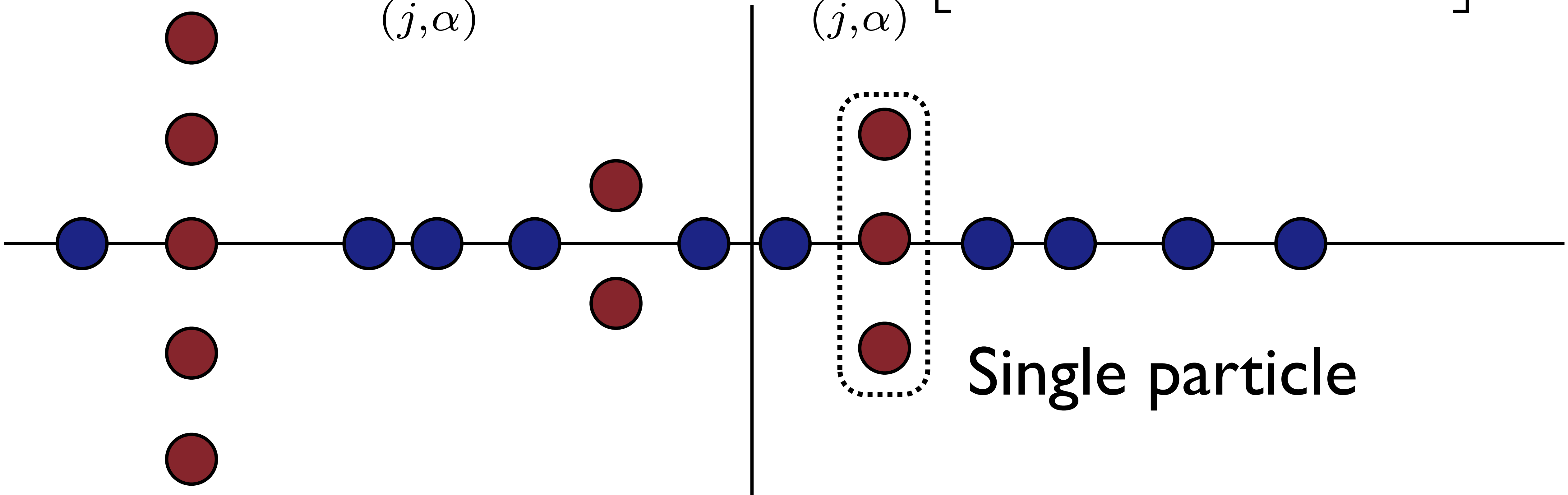
The attractive Lieb-Liniger model

(J. B. McGuire, 1964; F. Calogero & A. DeGasperis, 1975; Y. Castin & C. Herzog, 2001)

Ground state: single N string with zero momentum

Excitations: ‘partition’ N atoms into bound states

$$P = \sum_{(j,\alpha)} j\lambda_\alpha^j\,, \qquad E = \sum_{(j,\alpha)} \left[j{\lambda_\alpha^j}^2 - \frac{\bar{c}^2}{12} j(j^2-1) \right]$$



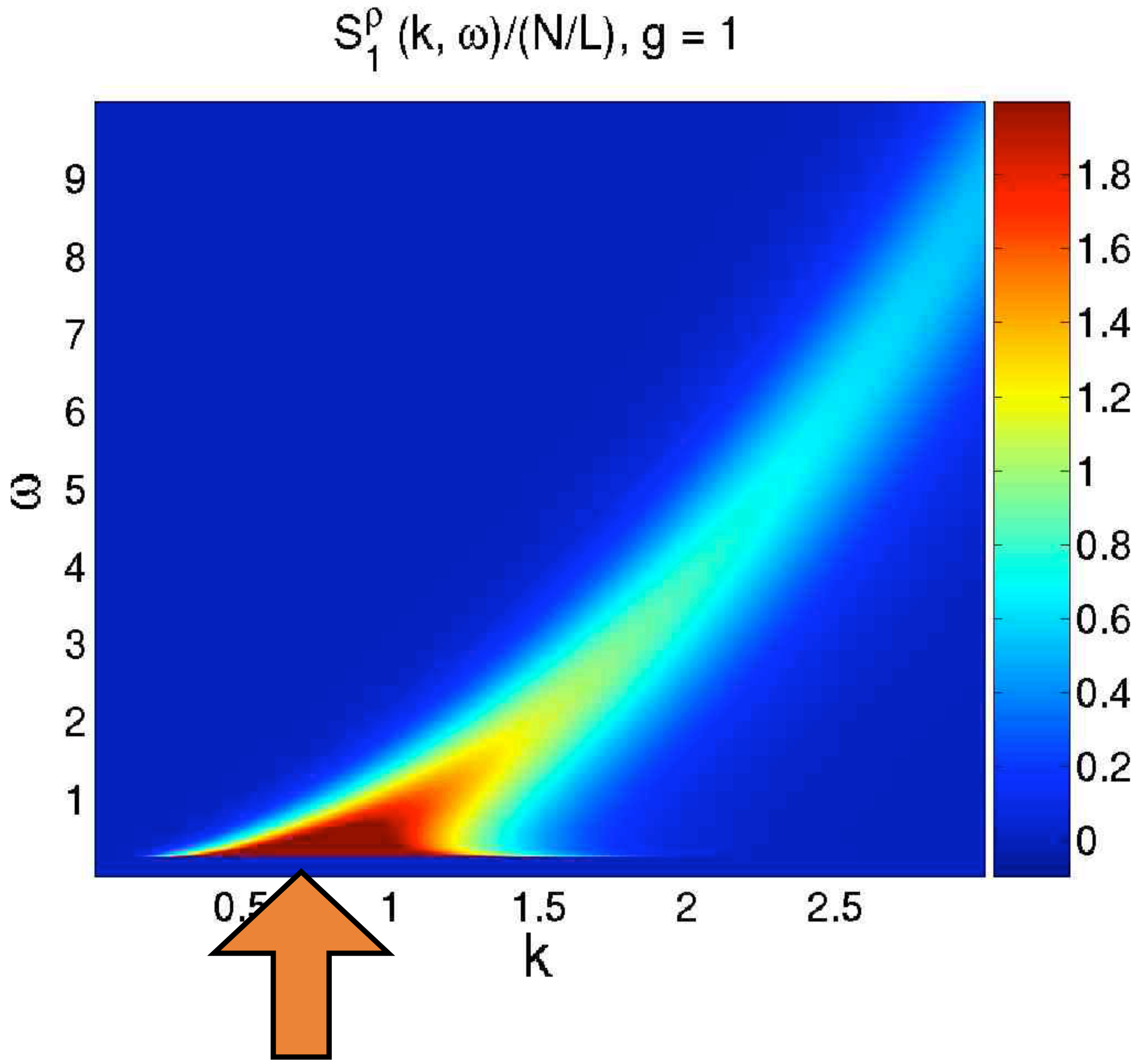
Bethe equations for GS solved to exponential accuracy: determinants can be calculated explicitly !!

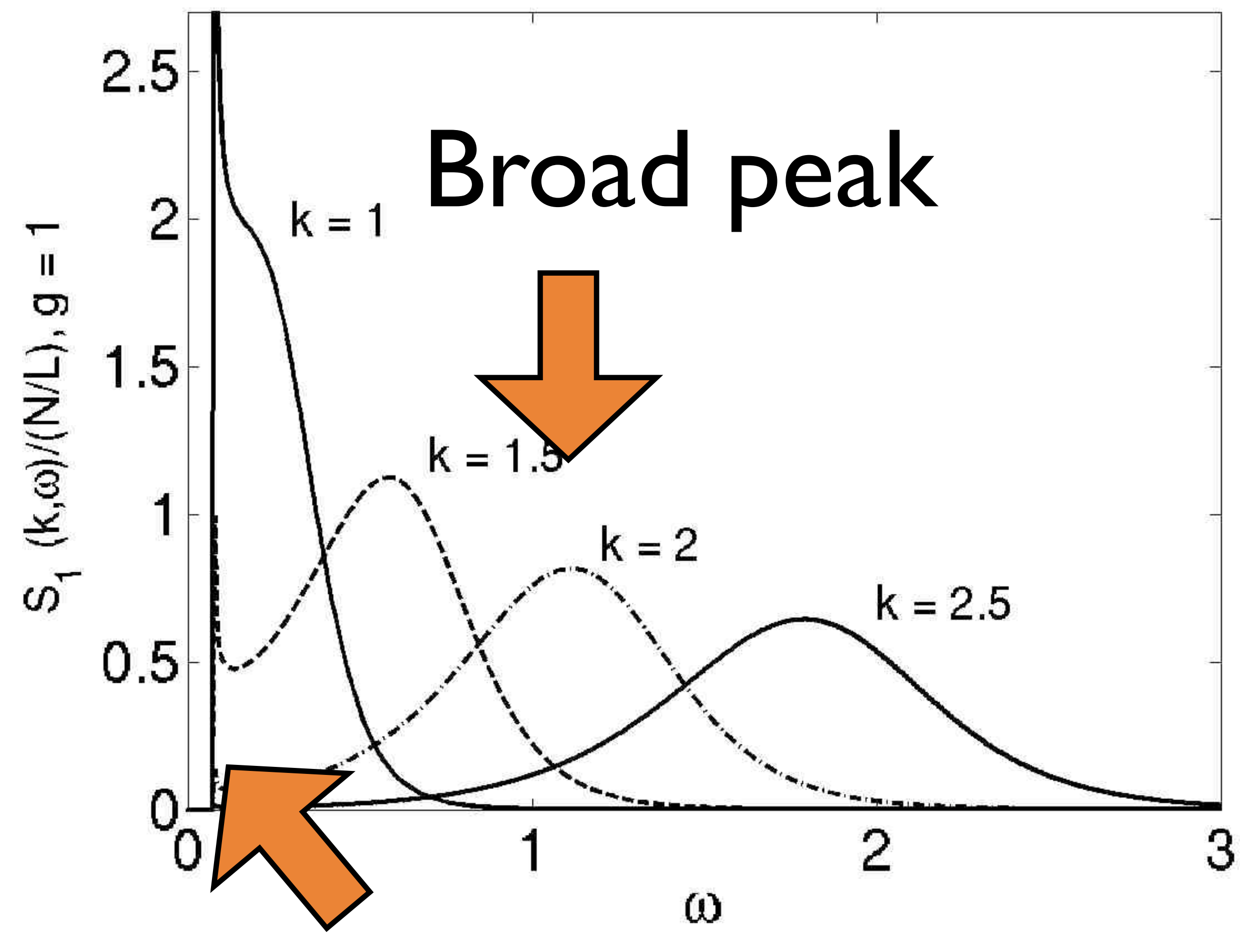
(J.-S.C & P. Calabrese PRL 2007; JSTAT 2007)

Analytical solution for CFs

(J.-S.C & P. Calabrese PRL 2007; JSTAT 2007)

Single-particle coherent part + two-particle continuum



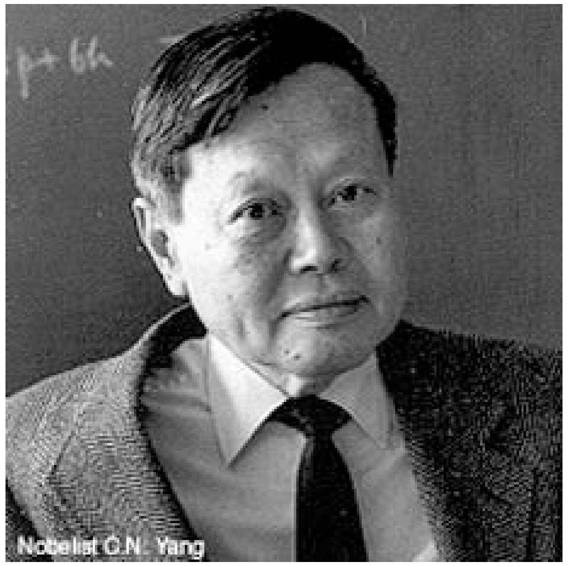


Finite threshold

Square-root singularity

Single-particle part: leads to Mössbauer-like effect
(gas reacts like a single massive particle)

The 2-component Bose gas
(special case of Yang permutation model)



$$H = -\sum_{a=1}^{N_C}\sum_{i=1}^{N_a}\frac{\partial^2}{\partial x_{a,i}^2} + 2c\sum_{(a,i)<(b,j)}\delta(x_{a,i}-x_{b,j})$$

- Dynamics: hum... nested BA
- Equilibrium thermodynamics: OK !

$$\epsilon(\lambda) = \lambda^2 - \mu - \Omega - a_2 * T\ln(1+e^{-\epsilon(\lambda)/T}) - \sum_{n=1}^{\infty} a_n * T\ln(1+e^{-\epsilon_n(\lambda)/T})$$

$$\epsilon_1(\lambda) = f * T\ln(1+e^{-\epsilon(\lambda)/T}) + f * T\ln(1+e^{\epsilon_2(\lambda)/T})$$

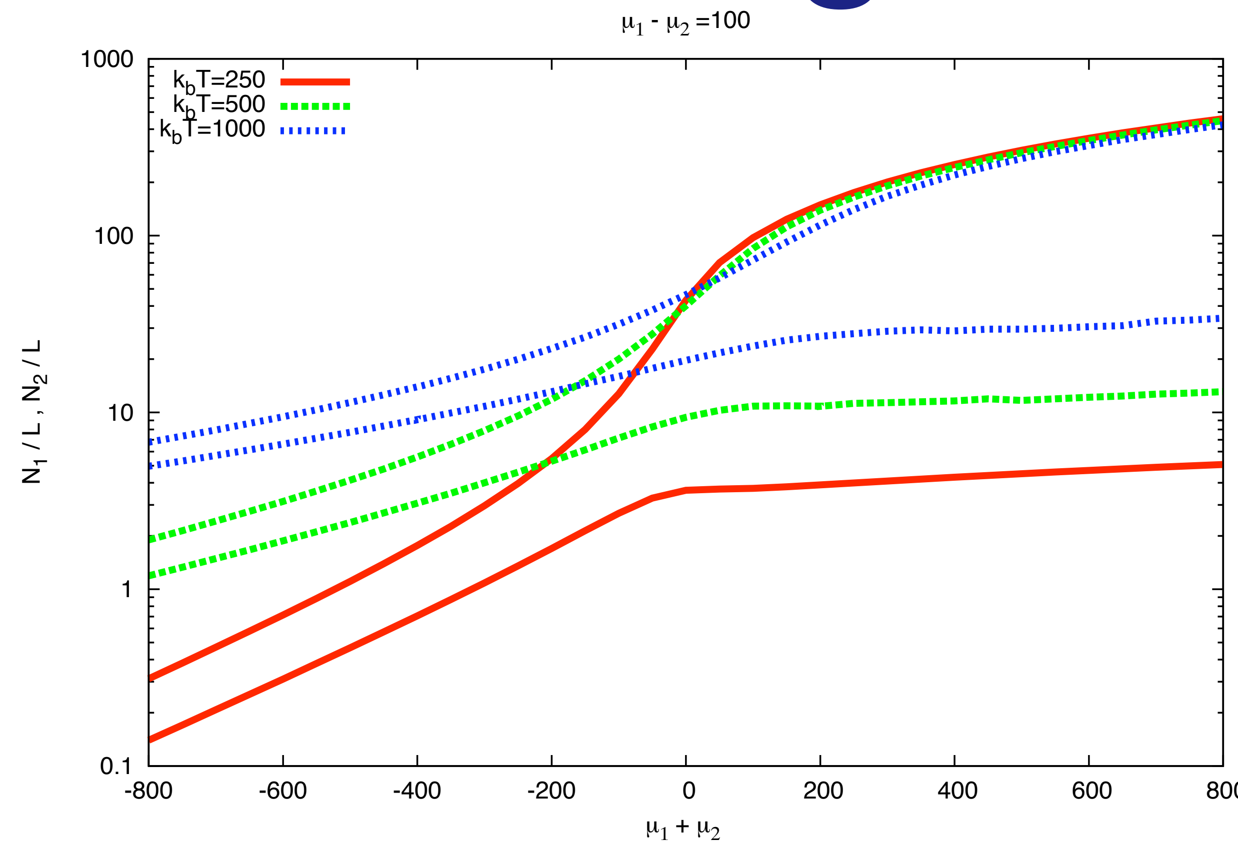
$$\epsilon_n(\lambda) = f * T\ln(1+e^{\epsilon_{n-1}(\lambda)/T}) + f * T\ln(1+e^{\epsilon_{n+1}(\lambda)/T})$$

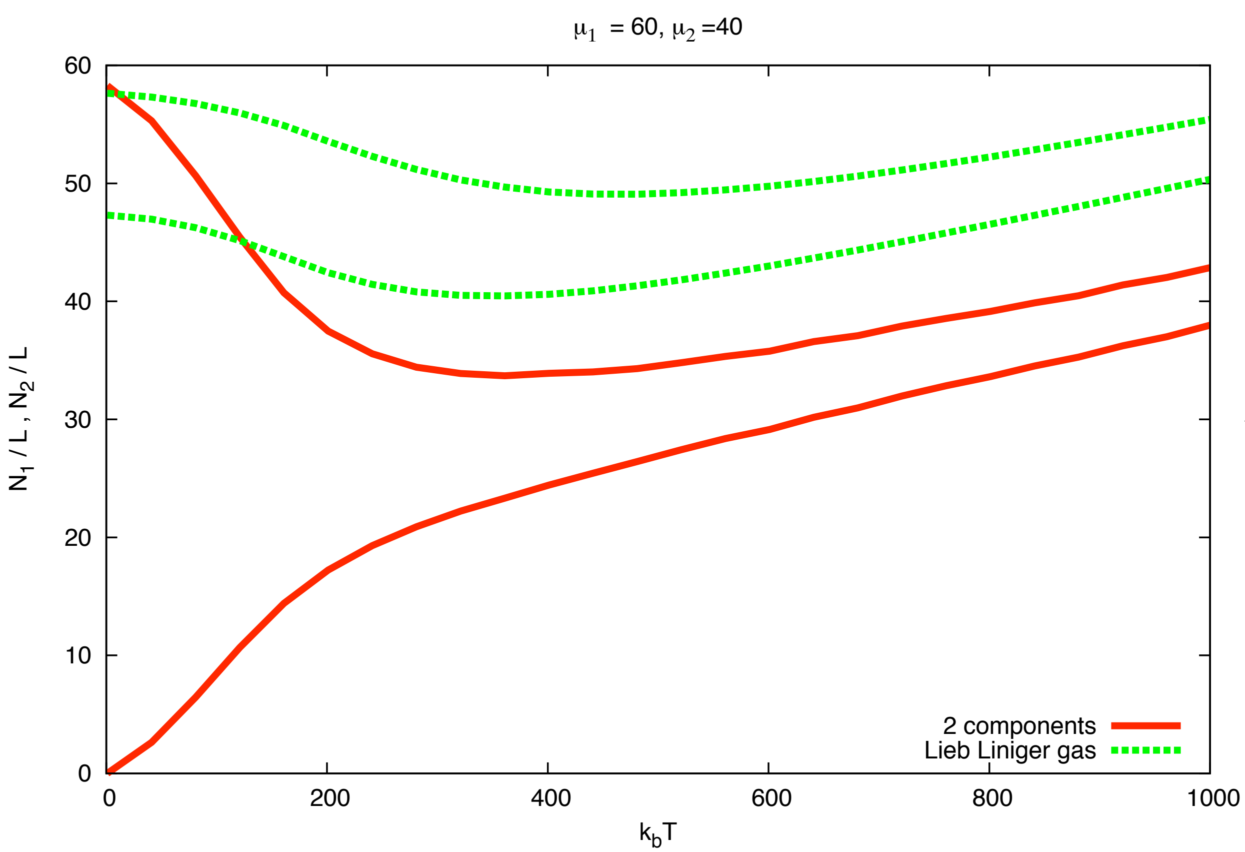
$$\lim_{n\to\infty}\frac{\epsilon_n(\lambda)}{n} = 2\Omega$$

⇒ Numerical solution

The 2-component Bose gas

Populations as a function of total chemical potential





Populations as a function of temperature: contrast with single component case

Waiting for experimental data...

The Richardson model

$$H_{BCS} = \sum_{\substack{\alpha=1 \\ \sigma=+,-}}^{N} \frac{\varepsilon_\alpha}{2} c^\dagger_{\alpha\sigma} c_{\alpha\sigma} - g \sum_{\alpha,\beta=1}^{N} c^\dagger_{\alpha+} c^\dagger_{\alpha-} c_{\beta-} c_{\beta+}$$

(R.W. Richardson, 1963; R.W. Richardon & N. Sherman, 1964)

"Reduced BCS": ground state is BCS in th. limit, grand-canonical.
Exactly solvable in canonical ensemble.

Eigenstates are Bethe, Rapidities: (Bethe) Richardson equations

$$|\{w_j\}\rangle = \prod_{k=1}^{N_r} \mathcal{B}(w_k)|0\rangle$$

$$\frac{1}{g} = \sum_{\alpha=1}^{N} \frac{1}{w_j - \varepsilon_\alpha} - \sum_{k\neq j}^{N_r} \frac{2}{w_j - w_k}, \qquad j = 1, \ldots, N_r$$

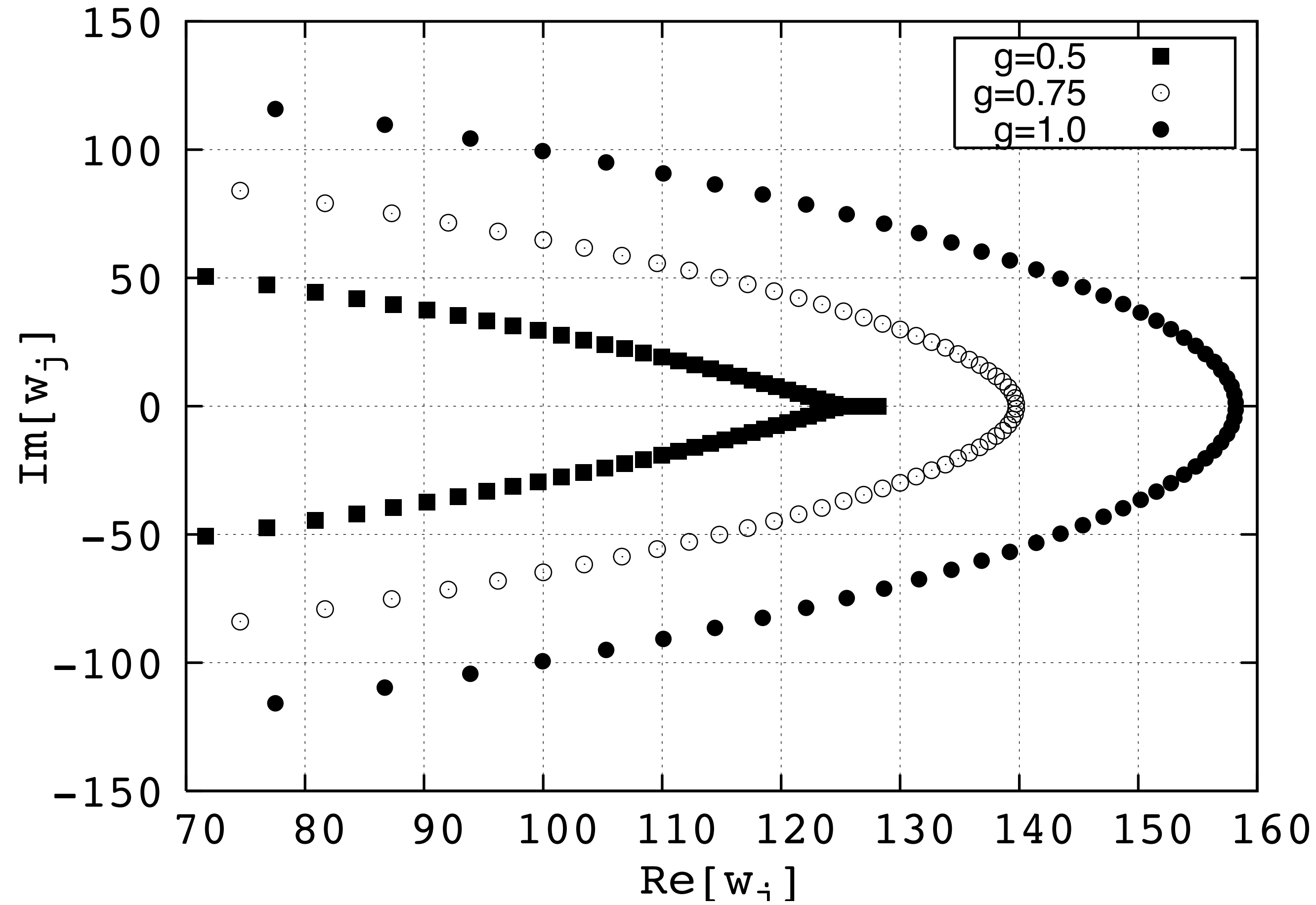
Pseudospin representation: $S^z_\alpha = b^\dagger_\alpha b_\alpha - 1/2, \quad S^-_\alpha = b_\alpha, \quad S^+_\alpha = b^\dagger_\alpha$

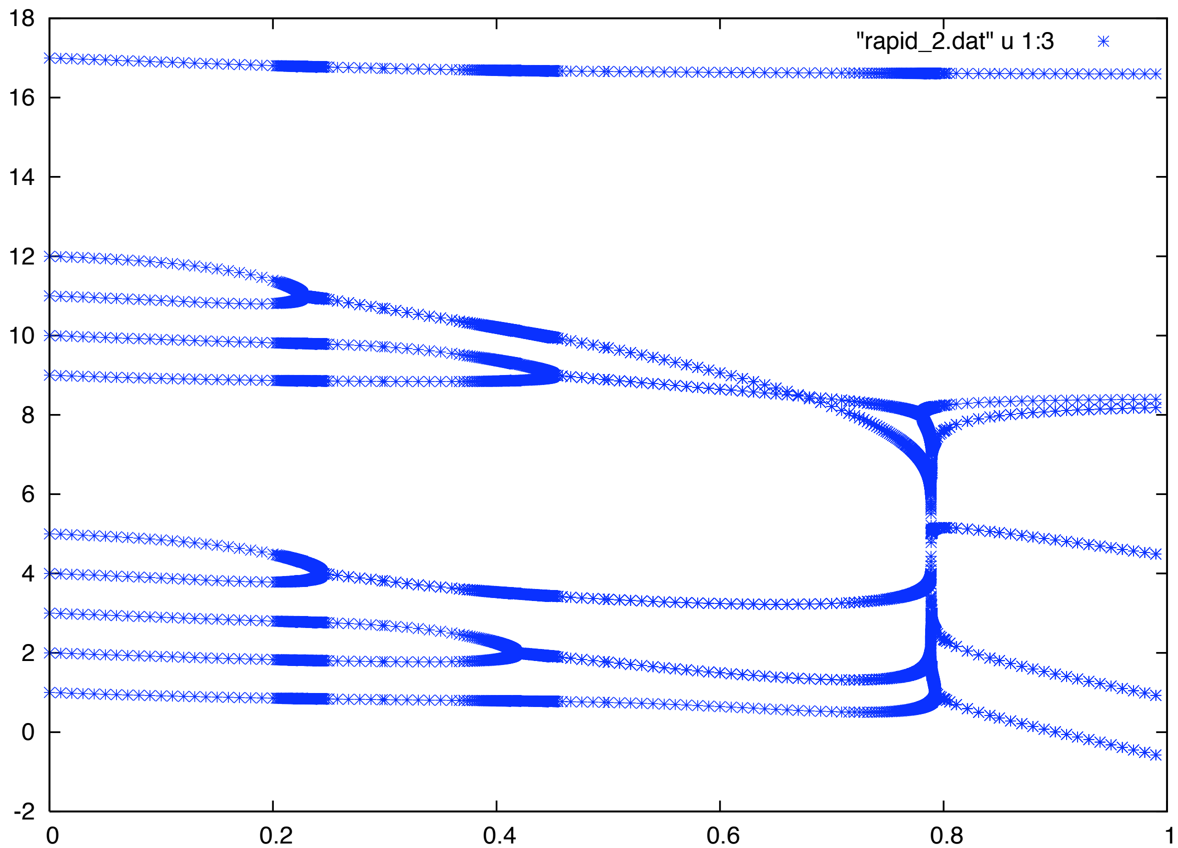
$$b_\alpha = c_{\alpha-} c_{\alpha+}, \qquad b^\dagger_\alpha = c^\dagger_{\alpha+} c^\dagger_{\alpha-}$$

$$H = \sum_{\alpha=1}^{N} \varepsilon_\alpha S^z_\alpha - g \sum_{\alpha,\beta=1}^{N} S^+_\alpha S^-_\beta$$

Solving the Richardson equations

(relatively) straightforward for the ground state





For excited states: can become a real challenge !!

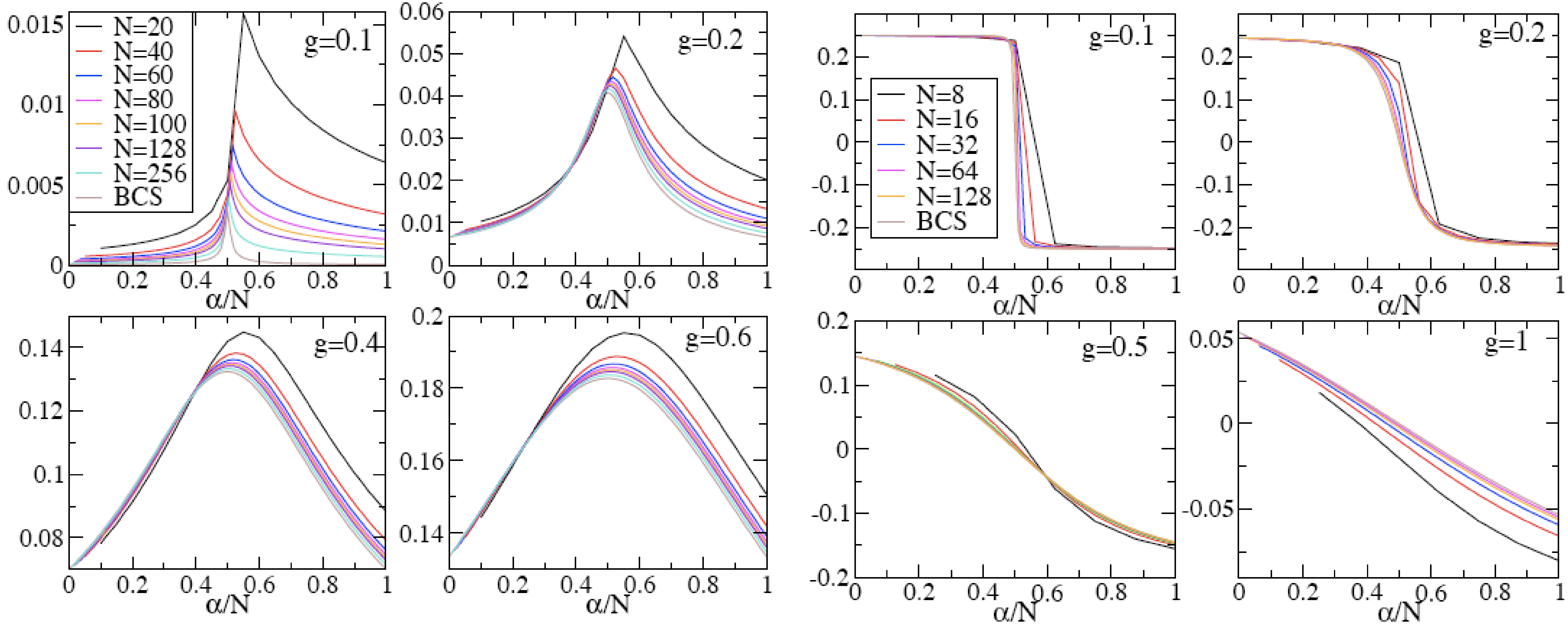
(Richardson, 1964; Schechter, Imry, Levinson & von Delft, 2001; von Delft & Ralph, 2001; Yuzbashyan, Baytin & Altshuler, 2003; Roman, Sierra & Dukelsky, 2003; Snyman & Geyer, 2006; Sambataro, 2007)

The Richardson model: (static) correlation functions

(A. Faribault, P. Calabrese & J-S C, PRB 2008)

(Following up on ABA work by J. von Delft & R. Poghossian, 2002
and H.-Q. Zhou, J. Links, R. H. McKenzie & M. D. Gould, 2002-3)

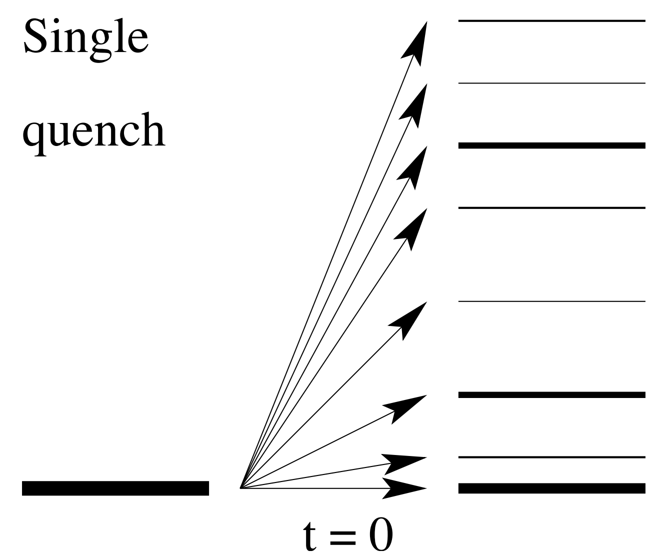
$\langle S_1^- S_\alpha^+ \rangle$ $\langle S_1^z S_\alpha^z \rangle$



Quenches: some trivialities

Sudden change of interaction parameter

(Barouch & McCoy, ..., Calabrese & Cardy, ... Cazalilla, Lamacraft, Klich, Lannert & Refael, ...)



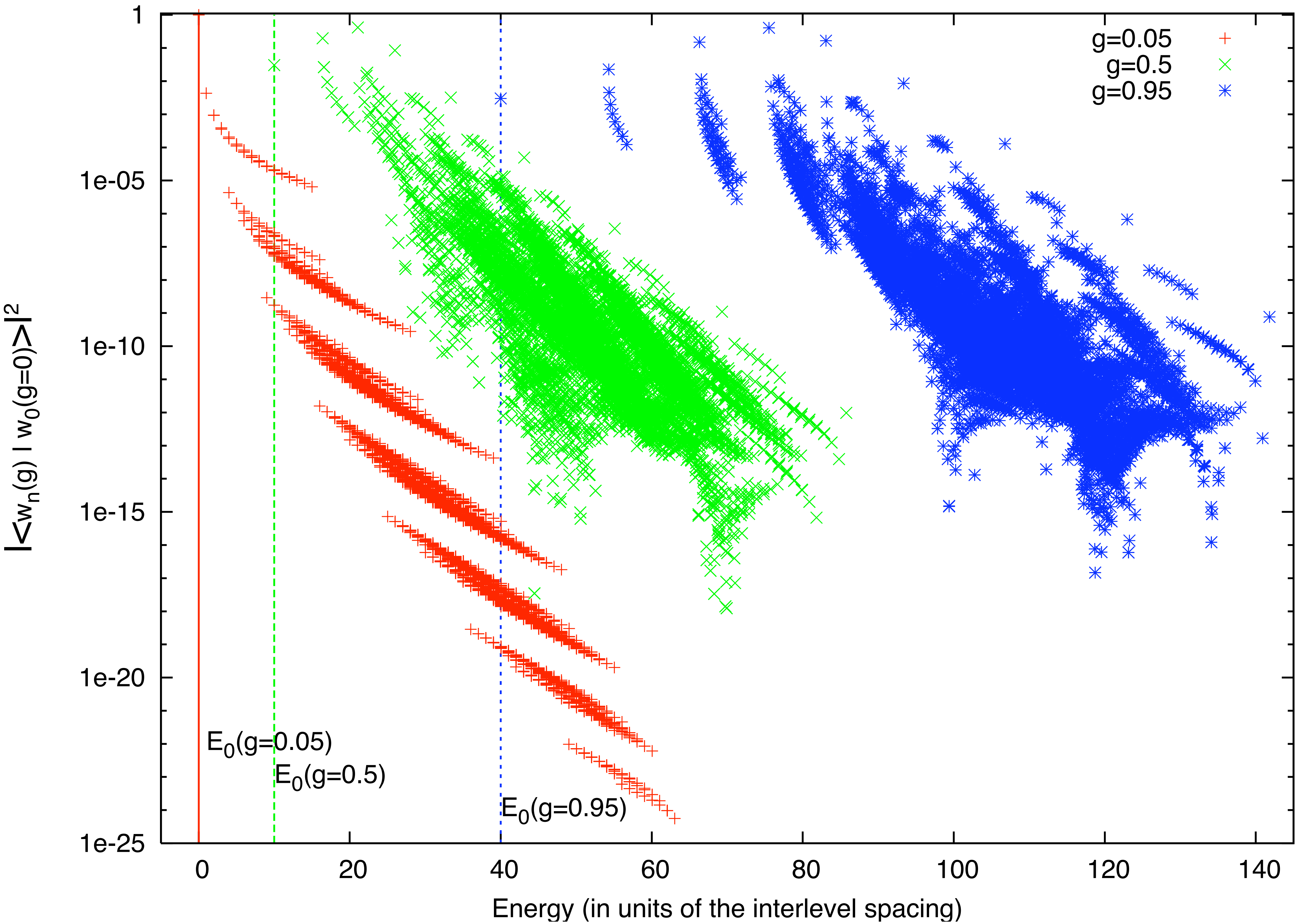
At quench time: $$|\Psi_g^0\rangle = \sum_\alpha |\Psi_{g'}^\alpha\rangle\langle\Psi_{g'}^\alpha|\Psi_g^0\rangle \equiv \sum_\alpha M_{g'g}^{\alpha 0}|\Psi_{g'}^\alpha\rangle$$

Subsequent time evolution: $$|\Psi(t)\rangle = \sum_\alpha M_{g'g}^{\alpha 0} e^{-i\omega_{g'}^\alpha t}|\Psi_{g'}^\alpha\rangle$$

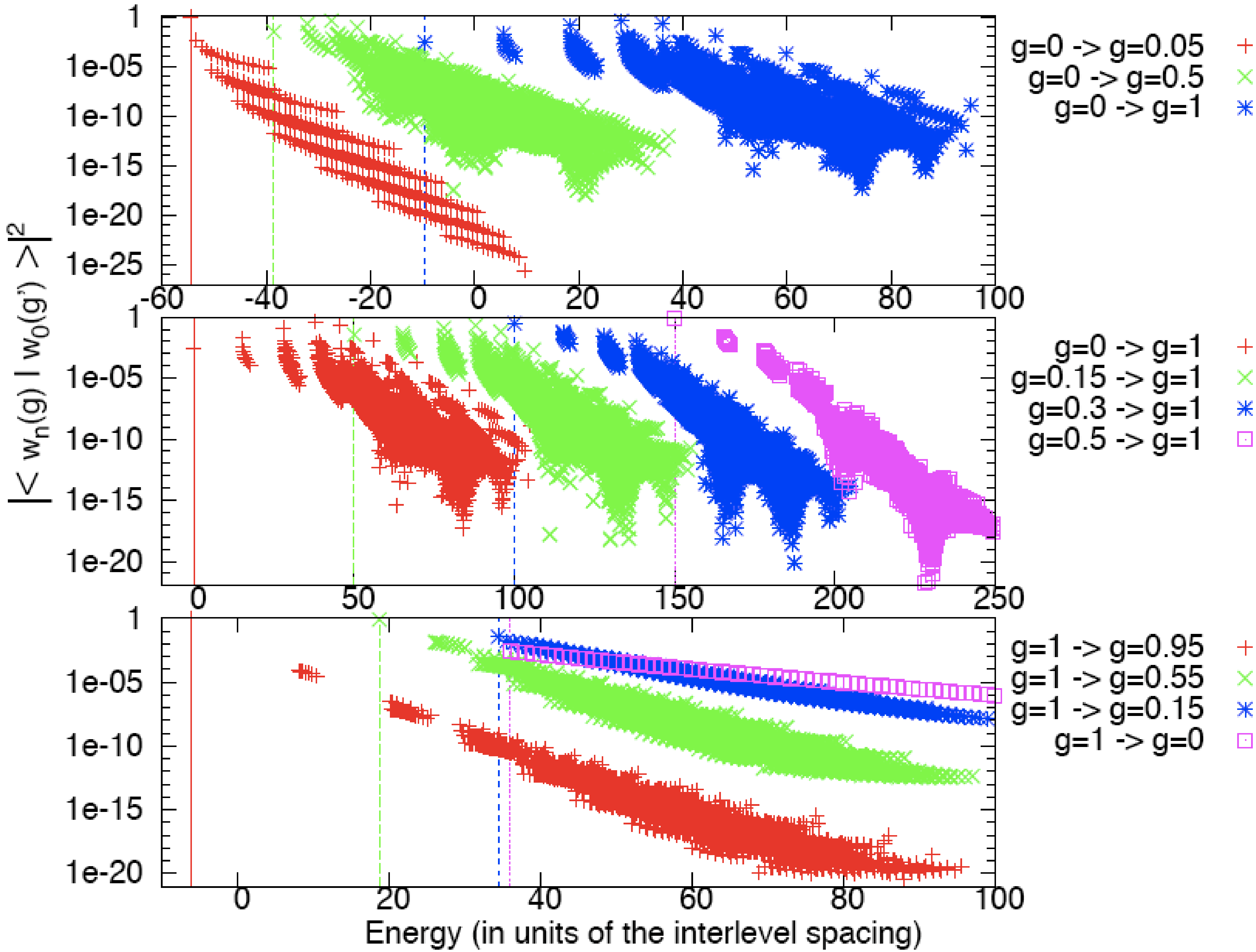
Crucial building block: $$\langle\Psi_{g'}^\alpha|\Psi_g^\beta\rangle \equiv M_{g'g}^{\alpha\beta}$$

We know how to calculate this for Richardson !!

Quench matrix elements

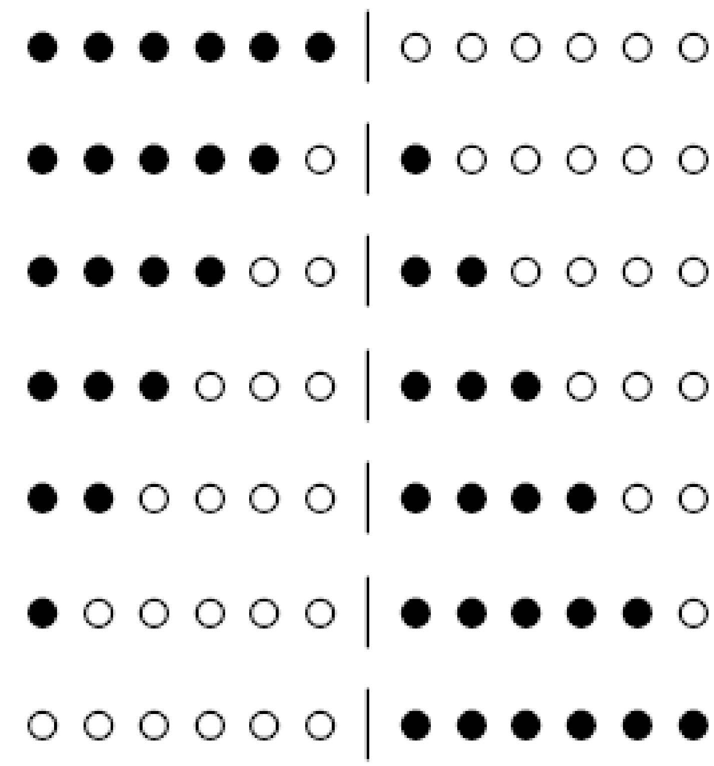


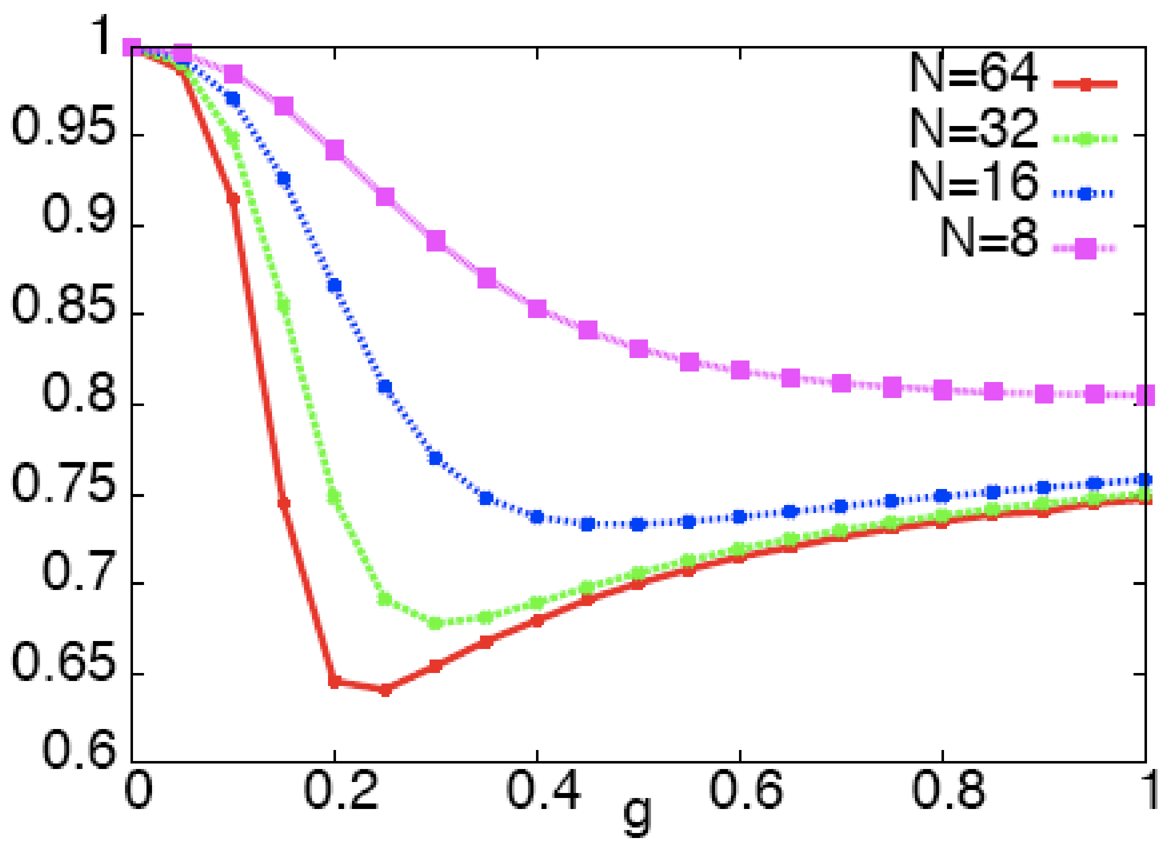
Quench matrix elements



Quench: dominant excitations

Promoting 'blocks' of spins from under to above the Fermi level





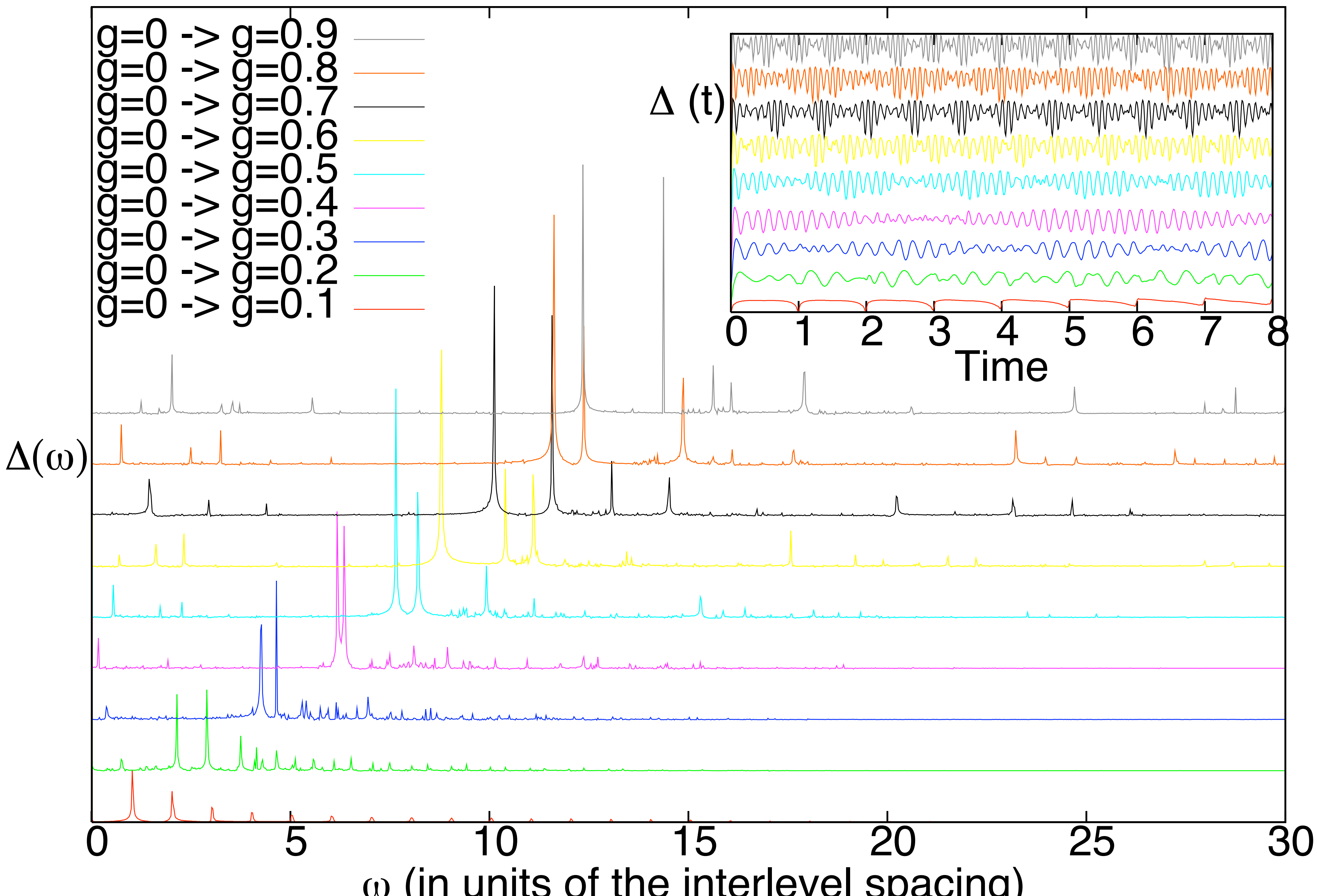
Contribution to square amplitude of resulting state

Importance of states: not same logic as for correlations, but BA basis still pretty good

Time dependence of observables

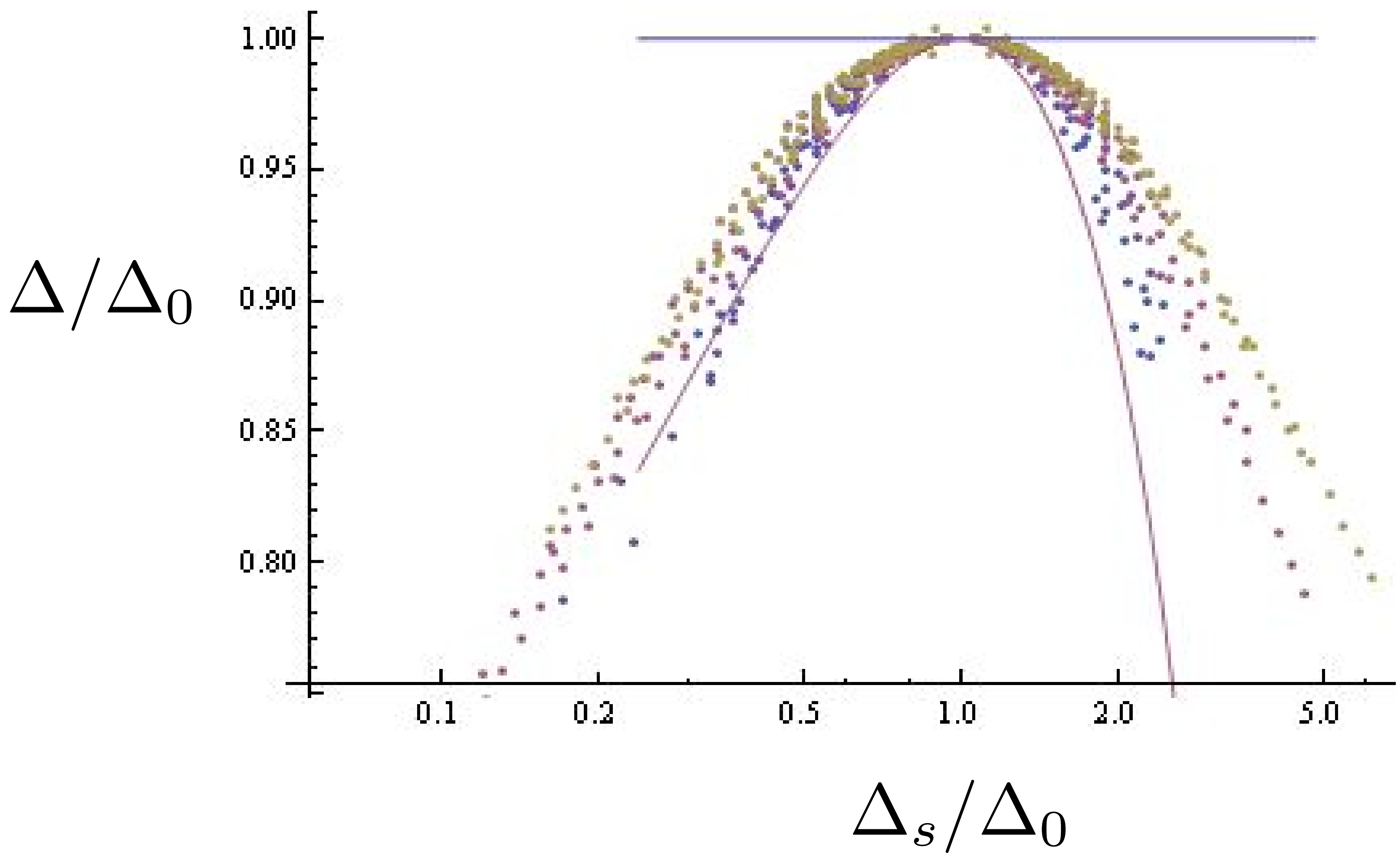
'Canonical order parameter'

$$\Psi(t) = \sum_{\alpha=1}^{N} \sqrt{\frac{1}{4} - \langle S_\alpha^z(t) \rangle^2}$$



Asymptotic pairing order parameter

Plotted against mean-field prediction (Barankov & Levitov, PRL 2006)



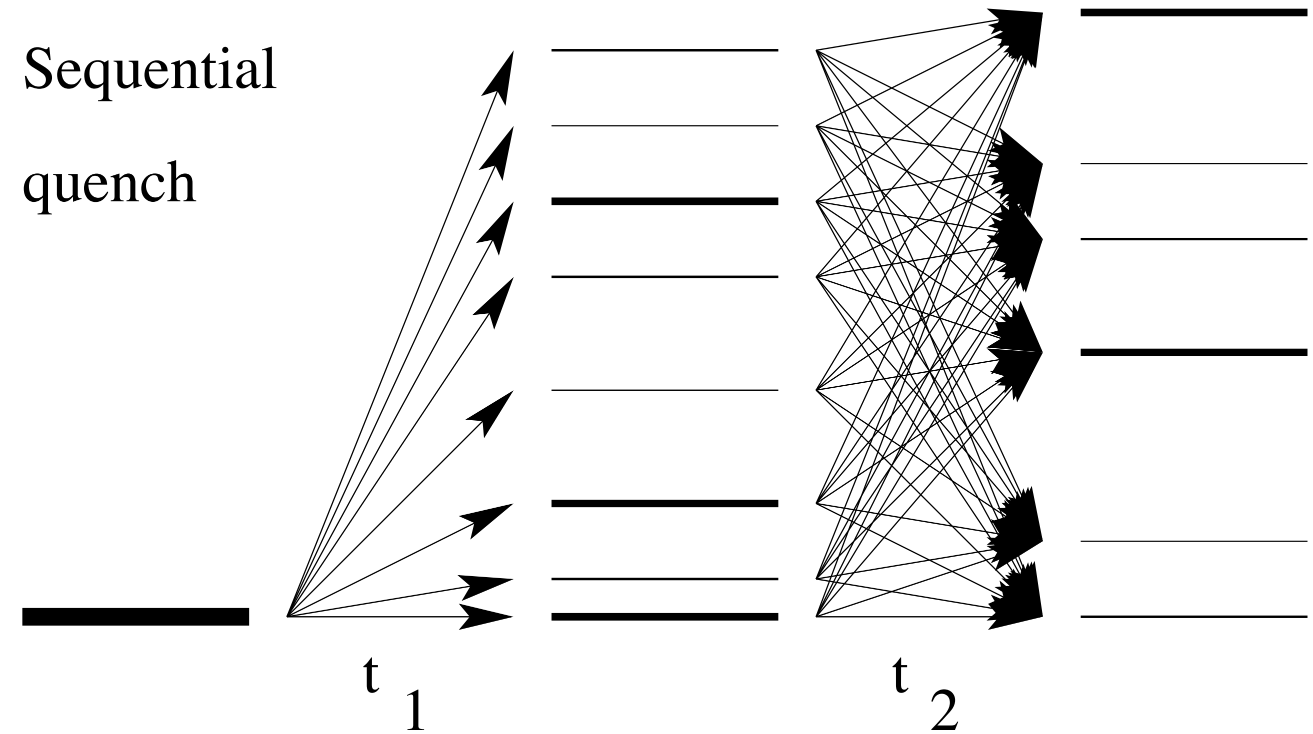
Δ_s BCS gap for initial g

Δ_0 BCS gap for final g

Δ actual OP after quench

Sequential quenches

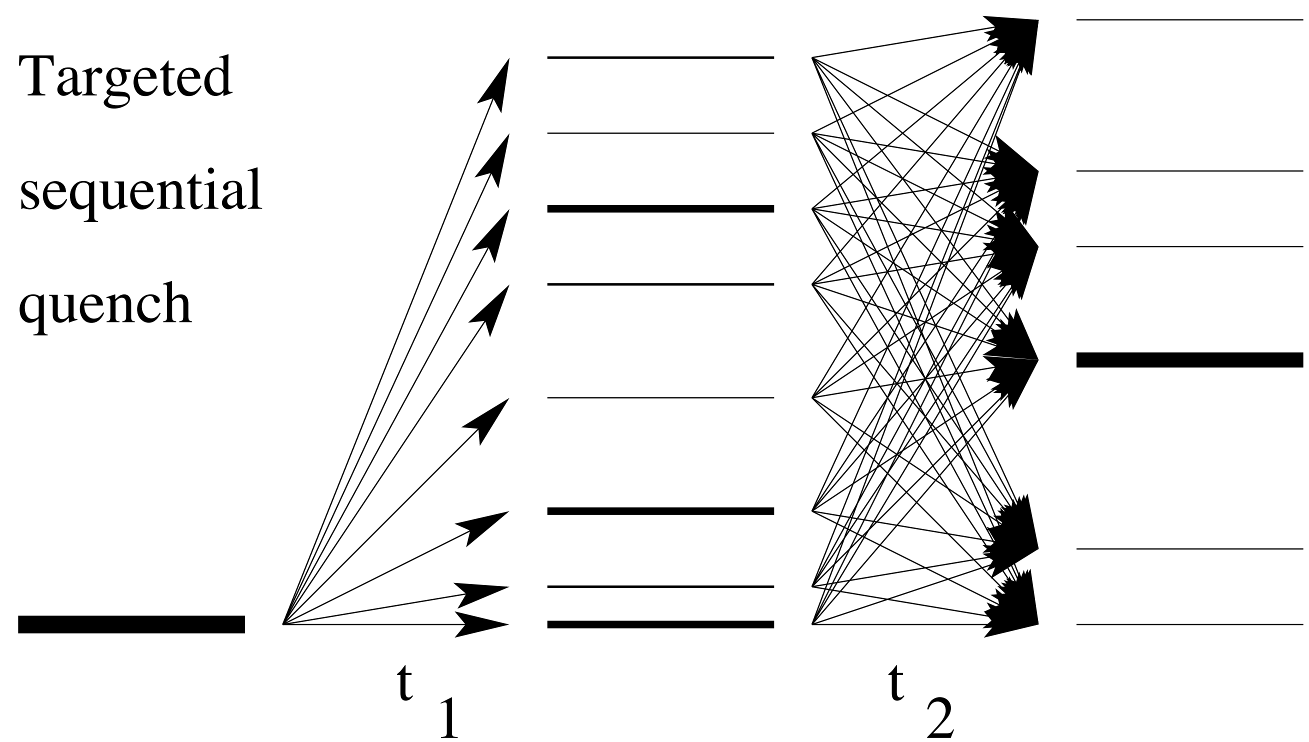
Generic situation, here for 2 quenches:



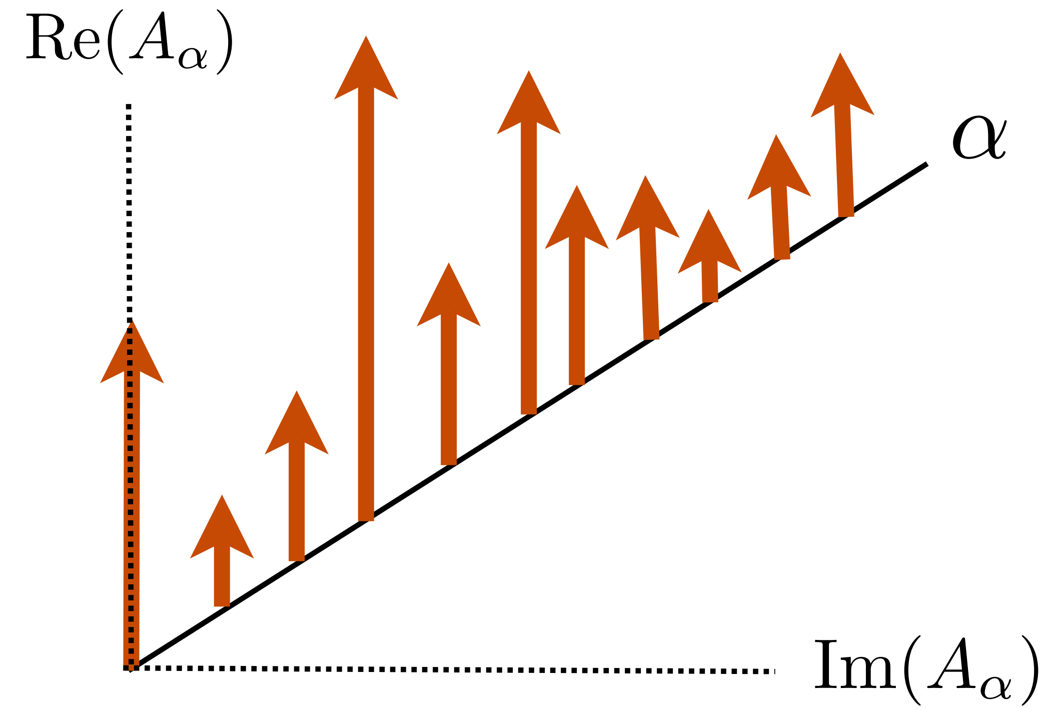
'Quench propagator' for quench-dequench

$$Q_{\beta\alpha}(t_q) = \sum_{\gamma \in \mathcal{H}_{g_1}} M^{\beta\gamma}_{g_0 g_1} M^{\gamma\alpha}_{g_1 g_0} e^{-i\omega_\gamma t_q}$$

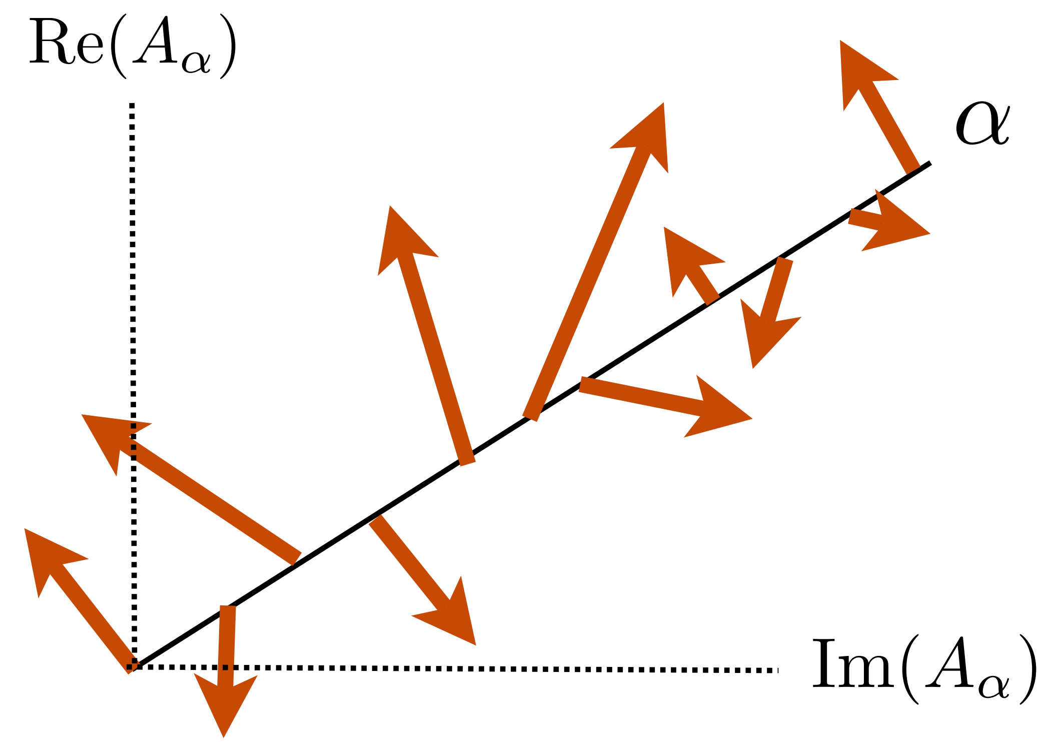
Possible to focus on specific excited states ?



At t = 0, the initial quench populates excited states of H_g



As the quench lasts, each 'arrow' rotates at the appropriate frequency



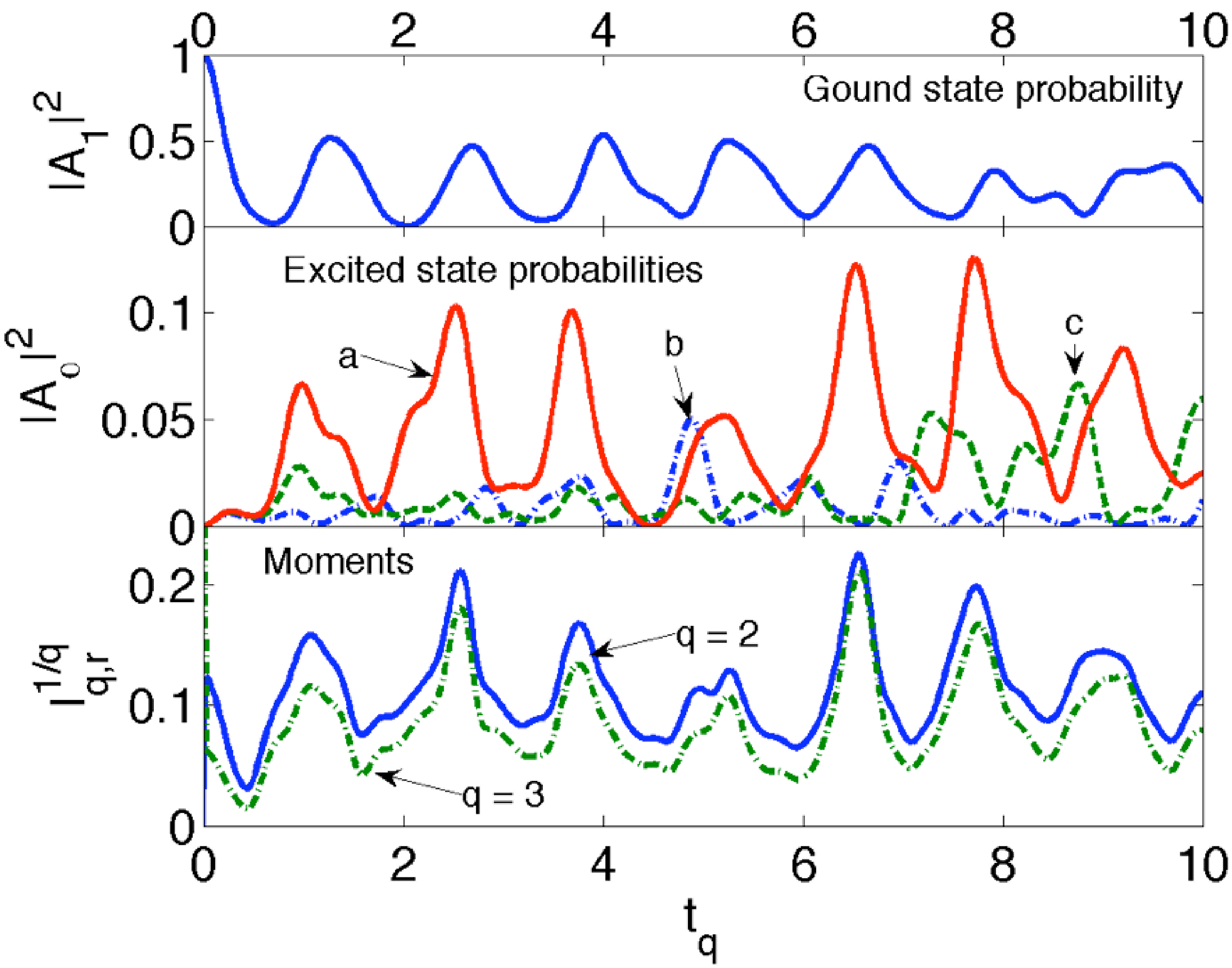
The dequench repopulates states of original Hamiltonian

When arrows 'add up to zero': state destruction

When arrows realign: state reconstruction

State occupation probabilities after double quench (quench-dequench)

Ground state disappears and reappears ('collapse and revival'); excited states nontrivially weighted



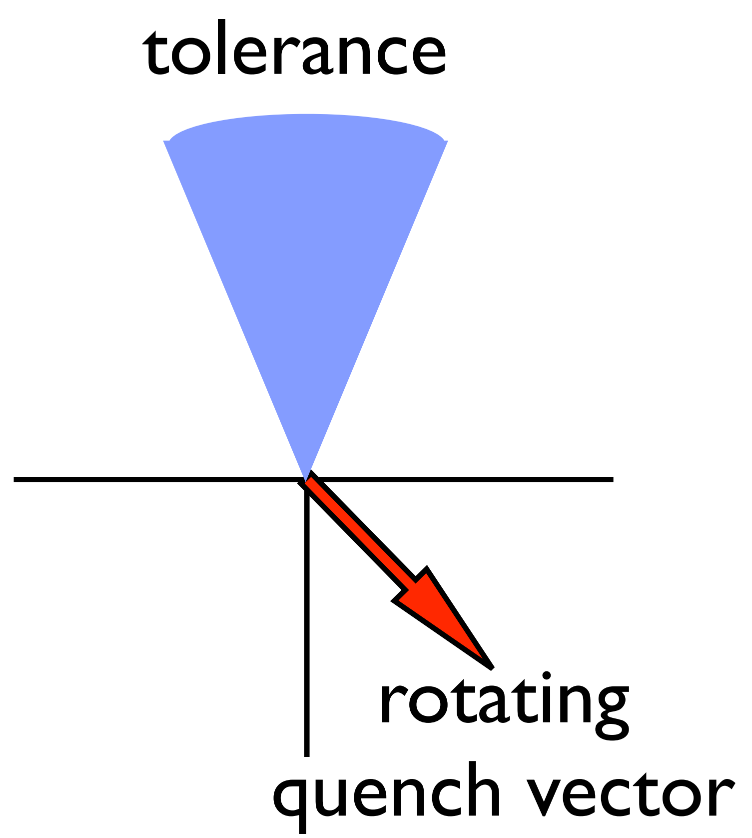
Weight distribution among excited states: look at IPRs

$$I_{q,r} = \sum_{\alpha>0} |A_\alpha|^{2q} / (\sum_{\alpha>0} |A_\alpha|^2)^q$$

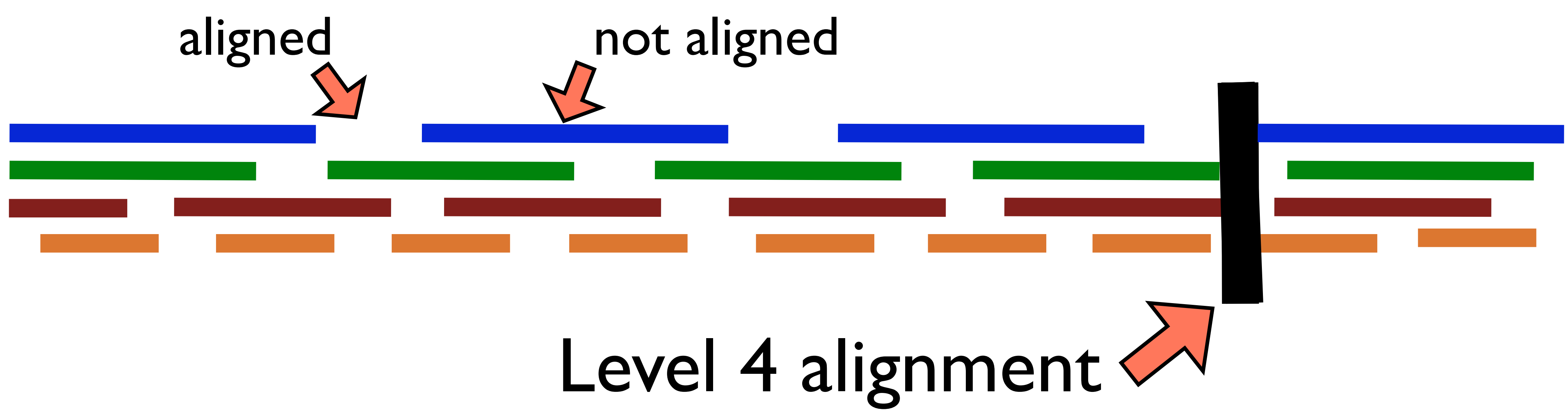
Predicting state occurrences

'Continuous' sieve of Eratosthenes:

- States ordered in decreasing quench weight
- Times kept: such that phases align to a specified tolerance
- High level alignment = constructive interference for that state



Phase timelines: progressively erase non-aligned times



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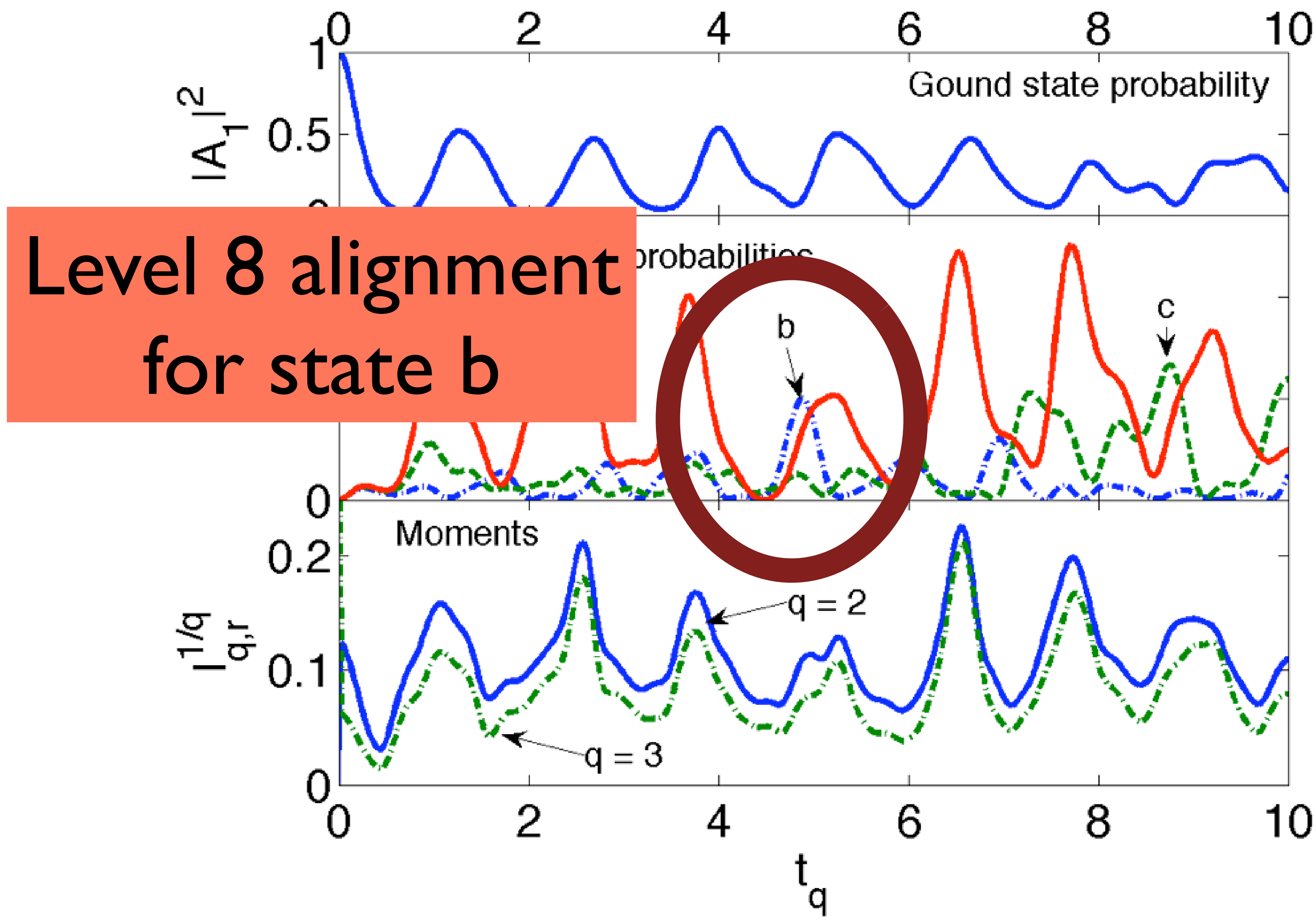

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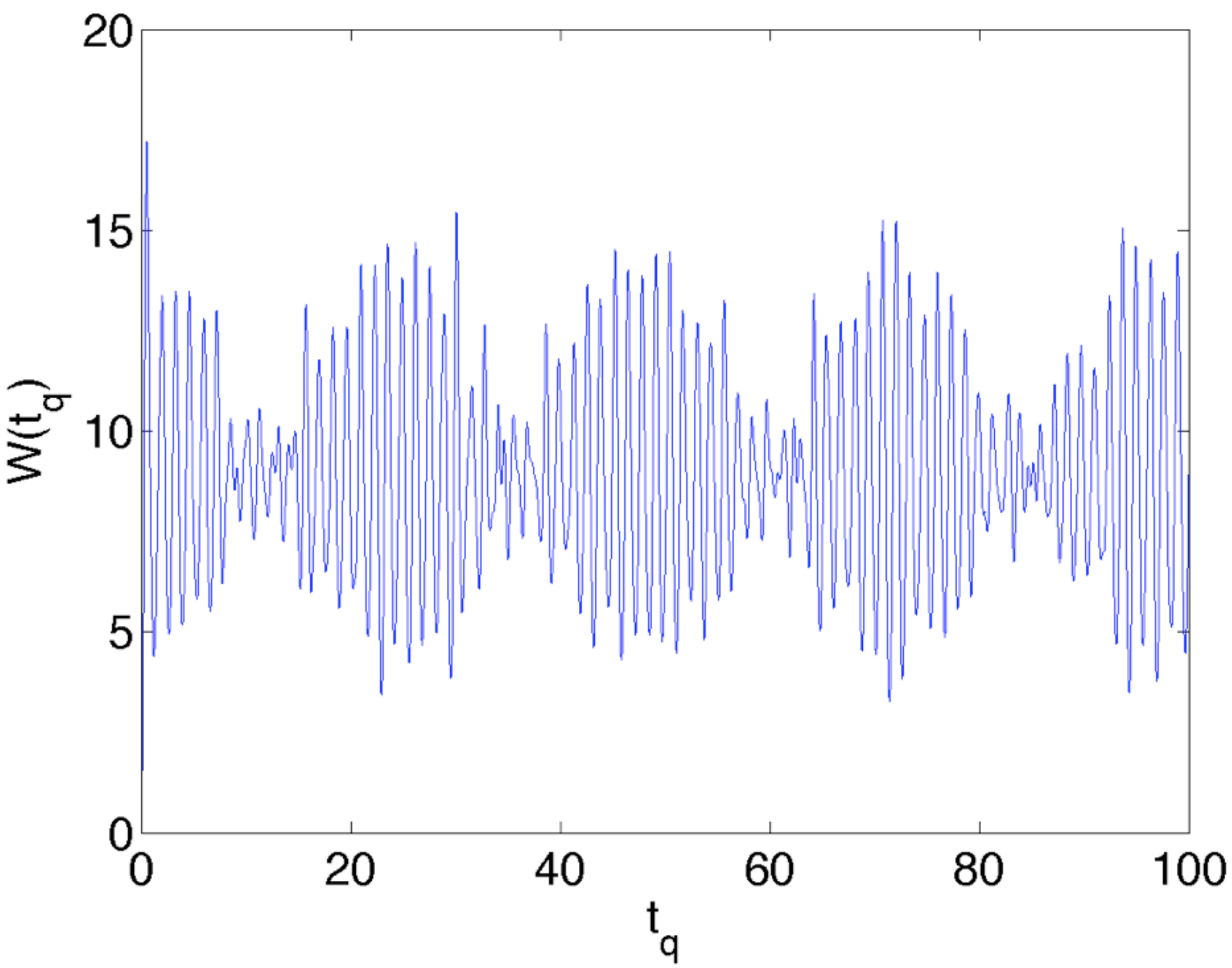
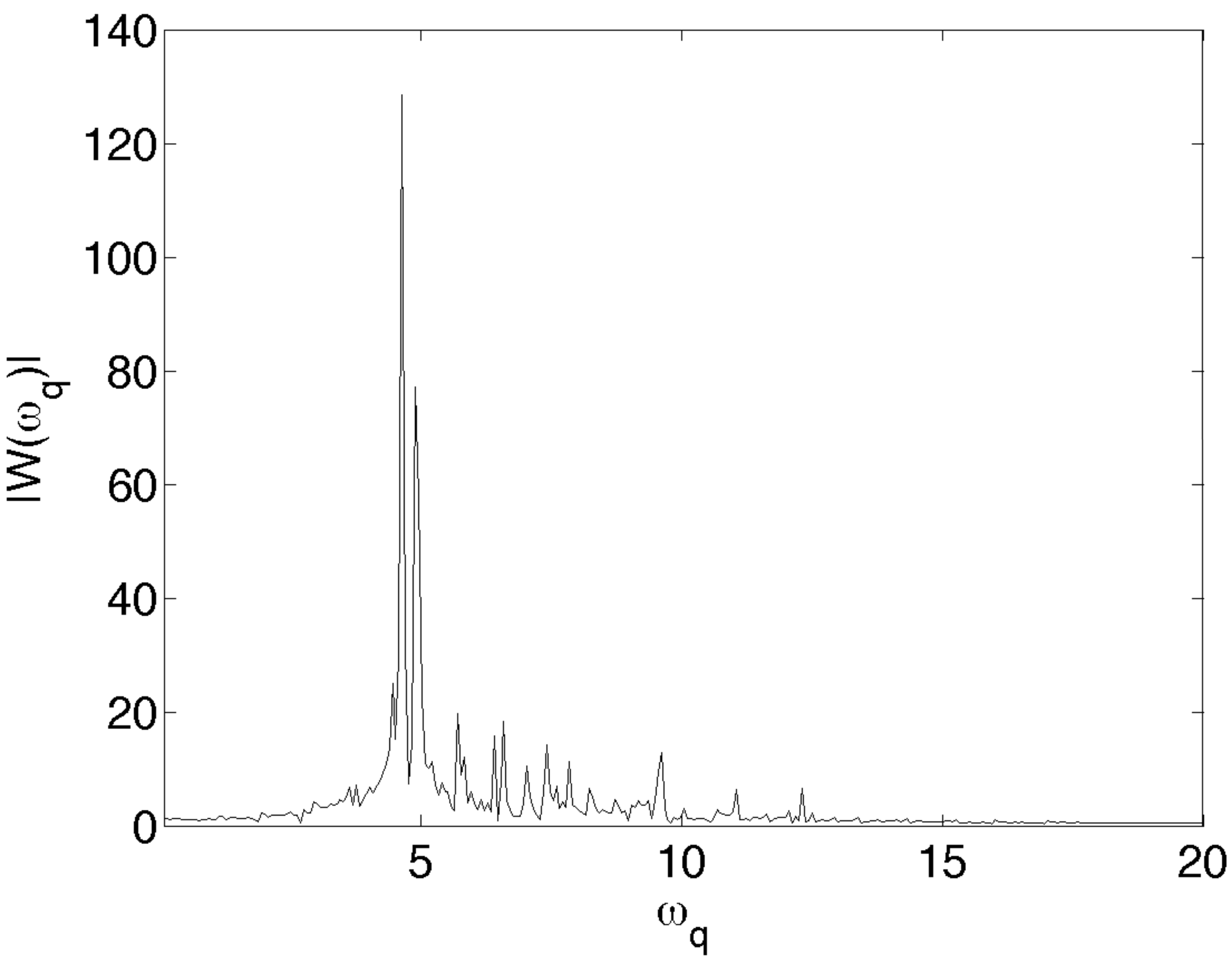
Work and its Fourier transform for quench/ dequench sequence





Conclusions & open problems

- Dynamical correlations in integrable models: now accessible from ABACUS, q groups
- Provides extensive, quantitative predictions for experiments

To do list/work in progress:

- Better classification of solutions to Bethe eqns
- Ferromagnetic spin chains
- Q group approach: other regimes/polarizations
- Finite temperatures
- Nested systems
- Quenches from integrability: other cases
- Non-integrable deformations: RG using integrability (TSA, NRG)

Postdoc positions available !!